

LNF-04/18 (P) 30 Luglio 2004

Papers presented at EPAC 2004

Accelerator Division

Contributions to the 9th European Particle Accelerator Conference (EPAC 2004) 5 to 7 July, 2004 Lucerne – Switzerland

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TOWARDS HIGHER LUMINOSITIES IN B AND PHI FACTORIES

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Abstract

A brief review of the performances of the existing Factories will be presented. Such machines have been proved extremely successful, for both particle and accelerator physics. To further extend their physics reach, several plans are under way to upgrade the existing colliders, in order to increase their luminosity up to an order of magnitude,. Will also be described several new schemes and ideas to realize full "Second Generation Factories" aimed at luminosities two order of magnitude higher then what achieved so far.

INTRODUCTION

The B and Phi factories began operations around 1999. Since then, the B factories (PEPII and KEK-B) have exceeded their design peak luminosity and greatly exceeded the expected integrated luminosity, whereas the DAFNE phi factory is still about a factor 5 below the design peak and total integrated luminosity. However it has to be pointed out that this is the only factory with two possible interaction regions, and already 3 different experiments have taken data. In particular the integrated luminosity requirement for DEAR [1] and FINUDA [2] have been met and these experiments have successfully completed their data taking. In Fig.1 is shown the luminosity history for the 3 factories.



Peak DAFNE Luminosity, red:KLOE, blue:DEAR, green:FINUDA







Fig. 2: Luminosity vs energy for "standard" colliders, factories and target for super-factories (red)

Five years of operations have proved extremely useful to understand all the important parameters to reach high luminosities. The accelerators have evolved through this period and have several significative differences with respect to the original design. The current parameters list is shown in tab.1. The acquired experience and know-how is driving all the near future upgrades and the design of the next generation factories.

Tab.1: Parameters set for the factories

	PEP-II	KEK	DAFNE	
LER energy	3.	3.5	0.51	GeV
HER energy	9.0	8.0	0.51	GeV
LER current	2.4	1.6	1.1	А
HER current	1.6	1.2	1.1	А
β _y *	10.0	6.5	27	mm
β_x^*	25	60	250	cm
X emittance	50	20	600	nm-rad
Estimated σ_y^*	5.0	2.2	6.0	μm
Bunch spacing	1.26	2.4	1.6	m
Number of bunches	s 1317	1284	50	
Collision angle	0	22	24	mrads
Luminosity $9.2 \times 10^{33} 13.9 \times 10^{33} 7.5 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$				

BEAM SIZES DECREASE

As shown in tab.1, KEK has been able to reach an higher luminosity with less beam current, thanks to a smaller β_y at the IP and a better coupling correction. During the years, all the machines have constantly improved the specific luminosity with an "adiabatic" reduction of β_y and vertical emittance.

The need to further decrease the vertical beam size and the effect of the parasitic crossings has driven a redesign of the interaction regions. Tab.2 shows the new parameters set for PEP-II and DAFNE.

PEP-II maintains the head-on collision scheme to avoid the luminosity reduction due to the crossing angle, that has been estimated to be about 40% for a 6mrad crossing angle. The main differences are in an increased separation at the first parasitic crossing thanks to the stronger IR bend and a lower β_y thanks to a stronger IR QD. The new design is still under study and should be implemented around year 2006 [3].

DAFNE goes from a QF-QD-QF triplet configuration to a more standard QD-QF. This allows a simultaneous reduction of β_x , β_y and the vertical chromaticity, together with an increase of the crossing angle. The effect of the parasitic crossings is greatly reduced, thus allowing for doubling the number of bunches. The price to pay is an increased luminosity reduction (of about 20%) due to the higher crossing angle. The new IR is already installed and operations with 100 bunches have just started last May

Tab.2: Parameters set for the short-term upgrades

	PEP-II	DAFN	E
LER energy	3.	0.51	GeV
HER energy	9.0	0.51	GeV
LER current >	3.6	1.5	А
HER current >	2.0	1.5	А
$\beta_y^* <$	7.0	19	mm
β_x^*	25	130	cm
X emittance	40	380	nm-rad
$\sigma_y^* <$	2.6	5.0	μm
Bunch spacing	1.26	0.8	m
Number of bunche	s 1700	100	
Collision angle	0	32	mrads
Luminosity>	30×10 ³³	$1.5*10^{32}$	$cm^{-2} sec^{-1}$

BEAM CURRENT GROWTH

The increase of the beam currents while preserving as much as possible the "low current" beam parameters and acceptable background level in the detectors has been very impressive.

The RF system plays an important rule for the high current and all the B-factories have upgraded the RF power the controls and the RF feedbacks several times. More RF stations will be installed in the near future to meet the higher currents goals The DAFNE RF system has been already dimensioned for currents above 3Amps and does not need any upgrade.

The requirements for the longitudinal and the transverse feedbacks becomes more and more demanding, in particular for DAFNE that now has the smaller bunch spacing and the smaller beam stiffness due to the lower operating energy.

The Electron Cloud Instability for the B-factories positron rings has been successfully damped with added solenoids. This instability has not been seen so far in DAFNE.

The collimation system has been upgraded as well with more and more collimators added in all the factories, several modifications have been implemented in the new IRs in order to further reduce the background from SR, vacuum scattering and Touschek (in DAFNE). So far the background requirements from the experiments have always been met, but it will be harder has the currents increase and the beam lifetimes decrease.

BUNCH LENGTH SHORTENING

The bunch length does not appear naturally in the luminosity equation, however since the machines do mostly operate in a vertical beam-beam limited regime, the luminosity is inversely proportional to the β_v . The minimum value for β_v is equal to the bunch length, for smaller values the hourglass effect causes a big loss in luminosity. Additional luminosity reduction comes from the crossing angle, that introduces synchro-betatron coupling and an additional increase of the horizontal size, since the projected beam size along the interaction region will be larger (Piwinski angle > 0). Finally the beambeam effects in the vertical plane are enlarged by the crossing angle together with a finite bunch length. All these combined effects make the luminosity decrease faster then $1/\sigma_{z}$.

The current β_v for PEPII and KEKB are getting closer and closer to the bunch lengths, although the hourglass limit will not be exceeded in the mid-term upgrades. In DAFNE the limit has been already reached, since the microwave instability appears at very low bunch charge. At the operating currents the bunch is about 27mm long, causing a severe limit in the attainable luminosity. In this regime the RF voltage is a very weak parameter to squeeze to bunch. A possible solution to such problem is to change sign to the ring momentum compaction α_c . If α_c <0 the longitudinal wake field becomes focusing reducing the bunch length a low current. At higher currents it becomes overfocusing and the bunch starts to grow again. The bunch shape changes as well from a more rectangular shape to a triangular like. In DAFNE a lattice with a negative α_c has been already tested and it has been observed a bunch length decrease up to a factor 2 as shown in fig. 2, leading to a potential correspondent gain



in luminosity. Tests with colliding beams will be

performed in the next few months.

Fig.2: DAFNE bunch length vs current with positive and negative momentum compaction α_c for the electron ring

NEXT GENERATION FACTORIES

The next generation factories designs aim to a luminosity of the order of 10^{36} for the B factories and 10^{34} for the phi. These projects are targeted to begin operations around 2011 [3] [4] [5].

	Tab.3: 1	Parameters	set for	super	facto	ries
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	PEP-II	KEK	DAFNE	
LER energy	3.	3.5	0.51	GeV
HER energy	9.7	8.0	0.51	GeV
LER current	22.0	9.0	3.5	А
HER current	10.1	4.1	3.5	А
β _y *	1.5	3.0	2.5	mm
β_x^*	15	20	30	cm
X emittance	79	18	260	nm-rad
Estimated σ_y^*	1.1	0.7	1.6	μm
Bunch spacing	0.5	0.6	0.5	m
Number of bunche	es 6900	5000	150	
Collision angle	30	30	30	mrads
Luminosity >	1.0×10^{36}	0.5×10^{30}	6 1.0 ³⁴ cr	$n^{-2} \text{ sec}^{-1}$

Tab.3 shows a parameter list for such machines. Some of their most important characteristic are listed below.

Very short lifetimes (few minutes), so the injection has to be as continuos as possible.

Very small β_v^* (<2mm), this will require very strong IR

quadrupoles, probably superconducting and possibly a dedicated chromaticity correction to preserve a good dynamic aperture.

Very small bunch lengths (<2mm) and high currents (>10Amps), demand very powerful RF systems, for example SUPER-KEKB plans for more than double the

RF stations with respect to KEKB. Bellows, pumps and vacuum chamber are being redesigned, to reduce as much as possible higher order modes, resistive walls, electron clouds and to handle the higher synchrotron radiation flux.



Fig. 3:Schematic view of a vacumm chamber with antichamber and simulation of the electron cloud with (a) and without (b) anti-chamber.

Higher RF frequency to increase the number of bunches is considered for all the upgrades.

Damping rates of the bunch by bunch feedbacks have to be decreased and their frequency response improved to meet the shorter bunch spacing. New designs are currently under study.

Crab cavities to reduce the luminosity loss due to the crossing angle will be necessary, a first cavity that will make the beam to crab all along the ring, will be soon installed at KEKB.

Arc lattices have designs very similar to the present ones and allow to reuse a lot of the existing magnets. Fig.4 shows the non-interleaved 2.5-pi cell adopted by SUPER-KEKB, that has a wide tunability of all the critical parameters, togheter with a large dynamic aperture, thanks to the paired sextupoles.

The phi factory design presents additional challenges, due to the lower operating energy; the damping time has to be reduced as much as possible and the tousheck lifetime has to be maximized

The lattice proposed for DAFNE [5] is shown in fig.5. It provides high radiation damping since the paired positive and negative bending. The dispersion is maximum for both the high β_x and β_y points, ensuring a good chromatic correction. A most important feature is that it naturally generates a very high negative momentum compation, such that the microwave instability threshold occurs at a much higher single bunch currents (>10mAmps). Moreover with a big RF voltage, the longitudinal tune can be made very high (120-150 degrees), in such condition the bunch length along the ring varies (fig.6) allowing very short bunches at the IP

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and much longer bunches in the more harmful locations, like RF cavities and kickers [6] .

Finally it has to be pointed out that all the new designs tend to maintain the same footprint of the current accelerators, mainly to reduce costs and time necessary for the installation, with the exception of a possible positron damping ring for SUPER-KEKB.



Fig. 4: Super-KEKB Arc Optic functions



Fig. 5a: Particular of the Super-DAFNE Arc and Super-DAFNE layout



Fig. 5b: Super-DAFNE Arc Optic functions



Fig. 6: Bunch length along the Super-DAFNE ring for V_{rf} =10MV, α_c =-0.16, v_{rf} = 503MHz

CONCLUSIONS

The factories have so far met and exceeded the design luminosity with exception of DAFNE that had an even more ambitious target, considering the lower energy and smaller ring.

Almost 5 years of experience proved that was much easier, although not without hard work, to bring the IP sizes way below the original design values than to bring the ring currents up to the specs. This last point has been very challenging and a lot of different problems have been met and solved to reach the present very high currents. Therefore this will be the most important key for the super-factories that require an increase of about a factor 5-10 in the operating currents, with a lot of foreseen and unknown problems to be faced.

The currently operating factories are still providing useful data for particle physics and are constantly stimulating the accelerators physicist to go further beyond in exploiting as much as possible the potential of the existing machines. The physics community is looking forward with great expectations for the next step, that should provide useful physics in the low and mid energy range for the next decade.

- C. Guaraldo et al., "First results on kaonic hydrogen from DEAR at DAFNE, Proc. Of the 4th Int. Conf. On Perspectives in Hadronic Physics, Trieste, Italy, May 2003
- [2] M. Agnello et al., "Preliminary results of the FINUDA experiment at DAFNE", XLII Inernational Winter Meeting, Bormio, Italy, Jan 2004
- [3] J. Seeman, "Accelerator plans at SLAC", SUPERB-Factory workshop, Hawaii 2004
- [4] J. Flanagan, "Accelerator plans at KEK", SUPERB-Factory workshop, Hawaii 2004
- [5] C. Biscari et al.,"Feasibility study for a very high luminosity phi-factory",EPAC04, Lucerne 2004
- [6] A. Gallo et al., "Proposal of a strong RF focusing experiment at DAFNE", EPAC04, Lucerne 2004

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DA Φ NE OPERATION WITH THE FINUDA EXPERIMENT

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Abstract

DA Φ NE operation restarted in September 2003, after a six months shut-down for the installation of FINUDA, a magnetic detector dedicated to the study of hypernuclear physics. FINUDA is the third experiment running on DA Φ NE and operates while keeping on place the other detector KLOE. During the shut-down both Interaction Regions have been equipped with remotely controlled rotating quadrupoles in order to operate at different solenoid fields. Among many other hardware upgrades one of the most significant is the reshaping of the wiggler pole profile to improve the field quality and the machine dynamic aperture. Commissioning of the collider in the new configuration has been completed in short time. The peak luminosity delivered to FINUDA has reached 6 10^{31} s⁻¹ cm⁻², with a daily integrated value close to 4 pb⁻¹.

INTRODUCTION

DA Φ NE is the Frascati electron-positron collider running at the energy of the Φ resonance [1]. It is based on two independent rings merging in two straight sections the Interaction Regions (IR) and on an injection system including a Linac, an intermediate damping ring and 180 meter long transfer lines joining the different accelerators.

The KLOE detector is permanently installed in IR1, while the DEAR and FINUDA experiments can be placed, one at a time, in IR2. The KLOE experiment studies CP violation in kaon decays and DEAR investigates exotic atoms.

The FINUDA experiment [2] consists in a magnetic spectrometer designed for the study of hypernuclear spectroscopy. With its cylindrical geometry around the collider interaction point (IP), it represents a relevant novelty element with respect to the existing experiments relying on fixed target setups. In fact, being a 2π detector, FINUDA can observe both the particles emitted in the hypernucleus formation and in its decay and provides a larger acceptance since the kaons are emitted isotropically. Moreover, the low energy DA Φ NE kaons can be stopped in thinner targets, thus improving the resolution in the hypernuclear level measurements.

LAYOUT EVOLUTION

A top luminosity of $\approx 7.5 \ 10^{31} \ \text{cm}^{-2} \ \text{s}^{-1}$ was reached during the year 2002. To go further towards luminosities beyond of $10^{32} \ \text{cm}^{-2} \ \text{s}^{-1}$ it was necessary to undertake major upgrades in the collider. The magnetic layout of

the DA Φ NE rings has been deeply reorganized, new IRs and the FINUDA detector have been installed. The straight sections used for injection have been disassembled and completely rearranged by adding a new sextupole and two quadrupoles and removing one out of the 3 injection kickers, which was not used. All the wigglers have been modified by changing their pole profile.

Interaction Regions

The KLOE IR has been rebuilt relying on the experience gathered during the runs for the DEAR experiment, where it was possible to let 100 consecutive bunches collide, while keeping the β_v^* low at the hourglass limit. The permanent magnet quadrupole triplets have been substituted with doublet ones; the inner quadrupoles, the closest to the interaction point (IP), have been removed and the outer ones have been strengthened, going from a FDF configuration to a DF one. All the quadrupoles have been equipped with independently rotating supports in order to improve the coupling correction efficiency and the ring flexibility. In this way it is possible to set the quadrupole rotation for arbitrary values of the KLOE solenoidal field. Printed circuit quadrupoles have been added around the IP for diagnostic purposes. The thin vacuum chamber has been substituted with a new one in beryllium alloy (ALBeMet) suitable for the new element configuration.

The FINUDA IR relays on four permanent magnet quadrupoles placed inside the FINUDA 1.1 T solenoidal field and on four conventional quadrupoles installed outside it. The new feature allowing quadrupole rotation has been integrated in the FINUDA IR original design; all the permanent quadrupoles can rotate independently within a range of 135 degrees and the conventional ones within 23 degrees. This mechanical solution allows for a wide operation flexibility, ranging from the low- β configuration suitable for collisions to the high- β one required for an efficient beam separation. Operation with the solenoid off is also possible.

Wiggler upgrade

Beam measurements performed during 2002 pointed out relevant nonlinear terms in the wigglers. Simulations confirmed that such terms reduce the dynamic aperture and the beam lifetime, affecting beam-beam behaviour and beam dynamics. All these features led to a significant luminosity limitation. The upgraded wigglers showed a significant reduction of the 2^{nd} and 3^{rd} order terms in the field, around the wiggling trajectory, the latter being responsible for the quadratic behaviour of the horizontal betatron tune versus beam displacement in the wiggler.

Tests with the beams confirmed the reduction of the non-linear terms, as well as an improvement by a factor 2 in the dynamic aperture and in the energy acceptance (see Fig. 1).



Figure 1: Tune shift dependence on energy measured in the positron ring before and after the wiggler upgrade.

HARDWARE MAINTENANCE AND UPGRADE

During the shut-down all the collider hardware components have been carefully checked and maintained, substituted and upgraded where necessary.

Half of the ion clearing electrodes, which cope with ion induced instability in the electron ring, have been substituted with welding-free devices.

In DA Φ NE tungsten scrapers are used to reduce background showers on the detectors. The scrapers are tapered by means of thin copper shields to avoid detrimental effects on the overall impedance. These shields have been modified because they were intercepting the beam. The tapers on the horizontal scrapers have been removed while the vertical ones have been properly adjusted. Some damaged bellows have been substituted and their structure reinforced by means of pin insertion.

The strip-lines used to measure the beam position along the Transfer Lines have been equipped with new electronics in order to improve the trajectory control and to speed up the injection process. For the same reason the Linac 50 Hz operation mode has been implemented: it is now possible to inject both beams at 50 Hz in the damping ring and at 2 Hz in the Main Rings.

TUNING THE NEW DAΦNE CONFIGURATION

Model

All the modifications in the DA Φ NE layout have been included in the machine model. Special care has been devoted to the new wiggler model [4] which has been described as a sequence of 2 m long hard edge dipoles and straight sections representing the linear part of the beam motion. The non-linear terms have been introduced by adding at both pole sides higher order multipoles. All the physical parameters have been derived from the vertical component of the magnetic field in the horizontal midplane, measured on a spare modified wiggler.

It is worth reminding that the new KLOE IR gives a smaller contribution to the main rings natural chromaticity, which, due to the focusing sextupole in the wigglers, is almost zero in the horizontal plane.

The new DA Φ NE model [5] has been validated by comparing its predictions with the beam measurements. Simulations and experimental data are in satisfactory agreement both for the linear part (betatron function, betatron tunes and dispersion function) and for the nonlinear one (second order dispersion, second order chromaticity and tune shift on amplitude).



Figure 2: $DA\Phi NE$ model compared with beam measurements – up: first order and second order dispersion; down: beta functions.

$DA\Phi NE$ Optics for collision at FINUDA IP

To perform collisions at the FINUDA IP, the KLOE solenoidal field (Bdl = 2.4 Tm) is off since it represents a huge perturbation with respect to the ring magnetic structure (B ρ = 1.7 Tm).

A new optics for this operation mode has been designed. The horizontal beam emittance has been reduced by 44%, becoming $\varepsilon_x = .34 \mu m$, allowing for a separation of ~ 13 σ_x at the first parasitic crossing, 0.4 m from the IP. In fact, in order to achieve collisions with 100 consecutive bunches, it is mandatory to reduce the parasitic crossings.

The dynamic aperture has been improved by optimizing the relative phase advance between sextupoles in their new configuration. The betatron functions at the IP have been set to $\beta_x^* = 2.33$ m, a reasonable trade off between the need to keep β_x low at the IP and at the first parasitic crossing, and $\beta_v^* = .024$ m, compatible with the limit imposed by the hourglass effect. The horizontal crossing angle at the IP has been set to $\theta_x = .021$ rad in order to reduce background on the detector.

With these parameters the Piwinski angle is $\phi = .29$ similar to the values already used in the past.

Coupling correction

A local betatron coupling correction has been implemented. The coupling terms from the measured Response Matrix for the two rings (C matrix) have been minimized by means of the 8 permanent quadrupoles rotations in the two IRs ($\Delta \phi$ array), using the M matrix computed from the machine model and describing the coupling terms as a function of the IR quadrupole rotation [6]. The linear equation system:

$$M\Delta\phi = C$$

has been solved by using the singular value decomposition method, and, after few iterations, the rms value of the coupling terms has been reduced by 40%.

The fine betatron coupling correction has been obtained, as usual, using skew quadrupoles achieving a final coupling $\kappa = .3\%$.

HIGH CURRENT ISSUES

The DAFNE rings are equipped with transverse and longitudinal feedbacks to cope with the effects of coupled-bunch instabilities. After the DA Φ NE upgrade all the feedbacks have been carefully tuned, especially the horizontal one whose power amplifiers have been improved [7].

Despite the relevant evolution, the ring impedance, obtained from the bunch length measurements has turned out to be almost unchanged (see Fig. 3) [8], yielding a reasonable indication for an unaffected beam instability scenario.



Figure 3: Bunch length measurements and theoretical predictions as a function of the bunch current for the positron ring.

Hundred bunches per beam have been routinely put in collision, with maximum colliding currents: $I^+ = .8 A$, I = 1.1 A. A positron current threshold has been observed at start-up and cured by a careful feedback systems tuning.

LUMINOSITY

In a short time $DA\Phi NE$ luminosity has reached performances comparable to the best obtained in 2002, delivering to FINUDA a peak luminosity, $L_{peck} = 0.6 \ 10^{32}$ $cm^{-2}s^{-1}$ and a total integrated luminosity close to $L_{int} = 256$ pb⁻¹ with excellent background rates.

Peak luminosity was mainly limited by the residual parasitic crossing in the KLOE IR, where the two beams cannot be efficiently separated in the vertical plane due to the presence of the permanent magnet quads.



Figure 4: Daily integrated luminosity during the FINUDA runs.

CONCLUSIONS

The DA Φ NE collider has been successfully commissioned after a major upgrade. During this period all the efforts have been addressed to check the effectiveness of the changes, and to improve the collider performances. The FINUDA experiment has completed the first stage of its scientific program and data analysis is under way.

Presently DA Φ NE has restarted operation for the KLOE experiment and has reached a peak luminosity $L_{peck} = 0.85 \ 10^{32} \ cm^{-2} s^{-1}$ and currents exceeding 1.1 A in both beams have been stored in collision.

- [1] G. Vignola, The DAΦNE Project Team, "DAΦNE: the Frascati Phi-Factory", PAC'91, San Francisco. C. Milardi et al., "Status of DAFNE", Frascati Phys. Ser.
 - 16: 75-84, 1999.
- [2] A. Zenoni et al., "First results in hypernuclear weak decay in FINUDA", proceedings of the VIII International Conference on Hypernuclear and Strange Particle Physics, TJNL, Oct 2003, to be published.
- M. Preger et al., "The Modified Wiggler of the DAΦNE Main Rings", DAΦNE Technical note, MM-34, January [3] 2004
- G. Benedetti et al., "Hard-Edge Model of the DAΦNE Wigglers", DAΦNE Technical note, L-35, March 2004. [4]
- [5] C. Milardi et al., "Developments in Linear and Non-Linear DAΦNE Lattice", PAC 2003, Portland.
 [6] C. Milardi et al., "Coupling correction at DAΦNE by low-β
- quadrupoles rotation.", under publication.
- A. Drago "Horizontal instability measurements and [7] feedback performance in the DA Φ NE positron ring", this conference
- M. Zobov et al., "Bunch Lengthening and microwave [8] instability in the DAΦNE positron ring", e-Print Archive: physics/0312072.

SPARC PHOTOINJECTOR WORKING POINT OPTIMIZATION, TOLERANCES AND SENSITIVITY TO ERRORS

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Abstract

A new optimization of the SPARC photo-injector, aiming to reduce the FEL saturation length, is presented together with Start-to-End simulations. A systematic scan of the main parameters around the operating point showed that the probability to get a projected emittance exceeding 1 μ m is only 10 % and the slice emittance remains below 1 μ m in all cases.

INTRODUCTION

The SPARC [1] injector will be the first one driving a saturating SASE FEL without the use of a compressor scheme. The FEL requirements in terms of beam current have pushed the design towards the limits of the state-ofthe-art for what concerns pulse charge and pulse shape. In order to reach this goal with a good level of confidence we have explored a range of parameters that are not far from the previous best performances obtained in photoinjector laboratories [2]. The design goal of the SPARC accelerator is to provide a 155 MeV bunch with less than 2 um for the projected emittance and less than 1 um for the slice emittance of 50% of slices. Detailed analysis of the SPARC-FEL operation including different errors in the undulator showed that the previous set of beam parameters [3] giving a peak current I ≈ 85 A does not leave a significant contingency margin to ensure full saturation and testing of harmonic generation in the 14.5 m allocated for the undulator. The peak current, which, in the range of the diffraction dominated SPARC FEL is the key parameter for shortening the FEL gain length, should then be increased. A safer set of parameters requires a beam having 100 A in 50% of the slices with a slice emittance $\leq 1 \mu m$. For this purpose a new optimization, with Start-to-End simulations and parametric sensitivity studies aiming to reduce the FEL saturation length, was performed. The best performance in terms of increasing final current was obtained with a scaling approach [4] in which more charge is launched from the cathode. The scaling law indicates that the preservation of the beam plasma frequency requires that the spot size be scaled according to $\sigma_r \propto (Q/\sigma_z)^{1/2}$. The configuration that meets the requirement with the minimum emittance

corresponds to a working point with 1.1 nC and a pulse length of 10 psec.

START TO END SIMULATIONS

The accelerator consists of a 1.6 cell RF gun operated at S-band with a peak field on the cathode of 120 MV/m and an incorporated metallic photo-cathode followed by an emittance compensating solenoid and three accelerating sections of the SLAC type (S-band, travelling wave), the first one embedded in an array of 13 coils. A transfer line allows the matching with the undulator optics.



Figure 1: PARMELA computed rms normalized emittance and rms horizontal envelope vs z from gun to the linac output for Q=1.1 nC, τ =10 psec, ϵ_{th} =0.34 µm, laser spot radius=1.13 mm.



Figure 2: Computed slice parameters: slice energy spread, slice current, x and y rms normalized slice emittance

In Fig. 1 the rms normalised emittance and the rms envelope from the gun to the linac output, as computed by PARMELA [5], are shown for the best case ($\varepsilon_n = 0.71 \mu m$) with increased current (I=100 A) [6]. In this study, a thermal emittance linearly increasing with the radius and equal to 0.3 µm/1 mm of radius and a rise time of 1 psec (derived from previous optimization studies) were assumed. It has to be noted that the charge/pulse-length scaling from the parameters found for the original 85 A working point ($\phi_{gun}=33^\circ$, $B_{sol}=2.73$ kG, and average longitudinal fields in TW section 1 of B=750 G, E=25 MV/m, TW sections 2 and 3 E =12.5MV/m) preserves the emittance compensation scheme. The plots of Fig. 2 refer to the slice analysis for the same case: 85% of the particles are in slices with an emittance smaller than 0.7 μ m, 54% have current \geq 100 A and 70% have a current \geq 90 A. In this analysis the slice length has been taken approximately equal to one cooperation length (~300 μm).

Two triplets are used to match the optical functions of the beam at linac exit to the values desired at the undulator entrance. This solution, as compared to a doublet and a triplet configuration which was also suitable, has been chosen in order to assure flexibility to the line [7]. In Fig. 3, the rms horizontal beam size from the end of the linac (corresponding to z=0 in the plot) to the undulator input is shown. The matching has been performed with MAD [12] including the focal effects of 6 undulator sections interleaved by small horizontally focusing quadrupoles. The effect of each undulator section on the beam has been simulated as a vertically focusing quadrupole.



Figure 3: rms beam sizes in mm (black horizontal, red vertical) from the Linac output to the undulator output.

A slice analysis has been carried out in order to evaluate the mismatch of the single slices of the bunch. The relative mismatching parameter:

$$M = 0.5(\beta_o \gamma - 2\alpha_o \alpha + \gamma_o \beta)$$

(α_o , β_o and γ_o being the undulator matched parameters) results to be lower than 1.2 for 85% of the beam.

The undulator parameter set used for the simulation of the SPARC FEL are summarized in Table 1 [8].

Table 1: Undulator parameter set

Period	2.8 cm
# Periods/section	77 (+1 for matching)
Number of Sections	6
K	2.145

The simulation has been performed by using GENESIS 1.3 [9] in time dependent mode, and taking into account the bunch distribution as provided by PARMELA. In Fig.4 the FEL power as a function of z is shown. The saturation length is shorter than 9 m, with a net gain of 2 m compared to the previous optimization.



Figure 4: Power vs. z for the SPARC FEL, from GENESIS (final step in STE) simulation

PARAMETER SENSITIVITIES

In order to investigate the stability of the SPARC working point and to predict the most probable values of the projected and slice emittance in realistic conditions, a sensitivity study to various types of random errors in the SPARC accelerator was performed [10]. The study was divided in two steps. In the first one the tolerances of the main tuning parameters were set using the criterion of having a maximum increase of the projected emittance of 10% with respect to the nominal case (0.71 μ m). In the second step these errors were combined in the defined tolerance ranges and a statistical analysis was performed in order to study the effect of the combination of errors on the projected and slice emittance and on the mismatching at the entrance of the undulator. The sensitivity of the projected emittance to errors of individual parameters that can fluctuate during the machine operation was studied by PARMELA code extensive simulations. The parameters that have been considered are relative to the gun system only and the data were studied at the linac exit.

Table 2: Minimum variation of the single parameters value for a 10% emittance increase

Gun Phase jitter	± 3°
Charge fluctuation	+ 10%
Gun magnetic field	± 0.4%
Gun electric field	± 0.5 %
Spot radius dimension	± 10%
Spot ellipticity	3.5% (xmax/ymax=1-1.035)

Step 1: the resulting tolerances on the different tuning parameters are listed in Table 2. It can be seen that the most critical parameters are the electric field amplitude and the spot ellipticity.

Step 2: one hundred PARMELA runs were performed, each one with random error sets within the tolerance limits. PARMELA was interfaced with a MATLAB based program that accepts in input the limits of variation of the single parameters and generates a number of input files in which the six parameters of interest are varied randomly in the pre-defined ranges according with the sampling technique of the "latin hypercube", an algorithm implemented in the MATLAB statistical toolbox. The numbers used are uniform distributions with average values and rms widths listed in Table 3. The interval of errors distribution is $\pm\sqrt{3} \sigma$ around the average value.

Table 3: Variation of parameters for combined tolerance study of errors in SPARC gun

Parameter	Average value	RMS value
Gun phase	31.5°	1.74°
Charge	1.15 nC	0.032 nC
Gun B field amplitude	2733 gauss	5.8 gauss
Gun E field amplitude	119.9 MV/m	0.32 MV/m
spot radius	1.132	0.068 mm
Ellipticity	1	0.02

The results of the simulations were used to construct the curve plotted in Fig. 5 that gives the probability to obtain an emittance greater or equal than the corresponding value on the abscissa: for example the probability to get a normalized projected emittance $\ge 1 \ \mu m$ is less than 10%.



Figure 5: Probability vs emittance over 100 simulations

Concerning the slice emittance, in the 100 simulations it does not exceed 0.9 μ m for the 9 central slices out of 13 slices, as it can be seen in Fig. 6 in which two extreme cases obtained from the error simulations are compared with the ideal case.

The effect of random errors on the transverse phase space orientation at the entrance of the undulator has also been investigated. The distribution of the average and the rms mismatching factor are respectively 1.3 and 0.32.



Figure 6: Interval of variation of slice emittance over 100 simulations

CONCLUSIONS

Start-to-End simulations showed that, with a 1.1 nC charge in a 10 ps long bunch we can deliver at the undulator entrance a beam having 100 A in 50% of the slices with a slice emittance $\leq 1 \mu$ m, thus reducing the FEL-SASE saturation length to 9 m at 500 nm wavelength. The stability of the nominal working point and its sensitivity to various types of random errors, under realistic conditions of the SPARC photo-injector operation has also been studied. On this basis it can be concluded that combining multiple errors on tuning parameters the projected and slice emittance values remain within the limits of the SPARC design. Additional systematic investigations taking into account element misalignments, orbit steering and wake fields [11] effects are under way.

- [1] D. Alesini et al., "Status of the SPARC Project", this Conference
- [2] J. Yang, J. of Appl. Phys., V. 92, N. 1, (2002)
- [3] M. Biagini et al., Beam Dynamics Studies for the SPARC Project, Proc of PAC 2003
- [4] J.B. Rosenzweig and E. Colby, Advanced Accelerator Concepts p. 724 (AIP Conf. Proc. 335, 1995)
- [5] J. Billen, "PARMELA", LA-UR-96-1835, 1996
- [6] M. Biagini et al., "SPARC injector working point optimisation" SPARC-BD-03/007
- [7] L. Giannessi, L. Mezi, C. Ronsivalle, M. Biagini, M. Migliorati, G. Di Pirro, "SPARC Transfer Line", SPARC-FEL-03/006
- [8] F. Ciocci, G. Dattoli, L. Riannessi, "SPARC Undulator parameter set", SPARC-FEL-03/003
- [9] S. Reiche, Nucl. Instrum. & Meth. A429, 243 (1999)
- [10] C. Ronsivalle, SPARC-BD-03 / 008
- [11] M.Ferrario, V.Fusco, M.Migliorati, L.Palumbo, B.Spataro, "Wake Fields Effects In The Photoinjector of The Sparc Project", this Conference
- [12] CERN Report CERN/SL/90-13 (AP) (1995)

STATUS OF THE SPARC PROJECT*

D.Alesini, S.Bertolucci, M. Bellaveglia, M.E.Biagini, R.Boni, M.Boscolo, M.Castellano, A.Clozza,
 G.Di Pirro, A.Drago, A.Esposito, M.Ferrario, D. Filippetto, V.Fusco, A.Gallo, A.Ghigo, S.Guiducci,
 M.Incurvati, C.Ligi, F.Marcellini, M.Migliorati, A.Mostacci, L.Palumbo, L.Pellegrino, M.Preger,
 R.Ricci, C.Sanelli, M.Serio, F.Sgamma, B.Spataro, A.Stecchi, A.Stella, F.Tazzioli, C.Vaccarezza,
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Abstract

The aim of the SPARC project is to promote an R&D activity oriented to the development of a high brightness photoinjector to drive SASE-FEL experiments at 500 nm and higher harmonics generation. Proposed by the research institutions ENEA, INFN, CNR with the collaboration of Universita' di Roma Tor Vergata and INFM-ST, it has been funded in 2003 by the Italian Government with a 3 year time schedule. The machine will be installed at LNF, inside an existing underground bunker. It is comprised of an rf gun driven by a Ti:Sa laser to produce 10-ps flat top pulses on the photocathode, injecting into three SLAC accelerating sections. In this paper we present the status of the design activities of the injector and of the undulator. The first test on the RF deflector prototype and the first experimental achievements of the flat top laser pulse production are also discussed.

INTRODUCTION

The *SPARC* project is an R&D activity to develop a high brightness photoinjector for SASE-FEL experiments funded by the Italian Government in 2003 with a 3 year time schedule. The installation of the machine at LNF will start on September 2004, and the first beam is expected on June 2006. The SPARC [1] complex is composed of an rf gun driven by a Ti:Sa laser producing 10-ps flat top pulses that hit on a photocathode. The out coming beam is injected into three SLAC accelerating sections to feed a 14 m long undulator, see Fig.1. The main goals of the project are:

(1) the generation of a high brightness electron beam able to drive a self-amplified spontaneous free-electron laser (SASE FEL) experiment in the green visible light and higher harmonics generation,

(2) the development of an ultra-brilliant beam photoinjector needed for the future SASE FEL-based X-ray sources.



Figure 1.SPARC project layout.

The project is also aiming at the development of sub-ps bunch length diagnostic, at the investigation of the beam emittance degradation due to the CSR in the dogleg magnetic compressor and the effects induced by the surface-roughness wake fields on the beam quality.

In the next section of this report the status of the design activities of the injector and undulator is presented. In the following sections the first test results on the SPARC RF deflector are described and finally those obtained in the flat top laser pulse production are also presented.

SPARC PHOTOINJECTOR WORKING POINT OPTIMIZATION

The beam current required by the FEL experiment pushes the injector design towards the limits of the stateof-the-art for what concerns pulse charge and pulse shape. The design goal of the SPARC accelerator is to provide a 155 MeV bunch with less than 2 um for the projected emittance and less than 1 µm for the slice emittance. The SPARC FEL operates in the diffraction dominated range and peak current, which, in the range of the diffraction dominated SPARC FEL the beam current is a key parameter for shortening the FEL gain length. Once including possible errors in the undulator system the analysis [2] of the SPARC-FEL operation shows that in order to leave a significant contingency margin to ensure full saturation and testing of harmonic generation a safer parameter set requires a beam having 100 A in 50% of the slices with a slice emittance $\leq 1 \mu m$. For this purpose a new optimization, with Start-to-End simulations and parametric sensitivity studies aiming to reduce the FEL saturation length, was performed [3].



Figure 2: PARMELA computed rms normalized emittance and rms horizontal envelope vs z from gun to the linac output for Q=1.1 nC, τ =10 psec, ε_{th} =0.34 µm, laser spot radius=1.13 mm.



Figure 3: Power vs. z for the SPARC FEL, from GENESIS (final step in STE) simulation.

The best result was obtained with a scaling approach [4] in which more charge is launched from the cathode. The configuration that gives the minimum emittance

corresponds to a working point with 1.1 nC and a pulse length of 10 psec. The overall result is the reduction of the FEL-SASE saturation length from 12 to 9 m at 500 nm wavelength, see Fig. 2-3.

Table 1 – Injector Parameters

ELECTRON BEAM	Α
Electron Beam Energy (MeV)	155
Bunch charge (nC)	1.1
Repetition rate (Hz)	1-10
Cathode peak field (MV/m)	120
Peak solenoid field @ 0.19 m (T)	0.273
Photocathode spot size (mm, hard edge radius)	
	1.13
Central RF launch phase (RF deg)	33
Laser pulse duration, flat top (ps)	10
Laser pulse rise time (ps) 10%→90%	1
Bunch energy @ gun exit (MeV)	5.6
Bunch peak current @ linac exit (A)	100
Rms normalized transverse emittance @ linac exit	< 2
(mm-mrad); includes thermal comp. (0.3)	
Rms slice norm. emittance (300 µm slice)	< 1
Rms longitudinal emittance (deg.keV)	1000
Rms total correlated energy spread (%)	0.2
Rms incorrelated energy spread (%)	0.06
Rms beam spot size @ linac exit (mm)	0.4
Rms bunch length @ linac exit (mm)	1

Table 2 – FEL Parameters

UNDULATOR & FEL	Α
Undulator period (cm)	3.0
# Undulator sections	6
Undulator parameter	1.4
Undulator field on axis (T)	
Undulator gap (mm)	11
Undulator section length (m)	2.13
Drifts between undulator sections (m)	0.36
FEL wavelength (nm)	500
Saturation length (m, geometrical)	< 14
FEL pulse length (ps)	8
FEL power @ saturation (MW)	> 80
Brilliance (st. units)	
# Photons/pulse	10 ¹⁵
FEL power @ sat. (MW) 3 rd harm.	> 10
FEL power @ sat. (MW) 5 th harm.	> 0.7

LASER TEMPORAL PULSE SHAPING

The need to minimize nonlinearities in the space charge field of the electron bunch, in particular during the early stages of acceleration from the photo-cathode surface, leads to the needs of shaping the temporal profile of the laser pulse as it strikes the photo-cathode - the required shape is a uniform intensity distribution in time, often termed a flat-top time distribution. Beam dynamics simulations show that flat-top profile should exhibit very sharp edges in the head and tail of the pulse. The associated rise times must be at least shorter than 1 ps, with 0.5 ps being a desirable optimum value

In collaboration with the Milano Politecnico ultra fast laser laboratory, a series of tests have been performed to demonstrate the fessibility of the pulse shaping with the **— 19 —**

Dazzler crystal. The preliminary results are of great interest to the SPARC laser pulse shaper design [5].

The obtained temporal intensity was measured by sampling the flat top pulse with the 20 fs reference pulses, delayed varying the optical path length by a translation stage with 100 nm resolution. The very short reference pulse assures a highly precise measurement of the shaped pulse. An interferometric filter was used to reduce the bandwidth of the incoming pulse. The measurements indicated that the acoustic optic crystal could produce pulse with duration up to 12 ps. Figure 4 reports the measurement of shaped intensity profile that approach the required pulse for SPARC photoinjector.

As shown in the plot, the pulse rise and fall time is less than 0.7 ps and the ripple peak to peak is less than 20% and the pulse's duration is thereabouts 11 ps FWHM. These preliminary results are very promising for producing the flat top temporal profile required in the SPARC photoinjector



Figure 4: Cross-correlation of the output shaped pulse in double-pass configuration.

RF DEFLECTOR DESIGN & TESTS

The characterization of the longitudinal and transverse phase space of the beam provided by the SPARC photoinjector at 150 MeV is a crucial point to establish the performance quality of the photoinjector itself. By means of an RF deflector it is possible to measure the bunch length: the longitudinal beam distribution can be projected along a transverse coordinate and the image is collected on the screen. Using the orthogonal transverse coordinate distribution, both the horizontal and vertical beam emittances can be measured with the quadrupole scan technique. With the combination of the RF deflector and a dispersive system the longitudinal beam phase space can be completely reconstructed, (flag location FD2). The schematic layout of the measurement is reported in Fig.5. An aluminum cold test model of the 5cell π -mode rf deflector has been manufactured to LNF specifications and tested (Fig. 6) at the University of Rome "La Sapienza" by members of the SPARC team.



Figure 5: Schematic SPARC measurement layout for high energy beam characterization.



Figure 6: Deflector alluminum prototype and measurement setup.

The results of the bead pull tests on the field profile of the rf deflector π -mode reveal a good level of magnetic field flatness.

CONCLUSIONS

The SPARC project has been approved by the Italian Government and funded in June 2003 with a schedule of three years. After the first year the project has been fully defined, the major components ordered and promising tests on laser pulse shaping with Dazzler and RF deflector for beam diagnostics performed. The installation of the system will start in January 2005.

- [1] SPARC Project Team, Sparc Injector TDR www.lnf.infn.it/acceleratori/sparc/
- [2] M. Biagini et al., Beam Dynamics Studies for the SPARC Project, Proc of PAC 2003
- [3] M. Ferrario, et al., "SPARC Photoinjector Working Point Optimization, Tolerances and Sensitivity to Errors", these Proceedings
- [4] J.B. Rosenzweig and E. Colby, Advanced Accelerator Concepts p. 724 (AIP Conf. Proc. 335, 1995)
- [5] C. Vicario, *et al.*, "Laser Temporal Pulse Shaping Experiment for SPARC photoinjector"
- [6] C. Vaccarezza, *et al.*, "6D Phase Space Characterization of the SPARC Beam

AN ULTRA-HIGH BRIGHTNESS, HIGH DUTY FACTOR, SUPERCONDUCTING RF PHOTOINJECTOR

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Abstract

Recent advances in superconducting rf technology and a better understanding of rf photoinjector design make possible to propose a superconducting rf gun producing beams with ultra-high peak brightness and high average current. The superconducting rf photoinjector presented here providing such high quality beam is scaled from the present state-of-the-art design of the normal conducting rf photoinjector that has been studied for LCLS SASE FEL.

INTRODUCTION

With the advent of proposed [1, 2] superconducting radio-frequency (SRF) electron linear accelerators dedicated to production of radiation or to high energy physics that operate at high average current (high duty factor), the demand for high quality beams, *i.e.* high peak brightness*, pushes one to consider the possibility of using a SRF photoinjector. Usually, to enhance brightness one has to expose emitting cathode to a very high electric field, and also to introduce magnetic solenoid fields within the photoinjector gun region. These focusing fields allow control and mitigation of space-charge effects, a process termed emittance compensation. Operation with high average beam current requires photocathodes having enhanced quantum efficiency (η) . When superconductor is used as a photoemitter, high η minimizes the thermal load on the superconducting surface. More generally, high η implies that one may keep the size and cost of the high duty cycle laser system used to illuminate the photocathode within reasonable limits.

In the past, for an implementation of SRF guns it was always assumed that one needs strong focusing inside the gun, near the photocathode. This assumption has been partially driven by relatively low achievable gradient in SRF guns in the past. An interesting solution which avoids use of solenoid fields in transverse beam control near the cathode, so-called "rf focusing", has been proposed in [3]. Unfortunately this method requires a deformation of the cathode plane, causing nonlinear field perturbations that may cause significant emittance growth in the injector. We discuss in the following sections an alternative scheme in which rf focusing is not required. This optimized SRF gun is based on the scaling of existing normal conducting high brightness sources to lower frequency and lower rf field.

Concerning the choice of the cathode material, it has been shown experimentally [11] that with various treatments of a Nb surface (mechanical diamond polishing or/and laser polishing), one can increase the Nb η from $2 \cdot 10^{-7}$ to $5 \cdot 10^{-5}$. Further increase of η is possible when emitting spot is exposed to high electric fields, through the Schottky effect. Since n scales proportional with electric field applied at the emitting spot one may expect that at gradients of 60 MV/m quantum efficiency will increase to 10⁻⁴, or above if higher energy photons can be used to illuminate Nb wall. An improvement in η is of great importance. Even with $\eta = 10^4$ the laser-deposited power in the Nb wall needed accompanying cw, few MHz 1 nC/bunch beam photoemission, would be to high to keep the illuminated spot superconducting [12]. In addition, the illuminating laser itself would be technically very challenging.

More recently, a new approach to the generation of high-current, high-brightness electron beams has been proposed by the BNL group [4]. In this scheme, primary electrons are produced by a photocathode and are accelerated to several keV. At that energy they strike a specially prepared diamond window. The large secondary electron yield (SEY) of diamond multiplies the number of secondary electrons by about two orders of magnitude. These electrons drift through the diamond under an electric field and emerge into the rf accelerating field in the gun through the diamond's negative electron affinity surface. The advantages of this approach are evident in the context of SRF photoinjectors.

BASIC DESIGN PARAMETERS

It is often remarked that production of a very high brightness beam from an rf photoinjector implies the use of a large accelerating gradient. For example, the design for the LCLS photoinjector, which is presently the highest brightness source proposed, utilizes a peak on-axis electric field of between 120 and 140 MV/m at an operating rf frequency of 2.856 GHz [5]. While such fields clearly exceed those achievable in superconducting rf cavities, one may easily scale the fields downward by moving to a different design frequency [6]. As the longitudinal beam dynamics are preserved in this case by scaling the fields as $E_0 \propto \lambda_{rf}^{-1}$, at L-band (1.3 GHz) the needed peak on-axis field is between 54 and 64 MV/m, which is roughly equivalent to an average accelerating field between 27 and 32 MV/m. These fields are within the current state-of-the-art in superconducting cavities [7].

^{*} Peak <u>Brightness</u>: $B = 2I_p / \varepsilon_n^2$ where I_p is the peak current and ε_n is the normalized transverse emittance.

The working point of the LCLS photoinjector is predicted to have a very high brightness, with a peak current at 1 nC charge of 100 A (10 psec flat-top pulse), and an emittance of 0.7 mm-mrad [8]. With these beam parameters, obtained from detailed PARMELA simulation, the calculated B is $5.6 \cdot 10^{14}$ A/m². One may scale the space-charge dominated beam dynamics naturally and exactly in rf wavelength, scaling the beam dimensions by the rf wavelength $\sigma_i \propto \lambda_{rf}$ the solenoid field as $B_z \propto \lambda_{rf}^{-1}$, and the beam charge by $Q \propto \lambda_{rf}$ [6]. Under these assumptions, the current is independent of λ_{rf} , and the emittance scales as λ_{rf} —thus the brightness scales as $B \propto \lambda_{rf}^{-2}$. Fortunately, if we scale back the charge at L-band from 2.2 nC (natural scaling), to 1 nC, we do not pay a strong penalty in brightness. For scaling of charge, we must keep the beam plasma frequency constant, which requires that $\sigma_i \propto Q^{1/3}$. Under these conditions of both charge and wavelength scaling, it can be shown that the brightness scales as

$$B(A/m^{2}) = \frac{2 \times 10^{12}}{a_{1}\lambda_{rf}^{2}(m) + a_{2}Q^{4/3}(nC)\lambda_{rf}^{2/3}(m) + a_{3}Q^{2}(nC)}$$

where the constants a_i are deduced from simulation scans. These constants have physical meaning: a_1 indicates the contribution of thermal emittance; a_2 the component due to space charge; a_3 the emittance arising from RF and chromatic effects. For the LCLS design "family" [9], these constants are determined to be $a_1 = 1.5$, $a_2 = 0.81$, $a_3 = 0.052$.

For our L-band scaled design at 1 nC charge, we obtain a current of 50 A, and an emittance, as before, of 0.7 mm-mrad, for a peak brightness of $B = 2 \times 10^{14} A/m^2$ which we expect from a potentially very high brightness superconducting source. The possibility is thus within reach that a scaled SRF version of the LCLS injector may give bunches of electrons with extremely high brightness,



at average repetition rates well in excess of the present state of the art.

Figure 2: 1.3 GHz 1.6 cell Nb SRF gun design

SRF CAVITY AND SOLENOID DESIGN

The proposed 1.3 GHz 1.6 cell Nb cavity, used here to design the injector is shown in Fig. 2. The full cell dimensions are the similar to an inner cell of a TESLA cavity, while the first cell is longer than a half cell $(0.6 \lambda_{rf}/2)$ in order to compensate for phase slippage occurring during the early, non-relativistic phase of beam acceleration. A coaxial input power coupler has been considered as in the normal conducting TESLA gun design [1], in order to avoid any asymmetry in the accelerating field and transverse RF kicks. The HOM coupler is located on the beam tube close to full cell iris.



Figure 3: design of the solenoid coils

Further, this nearly scaled configuration has a focusing solenoid geometry that keeps most of the magnetic field outside the cavity. In fact in the frequency-scaled, superconducting case, we have further constraints. The magnetic field must not penetrate the super-conducting cavity to avoid thermal breaks down when the critical field of 200 mT is exceeded. The residual fringing field (4 Gauss on the cavity iris see Fig. 4) is tolerable in that the focusing is applied only after cool down and the small field is excluded from the superconducting cavity through the Meissner effect, thus avoiding any residual flux trapping that may cause cavity Q_0 degradation. In Fig. 3 a schematic design of the solenoid coils and iron screen is shown and in Fig. 4 the on-axis E_z component of the RF field and solenoid B_z are displayed.

A more detailed study including the laser system and cryostat design will be discussed in a future work.



Figure 4: On-axis profiles of the RF field E_z , and B_z

BEAM DYNAMICS SIMULATIONS

PARMELA simulations performed with 50,000 macroparticles are shown in Fig. 5 and 6 up to the 1 mm-mrad emittance threshold. Longer distances have been studied by the fast running code HOMDYN and the results are shown in Fig 7.



Figure 5: Rms normalized emittance evolution in SC photoinjector, from PARMELA simulations

According to the scaling philosophy discussed in the previous section, in our simulation we consider a uniform density 1 nC bunch 19.8 ps long and radius of 1.69 mm, accelerated in the gun cavity up to an energy of 6.5 MeV, corresponding to a peak field on the cathode of 60 MV/m and an injection phase of 44.5 deg. Space charge induced beam expansion (up to σ_x =2.4 mm) and emittance growth in the gun are compensated in a downstream drift with a solenoid located at the gun exit, 36 cm from the cathode, producing a 3 kG maximum field on the axis.



Figure 6: Rms bunch length and energy evolution, in SC photoinjector, from PARMELA simulations.

As shown in Fig. 5 the emittance compensation process is clearly visible in the drift until the bunch is injected at z=3.3 m in a cryomodule housing 8 L-band superconducting cavities of the TESLA type. Matching conditions for optimum emittance compensation [10] sets the accelerating gradient to 13 MV/m. At the exit of the first cryomodule (z=14 m) the bunch has been accelerated up to 117 MeV (the beam is space charge dominated up to 90 MeV) and space charge induced emittance oscillations are totally damped (see Fig. 7). The final emittance is lower than 1 mm-mrad (with a thermal emittance contribution of 0.5 mm-mrad). A minor bunch elongation (see Fig 6.) in the drift results in a final peak current of 50 A. The total length of the injector system is 14 m.



Figure 7: Rms normalized emittance and rms envelope evolution up to the exit of the second cryomodule, HOMDYN simulations.

- [1] H. Weise, "The TESLA X-FEL project", this conference
- [2] J. Sekutowicz et al., "Proposed Continuous Wave Energy Recovery Operation of an XFEL", TESLA-FEL Report 2004-03, submitted to PRST-AB.
- [3] D. Janssen, V. Volkov, Nucl. Instr. and Meth. A 452 (2000), 34.
- [4] I. Ben-Zvi et al., "Secondary Emission Enhanced Photoinjector", BNL Report C-A/AP/#149
- [5] D. Dowell et al, "The Linac Coherent Light Source Photo-Injector", this conference
- [6] J.B. Rosenzweig and E. Colby, "Charge and Wavelength Scaling of RF Photoinjector Designs", *Advanced Accelerator Concepts* p. 724 (AIP Conf. Proc. 335, 1995).
- [7] L. Lilje, "Achievement of 35 MV/m in the TESLA Superconducting Cavities Using Electropolishing as a Surface Treatment", this conference
- [8] M. Ferrario et al., "HOMDYN study for the LCLS Photoinjector", in *The Physics of High Brightness Beams*, 534, World Scientific, 2000.
- [9] M. Biagini et al., "SPARC Photoinjector Working Point Optimization, Tolerances and Sensitivity to Errors", this conference
- [10] L. Serafini, J. B. Rosenzweig, Phys. Rev. E 55 (1997) 7565
- [11] T. Srinivasan-Rao et al., "Design, Construction and Status of All Niobium Superconducting Photoinjector at BNL", PAC03, Portland 2003, USA
- [12] T. Schultheiss et al., "Thermal/Structural analysis of a SCRF Photocathode Electron Gun Cavity", PAC01, Chicago 2001, USA.

WAKE FIELDS EFFECTS IN THE SPARC PHOTOINJECTOR

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Abstract

When a bunch travels off axis across structures whose shape is not uniform, such as RF cavity or bellows, generates longitudinal and transverse wake fields [1]. In addition transverse time dependent fields (like transverse RF components and wake fields) may induce correlated slice centroids displacement, so that each slice centroid motion is affected also by a different space charge force generated by the next slices. In this paper the analytical diffraction model for wake fields, developed by Bane and Sands has been implemented in the HOMDYN code taking into account also space charge forces acting on the slice centroids.

As a first application, the preliminary evaluation of the emittance degradation in the SPARC linac when structures are misaligned with respect to the nominal axis is reported.

WAKE FIELDS DIFFRACTION MODEL

Single cavity

When the bunch length σ is much smaller then the beam pipe radius a, $\sigma << a$, methods of diffraction theory [2] are used to calculate the impedance at high frequencies, $\omega >> c/a$, where c is the velocity of light.

The model suppose each structure as a pill box cavity, whose geometric dimensions are: a the beam pipe radius, b the cavity radius and g its length. When a bunch reaches the edge of the cavity, the electromagnetic field produced is just the one that would occur when a plane wave passes trough a hole; with this hypothesis it is possible to use the classical diffraction theory of optics to calculate the fields.

According to it, the longitudinal and transverse wake fields, in the high energy regime, are respectively [2]

$$W_{\parallel 0}(s) = \frac{Z_0 c}{\sqrt{2}\pi^2 a} \sqrt{\frac{g}{s}}$$
(1)
$$W_{\perp 0}(s) = \frac{2^{3/2} Z_0 c}{\pi^2 a^3} \sqrt{gs}$$
(2)

where Z_0 is the characteristic impedance and s the longitudinal coordinate inside the bunch, being s=0 the bunch's head.

The above expressions are given for the ultrarelativistic case $\beta \rightarrow 1$; the case of low energy regime was studied in [3-4] where It was shown a dependence of the energy loss and of the wake fields from the relativistic factor γ . However It was shown in [5] that the high energy regime represents an over estimation of the low energy one.

It's worth noting that both the longitudinal and transverse wakes do not depend on the cavity radius *b*.

Infact part of the diffracted field, generated when the leading edge of the bunch enters the cavity, will propagate in the cavity; if the bunch's rms length σ is shorter than the cavity radius *b*, then the geometrical condition

$$g < \frac{(b-a)^2}{2\sigma}$$

is verified and the scattered field coming from the upper wall of the cavity will never reach the tail of the bunch itself: this is called "cavity regime".

Using Eq. 1 and Eq. 2 as a green function we can calculate the transverse and longitudinal wake field:

$$E_{\parallel}^{w}(s) = \frac{q}{L} \frac{2}{\sqrt{2}\pi^{2}a\varepsilon_{0}} \sqrt{\frac{s}{g}}$$
$$E_{\perp}^{w}(x,s) = \frac{q}{L} \frac{2^{5/2}}{3\pi^{2}a^{3}\varepsilon_{0}} \frac{s^{3/2}}{\sqrt{g}} x$$

where q and L are the bunch's charge and length respectively.

BEAM DYMAMICS IN HOMDYN

Off-axis beam dynamics

We use the HOMDYN code to study the dynamic of an off axis bunch which travels along structures whose shape is not uniform. The code [6] describes a bunch as a uniformly charged cylinder of charge q and length L, divided in cylindrical slices of radius R_s . The evolution in the time domain of the slice's envelope R_s is described by its envelope differential equation [6] and the centroid longitudinal position z_c of each slice is described by

$$\ddot{z}_{c} = \begin{cases} \frac{e}{\gamma^{3}m} \frac{q}{2\pi\varepsilon_{0}R_{s}^{2}L\gamma_{s}} H(\xi_{s}, R_{s}, \gamma_{s}, L) + \\ \frac{e}{\gamma m} E_{\parallel}^{w}(\xi_{s}) - \frac{e}{2\gamma m} \left\{ \dot{x}(\gamma B'_{z} - \sum_{i} \gamma_{i,off} B'_{z,i}) + \right. \\ \left. - \dot{y}(xB'_{z} - \sum_{i} x_{i,off} B'_{z,i}) \right\} \end{cases}$$

where $\xi_s = z_s - z_t$ and z_t is the bunch's tail.

The first term on the right hand side describes the longitudinal space charge on each slice centroid [5], whilst the wake field is the second term on the right hand side. The remaining terms describe the longitudinal motion in a solenoid field; transverse components of the magnetic fields are approximate with the B_z derivative.



Figure 1: Bunch divided in slices in Homdyn.

In order to describe the displacement of each slice centroid x_c , y_c from the nominal axis of the bunch, it is necessary to include in the code the differential equation describing the centroid motion

$$\ddot{x}_{c} + \beta \gamma^{2} \dot{\beta} \dot{x}_{c} = \begin{cases} \frac{e}{\gamma^{3}m} \frac{q\gamma}{4\pi \epsilon R_{s}^{2}L} d_{xc} G(\xi, R_{s}, \gamma, L) + \frac{e}{\gamma m} \left\{ E_{\perp}^{w} (x_{c}^{-1}, \xi_{s}) + \dot{y} B_{z} + \frac{1}{2} \dot{z} (y B'_{z} - \sum_{i} y_{i,off} B'_{z,i}) \right\} \end{cases}$$

$$\ddot{y}_{c} + \beta \gamma^{2} \dot{\beta} \dot{y}_{c} = \begin{cases} \frac{e}{\gamma^{3}m} \frac{q\gamma}{4\pi \epsilon R_{s}^{2}L} d_{yc} G(\xi, R_{s}, \gamma, L) + \\ + \frac{e}{\gamma m} \{E_{\perp}^{w}(y_{c}^{-1}, \xi_{s}) - \dot{x}B_{z} + \\ -\frac{1}{2} \dot{z}(xB'_{z} - \sum_{i} x_{i,off}B'_{z,i}) \} \end{cases}$$

Each slice's centroid can be transversally displaced from the nominal axis; in this case it experiences a transverse deflection due to the space charge force produced by the neighbour slices (first term on the right hand side) [6] and the transverse wake force (second term on the right hand side). Finally the last terms describe the beam motion in a solenoid field, including the case of solenoid's coils misalignment $x_{i,off}$ and $y_{i,off}$ respect to the nominal axis.

We suppose the transverse wake force on each slice depends on the displacement of the first slice from the axis, $x_c^{\ l}$ or $y_c^{\ l}$ and the space charge on the centroid varies linearly with the distance d_{xc} or d_{yc} of the considered slice's centroid from the straight line *r* (see Fig. 1). The straight line is obtained interpolating the centroids along the bunch with the least square method.

The space charge on centroids was tested generating a bunch in a case where space charge on centroids is strong; then we compared centroid motion with Parmela results.

Emittance Computation

The total rms emittance is calculated in the code as follow [6]

$$\varepsilon_{ntot}^{2} = (\varepsilon_n^{th})^2 + (\varepsilon_n^{corr})^2$$
(3)

where ε_n^{th} is the thermal emittance.

When all the slices lies on the same axis, the correlated emittance is only given by the "envelope" emittance

$$(\varepsilon_n^{e})^2 = <\frac{X^2}{4} > <\frac{(\beta\gamma X')^2}{4} > -<\frac{X\beta\gamma X'}{4} >^2 =$$
$$=<\frac{a^2}{4} > <\frac{b^2}{4} > -<\frac{ab}{4} >$$

where X is the slice envelope.

On the contrary if the slices do not lie on the same axis then the correlated emittance is given by the quadratic sum of three terms: the "envelope" emittance mentioned above, the "centroids" and the "cross" emittance, respectively

$$(\varepsilon_n^{\ c})^2 = \begin{cases} <(x_c -)^2 > <(\beta \gamma x_c' - <\beta \gamma x_c' >)^2 > - \\ - <(x_c -)(\beta \gamma x_c' - <\beta \gamma x_c' >) >^2 \end{cases}$$
$$= - ^2 \end{cases}$$

$$\mathcal{E}_{n}^{cross})^{2} = \begin{cases} <\frac{a}{4} > < d^{2} > + <\frac{b}{4} > < e^{2} > + \\ -2 < \frac{ab}{4} > < de > \end{cases}$$

where $\ll = \frac{1}{S} \sum_{l}^{S}$ is performed over the *S* slices.



Figure 2: Centroid, cross, envelope and total emittance (light blue line) using Eq. 3, compared with Parmela's emittance results (black crossed line). The bunch is generated with an offset.

The emittance complete expression of an off axis bunch has been inserted in the Homdyn code. Using Parmela's output to obtain slice's envelope and centroid positions, we insert such results in the above equations and calculate analytically the emittance; then we compare the analytical result with the emittance as computed by Parmela. The excellent agreement validates the above computation.

For the Homdyn emittance calculation we assume that the bunch's charge distribution is uniform. The results of Fig.2 show a good agreement demonstrating the nonlinearities of the space charge force can be neglected.

EMITTANCE DEGRADATION IN THE SPARC PHOTOINJECTOR

We used the improved version of the Homdyn code described in the previous section to preliminary evaluate the emittance degradation at the end of the travelling wave structures (TW) of the SPARC's project [7].

The bunch is generated on axis whilst the TWs can be transversally displaced with respect to the nominal axis; besides the thirteen coils forming the solenoid of the first TW can be independently displaced as well. We looked for the coils' configuration giving the biggest offset of the bunch's centroid from the nominal axis thus enhancing the wake fields across the bunch. We combined it to a worst configuration for the TWs as specified in Table 1.

Device	Δx [mm]	Δy [mm]
Solenoid coil	0.	+0.1
1		
Solenoid coils	+0.1	0.
2-3-4-5-6		
Solenoid coils	0.	-0.1
7-8-9-10-11-12-13		
TW1	0.1	0.1
TW2	-0.1	-0.1
TW3	-0.1	-0.1

Table 1: Solenoid coils and TWs misaligned configuration

Finally we corrected the bunch trajectory inserting three steering coils placed at the entrance of each TW structure.





Fig.3 shows the bunch centroids positions with and without steerings in the case of the above misaligned configuration for an offset of 0.05mm and 0.1mm. Table2 shows the emittance degradation at the end of the TWs structures whilst Fig.4 shows the emittance behaviour along the structure for the two cases.

It's worth noting the main causes of emittance degradation are the wake fields in the TWs structures. Infact Fig. 5 shows the bunch's emittance when a bunch enters off axis, as an example, in the second TWs structure.

Table 2: Normalized emittance degradation without and with steering correction at the end of the TWs (z=12.0m).

Offset	ε _{nx}	ε _{nx}	ε _{ny}	ε _{ny}
	steer off	steer on	steer off	steer on
0.05mm	1.68µrad	0.84µrad	0.89µrad	0.85µrad
0.1mm	3.47µrad	1.08µrad	1.22µrad	1.06µrad



Figure 4: Normalized emittance behaviour along the structure without (black line) and with (red line) steering correction for the case of 0.05mm offset.



Figure 5: Normalized emittance along the second TW structure for a bunch' offset of 0.1mm when both wake and RF are on (black line) and when only RF is on (red line).

CONCLUSIONS

The analytical diffraction model for wake fields has been implemented in the Homdyn code; we included space charge force acting on each slice's centroids. As a consequence a new analytical calculation for emittance has been developed and inserted in Homdyn. As a first application, a preliminary evaluation of the emittance degradation and tolerances in the SPARC linac when structures are misaligned respect to the nominal axis, has been studied.

ACKNOWLEDGEMENT

The authors would like to thank Concetta Ronsivalle for many helpful and interesting discussions.

- [1] L. Palumbo et al., "Wake Fields and Impedance", CAS: 5th Advanced Accelerator Physics Course.
- [2] K. Bane, M. Sands, SLAC-Pub-4441
- [3] J.D. Lawson, RHEL/M144.
- [4] E. Keil, NIM 100 (1972) 419-427
- [5] H. Henke, CERN-LEP-RF/85-41
- [6] M. Ferrario et al., SLAC-PUB-8400
- [7] D. Alesini et al., "Status of the SPARC Project", this Conference

FEASIBILITY STUDY FOR A VERY HIGH LUMINOSITY Φ -FACTORY

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Abstract

Particle factories are facing their future by looking at the possibility of upgrading the luminosity by orders of magnitude. The upgrade challenges are more stringent at lower energies. Double symmetric rings, enhanced radiation damping, negative momentum compaction and very short bunches at the collision point are the main features of a Φ -factory feasibility study presented in this paper. The bunch length of few millimetres at the crossing point of the beams is obtained by applying the Strong RF Focusing principle. The collider design fits the existing DAFNE infrastructures with completely rebuilt rings and upgraded injection system.

INTRODUCTION

DA Φ NE, the Frascati Φ -factory, has reached a peak luminosity close to 10^{32} cm⁻²sec⁻¹[1] at 1.02GeV E_{cm}. The design of a super Φ -factory, DA Φ NE-II, with two order of magnitude higher luminosity, keeps the main DA Φ NE characteristics (double symmetric ring collider in multibunch configuration and flat beams). It incorporates new ideas, feasible with completely rebuilt rings (see Fig.1), namely the Strong RF Focusing (SRFF) principle[2], enhanced radiation damping and negative α_c .



Figure 1: DAΦNE-II layout

Strong RF Focusing

Very small vertical beam sizes at the Interaction Point (IP) demand for very short bunches. Going to the millimetre range in the vertical β^* is not conceivable for a low energy ring where the microwave instability appears at very low bunch charge. The SRFF overcomes this problem, by modulating the bunch length along the ring: bunches are very short at the IP, while the average bunch length is reasonably long and the bunch lengthening

regime is not reached. High RF voltage and strong correlation between longitudinal position in the bunch and energy deviation produce the high synchrotron phase advance necessary to focus the beam longitudinally. An experiment in DA Φ NE has been proposed [3] at low current to demonstrate the feasibility of such a regime.

High radiation damping

One of the limitations for reaching high beam-beam tune shifts at low energies is the naturally long radiation damping time. Any attempt to increase the single bunch luminosity must be based on enhancing the radiation emission, with the increase of the bending field along the ring, or, equivalently, of the synchrotron radiation integral I_2 , by introducing wigglers or alternating field dipoles.

Negative momentum compaction

The shorter bunch length and the more regular longitudinal distribution in a lattice with negative α_c are beneficial to the luminosity. All present storage rings work in the positive α_c regime. Experiments done in different storage rings confirm simulations. Recently in DA Φ NE a first test with a negative momentum compaction lattice has shown a very strong decrease of the bunch lengthening while keeping the same microwave instability threshold.

LATTICE CELL

The magnetic lattice of DA Φ NE-II copes with the three principles above. The arc structure is a series of cells with negative and positive bending magnets.



Figure 2: Schematic cell layout

The cell layout is sketched in Fig. 2 and the betatron functions and the dispersion in Fig. 3. The dipoles are sector combined function magnets, B = 1.8T, with field

index equal to 0.5, which gives the same focusing in the vertical and horizontal planes. Furthermore it gives vanishing contribution to the synchrotron radiation integral I_4 , thus minimizing the beam energy spread, which is enhanced by the high longitudinal phase advance and can be a limitation for the dynamic aperture [4].

The sign of the dispersion inside the dipoles is opposite to the bending radius' one: the contribution to the momentum compaction is negative from all the dipoles and large since the maximum of the absolute value of the dispersion function occurs inside the dipoles.



Figure 3: Betatron functions (left axis) and dispersion (right axis) in a cell (m)

The chromaticity is corrected by sextupole windings inside the quads, where the betatron functions are well separated. The phase advance per cell is similar in both planes and tunable by the quads.

STORAGE RING

The ring layout is similar to the DAFNE one, with a shorter inner arc composed of five cells and a longer outer one of seven (see Fig. 1). The rings cross in two points, one corresponding to the IP, the second one in the zone where RF cavities and injection will be placed. The minimum of the bunch length along the ring occurs at the position in which the longitudinal phase advance measured from the RF cavity is half the total one [4]: the R_{56} term of the first order transport matrix between the cavity position and the IP is equal on both sides of the ring. This is obtained by a slightly different behaviour of the dispersion in the short-arc and long-arc cells, as can be seen in Fig. 4 where the betatron and the dispersion functions along the whole ring are plotted. All high impedance elements (RF cavities, injection septa and kickers and feedback kickers) find their natural location in the long straight facing the IP, where the bunch is longer and the effect of impedances on beam dynamics less critical [2]. This zone is also used for the tuning of the betatron working point. In the second crossing point the beams are vertically separated, and so are the vacuum chambers, in order to eliminate any cross-talk between the two beams. The crossing angle is large enough $(\pm 13^{\circ})$ to separate the two beam lines in a short distance, with space for the RF system. Dispersion suppressors are placed between the arcs and the straights.

The Interaction Region [5] is 10 m long, with two sets of four symmetric quadrupoles, with $\beta_x^* = 0.5$ m, and β_y^* tunable between 2 and 4 mm. The Interaction Region is compatible with the present KLOE detector with minor modifications.

The main parameters of the ring are listed in table I.



Figure 4: Betatron functions (left axis) and dispersion (right axis) in m of the whole ring (IP is in the ring center) Table I: Main parameters

	r r
Parameters	
E (GeV)	.51
<i>C</i> (m)	114.2
$L(10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1})$	100
β * (m) (h / v)	0.5 / 0.0025
ϵ (µ rad) (h / v)	0.32 / 0.0013
$Q_{x/}/Q_{y}$	8.120 / 8.102
Q' _{x /} /Q' _y	-5. / -40.
σ_{z} (cm)	0.25-1.1
σ_{p}	1.1 10 ⁻³
$N_{b}(10^{10})$	5
ξ(h / v)	0.067 / 0.075
N bunches	160
I (A)	3.5
Uo (keV)	37
$\tau_x / \tau_y / \tau_s$ (msec)	10 / 10 / 5
f _{RF} (MHz)	500
V(MV)	10.
α_{c}	-0.167
μ _L (°)	152

SYNCHROTRON RADIATION AND STRONG RF FOCUSING PARAMETERS

The lattice can work with low RF voltage, or in SRFF regime. The choice of the best RF frequency is determined by the optimisation of the energy acceptance and the voltage level and 500 MHz fits the requirements.

By increasing the RF voltage, the ring enters in the SRFF regime. The longitudinal phase advance μ_L is:

$$\cos\mu_L = 1 - \pi \frac{\alpha_c C}{\lambda_{RF}} \frac{V_{RF}}{E} \tag{1}$$

The bunch length is shown in Fig. 5 for a weak focusing regime (V=1MV, μ_L =36°), and strong focusing one (V=10MV, μ_L = 152°). In the latter case σ_L = 2.5mm (*a*) IP with a modulation factor ~ 4. The corresponding energy spread in the first case is almost equal to the natural one (4.5 10⁻⁴) while it increases to 1.1 10⁻³ in the second.



Figure 5: Bunch length along the ring for 1 and 10 MV.

LUMINOSITY

The design single bunch geometric luminosity is very high thanks to the very small β_y^* . The bunch spacing is 2 nsec and crossing angle is necessary. Since the Piwinski angle Φ is very small thanks to the very short bunch a crossing angle of up to ±30 mrad is still safe, giving a geometrical reduction of the luminosity of about 2%. The beam-beam blow-up should be reduced thanks to the strong radiation damping. Single bunch luminosity of the order of 6.5 10^{31} corresponds to 22 mA per bunch, $\sigma_x=0.4$ mm, $\sigma_y=1.8$ m, $\sigma_L=2.5$ mm, $\Phi=0.19$, $\kappa=0.4$ %.

With these parameters and 160 bunches (17% ion clearing gap), the luminosity is about 10^{34} cm⁻²sec⁻¹. The total current per ring is 3.5 A (the maximum current stored up to now in DA Φ NE has been 2.4A in the e-ring).

DYNAMIC APERTURE

The dynamic aperture (DA) is governed by the high vertical natural chromaticity of the ring: $Q'_x \sim 5$, $Q'_y \sim 40$, so the vertical DA is more sensitive to different kind of imperfections[6]. The on-energy DA is large enough (around $20\sigma_x$ and $350\sigma_y$) and the structure can be used with both high and low synchrotron tunes without special efforts. However, the 6D tracking shows the significant reduction of the vertical aperture even for zero amplitude of synchrotron oscillation. The reason is the large momentum compaction factor and hence the large path lengthening due to the betatron oscillation [7]. Increasing of the synchrotron oscillation amplitude provides further shrinking of the dynamic aperture. This can be explained by synchro-betatron satellites excited by the horizontal dispersion in sextupole magnets. According to [8] the following main satellites are located close to the chosen betatron tune region: $2v_{x,y} \pm v_s = n$, $v_x \pm 2v_s = n$.

However the 3D DA can be improved by a careful choice of the working point: moving it closer to the integer resonance and farther from the region of dangerous satellites, longitudinal aperture around $8\sigma_E$ has been obtained (see Fig. 6). A further increase can be

obtained by the optimization of the lattice factors which define satellite band-with. For instance, in case of $2v_{x,y} \pm v_s = n$ this factor is [2] $\Delta Q_x \propto \hat{\delta} \left| \sum_k \left[(ml) \cdot \eta_x \cdot \beta_x \cdot e^{2i\psi_x} \right]_k \right|$,

and can be minimized by usign several sextupole families.



Figure 6: Horizontal and vertical DA in terms of σ_E

CONCLUSIONS

The increase by two orders of magnitude of the present performances of any accelerator is a very challenging task. In the case of a low energy collider this becomes really a very demanding process. A first analysis has shown that new concepts must be adopted to reach such a result. The idea of designing a collider on the strong rf focusing principle, together with the negative momentum compaction and the wiggling lattice covers in principle the required performances, but it needs experimental demonstrations. A first test of the negative α_c properties have been already done at DA Φ NE and if the foreseen developments will be positive the configuration can be adopted in the normal operation. A SRFF experiment has been proposed at DA Φ NE to demonstrate the regime feasibility. Many issues like for example the working point choice, the flexibility of the lattice, the background simulations, the continuous injection system due to the few minutes lifetime are still to be studied before this preliminary design becomes a real collider project.

- [1] C.Milardi and DAΦNE team, "DAΦNE Operation with the FINUDA experiment", these proceedings
- [2] A.Gallo, P.Raimondi, M.Zobov "The Strong RF Focusing: a Possible Approach to Get Short Bunches at the IP", Proceedings of the 31th ICFA Beam Dynamics workshop, SLAC, 2003
- [3] A.Gallo et al. "Strong RF Focusing experiment at DAΦNE", these proceedings.
- [4] C.Biscari, "Lattice for Longitudinal LowBeta", e-Print Archive: physics/0401029
- [5] M. Biagini, "Preliminary considerations for the Design of the Interaction Region", e-Print Archive: physics/0403117
- [6] E.Levichev, P.Piminov, M.Zobov "Preliminary results of the nonlinear beam dynamics simulation for the SRFF ring (DA Φ NE-II)", DA Φ NE note, in preparation
- [7] A.Piwinsky, A.Wrulich, DESY 76/07 (1976)).
- [8] A.Piwinski, DESY 93-189 (1993).

PROPOSAL OF A STRONG RF FOCUSING EXPERIMENT AT DA Φ NE

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Abstract

The strong RF focusing is a recently proposed technique to obtain short bunches at the interaction point in the next generation colliders. A large momentum compaction factor together with a very high RF gradient across the bunch provide a modulation of the bunch length along the ring, which can be minimized at the Interaction Point (IP). No storage ring has been so far operated in such a regime, since it requires uncommonly high synchrotron tune values. In this paper we present the proposal of creating the experimental conditions to study the strong RF focusing in DA Φ NE. The proposed machine lattice providing the required high momentum compaction value, the upgrade of the RF system including the installation of a multi-cell superconducting cavity, the upgrade of the cryogenic plant and a list of the possible beam experiments are illustrated and discussed.

INTRODUCTION

The required luminosity for the next generation "factory" colliders is from 1 to 2 orders of magnitude higher with respect to the present performances [1].

In flat beam colliders the luminosity can be increased by reducing the vertical beta-function at IP β_y to further squeeze the vertical beam size and decrease the effect of beam-beam interaction. This approach is effective only if the bunch length σ_z does not exceed the β_y value and the "hourglass" effect is avoided [2]. Bunch lengths of the order of 1 mm are needed, and this is very difficult to achieve with standard techniques.

Recently [3] a novel approach called Strong RF Focusing (SRFF) has been proposed to overcome this difficulty. It consists in combining highly dispersive lattices (providing momentum compaction factors α_c about 1 order of magnitude larger than usual) with very high RF voltages. This results in a regime where the bunch length is modulated along the ring, showing a maximum in the region around the RF section. Taking the position of the RF cavity as the origin s = 0 of the longitudinal reference frame, one gets:

$$\sigma_{z}(s) = \frac{\sigma_{E}}{E} \alpha_{c} L \sqrt{\frac{1}{2} \frac{1}{1 - \cos \mu} - \frac{R_{56}(s)}{\alpha_{c} L} \left(1 - \frac{R_{56}(s)}{\alpha_{c} L}\right)}$$
(1)

where L is the ring length, σ_E/E is the bunch relative energy spread, $R_{56}(s)$ is the path elongation from 0 to s normalized to the particle relative energy deviation, and μ is the one-turn synchrotron phase advance given by:

$$\cos \mu = 1 - \pi \frac{\alpha_c L}{\lambda_{RF}} \frac{V_{RF}}{E/e}$$
(2)

According to (1), the bunch is shortest at the azimuth s_{\min} where $R_{56}(s_{\min}) = \alpha_c L/2$. If the ring design is such that s_{\min} corresponds to the IP, one gets:

$$\frac{\sigma_z(IP)}{\sigma_z(RF)} = \sqrt{1 - \frac{\pi}{2} \frac{\alpha_c L}{\lambda_{RF}} \frac{V_{RF}}{E/e}} = \sqrt{\frac{1 + \cos\mu}{2}}$$
(3)

For μ values close to π the ratio between minimum and maximum bunch lengths can be very low. To correctly compute the bunch length values by means of (1) it must be noticed that the equilibrium energy spread σ_E/E in the SRFF regime is magnified by a factor G with respect to the unperturbed value $(\sigma_E/E)_0$, with G given by:

$$G^{2} = \frac{\oint \left[1 - (1 - \cos \mu) \frac{2R_{56}(s)}{\alpha_{c}L} \left(1 - \frac{R_{56}(s)}{\alpha_{c}L}\right)\right] \frac{ds}{\left|\rho(s)\right|^{3}}}{\oint \frac{ds}{\left|\rho(s)\right|^{3}}}$$
(4)

where $\rho(s)$ is the local bending radius.

The potentiality of the SRFF scheme is quite evident. It allows designing a collider where the bunch is extremely short at the IP and reasonably long elsewhere, especially near the RF cavities. Synchrotron light source can also benefit this scheme for time resolved experiments.

However, this idea has not been experimentally tested yet since none of the storage rings presently in operation can be pushed into this regime unless significant modifications in the lattices and/or in the RF systems are implemented. We are proposing to temporarily modify both the DA Φ NE lattice and RF system to make the first experimental observation and measurement of the bunch length modulation obtained with the SRFF scheme.

A SRFF EXPERIMENT AT DA Φ NE

The Φ -factory DA Φ NE is a double ring e⁺e⁻ collider working at the Φ resonance (1.02 GeV in the center of mass) in operation since 1999 at the Frascati National Labs of INFN [4]. A design study for a substantial upgrade of DA Φ NE aimed at increasing the luminosity by about 2 orders of magnitude is in progress [5] and relies mainly on the implementation of the SRFF scheme. An experimental proof of the feasibility of such a scheme is necessary to validate our approach to the luminosity upgrade and represents an important contribution to any other future project requiring very short bunches.

A list of the possible SRFF experimental activities that can be covered at DA Φ NE includes:

- Measuring the bunch length variation along the ring;
- Study the single bunch dynamics (effects of the distributed wake on the bunch length);
- Study the multibunch dynamics and the behaviour of the bunch-by bunch feedback system at very large synchrotron tunes;
- Study of the 3D coupled dynamics;
- Collisions of short bunches (with $\beta_v \leq 1 cm$);
- Study of the Coherent Synchrotron Radiation (CSR).

The goal is to demonstrate the SRFF effectiveness in various configurations, approaching as much as possible the operating conditions of a high luminosity collider: low current in a single bunch (I < 1mA), high current in a single bunch ($I \approx 10 \, mA$, to study the bunch lengthening process), high current in multibunch regime ($I \approx 0.5A$ in 60 bunches). The DA Φ NE parameters for the SRFF experiment are reported in Table 1.

Momentum Compaction	α_c	0.08
RF Frequency	f_{RF}	1288.973 MHz
RF Voltage	V_{RF}	7 MV
Harmonic Number	h	420 (= 3.5 x 120)
Long. Phase Advance	μ	$2\pi/3$
Natural Energy Spread	$(\sigma_E/E)_0$	$4 \cdot 10^{-4}$
Energy Spread	σ_E/E	6 · 10-4
@ $\mu = 2\pi/3$		
Bunch Length	σ_z	1.3 - 2.5 mm
RF Acceptance (IP/RF)	$(\Delta E/E)_{\rm max}$	7 · 10 ⁻³ / 5 · 10 ⁻³

Table 1: DA Φ NE parameters for the SRFF experiment

According to (3), a one-turn longitudinal phase advance $\mu \ge 2\pi/3$ is required to produce a bunch length variation of about a factor 2 or larger. A 50 % increase of the bunch energy spread is expected.

LATTICE DESIGN

The DA Φ NE layout is shown in Fig. 1. The extra SC cavity providing the very high voltage required by the SRFF scheme will be placed in one of the two Interaction Regions (IR2), while the KLOE experiment will remain installed in IR1. The optical functions of a possible solution for a high momentum compaction lattice $(\alpha_c = 0.08)$ are shown in Fig. 2, while the expected bunch length along the ring with and without the extra voltage provided by the SC cavity is reported in Fig. 3.



Figure 1: DAΦNE layout

All DA Φ NE quadrupoles are individually powered allowing a wide range of lattice flexibility. The high momentum compaction lattice is obtained with zero dispersion and dispersion derivative in both interaction points, and increasing the dispersion function only in the dipoles facing the two straight sections. A larger momentum compaction can be obtained by increasing the dispersion peaks in the zone near the wigglers and in the straight sections, but limitations in both physical and dynamical apertures begin to appear. Solutions for large and negative α_c values are also under study.



RF SYSTEM

According to (2), with $\mu = 2\pi/3$ and $\alpha_c = 0.08$, the ratio between the RF voltage and the RF wavelength (i.e. the RF slope) must be $V_{RF} / \lambda_{RF} \approx 30 MV/m$. Due to the very high RF slope required, the use of SC technology is mandatory. According to (5), high frequencies will require low voltages but will provide less RF acceptance. The use of the 1.3 GHz SC RF technology developed for TESLA is a good compromise. An RF voltage of 7 MV is necessary at that frequency, which can be safely provided by one 9-cells cavity powered at the moderate gradient of 7 MV/m. This choice is convenient and very compact.

The parameters of the SC RF system to be installed in DA Φ NE for the SRFF experiments are listed in Table 2.



Figure 3: Bunch length along the ring

Cavity type		SC TESLA like, 9 cells
R/Q geometric factor	R/Q	500 Ω
Quality factor (@ 1.8 K)	Q_0	$1\cdot 10^{10}$
Cavity wall power	P_{cav}	5 W
Loaded quality factor	Q_L	$2 \cdot 10^7$
Cavity detuning due to	Δf_{cav}	- 100 kHz
beam loading		(@ 7MV, I _b =1A)
RF generator power	Pgen	620 W
Cavity length	L _{cav}	1 m

The frequency of the SC cavity is about 0.85% lower than the standard TESLA one (1.289 GHz against 1.3 GHz) in order to be tuned on the 420th bunch revolution harmonic. Since the NC RF system of DA Φ NE is tuned on the 120th revolution harmonics, the two systems can operate simultaneously to store up to 60 equidistant bunches. In this way the standard NC RF system will provide the power to compensate the beam losses, while the SC system will provide the large focusing voltage over the bunch. The input coupler needs also to be modified in order to increase the external Q value to $Q_{ext} \approx 2 \cdot 10^{\prime}$. An RF power source of 1 kW is sufficient to power the cavity in this case.



Figure 4: 7-cells structure with large beam tubes



Figure 5: Damped propagating monopoles

Other modifications of the TESLA multicell cavity design are under study to decrease the number of the HOMs trapped in the structure. Reducing the number of cells and enlarging the beam tubes seems to be an effective approach. A 2D model of a 7-cells cavity with enlarged beam tubes is shown in Fig. 4. Only the 1st

monopole band remains trapped in this case. The other monopoles and the dipoles propagate in the beam tubes and can be damped by absorbing loads. The damped monopoles of the 2^{nd} and 3^{rd} band obtained with an HFSS simulation of the Fig. 4 model are reported in Fig. 5.

CRYOGENICS AND DIAGNOSTICS

The TESLA cavities have to be cooled with superfluid Helium at 1.8 K temperature. In the present configuration the DA Φ NE cryogenic plant supplies standard liquid Helium to the SC solenoids of the KLOE and FINUDA detectors, and to 4 small-size compensating solenoids placed on both sides of the two experiments. In order to produce superfluid Helium the plant needs to be upgraded. The SC cavity and cryostat will occupy the place of the FINUDA magnet, which has been already rolled out from the beamline. The FINUDA transfer line, now transporting 5.2 K and 70 K cold Helium, will be used to supply an interface box. Here the 1.8 K superfluid Helium will be produced by means of a pumping system directly connected to the Helium bath.

At present, the upgrade of the cryogenic plant is under study, in particular concerning the pumping system. The machine diagnostics has also to be upgraded. We have a 1.5 ps resolution streak camera looking at the sinchrotron light emitted by the first dipole after the short straight section. At least another sinchrotron light line has to be derived from one of the dipole magnets close to the KLOE IR to measure the bunch length in the region where it is shortest.

CONCLUSIONS

The proposal of a Strong RF Focusing experiment at DA Φ NE has been presented. A suitable high momentum compaction lattice ($\alpha_c = 0.08$) has been designed and will be experimentally tested by the end of this year. The very high RF voltage required by the SRFF scheme will be provided by a TESLA-like SC cavity placed in the 2nd interaction region.

The RF design of the cavity is in progress. If the proposal will be funded, the mechanical design of the cavity and its cryostat will start immediately and we expect to complete the construction of these items in 2 years. Meanwhile, the DA Φ NE cryogenic plant will be upgraded to provide 1.8 K liquid Helium to the cavity.

We have a two-months experimental activity plan for the end of 2006. The bunch length variation along the ring will be measured by means of a streak camera sampling the bunch length at least in t w o different positions. Storing high current (in the 0.5 A range) in multibunch mode in this regime is another important goal.

- [1] P. Raimondi, FRXBCH02, this conference
- [2] G. E. Fisher, SPEAR Note 154, SLAC, Dec. 1972
- [3] A. Gallo et al., e-Print Archive: physics/0404020
- [4] C. Milardi, THOBCH02, this conference
- [5] C. Biscari, MOPLT056, this conference

STATUS OF CTF3 STRETCHER-COMPRESSOR AND TRANSFER LINE

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Abstract

The first part of the CTF3 transfer line is already installed. It includes a chicane in which, because of its very flexible lattice and large aperture vacuum chamber, the bunch length can change in a wide range. The chicane can be used as a stretcher to lengthen the pulses coming from the linac in order to reduce the coherent synchrotron radiation (CSR) in the recombination rings. A possible use as a bunch compressor is also foreseen in order to make CSR experiments and to characterize beam instrumentation. This paper describes the final design of the vacuum chambers, including beam diagnostics components, and their laboratory tests. The installation status of the magnetic and vacuum chamber components together with the ancillary systems is reported.

INTRODUCTION

The Compact Linear Collider (CLIC) project is a multi-TeV electron-positron collider for particle physics based on the two-beam acceleration concept; a high-intensity drive beam powers the main beam of a high-frequency (30 GHz) linear accelerator with a gradient of 150 MV/m, by means of transfer structure sections [1].

The aim of the CLIC Test Facility (CTF3) is to make exhaustive tests of the main CLIC parameters. An international collaboration participates to the construction of the machine and the LNF contributes to the realization of a large part of the recombination system, consisting in two rings which will multiplicate the bunch frequency and peak current by a factor of ten [2,3].

CTF3 is under construction in the LEP preinjector complex existing building at CERN. It uses where possible the existing magnets, power supplies, equipments and ancillary system.

TRANSFER LINES

The first part of the INFN Frascati contribution to CTF3 project is the transfer line that join the Linac to the diagnostic station and to the spectrometer line. It is already installed in the experimental area. The layout is shown in Fig. 1.

Transfer lines design

The main part of the transfer line is a magnetic chicane that can be used as stretcher, isochronous line or compressor.

In the nominal configuration it will stretch the bunch length to lower the peak current before entering in the recombination rings in order to reduce the effects of the coherent synchrotron radiation emission and impedance that increase the energy spread of the beam. It can be used for experimental purpose as a bunch compressor, to study the effect of the coherent synchrotron radiation on very short bunches and high charge. It can also be used in the isochronous mode without changing the longitudinal beam distribution.

There is also a by-pass in which the beam can be transported, in the case that the chicane will not be used (see Fig.1).

The chicane has a symmetric design with four dipoles and seven quadrupoles. The tunability in the R_{56} transport matrix term is between +50, -30 cm, that allows to vary the bunch length in a very wide range, according to the energy spread of the beam and the longitudinal phase space correlation at the Linac exit.

The chicane is joined to the Linac exit by a line where a quadrupole triplet matches the optical function to the chicane input. A symmetric line follows the chicane, and the corresponding triplet can be independently powered, to add flexibility in the operation.

Because of the choice of reusing existing magnets the constraints in gradient, gap and external size must be taken into account.

Vacuum chamber and magnets

The vacuum chamber shape has been dictated by the beam stay clear considerations together with the overall optimisation of the available element position.

The vacuum chambers of the straight sections including the by-pass have round section with 40 mm stay clear aperture diameter. The beam position monitors (BPMs) design developed at CERN [4] and the small aperture quadrupole magnets, used in the Linac, are used in this section.



Figure 1: Transfer Line Layout.

The chicane vacuum chamber design follows the requirements of the beam taking into account the following constraints:

- the dipoles are the old EPA transfer line ones, and the vertical size of the corresponding vacuum chamber is the maximum possible compatibly with the magnets gap.
- the horizontal size of the chicane vacuum chamber is tapered with a maximum of the value at the chicane center, which corresponds to the highest dispersion function in the configuration of negative R₅₆.

For all the vacuum chamber components, like shielded bellows, pumping port sections, beam position monitors, we use the same design already developed for the Delay Loop and the Combiner Ring [5,6].

The vacuum chamber inner transverse dimensions must not present strong discontinuities in order to reduce the energy spread degradation due to the beam coupling impedance. The chicane vacuum chamber starts with round profile 40 mm diameter. In the first dipole it is splitted in two branches; the first curves to the chicane line, the second goes straight to the by-pass line.

After the first dipole one BPM, Linac type, is used, followed by a small quadrupole, then a tapered chamber change the beam stay clear aperture from 40 mm round to $90x37 \text{ mm}^2$ dimension, which is the size of the combining ring vacuum chamber. A square shape pumping port and a bellow are placed before the second dipole and a BPM is installed after the dipole before the straight.

Using a large aperture quadrupole magnet this straight vacuum chamber doubles its inner transverse dimensions on the horizontal and vertical plane at the central point, by means of two long tapers, and allow a wide variation of the beam size.



Figure 2: Dipole vacuum chambers under test.

The same components are symmetrically installed with respect to the chicane central point. The vacuum chamber of the third and fourth dipole have synchrotron radiation view ports which will be used for optical beam measurements.

All vacuum chambers are in aluminium, with the exception of the bellows and BPMs, and have been tested in the INFN laboratories before the shipment to CERN.

They all achieved a static pressure better than 5×10^{-10} Torr after the heating cycle at 150 0 C.

Measurement station

The installed transfer line is terminated with a measurement station that includes the spectrometer line.

The diagnostic equipments, that we describe in the following paragraph, are:

- RF deflector for the bunch length measurements.
- Beam position monitors.
- Beam profile monitor using OTR screen.
- High frequency current monitor.
- Spectrometer for energy and energy spread measurements.

These diagnostic tools are realised by CERN except for the RF deflector; this is the 3 GHz structure realised by INFN for the Combiner Ring and successfully used in the CTF3 Preliminary Phase [7].

BEAM MEASUREMENTS

The diagnostic tools of this transfer line are redundant and each beam measurement will be performed with at least two different methods.

Emittance measurements

Two emittance measurements systems are foreseen in this transfer line: in the OTR beam profile monitor the beam passing in the screen produce the image that is collected by an optical system on a CCD camera and captured and analysed by a frame grabber [8]. The emittance measurement is performed with the quadrupole scan method, acquiring the transverse beam distribution for different current sets of the quadrupoles.

The second emittance measurement is done with a synchrotron radiation monitor: the synchrotron radiation produced by the beam in the bending magnets escapes the vacuum chamber from optical windows with the maximum transmittivity in the visible range, in two positions: one in a point in which the value of the dispersion function is close to zero to perform the emittance measurement; the other one in a high dispersion point. The synchrotron radiation is collected by an optical system to a CCD camera; the video signal is digitised by a frame grabber and analysed.

Bunch length

Two alternative methods are also foreseen for the bunch length measurement. The synchrotron radiation produced in the dipole is sent to a streak camera with 2 ps resolution via an optical transfer line. The bunch length is directly determined measuring the light pulse distribution.

An alternative measurement will be also performed using an RF deflector in which the bunches of the train pass in the zero crossing point of the deflecting field.

The head and the tail of each bunch receive opposite kicks in the vertical direction; the bunch length measurement can be determined by the vertical distribution of the image create on an OTR screen.



Figure 3: Installed chicane fish-eye picture

Looking at a second OTR screen placed after the spectrometer dipole, the longitudinal phase space can be reconstructed. The expected resolution will be better than 0.5 ps. This system is described in a dedicated paper in these proceedings [9].

The RF deflector is the 3 GHz structure realised by INFN for the injection test of the CTF3 preliminary phase and that will be used in the second ring of the recombination system (Combiner Ring).

Energy measurements

The energy and energy spread can be measured with three systems.

The first is a classical spectrometer line placed at the end of the described transfer. The energy of the beam is determined measuring the position of the centre of mass of the beam on an OTR screen, knowing the magnet current; the beam energy spread is given by the horizontal transverse distribution. The bending angle, the OTR screen distance and the vacuum chamber aperture have been chosen in order to have the possibility to measure energy spreads up to OE/E=5%

An independent measurement of the energy spread will be performed making the imaging of the horizontal beam distribution with synchrotron radiation emitted from the beam in a high dispersion function point. The synchrotron light is extracted from a channel tangent to the third dipole vacuum chamber of the chicane and collected, acquired and analysed with a system similar to the emittance measurement system described before.

Finally also the RF deflector used for the longitudinal phase space characterization can be used as a spectrometer, shifting the phase of the deflector to make the beam pass on the crest of the field.

Current measurement

Current measurements will be done with the two wide band current monitors described in [10] placed at the exit of the Linac and before the spectrometer line. These measurements interlock the safety system because when part of the beam is lost an interlock system is activated.

Eight BPMs have been installed along the line to allow beam trajectory reconstruction. As an option, the beam current along the line can be derived from the sum of the signals coming from strip-lines of the BPMs.

CONCLUSIONS

The first part of the transfer line is almost ready for the commissioning. The Linac will be characterized measuring the beam parameters. The manipulation of the Linac bunches with the chicane will be tested. Direct and indirect measurements on CSR and its effect versus the bunch length and current are also foreseen.

AKNOWLEDGMENT

We thank G. Fontana, V. Lollo, A. Zolla for the project of the components, the layout, and supervision during hardware installation at the CERN site; all the Accelerator Division technical staff for the technical support and in particular the vacuum and alignment group components for the laboratory tests and the help in the final installation and tests; the CERN researchers for the continuous discussions on all aspects of the project; T. Chritin for helping us to interface CERN and INFN mechanical projects and Guy Yvon that made possible our installation.

- G.Guignard (ed.) et al., "A 3 TeV e+e- linear collider based on CLIC technology", CERN 2000-008.
- [2] G.Geschonke, A.Ghigo (ed.) et al., "CTF3 Designe Report", CERN/PS 2002-008(RF), LNF-02/008 (IR).
- [3] D.Alesini et al., "CTF3 compressor system", Proceedings of EPAC 2002, Paris, France
- [4] M.Gasior, "An inductive pick-up for beam position and current measurements", Proceedings of DIPAC 2003, Mainz, Germany. CERN-AB-2003-053 BDI.
- [5] A.Ghigo et al., "CTF3 Prototypes: design, test and measurements", Proceedings of PAC 2003, Portland, Oregon, USA.
- [6] A.Stella et al., "Design of a beam position monitor for the CTF3 combiner ring", CTFF3-008, Accelerator Division Technical Note, INFN-LNF 2002.
- [7] D. Alesini et al., "RF beam deflectors for CTF3 combiner ring", Proc. of EPAC 2002, Paris, France.
 [8] C.Bal et al., "CTF3 injector profile monitor", CTF3
- [8] C.Bal et al., "CTF3 injector profile monitor", CTF3 Note 065 (Tech), 2004.
- [9] D. Alesini et al., "Longitudinal phase space characterization of the CTF3 beam with RF deflector", these proceedings.
- [10]P.Odier, "A new wide band wall current monitor", Proceedings of DIPAC 2003, Mainz, Germany. CERN-AB-2003-063 BDI.

DESIGN OPTIONS FOR THE RF DEFLECTOR OF THE CTF3 DELAY LOOP

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Abstract

Injection and extraction of bunch trains in the CTF3 Delay Loop for the recombination between adjacent bunch trains is performed by a specially designed RF deflector. A standing wave structure has been chosen. Three possible solutions have been studied and designed, and a comparative analysis is presented. All of them satisfy the essential requirements of the system up to the maximum foreseen energy with the existing klystron.

INTRODUCTION

The process of bunch train compression in the DL is illustrated in Fig. 1 and more details can be found in [1].



Figure 1: Sketch of the bunch frequency multiplication in the CTF3 Delay Loop.

Even and odd trains are deflected by kicks of the same amplitude but opposite sign. Only the even trains are injected into the ring so they are delayed to interleave the following odd train.

The frequency of the Delay Loop deflector (1.4995 GHz) has to be half the linac frequency as described in Fig 1. Other design parameters are the required deflecting angle, which is about 15 mrad, the maximum beam energy (300 MeV) and the RF power that the klystron can provide to the deflecting structure. The klystron is already available and its output power is 20 MW.

According to these specifications, a travelling wave (TW) type deflector should be a structure about 1.5 meter long, but this in not compatible with the available space and the large angles of the beam trajectories. So the adoption of a standing wave (SW) solution is necessary. In fact, the efficiency (i.e. the deflection obtainable with a given RF power) per unit length is higher for SW than for TW structures.

The major drawback of this choice is due to the fact that the voltage filling time of a resonant cavity is generally slow if compared to the RF pulse length (5μ s). So the deflecting field is not constant during the passage of the train in the cavity and different bunches in the train sees different kicks. In order to reduce this spread of deflection angle between the head and the tail of the train, the Q of the cavity has to be reduced and this can be done externally loading the resonator. In Fig. 2 it is shown the time domain response of the cavity to a step pulse of 5μ s. The cavity Q is about 3000. The length of the train of bunches is also indicated and the resulting voltage spread is less than 1%, that is considered an acceptable value [2]. On the other hand it is not possible to further decrease the value of Q. Beyond a certain threshold the shunt impedance become too low and the field intensity in the cavity is no more sufficient to give the required angle to the beam.



Figure 2: Cavity voltage as a function of time.

POSSIBLE SCHEMES

Three possible solutions of a SW defector have been studied and their layouts are schematically represented in Fig. 3.

The first solution considered is the most standard one. A single cavity is excited through a coupling hole. The hole dimensions set the external Q of the cavity and its filling time as a consequence. A circulator has to be foreseen to protect the klystron from the power reflected at the cavity input.



The second solution is based on the SLED principle used in the linac technology [3] and consists of two cavities coupled through a hybrid junction. The power reflected by the cavities adds out of phase at the klystron port of the hybrid, so there is no need of circulator and in phase at its fourth port, where it is dissipated on an external load. The two cavities system is also more efficient for a factor $\sqrt{2}$ unless to use a double cell cavity in the previous scheme.

Finally, as third solution, a double cell cavity again is considered, but provided with two coupling holes of different size. On the side of the larger hole is connected the klystron, while on the other side is connected a load.



Figure 4: Scattering parameters of the option C cavity.

Tuning separately the size of the two holes it is possible to have no reflection at the klystron port for a pure sinusoidal excitation. In Fig. 4 it is shown that the reflection parameter S_{11} at the klystron port (blue line) is zero at the working frequency, therefore the input coupling coefficient is $\beta=1$ in this case. At the same time the desired value for Q (~3000) has been obtained.

Each of the three structure proposed seems to be able to satisfy the essential requirements of the system. Driving the deflectors with the already commissioned klystron, the right angle of deflection can be obtained for beams of energy up to twice the nominal energy.

SCHEMES EVALUATION AND THEIR COMPARISON

Another problem, arising with standing wave structure in this kind of utilization, is due to the RF power reflected at the cavity input back to the klystron. The need to overcouple the cavity (β >1) implies that the reflection coefficient is different from zero for the options *A* and *B*. In the examined case with β =5.6, the reflection coefficient is ρ =0.7, i.e. the 49% of the incident power is reflected back.



Figure 5: Time domain cavity response to a step input. Left: $\beta > 1$; Right: $\beta = 1$.

(Blue - RF input pulse. Red - cavity reflected power).

Moreover, when used in pulsed regime, the level of the reflected RF power is not a constant during the pulse length. Peaks of reflections are present correspondently to the transients of the pulse. The height of this peak depends on the loaded Q of the cavity and on the pulse rise time.

Fig. 5 shows the time dependence of the RF reflected power for two arbitrary slopes of the input pulse. This behavior is illustrated for both the cases $\beta > 1$ (option *A* and *B*) and $\beta=1$ (option *C*).

The klystron needs to be isolated respect to this reflected power and, according to a conventional scheme, this is generally done by the use of a circulator. The first proposed solution is based on this scheme. Since the circulator is an expensive device it is preferable, if possible, choosing one of the two remaining options.

In the scheme of option C the amount of reflected power is considerably lower than in the other two, but, even with very slow rise time, the peak of reflections are scarcely below the tolerable klystron threshold. It has been considered too hazardous for the system reliability that the klystron was subjected to these repeated stresses; therefore this solution has been rejected.

On the contrary, in the scheme examined as second option, the reflected power cannot reach the klystron and it is dissipated on a load. From this point of view the hybrid junction has the same function of the circulator.

Finally, although two ceramic windows are necessary in this scheme instead of one, they can be dimensioned to be able to support half of the RF power respect to the scheme of option A.

From all these considerations the solution proposed as option *B* appears very promising and it has been decided to develop it more in detail.

DEFLECTOR DESIGN

The cavity design

The cavity is externally coupled to a rectangular waveguide (WR650, the same standard of the klystron output) through a hole. The hole dimensions set the input coupling coefficient β and they have been chosen to obtain the wanted cavity loaded Q.



Figure 6: HFSS simulation: the loaded cavity geometry.

In Fig. 6 the geometry, which models the cavity coupled to the waveguide, used as input for HFSS [4] simulations is shown. From simulation results it is
possible to calculate the deflecting field seen by a particle crossing the cavity gap. In Fig.7 it is shown a representation of the magnetic field on the middle symmetry plane of the structure. The cavity, fed from the waveguide, resonates in the deflecting working mode, the TM_{110} .

Parasitic modes of the cavity can be excited by the beam. Apposite simulations have proved that the resonant frequencies of the modes most dangerous for the beam dynamics (monopoles and dipoles) are far enough from the lines of the beam power spectrum.

In particular, the vertical polarization of the TM_{110} results more than 40MHz apart from the horizontal one as it is visible in Fig. 8.



Figure 7: H field configuration of the TM_{110} mode in the deflecting cavity and in the feeding waveguide.



Figure 8: HFSS results: resonant frequencies of the vertical and horizontal polarization of the TM_{110} mode.

The whole deflector design

The following step it has been to design a hybrid 3 dB coupler having well balanced outputs, no reflections at the input and a decoupled fourth port.

The hybrid splits the power coming from the klystron in equal parts at the two ports connected to the cavities. The phase relation between the voltages at these two ports is 90°, so the cavities are fed 90° out of phase each other. Then the cavities have to be placed an odd multiple integer of $\lambda/4$ of the RF wavelength apart along the beam line in order that the kicks they deliver to the beam sum up in phase. For reasons of space the distance between the gaps has been chosen 250mm, i.e. $5/4\lambda_{RF}$.

Finally the feasibility of this innovative solution has been checked by means of simulations with HFSS code. Fig. 9 shows the full geometry used in the simulations.



Figure 9: Model of the whole deflector structure.



Figure 10: HFSS results: deflector frequency response; (Red – reflection at the klystron port.

Green – transmission between klystron and load ports).

In Fig. 10 are reported the results concerning the frequency response of the whole deflector structure. The peak in transmission (see S_{21} curve) between klystron and load ports is due to the power dissipated into the structure, while the not completely flatness of the reflection response (S_{11}) is probably caused by some small residual mismatches. However the effect of these mismatches is below the threshold reported in the klystron data sheet.

CONCLUSIONS

Three different schemes to realize the RF deflector of CTF3 Delay Loop has been considered, studied and compared. The chosen solution fulfils all the requirements; first of all, it is able to provide the large angle of deflection needed and it has a bandwidth large enough for responding rapidly to the klystron pulse. Furthermore, the novelty of the idea makes the design very interesting and stimulating.

- [1] "CTF3 Design Report", CERN PS 2002-008 (RF), Geneve, (2002).
- [2] D. Alesini, F. Marcellini, "Beam Loading in the RF Deflector of the CTF3 DL", proc. of this conference.
- [3] Z. D. Farkas et al, "SLED: A Method of Doubling the SLAC's Energy", SLAC-PUB-1453 (1974).
- [4] http://www.ansoft.com/products/hf/hfss/.

DESIGN STUDY FOR ADVANCED ACCELERATION EXPERIMENTS AND MONOCHROMATIC X-RAY PRODUCTION @ SPARC

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Abstract

We present a design study for an upgrade of the SPARC photo-injector system, whose main aim is the construction of an advanced beam test facility for conducting experiments on high gradient plasma acceleration and for the generation of monochromatic Xray beams to be used for applications like advanced medical diagnostics and condensed matter physics studies. Main components of the proposed plan of upgrade are: an additional beam line with interaction regions for synchronized high brightness electron and high intensity photon beams (co-propagating in plasmas or counter-propagating in vacuum) and the upgrade of the SPARC Ti:Sa laser system to reach pulse energies in excess of 1 J. Results of numerical simulations modelling the beam dynamics of ultra-short bunch production, based on a slit-selection technique combined with double RF deflection, are presented. Calculations of the monochromatic X-ray beam angular and frequency spectra, generated via Thomson back-scattering of the SPARC electron beam with the counter-propagating laser beam, are also presented. X-ray energies are tunable in the range 20 to 500 keV, with pulse duration from sub-ps to 20 ps. The proposed time schedule for this initiative, tightly correlated with the progress of the SPARC project, is finally shown.

INTRODUCTION

The SPARC photo-injector under installation at INFN-LNF will provide an ultra-bright electron beam at 150 MeV kinetic energy for the investigation of a SASE-FEL experiment, as extensively described elsewhere [1]. The beam is expected to be delivered in bunches of up to 1.1 nC of charge, rms normalized projected emittance smaller than 2 mmmrad, rms energy spread smaller than 0.2 % with rms bunch length of about 2-3 ps (uncompressed beam). The electron bunches will exit the photo-injector with 1 ps time jitter w.r.t. laser pulses: these are produced by a synchronized mode-locked Ti:Sa laser system delivering 20 mJ pulses in the IR (800 nm) at 10 Hz repetition rate, which are converted to UV (266 nm) to drive the electron beam production by hitting a photocathode located inside a RF gun. The foreseen availability of a bright electron beam and an intense synchronized laser is an ideal combination to pursue experiments by exploiting the interaction of the two beams (electrons and photons) either co-propagating or colliding them. High gradient plasma acceleration or mono-chromatic bright X-ray beam production in Thomson sources are noticeable examples of these beam interactions. For both of them a TW peak power laser beam and ultra-short (sub-ps) electron bunches are required. An upgrade of SPARC aimed at addressing these issues must conceive the development of 3 key components: the laser must be further amplified to reach the level of a few Joule of energy per pulse, the photoinjector has to be provided with an additional transport beam line to serve the interaction region, a dedicated diagnostic and control system has to be developed to operate the beam interaction efficiently. The Ti:Sa SPARC laser system will be installed starting this fall: it will comprise a diode-pumped 150 fs oscillator, a solidstate pumped regenerative amplifier (2 mJ) and a flashpumped multi-pass amplifier (20 mJ). We foresee to upgrade the laser in two steps: a first multi-pass amplifier to reach the level of 200 mJ energy per pulse with in air compressor down to 100-200 fs pulse length, and a second multi-pass amplifying stage, to reach the 1-3 J energy per pulse, equipped with in vacuum compressor to hold the 10-30 TW peak power delivered at this final stage. Since the specified time jitter for the SPARC laser system is smaller than 1 ps (with 0.5 being the desired value), we can foresee to achieve the correct space-time overlap of the colliding electron and laser pulses in the final focus region of the Thomson source for monochromatic X-ray production as far as the electron bunch is



Figure 1: Lay-out of SPARC photo-injector and SASE-FEL experiment with additional double dog-leg beam line

the standard uncompressed beam delivered by the SPARC photo-injector (2-6 ps rms bunch length). For the interaction of ultra-short pulses (rms length smaller than 0.5 ps) we need to improve the synchronization level between the two beams. The anticipated beams that we aim to deliver with the SPARC advanced beam facility are listed in Table 1, which contains the main beam parameters of interest, like bunch charge, kinetic energy, rms bunch length, normalized transverse emittance and energy spread (numbers in bold mark the most critical beam parameter for the specific application). The FEL-SASE application requires a very small emittance beam with peak current in excess of 100 A (hence the 1 nC bunch charge at a few ps rms bunch length), the plasma acceleration experiment (exploited by sending the laser into a gas jet to drive a plasma wave in a synchronized fashion to the ultra-short electron bunch injected in phase into the plasma wave for further acceleration) needs ultrashort bunches, while the Thomson source needs very small energy spread beams to avoid chromatic aberrations in the final focus system where the beam is focused down to sub-10 µm spot sizes to collide with the laser beam.

Application	Q	Т	σ_{t}	ε _n	σ_{γ}/γ
	(nC)	(MeV)	(ps)	(µm)	(%)
FEL-SASE	1	150	3	2	0.1
Plasma-Acc.	0.025	100	0.025	0.1	0.2
X-Thomson	1	30 -150	6-3	2	0.05 -0.2

Table 1: anticipated beams @ SPARC

TRANSPORT BEAM LINE

The lay-out of the SPARC photo-injector with additional transport beam line is plotted in Fig.1: the 3 linac sections, embedded in solenoids, launch the beam

through a triplet, followed by the first RF deflector, a double bend dog-leg containing a beam collimator (a slit in the beam vertical plane) and the second RF deflector, taking the beam into a final quadrupole triplet to apply final focusing in the interaction region. While the beam for the Thomson source is transported unchanged through the dog-leg, the ultra-short bunch is produced by properly selecting a thin slice (25 µm) of the SASE-FEL beam produced at 150 MeV by the SPARC photo-injector. The slice selection is accomplished as follows: the first RF deflector induces a correlation between vertical position of each bunch slice at the slit position (located at the symmetric plane of the double dog-leg) and its longitudinal coordinate within the bunch, the slit clips a specific slice, finally the second RF deflector removes the time-z correlation imparted by the first deflector. It should be noticed that this technique is somewhat similar to the one proposed[2] for LCLS with the aim to generate fs long electron bunches, but it differs from that in the use of RF deflectors, which remove the need of correlated energy spread (energy vs. slice position within the bunch).



Fig. 2: beam distribution in (x,y) along the beam line

The beam density distribution in the transverse (x,y) plane is plotted in Fig.2, at 4 different positions along the beam line, *i.e.* at the photo-injector exit (upper left diagram), after the first RF deflector (upper right), after the slit (lower left) and after the second RF deflector and the final focusing triplet: the focal spot sizes are 7 and 2 μ m (in x and y respectively) while the bunch rms length is 25 μ m (25 pC of bunch charge selected through the slit, simulations performed with PARMELA and ELEGANT). The longitudinal phase spaces are shown in Fig.3.



Fig. 3: beam distribution in $(\delta z, \delta p/p)$ before and after the double dog-leg with 2 RF deflectors and slit

THOMSON SOURCE

The collision of a relativistic electron beam and a powerful laser gives rise to X-ray photons generated via the Thomson back-scattering effect (when the energy of the emitted photon is much smaller than the electron rest mass energy, i.e. recoil effects are negligible). The energy w_x of the emitted X-ray photon is given by $w_x = w_{las} \left(1 - \beta \cos \alpha_l / 1 - \beta \cos \vartheta_{ob} \right)$, where w_{las} is the laser photon energy (1.5 eV for our case), α_1 is the colliding angle and ϑ_{ob} the observation angle. Head-on collisions ($\alpha_l = \pi$) observed on axis ($\vartheta_{ob} = 0$) give rise to X-ray photons of energy $w_x = 4\gamma^2 w_{las}$. A relevant range of energy is around 20 keV, in particular for advanced clinical diagnostics applications. Applying head-on collisions, which maximize the X-ray beam flux, it turns out that the electron beam energy must be 30 MeV, much smaller than the nominal SPARC value for which the photo-injector has been designed. Therefore, we had to derive a different operating point for the photoinjector, based on the launch of a longer bunch at the photo-cathode (30 ps laser pulse length, 1 nC, cathode spot size 0.6 mm) at lower phases, which generates a 20 ps electron bunch at the gun exit due to a weak bunching effect in the gun. The beam is accelerated by the first linac section up to 30 MeV, the second linac section is run at zero phase to remove the correlated energy spread while the third section is turned off. The combined effects of longitudinal wake-fields and a 4th harmonic X-band cavity are used to correct the longitudinal emittance by removing the RF curvature, thus achieving a final rms

energy spread lower than 0.05%. The transverse and longitudinal beam dynamics through the photo-injector are shown in Fig. 4 and Fig.5, respectively (simulations performed with ASTRA). A final lens focuses down the 30 MeV beam to a 10 µm spot size at the collision point.



Fig. 4: 30 MeV beam for Thomson source: transv. dyn.



Fig. 5: 30 MeV beam for Thomson source: longit. dyn.

The estimated energy spectrum of the X-ray beam generated by colliding the electron beam with a 3 J laser pulse, 3 ps long and focused down to a spot size of 20 μ m, is shown in Fig. 6. 2·10⁸ X-ray photons per collision are produced with 5% rms energy spread within a solid angle defined by $\vartheta_{ob} = \pm 6 \ mrad$.



Fig. 6: X-ray beam energy spectrum

- D. Alesini et al., "Status of the SPARC Project", this conference, see also D. Alesini et al., in publication on *NIM-A* 21566
- [2] P. Emma et al., Phys. Rev. Lett. 92, 074801-4.

THE DESIGN OF A PROTOTYPE RF COMPRESSOR FOR HIGH BRIGHTNESS ELECTRON BEAMS

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Abstract

The generation of high brightness electron beams with longitudinal length less of 1 ps is a crucial requirement in the design of injectors for new machines like the X-ray FEL facilities. In the last years the proposal to use a slow wave RF structure as a linear compressor in this range of interest, to overcome the difficulties related to magnetic compressors, has been widely discussed in the accelerator physics community.

In this paper we will review the work carried out in the last 2 years and focused on the design a RF compressor based on a 3 GHz copper structure. The rationale of the conceptual design along with a description of the main experimental activities will be presented and a possible application of such a scheme to the SPARC project will be discussed.

INTRODUCTION

The strategy to attain high brightness electron beams delivered in short (sub picosecond) bunches is based on the use of RF Linacs in conjunction with RF laser driven photo-injectors and magnetic compressors. The formers are needed as sources of low emittance high charge beams with moderate currents, the latter are used to enhance the peak current of such beams up to the design value of 2-3 kA by reduction of the bunch length achieved at relativistic energies (> 300 MeV). Nevertheless problems inherent to magnetic compression such as momentum spread and transverse emittance dilution due to the bunch self-interaction via coherent synchrotron radiation have brought back the idea of bunching the beam with radio-frequency (rf) structures.

Such a type of bunching (named velocity bunching) has been experimentally observed in laser driven rf electron sources[1]. Velocity bunching relies on the phase slippage between the electrons and the rf wave that occurs during the acceleration of non ultra relativistic electrons.

It has been recently proposed to integrate the velocity bunching scheme in the next photoinjector designs using a dedicated rf structure downstream of the rf electron source [2]. The basic idea is to develop a rectilinear RF compressor, based on slow wave RF fields, that works indeed as a standard accelerating structure which simultaneously accelerates the beam and reduces its bunch length.

BASIC RF RECTILINEAR COMPRESSOR THEORY

The figure of merit for the compression may be defined as the ratio between the initial phase spread and the final one at the extraction. A simple model for the compression process may be developed analyzing the motion equations for an electron travelling in a rf structure. The phase extent at the extraction is a function of the initial energy spread and of the phase at the injection. A suitable tuning of the latter will result in an increase of the compression value.

A remarkable improvement of this scheme may be obtained whenever a beam, slower than the synchronous velocity, is injected into an rf structure at the zero acceleration phase, allowing it to slip back in phase up to the peak accelerating phase, and is extracted at the synchronous velocity.

A detailed mathematical treatment of this process may be found elsewhere [2]. The basic behaviour of the RF compressor may be easily understood thinking about an iris loaded TW structure designed to sustain a wave whose phase velocity is slightly lower than c (i.e. where

we have that
$$k = k_0 + \Delta k = \frac{\omega}{c} + \Delta k$$
 with the detuning

parameter. $\Delta k \ll k_0$). In such a structure the velocity of the beam will match that of the wave when the resonant beta and gamma can be well approximated by the

expressions:
$$\beta_r = 1 - \frac{c\Delta k}{\omega}$$
 and $\gamma_r = \sqrt{\frac{\omega}{2c\Delta k}}$, where

beta r is the normalized phase velocity of the wave.

If beta_r is smaller than 1 the beam may advance in phase (i.e. slip forward on the wave) and the phase contour plots in the $[\gamma,\xi]$ phase space (ξ is the phase of the wave as seen by the beam) become closed curves. Figure 1 shows the phase compression picture achieved assuming the injection at $\xi=0$ and the extraction at $\gamma=\gamma_r$. The analytical expression for this phenomena becomes

$$\frac{1}{\gamma_r} - \alpha \cdot \cos(\xi_{ex}) = \gamma_0 - \beta_r \sqrt{\gamma_0^2 - 1} - \alpha \tag{1}$$

which shows that the extraction phase ξ_{ex} is a function of the injection conditions and the wave parameters. Using this expression it may be shown that compression values in excess of 9 may be obtainable and that the whole

compression process may be tunable in this range acting on the wave parameters.



Fig. 1: Phase space plots of a slow RF wave

A PROTOTYPE SLOW WAVE RF COMPRESSOR

In 2003 we started a two years development program aimed at the design and construction of a slow wave TW structure which can be used as a prototype for a RF compressor.

The Italian SPARC injector project [3], whose target is the development of an ultra-brilliant beam photo injector for future SASE FEL based X ray sources, foresees the possibility to use a source like the one

above discussed and we used its parameters as a general reference to define the scientific case to study. Table 1 shows the main parameters which we used for our investigations:

Parameter	Value
Frequency of the wave structure	2856 MHz
Linac structure	TW
Accelerating gradient	20 MV/m
Initial energy	5.7 MeV
Extraction energy	14 Mev
Compression factor (at 130 MeV)	7
RF pulse repetition rate	1÷10
Bunch length	10 ps

Table 1: Reference parameters for the study of the RF compressor

The expression (1) shows that the rf structure parameter which provides the metric of the compression process in a slow wave structure is the phase velocity (vf). In an iris loaded TW structure the phase velocity may be expressed as:

$$\frac{dv_f}{v_f} = \frac{df}{f} \cdot \left(1 - \frac{v_f}{v_g}\right)$$

The above relation shows that the v_f can be controlled by changing the excitation frequency or, in a equivalent way, by detuning the structure.

The first period of our study has been devoted to the

analysis of the way to detune in a controlled fashion the structure.

A preliminary analysis between possible alternatives showed that a thermal induced detuning of the rf structure, at a fixed exciting frequency, may be a suitable solution. The feasibility of this approach depends both on a detailed study of the compression factor as a function of the structure temperature and on a new design of the cooling system of the structure which takes into account all the requirements.

To investigate the effects of the temperature on the compression process we started evaluating the typical parameters of a standard SLAC structure. The required compression factor of 7 results in a change of the order of 1% of the phase velocity that is equivalent to a variation of the order of 0.6 °C in the temperature of the structure. This calls for a system able to control in real time the temperature set point with a resolution at least five times smaller (0.12 °C) both in term of sensibility and of stability. The RF power load on the structure, computed using the beam parameters of table 1, is of the order of 1.1 kW. The resolution required to the control system in such a situation was evaluated against the usual cooling plant specifications and in a survey of the available industrial components to be used as the building block of the new cooling facility. We evaluated that it would be too much difficult to achieve such a performance mainly due to the requirements in terms of stability. We decided to move toward a new TW structure designed to support slow waves and with the goal to decrease of a factor of 3 the thermal sensitivity, so that the required phase velocity modulation will ask for a temperature variation of the order of 2 °C. Table 2 shows the main parameters of the new structure (referenced as ALMA 5) which we propose for the RF compressor.

	SLAC Mark IV	Alma 5
Cell radius (mm)	41.24	42.48
Iris radius (mm)	11.30	15.40
Disk thickness (mm)	5.84	5.9
Cell length	35	35
Frequency (MHz)	2856	2856
Mode	2π/3	2π/3
Q	13200	13205
Shunt impedance (MOhm/m)	53	41
Vg/c	0.0122	0.0341
ΔT (equivalent to 1% V _f)	0.6 °C	2.0 °C
RF power required for a 3 meter long structure (MW)	-	66MW

Table 2: Main parameters of the Alma 5 TW structure

The group velocity has been increased of a factor of 3 to fulfil the requirement on thermal sensitivity. The subsequent decrease in shunt impedance has been considered acceptable since the maximum gradient required to the structure is lower than that of standard SLAC cavities. The last row in the table shows the power required to the Klystron that feeds the structure. This parameter has been carefully taken into account in the

design since, in principle, we may accept higher values of the group velocity (and consequently have a more comfortable thermal control) but this will results in an incompatibility with the RF power available for the SPARC project.

Using the parameters above reported a set of simulations have been carried out using codes as Homdyn and Astra to verify the behaviour of a full scale model composed of a slow wave structure followed by two standard SLAC cavities. The results have been plotted in fig. 2 and they show that the compression factor obtainable is at least a factor of two higher with respect to the result available using standard SLAC structures. The dependence of the compression factor on the thermal stability is of the order of 20% for 0.1 °C while for standard SLAC structures it is 3 times more.



Fig.3: Simulations of the compression process

The mechanical design of the cell has been carried out taking into account the requirements due both to the brazing process and to the tuning. The results of the studies about the effects of the allowed machining tolerances have shown that a maximum error of 0.5° will be obtained. Such a value may be corrected using dinging holes, foreseen in the body of the cells, during the tuning process. Measurements carried out using aluminium based cells confirmed this predicted behaviour.

The thermal control of the structure has been studied using finite elements analysis. The solution has been found embedding the channels for water flow within the cells body to take advantage of the whole copper mass available. The cooling water will be provided to the structure by a Neslab HX300 compact cooling unit. This refrigeration unit has been chosen as the basic element around which build the cooling plant. It provides the capabilities to handle a maximum power load of the order of 10kW with a stability of the operating point of 0.1 °C.

To study the real behaviour of the cooling plant a test bench has been prepared using a 3 meter long standard SLAC cavity thermal controlled by the HX 300 unit. The cavity has been thermal insulated from the outside to reproduce as close as possible the characteristics of the ALMA 5 cooling circuits. The RF power load has been simulated by a controlled resistive load. 20 temperature probes (Tc and RTD) have been installed on the cavity to measure the temperature in different points. A network analyzer measures in real time the resonant frequency of the structure which has been maintained under vacuum for the whole duration of the test.



Fig.4: Temperature and frequency measurements

A significant measure is reported in fig. 4. The results show that the structure can be controlled with a stability better than 0.1 °C and that a change in the set point of the HX 300 controller of 0.1 °C is reflected in the structure within a few minutes. The RF behaviour of the structure is fully compliant with the simulations carried out using Superfish and Ansys.

CONCLUSIONS

The development of a prototype structure for a RF compressor is close to the final stage. The cell detailed design has been finished and it has been validated by preliminary tests on samples. A nine cells copper brazed structure will be available in August 2004 for an extensive set of measurements. The thermal control scheme has been defined and validated on a 3 meter long structure using the final components.

ACKNOWLEDGEMENTS

We would like to acknowledge very helpful discussions with S. Mathot (CERN) and the valuable support received in the experimental work by Luigi Gini (INFN-Milan) and Luciano Grilli (University of Milan). We also acknowledge J. Rosenzweig (UCLA) for the donation of the 3 m long SLAC structure used for the thermal tests.

- [1] P.Piot "Subpicosecond Compression by Velocity Bunching in a Photoinjector", Physical Review, vol. 6 (2003)
- [2] L. Serafini et al. "Ultra-short Bunch Generation with a Rectlinear Compressor", PAC2001, Chicago, June 2001, p. 2242.
- [3] Sparc Collaboration "TDR for the Sparc Advanced Photoinjector" INFN-LNF rep., 12-1-2004

IR UPGRADE PLANS FOR THE PEP-II B-FACTORY*

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Abstract

PEP-II, the SLAC, LBNL, LLNL B-factory has achieved a peak luminosity of over 9×10^{33} cm⁻²s⁻¹, more than 3 times the design luminosity, and plans to obtain a luminosity of over 1×10^{34} cm⁻² sec⁻¹ in the next year. In order to push the luminosity performance of PEP-II to even higher levels an upgrade to the interaction region (IR) is being designed. In the present design, the interaction point (IP) is a head-on collision with two strong horizontal dipole magnets located between 21-70 cm from the IP that bring the beams together and separate the beams after the collision. The first parasitic crossing (PC) is 63 cm from the IP in the present by2 bunch spacing. Future improvements to PEP-II performance include lowering the β_v^* values of both rings. This will increase the β_v value at the PCs which increases the beambeam effect at these non-colliding crossings. Introducing a horizontal crossing angle at the IP quickly increases the beam separation at the PCs but recent beam-beam studies indicate that a significant luminosity reduction occurs when a crossing angle is introduced at the IP. We discuss these issues and describe the present interaction region upgrade design.

THE INTERACTION REGION

The PEP-II asymmetric-energy electron and positron beams are brought into a head-on collision by strong (~0.8T) horizontal dipole magnets located $\pm 21-70$ cm from the IP. The strong dipoles (called B1) are made of permanent magnet material (Sm₂Co₁₇) and are tapered for the first 22.5 cm in order to accommodate the Silicon Vertex Tracker (SVT) of the BaBar detector. Figure 1 is a photograph of the B1 magnets with half of the SVT installed.

The beam separation continues in the next magnet, a shared vertically focusing quadrupole (QD1) with a magnetic axis very close to the High-Energy Beam (HEB) trajectory. This maximizes the horizontal displacement for the Low-Energy Beam (LEB) thereby maximizing the beam separation. The beams are then separated enough to be able to enter individual beam pipes at about 2.5 m from the IP. Figure 2 shows a layout of the PEP-II interaction region. Note the expanded x scale on left of the drawing as compared to the z scale at the bottom.

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Figure 1. Picture of the tapered sections of the B1 magnets with half of the Silicon Vertex Tracker in place.



Figure 2. Layout of the PEP-II Interaction Region. The B1 magnets are shown closest to the IP. The 1st parasitic crossing when every other RF bucket is filled with charge is located at the outboard end of the B1 magnets.

PARASITIC CROSSINGS AND BEAM-BEAM EFFECTS

^{*}work supported by the Department of Energy under contract number DE-AC03-76SF00515.

2.1 Beam Bunch Spacing

There are a total of 3492 RF buckets in the PEP-II rings. Of these, about 92 buckets are reserved for the abort kicker ramp up time. This leaves about 3400 RF buckets that can be filled with charge.

Last fall the bunch spacing was changed from 1.89 m (by3 bunch pattern) to 1.26 m (by2 bunch pattern). We had filled up the by3 pattern so, in order to increase the total number of bunches, we moved to a smaller bunch spacing. The change moved the 1^{st} PC from 0.945 m to 0.630 m from the IP. The beam separation at the 1^{st} PC also decreased from 9.7 mm to 3.2 mm. Table 1 shows the design beam separation at all possible PCs.

Table 1. Beam separation at all of the possible parasitic crossings of PEP-II. Beyond 2.5 m the beams enter separate beam pipes. There is virtually no separation at the 0.315 m point because the B1 magnets only begin separating the beams at 0.21 m. This rules out the possibility of filling every RF bucket with charge without introducing a fairly large crossing angle at the IP.

Z (m)	Beam separation (mm)	Notes
0.315	0.139	1 st PC if every bucket is filled (by1)
0.630	3.231	1 st PC if every other bucket is filled (by2)
0.945	9.699	1 st PC if every third bucket is filled (by3)
1.260	17.780	1 st PC if every fourth bucket is filled (by4)
1.575	28.857	1 st PC if every fifth bucket is filled (by5)
1.890	43.600	1 st PC if every sixth bucket is filled (by6)
2.205	60.549	1 st PC if every seventh bucket is filled (by7)
2.520	77.665	1 st PC if every eighth bucket is filled (by8)

Increasing the number of bunches from about 1130 to 1580 and lowering the β_y^* of both beams from 12.5 mm to 10.5 mm are two of the reasons the PEP-II accelerator has a peak luminosity of 9.2×10^{33} cm⁻²s⁻¹ up from the 6.6×10^{33} cm⁻²s⁻¹ peak we had this past June 2003[1,2].

As seen in Table 1, increasing the number of bunches by moving out of a by3 pattern and going to a by2 bunch pattern has decreased the beam separation at the 1st PC and thereby has increased the beam-beam effects seen at these near-collisions. Indeed, although the amount is difficult to quantify, there was a noticeable drop in luminosity estimated at about 5-10% when we first moved to a by2 bunch pattern. We maintained approximately the same number of total bunches in the machine when the change was made by constructing mini-trains with gaps between the trains. However, after 1-2 weeks it was felt that much of the luminosity decrease had been regained by tuning with an overall loss of still perhaps 3-5% [3].

2.2 Beam-Beam Effect from Parasitic Crossings

The formulas for calculating the beam-beam tune shifts induced by a parasitic crossing are shown below [4,5].

$$\xi_x = -\frac{Nr_e}{2\pi\gamma} \frac{\beta_x \left(x^2 - y^2\right)}{\left(x^2 + y^2\right)^2} \tag{1}$$

$$\xi_{y} = + \frac{N r_{e}}{2\pi\gamma} \frac{\beta_{y} \left(x^{2} - y^{2}\right)}{\left(x^{2} + y^{2}\right)^{2}}$$
(2)

Where *x* and *y* are the horiz. and vert. beam separations at the PC.

As seen from the formulas, the tune shift is proportional to the beta function at the PC and inversely proportional to the square of the distance between the two beams. As the β_y^* at the IP is lowered the β_y value at the 1st PC gets larger increasing the PC tune shift.

CROSSING ANGLE

We considered the option of introducing a crossing angle at the IP in order to improve the beam separation at the 1^{st} PC. Table 2 shows how much the separation improves with the introduction of a small crossing angle at the IP. However, recent beam-beam studies [6,7] indicate a significant reduction in luminosity for even a small crossing angle.

UPGRADE PLANS

We plan to maintain our present head-on collision at the IP but keep open the option of introducing a small crossing angle. In order to improve the beam-beam effect from the 1st PC we plan to upgrade the B1 magnets. The magnets are made up of 12 slices of permanent magnet material; five slices are 25 mm thick and 7 slices are 50 mm thick. By increasing the bending field of the slices closest to the IP we will increase the beam separation at the 1st PC. We will keep the integrated strength of the magnet about the same by removing or weakening some of the slices farthest from the IP. These slices contribute nothing to the beam separation at the 1st PC since they are located either on top of or just after the crossing. Table 2 shows how much more beam separation we should get by increasing the strength of the B1 magnets.

Keeping the integrated strength constant helps minimize the difference between the new beam orbits and the design orbits. We are able to keep the orbit deviations below 2 mm for both beams in both planes until we can match the new orbit to the original design. This eliminates the need for further changes in the IR because of the new orbit. Figure 3 illustrates the changes planned for the IR.

In order to increase the field strength of the inboard slices we need a stronger permanent magnet material. The material we are presently using has a remanent field (Br) of 1.05T. We are looking at material with a Br of \sim 1.2T. The material must be somewhat radiation hard but the total radiation level this close to the SVT can not be very high. We estimate the material must be rad hard up to about 100 Mrads. This is ten times higher than any number the SVT might encounter.

In addition, we can decrease the inner radius of some of the slices as well as increase the outer radius of some of the slices. We think we can get about a 20% improvement in the field strength.

Table 2. The table shows the beam separation at the 1^{st} PC for the by2 bunch pattern for various crossing angles at the IP. In addition, the table has the separation increase for 2 cases of strengthened B1 magnet slices.

0		
Type of separation	(mm)	% increase
Design (head-on)	3.23	
±0.25 mrad crossing angle	3.54	10
± 0.5 mrad crossing angle	3.86	19
±0.75 mrad crossing angle	4.17	29
±1 mrad crossing angle	4.48	39
Head-on with modified B1s		
B1 slices increased +20%	3.46	7
B1 slices increased +30%	3.78	17



Figure 3. Layout of the Interaction Region showing the upgrade of the B1 magnets. The right hand side of the picture shows the modifications we would make to the B1 magnet. The darker blue slices would be the new stronger slices. For reference, the left hand side of the picture is unmodified and shows what we presently have. The gray boxes between the B1 and QD1 magnets are radial ions pumps that have become inoperable. We would replace these two pumps with new pumps.

SUMMARY

PEP-II has made good progress over the last year and has increased the luminosity peak from $6.6 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$ to $9.2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$. PEP-II is now in a by2 bunch pattern and will remain in that pattern. The by2 pattern has a 1^{st} parasitic crossing at 0.63 m from the IP and a beam separation of 3.2 mm. We have seen some effect on the luminosity of the machine and are looking at ways to improve the beam separation in order to minimize the tune shift from the 1^{st} PC. As we improve the luminosity by lowering the β_y^* values the effect of the 1^{st} PC on the beam will become more pronounced.

One way of improving the separation is to introduce a crossing angle at the IP. However, beam-beam simulations indicate a decrease in luminosity from even a small crossing angle. We have chosen to maintain head-on collisions but leave open the option of introducing a small crossing angle. We plan to increase the bending field of the B1 dipoles on the ends nearest to the IP in order to improve the beam separation at the 1st PC. In order to increase the strength of the B1 magnets we will use higher strength permanent magnet material and increase (slightly) the volume of the material.

ACKNOWLEDGEMENTS

We would like to thank the PEP-II team and the operations team who have done so well in getting the performance of PEP-II to where it is. We would also like to thank the general support staff who have worked tirelessly to keep the accelerator running.

REFERENCES

[1] J. Seeman, "Results and Plans of the PEP-II B-Factory", EPAC'04, July 2004, these proceedings.

- [2] U. Wienands, "Trickle-Charge: A New Operational Mode for PEP-II", EPAC'04, July 2004, these proceedings.
- [3] F.-J. Decker, "Bunch Pattern with More Bunches in PEP-II", EPAC'04, July 2004, these proceedings.
- [4] M. Biagini, Private communication

[5] J. Jowett, Handbook of Accelerator Physics and Engineering, World Scientific (there is a sign mistake in the formula quoted there).

[6] K. Ohmi, "Study of Beam-Beam Interactions with/without Crossing Angle", PAC'03, May 2003, pg 353.

[7] I. V. Narsky, "Study of Beam-beam Effects at PEP-II", EPAC'04, July 2004, these proceedings

LASER TEMPORAL PULSE SHAPING EXPERIMENT FOR SPARC PHOTOINJECTOR

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Abstract

Laser for driving high brightness photoinjector have to produce UV square pulse which is predicted to be the optimum profile for emittance compensation in advanced photoinjectors. The longitudinal laser pulse distribution, according to numerical simulations for the SPARC photoinjector, must be square with rise and fall time shorter than 1 ps and flat top variable up to 10 ps FWHM. In this paper we report the results of pulse shaping obtained using an acousto-optic (AO) programmable dispersive filter (DAZZLER). The DAZZLER was used to perform spectral amplitude and phase modulation of the incoming 100 fs Ti:Sapphire pulses. Because of the finite length of the crystal the maximum duration of the shaped pulse is 6 ps. To overcome this limitation we used a configuration in which the laser pulses pass twice through the AO filter. A dispersive glass section was also used to lengthen the pulse with a single pass in the DAZZLER. In this paper we report the experimental setup, hardware description and time and frequency domain measurements.

INTRODUCTION

The SPARC project (Sorgente Pulsata Autoamplificata di Radiazione Coerente) is a 150-MeV advanced photoinjector designed to drive a SASE-FEL in the visible and near UV range[1]. The machine consists of a Ti:Sa laser to illuminate a metal photocathode, an high gradient rf-gun and 3 SLAC s-band accelerating sections. The photoinjector, which is under construction at LNF, is conceived to explore the emittance correction technique and high current production, with proper preservation of the transverse emittance. The aim of the project is to explore the scientific and technological issues for the construction of SASE-FEL based X-ray source.

The photocathode drive lasers for high brightness electron beam applications must show very specific capabilities motivated by two major considerations: the low photo-emission efficiency of robust photocathodes requires high UV energy to extract the needed charge; the emittance compensation process is most successful with uniform temporal and spatial laser energy distribution. In particular beam dynamics simulations confirm that the optimal pulse shape has flat-top profile up to 10 ps, with ripple less than 30% and very sharp edges of the pulse: the rise and fall times must be at least shorter than 1 ps. To assure repeatable SASE-FEL performance, additional demands are low energy fluctuations (<5%), small time jitters from pulse-to-pulse (<1 ps) and good pointing stability. Finally, the laser pulses have to be synchronized with the accelerator master oscillator, in order to extract electrons at a precise phase of the RF field. To satisfy all these requirements it is necessary a pulse shaper device and a large bandwidth laser system; so the Ti:Sa technology was adopted. In Fig. 1 is reported the laser layout for SPARC.



Figure 1: Conceptual layout of SPARC laser system.

The 100 fs pulses delivered by Ti:Sa laser naturally display a sech² temporal profile. The device that convert this pulse shape in a flat top one works as a spectral filter. The pulse shaper has high insertion losses and low damage thresholds: therefore the filtering has to be applied before amplifying the laser pulse. Beside, the spectral manipulation has to retain almost all the spectrum of the incoming pulse because otherwise it would induce problems for the amplification process [2].

To produce the desired pulse shape it was proposed a liquid crystal matrix placed between two gratings [3]. The liquid crystal mask can operate as spectral amplitude filter or phase shifter.

Instead we tested a new technique based on a programmable AO dispersive filter produced by FASTLITE (named DAZZLER). This device is able to perform simultaneously amplitude and phase modulation.

Because of the filter behavior of the DAZZLER the output signal in the spectral domain is given by [4]:

where S_2 , S_1 and S_{ac} are respectively the complex output optical signal, the input signal and the acoustic transfer function.

In details inside the AO filter, a chirped acoustic wave and the optic pulse linear polarized along the ordinary axis interact in a TeO₂ crystal. The AO interaction occurs for different optical wavelengths, at different depths, where the AO phase matching condition is satisfied [5]. The interaction induces a rotation of the polarization toward the extraordinary axis. The refraction index along the extraordinary axis is different from that along the ordinary one and thus a frequency dependent phase delay is obtained. In practice the filter shifts in time the pulse frequencies thus stretching the pulse temporally. The intensity of the acoustic signal governs the amplitude modulation of the optical wavelengths. A radio frequency generator (with frequencies between 40 and 55 MHz) drives a piezo-transducer to produce the acoustic wave in the crystal.

EXPERIMENT OVERVIEW

We tested the DAZZLER at the ULTRAS laboratory of the Politecnico in Milan.

The source used for the experiment was an amplified Ti:Sapphire laser similar to the one expected for SPARC. The laser delivered 20 fs FHWM, 1 mJ pulses at 1 kHz repetition rate with the central wavelength at 800 nm, in horizontal linear polarization. A small fraction of the laser beam (20 μ J) was sent to the experimental setup; here the beam was divided in two arms by a 50% beam splitter.

In the first arm the beam was sent through a 10-nm band pass spectral filter, to obtain 100 fs FWHM pulses (as we expect for the SPARC laser), and then through the DAZZLER crystal. The second pulse (gate pulse) was sent to a delay line controlled by a 100 nm linear resolution stepper motor. For the measurement the shaped pulse and the gate signal overlapped in a non linear BBO crystal. The emerging double frequency pulse was proportional to the cross-correlation of the two pulses, and was measured by a photodiode. The measurement was based on the lock-in technique.

The cross-correlation corresponded in our case to the temporal intensity measurement of the shaped pulses, because the gate pulse was much shorter than the DAZZLER pulse. The resolution was about the duration of the gate optical signal (20 fs).

We developed the numerical code, in Labview environment, to simulate the optimal phase and amplitude modulation for the DAZZLER. The calculation allowed the control of the shaping in real time according to Eq. 1. The program simulates the behavior of the DAZZLER: it allows the modification of the amplitude and the spectral phase of the measured input spectrum, and then, through the FFT, calculate the output temporal profile. With the amplitude modulation we corrected also the non flat response of the DAZZLER due to the frequencydependent diffraction efficiency. A general comment is that we cannot impose the spectral modulation as sinc function which would give under Fourier Transform a perfect square profile in time. This is because the output pulse would have a too narrow spectral bandwidth, not compatible with Ti:Sa amplifier operation[2].

Because of the finite length of the crystal (2.5 cm) the maximum theoretical duration of the shaped pulse is 6 ps. To overcome this limitation we used a configuration in which the laser pulses pass twice through the AO filter. In this case we observed high energy losses ($\approx 80\%$). For this reasons we tested also a configuration with a single pass through the DAZZLER crystal and through 30 cm of dispersive glass (SF57). The glass introduced an extra second order phase modulation. The total dispersion of the glass sections was 0.2 ps². In this way the losses were reduced to 50%. The single passage simplified also the alignment of the AO crystal.



Figure 2: Cross-correlation of the output shaped pulse in double-pass configuration.

In Fig. 2 is reported the cross-correlation signal obtained with double passage configuration, with the estimated error bars. The measured pulse shows a very sharp rise and fall time, definitely less than 1 ps, and the pulse duration is about 10 ps FWHM. The ripple on the top of the pulse is very smoothed. The overshoots remains below 15% of the average value of the pulse intensity. The pulse's characteristics obtained are in good agreement with the SPARC requests for the pulse [6].

In Fig. 3 it is shown the input spectral intensity, the phase and amplitude modulation used to obtain the flat top pulse reported in Fig. 2.

The phase modulation is given by symmetric polynomial expansion up to 8^{th} order centered at 780 nm. The amplitude modulation (absolute value of the transfer function) is given by Eq. 1 assuming a Super-Gaussian output amplitude spectrum:

$$|S_{2}| = Exp\left[-\left(\frac{|v-v_{0}|}{\Delta v}\right)^{n}\right]$$
(2)

with the exponent n=9.35, bandwidth Δv =4.14 THz and v_0 is the central frequency. It is important to stress the fact that we did not impose the DAZZLER a phase curve which gives the same group delay (defined as the derivative of the phase respect to the frequency) for two different frequencies. This in fact could have very

deleterious consequences including unstable beat phenomena.



Figure 3: (a) input spectrum; (b) phase modulation; (c) amplitude modulation.

In Fig. 4 is reported the cross-correlation signal with the estimated error bars, obtained with single passage through the AO crystal and the dispersive glass. In this case the rise and fall time is more smooth than the double passage results.

The reason is that in this configuration the DAZZLER dynamics is reduced and the glass introduce only second order phase shift without high orders which are responsible for the rise and fall time duration. Thus we have a lower ripples as the Gibbs phenomenon asserts. However the result still satisfies the SPARC requirements. The duration of the shaped pulse is about 6.5 ps; if a longer temporal pulse duration is requested, it is necessary the insertion of additional dispersive glass.



Figure 4: Cross-correlation of the shaped pulse in single-pass configuration.

The best results were obtained with a feedback from cross-correlation measurements and by successive optimizations of the filter's parameters. The cycle went on until we found the best result achievable. For further improvements we think it will be helpful to develop a genetic algorithm with an automatic feedback loop. The results were reproducible with not appreciable differences, over a time scale compatible with the laser source stability. We observed also a very low influence by beam pointing instability of few mrad. This value is much larger than the typical Ti:Sa oscillator performances. Finally measurements showed that the DAZZLER filter is insensitive to microseconds jitters between acoustic wave and laser pulses.

In the SPARC laser layout the Dazzler is placed ahead of the laser amplifier, therefore the final temporal profile of the pulse on the cathode is determined by the successive processes that the pulse undergoes. The effects of amplification, UV conversion and propagation through the optical transfer line are to be investigated. However the flexibility of the DAZZLER device could also be used to compensate some of these effects. To integrate the DAZZLER in the whole laser system it is required the development of temporal UV diagnostic tools.

OUTLOOK

The experiment conducted was conceived as a proof of the flat top pulse generation by AO crystal.

The preliminary measurements conducted indicate the DAZZLER as a promising technique to produce the required flat top laser pulses up to 10 ps FWHM in double passage configuration. We believe also that, in the single passage configuration, it is possible to obtain longer pulse up to 10 ps with more external dispersion.

We think that better temporal profile can be achieved with a more careful control of the acoustic modulation; this task can be accomplished by improving the control code via genetic algorithm. More work should be devoted to the integration of the DAZZLER with the whole photoinjector laser system and optical diagnostics.

- [1] D. Alesini et al. An R&D program for a high brigthness electron source at LNF, Proceeding EPAC, Paris 2002, pag. 1807-1809.
- [2] P.Maine et al. IEEE J. Quantum Electronics 24 (1988) 398.
- [3] A. M. Wiener, D. E. Leaird, J. S. Patel and J. R. Wullert Opt. Lett. 15, 326 (1990).
- [4] P. Tournois, Optics Communication 140 (1997) 245.
- [5] A. Yariv, P. Yeh, Optical Wave in Crystals, Wiley, New York 1984.
- [6] L.Palumbo et al. Technical Design Report for the SPARC Advanced Photo-Injector, Preprint INFN-LNF, 12-1-2004.

THE MODIFIED DAFNE WIGGLERS

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Abstract

Modifications to the pole shape of a spare wiggler have been tested to increase the width of the good field region, with the aim of reducing the effect of nonlinearities affecting the dynamic aperture and the beam-beam interaction. Additional plates have been machined in several shapes and glued on the poles. Accurate measurements of the vertical field component on the horizontal symmetry plane of the magnet have been performed to find the best profile. The particle motion inside the measured field has been tracked to minimize the field integral on the trajectory, to determine the wiggler transfer matrix in both horizontal and vertical betatron oscillation planes and to estimate the amount of non linear contributions. All wigglers in the collider have been modified to the optimized pole shape. Measurements with beam performed with the modified wigglers show a significant reduction of nonlinearities.

INTRODUCTION

Each ring of the DAFNE collider [1] is equipped with 4 wigglers. The main parameters of the wiggler are given in Table 1 and a picture of the magnet is shown in Fig. 1. The wigglers are a strong source of non-linearity in the rings and their effects on the beam dynamics are extensively described in [2]: we recall here that the main effect on the beam is a quadratic dependence of the betatron tunes on the beam position in the wiggler, generated by an effective octupole component created by a decapole term in the wiggler field not centered on the wiggling trajectory of the beam inside the magnet.

In order to correct this non-linear term, a new spare wiggler has been purchased from the same builder of the wigglers installed on the collider. The magnet has been realized on the same design and with the same materials. We adopted the strategy of reshaping the pole faces by adding machined iron plates directly glued on the poles.

Beam energy (MeV)	510
Nominal field (T)	1.8
Number of full poles	5
Number of terminal poles	2
Pole width (cm)	14
Pole length (cm)	21
Gap (cm)	4.0

Table 1: Main wiggler parameters



Figure 1: The spare wiggler in the magnetic measurement hall.

The effect of a (2k+2)-pole term on the beam dynamics can be expressed as

$$K_{k} = \frac{1}{B\rho} \int \frac{\partial^{k} B(z, x)}{\partial x^{k}} dz$$
(1)

where the derivatives are calculated not on the wiggler axis, but along the wiggling trajectory of the beam. In terms of the derivatives calculated along the wiggler axis, indicated here with a suffix "0", the third order term is:

$$K_{3} = \frac{1}{B\rho} \left[\int (\frac{\partial^{3}B}{\partial x^{3}})_{0} dz + \int (\frac{\partial^{4}B}{\partial x^{4}})_{0} x(z) dz + \cdots \right]$$
(2)

The value of K₃, obtained from the measurements described in [2] on the original wiggler is of the order is $\approx -8 \ 10^2 \ m^{-3}$ and is mainly due to the second term in the square bracket in (2).

POLE SHAPING

In order to add the machined iron plates to the wiggler yoke, keeping the gap at the same value, the two halves of the magnet can be displaced by adding suitable spacers in the middle of the white C-shaped supports shown with black arrows in Fig. 1. This modification lengthens the magnetic circuit slightly reducing the peak field at the same gap value.

The vertical field component at the center pole and in the terminal ones has been measured on the original wiggler without any modification. Then, the two halves of the wiggler have been separated by means of 28 mm thick separators and the 14 mm thick iron plates glued on the poles without any modification of their shape. The peak field in this configuration is reduced by 6%.

The plates have been modified by modulating their thickness as a function of the distance from the wiggler axis, roughly following the criterion of keeping constant the resulting gap divided by the intensity of the field measured at the pole center on the original wiggler. The shape of the modified pole is shown in Fig. 2.



Figure 2 – Section of the shaped iron plate glued on the wiggler pole (horizontal and vertical sizes not in scale).

Due to the larger gap at the pole center, the peak field was further reduced by 5%, bringing the overall reduction with respect to the original wiggler to 11%, which would affect too much the damping effect on the beam. A first decision was taken to reduce the gap from 40 to 37 mm, still compatible with the vacuum chamber. The measured gain in peak field was 3%, still not enough for the beam dynamics. The final configuration was therefore obtained by reducing the maximum thickness of the plates from 14 to 7 mm, with a separator thickness of 11 mm, keeping the gap at 37 mm. The peak field is only 4% smaller than in the original wiggler. The dependence of the field at the longitudinal symmetry point of the magnet is shown in Fig. 3. The beneficial effect of pole shaping on field flatness is evident.



Figure 3: Vertical field component at wiggler center versus distance from longitudinal symmetry axis.

A second modification of the wiggler field comes from the requirement of a localized sextupole field at one of the terminal poles, which makes chromaticity correction in the collider easy due to the high dispersion and excellent beta functions separation at this position. Fig. 4 shows the shape of the additional iron plate at one of the two terminal poles.



Figure 4: Section of the shaped iron plate glued on the terminal pole (horizontal and vertical sizes not in scale).

RESULTS

In order to evaluate the effect of the field modification on the non linear term (2), the field has been measured on the horizontal symmetry plane in a mesh of 4920 points, 328 longitudinal positions spaced by 8.35 mm and 15 horizontal positions spaced by 10 mm.

The measurements at the same longitudinal positions have been fitted with a fourth order polynomial and the fourth order term of the fit yielding the major contribution to the octupole term (2) is shown in Fig. 5 as a function of the longitudinal position around the central pole. The new profile reduces the fourth order non linearity by more than a factor two.



Figure 5: Fourth order term of the transverse fit in the central pole.

The second order term of the same fit in the terminal pole with the sextupole profile of Fig. 4 is shown in Fig. 6, compared to the same quantity in the original wiggler. The corresponding value of K_2 changes from 2.0 m⁻² to 4.3 m⁻².

By interpolating the measured points, the trajectory of a test particle can be calculated both in the horizontal and vertical planes, making it possible to evaluate the full transfer matrix of the wiggler [3] and to estimate K₃. Fig. 7 shows the trajectories in the horizontal symmetry plane of two test particles, both starting from outside the wiggler at a distance of 11.8 mm from the wiggler axis, which is the geometry adopted in DAFNE to fully exploit the good field region of the wiggler. One of the two particles enters the wiggler from the terminal pole modified to enhance the sextupole contribution, the second from the other one. Both trajectories are parallel to the wiggler axis at the end of the wiggler, with a slight displacement (\approx 1 mm) with respect to the initial position due to the asymmetry in the field introduced by the terminal pole modification.



Figure 6: Second order term of the transverse fit in the terminal pole



Figure 7: Trajectories in the horizontal symmetry plane of two particles; full line = starting from modified terminal, dotted line = starting from normal one. The field on axis is shown for reference.

By integrating the product of the fourth order term of the transverse fit in Fig. 5 times the horizontal trajectory of the beam it is now possible to calculate the third order contribution to the motion defined in (2), where the contribution of the third order term of the field in the wiggler is negligible due to the symmetry of the magnet with respect to its longitudinal axis. K_3 has been reduced to -3.5 10² m⁻³, more than a factor 2 with respect to the original wigglers.

All DAFNE wigglers have been modified to the final configuration during the shutdown for the installation of

the FINUDA experiment during summer 2003 [4]. More details can be found in [5].

BEAM MEASUREMENTS

This result has been checked with the beam by measuring the tune shift as a function of localized orbit bumps in the wigglers [6], with the same procedure described in [2]. Of course, the additional sextupole term in the terminal pole is now the dominant contribution, making the measurement of the quadratic behaviour more critical. Fig. 8 shows the result of the measurement for two wigglers in the electron ring (empty dots) and in the positron one (full dots). The average value for K₃ comes out to be $(3.2\pm0.9) \ 10^2 \ m^{-3}$, in good agreement with the predictions from the magnetic measurements. The averaged sextupole term is K₂ = $(3.7\pm1.7) \ m^{-2}$ to be compared to the value of 4.3 m⁻² quoted in the preceding section.



Figure 8: Measured horizontal betatron tune versus beam displacement in 4 wigglers

CONCLUSIONS

The shape of the poles in the DAFNE wigglers has been modified to enlarge the good field region and to reduce the octupolar contribution to the beam dynamics. A reduction larger than a factor 2 has been obtained and confirmed by measurements with beam after wiggler modification.

- G. Vignola et. al, "DAΦNE, the Frascati F-factory" PAC'91, San Francisco, USA, May 1991, p. 68.
- [2] C. Milardi et. al, "Effects of non linear terms in the wiggler magnets at DAFNE" PAC'01, Chicago, USA, June 2001, p. 1720.
- [3] <u>http://www.lnf.infn.it/acceleratori/dafne/</u> <u>NOTEDAFNE/L/L-34.pdf</u>
- [4] C. Milardi et. al, "DAFNE performance for the FINUDA experiment" this Conference.
- [5] <u>http://www.lnf.infn.it/acceleratori/dafne/</u> NOTEDAFNE/MM/MM-34.pdf
- [6] <u>http://www.lnf.infn.it/acceleratori/dafne/</u> NOTEDAFNE/BM/BM-34.pdf

BEAM LOADING IN THE RF DEFLECTOR OF THE CTF3 DELAY LOOP

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Abstract

In this paper we describe the impact of the beam loading in the RF deflectors on the transverse beam dynamics of the CTF3 Delay Loop. The general expression for the single passage wake field is obtained. A dedicated tracking code has been written to study the multi-bunch multi-turn effects. A complete analysis for different machine parameters and injection errors is presented and discussed. The numerical simulations show that the beam emittance growth due to the wake field in the RF deflectors is small.

INTRODUCTION

The first stage of the bunch train compression scheme in the CLIC test Facility CTF3 [1] is realized in the 42 m circumference Delay Loop (DL) by using a transverse RF deflector (RFD) at 1.499 GHz. The process is illustrated in Fig. 1. The bunch timing of subsequent "even" and "odd" batches coming from the LINAC is adjusted in such a way that they have a phase difference of 180° with respect to the 1.499 GHz. The RFD deflects every "even" batch of 210 bunches into the DL, and, since the circumference of the DL corresponds to the length of one "even" batch of bunches, after one turn, it insert this batch between bunches of the following "odd" batch.

In this paper we investigate the beam loading effects in the RFD, which may result in transverse bunch emittance growth, particle loss, and degradation of the Drive Beam quality thus reducing the effectiveness of power conversion at 30 GHz. In particular, in par. 1 we will derive a general expression for the wake field generated by the single bunch passage in the RFD. In par. 2 and 3 we will illustrate the results obtained by a tracking code written to study the multi-passage effects in the case of a perfect injection of the bunches or considering different injection errors, respectively.



Fig. 1: Sketch of the bunch frequency multiplication in the DL.

SINGLE PASSAGE WAKE FIELD

The design options for the DL RFD are widely illustrated in [2]. The final device will be a standing wave double cavity working on the TM_{110} mode at the frequency of 1.499 GHz. The main parameters of the RFD and of the DL are reported in Table 1.

Table 1: main parameters of the DL and R.		
Beam Energy [MeV]	150 (min)-300 (max)	
Bunch length [mm]	1-3	
DL length [m]	42	
RFD frequency [GHz]	1.499 GHz	
Quality factor Q	3200	
R/Q per cell [Ω/m]	27	

Referring to the case of a simple single cell deflecting cavity (Fig. 2a), the field component in the plane $\vartheta = 0$ are given by [3]:

$$\underline{E}_{D} \begin{cases} E_{Dz} = E_0 J_1 e^{j\omega t} \\ E_{Dr} = 0 \\ E_{D_{\theta}} = 0 \end{cases} \begin{cases} B_{Dz} = 0 \\ B_{Dr} = 0 \\ B_{Dr} = 0 \\ B_{D\theta} = -j\omega a / p_{11} c^2 E_0 J_1 e^{j\omega t} \end{cases}$$
(1)

where $J_1 = J_1(p_{11}r/a)$ and $J'_1 = J'_1(p_{11}r/a)$ with p_{11} first zero of the J_1 Bessel function. In (1) we have considered the cavity like a pure pillbox cavity neglecting all field components given by the presence of the beam pipe tubes (E_{Dr}, B_{Dz}) . For the scope of this work and, in general, for small beam pipes, these components can be neglected.



Fig. 2: (a) Sketch of a RFD cavity with the E_{Dz} field lines; (b) sketch of a particle passing through the RFD.

The general expression, in frequency domain, of a field excited by a charge passing through a cavity [4] is:

$$\underline{E}_{exc} = E_{excz} \underline{z}_0 = -\frac{1}{1 + jQ\delta} \frac{E_{Dz} \int_{crvity} J_z \cdot E_{Dz}^* dV}{2P_T} \underline{z}_0 \quad (2)$$

where $\delta = (\omega_r / \omega - \omega / \omega_r)$, P_T is the total dissipated power in the cavity plus external load, Q is the quality factor and J_z is the longitudinal component of the electric density current corresponding to the charge. Assuming a charge passing in z=0 at the time t=0 (see Fig. 2b) whose density current is $\underline{J} = q \delta(x') \delta(y') \exp(-j\omega z / c) \underline{s}_0(z)$ we have that:

$$E_{excz} = -\frac{1}{1+jQ\delta} \frac{E_{Dz} \int_{cavity} q e^{-j\frac{\omega}{c} z_1} E_{Dz}^* [r_q(z_1)] dz_1}{2P_T}$$
(3)

where, $r_q(z_1)$ is the particle trajectory. In (3) we have neglected the transverse component of the particle

velocity $(\underline{s}_0 \cong \underline{z}_0)$. The longitudinal voltage induced in the cavity is given by:

$$V_{exc\,z} = \int_{cavity} E_{exc\,z} e^{j\frac{\omega}{c}z} dz \tag{4}$$

By means of the Panofsky-Wenzel theorem it is possible to calculate the transverse deflecting voltage induced in the cavity:

$$V_{excr} = \frac{qc}{j\omega} \cdot \frac{1}{1 + jQ\delta} \int_{avity} \frac{dE_{Dz}}{dr} e^{j\frac{\omega}{c}z} dz \frac{\int_{avity} E_{Dz}^*(r_q) e^{-j\frac{-z_1}{c}} dz_1}{2P_T}$$
(5)

Considering bunches passing near the cavity axis, it is possible to develop to the first order in r the E_{Dz} field in the form $E_{Dz} \cong E'_{0Dz}r$. Moreover, considering a generic trajectory in the deflector of the type $r_q = a_1z^2 + a_2z + a_3$ we obtain:

$$V_{excr} \cong K(R_1a_1 + R_2a_2 + R_3a_3) = V_1a_1 + V_2a_2 + V_3a_3 \quad (6)$$

where:

$$K = qc /(2j\omega P_{T})/(1+jQ\delta) \int_{cavity} E_{0Dz}^{i} e^{j\frac{c}{c}z} dz$$

$$R_{1} = \int_{cavity} E_{0Dz}^{i} z_{1}^{2} e^{-j\frac{\omega}{c}z_{1}} dz_{1}, R_{2} = \int_{cavity} E_{0Dz}^{i} z_{1} e^{-j\frac{\omega}{c}z_{1}} dz_{1}$$

$$R_{3} = \int_{cavity} E_{0Dz}^{i} e^{-j\frac{\omega}{c}z_{1}} dz_{1}$$

The corresponding induced wake fields in case of a cavity symmetric with respect to the plane z=0 are:

$$V_{1,3}(t) \cong q_L c R_{1,3} / Q e^{\frac{\omega_r}{2Q^t}} \sin(\omega_r t)$$
(8)

$$V_2(t) = q_L c R_2 / Q e^{\frac{-\omega}{2Q}t} \cos(\omega_r t)$$

Bunches whose trajectories have zero angle at the center of the deflector ($a_2=0$) generates a pure wake field 90° out-of-phase, while particles whose trajectories have $a_{1,3}=0$ generates a wake field in phase. This situation is illustrated in Fig. 3. In the figure we have considered the case of two recombined trains and we have plotted the wake field produced by the first bunch considered with a generic trajectory. The numerical values of the coefficient $R_{1,2,3}$ can be easily calculated by e.m. codes.

TRACKING CODE RESULTS

A dedicated tracking code has been written to study the multi-bunch multi-passage effects. The tracking code scheme is sketched in Fig. 4. Each gaussian bunch of $\sigma_z = 3mm$ has been discretized in 9 equally spaced slices. In the code even the case of perfectly injected bunches ($x_{in}=0$ and $x'_{in}=7.5$ mrad with respect to the deflector axis) than the case of bunches injected with errors can be considered.

The output positions and angles of the central slice of bunches with and without considering the effect of the beam loading are reported in Fig. 5. In the case of no beam loading the differences with respect to the "nominal values" $x_{out}=0$ and $x'_{out}=-7.5$ mrad are due to the finite filling time of cavities. In Fig. 6 it is reported the rms emittance referred to the central slice of each bunch in the same cases. It is clear that the effect of the beam loading time of

cavities while the effect in the beam emittance growth is a small fraction of the design emittance.



Fig. 3: Transverse wake fields induced by bunches with different trajectories.



Fig. 4: Tracking code scheme.

All these results have been obtained considering a DL phase advance of $\approx 260^{\circ}$. Different phases advances gives different results as shown in Figs. 7 and 8 where the average positions, angles and rms emittances (with error bars) are plotted as a function of the phase advance. In all cases for the average positions and angles, the effects of the beam loading are comparable with the effect of the finite filling time of cavities. In particular, even in the case in the case of no beam loading, there is a compensation effect between the first and second passage through the deflector if the DL phase advance is $\approx 180^{\circ}$. Considering the rms emittances there is, also, a minimum of the beam loading effect if the DL phase advance is $\approx 180^{\circ}$.



Fig. 5: Output positions and angles of bunches in case of perfect injection.

The effect of an injection error in position is shown in Figs. 9 and 10. Concerning the output positions and

angles the initial error is "transferred", for the trains 1, at the exit of the deflectors, after the recombination, practically unchanged and slightly reduced for the train of type 2. Moreover the effect of the beam loading is that to increase of about 20% the spread around the average positions with respect to the case without beam loading effects. Concerning the r.m.s emittance the effect is practically the same for all injection errors. This is due to the fact that the effect of the wake generated in the first deflector is partially compensated by the second one.



Fig. 6: rms emittance in case of perfect injection



Fig. 7: Output positions and angles of bunches without injection errors as a function of the DL phase advance.



Fig. 8: r.m.s emittances without injection errors as a function of the DL phase advance.



Fig. 9: Average output positions and angles (with error bars) of bunches in case of an injection error in position (x_{in}) between $\pm 1mm$.



Fig. 10: rms emittances of bunches in case of an injection error in position.

CONCLUSIONS

The effects on transverse beam dynamics of the beam loading in the CTF3 Delay Loop RF deflector have been studied. For this porpuose:

- a) we have calculated the single passage transverse wake induced by a charge considering different trajectories in the deflector;
- b) we have written a tracking code to study the multibunch multi-passage effects.

The main results are:

 in case of perfect injection the beam loading effects are comparable with the effect due to the finite filling time of deflector;2) in case of injection errors the beam loading does not amplify significantly the initial error;3) different phase advances of the DL give different results but, in any case, the beam loading effects are controllable.

- [1] "CTF3 Design Report", CERN PS 2002-008, 2002.
- [2] F. Marcellini and D. Alesini, this conference.
- [3] see for example R.E. Collin, "Foundation for Microwave Engineering", McGraw Hill, 1992.
- [4] G. Dôme, "RF Theory", CERN 92-03, Vol. I, 1992.

EXPERIENCE WITH LONG TERM OPERATION WITH DEMINERALIZED WATER SYSTEMS AT DA Φ NE

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Abstract

During eight years operation of the DAΦNE water cooling system some critical situations have been successfully managed by upgrading the demineralized water system. The collected data and the experience gained in the field of copper corrosion and related water treatment are critically revised.

INTRODUCTION

The water cooling system for the Da ne complex has been operated successfully since mid nineties.

More than 1200 meters of piping convey low conductivity cooled water from pumping stations to end users in the accelerator buildings. The piping is made of AISI 316 stainless steel, jointed in place with high quality TIG welding. The end users are magnets and the RF structures. All their cooling passages are OFHC copper channels with stainless steel fittings, with no other metals included. A treatment system maintains the characteristics of the water, mainly the conductivity and the dissolved oxygen contents.

Some crucial improvements have been done during the early functioning period, sometimes following failure episodes, as reported in the next chapters.

First, a short review of the topic of low conductivity water cooling in accelerators is presented.

CORROSION IN ACCELERATORS

In the accelerator cooling systems the copper corrosion in demineralised water is an unavoidable drawback but can be limited to a sustainable level.

The corrosion rate depends on conductivity, dissolved O_2 and CO_2 , pH, temperature, flow velocity and conditions, imposed electrical potential difference, galvanic potential difference (due to different metallurgy). The conductivity and other parameters can be maintained in set by polishing on line and controlled make up.

In addition, the oxygen inlet should be limited by adopting closed water circuit (sealed or inert gas cushioned, yet taking advantage by O_2 pumping away with inert gas flow). Any possible depression in the piping should be checked. As a rule, it should be avoided any unnecessary stop and opening of circuits, as well as allowing dead leg in piping with differential aeration. Furthermore recommendable are vacuum deaeration and UV hygienization technologies, both on-line and on the make-up.

Finally, it should be reminded that employing different metals and allowing unwanted electric potential difference are both possible cause of corrosion intake.

Several papers deal with the problem of managing low conductivity water plant in accelerators [1,2], but outside of this field, only electric power generation plants (cooling of high voltage stator windings) seems to suffer from similar troubles.

Typical values of water characteristics are: conductivity $< 0.2 \mu$ S/cm, dissolved oxygen <20 ppb, 6.8 < pH < 7.2.

In the specific case of accelerator magnets, the leading corrosion process could be the electrochemical one. The Coulomb law (1) gives an estimation of the rate of metal mass (m) loss, knowing the expected current I through the electrolyte and the Faraday constant F:

 $\frac{dm}{dt} = \frac{M}{Fn}I \quad (M \text{ atomic weight, n ion charge}) \quad (1)$

Loss of copper of some mg to some 10 mg per year could be expected in good operating conditions.

THE DAΦNE COOLING SYSTEM

In figure 1 is represented the Main Rings cooling system. Note the position of the cushioned expansion tank, affecting the pressurization level of the whole secondary circuit, as well as the polishing on-line, whose insertion point plays a crucial role in its effectiveness.



Figure 1: Cooling system (secondary circuit) design.

A simple hydrostatic device is employed to guarantee a stable and safe nitrogen pressure level.

The polishing system, as well as the final stage of the make-up one, consists in a row of mixed-bed ion exchanger resin bottles, with micrometric filtration stages against resin pollution and loss of containment of the sand-like resin particles.

The make-up system has in series: mechanical prefilters, chlorine- and iron- removing units, micrometric filters, reverse osmosis membrane units, again micrometric filters, a buffer tank, a booster/recirculating pump and mixed bed ion exchanger stage. All the components are redundant. Timers make self polishing of reverse osmosis membranes as well as of the water stored in the buffer tank through the ion exchanger stage.

Water Treatment design

While the process characteristics of the make-up water treatment depends mainly on the quality of the available water, its sizing rely on the foreseeable rate of spilling in the users and in the piping, and finally on the volume of the water circuit.

On the other hand, the sizing of the polishing on-line system could be related basically to the rate of users' corrosion and to the total recirculating flow. In addition, it affects the velocity of recovery after a scheduled shut-down or a failure. Typical values adopted in Da ne are reported in the table below.

Main circuit	flow	400 m ³ /h
	Total volume	110 m ³
Polishing	flow	4 m ³ /h
Make-up	flow	0.5 m ³ /h
	Buffer volume	0.5 m ³

Table	1:	Sizing	of water	treatment	systems
					~ / ~ ~

DEMINERALIZED SYSTEMS OPERATION

From the operation experience, the capacity of systems above mentioned has revealed adequate.

The use of mixed bed resins bottles allowed safe, clean and fast maintenance operation. The make-up buffer was extremely useful to constantly maintain the proper level in the expansion tank in case of little spilling due for example to the maintenance of pumps.

With the best operating conditions, the polishing leads to reduce the circulating water conductivity to less than 0.2μ S/cm. The total mean per year consumption of resins between 1997 and 2003 has been of 483 kg compared to 420 kg installed.

Reduced polishing stage efficiency during accelerator operation produces a fast increase of the circulating water conductivity, some 0.1 μ S/cm in few days. Because we experienced failure as those reported in the next chapter when conductivity rise towards 1 μ S/cm, the main maintenance threshold is set to 0.5 μ S/cm. Before reaching this stage, the replacement of bottles has to be done.

A further early warning is the pressure lowering in the polishing circuit, meaning the clogging of micrometric filters upstream of the bottles. This requires a weekly (or little more frequent) light maintenance. The same threshold of $0.5 \,\mu$ S/cm is applied when recovering from a prolonged shut-down of the plant, to set the start of accelerator operation.

The time of recovery is quite long, as reported in figure 2, so the full stop, leading in few days to conductivity of more than 2 S/cm, is limited only to

the case of scheduled long pauses for major accelerator improvements or new experiments set up.



Figure 2: water conductivity vs. time after a shut-down.

THE DAΦNE WIGGLERS: A CASE STUDY

At the end of nineties we experienced repeated failures due to obstruction of the coolant passages in the Wiggler magnets of the Da ne Main Rings.

All the coils of a magnet are in hydraulic parallel. The inlet water temperature is 32°C, the outlet reaches 65°C maximum. The coils are made of OFHC copper; they are joined to the manifolds in AISI 304L SS by EPDM rubber hoses.

The rubber hose between the manifold spigot and the coil end forms a flow section enlargement, with internal diameter going from 4 to 6 and again to 4 mm, as a little "chamber". Solid pebbles (D>5 mm) formed in some of these "chambers" inside the hoses and, there, moved back and forth, obstructing sometime the flow in one or more coils. Therefore the coils, no more cooled, heated until safety thermal device switched down the whole chain of four wiggler magnets.



Figure 3: copper oxide pebbles.

After a while, the pebble moved and the flow went right making impossible to find the cause of the failure.

Only once a persistent obstruction permitted us to catch the problem and start finding a solution.

The material of obstruction was analysed by the CSM of Pomezia, Italy, (SEM microscopy with EDS spectrometer), showing copper and copper oxides as the only component. as well as the water at inlet and outlet of the polishing system, as in table 2. In figure 3 is the micrographic picture of a pebble.

The surface of pieces of copper conductor with some months of operating life, as well as the pebbles and the powder were checked with micrographic imaging and "energy dispersion" X-ray surface analysis.

Table 2: Water analysis after the failure.

	sample 1	O ₂ (mg/l)	μ S/cm)	pН	T (°C)	Cu g/l
	before	12.50	0.8	7.55	23.1	92.0
	after	12.40	0.3	7.87	23.0	4.0
Î	TE1			.4	4	1 1 1 1

The conclusion was that the relatively high conductivity, the relevant dissolved oxygen contents of cooling water and the high electric potential of some coils with respect to the grounded piping yield the production of copper oxides and their migration according to the potential difference. Probably, sulphide-reducing bacteria catalysed the agglomeration process of the oxide, starting on the lips of the inlet copper spigots, in a slower flow region.

The deposits grew until detached and continued growing, probably without leaving the "chamber".

The successful corrective actions

We modified the polishing circuit and its location in the plant, to assure a continuous treatment of the whole water mass with the proper flow in the mixed bed bottles, and added new instruments and a data logger; the N_2 cushion system was reviewed and frequently checked; the whole plant pressurization scheme was reviewed, to ensure a positive pressure everywhere, avoiding unwanted air intakes.

As soon as a stable operating condition was reached, the failure did not present anymore.

A mock-up with the same dimensions of a wiggler magnet coil was installed, without any applied electrical potential, to further investigate the phenomenon. After four years of operation, recently the mock-up was sampled and sectioned. The internal surface was uniformly black, denoting copper oxidation to CuO, but no evidence of material loss or deposition was detected. This fact probably endorses the electrochemical origin of the corrosion described in the preceding paragraphs.

THE DA **(NE SYNCHROTRON LIGHT**) ABSORBERS: A SECOND CASE STUDY

In the vacuum chambers of Da ne Main Rings are mounted 88 synchrotron light absorbers, with different sizes. They are made of copper, and are water cooled from the same circuit of magnets. The cooling of the absorber is realized by two parallel channels drilled in the body, connected each other by a transversal hole grooved with a long tool through the channels itself.

The synchrotron light hits the absorber far from the channels, avoiding any direct thermal stress

concentration in a potentially harmful area for spilling water into vacuum.

Nevertheless, after some year of operation, a tiny crack opened a way to the water. The alarm was early on, so the damage was limited, but the probability of other occurrences of a similar failure was high, due to the large number of absorbers installed.

A visual endoscopic inspection revealed a pitted area downstream of the hole between the inlet and the outlet channels (figure 4). Moreover, the water flow was measured as more than twice the design one.

Because of the local narrowing of the water passage, a very high velocity was reached in the water flow, leading to cavitation that damaged the internal surface of the outlet channel. This phenomenon was surely enhanced by corrosion, until the opening of the crack. Some similar cases are reported in literature.

Following this analysis, a proper flow velocity was restored, with no further consequences.



Figure 4: the tip of an absorber and a section showing the internal of the crack area.

CONCLUSIONS

The commissioning and the improvements done on the Da ne cooling plant have been effective in yielding a long period of stable operation.

Nevertheless, there is evidence that any interruption in and maintenance of the water cooling system could cause severe failures and shutdown. This is especially true in the field of corrosion, where silent or hiding phenomena could produce sudden unexpected damages.

- R. Dortwegt, E.V. Maughan, "The chemistry of copper in water and related studies planned in the Advanced Photon Source", PAC'01, Chicago, 2001.
- [2] H. Poggensee, "Korrosionsursachen und korrosionverhinderung in kupferkuhlleitungen im LINAC II", internal report DESY M-93-04, DESY, Hamburg, June 1994.

LONGITUDINAL PHASE SPACE CHARACTERIZATION OF THE CTF3 BEAM WITH THE RF DEFLECTOR

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Abstract

The characterization of the longitudinal phase space of the CTF3 beam is an important item for tuning all machine parameters and increase the 30 GHz RF power production. By means of an RF deflector and a dispersive system the longitudinal phase space can be completely characterized. In this paper we present the simulation of the measurement and the mechanical layout of the full system.

INTRODUCTION

The recombination process in the CLIC test facility CTF3 has been already successfully tested in the Preliminary Phase [1]. Bunch length and energy spread of the beam should be carefully controlled before and during the recombination process to optimise the power generation at 30 GHz. Different bunch profile measurements have already been done during the commissioning of the fullloaded LINAC. In this paper we study the possibility to adopt a different method based on the use of RF deflectors [2] to completely characterize the longitudinal phase space of the CTF3 beam. The proposal is to do this measure at the end of the Drive Beam injector after the chicane using the travelling wave RF deflectors (RFD) already constructed for the Combiner Ring (CR) [3]. The nominal beam parameters after the chicane are reported in Table 1. In par. 1 we discuss the layout of the overall system looking at the main key parameters. In par. 2 we briefly discuss the perturbation induced on the beam by the RFD and, finally, in par. 3 we illustrate the optics parameters and the simulation results of this measure.

Table 1: CTF3 beam parameters	s after the chicane
Beam Energy E [MeV]	150
Bunch length σ_z [mm]	1-3
Bunch spacing [cm]	20
Number of bunches	2100
Energy spread $\Delta E / E$	0.8%
Beam emittance ε [mm mrad]	~ 0.4

Table 1: CTF3 beam parameters after the chicane

LAYOUT AND MAIN KEY PARAMETERS

2.33

Bunch charge [nC]

The layout of the beam line after the chicane is reported in Fig. 1. The measurement is illustrated in Fig. 2: the head and the tail of each bunch are deflected vertically and with opposite sign by the RFD (whose main parameters are reported in Table 2). The bunch length can be determined by measuring the vertical distribution of the bunch at the OTR1 position while the whole longitudinal phase space can be reconstructed by measuring the transverse distribution on the OTR2 position after the dipole. The transverse image of each bunch at the OTR positions can be digitalized by a gated camera.

Table 2: RFD main parameters				
Frequency (f _{RFD})	2.99855 [GHz]			
Iris internal radius (a)	21.43 [mm]			
Number of active cells	10			
Phase advance per cell	$2\pi/3$			
Deflector length	33 [cm]			
Filling time	47 [ns]			
r _s /Q	1425 Ω/m			
Transv. Defl. Voltage	2 MV @ P _{RFIN} =10 MW			



Fig. 1: Layout of the CTF3 beam line for measurements with RFD.



Fig. 2: Sketch of the bunch length and longitudinal phase space measurements with RFD.

Let us consider first the bunch length measurement. The transverse distribution of the bunch at the OTR1 position is the convolution between the deflected longitudinal profile and the vertical dimensions of the bunch at the same positions (σ_y). In order to measure the bunch length with a certain resolution, the vertical displacement induced by the deflector should be bigger than σ_y . The resolution length (L_{res}) can be defined as the bunch length that give, on OTR1, a vertical spot exactly equal to σ_y . It is easy to find that:

 $L_{res} \cong \frac{2c(E/e)\sqrt{\varepsilon}}{\omega_{RFD}\sqrt{\beta_{y_{-}defl}}\sin(\Delta\Phi)V_{T}}$ (1)

where β_{y_defl} is the vertical β -function at the deflector position and $\Delta \Phi$ is the phase advance between the deflector and the OTR1 position. Moreover the transverse dimension of the beam at the deflector position should be much less than the RFD irises diameter (a), that is:

$$\beta_{y_{_defl}} \ll \frac{(2a)^2}{\varepsilon} \cong 4600 \tag{2}$$

The resolution length is plotted in Fig 3 as a function of β_{y_defl} and for different RFD input powers assuming $\Delta \Phi = 90^{\circ}$.

Concerning the energy spread distribution on OTR2 we can define the energy spread resolution as the minimum energy spread that give a transverse spot exactly equal to the horizontal dimension σ_x , that is:

$$\frac{\Delta p}{p}\Big|_{res} = \frac{\sqrt{\varepsilon \beta_{x_defl}}}{D_{OTR2}}$$
(3)

where D_{OTR2} is the dispersion function on OTR2.



Fig. 3: Resolution length as a function of β_{y_defl} and for different RFD input powers assuming $\Delta \Phi = 90^{\circ}$.

EFFECTS OF THE BEAM LOADING IN THE RFD

The effect of RFD on transverse beam dynamics is mainly due to the out-of-phase wake generated by the beam offaxis passage. The analysis of this wake field and the related effects in the CR dynamics is widely discussed in [4]. Here it is important to investigate the impact on transverse dynamics to establish the beam alignment requirements in the RFD itself. Since the wake is a 90°out-of-phase wake and the bunches are spaced by $2T_{RED}$ the transverse wake has a zero crossing in the center of each bunch and has a longitudinal slope different from zero over the bunch length. This transverse slope can perturb the main deflecting field and, therefore, the bunch length measurement. In Fig. 4 the ratio between the wake field slope and the main RF field slope is plotted as a function of the bunch number and for different beam displacement. In the plot only the first 150 bunches are reported since after ≈ 70 bunches the steady state regime is reached (the deflector filling time is 47 ns). From this plot it is possible to conclude that an alignment precision of $\pm 3mm$ give a perturbation of about 3%.



Fig. 4: Ratio between the wake field slope and the main RF field slope as a function of the bunch number and for different off-axis ($P_{RFIN}=10MW$).

EXAMPLE OF MEASUREMENT SETUP

The chicane and the injection line to the Delay Loop is tunable in term of R_{56} between $\pm 40_{Cm}$. This means that the longitudinal phase space at the deflector position can be varied in a wide range supposing compression, stretching or isochronicity conditions. In the nominal configuration the chicane and the side quadrupoles triplets are symmetric with respect to the chicane center. For the measurement this symmetry condition can be relaxed and the quadrupole set points between the chicane and the diagnostics can be changed for optimising the measurement resolution for any R_{56} configuration.

As example the optical functions reported in Fig. 5 are referred to the case of a chicane set with $R_{56}=30$ cm. The longitudinal and transverse planes at different points of the beam line obtained by the ELEGANT code [5] are reported in Fig. 6 (CSR effect is not included in the simulations). In this case it has been considered an uncorrelated σ_z of 1 mm at the entrance of the chicane and $V_T=2MV$. The chicane set give a correlation between

energy and longitudinal position so that $\sigma_z = 3mm$ at the RFD position. In the considered case $L_{res}=0.3$ mm at the OTR1 position and $L_{res}=0.5$ mm at the OTR2 position while the energy spread resolution is $\Delta p / p|_{res} = 0.1\%$. By simply scaling the plots in the transverse phase space xy it is possible to measure the bunch length and energy spread distribution with the resolution previously discussed.



Fig. 5: Example of optical functions for measurements with the RFD.



Fig. 6: Longitudinal phase space and transverse plane distribution along the beam line in case of measurements with RFD (obtained by ELEGANT).

Finally, in Fig. 7 it is plotted what we expect in term of transverse plane distribution at the OTR2 position with the RFD on/off.

It is important to remark that, with this method, it is possible to completely characterize the longitudinal phase space of bunches after the chicane with a good resolution. We expect, therefore, to measure the effects of the Coherent Synchrotron Radiation in case of high charge and strong compression factors in the chicane as headtails energy spread growth and so on.



Fig. 7: Transverse plane distribution at the OTR2 position with the RFD on/off (obtained by ELEGANT).

CONCLUSIONS

In the paper we have studied the possibility to measure the bunch length and the longitudinal phase space of the CTF3 injector by using an RF deflector. We have proposed to use the travelling wave RF deflectors already constructed for the Combiner Ring. The main key parameters that allow increasing the resolution of the measure have been introduced. We have also discussed the perturbation induced on the beam dynamics by the RF deflector and we have concluded that a beam alignment precision of $\pm 3mm$ in the deflector gives a perturbation of about 3% in the measure. For any different chicane configuration it is possible to find an optical solution that optimise the measurement resolution in term of bunch length and energy spread. An example of optical functions and measurement simulation results has been, finally, shown.

- [1] R. Corsini et al., Phys. Rew. ST, 7, 040101,2004.
- [2] see for example P. Emma, et al., LCLS-TN-00-12, 2000; D. Alesini and C. Vaccarezza, SPARC-BD-03/001, LNF, Frascati, 2003.
- [3] D. Alesini, et al., "RF Beam Deflectors for CTF3 Combiner Ring", EPAC02, Paris.
- [4] D. Alesini and A. Gallo, Phys. Rev. ST Accel. Beams 7, 034403 (2004).
- [5] M. Borland, "Elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation" LS-287, ANL, USA.

HORIZONTAL INSTABILITY AND FEEDBACK PERFORMANCE IN DAΦNE E+ RING

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Abstract

In DA Φ NE, after the 2003 shutdown for the installation of FINUDA, a strong horizontal multibunch instability was found to limit the positron beam for currents >450mA. The author has performed transverse growdamp measurements in order to estimate the instability growth rates as well as the feedback damping rates for each bunch at different beam currents and to evaluate the tune shift along the bunch train. In particular, a strong dependence of oscillation amplitudes on the position of the bunch in the train has been observed. In this paper, the author describes the set-up for multibunch oscillation amplitude recording, summarizing some observations on the transverse instability and discussing the feedback performance. The feedback raises the threshold by about a factor of two, depending on the machine configuration.

INTRODUCTION

In DAΦNE, after the 2003 shutdown for the installation of FINUDA [1], a strong horizontal multibunch instability was found to limit the positron beam for currents >450mA. Measurements have been planned to understand the behaviour and characteristics of the instability.

ACQUISITION SYSTEM DESCRIPTION

To study the strong horizontal multibunch instability, the author has carried out measurements by recording the transverse displacements for each bunch on a turn-by-turn basis.

Switching off the horizontal feedback for short periods, data have recorded during transverse grow-damp to estimate the instability growth rates for each bunch at different beam currents and to evaluate the tune shift along the bunch train. In particular, a strong dependence of oscillation amplitudes on the bunch position along the train has been observed.

In this part of the paper, we describe the apparatus for tracking multibunch oscillation amplitude. A scheme of the system is in Fig. 1.

A pulse generator HP8116A is used to generate two synchronous output triggers in manual mode. The operator can easily modify the pulse widths by the instrument panel in a large range of values. One of the output signals, of variable duration, is used as a gate to switch off the horizontal (and/or the vertical) feedback for the duration of the pulse. The other pulse triggers the start of data acquisition.



Figure 1: Scheme of the apparatus used to make the measurements: the off signal can be applied to one or both the transverse feedbacks.

The Lecroy LC574A oscilloscope has the feature to accept an external signal as sampling clock for frequencies included in the range 50-500MHz. The DA Φ NE timing system [2] can provide triggers at RF (~368 MHz), RF/5 or RF/6 to the acquisition system. The signals to be recorded come from a four buttons pick up. Two H9 hybrid junctions provide the horizontal and vertical sum and difference. The oscilloscope acquires these four signals during a grow-damp recording. Several programs on a SUN workstation allow data storage and off-line analysis [3]. The transverse feedbacks use the same type of pickup and hybrid junctions as input to the low power electronics. The system generates the correction signal by a partially digital approach [4]. Each feedback makes use of two 250W power amplifiers.

OBSERVATIONS ON THE INSTABILITY

Measurements on the e+ horizontal instability have been done in two days of December 2003. The author has turned off the horizontal feedback for periods in the range 100-500 μ s, recording the x and y bunch-by-bunch displacements [5], [6]. The injected patterns have been 60 or 90 or 120 bunches with just one gap or no gap at all (the harmonic number is 120). The analysis programs have highlighted a first characteristic of the instability: it becomes progressively stronger toward the end of the bunch train. Figure 2 shows a grow-damp record of the horizontal instability for bunch 75, 80, 85 and 90 versus revolution turns. The bunch #90 is the last of the train and it has the largest horizontal displacement.



Figure 2 – Hor.instability grow/damp for the bunches 75, 80, 85, 90 versus revolution turns (1 turn = 324 nsec)

In Fig. 3, the maxima horizontal displacements provided by a data record are plotted for all bunches, and

it is remarkable to observe that bunches in the first part of the train are not oscillating at all.



Figure 3 – Maxima horizontal displacements (during a grow/damp record) versus bunch number.

Another characteristic that is possible to evaluate by the acquisition system is the bunch-by-bunch tune shift. The algorithm makes use of an fft routine working with selectable number of points. In Fig. 4 (on the left), the horizontal x tune is plotted versus the corresponding bunch number over a grow-damp record. The tune does not seem to change meaningfully over the train (it is .1211), still if the signal magnitude changes very much as plotted in Fig. 4 on the right. In this example, the fft routine provides a $\sim 1/500$ resolution.



Figure 4 – Bunch-by-bunch horizontal tune (value and magnitude) during a grow/damp record for all 90 bunches

The horizontal tune evolution of a bunch during subsequent time slots has been evaluated too. In fact, in fig. 5, another analysis program shows the behaviour of bunch #90. In this case, the horizontal tune changes slightly during the grow-damp moving from .1202 to .1211, up to .1216.



Figure 5 – Bunch #90 horizontal tune during a grow/damp record (magnitude versus value on the left plot, value versus time slot on the right plot)

The recorded data make possible to evaluate the instability grow rate at different beam current for all the bunches and for each bunch of the train: no meaningful differences have been found between the two cases. In the table 1 the instability grow rates and the horizontal feedback damping rates are summarized.

Table 1: horizontal instability inverse grow rates and horizontal feedback inverse damping rates

Injected bunches	Beam current [mA]	1/ inst. grow rate [μs]	1/ fb damping rate [μs]
90	535	35	16.8
90	500	70	18.9
90	484	no instability	no measure
60	525	52	28.3
60	500	68	34.2

FEEDBACK PERFORMANCE

From the table 1, the transverse feedback performance is very good, even if the horizontal instability grows very fast with the beam current. The best damping time measured is 16.8 μ s. To summarize, the feedback system raises the instability threshold by a factor of two depending on the machine configuration.

CONCLUSIONS

Feedback damping rates and some characteristics of the horizontal instability have been measured, even if the source of the instability has to be identified yet. The horizontal instability behaviour can be summarized in the following points:

a) progressively larger oscillations at the end of the bunch train;

b) inverse grow rates $\leq 35 \mu s$, still decreasing with the beam current;

c) weak influence of the bunch pattern on the instability threshold due to the small harmonic number (see table 1); the gap is useful;

d) very small tune shift both versus bunch position in the train and versus beam current.

It is remarkable to note besides these points, that the injection kickers, if not perfectly timed, can interact with the instability because they work in the horizontal plane. This can produce beam current saturation or, in the worst cases, loss of bunches during injection. Given that feedback performance is very good, a smaller impact of the instability can be found in different machine working point. This means, in particular, evaluating accurately betatron tunes, RF frequency and taking the best advantage of the Landau damping given in collision by the other beam.

ACKNOLEDGEMENTS

Thanks to D.Pellegrini and O.Coiro for the accurate installation and cabling, to F.Ronci and U.Frasacco for the board assembly. A.Stella has designed the calibration routines.

- [1] C.Milardi et al., "DAΦNE performance for the FINUDA experiment", this conference.
- [2] A.Drago et al., "Implementation and Performance of the DAΦNE Timing System", 6th European Particle Accelerator Conference (EPAC 98), Stockholm, Sweden, 22-26 June 1998, p.1661, LNF-98/023 (P).
- [3] A.Drago, A.Stella, "The Dynamic Tracking Acquisition System for DAΦNE e+/e- Collider", DIPAC2001 Proceedings, 5th European Workshop on Diagnostics and Beam Instrumentation, may 13-15, 2001, Grenoble, France.
- [4] A.Drago et al., "Fast Electronics for the DAΦNE Transverse Feedback Systems", ICALEPCS-2001-WEAP048, Nov 2001. 3pp. Contributed to 8th International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS 2001), San Jose, California, 27-30 Nov 2001. Published in eConf C011127: WEAP048,2001. e-Print Archive: physics/0111209.
- [5] S.Prabhakar, "New diagnostic and Cure for Coupled Bunch Instabilities", PHD Thesis, Stanford Un., SLAC-Report-554, February 2000.
- [6] J.D. Fox et al., "Programmable DSP Based Multibunch Feedback: Operational Experience from Six Installations". BIW 2000, Cambridge, Mass., May 2000. SLAC-PUB-8410.

AN RF DEFLECTOR DESIGN FOR 6D PHASE SPACE CHARACTERIZATION OF THE SPARC BEAM *

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Abstract

The characterization of the longitudinal and transverse phase space of the beam provided by the *SPARC* photoinjector is a crucial point to establish the performance quality of the photoinjector itself. By means of an RF deflector and a dispersive system, the six dimensional beam phase space can be analysed. A fivecell SW aluminum prototype of the *SPARC* RF deflector has been realized and tested. We report in this paper the design issues together with the RF measurement results. The simulation results of the 6D phase space reconstruction of the *SPARC* beam are also presented.

INTRODUCTION

The characterization of the longitudinal and transverse phase space of the beam at the exit of the third LINAC section, ($E \approx 150$ MeV), is a tool to verify and tune the photoinjector performance. With a RF deflector it is possible to measure the bunch length and, together with a dispersive system, the longitudinal beam phase space can be reconstructed [1]. A schematic layout of the measurement is reported in Fig. 1. The effect of the RF deflector is null in the longitudinal center of the bunch and gives a linear transverse deflection to the bunch itself. If we consider the beam distribution and a drift space of length *L* after the deflector, the transverse kick results in a transverse displacement of the centroid of the bunch slice. The displacement is proportional to the slice longitudinal offset *L*_B, and RF voltage according to the expression:

$$x_B = \frac{\pi f_{RF} L L_B V_\perp}{c E/e} \tag{1}$$

where V_{\perp} is the peak transverse voltage, and E/e is the beam energy in eV units.

Equation (1) shows that the longitudinal bunch distribution can be obtained by measuring the transverse bunch distribution at the position z_s . To measure the bunch length with a proper accuracy, the "displacement" x_B has to be greater than the rms transverse beam size σ_x . The resolution length L_{res} can be defined, therefore, as the relative slice longitudinal position that gives, on the screen, an x_B equal to σ_x . From Eq. (1) we can calculate the transverse voltage V_{\perp} necessary to achieve the desired resolution:

$$V_{\perp} = \frac{\sigma_x cE/e}{\pi f_{RF} LL_{res}} \tag{2}$$

A voltage V_{\perp} = 1.0 MV has been chosen for the RF deflector, obtaining a resolution of ≈ 2 %. The complete longitudinal phase space measurement can be obtained adding the effect of a dispersive system. In this scenario, the bunch is vertically deflected by the RF deflector and horizontally by a magnetic dipole. The dispersion properties of the dipole allow characterizing the energy distribution of the bunch and the total longitudinal phase space can be displayed on the screen. The transverse phase space characterization is obtained measuring the beam slice emittance in both the transverse planes with the quadrupole scan technique.

SIMULATION RESULTS

A 150k particle beam obtained from PARMELA [2] simulation at the end of the linac section has been tracked with the ELEGANT code [3] along the SPARC transfer lines.



Figure 1: SPARC measurement layout for high energy beam characterization

The images of the beam obtained at the screen location, FT2, are shown in Fig. 2 with the RF voltage OFF and ON, respectively.



Figure 2: Bunch transverse distribution at the FT2 location with the RF deflector voltage OFF (left) and ON (right) respectively.

The results of the data analysis are shown in Fig. 3 where the vertical projected and the longitudinal distributions of the bunch are displayed.



Figure 3: Above: the longitudinal bunch distribution as projected by the RF deflector on the vertical coordinate of the screen FT2; below: the particle distribution vs. time.

The value of σ_z , as obtained by applying Eq. (1), and by the longitudinal analysis of the raw data from ELEGANT tracking agree with an error less than 1%. The images collected on the dogleg at the screen located in FD2 show the reconstruction of the longitudinal phase space as shown in Fig. 4 where the time-energy $(z, \delta p/p)$ distribution is replicated in the transverse plane (y,x).



Figure 4: Above: Longitudinal phase space distribution of the SPARC beam . Below: Beam transverse distribution at the FD2 screen location as obtained tracking the beam through the SPARC dogleg with the RF deflector ON. The "reconstructed" rms energy spread value is in very good agreement with the real one, and the same holds for the slice analysis. To measure the beam slice emittance in the horizontal plane the RF deflector is used to scan the beam rms size at the screen locations FT2.

In Fig. 5 the beam horizontal slice emittance is given for the simulated measurement: (left figure),on the right the result of the temporal analysis of the raw data is reported.



Figure 5: Reconstructed horizontal beam slice emittance (in mm-mrad) as a function of slice number with the beam size scanning at FT2. The left curve is the horizontal emittance as calculated by slicing the beam output file (tracked with Elegant) along the temporal coordinate, the right curve is the result of the simulated quadrupole scan at the screen location.

RF DEFLECTOR DESIGN

The simplest and more efficient multi-cell deflecting structure that can be used to deflect the bunch is a standing wave structure operating in the π -MODE. The choice of the number of cells has been done according to the following considerations:

- a) the available transverse deflecting voltage for a given input power;
- b) the available space in the SPARC transfer line;
- c) the mode separation with different number of cells to avoid problems of mode overlapping;
- d) the maximum acceptable surface peak electric field to avoid problems related to high field intensities, discharges and so on.

A 5-cell deflecting structure fulfils all of the stated requirements. In fact, it allows operating with a very low input power ($P_{RF} \le 2$ MW) obtaining contemporary low peak surface electric field and resolution length up to $\approx 25 \mu m$. These characteristics permit measurement of the longitudinal beam profile with good accuracy, even considering the possibility of longitudinal compression factors of up to 20. Moreover the operation at low input power allows simplifying the power line design.

The 2D profile of the 5-cell RF deflector has been studied using the MAFIA 2D code. The simulated 5-cell profile is reported in Fig. 6 with the final dimensions and parameters shown in Table 1. The radius of the cells connected to the beam pipe tube in this design has been changed in order to achieve a field flatness of 3%. The on-axis magnetic field profile in the structure is plotted in Fig. 7.

_	a	20.00
mension [mm	b2=b3	59.97
	b1	60.67
	t	9.50
Dii	d	52.48
	Frequency [GHz]	2.85699
am.	Q	16800
Paı	$R_{\perp}[M\Omega]$	2.47

Table 1: Final dimensions and parameters of the 5-cell deflecting structure.



Figure 6: 5-cells deflecting cavity simulated by MAFIA2D.



Figure 7: Absolute value of the magnetic field for the 5-cells cavity obtained by MAFIA 2D simulations.

The coupler design has been chosen to adapt a rectangular waveguide; more details about the design procedure can be found in [1].

PROTOTYPE MEASUREMENT RESULTS

A full-scale aluminum prototype, see Fig. 8, has been constructed to make field measurements and to implement tuning procedures. Bead-pull measurements have been done to measure the field flatness in the cavity [4]. Different perturbing objects have been used to measure the H-E field components. The tuning procedure that we have implemented is based on the study of field and frequency sensitivities with respect to the 5-tuners and is widely discussed in [5]. The reflection coefficient at the input coupler port is plotted in Fig. 9. The comparison between the measured quantities and the simulated ones is reported in Table 2. The external quality factor should be slightly increased by adjusting, experimentally, the window coupler dimensions.



Figure 8: Deflector aluminum prototype and measurement setup.



Figure 9: Measured reflection coefficient at the input coupler port.

Table 2: compare between the measured quantities and the simulated ones

	Q0	QEXT	R _T /Q
Simulations	13200	16800	147
Measurements	6600	12900	149

CONCLUSIONS

A five-cell SW aluminum prototype of the SPARC RF deflector has been realized and test results are in agreement with the design predictions. The SPARC diagnostic layout has been presented together with the measurement simulation and the results of the 6D phase space reconstruction show the feasibility of a complete characterization of the longitudinal and transverse phase space of the beam provided by the SPARC photoinjector.

- D. Alesini and C. Vaccarezza, SPARC Note, SPARC-BD-03/001, Frascati, November 2003.
- [2] J. Billen, "PARMELA", LA-|UR-96-1835, 1996.
- [3] M. Borland, "Elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation" LS-287, ANL, USA.
- [4] M. Amadei, Tesi di Laurea, Univ. of Rome "La Sapienza", 2003.
- [5] P. Casavola, Tesi di Laurea, Univ. of Rome "La Sapienza", 2004.

COMMISSIONING OF THE OTR BEAM PROFILE MONITOR SYSTEM AT THE TTF/VUV-FEL INJECTOR

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Abstract

The TESLA Test Facility (TTF) linac at DESY has been extended to an energy of 1 GeV to drive a new Free Electron Laser facility (VUV-FEL) with wavelengths from 100 nm to 6 nm. Beam profile monitors based on optical transition radiation (OTR) provide an essential beam diagnostics tool. The OTR diagnostic system is routinely used to optimize the beam transport and to measure the transverse beam size and shape with a resolution down to 10 µm. The imaging system, using digital CCD cameras connected to local controllers, provides the operators realtime beam images and tools for image analysis and measurements such as beam emittance. This paper presents the commissioning of the OTR diagnostic system. It provided a valuable tool for the first running period of the TTF/VUV-FEL injector in spring 2004.

INTRODUCTION

The TTF linac is being extended to a new free electron laser facility, the VUV-FEL. Based on the superconducting TESLA technology the beam is accelerated up to 1 GeV to drive a SASE FEL in the wavelength range from VUV to soft X-rays [1].

Compared to TTF phase 1, the VUV-FEL is built to be a user-facility, which implies strong requirements in term of reliability and remote control of subsystems. For this reason, the optical electron beam diagnostics was completely redesigned in respect to the phase 1.

The measurement of transverse electron beam shapes is based on optical transition radiation (OTR) providing a fast and single shot measurement with linear response.

A fundamental issue was on one hand the requirement to have an rms resolution below 50 μ m to measure small beam sizes and on the other hand to have the flexibility to change the optical magnification of the imaging system. To improve the reliability the system is shielded from light, hands intrusion and radiation. Digital cameras were chosen to acquire the beam images. A distributed image acquisition system based on industrial computers collects the data and makes them available to the operator.

The OTR beam profile monitor is realized mainly by INFN (LNF Frascati and Roma 2) in collaboration with DESY.

The commissioning of the injector has been performed from middle of February to beginning of June 2004 [2], which included the commissioning of the first five stations of the OTR beam profile monitor system.

OTR BEAM PROFILE MONITOR

The OTR beam profile monitor is composed of several elements: a stepper motor actuator that inserts the OTR target into the electron beam line, an optical system to image the beam, an acquisition and processing system to deliver images and beam parameters to operators.

Vacuum components

Compared to TTF phase 1, an improved version of the stepper motor actuator with an improved mechanical stability is used to bring the target holder in the beam line. A calibration screen is embedded on the target holder. Most of the optical stations are equipped with two OTR radiators, a polished silicon wafer with and without aluminium coating. The aluminium coated radiator produces larger light intensity while the polished silicon radiator is suited for higher beam charge densities due to its higher melting point.

Optical system

The optical system consists of three lenses for three magnifications (1, 0.389, and 0.25) and three neutral density filters. Only one lens at a time is used, while it is possible to have more than one filter inserted to decrease the signal intensity. Every optical element is driven in and out of the optical axis with a DC motor. All motors are remotely controlled by means of CAN-BUS interface.

To improve the resolution of the optical system, a diaphragm is mounted in front of each lens. Their sizes are adapted to each lens in order to reduce the depth of field keeping the light intensity at the CCD large enough for camera sensitivity. One of the main requirements is the precision and the reproducibility in the positioning of the lenses into the optical axis. The system is mounted on a robust base and every element can be moved on two rods that guarantee the linearity of the motors 1 to 2 mm before the lens or filter holders touch the stopping block. Inertia brings the holder smoothly to the stops. They are well machined parts with small tolerances. We verified the precision and the reproducibility of the position and found that both are better than 10 μ m.

A digital CCD camera is used to acquire the beam image. A black enclosure provides light shielding, while lead bricks protect the camera from radiation.

All systems have been aligned in Frascati and the lens positions have been carefully adjusted using computer codes that compute images of calibration standard in order to measure the resolution. The average rms resolution measured with 1:1 magnification is 11 $\mu m.$

More details on the system can be found on the reference [3].

Acquisition system

The use of digital CCD cameras has several advantages: the signal is digitized already in the camera without the use of a frame grabber. Since the outgoing signal is already digital, electronic and environmental noise have little effect on the image quality. In addition, the IEEE1394 link (Firewire) allows control of the camera remotely. A common problem of the Firewire link is the degradation of the signal with increased cable length. This limits its length to 10 meters. Since the stations are distributes in the TTF linac over more than 200 m, some kind of repeaters or hubs would be needed. We preferred to connect the digital cameras to "industrial" compact Personal Computers, up to 6 cameras each. They act as local controllers and are installed into the accelerator tunnel. They can be accessed from the image server in the control room through the network to read images and control the camera settings.



Figure 1: Topology of acquisition system.

With such a solution the topology of the whole system is simplified and also compatible with the specifications of the IEEE1394 link used to control the digital cameras. The image server provides display and control tools, highlevel applications for image analysis and measurements and an interface for remote display (web server).

Display and measurement system

We have chosen Windows operating system for the image server because we use LabView tools for image acquisition and analysis and the support for different platforms is not yet available.

Beam images are displayed with on-line parameters, like projections, rms and FWHM sizes of the beam spot. Also a history of the beam parameters is available on the display screen. A camera control panel allows operators to select a camera and to modify its parameters, such as gain, shutter time and brightness.

The beam image including some relevant parameters is also sent embedded in an html page and delivered to internet for a fast and easy access worldwide.



Figure 2: Appearance of the image display and camera control panel with a simulated beam.

OPERATING EXPERIENCE OF OTR MONITORS IN THE INJECTOR

The TTF and VUV-FEL injector is composed by an RF Gun followed by an accelerating module, the first bunch compressor, a matching section and a FODO lattice to be used for the emittance measurements with the 4 monitors method [4]. More detailed description of the injector is in [2].

There are totally 9 cameras in the injector area, but only 5 of them are equipped with the optical system described above. However, all cameras use the above described image acquisition system and are controlled by the local computers. The four optical systems in the FODO lattice have been aligned using a laser beam on the nominal electron beam axis. With beam, the alignment has been cross checked and only one system required a slight readjustment.

Measurements

The OTR beam profile monitors were daily used to measure several beam parameters: the transverse beam shape and size and the energy and the energy spread in the dispersive sections.

Particular attention was dedicated to the commissioning of the 4-screens emittance measurement. In the quasiautomated procedure the operator has to prepare the configuration of the optical system choosing the magnification and inserting or extracting the OTR screens. Also several others parameters have to be defined like number of images to average, background subtraction, and image filtering settings.

We developed for this measurement a LabView program that displays the images collected by the four screens, together with the live image to allow the operator to change camera gain or filter intensity to prevent pixel saturation.



Figure 3: Appearance of the 4 screens emittance measurement panel.

At the end of the acquisition procedure, images are filtered to remove noise. Background is subtracted to clean images from dark current and other residual light. An estimation of the Twiss parameters and the emittance is also performed on-line.

During the commissioning phase the main goal was to optimize the beam properties and its transport through the accelerating module. Systematic emittance measurements have been started, but could not been completed yet. Nevertheless it was possible to determine the working point of the injector in terms of transverse emittance.

Two methods have been used to determine the rms beam size. In the first method, the horizontal and vertical projections are fitted with a Gaussian shape. In the second, a cut of 10% of the total intensity was performed on the 2D image and after this the rms is calculated on the projections. Obviously, when the beam shape is very irregular the results of the two methods are quite different. For irregular beams the rms value is strongly dependent on the particular beam distribution.

For accurate emittance measurements, it is important to have a well matched FODO lattice such that the beam image on each screen is regular and has similar dimensions. During the first phase of the injector commissioning this was not always the case. Therefore, the results obtained so far have to be considered preliminary and still object to further analysis, giving however a clear indication that the normalized emittance at 100 MeV, with 1 nC charge, is below the value of 6 mm-mrad, which is required for the start-up lasing of the VUV-FEL at 30 nm.

Improvement

The only serious problem that we had during the commissioning of the system was related to the cameras. Sometimes a few cameras were hanging up making it impossible to reset them without disconnecting the firewire cable. We didn't encounter this problem before because we never ran such large number of cameras for so many hours in a noisy environment like the accelerator tunnel. To avoid beam down time due to the cable disconnection in the accelerator tunnel, we plan in the

summer shut down to include the possibility to turn off remotely the cameras in our system.

REMOTE OPERATION AND MAINTENANCE

Remote operation has been tested from Frascati several times, and we succeeded to work remotely with the help of a DESY operator. We didn't encounter particular problems in the video conferencing and in transferring and displaying the beam images. We also succeeded to test and commissioning all our software remotely.

On a regular basis, maintenance and upgrading of the system has been done from Italy without any problem.

CONCLUSION

The OTR beam profile monitors in the TTF/VUV-FEL injector have been successfully commissioned. The system is used to measure beam shape and size, energy, energy spread and emittance. The optical system worked satisfactory, no failure has been observed. However, to solve the occasional hang of the cameras, a remote reset is in development and will be made available soon.

Acknowledgement

We want to point out, that R.Sorchetti has drafted the mechanical part of the optical system, and followed the realization. He participated in the installation of the systems as well as L.Caccioti, who designed the interface between the CAN-BUS and the optical system. We are also grateful to O.Giacinti that helped in cabling and mounting the systems. Without their work and help we couldn't done this job. We want also to remember the work on the CAN-BUS module and stepper motor drivers by J. Thomas and O.Hensler. Thanks also to the FEA group at DESY for their work on the trigger electronics.

- [1] "SASE FEL at the TESLA Facility Phase2", TESLA-FEL note 2002-01, DESY, 2002.
- [2] S. Schreiber and K. Floettmann, "Commissioning of the VUV-FEL Injector at TTF", in this proceedings
- [3] K. Honkavaara et al. "Design of the OTR beam profile monitors for the TESLA Test Facility, Phase 2 (TTF2)", Proc. PAC2003 Portland
- [4] M.G.Minty, F. Zimmermann, "Measurement and Control of Charged Particle Beams", Ed. Springer 2003

DESIGN STUDY OF A MOVABLE EMITTANCE METER DEVICE FOR THE SPARC PHOTOINJECTOR

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Abstract

Preliminary studies of the SPARC RF-Gun are planned to obtain an accurate analysis and optimization of the emittance compensation scheme, measuring the beam emittance evolution downstream the RF-Gun with an appropriate diagnostic system. Since in a space charge dominated beam the use of the quad-scan method is not applicable a 1D pepper-pot method will be used instead. A metallic mask with narrow slits will be installed on a longitudinally movable support, spanning a 1.5 m long region, to measure the emittance in several positions and reconstruct its evolution in the post gun section. Numerical simulations of the measurement, mainly based on PARMELA, have been used to estimate the achievable accuracy and to optimize the experimental setup. Wake field effects induced by the beam propagation through the long bellows have been also investigated with HOMDYN. Based on these simulations the design of the apparatus, called emittance-meter, has been realized and is under construction at LNF.

INTRODUCTION

The aim of the SPARC project is to promote an R&D activity to develop a high brightness photo-injector suited to drive a SASE-FEL experiment.

The first phase of the SPARC Project foresees the systematic emittance measurement along the post-RF gun drift where the emittance compensation process occurs. The complete characterization of the beam parameters at different distances from the cathode is important for code validation and to place the first accelerator module in the best position according to the emittance compensation scheme.

For this measurement a dedicated movable (in z) emittance measurement tool will be used giving the possibility to perform measurements from about z=83 cm to z=233 cm (the cathode is at z=0). The technique that will be employed for the emittance measurement consists in the use of a double system of emittance slit-arrays, horizontal and vertical, to measure the emittance and the Twiss parameters in both planes.

Numerical simulations of measurement based on this apparatus, mainly using ad-hoc simulation codes and PARMELA beam dynamics calculation, have been done [2] in order to optimize the mechanical design and the overall system performances.

THE EMITTANCE-METER

General Layout

The technique that will be employed for the emittance measurement consists in selecting one or several beamlets by means of an intercepting multi-slit mask (fig.1) or a single slit moving transversally over the beam spot.



Figure 1: Multi-slits mask intercepting a space charge dominated beam.

The slits reduce the dominated space charge incoming beam into some emittance-dominated beamlets that drift up to an intercepting screen. If the screen response is linear, the intensity of beamlets spots on the screen are directly proportional to the number of particles in the beamlets which hit the screen and the rms un-normalized emittance value can be retrieved by the formula [1].

The slits mask must stop, or largely degrade, the intercepted components of the beam. High-Z material, 2 mm thick tungsten in our case, will be used. The design of the apparatus is sketched in Fig.2. Two 1.5 m long bellows allow the cross, housing the slits mask, to be moved along a region where the most relevant part of the emittance compensation process occurs.

The measurement conditions change at different longitudinal positions, as consequence the distance between the slits mask and the analyzing screen cannot be fixed. For instance, when the value of the Twiss parameter α is close to zero (beam is highly collimated) a long drift is needed to produce a noticeable difference in the beamlets size respect to the slits width. On the opposite when the beam is strongly diverging a long drift is unadvisable because the beamlets spread on a large area. In this case the possible beamlets overlapping and the lower signal-to-noise ratio might reduce the accuracy of the measurement. For this reason another bellow is foreseen between the slits mask and the screen, allowing

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changing their distance from 20 to 40 cm, a measure that the simulations demonstrated to be a good compromise for the different scenarios.



Figure 2: Emittance-meter design.

The beam will be spent in a dump after a bending magnet. Before the dump, beam energy and energy spread will be measured.

Slits Mask

Two slit masks, mounted on two independent holders 90° with respect to each other, will be used to measure the emittance in the horizontal and vertical planes. A 2 mm thick tungsten mask was considered as sufficient to completely stop the 5.6 MeV electron beam. The slits width will be 50 μ m, being it a compromise between the requirement to produce emittance dominated beamlets, so the space charge contribution is negligible after the mask, and the practical requirement to have still enough electrons for the sensitivity of the analysis system. PAMELA code was run with 450K particles to check the influence of the residual space charge and, as evident from Fig.3, the contribution is negligible.



Figure 3: Analysis of the residual space charge effect after the metallic mask.

Every single slits are realized precisely machining a tungsten piece, and removing in the central part 50 μ m of metal. Then the parts are stacked to build the multi-slits mask (see Fig.4) and two single slits mask 50 μ m and 100 μ m respectively. A prototype of the pepper-pot has been realized to verify the achievable machining accuracy for this design. In the first set of slits produced, 8 over 9 shown machining accuracy better than 10%, thus compatible with the needed tolerances. Since the multi-slits masks are made assembling single metallic parts,

they will be built selecting the best slits among those being produced. It is worth to mention that the precise values of the slit widths will be included into the analysis formula avoiding systematic errors in the evaluation of the beam emittance.

In the slits-array the distance between slits is $500 \ \mu m$ providing an adequate transverse sampling of the beam and compatibility with machining tools. The main advantage of a multi-slits mask is the possibility to have single-shot measurements, thus not affected by possible shot-to-shot beam fluctuations.



Figure 4: Slit mask design.

In spite of that, the multi-slits system might not be suited in such conditions where the beam is well focused and highly collimated, i.e. in the proximity of a beam waist, because the number of beamlets emerging form the multi-slit mask might not be sufficient for a good reconstruction of the phase space, as illustrated in Fig.5.



Figure 5: Phase space and multi-slit option for different scenario.

In this case we'll use a single slit to transversally scan the beam collecting together the image from different positions. In this case the measurement is not single shot and beam fluctuations must be taken into account.

The thickness (z-direction) of the slits defines the angular acceptance of the mask, i.e. the maximum divergence allowed for particle trajectories selected from the mask. As consequence, this value cannot be lower than the beam angular divergence otherwise the particles will be also selected because of their divergence and not just because their transverse position. Following a detailed analysis by simulations we decided to design the mechanical support in such a way to allow tilting of the metallic mask in order to optimize the measurements.
Screens and Image Acquisition

Two main requirement must be fulfilled by the radiator screen: it needs to have a linear response with beam charge in the range of few tenths of pC and it must guarantee a resolution better than 20 μ m. Although OTR (Optical Transition Radiation) radiators, like aluminum foils, provide both high resolution and perfect linear response they have the disadvantage of a low intensity radiation. For our application, possible alternatives are Ce:YAG radiators and fluorescent material like BeO, that we are currently testing in the DAFNE Beam Test Facility.

For the image acquisition we'll use digital CCD cameras. They offer the advantage that the signal is digitalized directly from the camera electronics and there is no need of frame grabber, as result the outgoing signal, being it digital, will not be disturbed by the environmental noise, Furthermore the IEEE1394 (firewire) link allows simpler cabling topology because it carries both pixels readout and commands to the camera. A simple "macro" type objective will be used as imaging system.

Bellows

The influence on the beam quality of the 1.5 m long bellow has been investigated [3]. Wake fields perturbations due to the corrugated structure, especially when beam will not be well-aligned on-axis, were studied using HOMYDIN code and the wake fields were computed with the diffractive model Bane Sands.

The graph in Fig.6 shows the variation in percent of the beam emittance (at position z=150 cm from the cathode) due to a bellow misalignment for different values of the beam transverse position with respect to the bellow axis. In the worst case of 1 mm misalignment the contribution of the wakes to the emittance degradation is lower than 2%, thus practically negligible.



Figure 6: Degradation of the emittance due to a possible bellow misalignment.

The increasing of the energy spread due to the beam flight through the long bellows is analyzed in the plot of Figure 7. As for the emittance, the degradation of the beam has not practical relevance.



Figure 7: Energy spread vs z with (red curve) and without bellow.

CONCLUSION

The SPARC Emittance-meter will be built to perform a detailed study of the emittance compensation process in the SPARC photo-injector and to optimize the RF-gun and the accelerator working point. Installing the measurement system, based on the so-called "pepper-pot" method, between two long bellows we will have the possibility to scan a region 1.5 m long downstream the RF-gun.

Simulation codes have been used to study the layout and the mechanical design of the apparatus. Mask thickness, slits width, drift length between mask and screen, single slit vs. multi-slits option, alignment errors etc. have been studied to optimize the design and evaluate the performance of the system.

A prototype of the metallic mask has been already realized and measured. The overall apparatus design has been completed and the components are under construction at the LNF to be finally assembled by the end of 2004.

Acknowledgements

The authors want to acknowledge Valerio Lollo for his contribution to the design of the Emittance-meter.

REFERENCES

- [1] M. Zhang "Emittance Formula for Slits and Pepperpot measurement", FERMILAB-TM-1998.
- [2] M. Boscolo, A. Cianchi, M. Ferrario, L. Picardi, M. Quattromini, C. Ronsivalle, J. Rosenzweig, "Status of the low-energy emittance measurement simulation for the SPARC project", SPARC-BD-03/005.
- [3] V. Fusco et al., "Wake Fields Effects in the Photoinjector of the SPARC Project", this proceedings.