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CONTRIBUTIONS TO FEL 2002

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- SPARC project and SPARX proposal

- The SPARC project: a high-brightness electron beam source at LNF to drive a SASE-FEL experiment

- Conceptual design of a high-brightness linac for soft X-ray SASE-FEL source

- Overview of proposed VUV and soft X-ray projects in the world

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SPARC project and SPARX proposal

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On behalf of SPARC and SPARX Groups

Abstract

SPARC and SPARX are two distinct phases of an Italian FEL SASE project involving different national institutions. SPARC is a high gain FEL project aimed at developing a source of visible and VUV radiation exploiting SASE mechanisms. A 150 MeV Linac will provide a high quality e-beam to generate high brilliance FEL radiation at visible region at the fundamental wavelength and at VUV wavelengths with the harmonics. SPARC will allow to investigate velocity bunching mechanisms in the bunch compressor and coherent harmonic generation in the undulators. SPARX is a project aimed at the realization of an FEL SASE source operating at 13.5 and 1.5 nm in two separate undulators channels with a 2.5 GeV electron beam. SPARX development is expected to take profit of the SPARC activities and part of the equipment. We describe here the main features of these two projects including accelerators system, FEL sections and applications.

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Keywords: Synchrotron radiation; Storage-rings; Free electron laser; Laser; Linac

1. Introduction: the origin of the X-ray FEL project in Italy

The interest for the realization in Italy of an Ultra-high Brilliance X-ray Source arouse since 1998. The Italian Government, after the verification of the existence of a wide and interdisciplinary interest of the scientific community, allocated, in the frame of the 2000 National Research Plan (FIRB: Basic Research Investment Fund), 96 M€ for a Multi-purpose X-ray Laser with Ultra-High Brilliance. In the meantime (February 2001) in the frame of the Special Integrative Research Fund (FISR), issued a call for proposal (11 M€) for R&D activity on the field of Innovative Components for High Intensity VUV and X, Coherent and Incoherent Multi-purpose Sources. A joint proposal (SPARC: Coherent Radiation Self Amplified Pulsed Source) has been presented in the FISR frame by CNR, ENEA, INFM, INFN, Univ. Rome (Tor Vergata) and Sincrotrone Trieste aiming at building a 150 MeV ultrabrilliant photoinjector and a UV-SASE experiment. This proposal has been approved and the specific R&D activity is starting just now. The call for proposal for the Ultra-High Brilliance X-ray Laser in the FIRB frame was published in December 2001 and

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a joint proposal (SPARX: X-ray Self Amplified Pulsed Source) has been presented by part of the SPARC partners (CNR, ENEA, INFN, Univ. Rome (Tor Vergata)) aiming at building a 1.5 nm SASE FEL. The evaluation process is presently under way.

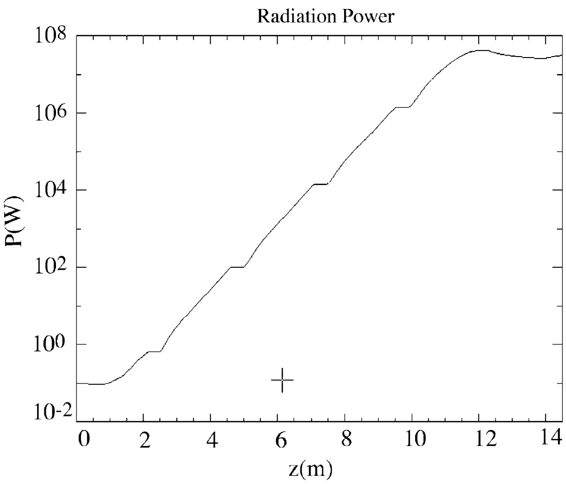

Fig. 1. 3D (GENESIS) Simulation for SPARC at 535 nm ($E = 142.5$ MeV, $I = 150$ A, $\varepsilon_n = 1$ mm mrad, $\Delta E/E = 0.1\%$, $\lambda_u = 3$ cm).

2. The SPARC project [1]

SPARC is a project devoted to the realization of a ultrabrilliant photoinjector and of a SASE FEL (see e.g. Ref. [2]) source of visible and VUV radiation.

The device will be located in an existing underground bunker at LNF in Frascati (Rome). A 150 MeV Linac will provide a high quality e-beam to generate high brilliance FEL radiation at visible region at the fundamental wavelength and at VUV wavelengths with the harmonics. In Fig. 1 it is reported a 3D (GENESIS) simulation for SPARC at 535 nm (1st harmonic) [1]. In addition SPARC will allow to test one important innovative concept, i.e. the velocity bunching mechanisms in a longitudinal bunch compressor [3].

Table 1
Cost of SPARX SASE FEL M€

Linac S-band/L-band (injector included)	36/47
Undulators	10
Radiation Beam Lines	10
Infrastructures (external funding)	16
Contingency	11

Table 2
Time Schedule of SPARX SASE FEL

	1st year		*2nd year*		*3rd year*		*4th year*		*5th year*		*6th year*	
Design	■	■	■									
Injector		■	■	■	■							
Linac (2.5 GeV)			■	■	■	■	■	■	■	■		
Undulator (13.5 nm)		■	■	■	■	■	■					
Undulator (1.5 nm)					■	■	■	■	■	■		
Photon lines (R&D)		■	■	■								
Photon lines (construction)					■	■	■	■	■	■		
Commissioning											■	■
Infrastructure design	■	■										
Civil construction			■	■	■	■	■					

3. The SPARX proposal [4]

This proposal is not based on available or provided by other programs accelerators. For this reason the study group decided to start a broad band investigation to compare different schemes and technologies. The aim was to develop a program able to reach a wavelength of interest (i.e. with a good scientific case), consistent with the available budget. In addition the Project is meant to be *evolutionary*, i.e. compatible with a long-term upgrade expected to reach the final goal of 1 Å Coherent Radiation Source. A quite good and appealing Scientific Case has been identified in the region $\lambda = 10 - 1$ nm. In the meantime 10–1 nm are quite suitable steps along the road toward 1 Å [4].

In the proposal two alternative solutions have been examined:

1. S-band room temperature injector and Linac,
2. L-band Superconducting Linac with S-band room temperature injector.

The costs and time schedule of the 1.5 nm SPARX source are reported in Tables 1 and 2, respectively.

The location of the facility is foreseen the "Tor Vergata" Campus of University of Rome.

References

[1] D. Alesini et al., The SPARC Project: a high-brightness electron beam source at LNF to drive a SASE-FEL experiment, Nucl. Instr. and Meth. A, these proceedings.

[2] F. Ciocci, et al., Insertion Devices for Synchrotron Radiation and FEL, World Scientific, Singapore, 1980.

[3] L. Serafini et al., Velocity bunching in photoinjectors, Proceedings of the 18th ICFA Beam Dynamics Workshop on Physics of and Science with X-ray FEL's, Arcidosso, Italy, September 2000.

[4] D. Alesini et al., Conceptual design of a high-brightness Linac for soft X-ray SASE-FEL source, Nucl. Instr. and Meth. A, these proceedings.

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The SPARC project: a high-brightness electron beam source at LNF to drive a SASE-FEL experiment

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Abstract

The Project Sorgente Pulsata e Amplificata di Radiazione Coerente (SPARC), proposed by a collaboration among ENEA–INFN–CNR–Universita' di Tor Vergata–INFM–ST, was recently approved by the Italian Government and will be built at LNF. The aim of the project is to promote an R&D activity oriented to the development of a coherent

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ultra-brilliant X-ray source in Italy. This collaboration has identified a program founded on two main issues: the generation of ultra-high peak brightness electron beams and of resonant higher harmonics in the SASE-FEL process, as presented in this paper.

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Keywords: High-brightness electron beams; SASE-FEL

1. The SPARC project

The overall SPARC project consists of four main lines of activity aiming at several goals: their common denominator is to explore the scientific and technological issues that set up the most crucial challenges on the way to the realisation of a SASE-FEL based X-ray source, the SPARX proposal [1]. These are:

(1) 150 *Mev advanced photo-injector*: Since the performances of X-ray SASE-FELs are critically dependent on the peak brightness of the electron beam delivered at the undulator entrance, we want to investigate two main issues—generation of the electron beam and bunch compression via magnetic and/or RF velocity bunching—by means of an advanced system delivering 150 MeV electrons, the minimum energy to avoid further emittance dilutions due to time-dependent space charge effects.

(2) *SASE-FEL visible-VUV experiment*: In order to investigate the problems related to matching the beam into an undulator and keeping it well aligned to the radiation beam, as well as the generation of non-linear coherent higher harmonics, we want to perform a SASE-FEL experiment with the 150 MeV beam, using a segmented undulator with additional strong focusing, to observe FEL radiation at 530 nm [2] and below.

(3) *X-ray optics/monochromators*: The X-ray FEL radiation will provide unique radiation beams to users in terms of peak brightness and pulse time duration (100 fs), posing at the same time severe challenges to the optics necessary to guide and handle such radiation. This project will pursue also a vigorous R&D activity on the analysis of radiation–matter interactions in the spectral range typical of SASE X-ray FELs (from 0.1 to 10 nm), as well as the design of new optics and monochromators compatible with these beams.

(4) *Soft X-ray table-top source*: In order to test these optics and to start the R&D on applications, the project will undertake an upgrade of the presently operated table-top source of X-rays at INFM-Politecnico Milano, delivering 10^7 soft X-ray photons in 10–20 fs pulses by means of high harmonic generation in a gas.

In the following, the layout and planned activities for items (1) and (2) will be presented in more detail.

2. Advanced photo-injector

The main goals of this activity are acquiring an expertise in the construction, commissioning and characterisation of an advanced photo-injector system and performing an experimental investigation of two theoretical predictions that have been recently conceived and presented by members of this study group. These are the new working point [3] for high brightness RF photo-injectors and the velocity bunching technique to apply RF bunch compression through the photo-injector, with emittance preservation [4]. The 150 MeV injector will be built inside an available bunker of the Frascati INFN National Laboratories: the general layout of the system is shown in Fig. 1.

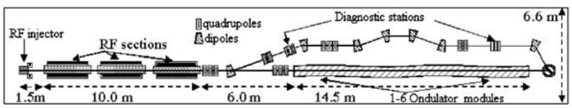

Fig. 1. Layout of SPARC R&D project.

The proposed system to be built consists of a 1.6 cell RF gun operated at S-band (2.856 GHz, of the BNL/UCLA/SLAC type [5]) and high peak field on the cathode (120–140 MeV/m) with incorporated metallic photo-cathode (Copper or Mg), generating a 6 MeV beam which is properly focused and matched into two accelerating sections of the SLAC type (S-band, travelling wave) the third section is foreseen for the rectilinear compressor experiment, as explained later.

The laser system driving the photocathode will use the radiation from a Ti:Sa laser with the oscillator pulse train locked to the RF (see Fig. 2). Ti:Sa mode locked oscillator and amplifiers able to produce the requested energy per pulse (500 μJ at 266 nm) are commercially available. To obtain the time pulse shape we are going to test the manipulation of frequency lines in the large bandwidth of Ti:Sa, in order to produce the 10 ps long flat top shape. We can use a liquid crystals mask in the Fourier plane of the non-dispersive optic arrangement or a collinear acusto-optic modulator for line frequency manipulation.

Liquid crystals act as pixels that introduce a controlled phase delay on different parts of the spatially dispersed spectrum. The acusto-optic modulator performs a continuos frequency modulation and can operate on a bandwidth up to 200 nm, one order of magnitude larger than the capability of liquid crystals. The transverse homogeneity is produced with a pinhole and a position dependent transmission filter. The time and energy stability can be achieved by proper feedback loops and by the control of the laser environment. Laser pulse shaping technique has been recently demonstrated to be a useful tool for the reduction of non-linear space charge forces, achieving an emittance of 1.2 μm with a 1 nC, 9 ps long bunch [6].

The first experiment with the electron beam we have planned to do is the verification of the beam emittance compensation process predicted by the new working point described in Ref. [3] in combination with the laser pulse shaping. The key point is the measurement of the emittance oscillation in the drift after the gun where a double minima behaviour is expected. Since the optimum beam matching to the booster is predicted on the relative emittance maximum, see Fig. 3, a dedicated movable emittance measurement station has been designed, as shown in Fig. 4.

A pepperpot and a screen are connected with three long bellows in order to scan the emittance along a 1 m long drift and to find experimentally the optimum location of the first TW structure.

The chromatic origin of the double emittance minima behaviour [7], due to the solenoid energy-dependent focal length, and the charge and gun peak field scaling will also be investigated at the beginning of the experimental program.

Our PARMELA [8] simulations show an rms normalised emittance as low as 0.6 μm (1.2 μm) for

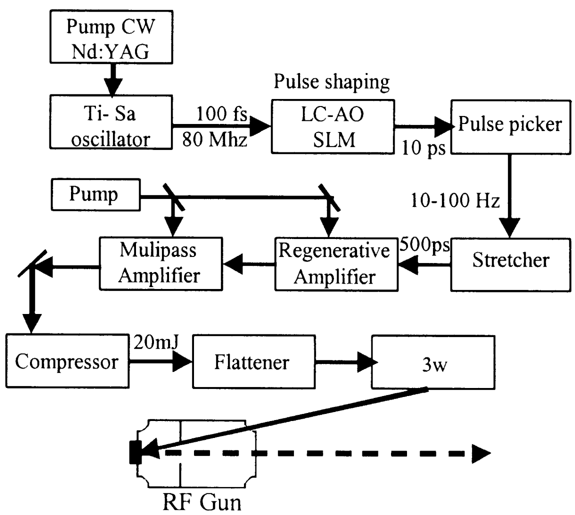

Fig. 2. Layout of the photocathode Laser system.

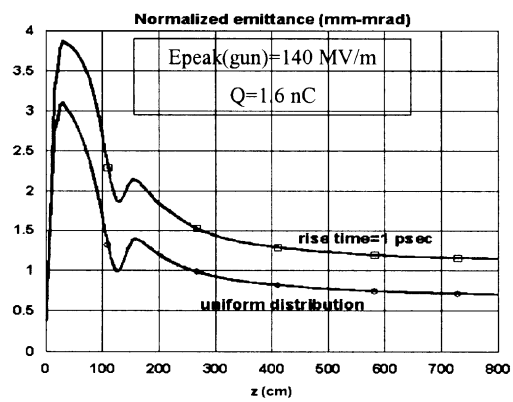

Fig. 3. PARMELA simulation of emittance evolution along the injector (gun + 2 TW structures).

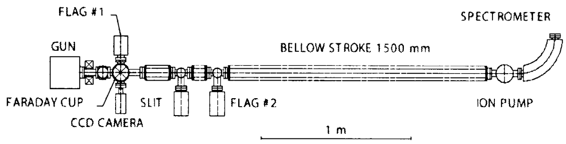

Fig. 4. Movable emittance measurement station.

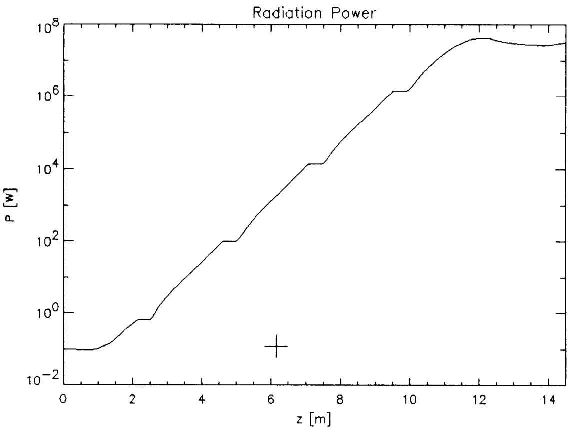

Fig. 5. Radiation power at 530 nm growth along the undulator.

a 1 nC (1.6 nC) bunch. We can generate with this system a beam like that needed by the FEL experiment at 150 MeV. The rms correlated energy spread over the bunch is 0.14% with a rms normalised emittance of 1.2 μm (at 1.6 nC bunch charge, 150 A peak current), but the slice energy spread and the slice normalised emittance, calculated over a 300 μm slice length (comparable to the anticipated cooperation length), are well below 0.05% and 0.5 μm, respectively, all over the bunch.

3. The FEL SASE source

The FEL SASE experiment will be conducted using a permanent magnet undulator made of 6 sections, each 2.5 m long, separated by 0.3 m gaps hosting single quadrupoles which focus in the horizontal plane. The undulator period is set at 3.3 cm, with an undulator parameter $k_w = 1.88$.

A simulation performed with GENESIS [9] is reported in Fig. 5, showing the exponential growth of the radiation power at 530 nm along the undulator: almost 10^8 W can be reached after 14 m of total undulator length. Preliminary evaluations of the radiation power generated into the non-linear coherent odd higher harmonics show that 10^7 and 7×10^5 W can be reached on the third and fifth harmonics, respectively.

4. Further experiments

As shown in Fig. 1, the SPARC layout displays two main upgrades that will be implemented in a second phase of the project: a third accelerating section which will be inserted downstream the RF gun and a parallel beam line containing a magnetic compressor.

The new section will be designed to study RF compression: it will support travelling waves at an adjustable phase velocity (from $v = c$ down to $v = 0.999c$) in order to exploit the full potentialities of the velocity bunching technique [3]. Its design and construction will proceed in parallel to the commissioning of the SPARC injector system (RF gun + 2 standard SLAC-type 3 m sections). These tests of RF compression assume great relevance in our R&D program [1] since the general lay-out for SPARX foresees the use of a mixed compression scheme, RF compression in the photoinjector up to 700 A and one single stage of magnetic compression at 1 GeV up to the final peak current of 2.5 kA.

The second beam line will allow us to conduct experiments on magnetic compression. We also plan to investigate experimentally CSR induced effects on emittance degradation and surface roughness wake-field effects, without interfering with the ongoing FEL experiment.

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References

[1] D. Alesini, et al., Nucl. Instr. and Meth. A 507 (2003) 503.
[2] S. Milton, et al., Science 292 (2001) 2037.

[3] M. Ferrario, et al., Homdyn study for the LCLS RF photoinjector, SLAC-PUB 8400.
[4] L. Serafini, M. Ferrario, AIP Conf. Proc. 581 (2001) 87.
[5] D.T. Palmer, The next generation photoinjector, Ph.D. Thesis, Stanford University.
[6] J. Yang, et al., J. Appl. Phys. 92 (3) (2002).
[7] M. Ferrario, et al., in: J. Rosenzweig, L. Serafini, (Eds.), The Physics & Applications of High Brightness Electron Beams, World Scientific, Singapore, to be published.
[8] L.M. Young, J.H. Billen, PARMELA, LA-UR-96-1835, 2000.
[9] S. Reiche, Nucl. Instr. and Meth. A 429 (1999) 243.

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Conceptual design of a high-brightness linac for soft X-ray SASE-FEL source

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Abstract

FELs based on SASE are believed to be powerful tools to explore the frontiers of basic sciences, from physics to chemistry to biology. Intense R&D programs have started in the USA and Europe in order to understand the SASE physics and to prove the feasibility of these sources. The allocation of considerable resources in the Italian National

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Research Plan (PNR) brought about the formation of a CNR–ENEA–INFN–University of Roma "Tor Vergata" study group. A conceptual design study has been developed and possible schemes for linac sources have been investigated, leading to the SPARX proposal. We report in this paper the results of a preliminary start to end simulation concerning one option we are considering based on an S-band normal conducting linac with high-brightness photoinjector integrated in an RF compressor.

PACS: 41.60.Cr

Keywords: High-brightness beams; Soft X-ray FEL

1. The SPARX proposal

Driven by the large interest that X-ray SASE FEL's light sources have raised world-wide in the synchrotron light scientific community, as well as in the particle accelerator community and following solicitations arising from several Italian national research institutions, the Italian Government launched in 2001 a long-term initiative devoted to the realization in Italy of a large-scale ultra-brilliant and coherent X-ray source. The allocation of considerable resources in the Italian National Research Plan (PNR) brought about the formation of a CNR–ENEA–INFN–University of Roma "Tor Vergata" study group. A conceptual design study has been developed and possible schemes for linac sources have been investigated leading to the SPARX proposal.

Two spectral complementary regions around 13.5 and 1.5 nm, are considered for the radiation source. In order to generate the SASE-FEL at these wavelengths, it is necessary to produce a high-brightness beam to inject inside two long undulators. A preliminary analysis of the beam parameters required for such a source leads to values reported in Table 1.

We report in the next sections the results of a preliminary start-to-end simulation concerning one option we are considering based on an S-band normal conducting linac.

The basic scheme is shown in Fig. 1 and consists of an advanced high-brightness photoinjector followed by a first linac that drives the beam up to 1 GeV with the correlated energy spread required to compress the beam in a subsequent magnetic chicane. The second linac drives the beam up to 2.5 GeV while damping the correlated energy spread taking profit of the effective contribution of the longitudinal wake fields provided by the S-band accelerating structures. A peculiarity of this linac design is the choice to integrate a high-brightness photoinjector in a rectilinear RF compressor, as recently proposed [1], thus producing a 300–500 A beam in the early stage of the acceleration. The potentially dangerous choice to compress the beam at low energy (<150 MeV) when it is still in the space charge dominated regime, turns out not to be a concern provided that a proper emittance compensation technique is adopted [2], a possibility that is not viable in a magnetic chicane. In addition, the propagation of a shorter bunch in the first linac reduces the potential emittance degradation caused by transverse wake fields, and longitudinal wake fields can be controlled by a proper phasing of the linac.

Table 1
Electron beam parameter

Beam energy	2.5	GeV
Peak current	2.5	kA
Emittance (average)	2	mm-mrad
Emittance (slice)	1	mm-mrad
Energy spread (correlated)	0.1	%

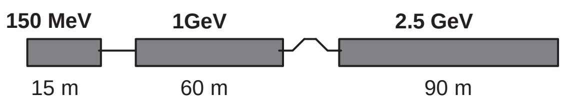

Fig. 1. Linac scheme of SPARX project.

2. High-brigthness photoinjector with RF compressor

The injector preliminary design considers a 1.6 nC bunch 10 ps long (flat top) with 1.2 mm radius, generated inside a 1.6-cell S-band RF gun of the same type of the BNL-SLAC-UCLA one [3] operating at 140 MV/m peak field equipped with an emittance compensating solenoid. Three standard SLAC 3-m TW structures, each one embedded in a solenoid, boost the beam up to 150 MeV. With a proper setting of accelerating sections phase and solenoids strength, applying the compression method described in Ref. [2], it is possible to increase the peak current preserving the beam transverse emittance. In the present case, we have got with PARMELA simulation a bunch average current of 440 A with a normalized rms emittance below 1 mm mrad. The low compression ratio (a factor of 3) has been chosen to keep the longitudinal emittance as low as possible in order to simplify the second compression stage. We used the first two TW sections as compressor stages in order to achieve a gradual and controlled bunching, the current has to grow about at the same rate of the energy, and we increased the focusing magnetic field during the compression process. An optimized RF compressor parameters set is reported in Table 2.

Fig. 2 (above) shows the current growth during bunch compression until 150 MeV, envelope and emittance evolution are also reported (below), showing the emittance compensation process driven by the solenoids around the accelerating section that keep the bunch envelope close to an equilibrium size during compression [2].

A dedicated R&D program (SPARC project [5]) is envisaged at LNF-INFN in collaboration with CNR–ENEA–INFM–ST–Tor Vergata University.

Table 2
RF compressor parameters

TW section	I	II	III
Gradient (MV/m)	15	25	25
Phase (deg.)	−88.5	−67	0 (on crest)
Solenoid field (G)	1120	1400	0

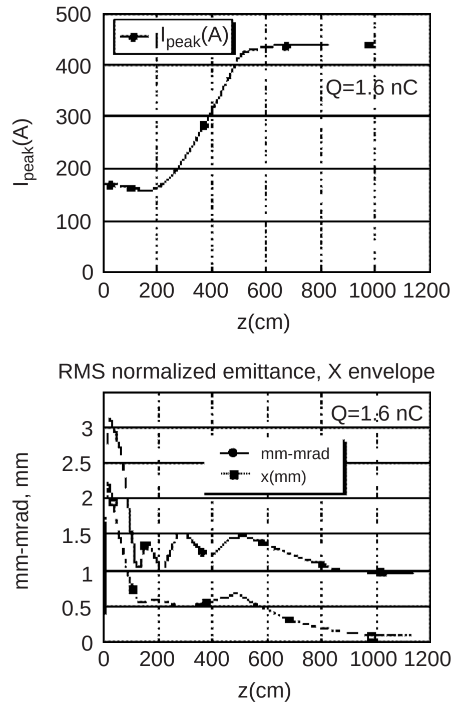

Fig. 2. Rms current (above), rms norm. emittance and rms beam envelope (below) along the injector, up to 150 MeV.

Its aim is the generation of electron beams with ultra-high peak brightness to drive a SASE-FEL experiment at 520 nm, performed with a 12 m undulator after the linac.

3. The linac

The accelerator dedicated to the FEL-SASE source has the task of accelerating high-brightness electron bunches up to the energy of 2.5 GeV including a second compression stage. Linac1 consists of 15 S-band TW structures, operating at 20 MV/m and the beam is propagated 20° off crest. In Linac2, additional 24 accelerating structures are foreseen with the same gradient and the beam is propagating on crest. The beam optics consists in a FODO lattice. The nominal values for the proposed source have been reported in Table 1.

The 10 k macro-particles beam generated by PARMELA has been propagated through Linac1,

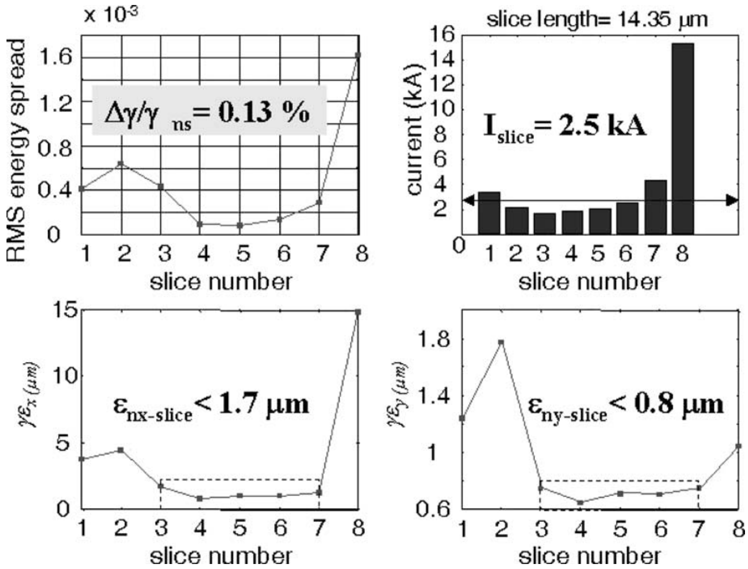

Fig. 3. Energy spread, peak current and transverse emittances along the bunch.

Magnetic Compressor and Linac2 with the code ELEGANT. The correlated energy spread induced by Linac1 is 0.6% in order to compress the beam by a factor of 6 in the 15 m-long magnetic chicane with an $R_{56} = 48$ mm. At the exit of Linac2, the required parameters for FEL operation have been achieved over more than 50% of the bunch length, as shown in Fig. 3.

A further improvement is expected by fully optimizing the compression scheme and by using a fourth harmonic cavity [4] for the linearization of the longitudinal phase space distribution.

4. The FEL-SASE source

We envisage using the same beam to feed two undulators whose characteristics are reported in Table 3. The characteristics of the FEL-SASE radiation up to the fifth harmonics, have been investigated by means of several codes: GINGER, GENESIS, MEDUSA, PROMETEO, PERSEO, and the results are shown in Table 4 and Fig. 4.

With the two undulators, it is possible to cover a bandwidth from 1.2 to 13.5 nm, with the first harmonic, and a bandwidth from about

Table 3
Undulators characteristics

	Undulator 1 at 1.5 nm	Undulator 2 at 13.5 nm
Type	Halbach	Halbach
Period	3 cm	5 cm
K	1.67	4.88
Gap	12.67 mm	12.16 mm
Residual field	1.25 T	1.25 T

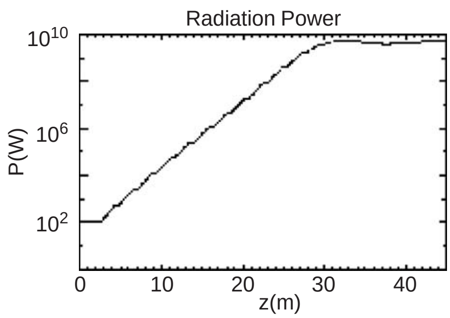

Fig. 4. FEL signal evolution ($\lambda = 1.5$ nm) along undulator 2. The typical "steps" in the exponential rise are due to beam focusing regions where there are no undulators.

Table 4
FEL-SASE expected performances

Wavelength (λ)	1.5 nm	13.5 nm
Saturation length	24.5 m	14.5 m
Peak power	10^{10} W	4×10^{10} W
Peak power 3° harm.	2×10^{8} W	5×10^{9} W
Peak power 5° harm.	3×10^{7} W	2×10^{8} W
Brilliance[a]	1.8×10^{31}	2×10^{32}
Brilliance* 3° harm.	10^{29}	10^{31}
Brilliance* 5° harm.	9×10^{28}	3×10^{29}

[a] The brilliance is given in photons/s/0.1% bw/(mm mrad).

0.4–4 nm, using the third harmonic, which exhibits still a considerable peak power, as reported in Table 4.

Time-dependent FEL simulations, performed using the particle distributions produced by the start-to-end simulations presented in the previous section, are in progress, showing saturation for 50% of bunch slices after 30 m of active undulator length. These first preliminary results are encouraging and will be the starting point for further optimizations.

5. Conclusions

A preliminary start-to-end simulation of the SPARX proposal has been presented. The possibility to integrate an RF compressor into a linac for FEL application has been investigated for the first time. The 1 nC case with 120 MV/m peak field on the gun is also under investigation.

References

[1] L. Serafini, M. Ferrario, Velocity bunching in photoinjectors, AIP Conference Proceedings, New York, Vol. 581, 2001, p. 87.

[2] M. Boscolo, et al., Beam dynamics study of RF bunch compressors for high brightness beam injectors, Proceedings of EPAC, Paris, 2002.

[3] D.T. Palmer, The next generation photoinjector, Ph.D. Thesis, Stanford University.

[4] M. Ferrario, K. Flottmann, T. Limberg, Ph. Piot, B. Grygorian, TESLA-FEL 2001-03.

[5] D. Alesini, et al., The SPARC Project, Nucl. Instr. and Meth. A, these proceedings.

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

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Overview of proposed VUV and soft X-ray projects in the world

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Abstract

The status of the art of the VUV-X-ray FEL sources, the limit of the relevant technologies and the future perspectives are analysed. Possible strategies aimed at developing the design of a road map toward very short wavelengths, very high brilliance and very short pulses are discussed. Within such a framework we report and comment on the proposed devices.

PACS: 41.70; 42.55.T; 29.20.D

Keywords: Synchrotron radiation; Storage-rings; Free electron laser; Laser; Linac

1. Introduction

Synchrotron Radiation (SR) devices developed from the stage of parasitic devices to the so-called 3rd generation sources, which have now been operated for about 8 years, and are capable of providing photon beams with peak brilliance of at least 10^{18} c.u. (photons/s/0.1%bw/(mm mrad)^2).

In a typical 3rd generation light source, the horizontal (vertical) r.m.s. emittance ε_x (ε_y) is about 10^{-9} (10^{-10}) mrad, thus ensuring good transverse coherence in the UV region and partial coherence down to tens of Å or shorter. The development and the operation of 3rd generation sources did not determine automatically the death of the 2nd generation counterparts [1]. Third generation sources are indeed coexisting with 2nd generation devices, which have recently provided very important and crucial results in condensed matter Physics [2]. Such a lesson from the past is not of secondary importance and is a key point to be kept in mind when discussing of any further improvement beyond 3rd generation.

Since 1976 Free Electron Lasers (FEL) produce highly coherent radiation beams with brightness many orders of magnitude larger than that of undulator radiation. The shortest wavelength record of a FEL oscillator (1st harmonic) is 190 nm from the Storage Ring based FEL oscillator in Trieste [3]. The present wavelength limit of FEL oscillators is mainly due to mirror availability and the relevant technological improvements will certainly allow, in the next future, the operation at shorter wavelengths. By keeping as figure of merit the electron beam (e.b.) characteristics of third generation sources we can safely conclude that storage ring FEL oscillators are technologically mature devices, capable of providing highly coherent radiation with peak

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brilliance exceeding 10^{28} c.u. in the region around 150 nm. Storage ring based FELs have provided us with an important tool of research not fully explored and recognized. Important contribution to the understanding of microwave instability evolution in storage rings has been made possible by the study of e.b. + FEL radiation combined dynamics [4]. These results could provide a deeper insight into the phenomenology of coherent synchrotron radiation (CSR) [5] and on its cures.

The possible options as next generation SR sources are Storage Ring Upgrade, Linac Based SASE FELs, Energy Recovery Linacs (ERL). Storage rings provide e.b. with a brightness which is a result of the damping and quantum excitation processes occurring in the ring bending magnets. Unfortunately, the demands for high brilliance coherent radiation at shorter wavelengths is conflicting with the request of small emittance, which increases quadratically with energy. Its minimization requires the design of a lattice which compensates the dilution effect induced by the quantum excitations. The price to be paid to have a low emittance is to have a high energy storage ring with a large circumference to allow the insertion of the optical elements necessary for the quantum diffusion compensation. The design of an ultimate Hard X-ray Source (UHXRS) [6] foresees a circumference of 2200 m necessary to allocate 160 bending magnets and 720 quadrupoles. Such a magnet array would provide at 7 GeV, with respect to ESRF at 6 GeV, e.b. with horizontal (vertical) emittance 20 (2) times smaller with a bunch length about 1/3 shorter at 12 keV of photon with average and peak brilliance more than 2 order of magnitudes larger (i.e. 3.5×10^{22} and 1.0×10^{25} c.u., respectively) [7]. The use of ERL is an interesting candidate which prevents all the unpleasing features of storage ring sources. After the successful operation of the high power IR FEL at the Jefferson Lab., in which a quite efficient e.b. recovery scheme has been exploited, interesting proposals have been issued by many laboratories, aimed at the enhancement of the brilliance, together with the possibility to generate very short radiation pulses (hundred of femtosecond or even less) in the X-ray region.

2. Road map toward VUV-X spectral region

In Tables 1 and 2 have been reported the scenarios of the under development and proposed VUV and soft X-ray FEL projects, respectively.

Table 1
Under development VUV and soft X-ray projects scenario

Project	Location	Type	e-beam energy	λ	Notes	Ref.
TTF2	DESY, Hamburg (D)	SASE	1 GeV	6 nm	Start of operation: 2004	[8]
SCSS	SPring-8 (J)	SASE	230 MeV (phase I) 1 GeV (phase II)	40 nm 3.6 nm	"Compact": Short period in vacuum undulator High gradient C-Band accelerator Low emittance beam injector Start of operation at 40 nm: 2005	[9]
DUV-FEL	NSLS, BNL (USA)	SASE HGHG (laser seed)	200 MeV	200–50 nm	Achieved 400-nm light by SASE on February 2002	[10]
LEUTL	APS, Argonne (USA)	SASE HGHG	220 MeV	660–130 nm	Achieved 130 nm light by HGHG	[11]

Table 2
Proposed VUV and soft X-ray projects scenario

Project	Location	Type	e-beam energy	λ	Notes	Ref.
TESLA X-FEL	DESY, Hamburg (D)	SASE	25 GeV	0.1 nm	Considered to be worthy of support by German Science Council (Pressemitteilung 20/2002) start of operation: 2011	[12]
Soft X-ray FEL	BESSY, Berlin (D)	SASE	2.25 GeV	1.2 nm		[13]
LCLS	SLAC, Stanford (USA)	SASE	15 GeV	0.15 nm	The project has been receiving funding of $1.5 million per year from the Department of Energy, Basic Energy Sciences for the four-year period FY1999–FY2002. Funding is expected to increase in FY2003 to $6.0 million as listed in the Presidents Budget for FY2003 start of operation: 2008	[14]
SPARC	ENEA,INFN,INFM, CNR,Sync. Trieste, Un. Roma II (I)	SASE	150 MeV	VIS-VUV	(Funded) start of operation: 2005	[15]
SPARX	ENEA,INFN,CNR, Un. Roma II (I)	SASE	2.5 GeV	1.5 nm	It is intended as a second step after SPARC (awaiting for Government decision) start of operation: 2008	[15]
VXFEL	INFM, Sync. Trieste, Pirelli S.p.A. (I)	SASE FEL oscillator + harmonic generation	1 GeV	6.4 nm		[16]
FERMI	INFM, Sync. Trieste (I)	SASE	3 GeV	1.2 nm	(Awaiting for Government decision) start of operation: 2008	[16]
4GLS	Daresbury (UK)	SASE (XUV) FEL oscillator (VUV)	600 MeV	VUV-XUV (IR FEL osc.) ERL scheme	Secretary of State for Trade and Industry: on 16th April 2002 it was agreed that 4GLS should proceed to the next stage of the Office of Government Commerce Gateway review process	[17]
SOLEIL FEL	SOLEIL (F)	FEL oscillator	1.5 GeV	150 nm up to 30 nm (5th harmonic)	Storage ring FEL	[18]

All these projects, with the exception of SOLEIL FEL, are based on a SASE FEL scheme driven by RF linac, which appears to be the only suitable for operation in the soft X-ray region.

Many laboratories are studying new strategies in which a reliable road map toward VUV-X region has to be designed. We shall limit ourselves to the case of single passage SASE FEL devices.

Alternative options do not appear suitable, for operation up to the Å region.

2.1. Physics of the SASE FEL process

Physics of SASE FEL has been investigated many years ago in a series of papers (see Ref. [19]) in which the main features of the process have been clarified. The main experimental milestones can be single out as it follows:

- *1984* LLNL (Livermore, USA) [20]: 34.6 GHz radiation propagating along a wave-guide, driven by induction accelerator (very high efficiency: saturation with tapered undulator),
- *1989* MIT (USA) [21]: 240–470 GHz radiation propagating along a wave-guide (FEL (weakly) collective Raman regime),
- *1998* UCLA (Los Angeles, USA) [22]: $\lambda = 12\,\mu m$, free space propagation (not saturated) With this last experimental result there was a quantitative and qualitative improvement of our knowledge on SASE process. Namely the operating wavelength was about three orders of magnitude shorter than LLNL 1984 device and a factor 50 shorter than MIT 1989, and, in addition, the optical radiation propagates in free space and not along a wave-guide.
- *2001* TTF1 (Hamburg, D) [23]: $\lambda = 80-120\,nm$ saturation): good agreement with the theory.

Lasing at 100 nm was a quite big step toward VUV—X-ray spectral region (more than two orders of magnitude with respect to first UCLA 1998 result).

SASE FEL theory is now mature. The process is well understood and, if the requested experimental conditions are met, it will be possible to operate with the desired spectral and brilliance characteristics up to the soft X-ray region. In Fig. 1 the operating wavelengths of existing and proposed SASE FEL sources are reported.

On the other side, a lot of additional work is still required for the investigation and analysis of new schemes, in particular aimed at improving spectral and/or coherence properties of the generated VUV-X radiation. Specific experimental activity is foreseen in the presently under development devices (Table 1) and in the new proposal (Table 2).

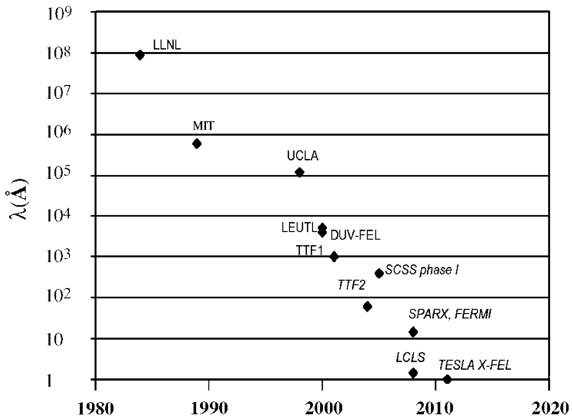

Fig. 1. SASE FEL devices operating wavelength (Ångstrom) vs. (foreseen) year of start of the operation.

2.2. Generation and shaping of suitable electron beams

For the past we can single out the following milestones:

- Photo-cathodes and driver lasers development: first devices (at that time called "Lasertron") were developed at SLAC (USA), KEK (J), LAL (Orsay, F) and LANL (USA) in the middle of 80s. In particular it must be underlined the quite big effort made in LANL, where high efficiency photocathodes have been developed just for FEL applications [24].
- Magnetic beam compression: it is interesting to note that this technique have been utilized in a FEL device many years ago (in the middle of 80s) in order to have just the opposite effect, i.e. to reduce the energy spread at the expense of bunch length and peak current (FELIX (Glasgow, UK) [25]).

  For the future, a first milestone certainly concerns further important improvements of performance and reliability of the photoinjectors and R&D on alternative cathode schemes (e.g. single crystal thermionic gun, plasma ore "needle" cathodes). Furthermore we must underline a milestone related to the realization of a superconducting (s.c.) RF photo-injector.

Namely, the possibility to exploit at the best the high duty cycle of a s.c. linac is related to the availability of a full s.c. device, gun included. Finally, as to the e.b. shaping, due to the fact that the CSR emitted in the curved electron path can generate severe damage to the e.b. emittance and energy spread, a further milestone related to a non-magnetic beam compression scheme [26] must be foreseen.

- High brilliance cathode development
  - SCSS: CeB6 single crystal thermionic gun [9].
  - TESLA X FEL –first measurements at the PITZ (photo-injector test facility at DESY Zeuthen) [27].
  - S.c. RF photo-injector: first results of collaboration FZR-BINP-DESY-ACCEL-MBI [28,29].
- Non magnetic compression schemes
  - UCLA [30]: Velocity bunching observed.
  - DUVFEL[31]: RF compression (factor 5 of current enhancement).
  - SPARC—SPARX: longitudinal bunch compressor R&D [15].

2.3. Electron beam acceleration and transport

The acceleration and transport of a quite bright, short and monochromatic e.b. is a challenging task. Namely, it is mandatory to preserve the high quality characteristics of the beam in all the stages of injection, acceleration and steering into the undulator magnet. The relevant milestones are:

- Compact Linac R&D
  - SCSS: C-band linac (40 MV/m) [9].
- Understanding of CSR effects (micro-bunches instability).
  - UCLA: numerical and theoretical effort [32]
- Characterizing the interaction between electrons and pipe surface (resistive wall, corrugation).
  - TTF (DESY): experimental activity and comparison with predictions on wake fields generated by picosecond electron bunches on artificially corrugated narrow beam pipes [33].
  - ATF (BNL): experimental activity and comparison with predictions on wake fields generated on periodically and randomly corrugated beam pipes [34]. Results show that the energy loss is greatly reduced in the random case.

2.4. Undulator magnets

The realization of undulators for SASE FEL devices operating in the VUV—X region is still a challenging task. Namely, just to mention some of the most important issues, we have to consider that tight tolerances required for SASE FEL operation have to be maintained along quit long devices (many tens of meters), the undulator design has to allow to insert a large variety of diagnostics systems. In addition, due to the interest to operate at very short wavelengths at lower e.b. energy, new undulator schemes have been proposed [35]. A quite promising scheme is the so-called dual-harmonic undulator [36,37] for which theoretical and experimental activity is planned.

3. Conclusions

Theoretical and experimental status of the art in the field of VUV—Soft X-ray FELs appears quite adequate for a further step toward the Å spectral region. Namely the first results coming from the devices under development give us a pretty good confidence on the reliability of the theoretical scaling laws governing the SASE FEL process. In the mean time the recent advances in the e.b. generation and manipulation make the technology level quite close to that required for that ambitious goal. It must be again strongly underlined that the 4th generation SR source will not replace the previous ones but it can fruitfully complement them. The same applies to the UV-VUV FEL oscillators whose potentialities appear far from being completely exploited.

References

[1] M. Altarelli, Synchrotron radiation: perspectives and new technologies, Atti dei Convegni Lincei 179, Roma 2002.

[2] D.W. Lynch, C.G. Olson, Photoemission Studies of High Temperature Superconductors, Cambridge University Press, Cambridge, 1998 and references therein.
[3] M. Trovò, et al., Nucl. Instr. and Meth. A483 (2002) 157.
[4] R. Bartolini, et al., Phys. Rev. Lett. 87 (2001) 134801.
[5] Z. Huang, K. Je Kim, Phys. Rev. Special Topics—Accelerators Beams 5 (2002) 074401.
[6] I. Ben Zvi, PERL Photoinjector Workshop, BNL, January 2001, 22–23.
[7] P. Ellaume, in: M. Altarelli, Synchrotron radiation: perspectives and new technologies, Atti dei Convegni Lincei 179, Roma 2002.
[8] The TESLA Test Facility FEL Team: SASE FEL at the TESLA Facility, Phase 2, DESY Report TESLA-FEL 2002-01, June 2002.
[9] T. Shintake, et al., Status of SCSS: SPring-8 Compact SASE Source Project, EPAC2002.
[10] E. Johnson, DUV-FEL Current Status and Plans, TJNAF LPC Workshop, January 2001.
[11] A. Doyuran, et al., Phys. Rev. Lett. 86 (2001) 5902;
S.G. Biedron, et al., Exotic harmonic generation schemes in high-gain free-electron lasers, LASER 2002, Proc. SPIE p. 4632 (2002).
[12] G. Materlik, Th. Tschentscher (Eds.), TESLA Technical Design Report, Part V, DESY Report TESLA-FEL, 2001-05, Hamburg, 2001.
[13] M. Abo-Bakr, et al., Nucl. Instr. and Meth. A483 (2002) 470.
[14] LCLS Design Study Report, Report SLAC-R-521, 1998; Conceptual Design Report for the LCLS project of the US Department of Energy, April 2002 (http://www-ssrl.slac.stanford.edu/lcls/).
[15] A. Renieri, SPARC Project and SPARX Proposal, Nucl. Instr. and Meth. A (2003), these proceedings.
[16] C.J. Bocchetta, et al., Overview of fermi@elettra, A proposed Ultra Bright Coherent X-ray Source in Italy, Nucl. Instr. and Meth. A (2003), these proceedings.
[17] M.W. Poole, B.W.J. McNeal, FEL Options for the Proposed UK Fourth Generation Light Source (4GLS), Nucl. Instr. and Meth. A (2003), these proceedings.
[18] see: http://www.soleil.u-psud.fr/workshops/LEL/Notice-LEL_2001.pdf.
[19] P. Sprangle, et al., Phys Rev. A21 (1980) 302;
G. Dattoli, et al., IEEE J. Quantum Electron. QE-17 (1981) 1371;
R. Bonifacio, et al., Opt. Commun. 50 (1984) 373;
K. Kwang-Je Kim, Nucl. Instr. and Meth. A250 (1986) 396.
[20] T.J. Orzechowski, et al., Phys. Rev. Lett. 54 (1985) 889.
[21] D.A. Kirkpatrick, et al., Phys. Fluids B1 (1989) 1511.
[22] M.J. Hogan, et al., Phys. Rev. Lett. 81 (1998) 4867.
[23] V. Ayvazyan, et al., Phys. Rev. Lett. 88 (2002) 104802;
J. Rossbach, Demonstration of Gain Saturation and Controlled Variation of Pulse Length at the TESLA Test Facility FEL, Nucl. Instr. and Meth. A (2003), these proceedings.
[24] P.J. Tallerico, Nucl. Instr. and Meth. A272 (1988) 218 and ref. therein.
[25] M.W. Poole, et al., A237 (1985) 207.
[26] L. Serafini, M. Ferrario, AIP CP 581 (2001) 87.
[27] J.W. Baher, First Measurements at the Photo Injector TEST Facility at DESY Zeuthen, these proceedings.
[28] E. Barhels, et al., Nucl. Instr. and Meth. A445 (2000) 408.
[29] H. Büttig, et al., First Operation of a Superconducting RF Electron Gun, Nucl. Instr. and Meth. A (2003), these proceedings.
[30] P. Musumeci, J.B. Rosenzweig, Velocity Bunching: experiment at Neptune Photo-Injector. Proceedings of ICFA Workshop on The Physics and Applications of High Brightness Electron Beams, Chia Laguna, Italy, July 1–5, 2002, in press.
[31] P. Piot, et al., Subpicosecond compression by velocity bunching in the DUV-FEL photo-injector at BNL. in: Proceedings of ICFA Workshop on The Physics and Applications of High Brightness Electron Beams, Chia Laguna, Italy, July 1–5, 2002, in press.
[32] S. Reiche, J.B. Rosenzweig, A Fast Method to Estimate the Gain of the Microbunch Instability in a Bunch Compressor, Nucl. Instr. and Meth. A (2003), these proceedings;
Jan Menzel, et al., Experimental Investigations on Coherent Diffraction, Synchrotron, and Transition Radiation, Nucl. Instr. and Meth. A (2003), these proceedings.
[33] M. Huening, Phys. Rev. Lett. 88 (2002) 074802;
M. Huening, Measurements and Simulation of Surface Roughness Wake Fields, Nucl. Instr. and Meth. A (2003), these proceedings.
[34] F. Zhou, et al., Experimental Characterization of Surface Roughness Wakefield at the ATF, Nucl. Instr. and Meth. A (2003), these proceedings.
[35] Y. Yang, W. Ding, Nucl. Instr. and Meth. A 407 (1998) 60.
[36] G. Dattoli, et al., Bunching and Exotic Undulator Configurations in SASE FELs, Nucl. Instr. and Meth. A (2003), these proceedings.
[37] S.G. Biedron, et al., Spectral Properties of Two Harmonic Undulator Radiation and their Influence on FEL Performance, Nucl. Instr. and Meth. A (2003), these proceedings.