DAΦNE e^+e^- COLLIDER COMMISSIONING RESULTS

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Abstract

The Φ - factory DAΦNE [1], e+e- collider with a design luminosity of 5.2x10^{32} $cm^{-2}s^{-1}$ at the energy of Φ resonance (1020 MeV in the center of mass), is being commissioned at the INFN Frascati National Laboratory, Italy.

Here we describe the performance of the accelerators of the DAΦNE complex: the electron-positron Linac, the intermediate accumulator ring and the two main rings. The principal subsystems, such as RF, longitudinal feedbacks etc., are addressed in details.

We also present our observations and experience gained during the machine commissioning in single and multibunch regimes and discuss the measurements undertaken to optimize the collider luminosity and lifetime.

1 INTRODUCTION

In order to reach the design luminosity, which exceeds by almost two orders of magnitude the maximum luminosity achieved, in the same energy range, at VEPP-2M collider [2], a high current multibunch flat beam approach has been adopted for DAΦNE, similar to that of the B-Factories PEP-II [3] and KEK-B [4].

Electron and positron beams with a maximum average current of ~ 5 A are stored in two separate rings and collide in two Interaction Points (IP). The crossing at a horizontal angle of 25 mrad minimizes the effect of parasitic collisions and it allows to store up to 120 bunches per ring, corresponding to a colliding frequency of 368.26 MHz. The high rate of bunch collisions relaxes the single bunch luminosity parameters. The main design parameters are summarized in Table 1.

The DAΦNE accelerator complex consists of a ~ 60 m long full energy Linac, an intermediate damping ring, called “Accumulator” and two intersecting collider Main Rings. Transfer Lines, ~180 m long, connect the Linac to the Accumulator and the Accumulator to the Main Rings. The construction and installation phases of the DAΦNE complex were completed in Autumn 1997 (see Fig. 1). The injector commissioning has been carried out in parallel with the main rings installation, for a total period of two months spread along two years. The Linac and Accumulator performance have exceeded the design values and both accelerators operate in a reliable way.

The collider commissioning without the experimental detectors (*day-one* configuration) is well advanced. The roll in of KLOE [5] detector on the first IP is scheduled by next fall with the start of physics run by the end of the year. FINUDA [6] roll-in will come later and in the meantime the DEAR [7] experiment will take data on the second IP.

Table 1: DAΦNE Design Parameters

Energy [GeV]	0.51
Maximum luminosity [$cm^{-2}s^{-1}$]	5.3×10^{32}
Single bunch luminosity [$cm^{-2}s^{-1}$]	4.4×10^{30}
Trajectory length (each ring) [m]	97.69
Emittance, $\varepsilon_x / \varepsilon_y$ [mm·mrad]	1/0.01
Beta function, β_x^* / β_y^* [m]	4.5/0.045
Transverse size σ_x^* / σ_y^* [mm]	2/0.02
Beam-beam tune shift, ξ_x / ξ_y	0.04/0.04
Crossing angle, θ_x [mrad]	25
Betatron tune, ν_x / ν_y	5.09/5.07
RF frequency, f_{RF} [MHz]	368.26
Number of bunches	120
Minimum bunch separation [cm]	81.4
Particles/bunch [10^{10}]	8.9
RF voltage [MV]	0.250
Bunch length σ_L [cm]	3.0
Synchrotron radiation loss [keV/turn]	9.3
Damping time, $\tau_\varepsilon / \tau_x$ [ms]	17.8/36.0

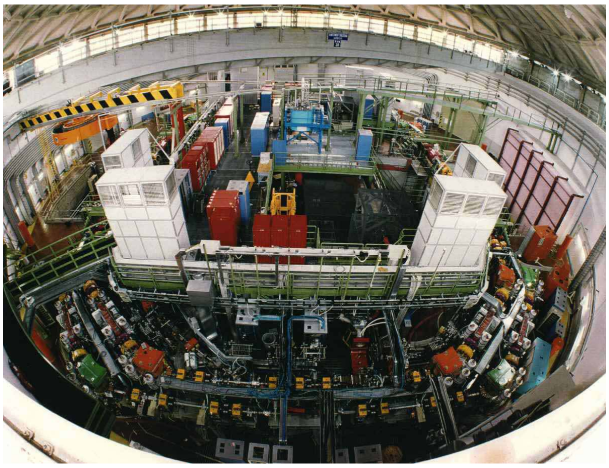

Figure 1: DAΦNE hall (June 1998).

2 INJECTION SYSTEM

The DAΦNE injection system has been sized to fill in few minutes from scratch the large required current in the Main Rings in the single bunch mode in order to ensure the maximum flexibility in the stored bunch patterns. The whole system runs at the operating energy of the collider, so that the current decay (mainly due to the Touschek effect) can be compensated by refilling the rings on top of the already circulating current (this injection mode is called "top up").

2.1 DAΦNE Linac

The first part of the DAΦNE injector is a ~ 60 m long Linac which alternately produces and accelerates the electron and positron beams up to the collider operation energy of 510 MeV. It is an S-band accelerator (2.856 GHz) driven by four 45 MW klystrons each followed by a SLED peak power doubling system. It delivers 10 ns pulses at a maximum repetition rate of 50 Hz. A quadrupole FODO focusing system is distributed along the entire structure.

A triode gun delivers up to 10 A electrons at 120 kV. The beam is then accelerated at about 200 MeV by five 3 m long accelerating sections up to a removable target, where it is focused by a quadrupole system to a 1 mm radius spot to produce positrons with an efficiency of 1.8%. The positrons are collected by a high field pulsed magnetic lens, separated from the electrons by means of a "chicane" of dipoles, and then accelerated up to a maximum energy of 540 MeV by 10 accelerating sections.

Table 2: DAΦNE Linac beam parameters.

	Electron Mode		Positron Mode	
	Design	Achieved	Design	Achieved
Operation Energy (MeV)	510 800 max unloaded	510 740 max	510 550 max unloaded	510 540 max
rms Energy Spread (%)	0.5	0.56	1.0	0.95
Macrobunch Current (mA)	150	>300	36	100
Macrobunch Length (ns)	10 FWHM	10 FWHM	10 FWHM	10 FWHM
Emittance (mm mrad)	1.0	< 10	10.0	< 10
Repetition Rate (pps)	50	50	50	50

In the electron mode of operation the converter is removed from the beam and the electrons are accelerated through the whole structure up to a maximum energy of 740 MeV.

The Linac has been designed, built and installed by the USA firm TITAN BETA [8], the system check-out has been done by TITAN and LNF personnel jointly, while the commissioning of both beams has been entirely performed by the LNF staff [9]. The commissioning phase started on April 1996 and was concluded on February 1997. Since then the Linac has been operating on a base of 15 days per month. The design parameters have been achieved with both electrons and positrons and some of the parameter values are above specs. In particular, the current exceeds the nominal value by a factor of 2 for electron beam and by about a factor of 3 for positrons. Table 2 compares the main design and achieved parameters of the Linac.

2.2 Accumulator ring

The DAΦNE Accumulator is a small storage ring, which has been included into the DAΦNE injection system for the following reasons:

- With the maximum positron design current from the Linac, ~ 10^4 injection pulses would be necessary to fill the positron ring. With such a large number of pulses, strict requirements on the injection aperture are mandatory to avoid saturation. With an intermediate booster between the Linac and the collider this large number can be split into two factors, the number of injection pulses into the booster (≈ 80) to reach the full current of a single Main Ring bunch times the number of bunches (120).
- The RF system runs at the 120th harmonic of the revolution frequency in order to store a large number of bunches. This is not necessary in an intermediate ring, where only a single bunch is needed. It is therefore possible to run the Accumulator at an RF frequency lower than that of the Main Rings, allowing to accept the full Linac pulse in a single bunch.
- After accumulating the desired current, injection into the Accumulator can be stopped for a short time to allow the beam to damp down to its equilibrium energy spread and emittance, which are typically two orders of magnitude smaller than the corresponding Linac values. In this way a high quality beam can be extracted from the Accumulator and injected into the Main Rings, thus avoiding the necessity of designing the Main Rings lattice with a larger physical and dynamic acceptance, and relaxing the requirements on the Main Rings magnets with substantial savings on the overall cost of the facility. The Accumulator layout is shown in Fig.2.

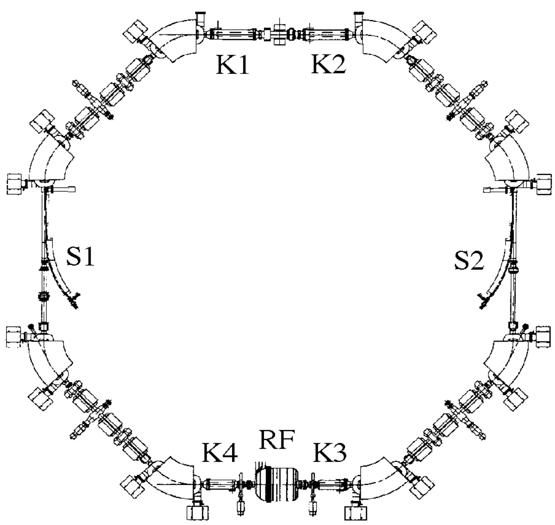

Figure 2: Accumulator layout

The following considerations were taken into account while designing the Accumulator:

- reference orbit length exactly 1/3 of the DAΦNE Main Ring one to allow easy synchronization;
- symmetric structure to allow injection/extraction of both electron and positron beams without changing the magnetic fields;
- low emittance and energy spread, short damping time;
- low dispersion in the injection/extraction sections.

These requirements are fulfilled by designing the lattice as a symmetric structure of four quasi-achromatic sections, each one with two small radius (1.1 m) dipoles with a field index of 0.5 and three quadrupoles, separated by long straight sections to accommodate the injection/extraction septa, the kicker magnets and the RF cavity. The chromaticity is corrected by means of 8 sextupoles, 2 in each achromat.

The Accumulator construction was completed in December 1995. After completing the installation of the Transfer Line from the Linac inside the Accumulator Hall and the electric and cooling systems, commissioning of the ring was easily and rapidly carried out. The first electron beam was stored in June 1996. The first positron beam was stored and extracted in November 97, and design performance with both beams achieved at the beginning of 1998. In the commissioning phase the Linac runs at half the nominal repetition rate , and ≈ 50 mA positrons are routinely stacked at 25 Hz in less than one second in a single bunch. The design current corresponding to the required charge per bunch in the Main Rings (132 mA) can be easily reached. The maximum single bunch current stored under stable conditions exceeds 200 mA. The lifetime of the stored beam is largely sufficient for injection into the Main Rings, being more than half an hour at the maximum operating current.

The operation of the Accumulator for the collider commissioning is reliable and downtime negligible.

Figure 3 shows the output of a DC beam current transformer during a typical injection/extraction cycle with electrons for the commissioning of the Main Rings. In this configuration 5 electron pulses are stored in the Accumulator; then the beam is damped and extracted. The repetition rate of this sequence is 1 Hz.

Figure 3: A typical injection/extraction cycle as seen on the DCCT monitor

3 MAIN RINGS

3.1 Machine Optics

Electrons and positrons are stored in two symmetric rings, intersecting in two points and sharing two Interaction Regions (IR), where beams travel in the same vacuum chamber, passing off-axis in the low beta quadrupoles. At the end of each IR the beams are separated by 12 cm and a split field magnet drives the two beams in the corresponding rings. The DAΦNE layout is shown in Fig.4.

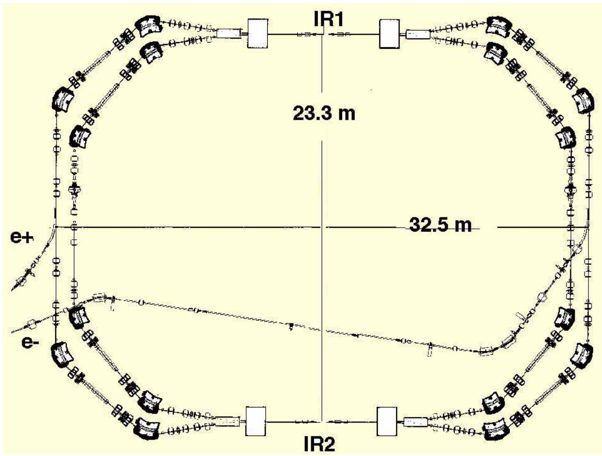

Figure 4: DAΦNE magnetic layout.

The ring periodic structure consists of four arcs. The straight sections orthogonal to the IRs are used for injection, RF and feedback kickers. The arc cell, named BWB (Bending-Wiggler-Bending) [11], is quasi-achromatic, its special feature being the presence of a 1.8 T wiggler, 2 m long, in the region of maximum dispersion, which doubles up the synchrotron radiation emitted in the dipoles. The damping times are shortened and instabilities thresholds are raised. The wiggler allows also emittance tuning at constant field by appropriate control of the dispersion function.Moreover, the resulting increase of the natural energy fluctuation should raise the beam-beam tune shift limit [12].

All quadrupoles and sextupoles are independently powered for maximum flexibility. There are 480 power supplies [13], ranging from 100 VA to 1500 kVA. The very different output currents (10÷2300 A) and output voltages (8÷1300 V) have led to different technical solution realized by various industries.

3.2. Principal subsystems.

Special RF cavities, with low impedance parasitic high order mode (HOM) content, have been developed [14] to allow stable high current-multibunch operation. The cavities, one per ring, are normal conducting copper single cells, with a system of HOM damping waveguides which couple out and dissipate the HOM energy induced by the beam on external 50 Ω loads. The HOM shunt impedances have been reduced by up to three orders of magnitude. The operation of the damped cavities has been until now very successful, without any evidence of arcing or multipacting effects due to the loading waveguides.

A longitudinal bunch-by-bunch feedback system [15] has been implemented in collaboration with the SLAC/LBL PEP II group to damp beam residual oscillations. It consists of a scalable time domain system employing digital techniques. A wideband kicker cavity has been developed at LNF [16]. The longitudinal bunch by bunch feedback systems have been set-up [15] and are operational in both rings. In particular, damping times in the millisecond region are routinely obtained and consistently measured. A damping time faster than ~ 200 μsec has been demonstrated in the positron ring with 30 bunches. Figure 5 shows the beam spectrum with feedback off and on in the positron ring.

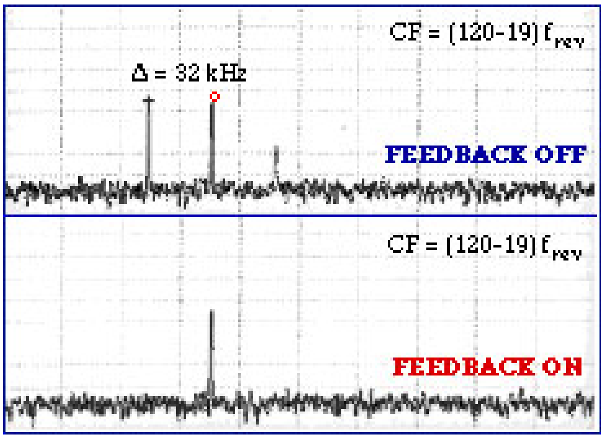

Figure 5: Beam spectrum without and with feedback in the positron ring, 30 bunches, 70 mA

A timing system [17] provides the synchronization of the Main Ring (MR) RF cavities, the Accumulator RF phase, the firing instant of the Linac, the injection/extraction kickers in the accumulator ring and the MR injection kickers in order to fill the selected bucket, with a precision down to a few picoseconds.

The Control System [18] is completely based on personal computers. The commercial software LabVIEW has been chosen at any level and the hardware interface is based on specially developed MacIntosh boards in a VME environment. The machine devices are driven by several distributed CPUs. A shared memory instead of a network permits fast, easy, and high bandwidth communications. The Control System has allowed the step by step commissioning of the major DAΦNE subsystems as they were installed, proving to be modular and extensible.

3.3. Single beam commissioning.

The initial commissioning phase of the collider has been dedicated to optimize the single bunch luminosity. The start up has been done directly on design IP parameters, i.e., nominal betatron functions (β^*) at the IP and nominal crossing angle. However, in order to reduce closed orbits and make first injection and storage easier, the first working point (5.15, 5.21) was far from the nominal one (5.09, 5.07) [19]. After gaining the experience with this lattice and having first successful beam-beam collisions, in order to optimize the luminosity the working point has been moved closer to nominal tunes (5.11, 5.07) keeping low β^* and the nominal coupling. As a final step, the lattice will be tuned on the nominal working point after fine closed orbit correction.

Extensive measurements of optical functions and chromaticity have been done for both working points [11]. A quite satisfactory agreement has been reached between measurements and a machine model which includes fringing effects of wigglers, small curvature radius dipoles, quadrupoles and off-axis effects of low-beta quadrupoles.No evidence of dynamic aperture limits has been found. The closed orbit has been corrected in both rings to rms values of 1 - 2 mm. Coupling has been measured and corrected by powering few of the installed skew quadrupoles. The estimated value of coupling after the correction is around the nominal 1% for the positron beam. In the e^- ring the ratio of the vertical emittance to the horizontal one is also ~ 1% at low current. However, as the current increases the vertical dimension blows up due to ion trapping.

In order to minimize the ion trapping effect the ion clearing system, which has been preliminary tested with several bunch filling configurations, will be used in DAΦNE. Although only partially powered at present, the clearing system has allowed to reduce substantially the tune spread and tune shift due to ions in the electron beam and decreased coupling at high currents. Further vacuum improvement is expected after vacuum chamber beam conditioning.

We have measured bunch length as a function of the bunch current in the positron ring and have found a very satisfactory agreement between the measurements and numerical simulations based on the machine impedance estimates [20]. According to these data, the normalized longitudinal coupling impedance $|Z/n|$ is below 0.6 Ω. The transverse impedance is very low. This is confirmed by the fact that, for single bunch, the head-tail instability threshold without sextupoles is 10 mA. The maximum current in the single bunch mode has reached 110 mA for both positrons and electrons without any active feedback. This value is by a factor of 2.5 higher than the design current of 44 mA necessary for two beams operation.

In the multibunch mode (all 120 buckets filled) 0.30 A in the positron beam and 0.23 A in the electron one have been stored without feedback. The full month of July has been dedicated to high current multibunch operation and optimization of the ring lattice on the new working point at (5.11, 5.07). The longitudinal multibunch feedback systems have been tuned up with the beam: up to 0.55 A have been stored in 25 bunches with the spacing of four RF buckets and an ion clearing gap of 5 consecutive bunches. With the positron beam, 0.47 A have been stored in 28/30 equispaced bunches. The uniformity of the stored current among different bunches is quite satisfactory for both beams (see Fig. 6). The behavior of both rings on the new working point is now well under control.

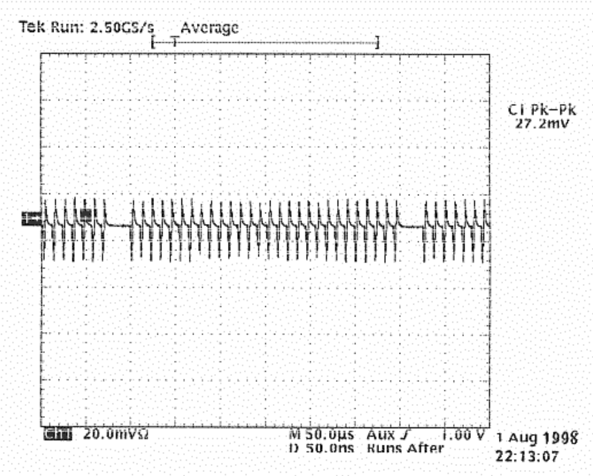

Figure 6: Typical positron fill (the gap of two missing bunches separates two successive revolutions).

3.4 Two beam commissioning

Since during the first runs of single ring operation the rings were tuned on working points far from the integer, we have decided to make the first collisions in the tune zone already explored. According to simulations the chosen working point in this tune region is (5.15, 5.21) which provides a reasonable beam-beam tune shift parameters of $\xi = 0.02$. The corresponding current is 20 mA per bunch. Tail growth and beam blow up at larger currents are predicted.

The two rings have been separately tuned on the collision configuration, checking the symmetry of the two distinct β_y; the two beam trajectories in the IR were aligned, especially benefiting of one BPM at the IP installed in the *day-one* vacuum chamber.

The longitudinal overlap of collisions at the nominal IP has been timed by monitoring the distance between the combined signals left on two sets of symmetric BPMs around the IP by the incoming beam toward the IP and the outcoming one. The transverse scan of the two beam was provided by the variable local interaction region closed bump. The collisions have been done on one IP with the beams kept vertically separated at the other one.

A luminosity monitor [21] based on the measurement of the photons from the single bremsstrahlung (SB) reaction was used for luminosity measurements. The luminosity has been also evaluated from beam-beam tune shift measurements and results are in good agreement with the luminosity monitor ones.

The maximum single bunch luminosity obtained in the colliding beam mode is 3×10^{29} $cm^{-2}s^{-1}$, to be compared with the design luminosity of 4×10^{30} $cm^{-2}s^{-1}$. The interactions were observed with single bunch currents up to ~15 mA in both beams. The measured luminosity is 60% of that expected at the same current and design interaction point parameters. Considering that the e^- emittance is enhanced by ion trapping, we can conclude that the basic single bunch luminosity parameters are in agreement with the design ones.

For the given working point a maximum linear tune shift of 0.02 has been measured in the weaker bunch with the current of ~ 20 mA in the stronger one, as foreseen by our beam-beam simulations. The beam-beam collisions were stable with good beam lifetime in both beams. Larger currents showed, as expected, emittance blow-up in the weaker beam and poor lifetime.

3.5 Future plans

During the next accelerator shift (September 1998) we plan to collide the beams on a new working point closer to integer tunes (5.11, 5.07), where we expect to reach the design beam-beam tune shift of 0.04 with nominal currents per bunch, i. e. the design single bunch luminosity. Once the goal is achieved, we will pass to the multibunch beam collisions pushing the luminosity to the design project value.

4 REMARKS

The work presented in this paper and the results achieved have been carried out by the DAΦNE commissioning team [22].

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