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DAΦNE OPERATION AND PLANS FOR DAΦNE2

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Abstract

The e+e- collider DAΦNE, a 1.02 GeV c.m. Φ-factory, has reached a peak luminosity of about 1.4×10^{32} cm^{-2} s^{-1} and a peak integrated luminosity in one day of about 8.6 pb^{-1}. With the current rates the physics program of the three main experiments DEAR, FINUDA and KLOE will be completed by the end of 2007. In this paper we describe in detail the steps which have led to the luminosity improvement and the options for the upgrade of the collider towards higher energy and/or luminosity.

INTRODUCTION

The DAΦNE [1] complex consists of two independent rings having two common interaction regions (IR) and an injection system composed of a full energy linear accelerator, a damping/accumulator ring and the relative transfer lines. The main present DAΦNE parameters during operations are listed in Table 1.

Table 1: DAΦNE parameters

Energy [GeV]	0.51
Trajectory length [m]	97.69
RF frequency [MHz]	368.26
Harmonic number	120
Damping time, τ_E/τ_x [ms]	17.8/36.0
Bunch length at 0 current [cm]	1.0
Bunch length at full current [cm]	2.5
Beam currents e-/e+ [Amps]	1.7/1.3
Number of colliding bunches	107
Beta functions β_x/β_y [m]	1.6/0.017
Emittance, ε_x [mm·mrad] (KLOE)	0.34
Emittance ratio at 0 current [%]	0.25
Emittance ratio at full current [%]	0.60
e- Tunes Qx/Qy	0.091/0.1660
e+ Tunes Qx/Qy	0.1090/0.1910

Since 2000 DAΦNE has been delivering luminosity to three experiments: KLOE [2], FINUDA [3] and DEAR [4]. The KLOE detector has been permanently installed in the first interaction region (IR1), FINUDA and DEAR detectors share, one at a time, the second interaction region (IR2).

A wide spectrum of experiments is also being carried out at the DAΦNE beam test facility (BTF) [5], a dedicated beam transfer line delivering electron or positron beams in the energy range 25-725 MeV with intensities varying from 10^{10} particle/pulse down to a single-electron. Moreover, two separate beam lines are used for synchrotron radiation (SR) studies, extracting the SR light from a wiggler and a bending magnet, respectively [6].

The luminosity performances for the 3 experiments are shown in Figure 1, while the details of 2004-5 KLOE run are shown in Figure 2.

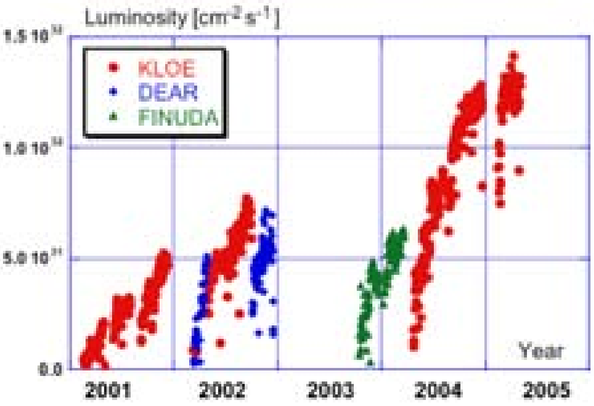

Figure 1: DAΦNE peak luminosity history. Red: Kloe runs, Blue: Dear runs, Green: FINUDA runs.

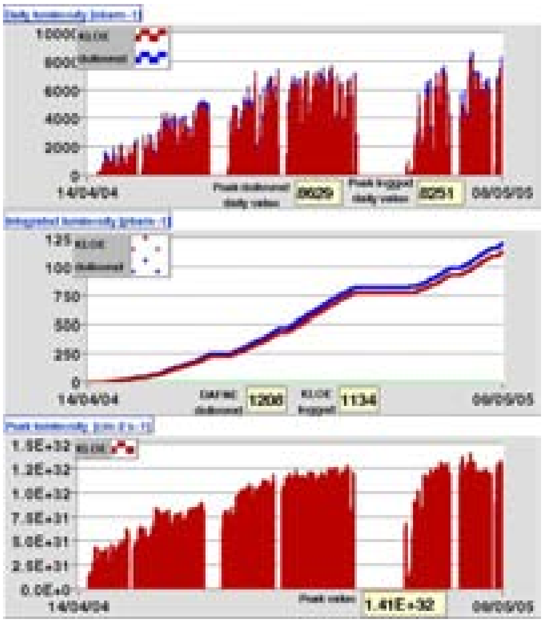

Figure 2: DAΦNE performances in the 2004-5 KLOE run.

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As shown in Table 2 the high energy and nuclear physics programs on DAΦNE is scheduled to be completed by end 2007. For this reason the DAΦNE team, in collaboration with the Frascati physics community has started a study for a possible upgrade of the collider to extend its physics reach. In addition we are also studying possible machine experiments to explore novel techniques to further increase the design luminosity of a new collider.

Table 2: Schedule of physics experiments at DAΦNE

	2004	2005	2006	2007
KLOE	**> 2 fb^{-1}**			
FINUDA			**1**	
SIDDHARTA				**.5**

LUMINOSITY OPTIMISATION

The steady luminosity progress shown in Fig. 1 was achieved by the optimization of the machine parameters and hardware changes implemented during a 6 months long shut down in 2003 with the goal of doubling the luminosity and beam lifetime (and also to install the FINUDA detector on IR2). The main accelerator physics issues that have been studied and optimized can be summarized as follows [7]:

- Working point choice.
- Coupling correction.
- Optimization of collision point parameters (betas, emittances, crossing angles etc.)
- Collider optics modeling.
- Nonlinear beam dynamics study.
- Single and multibunch instability cures.
- Fine tuning of all parameters in collisions during data taking.

The most relevant hardware changes made during the 2003 shut down [8] are:

- New KLOE and FINUDA Interaction Regions.
- Long straight sections modification.
- Wiggler magnets modification.
- Shorter injection kicker pulse.
- Additional feedback amplifiers.
- Maintenance of bellows and scrapers.

Continuous work on the optics with a particular care on wiggler modeling resulted in a satisfactory agreement between model predictions and measurements of beta functions, dispersion, second order dispersion, chromaticities etc. [9]. The model reliably reproduces and predicts the machine optical functions allowing us to test very quickly for a wide range of lattice configurations (e.g. lattices with a momentum compaction factor varying from +0.04 to –0.02). The linear optics model has proven to be a good base for coupling correction, dynamic aperture optimization and nonlinear dynamics studies. At present DAΦNE operates with coupling corrected down 0.2-0.3% and the dynamic aperture as large as 14-15 σ_x.

The new KLOE IR (doublet configuration) allowed a reduction of both the IP beta functions without chromaticity increase together with a reduction of the nonlinear forces due to the parasitic beam-beam crossings. Independent rotations of all IR quadrupoles provides local coupling correction and possibility of operation with arbitrary values of the KLOE solenoid field. For the KLOE lattice configuration the values of β_x=1.6 m and β_y=1.7cm at the IP have been reached, to be compared to 4.5 m and 4.5 cm, respectively, of the initial design values. The horizontal emittance has also been reduced by about a factor 3 with respect to the design to further reduce the effect of the parasitic collisions. As a result we now collide routinely with 108 consecutive bunches out of available 120, the short gap is still needed for ion clearing in the e- ring.

The poles of the wiggler magnets have been modified by adding longitudinally and horizontally shimmed plates [10]. Moreover, an extra sextupole component has been added on one of the terminal poles of each wiggler to ease the dynamic aperture optimization. Field measurements and beam tests showed a significant reduction of the second and fourth order terms in the fields and revealed almost a factor 2 improvement in the energy acceptance. These modifications were essential for keeping satisfactory lifetime despite the emittance reduction.

The longitudinal feedback systems were originally designed to damp only dipole multibunch oscillations excited by the beam interaction with parasitic high order modes. However, after filter modifications and overall tuning now they are capable to damp also the 0-mode and quadrupole instabilities [11]. In turn, with additional power amplifiers the transverse feedbacks can keep under control the transverse multibunch instabilities with a rise time as fast as 17 μs [12].

Installation of three octupoles in each ring (the number is limited by allowable space) [13] helped to increase the dynamic aperture and to compensate the lattice cubic nonlinearity that is a necessary condition to obtain good luminosity performance [14]. They proved particularly useful to compensate the effect of the nonlinearities from the parasitic beam-beam crossings, increasing the lifetime by about 30% when colliding at the maximum currents.

A dedicated work on background reduction including orbits and optical functions correction, working point fine tuning, sextupole and octupole strengths and scraper position optimization have allowed to operate the collider in the “topping up” mode without switching off the KLOE drift chamber during injection. This resulted in a significant increase of the integrated luminosity .

PERFORMANCE LIMITATIONS

The major limits to a further increase of the luminosity in DAΦNE at present are:

- Positron beam instability.
- Single beam (bunch) transverse size enlargement with current.
- Lifetime due to the parasitic crossings.
- Vertical size enlargement due to the beam-beam interaction.

At present the maximum storable positron beam current is limited at 1.3 A by a very fast horizontal instability. Several indications are in favour of interpreting it as an electron cloud instability. In particular, we measure a large positive tune shift with the beam current and observe an anomalous vacuum pressure rise. Moreover, such a fast instability rise time can not be explained only by the beam interaction with parasitic HOM or resistive walls.

The instability has a beam break up nature: it is faster than the synchrotron period and depends strongly on injection conditions. We have increased substantially the maximum storable current by shortening the injection kickers pulse and optimizing the 2 kickers injection closed bump. The threshold of the instability decreased by at least a factor 2 after the 2003 shut down and it is still not clear why. The smaller emittance and/or the longer Landau damping due the reduction of the machine non linearities are possible candidates and we plan to test their influence.

Several simulations are being made with particular attention on the e-cloud creation in the wiggler sections since nonlinear field components of the wigglers were modified [15].

The transverse beam size enlargement with current, takes place even with single beams and depends on the single bunch current. Recent machine studies showed a clear correlation between the observed effect and the longitudinal microwave instability:

- the transverse beam blow up and the instability have the same single bunch current threshold;
- the threshold scales as the square root of the RF voltage;
- the threshold increases more than linearly for higher momentum compaction factors;
- the effect is more pronounced for the electron ring, which has a higher beam coupling impedance.

The mechanism of the coupling of the instability between the transverse and longitudinal axis is still to be understood.

The main lifetime limitation in collisions comes from parasitic crossings of the closely spaced bunches in DAΦNE. Some further optimization it is still possible, but we think that significant improvements now can be made only with additional hardware upgrades.

The vertical enlargement due to the beam-beam could be further reduced by a refinement of the coupling correction and by changing the machine working points, either closer to the integer (around 0.06/0.09) or to the half integer like in the B-Factories (around 0.53/0.56)

LUMINOSITY UPGRADE PLANS

A scientific program beyond the scheduled physics runs (Table 2) is a matter of discussion in the physics and accelerator communities at Frascati. There are a few options being considered as a basis for the future DAΦNE upgrade [16]. These are briefly discussed in the following.

Energy upgrade (DAΦNE2)

The first proposal of DAΦNE upgrade consists in extending the collider energy from the Φ-resonance to the threshold of n-nbar production (1.1 GeV/beam) preserving the present machine layout [17]. This essentially requires:

- new dipole magnets fitting the existing vacuum chamber and providing 2.4 T magnetic field;
- new low beta superconducting quadrupoles;
- energy upgrade of the injection system or implementation of a ramping scheme in the main rings.

All other magnets, their power supplies and existing accelerator subsystems (such as vacuum, RF, feedbacks etc.) are basically compatible with high-energy operation.

Preliminary studies have shown that the high field dipole magnets are feasible, but still more work is needed to get a reliable design that provides the required field quality [18].

Concerning injection, the upgrade of the linac to full energy (without damping ring) [19] would allow for a fast and flexible injection procedure. The main drawbacks is obviously the cost. This solution would also require upgrading the kickers and injection septum magnets in each ring. In turn, energy ramping is possible with existing hardware [20], but this option does not allow topping-up injection during high-energy operation.

The required luminosity at the energy of the n-nbar threshold of 10^{32} $cm^{-2}s^{-1}$ can be obtained with 0.5 A in each beam of 30 bunches. These parameters are conservative since the lower operating current with respect to DAΦNE is largely overcome by all the advantages that come from the higher energy (increased damping, reduced beam-beam, weaker instabilities etc.). The operation at the Φ energy should still be possible since the hardware and the layout basically remain the same, although with a small increase of the damping time.

Luminosity upgrade (DAΦNE2)

The second possibility is DAΦNE2, a collider with a peak luminosity in the range $1\text{-}3\times10^{33}$ $cm^{-2}s^{-1}$. Our studies are based on maintaining as much as possible the present layout and infrastructures. The key ingredients for the upgrade are:

- Shorter bunch and lower β_y.
- Stronger damping.
- Higher number of bunches.
- Increasing colliding currents (between 2 and 3 Amps)
- Lower tunes (closer to the integers or half-integers).

We expect to decrease the bunch length and, respectively the vertical beta at the IP, by a factor of 2-2.5. This can be done by means of a lattice with a large negative momentum compaction (see following Section) and/or reducing the beam vacuum chamber coupling impedance.

More bunches can be put in collisions by increasing the RF frequency from the present 368 MHz to 500 MHz. The IR must be redesigned in order to decrease the harmful effects of the parasitic collisions and to provide smaller beta functions at the IP. This could be done with stronger quadrupoles (permanent magnets should work, but we do not exclude a SC solution).

We also plan to reduce the damping time by a factor >2. This can be done, first, by reducing the gap of the existing wigglers, thus increasing the gap field and at the same time improving the field quality in the beam region and by adding new wigglers in the second IR (possibly superconducting).

At present there are no severe limitations on the maximum current in the electron beam. We plan also to overcome the positron beam limit due to the e-cloud instability: one of the possible cures is Ti coating of the positron ring vacuum chamber and enlargement of the antechamber gap.

Optimisation of the dynamic aperture would give a possibility to move the working points closer to the integer (or half integer) tunes where, according to numerical simulations, another factor 1.5-2 in luminosity can be gained.

Tau-Charm Factory

There is interest in the Frascati particle physics community to build a tau-charm factory with peak luminosity of the order of 10^{34} $cm^{-2}s^{-1}$ at the energy of 3.8 GeV (c. m.). Neither detailed nor feasibility study has started yet, but preliminary evaluations have shown that such a factory could be housed inside the existing DAΦNE building. A set of parameters providing the required luminosity is illustrated in Table 3.

Table 3: Parameters of a tau-charm factory

E, GeV	1.89	B, T	1.8
C, m	105	U_o, keV	328
L, cm^{-2} s^{-1}	1034	V_{RF}, MV	2
f_{RF}, MHz	500	V_{3RF},MV	2
ε_x, m rad	$1.5x10^{-7}$	α_c	0.022
β_x, β_y, m	0.5-0.005	σ_E/E	$8.7x10^{-4}$
k	0.003	P_{rad}, kW	900
N_{bunch}	160	σ_z, mm	6
N_{part}	$3.5x10^{10}$	I_{thresh}, mA	25
ξ_x, ξ_y	0.03-0.05	I_{tot}, A	2.7

EXPERIMENTAL ACTIVITIES

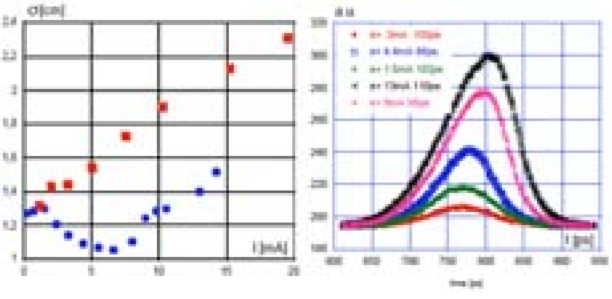
It is known that there can be several advantages for collider operation with a negative momentum compaction lattice (see, for example, [21] and references therein):

- the bunches are shorter and exhibit a more regular shape;
- longitudinal beam-beam effects, such as coherent and incoherent instabilities and synchrobetatron resonances are less dangerous;
- since the head-tail instability with a negative α_c takes place with a positive chromaticity, requirements on sextupole strength can be relaxed.

Lattices with a negative momentum compaction factor have been tried successfully in a few storage rings. However, to our knowledge, high current multibunch operation and beam-beam collisions have never been tested with a negative α_c. This was one of the reasons why we dedicated some machine time to study DAΦNE operation with α_c<0. Yet another point in favour of $\alpha_c < 0$ is that, if successful, the principle can be used in all the DAΦNE upgrade options: energy or luminosity upgrade, super Φ-factory or tau-charm factory. Briefly summarising the results of these studies:

- the bunches shorten (see Fig. 3) as predicted by numerical simulations;
- the DAΦNE optical model reproduces well optical functions with α_c<0. This also makes us confident that the model will be reliable for a proposed experiment on Terahertz CSR requiring low momentum compaction factors [22];
- a single bunch with a current of 40 mA is stable with negative chromaticity;
- there are no problems with RF cavities and feedbacks: about 1 A of stable current has been stored in both beams;
- coupling and geometric luminosity is as in usual operating conditions (or even better for the e- ring);
- first collisions have been tested at low current (about 300mAmps) obtaining about L~$2.5x10^{31}$ cm^{-2} s^{-1}.

Unfortunately above 3mAmps/bunch the electron vertical sizes grows very fast due to microwave instability threshold. The problem can be overcome either by increasing the absolute value of α_c or by decreasing the electron ring impedance (higher because the presence of the ion-clearing electrodes). Both these solutions can be implemented only with hardware changes, so have to be considered only for future upgrades.



a) b)

Figure 3: a) Bunch length with negative (blue) and positive (red) momentum compaction factor; b) bunch shape for different bunch currents with $\alpha_c < 0$.

The DAΦNE team is working also at the project of a super Φ-factory with a luminosity of the order of 10^{34} $cm^{-2}s^{-1}$. A preliminary proposal has been published [23]. The ultra-high luminosity design is based on standard together with new accelerator physics concepts, the most relevant being:

- strong radiation emission to increase the radiation damping (all wiggling machine);
- lattice with a high negative momentum compaction α_c.
- strong RF focusing (longitudinal bunch length modulation) scheme to get bunch length in the mm scale at the interaction point [24,25].

Before going on with the super factory design, the new concepts should be tested experimentally. In particular, the longitudinal bunch length modulation along the ring has never been tried in any storage ring. For this reason we are considering the possibility to perform an experiment on bunch length modulation in DAΦNE [26].

Moreover, in the strong longitudinal focusing regime the beam dynamics becomes essentially three-dimensional. This means that all dynamical features, such as dynamic aperture, lifetime, high current operation, beam-beam collision etc. need to be fully investigated.

CONCLUSIONS

The Φ-factory DAΦNE has proved very successful to increase the know-how and expertise of the accelerator physics community. The particle physics programs have also been extremely important. These results have stimulated the Frascati community to push the frontier even further:

1) energy upgrade to reach the n-nbar threshold by building new dipoles and changing the injection procedure;
2) luminosity upgrade to $L > 2x10^{32}$ cm^{-2} s^{-1} requiring major changes of the existing facilities;
3) a tau-charm factory inside the DAΦNE building with peak luminosity of the order of 10^{34} cm^{-2} s^{-1}.

An experimental activity aimed at testing accelerators concepts that could help pushing the luminosity at the Φ resonance energy towards 10^{34} cm^{-2} s^{-1} level is well under way.

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