DAΦNE upgrade at LNF-INFN

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The Frascati Φ-Factory DAΦNE has been delivering luminosity to the KLOE, DEAR and FINUDA experiments since year 2000. During the current run for the KLOE experiment peak luminosity of $1.4 \cdot 10^{32} cm^{-2} s^{-1}$ and integrated luminosity of $8.6 pb^{-1}/day$ have been achieved. The scientific program of the three high-energy experiments sharing DAΦNE operation will be completed approximately by the end of year 2007. A scientific program for DAΦNE beyond that date has not been defined yet and it is a matter of discussion in the high-energy physics and accelerator physics communities. In this paper we present some future scenarios for DAΦNE discussing the expected ultimate performances of the machine as it is now and addressing the design for an energy and/or luminosity upgrade. The options presented in the following are not exhaustive and they are intended to give a glance of what is doable using the existing infrastructures.

1 Introduction

The Φ-factory DAΦNE is the Frascati electron-positron collider [1] running at the energy of the Φ resonance ($1.02 GeV$ in the centre of mass) and capable of providing an average luminosity exceeding $10^{32} cm^{-2} s^{-1}$. The accelerator complex consists of two independent rings having two common interaction regions (IR) and a powerful injection system including a full energy linear accelerator and an intermediate damping ring. Transfer lines, $180m$ long, join the different accelerators. The main DAΦNE parameters are listed in Table 1a. Since 2000 DAΦNE has been delivering luminosity to three subnuclear, nuclear and atomic physics experiments: KLOE [2], FINUDA [3] and DEAR [4]. The KLOE detector is permanently installed in the first interaction region (IR1) and is used for CP violation studies in kaon decays. The FINUDA and DEAR detectors share, one at a time, the second interaction region (IR2). The aim of the FINUDA experiment is to study the

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Table 1: (a) DAΦNE parameters; (b) Maximum DAΦNE peak luminosity measured by the KLOE detector

Energy [GeV]	0.51
Trajectory lenght [m]	97.69
RF frequency [MHz]	368.26
Harmonic number	120
Damping time, τ_E τ_x [ms]	17.8 36
Bunch lenght [cm]	$1-3$
Emittance, ε_x [mm·mrad] (KLOE)	0.34
Coupling, %	$0.2-0.3$
IP beta function, β_x β_y [m]	1.7 0.017

(a)

(b)

spectroscopy and decay modes of hypernuclei, while the smaller non-magnetic experiment DEAR investigates properties of kaonic atoms.

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 $25 \div 725\ MeV$ 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 DAΦNE peak luminosity has reached $1.4 \cdot 10^{32} cm^{-2}s^{-1}$ (see Table 1b), while the maximum daily-integrated luminosity has exceeded $8.6pb^{-1}$, which corresponds to an average luminosity of $10^{32}cm^{-2}s^{-1}$.

At this rate the present high energy and nuclear physics programs on DAΦNE should be completed by end 2007. For this reason the DAΦNE team, in collaboration with the Frascati physics community has started preparing proposals for the upgrade of the collider. In parallel, we are planning dedicated machine experiments and have already started first experimental shifts testing ways and techniques to increase the luminosity.

In this paper we describe our experience in DAΦNE luminosity optimisation, present possible scenarios and options of the collider upgrade and discuss main accelerator issues and experimental activities aimed at further luminosity enhancement.

2 Luminosity optimization

The steady luminosity progress shown in Table 1 was achieved by means of continuous machine physics studies. Besides, during a 6 months long shut down in 2003 substantial hardware changes were implemented with the goal of doubling the luminosity and beam lifetime. Many accelerator physics issues, such as working point choice, coupling correction, linear and non-linear optics modeling, single and multibunch instability cures, have been studied, understood and optimized for the luminosity performance improvement[7]. Many relevant hardware changes, such as new KLOE and FINUDA Interaction Regions, long straight sections modification, wiggler magnets modification, new octupoles, have

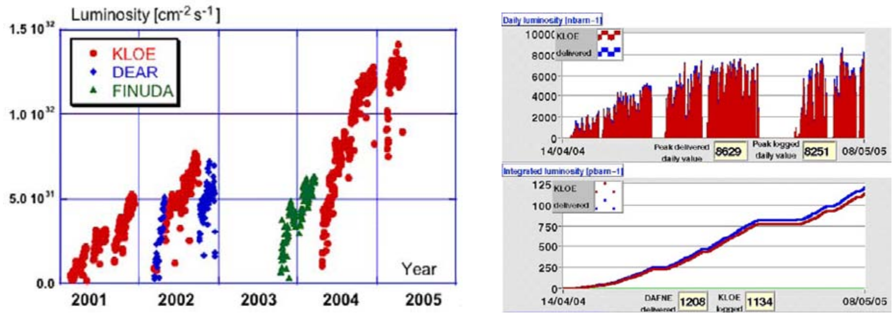

Figure 1: DAΦNE luminosity history

been made during the 2003 shut down [8]. These activities have given many fruitful results. Here we briefly describe some of them.

Continuous work on 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 optical functions for a wide range of possible lattice configurations 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 $0.2 \div 0.3$ % and the dynamic aperture as large as $14 \div 15$ σ_x.

The new KLOE IR allowed squeezing both beta functions at the interaction point (IP) without chromaticity increase. Independent rotations of all IR quadrupoles provide local coupling correction and possibility of operation with arbitrary values of the KLOE solenoid field. For the KLOE lattice configuration the values of $\beta_x = 1.7m$ and $\beta_y = 1.7cm$ at the IP have been reached, to be compared to $4.5m$ and $4.5cm$, respectively, of the initial design values. Besides, after the 2003 shutdown, the horizontal emittance was reduced by approximately a factor of two, reducing the effect of parasitic collisions in the new IR and 108 consecutive bunches out of available 120 have been put in collision. The short gap is still needed for ion clearing.

The poles of the wiggler magnets have been modified by adding longitudinally and horizontally shimmed plated [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 strong 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

Table 2: Schedule of the physics experiments at DAΦNE

	2004	2005	2006	2007
KLOE	$> 2fb^{-1}$			
FINUDA			$1fb^{-1}$	
DEAR				$.5fb^{-1}$
SRFFD				

a rise time as fast as $17ms$ [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]. The lifetime improvement due to the octupoles in collision is estimated to be between 10 and 40 percent depending on the operating conditions (tunes, current etc.).

There are three major limitations of the luminosity performance that we are trying to understand and find out ways to overcome. These are: positron beam instability, single beam transverse size enlargement with current, lifetime in beam-beam collision.

At present the maximum storable positron beam current is limited at 1.3 A by a very fast horizontal instability. Several indications are in favor of interpreting it as an electron cloud instability. In particular, we have measured 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 kicker pulse and carefully adjusting the injection closed bump. The threshold of the instability decreased by at least a factor 2 after the 2003 shut down and our efforts are aimed at finding out a reason for this. Simulations are under way with particular attention on the e-cloud creation in the wiggler sections since nonlinear field components of the wigglers were modified [15]. Besides, we are planning to measure the instability threshold as a function of the horizontal emittance.

The second harmful effect, the transverse beam size enlargement with current, appears also with single beam and depends on the single bunch current. Recent machine studies showed a clear correlation between the observed effect and the longitudinal microwave instability [16].

The threshold can be shifted beyond the nominal single bunch current by increasing the momentum compaction by $70 \div 80$ %. However, a mechanism of coupling between the transverse and longitudinal motion of the particle in the bunch is still to be understood.

To our understanding, the main lifetime limitation in collisions comes from parasitic crossings of the closely spaced bunches in DAΦNE. We hope that some improvement can be obtained by fine tuning all the accelerator parameters and shifting the working points (i.e. the betatron tunes) closer to the integers. Dedicated beam measurements with the modified wiggler have shown that a satisfactory dynamic aperture can be provided for tunes as low as $(0.05, 0.09)$ in both rings.

There are some margins for luminosity increase in DAΦNE. However, even keeping the

Table 3: Parameters of the high energy option

Beam energy E	$0.51 GeV$	$1.1 GeV$
Total beam current I_{tot}	$1 \div 2\ A$	$0.5A$
Luminosity L	$1.5 \cdot 10^{32} cm^{-2} s^{-1}$	$1 \cdot 10^{32} cm^{-2} s^{-1}$
Number of bunches N	100	30
Bunch current I_b	$10 \div 20\ mA$	$17mA$
Damping time τ (dipoles/total)	70/40 ms	11/9 ms
Radiation losses U_0 (dipoles/total)	4.3/9.3 $keV/turn$	64/84 $keV/turn$
Lifetime τ_L	$< 1h$	$> 4h$

achieved luminosity performance the present physics program on DAΦNE can be completed approximately by end 2007 (see Table 2). A scientific program beyond this date is a matter of discussion in the physics and accelerator communities at Frascati. A final decision has not been made yet, however there are only few options being considered as a basis for the future DAΦNE upgrade [17]. These are briefly discussed in the following.

3 Energy upgrade (DAFNE2)

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 [18]. This essentially requires: new dipole magnets fitting the existing vacuum chamber and providing $2.4T$ magnetic field, new low beta superconducting quadrupoles, energy upgrade of the injection system or implementation of an energy 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 the 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 [19].

Concerning injection, the upgrade of the linac to full energy (without damping ring) [20] would allow for a fast and flexible injection procedure. The main drawback 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 [21], 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 30 bunches and $0.5A$ in each beam. These parameters are conservative since the lower operating current with respect to the present operation is largely compensated by all the advantages that come from the higher energy (increased damping, reduced beam-beam, weaker instabilities etc.). The operation at the Φ energy would still be possible since the hardware and the layout basically remain the same, although with a small increase of the damping time. The main machine parameters of this option are reported in Table 3 for both operations at $1.1 GeV$ and $0.51 GeV$ per beam.

Table 4: Parameters of the Φ and τ factory proposals

Parameters list	**Φ factory**	**τ factory**	**Parameters list**	**Φ factory**	**τ factory**
Beam energy E $[GeV]$	0.51	1.89	Radiation losses U_0 $[keV/turn]$	25	328
Ring circumference C $[m]$	100	105	Power losses P_{rad} $[kW]$	50	900
Luminosity L $[cm^{-2}s^{-1}]$	$2 \cdot 10^{33}$	10^{34}	RF voltage V_{RF}[MV]	2.7	2
RF frequency f_{RF} $[MHz]$	500	500	3^{rd} harmonic RF voltage V_{RF_3} $[MV]$	$0 \div 2$	
Beam emittance ε_x $[m]$	$3 \cdot 10^{-7}$	$1.5 \cdot 10^{-7}$	Momentum compaction α_c	$-0.04 \div 0.04$	0.022
IP Beta-functions β_x^* β_y^* $[mm]$	500 4	500 5	Energy spread σ_E/E	$5 \cdot 10^{-4}$	$8.7 \cdot 10^{-4}$
Emittance coupling $\boldsymbol{\kappa}= \varepsilon_y/\varepsilon_x$	0.05	0.003	Dipole–wiggler Magnetic field B $[T]$	$1.7 \div 4$	1.8
Number of bunches N_{bun}	150	160	Bunch length σ_L $[mm]$	4	6
Particle/bunch $N^{\pm}$	$2.5 \cdot 10^{10}$ ($\equiv 13mA$)	$3.5 \cdot 10^{10}$	Single bunch μ-wave current treshold I_{th} $[mA]$	6.5 @$Z/n = 0.5\Omega$	25
Linear tune shifts ξ_x ξ_y	0.04 0.05	0.03 0.05	Total beam current I_{tot} $[A]$	1.9	2.7

4 Luminosity upgrade (DAΦNE2)

The second upgrade possibility is DAΦNE2, an upgraded or a new Φ-factory with a peak luminosity in the range $1 \div 3 \cdot 10^{33} cm^{-2}s^{-1}$. The main machine parameters concerning this option are reported in Table 4. The key ingredients for this kind of upgrade are: shorter bunch and lower β_y, stronger damping, higher number of bunches, larger colliding currents ($2 \div 3$ A), 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 $2 \div 4$. There are several ideas to reduce the bunch length in high current storage rings. The most straightforward strategy is based on lattices with large and negative momentum compaction factors and/or small coupling impedance of the beam vacuum chamber. Beyond that, a new scheme called Strong RF Focusing (SRFF) [22] has been recently proposed to obtain a bunch length modulation along the ring to focus it down to a longitudinal dimension of the order of $1mm$ at the IP. To proof the effectiveness of this scheme, we are proposing to perform a dedicated experiment at DAΦNE in 2007, as reported in the following.

More bunches can be put in collisions by increasing the RF frequency from the present $368MHz$ to $500MHz$. 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 $1.5 \div 2$ in luminosity can be gained.

5 Tau-charm factory

Recently, the LNF accelerator physics division has been also asked to evaluate the feasibility of a τ-charm factory with peak luminosity of the order of $10^{34} cm^{-2} s^{-1}$ at the energy of $3.8 GeV$ c.m. to be built in Frascati. Very 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 4.

6 The strong RF focusing experiment at DAΦNE

Short bunches are becoming interesting for both e+e- circular colliders and synchrotron light sources, the first to overcome the luminosity degradation due to the hourglass effect at very low β^*, the second to produce in a controlled way Coherent Synchrotron Radiation (CSR). All factory upgrades use minimization of the bunch length by high rf voltages as an essential feature of their projects, while CSR sources base the feasibility of very short bunches on the isochronicity regime.

In the framework of superfactories studies the strong rf focusing regime [22] was firstly proposed as one of the principles for a next generation Φ-factory design. This regime is based on a high rf voltage and a high momentum compaction (α_c) ring lattice which together produce a bunch length modulation along the ring. The microwave instability effects on the bunch lengthening in principle can be kept under control by placing the high impedance objects in the ring zones corresponding to the longer bunch, with the collision point placed at the shorter bunch position.

An evolution of the SRFF principle has been also recently proposed [23]: a ring structure where the dependence of the longitudinal position of a particle on its energy oscillates between large positive and negative values along the ring can also produce a bunch length modulation. The synchrotron frequency can be controlled by means of the rf voltage and the momentum compaction. This regime overcomes one of the critical points of the SRFF principle, where due to the large synchrotron tune Q_s both the dynamic aperture and beam-beam effect depend critically on the 3D working point choice [24]. No storage ring has been so far operated in such a regime. We are therefore proposing a dedicated machine physics experiment at DAΦNE [23] to observe the SRFF and investigate its potentiality and limitations. To do that the DAΦNE lattice has to be tuned on a proper dispersive structure [25], and a new superconducting (SC) RF system at $1.3 GHz$ [26] has to be installed.

6.1 DAΦNE lattices for the SRFF experiment

The dispersion in DAΦNE can be tuned in a wide range due to the independently powered quadrupoles, while the RF system is dimensioned for the usual collider operation: the RF

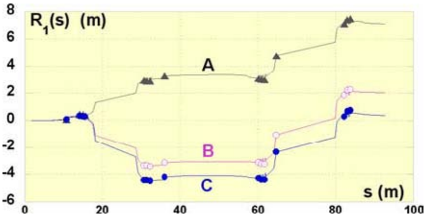

Figure 2: $R_1(s)$ along the ring ($s_{rf} = 0$)

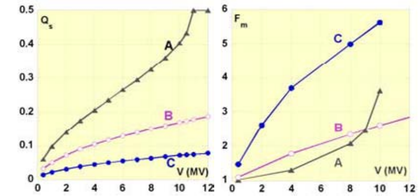

Figure 3: Q_s and F_m as a function of V

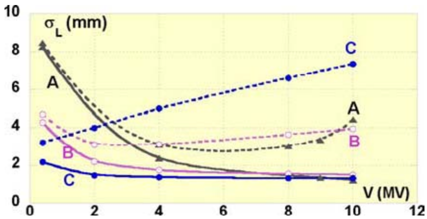

Figure 4: σ_{Lmin} (full), σ_{Lmax} (dash) vs. V

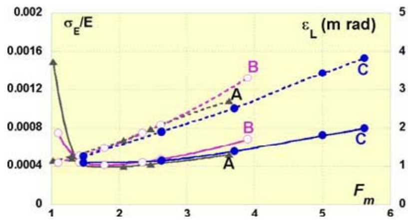

Figure 5: σ_E/E (dash), ε_L (full) vs. F_m

gradient must be increased by more than one order of magnitude to reach a measurable bunch length modulation with a bunch current of the order of $1mA$. An extra SC RF cavity at $1.3GHz$, with a maximum voltage of $10MV$ can be installed in either of the two Interaction Regions (IRs), serving both rings.

The maximum α_c value and $R_1(s)$ variation are limited by the physical and dynamic aperture of the ring. Three different structures are considered. The structure A) has the $R_1(s)$ function tuned in *monotonic* regime, with positive contributions of all dipoles to the drift function, as shown in black in Fig. 2; α_c is 0.073, about three times larger than the present one. With high values of V, Q_s approaches the half integer, as shown in Fig. 3. Structure B) (violet empty dot in figures) corresponds to *non-monotonic* regime with negative dispersion in two of the short arc dipoles, and a value of α_c similar to the present one (0.02). Structure C) (blue full dot in figures) is also *non-monotonic* but with a much lower value of α_c (0.004).

The main goal of the experiment is to measure the bunch length modulation factor, $F_m = \sigma_{Lmax}/\sigma_{Lmin}$. For structure A) F_m becomes noticeably larger than unity for high V (see Fig. 3), when μ approaches π. In structure B) F_m is measurable also with lower RF voltage. In C) F_m is larger since it is enhanced when approaching isochronicity.

In the monotonic case A) the minimum bunch length is in the IR opposite to the cavity position, since it occurs in the point where $R_1(s) = \alpha_c L/2$ [22], while in B) and C) it is near the RF cavity position. In the whole range the bunch length is of the order of few mm, as shown in Fig. 4, which represents σ_{Lmax} and σ_{Lmin} for the three structures.

The energy spread increases with F_m, while the longitudinal emittance ε_L is large for low V, decreases up to a minimum, and then increases again. An interesting result is that the behaviour of σ_E/E and ε_L with F_m is very similar for all the structures (see Fig. 5).

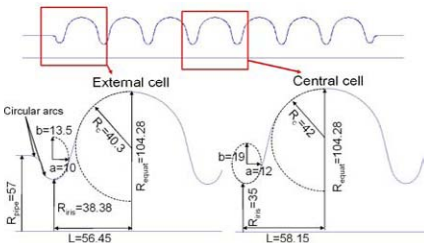

Figure 6: Cavity profile

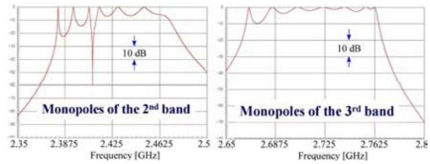

Figure 7: Damped monopoles of the 2^{nd} and 3^{rd} band

Table 5: SC cavity parameters for the DAΦNE SRFF experiment

RF frequency	$1288.9MHz$
Max RF voltage	$8MV$
R/Q geometric factor	390Ω
Quality factor (@$1.8K$)	10^{10}
Cavity wall power (@$1.8K$)	$8W$
Loaded quality factor	$2 \div 4 \cdot 10^7$
Cavity detuning for Beam Loading (@$8MV,\ I_b = 1A$)	$-60kHz$
RF generator power	$1kW$
Cavity length	$0.8m$

6.2 Superconducting RF cavity for the SRFF experiment

A $1.3GHz$ 7-cells cavity based on the TESLA geometry [27] with small modifications of the basic cell to comply with the DAΦNE revolution frequency has been designed, and a sketch is shown in Fig. 6. The number of cells has been changed from 9 to 7 to reduce the number of the cavity HOMs, while the beam tubes have been enlarged to let most of the HOMs propagate and be damped by room-temperature ferrite rings. As an example, the transmission coefficient between the two enlarged beam tubes for the 2^{nd} and 3^{rd} monopole bands is plotted in Fig. 7. The highest quality factors are of the order of 10^3. The main parameters of the cavity are reported in Table 5.

Conclusions

DAΦNE is running regularly for the KLOE, FINUDA and DEAR/SIDDHARTHA experiments, with a continuous improvement of its performances and reliability. The scientific program of the experiments should be completed by the end of 2007 and a new high-energy scientific program beyond that date has not been yet defined. Different upgrade options of the collider fitting the existing infrastructures have been presented: energy upgrade to reach the N-Nbar threshold with minimal changes, an upgraded or new Φ-factory for a luminosity in excess of $10^{33}cm^{-2}s^{-1}$, a τ-charm factory for a luminosity of $10^{34}cm^{-2}s^{-1}$.

The LNF high-energy physics and the accelerator communities are working together to refine these proposals and converge to a new common enterprise renewing the well-established tradition of these laboratories.

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