EXPERIENCE WITH DAΦNE UPGRADE INCLUDING CRAB WAIST

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Abstract

In 2007 DAΦNE was upgraded to operate in a regime of large Piwinski angle, with a novel interaction region optics, reduced vertical beta at the interaction point, and additional sextupoles providing for *Crab-Waist* collisions. The specific luminosity has been boosted by more than a factor of four at low currents, and the present peak luminosity is by about a factor of 3 higher than the maximum value obtained with the original collider configuration. The DAΦNE commissioning as well as the first experience with large Piwinski angle and *Crab-Waist* collisions scheme will be reported.

INTRODUCTION

Existing factories, designed more than ten years ago, rely on flat multi-bunch beams colliding under a horizontal angle θ and having a normalized crossing angle ψ (also known as Piwinski angle) smaller than 1, according to Eq. (1) where σ_z and σ^*_x are the r.m.s. longitudinal and horizontal bunch sizes at the interaction point (IP) respectively.

$$\psi = \frac{\sigma_z}{\sigma^*_x} tg\left(\frac{\theta}{2}\right) \sim \frac{\sigma_z}{\sigma^*_x}\frac{\theta}{2} < 1. \qquad (1)$$

This criterion is intended to cope with the synchro-betatron resonances arising from the horizontal angle required to minimize secondary bunch crossings around the IP. In this context, to increase the luminosity it is necessary to reduce the vertical betatron function β^*_y at the IP and the vertical beam emittance ε_y, and to increase the beam intensity I, the horizontal beam size σ_x and the horizontal emittance ε_x, the last condition being required to keep under control the beam-beam effects. This approach is subject to severe limitations; in fact β^*_y can not be much smaller than the bunch length σ_z, high intensity currents stored in circular rings require relevant RF power to compensate the beam losses due to the synchrotron radiation emission and short bunches carrying high currents are affected by instabilities, which become more harmful as the currents increase.

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The new collision scheme based on large Piwinski angle and *Crab-Waist* compensation proposed and implemented at DAΦNE [1] allows getting through all these limitations.

DAΦNE [2] is an accelerator complex consisting of a double ring lepton collider working at the c.m. energy of the Φ-resonance (1.02 GeV) and an injection system. The collider consists of two independent rings, each ~ 97 m long. In the original configuration the rings shared two 10 m long interaction regions (IR1 and IR2) where the KLOE [3] and FINUDA [4] or DEAR [5] detectors were respectively installed. A full energy injection system, including an S-band linac, 180 m long transfer lines and an accumulator/damping ring, provides fast and high efficiency electron–positron injection also in topping-up mode during collisions.

DAΦNE UPGRADE

Upgrade Motivations

At DAΦNE the standard approach towards higher luminosity has been pursued for long years by progressive upgrades implemented during the shutdowns necessary for experiment turn over leading to a relevant improvement in terms of peak and integrated luminosity. At the end of the KLOE run in 2005 the achieved peak luminosity was $1.5 \cdot 10^{32}$ cm^{-2}s^{-1}, with a maximum daily integrated luminosity of ~10 pb^{-1} [6]. Comparable values have been measured during the operation for the FINUDA detector in 2007 [7].

The experimental activity on DAΦNE outlined the following factors limiting any further relevant luminosity improvement.

Long-range beam-beam interactions [8] (parasitic crossings) occurring in the two 10 m long interaction regions led to a substantial lifetime reduction of both beams in collision, limiting the maximum storable current and, as a consequence, the achievable peak and integrated luminosity.

The colliding bunches transverse spot size at the IP depends on the local values of the transverse betatron functions $\beta^*_{x,y}$ and the minimum value of β^*_y is set by the bunch overlap length, to avoid the detrimental features arising from the hourglass effect. For head-on or small angle collisions the overlap length is ~√2 times the longitudinal bunch length, which in DAΦNE, after a careful optimization of the main rings coupling impedance [9], was ~2.5 cm for both beams at the operating bunch current (~15 mA).

The positron beam showed a threshold in the maximum storable current due to a fast horizontal instability, faster than the synchrotron period, depending on the injection conditions, on the stored current and on the beam fill pattern, compatible with an e-cloud driven instability. The current threshold appeared after the 2003 shut down, when the beam emittance and the nonlinear contributions coming from the eight wiggler magnets installed in the colliding rings have been reduced. The instability was mitigated by using transverse feedbacks, reducing strength and pulse length of the injection kickers and tuning the phase advance between the two injection kickers.

New Collision Scheme

The large Piwinski angle, obtained by increasing the horizontal crossing angle and reducing the horizontal beam size at the IP, provides several advantages: it reduces the beam-beam tune shift in horizontal plane, shrinks the longitudinal size of the overlap between colliding bunches, thus allowing for a lower β^*_y at the IP and cancels almost all the parasitic crossings: in the case of DAΦNE it becomes possible to completely separate the vacuum chambers of the two beams just after the first low-β quadrupole in the IR. A couple of *Crab-Waist* sextupoles, installed in symmetric position with a proper phase advance with respect to the IP, suppresses the betatron and synchro-betatron resonances coming from the vertical motion modulation due to the horizontal oscillation.

According to the simulations this new collision scheme was expected to increase the luminosity by more than a factor of 3 with the same bunch length and moderate colliding currents.

The evolution of the main DAΦNE parameters are summarized in Table 1.

Table 1: DAΦNE beam parameters

	DAΦNE (KLOE run)	DAΦNE Upgrade Achieved (Nominal)
β^*_y (cm)	1.7	0.9 (0.65)
β^*_x (cm)	170	25 (20)
σ^*_x (μm)	760	200
σ^*_y (μm)	5.4	3.5 (2.6)
σ_z (cm)	2.5	1.7 (2.0)
$\theta_{cross}/2$ (mrad)	12.5	25
ψ (mrad)	0.6	1.9
ε (mm mrad)	0.34	0.26
L •10^{32} (cm^{-2} s^{-1})	1.5	4.36 (~ 5)

The SIDDHARTA experiment [10] (an evolution of DEAR) has been installed on the new IR. It is a compact device without solenoidal field providing a simple environment to test the effectiveness of the new collision scheme.

The DAΦNE upgrade included several other improvements and modifications. Some devices, such as bellows and injection kickers have been redesigned in order to improve their performances and to reduce their contribution to the ring total coupling impedance [11]. As a result a bunch length of 1.7 cm has been measured for both beams at 10 mA/bunch, which, for the electron beam, is consistent with a 20% bunch length reduction.

The four electron and positron transverse feedbacks have been upgraded by adopting a new generation feedback unit [12], which beyond its stabilization function provides a variety of diagnostic tools. Two new different monitors have been built to measure the luminosity [13]. Moreover the kaon counting rate is yielded by the SIDDHARTA experiment trigger system.

DAΦNE OPERATION AFTER THE UPGRADE

Colliding Rings Optics

The *low-beta* section in the SIDDHARTA IR is based on permanent magnet quadrupole doublets. The quadrupoles are made of SmCo alloy: the first one from the IP has a gradient of 29.2 T/m, the second 12.6 T/m. The first is horizontally defocusing and is shared by the two beams; due to the off-axis beam trajectory, it increases the horizontal crossing angle from 25 to 71 mrad. The second quadrupole, the focusing one, is installed just after the beam pipe separation and is therefore on axis (see Fig. 2). The new configuration almost cancels the problems related to beam-beam long range interactions, because the two beams experience only one parasitic crossing inside the defocusing quadrupole where, due to the large horizontal crossing angle, they are very well separated ($\Delta x \sim 40\sigma_x$). It is worth reminding that in the old configuration the colliding beams had 24 parasitic crossing in the IRs and in the main one the separation at the first crossing was $\Delta x \sim 7\sigma_x$ [8].

The DAΦNE main rings have been commissioned using a detuned optics, with ν_x slightly above 5, ν_y above 4, and without *Crab-Waist* sextupoles in order to speed up beam injection, put the diagnostics in operation and perform a satisfactory machine modeling. The beam closed orbit has been minimized together with the steering magnet strengths relying also on beam based procedures to point out and fix misalignment errors. The vertical dispersion has been minimized by global vertical orbit correction and by centering the beam vertical position in the arc sextupoles. Once a reliable machine model has been defined (presently the agreement between computed and measured twiss parameters is better than 5%), the ring optics has been moved progressively towards the nominal one with both tunes above 5. The β functions are now $\beta^*_{y,x} \sim 0.009/0.25$ m at the IP, slightly larger than the *Crab-Waist* design values ($\beta^*_{y,x} \sim 0.0065/0.20$ m).

The transverse betatron coupling has been corrected mainly by correcting rotation errors in the low-β focusing quadrupoles, now independent for the two rings. The best value obtained so far is $\kappa \sim 0.4\%$ for both beams measured at the synchrotron light monitor. The vertical bunch size at the IP, obtained by scanning one beam vertically across the other and taking into account the hourglass effect, is $\sigma_y \sim 3.5\ \mu m$, a factor ~1.5 lower than in the past.

The *Crab-Waist* sextupoles are electromagnetic devices; their optimal strength depends on the values of the horizontal crossing angle and of the betatron functions at the IP and at the sextupole according to

$$k_s = \frac{\chi}{\theta} \frac{1}{\beta_y^* \beta_y^{sext}} \sqrt{\frac{\beta_x^*}{\beta_x^{sext}}} \quad (2)$$

The χ value in our case should be about 0.6 [1]. The nominal strength with the present parameters is larger than the maximum available with our sextupoles, which now provide χ=0.5. The *Crab-Waist* sextupoles compensate exactly each other and do not add any contribution to the ring chromaticity. The transverse beam trajectory in the *Crab-Waist* sextupoles must be carefully aligned to avoid any tune and betatron coupling variation, which, in turn, might influence the luminosity and the background hitting the experimental detector.

High Currents Issues

In the early stage of the commissioning operation at high current has been limited by the maximum achievable positron current that was affected by a transverse horizontal instability observed even before the upgrade, but with a lower grow rate. Several studies have been aimed at ruling out trapped high order modes and anomalous wake fields as possible sources of the positron current limit [14]. The measurements indicate the e-cloud instability as a possible explanation for the observed behaviour. The current limit has been cured by halving the damping time of the transverse horizontal feedback used to cope with the instability by means of a second feedback system kicking the beam by using two out of the four injection kickers striplines powered by spare hardware.

It has been proved that the effects of the two systems add up linearly and the horizontal instability is now damped in less than 15 turns (~5 μs). The use of two independent systems represents an efficient way to exploit the feedback power since the kick strength scales as the square root of the power itself. Moreover the stripline shunt impedance is larger at the low frequencies typical of the unstable modes. In this way it has been possible to store more than 1.1 A of positron in a stable beam with the design transverse beam dimensions.

Another source of luminosity limitation has been identified in a 2-beams barycentric instability occurring at high current when both the "0-mode" feedback systems embedded in the low level RF (LLRF) are switched on at the same time. This effect had never been observed during the past runs and has been temporary avoided by switching off the "0-mode" feedback system operating on the positron beam. Implementing a new dedicated feedback system in the LLRF operating around each tube has compensated RF phase noise generated by the HV ripple of the main ring klystrons.

Luminosity and operation reliability profited also from reducing the noise in the DAΦNE equipotential network, that was affecting RF, bunch-by bunch feedback and diagnostics.

LUMINOSITY ACHIEVEMENTS

The most relevant results obtained after the DAΦNE upgrade concern the luminosity and the background shower hitting the experimental detector.

Peak Luminosity

Commissioning has been completed in six months. In May 2008 a considerably higher (~30%) luminosity with respect to the past had already measured, as can be seen comparing the green data presented in Fig. 1 with those (yellow, red and blue) taken while operating DAΦNE in the original collision scheme. It is worth noticing that in May the luminosity given by the Bhabha monitor was underestimated (~ 15%) due to the insertion of new background shields around the IP, which was not yet accounted for.

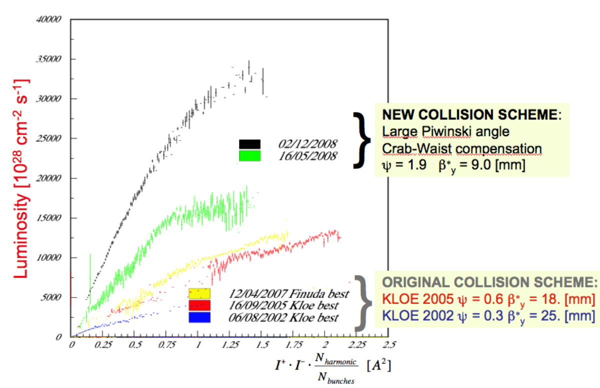

Figure 1: Luminosity versus the product of the colliding currents normalized to the number of colliding bunches. Data refer to runs acquired before (bottom) and after (top) implementing the new collision scheme.

The impact of the Piwinski angle had already been tested during the KLOE experiment data taking in 2005 when ψ was doubled and β^*_y considerably reduced resulting in an almost doubled peak luminosity (red and blue curve in Fig. 1).

The peak luminosity has been progressively improved by tuning the collider and increasing the beam currents; the maximum value achieved by now is $4.36 \cdot 10^{32}\ cm^{-2}\ s^{-1}$ measured in several runs (see blue and red dots in Fig. 2) with good luminosity to background ratio.

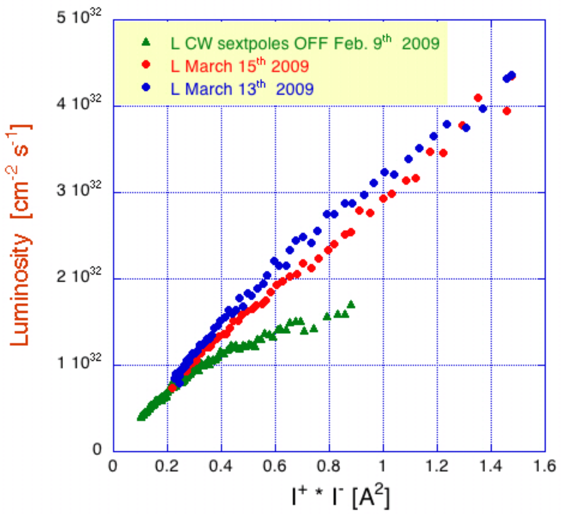

Figure 2: Luminosity versus the product of the colliding currents during two of the best runs (blue and red dots) and with *Crab-Waist* sextupoles off (green triangles).

The present peak luminosity is satisfactorily close to the nominal one predicted by numerical simulations [15].

The highest single bunch luminosity achieved so far is $L \sim 5 \cdot 10^{30}$ cm^{-2} s^{-1} measured with 20 bunches in collision instead of the usual 105.

The single bunch specific luminosity, defined as the single bunch luminosity divided by the product of the single bunch currents, at low currents exceeds by 4 times the best value measured during the past DAΦNE runs (present values are red and blue dots in Fig. 3). It gradually decreases with colliding beam currents, as it is seen in Fig. 3. This reduction can be only partially explained by the growing beam size blowup due to the beam-beam interaction [16]. Another factor comes from the fact that in the large Piwinski angle regime the luminosity decreases with the bunch length, which in turn is affected by the ring coupling impedance [11].

Crab-Waist Collisions and Luminosity

The impact of the *Crab-Waist* sextupoles has been studied and discussed in detail [17]. It can be recognized at a glance comparing runs taken with *Crab-Waist* sextupoles on and off (see Fig. 2). At low current the luminosity is the same in the two cases, and it is significantly higher than the one measured during the operation with the DAΦNE original collision scheme. As the product of the stored currents exceeds 0.3 A the luminosity measured with the *Crab-Waist* sextupoles off becomes lower and a correspondent transverse beam size blow up and beam lifetime reduction are observed as a consequence of the uncompensated beam-beam resonances.

The effect is even more evident when looking at the single bunch specific luminosity with *Crab-Waist* sextupoles off (green triangles in Fig. 3).

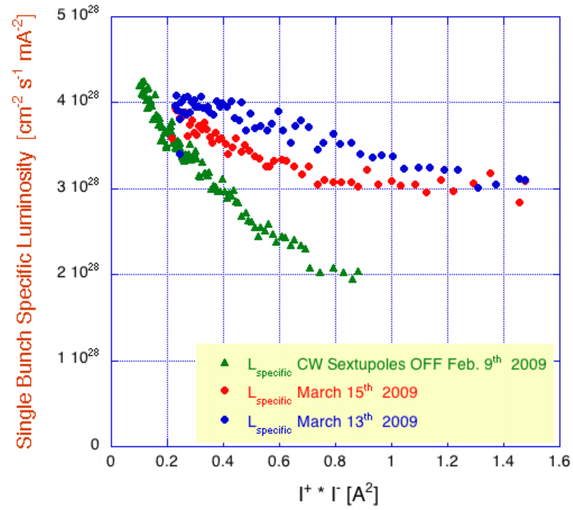

Figure 3: Single bunch specific luminosity versus the product of the colliding currents for two of the best run (blue and red dots) and for the *Crab-Waist* sextupoles off (green triangle).

Integrated Luminosity

The integrated luminosity profited from implementing a new software procedure to switch the injection system from electrons to positrons and the other way round. The switch time has been reduced by a factor of three and now it is less than one minute.

A continuous switching regime provides $L_{\int 1\ \mathrm{hour}} \sim 1.0$ pb^{-1} hourly integrated luminosity (see Fig. 4), which is not compatible with the SIDDHARTA experiment data taking since the acquisition is vetoed during injection due to the higher background level. However this result opens significant perspectives for the KLOE experiment, which is much less sensitive to background and is presently scheduled to start by the end of 2009. Scaling this best integrated luminosity measured over two hours it is reasonable to expect a daily integrated luminosity larger than 20 pb^{-1}, and assuming 80% collider uptime, as during the past runs, a monthly integrated luminosity of ~ 0.5 fb^{-1}.

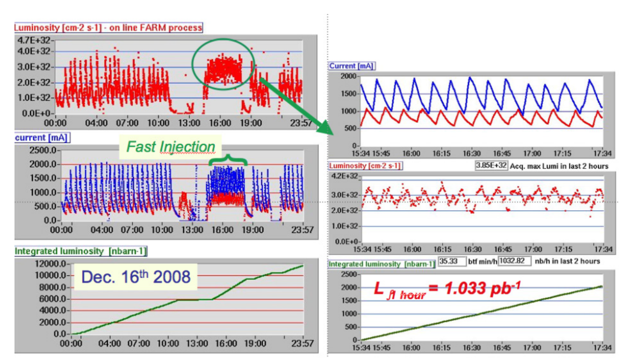

Figure 4: Integrated luminosity in continuous switch regime.

A satisfactory integrated luminosity has been obtained also in a moderate injection regime compatible with the

SIDDHARTA operation with a ~50% duty cycle. In this context the best hourly and daily integrated luminosity measured by now are: $L_{\int 1\ hour}$ ~0.79 pb^{-1} averaged over two hours, and $L_{\int day}$ ~15 pb^{-1} (see Fig 5). Luminosity achievements are even more relevant since they have been obtained with lower currents stored in less bunches than in the past (see Table 2).

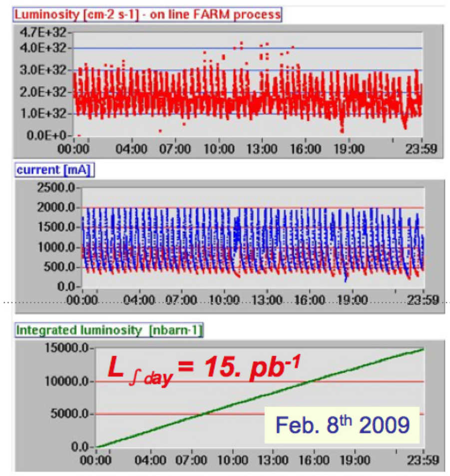

Figure 5: Best daily integrated luminosity.

Beam-Beam Tune Shift

The beam-beam vertical tune shift evaluated from the measured peak luminosity taking into account the hourglass effect is now ξ_y = 0.042, a factor ~1.5 higher than the best value achieved with the original collision scheme: ξ_y = 0.025 and ξ_y = 0.029 for the KLOE and the FINUDA runs respectively.

In weak-strong collision regime an even higher ξ_y = 0.063 has been attained. In this case a luminosity $1.31 \cdot 10^{32}$ cm^{-2} s^{-1} has been measured with I^- ~2.0 A against I^+ ~ 0.2 A.

Since the damping time is the same as in the past in the case of the FINUDA data, and it is even longer than in the case of the KLOE ones, the present tune-shift represents a further evidence of the *Crab-Waist* sestupoles effectiveness in compensating the bem-beam coupling resonances in strong-strong as well as in weak-strong regimes.

Table 2: DAΦNE present achievements

	Upgrade	KLOE run	FINUDA run
$L_{peak} \cdot 10^{32}$ ($cm^{-2}s^{-1}$)	4.36	1.5	1.6
$L_{\int 1\ hour}$ (pb^{-1})	1.03	0.44	0.5
$L_{\int day}$ (pb^{-1})	14.98	9.8	9.4
I^- at L_{peak} (A)	1.4	1.4	1.5
I^+ at L_{peak} (A)	1.0	1.2	1.1
$N_{bunches}$	105	111	106
ξ_y	0.042	0.025	0.029

CONCLUSIONS

The new collision scheme based on large Piwinski angle and *Crab-Waist* implemented on DAΦNE worked as expected from the preliminary studies and numerical simulations. The present achievements are summarized and compared with the old ones in Table 2.

The principle of *Crab-Waist* compensation has been widely recognized as a major advance in the field of the beam-beam interaction in lepton colliders.

The present luminosity achievements have opened new perspectives for the DAΦNE collider, and a new run for the KLOE experiment has been planned for end 2009.

The new collision scheme is the main design concept for a new project aimed at building a Super-B factory [18] that is expected to achieve a luminosity of the order of 10^{36} cm^{-2} s^{-1} and it has been also taken into account to upgrade one of the LHC interaction regions.

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