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A REVIEW OF DAΦNE PERFORMANCES DURING THE KLOE-2 RUN

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Abstract

DAΦNE, the Frascati electron-positron collider, has completed the last, and more challenging, period of operation for the KLOE-2 detector.

In this context the performances of the collider, based on the Crab-Waist collision scheme, are reviewed and the limiting factors discussed.

INTRODUCTION

The DAΦNE [1] accelerator complex consists 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 includes two independent rings, each ~ 97 m long. The two rings share an interaction region (IR), where the KLOE-2 detector is installed. Beam injection is performed on energy, also in topping-up mode during collisions as well, by a system including an S-band linac, 180 m long transfer lines and an accumulator damping ring. DAΦNE became operational in 2001, and it still is an attractive collider to perform relevant experiments aimed at understanding flavour physics. This has been possible thanks to a continuous effort finalized at increasing the collider performances, which culminated in 2009 with the realization of a new approach to the beam-beam interaction: the Crab-Waist collision scheme [2, 3, 4]. Such developments paved the way to a new run with a revised KLOE detector: KLOE-2 [5], which, in view of a higher luminosity, extended its physics search programs. In fact, the upgraded KLOE-2 setup includes tracking and calorimeter devices close to the Interaction Region (IR), as well as a cylindrical GEM detector, the Inner Tracker (IT), installed at a distance of 15 cm from the Interaction Point (IP). However, a long-term run finalized to deliver a large statistical sample of data can only be planned if all the collider subsystems perform in a highly reliable way. For this reason, in the first six months of 2013, before starting the data-delivery phase, the DAΦNE infrastructure underwent a general consolidation program [6]; exploiting the long planned shutdown foreseen to install the new detector layers. Still some activities were not completed at that time, due to delays in the spare parts procurement, thus they have been finalized during the data taking, profiting from the seasonal shutdowns.

MAINTENANCE AND CONSOLIDATION

The consolidation activities produced the expected positive effects in terms of machine uptime and reliability. Despite several unpredictable failures in the water and power supply networks serving the laboratories, exceptional weather conditions and even earthquakes the collider uptime all along the 40 months of operations has been in average of the order of 75%. It is worth noticing that the DAΦNE uptime is defined as the fraction of time in which the collider has been delivering a luminosity suitable for acquisition, e.g. greater than $0.1 \bullet 10^{32}$ $cm^{-2}s^{-1}$.

Operations have been interspersed with several relevant mending activities. In November 2015 the flow rate of the water cooling the wiggler magnets has been halved in order to prevent holes formation in the magnet coils and damages to hoses. In spring 2016 the water cooling circuit serving: KLOE power supply, the electronics of the new detector layers, and the IR vacuum chamber has been deeply revised in order to improve its efficiency and disentangle the temperature of the water flowing in the IR vacuum chamber circuit from the one circulating in the new detector layers. During summer 2016 the compressor of the cryogenic plant, that had been running well beyond the specification, has been replaced in order to assure stable and reliable operations till the completion of the run. The control system procedure dealing with the commutation of the injection system has been optimized, from both hardware and software points of view, in order to setup the magnet configuration for the opposite beam injection in less than 100 seconds. One of the most relevant criticalities of the machine is the availability of the RF klystrons powering the main ring cavities. The CW 150 kW 368 MHz tube TH2145, formerly produced by Thomson/THALES, is no longer in production. LNF own a total of 4 tubes delivered between 1994 and 1998, 2 of them used to power the e^- and e^+ ring cavities, and 2 stored as spares. In February 2015 the klystron powering the e^- ring cavity had to be replaced. Moreover, during the KLOE-2 run it has been necessary to substitute an electronic phase shifter in electron ring LLRF. The device failure caused the cavity RF phase, and consequently the beam, to shift slowly and randomly by about 10 degrees during operations. Thus, a dedicated longitudinal beam position diagnostics was implemented, at first to identify the problem and, after the cause was identified and fixed, to monitor the beam relative arrival time at IP.

A vacuum leakage in a sputter ion pump near the IR has been fixed in situ, avoiding harmful vacuum vent in the IR vacuum chamber common to both beams.

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COLLISIONS OPTIMIZATION

DAΦNE and KLOE-2 restarted operations by January 2014 with a commissioning phase aimed at optimizing beam orbit, setting up the Crab-Waist optics, correcting transverse betatron coupling, and timing the 6 independent bunch by bunch feedbacks, 3 in each ring, which are fundamental in order to maintain stable high current operations and, in the e^+ ring, to keep under control the e-cloud induced instabilities. This time has also been efficiently used to test the new machine equipment and to recover optimal dynamic vacuum.

The first working points selected for collisions was: $\nu_x^- = 5.098$, $\nu_y^- = 5.164$ and $\nu_x^+ = 5.1023$, $\nu_y^+ = 5.139$, which, confirming *LIFETRAC* [7] simulations, allowed to achieve rather higher luminosity, $L = 1.8 \bullet 10^{32}$ $cm^{-2}s^{-1}$ with respect to the preliminary KLOE test run. Unfortunately in that configuration the background on the detector endcaps and the current driven by the drift chamber were non compatible with efficient data taking.

Machine developments have been limited to very few aspects in favour of the experiment's data taking. The number of colliding bunches has been progressively increased in the range of 93 ÷ 108 maintaining almost the same total current; thus reducing the Touschek contribution to the background as well as the impact of the microwave instability threshold.

The new detector layers installed around the beam pipe posed new tight requirements on cooling and background control. The working temperature of the water cooling system serving the IR had to be set to a lower value in order to cope with the heat loading due to the circulating beams and to the IT electronic equipment. As a consequence, the permanent magnet defocusing quadrupoles of the low-β was operating at a temperature around 18 ^{0}C, 6 ^{0}C below the one in the magnet specifications. Differently from the past the criterion for acceptable background level was set by the discharge threshold on the innermost IT layer, instead of the counting rate on the detector endcaps and the current amplitude measured by the different drift chamber sectors.

A new working point has been adopted for the e^- ring [8] having: $\nu_x^- = 5.135$, $\nu_y^- = 5.17$. The new configuration provided: improved injection efficiency, 20% lower background due to the e^- beam, and about 10 % higher luminosity. The background reduction was very relevant for the KLOE-2 data taking, it had a very positive impact on the accidental counting rate as well as on the event size, which are a main issue in terms of data storage. Moreover the background optimization has been propaedeutical to switch on the IT acquisition.

The operational frequency of the RF cavities of the main rings has been tuned relying on the experimental evaluation of the energy acceptance, which was clearly asymmetric with respect to the nominal frequency set point. In the e^+ ring, for instance, the energy acceptance, $A_{E,}$ was in the range -75 kHz $\leq A_E \leq$ 25 kHz. Lowering the RF frequency by 4 kHz, provided improved performances such as: lower background on the detector, less harmful reduction of the e^- beam lifetime at high current while injecting the e^+ one, smoother injections, and stable and reproducible luminosity trend.

BEAM DYNAMICS

The maximum e^- current accumulated during operations has been $I^- \sim 1.7$ A, stored in 98 consecutive bunches. However, at regime in collision, only currents in the range 1.4 ÷ 1.5 A have been injected. The quality of the e^- beam depends heavily on the mitigation of the effect induced by the ions of the residual vacuum, such effect is counteracted by leaving a suitable empty gap. The width of such gap is a compromise between opposite requirements posed by e^- beam dynamics and high luminosity. It depends greatly on the vacuum condition which improve with the stored beam dose. In fact the best results in terms of luminosity have been achieved, by the second half of the run, through collisions of 106 consecutive bunches.

Concerning the e^+ current, it is strongly dominated by the e-cloud effects [9] which are mitigated by using solenoidal winding around the beam pipe, clearing electrodes and feedback systems. During the first period, operations profited from the clearing electrodes, ECE, installed in the e^+ ring in order to mitigate the e-cloud formation. DAΦNE is the first collider to operate with and thanks to the ECE. They have been fundamental when the vacuum level in the e^+ ring was not optimal yet. At that stage a careful tuning of each stripline polarization voltage has been done in order to avoid sudden variation in the e^+ beam orbit. Then, progressively during the data taking, several ECE had to be switched off due to faulty behaviour. The KLOE-2 run finished with only 2 ECE fully operative, but, at that point, the benefits coming from the scrubbing process helped in keeping the e-cloud instabilities under control, as confirmed by comparing the pressure rise in the arcs of the e^+ ring for the two periods with 80% and only 2 ECE working properly. A conclusive explanation of the process leading the ECE to exhibit a faulty behaviour, after having worked for some time, is under way since it requires to extract and analyse in detail the faulty striplines. During the whole KLOE-2 run the maximum current stored in the e^+ beam has been of the order of $I^+ \sim 1.2$ A, although, at regime in collision, a current $I^+ > 0.95$ has been rarely injected; a value considerably lower than the one achieved during the previous DAΦNE's run periods.

Beam currents were affected by longitudinal quadrupole oscillations. This instability has been controlled by a special technique [10] implemented at DAΦNE in the synchrotron (dipole) feedback system. This is done by detuning the QPSK modulation in the feedback back end for damping both dipole and quadrupole beam motions. Also the environmental RF and DC noise coming from pickups, and leading to undesirable vertical beam size growth, has been minimized by installing a low noise front end, designed in collaboration with SuperKEK feedback team, on the vertical feedback.

In general beam dynamics has been affected by the several new components installed on the two rings during the preparatory phase for the KLOE-2 run [11, 12]. In fact the new

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kicker developed for the transverse horizontal positron feedback has also been used for the horizontal electron feedback, and as beam dumper. This adds a new kicker per ring in the opposite section with respect to the IR. The IP vacuum chamber has been replaced with a new section having a slightly different mechanical design. The rectangular vacuum chambers of the collimators close to the IP, the most effective ones, have been replaced with a chambers of reduced volume in order to increase the blade insertion length. The four wigglers installed in each ring have been modified to reduce the higher order multipoles of the magnetic field, and by removing a purpose built sextupole component, which was efficiently used to implement a smooth and distributed chromaticity control.

LUMINOSITY RESULTS

Luminosity in DAΦNE is evaluated by using different approaches. A fast γ monitor measures the photons emitted at small angle (~1 mrad) in the e^+e^- inelastic scattering, by means of two detectors aligned along the direction of each beam from the IP. They are used for relative luminosity measurements only, during collision optimization. The absolute luminosity measurement is provided by the experimental detector. A dedicated tool based on the direct signals of CCALT, one of the new KLOE-2 layers, provides bunch by bunch luminosity measurements [13].

The data taking for the KLOE-2 detector has been organized in four runs, as shown in Fig. 1. For each run milestones have been agreed upon, in order to grant to the experiment a total integrated delivered luminosity of the order of 6 fb^{-1}, after 40 months of operations.

Trends in integrated luminosity show how the agreed milestones have been achieved for each data taking period, often even exceeded. By the end of operations, the DAΦNE collider has been able to provide a total integrated luminosity of the order of $L_{\int del} \sim 6.8\ fb^{-1}$, of which $L_{\int acq} \sim 5.5\ fb^{-1}$ has been stored on disk by the experiment.

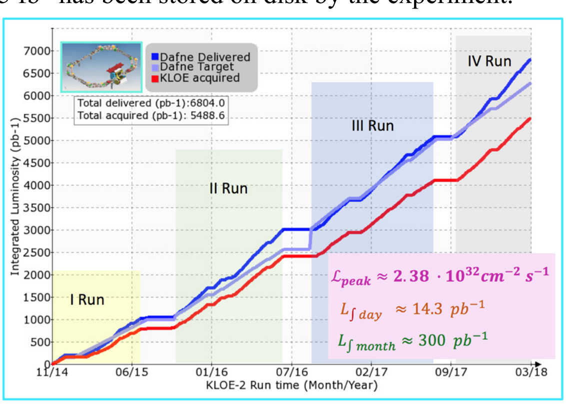

Figure 1: KLOE-2 data taking summary.

The maximum instantaneous luminosity measured has been $L_{peak} \sim 2.38 \cdot 10^{32}\ cm^{-2}s^{-1}$ which is the highest luminosity ever measured by KLOE. Such a result could, without any doubt, only be achieved thanks to an effective integration of the Crab-Waist collision scheme with the experimental apparatus that strongly perturbs machine optics and beam dynamics [14]. The peak luminosity achieved day by day as a function of the day number since the beginning of operations is reported in Fig. 2 for Crab-Waist and conventional collisions, red and blue dots respectively. Crab-Waist provides a 59% increase in terms of peak luminosity as evidenceded by data taken by the same detector with the same accuracy.

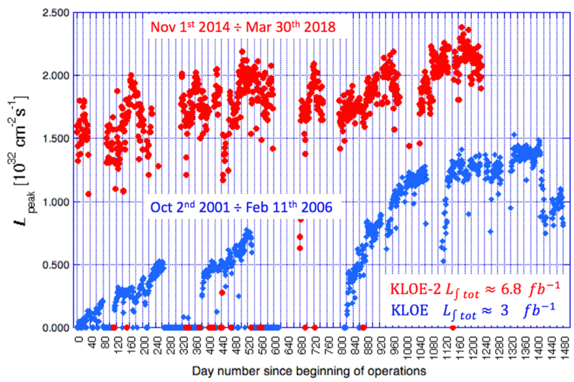

Figure 2: Instantaneous luminosity trend.

Still, the instantaneous luminosity trend exhibits an evident positive slope, regardless the lack of suitable time and manpower for dedicated extended machine studies. Furthermore a rather promising instantaneous luminosity, $L \sim 3 \cdot 10^{31}\ cm^{-2}s^{-1}$, has been measured with 10 colliding bunches, thus minimising the impact of e-cloud and multi-bunch effects.

As far as the integrated luminosity is concerned, the Crab-Waist collisions at DAΦNE have been able to more than double the integrated delivered luminosity, in fact 3 fb^{-1} only had been delivered with the nominal collision scheme, in almost the same period of previous operations. Remarkable performances have been achieved also in terms of delivered daily and monthly integrated luminosities, which have been of the order of $L_{\int day} \sim 14.3\ pb^{-1}$ and $L_{\int month} \sim 300\ pb^{-1}$ respectively. It is worth noticing that the best delivered monthly luminosity has been obtained in 26 days only. Furthermore, the maximum daily integrated luminosity is comparable with the highest ever achieved at DAΦNE, $L_{\int day} \sim 15\ pb^{-1}$, occasionally measured [15] during the test of the Crab-Waist Collision Scheme with the SIDDHARTA experiment. Last, but not least, the aforementioned record luminosities have been achieved regardless of the fact that the maximum currents in collision were considerably lower than the ones used during the past DAΦNE runs. Such current reduction can be estimated to be of the order of 30% and 20% for the electron and the positron beam respectively.

CONCLUSION

DAΦNE has just concluded the run for the KLOE-2 experiment achieving unprecedented results in terms of luminosity. This has been possible thanks to an effective integration of the Crab-Waist Collision Scheme with the high field detector solenoid. The Crab-Waist Collision Scheme has proven to be a viable approach to increase luminosity in circular colliders even in presence of an experimental apparatus strongly perturbing beam dynamics. Definitely

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good news for all the new machines and projects around the world that have adopted Crab-Waist as their main design concept.

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