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DAΦNE COLLIDER WITH CRAB WAIST SCHEME: FROM KLOE-2 TO SIDDHARTA-2 EXPERIMENT

M. Zobov†, D. Alesini, S. Bini, O. R. Blanco-García, M. Boscolo, B. Buonomo, S. Cantarella, S. Caschera, A. De Santis, G. Delle Monache, C. Di Giulio, G. Di Pirro, A. Drago, A. D'Uffizi, L. G. Foggetta, A. Gallo, R. Gargana, A. Ghigo, S. Guiducci, S. Incremona, F. Iungo, C. Ligi, M. Maestri, A. Michelotti, C. Milardi, L. Pellegrino, R. Ricci, U. Rotundo, L. Sabbatini, C. Sanelli, G. Sensolini, A. Stecchi, A. Stella, A. Vannozzi, LNF-INFN, Frascati, Italy
J. Chavanne, G. Le Bec, P. Raimondi, ESRF, Grenoble, France
G. Castorina, Roma1-INFN, Roma, Italy

Abstract

In March 2018 DAΦNE, the Italian electron-positron Φ-factory based on the Crab Waist (CW) collision concept, has successfully completed the challenging experimental run for the KLOE-2 detector. At present, installation of the SIDDHARTA-2 detector is underway in order to start data acquisition with the new experimental apparatus in the year 2019. In this paper we review the collider performances during the KLOE-2 run in terms of the achieved beam currents, the peak and integrated luminosity and encountered beam dynamics challenges. The design and development work done in view of the SIDDHARTA-2 operation is presented and discussed.

INTRODUCTION

DAΦNE [1, 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 includes two independent rings, each ~ 97 m long. The two rings share a common interaction region (IR), where the detector on duty is 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 while delivering luminosity.

DAΦNE became operational in 2001 and it is still an attractive collider to perform relevant high energy and nuclear physics experiments. This has been possible due to a continuous effort aimed at improving collider performances, which culminated with the realization of a new approach to the beam-beam interaction, Crab Waist (CW) collision scheme [3, 4], during DAΦNE operation with the SIDDHARTA apparatus [5, 6]. Such developments paved the way to a new run with a revised KLOE detector, KLOE-2 [7], which in view of a higher luminosity extended its physics search program.

Presently DAΦNE, after having successfully completed the KLOE-2 run in March 2018, is facing the preparatory phase for a new operational period aimed at delivering data to the SIDDHARTA-2 detector [8], an upgraded version of the old apparatus. The new experimental program aims at performing the first kaonic deuterium measurement by improving its measurement resolution. The experiment aims at integrating a sample of data of the order of 1.0 fb^{-1}. This target should be achieved in one year operations.

† Mikhail.Zobov@lnf.infn.it

KLOE-2 INTERACTION REGION

Using the Crab Waist collision scheme the highest DAΦNE peak luminosity of 4.5×10^{32} $cm^{-2}s^{-1}$ was achieved with the SIDDHARTA apparatus that is a small detector without solenoidal field [5]. For the KLOE-2 run the high luminosity IR was modified to host a large detector with a strong solenoidal field which significantly perturbs beam dynamics introducing new design challenges in terms of interaction region optics design, beam transverse coupling control and beam stay clear requirements [9]. Figure 1 shows a schematic drawing of the KLOE-2 interaction region.

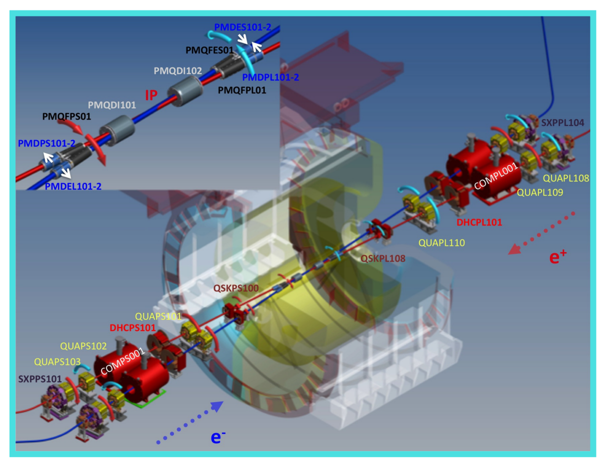

Figure 1: Schematic drawing of the KLOE-2 IR.

The KLOE-2 detector superconducting solenoid has an intense 2.3 Tm integrated magnetic field which, due to the low collider energy, results in the beam transverse oscillation plane rotation by an angle of about 39 degrees. The field integral introduced by the solenoidal detector is almost cancelled by means of two anti-solenoids, installed in each ring symmetrically with respect to the interaction point (IP), which provide compensation also for off-energy particles. The rotation of the beam transverse plane is compensated by co-rotating the IR quadrupoles. Only the first low beta quadruples have been kept in the upright position in order to avoid a significant displacement of the vertical beam trajectory. In addition, in order to keep the vertical trajectory within reasonable values a

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small permanent magnet dipole has been added in each of the four IR branches. Coupling correction fine-tuning for each beam is assured by adding in the IR skew quadrupoles and by the two anti-solenoids powered independently. Despite the above complications a good IR optics solution satisfying the Crab Waist and stay clear requirements has been found [9] and verified experimentally in the KLOE test run [10].

COLLIDER TUNING

After installation of the final setup of the upgraded detector and intensive efforts on the collider infrastructure maintenance and general consolidation [11, 12] DAΦNE and KLOE-2 restarted operations in January 2014. An initial commissioning phase was aimed at optimizing beam orbit, setting up the Crab-Waist optics, correcting transverse betatron coupling, and tuning 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 were: $\nu_x^- = 5.098$, $\nu_y^- = 5.164$ and $\nu_x^+ = 5.1023$, $\nu_y^+ = 5.139$, which allowed achieving a luminosity of $L = 1.8 \times 10^{32}$ $cm^{-2}s^{-1}$, higher 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. Moreover, the new layers of the upgraded detector 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 load due to the circulating beams and to the electronic equipment of the new detector inner tracker (IT). As a consequence, the permanent magnet defocusing quadrupoles of the low-β IR were operating at a temperature by 6 ^{0}C below the one defined by the magnet specifications. Differently from the past the criterion for acceptable background level was set also by the discharge threshold on the innermost IT layer, in addition to the counting rate on the detector endcaps and the current amplitude measured by the different detector drift chamber sectors.

So, machine developments have been limited to very few aspects in favour of the experiment 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. A new working point has been adopted for the e^- ring [13] 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 the main issues in terms of data storage. Moreover the background optimization has been decisive 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 ≤ A_E ≤ 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. The RF cavity voltage reduction from the design 200-250 kV down to 130-150 kV was also found to be beneficial for both beam dynamics and for further background suppression.

BEAM DYNAMICS ISSUES

The stored beam currents in both rings were somewhat lower than those achieved during the SIDDHARTA run owing to more strict background requirements and a few beam dynamics issues. The maximum current accumulated in the electron ring was about 1.7 A to be compared with 2.4 A in the previous run while the maximum achieved positron beam current was limited by 1.2 A.

Several required vacuum chamber modifications and installation of new hardware have resulted in the beam coupling impedance increase. These are: new IR vacuum pipe, additional dump kickers, electron cloud clearing electrodes, narrower vacuum chamber of the modified collimators etc. The resulting consequences have been observed as the transverse beam sizes enlargement having a lower single bunch current threshold and longitudinal quadrupole oscillations arising at high beam current. A partial solution of the transverse size growth problem has been found by decreasing the RF voltage leading to the bunch current threshold increase. In turn, the longitudinal quadrupole oscillations have been controlled by a special technique implemented at the DAΦNE synchrotron (dipole) feedback system, as it was done also in the past [14].

Concerning the positron beam current, it is strongly dominated by the e-cloud effects which are mitigated in DAΦNE by using solenoidal winding around the beam pipe, feedback systems and clearing electrodes [15]. It is worthwhile mentioning that the electron cloud electrodes, ECE, have been installed for the first time for the KLOE-2 run and DAΦNE is the first collider to operate with such electrodes. During the initial period, when the vacuum level in the positron ring operations was not optimal, ECE have been fundamental in suppression of the electron cloud effects reducing the growth rate of the positron beam horizontal instability, decreasing the vertical beam size blow-up and practically eliminating the betatron tune variation along the bunch train. Unfortunately, progressively during the data taking, several ECE had to be switched off due to a faulty behaviour. The

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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 positron ring for the two periods with 80% and only 2 ECE working properly. A conclusive explanation of the process leading the ECE to exhibit the faulty behaviour, after having worked for some time, is under way since it requires extracting and analysing in detail the faulty strip-lines.

Yet another important feature affecting the beam non-linear dynamics is that 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.

The data taking for the KLOE-2 detector has been organized in four runs, as shown in Fig. 2. 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 $L_{\int del}$ ~ 6.8 fb^{-1}, of which $L_{\int acq}$ ~ 5.5 fb^{-1} has been stored on disk by the experiment.

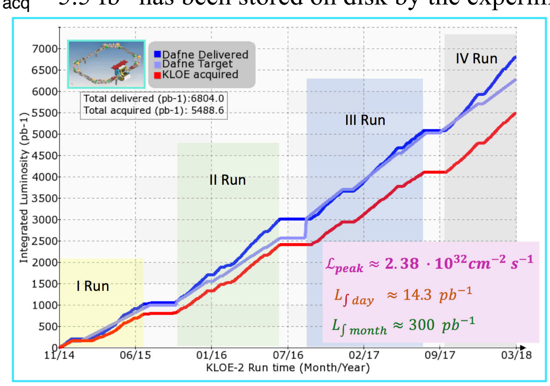

Figure 2: KLOE-2 data taking summary.

The maximum instantaneous luminosity measured has been L_{peak} ~ 2.38•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 [9]. The peak luminosity achieved day by day as a function of the day number since the beginning of operations is reported in Fig. 3 for Crab-Waist and conventional collisions, red and blue dots respectively. Crab-Waist provides about a 60% increase in terms of peak luminosity as evidenced by data taken by the same detector with the same accuracy.

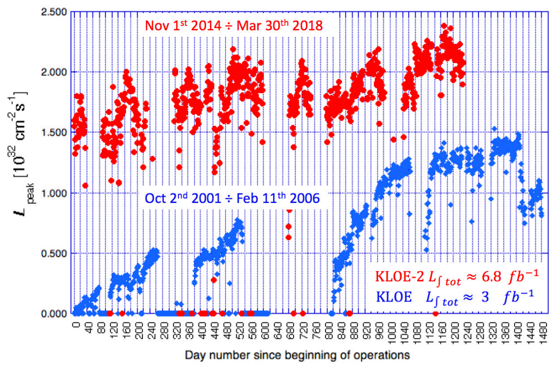

Figure 3: Instantaneous luminosity trend.

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 ~ 3x10^{31} $cm^{-2}s^{-1}$, has been measured with 10 colliding bunches, thus minimising the impact of e-cloud and multibunch 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 $L_{\int day}$ ~ 14.3 pb^{-1} and $L_{\int month}$ ~ 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, $L_{\int day}$ ~ 15 pb^{-1}, occasionally measured [16] 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.

SIDDHARTA-2 INTERACTION REGION

In view of the coming SIDDHARTA-2 physics run many collider subsystems and machine components are being revamped and upgraded [17]. The KLOE-2 detector has been moved back into its hangar and there are preparations under way to install the new SIDDHARTA-2 IR on the place of the KLOE-2 one. The Crab Waist beam optics of the SIDDHARTA-2 IR is essentially the same as it was in the former SIDDHARTA IR. However, there are important differences in the IR vacuum chamber and the low-β insertion quadrupole's design. In particular,

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a decision has been taken to build new permanent magnet quadrupoles (PMQ) of the IR in order to speed up the IR installation procedure, to improve the magnet field quality and to provide a larger stay clear aperture for the detector background reduction. Respectively, the IR beam pipe will have larger dimensions. Besides, a new dedicated thin (150 μm) Al beam pipe with carbon fiber reinforcement (500 μm) will be placed in the central part of the IR in the vicinity of the interaction point. The pipe is optimised to minimize background showers developed due to a high flux of collider lost particles.

Low-β Quadrupoles

The low-β insertion of the SIDDHARTA-2 IR requires 6 magnets: 2 defocusing quadrupoles, PMQD, common for the two beams, and 4 focusing magnets, PMQF, one for each branch of the IR.

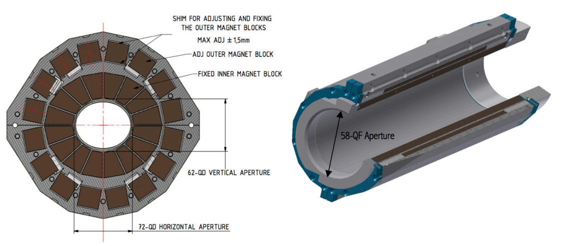

Figure 4: PMQD mechanical cross section (left), and PMQF 3-quarter section (right).

The new PMQ, shown in Fig. 4, have been designed in collaboration with the ESRF magnet group with the intent to improve: good field region, gradient uniformity, aperture, and mechanical assembly. The last aspect has special relevance for the PMQF which are installed very close to each other, see Fig. 5.

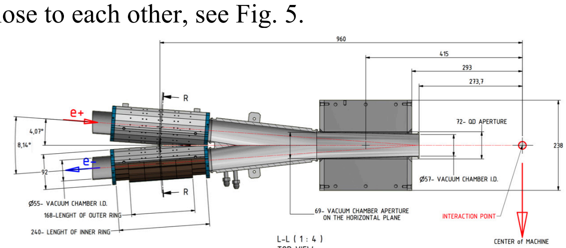

Figure 5: Half IR mechanical assembly, top view.

Bore radius is the main issue in order to provide a proper stay clear aperture for the beams and reduce background on the detector. A larger horizontal aperture is very relevant mainly for the PMQD, in which colliding beams trajectories passes of axis. The new PMQ are Halbach type magnets made of SmCo2:17. PMQD consist of 2 rings of permanent magnet wedges, as in Fig. 4, the inner blocks are arranged according a fixed elliptical symmetry, while the outermost ones are disposed with circular symmetry and can be moved radially to shim the gradient strength and its inhomogeneity. PMQF are based on 2 concentric cylinders of PM wedges having different lengths, see Fig. 4, also in this configuration the PM blocks of the outer cylinder can be moved radially for shimming purpose. Aluminium casing has been designed relying on a comprehensive analysis of the magnetic forces among the different PM wedges and paying attention to installation requirements as well. The new PMQD vacuum chamber has a tapered design allowing matching the elliptical quadrupole aperture, on the side of the Y-shape beam pipe, and the IR circular one at the entrance of the common vacuum chamber, as shown in Fig. 5.

IR Vacuum Chamber

The vacuum chamber of the low-β section has been designed in order to fit with the new quadrupole apertures, paying great attention to the impedance budget of the new structure. In a collider composed of two separate rings having a common IR it is unavoidable to create electromagnetic higher order modes (HOM) in the area where the vacuum beam pipes of the two rings merge in the common beam pipe (Y-shape chamber) [18, 19].

The numerical simulations with HFSS [20] have revealed the existence of two HOMs trapped in the Y-chamber of the new SIDDHARTA-2 IR at frequencies of 1.863 MHz and 2.299 MHz respectively. These modes are rather weak to create any dangerous multi-bunch instability that can be always controlled by the power feedback systems of DAΦNE. However, despite these are the TE-like modes, there are non-negligible longitudinal fields along the beam trajectory contributing into the longitudinal beam coupling impedance. Since the mode frequencies are rather close to the beam power spectrum lines there is a high probability of power loss enhancement in multi-bunch operations. For example, the first mode frequency is very close to the 5th harmonic of the RF frequency at 1.843 MHz. In the worst scenario of the full coupling of the spectrum line with the mode frequency the released power is estimated to be of the order of 0.5 kW. In order to avoid excessive overheating of the Y-chamber, and a resulting vacuum pressure rise in the vicinity of IR, it has been decided to apply cooling pipes on the top of the chamber. The simulations with ANSYS [21] have confirmed that the chamber temperature is kept under control in that case. Moreover, the temperature variation can also help in shifting the mode frequency with respect to the spectrum line thus providing another safety knob.

COLLIDER SYSTEM UPGRADES

Feedback Systems

In a low energy machine as DAΦNE high current performances depend greatly on bunch by bunch feedback systems. DAΦNE works routinely thanks to the 3 bunch by bunch feedbacks installed in each ring, one dedicated to stabilize longitudinal motion, and the other two intended to dampen transverse horizontal and vertical oscillations. The total power available for each apparatus is of the order of 500 W and 750 W for transverse and longitudinal feedbacks respectively. In view of the SIDDHARTA-2 run these systems will be upgraded in order to assure the highest possible stable beam intensities.

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The longitudinal feedbacks will be upgraded adopting the back end timing remote control module based on the QPSK modulator, in order to achieve a more effective tradeoff between dipole and quadrupole longitudinal motion control at the same time [14]. As far as the vertical feedback systems are concerned the low noise front end module will be upgraded in terms of user interface, and by providing the phase shifter with remote control to achieve an easier and cleaner response. Moreover the environmental RF and DC noise coming from pickups, which can lead to anomalous vertical beam size growth, will be mitigated by adopting a low noise front end; the one that has been designed, in the past years, in collaboration with SuperKEKB feedback Team.

High intensity positron beam current deserves special attention since it is limited by the e-cloud induced instabilities. It is expected that the e-cloud effects will be more pronounced during the SIDDHARTA-2 run, especially at the initial stage of operations. This is explained by the fact that, as discussed previously, the most part of the e-cloud clearing electrodes have been damaged during the long KLOE-2 run. Moreover, it is reasonable to expect that the installation of the new Al beam pipe in the IR will result in a higher electron cloud density due to lack of beam conditioning and scrubbing in that area. In this context, it has been decided to add a second transverse horizontal feedback in the e^+ ring, thus doubling the total power available to keep under control the e-cloud detrimental effects. A dedicated test experiment on the two horizontal feedback implementation in DAΦNE has been successful (see [22], for example).

Machine-Experiment Data Exchange

Dynamic Data exchange between machine and experimental staffs is a key feature. Having data reporting machine operating conditions and experiment meaningful parameters helps both teams to run in the most effective way. A typical example is the continuous machine tune up needed to provide the highest luminosity rate while decreasing the background level on the experiment apparatus.

Data exchange requires a proper network interconnection between the computers handling the experiment and the machine Control System. Those systems are often independent from each other because experimental groups are used to managing their systems with hardware and software tools specifically targeted. In the DAΦNE-SIDDHARTA collaboration the network set up has been kept as simple as possible, using a dedicated vLAN for the computers dedicated to the front-end acquisition and the experiment slow control. Such vLAN is then routed on the laboratories LAN which the users' consoles are connected to.

Two data records have been defined; one being sourced from the machine Control System and the other from the experiment. The records are then continuously written in plain text format by the two counterparts to files mutually shared with NFS. Besides this conservative approach, it has also been decided to stream the same information in JSON packets sent through http REST queries to a !CHAOS [23] installation, in order to make them available also in this new control framework, recently implemented at LNF.

Luminosity Measurement

In order to ensure a fast luminosity measurement the IR will be equipped with two independent diagnostic tools.
The main luminosity measurement will rely on the small angle Crystal CALorimeters with Time measurement, CCALT [24], that was part of the KLOE-2 detector, in order to measure the Bhabha scattering events at small angle. The CCALT consists of two identical crystal calorimeters installed in front of each PMQD. This detector has been efficiently used, while providing data to the KLOE-2 experiment, to implement an absolute instantaneous luminosity measurement with accuracy of the order of 5÷10% depending on repetition rate and threshold settings [25]. The CCALT luminosity measurement has been successfully cross-checked with the more accurate one provided by KLOE-2 apparatus. Moreover, the diagnostics time resolution has proven to be suitable to implement bunch by bunch luminosity measurement. A second diagnostics based on a gamma bremsstrahlung proportional counter [26] will be installed as well. These detectors, thanks to the very high rates, can be efficiently used as a real time tool during machine luminosity optimization. However, they cannot provide a reliable absolute luminosity measurement since they are heavily affected by beam losses due to interaction with the residual gas, Touschek effect, and low angle scattered particles generated along the IR. In addition to the DAΦNE diagnostics, the SIDDHARTA-2 experiment will provide a dedicated detector for the determination of the charged kaon production rate. This tool is designed to measure the integrated luminosity and could provide averaged value of the instantaneous luminosity to cross-calibrate the DAΦNE luminosity monitors.

CONCLUSION

DAΦNE has just concluded the run for the KLOE-2 experiment achieving the high peak luminosity and exceeding the design integrated one. This has become possible due 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. An extensive program has been defined, and is under way to prepare the run for the SIDDHARTA-2 experiment at DAΦNE. Several aspects of the collider and many subsystems have been upgraded in order to provide the highest performances in terms of luminosity and the lowest background contamination on the acquired data.

The run for SIDDHARTA-2 will be the very last physics run of DAΦNE as a collider; thereafter the accelerator complex will most likely be converted into a test facility.

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