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DAΦNE RUN FOR THE SIDDHARTA-2 EXPERIMENT

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Abstract

DAΦNE, the Frascati electron-positron collider, based on the Crab-Waist collision scheme, has completed the preliminary phase with the SIDDHARTA-2 detector aimed at testing and optimizing the performances of the machine and the experimental apparatus. In this configuration the collider has delivered to the experiment, using gaseous 4He targets, a data sample suitable to perform studies on the kaonic helium transitions with an accuracy which is the status of the art in the field. As a next step, DAΦNE is planning a new run finalized to deliver data to the detector in order to study the more elusive kaonic deuterium transition. In this context, the setup and the performances of the collider are presented with special attention to the strategy adopted to reduce the background shower on the experimental apparatus.

INTRODUCTION

The DAΦNE accelerator complex [1] 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 infrastructure includes two independent rings, each about 97 m long. The two Main Rings (MR) cross in two symmetrical sections: the Interaction Region (IR) specifically designed for hosting the experiment taking data, and the Ring Crossing Region (RCR) where the beams travel in two vertically separated beam pipes, intersecting with a 50 mrad horizontal crossing angle, as in the IR. 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 during collisions. Besides, DAΦNE supplies 4 synchrotron light lines, and a beam test facility, BTF [2].

The enduring interest in carrying out physics experiments at DAΦNE is based on two relevant motivations. Regardless of the accelerator complex was built in the years 90', it is still a unique machine in the world for physics studies using low-energy charged kaons with momenta below 140 MeV/c. In addition, at DAΦNE a new approach to collisions, the Crab-Waist collision scheme [3], has been developed and successfully tested, with different kinds of detectors [4, 5], allowing to increase the machine luminosity up to a factor of 3. Nowadays, luminosity achieved at DAΦNE is one order of magnitude higher than the one measured in colliders working at the same energy, and Crab-Waist has become the main approach to collision for present and future lepton colliders [6–10].

In this context, since 2021 DAΦNE has been providing physics events [11] to the SIDDHARTA collaboration [12] which in 2021 completed a high precision kaonic Helium measurement [13, 14] during a test run of their preliminary experimental apparatus, SIDDHARTINO [15], and then reproduced it with the final experimental setup SIDDHARTA-2. However, in these last 2 years, DAΦNE operations have been very discontinuous and spoiled by a very high fault rate affecting mainly LINAC, and magnets power supplies. Moreover, the dramatic surge in the electric power costs, forced to ramp down the accelerator complex for pauses in operations longer than one hour. These circumstances prevented proper subsystem tuning, to achieve high beam current intensities, and in general, optimize the collider performances.

PRESENT RUN PROGRAM

DAΦNE operations resumed by mid of past March, after eight month long stop that was exploited to recover full LINAC operability and to implement some maintenance intervention on the power supplies. The long inactivity period imposed to undertake an extensive commissioning program. The present run aims at setting up data taking to perform the first-ever measurement of kaonic deuterium X-ray transitions to the fundamental level [16]. However, before facing this challenging measurement the physicists working on the experiment need to study and carefully tune their detector. This is going to be done by measuring the kaonic-Ne atom which, having never been measured, has itself physics relevance.

The first 10 days of operations have been spent to setup all subsystems, and to fix several faults. It was indeed necessary to fix problems concerning cooling systems, power supplies, electron ring injection kicker, and klystron of the positron ring RF-Cavity required short conditioning. Beams have been stored for the first time at the end of March and after 8 days the first luminosity was delivered to the experiment. Thereafter, operations continued sharing time between data delivery and machine optimization.

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COLLIDER SETUP

Injection

Thanks to the recovered stability and reproducibility of the injector system it has been possible to drastically improve injection efficiency, which is now in the range of 70% - 80% for both beams, with a transport efficiency along the transfer lines close to 100%. These performances have contributed significantly to store high beam currents and to setup properly all the subsystems responsible for beam stability.

Linear and Non-Linear Optics

New optics has been applied to the MRs in order to simplify the focusing structure of the RCR. The original quadrupole triplet (D-F-D) based on large bore radius and high gradient quadrupoles was modified by switching off the two side magnets. This allowed us to eliminate the spurious component in the quadrupole magnetic field seen by the beams that, in those quadrupoles, pass off-axis both in the horizontal and in the vertical plane. The new optics does not modify the IR and maintains all the prescriptions required by the Crab-Waist Collision Scheme, but it allows to improve beam closed orbit correction by reducing the total strength of the steering magnets used, which contributed also to minimize vertical dispersion in both rings. Linear optics has been also used to verify that transverse betatron coupling was properly corrected in both rings. After global orbit correction, the alignment of each sextupole magnet has been verified by beam-based measurements, in a few cases small closed orbit bumps have been applied to restore optimal alignment conditions, one of the Crab-Waist sextupole in the MRp required 1 mm mechanical alignment in the horizontal plane. Initially, sextupole magnets were set to correct chromaticity to zero, then they have individually tuned in order to reduce the background shower on the detector and to improve the ring acceptance in injection. At some point this iterative procedure required revising vertical dispersion correction, this was done by applying vertical closed orbit bumps at some of the modified sextupoles. Crab-Waist sextupoles have been progressively switched on, presently they are set at approximately 70% of their optimal strength.

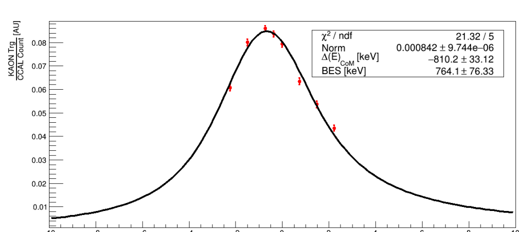

Figure 1: Energy scan as a function of the absolute energy deviation with respect to the starting point of the scan; the fitting function includes radiative corrections and the beam energy spread is left as a free parameter.

The center of mass energy of the colliding beams was moved by -760 keV, -0.7% variation for each beam, by changing the magnetic field of the MRs dipole magnets, and of the C-type horizontal steering magnets installed in the IR and in the RCR that contribute to define the ring nominal orbit. Beam energy tuning was motivated by the indication coming from a detailed energy scan of the *Phi*-resonance done at the end of the previous DAΦNE run combining data coming from the collider and experiment luminosity monitors, see Fig. 1. It gave about a 7% gain in terms of charged kaon yield.

Beam Dynamics

Optimal dynamic vacuum conditions are mandatory in order to store high-intensity, stable beam currents. Therefore, in the first stage of the commissioning dedicated beam conditioning, and beam scrubbing runs were carried out. E-cloud effects strongly perturb e^+ beam dynamics and, at DAΦNE, they are mitigated by: solenoid windings wounded around beam pipes in the straight sections, powerful transverse feedback systems, properly tuning e^+ beam parameters, reducing the RF-Cavity voltage so to increase bunch length, and adding Landau damping by means of octupole magnets. Dedicated scrubbing runs have been done using 40 bunches pattern with 2 empty buckets spacing and switching off solenoids to enhance e-cloud activity. Electron beam, on the contrary, is strongly influenced by ion trapping which is contrasted by inserting a suitable gap in the batch.

Being DAΦNE a low-energy machine, operating with beams having long damping times, high current performances significantly depend on RF-Cavity (RF) and bunch-by-bunch feedback systems (FBK). Each DAΦNE ring is equipped with one RF and three independent FBK systems dedicated to mitigate longitudinal, horizontal, and vertical instabilities. All major components of RF and FBK systems were inspected, damaged amplifier in the low-level RF feedback chassis of the MRe RF, and some minor components such as attenuators and filters installed in the FBK chains were replaced. Afterward, the different system operation setups were tuned, at first in single beam operation mode and moderate current, eventually, setups were refined in collision and at high current, taking special care to avoid destructive interference among different systems, and between systems and beam-beam interaction. In this regard, harmful interference between longitudinal instabilities and beam-beam interaction was cured by tuning the mode-0 feedback of the RF in MRp, that at high current was in anti-damping. A rather large difference in the spread of the synchronous phases between the two beams has been eliminated by tuning the phase loop of the RF in MRp. This allowed to restore uniform beam current distribution along the e^+ batch and, in turn, to equalize beam-beam kick for different bunch pairs. Sudden electron beam losses occurring above a current threshold in the range 1 ÷ 1.1 A have been cured after a meticulous fine-tuning of the low-level RF feedback amplifier and mode-0 feedback.

This comprehensive and iterative effort led to a substantial increase in terms of maximum stable beam currents stored in collision, which presently are of the order of $I^+ = 1.06$ A,

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$I^- = 1.47$ A. These values are considerably higher than the ones measured during the previous run in 2022 ($I^- = 0.95$ A, $I^+ = 0.6$ A). Positron beam stability also profited from increasing the vertical chromaticity to +2, which helped in mitigating e-cloud induced instabilities.

COLLIDER PERFORMANCES

Luminosity

DAΦNE luminosity measurement relies on two devices CCAL and Gamma monitors. The Crystal CALorimeters, CCAL [17] measures the Bhabha scattering events at small angle. CCAL consists of two identical crystal calorimeters installed in front of each permanent magnet defocusing quadrupoles of the low-β in the IR. The gamma bremsstrahlung proportional counters are installed on both sides of the IR where the two beam pipes split. These detectors, thanks to the very high rates, can be efficiently used as real-time tools during machine luminosity optimization. However, they cannot provide a reliable absolute luminosity measurement since CCAL has not yet been properly calibrated, and the gamma monitor is heavily affected by beam losses. In this context, the only absolute measurement of the collider luminosity is the one provided by the SIDDHARTA-2 detector based on charged kaon flux measurement. Optimal luminosity conditions have been attained by scanning one beam through the other at the IP by means of position and angle closed bumps in the transverse plane, moving the phase of one of the two beam RF cavity to perform longitudinal overlap, and moving the waist of each beam using orthogonal $\alpha^*_{x,y}$ closed bumps. It should be emphasized that waist overlap gave a 15% increase in terms of luminosity.

The highest instantaneous luminosity measured so far is about 2 $10^{32} cm^{-2} s^{-1}$. It has been achieved by colliding 1 A e^- beam current against 0.89 A e^+ beam current stored in 110 bunches. The maximum daily integrated luminosity evaluated by the kaon monitor is of the order of 7.9 pb^{-1}. It's worth reminding that the SIDDHARTA-2 kaon monitor does not account for the events delivered during injection, which in order to be included in the experimental data sample requires time-consuming offline analysis. Therefore, at this stage, integrated luminosity is largely underestimated. Specific luminosity L_{sp} defined as the single bunch luminosity normalized by the product of the single bunch beam currents is presented as a function of the single bunch currents in Fig. 2. In the plot L_{sp} derived by the kaon monitor and from geometric luminosity are shown. It is worth noticing that the two data sets exhibit the same trend, thus indicating that collisions are very well optimized.

Moreover, the weak dependence of L_{sp} on bunch currents clearly indicates that there is no relevant evidence of beam size blow-up. This is in accordance with what is expected since Crab-Waist Sextupoles suppress beam-beam resonances. DAΦNE performances can be summarized by looking at the plots, see Fig. 2, showing the typical operation over a 3-hour run: instantaneous luminosity reach often the value of 2.0 $10^{32} cm^{-2} s^{-1}$, average instantaneous luminosity is well above 1.0 $10^{32} cm^{-2} s^{-1}$, and the integrated luminosity given by the experiment stands at 1.2 pb^{-1}.

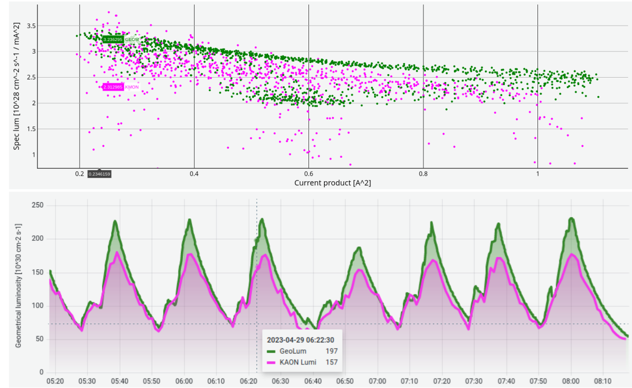

Figure 2: Top: Specific luminosity as a function of the bunch current. Bottom: Standard luminosity trend during operations.

Background

In the first stage of the collider setup background optimization process was largely based on the counting rate out of coincidence provided by the CCAL luminometer. CCAL data have been used to reduce the background at a level compatible with the detector operation. At regime, the background level on the experimental apparatus is monitored, in real-time, by counters based on Kaon/Mip rate, and Kaon/SDD rate provided by the SIDDHARTA-2 detector. Presently, these counting rates have been considerably improved, in fact, Kaon/Mip and Kaon/SDD increased by a factor of 1.4 and 3, respectively. This result has been achieved by optimizing the placement of collimators. It has also been crucial, as outlined before, to tune non-linear optics, and revise RF and FBK systems. A strong correlation between the background hitting the detector and the voltage of the ring RF cavities has also been observed. Increasing the RF voltage by 15 kV and 30 kV in the MRe and in the MRp respectively a deterioration of the order of 15% in terms of Kaon/SDD ratio was measured. Injection optimization also played a role especially as far as the background during injection is concerned.

CONCLUSION

DAΦNE commissioning has been completed in a very short time. Collider performances are almost at the level of the best achieved in previous runs. The background has been considerably reduced and is compatible with efficient detector data taking.

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REFERENCES

[1] G. Vignola *et al.*, “Status report on DAFNE”, *Frascati Phys. Ser.* vol. 4, pp. 19-30, Oct. 1996.

[2] L. Foggetta *et al.*, "The Extended Operative Range of the LNF LINAC and BTF Facilities", in *Proc. of IPAC21*, Campinas, Brazil, 2021, paper THPAB113, p. 3987 doi:10.18429/JACoW-IPAC2021-THPAB113

[3] M. Zobov *et al.*, "Test of crab-waist collisions at DAFNE Phi factory", *Phys. Rev. Lett.* vol. 104, p. 174801, Apr. 2010. doi:10.1103/PhysRevLett.104.174801

[4] C. Milardi *et al.*, "Experience with DAFNE upgrade including crab waist", in *Proc. of PAC09*, Vancouver, Canada, 2009, paper MO4RAI01, p. 80.

[5] C. Milardi *et al.*, “A Review of DAFNE Performances During the KLOE-2 Run”, in *Proc. IPAC’18*, Vancouver, Canada, Apr.-May 2018, pp. 624–627. doi:10.18429/JACoW-IPAC2018-TUYGBD2

[6] Y. Funakoshi *et al.*, “The SuperKEKB Has Broken the World Record of the Luminosity”, in *Proc. IPAC’22*, Bangkok, Thailand, Jun. 2022, pp. 1-5. doi:10.18429/JACoW-IPAC2022-MOPLXGD1

[7] A. Abada *et al.*, “FCC-ee: The Lepton Collider: Future Circular Collider conceptual design report. Volume 2”, *Eur. Phys. Jour. ST*, vol. 228, p. 261, Jun. 2019. doi:10.1140/epjst/e2019-900045-4

[8] CEPC Study Group, “CEPC Conceptual Design Report: Volume 1 – Accelerator”, 2018. doi:10.48550/arXiv.1809.00285

[9] A.E. Bondar *et al.*, “Project of a Super Charm factory at the Budker Institute of Nuclear Physics in Novosibirsk”, *Phys. Atom. Nucl.*, vol. 76, p. 1072, Sep. 2013. doi:10.1134/S1063778813090032

[10] Luo, Q. *et al.*, “Progress of Conceptual Study for the Accelerators of a 2-7GeV Super Tau Charm Facility at China”, in *Proc. IPAC’19*, Melbourne, Australia, May 2019, pp. 643-645. doi:10.18429/JACoW-IPAC2019-MOPRB031

[11] C. Milardi *et al.*, “DAFNE Commissioning for SIDDHARTA-2 Experiment”, in *Proc. IPAC’21*, Campinas, Brazil, May 2021, pp. 1322-1325. doi:10.18429/JACoW-IPAC2021-TUPAB001

[12] C. Curceanu *et al.*, "The modern era of light kaonic atom experiments", *Rev. Mod. Phys.* Vol. 91, p. 025006, Jun. 2019, doi:10.1103/RevModPhys.91.025006

[13] D. Sirghi *et al.*, "A new kaonic helium measurement in gas by SIDDHARTINO at the DAFNE collider", *J. Phys. G*, vol. 49, no. 5, p. 055106, Apr. 2022. doi:10.1088/1361-6471/ac5dac

[14] D. Sirghi *et al.*, "New measurements of kaonic helium-4 L-series X-rays yields in gas with the SIDDHARTINO setup", *Nucl. Phys. A*, vol. 1029, p. 122567, 2023. doi:10.1016/j.nuclphysa.2022.122567

[15] M. Skurzok *et al.*, "Characterization of the SIDDHARTA-2 luminosity monitor", *Journ. of Instr.*, vol. 15, p. P10010, Oct. 2020. doi:10.1088/1748-0221/15/10/P10010

[16] M. Tüchler *et al.*, "A charged particle veto detector for kaonic deuterium measurements at DAFNE", *J. Phys.: Conf. Ser.*, vol. 1138, p. 012012, May 2018. doi:10.1088/1742-6596/1138/1/012012

[17] A. De Santis *et al.*, “DAΦNE Luminosity Monitor”, in *Proc. IBIC’18*, Shanghai, China, Sep. 2018, pp. 81–84. doi:10.18429/JACoW-IBIC2018-MOPB06