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DAΦNE OPERATION STRATEGY FOR THE OBSERVATION OF THE KAONIC DEUTERIUM

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Abstract

DAΦNE, the Frascati Φ-factory, the lepton collider where the Crab-Waist collision scheme has been implemented and successfully tested, is presently working for a physics program in the field of exotic atoms. The present scientific activity foresees the study and the characterization of the never observed before kaonic deuterium. Providing a suitable data sample for such measurement requires the collider to provide the highest flux of K^- meson and the lowest possible background shower on the detector. The operation strategy, and the machine setup in terms of collisions, and beam dynamics are presented, and discussed.

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 during collisions. Besides, DAΦNE supplies 4 synchrotron light lines [2], and a beam test facility, BTF [3].

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 [4], has been developed and successfully tested, with different kinds of detectors [5, 6], 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 [7–12]. In this context, since 2021 DAΦNE has been providing physics events [13] to the SIDDHARTA collaboration [14] which in 2021 completed a high precision kaonic helium measurement [15,16] during a test run of their preliminary experimental apparatus, SIDDHARTINO [17], and then reproduced it with the final experimental setup SIDDHARTA-2.

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PRESENT RUN PROGRAM

The present DAΦNE operations aim at delivering a statistically significant data sample to perform the first-ever measurement of kaonic deuterium X-ray transitions to the fundamental level [18]. Operations for the SIDDHARTA-2 detector using a deuterium gas target started officially on the second half of May 2023, and have been organized in several runs. Initially efforts on the DAΦNE side were aimed at optimizing injection and collisions setup, while SIDDHARTA-2 group concentrated on testing the new experimental apparatus, and tuning the setup to maximize the signal to noise ratio. Thereafter, operations continued privileging data delivery with short periods dedicated to machine studies. After completing operations with the deuterium target, a calibration run with hydrogen gas followed, intended for further detector characterization and background studies.

COLLIDER TUNING

Maximum injection efficiency 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 significantly contributed to store high beam currents, and to tune collisions.

Linear and Non-Linear Optics

Optics in use for the MRs is the one computed and optimized during preparation run, which has been extensively discussed in a previous paper [19]. The strengths of Crab-Waist sextupole have been progressively increased, presently they are set at approximately 77% of their nominal value. This allowed to improve instantaneous luminosity and background level control. The set-point of chromatic sextupoles and octupoles has been refined according a comprehensive iterative optimization process, implemented experimentally during data delivery with the purpose of increasing beam

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lifetime, injection efficiency, and to reduce the signal to noise ratio measured by the detector. This procedure led to a remarkable reduction of the background affecting the measurements indeed, how it will be discussed in the following.

Beam Dynamics

Optimal dynamic vacuum conditions are mandatory in order to store high-intensity, stable beam currents.

Since fall 2023 several anomalous beam dynamics trends, affecting e^- beam, have been detected. The vertical tune had to be lowered with respect to the nominal one to assure beam stability; lifetime was lower than usual; a strong vertical instability appeared, even in single beam operation mode, at rather low current; sudden beam losses occurred for electron beam intensities above 1.5 A. In collision beams were frequently affected by flip-flop effect. The vertical instability was damped in collision by the beam-beam interaction, even though this positive effect worked only for e^+ beam current below 0.75 A, above this threshold the electron beam blew up vertically, luminosity dropped and background increased suddenly. All these symptoms were a clear signature of ion trapping induced instabilities, although there was no clear evidence of vacuum issues. Symptoms were mitigated by reducing the number of bunch in collision from 110 down to 95. In this way it was possible to go on delivering data to the experiment, while preparing for vacuum leak inspection that, after quite some efforts, outlined an elusive leakage of the order of 10^{-8} mbar in the first short arc of MRe. After vacuum leakage fixing all the aforementioned e^- beam dynamics issues disappeared, and 110 bunches collisions were restored.

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.

Being the electron cloud beam instability so relevant to the DAΦNE performances, a new campaign of e-cloud simulations and measurements has been launched. Besides, these studies can be also useful for the future FCC-ee project [8] helping to benchmark existing numerical codes [20].

The electron-cloud density induced by the e^+ beam in a non-colliding configuration was evaluated, at different currents (up to 800 mA), by performing horizontal tune-shift measurements along the batch [20]. The tunes of the different bunches were obtained by discrete Fourier transform of the bunch-position signals, collected and digitized by the bunch-by-bunch horizontal feedback signal processing unit (DIMTEL iGp12-120F). Each bunch-position signal was recorded every machine turn for 30 ms, corresponding to a resolution of 10^{-5} in the computed fractional tune. A moving average filter was applied to the Fourier-transformed signal, so to better identify the betatron frequency. For the typical filling pattern of 105 consecutive bunches, and a beam current of 800 mA, the width of tune shifts measured was of the order of 0.007 (from 0.1096 to 0.1166). This tune shift excursion, was used to evaluate the maximum electron-cloud density, which is as large as 10^{14} [20], one of the highest densities ever observed in circular colliders. Maximum electron-cloud density computed by simulations is about 20% smaller than the measured one, which features ultimately a reasonable agreement.

To study the horizontal multi-bunch instability of the e^+ beam due to electron cloud, grow-damp measurements were performed. The e^+ beam instability was artfully induced by switching off the horizontal feedback for a given time interval. The recorded bunch-position signals were used as input for the modal analysis, which provided the growth rates of the different modes. The dominant mode is $m = -1$, which is typical for electron cloud localized in wigglers and bending magnets. Collision bunch pattern consisting of 105 consecutive bunches, was studied at a beam current of 650 mA, in non-collision operation mode. The modal analysis revealed a growth rate of $22\,\mathrm{ms}^{-1}$ for the mode -1, which is in good agreement with the growth rate of $18\,\mathrm{ms}^{-1}$ determined by a similar mode analysis in 2008 [21].

Being DAΦNE a low-energy machine, operating with beams having long damping times, and short bunch separation, of the order of 2.7 nsec, high current performances significantly depend on RF-Cavity (RF) and bunch-by-bunch feedback systems (FBK), 3 for each ring.

Achieving high intensity stable beam currents implies a comprehensive iterative tuning of all the systems responsible for beam dynamics stability. Presently maximum stable beam currents stored in collision are of the order of $I^+ = 1.$ A, $I^- = 1.65$ A. The e^+ beam stability also profited from increasing the vertical chromaticity to +1,5, which helped in mitigating e-cloud effects.

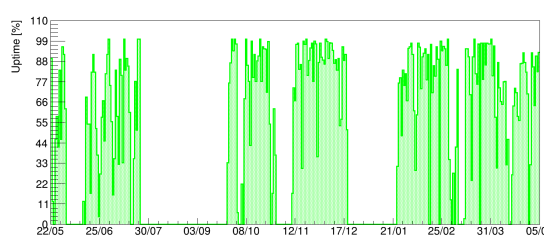

Figure 1: Luminosity delivering efficiency.

COLLIDER PERFORMANCES

Luminosity

DAΦNE luminosity measurement relies on two devices CCAL and Gamma monitors. The Crystal CALorimeters, CCAL [22] measures the Bhabha scattering events at small angle. 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. Thusly, the only absolute measurement of the collider luminosity is the one provided by the SIDDHARTA-2 detector based on charged kaon flux

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measurement. The background level on the experimental apparatus is monitored, in real-time, by counters based on Kaon over Minimum Ionising Particle rate (Kaon/MIP), and Kaon over Silicon Drift Detector rate (Kaon/SDD) also provided by the SIDDHARTA-2 experiment. Kaon/SDD is actually used as a main data quality parameter, L_{HQ}, to discriminates whether data can be used for physics analysis or not.

The highest instantaneous luminosity measured so far is about $2.4 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. It has been achieved by colliding 1.14 A e^- beam current against 0.89 A e^+ beam current stored in 110 bunches. The collider efficiency in delivering luminosity, defined as the percentage of day the collider has been able to deliver a luminosity in excess of $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ after beams refilling, is shown in Fig. 1.

Downtime includes not only collider fault events, but also maintenance, dissemination and formation stops, as well as other institutional duties. Thereby, the DAΦNE net average efficiency in delivering luminosity is of the order of 75%. The daily delivered luminosity measured by the kaon monitor, see Fig. 2, shows constant positive trends, its maximum value, so far, is of the order of 9.5 pb^{-1}.

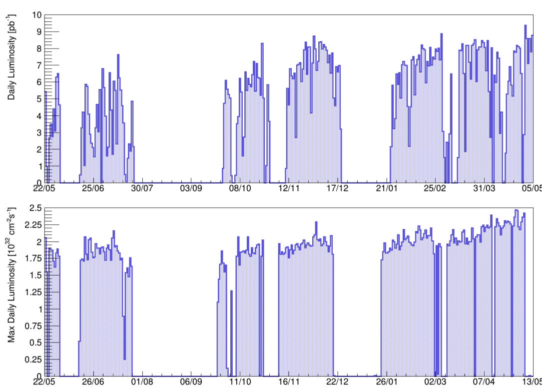

Figure 2: Daily delivered luminosity (top) and maximum daily luminosity (bottom).

The total delivered luminosity is presented in Fig. 3, together with the time evolution of the operations. Data show a remarkable improvements in the collider performances. Delivered luminosity is considerably growing during the 3 different runs, which have almost the same time span, and comparable machine up-time. Delivered luminosity in Run 3 was more than doubled with respect to Run 1.

Background

Background reduction is another noticeable result achieved during the present DAΦNE operations. In a collider like DAΦNE there are two different kinds of backgrounds produced during the injection and costing phase respectively. They require completely different analysis and mitigation approaches. Injection background has been considerably reduced by optimizing injection efficiency, and by properly steering the stored beam orbit in the injection sections. This reduced the background down to acceptable levels for the e^- beam, but did not work as well for e^+ one. For this reason the vertical dimension of the e^- beam are artificially increased during injection, by using a calibrated skew quadrupoles bump. This in order to reduce the beam-beam kick on the weak e^+ beam, and to avoid rapid lifetime drops and sudden background bursts. Costing background was optimized minimizing Kaon/MIP and Kaon/SDD counting rates. This was achieved by a comprehensive optimization of the non-linear ring optics, mainly by experimentally tuning sextupole and octupole magnets in both rings. This procedure allowed to increase energy acceptance, and dynamic aperture, leading to gain almost a factor of 2, and 1.45 in terms of Kaon/MIP, and Kaon/SDD rates respectively. The signal to noise ratio achieved during present operations has been compared with the one measured during the Crab-Waist test run with the SIDDHARTA detector in 2009 [23]. Physics events delivered to SIDDHARTA-2 exhibit now a signal to noise ratio 3 time higher with respect to the one measured in 2009. This was evaluated taking into account the acceptance of the new detector components: kaon, trigger, and SDD. Other analysis parameters such as trigger efficiency, and veto system have not yet been included. Preliminary analysis indicates that this improvement is in large part due to the collider configuration optimization, and to the new design of the PMQD installed in the low-beta of the IR [24].

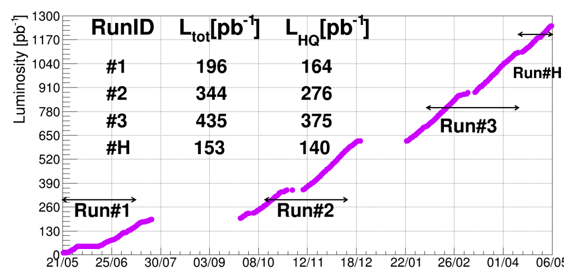

Figure 3: Total acquired luminosity. In the table the total delivered (L_{tot}) and the high quality (L_{HQ}) integrated luminosity is reported for each run period. The fraction of high-quality data increased significantly along the time as a result of the tuning of the DAFNE collider.

CONCLUSION

The DAΦNE lepton collider has delivered to the SIDDHARTA-2 detector using a deuterium gas target a data sample of the order of 1.24 fb^{-1}, well beyond the experiment request. Large part of these data, about 85 %, have very high quality: Kaon/SDD ≥0.6. Such remarkable results have been achieved thanks to the continued machine tuning, and to few selected machine studies. Presently, data taking is going on in order to study the detector response as a function of the target gas density in view of the physics analysis.

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