The DAΦNE Φ-Factory status and perspectives

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The status of the DAΦNE storage rings is reported. In 2002 important improvements both in peak and integrated luminosity have been achieved. During a 7 months shutdown in 2003 the two rings have been restyled and important modifications have been introduced in the 8 wiggler magnets. The two Interaction Regions have been modified in order to allow for an increased number of colliding bunches by reducing the parasitic crossing effect. The operation has resumed last September. The re-commissioning of the machine is at present in progress. Ideas for future upgrades are also presented.

1. INTRODUCTION

The electron-positron collider DAΦNE has been the first "factory" in operation at the Φ energy. The accelerator complex consists of a double ring collider, a linear accelerator (LINAC), an intermediate damping ring to make injection easier and faster and about 180 m of transfer lines connecting these machines. The geometry of this complex has been designed to reuse the buildings hosting ADONE (the 3 GeV center of mass e^+e^- collider in operation at LNF from 1969 to 1993) and its injector, a LINAC used both to refill the collider and to perform nuclear physics experiments. The complex is shown schematically in Fig. 1.

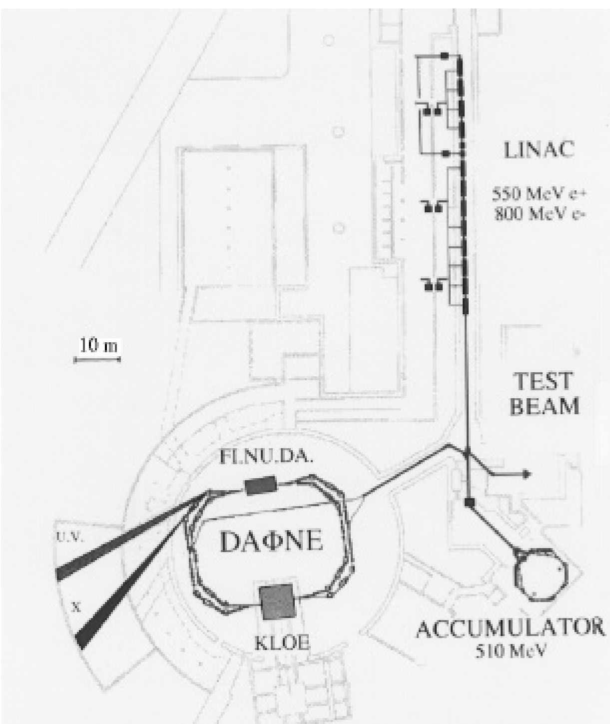

Figure 1: The DAΦNE complex.

A double ring scheme with many bunches has been chosen in order to increase the number of colliding bunches, and therefore the achievable luminosity. The structure of the collider consists of two rings, laying in the same horizontal plane and crossing in two Interaction Points (IP) at a small, tunable horizontal angle of ±12.5 mrad. Two experiments can be installed in the Interaction Regions (IR): three detectors have been realized until now, KLOE, DEAR and FINUDA. The first two have been installed in the two IR's since May 1999, and have taken data until December 2002, while the third has been installed in September 2003 in the IR previously occupied by DEAR (IR2).

The detectors of KLOE (IR1) and FINUDA (IR2) are surrounded by large superconducting solenoid magnets for the momentum analysis of the decay particles and their magnetic fields represent a strong perturbation on the beam dynamics. To correct the x-y coupling a superconducting solenoid magnet with half the field integral of the detector one and of opposite direction is placed at both ends of the detectors; in such a way that the overall field integral in the IRs vanishes. Moreover, in order to obtain a good compensation outside the IR and at the IP, the Permanent Magnet quadrupoles inside the detectors are rotated around their longitudinal axis by angles between 10 and 20 degrees and are provided with actuators to finely adjust their position and rotation

In the original IR1 design the low-β at the IP was realized by means of two quadrupole triplets. However it has been redesigned and modified to a doublet structure in the 2003 shutdown.

The structure of IR2, where the FINUDA detector has been recently installed, is quite similar. Since its superconducting solenoid magnet has half the length (but twice the field) of the KLOE one, the low-β focusing at the IP is obtained by means of two Permanent Magnet quadrupole doublets inside the detector and completed with two other conventional doublets outside. The coupling correction scheme is similar to the KLOE one. Measured coupling in DAΦNE is ~0.2 to 0.3 % for both rings.

The DEAR experiment, which was installed in IR2 for 2002 operation, did not need magnetic field and therefore only conventional quadrupoles were used.

2. DAΦNE ACHIEVEMENTS

The peak luminosity was increased by more than a factor 10 during the past three years (from November 1999 to October 2002), reaching a maximum value of about 0.8×10^{32} $cm^{-2}s^{-1}$.

As shown in Fig. 2, during 2002 the peak luminosity was steadily increasing, while the integrated luminosity per day grows faster, indicating an improvement of the overall efficiency. The peak luminosity for the two experiments (blue for KLOE, green for DEAR) is shown in the top picture, the daily integrated luminosity (red for KLOE, gray for DEAR) is reported in the middle plot, and in the bottom one there is the total 2002 DAΦNE (green), KLOE (red), DEAR (gray) integrated luminosity.

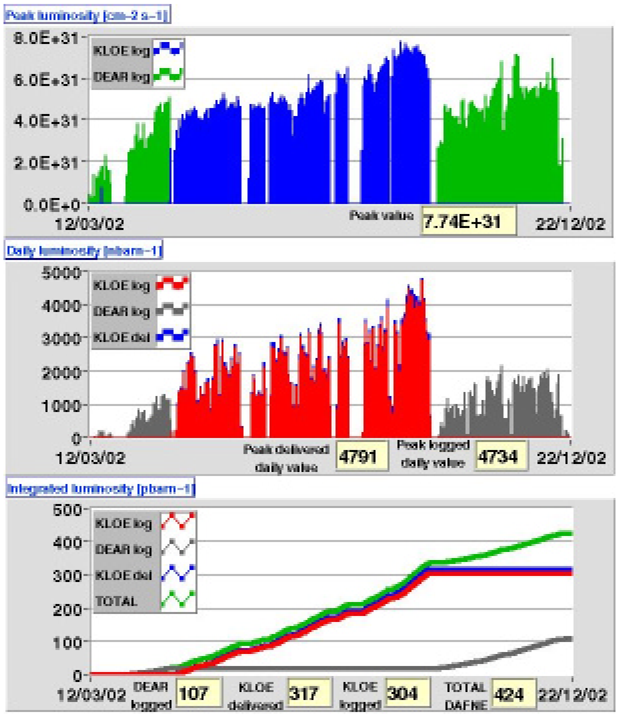

Figure 2: Collected luminosity in 2002.

Collisions in one IR at a time are routine operation. Less than 5 months have been devoted to each experiment in 2002. Summarizing, the DAΦNE achievements last year have been the following:

- 317 pb^{-1} delivered to KLOE;
- $0.8x10^{32}$ $cm^{-2}s^{-1}$ peak luminosity for KLOE;
- 5. pb^{-1}/day, 30 pb^{-1}/week, 100 pb^{-1}/month integrated luminosity for KLOE;
- 107 pb^{-1} delivered to DEAR;
- 95 bunches operation "routine" for DEAR;
- $0.7x10^{32}$ $cm^{-2}s^{-1}$ peak luminosity for DEAR;
- 2.2 pb^{-1}/day, 12 pb^{-1}/week integrated luminosity for DEAR;
- strong reduction of backgrounds levels in both detectors.

The details on how these performances were achieved are described in the following two sections.

3. 2002 OPERATION FOR DEAR

In a low energy electron-positron collider, such as DAΦNE, the lifetime of the stored current is mainly limited by the Touschek effect, namely the particle loss due to the scattering of the particles inside the bunches. A low beam lifetime is not only a limitation to the integrated luminosity delivered, since injection of fresh beams is more frequent, but also a source of backgrounds for the detectors. For this reason, besides the optimization of the machine parameters aimed at increasing the peak luminosity, the main effort during operation has been also the optimization of the beam lifetimes, together with the decrease of the detector backgrounds. With this goal, the first DEAR runs were devoted to machine optimization, in particular:

- background rates were reduced thanks to the installation of new movable collimators (scrapers), the beam orbit optimization and sextupole and octupoles optimization. The levels were reduced by a factor 10 with respect to the previous year;
- the value of β_x at the DEAR IP was lowered from 4.4 m to 1.7 m;
- non-linearities were cured both by optimizing sextupoles (with a resulting 15% improvement) and octupoles configuration (15% improvement as well). The octupoles have been also found useful to improve the lifetime in collision (about 10% improvement), compensating the strong beam-beam nonlinearities.

Due to machine and detector improvements, the signal-to-noise ratio was also enhanced by a factor 40. An important contribution to the background reduction, of crucial importance for the experiment, came from the decrease of the horizontal beta function at the IP.

The reduction of the IP β functions was done not only in order to increase the luminosity in single bunch collisions, but also to relax the influence of the parasitic crossings (PC) to allow doubling the number of colliding bunches. In particular it was possible, by decreasing the horizontal emittance and with a lower β_x, to successfully collide with 95+95 bunches, with an increment of 40% in the peak luminosity, the record being $0.7x10^{32}$ $cm^{-2}s^{-1}$. It was possible to store up to 1.3 A of stable positrons and 1.8 A of electrons in this bunch pattern, routinely used in collision for the DEAR experiment.

As a consequence, there has been a large improvement on the integrated luminosity as well. Due to the lower bunch currents both beam lifetimes and backgrounds were also improved in this configuration.

During 2002 DEAR has acquired 107 pb^{-1} in total. The machine performances with DEAR are summarized in Table 1:

Table 1: DEAR Runs Performances

N_b/beam	95
I_{tot}/beam e^-/e^+ (A)	1.3/1.
L_{peak} ($cm^{-2}s^{-1}$)	$0.7x10^{32}$
<L> ($cm^{-2}s^{-1}$)	$0.2x10^{32}$
Max L_{int}/day (pb^{-1})	2.2
ξ_y	~0.016
Luminosity lifetime (h)	0.6
N. filling/hour	1.7
Injection frequency e^-/e^+ (Hz)	2/1
Data acquisition during injection	OFF

4. 2002 OPERATION FOR KLOE

The runs of the KLOE experiment lasted from May to September 2002. The same optimization procedure applied to the DEAR configuration was performed for KLOE. Particular care was dedicated to the optimization of the background rates that were decreased by a factor 4. In summary, the background reduction came from:

- orbit optimization;
- old and new scrapers optimization;
- sextupoles optimization;
- octupoles optimization;
- improved linear and non-linear knowledge of the machine;
- increased dynamic aperture with optimized β functions at sextupoles and wigglers;
- increased lifetimes from all of the above.

In the KLOE runs a peak luminosity of about 0.8×10^{32} $cm^{2}s^{-1}$ was measured, with a record integrated luminosity per day of about 5 pb^{-1}. The progress in peak luminosity was achieved mainly with a "step-by-step" gradual reduction of the IP β functions, and also by:

- adiabatic machine tuning;
- different working point for the electron beam;
- smaller IP β_y (from 3.0 cm to 2.6 cm);
- smaller IP β_x (from 5.6 m to 2.7 m);
- smaller horizontal emittance (from 0.96 mm mrad to 0.76 mm mrad).

Operation with 100 bunches in KLOE was also tested. The results were good in terms of beam stability, but the peak luminosity was not improved with respect to the standard bunch pattern (49+49) operation. The IP β_x was still too high, and did not allow increasing beam currents with reasonable background. A further decrease of the IP β_x was very difficult without the upgrade of the IR, which has taken place in the 2003 shutdown.

In summary, the performances obtained by DAΦNE during the KLOE runs are reported in Table 2:

Table 2: KLOE Runs Performances

N_b/beam	49
I_{tot}/beam e^-/e^+ (A)	0.8/1.1
L_{peak} ($cm^{-2}s^{-1}$)	0.8×10^{32}
<L> ($cm^{-2}s^{-1}$)	0.5×10^{32}
Max L_{int}/day (pb^{-1})	5.
ξ_y	~0.02
Luminosity lifetime (h)	0.6
N. filling/hour	3-4
Injection frequency e^-/e^+ (Hz)	2/1
Data acquisition during injection	ON

5. BEAM DYNAMICS

In DAΦNE strong, coupled bunch synchrotron oscillations make active damping systems necessary in multibunch operation. In each ring, a broadband bunch-by-bunch Longitudinal Feedback (LFB) is operating since 1998. The systems have been developed in collaboration with PEP-II/SLAC and ALS/Berkeley. The LFB works fairly well, but in 2002 an unexpected longitudinal quadrupole instability was limiting the total storable current to about 700 to 800 mA in the electron ring, even with the LFB on, with a significant luminosity reduction. This instability appeared in the positron ring also but with a 20% higher current threshold. Fig. 3 shows the positron beam spectrum as observed by the spectrum analyzer.

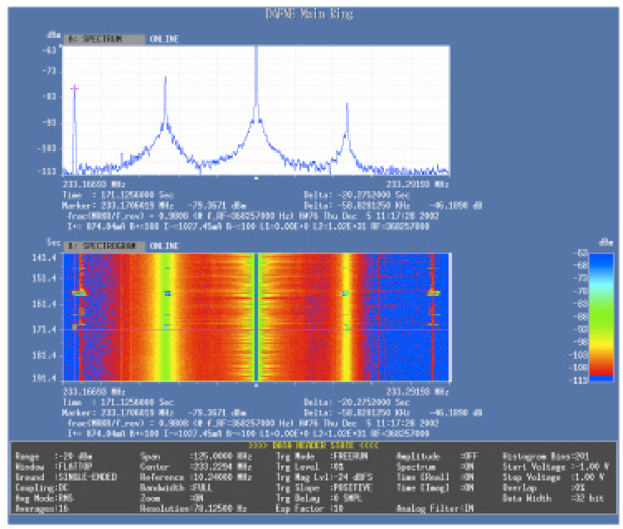

Figure 3: Quadrupole instability (with the cursor) in e^+ ring at 700 mA with LFB on. The largest peak on the left is the revolution harmonic; the small peak in the middle is the dipole mode (under feedback control).

The current limit means that new injections can produce loss of bunches and/or loss of LFB control with successive large decrease of the total beam current. In order to overcome this limit, a strong effort, both theoretical and experimental, was focused on this problem. The quadrupole instability threshold was measured as a function of: RF voltage, momentum compaction, orbit (considering the eventuality of a trapped mode), injection patterns and number of bunches, bunch length and LFB Back-End setup [2].

A clear variation of the quadrupole threshold was observed as a function of the RF voltage. The dependence on the momentum compaction was also evaluated. A 10% increase of the momentum compaction value improved the quadrupole threshold by about 17%. However, variations of this parameter have not given a definitive solution for the instability damping. It has been also found that the threshold increased with the number of bunches.

Finally, the measurement of the single bunch quadrupole threshold as a function of the RF cavity voltage, with LFB OFF and ON, has allowed identifying the problem. It was observed that a bunch length comparable to the LFB Back-End period could drive an interaction between the LFB and the quadrupole instability threshold. By measuring the quadrupole threshold versus the LFB BE delay, it was found that increasing conveniently the BE timing (i.e. kicking the bunch tail) produces higher or no thresholds, while decreasing delay (i.e. kicking the bunch head) lowers the quadrupole threshold. This cure has turned out to be very reliable if used together with a feedback Front-End setup giving an offset of the same sign for all bunches. This study has allowed adjusting the LFB BE delay to avoid the quadrupole instability for all the typical collision patterns, and to store more than 1850 mA of stable electron beam. A similar LFB setup has given better control of the beam at very high currents also for the positron beam.

6. 2003 MACHINE UPGRADES

In 2003 a long shutdown was devoted to important modifications of the rings hardware. They are listed below:

- new KLOE IR;
- new FINUDA IR;
- better detector shielding;
- additional quadrupoles for machine tunability;
- improved injection kickers;
- ion clearing electrodes modifications;
- bellows and scrapers modifications;
- magnetic measurements on a new spare wiggler and subsequent modifications on the 8 wigglers;
- 3rd harmonic cavity test.

6.1. New Interaction Regions

Major modifications to the KLOE IR have taken place. It has been extracted from the detector and reassembled according to a new design, with a modified optics and supports in order to decrease the IP β functions, optimize background rejection and provide variable quadrupole rotation to operate at different magnetic fields (from 0 to maximum) in the solenoids. This will allow obtaining a better correction of coupling in the machine for any value of the KLOE solenoidal field. It makes also possible to run the machine with the KLOE solenoid off, in order to guarantee the maximum flexibility to the collider operation. Therefore, the mechanics has been modified, in order to allow the PM quadrupoles to rotate by any angle between the horizontal symmetry plane of the ring and that corresponding to the full field of the solenoid. This rotation is be performed by stepping motors and remotely controlled.

The vacuum chamber has been modified with a new structure in beryllium alloy (AlBeMet) similar to the existing one but shorter, in order to allow the insertion of two new beam position monitors. Tungsten masks have also been installed to better shield the detector from machine background.

The IR lattice has also been changed. The first quadrupole (QF i.e. focusing in the horizontal plane) has been removed and the third has been reinforced with another quadrupole to get a factor 1.5 higher integrated gradient. In such a way the old FDF triplet has been converted into a DF doublet. The DF scheme allows obtaining the same IP β_y with a lower chromaticity, leading to longer beam lifetimes and better beam-beam performances. Moreover it will allow to decrease in the future the IP β_x from 2.7 m down to 1.5 m. This is needed to double the number of colliding bunches (from 50 to 100) in the KLOE configuration without losing luminosity by the parasitic crossings. The FDF scheme was adopted in the original DAΦNE design in order to allow for good beam separation at the splitter magnets with a low value of the horizontal crossing angle (about ±12.5 mrad), while the DF solution needs an angle of the order of ±15 mrad. However, during recent runs, it has been shown that a crossing angle as large as ±15 mrad can be used without performance limitations.

Fig.4 shows the new KLOE IR PM quadrupoles under assembly.

Figure 4: KLOE IR quadrupoles assembly.

For what concerns IR2, where the FINUDA detector has been installed, a new thin Be chamber with four PM quadrupoles has been inserted in the detector. The original design has been improved by adopting some of the solutions used for the KLOE IR. The mechanics has been modified in order to allow the four PM quadrupoles around the IP to rotate by 135 degrees, so that it will be possible to run DAΦNE with the FINUDA solenoid off as well. With this range of rotation it will be also possible to change the sign of the quadrupole focusing, thus allowing realizing a detuned lattice when running with a single IP. The four conventional quadrupoles outside the detector have also been equipped with rotating supports, allowing rotation in a range of 23 degrees, corresponding to the difference between the solenoidal field on and off. Fig. 5 is a picture of the present IR during its insertion into the detector.

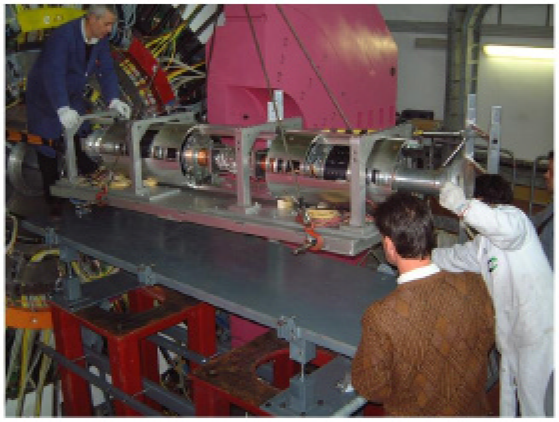

Figure 5: FINUDA IR during installation.

6.2. Wiggler modifications

This item is very important for a better understanding of the performance of the machine. A strong sextupole component and the field roll off at large offsets in the 8 wigglers magnetic field produced a significant reduction of the dynamic aperture [3,4]. A new wiggler, identical to those installed on the collider, was purchased from the same builder, and used to find a proper pole shape capable of reducing the nonlinearities. The resulting profile [5] was applied to a set of iron plates glued on the poles of all wigglers in the rings. The horizontal distribution of the field at pole center is shown in Fig. 6 for the different pole profiles tried during the optimization. Comparison between the field with new plates, not modified, and the final configuration shows a larger extension of the flat field region.

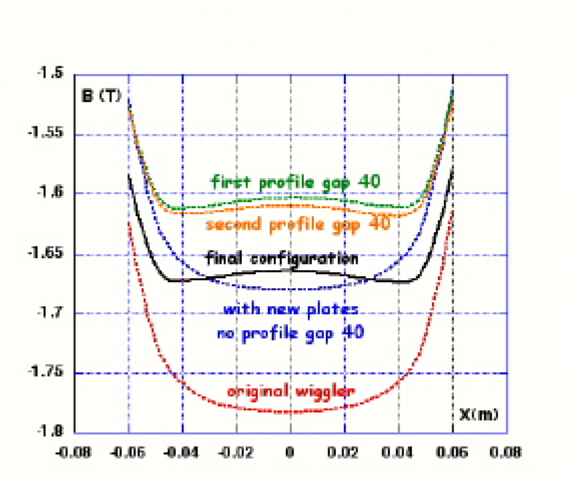

Figure 6: Horizontal field distribution at pole center for different configurations. The solid line (black) is the final one.

The sextupolar component on the beam axis has been significantly reduced in the final configuration so that its average over the pole almost vanishes as shown in Fig. 7. Moreover one of the two terminal poles has been modified in order to increase its sextupolar component (horizontal focusing), this modification being beneficial to the dynamic aperture. According to tracking simulations, the dynamic aperture and lifetimes should double.

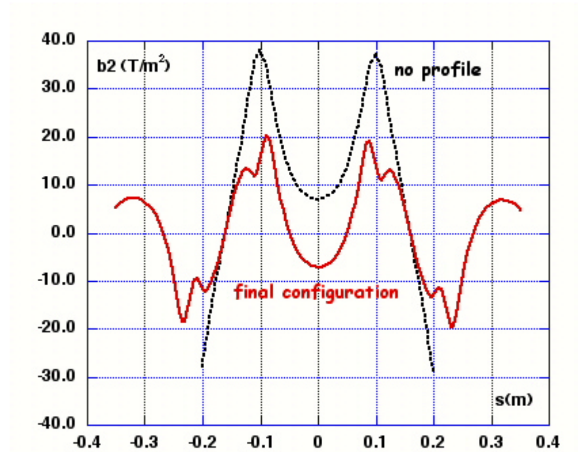

Fig. 7: Sextupole component on the beam axis for the original (dashed) and modified (solid) wiggler pole profile.

6.3. Scrapers, Bellows and Ion Clearing Electrodes

Scrapers were very useful in reducing the beam backgrounds for both experiments. However few jaws were not properly working. They were inspected in the shutdown and it was found that there were problems with the tapers. It was decided to remove the horizontal tapers, that are the least critical to the ring impedance, and to modify the vertical ones, that were intercepting the beam instead of the jaws.

Some copper bellows were found to be distorted and have been flattened with the insertion of pins, as shown in Fig. 8.

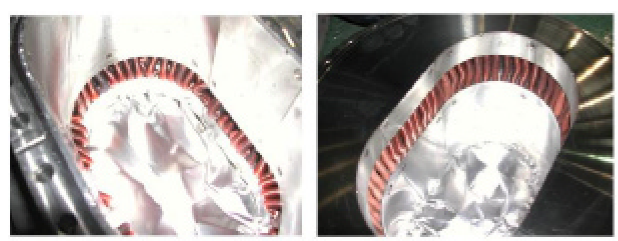

Fig. 8: Damaged bellow: as found (left) and after pin insertion (right).

About 50% of the Ion Clearing Electrodes installed in the electron ring were broken due to faulty welding. Most of them were replaced with welding-free electrodes.

6.4. Injection Straight Sections

The "long" straight sections, where beams are injected, have been rearranged, adding two quadrupoles and one sextupole and removing a kicker magnet, in order to:

- improve injection efficiency;
- decrease injection sensitivity of the stored beam (kick angle and duration both reduced by 50%);
- reduce dispersion at the septum;
- optimize optical functions and phase advance in the section with .respect to dynamic aperture.

6.5. 3rd Harmonic Cavity

The installation of a passive 3rd harmonic cavity in each DAΦNE ring has been proposed to control the bunch length and therefore the Touschek lifetime and the coherent instabilities by increasing the Landau damping due to the non-linearity of the longitudinal potential well.

Due to the peculiarity of the DAΦNE parameters (low RF voltage, high beam current), powering the cavity in a passive way is the simplest and the most effective choice. The required harmonic voltage can be obtained with modest cavity shunt impedance and over a wide range of beam currents. The choice of the harmonic number 3 is a compromise between beam dynamics requirements and constraints related to the space available for the cavity installation. Details on the design and measurements of the cavity can be found in Ref. [6]. A picture of the actual cavity is shown in Fig. 9.

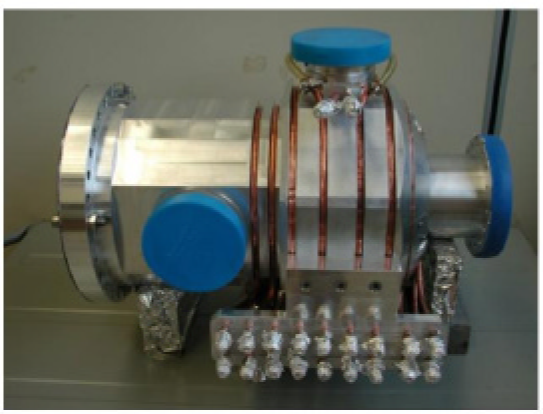

Fig. 9: 3rd harmonic cavity on bench.

The damping of the cavity HOM has been obtained by means of a special ferrite ring developed for the superconducting cavities installed on the High Energy Ring (HER) of the KEK-B collider in Japan. The cavity has been designed by means of an extensive use of the e.m. codes MAFIA and HFSS. The measurements performed on the real cavities are in good agreement with the results obtained by e.m. simulations. Two harmonic cavities have been fully tested on bench. One cavity has been also installed in one ring to check beam pipe and connections, and uninstalled before the operation resumed. The final installation is foreseen for next year.

6.6. Additional hardware modifications

Other hardware modifications and upgrades were performed during the shutdown. Briefly:

- increased horizontal feedback power;
- one injection kicker per ring removed (2 kickers/ring remain), two valves and two bellows in each IR removed to further reduce ring impedance;
- a faulty injection kicker found (in the last days of the DEAR run) and repaired, source of the e- current limit;
- a faulty power supply and bend coil found and repaired, responsible for horizontal drifts of the positron beam;
- new cameras for the Synchrotron Light Monitor for better emittance diagnostic;
- new electronics for the Transfer Lines BPMs to read position and optimize the beam transmission in non-invasive mode;
- 50 Hz linac operation in order to inject positrons at 2 Hz (electron injection is at 2 Hz already);
- new (custom) Helium transfer lines to cool the solenoidal compensators with the existing crio-plant

6.7. Optics modifications

A new lattice for the FINUDA operation in IR2 has been designed by taking into account all the hardware modifications. Its main characteristics are summarized in the following:

- lower emittance (0.42μm);
- lower β in the wigglers to minimize the effect of non-linearities;
- β_x*=1.7m to allow for 100 bunches operation;
- β_y*= 27 mm, close to the bunch length;
- additional sextupoles in the wigglers and at the septum;
- optimized phase advance between sextupoles;
- low beam invariants to minimize background;
- straight sections optimized for injection efficiency and dynamic aperture.

The lattice for the KLOE operation in IR1 will have the same characteristics, but the low-β in IR2 will be removed, thus lowering the ring chromaticity and allowing for a larger beam separation in IR2 during collision in IR1.

7. PRESENT STATUS (OCT. 2003)

The hardware installation was completed beginning of July. Some bugs were fixed from old and new hardware and by mid-July the beams performed the first turns in the rings. Unfortunately the run was stopped because of a severe water shortage in the Lab (the spring dried out due to an unexpected summer heat wave). The operation could resume only at the end of August with an increased water flow barely enough to run. The rings have been commissioned with the new layout and optics, the beam pipe has been conditioned to decrease the vacuum from initial 10^{-5} to operational 10^{-9} (dynamic), the coupling has been corrected from initial 50% to 1% for both beams. Orbits have been corrected by minimizing corrector strengths and 1.3 A of electrons, 0.6 A of positrons have been stored, ready for collisions in IR2.

8. 2004 PERSPECTIVES AND PLANS

During 2004 operation we expect to routinely perform 100-110 bunches collisions operation, the goal being to reach asymptotically in 2 year beam currents of the order of 2 A/beam.

A single bunch luminosity of 2×10^{30} cm^{-2} s^{-1} at 20 mA, with the present Working Point (WP), seems feasible if we linearly extrapolate the obtained results. The expected performances based on extrapolations of 2002 results and taking into account all the hardware improvements and the new low-β IRs are summarized in Table 3.

Table 3: Expected 2004 performances

N_b/beam	100-110
I_{tot}/beam e^-/e^+ (A)	2.
L_{sb} ($cm^{-2}s^{-1}$)	$2.x10^{30}$
Max L_{int}/day (pb^{-1})	10.
Lifetime (h)	>1
L_{int}/year (fb^{-1})	2.

Studies to further improve the specific luminosity by minimizing the beam blow-up due to beam-beam effects are in progress. The DAΦNE fractional tunes used during 2002 operation are (0.11,0.15) for the electron beam and (0.15,0.21) for the positron one. Beam-beam simulations predicted for this WP a single beam luminosity of 2×10^{30} cm^{-2} s^{-1}, which was nearly achieved. Following the experience of KEK-B and PEP-II B-Factories we plan to explore different WPs much closer to the integer or half-integer, where the predictions show almost no-blow-up.

The single bunch luminosity in the (ν_x, ν_y) plan, as computed by the beam-beam simulation code, is plotted in Fig. 10. Yellow areas are those with higher luminosity.

The reduction of the bunch length from 20 mm down to 15 mm, by changing sign to the momentum compaction [7], as already tested at KEK-B, has also been proposed, thus allowing for further lowering β_y* and increasing luminosity, possibly by a factor 2. Tests will be performed in DAΦNE with a modified lattice.

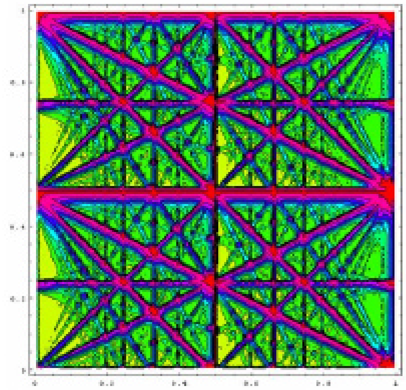

Fig. 10: Single bunch luminosity in the (ν_x, ν_y) plan.

For all these points it is essential to reach the predicted dynamic aperture that is strongly affected by the non-linearities in the near-integer tune space. Moreover in a non blow-up regime, the lifetimes are consequently smaller (Touschek limited). If the machine can operate in such areas, a further factor of 2 is predicted by the tracking codes.

We do not expect such order of magnitude of improvements, but we do have clear theoretical and experimental indications (PEP-II & KEK-B) that this could be a very promising approach to higher luminosities.

9. FUTURE PLANS

Currently under study are two options for the future of DAΦNE beyond 2006, with major modifications needed:

- to increase the maximum center of mass energy from 1.4 GeV to > 2.2GeV;
- to increase the luminosity by a factor >100 with respect to the years 2002-2005 best performances, possibly in the 10^{34}-10^{35} cm^{-2} s^{-1} range.

A joint Physics & Accelerator Workshop was held in Alghero (Sardinia, Italy) last September to study both the machine feasibility and the physics case [8].

The solution studied so far for the first option requires:

- to replace the ring main bends;
- to replace the permanent quadrupoles in the IRs;
- to upgrade the Linac energy for on-energy injection, this feature being highly desirable.

The overall ring lattice in this design can be mostly maintained as it is at present.

For the very high luminosity option the most promising solution studied so far requires:

- to rebuild the Main Rings (all magnets and vacuum chamber);

- to keep only one IR;
- to study a new approach (strong RF focusing) to get very short bunches at the IP [9];
- to rebuild the RF System (for example like the SC KEK-B one) to fulfill the requirements of the new scheme.

Both options are under study at present. It is still matter of discussion if the two designs are compatible or not.

10. CONCLUSIONS

For a check of the real machine improvement coming from the hardware upgrades and lattice modifications the next months will be essential.

At the moment it seems possible to complete all the physics goals initially proposed for the three experiments KLOE, FINUDA and DEAR by 2006.

A "Second Generation" Factory looks very interesting from machine and physics point of view, its feasibility being presently under study.

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