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Design and Status of DAΦNE: the Frascati Φ-Factory

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ABSTRACT

The status of the e^+e^- Φ-factory DAΦNE, now under construction at LNF, and the main accelerator physics and technology issues are discussed.

1. INTRODUCTION

The Φ-Factory project at Frascati National Laboratories (LNF) was approved and funded in 1990 and the detailed engineering design started in 1991. The construction of machine and experiments is proceeding steadily. The accelerator complex consists of a symmetric 510 MeV e^+e^- Two-Ring Collider, intersecting in two 10 m long Interaction Regions, where the beams are brought to collision at a horizontal angle; a full energy Linac and an Accumulator-Damping Ring for "topping-up" injection. The complex occupies the already existing LNF buildings where the long-lived ADONE was housed. One of the two IRs will accommodate the detector KLOE [1], designed mainly to study CP violation in neutral K decays. The other one is assigned to a smaller detector FINUDA [2], designed to study Λ-hypernuclei formation and decay. A third, compact experiment, DEAR [3], for exotic atom research, will be installed during commissioning and will run at an early stage of the machine. The beginning of the collider commissioning, with a short term luminosity goal $L \approx 1.3\ 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$, with 30 bunches, is scheduled for the end of 1996. The start of experimental program is planned for mid 1997.

2. LUMINOSITY STRATEGY

To measure the ratio of the CP violating parameter ε'/ε down to 10^{-4}, a luminosity $L = 5\ 10^{32}\ \mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ integrated over an effective year of 10^7 seconds is required.

To get such a luminosity DAΦNE is designed as a high current double ring system with a high number of bunches.

The maximum single bunch luminosity L_o is determined by the beam-beam interaction, whose effect is described by the beam-beam linear tune shift parameter ξ:

$$\xi_{x,y} = \frac{r_e\ N\ \beta_{x,y}}{2\pi\ \gamma\ \sigma_{x,y}\ (\sigma_x + \sigma_y)}$$

with r_e the classical electron radius, $\beta_{x,y}$ the betatron functions at the IP, and γ the particle energy in units of rest mass. There is experimental evidence of a limit on the maximum value that ξ can reach, beyond which the beam-beam effect is so strong that instability and beam blow-up occur so that lifetime and luminosity are substantially reduced.

Maximum luminosity can be reached with maximum and equal tune shifts in both planes ($\xi = \xi_x = \xi_y$). This condition is obtained when the ratio κ between beam emittances (ε_x, ε_y) is equal to the ratio of beam rms sizes at the IP. With $\varepsilon = \varepsilon_x + \varepsilon_y$, we can express the luminosity in terms of ξ :

$$L = h\, L_o = h\, f_{rev} \frac{\pi \gamma^2 \xi^2}{r_e^2\, \beta_y}\, \varepsilon\, (1 + \kappa)$$

The ξ value assumed for DAΦNE is obtained by a world average over most $e^+ e^-$ colliders: $\xi = .04$.

To gain the factor h in the luminosity, without a reduction of the maximum tune shift, the bunches have to be kept separated out of the interaction point, and this is the reason for the choice of two rings collider, so allowing multibunch operation (h=1,30,60,120). The multibunch instabilities, rising because of the high total current, are cured by specially designed feedback systems and new RF cavity design with strong suppression of High Order Modes (HOM). To avoid parasitic crossings the beams will cross in the horizontal plane at a small, tunable, angle θ_x ($\pm 10 \div \pm 15$ mrad).

A very small value of β_y at the IP has strong impact on the whole ring lattice design, leading to a high vertical chromaticity. Moreover due to the parabolic increase of β around the IP, the transverse size increases along the bunch length and to keep the advantage of having small dimensions at the IP, the bunch length σ_z must be shorter or at most of the same order of β_y, otherwise geometric reduction of the luminosity occurs. According to these considerations we have chosen $\beta_y = 4.5$ cm and $\sigma_z = 3$ cm.

A very flat beam scheme ($\kappa = \varepsilon_y / \varepsilon_x = 1\%$) has been adopted, with strong focusing only in the vertical plane. For flat beams the horizontal crossing angle θ_x, due to the design values of horizontal and longitudinal rms beam sizes at the IP, should not excite synchro-betatron resonances, which may limit the maximum achievable tune shift.

Large emittance is beneficial to luminosity in case of tune shift limited colliders, like Φ–factories, where wigglers are present to increase the emittance and to contribute additional damping, since beam-beam interaction experience suggests that the tune shift limit increases with the amount of radiated power. A relatively large value was chosen for DAΦNE: $\varepsilon = 10^{-6}$ m rad.

For the single bunch luminosity a value of $\approx 4.3\ 10^{30}$ cm^{-2} sec^{-1} has been assumed, comparable to that achieved in VEPP-2M [4].

In Table 1 the parameters relevant to the luminosity are summarised.

TABLE 1. DAΦNE Luminosity Parameters

E (MeV)	510.	θ_x (mrad)	10÷15
L_o (cm^{-2}s^{-1})	4.3 10^{30}	κ	.01
ξ	.04	σ_z (m)	.03
ε^{max}(m rad)	10^{-6}	h^{max}	120
f_o (MHz)	3.17	β_y^* (m)	.045

3. THE ACCELERATOR COMPLEX

The accelerator complex layout is shown in Fig. 1. It consists of:

- $e^+ e^-$ LINAC;
- $e^+ e^-$ Damping Ring;
- twin ring collider.

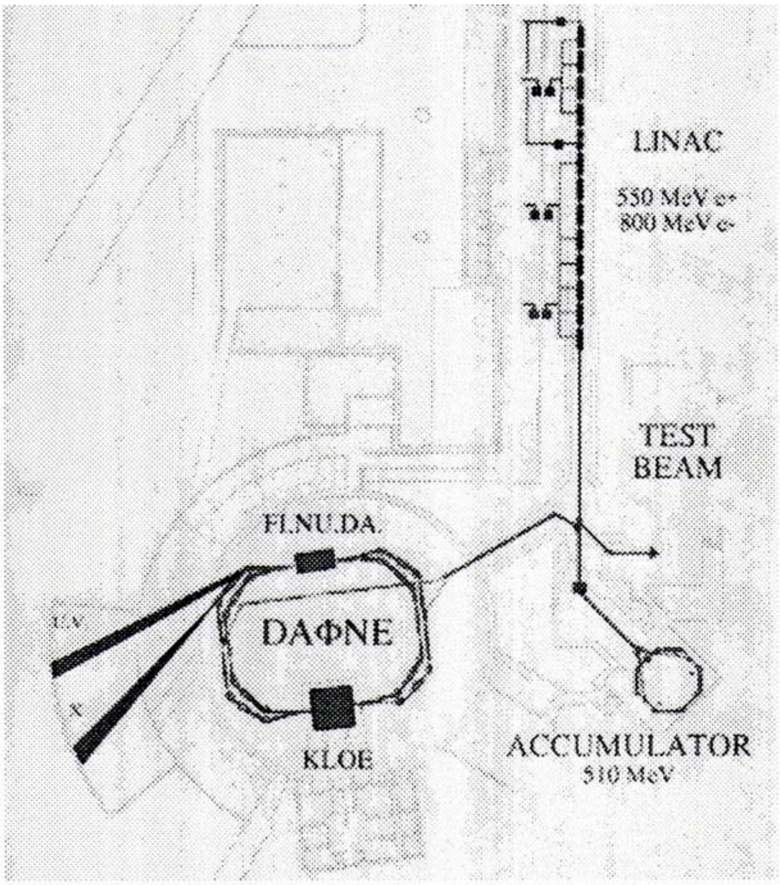

FIGURE 1. Layout of DAΦNE and its injector

3.1 Linac and Damping Ring

The LINAC [5], manufactured by TITAN BETA, is capable of accelerating electrons up to 800 MeV at 50 pps. In the positron mode of operation the first part of the LINAC (from the gun to the positron converter) is used to accelerate a 4 A-10 ns electron pulse at 250 MeV. The LINAC has been installed at LNF in September '95, and in November the first electron beam was accelerated to the end. Positron production is foreseen for Spring '96.

The Damping Ring, manufactured by OXFORD, has a compact 4 period structure, with a total length 1/3 of each ring and will be used to store at 50 pps the required number of electrons (positrons) in one RF bucket and to damp the transverse and longitudinal emittance of the LINAC beam. The damped beam is extracted at ~ 1 pps and injected into a single bucket in the main rings. It has been installed in Autumn '95, and commissioning is foreseen for May '96.

3.2 Main Rings

The Main Rings salient features are:

- electrons and positrons circulate in two separate storage rings and collide at a horizontal half-angle $\theta_x = 10 \div 15$ mrad, depending on the number of bunches, in order to minimise the effect of parasitic crossings. The crossing angle can be changed by powering a small (±20 mrad) dipole, located after the splitter magnet that separates the trajectories of the two beams;

- the beams will collide in two 10 m long Interaction Regions (IR), where the detector solenoids will be installed. The correction of the coupling introduced by the detector solenoidal fields is performed in each IR by two 1.5 T, 1.15 m, compensating solenoids, plus a tilt of the low-β quadrupoles, increasing outward from the IP [6]. The small residual coupling will be corrected by means of 8 weak skew quadrupoles per ring, located in the arcs;
- the lattice is a 4-period modified Chasman-Green type, with a 2 meters-1.8 Tesla normal conducting wiggler magnet inside each achromat. This choice allows ample emittance tunability, without changing the wiggler magnetic field, and it gives, at the same time, strong radiation damping which is one of the fundamental properties that lead to high luminosity. The magnetic structure design has built-in enough flexibility to tune other lattice parameters such as momentum compaction, beta at the interaction point, etc. Moreover a wide range of betatron tunes is achievable by just varying the quadrupole settings;
- the straight sections orthogonal to the IRs are used for injection, RF, feedbacks and horizontal and vertical scrapers for reducing the lost particles background inside the detectors.

A sketch of the two rings lattice is shown in Fig. 2. The single ring parameters are summarised in Table 2.

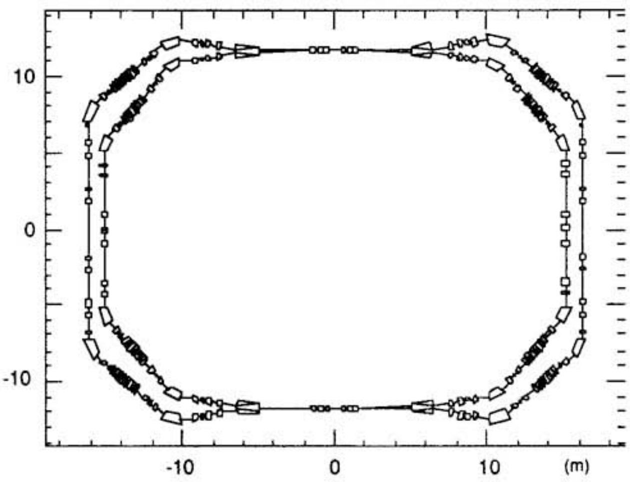

FIGURE 2. Magnetic layout of the main ring

TABLE 2. DAΦNE Single Ring Parameters

Energy (MeV)	510.
Luminosity [$cm^{-2} s^{-1}$]	$5.\times10^{32}$
Trajectory length [m]	97.69
Emittance, $\varepsilon_x, \varepsilon_y$ [mm·mrad]	1, 0.01
Beta function at IP, β_x^*, β_y^* [m]	4.5, .045
Beam dimension at IP, σ_x^*, σ_y^* [mm]	2, .02
RF frequency, f_{RF} [MHz]	368.25
Max. number of bunches, h_{RF}	120
Minimum bunch separation [ns]	2.7
Bunch average current [mA]	44.
RF voltage [kV]	250.
Bunch length σ_z [cm]	3.
Synchrotron radiation loss [keV/turn]	9.3
Damping time, τ_ε, τ_x [ms]	18., 36.
N^{max} /bunch	$8.9\ 10^{10}$

A careful study of the betatron tune working point has been performed, with the help of a beam-beam simulation code [7]. A choice of two candidates, both with equal vertical betatron phase advance between the two IPs, has been performed: $\nu_x = 5.09$, $\nu_y = 6.07$ and $\nu_x = 4.53$, $\nu_y = 6.06$. For these two sets the luminosity reaches respectively 95% and 98% of the nominal value. Figure 3 shows the contour plot of the relative luminosity L/L_0 for the first working point (above the integer), as a function of the horizontal and vertical tunes. The darker islands represent peaks in L/L_0. For the second one a lattice with equal horizontal phase advance, between the IPs, has also been computed.

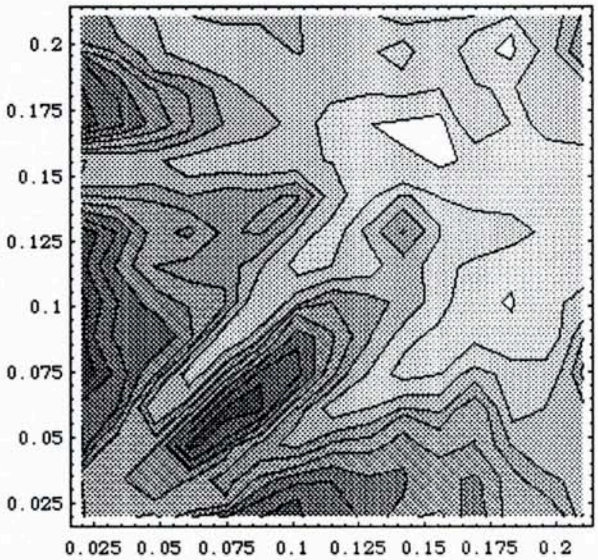

FIGURE 3. Relative Luminosity Contour Plot (scan) for working point 5.09,6.07

The installation of the main rings has began in February '96 and its completion is foreseen for December '96. The commissioning will start in early '97.

4. VACUUM SYSTEM

The DAΦNE vacuum system [8] is dimensioned for an operating pressure of ~ 1 nTorr with ~ 5 A of circulating current. A design, similar to ALS, has been adopted for the vacuum vessel inside the achromat, consisting of two chambers connected through a narrow slot. The beam circulates in the first chamber, while the synchrotron radiation photons hit a system of copper absorbers located in the second one (antechamber) in such a way that more than 95% of the photon flux is intercepted in the antechamber.

The achromat vessel (~ 10 m long) is made by two halves of Al alloy 5083-H321 plates, which, after machining, are welded along the middle plane. The total weight of each chamber is ~ 1.5 ton. The inner surface is mirror finished (roughness = 0.2 Ra). Figure 4 shows one half of the arc vacuum vessel, fully machined.

Water cooled copper absorbers of the synchrotron radiation produced in the wigglers and dipoles are used. The value of the desorption coefficient adopted in the calculations is $\eta_e \leq 3\ 10^{-6}$ (molec/photon), as measured at NSLS-BNL, in an experimental set-up similar to the DAΦNE vacuum chamber. In addition to sputter ion pumps, used all along the ring to pump down CH_4 and noble gases, Ti sublimators are located in the vacuum antechamber of the arc sections, right close to the copper absorbers and above the ion pumps, to achieve the required pumping speed.

The total pumping speed installed in each storage ring is ~ 125000 l/s.

The four arc Al vacuum vessels for the positron ring have been already assembled and delivered at LNF, the electron ring ones will be delivered this Summer.

In order to avoid the effects on the electron beam due to the residual gas ionisation, the Ion Trapping effect, a system of DC ion clearing electrodes has been designed.

About 40 DC ion clearing electrodes have been located along the electron ring in the minima of the potential well due to the electron beam [9]. The mirror effect determined by the dipole fringe field of the bending sections has been also considered [10]. Each electrode is made of an alumina body (0.6 mm tick) coated with a ≈30 μ resistive layer ($R_{square} \approx 100$ kΩ) [11]. The resistive coating is made of a glass-metallic compound paste (Resistor Series R 8900-Heraeus).

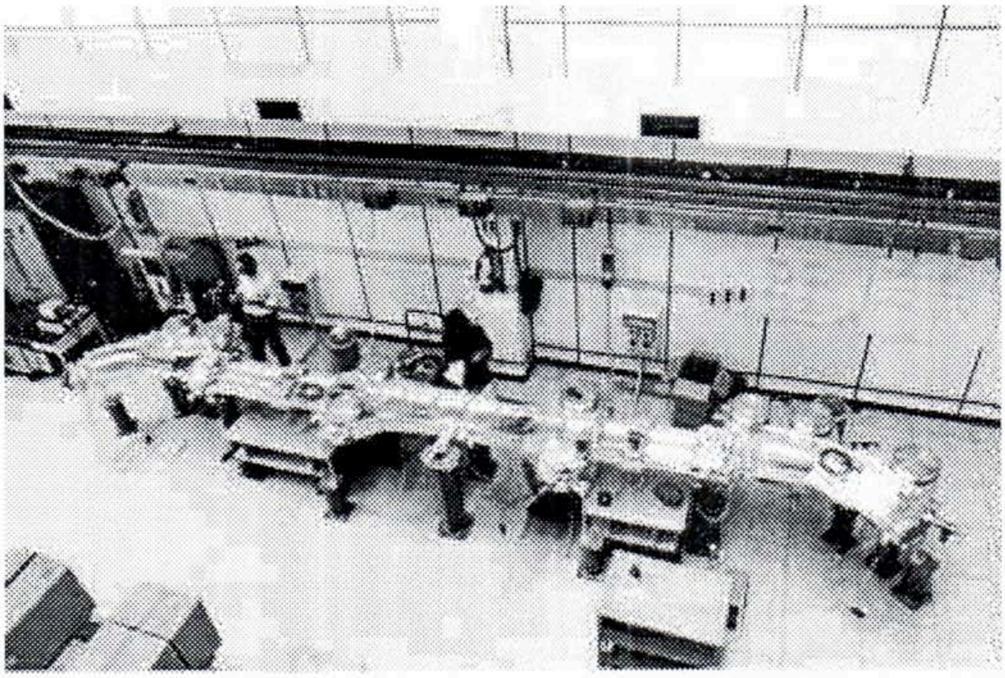

FIGURE 4. Arc Al vacuum vessel

5. RF SYSTEM

Because of the large current and large number of bunches, the reduction of the beam-cavity spectra interaction is the most demanding feature of the RF system.

The RF system of each ring consists of a normal conducting single cell cavity, fed by a 150 kW/cw klystron developed by Thomson. The klystron is protected against the reflected cavity power by a ferrite circulator. The central body (see Fig. 5) is obtained from a single forged OFHC copper billet and the internal surface is fully manufactured with an automatic milling machine.

The cavity design aimed at reducing significantly the impedance of the HOM [12] by a proper shape of the resonator and, more effectively, by coupling off the HOM electromagnetic fields with long tapered beam tubes and three wave guides (WG), which couple out the parasitic modes that are then dissipated into external 50 Ω loads. Low power tests, performed on a copper cavity prototype, have shown that a considerable reduction of the HOM Qs over a 2 GHz bandwidth is achieved. The WGs, also made of OFHC copper, have been power tested successfully on bench under vacuum. The 7/8" coaxial output port is a wide band 50 Ω ceramic window designed at LNF.

The first main ring cavity has already been shipped and measured at LNF.

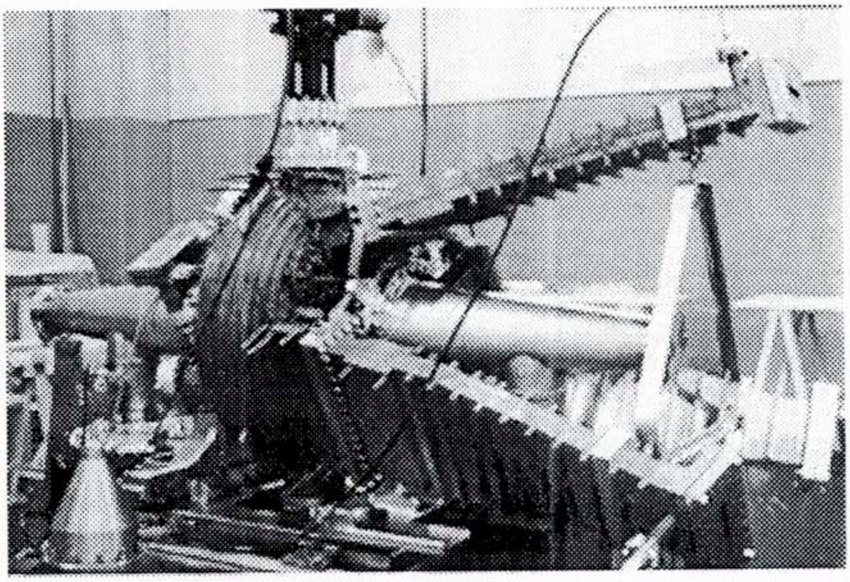

FIGURE 5. RF cavity

6. LONGITUDINAL FEEDBACK SYSTEM

Longitudinal multibunch instabilities may limit the current intensity achievable in DAΦNE, even though the HOM's in the accelerating cavities are heavily damped. We are working on a powerful active feedback system, capable of damping all the coupled modes and injection transients with a damping rate at least two orders of magnitude larger than the natural damping.

From the results of a preliminary study we are convinced that a longitudinal feedback system largely based on analog/digital techniques is feasible and works well. The system under development at DAΦNE is a bunch by bunch, time-domain feedback capable of a damping time of ~ 0.1 ms. It is sized for 30 bunches and upgradable to a full complement of 120 bunches, thanks to its modular architecture. A wide bandwidth power amplifier of ~ 500 W is enough to damp an initial offset of 100 ps of one bunch at injection, with the other 29 bunches at the full design current. A prototype system with a single-board digital section has been running at ALS [13]. The complete modular system has been installed in July '95 in ALS and went into operation smoothly, providing damping of all coupled modes at the design current of 400 mA.

The maximum power at the longitudinal feedback kicker is determined by the voltage gain needed to achieve the required damping rate and the maximum synchrotron phase error allowed during injection. Due to difficulties in building and tuning a stripline kicker we have designed at LNF a RF kicker with a resonant frequency of 1.2 GHz, (3.25 times the main RF frequency) [14]. Figure 6 shows a cutaway view of the cavity. The 88 mm diameter beam tube opens into a 200 mm diameter, 72 mm long, pill-box cavity. To obtain the very large bandwidth required (~180 MHz at least, for 120 bunches operation), the cavity is loaded by 6 ridged wave guides followed by broadband transitions to 7/8" standard coax, very similar to those in the main RF cavity, except that in this case the coupling is extended to the fundamental mode. The 6 WGs are placed symmetrically with respect to the accelerating mode. Three WGs are used as input ports and the other three as termination loads. In this way, thanks to the symmetry, the system is perfectly matched.

Being broadband, the kicker cavity does not need to be tuned in operation, nor cooled, since almost all the power is dissipated in the external loads. Moreover, the damping wave guides couple out the HOMs as well.

Not being the kicker cavity a directional device like the stripline kicker, it extracts power from the beam. Ferrite circulators are then necessary to isolate the output section of the power amplifier feeding the cavity.

A peak shunt impedance of 750 Ω, together with a bandwidth larger than 220 MHz, have been calculated with 3D simulations with the HFSS code by HP. Measurements on a prototype have been performed at LNF and show a fair agreement with calculations.

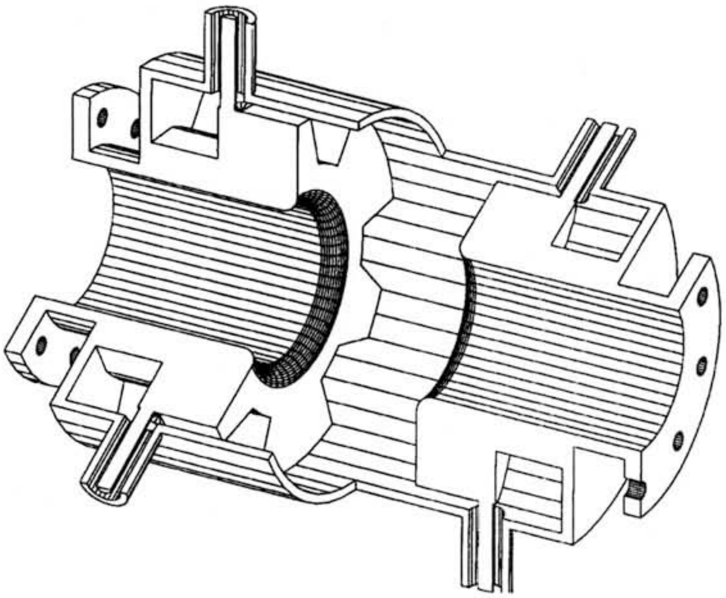

FIGURE 6. View of the overdamped kicker cavity

7. INTERACTION REGION DESIGN

Four different IRs have been designed: DAY-ONE (2 IRs, for commissioning phase), DEAR, KLOE and FINUDA IRs. They differ for the number, type and dimension of quadrupoles, and for the presence or not of a detector solenoid. In Table 3 their main features are reported.

TABLE 3. Interaction Region Summary

Name (#)	# Quads	Type	Solenoid
DAY-ONE (2)	7 (14)	Normal	NO
DEAR (1)	6	Normal	NO
KLOE (1)	6	Permanent Magnet	YES
FINUDA (1)	8	4 PM + 4 Normal	YES

The design of the DAY-ONE IR is completed, included the design of the supporting structures, different in the two IRs since the holes which will house the detectors have different depths in the two IPs. Six out of the 14 quadrupoles were already shipped and measured at LNF. The other 8 have been ordered to Ansaldo.

The DEAR IR is the same as the DAY-ONE, except for the quadrupole sitting on the IP which will be removed and for the quadrupole strengths. A special vacuum chamber will be designed for the experiment.

For the FINUDA IR four, small permanent magnet quadrupoles have been already ordered to Aster Enterprises (U.S.A.) and the other four are similar to the DAY-ONE ones, ordered to Ansaldo. The supporting device is presently under study.

The IR occupied by the KLOE detector is in a more advanced status [15]. The low-β quadrupole triplets, of permanent type, are 46 cm far from the IP and are confined in a cone of 9° half aperture, leaving a material-free solid angle for the apparatus of ~ 99%. The first 2 quadrupoles of the triplets have already been built by Aster Enterprises and the measured field quality exceed our specifications. It is a requirement of the experiment to have a large (radius ~ 10 cm) aperture vacuum chamber at the IP as transparent as possible to the produced particles. The outer parts of the IR vacuum chamber are made of stainless steel with a copper coating inside to reduce the ohmic losses.The inner section, bulb-shaped at the IP, is made of 0.5 mm thick pure beryllium, directly brazed onto the stainless steel pipe. Inside the spherical part of the chamber a 50 micron beryllium shield provides a continuous profile to the vacuum chamber to reduce RF losses. Water pipes, brazed as close as possible to the IP, provide the cooling needed to compensate for the thermal load on the vacuum chamber. The supporting system consists of two independent structures: the detector support and the triplet assembly support, to allow relative freedom of mechanical alignment of the permanent magnet quadrupoles without affecting the detector. The detector supporting structure holds also the vacuum chamber. The pumping system, which has to be able to reach a mean pressure of about $5 \cdot 10^{-10}$ Torr at full beam current after 2 or 3 months of conditioning, is a combination of lumped sputter ion pumps, distributed sputter ion pumps and non evaporable getter pumps. There are no pumps inside the detector near the IP.

The four compensating solenoids which will be used in the KLOE and FINUDA operation, built by Oxford, have already been shipped and measured at LNF. Their characteristics fulfill our specifications.

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