DAΦNE Interaction Region Design

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Abstract

The strategy adopted in designing the DAΦNE Interaction Regions is presented, and the basic theory for the novel compensation scheme of the high field detector solenoid is discussed. A preliminary mechanical design is also illustrated.

I. INTRODUCTION

DAΦNE, the Frascati Φ factory [1], is a double ring collider with a maximum number of 120 stored bunches. In order to avoid parasitic crossings near the Interaction Point (IP), the beams cross at a horizontal angle of 25 mrad, whose harmful effects are overcome by a large horizontal beam size at the IP. To achieve the target luminosity, $L = 5 \times 10^{32} cm^{-2} s^{-1}$, the betatron coupling should not exceed 1%. In the following we call Interaction Region (IR) the part of DAΦNE shared by the two rings, which corresponds to a total length of 10.1 m. In the IR the two beams follow separate trajectories and they pass off axis in all the magnetic elements crossing only at the IP.

One IR is dedicated to the KLOE [2] experiment, and the other one to FI.NU.DA. [3]. Three different IR lattices have been designed: two for the experiments and one for commissioning. The latter consists of two conventional quadrupole triplets. The total IR first order transport matrix is the same for the three designs, thus allowing to interchange the three IRs with minor changes in the regular ring lattice. FI.NU.DA., an experiment to study Hypernuclei, K-nucleon and K-nucleus at very low energy, has been approved lately and its design is still in a very preliminary stage. We will describe in the following the KLOE IR. The KLOE detector is designed primarily to detect direct CP violation in K^0 decays. Its main features are: a cylindrical structure surrounding the beam pipe consisting of a vertex chamber, a large tracking device, an electromagnetic calorimeter and a solenoidal magnet, in order of increasing radius, as shown in Fig. 1.

The magnetic field, 0.6Tx4.32m, has a strong effect on the beam, due to the relatively low energy of DAΦNE (0.51 GeV). Since a very large solid angle is required, the machine components must be installed within a cone of 9° maximum half-aperture. The small vertical β value at the IP is obtained with a permanent magnet quadrupole triplet on each side. A sophisticated compensation scheme, including the rotation of the low-β quadrupoles, has been adopted to locally decouple horizontal and vertical betatron motions.

II. ROTATING FRAME METHOD

The main effect of a solenoidal magnetic field is to focus and to couple the horizontal and vertical betatron phase spaces. In the following we refer to the 4-dimensional (x, x', y, y') phase space. To decouple the transverse planes the skew quadrupole method [4] needs 4 skew quadrupoles. In fact 4 is the difference between the 10 degrees of freedom of a general coupled 4x4 simplectic matrix and the 6 of an uncoupled block diagonal one. In our case, to decouple the normal modes at the IP, both the matrices corresponding to half IR before and after the IP must be block diagonal, so that 8 skew quadrupoles should be necessary.

The Rotating Frame Method (RFM) [5] in principle block diagonalizes a matrix with only 2 independent parameters. This scheme cannot be exactly applied when the quadrupoles are immersed in the detector longitudinal field as it is in DAΦNE. Nevertheless, the residual coupling can be corrected by adopting a generalization of the Guignard scheme.

A uniform solenoid, with a longitudinal field B_z, can be identified, from the optical point of view, by its length l_s and its normalized gradient k_z:

$$k_z = \frac{B_z}{2\, B\rho} \quad .$$

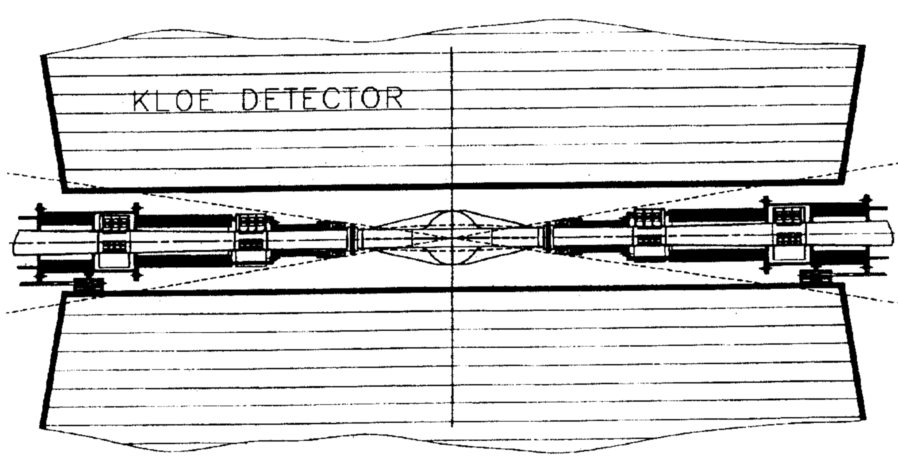

Figure 1. KLOE Interaction Region.

Its transport matrix P_S can be expressed [5] as the product of a rotational and a focusing part:

$$P_S = R(\theta_r) \cdot F(\theta_r)$$

where $\theta_r = k_Z\, l_S$.

The R matrix rotates the transverse plane around the longitudinal direction by an angle θ_r:

$$R = \begin{pmatrix} I \cos \theta_r & I \sin \theta_r \\ -I \sin \theta_r & I \cos \theta_r \end{pmatrix}$$

where I is the 2x2 identity matrix. This rotation couples the radial and vertical phase spaces. F is a diagonal block matrix:

$$F = \begin{pmatrix} A & 0 \\ 0 & A \end{pmatrix}$$

being A the 2x2 matrix:

$$A = \begin{pmatrix} \cos \theta_r & \frac{1}{k_Z} \sin \theta_r \\ -k_Z \sin \theta_r & \cos \theta_r \end{pmatrix}$$

Given the block diagonality of F, FR = RF. The F matrix focuses both transverse motions. So, once fixed θ_r, the focusing action of a solenoid strongly depends on its length.

In the following we limit our considerations to one half of the KLOE IR. The rules of the RFM are two:

1) The total rotating angle must vanish:

$$\int_{IR} B_Z\, ds = 0$$

A compensator solenoid at the end of the IR, with an angle θ_r opposite to the half detector one, satisfies this condition.

2) Each quadrupole must be rotated exactly by the angle:

$$\theta(z) = \int k_Z\, dz$$

where the integral is calculated from the IP to its longitudinal position. This means that each quadrupole should be rotated as an helix, which cannot be easily accomplished. Practically the best one can do is to rotate each quadrupole by the angle corresponding to its longitudinal midpoint.

In order to compute the matrix belonging to quadrupoles immersed in a longitudinal field, each quadrupole is represented as a large number of equally spaced thin lenses, interleaved with small uniform solenoids. The resulting IR matrix exhibits, as expected, a small residual coupling which must be corrected, the design coupling being very small. In order to perfectly diagonalize our system we need 4 more parameters: we choose three independent supplementary rotations, $\delta\theta_i$ (i = 1,2,3), of the three quadrupoles, plus a correction $\delta\theta_C$ of the compensator field. The quadrupole rotations θ_i, the rotation inside the compensator and their respective small corrections are shown in Table I. The angle associated to the KLOE field is assumed to be positive.

Table I - IR element rotations

Elements	θ	$\delta\theta$
Q1	+5.66°	+0.31°
Q2	+10.15°	+0.02°
Q3	+14.80°	+0.27°
Compensator	-21.84°	+0.12°

Finally, the complete IR layout, proceeding from the left to the right side of KLOE, is as follows:

- a compensator rotating the phase plane by $\theta_C+\delta\theta_C$,
- three quadrupoles rotated by $-(\theta_i+\delta\theta_i)$,
- the IP,
- three quadrupoles with $\theta_i+\delta\theta_i$,
- a compensator with $\theta_C+\delta\theta_C$.

Superimposed is the KLOE solenoidal field which rotates the normal modes by $-2\theta_C$.

The optical functions and the horizontal and vertical beam trajectories in half IR are plotted in Fig. 2. The optical functions are computed in a frame following the rotation or the normal betatron modes.

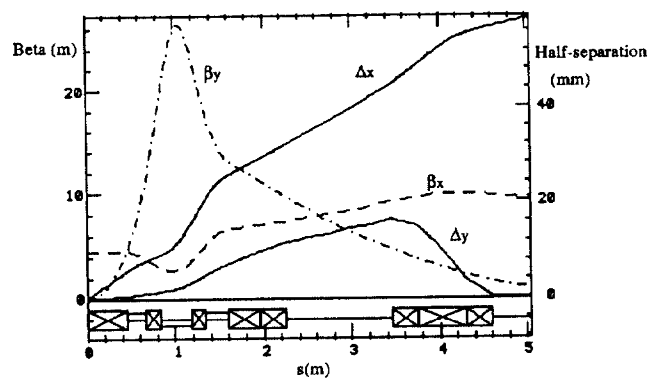

Figure 2. Optical functions and beam trajectory in KLOE IR.

III. LINEARITY STUDIES

In order to study the linearity of our scheme, taking into account that relatively low energy beams pass off axis in the magnetic elements, a naïf method has been applied to a preliminary design of the compensator solenoid field [6]. In our IR's lattice design the solenoidal field on the axis is approximated by uniform field slices. In this model the transverse field thin lenses are linear, and the longitudinal field does not depend locally on the distance from the solenoid axis. Therefore the total matrix does not depend on the initial conditions, which is of course an approximation. An analytical formula for the field $B_Z(0,z)$ on the solenoid axis has been obtained by fitting the numerically computed field. Given the field $B_Z(0,z)$, in cylindrical symmetry, the field in the region delimited by the iron and the magnet coils can be calculated from the expansion [7]:

$$B_z(r,z) = \sum_{0}^{\infty} n\,(-1)^n \frac{B^{[2n]}(0,z)}{(n!)^2}$$

$$B_r(r,z) = \sum_{1}^{\infty} n\,(-1)^n \left(\frac{r}{2}\right)^{2n-1} \frac{n\,B^{[2n-1]}(0,z)}{(n!)^2}$$

where $B^{[2n]}(0,z)$ is the 2n-th order derivative of $B_z(0,z)$. Derivatives up to the fifth order have been retained. These expressions have been used to track large amplitude particles by simply integrating the Lorentz force equations. Fig. 3 shows, as an example, the vertical angle of the trajectory as a function of the initial horizontal position. We have verified that the system is linear up to ≈10 cm from the beam axis, providing a good safety margin for the divergent trajectories of electrons and positrons in the IR. For our design values, the obtained trajectories agree very well with the results of tracking through uniform field slices, so we are confident that the method used in the calculation of the optical effects in the IR is correct.

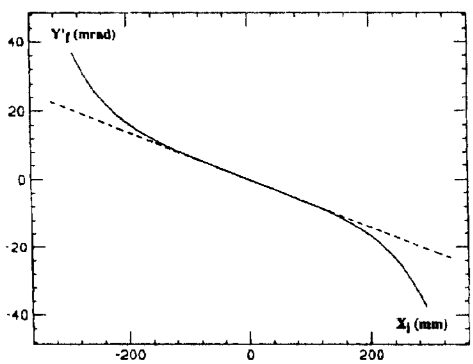

Figure 3. Vertical trajectory slope vs. horizontal initial position.

V. MECHANICAL DESIGN

The IR beam pipe is about 0.7 m long and the cross-section diameter ranges from 68 mm to 200 mm in the interaction region; 0.5 mm thick pure beryllium has been chosen to provide a very good transparency, in terms of radiation lengths, and scattering angle. The use of beryllium is the "crucial part" of the design as preventive maintenance has to be minimized as well as the risks during weldings, brazings or handlings of components close to the IR beam pipe. An inner, very thin, beryllium strip shields the outer chamber to prevent the rf power losses which can lead to huge thermal loads. The inner strip is one-side brazed or simply free to minimize its thermal stresses. Two rigid copper end flanges brazed onto the beryllium tube should prevent the buckling and make handling of the chamber easier; at the same time the flanges may house two cooling rings (water or freon heat sinks) which keep the wall temperatures below a given limit.

An outer additional "inert gas" cooling must surround the chamber when the machine is running in order both to avoid contact with air and to cool the chamber in the case of possible overheating due to an accidental disruption of the inner rf shield. For this last reason a smoothly tapered outer shape of the beryllium chamber is preferred to a spherical one even if the buckling safety factor is much lower. The possible above mentioned overheatings are strongly dependent upon both the shape of the chamber and the beam parameters and can cover a potentially very wide range of power losses; such hard and uncertain working conditions must be carefully checked to assure the safety norms otherwise an alternative material for the outer chamber must be considered.

The inner 50 μm rf shield has a small outward curvature to prevent the synchrotron radiation to illuminate this very thin strip. A finite element analysis on the thin strip can not be easily carried out without experimental data as the commonly used failure criteria (as the maximum strain energy or the maximum shearing stress) lose their effectiveness when applied to beryllium foils; even if at a first sight the thermal stresses are small, a thermo-structural study as well as a thermal fatigue life expectancy must be carefully estimated in extreme working conditions before going on with the design. Because of the reasons herein described the design of the IR beam pipe is still in a preliminary stage.

The remaining part of the beam pipe is made of copper for its good thermal conductivity and is shielded by a multi-layer super-insulation material in order to protect the surrounding permanent magnets during baking and to make the latter easier.

The low-β triplet support barrel allows remote control of its degrees of freedom (vertical and horizontal positions and roll, pitch and yaw angles). It will be made of a rigid composite material in order both to minimize the amount of material inside the detector and to obtain an acceptable bending at its end; it will be simply supported in two points: one inside the detector, right on the end of the tracker cone, the other outside the detector near the compensator solenoid. This support must be split across its diameter or divided into three pieces to allow beam pipe and permanent magnets installation.

Each quadrupole is confined with two aluminium collars. The space between the ion pumps and the magnet ends allows TIG welding to close the vacuum chamber after the quadrupoles have been introduced around the pipe; of course this assembly requires great deal, and splitting of the permanent magnets into two parts is advisable in spite of the need for larger collars. The water cooled trim coils are mounted inside the inner collar of the permanent magnets and follows the rotation of the triplet support; the space at the ends of the coils needs a limited reduction in coil length resulting in lesser turning ability. Careful study on the size of the components and the assembly sequence must be carried out to fulfill proper alignment requirements; improvements on the design are still in progress.

VI. REFERENCES

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