ADVANCES IN THE DESIGN OF THE SuperB FINAL DOUBLET

E. Paoloni, N. Carmignani, F. Pilo, University of Pisa and INFN, Pisa, Italy
S. Bettoni, CERN, Geneva, Switzerland
P. Fabbricatore, S. Farinon, R. Musenich, INFN Genova, Italy
F. Bosi, INFN sezione di Pisa, Pisa, Italy
M.E. Biagini, P. Raimondi, INFN/LNF, Frascati (Roma), Italy
M. Sullivan, SLAC, Menlo Park, California, USA

Abstract

Super$B$ is an asymmetric energy e^+e^- collider operating at the $\Upsilon(4S)$ peak with a design peak luminosity of $10^{36}\,\mathrm{Hz/cm^2}$ to be built in Italy in the very near future. The design luminosity is almost a factor hundred higher than that of the present generation comparable facilities. To get the design luminosity a novel collision scheme, the so called "large Piwinski angle with crab waist", has been designed. The scheme requires a short focus final doublet to reduce the vertical beta function down to $\beta_y^\star = 0.2\,\mathrm{mm}$ at the interaction point (IP). The final doublet will be composed by a set of permanent and superconducting (SC) quadrupoles. The SC quadrupole doublets QD0/QF1 will be placed as close to the IP as possible. This layout is critical because the space available for the doublets is very small. An advanced design of the quadrupole has been developed, based on the so-called helical coil concept. The paper discusses the design concept, the construction and the results of test of a model of the superconducting quadrupole based on NbTi technology. Future developments are also presented.

INTRODUCTION

The Super$B$ [1] collider has been approved by the Italian Research Minister as part of the Italian National Research Plan, with a 5 years construction budget. It is an e^+e^- machine operating at the $\Upsilon(4S)$ peak composed by an High Energy Ring (HER) and a Low Energy Ring (LER) storing respectively positrons at 6.7 GeV and electrons at 4.18 GeV. The design peak luminosity of $10^{36}\,\mathrm{Hz/cm^2}$ is two order of magnitudes higher than the comparable present facilities and it is one of the key ingredients for the success of the challenging physics research program of the experiment. In the next sections the Interaction Region (IR) layout will be presented together with a possible magnetic design of the superconducting (SC) quadrupoles a prototype of which is at present in construction.

IR LAYOUT

The Super$B$ collision scheme requires a short focus final doublet to reduce the vertical beta function down to $\beta_y^\star = 0.2\,\mathrm{mm}$ at the IP. The final doublet (see Fig. 1) will be composed by a set of permanent samarium cobalt magnets (PM) and superconducting (SC) quadrupoles. In the present design the HER (LER in parentheses) PM quadrupoles provide an integrated gradient of 23.1 T (11.2 T) over a magnetic length of 11 cm (7cm). The front pole face will be placed at 38 cm (30 cm) from the IP. The remaining vertical focusing strength will be provided by two (one) SC quadrupoles having an integrated gradient of 39.2 T (28.7 T) over a total magnetic length of 45 cm (30 cm) . A cold bore design for the SC quadrupoles is not viable since the synchrotron radiation coming from the upstream dipoles will deposit $\sim 200W$ on the beam pipe section inside the SC. The requested horizontal beam stay clear fixes both the warm bore diameter to 24 mm and the maximum thickness allowed for the cryostat and the SC cold mass to 22 mm. The limited amount of available space together with the requested field purity and gradient strength pose very demanding constraints on the SC magnets design.

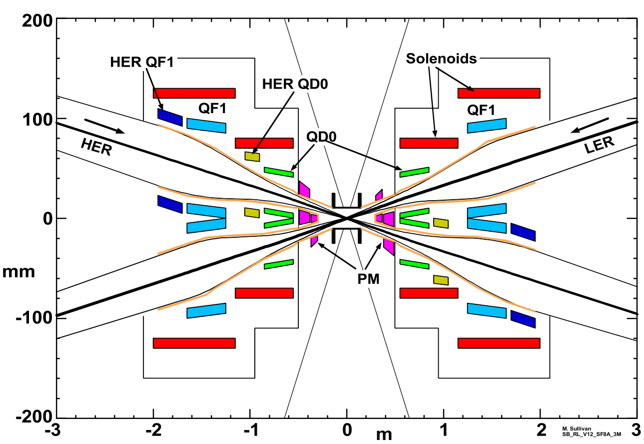

Figure 1: Top view of the IR layout. The PM and the cold masses of the SC magnets are represented together with the horizontal LER and HER beam stay clear.

DOUBLE HELIX QUADRUPOLE MODEL

The double helix magnet (DHM) design [2] is an attractive option for the QD0. DHM are composed by two concentric layers of solenoid coils whose helical turns are modulated to produce the desired field. The advantage of the solution is the small thickness of the cold mass and the possibility to produce arbitrary combination of multipolar fields, moreover the good field region extends very near the DHM conductors. The most critical aspect is related to the small temperature margin to quench of the QD0: the current needed to generate the design gradient of $0.96T/\,\mathrm{cm}$ over a mechanical aperture of $35\,\mathrm{mm}$ is ~ 2600 A, using a state of the art NbTi wire like the Luvata CMS one, the temperature margin to quench is expected to be only 1.5 K, hence the protection of the magnet and the development of a quench model is of the uttermost importance. In this respect an SC quadrupole model is presently under construction.

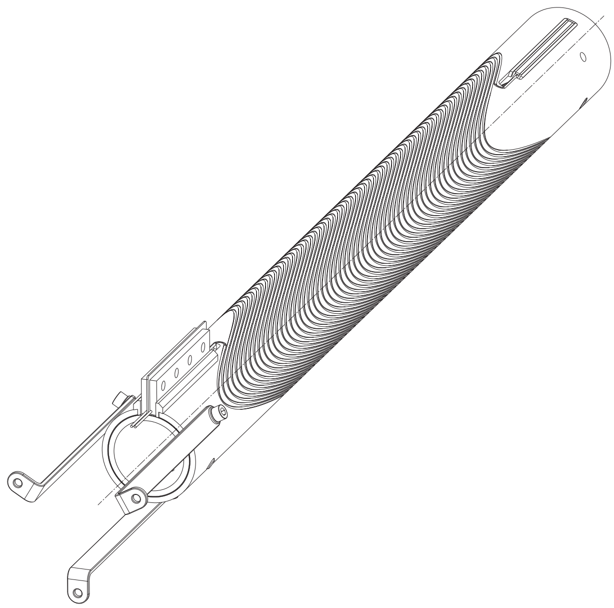

Figure 2: Assembly view of the SC quadrupole prototype. The current feeders and the mechanical fixture are on the bottom left side and the junction is on the top right side.

The quadrupole model (see Fig. 2 and Fig. 3) is composed by two aluminium alloy cylinders on whose surface helicoidal grooves are milled with a CNC milling machine to hold in place the SC wire. The two mechanical support are anodized for insulation purposes. The CMS NbTi wire (kindly gifted by Luvata) was insulated with a $0.125\,\mathrm{mm}$ polyester braid and will be deposed in the milled grooves. The model will be hopefully ready for tests by the end of this year. The main goal of the project is to determine the maximum achievable gradient, develop a thermal model of the transition to the normal conducting state and finally to measure at room temperature the purity of the generated field.

FIELD QUALITY OPTIMIZATION

The spurious harmonics of the QD0 must be kept at a minimum both to achieve the extremely small vertical beam size at the IP and to preserve the ring dynamical aperture that can be easily deteriorated by the spurious sextupolar component of the QD0 where the vertical β function reaches her maximum. The spurious harmonics are hard

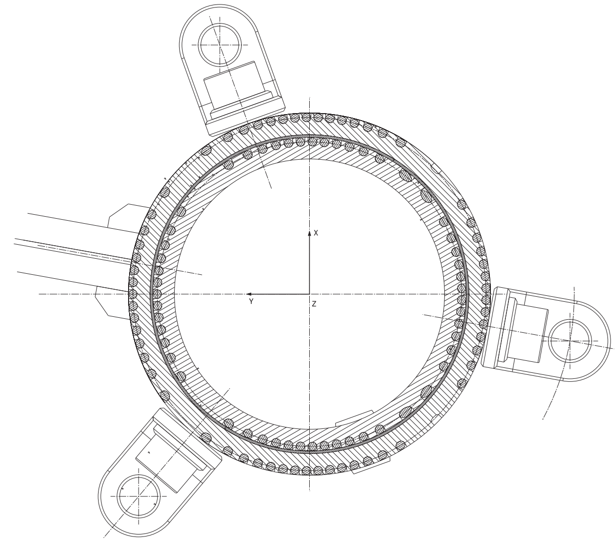

Figure 3: A typical cross section of the SC quadrupole prototype representing the two SC winding layers and the groove geometry.

to control since the distance of the axis of the LER QD0 from that of the HER QD0 is comparable with the radius of cold mass, hence cross talk effects are very far from being negligible, moreover the thickness of the cold mass cannot exceed a few millimeters, a novel compensation technique had been developed to solve this problem. In a previous work [3] the authors developed an algebraic algorithm to compensate the cross talk of two adjacent and parallel DHM by a proper modulation of the helical turns of the DHM. The algorithm cancel the spurious harmonics integrated over a straight line parallel to the mechanical axis of the cylinders, however the finite crossing angle at the IP spoils the result of the optimization since the nominal trajectories of the LER and of the HER cannot be both parallel to the mechanical axis of the two DHM. To overcome this problem a new algorithm had been developed. The integrated field harmonics can be readily evaluated using the integrated field $\vec{\mathcal{B}}$ defined as:

$$\vec{\mathcal{B}}(\vec{\mathbf{r}}) = \int_{-\infty}^{+\infty} \vec{\mathbf{B}}(\vec{\mathbf{r}} + \lambda\hat{\mathbf{s}})\, d\lambda \qquad (1)$$

where $\vec{\mathbf{B}}$ is the magnetic induction field, $\vec{\mathbf{r}}$ is a point in space and $\hat{s}$ is the versor directed along the reference trajectory velocity. The $\vec{\mathcal{B}}$ field is a solution of the magnetostatic equations (ME) since it can be interpreted as a linear superposition of solutions of the ME. From its very definition $\vec{\mathcal{B}}$ is invariant under translations along $\hat{s}$, that is $\vec{\mathcal{B}}(\vec{\mathbf{r}}) = \vec{\mathcal{B}}(\vec{\mathbf{r}} + \delta\hat{\mathbf{s}})$, then in particular $\vec{\mathcal{B}}$ is a solution of the two dimensional ME and its components transverse to $\hat{s}$ can be represented inside the domain in which there are no field sources by an harmonic function defined as:

$$f(x+iy) = \mathcal{B}_y(x\hat{\mathbf{x}} + y\hat{\mathbf{y}}) + i\mathcal{B}_x(x\hat{\mathbf{x}} + y\hat{\mathbf{y}}) \qquad (2)$$

A good approximation of $\vec{\mathbf{B}}$ for DHM made by thin round SC wires is given by the Biot Savart law

$$\vec{\mathbf{B}}(\vec{\mathbf{r}}) = I\frac{\mu_0}{4\pi}\int \frac{\vec{\mathbf{w}}'(l)\times(\vec{\mathbf{r}}-\vec{\mathbf{w}}(l))}{|\vec{\mathbf{r}}-\vec{\mathbf{w}}(l)|^3}\,dl$$

where $\vec{\mathbf{w}}(l)$ gives the position of the center of the SC wires as a function of some continuous parameters l and I is the current flowing in the wire. From this expression one can write for $\vec{\mathcal{B}}$ the following expression:

$$\vec{\mathcal{B}}(\vec{\mathbf{r}}) = I\frac{\mu_0}{2\pi}\cdot \int \frac{\vec{\mathbf{w}}'_{\parallel}(l)\times(\vec{\mathbf{r}}-\vec{\mathbf{w}}(l))+\vec{\mathbf{w}}'_{\perp}(l)\times(\vec{\mathbf{r}}_{\perp}-\vec{\mathbf{w}}_{\perp}(l))}{|\vec{\mathbf{r}}_{\perp}-\vec{\mathbf{w}}_{\perp}(l)|^2}\,dl \quad (3)$$

where $\vec{\mathbf{w}}_{\perp} = \vec{\mathbf{w}} - \hat{\mathbf{s}}\,(\hat{\mathbf{s}}\cdot\vec{\mathbf{w}})$, $\vec{\mathbf{w}}_{\parallel} = \hat{\mathbf{s}}\,(\hat{\mathbf{s}}\cdot\vec{\mathbf{w}})$ and analogously for $\vec{\mathbf{r}}_{\parallel}$ and $\vec{\mathbf{r}}_{\perp}$.

The optimization algorithm consist in approximating $\vec{\mathbf{w}}$ (that is, physically, the shape of the helical coil) with an Hermite interpolation function controlled by $2N$ points the position of which is determined by requiring that the set of N complex equations

$$\begin{aligned} f(R_{ref}) &= kR_{ref} \\ f(R_{ref}e^{i2\pi/N}) &= kR_{ref}e^{i2\pi/N} \\ &\vdots \\ f(R_{ref}e^{i(N-1)2\pi/N}) &= kR_{ref}e^{i(N-1)2\pi/N} \end{aligned}$$

are satisfied. As a test of the method sketched here the coil shape obtained with this method was compared against the result obtained with the method presented in [3], the two shape of the coils was identical whitin less than a micron when $N = 48$.

REFERENCES

[1] Super$B$ Progress Report - Accelerator, arXiv:1009.6178v3.

[2] R.B. Meinke, M.J. Ball,C.L. Goodzeit, Advanced Magnet Laboratory, "Combined Function Magnets Using Double-Helix Coils," In the Proceedings of the 2007 Particle Accelerator Conference, Albuquerque, New Mexico, USA.

[3] E. Paoloni, S. Bettoni, M. E. Biagini and P. Raimondi, "Magnetic Design Studies For The Final Focus Quadrupoles Of The Super$B$ Large Crossing Angle Collision Scheme," In the Proceedings of 11th European Particle Accelerator Conference (EPAC 08), Magazzini del Cotone, Genoa, Italy, 23-27 Jun 2008, pp WEPD002.