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Design, Construction and Test of a Model Superconducting Quadrupole for the Interaction Region of Super*B* Factory

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Abstract—SuperB is an asymmetric energy e^+e^- collider operating at the $\Upsilon(4S)$ peak ($\sqrt{s}\sim 10.58\,GeV$) to be built in Italy, with a design peak luminosity of $10^{36}\,Hz/cm^2$. In order to get the required high luminosity, a novel collision scheme, the so called "large Piwinski angle and crab waist", has been designed. This scheme requires that two doublets of high gradient superconducting quadrupoles (denominated in the SuperB naming scheme as QD0 and QF1) are placed as close as possible to the interaction point. This layout is critical because the space allowed to 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 and construction concept of a model of the superconducting quadrupole based on NbTi technology.

Index Terms—Helical coils, Superconducting coils, Quadrupole.

I. INTRODUCTION

C UPERB [1], [2] is one of the two next generation B factories that will be built and operated in the next decade. Its design peak luminosity ($\mathcal{L} = 10^{36} \, \text{Hz/cm}^2$) will exceed by two order of magnitudes that of the present comparable facility enabling for measurements with unprecedented accuracy in the B mesons, τ leptons and c quark sectors. The goal is to challenge the Standard Model (SM) of the electro-weak and strong interactions by comparing the SM-based predictions with experimental results. Any statistically significant discrepancy among the two or, more hopefully, a pattern of significant discrepancies will help to understand how Nature behaves at the scale of the tens of TeV [3]. To reach this ambitious goal it will be needed a sample of $\sim 150 \ 10^9 \ B$ mesons, and a comparable one of τ leptons and D mesons. This sample can be produced by Super B in five "revised Snowmass years" of running at nominal luminosity. The Snowmass Year was defined at the Snowmass '88 Meeting as 10^7 s on the basis of the established performances of CESR and CLEO at that time. It was an empirical proportionality factor that relates the integrated luminosity collected in a solar year with the peak luminosity achieved in the same period of time. The PEP-II and KEKB reliability, and the commitment of their teams

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showed that it is reasonable to revise the *Snowmass Year* definition to $1.5 \cdot 10^{36}s$.

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II. THE COLLIDER AND ITS INTERACTION REGION (IR)

Super *B* is designed as an High Energy Ring (HER) and a Low Energy Ring (LER) storing respectively positrons at 6.7 GeV and electrons at 4.18 GeV injected at nominal energy by a linac. The Super*B* collision scheme requires a short focus final doublet to reduce the vertical beta function down to $\beta_y^{\star} =$ 0.2 mm at the Interaction Point (IP). The final doublet (see Fig. 1) will be composed by a set of permanent samarium cobalt magnets (PM) and superconducting (SC) quadrupoles.



Fig. 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.

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 (7 cm). 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 produced by the beams in the upstream dipoles will deposit $\sim 200 \text{ W}$ on the beam pipe section inside the SC quadrupole. 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

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the requested field purity and gradient strength pose very demanding constraints on the SC magnets design.

III. DOUBLE HELIX QUADRUPOLE MODEL

The double helix magnet (DHM) design [4], [5] is an attractive option for the QD0. DHM are composed by two concentric layers of solenoid coils whose helical turns are longitudinally deformed 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 (see Fig. 2): the current needed to generate the design gradient of 0.96 T/cm over a mechanical aperture of 35 mm is $\sim 2600 \text{ A}$ ($I/I_c = 64\%$ at 4.2 K), using a state of the art NbTi wire like the Luvata CMS one [6], 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, while the current margin

In this respect an SC quadrupole model is presently under construction.

The quadrupole model (see Fig. 3 and Fig. 4) is composed by two aluminium alloy cylinders on whose surface helicoidal grooves are milled with a computer numerical controlled 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 mm polyester braid and will be deposed in the milled grooves. The model will be hopefully ready for tests by the end of 2011. The main goal of the project is to determine the maximum achievable gradient, develop a thermal model of the



Fig. 2. The load line of the QD0 is represented with a dashed line superimposed to the critical current of the CMS strand represented with a continuous line. The working point is represented by the square mark.



Fig. 3. 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.



Fig. 4. A typical cross section of the SC quadrupole prototype representing the two SC winding layers and the groove geometry.

transition to the normal conducting state and finally to measure at room temperature the quality of the generated field.

IV. 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 its maximum. The spurious harmonics are hard to control in the present case since the distance of the axis of the LER QD0 with respect to that of the HER QD0 is comparable with the radius of the cold mass, hence cross talk effects are sizable.

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The small thickness of the cold mass (that cannot exceed a few millimeters) impedes a conventional design, hence a novel compensation technique had been developed to solve this problem. An algebraic approach to compensate the cross talk of two adjacent and parallel DHM by a proper modulation of the helical turns of the DHM had been presented in [7]. The algorithm cancels exactly all 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{B} defined as:

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

where \vec{B} is the magnetic induction field, \vec{r} is a point in space and \hat{s} is the versor directed along the reference trajectory velocity. The \vec{B} field is a solution of the magnetostatic equations (ME) since it can be interpreted as a linear superposition of solutions of the ME and it is invariant under translations along \hat{s} , that is $\vec{B}(\vec{r}) = \vec{B}(\vec{r} + \delta \hat{s})$, hence \vec{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 analytic function defined as:

$$f(x+iy) = \mathcal{B}_y(x\hat{\mathbf{x}} + y\hat{\mathbf{y}}) + i\mathcal{B}_x(x\hat{\mathbf{x}} + y\hat{\mathbf{y}}) =$$
$$= \sum_{n=1}^{\infty} C_n \left(x+iy\right)^{n-1} \qquad (2)$$

where the C_n (that are directly proportional to the integrated field harmonics) can be obtained from the Cauchy formula:

$$C_n = \frac{1}{2\pi i} \oint \frac{f(z)}{z^n} dz \tag{3}$$

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

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

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 obtain for $\vec{\mathcal{B}}$:

$$\vec{\mathcal{B}}(\vec{\mathbf{r}}) = I \frac{\mu_0}{2\pi} \int \frac{\vec{\mathbf{w}}_{\parallel}'(l) \times (\vec{\mathbf{r}} - \vec{\mathbf{w}}(l)) + \vec{\mathbf{w}}_{\perp}'(l) \times (\vec{\mathbf{r}}_{\perp} - \vec{\mathbf{w}}_{\perp}(l))}{\left|\vec{\mathbf{r}}_{\perp} - \vec{\mathbf{w}}_{\perp}(l)\right|^2} dl$$
(4)

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

The optimization algorithm consist in approximating \vec{w} (that is, physically, the shape of the helical coil) with an Hermite

interpolation function controlled by 2N points whose position is determined by solving the set of N complex equations

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$$f(R_{ref}) = kR_{ref}$$

$$f(R_{ref}e^{i2\pi/N}) = kR_{ref}e^{i2\pi/N}$$

$$\vdots$$

$$r(R_{ref}e^{i(N-1)2\pi/N}) = kR_{ref}e^{i(N-1)2\pi/N}$$

. To test the correctness of the procedure sketched here we compared the coil shape obtained with this method against the result obtained with the technique presented in [7], the shapes of the two coils are identical whitin less than a micron when N = 48.

The optimization algorithm is applied to determine separately the shape of each single winding of the QD0.



Fig. 5. The LER QD0 longitudinal current density and the winding modulation obtained with the compensation algorithm are presented in the top and bottom plot respectively with a continuous line. The corresponding quantities for a single ideal quadrupole are represented with a dashed line.

The result of this method applied to the first winding of the LER QD0 is represented in Fig. 5 together with the analytical solution for a single quadrupole. The angle $\varphi = 0$ in which the cross talk compensated shape departs more evidently from the single quadrupole ideal one, corresponds to the point of the LER QD0 winding closest to the nearby HER one.

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V. CONCLUSION

The very demanding requirements of the SC magnets of the final doublet of Super*B* had been presented together with a proposal to satisfy them with DHMs. The main source of concern stems from the combination of the very high current densities needed to generate the requested field gradient that pushes the working point of the SC toward its critical surface, together with the very limited amount of space available for the thermal stabilization of the wire. A model of a single DHM SC quadrupole is presently (September 2011) under construction. The warm test of field quality together with the cold test to determine the maximum achievable gradient and thermal behaviour of the magnet during quench will be ready by the end of 2011.

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