Compact Superconducting High Gradient Quadrupole Magnets for the Interaction Regions of High Luminosity Colliders

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Abstract— Recent developments in the high luminosity e⁺e⁻ colliders are based on a collision scheme with a large Piwinski angle, a vertical beta function β_v much smaller than the bunch length and a crab waist transformation. This scheme is being adopted in the SuperB asymmetric collider, to be built in Italy, with a design peak luminosity of 10³⁶ cm⁻²sec⁻¹. A crucial role is played by the quadrupole doublets QD0/QF1 which are placed close to the interaction point and generate gradients close to 100 T/m. The available space for the doublets is very small, causing the magnets to be operated with a high engineering current density (2000 A/mm²). Starting from the helical coil concept, an advanced design of the quadrupole has been developed. The paper discusses the basic design concepts and the development of a coil model aimed at assessing the design criteria and demonstrating the feasibility of the quadrupole. The successful test of the coil model opens the way to new compact superconducting high gradient quadrupole magnets for the interaction regions of high luminosity colliders.

Index Terms—Superconducting quadrupole, helical coils.

I. INTRODUCTION

S uperB is the new e⁺e⁻ collider [1-4] which is going to be built near Rome, Italy. The Interaction Region (IR) [5,6] is being designed with the final doublets very close to the Interaction Point (IP), well inside the detector tracking volume; the doublets are in facts constituted by a composite set of permanent magnets and superconducting quadrupoles [7]. The superconducting quadrupole closer to the IP, QD0, shall provide a field gradient of 97 T/m in a warm bore of minimum 14 mm. A second quadrupole QF1 generates a gradient of 40.9 T/m in a warm bore of 42 mm. Given these constraints the maximum allowed radial thickness of the cold mass of all the quadrupoles is 5.5 mm.

From the magnet designer point of view two main problems have to be faced: coil protection and field quality. Indeed, the current needed to generate the target gradient is ranging from 2300A of QF1 to 2830A of QD0. The engineering current density (i.e. the current density in the insulated wire cross section) is in the order of 2000 A/mm², which is a value 4-5 times higher than that of typical superconducting accelerator magnets and may cause problems of excessive heating during quenches. Considering that the joule heating depends on the square of the current density, the stability and protection issue is a serious concern.

The quadrupoles placed on the two beam lines are very close each other. The limited available space does not allow for a conventional magnetic shield of the leakage field whose spurious harmonic components are harmful for the dynamical aperture of the ring. The latter problem was solved with the choice of a double helical layout for all the quadrupoles of the final doublet. This layout, proposed by Meinke [8-11] and coworkers for accelerator magnets, is based on the winding of two concentric layers of solenoid coils whose helical turns are modulated to produce the desired transverse magnetic field, the solenoid field being cancelled. The advantages of the solution stay both in the possibility to produce arbitrary combination of multipolar fields and in the large extension of the good field region, also very close to the conductors. A field quality optimization has been carried out in [12], where a robust magnetic design was proposed with a satisfactory solution to the problem of the cross talk compensation.

II. THE QUADRUPOLE MODEL

The construction of the model coil has several important justifications: the development of the constructive techniques, the fulfillment of the required engineering current density and the study of the parameters affecting the field quality.

The proposed magnetic structure, having geometrical and magnetic characteristics averaged among the different magnets of the SuperB IR, is shown in Fig. 1. A superconducting wire is wound on a cylinder to form a layer of turns generating a current depending on the angle as $\cos\vartheta$. A second layer with opposite winding direction (current proportional to $-\cos\vartheta$) has to be wound around the first one on a co-axial cylinder (more details in [13]).

The two cylinders, 4 mm in thickness, are made of aluminum alloy and present on their external surfaces helical grooves milled with a CNC milling machine. The groves hold in place the superconducting wire. The two mechanical supports are anodized for insulation purposes. The wire is a NbTi strand of the same type used for CMS conductor [14] and provided by Luvata Pori. The reason of this choice stays in the low copper to superconductor ratio of the 1.28 mm

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Fig. 1. Top: winding of a double helical coil for generating a quadrupolar magnetic field. Bottom: a winding test with a dummy wire.



Fig. 2. The load line $I(B_{peak})$ of the quadrupole shown together the $I_C(B)$ curve of the wire. At the nominal current the magnet is operating at 58% of the critical current at fixed field.

diameter CMS wire: Cu/SC=1.1/1. With a superconductor cross section of 0.61 mm^2 , the wire is able to carry a current as high as 2000 A at B=5 T and T=4.2 K. The wire was later insulated with a 0.125 mm polyester braid and deposed in the milled grooves with a technique developed at ASG Superconductors in Genova. The quadrupole generates a magnetic field gradient of 50 T/m in a bore of 50 mm with a current of 2650 A and a stored energy of 1165 J. The peak field on the winding is 1.9 T. The load line and the critical current curve I_C(B) at a temperature of 4.2 K are shown in Fig. 2. One can see that the magnet is operating at 58% of the critical current. Under this condition the temperature margin is 1.8 K. The maximum current (where the load line intercepts the critical current curve) is 3600 A. In principle there are no reasons limiting the magnet operating current, even up to 3600 A (gradient of 68 T/m). From a mechanical point of view, the stresses are quite low (about 3 MPa in the supporting structure at 2650 A) and no problems are envisaged even with a factor of 2 in stress increase.

III. ELECTRICAL CIRCUIT

The current supply to the coil is a fundamental issue. If a usual method with a DC current power supply were involved, we had to find a solution to the problem of disconnecting the power supply in case of quench. The total time from a quench start and protection intervention can be hardly reduced under 25-30 ms, which is a too long delay for the magnet we are dealing with. As shown in next section in few ms the quenched zone can get temperature higher than 300 K, causing a severe damaging of the wire. A solution is to have a self-



Fig. 3. The transformer used for energizing the quadrupole here denoted through its inductance L_c . L_p and L_s are the primary and secondary inductances, respectively.

protected current feeding circuit, allowing the current to decay immediately after quench is started. At this aim we used a superconducting transformer for energizing the coil. The scheme of the current feeding circuit is shown in Fig. 3. The coil is not directly connected to a power supply, but rather it is part of a circuit including also a secondary of a transformer. The current transform ratio is given by the relation [15]:

$$\alpha = \frac{I_{s}(t)}{I_{p}(t) - I_{p}(t_{0})} = \frac{M}{L_{s} + L_{q}} = \frac{k\sqrt{L_{p}L_{s}}}{L_{s} + L_{q}}$$
(1)

where $I_p(t)$ is the current in the primary winding at time t, $I_s(t)$ the current in the secondary winding, L_p, L_s and L_q the inductances of primary, secondary and quadrupole, M the mutual inductance between primary and secondary and k the magnetic coupling. Using a feeding method of this kind the maximum energy convertible into heat is fixed and furthermore as the coil quenches the current decays with a time constant depending on the coil resistance growth r(t): $\tau = (L_s + L_q)/r(t)$. As can be seen in (1) the maximum current transformer ratio is for L_s=L_a, but the energy would double, causing even larger temperature increases of the hottest point. Using a smaller secondary inductance $L_s=L_q/4$ the current transformer ratio is still acceptable and the total energy is only 25% higher than the energy of the quadrupole. In order to fast dump the current and extract energy from the coil, a heater was also placed in the secondary winding. As a quench is detected the heater is powered up causing the secondary coil to switch to normal state and the current to be fast dumped. However in our purposes this protection is only a redundancy system, since our aim is a passive protection. In our case the large superconducting magnet of the facility Ma.Ri.S.A [16] is the primary winding. The secondary winding is a solenoidal coil constructed to this aim.

IV. QUENCH ANALYSIS

A very basic consideration is that if the 60 m long wire composing the magnet quenched as a whole, the stored energy would be dissipated uniformly in the wire causing a temperature rise from 4.2 K to 46 K. Unfortunately, the quench could start in any point and propagate with a finite velocity. In this case, though the current starts to decay immediately, due to the adopted electrical circuit, the location where quench starts can heat up to dangerous values. The quadrupole has a complex structure and consequently a finite element 3D quench analysis appears to be a very difficult task. We approached this problem through a 1D numerical analysis followed by a 2D FE study. The 1D analysis was performed considering a quench starting in a given position of the wire



Fig. 4. Left: current decay (squares) and hottest point temperature (circles) for a quench starting in a given position and propagating both sides. Right: electrical resistance (circles) and current decay (squares). After getting a maximum value both temperature and resistance decreases due to the thermal contact with the mandrel considered remaining at 4.2 K.

and propagating only along the wire in one or both directions. The quench velocity was computed according to the Wilson formula for adiabatic propagation [17]. The temperature of the hottest point, coinciding with the quench initiation, was calculated keeping into account the dependence on temperature of the material properties, namely electrical resistivity and specific heat. Fig. 4 shows the current decay, the electrical resistance growth and the temperature increase of the hottest point for a quench propagating along the two directions of the wire with an initial velocity of 185 m/s. One can see that in about 35 ms the current decays to 10% of its initial value and the temperature of the hottest point increases up to 350 K. The quenched zone is quite small (9 m) and hot. The heat exchange with the mandrel re-cools the coil down to 4:2 K. Indeed the real quench shall behave differently because the fast current decay causes a heating of the Al mandrels (due to eddy currents) and the dB/dt imposed to the wire causes AC losses able to quench longer part of conductors. To study the effects of the eddy currents and AC losses we developed a simple 2D model with an equivalent quadrupole magnet generating the same field of our magnet with the same current. The model, developed with COMSOLTM, includes the two mandrels, the turns, the wire insulation and the insulating layer between the two mandrels. The electrical and thermal properties of the materials depending on the temperature were evaluated with CRYOCOMPTM. Starting from a DC current of 2750 A, the current was forced to decay according to the data shown in Fig. 4. The eddy currents in the mandrels are automatically computed by the electromagnetic solver on the basis of the dB/dt and the electrical resistivity of the material. The AC losses in the wire were separately evaluated with analytical formulae and the resulting power dissipation was assigned to the conductors.

Two kind of AC losses were taken into consideration: hysteretic losses in the superconducting filaments and losses due to coupling currents among the filaments. The hysteretic losses within superconducting filaments for the case of one round filament of diameter d_f and critical current J_C , exposed to a variable magnetic field perpendicular to its axis with field rate \dot{B} , can be calculated through [17]:

$$P_{hyst}(t) = M(B(t)) \cdot \dot{B} = \frac{2}{3\pi} J_C(B) d_f \dot{B} W/m^3$$
 (2)

where M(B(t)) is the magnetization depending on magnetic field amplitude. These losses are occurring in the



Fig. 5. The magnet heating after 10 ms. The AC losses in the wires causes the temperature to increase from 4.5K (dark blue) up to 10.5 K (dark yellow), 11 K (orange), 14 K(brown) quenching almost the all magnet. The lines are the potential vector iso-lines.

superconducting filaments only. The losses per unit volume due to the interfilamentary currents, occurring in the matrix only, are given by [14]:

$$P_{\rm if} = \frac{\dot{B}^2(t)}{\rho_t} \left(\frac{L_p}{2\pi}\right)^2 W/m^3 \tag{3}$$

where L_{p} is the filament transposition pitch and ρ_{t} is the transverse resistance. In our case $L_p=45$ mm and we evaluated $\rho_t=3 \ 10^{-10} \ \Omega m$. The expressions (2) and (3) are not generally valid; in particular (3) can be applied only if the field variation occurs in a long time if compared with a characteristic time constant given by ~100 ms. In our case this condition is fulfilled only in the first 10 ms. As the current, and hence the field, starts fast decaying (3) over evaluates the real losses. In our approximation, both losses can be simply evaluated through the knowledge of B(t), which is obtained by a magnetic field computation with COMSOLTM. From a preliminary analysis one can see that the coupling current losses at a field rate of 1-10 T/s (initial rate of magnetic field decay) are largely dominant by a factor $10-10^2$, consequently we performed a thermal analysis considering only the losses expressed by (3) and only considering the first 10 ms time period. The results are shown in Fig. 5. In particular we can see the temperature distribution after 10 ms. The temperature in the wires is larger than 7.5 K with a maximum over 10 K. In these conditions, considering that the magnetic field in the winding is as high as 1.9 T at 2650 A, almost all the magnet is quenched. Consequently after 10 ms the energy is dissipated in the whole wire and the temperature increase is limited to 50 K, but the hottest point, where quench started and after 8 ms is already at T=60 K. This point could heat up to 80 K. We have also seen that the eddy currents in the mandrel take more time for heating the mandrels and hence the conductor. The quench back takes place after 15 ms, i.e. too late for avoiding conductor overheating. However about 200 J are dissipated in the mandrel, so reducing the amount of energy dissipated in the winding. As concluding remarks of this section we can say that the high current density in the matrix could cause excessive and potentially dangerous heating of the hottest

point during quench. However the AC losses, and namely the coupling current losses, seem to mitigate the wire overheating through a mechanism involving the fast quench of the whole wire. The stored energy is consequently uniformly dissipated and the temperature increase limited to acceptable values.

V. MAGNET TEST

The quadrupole is supplied via a superconducting transformer, the primary of which is a 6 T, 1000A solenoid. The secondary winding, placed in an anti-cryostat, is a tenturns, bifilar coil wound onto a cylindrical aluminum mandrel. The bifilar coil is made with the same wire of the quadrupole, doubled in a way not to limit the current flowing in the quadrupole. The quadrupole was placed with the axis along the vertical direction and it was electrically connected to the secondary winding. Both secondary winding and quadrupole are equipped with electrical heaters to quench the magnets. Hall probes are included in the set-up with the aim to measure the field generated by the current circulating in the quadrupole. The current rate was measured with a pick-up coil close to the secondary winding. The test was performed at 4:2K in a liquid helium bath at atmospheric pressure.

The secondary winding was preliminary tested, independently from the quadrupole, by joining its electrical exits. It reached 6 kA before quenching.

A typical test is performed according to the following steps:

- The current in the primary winding is raised to about 150A keeping the secondary circuit in the normal state.

- The heaters are deactivated and the secondary circuit switches to superconducting state.

- The current in the primary winding is progressively decreased at a rate of 0.7 A/s; a variation of 1 A in the primary circuit induces a current of about 20 A in the secondary one.

- When the current in the primary winding is approaching to zero, the current in the secondary circuit approaches 3 kA; since the electrical resistance of the secondary circuit (including three electrical joints) is 30 n Ω , the time constant for the current decay is 1400 s. i.e. a long time compared with the current charge (200 s).

We have observed the following features:

- The first time the quadrupole was energized, a training was observed with a first quench at 2300 A. A current of 2750A was achieved after four quenches. After warming up the system at room temperature and cooling it again, some training is observed starting at higher currents (2500-2600 A). In the last test (out of total four test runs) the quadrupole was charged up to 2830 A.

- After the quench, the quadrupole quickly restores the superconducting state and can be charged again.

From these tests we drew the conclusion that the quadrupole works well, achieving the nominal current with some margin. More important, the magnet looks to be self-protected with no need of a quench detection activating a protection system. In order to better understand the dynamics of the quench, we implemented a fast acquisition of the voltages at the layer ends and of the current with pick-up coil. From these quantities it is



Fig. 6. Comparison between 1D analysis and measured behavior of current decay (left) and electrical resistance increase (right). For the electrical resistance the experimental result shown here is given by the sum of the resistance of the two layers.

possible to calculate the time evolution of the quadrupole electrical resistance. The results of these measurements are shown in Fig. 6 and are in coarse agreement with the 1D model. Few ms after the quench initiation, a fast current decrease is started corresponding to a significant increase of electrical resistance of both layers, getting the maximum value in 17 ms. In a time interval of 24 ms the current is lowered to 1/e of its initial value. The measured current decay and resistance increase start soon after the quench. In particular it can be seen that the measured electrical resistances of the two layers grow up very fast (15 ms after quench initiation) up to a maximum and then a decrease is observed. This behavior is compatible with a scenario involving a quench of the entire winding. If a limited zone were quenched (as in simulation shown in Fig. 5) the electrical resistance would increase slowly (35 ms) and achieve a higher value. From this measurement we have a confirmation of our hypothesis of fast quench propagation due to AC losses. To be noted that, supposing a quench of the whole magnet, the measured resistance (0.03 Ω in total) corresponds to a winding temperature of 40 K.

VI. CONCLUSION

The prototyping activities followed by many cold tests of a double helical model quadrupole gave a clear indication about the feasibility of the compact superconducting high gradient quadrupole magnets for the interaction regions of SuperB. In particular we have observed that very high current densities in the wire (2 kA/mm^2) can be reached without negative effects on magnet reliability and safety. The main reason of this encouraging result is related to the low stored energy (1 kJ), which is not able to heat-up the winding if it is uniformly dissipated, as it appears to happen looking at the measured fast resistance increase. The AC losses due to filament couplings seem to be the best candidate for causing a sudden quench of the whole magnet soon after a normal zone is generated in some part of the winding. A fundamental ingredient of a safely quench behavior is the adopted electrical circuit based on a superconducting flux transformer for feeding the magnet with current. This solution helps in limiting the total energy which can be converted into heat. The drawback is linked to the complexity of the electrical power supply system of the magnets of IR.

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