USING PERMANENT MAGNETS TO BOOST THE DIPOLE FIELD FOR THE HIGH-ENERGY LHC *

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Abstract

The High-Energy LHC (HE-LHC) will be a new accelerator in the LHC tunnel based on novel dipole magnets, with a field up to 20 T, which are proposed to be realized by a hybrid-coil design, comprising blocks made from Nb-Ti, Nb_3Sn and HTS, respectively. Without the HTS the field would be only 15 T. In this note we propose and study the possibility of replacing the inner HTS layer by (weaker) permanent magnets that might contribute a field of 1-2 T, so that the final field would reach 16-17 T. Advantages would be the lower price of permanent magnets compared with HTS magnets and their availability in principle.

INTRODUCTION

The High-Energy LHC (HE-LHC) is a future accelerator in the LHC tunnel based on 20-T dipole magnets, corresponding to a proton beam energy of 16.5 TeV [1, 2]. The 20-T magnets for the HE-LHC are proposed to be realized by a hybrid-coil design [3], comprising blocks made from Nb-Ti, Nb_3Sn and HTS superconductor, respectively, where an outer layer of Nb-Ti provides a field of 8 T, a central layer of Nb_3Sn an additional 7 T, and the remaining 5 T should come from the innermost layer of HTS. Nb_3Sn is estimated to be more than a factor five more expensive than Nb-Ti, and the HTS price to be higher by yet another factor 3-5 compared with Nb_3Sn. It is unlikely that the large difference in price between the three superconductors will disappear over the next 15 years. In addition to the issue of cost, for the high temperature superconductors (HTS) a substantial improvement of the basic performance of the conductor itself is needed, both in terms of current density and in terms of strain degradation [3, 4]. Figure 1 shows the block layout of an HE-LHC dipole. In the LHC, the coil stress due to electromagnetic forces is of the order of 70 MPa. Going to 20 T with the same current density brings stresses to 150-200 MPa, where considerable degradation of the Nb_3Sn material starts. In the framework of EuCARD WP7 Task 4 there is an ongoing effort to build and test an HTS dipole insert coil for a dipole background magnet aiming at a field increase of about 6 T [5].

In this note we propose and study the possibility of replacing the inner HTS layer by a permanent magnet (PM). Advantages would be the much lower price of permanent magnets compared with HTS and that they may be more readily available.

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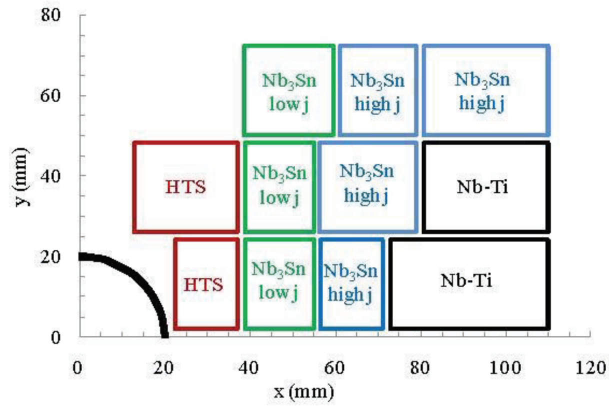

Figure 1: Block layout of the hybrid Nb-Ti/Nb_3Sn/HTS dipole-magnet coil design for the HE-LHC [3]. Only one quarter of one aperture is shown.

PERMANENT MAGNET PROPERTIES

The field of a permanent dipole magnet consisting of M blocks is [6, 7]

$$B = B_r \frac{\sin\left(\frac{2\pi}{M}\right)}{\frac{2\pi}{M}} \ln \frac{r_2}{r_1} \,, \qquad (1)$$

where r_2 and r_1 are the outer and inner radius of the PM magnet, and B_r is the remanent field. For example, with $M = 16$ blocks the factor $\sin(2\pi/M)/(2\pi/M)$ is 0.974, and with 32 blocks 0.994. If we replace the HTS layer in Fig. 1 by a block-PM dipole the ratio r_2/r_1 is about 2 (40 mm over 20 mm); see Fig. 2. Since $\ln(2) \approx 0.69$, the field of a 16-block PM dipole is about $B \approx 0.67 B_r$. With a remanent field of 1.5 T the additional dipole field provided by the permanent magnet imsert would be 1 T. To obtain a higher PM field we would need to use a material or a condition with higher remanent field, to increase the ratio of outer and inner radius, and/or to find a better PM magnet design.

Conventional NdFeB permanent magnets show a gradual small increase of remanent field B_r with decreasing temperature up to a turning point attributed to spin reorientation [8]. Below this phase transition, which occurs at cryogenic temperature, the remanent field strongly degrades. PrFeB magnets containing praseodymium (Pr) in substitution for neodymium (Nd) do not show such degradation. The remanent field of such magnets continues to increase even at low temperatures as is illustrated for Neomax53CR (Hitachi Metals, Ltd., also called NM53CR or simply 53CR), in Fig. 3. As for the coercitivity, 53CR seems to work at high reverse field close to 7 T at 100 K

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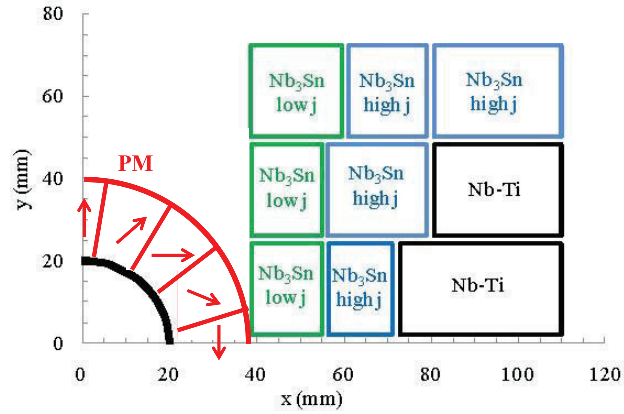

Figure 2: Block layout of a newly proposed hybrid Nb-Ti/Nb_3Sn/PM HE-LHC dipole-magnet coil (modified Fig. 1). Only one quarter of one aperture is shown. The easy axes of the permanent magnets are indicated by the red arrows.

and its ${}_iH_c$ more rapidly increases than for NdFeB magnets (see Fig. 3 of [8]). A naive extention down to ~4 K would reach 10 T, whose order of magnitude is close to the magnetic field level that would be generated without the HTS part. Another issue is demagnetization from radiation. For NdFeB magnets the resistance of the magnetization against radiation by electron or proton beams is related to the coercivity [8, 9, 10], and a similar behavior is expected for PrFeB [8].

For the HE-LHC application, it would be interesting to know the behaviour of this material down to 4 K. Also the effect of pressure and of the high background magnetic field on the PM material would be of importance. It is likely that the material properties can further be improved by additives, but this would require an R&D effort (cost and time).

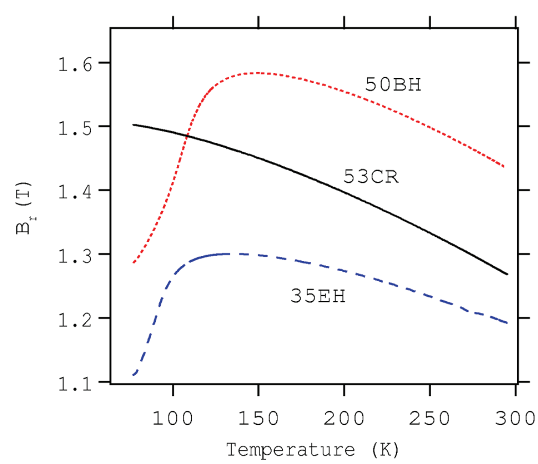

Figure 3: Temperature dependence of the remanent fields (B_r) of sintered NdFeB magnets (35EH and 50 BH) and of a PrFeB magnet (53CR), from Ref. [8].

FIELD ENHANCEMENT TEST

For a simple configuration modeling a test of the proposed PM insert, 2-D field calculations were performed with PANDIRA. The external SC coil field was initially simulated by a Helmholtz-like coil generating a 15-T flat field at the origin. The magnetization directions were chosen so that the easy axes were perpendicular to the flux lines in order to relax the demagnetization hazard from the coil field. These directions could be improved in order to enhance and optimize the field, if the permanent magnets can resist the strong background field. The layout the of magnetic material is also a subject to be improved including the arrangement of the outer coil. Although the field enhancement, did not reach 2 T yet for this configuration, it should be a good start for further research.

A preliminary measurement of the field enhancement could be performed with a small 20-mm cube PM magnet. At KEK a 10-T magnet exists with a bore diameter of 60 mm [12]. If a field higher than 10 T is needed, collaboration with NIMS may be considered. Another possibility could be the FRESCA2 magnet at CERN, with a 100-mm aperture. FRESCA2 should provide a field of 13 T at 4.2 K, and 15 T at 1.9 K [13]. It is scheduled to become operational in 2012. At both locations cryogenics would be available to cool down the PM material inside the strong magnetic field.

A realistic setup for the measurement is sketched in Fig. 4, which shows a cross sectional view of the KEK 10-T magnet with a measurement cylinder inserted. The setup should be equipped with Hall probes, temperature sensors, and magnet rotating mechanism. Since the magnet has a warm bore, a cooling control system should be installed in the cylinder. The warm magnet bore tube might need to be modified to cold bore for this measurement.

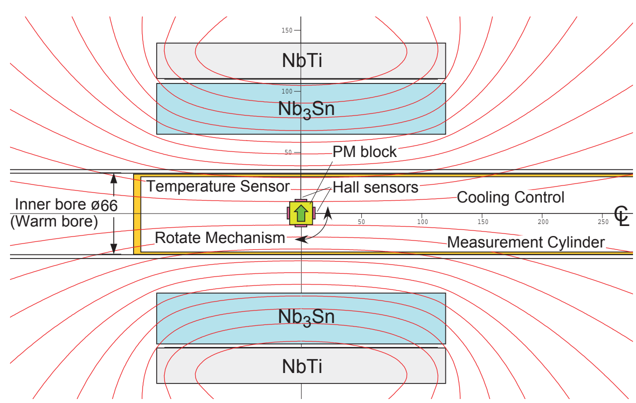

Figure 4: Setup for field-enhancement measurement.

QUESTIONS AND STUDIES

An increase of the field by only 1 T might be too little return on investment. It would be desirable to boost the field increase to 2 T, e.g. by

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- finding a better permanent magnet material with higher remanent field at cryogenic temperatures, or
- using another permanent-magnet configuration (i.e. not a ring form, e.g. see [11]; an example arrangement for the HE-LHC with higher field is shown in Fig. 5, where half of the enhancement comes from permendur (Co49/Fe49/V2) [permendur can generate more flux density than PM at the operating point] and the other half is contributed by the PMs. Even with this configuration, the enhancement falls short of 2 T), and/or
- introducing movable PM blocks to reduce the aperture at top energy in order to further raise the field.

Other outstanding issues are the behavior of the permanent magnet material at high pressure and at extremely low temperature (4-20 K), and the field quality.

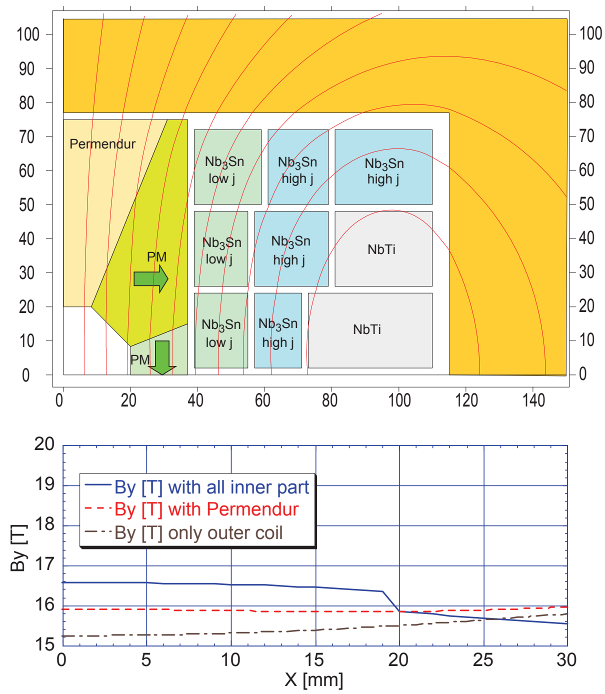

Figure 5: Block layout of an alternative higher-field NbTi/Nb_3Sn/PM HE-LHC dipole-magnet coil modeled with PANDIRA. The magnet is surrounded by an iron return yoke. Three calculations were carried out: (1) with outer coils only; (2) with permendur added, and (3) with all inner parts. Only one quarter of one aperture is shown. The easy axes of the permanent magnets are indicated by the green arrows.

Generally speaking, since rare earth materials are getting expensive, PM would also be expensive. On the other hand, the demand for Pr seems not high, which helps to suppress the cost. Though the cost depends on the material, a typical number is \$1/g which may be comparable to the cost of Nb_3Sn conductor, and still be cheaper than the HTS (Bi-2122), with a price of \$5 to \$10/g.

For a regular configuration, demagnetization would be a problem. The coercive field ($_iH_c$) at 4 K may not easily exceed 12 T, but it should be measured for verification purposes. While at room temperature the demagnetization by a perpendicular external field may be similar to the parallel case, if the temperature is low enough we may be able to overcome the demagnetization by applying a perpendicular superposition. PrFeB magnet would be the choice in this case. According to informal data, the 53CR behavior should be adequate down to 0 K, but detailed tests at cryogenic temperature are indispensable.

STATUS AND PLAN

Since December 2011, discussions have been ongoing with the company Hitachi Metals concerning a sample of the PrFeB PM material NM53CR. Due to lack of demand for this material it is not on the production line, and the availability is not good. Recently just one sample has been found to be available for us. Concrete test setups at KEK, NIMS and CERN will now be pursued.

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