High Field Magnet R&D for VLHC

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Overview

Two approaches for a VLHC machine involve the use of low-field magnets (i.e., Pipetron) and high field magnets (HFM). In a machine with the nominal Snowmass-96 parameters, 50 TeV on 50 Tev, the HFM option has the advantages of utilizing synchrotron radiation damping to improve beam stability, and also to minimize tunnel circumference [1]. The required fields have yet to be determined, although an operational field between 9 – 13 T is probably what is needed. A 9 T dipole may be sufficient to provide radiation damping in a 50 TeV machine; damping would be improved at higher fields, and the Snowmass group chose 12.5 T as a nominal field.

The choice of magnet technology and the required level of R&D will significantly depend on the field one chooses. Magnets with 9 T fields will be achievable through continued improvements in NbTi. The technology for producing cos-theta magnets in the 10-12 T range using Nb_3Sn is a reasonable goal in the next few years, while a magnet with fields > 12 T will require new magnet designs and significant improvements in the utilization of superconducting materials with higher H_c and J_c than what is attainable with NbTi; these include the A15 materials (e.g., Nb_3Sn) and the less well known high temperature superconductors (HTS).

LHC HGQ program

A natural bridge to a VLHC magnet is the High Gradient Quadrupole (HGQ) program now getting underway in the Technical Division. This project will result in the construction of a number of quads with gradients in the range 210-250 T/m and a bore of 70 mm. These magnets will be used in the low beta interaction regions of the LHC. Arc quadrupoles in a VLHC will undoubtedly have gradients at least as large, most likely in the 250-300 T/m range, but with smaller magnet bore.

Fermilab will construct low-beta triplets for the LHC. Each triplet will consist of 4 cold masses each of length ~6 m. A major milestone in this project will be the construction of a full-scale prototype in FY2000. Prior to this, we will need to have completed short model R&D. Production will result in about 20 magnets to be completed by FY2004. These magnets will use NbTi conductor made from SSC strands cooled with superfluid He at 1.9 K.

The high-field in the LHC quads will be about 9.5 T. Hence, the HGQ program naturally leads to development of dipoles in the 9 T to 10 T range.

Dipole options

Lessons learned from the HGQ program can be applied to a 9 T or perhaps 10 T dipole made with NbTi. Two key issues in the structural design of a high field dipole are: 1) Sufficient control of global winding deflections to preserve field quality, and 2) Sufficient control of local conductor motions to avoid premature quenches. Both issues become more difficult as the magnetic field increases [2].

NbTi:

The advantage of building magnets with NbTi is obviously that we know this material so well, and we have a lengthy experience with this magnet technology. Hundreds of short (~1 m long) and full-scale (6-15 m long) SC NbTi magnets have been fabricated and tested in large accelerator/collider projects as Tevatron, UNK, HERA, SSC, RHIC, LHC. The key points can be summarized as follow:

- NbTi magnets allow one to achieve 7.5-8 T maximum field (6-7 T operating field) at 4.4 K and 10 T at 1.8 K in the magnet bore of 50 mm. The required field quality in the magnet bore of 50 mm, reproducible from magnet to magnet, has been obtained. All sources of the field errors are well understood.
- Magnets show reliable behavior in thermal and current cycles over long times in hard radiation environments.
- Coil cooling can be provided by liquid helium at 4.2-4.8 K or superfluid helium at 1.9 K. Liquid helium cryogenic systems can provide the magnet thermal stabilization at levels of localized heat deposition up to ~10 W/m.
- Magnet quench protection is provided by internal quench heaters.
- The technology of NbTi magnets has been demonstrated in mass production in industry (HERA, RHIC) at acceptable costs.

Nb_3Sn:

Significant progress in attaining higher magnetic fields has been achieved using Nb_3Sn in the past 3-5 years. The High Field Magnet group at LBNL has had some success at building R&D magnets using a hybrid scheme [3] using an inner coil of Nb_3Sn and an outer coil of NbTi. This magnet reached a quench plateau of 7.56 T at 4.3 K, and is expected to reach nearly 10 T at 1.9 K. More recently, the LBNL group had a significant success with an all Nb_3Sn dipole (D20) which reached fields above 13T at 1.8K [4]. The magnet group at Twente University (Netherlands) had achieved 11 T with a Nb_3Sn model magnet[5].

The main problem is that unlike NbTi, Nb_3Sn is brittle. Even worse, Jc degrades when it is subjected to strain. An alternative which may have lower strain sensitivity is Nb3Al. To minimize the strain problem, one usually winds the Nb_3Sn into a coil shape prior to preparing the material in its final state. In this wind-and-react method, the coil must be reacted at high temperatures (~650 C) for many days. Coil insulations which can withstand this temperature include fiberglas and ceramics.

Some useful results obtained with Nb_3Sn short dipole models are:

- A magnetic field of 13 T has been achieved in the magnet bore of 50 mm at 4.3 K with a Nb_3Sn shell type dipole magnet. The magnet critical current degradation of 5-10% was observed in the magnets for both wind+react and react+wind winding technologies.
- Coil cooling by pressurized liquid helium at ~4.4 K provides the magnet thermal stabilization at high heat depositions. These magnets have a bigger temperature margin and therefore they are good for fast cycle or high heat load operation.
- Well understood quench protection systems based on internal quench heaters can provide reliable magnet protection.

- Field quality and its reproducibility from magnet to magnet as well as long term magnet behavior are not well known because of the small number of models built.

Magnets employing coil designs other than the proven cosine theta design are being investigated at various facilities. For example, A block-coil design using Nb_3Sn is being developed [6] with the goal of achieving 16 T. These designs are driven by the need to provide better mechanical support for the conducter, which is subject to very high forces at high fields. Unfortunately, such designs are not efficient in their use of conductor, typically requiring twice the conductor of cosine-theta geometries.

High Temperature Superconductors (HTS):

The most promising of the new materials include $Bi_2Sr_2CaCu_2O_x$ (BSCCO-2212), with T_c ~ 85K, and $Bi_2Sr_2Ca_2Cu_3O_x$ (BSCCO-2223), having T_c ~110K. Kilometer-length quantities of these materials have been made in the form of multifilamentary tapes (typically 10:1 aspect ratio), suitable for a magnet using the parallel wall design [2].

Another material, YBCO, shows even more promise of being useful at high fields. Very high critical current densities have been achieved at high fields in short samples. Commercial production of this material lags well behind BSCCO. A good review of the new HTS materials is given in [7].

The first direction to be taken at Fermilab in the immediate future will be investigating the use of HTS materials in superconducting leads with the possibility of replacing the existing 5kA leads in the Tevatron to reduce the overall thermal load on the 4K system. An additional R&D step to be taken soon will be the installation of an HTS short sample test facility.

Other issues which have not been addressed here, but will clearly need attention in a HFM program, include quench protection, cryogenics, and structural issues. All of these areas should be addressed concurrently with the conductor R&D outlined above. A comprehensive program is needed to develop the magnet technology for a future collider, but we believe this program has a high probability of success given appropriate R&D support from DOE.

References:

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