THE HIGH FIELD MAGNET PROGRAM IN EUROPE

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Abstract

With the LHC, magnets of 10 T peak flux density Nb-Ti technology were developed and this technology reached full maturity. The next step in flux density level, with a peak in the range of 15 T, will be needed for the LHC Phase II upgrade. For this upgrade the temperature margin and radiation resistance of the Nb-Ti coil technology is not sufficient. Beginning 2008 CERN started a program to develop high field magnets for LHC upgrades and other future programs. For this mostly Nb_3Sn conductors will be employed, but also HTS conductors will be considered. In this paper an overview will be presented of the projects for which this HFM technology will be needed. The program will be presented in terms of R&D chapters and work packages. The need and opportunities for collaborations with other institutes will be discussed.

MOTIVATION

The physics potential of hadron colliders is determined by the maximum beam energy and the luminosity. The maximum energy of circular hadron accelerators is in its turn determined by the flux density in the main bending magnets and the circumference of the machine, whereas the maximum machine circumference is limited by economic and organizational parameters. On the other hand, the luminosity is fixed by a set of parameters where the gradient of the quadrupoles in the low-β insertions and their aperture play an important role. Thus any technology step which allows to increase the flux density in accelerator magnets also enables the construction of more powerful machines with a larger physics potential.

In this respect the technology of Nb-Ti superconducting magnets with an operational flux density around 4 T was inaugurated by the ISR low-β upgrade (1983) and it opened the way for building the Tevatron at FNAL in the early eighties. HERA at DESY and RHIC at BNL soon followed with magnets based on a similar technology. A major R&D program permitted CERN to stretch the technology to its limit and thus to double the operational flux density range of Nb-Ti accelerator magnets to 8 T, enabling the construction of the LHC, which will see its first beams in summer 2008.

To prepare for future luminosity upgrades of the LHC or for the construction of higher energy machines new high field magnet technology based on other conductors than Nb-Ti will have to be developed.

LHC LUMINOSITY UPGRADE

The luminosity limit of the LHC is estimated to be $L = 10^{34}$ $cm^{-2}s^{-1}$. The β* value in the two high luminosity interaction points is limited to 0.55 m mostly due to the available aperture in the positions of the highest β values in the insertion. The coil inner diameter of the quadrupoles at this position is 70 mm. It should be noted that the cold bore and the beam screen reduce the available beam aperture even further to 60 mm. In order to squeeze the beam down to smaller β* values, the aperture in the quadrupoles has to be significantly increased. A program, called SLHC Phase I upgrade, has been started at CERN to double the peak luminosity by using a β* value of 0.25 m and a larger beam current and should be implemented by 2013. Magnet modelling has started for quadrupoles, which will have a 120 mm inner coil diameter, an operational gradient of about 120 T/m and will be made with Nb-Ti technology [1]. On a longer timescale (>2017) more powerful magnets with a gradient of around 180 T/m and with an aperture of up to 150 mm will be needed to reach luminosities of $\geq 10^{35}$ $cm^{-2}s^{-1}$ [2][3][4]. Such magnets are beyond what can be done with Nb-Ti conductors and will have to be made with Nb_3Sn conductors, as the peak flux density on the coils will exceed 10 T. These magnets will have to face large radiation doses coming from the debris of the interactions in the experiments from which the most damaging is the neutron flux of up to a few times 10^{17} $cm^{-2}year^{-1}$ on an unprotected coil. The interaction debris will also impose a large heat load on the coil, which can locally go over 50 mW/cm^3, necessitating a very good heat removal from the coil and a large temperature margin of the superconductor.

Low-β insertion upgrade scenarios also comprise options with an early separation dipole placed in the experimental straight section [5]. This 1.5 m long magnet should have a flux density of 5 T in a 300 mm aperture. Due to its forward position, radiation and heat load (~75 W in total) will be very important on this magnet. A large, multi Kelvin, temperature margin will be needed, for which Nb_3Sn conductors might be required.

LHC luminosity upgrades will also include improvements to the collimation [6]. One candidate upgrade is to add an off-momentum particle collimator in the dispersion suppressors around the two high luminosity insertions. To position this collimator, a space of 5 m has to be created in the dispersion suppressor. For this a standard 15 m long 8 T two-in-one dipole should be replaced with a 10 m long 12 T two-in-one dipole. This type of magnet has to be made with Nb_3Sn conductor due to the flux density level. In a separate upgrade proposal the dog-leg in the cleaning insertions could be increased in order to improve the cleaning efficiency. For this 5 T dipoles would be needed. These magnets required Nb_3Sn conductors for their large temperature margin as they are subjected to the particle showers from the collimators.

For similar reasons the very forwardly positioned corrector magnets will also have to be made with high temperature margin Nb_3Sn conductors.

For the operation of the LHC with Pb ions a beam profile monitor is foreseen based on the detection of the synchrotron light emitted by the beam in an undulator. For this a small period (< 150 mm) with a flux density around 5 T in a 60 mm gap is needed. Due to the high peak flux density on the coil, this magnet will have to be made with Nb_3Sn conductor.

LHC ENERGY UPGRADE

On a timescale of 20 years it would be possible to consider an LHC successor machine with 2 - 3 times the LHC energy (DLHC). Such a machine would need magnets of the 20 T range. For flux densities above 15 T in accelerator magnets a hybrid HTS-Nb_3Sn coil system should be considered. Knowing the very long lead-time of 10 - 20 years for the development of new magnet technology, this development should start now if the HEP community wants to consider such a machine in the 2020-ies.

NEUTRINO AND MUON FACTORY

The neutrino community is presently considering a neutrino factory [7]. Two types of factories are being discussed, the first type is based on beams of radioactive isotopes (beta-beam) [8] and the second type is based on beams of decaying muons. The generation of the muon beams for the latter option is very much similar to what would be needed for a muon collider and hence these two programs present a common approach and operate from one collaboration. For both types of beam, unstable particles are stored in a storage machine where the decays in the long straight sections give rise to collimated neutrino beams. The other decay products, an ion and an electron or positron for the beta beam and an electron or positron for the muon machines, impose a very large radiation load on the magnets of the accelerators. These debris particles are swept out of the beam mostly in the horizontal plane thus impinging on the coil. For this application the development of open mid plane magnets with a flux density range of 4 T - 8 T is needed. Also here, Nb_3Sn conductors are required for their large temperature margin as they are subjected to the particle showers from the collimators.

HIGH FIELD MAGNET PROGRAM

Now that the construction of the LHC is complete, CERN has started a High Field Magnet R&D program, which is defined for the next 6 years. The main aim of the program is to develop the technologies necessary for high field accelerator magnets and to build demonstrators to show the feasibility of these magnets. In this respect CERN is joining into the efforts, which are already ongoing in the US since a few years within the LARP collaboration [9] and core programs at BNL, FNAL and LBNL, on the development of large aperture high gradient quadrupoles for LHC upgrades and very high field dipoles. It has to be kept in mind that to date there exists no "accelerator grade" Nb_3Sn magnet. The presently existing Nb_3Sn magnets are either short models, racetrack magnets without apertures and none of them has yet the required field quality or stability suitable for an accelerator like the LHC. A comprehensive effort in all institutes in a collaborative spirit is needed to make the next step and produce 'installable" Nb_3Sn magnets.

CERN HFM program

The HFM program is divided up in 4 chapters: Conductor, Enabling technologies, Model Magnet and Prototype magnet. In these chapters a total of 49 work packages are defined. The program comprises collaborations with other laboratories and universities and the HFM work-package of the FP7-EuCARD proposal is anchored in this program.

A description of the chapters can be found below:.

1. Conductor.

The core of HFM development is the conductor. The critical current density (J_c) is a key parameter of the conductor to be developed. Nb_3Sn conductor displays a degradation of J_c with the imposed mechanical strain. The aim of the development is to get Nb_3Sn strand commercially available in large lengths with the following parameters: J_c (non-Cu part) ≥ 3 kA/mm^2 at 12 T and 150 MPa imposed stress. This conductor has to be stabilized at low flux density against instabilities. The strand has to be worked into a Rutherford type cable where the loss of J_c due to the cabling deformations should be below 5%. Furthermore the inter-strand resistance has to be controlled. The activities in the conductor chapter will run over the full 6 years.

2. Enabling technologies.

In order to prepare for the first construction of model magnets several outstanding technology issues have to be resolved.

A coil geometry concept has to be found for dipoles and quadrupoles such as to provide high flux density (e.g. $B > 12$ T in a dipole) with a good field quality ($\Delta B/B \sim 10^{-4}$) while keeping the maximum stress in the coil limited to manageable levels ($\sigma \leq 150$ MPa).

In order to evacuate the heat generated by the radiation impinging on the coil, a solution has to be found to circulate liquid helium in the coil. For this, either porous epoxy based impregnation or porous ceramic insulators have to be developed. The radiation resistance of the superconductor and the insulation materials have to be certified. The thermal behaviour of the coil will be modelled and verified with a thermal properties measurement program. The mechanical behaviour of the various candidate coil and magnet structures will be tested on samples and small mechanical models. Quench behaviour and quench protection schemes will be modelled. The coil and magnet concepts will be first checked in sub-scale models. In this chapter also the first steps will be made towards HTS insert magnets for dipoles. The undulator-wiggler development is also situated here. Most of these activities will be done in the first 3-4 years of the 6 year program.

3. Model Magnet

Three types of model magnets should be constructed to try out the concepts proposed in the technology chapter.

A 13 T dipole model of 1.5 m length and with a 100 mm aperture is to be constructed in the years 2009-2012. In the latter 3 years of the program a quadupole model with a 150 mm aperture and a gradient of 180 T/m will be constructed. During the last 2 years, models for the various corrector magnet types will also be constructed.

4. Prototype magnet

A last step in the 6 year development program is the construction of a 4 m long prototype magnet. The type (dipole or quadrupole) is still to be determined and is to be coordinated with the work by the LARP collaboration in the US.

EuCARD proposal

In the first quarter of 2008 a consortium of 40 institutes and universities has submitted the EuCARD proposal on a EU FP7 infrastructures call. Work Package 8 of this proposal concerns the high field magnets for the upgrades of European accelerator infrastructures. This proposal is closely intertwined with the CERN HFM program. It comprises 6 R&D tasks from which 5 have their CERN component in the CERN HFM program. The 6 tasks are: Support studies, High field model, Very high field dipole insert, High T_c superconducting link, Superconducting wiggler for ANKA, Short period helical superconducting undulator. Only the task on the superconducting high T_c link is based in a different activity at CERN. For this proposal the result of the selection will be known this summer. The EuCARD proposal is a very good occasion to link the activities and programs of all the laboratories involved in HFM development together and to give them a good starting point for further collaboration.

The large aperture dipole model of this program will, apart from being a test bed for Nb_3Sn accelerator magnets, later on serve to upgrade the CERN cable test facility FRESCA from an operational flux density of 10 T to 12 T. The same magnet can then also be used to provide the background field for the HTS dipole insert magnet, which is to be a very first step to hybrid HTS-Nb_3Sn accelerator magnets in the 20 T range.

Present activities

During the first half of 2008 the activities which have already been started:

- Construction of a sub-scale race-track models in a collaboration between CEA, LBNL, STFC-RAL and CERN.
- Detailed re-testing in the CERN test station of a TQS model quadrupole, made by the LARP collaboration in the US. This re-test is done in an LBNL - CERN collaboration.
- Pre-design studies of the dipole model

At present the main work is on consolidating the program and to form a larger collaboration on high field magnet development for accelerator applications.

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