SUMMARY OF SESSION 2: MAGNETS FOR THE HE-LHC

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Abstract

This second session of the workshop is devoted to the status of high field magnets research in the world. Overview of the main programs for accelerators magnets based on Nb_3Sn and Nb_3Al conductors are given. The statues of high temperature superconductors, which are an essential ingredient to bring the field from 15 to 20 T, are also addressed.

SESSION OVERVIEW

The session consisted of seven talks:

- LHC accelerator R&D program (LARP) by G. Sabbi: this is the Department of Energy program active since 2004, whose main aim is to develop large aperture (90 mm to 120 mm) Nb_3Sn quadrupoles for the LHC interaction regions with peak fields of the order of 12-15 T.
- 'Core' program of LBL, by S. Caspi, giving an overview of the program in Berkeley, mainly focused on high field Nb_3Sn dipoles (13-16 T) with 40 mm aperture and accelerator field quality.
- 'Core' program of FNAL, by A. Zlobin, giving an overview on the high field Nb_3Sn magnets program in Fermilab, focused on dipoles in the range of 11-12 T.
- European program in high field magnets, by G. De Rijk; the European Union, has launched a research program to first develop a Nb_3Sn conductor (CARE-NED) and then to master the technology through the construction of a challenging large aperture (100 mm) magnet in the range of 13-15 T (EUCARD-HFM, Fresca2 test station).
- Development program in KEK on Nb_3Al, given by T. Nakamoto; Japan is pushing for the development of this material since many years. At his stage, the main challenges are at the level of the conductor development.
- Status report on the magnets based on High Temperature Superconductors (HTS), by J. Schwartz.
- An overview on the construction of magnets based on HTS in BNL, by R. Gupta.
- An overview of the path towards 20 T magnets, by P. McIntyre, University of Texas, who first proposed such a magnet for an LHC tripler.

Nb_3Sn

Is Nb_3Sn an eternal promise of higher fields for the accelerator community, which will never be fulfilled? Or will it be really able to bring the operational field from the 8 T Nb-Ti limit to 12 T, and possibly up to 15 T? Already at the end of to 80's, the fathers of the LHC were considering the option of main dipoles in Nb_3Sn at 4.2 K, as an alternative to the Nb-Ti technology at 1.9 K. The CERN-Elin Nb_3Sn prototype successfully went close to 10 T, and the final choice on Nb-Ti has been dictated by manufacturing feasibility, experience with the technology, and price considerations. Since then, in a few years the record of Nb_3Sn magnets was brought to 11 T (MSUT, University of Twente, 1995), and above 13 T (D20, Berkeley, 1997). These successive records went hand in hand with an impressive progress in the cable performance: the current density of Nb_3Sn (at 12 T and 4.2 K) increased by more than a factor two, jumping from 1200 A/mm^2 to almost 3000 A/mm^2 during the first decade of the century. FNAL launched at the end of the 90's a program to build 11 T magnets for the VLHC based on Nb_3Sn technology, fully satisfying accelerator requirements. Indeed, the program was blocked for a few years on what has been understood later as a conductor instability, limiting the magnet performances at 60% of the short sample field. The last three magnets of these type (HFDA05-07) managed to reach about 80% of the short sample after some training, reaching the 10 T barrier for an accelerator dipole.

Thanks to the massive DOE investment in LARP, in the past decade the Nb_3Sn technology has been proved for quadrupoles in the range of 10 T operational peak field with the TQ models. The program has also showed that (i) several models are needed to master all the details relative to the manufacturing; (ii) the LARP Nb_3Sn conductor has shown to be able to withstand stresses up to 200 MPa with moderate degradation; (iii) a collarless bladder & shell structure where the stress is mainly imposed during the cool down is extremely efficient; (iv) a collar structure seems less forgiving on errors and tolerances, but can anyway provide equivalent results as the TQE models proved; (v) the performance at 1.9 K is still affected by instability issues, and the additional 10% given by lowering temperature from 4.2 K to 1.9 K is not at hand; (vi) training appears longer than in Nb-Ti magnets but in many cases the 80% operational level can be reached very rapidly or without quenches; (vii) the scaling from 1 m to 3.4 m long magnet can be mastered successfully (LQ model). On the other hand, the technology still shown to be fragile and sensitive to many issues that are not totally mastered: the first results of HQ, the 120 mm aperture quadrupole, gives a magnet well above 70% of the short sample, but limited at less than 80%, and affected by electrical problems: this after many years of development of short models in the LARP framework.

Novel layouts as the block coil have been explored for Nb_3Sn dipoles by LBL (HD2 model). Also in this case, the results are mixed: the magnet is above 70% of the short sample field but is blocked at around 80% by quenches in the transition to the coil heads. A design, which would charm everybody by its beautiful simplicity (squared block coils, no copper wedges), shows to have more hidden issues than the cosθ.

Summarizing, the Nb_3Sn technology, which was proved to bring the operational field from above 8 T to up to 12-13 T in the 90's, has been extensively studied in the past decade, showing several problems and hidden issues, but also significant advancements. Today it is very close to maturity, but still a few steps are needed before installation in an accelerator.

Nb_3Al

Nb_3Al is an interesting material since it allows to go beyond 10 T and, contrary to Nb_3Sn, has a limited degradation with strain. Whereas it has been abandoned in US, Japan has decided to pursue this technological development, with important investments on the conductor. At the level of 15 T, Nb_3Al can provide about 800-1000 A/mm^2, i.e., 50-70% of Nb_3Sn. At the same time, wire manufacturing has not yet been mastered, and R&D is still ongoing to finalize the strand lay-out. In parallel with cable development, KEK is planning to build short racetracks to test the cable in its field and master the issues related to coil fabrication. Compared to Nb_3Sn, there is still an evident gap, both in terms of development and of resources. In the next years it will be possible to judge if this promising material can become a reality for accelerator magnets.

HTS

The ultimate limit of Nb3Sn is probably an operational field of 15 T, i.e., 18 T short sample field with a 20% margin. To get the last five T needed to reach 20 T, one has to use HTS, which can tolerate very high magnetic fields, i.e., well above 30 T.

In solenoids, HTS have been successfully used to reach field of the order of 25-30 T (six demonstrators for 25 T, and two for 30 T). Solenoids have much easier geometry with respect to accelerator magnets, and coils are self supporting under the electromagnetic forces.

REBCO (YBCO) has a very large current density in the superconductor, but needs a very large dilution (1-2%), greatly reducing the engineering current density, i.e., the current density over the whole cable. Moreover, it is manufactured only in tapes which are good for small solenoids but not for large accelerator magnets. Finally, the material is highly anisotropic and in a dipole or quadrupole one cannot minimize the perpendicular field as in solenoids. It is also limited to the react-and-wind technique. Bi-2212 can be cabled and has a large filling factor (30%), but it has a lower current density. It can be used with the wind-and-react technique, and due to chemical reasons it is more challenging than for the Nb_3Sn. Today is the natural choice for accelerator magnets, starting from small racetracks which are the first step to prove the technology.

Quench detection is an additional challenge, since the velocity of propagation of the quench is slower than for Nb_3Sn or Nb-Ti case, thus inducing higher spot temperature before than the quench can be detected. Optical fibers are being studied to solve this issue.

HTS programs for accelerator magnet are active in BNL (talk by R. Gupta), LBL, FNAL, and Eucard (high field insert in Fresca2).

HYBRID COILS

A 20 T magnet would need an hybrid coil to minimize the cost: even in the time scale of 20 years it is difficult to imagine that the prices of Nb_3Sn and HTS could converge to the Nb-Ti price. The construction of an hybrid magnet poses additional challenges since each material needs a different heat treatment, and has different mechanical properties. A very limited experience is present in the field, which could be one of the most difficult issues of the project.

DISCUSSION

- G. L. Sabbi points out that the presence of very few producers in Nb_3Sn strands is an intrinsic fragility of the project: in US all the strands is made by OST, and after many efforts another producer is reaching the specifications in Europe. One should avoid to be dependent on a few manufacturers, also in view of the large production load that will be induced by ITER, which could exhaust the production capabilities.
- L. Rossi points out that the magnet has to be designed for 20 T. The 80% limit means that, from a purely electromagnetic point of view, the magnet should reach 25 T at short sample. Indeed, all the other aspects of the magnet (mechanical structure, protection, …) should be designed to withstand 20 T, and not 25 T.
- J.-P. Koutchouk asks about if instabilities at 1.9 K could limit the performance. This is possible, even though the loadline of the magnet is very flat (high field and low current density) so probably the problem should be less relevant.
- E. Todesco asks about the time needed to get an existing strand from a producer: 15 months in average.
- L. Rossi asks about the training retention in the Nb3Sn LARP quadrupoles: in general there is a good memory.
- A. Yamamoto points out that a block structure as it has been used for HD2 requires more conductor, and that the flared end are not straightforward. On the other hand, the cos 2θ LARP quadrupoles rarely showed problems with ends. S. Caspi replies that the experience of HD3 will be crucial to validate this challenging design.
- R. Gupta asked about the absence of wedges in the Fresca2 design: G. De Rijk answered that the required field quality is about 0.1%, and therefore there is no need of copper wedges.

- L. Bottura pointed out that the aspect related to radiation on insulation are very critical and underestimated: there are no facilities, and it is a complex study to which more resources should be allocated. The use of the HighRadMat facility at CERN, as suggested by S. Myers, would be difficult since one needs cryogenics. F. Bordry asks about how this problem is solved for ITER: the spectrum is pretty different the the facilities have been now dismantled. After a wide discussion, there is a general consensus on the need of well specifying doses and spectra, and to find/build a facility to perform the necessary tests.
- The necessity of a cored cables is questioned by E. Todesco, who points out that the strong effects on field quality visible at 70 A/s (ramp rate of Tevatron) disappear at 10 A/s. L. Rossi and L. Bottura point out that a core could be needed to avoid quenching during a fast discharge.
- G. De Rijk remarks that FNAL and LARP data show a longer training in Nb_3Sn dipoles than in quadrupoles.
- L. Rossi points out that the main challenge for REBCO conductors is to manufacture a round wire. J. Schwartz answers that many tentative are ongoing. Justin also points out that the application should drive the research on the conductor: up to now HTS research has not been driven by accelerator magnets applications.
- The HTS needed to add the last 5 T opens a wide debate. G. Sabbi points out that today it would be short-sighted to limit the magnet at 15 T and to exclude HTS. E. Prebys observes that the 20 years span from today to 2030 is not so wide: 10 years ago Nb_3Sn was in a much better state than what is HTS today, and nevertheless Nb_3Sn accelerator magnets are still not at hand. J. P. Koutchouk points out that the cost looks today as one the main issues, the HTS part to reach 20 T having approximately the same cost as what is needed to go to 15 T.
- E. Todesco asks to R. Gupta the field level achieved in the HTS racetracks: around 2 T.
- L. Bottura comments on the talk by S. Gourlay on future directions in the high field magnets: for the HTS, the strong requirements are a cable with high current density and small filament size, with round wire. For Nb3Sn, one should manufacture a magnet with all features needed to be installed in a machine.
- R. Garoby observes that one should also consider the option of an accelerator with a longer tunnel and a smaller field. K. H. Mess points out that the practical issues related to a very large size (above 50 km) should not be neglected.

CONCLUSION

One can draw three main conclusions: (i) there is no apparent showstopper for a dipole in a with a 16-20 T operational field; (ii) 20T should be kept as ultimate limit for the design, with a 20% margin, and (iii) high temperature superconductors are necessary to go beyond 15 T: the feasibility of a HTS coil pushing the field from 15 to 20 T should be addressed in the next 5 years.