Fast-cycling HTS-based accelerator magnet R&D

Snowmass 21: Contribution *May 25, 2020*

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Fast-cycling HTS-based magnets offer cost-effective solutions for many future particle accelerators. We review the progress to date and call to expand the R&D on such magnets

Development of high-current cables based on NbTi superconductor wire revolutionized magnet technology for the energy frontier accelerators, such as Tevatron, RHIC and LHC. The NbTi wire based accelerator magnets offered advantage of high fields *B* and much lower electric wall plug power consumption if operated at 4.5 K. But their narrow operational temperature margin (< 2 K) limits allowable ramping rates to *dB/dt* < 0.1 T/s to prevent magnet quench due to conductor heating induced by fast-cycling magnetic field crossing the cable space. The record field ramping rate achieved to date in NbTi magnets is about **4 T/s** (Dubna/FAIR). Such low ramping rates preclude their application for construction of magnets for the accelerators aimed to operate at high repetition rates necessary for production of high intensity short-lived beam particles as in the muon collider [1], for the injector to the high-luminosity proton-proton collider [2] as well as for the production of high power proton beams for the neutrino physics [3]. The high temperature superconductors (HTS) allow to widen magnet power cable operational temperature range by at least 20-30 K creating in this way a15-25 K quench safety margin if conductor is operated at 5 K. If the HTS cable is used to power the super-ferric type accelerator magnet, the *B* field crossing the cable space can be suppressed by at least an order of magnitude relative to that of the beam gap. This in turn minimizes the *dB/dt* heating power rate through the magnet cable space leading to a near suppression of the generated heat in the conductor and thus strongly minimizing required cable cooling cryogenic power. For the rapid-cycling accelerators the dominant construction cost is due to magnetic cores which require very thin (< 0.1mm) silicon steel laminations to minimize core heating and thus the power loss in the cores. In this respect the superconductor-based magnets significantly reduce the accelerator construction cost as the cable space inside the magnetic core, and consequently the core itself, can be reduced up to a factor of 5-10.

Recently, we have reported the first application of the HTS for fast-cycling magnet technology with a substantially low AC losses at the record high ramping rate of **12 T/s** [4]. A dual-aperture prototype accelerator magnet was powered by the conductor coil based on the REBCO type superconductor. Application of a dual-aperture magnet allows for simultaneous acceleration of two-particle beams, therefore, significantly improving collider injector accelerator operation by cutting in half both the beams stacking time in collider ring and the power used in the injectors chain. In the magnet design reported in [4] the two beam gaps are arranged in the vertical plane. The vertical alignment of the beam gaps equalizes orbits for the both beams thus eliminating the swapping of beams orbit required to equalize the circulation period through the common RF section. In addition, the beam loss and/or beam particle decays are emitted into the space away from the magnet core suppressing potential for radiation damage of superconductor cable. In this magnet design high current density of superconductor strongly minimized the size and total mass of power cable as well as its exposed area to the magnetic field descending form the magnet core. The small size of power cable strongly minimizes in turn the required size of the magnetic core making the use of dual-bore magnetic core cost-effective.

The critical current for the HTS strands depends on both the crossing *B*-field strength and its orientation toward the strand surface. At the very low *B*-fields (e.g. < 0.1 T) however, strand orientation toward the magnetic field has only minor effect on the critical current, and the conductor power loss is dominated by the magnetic hysteresis rather than eddy currents making cryogenic power loss to scale mostly linearly with the *dB/dt* rate. The HTS magnet power test reported in [4] provided only an upper limit of < 1.6 W/m for the cryogenic power loss at *dB/dt* magnet ramping rate of 12 T/s. This was determined based on the temperature sensors sensitivity of +/- 0.1 K. But analysis of the combined cryogenic power loss data for the HTS conductors exposed to 12 T/s in [4] and to 24 T/s in [5] indicates that the actual cryogenic power loss is likely to be only at about 0.12 W/m, or an order of magnitude less than that the upper limit deduced in [4].

Based on this analysis new tests are planned to extend magnet operation up to the *dB/dt* rate of **200 T/s** with expectation of the cryogenic power loss to be in the range of just a few W/m. The measurement of the electrical power loss due to high ramping current rate in the resistive portion of magnet power system components will also be carried out. The total power loss for the fast-cycling HTS magnet system will be projected and the power requirement expectations for its use in e.g. the muon collider [1] and the proton booster [3] accelerators will be outlined. In the process of fabrication of HTS rapid-cycling magnet prototype we found that the multi-strand power cable assembly as well as its installation within the magnetic core space requires further engineering work to simplify and lower the cost of assembly technique. In addition to the REBCO type strands used in [4,5] the newly developed MgB_2 strands [6] should also be tested as they are much less expensive and mechanically easier for magnet power cable assembly. Although their critical temperature of slightly under 40 K is about half of that for the REBCO strands it is still high enough to consider for the magnet fast-cycling operations.

The R&D of both the short-sample variety of HTS cables and magnet prototypes need to be carried out in order to develop the cost-effective rapid-cycling HTS magnet assembly techniques which will be suitable for the large-scale accelerator magnet production. We believe that a comprehensive R&D program towards development of the fast-cycling accelerator magnet technology based on the HTS superconductors should be started in the US.

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