Fiber-optic quench detection system for future accelerator magnets

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Accelerator magnets fabricated using high temperature superconductors are going to be an essential element for the next generation of high energy physics machines (Muon Collider, HE-LHC, future proton-proton collider).

Indeed, Muon collider will require the employment of magnets capable to operate at a high ramping rate that cannot be guaranteed with the present NbTi and Nb_3Sn technology. Future hadron-hadron colliders will need a magnetic field above 16 T. Indeed, one of the high priorities identified by the European Strategy for Particle physics has been the ramping up of the R&D efforts on developing high field superconducting magnet. A very similar goal has been identified by the US Magnet development program (US-MDP).

The NbTi dipole magnets currently installed in the LHC can generate a 9 T field. The US Accelerator Upgrade project together with CERN is fabricating 25 Nb_3Sn quadrupoles for the upgrade of the LHC interaction region [1]. Those quadrupoles are the state of the art of Nb_3Sn technology with a peak magnetic field of around 12 T. In within the US-MDP program, several efforts have been dedicated to the fabrication Nb_3Sn dipole with a field > 15T. A 14.5 T record field has been recently measured during a vertical test in superfluid He carried on at Fermi National Laboratory [2].

In this scenario, it is evident that HTS magnets will be the fundamental ingredient to produce a field in the 16 T region for future HEP machines.

Considering the high cost of high temperature conductors: REBCO and Bi-2212, several R&D efforts have been already focused in designing hybrid magnets [3-7], with a field of 11-12 T generated by Nb_3Sn dipole and a field of 5 T generated by the HTS magnet insert. Hybrid magnets represent the best opportunity of generating field above 20 T.

However, HTS technology still present several challenges.

We perceive that one of the most significant issue in HTS technology is the lack of a robust quench detection system. Indeed, quench development and propagation are much slower in HTS coils: the order of magnitude being around mm/s for HTS [8,9] and around m/s for LTS magnets. Discrete voltage taps are ineffective for slow quench propagation and local temperature in HTS system may cross the safe threshold for conductor degradation before a quench is detected.

Over the past 20 years, fiber optic sensors have been identified as a very promising diagnostic tool for superconductive magnets [10]. Fiber optics are cheap and well-established technologies employed in several industrial sectors. The working principle of those sensors is very simple: the spectral shift observed in the fiber can be directly connected to strain and temperature variations [11]. Therefore, those sensors can be used to monitor strain and temperature variations over the entire lifetime of a magnet: cooldown, energization and quench [12].

The employment of fibers presents several advantages: fibers are not sensitive to electromagnetic fields and can in principle being co-wound with a coil [12] and used to exactly identify quench location and energy spectrum in superconducting magnets. Those sensors can be divided in two main categories: discrete sensors based on Bragg grating principle (FBG) or distributed sensors based on Rayleigh, Raman or Brilluoin backscattering.

Several studies have demonstrated the potential use of fiber optic sensors in Nb_3Sn magnets and in HTS coils.

FBG fibers have been found to be effective in measuring coil and structure strain in MQXF magnets [13]. Moreover, it has been proved that those fibers can be successfully wounded in a coil and can survive epoxy impregnation process.

Distribute fibers based on Rayleigh backscattering appears be a very promising tool for quench detection in HTS coil. Those sensors could provide significant advantages over traditional techniques for detecting normal zones [14]. Fibers were also integrated into a REBCO conductor architecture and demonstrated strain sensing capabilities as well as thermal perturbation detection and localization with higher spatial resolution than taps [15]. In addition to the quench detection, the distributed sensing capability offered by fiber optics can be useful to understand the origin of the onset of flux-flow voltages.

Although those sensors have strong potential, recent results suggest that the claim of a shorter time response of optical fibers [14] compared to other diagnostic tools deserves further investigations [16]. It is evident that significant technical challenges still need to be addressed to make this technology mature and robust to be integrated in future HEP machines.

The more urgent need is to increase the sensitivity of those sensors. Indeed, later attempts to use fibers to detect quench in HTS have shown that signals were too weak to be detected. Moreover, fiber optics are not sensitive to temperature below 50 K. Future machines will probably work at relative low temperature ($T < 4.5$ K). The short-term R&D efforts should build on the work already performed on coating for FBG sensors [17, 18, 19]. Further developments are required in order to identify the best coating material to improve sensitivity and optimize signal to use those fibers as temperature sensors.

Strain and temperature effects cannot be separated in an easy way. Proof of principle experiment have demonstrated that the fiber can be wound and used in a strain free configuration. A practical and efficient solution need to be found in order to distinguish the two effects and use those sensors to separately detect small temperature and strain variations.

Fibers are fragile and can be fabricated with several coating materials. Mechanical properties and installation process need to be defined and scaled up to industrial level if we want to install them on a large amount of large superconducting magnets.

A trade-off between spatial and temporal resolution needs to be identified to use those sensors. Technical solutions for improving the data acquisition system deserve further investigation in order to optimize the signal processing. Indeed, the capacity of detecting a quench is correlated to a real time signal processing of time variations of the spectral shift. In principle spatial/temporal resolutions can be tuned and modified according to the needs, making those fibers a very promising quench detection tool for LTS-HTS hybrid magnets where integration is the major challenge.

At present fibers have proven to be promising tools at the level of proof of principle experiments. The work performed over the next 5-6 years will be crucial to identify optimal materials to improve sensor sensitivity and to find practical solution to separate strain and temperature measurements. The

HTS magnets fabricated in within the US-MDP program could provide excellent testbeds for the proposed studies.

Further developments and novel technical solutions for optimization of data acquisition will be necessary to make those sensors a robust and reliable tool. The long-term goal would be to integrate fibers in above 20 T hybrid magnets making them a solid quench detection system for future HEP machines.

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