Rayleigh-backscattering Interrogated Optical Fibers as part of a Quench Protection Approach and as a supporting technology for the Development of REBCO-based Accelerator Magnets

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Introduction and background

High temperature superconducting (HTS) materials offer unprecedented advantages to generate high magnetic fields required by future particle accelerators, fusion energy systems and other applications in power, medical and defense systems. HTS conductors have achieved performance levels and homogeneity that are relevant for accelerator magnet applications [1]–[3]. Remaining challenges, however, continue to limit the implementation of HTS conductors. One such limiting factor is the lack of an adequate monitoring system that ideally measures temperature and strain within the superconducting magnet (SCM) for rapid and early detection of incipient failure [4]. The primary failure mechanism, and the most critical one, for all superconducting materials is referred to as quench, and corresponds to the transition of the superconductor to the normal state. The transition to the normal state, which starts locally from what is referred to as a normal zone, is accompanied by the generation of Joule heating. Normal zones are created unexpectedly and unpredictably by external perturbations, such as particle showers or loss of coolant, or by internal perturbations such as materials defects or local, excessive strain [5]. Once a normal zone is initiated, it spreads with a characteristic speed, known as the normal zone propagation velocity (NZPV). HTS have a significantly lower NZPV compared to their low temperature counterparts, such as NbTi and Nb_3Sn [6]–[9]. Due to a slow NZPV and potential electromagnetic background noise, quench detection based on voltage monitoring is not adequate to ensure effective protection of HTS devices in any operating condition.

The aim of any quench protection system is to prevent permanent conductor degradation in the event of a fault condition that induces a quench. Quench protection involves three steps which must be accomplished within a short time-budget determined by the resilience of the conductor: (1) detection of a disturbance or hot-spot, historically accomplished via voltage measurements, (2) assessment of the disturbance to identify an incipient quench while preventing false-positives, and (3) protective action to prevent degradation if the magnet is quenching. For large magnets with a large stored energy, step (3) is typically accomplished through heaters embedded in the magnet and a dump circuit into which the stored energy is dissipated. The key to quench protection is preventing degradation by limiting the localized temperature rise relative to the ability to detect and protect within the time available before degradation occurs [5]. To determine the time budget, one must understand both the quench dynamics and the operational limits of the conductors; these two factors determine the time budget for protection.

Rayleigh backscattering interrogated optical fibers (RIOF) have shown to be a valuable approach to quench detection in HTS. One of the several intrinsic advantages of optical fiber sensing over voltage based approach is their immunity to electromagnetic noise [10]. RIOF can be integrated with conductor or cables providing a distributed measurement of temperature and strain with very high spatial and temporal resolutions [11]–[14]. So far, the RIOF technique has been demonstrated in HTS via co-winding optical fibers with HTS conductor [12], [15], via direct integration into REBCO conductors, and via integration into REBCO-based CORC® cables. Embedding optical fibers into single REBCO conductors gave rise to a self-monitoring, "SMART" conductor that is able to monitor its health via temperature and strain measurement along the conductor length with spatial resolution of a few millimeters [11]. Analogously, integration of optical fibers into the architecture of HTS cables give rise to a "SMART" cable with unchanged electrical and magnetic performance, but with the added temperature and strain monitoring capability [13], [14].
On-going R&D is advancing prior accomplishments and addressing key technical issues of RIOF quench detection by demonstrating the essential elements required to become an accepted sensor within SCMs. Furthermore, customer confidence, a key non-technical issue for implementation of RIOF in magnets, has improved through joint experiments in collaboration with Lawrence Berkeley National Laboratory.

Proposed work that would benefit HTS accelerator magnets

HTS accelerator magnets would benefit from the development of a RIOF-based magnet management system tailored specifically to meet particle accelerator magnet designs and prototype developments. The benefit to the particle accelerator community would be two-fold:

- a quench detection system based on RIOF and tailored to the needs of particle accelerators would make the accelerator's magnet system more resilient towards potentially destructive quenches;
- the use of the current RIOF technology would already be able to enhance and accelerate the development of innovative accelerator magnet concepts, such as the Canted Cosine Theta (CCT).

As innovative accelerator magnet designs are emerging, such as the Canted Cosine Theta (CCT) concept, a health monitoring system based on RIOF would facilitate their technical advancement as well as guide the magnet development towards maximum failure resilience. This can be achieved through an enhanced understanding of CCT magnet stability, quench behavior, strengths and weaknesses of the CCT design, such as the influence on quench behavior of radius of curvature of the conductor, groove design, and mandrel architecture. The aforementioned challenges cannot be addressed simply by monitoring the voltage. In addition to the R&D work that would enhance and accelerate the development of CCT coils as a dipole magnet technology for accelerators, the advancement of a RIOF magnet monitoring system tailored on accelerator needs would also provide unparalleled failure detection capabilities. RIOF R&D goals that are specific to accelerator magnet systems are an increased fiber interrogation length, dedicated fiber integration method that is compatible with the large Lorentz forces generated during accelerator operation, and enhanced thermal sensitivity at and below 4.2 K.

Although the RIOF technology is best suited to HTS magnets simply because it represents a solution to the most pressing technical challenge associated with HTS, it can be applied to any superconducting magnet, via a dedicated design of the optical fiber integration method.

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