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Acoustic emission during quench training of superconducting accelerator magnets

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ABSTRACT

Acoustic emission (AE) sensing is a viable tool for superconducting magnet diagnostics. Using in-house developed cryogenic amplified piezoelectric sensors, we conducted AE studies during quench training of the US LARP's high-field quadrupole HQ02 and the LBNL's high-field dipole HD3. For both magnets, AE bursts were observed, with spike amplitude and frequency increasing toward the quench current during current up-ramps. In the HQ02, the AE onset upon current ramping is distinct and exhibits a clear memory of the previously-reached quench current (Kaiser effect). On the other hand, in the HD3 magnet the AE amplitude begins to increase well before the previously-reached quench current (felicity effect), suggesting an ongoing progressive mechanical motion in the coils. A clear difference in the AE signature exists between the untrained and trained mechanical states in HD3. Time intervals between the AE signals detected at the opposite ends of HD3 coils were processed using a combination of narrow-band pass filtering; threshold crossing and correlation algorithms, and the spatial distributions of AE sources and the mechanical energy release were calculated. Both distributions appear to be consistent with the quench location distribution. Energy statistics of the AE spikes exhibits a power-law scaling typical for the self-organized critical state.

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1. Introduction

Superconducting accelerator magnets are engineered and built with a goal of achieving the design field within a minimal number of quenches. The process of gradual improvement of the spontaneous quench current with every consecutive quench toward reaching a plateau is known as "training" [1–5]. It is a complex phenomenon that involves various types of mechanical motion, micro-crack formation and structural adjustments caused by the Lorentz forces and the associated strain. Lengthy training is not considered acceptable for magnet production and operation in particle accelerators. Minimizing it is considered critical when choosing the best-suited magnet technology for the large accelerator projects, such as the high-luminosity LHC. In order to understand training and properly address it with improvements in magnet design, an adequate set of quench diagnostics and analysis techniques is required. However, despite a long history of accelerator magnet development, such techniques remain limited. In a typical accelerator magnet access for various quench probes is severely constrained by the tight structural packing; the probes may also interfere with the strict requirements for the mechanical and electrical magnet integrity. Strain gauges attached to coils and magnet structural elements, pickup-up loop arrays (quench antennas) in the magnet bore, and voltages from coil segments are typically employed for quench studies. Spatial resolution of all these probes is generally limited by the sparse separation between sensing elements; this limitation becomes more severe for longer magnets, as progressively larger sensor arrays are required. Another challenge for understanding magnet training comes from the complexity of a typical magnet structure, as multiple elements can simultaneously contribute to the premature quenching.

An ideal diagnostic technique should therefore be able to provide spatial information, yet be non-intrusive – preferably using sensors located outside of the magnet structure. One such promising technique is acoustic emission (AE) diagnostics that has a long history [6–11] and nowadays is used extensively for non-destructive evaluation of mechanical stability in various engineering and manufacturing fields. The first use of AE for diagnostics of quench origins in current-carrying superconductors was demonstrated in 1981 [6]. The technique was later used for diagnostics of a superconducting solenoid [7], and adopted for quench localization [8]. Attempts were made to relate the amplitude of AE bursts to the

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energy released in the mechanical events during magnet operation [9]. Among advantages of the AE technique are its speed, insensitivity to magnetic fields, excellent adaptability and portability, noninvasiveness, and low cost of setup and operation.

In the present paper, we first review known origins and mechanisms of AE in the superconducting accelerator magnets, and discuss our AE instrumentation, calibration and signal analysis tools. Next, we present an investigation in the AEs measured during training of Nb_3Sn superconducting accelerator magnets recently built and tested by a LBNL and US LARP collaboration. We demonstrate localization of the AE sources during magnet operation and discuss spatial correlation between AE sources and quench locations in the LBNL's high-field dipole HD3. Energy statistics of the AE events is collected during current ramping to quench and results are discussed in connection with the self-organized criticality model that is universally applicable to a large class of complex physical systems.

2. AE sources in superconducting magnets

When a superconducting magnet is energized and brought to a quench, a number of mechanical and electromechanical phenomena are taking place that can result in AE [10,11]. A high-field Nb_3Sn accelerator magnet is typically pre-loaded at room temperature azimuthally and axially, in order to prevent motion in the coils under the Lorentz forces. Significant (>100 MPa) stresses within the magnet coil windings during assembly, cooldown and energizing lead to local deformations, epoxy cracking and slip-stick motion of the conductor and coil parts. These mechanical events are typically the strongest sources of AE. As magnet training continues, new regions of the coil explore progressively larger force variations. The acoustic activity is expected to reflect this process. Apart from purely mechanical events, some AE activity also originates from the numerous flux jumps occurring in the Nb_3Sn conductor when the magnet is energized, typically at ~10–20% of the operational current. Flux jumps cause transient local redistribution of the current path in the cable at a sub-millisecond timescale. In a background of a strong magnetic field, these current excursions translate into perturbations of the local Lorentz force and hence produce stress waves in the material propagating away from the source with a speed of sound. This mechanism of AE is similar to the one used in electromagnetic ultrasonic transducers (EMATSs) to generate high-frequency ultrasound [12]. The flux jump induced AE bursts are typically smaller in amplitude than those induced mechanically, and also shifted to higher frequencies [13]. Finally, the most prominent AE event occurs upon quenching of the superconducting magnet. In this case, a sudden formation of a hot spot within the cable generates a volume of locally-elevated stress that subsequently relaxes via acoustic wave generation, followed by a "shake-up" of the entire structure upon current extraction.

Micro-cracks, conductor slip-stick motion and flux jumps are normally local in nature, and therefore can be treated as AE "point sources" for analysis purposes. Stress waves emitted by such point sources propagate within the magnet and become partially converted into the resonant vibrational modes of the magnet structure. Those vibrations can persist over a much longer period of time than the duration of the initial stress wave burst, due to relatively high (~100) mechanical *Q*-factor of the magnet structure at low temperatures [13]. The background mechanical vibrations may complicate instrumental separation of the acoustic events that are closely-spaced in time. There also exist other generic sources of background noise associated with the cryogen boiling and the magnet test facility operations. Those disturbances, however, are not localized and typically external to the magnet. Therefore AE source localization techniques can be effective for separating the useful signals. In reality, external noises are not too significant, as high mechanical *Q*-factor of the magnet impedes acoustic energy exchange with the environment.

3. Instrumentation

The main components of the AE detection system are amplified piezoelectric sensors, fast DAQ and post-processing software. We use ring-shaped transducers made of SM118 (PZT-8) type piezoceramics (Steminc, Inc.). The transducer dimensions are 10 mm outer diameter, 5 mm inner diameter and 2 mm thickness. The transducer is integrated mechanically and electrically with a preamplifier board (see Fig. 1a), and the entire assembly is installed on a magnet using a single aluminum set screw passing through the center of the transducer. The preamplifier (gain ~ 3–5) compensates for the reduction of the piezo-transducer sensitivity upon cooling, and converts the high impedance of the bare sensor down to several kΩ, thus significantly reducing electrical background noise at the ADC input. It is based on a single *p*-channel enhancement-mode GaAs MOSFET allowing operation in a wide range of temperatures from ambient down to liquid helium temperature [14]. Cryogenic operation of the transducer/preamplifier assemblies was verified using a "stick" cryogenic insert to the transport helium Dewar, prior to installation on the magnet. The preamplifier is interfaced to the ADC through an ambient-

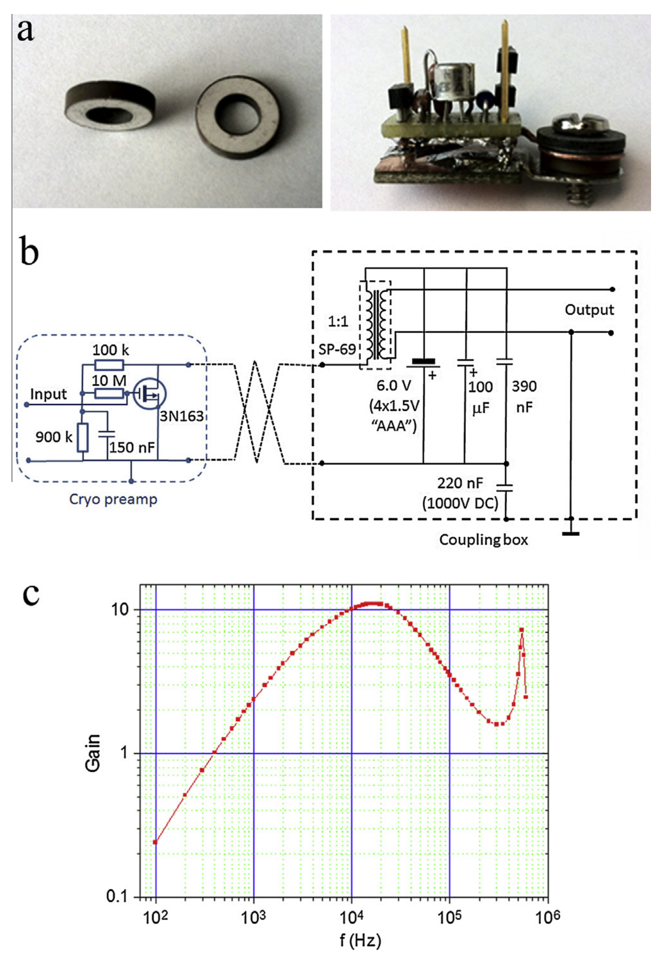

Fig. 1. (a) (left) Ring piezoelectric element used as sensing element; (right) an assembled sensor with integrated cryogenic preamplifier. (b) Electrical schematics of the cryogenic preamplifier and the coupling box. (c) Frequency response curve of the MOSFET preamplifier (measured at ambient temperature).