Understanding and mitigating training in superconducting accelerator magnets using acoustic techniques

Maxim Marchevsky
Accelerator Technology and Applied Physics Division, Lawrence Berkeley National Laboratory
mmartchevskii@lbl.gov

The phenomenon of "training" has baffled superconducting magnet designers for over 40 years [1-7]. Training is a process of gradually improving magnet performance with repetitive quenches required to reach the design current. It is a costly and time consuming procedure that nearly every newly constructed magnet has to undergo prior to its intended use. A striking example is the commissioning and training campaign of 1232 dipoles of the LHC that has consumed several years of magnet test facility operations [8]. Upon thermal cycling magnets would typically sustain the "memory" of the previously reached current level, but eventual de-training may also occur [9]. Finding causes of training and eliminating them would dramatically reduce costs and shorten development time for future colliders. High-temperature superconductors (HTS) are being increasingly advertised as a training-free alternative to the present technology [10] but given their high manufacturing costs and uncertainty with respect to stress-tolerance [11] and protection [12] it is likely that either Nb_3Sn or Nb_3Sn/HTS hybrids will be used in next generation accelerators and so the training issue will remain standing for a foreseeable future. Certain empirical recommendations have been developed early on by the superconducting magnet community with respect to training reduction [13,14], and successful implementation of those recommendations allowed to accelerate or even completely eliminate training for some magnets [15]. However, no *universal* solution has ever been found, and every newly built magnet still represents an unknown with respect to its training behavior. With the present proposal we aim at using advanced instrumentation to address the physics of training and seek a universal solution to this problem that would be independent of a particular magnet design.

It can be argued that training is such a hard problem to solve because our means of studying its underlying physics remain very limited. Also, there are significant unknown factors complicating a meaningful analysis. The first such factor is the elastic energy U_{el} stored in the magnet at a given time. It is proportional to the accumulated strain ($\sim\varepsilon^2$), and depends upon structural and material aspects of magnet fabrication, amount of pre-stress, number of cooling cycles and energization history. Magnets are mechanically non-conservative: U_{el} is partially converted into heat during energization thought slip-stick conductor motion or cracking of the impregnation material, and training can be seen as a process that gradually "clears" this non-conservative behavior. Since for untrained magnets stress and strain distributions are not uniquely related, a "stress management" approach recently adopted by high-field magnet designers [16,17] was only occasionally successful in reducing training. Secondly, the exact nature of transient energy releases remains elusive, and it unclear if a particular quench triggering event is in any way "special" compared to other mechanical transients (and therefore can be identified as a "quench precursor"). Cracking and slip-stick motion occur deep inside the magnet coil windings and only take a fraction of a millisecond in most cases. This makes them inaccessible to the majority of existing diagnostic techniques. Finally, it is unclear if the mechanical memory is a statistical phenomenon or a result of some self-organizing behavior, and if any macroscopic parameters can be measured in the magnet to evaluate such memory without actually going through the quenching process.

Addressing these standing questions is crucial for understanding training. We intend to do so using acoustic diagnostic methods [18,19] that are uniquely suitable for this purpose. They allow for a direct yet non-invasive monitoring of mechanical transients, structural integrity and thermal releases in the bulk of the magnet. Acoustic instrumentation is robust and inexpensive compared to other diagnostics (such as fiber-optics) that are under development to gain similar capabilities. Acoustic methods were shown to:

i. Spatially localize mechanical transients and quench locations using time of flight techniques [20,21]
ii. Measure local energy release in those transients by relying on the known calibration methods [22]
iii. Record transient acoustic waveforms with a high temporal resolution and apply advanced spectral analysis techniques based on deep learning to classify various mechanical event types

In addition to passive methods, active techniques have been developed recently that involve sending a pulsed acoustic excitation to the magnet and monitoring its response. Active acoustics allows to:

iv. Access interfacial stability during magnet energization and training cycle [23]
v. Measure real-time temperature variations in the bulk of the magnet [24]

A technique expanding capabilities of (v) to spatially localize heat sources in the magnet is presently under development at LBNL, and first results have already been demonstrated on conductor samples. Another promising application of active acoustics could be a precise focusing of ultrasonic excitation into a particular target volume within the magnet winding using time-reversal principles [25]. We aim to adapt it for direct measurements of non-elasticity (= dissipation) at a specified location in the bulk of the magnet through second harmonic generation [26]. Hypothetically, same approach can also be used to directly affect magnet behavior by enabling or facilitating local slip stick-motion with ultrasonic vibrations [27] of sufficiently large amplitude. If successful, it would open up a practical way for mitigating premature quenching and accelerating or bypassing the training process altogether without quenching the magnet.

It is important to stress that all these diverse capabilities can be achieved using a unified instrumentation suite that would include an array of cryogenic acoustic sensors mounted along free magnet surfaces, several ultrasonic transducers to provide pulsed and arbitrary waveform ultrasonic excitation, and a specialized software for transducer control and signal analysis. Several key components of such package already exist or under development by the US Magnet Development Program (US MDP). In a short term (2-3 years) we propose to finalize and complete this package, compile a unified diagnostic measurement protocol associated with it, and develop a synergistic analysis approach to correlate acoustic data with the data obtained with other diagnostics such as voltage taps, quench antennas, optical fibers, etc. Then, in a longer time frame (5-10 years) we would systematically deploy our acoustic diagnostic package for accelerator magnet tests conducted by the US MDP, as well as tests conducted for various specialty magnet projects (medical gantries, test facility dipole, fusion magnets) and large international collaboration such as AUP.

This way, a significant amount of unique diagnostic data will be collected, deeper understanding of transient mechanics in magnets under stress will be gained in a systematic way, and practical recommendation will be made for designing training-free accelerator magnets. This effort can be accomplished with a modest investment, and in a way that is minimally intrusive to magnets under test. It will have a significant impact on solving the training problem for the next generation of high-field accelerator magnets in future particle colliders.

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