Advancing superconducting magnet diagnostics for future colliders

M. Marchevsky*, R. Teyber, M. Turqueti, *Lawrence Berkeley National Laboratory*
M. Baldini, E. Barzi, D. Hoang, S. Stoynev, S. Krave, J. DiMarco*, Fermi National Accelerator Laboratory*
P. Joshi, H. Song, J. Muratore, *Brookhaven National Laboratory*
*mmartchevskii@lbl.gov

Future colliders will operate at increasingly high magnetic fields, pushing the limits of electromagnetic and mechanical stress on the conductor [1]. Understanding factors affecting superconducting (SC) magnet performance in challenging conditions of high mechanical stress and cryogenic temperatures is only possible with the use of advanced magnet diagnostics. Diagnostics provide a unique “observation window” into mechanical and electromagnetic processes associated with magnet operation, and give essential feedback to magnet design, simulations and material research activities. Development of novel diagnostic capabilities is therefore an integral part of the next-generation magnet development, and the following technical questions are expected to shape it for the near future:

1. How do we resolve and properly identify mechanical and electromagnetic disturbances in SC Nb_3Sn magnets [2,3] and understand the physics of the training process?
2. How do we non-invasively localize weak points and interfaces where mechanical disturbances that cause premature quenching are taking place? Can we manipulate those interfaces *in situ* to improve magnet performance?
3. How do we achieve a reliable and minimally invasive quench detection and localization capability for HTS [4-7] and hybrid HTS/LTS [8] magnets? Can we practically realize a new paradigm of HTS magnet operation where quenching can be avoided altogether through an early detection?
4. How do we resolve current sharing patterns and stress-driven defect accumulation in HTS coils and cables to ensure their long-term operational stability and quenching resilience?
5. Can we advance magnetic field measurements to the next level using arrays of miniature magnetic sensors combined with computationally-advanced field reconstruction algorithms?
6. Can we drastically simplify diagnostics instrumentation while making it more efficient and reliable by using cryogenic electronics, in particular FPGAs and quantum sensors?

A broad spectrum of novel diagnostic approaches is already being explored to address some of these critical questions by the multi-lab Diagnostics Working Group collaborating in the framework of the U.S. Magnet Development Program [9]. Acoustic instrumentation leveraging advances in piezo-sensors and compact cryogenic amplifiers allow for non-invasive measurements of mechanical energy release in magnets, 3D triangulation of mechanical disturbances and quenches in complex magnet systems with an accuracy of few centimeters [10], as well as “fingerprinting” the disturbances using machine learning techniques. Diffuse-field ultrasonic methods allows for a non-invasive detection of hot spots in HTS coils and conductors [11] and structural integrity monitoring. Magnetic quench antennas [12] and Hall sensor arrays [13] enable mapping of current redistribution, conductor instabilities and quench development in LTS and HTS magnets. New techniques such as fiber-optics [14] and capacitive sensing [15] are being actively explored, aiming at a local real-time monitoring of magnet strain and temperature. Novel analog and digital electronics for liquid helium temperature operation empowering new diagnostic instrumentation are being designed and tested.

An optimal diagnostics plan for the next 10-15 years is to develop and implement an integrated diagnostics package of novel sensor hardware, electronics and data analysis techniques for real-time, non-invasive monitoring of LTS, HTS and hybrid magnets. This entails synchronous acquisition of voltages, acoustic, magnetic and optical data for magnets under test, and a synergistic data analysis. The end goal of such development would be the application of this advanced diagnostic system to existing and future accelerator magnets and magnet test facilities. Our R&D proposals for SC magnets diagnostics include the following:

- Develop a next-generation acoustic emission diagnostic hardware capable of self-calibration to drastically improve disturbance triangulation accuracy and “fingerprinting”. Use it to study physics of quench-triggering disturbances and mechanisms of mechanical memory and training in Nb_3Sn magnets.
- Establish fiber-optic based diagnostic capabilities through the use of Fiber Bragg Grating (FBG) and Rayleigh scattering-based sensors to measure elastic deformations, localize hot spots (especially in HTS magnets) and probe mechanical disturbances in SC cables [16].
- Improve accuracy of voltage, magnetic and acoustic-based diagnostics through calibration using distributed spot heater and piezo-transducer arrays.
- Bring magnetic diagnostics to the next level through development and use of flexible multi-element quench antennas, large-scale Hall sensor arrays and non-rotating field quality probes, aiming at understanding electromagnetic instabilities in LTS magnets and imaging current-sharing patterns in superconducting cables and HTS magnet coils. Develop new algorithms for current flow reconstruction and disturbance localizations.
- Design and conduct innovative small-scale experiments to probe training behavior and energy release in impregnated cables under similar loads as in the magnets [17,18].
- Develop new methods for reliable and robust quench detection and localization for HTS magnets and hybrid LTS/HTS magnets.
- Use diffuse field ultrasonic techniques to enable targeted delivery of vibrational excitation to the conductor, for a non-invasive structural local probing of SC coils and mitigation of their training behavior.
- Apply machine learning and deep learning approaches to process diagnostic data and identify real-time predictors of magnet quenching
- Develop cryogenic digital and analog electronics to facilitate, simplify and improve reliability of diagnostic instrumentation by enabling pre-processing of magnet diagnostic data in the cryogenic environment.

A synergistic analysis of data acquired by these diverse diagnostic techniques will bring us closer to answering key technical questions that define SC magnet performance. It is an ample and comprehensive program with the aim of developing an integrated system of hardware and software solutions applicable not only to the U.S. MDP SC magnets, but to any other SC accelerator magnet and also magnets for test facilities. The effort should extend well beyond MDP and engage instrumentation experts across national and international labs.

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