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# Artificial Intelligence and Machine Learning Techniques for Superconducting Magnets: Towards Design, Optimization, Operation, Predictive Maintenance, and Smart Manufacturing[1]

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***Abstract*–Superconducting magnet is one of the most advanced and commercially available applications of superconducting technology. It has various types including research, Magnetic Resonance Imaging (MRI), Nuclear Magnetic Resonance (NMR), accelerators, high-field, and fusion magnets. These magnets are (or will be) significantly contributing to healthcare, physics, materials, energy and potentially power, transportation and space sectors. Fusion energy is now one of the promising trends of decarbonization for curbing the emissions, and decelerating the global warming, and it is expected to be one of the main drivers of superconductor manufacturing in near future.**

**The research in applied superconductivity, including magnets, is historically rooted in physics, material science/engineering, and electrical engineering. Traditionally, experimental tests at cryogenic temperature (fairly expensive), deterministic methods (occasionally inflexible to explain all the physics), rigorous mathematical modelling (sometimes inflexible in applying to new problems), and conventional modelling techniques (such as finite element methods (FEMs)), were used to solve problems within superconductivity. In terms of superconducting magnets, existing analytical and FEMs for design development and modelling of magnets largely focus on their application in narrowly defined areas tailored specifically to magnet design and development. However, superconductivity and specifically superconducting magnet technology now face the necessity of integrating data-driven and intelligent approaches to keep pace with new demands of technology to expand beyond its traditionally known and focused applications. This fortunately coincides with a transformative evolution in science and engineering, driven by the rapid advancements in artificial intelligence (AI). AI techniques have demonstrated unprecedented capabilities in design optimization, operation-level performance evaluation, predictive analytics, process automation, and real-time decision-making, all of which are becoming indispensable across magnet technology domain. On the other hand, recent advancements in AI, such as generative models, reinforcement learning,**

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**and advanced intelligent models, will enable solutions and unlock opportunities that were previously unattainable. For instance, AI-powered design optimization of superconducting magnets can drastically shorten development cycles; it will improve superconducting magnet's performance, manufacturing process and energy and cooling managements. Additionally, the global push toward sustainability, decarbonization, and digital transformation has created an urgent need for magnet engineers to integrate AI to address complex, and multidisciplinary challenges related to the predictive diagnostics and prognostics of such magnets especially in fusion applications.**

**Superconducting magnet designers, researchers, and manufacturers need guidance on adopting AI tools and methodologies to improve system efficiency, optimize designs, and address complex challenges including those related to fault, quench, deformations, sensor placement, etc. Practical examples and case studies showing real-world applications of AI in applied superconductivity are essential for translating theoretical concepts into actionable strategies. This necessitates some timely resources that bridges these gaps, offering insights into the latest AI tools, methodologies, and their potential applications in superconducting magnet technology. This goal requires a roadmap for implementing AI into superconducting magnet technology, ensuring that researchers/engineers across all levels understand the necessity to grasp AI's transformative potential.**

**According to my insights, I believe AI can provide solutions to many problems (which some of them are currently under research in my group), such as:**

- **AI-powered Optimisation of stellarator coils**
- **Design optimisation of superconducting magnets based on heuristic or meta-heuristic, or swarm-based algorithms.**
- **Data-driven loss prediction using machine learning techniques.**
- **Automating complex simulations for superconducting magnets.**
- **Quench detection/prediction using AI-enabled data-analytics.**
- **Mechanical defect detection using ML/DL-assisted techniques.**
- **AI for critical current density prediction of superconductors under Neutron, Ions, and Gamma ray irradiations in superconducting magnet in fusion reactors**
- **AI-assisted RUL estimation for magnet cryocoolers and cryogenic systems.**
- **Predictive maintenance of superconducting magnet systems.**
- **Smart manufacturing of superconducting magnets.**
- **Addressing sustainability challenges of magnet systems through AI-enabled resource optimization, and lifecycle assessments.**
- **Next step: Digital twins for superconducting magnets.**
- **Future trends: GenAI for superconducting magnets: manufacturing and operation.**

**The use of AI for advancement of the superconducting magnet technology directly supports 5 UN's Sustainable Development Goals (SDGs), including:**

- **Goal 3: Good Health and Well-Being – By presenting AI methodologies for superconducting MRI magnets to ensuring healthy lives and promote well-being for all at all ages.**

- **Goal 7: Affordable and Clean Energy – By utilizing AI techniques for superconducting fusion magnets to improving the efficiency of fusion energy systems and decarbonization technologies.**
- **Goal 8: Decent Work and Economic Growth – By promoting the adoption of AI to drive innovation, modernize magnet systems, and enhance magnet production and manufacturer's bottom line**
- **Goal 9: Industry, Innovation, and Infrastructure – By implementing AI to achieve smart magnet manufacturing process as well as new applications for superconducting magnets including in space applications.**
- **Goal 13: Climate Action – By focusing on AI applications for adopting the superconducting magnet technology to new industrial applications, accelerating the superconducting magnets development for fusion energy, sustainable design, and lifecycle assessments, contributing to global efforts in combating climate change.**

**This article is a resource for navigating the intersection of traditional superconducting magnet and AI technologies. By addressing the current and future needs of the domain, it empowers the researchers to contribute to a sustainable, innovative, and technologically advanced magnet landscape.**

***Keywords (Index Terms)*– Artificial Intelligence, Digital Twins, Fault Detection, Generative AI, Machine Learning, Superconducting Magnet, Surrogate Modelling**

Further reading:

[1] M. Yazdani-Asrami, et al. Roadmap on artificial intelligence and big data techniques for superconductivity. Superconductor Science and Technology, 36(4), 043501, 2023. DOI: 10.1088/1361-6668/acbb34

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[3] M. Yazdani-Asrami, et al. Smart fault detection of HTS coils using artificial intelligence techniques for large-scale superconducting electric transport applications. Superconductor Science and Technology, 36(8), 085021, 2023. DOI: 10.1088/1361-6668/ace3fb

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