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$15,000 "Move it!" Lemelson-MIT Student Prize Graduate Winner

SMART Conductor: optical fibers embedded within superconducting wiring to monitor for failures in High Temperature Superconductor systems and Enhanced Optical Fiber Sensors: optical fibers with increased thermal sensitivity at cryogenic temperatures

The Challenge: Superconducting electric motors have several advantages compared to conventional, copper-based electric motors. Due to a higher current density and extremely small or absent power losses, superconducting motors can achieve higher efficiencies and higher power-to-weight ratio compared to conventional motors. Unlike stationary applications, when a motor is used for propulsion (such as with aircrafts), maximizing the power-to-weight ratio is essential to increasing efficiency and range. Amongst all types of superconducting materials, High Temperature Superconductors (HTS) are by far the best option to build electric motors, because of their significantly higher current densities and operating temperatures, compared to Low Temperature Superconductors (LTS). Therefore, HTS' are the best option to build high efficiency, high power-density and carbon-free electric motors for ships, aircraft, and Magnetic Levitation (MagLev) trains. Additionally, HTS can enable a new concept of compact nuclear fusion reactor for power generation: the extremely high magnetic field produced by HTS' confines and shapes the plasma, which is the fuel for the reaction.

However, the use of HTS in any commercial application is being hindered by one major technical challenge: prevention of failures, which is mainly due to the lack of an effective failure detection system. When a superconducting material is in operation, the superconducting property can be lost unpredictably due to mechanical or thermal perturbations. When this happens, the superconducting region transitions to a normal state and generates a high level of heat. The heat generated is capable of irreversibly damaging the superconductor and destroying the magnet that is essential for operation, resulting in catastrophic failure of the motor, train or reactor. The high risk for failure

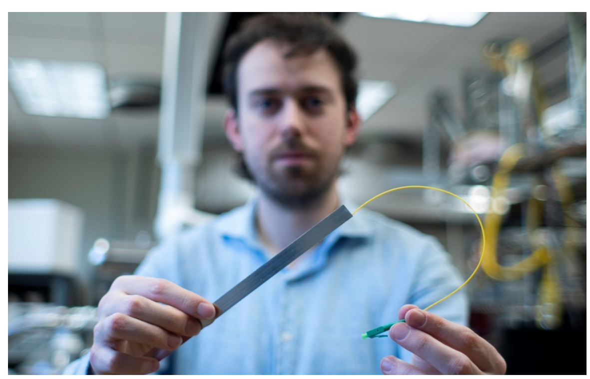

Figure 1: Federico with his primary invention, the SMART Conductor. Photo credit: Penn State College of Engineering.

of the superconductor is the primary factor hindering the application of HTS materials to build high power-density, high efficiency motors and MagLev trains.

The Solutions: Federico's primary invention aims to prevent superconductors from overheating and ultimately failing. His primary invention is an internal monitoring system for HTS, consisting of a sensing system to detect local, incipient failures in the HTS wire that generates the magnetic field needed to operate electric motors for carbon-free ships and aircrafts, carbon-free, high-speed MagLev trains, and nuclear fusion reactors for power generation. The sensing system is based on optical fibers embedded into superconducting wires that are able to prevent failure of the superconductor. Both strain and temperature changes are tightly correlated with the initiation of a failure event in superconducting materials. Federico's invention consists of an optical fiber co-wound with superconducting wire to form a fully monitored superconducting magnet, or the direct integration of optical fiber into the superconducting wire architecture, which he refers to as a "SMART Conductor." When the superconducting wire is disturbed (thermally or mechanically), the optical fiber detects and localizes a change in temperature or strain. The failure detection signal is then analyzed in real time and criteria are used to flag whether the event is an incipient failure. If so, the SMART Conductor allows for corrections to be made to prevent the failure from happening.

Relatedly, Federico's secondary invention consists of a method and materials to improve the thermal sensitivity of optical fiber sensors at cryogenic (extremely low) temperatures, typical of large current, large magnetic field applications, such as particle accelerators for fundamental physics research and cancer therapy. Commercial optical fiber sensors are effective and robust when used at room temperature, but have a very low sensitivity when operated at cryogenic temperatures. Federico's enhanced optical fiber invention increases the cryogenic sensitivity and response time via the application of a composite coating consisting of a unique combination of polymeric and metallic materials. Lastly, Federico's tertiary invention, which he refers to as "SMART Cables," is a method to monitor and sense failure of high current superconducting cables. Superconducting cables can be used for lossless power transmission, particle accelerators for high energy physics or radiation therapy (for example, a synchrotron for proton therapy for cancer), and nuclear fusion reactors.

Figure 2: Federico with his enhanced optical fiber sensor (secondary invention). Photo credit: Penn State College of Engineering.

Federico's secondary and tertiary inventions cover the remaining application realm of superconducting systems. In particular, they address challenges that are associated with larger currents and magnetic fields, and lower temperature, compared to the operating conditions of electric motors. Furthermore, all of his inventions have a significant social and environmental impact in that they could enable a new generation of transportation systems based on using carbon-free, high-efficiency electric motors and MagLev trains, leading to a drastic reduction of carbon emissions and energy resources.

Commercialization: All three of Federico's inventions have been patented and are licensed to a startup company, Lupine Materials and Technology (LMT). Some of his research has been supported by one of LMT's Department of Energy contracts and he anticipates a larger role in the company after finishing his PhD degree. Additionally, several companies are interacting with LMT to adopt its technologies in various applications. LMT also has existing programs in place and strong interest from government agencies such as the U.S. Navy, U.S. Air Force, and the Department of Energy.

Federico's inventions seek to satisfy the needs of customers who are looking to manufacture HTS electric motors and high-speed trains, but understandably have not had enough confidence in the reliability of HTS to previously bring these technologies to fruition. LMT aims to provide customized solutions for its clients by tailoring the implementation of the sensing technology to each company's specific needs and applications. Currently there are no competitors offering similar products and services, other than the conventional, state-of-the-art voltage monitoring system, which is known to be ineffective with HTS.

The available market for the commercialization of Federico's inventions is expected to grow significantly in the next decade due to the rapidly increasing introduction of electric propulsion in the transportation industry. The market analysis firm Research and Markets conducted a global market study for high-speed trains and estimated a compound annual growth rate of 5.5% from 2018 to 2025. The study noted that within all high-speed train technologies, the MagLev technology is projected to record the fastest growth, due to a high adoption rate.[1] In addition to high-speed trains, Federico's inventions are capable of penetrating other large markets, including electric motors for ships and aircrafts, compact fusion reactors, wind generators, and power grid devices such as transformers and fault current limiters. Furthermore, the reduction of fossil fuel used for transportation is an essential step in the fight to reverse climate change. Given that Federico's inventions enable carbon-free technologies, that market share should also grow. When each of these potential markets is considered, the overall market share for his inventions is significant and should continue to grow considerably throughout the future.

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[1] https://www.marketsandmarkets.com/Market-Reports/bullet-train-high-speed-market-203819069.html