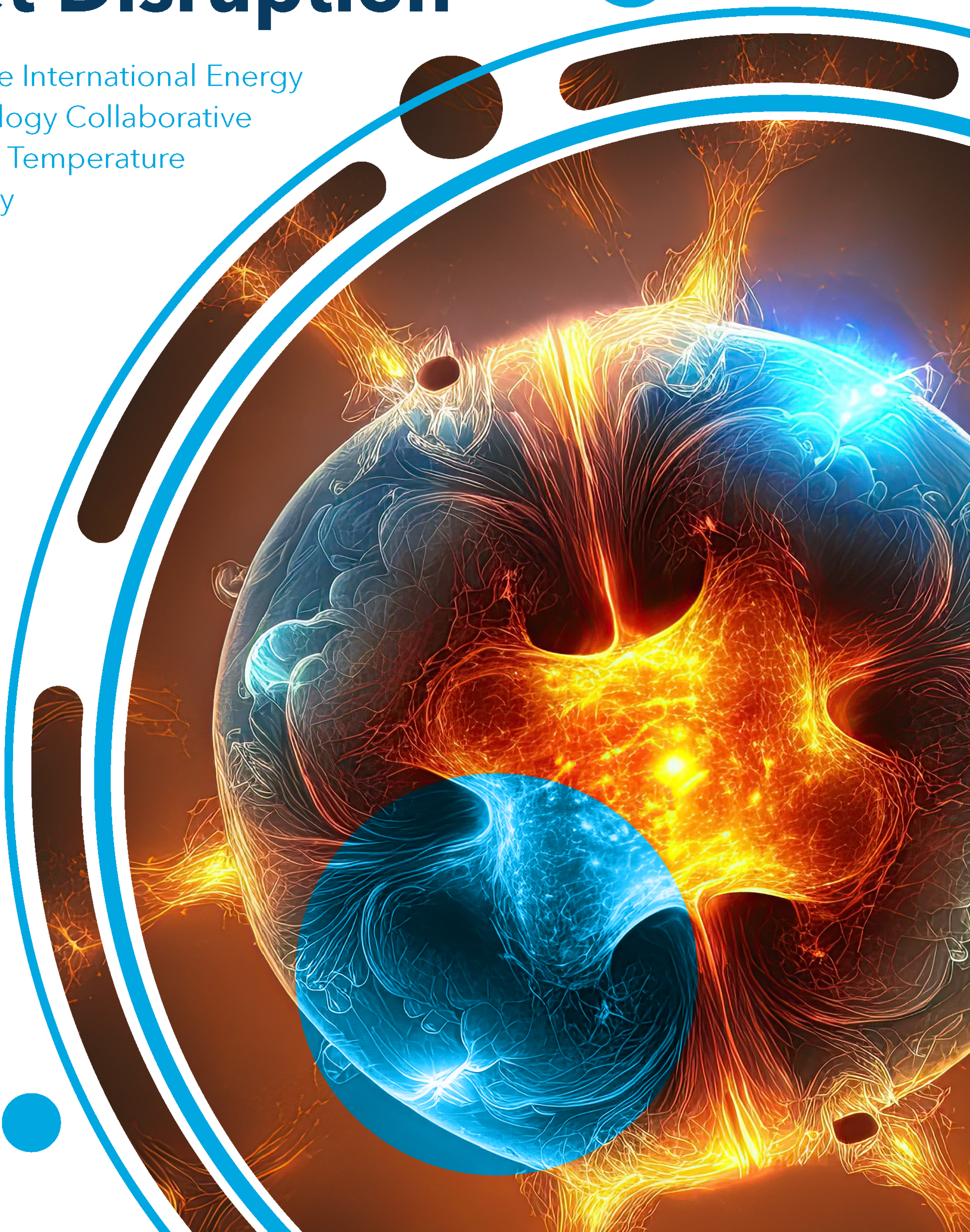
Superconductivity
INTERNATIONAL ENERGY AGENCY

HTS Wire Enabling Market Disruption

Developed by the International Energy Agency's Technology Collaborative Program on High Temperature Superconductivity



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Abstract

This document explores how various applications of high temperature superconducting wire can potentially disrupt markets. Several economic sectors use superconducting-based technologies, such as electric power, scientific research, industry, transportation and electronics. These applications use low temperature superconductivity (LTS) and/or high temperature superconductivity (HTS). HTS wire has the potential to disrupt some market sectors. However, there are several challenges, including the cost of the wire, manufacturing capacity, and heavily entrenched conventional technology solutions. Key developments that can overcome these challenges include increased manufacturing infrastructure and production throughput for wire. For example, HTS magnets enable significant space reductions for fusion reactors. Since these reactors will use thousands of kilometers of HTS wire, the manufacturing scale-up and resulting reduced wire cost have the potential to benefit other application areas that use superconducting wire. Superconductor-based applications provide improvements over conventional technologies, but they also offer unique capabilities that cannot be otherwise obtained. In addition, recent global efforts to significantly reduce or eliminate dependence on fossil fuels have presented opportunities for emerging technologies to help solve impending geopolitical and climate challenges. These efforts are encouraging countries to make investments that could improve the deployment of HTS applications.

Background

Superconductivity is a phenomenon that causes certain materials, at low temperatures, to lose essentially all resistance to the flow of electricity. The lack of resistance enables a range of innovative technology applications. The temperature at which resistance ceases is referred to as the “transition temperature,” or critical temperature (Tc). The temperature is usually measured in kelvin (K), with 0 K being absolute zero. HTS is so named because it has a higher transition temperature than low temperature superconductivity (LTS). Tc for HTS is higher than 77 K, which leads to the use of liquid nitrogen for cooling. Tc for LTS is slightly higher than 4.2 K, which which leads to the use of liquid helium for cooling Appendix A shows some general comparisons between LTS and HTS materials.

Devices based on LTS have been available in certain markets for decades. Superconducting magnets, in particular, are well-established in many applications that require very high magnetic fields—for example, powerful electromagnets, including high-energy physics particle accelerators and magnetic resonance and imaging (MRI) systems.

Starting from the discovery of HTS materials in the late 1980s, more than 30 years of research and development have brought new equipment incorporating HTS to the threshold of greatly improving the electric infrastructure. Laboratory scale tests have transitioned to large-scale HTS based projects that serve utility customers. HTS projects are being considered as permanent infrastructure to solve real-world electric grid problems. HTS materials have been employed or proposed for use in a variety of applications and sectors, including the energy, transportation, industrial, medical and defense sectors. HTS wire is the key enabler for making devices for the electric power system that are more efficient and compact, and offer greater resiliency, than conventional solutions.

Several examples of well-recognized types of superconducting materials include:

- BSCCO (Bismuth - Strontium - Calcium - Copper – Oxide), known as HTS first generation (1G)
- REBCO (Rare earth - Barium - Copper Oxide), known as HTS second generation (2G) REBCO may also be referred to as YBCO or GdBCO since they are the most commonly used rare earths in the manufacturing process

- MgB_2 (Magnesium diboride) with critical temperature around 35 K
- Nb_3Sn (Niobium-Tin) and Nb-Ti (Niobium-Titanium) used in LTS applications

Table 1 below provides several examples of applications for low temperature superconductivity and high temperature superconductivity as of 2022. In some cases, LTS is the predominant application, with little to no deployment of HTS. The converse is also true. In some instances, the applications are only at the research and development (R&D) stage.

Table 1. Examples of Superconducting Applications

	LTS	HTS
Magnetic Resonance Imaging machines	Available in major hospitals	R&D
Nuclear Magnetic Resonance (NMR)	Limited deployed in research facilities	Limited deployment in research facilities[1]; established market niche in high-field NMR spectrometers
Fusion reactors	Under development – International Thermonuclear Experimental Reactor (ITER)	Under development – examples include: Commonwealth Fusion Systems and Tokamak Fusion
Transmission and distribution cables	None	Limited deployment
Fault current limiters	None	Limited deployment
Ship degaussing systems	None	Limited deployment
Magnetically levitated transportation systems	Limited deployment	R&D
Rotating machines	R&D	R&D

One of the most critical components of a superconductive device is the cryogenic (refrigeration) system for achieving operating temperatures. HTS power applications use liquid nitrogen operating in the range of some tens of K, which is relatively ubiquitous and less expensive than liquid helium at 4 K used by LTS. Thus, HTS technologies have greater potential for achieving cost-effective solutions.

Superconducting-based devices do not simply provide improvements over conventional technologies; they provide unique solutions to challenges that cannot be achieved otherwise. Examples include fault current limiters, compact generators for offshore wind turbines, instantaneous high-power output energy storage, and high-power transmission cables that transmit at distribution voltage.

Market Disruption

Market disruption has become a general term to describe large-scale changes affecting businesses. David Edelman, an analyst at McKinsey and Co., defines market disruption as "a profound change in the business landscape that forces organizations to undergo significant transformation rather than steady incremental changes."[2] Historical

[1] Magnetic field in LTS NMR devices levelled off at around 23.5 Tesla because the engineering critical current density (J_e) for LTS-based magnets dramatically decreases above this value. In 2014, researchers overcame the 23.5 T upper limit for high-resolution NMR magnets by combining LTS outer coils with inner coils made from HTS, which retain a high J_e even at higher magnetic fields

[2] David Edelman and Jason Heller, McKinsey & Company, Marketing disruption: Five blind spots on the road to marketing's potential, October 1, 2014

examples include inventions such as the telegraph, electric power distribution, the automobile, rail travel and the internet. Each of these innovations caused an upheaval in traditional business practices.

This paper discusses how HTS wire could be a disruptive technology that would enable entirely new market developments in a some key business areas. The principle hurdle is the cost of consistently high-performing HTS wire. Studies have shown that viable HTS prices can be reached through high-volume manufacturing. Thus, an application that would use large volumes of wire could result in the necessary economies of scale.

Assessment of Market Applications

A potential application that would enable HTS wire to become a market disruptor would be deployment of magnetic fusion reactors, which would use large volumes of wire.

Electricity Generation from Fusion

Fusion power generates electricity by using heat from nuclear fusion reactions. In a fusion process, two lighter atomic nuclei combine to form a heavier nucleus and release energy. Devices designed to harness this energy are known as fusion reactors. A single gram of fuel (hydrogen) can yield 90,000-kilowatt hours of energy. For comparison, it would take 10 million pounds of coal to yield as much energy as one pound of fusion fuel.[3] Once the science and engineering is proven, commercial power plants have the potential to provide clean, safe, and abundant energy anywhere in the world.

Among various approaches to achieving a practical fusion power reactor, the tokamak is generally acknowledged as the low-hanging fruit accessible with current technology and experience. In a tokamak fusion reactor multiple "D-shaped" superconducting magnets, arranged in a ring, produce a toroidal magnetic field that confines a hydrogen isotope plasma, which is then heated to ignition temperature. At this temperature, the fusion reaction becomes self-sustaining (self-heating). The heat from the fusion plasma is mechanically converted to electrical energy. This type of reactor is also known as magnetic fusion.

The multi-national International Thermonuclear Experimental Reactor (ITER), being built in the south of France, will be the largest tokamak built to date at a cost of $20 billion. The project started in 2007 and is scheduled to produce a self-heating plasma in 2035. ITER was planned to be a research reactor and to produce a surplus of energy. ITER magnets use low temperature superconductors (LTS), which were the best available at the time the project started. Operating at supercritical helium temperature (4.6 K), LTS magnets produce a maximum field of 11 T.

The advent of 2G HTS (REBCO) wire has the potential to become a game changer for magnetic fusion. HTS magnets, which were not commercially feasible when ITER began, operate at a much higher and easier to achieve temperature of 20 K. As such, they can more than double the magnetic field, with concomitant increases in plasma temperature and power density. The current wire performance specification of 20 T, 20 K, Je = 750 A/mm^2 is acceptable for a Smallest Possible Affordable, Robust, Compact (SPARC) fusion reactor. Higher performance wire of 1000 A/mm2 has some benefits, but is not required. Manufacturing scale-up is the most important aspectt at this point.[4]

A tokamak with HTS magnets is conservatively estimated to be one-sixteenth the size of one using LTS. See Appendix B for more details. The benefits of HTS, according to proponents, will lead to lower costs, smaller organizations and a faster construction schedule than large tokamaks like ITER. While HTS wire is the

[3] Fusion Industry Association

[4] Brandon Sorbom, Commonwealth Fusion Systems, Presentation at the Applied Superconductivity Conference, October 2022.

enabling technology for SPARC and Affordable, Robust, Compact (ARC) fusion reactors, the cost of the wire is 10-20% and 5%, respectively, of the overall system cost.[5]

Figure 1 depicts the potential performance and market penetration of fusion reactors over time. The lower curve shows the ITER fusion reactor being developed using LTS. The upper curve shows that over time and engineering progress, HTS has higher performance characteristics.

The HTS transmission and distribution cable market, for instance, has the potential to benefit from fusion reactor market penetration. Some studies of wire cost versus production volume suggest that the requirement for a commercial reactors could yield wire costs that would make HTS applications viable, such as transmission and distribution cable.[6] A SPARC reactor requires 10,000 km of wire; ARC doubles that.[7] However, there are challenges to HTS cables becoming more widespread. These challenges are outlined in the next section.

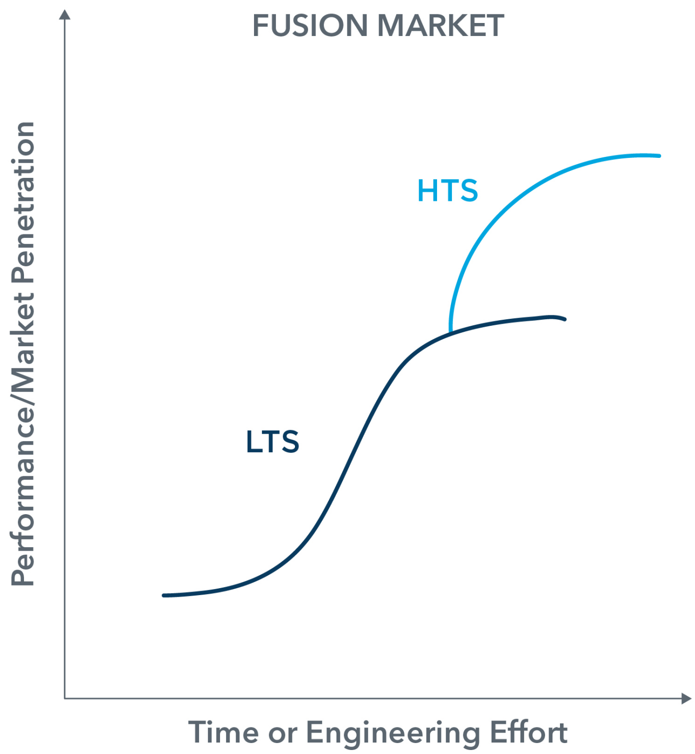

Figure 1. Performance vs time for the fusion market. *Source IEA HTS TCP*

Challenges to HTS Cables Becoming More Widespread

Factory Testing. Underground conventional cable is shipped from the manufacturing plant on large reels. The capacity of a shipping reel is limited to between 0.5 and 1 km, typically, depending on cable design and transportation methods. Factory acceptance testing for voltage integrity of solid electrical insulation is necessary for 100% of all reels shipped to the project site. Otherwise, a reel with potential insulation defects may produce failure in the field when first energized. Location of the failed section, removal, reinstallation and recommissioning is a costly and time-consuming process. Projects involving more than a very few reels of untested cable have a statistically high probability of encountering a faulty reel due to the inherent variability in any manufacturing process. Acceptance testing is therefore a standardized step in the manufacture of conventional cable. On one hand, at present, there is no means to perform HTS cable acceptance testing because today's HTS cable insulation requires wetting paper tapes with a liquid cryogen. Factory testing would require immersing an entire shipping reel in the liquid cryogen, which is clearly impractical. On the other hand, the HTS cable electrical insulation is the combination of lapped material, for instance polypropylene laminated paper (PPLP), and liquid nitrogen. Impregnation with liquid nitrogen will be performed on-site after cable installation. The likelihood of an insulation defect is lower than in the case of a conventional cable with a solid dielectric insulation. One option to further secure insulation is to develop standardized surrogate tests on cable samples from each reel, the results for which can be shown to apply

[5] Ibid.

[6] Molodyk, A., Samoilenkov, S., Markelov, A. et al. Development and large volume production of extremely high current density YBa2Cu3O7 superconducting wires for fusion. Sci Rep 11, 2084 (2021). https://doi.org/10.1038/s41598-021-81559-z

[7] Private correspondence with B. Moeckly, Commonwealth Fusion Systems, November 15, 2019.

to all of the cable on the reel with more than reasonable certainty. Another option is obviously to duplicate conventional cables, developing and testing an extrudable solid dielectric capable of performing at cryogenic temperatures but not requiring the reduced temperatures for its electrical insulating properties. The resulting cable could be factory-tested with essentially the same methods as conventional cable. There is research in the U.S. underway to develop such a dielectric.

Cryogenic and Vacuum Systems. There is a need for optimized and field-proven cryogenic systems for HTS cable installations that are essentially "invisible" to the end-user. Cryogenic refrigeration is a well-established industry for many applications, but for medium-sized systems in the range of few dozen kW@70K of cold power, there are no available systems designed specifically for HTS cables, whereas for larger-sized systems in the range of several 100 kW@70 K of cold power, cryocoolers for the liquified natural gas industry (reliquefication of methane on board) are perfectly suitable. Available refrigerator sizes also are not optimal today for medium-sized cable projects. Space within a substation is required to install the cooling system. In the dense urban locations which are the most attractive for this application, the refrigerator is to be installed in the substation which is the farthest from the city center. Operational characteristics and maintenance procedures are progressing towards unmanned systems with remote controlled systems and maintenance periodicity of 2 to 5 years. Additionally, there is little or no precedent for mechanical equipment installed inside utility substations beside chilling units for power electronics, nor for the presence of non-utility maintenance personnel that would be required to place the cooling station in areas where no electrical habilitation is required (possible thanks to cryogenic transfer lines). Electric utilities are generally very conservative and risk-averse, preferring equipment that is well-proven for the application and operations that are entirely under their control. Thus, achieving a higher TRL requires cryogenic systems that have been fully optimized, such as cryocoolers for the liquified natural gas industry. Operation and maintenance practices that are consistent with current electric utility industry standards are also needed, and Significant progress has been made through the publication in 2019 of IEC standards for AC superconducting cable from 6 to 500kV.

Cable Splices. Cable splices between installed sections are necessary for all underground cable systems. Cable splices are by far the weakest link in the cable system and are prone to failure if not properly constructed. Splicing must occur in the field, whether in permanent underground vaults or in temporary field facilities for later direct burial. Splicing is as much an art as it is a science. It requires clean conditions and a high degree of training. HTS cable splices have greater complexity which requires a longer repair time in case of failure. Indeed, splicing HTS cables involves integrating the vacuum cryostat in the splice joint. Several HTS cable systems in existence have demonstrated the feasibility of cable splices at both medium and high voltage. The methods for achieving highly reliable splices in the field can take advantage of increasing the use of prefabricated components and reducing on-site assembly.

Demand. Demand for HTS cables is currently not steady. Investments in these large capital intensive projects are not made routinely and are considered lumpy (i.e., long-term investments that are difficult to liquidate). Steady demand for wire going into cables and other applications would help stimulate manufacturing supply. As mentioned earlier, the use of HTS wire in several fusion projects would result in a long-term need for wire.

Conclusions

Manufacturing scale-up of HTS wire used in various applications can potentially enable market disruption if several challenges are overcome.

Policy to value CO_2. New policies to value CO_2 emissions could help to improve the penetration of HTS. Recent global efforts to significantly reduce or eliminate dependence on fossil fuels have presented opportunities for emerging technologies to help solve impending geopolitical and climate challenges. These efforts are encouraging investments by countries that could improve the deployment of HTS applications.

Synergistic applications. Other HTS applications can reduce costs by increasing manufacturing volume. Some paper studies of wire cost versus production volume suggest that the 20,000 km requirement for a commercial fusion reactor could yield wire costs that would make HTS transmission cable viable. This may be a "chicken and egg" situation, with fusion needing a viable transmission cable market and vice-versa, with neither ultimately happening. Other niche markets like rotating machines, mobility applications and FCLs could expand HTS.

Improved economics. The costs associated with manufacturing HTS wire due to sophisticated processes, low yields and limited throughput of the manufacturing processes makes it several times more expensive than copper wire. However, a very significant reduction of the REBCO tape cost can be envisioned for three reasons:

1. the cost is mainly process-driven, not material-driven, which means that it will decrease drastically with volume,
2. manufacturers gradually increase the deposition substrate width before slitting it in 3 or 4-millimeter wide tapes, which increases lot productivity,
3. any current increase translates into an almost proportional reduction of the number of tapes.

In addition, it is not reasonable to simply compare the cost of an HTS-based device to a conventional one. Because of the unique attributes of HTS devices, a *system* cost analysis should be conducted. Furthermore, if the raw material costs of conventional materials increase, HTS-based solutions could become more economical.

Improved process control. There is a general lack of manufacturing knowledge about producing HTS wires with nanometer-sized precipitates or phases uniformly distributed over kilometer lengths.

Proven long term reliability. End users are generally unfamiliar with the materials used in HTS devices and cryogenic systems. Data are not available that proves undiminished product-performance HTS components life-times of more than 30 to 40 years. However, most of the HTS cable system is maintained at -200°C, which virtually eliminates any aging.

Reduced business risk. Uncertainty for total cost of ownership and cost and availability of parts from suppliers in a relatively nascent market should be addressed.

It may be a matter of timing before market disruption occurs. Simply being in the right place at the right time is beneficial. The steepness of any market disruption trajectory is a function of how quickly the enabling technology improves. In the steel industry, for instance, continuous-casting technology improved quite slowly, and more than 40 years passed before a minimill developed by Nucor matched the revenue of the largest integrated steelmakers.[8]

Acknowledgements

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[8] Harvard Business Review, What is Disruptive Innovation, Clayton M Christensen, Michael Raynor, Rory McDonald, December 2015

Appendix A. General comparison of LTS and HTS materials

	NbTi (LTS)	Nb3Sn (LTS)	YBCO (HTS)
Limitation solving	• Exceeding the currents and (homogeneous) fields produced by copper or permanent magnets	• Exceeding the currents and (homogeneous) fields produced by NbTi	• Exceeding the currents and (homogeneous) fields produced by LTS • Enabling high-currents & high-magnetic fields at low cooling power • Enabling devices withstanding high parasitic heat loads • Enabling more compact devices due to reduced cryogenic complexity
Reasons to choose	• Very high-currents in low fields at low cost • High mechanical strength • Easy control of performance by mechanical deformation • Established persistent current operation	• High-currents in high-fields at moderate cost • Established persistent current operation	• High currents in high-fields • High currents at elevated temperatures • Low effort in cryogenic system design • Beneficial properties of supporting materials at operating temperatures • New options, e.g. NI-windings, reduced importance of parasitic heat loads • Customized layer architecture • Low cooling penalty • Simplified situation in cooling, stabilization and quenching
Reasons to reject	• High effort in cryogenic system design • Poor physical properties of supporting material at operating temperatures • High effort/ consideration of stabilizing and quenching • High cooling penalty	• High effort in cryogenic system design • More challenging control of performance by reaction • High effort/ consideration of stabilizing and quenching • W&R technology • Limited mechanical strength • High cooling penalty	• High(er) cost (than NbTi) • Anisotropy • More challenging winding process due to layer architecture • Smaller unit-lengths • Increased difficulty to use persistent current operation

Appendix B. Estimates of Size Comparison for Fusion Reactors

A paper by Brandon Sorbom, et al. claims fusion power scales as B to the fourth power.[9] "*The volumetric fusion power scales as ~ B^4 and, at constant safety factor, the plasma confinement strongly improves with magnetic field strength.*" This is the basis for being able to compare the size of LTS vs HTS based reactors.

Joseph Minervini showed that a proposed HTS fusion magnet, using the conceptual Affordable, Robust, Compact (ARC) fusion reaction design, has "about" one-tenth the volume as ITER.[10] The rationale is that B[T] for ITER is 5.3 and B[T] for an ARC is 9.2. The ratio is 9.2/5.3 = 1.74. Since volume scales as B to the fourth power, $1.74^4 = 9.1$, which is "about" one-tenth the size. Dr. Minervini also showed that the SPARC (Smallest Possible ARC) will operate in the range 10 to 13 Tesla. If we were to use the SPARC at, conservatively, 10.6 Tesla, the SPARC would have twice the field of ITER (10.6/5.3 = 2). That gives a volume ratio improvement of $2^4 = 16$, which is one-sixteenth the size of ITER.

Another source is from a presentation by Dennis Whyte given at UC Berkeley on March 18, 2019.[11] He includes volume specifications for the three machines and his numbers make HTS fusion as much as 80 times smaller than LTS fusion. Table B-1 summarizes these estimates.

Table B-1. Two estimates of reactor size based on design.

	Dennis Whyte	Joseph Minervini
ITER fusion reactor in France	880 m^3	--
Affordable, Robust, Compact (ARC) fusion reactor	140 m3 (estimated to be 1/6 the size of ITER)	Estimated to be 1/9 the size of ITER
Smallest possible ARC (SPARC) fusion reactor	11 m^3 (estimated to be 1/80 the size of ITER)	Estimated to be 1/16 the size of ITER

In summary, HTS fusion machines will be smaller than LTS machines simply because they can achieve a higher magnetic field. Since power density scales as fourth power of field and HTS permits magnetic fields two to three times what LTS can provide, we conclude that the 1/16 number cited is only an approximate number and a conservative one at that.

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[9] "ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets." B.N. Sorbom, J. Ball, T.R. Palmer, F.J. Mangiarotti, J.M. Sierchio, P. Bonoli, C. Kasten, D.A. Sutherland, H.S. Barnard, C.B. Haakonsen, J. Goh, C. Sung, and D.G. Whyte, Fusion Engineering and Design Volume 100, November 2015, Pages 378-405 https://www.sciencedirect.com/science/article/pii/S0920379615302337, Accessed January 27, 2023

[10] "A Pathway to Fusion Energy Based on High-field REBCO Superconducting Magnets." Joseph V. Minervini, MIT, Cambridge, MA USA. WAMHTS-5, Budapest, Hungary. April 11-12, 2019

[11] "Small, modular and economically attractive fusion enabled by HTS superconductors." Dennis Whyte, MIT Plasma Science & Fusion Center. Presesntation delivered 3/18/2019 at UC Berkeley Nuclear Engineering Weekly Colloquiums, UC Berkeley, Berkeley, CA.