MATERIALS SCIENCE

The prospects of high-temperature superconductors

Overcoming cost barriers could make high-temperature superconductors pervasive

By **Alexander Molodyk**[1] and **David C. Larbalestier**[2]

Superconductors conduct electricity with essentially zero resistance, avoiding many of the power losses in present electric power transmission, conversion, and use. Strong electromagnetic fields have so far been the principal application of superconductors, with widespread commercial superconductivity limited to magnetic resonance imaging (MRI) electromagnets composed of the low-temperature superconductor (LTS) Nb47Ti. Broader applications of LTSs have been hindered by the need to cool them with liquid helium (at or below 4.2 K). High-temperature superconductors (HTSs) (*1*) that can operate at liquid nitrogen temperatures (between 65 and 80 K) promised ubiquitous applications that could escape the constraint of LTSs. Achieving the International Energy Agency roadmap to carbon-free economies by 2050 would be greatly facilitated by the use of nuclear fusion–generated electricity. HTSs have been used in prototype nuclear fusion reactors (*2*), thereby creating the opportunity to overcome the cost barriers that have so far prevented the commercial development of HTS technologies.

Since the unexpected report in 1987 of high-temperature superconductivity at 93 K (*1*), the idea that HTSs could revolutionize the electric power industry (*3*), going far beyond the classical application of superconductivity to electromagnets, has been pursued. Despite many technical successes (*4*), electric industry applications of HTSs are few, largely because the high cost of HTS materials made replacement of copper and iron electric infrastructure economically infeasible. HTS research over the past decade thus fell back to making ultra–high field electromagnets that were impossible with "classical" LTS conductors, a scientifically exciting but limited market (*5*). However, HTSs could enable economical compact fusion reactors as the means to contribute to the 2050 zero-carbon goal, and the development of fusion synergistically creates a demand for HTSs, promoting new production capacity that will result in HTS cost reduction. This could transform the economics of HTSs, especially for replacement of copper and iron in electrotechnology.

Major investments in developing compact tokamak fusion reactors (*6*, *7*) have successfully yielded an ~1.8 m by 0.5 m toroidal field coil prototype composed of the best-performing HTS, $REBa_2Cu_3O_{7-\delta}$ (REBCO; RE, rare-earth element), in coated conductor (CC) form (*8*) that operates at 20 K and 20 T (*9*). In a compact fusion tokamak, a set of D-shaped coils of HTS CC generates a toroidal magnetic field that confines the plasma (see the figure). This prototype used 270 km of REBCO, several times the quantity of all REBCO CCs used in all high-field magnets made so far. This achievement required a major expansion of CC production that now provides the opportunity to make REBCO CC available by the ton at prices that are suitable for broad application, not just to fusion but also to electric utilities and a liquid hydrogen economy.

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Historically, the high-energy physics community has provided the dominant demand for new superconductors, and indeed it is now driving the demand for both LTSs and HTSs as essential components of ultra–high energy particle colliders. The demonstration of a 20 T, 20 K toroidal field fusion magnet (*9*) has created a strong argument for design and operation of HTS-enabled dipole magnets for any Future Circular Collider at CERN (*10*). HTSs operating at 15 to 25 K could offer vast cryogenic savings compared with current superfluid helium at 1.8 K, today's expensive solution for cooling LTS magnets at the Large Hadron Collider.

The prospect of operating helium-free, perhaps even in liquid nitrogen at 65 to 80 K, is what originally drove expectations for pervasive applications of HTSs, especially REBCO. But attempts to apply HTSs soon showed that it is not just their high transition temperatures (or critical temperatures, T_c) that make superconductors useful by allowing savings on cryogenics, but more importantly, the ability to carry high current densities (J_c) in strong magnetic fields. High J_c depends on how well the quantized vortices inside the superconductor are "pinned" from moving by various structural defects. Attaining high J_c was an intense research activity for more than 20 years that first required understanding the pronounced anisotropy of superconducting properties in REBCO that results from its structural anisotropy and makes strong vortex pinning difficult (*11*). The ability of the REBCO compound to be grown as thin films, while incorporating high densities of insulating nanoscale RE_2O_3 and perovskite compounds such as $BaZrO_3$, enabled the very strong vortex pinning that makes high J_c possible, even at liquid nitrogen temperatures (*12*).

A second, independent problem also stood in the way of HTS applications: the large sensitivity to any disorder that locally depresses the superconducting properties, as occurs between virtually all grains within the polycrystalline conductor (at grain boundaries, GBs) (*13*). Whereas the two principal LTS materials, Nb47Ti and Nb_3Sn, are high-carrier density, isotropic, s-wave superconductors, the cuprate HTSs are markedly anisotropic d-wave superconductors in which GB carrier densities and superconducting properties are strongly depressed in all except very low-angle GBs (when the difference in crystallographic orientation between two adjacent grains is very small). This results in a strong degradation of grain-to-grain connectivity and J_c of polycrystalline material (*13*). Accordingly, it took more than 15 years for HTS conductors to emerge, even in lengths of much less than 1 km. By contrast, LTS conductors are generally made in single lengths of much more than 10 km.

For each of the three commercial HTS materials available today—REBCO and the bismuth strontium calcium copper oxide (BSCCO) compounds Bi-2223 and Bi-2212—the path to high J_c has only been possible by development of high crystallographic texture fabrication that minimizes obstructions to long-range supercurrent transport. In the case of REBCO, a totally

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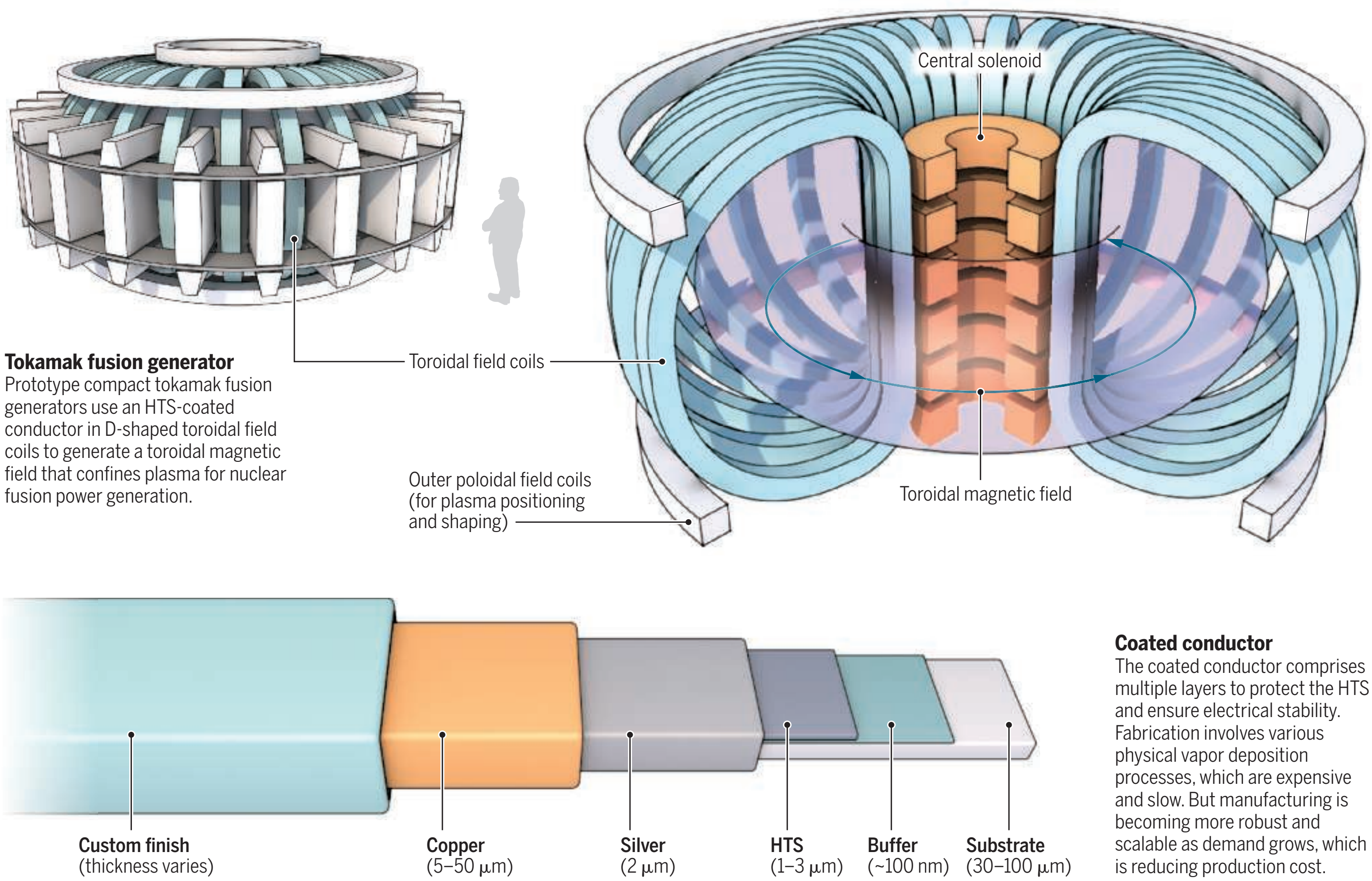
High-temperature superconductors in a tokamak fusion reactor

The development of nuclear fusion power generation, such as with compact tokamak fusion reactors, is driving the growth and commercialization of high-temperature superconductor (HTS)–coated conductors.



Tokamak fusion generator
Prototype compact tokamak fusion generators use an HTS-coated conductor in D-shaped toroidal field coils to generate a toroidal magnetic field that confines plasma for nuclear fusion power generation.

Coated conductor
The coated conductor comprises multiple layers to protect the HTS and ensure electrical stability. Fabrication involves various physical vapor deposition processes, which are expensive and slow. But manufacturing is becoming more robust and scalable as demand grows, which is reducing production cost.

new, largely vapor deposition thin-film production route was needed (*12*). Notably, Bi-2212 and Bi-2223 can be made by conventional wire fabrication routes but at the price of having poorer texture and consequently lower J_c. By contrast, industrialization of thin-film CC fabrication processes has resolved both the problem of weak vortex pinning and GB supercurrent obstruction, now enabling mass production of economical HTSs.

Currently, lengths of 500 to 1000 m of REBCO CC with almost single-crystal texture are made worldwide. The dominant production route uses ion-beam–assisted deposition (IBAD) to grow a cube-textured MgO template, 10 to 50 nm thick, onto a strong, 30- to 100-µm-thick, untextured metallic substrate such as Hastelloy-C276. Some intermediate oxide layers ~100 nm thick then allow lattice matching of the MgO to the 1- to 3-µm-thick REBCO layer, which is then protected by 1 to 2 µm of sputtered silver and finally by a thicker 5- to 50-µm copper layer, which is generally electroplated to provide electrical stability and protection against loss of superconductivity in the REBCO. Most, or all, of the process requires multiple physical vapor deposition chambers, which come at high capital cost and have relatively slow throughput, making CC fabrication both complex and expensive. The increased demand on HTSs for the development of nuclear fusion power generation could have a transformative impact, driving REBCO CC manufacture into a full industrial operation with potentially huge cost reductions.

The commonly used cost metric for superconductors, dollars per kiloampere-meter ($/kA-m), defines the per-meter cost of conductor needed to transmit 1000 A of electric current, at 77 K in self-field (that is, with no magnetic field applied); or, more generally, at any user-desired temperature and magnetic field. Present-day volume prices of HTSs range from $150 to $200/kA-m. Many analyses of the commercial viability of superconducting applications show that a conductor cost of $50/kA-m is the tipping point for widespread application for electric power use. A long-range outlook projects HTS costs below $10/kA-m when produced on a very large scale (*14*).

It is remarkable that among all manufacturable superconductors, Nb47Ti, the least "potent" (in the sense of its available operational field and temperature space), is the only one to have reached commercial, tonnage scale. Despite expensive Nb, Nb47Ti became the economical enabler of mass-market applications of MRI, because MRI electromagnets made with Nb47Ti operate in the persistent current mode and require only a small cryocooler. Because compact fusion reactors require properties that are only attainable with REBCO CC, an opportunity to bring the distinct benefits of HTSs to many new markets that cannot tolerate the present high cost of HTSs is provided.

Prototype compact fusion reactors (*6, 7*) required a 10-fold increase in HTS supply, from hundreds to thousands of kilometers a year in the past 3 years. This demand enabled recent advances that made HTS manufacture robust and scalable (*8*), allowing the required production increase to

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an annual multi-ton level. This huge expansion of production scale could soon reduce conductor costs to ~$100/kA-m. HTS use cost also depends strongly on the superconductor J_c and production yield. Today's best laboratory samples have J_c exceeding that of commercial conductors by a factor of 2 or more (*15*), thus providing a further industrial improvement path. As production technology matures, manufacturing yield will also increase, further reducing cost. This will allow HTS CCs to become competitive for applications in which copper and iron are replaced in electric utilities and wind turbines, and perhaps even enabling electric aircraft with hydrogen-cooled superconducting motors.

Overall, the present outlook for HTS materials and their industrial applications is historic, because of the opportunity for REBCO superconductor use to expand, as happened 35 years ago for the production of Nb47Ti for MRI electromagnets. The development of compact nuclear fusion power generation (which is still at the prototype stage) is the immediate stimulus that has driven exponential annual volume increases. The applied superconductivity community is anticipating the virtuous cycle of price reduction and further demand from other electrotechnology applications that are not yet economic at today's REBCO CC prices compared with the present use of copper, iron, and LTSs. This prospective sustainable market of HTS materials and applications promises numerous public benefits for much human activity in energy production, distribution, and use; medicine; transportation; and research. ■

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ACKNOWLEDGMENTS

A.M. is R&D director, shareholder, and board member at Faraday Factory Japan.

10.1126/science.abq4137

PSYCHOLOGY

How AI can distort human beliefs

Models can convey biases and false information to users

By **Celeste Kidd**[1] and **Abeba Birhane**[2,3]

Individual humans form their beliefs by sampling a small subset of the available data in the world. Once those beliefs are formed with high certainty, they can become stubborn to revise. Fabrication and bias in generative artificial intelligence (AI) models are established phenomena that can occur as part of regular system use, in the absence of any malevolent forces seeking to push bias or disinformation. However, transmission of false information and bias from these models to people has been prominently absent from the discourse. Overhyped, unrealistic, and exaggerated capabilities permeate how generative AI models are presented, which contributes to the popular misconception that these models exceed human-level reasoning and exacerbates the risk of transmission of false information and negative stereotypes to people.

Generative AI models—including OpenAI's GPT variants, Google's Bard, OpenAI's DALL·E, Stable Diffusion, and Midjourney—have captured the minds of the public and inspired widespread adoption. Yet, these models contain known racial, gender, and class stereotypes and biases from their training data and other structural factors, which downstream into model outputs (*1*–*3*). Marginalized groups are the most negatively affected by these biases. Further, these models regularly fabricate information (*4*). Some model developers have acknowledged these problems but suggested that people must use the systems to reveal trends in problematic outputs to remedy them. This ignores that distortions to human beliefs caused by generative AI models cannot be easily corrected after problems are discovered. Further, the reactive nature of this approach does not acknowledge a key problem of current generative AI systems, the inability of their architecture to distinguish fact from fiction (*4*).

Three core tenets of human psychology can help build a bridge of understanding about what is at stake when discussing regulation and policy options. These ideas in psychology can connect to machine learning but also those in political science, education, communication, and the other fields that are considering the impact of bias and misinformation on population-level beliefs.

People form stronger, longer-lasting beliefs when they receive information from agents that they judge to be confident and knowledgeable, starting in early childhood. For example, children learned better when they learned from an agent who asserted their knowledgeability in the domain as compared with one who did not (*5*). That very young children track agents' knowledgeability and use it to inform their beliefs and exploratory behavior supports the theory that this ability reflects an evolved capacity central to our species' knowledge development.

Although humans sometimes communicate false or biased information, the rate of human errors would be an inappropriate baseline for judging AI because of fundamental differences in the types of exchanges between generative AI and people versus people and people. For example, people regularly communicate uncertainty through phrases such as "I think," response delays, corrections, and speech disfluencies. By contrast, generative models unilaterally generate confident, fluent responses with no uncertainty representations nor the ability to communicate their absence. This lack of uncertainty signals in generative models could cause greater distortion compared with human inputs.

Futher, people assign agency and intentionality readily. In a classic study, people read intentionality into the movements of simple animated geometric shapes (*6*). Likewise, people commonly read intentionality—and humanlike intelligence or emergent sentience—into generative models even though these attributes are unsubstantiated (*7*). This readiness to perceive generative models as knowledgeable, intentional agents implies a readiness to adopt the information that they provide more rapidly and with greater certainty. This tendency may be further strengthened because models support multimodal interactions that allow users to ask models to perform actions like "see," "draw," and "speak" that are associated with intentional agents. The potential influence of models' problematic outputs on human beliefs thus exceeds what is typically observed for the influence of other forms of algorithmic content suggestion such as search. These issues are exacerbated by financial and liability interests incentivizing companies to an-

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Science, **380** (6651), .
DOI: 10.1126/science.abq4137