Will doubling magnetic field strength halve the time to fusion energy?

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ventilators in power plants and factories create a seismic–infrasonic din, he explains. “The signals could give information about activities in a place of interest. You can’t tell what type of manufacturing, but you can tell that heavy lifting is going on.”

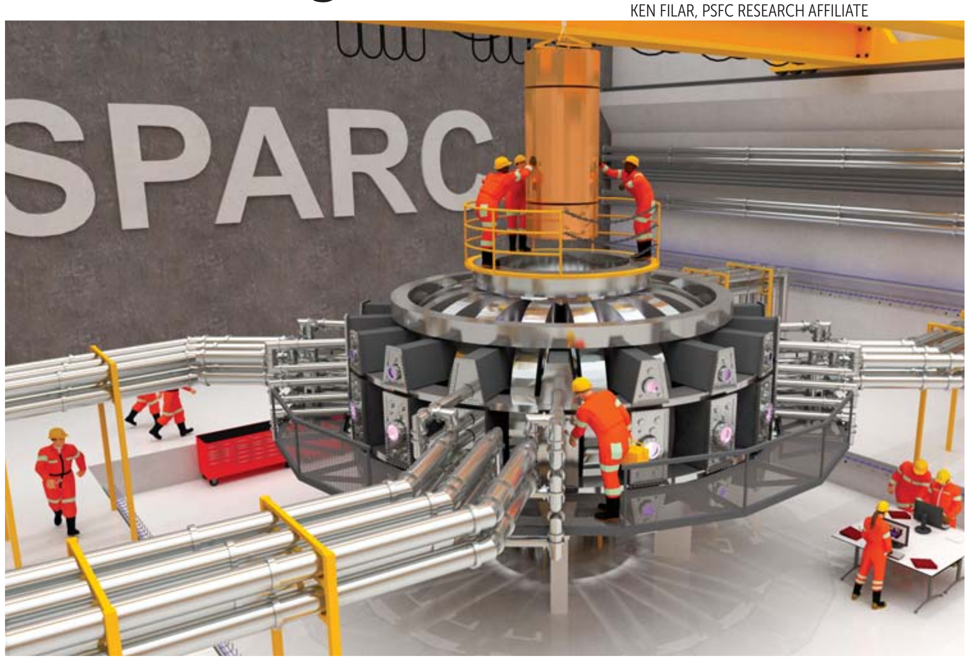
Qamar Shams of NASA’s Langley Research Center has developed an infrasonic polyurethane foam windscreen that he claims reduces wind noise by 10–20 dB. One potential application is for shielding detectors of clear-air turbulence, which he says could be used for early identification of tornadoes and hurricanes and for locating vortices in an aircraft’s wake. Microphones installed as a test at Virginia’s Newport News/Williamsburg International Airport in 2012–13 recorded the strong vortices behind aircraft as they took off and landed. Infrasound detection could be used in a wake-avoidance system, he says.

And infrasound could have lifesaving medical applications, says Shams. The human heart beats about 72 times per minute. That’s a fundamental frequency of 1.2 Hz, “so our blood circulation is in the infrasonic bandwidth.” An infrasonic stethoscope that he and colleagues developed is currently undergoing clinical tests at NASA’s Kennedy Space Center, he says. “More than 85% of the world population doesn’t have access to echocardiography, CT scans, or other advanced diagnostic tools.” The infrasonic stethoscope, he says, could provide a cheaper method for early screening of heart and lung diseases. **Toni Feder**

Will doubling magnetic field strength halve the time to fusion energy?

Magnets built with high-temperature superconductors are at the heart of efforts to demonstrate a burning plasma in a compact device.

KEN FILAR, PSFC RESEARCH AFFILIATE



A VISUALIZATION OF THE PROPOSED SPARC TOKAMAK experiment to be completed by Commonwealth Fusion Systems in the mid 2020s.

Two spin-off companies, one in the US and the other in the UK, hope to beat ITER, the massive seven-nation undertaking, by 10 years or more in proving that fusion is a viable energy source. Commonwealth Fusion Systems (CFS) in Cambridge, Massachusetts, and Tokamak Energy (TE) near Oxford, UK, each plan to build, by the mid 2020s, devices that can produce more energy than they consume. That’s a decade or more before ITER is expected to attain that milestone. If either company succeeds, fusion power plants could be a reality as early as 2030, say scientists from the two firms.

All three projects are developing variants of a tokamak, in which very hot plasmas of hydrogen isotopes are confined in toroidal chambers by intense magnetic fields. By using magnetic fields that are twice as strong as those from the 12-tesla magnets planned for ITER, both companies say they can create a sustainable fusion reaction in a machine as small as 1/70th the size of ITER. “We are increasing the amount of fusion power per volume [from ITER’s] by more than a factor of 10,” says CFS cofounder Dennis Whyte, who notes that “fusion power per volume is the closest thing you can come up with to indicate the amount of economic output versus cost.” Whyte, director of MIT’s Plasma Science and Fusion Center (PSFC), says he has no financial interest in CFS, a spin-off of the university.

In nuclear fusion, the long-sought goal is to create conditions in which self-heating of the plasma exceeds the amount of external energy needed to sustain the reaction—a so-called burning plasma. The gain is the ratio of output to input. Although ITER is due to begin operating with deuterium plasmas in 2025, experiments with tritium, necessary to produce a burning plasma, aren’t due to commence until around 2035. ITER is expected to produce a gain of 10 for up to 10 minutes; CFS will achieve a gain of at least 2. TE, which expects its device to need little external energy to sustain reactions, anticipates a gain of 30. No fusion device has yet achieved a break-even gain of 1; the world record gain, held by the UK’s Joint European Torus, is 0.67.

TE, founded by former scientists from the UK’s Culham Centre for Fusion Energy, and CFS, established by Whyte and five other MIT researchers, have proposed similarly sized devices. Each machine will be roughly the size of the DIII-D—the only operating tokamak in the

US, located at General Atomics in San Diego, California—and will have a plasma volume of 10–20 m^3. They would be considerably smaller than the Joint European Torus, located at Culham and currently the world's largest tokamak.

Similar technology

The two private efforts have several features in common; most significant is the use of magnet coils wound from the high-temperature superconductor (HTS) compound yttrium barium copper oxide. The micron-thick layer of YBCO is coated onto a 12-mm-wide steel tape and becomes superconducting at liquid-nitrogen temperature. Coils made with the material will generate about twice the field strength for confining plasmas compared with ITER's magnets, which are made from a conventional, low-temperature niobium–tin superconductor, says David Kingham, executive vice chairman of TE. (See PHYSICS TODAY, October 2015, page 23.) Both companies say they will operate the HTS magnets at 20 K to optimize performance.

CFS estimates that its burning-plasma device, SPARC, will cost around $400 million; the price tag for TE's as-yet-unnamed device will be "a bit higher," says Kingham. ITER will cost anywhere from $22 billion to $65 billion—the estimates provided by ITER's management and the US Department of Energy, respectively.

Both companies say they have raised at least $50 million. TE's investors include billionaire David Harding, founder of the Winton Group investment firm, and Legal & General, a financial services provider. The company has also received grants and R&D tax credits from the UK government.

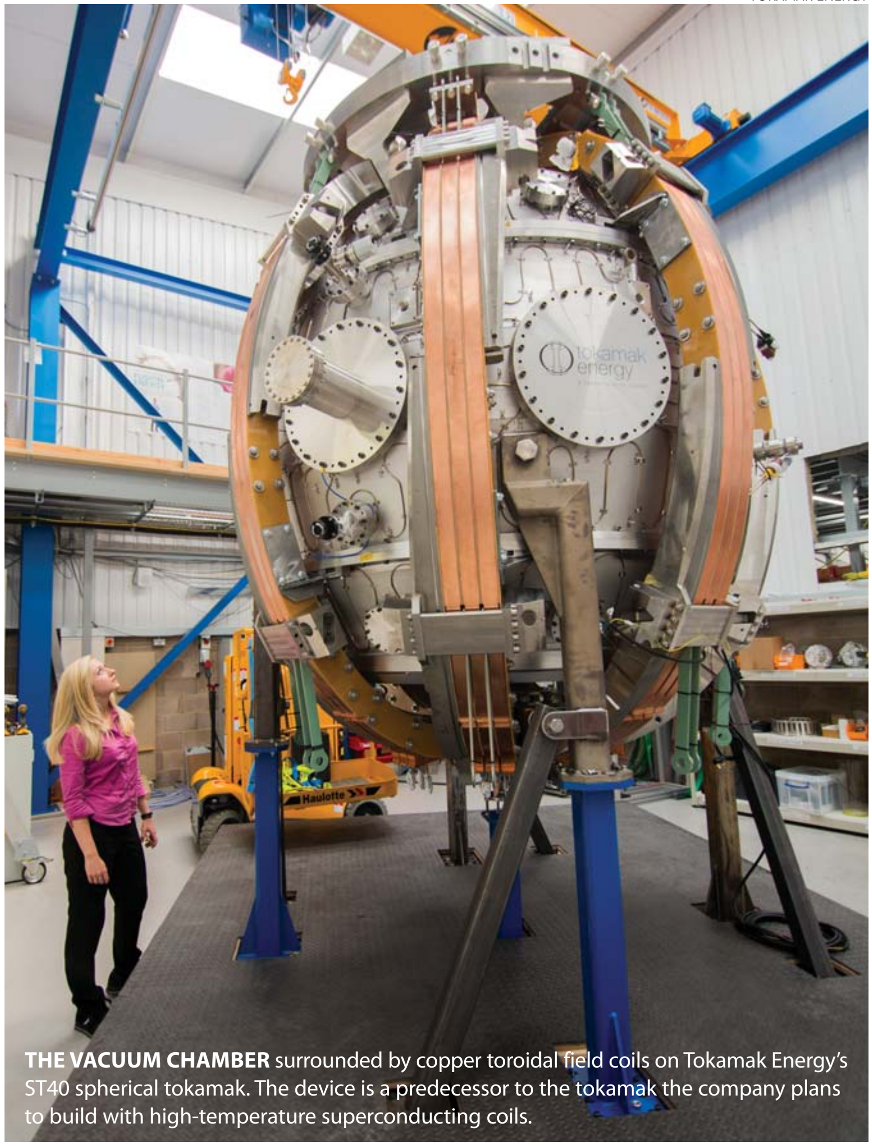
CFS estimates it needs $100 million to meet its initial milestone: building full-scale prototype HTS magnets. To date, it has announced a $50 million investment from the Italian oil and gas producer Eni. CFS is not seeking government funding; rather, it is soliciting donors who will commit to the effort beyond the three-year magnet development phase, says chief operating officer Steve Renter. CFS will pay for ongoing R&D by MIT's PSFC.

Building coils capable of generating a field in excess of 20 T at their surface will require the development of structural materials with higher strength than current stainless steels, according to a February report by DOE's Fusion Energy Sciences Advisory Committee. Martin Greenwald, a CFS cofounder and deputy director of the PSFC, says engineers will have to restrain forces equivalent to weights of nearly 100 000 tons to prevent the D-shaped toroidal magnets from blowing up like a balloon, while also keeping the conductor from being stretched or bent and losing superconductivity. The magnets will also need to both resist and survive a quench, the condition in which superconductivity is suddenly lost and the magnetic energy is dumped. "Building this into a tokamak is a mechanical engineering challenge, taking into account the larger pressures that the coils are producing on themselves. When you double the field, the problem is four times harder," says Whyte.

David Larbalestier, chief materials scientist at the National High Magnetic Field Laboratory in Florida, says the superconducting tapes, while not yet perfect, "are really coming out of industry in pretty good lengths and pretty good quality, and we're learning how to use them." They were used to build a research magnet at the laboratory last year that reached 32 T. "The dream of essentially doubling the field to which a plasma can be exposed and therefore confined seems to be appropriate," says Larbalestier. "The time is right, and the tech is finally coming together."

Whyte and Kingham agree that obtaining sufficient quantities of HTS tape from the 10 global suppliers could be difficult. TE needed about 10 km of tape for small tokamak coils, and hundreds of kilometers will be required to build a set of magnets for a burning-plasma experiment, says Kingham. The number of magnets on a tokamak can vary; TE's newest ST40 device has 24 to supply toroidal field and four pairs of vertical (poloidal) field coils. It plans to

TOKAMAK ENERGY



THE VACUUM CHAMBER surrounded by copper toroidal field coils on Tokamak Energy's ST40 spherical tokamak. The device is a predecessor to the tokamak the company plans to build with high-temperature superconducting coils.

add three more vertical field coils to improve plasma shape control. There are about 15 manufacturers of the tapes worldwide.

CFS initiated its magnet development work in June, the same month that ITER's governing council reported the reactor had passed the halfway point of completion. But CFS benefits from decades of experience by MIT researchers working on high-field, high-plasma-density tokamaks, including the Alcator C-Mod, which operated from 1991 to 2016. TE has built two machines, including a small tokamak with YBCO tape coils that maintained a plasma for 29 hours; Kingham says the temperature wasn't measured but "wasn't especially hot."

Differing configurations

The two companies' devices differ in other respects. CFS will use a mainstream toroidal, doughnut-shaped configuration, similar to that of ITER and the Alcator C-Mod. TE has chosen a spherical tokamak, which is shaped like a cored apple. Kingham says the spherical configuration offers some advantages, including a greatly improved capability for the plasma to self-generate, or "bootstrap" current that helps maintain plasma confinement. DOE's National Spherical Torus Experiment Upgrade—now undergoing repairs at the Princeton Plasma Physics Laboratory (see "Director forced to step down after Princeton Plasma Physics Laboratory reactor fails," 29 September 2016, PHYSICS TODAY online)—is a spherical tokamak, as is the Mega Ampere Spherical Tokamak at Culham. Neither machine is equipped with superconducting magnets.

The SPARC would in some ways constitute an update to a high-density burning-plasma experiment known as FIRE that was proposed to DOE in the late 1990s but not built. Since HTS technology hadn't matured, FIRE would have used copper coils. The US physics research community in 2002 elected to support US participation in ITER instead of FIRE. Dale Meade, a former Princeton Plasma Physics Laboratory physicist who led the FIRE design team, notes that ITER was at that time expected to cost the US \$500 million and begin operating with tritium in 2017.

Whyte says he nearly left fusion research a few years ago when it became apparent just how expensive ITER would be and how long it would take to produce a burning plasma. "I was dismayed that it wouldn't come to pass in my professional lifetime." He says no US fusion researcher would have chosen ITER over FIRE had ITER's true cost and completion date been known.

Assuming that the magnets will be successful and that further commercial funding can be raised, SPARC should take three to four years to build, Whyte says. If a burning plasma is then demonstrated, CFS would seek utility funding for a larger machine that would generate electricity. That device, which the company calls the affordable, robust, compact (ARC) reactor, would be about twice the size of SPARC and produce 200 MW of fusion power, roughly the output of a modern commercial power plant.

The ARC would feature a blanket of lithium-containing molten salt that would surround the vacuum vessel, carry away heat, and breed the tritium that's needed to sustain fusion. Tritium does not occur naturally, but it can be bred from lithium by the fusion neutrons. The trick will be to breed sufficient amounts of the isotope and get it from the salt to the plasma. The fluorine-lithium-beryllium salt in the ARC would also absorb neutrons that damage the magnets over time. Even so, the neutron flux would limit the reactor lifetime to just nine years. The design features built-in joints in the coils and structure to allow for the vacuum chamber to be replaced every year or two.

Kingham says TE doesn't yet have a detailed scheme for breeding tritium, but its researchers have published papers estimating the rate of tritium breeding on spherical tokamaks.

In June TE announced that its ST40 copper-magnet tokamak had achieved a plasma with a temperature of 15 million degrees. It's now upgrading power supplies with a goal of reaching the 100-million-degree regime necessary for a burning plasma. A separate two-year R&D effort at TE is scaling up the YBCO superconducting magnets.

"Our approach is to look at new ways of designing magnets for maximum efficiency to tackle the technical challenges at relatively small scale," Kingham says. "Then we have computational models that allow us to design the large-scale magnets we'll need in the future."

David Kramer PT