system and the high quality of college graduates it produces, says Alexander Chamorovskiy, senior researcher at Superlum, a company in County Cork that produces broadband semiconductor light sources. "It's getting hard for small companies to hire Irish students," he says. "We can't compete with big multinationals, which offer much higher salaries."

And it's not just scientists with the SFI centers who support a rebalancing of funding, with more going to fundamental research; the scientists who struggle for national funding say that the centers should continue. "I would not argue that the centers should get less funding," says Ryan. "Funding needs to be increased across the board and diversified to support excellence in all disciplines." She also wants to see Ireland join CERN.

Ciarán Seoighe, SFI deputy director general, notes that the agency's responsibility has always been for "oriented basic, with applied research added in 2013." Over several months in late 2018, he met with 1000 or so researchers to take the pulse of the community for a new five-year strategy, which SFI aims to set by year's end. "We are looking at the whole ecosystem and looking for gaps," he says. "We may come out of this quite a different organization. Our core objectives may change."

Meanwhile, not far from anyone's mind is Brexit, the impending departure of the UK from the European Union. (See PHYSICS TODAY, March 2017, page 24.) As Britain's close neighbor, Ireland will undoubtedly be strongly affected by Brexit. But what it means for science is still anyone's guess. Séamus Davis, who works in experimental quantum matter and in January moved to University College Cork and Oxford University after decades in the US, says the long-standing ties between Ireland and the UK will survive the change whatever form it takes. Seoighe points to Davis's new split position as part of the glue to keep the ties strong and says the science communities in both countries are looking for new ways to partner.

In Ireland as elsewhere in the European Union, researchers are backing away from UK partnerships in anticipation of funding difficulties. Irish universities are seeing an uptick in inquiries about faculty jobs. And in the wake of Brexit, Ireland could become more attractive for scientific partnerships by virtue of being the main English-speaking country in the European Union.

"Everybody is waiting to see what will happen," says Eucharia Meehan, head of the Dublin Institute for Advanced Studies and former director of the Irish Research Council. "But a lot of people are thinking creatively about how to keep the UK as part of the European scientific landscape."

Toni Feder

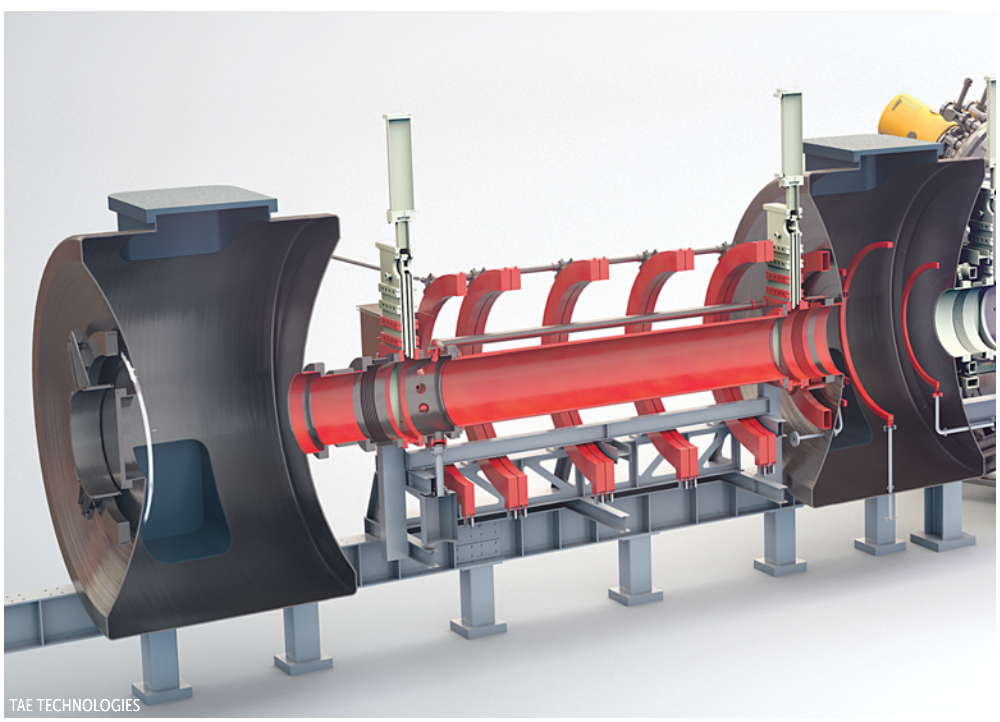
Side trips on the road to fusion

A private company pursuing an alternative path to fusion energy is banking on revenues from inventions it makes along the way.

A California startup has a multipronged approach to help pay for its decade-long quest to demonstrate fusion at a commercial scale. The approach includes a novel concept to become a part-time scientific user facility funded by the Department of Energy. TAE Technologies also is soliciting tax breaks and other financial inducements from state and local governments as it decides on a site for a new $500 million test reactor. The company is reporting initial success in commercializing several technologies it has developed as it has built its experimental devices.

Based in Orange County, the 160-employee TAE is the largest of a handful of privately held startups that are pursuing alternative approaches to controlled fusion. Others include General Fusion in British Columbia, Canada; Commonwealth Fusion Systems in Cambridge, Massachusetts; and Tokamak Energy, near Oxford, UK.

TAE remains focused on demonstrating commercially viable grid-scale fusion by the late 2020s, says CEO Michl Binderbauer. In the meantime, it is looking for revenue sources to offset some of the company's $50 million annual operating expenses and attract additional investors. Spin-off technologies, in particular, "create the opportunity for investors to feel we are more than a one-



TAE TECHNOLOGIES

trick pony, that there are hedging opportunities that can happen independent of the cadence in fusion."

To date, TAE has attracted more than $600 million in equity from investors, including financiers Arthur Samberg, who chairs its board; Charles Schwab; and former Morgan Stanley CEO John Mack. It has backing from venture capital firms New Enterprise Associates and Venrock, the UK's Wellcome Trust, and several sovereign funds. Shareholder Google also is a technical partner, says Binderbauer.

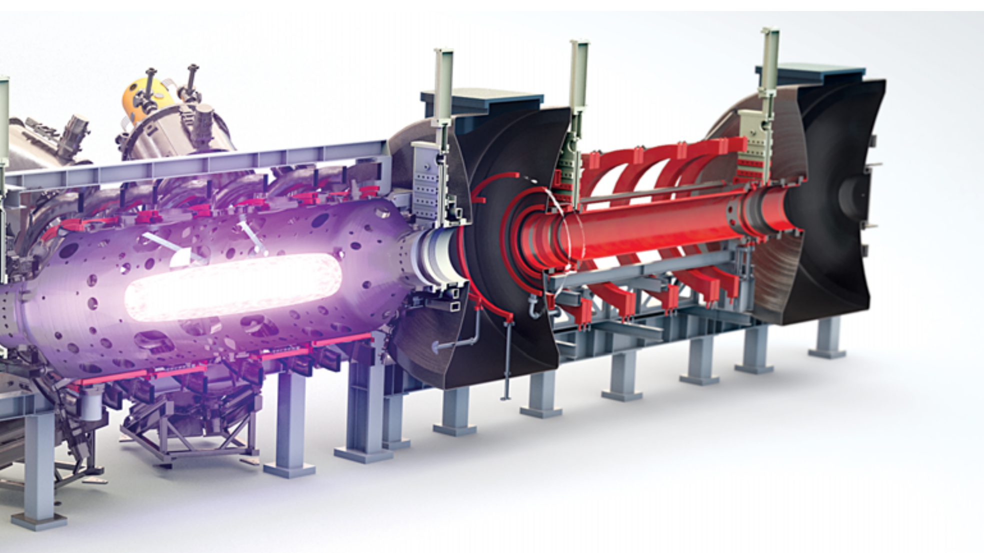
Departing from the mainstream

Rather than bottling a plasma in magnetic fields in a toroidal-shaped reactor—the mainstream tokamak approach that's being pursued at ITER in France, DOE's DIII-D device in California, and the Joint European Torus in the UK, among others—TAE's linear device uses a magnetic framework, known as a field-reversed configuration, to confine plasmas (see PHYSICS TODAY, October 2015, page 25). Plasmas formed at opposite ends of the machine are accelerated magnetically to collide at the center and create a larger, more energetic plasma that is sustained by particle-beam injectors.

TAE further departs from the fusion mainstream in aspiring to fuse protons and boron-11. That reaction will yield three alpha particles and few or no neutrons, thereby avoiding the neutron-induced damage and safety issues inherent in the conventional deuterium–tritium reaction. But p–^{11}B fusion requires a plasma temperature of about 3 billion kelvin, compared with the 100 million to 300 million kelvin needed for D–T. And p–^{11}B produces about half the energy of the D–T reaction.

In its current device, called Norman, TAE hopes to achieve plasmas of around 35 million kelvin for 30 milliseconds by midyear. Its next-generation experiment, Copernicus, is expected to produce plasmas more than three times as hot but still at least two orders of magnitude below the eventual goal. The plasmas in Copernicus will be formed from ordinary hydrogen, and results can be extrapolated to a D–T regime by other developers who may want to pursue that approach, Binderbauer says. Copernicus will "give us the confidence to build a machine that can burn p–^{11}B in the later part of the 2020s," he says.

TAE expects to choose a site for Copernicus by midyear and is weighing bids from local governments in at least two states that Binderbauer declined to identify. In addition to financial incentives, factors in the selection will include the availability of adequate power; the device will have a peak demand of 300 megawatts, which is more than the electricity infrastructure can accommodate at TAE's Southern California location.



A DIAGRAM OF TAE TECHNOLOGIES' EXPERIMENTAL DEVICE, NORMAN. Plasmas are created at opposite ends and accelerated to the center, where they collide and form a larger, hotter plasma. Eight beam injectors supply angular momentum to stabilize the football-shaped plasma.

Construction should get under way in 2020, with experiments commencing in late 2023 or early 2024.

Binderbauer says DOE officials have expressed "considerable interest" in his user-facility concept, and he plans to submit a more concrete proposal to the department later this year. Paul Dabbar, DOE undersecretary for science, says TAE's concept hasn't been discussed within the agency, but, he adds, "I'm not saying we wouldn't do something like that in the future. I'm very open to ideas, and I'm a big supporter of the private-sector fusion effort and engagement [with it]." Dabbar and Energy secretary Rick Perry both toured the TAE facilities last year.

Norman, named for the late TAE cofounder and noted fusion researcher Norman Rostoker (see PHYSICS TODAY, August 2015, page 64), is well suited to explore astrophysical phenomena having a high-pressure component, Binderbauer explains. Examples include differentially rotating plasmas, such as those found in accretion disks, and high-pressure, high-temperature collisionless plasmas to study conditions found in the solar corona, solar mass ejections, and stellar superflares.

E. Michael Campbell, director of the Laboratory for Laser Energetics at the University of Rochester, says astrophysics experiments of the type Binderbauer describes can be performed at his lab's Omega laser and at the National Ignition Facility. But Norman's time and space scales would be much larger than those achieved with the lasers, so the device would offer more opportunities for data gathering.

TAE's user-facility proposal is unrelated to a program now being finalized to improve access by the private sector to DOE's fusion facilities, national laboratories, and scientific computing assets, Dabbar says. That program will be patterned after an existing program at DOE's Office of Nuclear Energy (see PHYSICS TODAY, December 2018, page 26).

Cancer and electric vehicles

Last year the company spun off TAE Life Sciences to commercialize the accelerator technology developed for Norman. The low-energy neutrons the technology produces are well suited for the cancer treatment method known as boron–neutron capture therapy (BNCT). The first unit will be delivered to a Chinese company, NeuBoron Medtech, which is scheduled to begin treating patients with laryngeal and neck cancers in the fall. There is a particularly high rate of such cancers in southeast China.

In BNCT, a patient is injected with a drug that contains boron and is preferentially concentrated in cancerous tissue. When irradiated with neutrons, the ^{10}B fissions into lithium-7 and high-energy alpha particles. The alphas destroy DNA in the surrounding tumor, with minimal damage to healthy tissue. BNCT has not been approved for treatment in the US by the Food and Drug Administration. Binderbauer says the company is at the "advanced stage" of selling compact accelerators to medical centers in Italy, in the UK, and on the US West Coast for use in BNCT clinical trials. He declined to identify the customers.

To date, research reactors have been the source of neutrons used for nearly all BNCT studies, which have also been conducted on patients with glioblastomas, particularly lethal brain tumors. Neutron Therapeutics of Danvers, Massachusetts, last year delivered the first BNCT neutron-source accelerator to Helsinki University Central Hospital in Finland. It's now being commissioned for use in clinical trials, says Noah Smick, the company's vice president of business development. The company hasn't yet received another order, but Smick estimates the market for BNCT accelerators could reach $10 billion.

TAE is currently shopping around to electric vehicle (EV) equipment manufacturers a second spin-off technology: a vastly scaled-down version of software and electronics that it developed on Norman to control the power flows, which peak at about 750 megawatts. Binderbauer says laboratory experiments with full-scale EV components show TAE's technology could extend EV range by 30% or more, in part by reducing heat buildup. TAE is in "exploratory discussions" with a Chinese company he wouldn't name to license the technology for a new two-seat EV. In China, General Motors, Renault-Nissan, and domestic firms have been manufacturing such vehicles.

TAE is working with "joint ventures in the Barcelona and Paris areas" to apply power-management systems to electric buses and service vehicles such as garbage trucks, Binderbauer says. Citing nondisclosure agreements, he declined to identify the partnering organizations.

David Kramer PT