The hybrid returns

Slotting a fusion reactor into the heart of a nuclear fission plant could accelerate the development of waste-free nuclear energy. So why are all the designs still on paper, asks **Ed Gerstner**.

It seems like such a natural fit. Nuclear fission has proved that it can produce greenhouse-gas-free energy: the roughly 440 nuclear plants operating in 31 countries around the world collectively have the capacity to generate some 370 gigawatts of electrical power, or about 15% of the global total. But fission power also produces a stream of radioactive nuclear waste, laced with potentially bomb-grade plutonium — some 12,000 tonnes of waste per year, worldwide. That's quite a disposal problem.

Thermonuclear fusion, meanwhile, promises to generate an even greater supply of clean energy. But so far no human-induced fusion reaction has produced more energy than was used to fire it up.

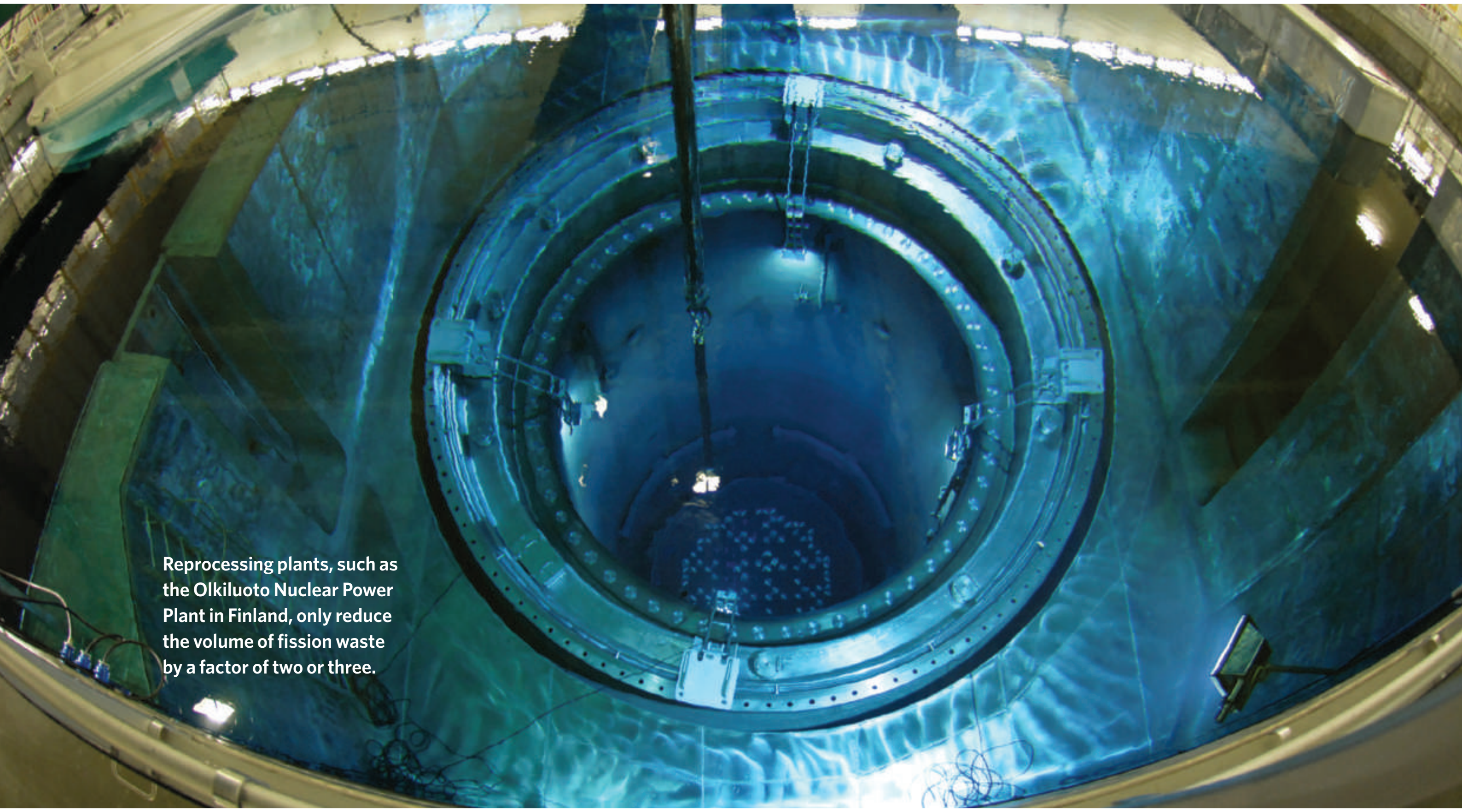
What fusion does generate, however, is neutrons. And therein lies the fit: fusion's neutrons could burn up fission's waste almost completely, leaving a residue greatly reduced in both volume and radioactivity. So why not combine the two into a fusion–fission hybrid reactor, and let each technology solve the problems of the other?

There are several reasons why not. One is that nobody knows how. Building a fusion reactor is complicated enough without trying to build one inside a nuclear fission reactor — which is why hybrids currently exist only as designs on paper. Another is the unquantified risk factor: a hybrid reactor would almost inevitably put a potentially unstable thermonuclear plasma next to radioactive fission products.

Still, a growing number of researchers around the world are convinced that it is worth tackling those challenges — because pure fusion power isn't getting much closer, and the piles of fission wastes are mounting ever faster. After decades of stagnation because of concerns about safety and waste, the fission-power industry seems on the verge of a renaissance. The need to cut greenhouse-gas emissions and to reduce the reliance on fossil fuels has prompted staunch opponents of nuclear power, such as Italy and Sweden, to reverse long-standing embargoes against the construction of new nuclear plants. Finland, France and the United Kingdom are preparing for new reactor building programmes. China is planning to build 40–50 fission plants within the next two decades. The US Nuclear Regulatory Commission has received applications for licenses to construct another 26 reactors in the United States, which has 104 already. And almost 45 fission plants are under construction around the globe.

Clearly, a plan is needed for dealing with the resulting increase in nuclear waste. Such plans generally centre on burying it deep underground. The question, is where?

H. HUOVILA/TVO



Reprocessing plants, such as the Olkiluoto Nuclear Power Plant in Finland, only reduce the volume of fission waste by a factor of two or three.

Disposal can be a very politically sensitive issue. For example, a site at Yucca Mountain in Nevada was considered for more than two decades for use as a US national repository for spent nuclear fuel. But the plan sparked so much resistance from local residents and politicians that the US energy secretary, Steven Chu, announced in March that the underground facility was no longer an option. For the foreseeable future, the spent fuel from each US nuclear plant will continue to be stored on site.

Many countries reduce the volume of waste by a factor of two or three by reprocessing the spent fuel — extracting the still-fissionable isotopes of uranium and plutonium, and fashioning them into new fuel elements. But reprocessing is expensive, inefficient and poses a nuclear proliferation risk: the extracted plutonium is usable in nuclear weapons. And it still leaves tonnes of highly radioactive residue to be disposed of.

All of which is why hybrid reactors are suddenly starting to look good again.

UKAEA CULHAM

"I'm not saying a hybrid can't be done, but we should focus on getting all the way to pure fusion first." — Steve Cowley

Nuclear roots

The hybrid idea dates back to the 1950s, when nuclear engineers were first struggling to harness nuclear reactions for generating electrical power.

They were already aware of the waste problem that arises from the nature of the fission reaction itself. The reaction starts when a neutron strikes the nucleus of a fissile isotope such as uranium-235 or plutonium-239, causing it to split apart. The result is a pair of lighter nuclei, a burst of energy and a number of new neutrons. The energy can be extracted as heat and used to drive an electricity turbine. But to keep the fission reaction going, some of the newly created neutrons must collide with other fissile nuclei, causing them to split and to release still more neutrons in a chain reaction. This happens easily as long as the fuel is fresh and there is nothing else for the neutrons to hit. As the reactions continue, however, the fuel accumulates more fission-product nuclei, most of which absorb the neutrons without doing anything else. Eventually, so many neutrons are absorbed that the chain reaction can no longer sustain itself, at which point the fuel becomes waste — even though most of the original fissile material is still there.

Engineers realized that they could get around this problem by supplementing the chain reaction with an independent source of neutrons. If there were enough neutrons, they would use up much more of the uranium and plutonium in the fuel, and would also burn through most of the long-lived radioactive fission products, greatly reducing waste.

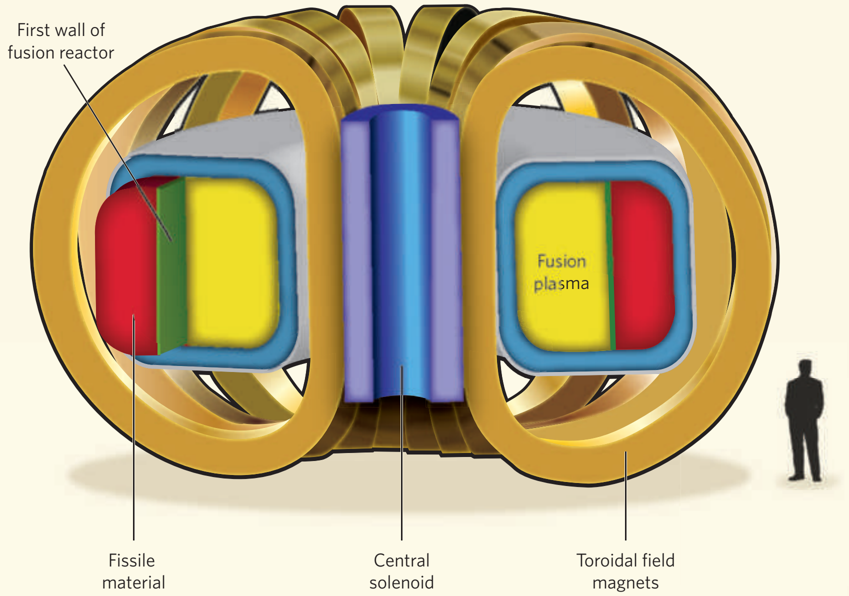
And so the idea of the fusion–fission hybrid was born, because fusion reactions — in which various isotopes of hydrogen fuse to become helium nuclei — produce a torrent of neutrons (one per fusion event). In principle, building a hybrid was simply a matter of wrapping a blanket of fissile material around a fusion reactor, and letting the energy flow (see graphic, below).

In practice, though, the technology of the day was not up to the task. Harnessing fusion, whether for neutrons or energy, amounts to recreating the conditions that drive the reaction in the Sun. Somehow, a gas of hydrogen isotopes — usually deuterium and tritium — has to be compressed and heated until it becomes plasma at more than 150 million °C. And somehow, that plasma has to be confined in its dense, superheated state for long enough for the reactions to proceed.

Faced with what seemed like insurmountable difficulties, the hybrid idea was shelved and physicists focused their efforts on the separate development of pure-fission and pure-fusion reactors. And except for a brief flurry of interest following the energy crisis of the late 1970s, when the Nobel laureate physicist Hans Bethe tried to drum up support for hybrids[1], the idea has stayed on the shelf — until now.

ANATOMY OF A FUSION–FISSION HYBRID

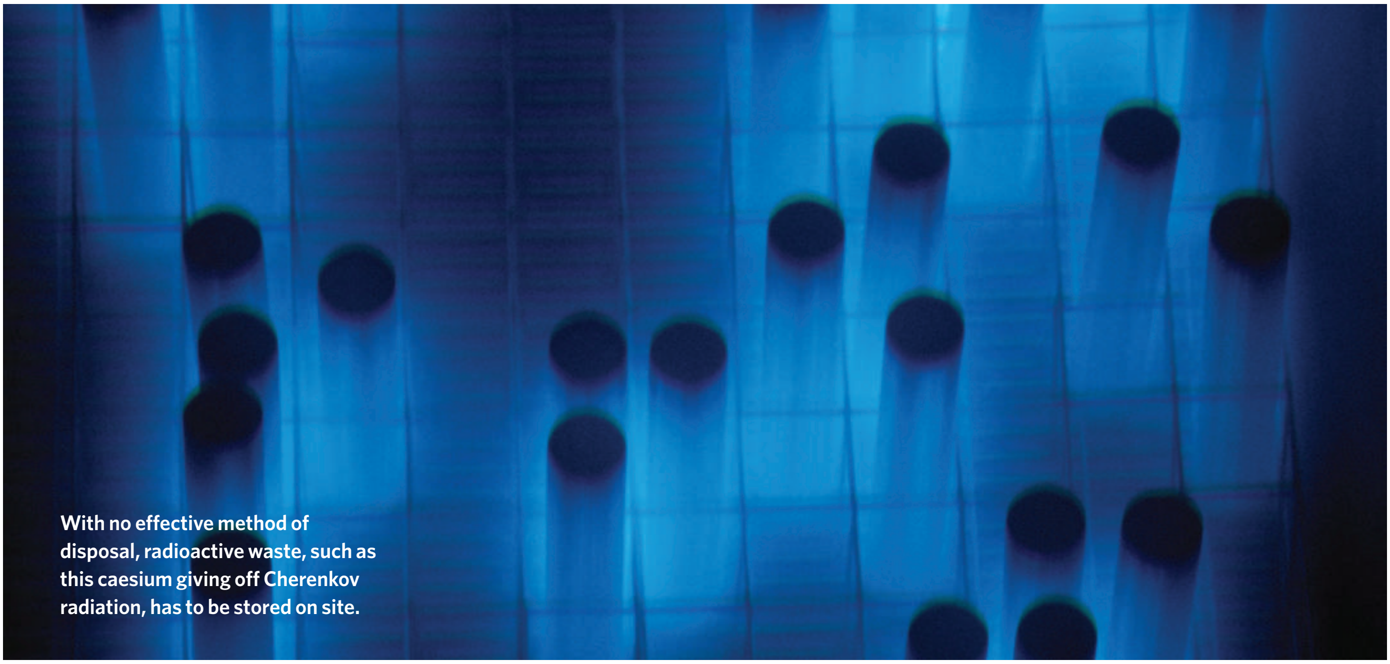
A fusion reactor, based on a doughnut-shaped tokamak, generates high-energy neutrons that drive fission in the surrounding blanket of fissile material. Putting nuclear waste in this blanket should in principle burn up all the long-lived radioactive by-products produced by the fission process.



The advance of fusion

One reason for the renewed optimism about hybrids is half a century of progress in plasma containment. The most common approach today is to trap the plasma inside a doughnut-shaped device known as a tokamak, which holds it in place with an intense magnetic field. It is a measure of the difficulty of the task that the longest-lived fusion reaction demonstrated so far, achieved in 1997 in the Joint European Torus at the UK Atomic Energy Authority's (UKAEA) Culham Science Centre near Oxford, lasted no more than a few seconds. It generated fusion energy equivalent to 70% of the energy that was used to produce it. But many scientists in the tokamak-fusion community think that the next big machine — the International Thermonuclear Experimental Reactor (ITER), being built at Cadarache in the south of France — will have an energy output up to ten times its input.

At about 19 metres wide and 11 metres tall, ITER's toroidal containment vessel will be twice



With no effective method of disposal, radioactive waste, such as this caesium giving off Cherenkov radiation, has to be stored on site.

P. ESSICK/AURORA/GETTY IMAGES

the size of that of the Joint European Torus and, at an estimated construction cost of some €10 billion (US$14 billion), it will be one of the most expensive experiments ever undertaken[2]. However, the project has come under criticism for its cost overruns and delays and it will not start operation until 2018. Experiments on whether fusion would be viable for power aren't planned to begin until the end of 2026.

Nonetheless, says Weston Stacey, a professor of nuclear engineering at the Georgia Institute of Technology in Atlanta, "the physics and technology that are being developed at ITER are more than enough to build a good neutron source for a hybrid".

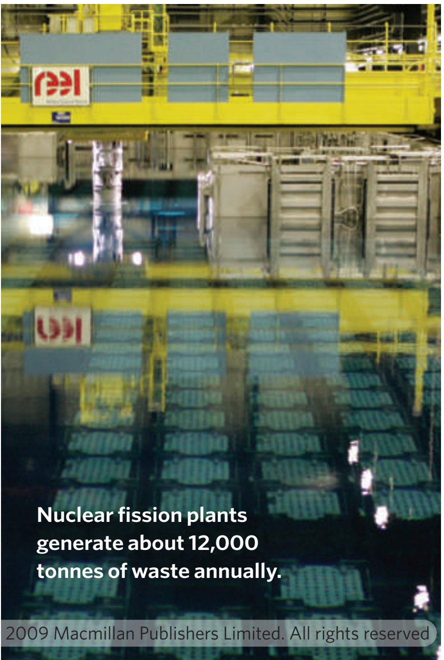
That's why Stacey, a leading proponent of the hybrid idea, has used the ITER design as the basis for the concept of a subcritical advance burner reactor[3], a fusion–fission hybrid design that he and his team at Georgia Tech have been working on for more than 10 years.

Once we have a fusion reactor, says Stacey, "the problem will be to fit all this together". He laughs at himself for implying that putting a fusion reactor the size of ITER into the core of a fission reactor will merely be 'an engineering challenge'. But it is his engineering approach to design that has prompted people to take notice.

"One of the problems with designs in the past was that nobody who was interested in the hybrid had done very much serious engineering," says Jeff Freidberg, a nuclear scientist and engineer at the Massachusetts Institute of Technology in Cambridge. "But the one that has perhaps done the best job so far is Stacey, because he's spent a lot of time to put some real engineering in there."

China is also pursuing the hybrid idea: it is one of the goals of the country's High-Tech Research and Development Programme. "At the moment it's mainly calculations to assess the various conceptual designs for a hybrid," says Jiangang Li, director of the Chinese Academy of Sciences' Institute of Plasma Physics in Hefei. But the country's big push into nuclear fission power gives the effort urgency, he says: "China will be faced by both a need to be able to reprocess a lot of radioactive waste and a shortage of nuclear fuel because the country has relatively limited fission fuel resources."

Freidberg is cautious about how realistic many of the ideas that are emerging in the field are in the short term, but is optimistic about their contribution in the longer term. In particular, he sees the hybrid as potentially easing some of the technical challenges posed by a pure fusion reactor.



Nuclear fission plants generate about 12,000 tonnes of waste annually.

F. MORI/AP

Because the fusion core of a hybrid would only have to generate neutrons, for example, it could be operated well below the power levels that a pure fusion reactor would need to work at to produce electricity. As a result, the plasma in a hybrid device would probably be less susceptible to instabilities and other disruptions.

A real beast

Lower power levels should also ease the 'first wall' problem — the difficulty of finding materials for a fusion reactor's inside wall, which will be exposed to such an intense flux of high-energy neutrons that it will probably need to be replaced after just a year or two of operation. "The problem of that first wall is a real beast," says Freidberg.

That will still leave Stacey's engineering challenge to solve: building a fusion reactor inside an equally complex fission device. But Freidberg remains optimistic. "None of these problems are insurmountable, but you can't solve them with paper studies, you ultimately need to build some devices. And maybe you can start to build things sooner than you could do for pure fusion electricity, because the end goal is a little bit nearer."

Not everyone is convinced, however. Steven Cowley, director of the Culham Science Centre, speaks for many in the fusion community who are sceptical of the need to revisit the hybrid concept, and who are concerned that it is a distraction from the goal of sustainable, clean, pure fusion power. "I'm not saying a hybrid can't be done," says Cowley. "But if what you need is post-ITER in its abilities, then you should focus your attention at getting all the way to pure fusion. Because even though in principle it looks easier, you have to solve all these other problems as well."

Beyond ITER

Hybrid designs don't have to be based on ITER. For example, a group of researchers at the Institute for Fusion Studies at the University of Texas in Austin argues that a practical hybrid will require a fusion core that is far smaller than that of ITER.

"A typical light-water fission reactor runs at about a gigawatt of electric power," explains Swadesh Mahajan, a senior research scientist with the institute. That gigawatt is generated within a certain volume, which means that the reactor has a power density of so many gigawatts per unit volume. And as it turns out, says Mahajan, that number is about five times higher than the power density of ITER. This creates a problem for the design of a hybrid. For the fission blanket to capture the fusion-generated neutrons efficiently, the fusion core and the blanket have to have roughly the same power density. So the fusion system has to have a power density about five times that of ITER, says Mahajan. Or to put it another way, the fusion core has to put out the same amount of energy (and neutrons) in a volume five times as small.

The problem is that ITER's planned power density is already at the limits of current technology. These limits are set by the materials used to construct the exhaust of the reactor — the diverter. The materials have to withstand the high volume of superheated gas that must be continually vented from its plasma.

To overcome this problem, Mahajan's group has come up with the Super-X Divertor[4]. The concept involves engineering the magnetic fields around the exhaust of a tokamak to increase the distance hot gases have to travel, giving them a chance to cool down before they come into contact with the solid walls of the exhaust. This enables the diverter to handle the exhaust from much higher power-density tokamaks.

"I think the Super-X Divertor is a big step forwards. A huge step forwards," says Cowley.

G. MEEK/WOODRUFF SCHOOL MECH. ENG., GEORGIA TECH

"Once we have a fusion reactor, the problem will be to fit all this together."
— Weston Stacey

He is excited about the prospect of a compact neutron source based on Mahajan's ideas, but nevertheless says that the UKAEA's fusion efforts are focused on ITER, and that it has no interests in developing a hybrid. "The Super-X Divertor could certainly enable the high-power devices that the Texas group want for their hybrid. But I think it'll do more than that. It will be the model of the kind of diverter that we will have on any demo reactor." As well as testing the Super-X concept itself, a compact neutron source built with its help could be used to develop and test the materials needed for a commercial fusion reactor. However, adding the untested diverter to ITER would be too risky.

Mahajan, for his part, is hoping that Cowley's work will further another of his group ideas, that of a disposable fusion 'battery'[4–5] — a much smaller fusion device than ITER that can be replaced in its entirety at the end of its operational life.

M. MILLER

"Our device operates in the plasma modes that every Tom, Dick and Harry in the plasma community can produce in their lab."
— Swadesh Mahajan

"The biggest engineering nightmare if you ask any fusion engineer is the problem of the first wall," says Mahajan. "So we decided that if we had a fusion neutron source that was sufficiently small, not in the sense that you could put it in your handbag, but small enough that a crane could easily lift it, we could design a neutron source that is replaceable."

With a reactor that can be lifted in an out of the middle of a hybrid's fission blanket, Mahajan argues, you no longer have to worry as much about the stability of the materials you use to make it. He envisages that the fusion part of such a device could be removed and replaced at the same time as the fission blanket's waste-fuel rods, about every 2 years. What's more, he says, in the test phase of such a device, this 2-year lifespan should enable the technology in the battery to be developed at a much faster pace than a conventional reactor. "If we needed five iterations to improve the stability of our device, with a turn-around time of just 2 years, that would take us only 10 years. For other designs the same process would take 50 years."

And it's not just the materials problems that the Texas approach would address, but the plasma physics as well. For ITER to produce ten times more energy from a fusion plasma than is put in, it will require the generation of unprecedented plasma temperatures, densities and confinement times. But because the fusion component of a hybrid need not produce energy, merely neutrons, the plasma conditions needed will be more modest.

"Because the Super-X Divertor takes care of the heat-flux issue, we can operate our device in the sorts of conventional plasma modes that every Tom, Dick and Harry in the plasma community are already producing in their laboratories," says Mahajan.

And it could even deal with potential concerns about generating a hot thermonuclear plasma in the middle of a blanket of concentrated, highly radioactive, nuclear waste. "Even if something did go wrong with the fusion module of our hybrid, the toroidal field coils of the module, which are made of strong metal, will shield the fission blanket from any stupid thing that the plasma is capable of doing," says Mahajan. This would not be the case in a conventional hybrid design, in which the components are more intimately connected.

The Texas group is in talks with groups at Princeton University in New Jersey and Oak Ridge National Laboratory in Tennessee to investigate these ideas.

Mahajan says he sees their work as essential to rebuilding the world's nuclear power capacity: "One of the things I've been arguing for — because in 20 years we will be ready to destroy the waste — is to start building nuclear reactors now. Don't wait. The rate at which nuclear capacity has been destroyed is an act of monumental stupidity." If scientist don't start aggressively pursuing this form of clean energy, he says, "We can forget about solving global warming. We will have screwed the planet royally if we don't take action fast." ■

Ed Gerstner is a senior editor of *Nature Physics*.

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