NSF launches funding schemes for medium-scale infrastructure

Funding across scientific disciplines could catalyze US competitiveness.

CORNELL UNIVERSITY

THE BLUE STRUCTURE is an artist's rendition of the housing for a high-magnetic-field beamline to be added to the Cornell High Energy Synchrotron Source. The adjacent brown structure represents the existing lab.

Does the research facility you want to build cost upwards of $100 million? Try lobbying Congress or chasing down the big money through NSF's major-facility awards or the Department of Energy. Need up to a few million dollars for lab equipment? Ask NSF or another funding agency. Those are the standard avenues for funding scientific infrastructure in the US. Until recently, however, scientists had few places to turn for medium-cost infrastructure.

Now NSF seeks to fill that gap with a pair of funding lines. Awards in the smaller midscale research infrastructure category (MidScale RI-1) are available for projects costing from $6 million to $20 million and can encompass design or implementation; the MidScale RI-2 line funds infrastructure costing from $20 million to $100 million. The two programs run in alternate years.

The funding gap had been recognized for a long time. Then in 2017, as part of the American Innovation and Competitiveness Act, Congress instructed NSF to address it. The agency came up with the specific approach as part of its 10 Big Ideas, an exercise for planning future investments. Medium-scale projects have been funded in a few divisions within NSF, but the new awards are open to all science and engineering fields. When the agency put out requests for proposals in late 2018, they poured in across all fields, says Allena Opper, NSF program director for experimental nuclear physics, who cochaired the working group for the MidScale RI-2 projects.

In late 2019 NSF announced the winners of the first round of MidScale RI-1 funding. Ten projects will receive a total of $121 million over five years. Then, on 29 October, NSF announced three awards totaling $125 million over five years for shovel-ready MidScale RI-2 projects: A high-magnetic-field beamline at Cornell University's synchrotron light source received nearly $33 million; a test bed for future power-grid architectures at the University of California, San Diego (UCSD), $39 million; and a network of global ocean-monitoring floats by a collaboration led by the Monterey Bay Aquarium Research Institute, $53 million.

A competitive edge

A MidScale RI-2 award will put a 20-tesla superconducting magnet on a new beamline at the Cornell High Energy Synchrotron Source (CHESS). It will be the strongest persistent magnet on any synchrotron worldwide. According to NSF division director for materials research Linda Sapochak, the project is part of a longer-term goal to keep the US competitive in high-magnetic-field science.

By combining it with strong magnetic fields, x-ray scattering can be brought to bear on phase changes induced in materials by magnetic fields. The prime science driver is to probe quantum materials such as spin liquids, frustrated magnets, and topological insulators. "Strong magnetic fields provide the most direct way to manipulate quantum states of matter," says Cornell physicist Brad Ramshaw. Jacob Ruff, director of the NSF-funded beamlines at CHESS, anticipates that scientists will also use the high-field beamline for structural biology, chemistry, and other studies.

Magnetic fields can induce big changes. "In some materials interesting behavior may occur at 2 T, while in others it takes 20 T or 200 T," says Ruff. Many synchrotron sources have beamlines equipped with magnetic fields of 2–7 T. The strongest persistent magnet used in structural studies is a 17 T solenoid that the UK's University of Birmingham dispatches to x-ray and neutron sources. Although a couple of synchrotron facilities have made "heroic measurements" with pulsed fields up to 30 T that have offered glimpses, Ruff says, "we have not yet been able to carefully study materials at those fields in detail."

The NSF award covers the cost to build a new beamline and install a commercial magnet, which partners at the National High Magnetic Field Laboratory (MagLab) will help choose. The partners will also work jointly on the experimental station so that it can eventually accommodate a 40 T magnet that the MagLab is developing.

To open in 2025 as planned, "we need to be in the dirt" by summer 2022, says CHESS director Joel Brock. Housing the magnet requires special infrastructure—

for example, the concrete cannot contain conventional rebar—for which Cornell needs to raise $24 million.

The high-field beamline team is collaborating with the University of Puerto Rico at Rio Piedras to bring doctoral students to Cornell. Starting in September, four students per year will come to design, test, and build instruments and parts for the new beamline. Ramshaw, the Cornell liaison for the partnership, sees "a lot of excitement on both sides." He notes a general need to train more people in x-ray instrumentation, and the collaboration gives students in Puerto Rico direct access to a world-class facility.

Flatter architecture

A team of engineers and computer scientists at UCSD won a MidScale RI-2 award to create a test bed to explore algorithms for controlling and monitoring energy use. To start with, the project will link existing applications, including 15 solar power generators, devices in a dozen classroom and administrative buildings, and roughly 300 electric-vehicle charging stations. A big chunk of the award will go to adding thousands of controllable light fixtures and hundreds of air-handling systems. "We have a large number of different types of devices and flexible loads," says John Dilliott, UCSD director of utilities and sustainability.

Today's power grids employ central communications systems, in which a single controller exchanges data with each device, says principal investigator Jan Kleissl, director of the university's Center for Energy Research. Future grid systems will have to deal with millions of devices—"every water heater, AC unit, electric vehicle, and so on," says Kleissl. A federated architecture, where responsibilities reside locally in neighborhood nodes and report only occasionally to a central entity, are expected to make communications in power systems—and ultimately power use—more efficient, he says.

Some 2000 devices will be connected by the test bed, which will make it the first of its kind in terms of size, device heterogeneity, number of devices, easy access for users, and the like. Sonia Martínez is a UCSD professor who researches distributed controls and coordination of power systems. "We have to break down decision making from top-down to a flatter architecture," she says. The facility's aim is to test ideas for the integration of renewable

UNIVERSITY OF CALIFORNIA, SAN DIEGO

ONE OF 15 SOLAR POWER GENERATORS that will be part of a set of 2000 devices linked to form a power-use test bed at the University of California, San Diego. The test bed will allow the exploration of algorithms to better manage power grids.

energy and load sharing using real loads and data. The team hopes that researchers from both academia and industry will use the test bed. "There is a barrier between the two worlds," she says. "It's hard for utilities to adopt new technologies. We hope that with the test bed they can be convinced that the power is reliable."

A longer-term goal, says Dilliott, is to expand to interactions with California's power grid. "What we do here can be extrapolated to grid stability and energy efficiency. We'll have granular control of buildings and employ algorithms to reduce energy use."

Float fleet

The third inaugural MidScale RI-2 award is for a network of 500 ocean floats known as the Global Ocean Biogeochemistry (GO-BGC) Array. The floats carry sensors for oxygen, chlorophyll, nitrates, pH, particles, and sunlight. They record data from the upper ocean, within about 300 meters of the surface, where phytoplankton grows. "The goal is to measure the ocean's metabolism," says principal investigator Ken Johnson, of the Monterey Bay Aquarium Research Institute. The University of Washington, Scripps Institution of Oceanography, Woods Hole Oceanographic Institution, and Princeton University are partners in the project.

Plankton plays a huge role in the globe's biological pump by taking carbon dioxide out of the air. How and where the microscopic plants do that is sensitive to ocean warming. "There are all kinds of questions about whether the mixing of deep water and warmer top water changes," Johnson says. "And if you reduce the plankton concentration in the upper ocean, will the ocean absorb less CO_2 from the atmosphere?"

The floats are to spend most of the time a kilometer below the surface. Every 10 days they automatically drop to 2 km and then rise to the surface. From there, they transmit data via satellite, and then sink again. "The data is offloaded in 15 minutes," says Johnson. "You don't want the floats at the surface for long, because things grow on them, or they could be crushed by ships." Parking them at 1 km prevents biofouling, he says. And the detour down to 2 km is useful for calibration, because measured variable values are stable there.

An extension of a pilot network in the Antarctic Ocean, the project is intended to form half of an international network. The best floats are made at the University of Washington, Johnson says, and the cost to acquire and deploy them is about $100 000 each; the team hopes to transfer those float-building skills to industry and bring down the price. Some countries deploy simpler floats with only an oxygen sensor, which cost about $30 000. But, says Johnson, "if you want the full carbon cycle, it helps to have all of the sensors.

"If we want climate signals, we will want to do this for decades," says Johnson. "But it's an NSF grant. We have to do cool science in five years and hit a home run." And, he says, few data exist about the open global oceans, "so there are plenty of home runs to hit." The "cool" areas of research that the team—and other scientists—may pursue, he says, include the effects on plankton of nonlinear interactions between the wind and ocean, the cycle of plankton production, the linkage between volcanic dust and plankton productivity, and the patchiness of uptake and outgassing of CO_2.

The first GO-BGC floats are scheduled to be deployed this spring. The data will be freely available.

GRETA SHUM

RESEARCHERS DEPLOY A FLOAT in the Antarctic Ocean. Starting this spring, a collaboration headed by the Monterey Bay Aquarium Research Institute will build and deploy 500 such floats, each carrying six sensors to monitor the carbon cycle and plankton growth. The project is one of the inaugural NSF midscale research infrastructure awards.

Smaller midscale infrastructure

Among the MidScale RI-1 awards for infrastructure is the neutron spin-echo spectrometer to be built at NIST in Maryland with $11.8 million. And for design, a team led by the Smithsonian Astrophysical Observatory won $12.7 million to plan an upgrade to the Event Horizon Telescope (EHT), the linked array of radio dishes that in April 2019 produced the first-ever image of a black hole. (See "What it took to capture a black hole," PHYSICS TODAY online, 11 April 2019.)

The spin-echo spectrometer takes advantage of an upgrade at NIST's neutron source that will more than double the flux. Combined with stronger and more controlled magnetic fields due to improved correction coils, the new instrument will "have better data and a 10 times better data acquisition rate," says Dan Neumann, director of the NSF-funded NIST Center for High Resolution Neutron Scattering.

Spin-echo spectrometry probes nanoscale dynamics—in both time and size—in systems such as soft matter, biological samples, colloidal systems, and nanomaterials. "It's an esoteric technique," says Neumann. Even so, the existing spectrometer is the facility's most oversubscribed instrument.

"The new instrument will let us look at slower processes, to over 300 ns for most samples, and 700 ns for others," says principal investigator Norman Wagner of the University of Delaware. The third partner on the award is the University of Maryland.

One company hopes to use the new spin-echo spectrometer to study the viscosity and longer-time-scale dynamics of a monoclonal antibody solution. The motivation is to understand the antibody solution at a molecular scale and then to adjust the interactions so that the monoclonal antibodies could be delivered by injection rather than intravenously.

The improved spin-echo spectrometer was on NIST's wish list, but in-house money was unavailable, says Neumann. "It would have taken many more years—if at all—if this money hadn't come through," he says. And the NIST instrument is an adaptation of one in Germany, which "makes it an easy sell. The risk is low and we know the costs rather accurately." The instrument will open to users in 2024.

Earth-sized video camera

Imagine making a movie of a black hole, says astronomer and EHT founding director Sheperd Doeleman. That's exactly what he and his collaborators are planning.

The extreme gravity of a supermassive black hole inexorably pulls in surrounding matter, which heats to billions of degrees. Magnetic fields are swept along by the gas and get caught up in the rotation of the black hole. The fields fling out jets of charged particles that can stretch for thousands of light-years. "If we could observe the orbits of gas around a black hole, we could devise new tests of Einstein's theory of gravity," says Doeleman. "We could see how the jets are formed and how matter and energy are redistributed on galactic scales." With the next-generation EHT, he says, "we aim to build an Earth-sized video camera to turn black holes into extreme cosmic laboratories."

The iconic image of a black hole was stitched together using data from eight radio telescopes scattered around the world and synchronized with atomic clocks. The award will be used to design new telescopes to increase the network to 20 dishes. The team will run simulations to determine the best dish size, radio frequencies, and locations for them.

A major part of the award will go toward outfitting the Large Millimeter Telescope near Puebla, Mexico, with a prototype superconducting receiver. The MidScale RI-1 award will put the team in a position to apply for the larger sums it will need to realize the next-generation EHT. Says Doeleman, "We want to make a black hole movie by the end of the decade."

Preliminary proposals for the next round of MidScale RI-1 grants are due this month; a new call for MidScale RI-2 proposals was issued in early December, with letters of intent due on 21 February.

Toni Feder

Canada's nuclear future brightens

Although the Canadian and US nuclear industries have shared origins in World War II, their paths soon diverged.

A RENDERING OF A SMALL MODULAR REACTOR design from SNC-Lavalin. The heavy-water-moderated reactor would produce 300 MW of electricity.

On a windswept field near the shores of Lake Ontario in mid-November, Canadian politicians and nuclear industry executives gathered to announce plans to build the country's first new nuclear reactor since the early 1990s. A month earlier US Department of Energy Secretary Dan Brouillette and Romania's Minister of Economy, Energy, and Business Environment Virgil Popescu signed an $8 billion agreement in Washington, DC, that paves the way for the construction of two new Canadian-origin reactors at a nuclear power plant on the Black Sea. Two Canadian reactors are already located there.

The two events highlight differences between the Canadian nuclear industry and its counterpart in the US. As competitive pressures have forced the closure of nuclear power stations and threaten many others south of the border, Canadians are in the midst of major refurbishments to extend the lives of a dozen reactors; another has already been updated. Six other aging reactors are due to be shut down by 2025, and it's likely that some new nuclear plants will eventually replace them.

Canada's 19 operating power reactors all have a markedly different design from the light-water reactors (LWRs) that predominate in the US and around the world. Known as CANDUs (Canadian deuterium uranium), they employ heavy water (deuterium oxide) as the neutron moderator and coolant. Should current plans proceed, however, the next Canadian reactor will be of a new type altogether.

Ontario Power Generation (OPG), the provincial government utility that owns the province's 18 reactors, is to select one of three competing designs for a single small modular reactor (SMR) to be built at its Darlington Nuclear Generating Station roughly 80 kilometers east of Toronto. GE Hitachi Nuclear Energy, X-Energy, and Terrestrial Energy are finalists in the competition, said Ken Hartwick, OPG's president and CEO. The target date for startup is 2028.

Additional SMR orders from Saskatchewan, New Brunswick, and Alberta will follow, predicted Greg Rickford, Ontario's minister of energy, northern development, and mines and of indigenous affairs. In a December 2019 memorandum of understanding, the four provinces agreed to cooperate on advancing development and deployment of SMRs.

Nuclear power in Canada has always been centered in Ontario, the most populous and industrialized of the 13 provinces and territories. Roughly 60% of the electricity consumed in the province is from nuclear. The only CANDU outside Ontario supplies about one-third of New Brunswick's electricity. British Columbia and Quebec have abundant hydroelectric resources, and Quebec, which exports power, closed its only CANDU in 2012, electing to forgo the expense of refurbishment. Alberta, Saskatchewan, and the maritime provinces are more sparsely populated and rely mainly on fossil fuels.

Heavy and light water

Canada's nuclear program dates to World War II, when the UK relocated its atomic bomb program from Cambridge University to its North American dominion. In Montreal and later at Chalk River Laboratories, about 180 kilometers upstream of Ottawa, British and Canadian scientists were focused on developing a heavy-water-moderated reactor to produce plutonium for the Manhattan Project. The British had brought along a large quantity of heavy water that had been smuggled out of occupied France. The Zero Energy Experimental Pile (ZEEP) at Chalk River, the first operating nuclear reactor outside the US, was a heavy-water design.

Ultimately, the US nuclear bomb development program chose graphite to be the neutron moderator for the reactors that made the plutonium for the Nagasaki bomb. But Canada's National Research Experimental (NRX) reactor, the successor to ZEEP, was the basis for the heavy-water plutonium and tritium production reactors at DOE's Savannah River Site, says historian Robert Bothwell, author of *Nucleus: The History of Atomic Energy of Canada Limited* (1988).

Some of the R&D in support of Hyman Rickover's nuclear propulsion program for the US Navy was done at the NRX, although the navy chose light water as the moderator and coolant for submarine reactors. President Jimmy Carter, who was then a navy lieutenant, was assigned to assist the cleanup of a 1952 partial meltdown of the NRX, the world's first major nuclear accident.

The National Research Universal (NRU) heavy-water research reactor began operating at Chalk River in 1957.

BRUCE POWER

THE BRUCE NUCLEAR GENERATING STATION on Lake Huron is the largest nuclear power plant in North America. Its eight CANDU reactors produce 30% of Ontario's electricity. Four of the reactors are in the foreground; the others are visible in the background.

In addition to developing fuels for CANDUs and conducting materials research, the NRX and NRU produced medical radioisotopes. At times the NRU supplied more than half the world's molybdenum-99, the precursor to technetium-99m, the most widely used medical isotope. When it was permanently shut down in 2018, the NRU was the world's oldest operating nuclear reactor. Two dedicated replacement isotope-production reactors at Chalk River, completed by a public–private partnership, were plagued by design faults and were abandoned in 2008.

Canada never developed nuclear weapons, but Canadian mines and uranium processing facilities played key roles in the Manhattan Project and in the postwar US nuclear arms buildup. In Port Hope, Ontario, a former radium processing plant now owned by Cameco Corp was converted during World War II to refine high-grade uranium from the Belgian Congo. Today it exports uranium hexafluoride to enrichment plants for peaceful purposes only. It also produces uranium dioxide for CANDU fuel.

The Cold War arms race fueled a boom in uranium mining at Elliot Lake in northern Ontario. Joseph Hirshhorn, whose collection of art now populates the Smithsonian museum that bears his name, made much of his fortune from Elliot Lake. When the US Atomic Energy Commission began cutting back on uranium orders in the late 1950s, the boomtown went bust. Canada is today the world's second-largest exporter of uranium, all of which is now mined in Saskatchewan's Athabasca River basin, whose ore has a higher grade than Elliot Lake's.

As partner in the North American Aerospace Defense Command and a NATO member, Canada once fielded US nuclear warheads on surface-to-air missiles and aircraft, says Tim Sayle, assistant professor of history at the University of Toronto. Canada has been free of nuclear weapons since the early 1980s.

Enrichment not required

With encouragement from the government, the US Navy submarine reactor technology was adapted by US utilities for electricity production. All operating commercial reactors in the US are LWRs. But Canada continued to develop its heavy-water technology. In large part, the CANDU design stemmed from Canada's inability to manufacture large castings for the pressure vessels that encapsulate LWR nuclear fuel assemblies, says Colin Hunt, cochair of the government and regulatory affairs committee of the Canadian Nuclear Society.

The CANDU reactor core consists of a calandria, an unpressurized vessel of heavy water with hundreds of tubes running through it to contain the nuclear fuel. Whereas LWRs must be shut down every 12–18 months to be refueled, CANDUs were designed to allow on-line refueling. The reactors remain operating as fresh fuel bundles are inserted into the tubes and the spent ones are ejected. LWR uranium fuel must be enriched to around 4% in the fissile uranium-235 isotope, but the CANDU burns naturally occurring uranium fuel containing about 0.7% ^{235}U. That feature eliminates the need for costly enrichment plants or services. And the CANDU can burn other fuels, including thorium, plutonium, and even spent fuel from LWRs.

The first CANDU, at Douglas Point on the shores of Lake Huron, operated commercially from 1968 to 1984. Four larger CANDUs came on line at the Pickering Nuclear Generating Station near Toronto in 1971, and four more units were added there in 1983. Six remain in operation. Twelve more CANDUs were built in Ontario, eight at the Bruce Nuclear Generating Station at Douglas Point and the newest four at Darlington. Today, Bruce is the largest nuclear generating station in North America, supplying more than 30% of Ontario's electricity.

Outside Canada, CANDUs have been installed in Argentina (1), China (2), India (2), Pakistan (1), Romania (2), and South Korea (4). Following India's 1974 test of a nuclear weapon, Ottawa ended nuclear cooperation with New Delhi. India went on to build more than a dozen reactors of a CANDU-derived design. Canada's assertive efforts to sell CANDUs to the UK were unsuccessful. Had the UK bought any, Bothwell says, the CANDU likely would have become a joint venture between the two nations, and the technology might have become the world's dominant reactor model.

An uncertain future

The aging Pickering reactors, which supply about 15% of Ontario's power, are scheduled to be permanently closed by 2025. It's an open question what will replace them. The other major power source in Ontario, hydroelectric, has been fully tapped, says Hunt. Coal-fired generation in the province is prohibited by law, and a recently enacted federal carbon tax of Can$30 ($23) per ton of carbon dioxide, rising to Can$50 in two years, should discourage new natural-gas-fired plants.

Although the province's electricity demand isn't growing now, it will likely

CANADIAN NUCLEAR LABORATORIES

CREATED DURING THE MANHATTAN PROJECT, the Chalk River Laboratories north of Ottawa were home to CANDU heavy-water-reactor development and several research reactors. Now known as Canadian Nuclear Laboratories, the facility is operated by a consortium of companies led by SNC-Lavalin for the federal government.

increase as demand for electric vehicles and hydrogen grows, says William Fox, executive vice president for nuclear at SNC-Lavalin, an architect and engineering firm that holds the rights to CANDU technology.

At the federal level, the Liberal-led government of Justin Trudeau has begun considering legislation with the aim of reducing Canada's carbon emissions to zero by 2050. On 30 November the government announced its intention "to launch an SMR Action Plan by the end of 2020 to lay out the next steps to develop and deploy this technology." It's a sign that Liberal members of Parliament have recognized that nuclear power is needed if Canada hopes to meet its 2015 Paris Agreement pledge that by 2030 it will have cut greenhouse gas emissions by 30% from their 2005 levels, says John Barrett, a consultant and former Canadian ambassador to the International Atomic Energy Agency.

Increasing wind and solar energy seems an obvious option to meet Ontario's future needs. But its leaders have soured on renewables since the previous Liberal provincial legislature's heavy subsidization of wind energy led to enormous increases in electricity rates. From 2010 to 2016, average home electricity costs rose by 32%, despite a 10% decline in average household electricity consumption, according to Ontario's Financial Accountability Office. The price hikes, which also caused many industrial operations to flee the province, were a major contributor to the Liberals' historic rout in the 2018 elections. The current Progressive Conservative provincial government tore up the still-outstanding wind turbine construction contracts, says Hunt.

Importing power from neighboring provinces isn't an option, Hunt says. Purchasing power from electricity-rich Quebec would put Ontario in competition with New England and New York State and drive up electricity rates further. Quebec's transmission system was built to export power to the US, so new transmission lines would be required to accommodate interprovincial flow, Hunt says. A further complication is that Quebec's electricity grid is out of phase with the rest of North America's: The peaks and valleys of its alternating current flow are asynchronous with the rest of the continent's. As a result, the power imported by Ontario would need to be converted to DC and then converted back to in-phase AC once across the border.

Hunt believes that no more CANDUs will be built in Canada; he sees the future belonging to SMRs. (See PHYSICS TODAY, December 2018, page 26.) Though SNC-Lavalin has a large SMR design (see the figure on page 23), Fox believes that large reactors will be needed to replace the 2400 MW that Pickering's CANDUs now supply. Because the entirety of Canada's nuclear experience with large reactors has been with CANDUs, Fox is confident that the same technology will be chosen if new conventional-size reactors are ordered.

Smaller SMRs could be ideal for providing electricity to remote off-grid communities in the vast Canadian north. The diesel-generated power they use now is expensive, dirty, and vulnerable to cutoffs of fuel supply during severe winter weather. SMRs also would be an attractive option to provide power to remote mining operations and to produce the steam used in extracting oil from Canadian tar sands, Barrett says. Several 300-MW-sized SMRs could meet Saskatchewan's needs, he notes.

Compared with the US, Canada has made far more progress on the disposition of nuclear waste. The federal Nuclear Waste Management Organization expects to select the location for a geological nuclear waste repository in 2023. Unlike the US, where the now-abandoned Yucca Mountain location was unsuccessfully forced on Nevada, the waste authority invited site proposals from communities; 22 were received. After each was characterized, two Ontario sites were named finalists: one in farmland about 45 kilometers east of Lake Huron and the other in the exposed rock of the Canadian Shield about 246 kilometers northwest of Thunder Bay.

David Kramer PT