work in parallel on other aspects of fusion power. In addition to the U.S. Department of Energy's earlier commitment to ITER, its Advanced Research Projects Agency-Energy (ARPA-E) last year announced nine research grants "to create… new, lower-cost pathways to fusion power and to enable more rapid progress in fusion research and development." The largest of these grants, awarded jointly to Los Alamos National Laboratory and HyperV Technologies Corp., comes in at about one thousandth the projected cost of the U.S. contribution to ITER.

The project leader, Los Alamos physicist Scott Hsu, explains that their work is one embodiment of an approach called magneto-inertial fusion (MIF), which combines the benefits of two large-scale fusion paradigms, magnetic confinement and inertial confinement. ITER, for instance, is a magnetic-confinement device, using ultra-powerful magnetic fields to contain the 150-million-degree plasma undergoing nuclear fusion. (Such high temperatures are necessary for fusion because only at high temperatures can positively charged atomic nuclei slam into each other with sufficient speed to overcome their mutual electrical repulsion and fuse into larger nuclei.) By contrast, the National Ignition Facility at Lawrence Livermore National Laboratory in California is an inertial-confinement device, using inward-directed lasers to implode a nuclear-fuel pellet.

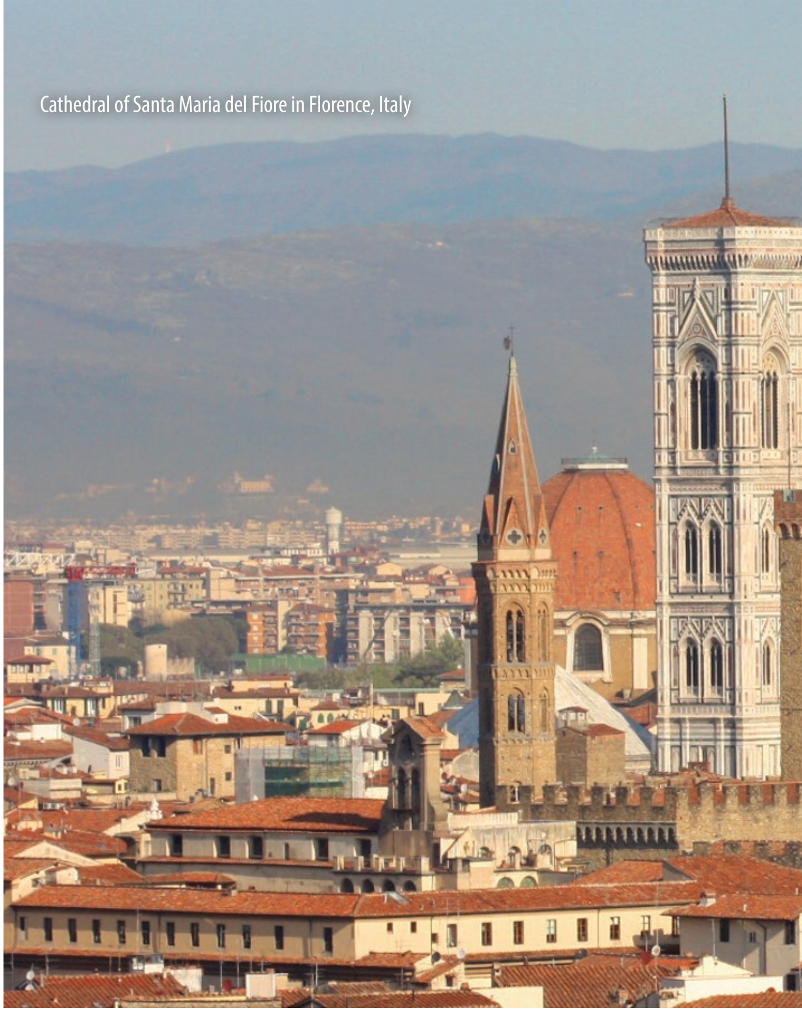
In an exploratory experiment of Hsu's approach to MIF, 60 electromagnetic plasma guns, designed and built by HyperV and mounted all around a spherical vacuum chamber, simultaneously fire supersonic jets of plasma. (A full-scale reactor would employ hundreds of plasma guns.) The jets converge at the center of the chamber for the purpose of compressing another plasma of laser-magnetized nuclear fuel, injected moments earlier.

Such plasma-jet driven MIF builds upon success obtained recently at Sandia National Laboratories. There, researchers obtained conditions suitable for fusion by compressing a solid liner surrounding the hot, magnetized fuel. However, the Sandia experiment was not designed for the repetitive pulsing required for fusion energy, as each compression, or "shot," severely damages the liner and other components. Hsu's plasma-jet compression is designed to overcome this by effectively constructing a plasma liner, instead of a solid one, that's reestablished with each shot.

"We will be able to fire one shot every second, continuously restoring fusion conditions without damaging the hardware," says Hsu. In theory, that could be sufficient to achieve ignition—the all-important and maddeningly elusive state of getting significantly more power out than what is put in. Initial simulations suggest that, in principle, the fusion energy output could be quite large, possibly reaching up to 30 times the energy supplied to the plasma jets. Of course, actually achieving such a large gain, or really any gain at all, will not be so straightforward.

"Remember, the closer you come to ignition, the more unforeseen problems arise," says Hsu. "The history of fusion-energy research has shown that time and time again." With each snag encountered, studied, and overcome along the way, he plans to progressively improve simulations of the system's performance for ever-more realistic predictions. "But if we do achieve ignition, then our technology should scale well for commercial power applications. In fact, that's one of the key reasons for taking this approach."

—Craig Tyler



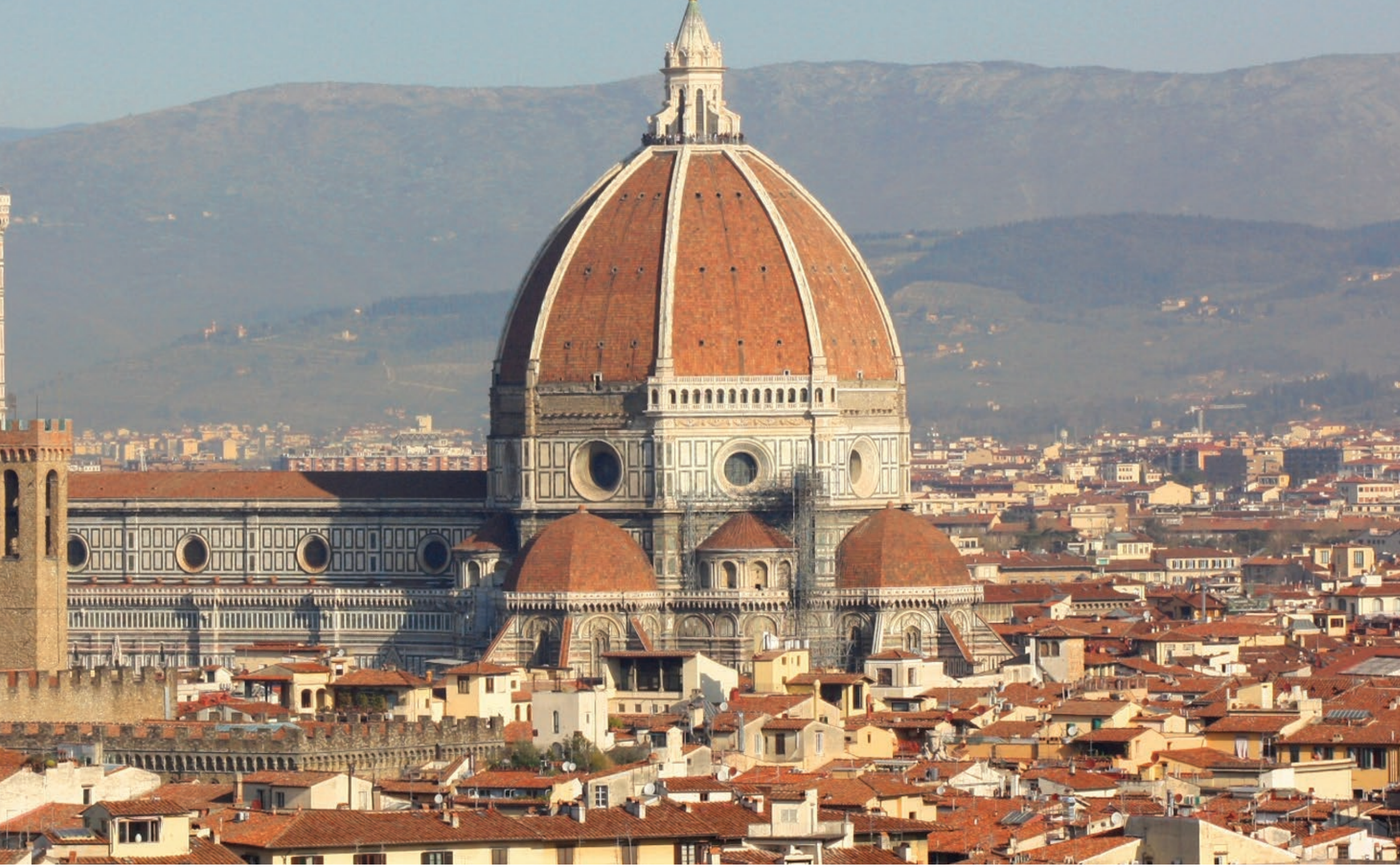
Cathedral of Santa Maria del Fiore in Florence, Italy

Can Free Particles Save a Priceless Treasure?

SADNESS COULD HAVE OVERWHELMED LOS ALAMOS particle physicist Elena Guardincerri last summer when she saw the ever-expanding cracks threatening the dome of the Cathedral of Santa Maria del Fiore (better known as the Duomo), a Renaissance icon in Florence, Italy. Engineered by famed master builder Filippo Brunelleschi, it was completed in 1436, and the secrets of what hidden supports or unidentified vulnerabilities might lie behind its walls have been lost to the ages. But Guardincerri was in Florence on a mission to aid restoration: to meet with the president of the Opera del Duomo, the corporation that has managed the cathedral since its construction, and present an innovative imaging solution sourced from the cosmos with which to peer inside.

Though widely renowned for his skill at solving engineering problems, Brunelleschi was considered foolish by some for abandoning flying buttresses and other conventional supports in favor of his own unorthodox ideas for constructing the dome. He deliberately left no drawings behind, and his design still poses a few riddles: Does the double-shell dome have an inner support system of iron chains inside the masonry, as alluded to in historical documents? Is the inner wall made of rubble masonry as well as bricks? Such information is essential as architects and engineers enhance their models of the dome and decide how to protect this world treasure from further damage—or outright collapse.

Instead of metal detectors, x-rays, or ultrasonic inspection, Guardincerri's team will use cosmic-ray muon trackers to create vivid images of hidden reinforcement elements inside the dome's masonry and exam-



ine the cracks deep inside the dome's 2.25-meter-thick inner wall. The award-winning technology pairs detectors with high-tech software to construct images from high-energy particles called muons created in collisions between cosmic rays from space and molecules in the earth's upper atmosphere. Most of the time, these muons rain down on us, pass through our bodies, and penetrate deep into the earth unnoticed. And from them, preservationists will get 3D-like images of the structural details they have sought for decades. The images will help them understand, for example, what keeps the 37,000-ton dome from toppling any time there's earthquake activity.

After Guardincerri presented the results of her team's feasibility study and obtained approval to build customized muon trackers for the dome, the Italian native entered the majestic Florence cathedral for the first time in her life. Architects showed her where she will eventually begin the search for iron reinforcements that other methods have failed to locate.

"This will be a great stage to show the world how well muon imaging works," she said.

Muon-imaging technology was originally invented in the 1950s. At that time, it didn't track muon scattering, but rather muon transmission and attenuation through objects. Archaeologists have exploited this method to search for hidden chambers inside the Egyptian pyramids. Los Alamos later invented the muon multiple-scattering technique, and following the September 11, 2001, terrorist attacks, its threat reduction team and commercial partner Decision Sciences Corporation developed muon-scattering tomography to expose smuggled nuclear material in ship cargo containers, vehicles, and rail cars—even when the material is shielded from conventional screening systems, such as x-rays. The Lab has found its muon-scattering tomography to be effective for arms treaty verification and nuclear reactor imaging as well, with Japan planning to use the technology to peek inside its tsunami-ravaged Fukushima Daiichi nuclear reactor.

In Florence, however, the Lab's existing muon trackers won't do because they weigh 800 pounds each, and it seems wise to presume that the dome shouldn't be subjected to that much additional weight. So the Los Alamos physicists and their collaborators are creating lightweight muon trackers that can be shipped to Italy, disassembled for transport up spiral staircases and through narrow passageways, and reassembled in different locations for measurements.

One muon tracker will be suspended inside the cathedral near Giorgio Vasari's *Last Judgment* fresco; another will be placed between the dome's two shells, in a walkway closed to the public. With the structure flanked on both sides by detectors, the team can collect multiple scattering angles from the muons striking denser objects hidden inside the overall structure; these scattering events are used to create a computer image. To obtain sufficient resolution, Guardincerri's team must measure the muons entering and exiting the structure for at least two weeks.

While making a critical contribution to stabilizing and preserving the Florence cathedral, the Los Alamos team will unveil the first application of muon tomography to infrastructure monitoring. Once miniaturized, the muon trackers could become inspection tools for imaging thick archaeological artifacts, assessing the structural stability of dams and bridges, diagnosing damage in pipes, and generally seeing through all manner of hard-to-access structures and systems of value to civilization.

— Diana Del Mauro