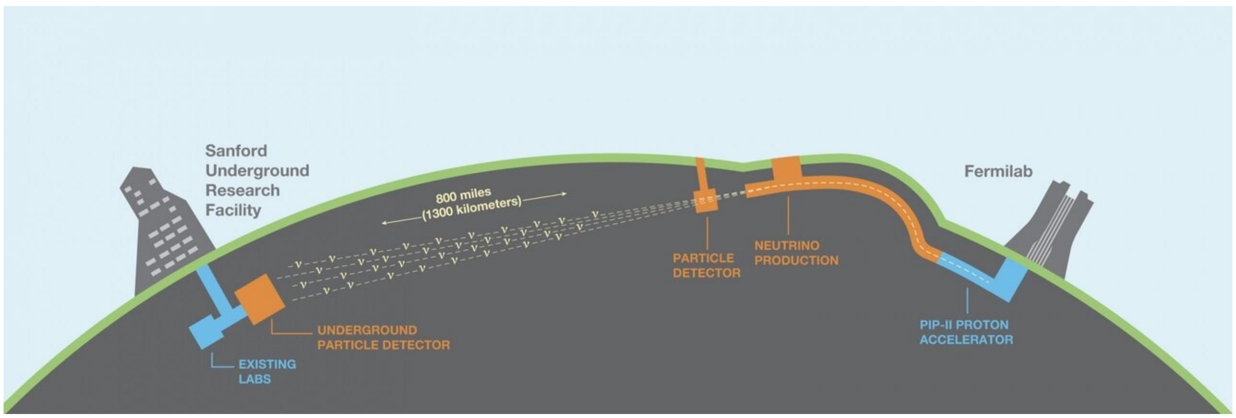
How do you make the world's most powerful neutrino beam?

November 14 2019, by Lauren Biron



The design of the experiment is elegant — produce neutrinos and measure them at Fermilab, send them straight through 1,300 kilometers of earth, then measure them again in giant liquid-argon detectors at Sanford Lab. Credit: Fermilab

What do you need to make the most intense beam of neutrinos in the world? Just a few magnets and some pencil lead. But not your usual household stuff. After all, this is the world's most intense high-energy neutrino beam, so we're talking about jumbo-sized parts: magnets the size of park benches and ultrapure rods of graphite as tall as Danny DeVito.

Physics experiments that push the extent of human knowledge tend to work at the extremes: the biggest and smallest scales, the highest intensities. All three are true for the international Deep Underground Neutrino Experiment, hosted by the Department of Energy's Fermilab. The experiment brings together more than 1,000 people from 30-plus countries to tackle questions that have kept many a person awake at night: Why is the universe full of matter and not antimatter, or no matter at all? Do protons, one of the building blocks of atoms (and of us), ever decay? How do black holes form? And did I leave the stove on?

Maybe not the last one.

To tackle the biggest questions, DUNE will look at mysterious subatomic particles called neutrinos: neutral, wispy wraiths that rarely interact with matter. Because neutrinos are so antisocial, scientists will build enormous particle detectors to catch and study them. More matter inside the DUNE detectors means more things for neutrinos to interact with, and these behemoth neutrino traps will contain a total of 70,000 tons of liquid argon. At their home 1.5 kilometers below the rock in the Sanford Underground Research Facility in South Dakota, they'll be shielded from interfering cosmic rays—though neutrinos will have no trouble passing through that buffer and hitting their mark. The detectors can pick up neutrinos from exploding stars that might evolve into black holes and capture interactions from a deliberately aimed beam of neutrinos.

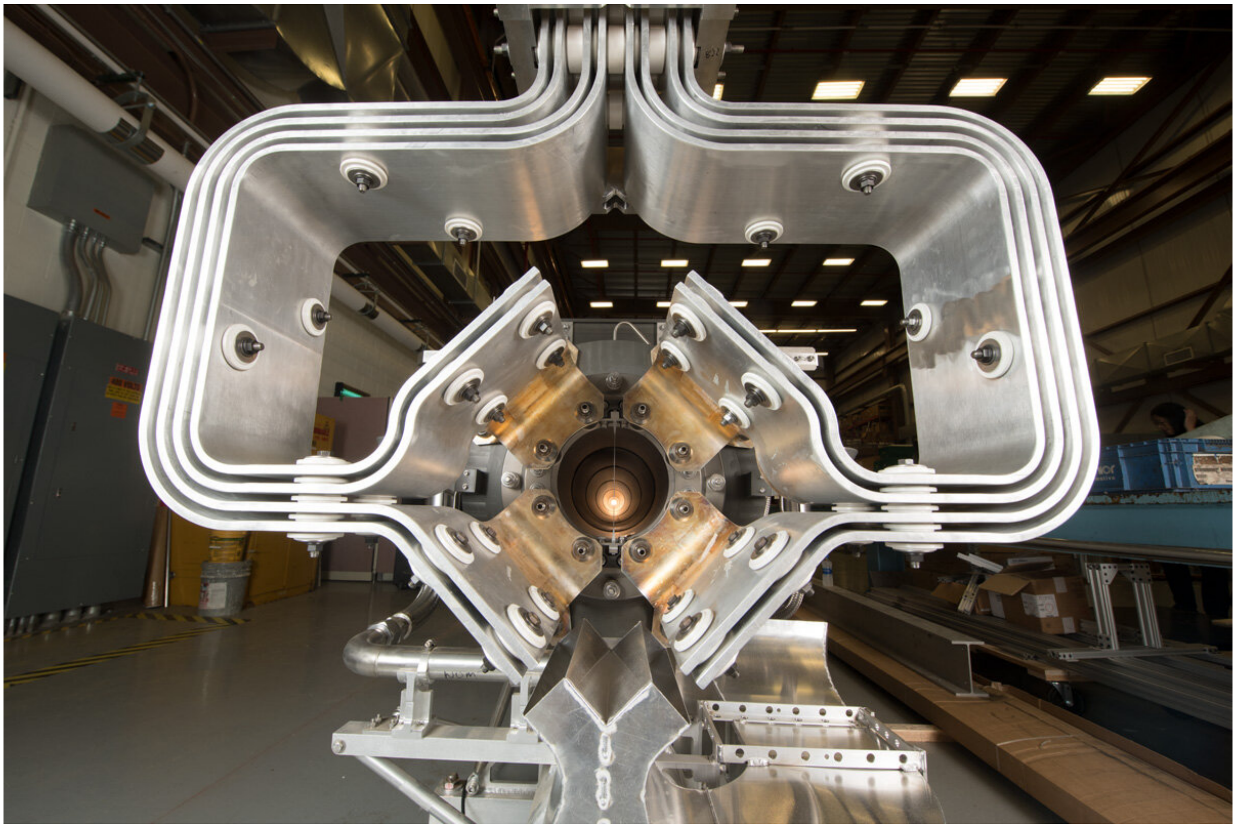
Neutrinos (and their antimatter counterparts, antineutrinos) are born as other particles decay, carrying away small amounts of energy to balance the cosmic ledger. You'll find them coming in droves from stars like our sun, inside Earth, even the potassium in bananas. But if you want to make trillions of high-energy neutrinos every second and send them to a particle detector deep underground, you'd be hard-pressed to do it by throwing fruit toward South Dakota.

That's where Fermilab's particle accelerator complex comes in.

Fermilab sends particles through a series of accelerators, each adding a burst of speed and energy. Work has started for an upgrade to the complex that will include a new linear accelerator at the start of the journey: PIP-II. This is the first accelerator project in the United States with major international contributions, and it will propel particles to 84% of the speed of light as they travel about the length of two football fields. Particles then enter the Booster Ring for another … well, boost, and finally head to the Main Injector, Fermilab's most powerful accelerator.

The twist? Fermilab's particle accelerators propel protons—useful particles, but not the ones that neutrino scientists want to study.

So how do researchers plan to turn Fermilab's first megawatt beam of protons into the trillions of high-energy neutrinos they need for DUNE every second? This calls for some extra infrastructure: The Long-Baseline Neutrino Facility, or LBNF. A long baseline means that LBNF will send its neutrinos a long distance—1,300 kilometers, from Fermilab to Sanford Lab—and the neutrino facility means … let's make some neutrinos.



The LBNF beamline will use a one-megawatt capable focusing horn to direct the charged particles that become neutrinos. Credit: Reidar Hahn, Fermilab

Step 1: Grab some protons

The first step is to siphon off particles from the Main Injector—otherwise, the circular accelerator will act more like a merry-go-round. Engineers will need to build and connect a new beamline. That's no easy feat, considering all the utilities, other beamlines, and Main Injector magnets around.

"It's in one of the most congested areas of the Fermilab accelerator complex," said Elaine McCluskey, the LBNF project manager at Fermilab. Site prep work starting at Fermilab in 2019 will move some of the utilities out of the way. Later, when it's time for the LBNF beamline construction, the accelerator complex will temporarily power down.

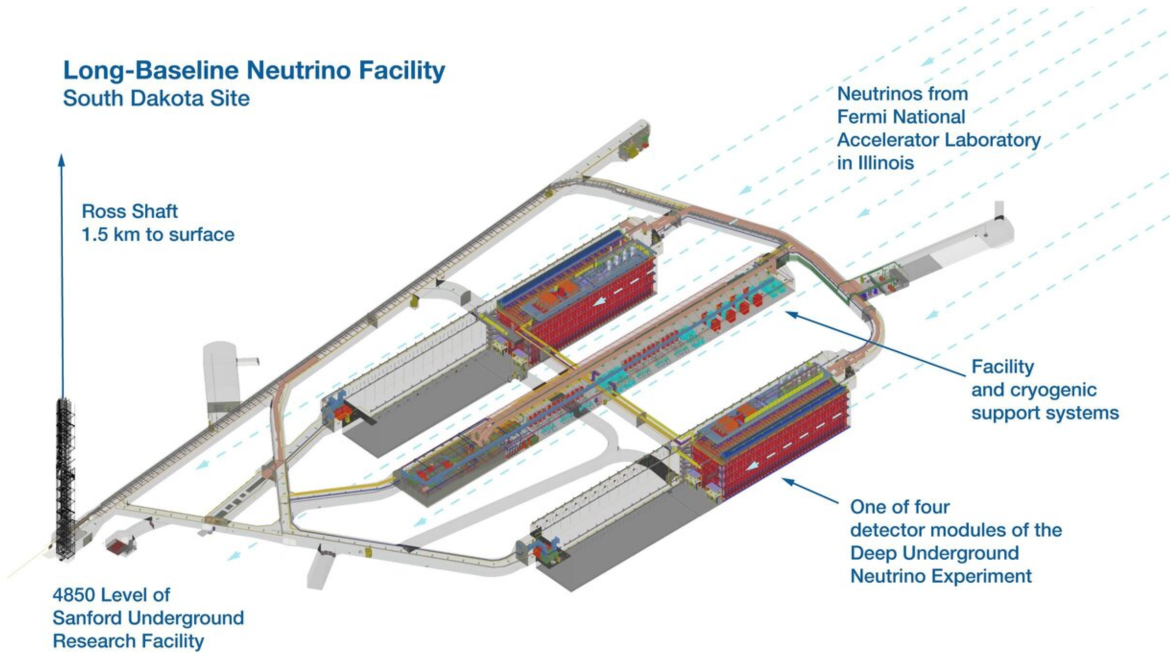
Crews will move some of the Main Injector magnets safely out of the way and punch into the accelerator's enclosure. They'll construct a new extraction area and beam enclosure, then reinstall the Main Injector magnets with a new Fermilab-built addition: kicker magnets to change the beam's course. They'll also build the new LBNF beamline itself, using 24 dipole and 17 quadrupole magnets, most of them built by the Bhabha Atomic Research Center in India.

Step 2: Aim

Neutrinos are tricky particles. Because they are neutral, they can't be steered by magnetic forces in the same way that charged particles (such as protons) are. Once a neutrino is born, it keeps heading in whatever direction it was going, like a kid riding the world's longest Slip "N Slide. This property makes neutrinos great cosmic messengers but means an extra step for Earth-bound engineers: aiming.

As they build the LBNF beamline, crews will drape it along the curve of an 18-meter-tall hill. When the protons descend the hill, they'll be pointed toward the DUNE detectors in South Dakota. Once the neutrinos are born, they'll continue in that same direction, no tunnel required.

With all the magnets in place and everything sealed up tight, accelerator operators will be able to direct protons down the new beamline, like switching a train on a track. But instead of pulling into a station, the particles will run full speed into a target.



DUNE's far detector will use four modules to capture interactions between argon atoms and the neutrinos sent from the LBNF beamline at Fermilab. Credit: Fermilab

Step 3: Smash things

The target is a crucial piece of engineering. While still being designed, it's likely to be a 1.5-meter-long rod of pure graphite—think of your pencil lead on steroids.

Together with some other equipment, it will sit inside the target hall, a sealed room filled with gaseous nitrogen. DUNE will start up with a proton beam that will run at more than 1 megawatt of power, and there are already plans to upgrade the beam to 2.4 megawatts. Almost everything being built for LBNF is designed to withstand that higher beam intensity.

Because of the record-breaking beam power, manipulating anything inside the sealed hall will likely require the help of some robot friends controlled from outside the thick walls. Engineers at KEK, the high-energy accelerator research organization in Japan, are working on prototypes for elements of the sealed LBNF target hall design.

The high-power beam of protons will enter the target hall and smash into the graphite like bowling balls hitting pins, depositing their energy and unleashing a spray of new particles—mostly pions and kaons.

"These targets have a very hard life," said Chris Densham, group leader for high-power targets at STFC's Rutherford Appleton Laboratory in the UK, which is responsible for the design and production of the target for the one-megawatt beam. "Each proton pulse causes the temperature to jump up by a few hundred degrees in a few microseconds."

The LBNF target will operate around 500 degrees Celsius in a sort of Goldilocks scenario. Graphite performs well when it's hot, but not too hot, so engineers will need to remove excess heat. But they can't let it get too cool, either. Water, which is used in some current target designs, would provide too much cooling, so specialists at RAL are also developing a new method. The current proposed design circulates gaseous helium, which will be moving about 720 kilometers per hour—the speed of a cruising airliner—by the time it exits the system.

Step 4: Focus the debris

As protons strike the target and produce pions and kaons, devices called focusing horns take over. The pions and kaons are electrically charged, and these giant magnets direct the spray back into a focused beam. A series of three horns that will be designed and built at Fermilab will correct the particle paths and aim them at the detectors at Sanford Lab.

For the design to work, the target—a cylindrical tube—must sit inside the first horn, cantilevered into place from the upstream side. This causes some interesting engineering challenges. It boils down to a balance between what physicists want—a lengthier target that can stay in service for longer—with what engineers can build. The target is only a couple of centimeters in diameter, and every extra centimeter of length makes it more likely to droop under the barrage of protons and the pull of Earth's gravity.

Much like a game of Operation, physicists don't want the target to touch the sides of the horn.

To create the focusing field, the metallic horns receive a 300,000-amp electromagnetic pulse about once per second—delivering more charge than a powerful lightning bolt. If you were standing next to it, you'd want to stick your fingers in your ears to block out the noise—and you certainly wouldn't want anything touching the horns, including graphite. Engineers could support the target from both ends, but that would make the inevitable removal and replacement much more complicated.

"The simpler you can make it, the better," Densham said. "There's always a temptation to make something clever and complicated, but we want to make it as dumb as possible, so there's less to go wrong."

Step 5: Physics happens

Focused into a beam, the pions and kaons exit the target hall and travel through a 200-meter-long tunnel full of helium. As they do, they decay, giving birth to neutrinos and some particle friends. Researchers can also switch the horns to focus particles with the opposite charge, which will then decay into antineutrinos. Shielding at the end of the tunnel absorbs the extra particles, while the neutrinos or antineutrinos sail on, unperturbed, straight through dirt and rock, toward their South Dakota destiny.

"LBNF is a complex project, with a lot of pieces that have to work together," said Jonathan Lewis, the LBNF Beamline project manager. "It's the future of the lab, the future of the field in the United States, and an exciting and challenging project. The prospect of uncovering the properties of neutrinos is exciting science."

DUNE scientists will examine the neutrino beam at Fermilab just after its production using a sophisticated particle detector on site, placed right in the path of the beam. Most neutrinos will pass straight through the detector, like they do with all matter. But a small fraction will collide with atoms inside the DUNE near-site detector, providing valuable information on the composition of the neutrino beam as well as high-energy neutrino interactions with matter.

Then it's time to wave farewell to the other neutrinos. Be quick—their 1,300-kilometer journey at close to the speed of light will take four milliseconds, not even close to how long it takes to blink your eye. But for DUNE scientists, the work will be only beginning.

Provided by Fermi National Accelerator Laboratory

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