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HL-LHC superconducting quadrupole successfully tested

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Advanced niobium-tin accelerator magnets for the LHC upgrade developed at US labs are also carving a path towards future energy-frontier colliders.

The quadrupole magnet being prepared for a test at Brookhaven National Laboratory. (Image: Brookhaven National Laboratory)

A quadrupole magnet for the high-luminosity LHC (HL-LHC) has been tested successfully in the

US, attaining a conductor peak field of 11.4 T – a record for a focusing magnet ready for installation in an accelerator. The 4.2 m-long, 150-mm-single-aperture device is based on the superconductor niobium tin (Nb3Sn) and is one of several quadrupoles being built by US labs and CERN for the HL-LHC, where they will squeeze the proton beams more tightly within the ATLAS and CMS experiments to produce a higher luminosity. The result follows successful tests carried out last year at CERN of the first accelerator-ready Nb3Sn dipole magnet, and both of these milestones are soon to be followed by tests of other 7.2 m and 4.2 m quadrupole magnets at CERN and the US.

“This copious harvest comes after significant recent R&D on niobium-tin superconducting magnet technology and is the best answer to the question if HL-LHC is on time: it is,” says HL-LHC project leader Lucio Rossi of CERN. “We should also underline that this full-length, accelerator-ready magnet performance record is a real textbook case for international collaboration in the accelerator domain: since the very beginning the three US labs and CERN teamed up and managed to have a common and very synergic R&D, particularly for the quadrupole magnet that is the cornerstone of the upgrade. This has resulted in substantial savings and improved output.”

The current LHC magnets, which have been tested to a bore field of 8.3 T and are currently operated at 7.7 T at 1.9 K for 6.5 TeV operation, are made from the superconductor niobium-titanium (Nb-Ti). As the transport properties of Nb-Ti are limited for fields beyond 10-11 T at 1.9 K, HL-LHC magnets call for a move to Nb3Sn, which remain superconducting for much higher fields. Although Nb3Sn has been studied for decades and is already in widespread use in solenoids for NMR — not to mention underpinning the large coils, presently being manufactured, that will be used to contain and control the plasma in the ITER fusion experiment – it is more challenging than Nb-Ti to work with: once formed, the Nb3Sn compound becomes brittle and strain sensitive and therefore much harder than niobium-titanium alloy to process into cables to be wound with the accuracy required to achieve the performance and field quality of state-of-the-art accelerator magnets.

Researchers at Fermilab, Brookhaven National Laboratory and Lawrence Berkeley National Laboratory are to provide a total of 16 quadrupole magnets for the interactions regions of the HL-LHC, which is due to operate from 2027. The purpose of a quadrupole magnet is to produce a field gradient in the radial direction with respect to the beam, allowing charged-particle beams to be focused. A test was carried out at Brookhaven in January, when the team operated the 8-tonne quadrupole magnet continuously at a nominal field gradient of around 130 T/m and a temperature of 1.9 K for five hours. Eight longer quadrupole magnets (each providing an equivalent “cold mass” as two US quadrupole magnets) are being produced by CERN.

“We’ve demonstrated that this first quadrupole magnet behaves successfully and according to design, based on the multiyear development effort made possible by DOE investments in this new technology,” said Fermilab’s Giorgio Apollinari, head of the US Accelerator Upgrade Project in a Fermilab press release. “It’s a very cutting-edge magnet,” added Kathleen Amm, who is Brookhaven’s representative for the project.

Dipole tests at CERN

In addition to stronger focusing magnets, the HL-LHC requires new dipole magnets positioned on either side of a collimator to correct off-momentum protons in the high-intensity beam. To gain the required space in the magnetic lattice, Nb3Sn dipole magnets of shorter length and higher field than the current LHC dipole magnets are needed. In July 2019 the CERN magnet group successfully tested a full-length, 5.3-m, 60-mm-twin-aperture dipole magnet – the longest Nb3Sn magnet tested so far – and achieved a nominal bore field of 11.2 T at 1.9 K (corresponding to a conductor peak field of 11.8 T).

"This multi-year effort on Nb3Sn, which we are running together with the US, and our partner laboratories in Europe, is leading to a major breakthrough in accelerator magnet technology, from which CERN, and the whole particle physics community, will profit for the years to come," says Luca Bottura, head of the CERN magnet group.

The dipole- and quadrupole-magnet milestones also send a positive signal about the viability of future hadron colliders beyond the LHC, which are expected to rely on Nb3Sn magnets with fields of up to 16 T. To this end, CERN and the US labs are achieving impressive results in the performance of Nb3Sn conductor in various demonstrator magnets. In February, the CERN magnet group produced a record field of 16.36 T at 1.9 K (16.5 T conductor peak field) in the centre of a short "enhanced racetrack model coil" demonstrator, with no useful aperture, which was developed in the framework of the Future Circular Collider study. In June 2019, as part of the US Magnet Development Programme, a short "cos-theta" dipole magnet with an aperture of 60 mm reached a bore field of 14.1 T at 4.5 K at Fermilab. Beyond magnets, says Rossi, the HL-LHC is also breaking new ground in superconducting-RF crab cavities, advanced material collimators and 120 kA links based on novel MgB2 superconductors.

Next steps

Before they can constitute fully operational accelerator magnets which could be installed in the HL-LHC, both these quadrupole magnets and the dipole magnets must be connected in pairs (the longer CERN quadrupole magnets are single units). Each magnet in a pair has the same winding, and differs only in its mechanical interfaces and details of its electrical circuitry. Tests of the remaining halves of the quadrupole- and dipole-magnet pairs were scheduled to take place in the US and at CERN during the coming months, with the dipole magnet pairs to be installed in the LHC tunnel this year. Given the current global situation, this plan will have to be reviewed, which is now the high-priority discussion within the HL-LHC project.

This news appeared first at the CERN Courier

This news was also featured at Fermilab