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Catching the Jets

EMCal, a calorimeter to capture jet-quenching at ALICE

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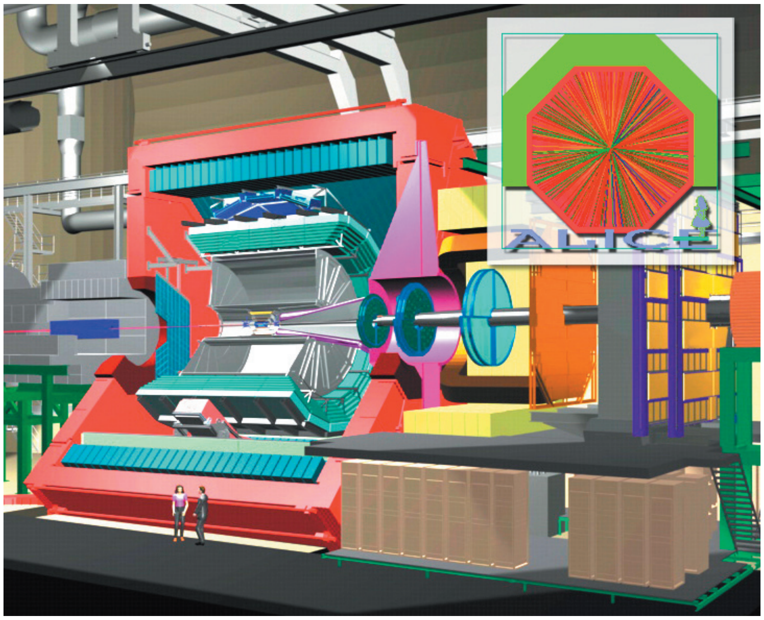
CERN's Large Hadron Collider (LHC) is known mainly as the accelerator that will soon begin searching for the Higgs particle, and other new physics, in proton collisions at unprecedented energies—up to 14 TeV (14 trillion electron volts) at the center of mass—and with unprecedented beam intensities. But the same machine will also collide massive nuclei, specifically lead ions, to energies never achieved before in the laboratory.

For four weeks each year the LHC will switch from proton-proton collisions to lead-lead collisions, devoting itself to the study of the evolution and structure of nuclear matter at high temperature. All the LHC's major experiments will collect data from these ion collisions, but one, ALICE, is being built specifically to study them.

"ALICE was designed to study the quark-gluon plasma, a fundamental state of very hot, very dense matter that filled the universe a few microseconds after the big bang," says Peter Jacobs of Berkeley Lab's Nuclear Science Division (NSD), a member of the Project Management Board for ALICE's EMCal, the Electromagnetic Calorimeter. "One way to recreate that state is to slam massive particles into each other at high energies. Neutron stars would be good, but in the laboratory we have to settle for heavy atomic nuclei, like gold or lead."



By using the Large Hadron Collider to collide high-energy lead nuclei and produce extremely high densities of matter and energy, CERN's ALICE will investigate the physics of the quark-gluon plasma.

The principal component of ALICE is a time projection chamber (TPC), a type of detector invented by David Nygren of Berkeley Lab's Physics Division. A cylindrical device filled with gas and incorporating uniform electric and magnetic fields, a TPC is ideal for separating, tracking, and identifying thousands of charged particles in a dense environment—such as the thousands of particles produced in an energetic heavy-nuclei collision. It is the main detector in many high-energy physics experiments.

For example, the TPC-equipped STAR experiment at Brookhaven's Relativistic Heavy Ion Collider (RHIC) has studied the quark-gluon plasma by collecting data from gold-gold collisions, in which each nucleon (proton or neutron in the nucleus) has an energy of 100 GeV (100 billion electron volts). The STAR TPC, which was built at Berkeley Lab and was the largest in the world when it was turned on in 2001, has been one of the centerpieces of the RHIC experimental program.

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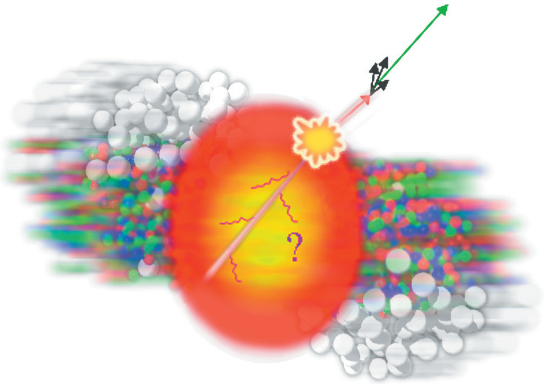
When the RHIC program started, ALICE was already under construction, looking forward to the day when the LHC would come online with the ability to accelerate lead ions to energies well over 2 TeV per nucleon, about 30 times greater than RHIC. But in 2003, discoveries by STAR and the other RHIC experiments revealed the significance of a phenomenon that ALICE had not been designed to study efficiently.

"When particles like protons collide at high energy, pairs of their constituent quarks or gluons may slam into each other and scatter back-to-back, quickly breaking up again into a 'jet' or spray of particles such as pions and kaons," Jacobs says. "Jets are fundamental to QCD"—the theory of quantum chromodynamics that underpins the interactions of quarks and gluons—"and they have been seen in high-energy physics experiments since the early 1980s. RHIC is the first accelerator in which jets and similar 'hard' processes can be seen in collisions of heavy nuclei ... and in 2003 we observed something predicted but never before seen in jet physics."



When back-to-back jets of particles occur inside the hot, dense energy and matter produced by colliding heavy nuclei, one jet may be unable to escape the fireball.

The fireball from a collision of two massive nuclei is bigger, hotter, and much denser than that from a collision of two protons. The farther a jet has to push through this dense nuclear matter, the more energy it loses—and if the interaction with matter is strong enough, it may not escape the fireball as a jet at all.

"It's called jet quenching," says Jacobs, "and it provides what's known as a hard probe." The theory that links jet quenching to the quark-gluon plasma was developed by Berkeley Lab's Xin-Nian Wang and Miklos Gyulassy, who was with Berkeley Lab at the time and is now at Columbia University.

"How the jets propagate through the fireball, and how much quenching occurs, tells us a lot about the properties of the hot matter generated in the collision," says Wang. "At RHIC we learned that jet-quenching effects are striking and experimentally robust, with the RNC group in the NSD playing a leading role in this discovery." (The RNC group is Berkeley Lab's Relativistic Nuclear Collisions group.) "There is now a lot of theoretical attention focused on understanding this phenomenon quantitatively, using the tools of QCD," says Wang. "Even some string theorists think they can calculate such processes—but that approach is much more speculative, and its connection to what we see in experiment is far from established."

High-energy jets are extremely rare, occurring in the most interesting cases only a few times in millions of collisions and detectable only as a spray of a few energetic particles, among the 8,000 or so that each lead-lead collision at the LHC will produce. While ALICE's TPC has the capacity to track all the charged particles in each event, storing such a vast amount of mostly-unremarkable data would soon overwhelm the system. To adequately study jet quenching meant ALICE had to incorporate a trigger to rapidly signal the TPC and other detectors to filter out the potentially interesting jet events from a noisy background. Enter the EMCal.

"ALICE was not initially designed to study jet quenching," says Jacobs, "but in the early 2000s, American nuclear scientists, including Thomas Cormier of Wayne State University and Grazyna Odyniec in our own NSD, formed a U.S. ALICE collaboration to explore the idea of a calorimeter for ALICE."

"It was a challenge making the case for participation in ALICE when RHIC had only just come on line," says Odyniec, who led the collaboration from 2001 to 2006, "but we knew all along that the unique scientific opportunities would eventually draw the U.S. into the LHC ion program."

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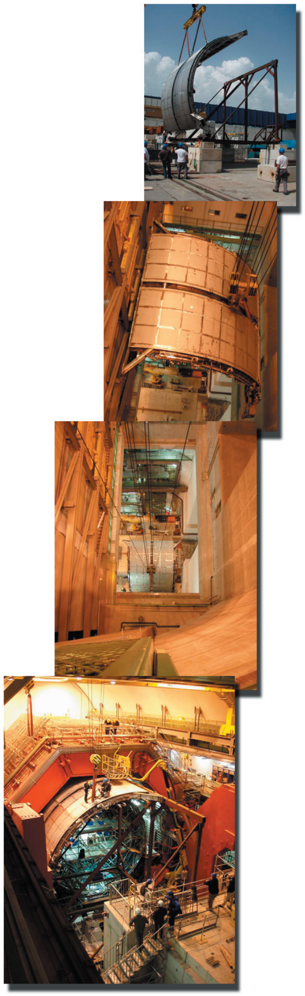
Joseph Rasson of Berkeley Lab's Engineering Division, the international EMCal Technical Coordinator, says that DOE's Office of Nuclear Physics got behind the project in 2004, when ALICE was already well under construction; thus the EMCal was initially launched as a kind of "pre-upgrade" while its design was still being explored.

"The first chunk of money came with the instructions to build a support structure, although we didn't have a project yet," Rasson says. The collaboration had to move fast to install the support frame before ALICE got too far along.

The finished frame was engineered at Berkeley Lab by a team of engineers lead by John Bercovitz and built by an Italian company; five meters long and weighing 25 tons, it was successfully installed in November, 2007. Installation was no simple task: the structure had to be lowered to ALICE's experimental cavern deep underground down a 50-meter access shaft with the narrowest of clearances. ALICE is accessible from only one end, so once inside the cavern the EMCal support frame had to be reoriented and then slid into place between the TPC and ALICE's magnet, millimeter by millimeter along two load-bearing rails (ALICE's magnet was originally built for a different experiment at CERN and is unable to bear the weight of the EMCal).

Meanwhile the EMCal detector design came together in detail, and test components and special tooling were built. The scientific challenge was to construct a detector with sufficient speed and resolution to recognize the tell-tale patterns and energies of particles in a jet.

Each finely segmented, energy-measuring channel of the calorimeter is a tower of 77 alternating layers of lead plates and plastic scintillators, coupled to optical fibers in a "shashlik" configuration (resembling the Middle Eastern delicacy better known as shish-kebab); the fibers are read out by a sensor called an avalanche photodiode. For handling purposes the towers are assembled into modules and the modules into supermodules, each weighing about nine tons. There are 12,288 separate towers in the full detector incorporating some 100,000 individual scintillator tiles, read out using 185 kilometers of optical fiber.



The 25-ton support structure for the EMCal was lowered 50 feet to the ALICE experimental cavern and installed in November, 2007.

The technical challenges of the detector design were at least as great as the scientific ones, since the stacks of lead and scintillator wafers had to fit side by side tightly, with no gaps that could miss particles of interest; for the same reason, the stacks have to be angled to point toward the center of the collision. Yet this heavy, tightly packed array of towers must be suspended with no support except at the base.

"If it were up to the physicists, they'd hang them in midair," says Rasson. "We came up with a compromise: the towers are essentially held together by friction," with the whole stack compressed to increase structural integrity. "Our French collaborators built a special tool to insert each supermodule assembly onto rails on the support frame."

Rasson thrives on the challenge of coordinating the manufacture of precision parts by different institutions in different countries and getting them all to fit together flawlessly. He doesn't mind even the awkwardness of having to do all the work from one end of the underground ALICE experiment, with clearances of only a couple of centimeters. "When you come in late there are a lot of complications," he says, "but I like the challenges."

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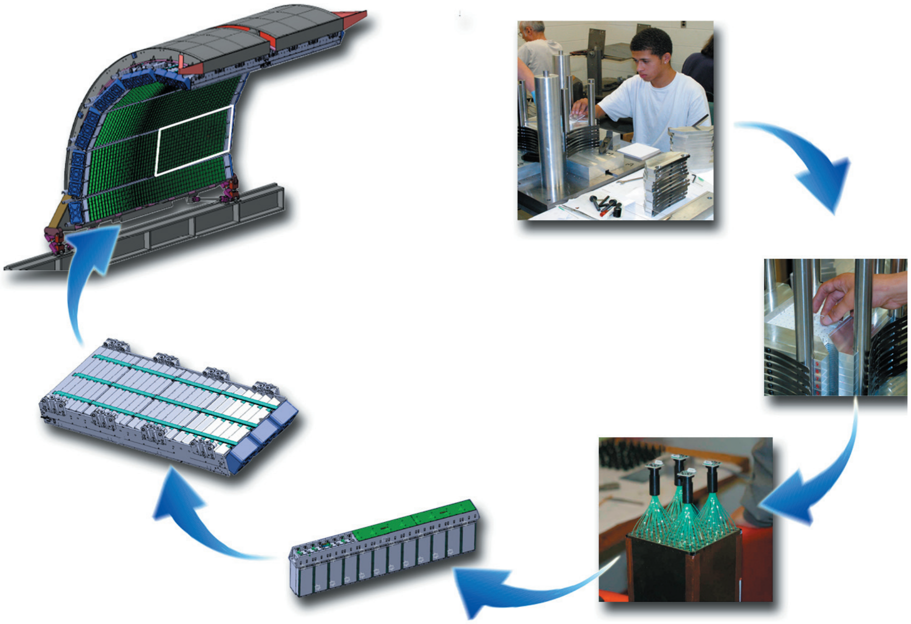
Within weeks of the successful installation of the support frame, the EMCal passed DOE's review stages (CD 2 and 3, conducted simultaneously) and was approved for construction. The Office of Nuclear Physics in DOE's Office of Science has committed $13.5 million to the EMCal, about 70 percent of the total cost, with the French and Italian partners supplying the remainder. In addition to Berkeley Lab and Wayne State University, the EMCal project collaboration includes Yale University and Oak Ridge National Laboratory, plus half a dozen other institutions in the U.S., along with Nantes, Grenoble, and Strasbourg Universities in France, the University of Catania and the Institute of Nuclear Physics at Frascati in Italy, and CERN in Switzerland.

The EMCal's late start, plus the fact that ALICE was not built from scratch (its previously used magnet complicating access and structural support), has meant that the EMCal does not have the full cylindrical shape that would comprise an ideal design; instead, it covers about a third of the circumference of the detector. While this means catching just one of the jets in a back-to-back pair, this is nevertheless enough to characterize virtually all events of interest and trigger the TPC for a full, detailed picture.



The EMCal consists of stacks of lead plates and plastic scintillators, threaded with optical fibers, and assembled into supermodules that will be slid into place on the support structure.

"The EMCal is a significant contribution to the ALICE experiment and will give U.S. scientists the opportunity to explore fundamental questions about the quark-gluon plasma that ALICE and the LHC make uniquely possible," says James Symons, Director of the Nuclear Science Division. "And Berkeley Lab's leadership of the project helps maintain this lab at the forefront of nuclear physics research."

Berkeley Lab participants in ALICE's EMCal Project include Peter Jacobs, Spencer Klein, Grazyna Odyniec, Mateusz Ploskon, Hans Georg Ritter, Sevil Salur, and James Symons of NSD; Joseph Rasson and Dennis Peterson of Engineering, and Dianna Jacobs of the Berkeley Lab Project Office.

Additional information

More about ALICE at the LHC is at http://aliceinfo.cern.ch/

More about STAR at RHIC is at http://www.star.bnl.gov/

More about jet quenching and the quark-gluon plasma is at http://www.lbl.gov/Science-Articles/Archive/NSD-RHIC-jet-quenching.html

More about "hard probes" is at http://www.lbl.gov/Science-Articles/Archive/sabl/2006/Oct/3.html