PARTICLE ACCELERATORS

AND HOW THEY HELP US ADVANCE OUR UNDERSTANDING OF PHYSICS

BREAKING BOUNDARIES IN EXPERIMENTAL PHYSICS
High energy experiments, made possible by particle accelerators, allow physicists to view phenomena that occur only in extreme conditions, like those at the beginning of the universe. These experiments can make particles that would be incredibly unlikely to appear on our planet today show up in experiment. With more energy in the beam, more exotic particles exist for longer, and may even exist long enough to be detected.

Achieving High Energies

Particle accelerators make these incredibly improbable events both likely and detectable, by sheer volume of interactions from the number of photons accelerated, and from the high energies that make unstable states more accessible. They allow physicists to confirm and learn about physics in conditions similar to the Big Bang, and confirm exotic predictions of particle physics.

A Powerful Microscope

Accelerated protons allow physicists to observe the particles that make up atoms at the very lowest levels. For something to be detectable in a microscope, it has to be larger than the wavelength of the photons hitting it. Wavelength is inversely proportional to momentum, so high-energy protons can see phenomena thousands of times smaller than any photon could detect.
What's an Accelerator?

A particle accelerator is some kind of machine that brings any type of particle to high speeds and energies for experiments. They come in a range of sizes, from under a foot to miles in diameter, and they are usually either linear (like a particle gun) or in a sort of ring shape (like a racetrack). Large accelerators are located near many physics laboratories, because many scientists want to run their experiments on the accelerator. For example, the Large Hadron Collider (LHC) in Switzerland has five particle detectors stationed at various locations around its perimeter. These detectors do things like looking at the "debris" from a collision and calculating which exotic particles were produced, and where, before they decayed.

Which Particles?

A beam needs to be able to be turned, in order to direct it to the experiment, focused, so that many particles make it to the site of the experiment at the same time, and accelerated, in order to reach the energies needed. Usually, charged particles are accelerated, because it's easy to use electromagnetic fields to exert forces on them. The LHC accelerates protons and lead ions, and UMER (the University of Maryland Electron Ring) accelerates electrons.
Driver's Ed for Hadrons

In nearly all accelerators, magnetic (or B) fields are used to steer and focus the beam (they’re like a steering wheel), and electric (or E) fields are used to give the beam more energy (they’re like the gas and brakes in a car). Magnetic fields can only turn the beam, rather than speed it up and slow it down. On the other hand, an electric field accelerates particles, but will not turn them.

Linear versus Cyclic Accelerators

Linear accelerators (linacs) pass a particle through stages of voltages to increase their energy. However, High voltages are a pain to work with, so confining them to one area makes it easier (from an engineering perspective) to deal with construction, safety, and complications coming from special relativity. Accelerators like UMER and the LHC drive a beam in circles with a magnetic field, and give it a kick with an electric field every time it crosses a certain point in the ring. This illustration shows how a cyclic accelerator does the same job as a linac, while using less space, and having less high-voltage areas to work with. The pink and blue segments represent voltage sections, or areas where the particle is gaining a set amount of energy.
BEAM DYNAMICS ON THE LHC

Pulsed Beam

Pulsed beam is a type of design where, rather than operating with a continuous stream of particles moving through the accelerator, small "bullets" are separated from one another, with gaps in between. This design allows all hardware to cool between pulses, which saves money and energy that would otherwise be used on cooling. It also makes it easier to precisely time to interactions inside detectors, allowing detectors time to register each separate collision and gather data. The reduced amount of data from each collision allows easier computing, and allows more certainty that certain particles were in fact produced in the collision.

Each pulse contains a bunch of about $1.15 \times 10^{11}$ protons. There are 2,808 thirty-centimeter bunches per beam. Most of the bunches are about 7.5 meters apart, but some are farther. They're carefully spaced, for example, there's one extra long gap that's intended to give the beam dump kickers time to get up to voltage so that the beam can be redirected and safely disposed of.
Energy

Protons in the LHC are moving at about 0.999999991 the speed of light when fully accelerated. This means that, according to the predictions of special relativity, a proton going at these speeds will interact with the outside world as if it weighted 7460 times its rest mass. If the protons were tiny clocks, we would see the clocks moving 7460 times slower than a clock at rest. It would take over four years of our time for an "accelerated clock" like this to register even four hours.

Each beam carries seven tera-electron-volts (TeV) of energy. Collisions between the two beams have 14 TeV of energy. 7 TeV is enough to propel an American aircraft carrier at 10.4 mph, and one beam has the energy of about 75kg of TNT.
Focusing

Quadrupole, sextupole, octupole, and decapole magnets act to focus the beam as it moves through the accelerator, and to correct imperfections in other focusing and steering fields. These magnets act as lenses, bending particles that are further out of line strongly into the center, and acting less strongly on particles that are behaving ideally. These different types of magnetic fields influence particles in different ways depending on how "unfocused" they are, which allows for strong focusing effects. These magnets are constantly fighting against how protons naturally repel each other, and are constantly correcting for various other forces like magnet imperfections, the Earth's magnetic field, and other small interactions.

While traveling around the ring, the beam is about a millimeter in diameter, but when it is fully focused before a collision, the beam is less than 0.02mm in diameter. You can see the drastic 50-fold reduction in size below.
Steering

According to some estimates, the problem of getting the two beams to hit each other is equivalent to firing two needles at each other from 10 km away, and trying to get them to hit. It's pretty tough to do! Therefore, steering and focusing the beam properly is a big problem in accelerator physics.

If we had unlimited magnets and magnet strength, and unlimited control over the initial conditions of the beam, it would be super easy to control the beam however we want. However, each dipole costs half a million dollars and uses a ton of energy. LHC ended up needing 1,232 dipoles, each one 15 meters long and weighing 35 tons. Each one generates an astounding 8.3 Tesla magnetic field, with 11 gigajoules of energy (that's 2.63 million kilocalories, or the equivalent of over 12,000 Snickers bars) stored in each magnet, and 400 tons of force acting on the metal collars keeping the magnets from tearing themselves apart with their own fields.
Vertical Steering on UMER

UMER is a sort of test accelerator, not used for particle physics experiments, but instead is employed to learn more about accelerator design and what sorts of beam focusing schemes will work best on larger accelerators. UMER has fantastic horizontal steering, plus or minus a millimeter from the centers of the quadrupole focusing magnets. However, its vertical steering isn't great, because there are only 18 weak magnets working vertically rather than the 36 strong ones that do horizontal steering.

An Optimization Problem

Power supplies are expensive, but we can't get a satisfactory vertical steering solution with the current magnets. The Earth's field causes massive oscillations in the vertical position that throw off the results of many experiments. My research right now is aimed at calculating the best possible magnet setup that will balance cost with good steering. I'm currently running computer simulations to calculate where to place magnets to improve the orbit. This research will be useful to increase UMER's precision for other experiments at UMD that test new magnet setups for more powerful focusing in accelerators used for particle physics experiments.
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Created by Claudia Richoux, TREND 2016. Learn more about UMER here.