What is an accelerator?

An accelerator is a device to produce beams of charged particles and accelerate them to high velocity or energy (much greater than that for electrons or nuclei in atoms) with:

- Nearly constant velocity or energy
- Parallel trajectories
- Small beam cross section

and to deliver these particles to a target where they scatter from the target constituents and:

- Reveal the structure of the constituents (a microscope)
- Create new particles for study
- Modify the character of the target (e.g. a tumor)
Why build accelerators?

In the 1930’s, physicists wanted to understand the structure of the atomic nucleus, and the strong force that binds it together. Naturally occurring radioactive decays give particles of energies of a few MeV; need to produce particles of higher energy.

In 1931, E.O. Lawrence made the first modern particle accelerator – the cyclotron – with successive versions reaching over 100 MeV.

The need for higher energy is two-fold:

1. Creation of new nuclei/particles of higher mass than the natural elements requires energy: \( E = mc^2 \). Nowadays we seek new states of matter at the millions of MeV level. Today’s accelerators deliver beams of \( \sim 10 \) TeV.

2. In analogy with the microscope, seeing finer detail within subatomic particles requires a wavelength \( \lambda \) smaller than the size of the object. deBroglie told us that \( \lambda = \frac{h}{p} \), and the momentum \( p \sim E \). Modern accelerators probe structure at the \( 10^{-19} \) m level.

1 eV = energy gained by electron by 1 V battery.
1 keV = 1000 eV
1 MeV = \( 10^6 \) eV
1 GeV = \( 10^9 \) eV
1 TeV = \( 10^{12} \) eV
electron binding in atoms \( \approx 1 \) eV
proton binding in nuclei \( \approx 1 \) MeV
proton mass energy \( \approx 1 \) GeV
What can we accelerate?

All accelerators are based on acceleration of charged particles by electric forces.

We accelerate elementary particles and nuclei which have small mass ($F = ma$, so $a = F/m$) to get beams of high velocity (and energy).

Bringing a charged particle from nearly at rest to high energy requires that it be sufficiently stable to not decay in flight.

The particles must exist in sufficient abundance to give high intensity beams (the collision processes are rare).

⇒ This limits the available particles to electrons and positrons, protons, nuclei (atoms stripped of their electrons) and antiprotons (though making them in abundance is hard). Maybe in future can use muons (but they decay in a microsecond!).

**Electric field** $\vec{E}$

**Force** $\vec{F} = q \vec{E}$

proton of charge $q$
As usual, Nature is more clever than we are: many galaxies show ‘jets’ of light, X-rays resulting from electrons accelerated to high velocity by the spinning black hole at their center. The light results from radiation by the electrons curling around very strong magnetic fields.

But assembling a supermassive black hole on earth is not recommended.
How to accelerate?

We surf the wave!
How to accelerate?

Make the rf wave travel at the speed of the particles, so get a continuous push. Synchronize the particle bunches just ahead of the peak of the wave. Thus a particle that is a little too low in velocity falls behind where $E$ is larger, and so gets a larger push to catch up with the bunch.

Energy gain = force x distance = $q E \ell$
Energy gain/meter of 30 – 100 MeV/m is possible using rf cavities.

The rf wave is confined in a set of ‘cavities’ whose shape controls the speed of the wave.

Provide the accelerating electric field as travelling radio frequency (rf) wave (higher $E$ than static fields). Input particles in bunches that ‘surf the wave’, gaining energy due to the electric force.
How to contain the beams?

The particles tend to stray from the straight and narrow. Any deviation of particle direction from the desired axis would lead to beam blow-up.

Such divergence occurs due to the particle source, mutual repulsion of beam particles, imperfections in the accelerator, etc.

We need a way to restore directions to the desired axis.
How to contain the beams?

Strong focusing principle:

Quadrupole magnets focus the beams, similar to lenses in ordinary optics (4 poles rather than 2 for dipole) and magnetic field pattern as shown. Field grows linearly with distance from center. Particle ● is deflected toward center. Particle ○ is deflected away from center. So focus horizontally and defocus vertically (and vice versa).

Alternate F and D elements to oscillate the particles around the beam axis (betatron oscillations).

Ray hits the horizontal focusing element further out and bends more than at the defocussing element. So get net focussing effect. Same in vertical plane.
Betatron oscillations

Individual particles oscillate around their central orbit, but stay confined.

Alternate focusing and defocusing lenses for stability.

Horizontal Betatron Oscillation with tune: $Q_h = 6.3$, i.e., 6.3 oscillations per turn.

Vertical Betatron Oscillation with tune: $Q_v = 7.5$, i.e., 7.5 oscillations per turn.
Clever idea #1

Conserve real estate and save on components by bending the beams into a circular path so that they repeatedly traverse the same rf accelerating cavities and quadrupoles. Do this by passing the beams through bending magnets.

\[ F = ma \Rightarrow qvB = \frac{mv^2}{R} \quad \text{or} \quad E(\text{GeV}) = 0.3 \times B(\text{T}) \times R(\text{m}) \]

(at large velocities \( \approx c \))

The world’s most powerful accelerator – LHC at CERN, starting this year – has average magnetic field of 5.5T (8.3T in the magnets), and will accelerate protons to 7 TeV (7000 GeV). Thus \( R = 4.3 \text{ km} \).

If we wanted 100 TeV, would need a circular ring 125 km in diameter!
Limits on circular accelerators

When charged particles are accelerated, they radiate EM waves (for example acceleration in radio antennas creates the radio signal). Charges going in a circle are accelerated (centripetal), so they emit synchrotron radiation.

Energy radiated per turn $\sim E^4/(R \, m^4)$  
($E =$ beam energy, $m =$ particle mass)

**Lessons:** power radiated grows very rapidly with beam energy. Making the circle larger helps but not very fast. And the radiation for electron accelerators is very much more than for protons ($m_p/m_e = 2000$).

For the LEP electron accelerator at CERN (100 GeV electron beams with $R = 4.3$ km) an electron loses 4% of its energy every time around the circle, and requires 20 MW of rf power just to break even. This is about the end of the road for circular electron accelerators, so must consider linear accelerators.

Radiation is along particle direction, like a searchlight – X-rays, UV and visible light. Used to study biological processes and materials in ‘light sources’.
Old way of using beams

Accelerate protons in Tevatron to 100’s of GeV

Extract protons from Tevatron and send to a target.

A spray of many particles of all types are produced in the collisions in the target – $\pi$ mesons, K mesons, photons, protons, neutrons etc.

Select and focus one stream of secondary particles and send to the experiment.

In the collision of beam and target particles, we must conserve momentum so produced particles must move to right, limiting the energy available to produce new particles.
Clever idea #2

Use 2 opposing beams colliding head-on. Now the net momentum is zero, so no energy is wasted on unneeded motion of final particles. The full energy of the beams is available for creating new particles.

Colliding beam accelerator

New complications: must accelerate 2 beams, and control both carefully to bring them into collision at the same very small spot.

In circular collider, if oppositely charged particles like p and $\bar{p}$ (Tevatron), $e^+ e^-$ (LEP), need just one set of magnets to guide both beams. If same sign particles (RHIC, LHC), need two sets of magnets.
1. Three circular accelerators (8, 120, 1000 GeV), plus two injector pre-accelerators

2. MI shoots protons on target, makes $\bar{p}$ collected in accumulator.

3. MI shoots protons into Tevatron.

4. $\bar{p}$ back from accumulator to MI; accelerate, transfer to Tevatron in opposite direction to $p$.

Collisions at the experiment! 2 TeV available energy for particle creation.
Fermilab complex

Five accelerators in the complex for successive energy gains.
Accelerates nuclei (e.g. Au). Both beams are positively charged, so need two magnet rings since directions of beams are opposite.
3 mile long linac, accelerating electrons or positrons to 50 GeV, used for fundamental studies of quarks until 2008. Now being converted to a free electron laser light source.

The Linac crosses above the foothills near San Francisco Bay, across the San Andreas fault and I-280.
CERN and the Large Hadron Collider

The 5.5 mile diameter underground tunnel originally housed the $e^+e^-$ collider LEP. It is now being readied for 14 TeV proton-proton collisions at the LHC.

Mt. Blanc
City of Geneva
Lake Geneva
Airport
LHC

Tunnel housing LHC is ~100m underground. The energy stored in the beams is equivalent to an aircraft carrier moving at 12 knots, enough to melt 1 ton of Cu (be careful where the beam goes!!)

(LHC will not make black holes that swallow the earth!)
We strongly believe that the LHC will discover new phenomena. To explain those new discoveries, we will need a complementary electron-positron collider operating at 500 – 1000 TeV. The ILC is being designed to do that job.

Two opposing linear (to eliminate synchrotron radiation) accelerators ($e^- \& e^+$) of about 10 km length each, bringing beams to a collision spot about 6 nm high by 100 nm wide. Initially each linac has $E=250$ GeV, upgradable to 500 GeV (1 TeV collisions).
ILC systems

Show one-half of ILC – the electron linac. Positron side is nearly identical.

1. Source provides the polarized electrons
2. Pre-acceleration linac to 5 GeV
3. Damping ring to make the beam cross section very small
4. Bunch compressor squeeze bunch along beam direction
5. Main linac to accelerate to full energy
6. Bring beams to collision and remove them safely to dump
**ILC Sources**

**Electron source:** Shine a laser (polarized light) on GaAs crystal and eject polarized electrons. Pre-accelerate to 5 GeV.

**Positron source:** Pass the accelerated electron beam through a magnet that wiggles the electrons in a helix, emitting polarized photons (synchrotron radiation). Let the photons strike a target creating positrons (and electrons). Send the polarized positrons to their damping ring and linac. Original electrons continue down their original path in the linac.
Damping rings function is to reduce the size of the beam (in transverse positions and velocities). Bend the beams, emitting synchrotron radiation and reducing all components of momentum. Then boost just the momentum along the beam direction. Fractional transverse momenta are lowered.

Test damping ring in Japan has achieved the small beam size required for ILC.

R&D needed to control buildup of electrons in rings that destroy the small size.
Main Linacs (heart of ILC)

Ultra-pure Nb superconducting cavities made from 9 clam shells welded together. Inject rf wave to provide 35 MeV gain in 1 meter.

Require cavities with 35 MV/m and low loss (high Q). Some have reached this specification. But reliably preparing the very smooth surfaces needed is still a problem.
Generating the rf electric field

Modulator: convert AC power from grid to 120 kV, 140 A pulses, 1 msec long.

Klystron tube: convert pulse to 10 MW rf wave at 1.3 MHz.

26 cavities (1 quadrupole focus magnet) in three cryomodules, all fed by 1 klystron.

Need 800 of these (they last for about 50,000 hours.)
Beam particles induce electromagnetic fields and currents in the walls of the enclosure: “**wakefields**”. If the beam is exactly on central axis, these fields cancel at the beam location.

If not, they create an net force on the beam that tries to blow it up.

Wakefield from head of bunch gives extra kick to tail of bunch, skewing the beam.
Controlling the wakefields:

1. Align the beam cavities, magnets very accurately (micron level) – won’t work completely due to ground motion and environmental noise.

2. So need very sensitive detectors to measure the beam positions and give feedback to reposition the beams on the proper axis (on 1 sec level).

3. Wakefield mitigation by making the tail of the beam a little lower in energy so the quadrupole focussing restores the tail more than the head.

Wakefields can also affect subsequent bunches of particles; control by making the walls a bit resistive to damp the currents before the next beam bunch arrives.

Beam quality (size) control is a tricky business and gives much complexity.
Machines like LHC and ILC are pushing the limits of technology and cost.

- Making magnets with > 10 Tesla fields is not presently possible. So circular machines must grow as energy grows.
- Synchrotron energy grows rapidly as energy increases – ultimately a limit for proton accelerators as well as electrons.
- Electron linacs like ILC are limited by the available accelerating gradients in the cavities: We run into intrinsic materials breakdowns for > 50 MV/m; so can increase energy only by making longer accelerator.

Increased size ⇒ cost (most of cost is related to civil construction, or components that fill the accelerator length).

How might accelerators of the future evade today’s limits?
**Plasma accelerators** (good wakefields?)

R&D effort to develop plasma wakefield accelerators with accelerating gradients ~1000 times that available with conventional RF cavities.

Plasma = A hot soup of electrons and ions, ordinary atoms dissociated by heat or electricity. For accelerator use, create the plasma by intense lasers, or electrical discharge, and contain the plasma within the beam tube.

**Variant A:** Send a conventional beam of electrons (or positive particles) into a plasma. The beam expels the plasma electrons and causes periodic regions of high and low electron density = plasma wakefield. Electrons ejected at point A are attracted to the ion excess at B. The electron pattern is wavelike and gives electric fields that accelerates the beam.
Plasma wakefield is standing wave that can accelerate subsequent bunches of particles.

Experiment at SLAC showed that some 42 GeV electrons (accelerated over 3 miles by conventional rf) were doubled in energy in 84 cm of plasma!

But only a small fraction of beam is accelerated. And beam size is rather large. More R&D!
Variant B. Create a plasma in a thin tubular channel using lasers. A subsequent high power laser pulse is confined to the tube, and its electric fields accelerate plasma electrons from rest. (no prior accelerator!) Earlier problems of keeping the laser light focussed, and the effect of light outrunning the particles have been solved for 3 cm long acceleration cells.

Group at Berkeley has succeed in accelerating electrons from rest in the plasma to 1 GeV in 3.3 cm. 

30 GeV/m (1000xILC!)

The beam has small spatial and energy spread, so R&D will now focus on capturing the beam and accelerating further in subsequent cells.
New ideas and tools invented for a particular scientific purpose have a way of finding applications in broader contexts.

- Quantum mechanics, devised to explain the workings of the atoms, led to transistors, computers, lasers …
- Studies of nuclear spin transitions led to MRI tomography
- Superconductivity led to high field magnets, train levitation, cryo-treatments …

So it has been for particle accelerators. The ability of high energy particle beams to probe small structures and create new forms of matter now find use elsewhere:

**ACCELERATORS IN USE WORLDWIDE**

<table>
<thead>
<tr>
<th>Category</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle/nuclear</td>
<td>~120</td>
</tr>
<tr>
<td>Synchrotron light sources</td>
<td>~50</td>
</tr>
<tr>
<td>Medical radioisotopes</td>
<td>~200</td>
</tr>
<tr>
<td>Radiotherapy</td>
<td>~7500</td>
</tr>
<tr>
<td>Biomedical research</td>
<td>~1000</td>
</tr>
<tr>
<td>Industrial processing/R&amp;D</td>
<td>&gt;1500</td>
</tr>
<tr>
<td>Ion implantation etc.</td>
<td>&gt;7000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>~17,500</td>
</tr>
</tbody>
</table>
Synchrotron light source

Synchrotron radiation is used to study protein structure, materials properties, environmental effects, chemical reactions, nanofabrication and much more. Typically a few GeV electron accelerator is used.

Much of the cutting edge research in biology, solid state physics, materials science, chemistry & environmental science is done at light sources around the world – operating on principles established in particle physics accelerators.
Most medical imaging for diagnostics came from accelerator technology:
- Computer assisted tomography
- MRI
- PET scans

Accelerators are also used for:
- making nuclear isotopes for diagnostics/treatment
- microlithography of electronic circuits
- ion implantation for electronics
- sterilizing foods

Possible future uses:
- Linac induced nuclear reactors – safe, clean, non-uranium fuels, efficient
- Security – naval vessel protection, container scanning etc.
Proton cancer treatment

Traditional X-ray radiation does not penetrate far, loses much of its energy near the surface (burns), has broad spectrum of energy.

Protons from 50 – 200 MeV penetrate to any place in the body. They lose little energy until the last few cm, so dose is concentrated on tumor.

X-rays deposit most of their dose near the surface (skin) of the patient.

Most proton dose is deposited in the sharp "Bragg Peak", with no dose beyond.

Proton facilities are large and costly – only two in the US. This is a place where the plasma wakefield acceleration R&D could pay off handsomely by drastically reducing the size and cost of the accelerator.

Vary proton energy to cover the tumor.
Medical accelerators

Loma Linda (California)
- synchrotron source
- built/commissioned at Fermilab
- world leading patient throughput
For some years, people have advanced the notion of high energy proton initiation of nuclear reactors (Energy Amplifier). This idea is re-vitalized with the advent of high power proton linacs based on the ILC SC cavities.

Proton linac working at several GeV, ~10 MW power creates fast neutrons in the Th reactor core. Th$^{232}$ has 14x10$^9$ yrs half life and 5x abundance of U$^{238}$.

Th captures fast neutrons (~100 keV); is a fertile (breeder) nucleus; $n + \text{Th}^{232} \rightarrow \text{Th}^{233} \rightarrow (\beta) \text{Pa}^{233} \rightarrow (\beta) \text{U}^{233}$.

Linac beam power of ~ 10 MW, consuming ~40 MW from grid Reactor produces ~700 MW to the grid.
Proton beam induced nuclear reactors

Breeder reactions are subcritical – k factor ~ 0.98 (safe).

Fission products are relatively short lived.

EA viability still debated by nuclear community; much R&D still needed on accelerator systems and system issues.
Who develops accelerator science?

Accelerator science is a very rich mixture of disciplines
- Classical and quantum physics
- Applied mathematics
- Computer science
- Materials science
- Electrical engineering
- Mechanical and civil engineering

People have come from all of these fields.

But there aren’t enough of them.

There are no dedicated educational programs for accelerator science in US universities. Some universities situated near major accelerators train students from other disciplines (including Stony Brook) with supervisors from Labs.

Stony Brook and Brookhaven Laboratory offer a nearly unique pairing of a laboratory with world class facilities, and university with good students and strong departments.

Scientists in both institutions are working to develop an Accelerator Science graduate program.
Conclusion

- Accelerators arising from needs in basic research have increased in power by million-fold in 75 years, and have revealed the microscopic world in great detail.

- Many wonderful new ideas enabled this growth, but we are still limited by fundamental physical parameters – materials breakdown, magnet strength etc. Current research on plasma wakefield acceleration is promising.

- Accelerators have entered the mainstream of society, particularly in medicine and electronics industry. Trend toward miniaturization and cost reduction will only enhance this.