Fermilab

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Introduction to Accelerator Physics

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FNAL Undergraduate Lecture Series

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Disclaimer

- I’ve tuned this talk so that the complex math isn’t required to understand the topic, but sometimes it’s there to give context to some things
- The math is there, and it can be as high-speed as you want it to be, but the concepts should be approachable
- Sometimes this means losing a little precision for clarity, but the core message is right
- If you have questions, raise your hand! A lecture without questions is boring, no matter how much I wave my hands. If you have a question, it’s almost certain you’re not alone and I’m not explaining something clearly.
- Some images and slides are taken from the outstanding US Particle Accelerator School class: Fundamentals of Accelerator Physics and Technology (http://nicadd.niu.edu/~syphers/uspas/2018w) by Mike Syphers (anytime you see MJS on an image/slide)
- *jeremiah@fnal.gov*

About Me

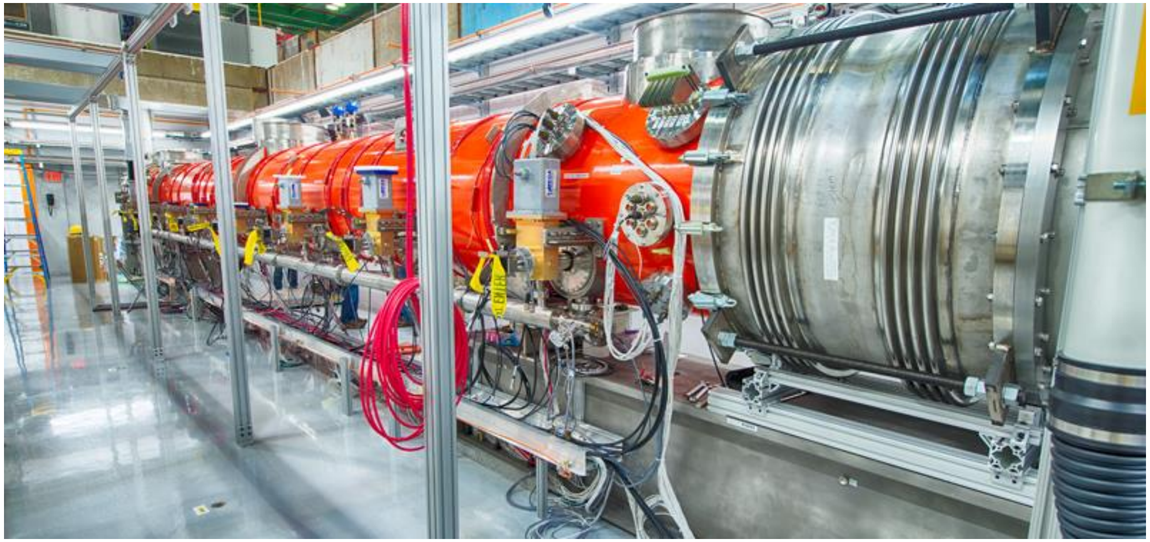
- University of Wisconsin
  - Applied Math, Engineering, and Physics B.S. (2006)
  - Nuclear Engineering
  - Plasma Physics (Madison Symmetric Torus)
- Michigan State University
  - Physics Ph.D. (2011)
  - Worked at the NSCL
  - Designed accelerator components for the Facility for Rare Isotope Beams

About Me (2)

- Postdoc at Argonne National Laboratory
  - Advanced Photon Source Upgrade
- Fermilab
  - Guest/Associate/Full Scientist
  - Accelerator component design, integration, and testing
  - Algorithm development (noise cancelling for accelerators)
  - High level troubleshooting (diagnose, fix complex technical issues)
    - Transportation failures
    - Integrated system stability
  - SRF Coordinator for PIP-II Project Technical Integration Team
    - Planning and Implementation of complex systems

What Appeals to Me about Accelerator Physics

- I’ve always loved learning about new technologies, working on complex problems, and making technologies practical
- Accelerator Physics lives at the boundary between theoretical physics and practical engineering, conceiving, designing, building, and operating extreme and complex machines
- Always pushing the technological boundaries, always something new



Why Accelerator Physics?

Studying Different Sizes

- Scientists want to study everything, but are limited by their tools
- Eyes are great, but only visible light, and only from ~millimeter to ~mile size
- Telescopes push the size and distance up, microscopes push the scale down
  - Although with astronomy, it's giant things VERY far away, so also detecting fainter and smaller things
- When the eye is what actually detects the light, both are limited
- The last 150 years has been a continuous effort to find and develop new tools
  - More sensitive cameras that detect more things
  - Better sources of light, brighter, etc.

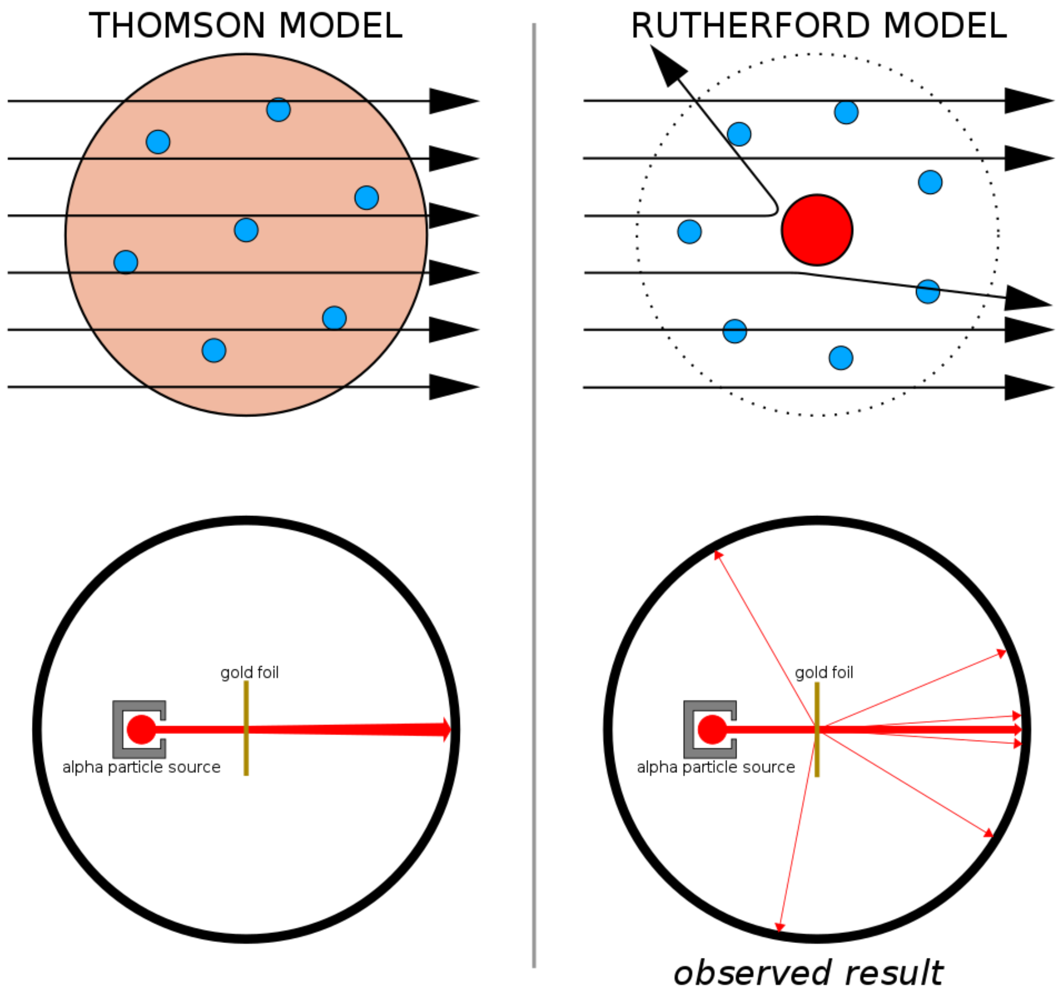
https://en.wikipedia.org/wiki/Orders_of_magnitude_(length)

Atoms to Study Atoms

With a microscope, you can see germs (10s of μm), parts of germs, etc, but we knew they were made of smaller bits (atoms)

It was known that radioactive material gave off these atoms

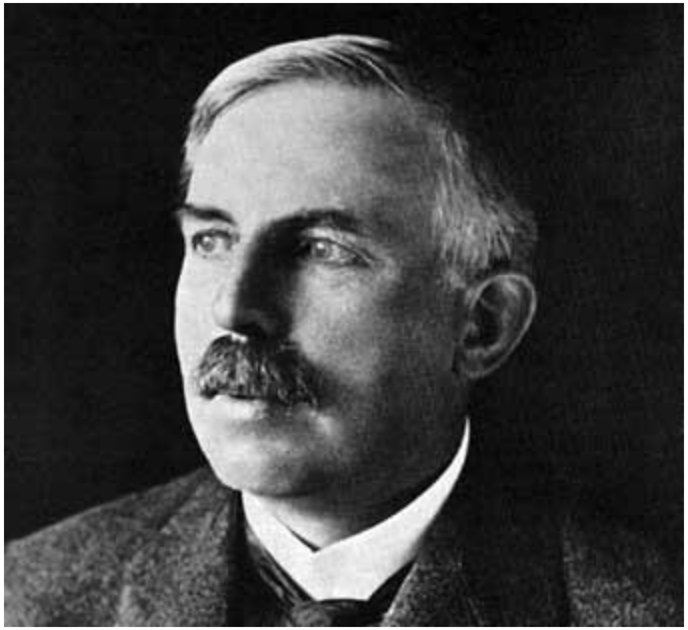
Famous experiment shot atoms at atoms to investigate their structure



https://en.wikipedia.org/wiki/Geiger-Marsden_experiments

Rutherford's Desire

- Ernest Rutherford's discovery of the structure of the nucleus in 1909 opened new fields of experimentation
  - Nuclear Physics
  - Eventually, High Energy Physics, Light Sources, etc.
- These fields (and eventually others) require particle "accelerators"
  - Rutherford expressed a long-standing "ambition to have available for study a copious supply of atoms and electrons which have individual energy far transcending that of the alpha and beta particles" available from natural sources.
  - This desire has led to a century of accelerator physics research



Why High Energy Particles?

- What does the science want?
  - More Energy!
    - Different science available
  - Controllable/Tunable Energy!
    - Dynamic behavior studies
    - Fine structure investigations like resonances
  - More Intensity!
    - Take data faster
    - Study rare processes
      - Rare isotopes
      - Neutrinos
      - Rare particle decays
  - Variety of Particle Beams!
    - The ability to create and use beams of any element/isotopes

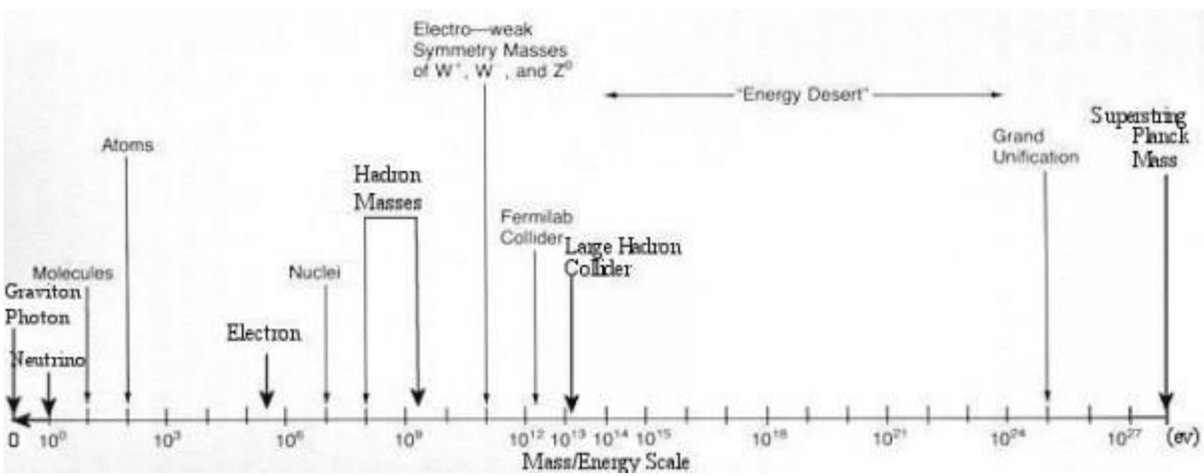
- What do they REALLY want?

Wall power

Desired Beam

Energy Scales

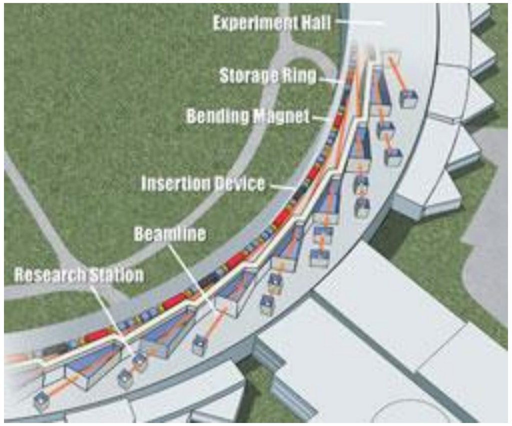
- 1 eV = 1 electron Volt = the energy 1 electron gains going down 1 Volt potential difference (9 V battery gets us 9 eV)
- Energy for an experiment is determined by what they want to do (even if the energy gets turned into X-rays or other particles first!)
- Also, $E = \frac{hc}{\lambda} = mc^2$, where λ is the wavelength, higher energy lets you look at smaller things (visible light goes down to 400μm)

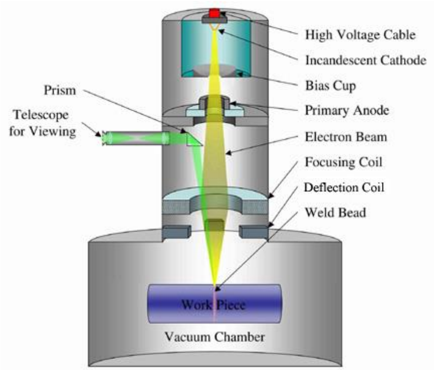


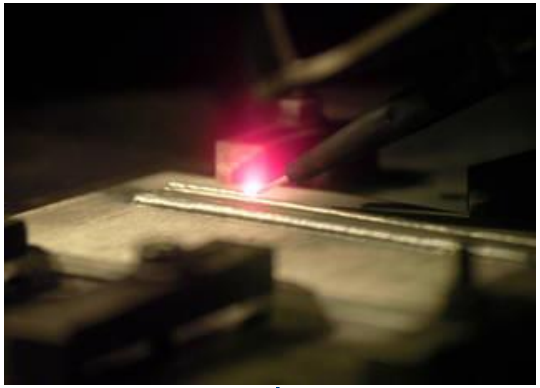
http://sten.astronomycafe.net/the-particle-desert/

Accelerators in Society

- Accelerators can be used to make powerful light sources
  - High energy X-rays, very powerful microscope for proteins/materials research, etc.
- Medical therapy for cancers and imaging
- Tons of industrial applications
  - Clean welding, cutting, 3D printing
  - Material hardening and processing
  - Treatment of wastes/sterilization



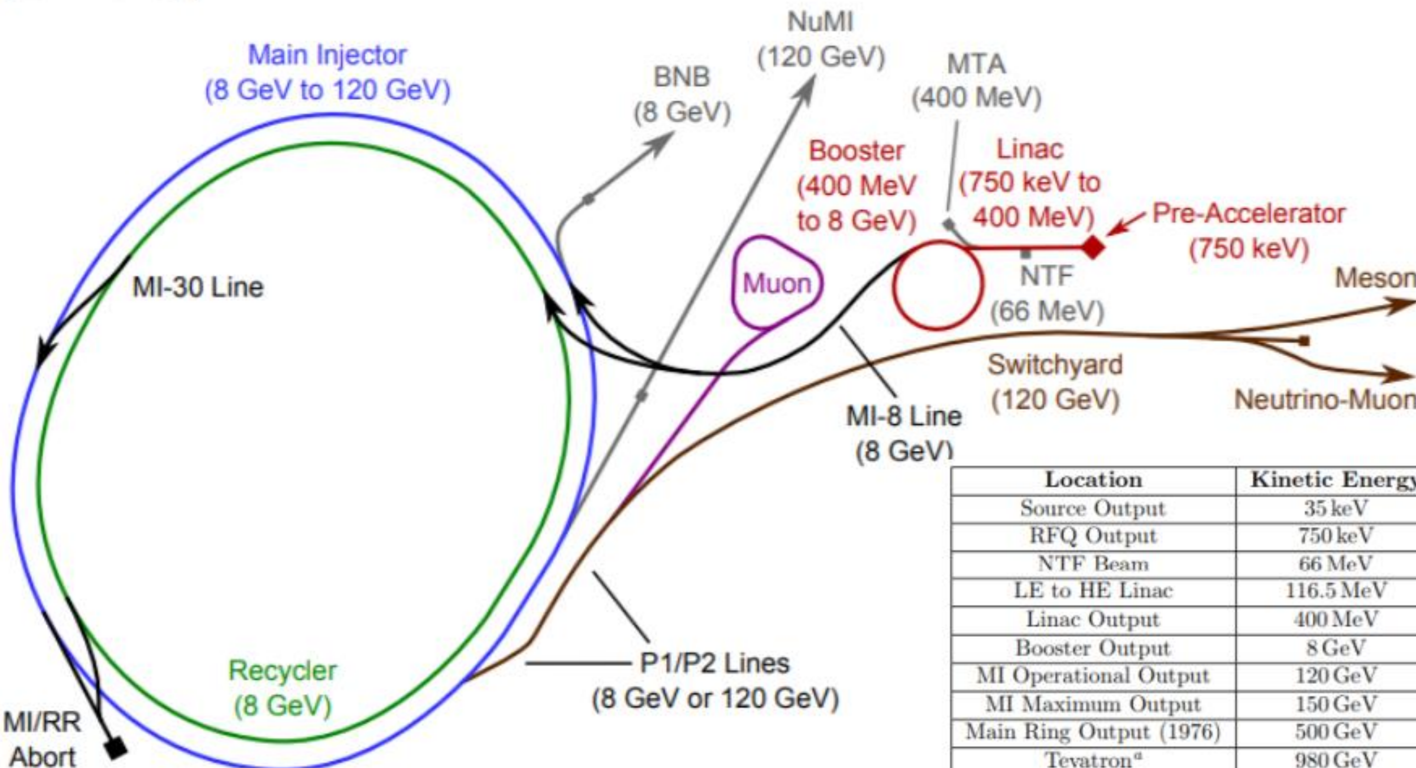




http://www.accelerators-for-society.org/

Fermilab Accelerators and Beamlines

The Fermilab Accelerator complex consists of a linear accelerator, two synchrotron accelerators, and several experimental beamlines. We deliver beam to a long-baseline neutrino oscillation experimental program (NOvA, MINERvA), a short-baseline neutrino oscillation program (MicroBooNE, SBND, ANNIE), a Nuclear Physics experiment (SpinQuest), the Fermi Test Beam Facility (Meson line), and a rare-process Muon experimental program (G-2 and Mu2e experiments).



Location	Kinetic Energy	Velocity (m/s)	Velocity (c)
Source Output	35 keV	2.6E6	0.0086
RFQ Output	750 keV	1.2E7	0.04
NTF Beam	66 MeV	1.07E8	0.357
LE to HE Linac	116.5 MeV	1.37E8	0.457
Linac Output	400 MeV	2.14E8	0.713
Booster Output	8 GeV	2.98E8	0.994
MI Operational Output	120 GeV	2.9978E8	0.999969
MI Maximum Output	150 GeV	2.9978E8	0.999981
Main Ring Output (1976)	500 GeV	2.9979E8	0.9999982
Tevatron[a]	980 GeV	2.9979E8	0.99999954
LHC[b]	8 TeV	2.9979E8	0.9999999931

[a]No longer operational
[b]The Large Hadron Collider is located at CERN in Geneva, Switzerland

Building a Particle Accelerator

Fundamental Parts of a Particle Accelerator

1. Source of particles
   – Right type, large enough number, organized in a way we can use
2. Way to confine and manipulate
   – Get them going in the same direction, keep them contained, focus them where we want them to go, make sure they aren’t wasted
3. Get them all this energy we want them to have
   – Generally, they don’t ‘start’ with a lot of energy, and we need to give them a controllable amount of energy
4. A detector/camera designed to get the data we need
   – What kind of energy/wave/precision do we need?

Important Parts that don't get much love

- Particles don't like air! Everywhere they go must be very good vacuum
- An accelerator is 10,000's of parts, they all need to be controlled, integrated, monitored, recorded
- All the main components need to be powered, usually with lots of energy (high current, high power microwaves, etc.)
- Timing and stability is critical! Everything is going very fast and must be synchronized
- Error tolerance is low, everything must be very carefully positioned and aligned
- Particles are weird! Measuring them is also hard, but critical
- Everything must be SAFE, people getting hurt or major damage to the machine are intolerable
- You need people that know all these things, can design them, maintain them, and operate them on a daily basis, which is a ton of people and specialties!

Take a step back: What force to use?

- Strong
- Weak
- $\boxed{\text{Electromagnetic}}$
- Gravity

$$\frac{d\vec{p}}{dt} = \vec{F}$$

- Radioactive decay
  - Limited Natural Sources (some artificial sources, not much better)
  - Limited Intensity
  - Very specific energies
  - Limited set of available beams
- Extremely weak
  - Using the Sun's gravity well, you could get a proton up to ~22 MeV (about the same as Rutherford used, ~5.5 MeV)
  - No comments on the practicality
- Electric Fields!
  - Strong
  - Easy(ish) to control and modify
  - Only limitation is that particles must be charged… sort of

Let's dig a little more into Gravity vs E&M

- Very similar in form (for pretty deep reasons, actually)
- Let's compare the relative stored energy in gravity and charge between two protons at 1 cm:
- $\frac{U_e}{U_G} = \frac{k_e q^2}{G m_e^2} \approx \frac{9\times10^9 * \left(1.6\times10^{-19}\right)^2}{6.6\times10^{-11} * (1.6\times10^{-27})^2} \approx 10^{36}$ (!!!!!!!!)

Gravitational Potential Energy

$$U = -\frac{GMm}{R}$$

$$U_E(r) = k_e \frac{qQ}{r},$$

What you NEED to know about Electromagnetism

- Two charges (positive and negative)
  - Opposites attract, like charges repel
- Charges flow easily on/in metals, but not ceramics/insulators
- Electric fields are created by all charges, from positive to negative charges, more charge, stronger fields
  - Same for magnetic fields, except only MOVING charges create magnetic fields, move charge, moving faster, more magnetic fields
- Charged particles in EM fields feel force, gaining energy from electric fields and being deflected by magnetic fields
- Magnetic fields can't do work (dig deeper on the next slide)

Little Deeper Dig into EM fields and charged particles

- $\vec{F}_E = q \cdot \vec{E}$ for electric fields
- Particle with charge q feels a force proportional to the electric field strength, *in the same direction of the field*
- Can be effective at very low energy, but not much at high energy

- $\vec{F}_B = q(\vec{v} \times \vec{B})$ for magnetic fields
- Particle with charge q feels forces proportional to the magnetic field strength and the particle's velocity, *but always at right angles to the particle's velocity*

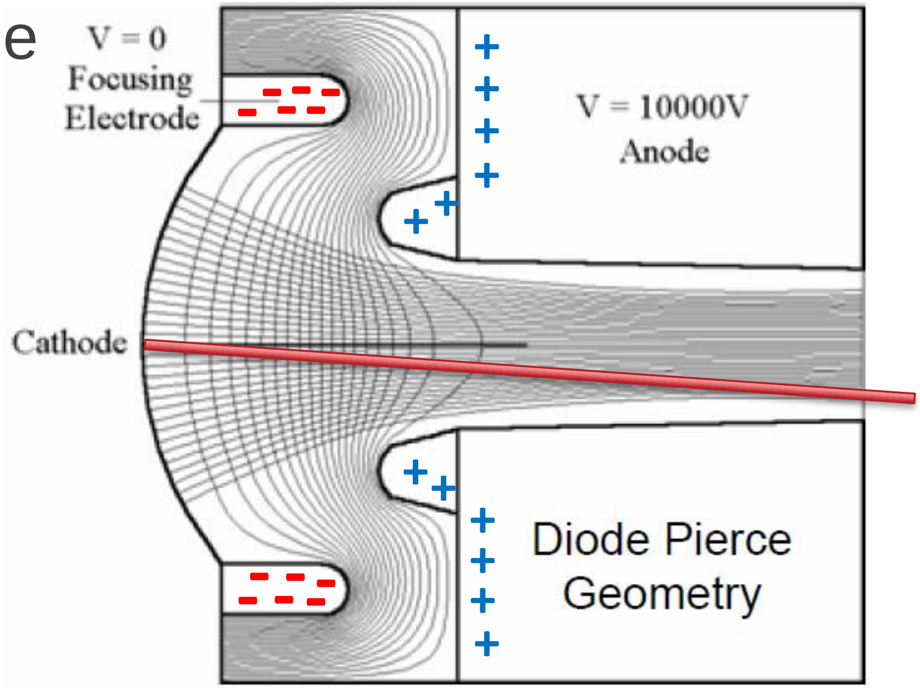
- It all comes down to work (change in energy):
- $\Delta E = F \cdot \Delta x = (q\vec{v} \times \vec{B}) \cdot \vec{v}\Delta t = 0$ (magnetic fields defect, but don't change energy)

1) Particle Sources

- Some particles are easy!
  - Electrons just pop off metals with some encouragement, either get it hot, or hit it with a laser of sufficiently high frequency
    - Work function (energy needed to liberate electrons) is ~ few eV for most metals $\frac{1.24\ eV\mu m}{4\ eV} \approx 300\ nm$, so a standard UV laser will do it!
  - Protons are slightly harder, but all you have to do is strip an electron from a hydrogen atom (13.6 eV), and hydrogen gas is cheap
- Some particles are harder…
  - Heavy ions need lots of electrons stripped, harder to vaporize
  - Radioactive particles need radioactive sources
  - Exotic particles (muons, neutrons, etc.) need lots of energy, and the source just becomes another particle accelerator

Most Simple Accelerator

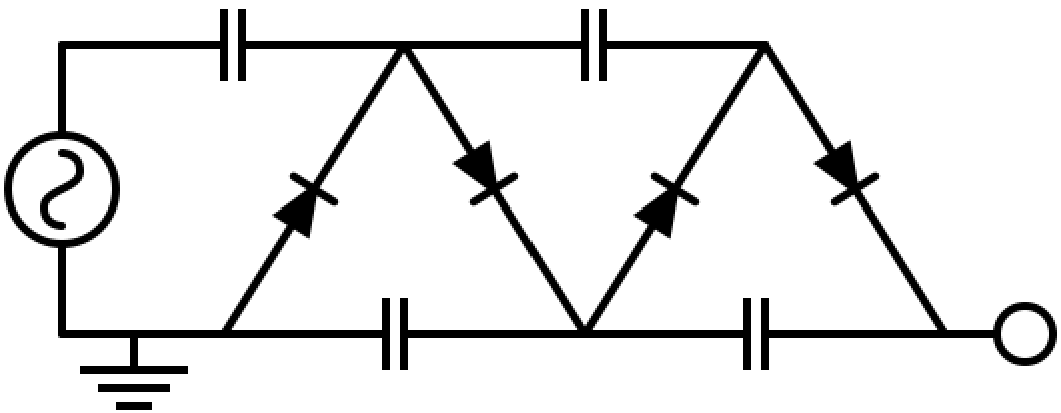
- We don't need Magnetic Fields, just a particle source and some electric fields
  - Take two plates, one with lots of positive charge, the other with lots of negative charge, lots of E-field
  - We only get *static* electric fields, no moving charges
  - We shape the plates to tune the electric fields, strong in the desired direction and focusing
- Fire a laser at one wall to make electrons that are accelerated by the fields



Annotate particles

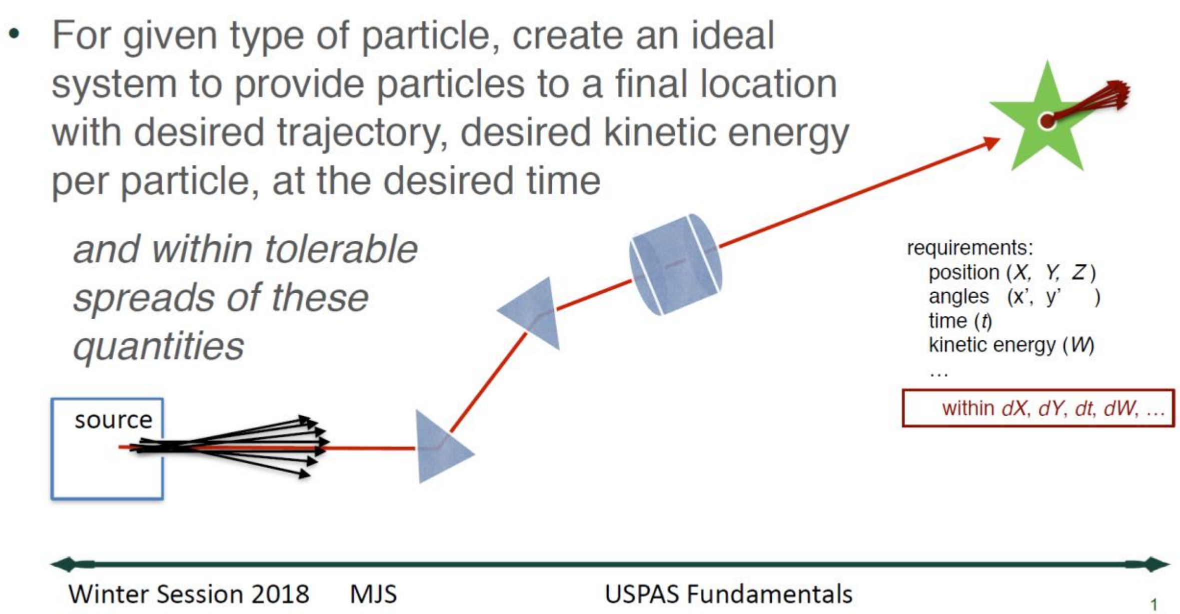
Actual Particle Sources

- Electrostatic Accelerators
  - Limited energy gain (60 MeV/q)
  - Can accelerate DC beams (used often for particle sources)
- Tandem Accelerators
  - By changing the particle charge from negative to positive, twice the energy can be achieved (limited current)



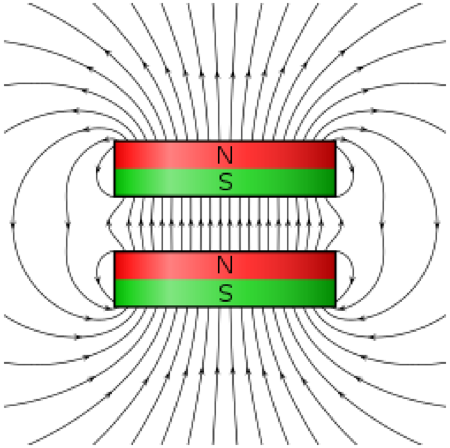
2) Confining and Manipulating

- There are two major goals here:
  - Bend particles: change their average direction, bend in a circle, point them at things
  - Gather particles: like particles repel, and no particle stream starts all pointing in the exact same direction, so as they drift apart, they must be herded back together

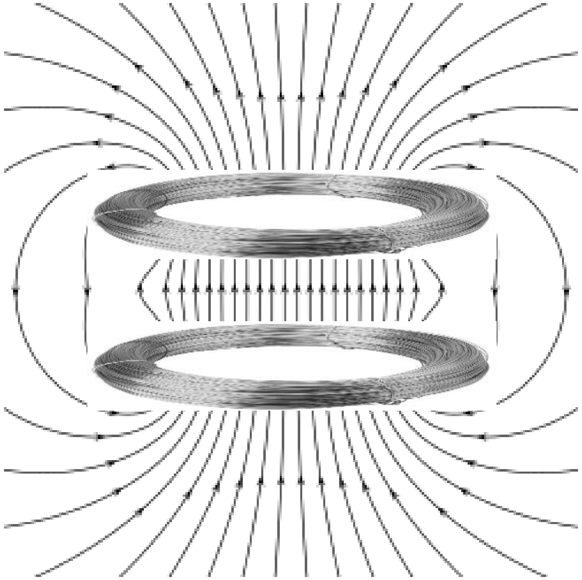


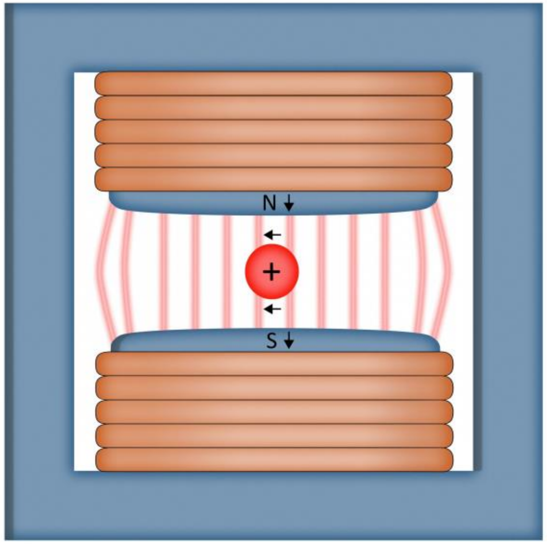
Magnets that Bend/Deflect

- You want all particles deflected the same amount:
  - Strong fields, uniform distribution: “Dipole Magnet”
  - Magnetic materials are sometimes used, but that’s not very strong
  - Current in wire makes magnetic fields, so if we carefully shape the wires and guide the fields, we can make great dipoles



Wikipedia





Really Strong Dipoles for High Energy Particles

$$F_c = \frac{mv^2}{\rho} = F_B = qvB$$

$$B\rho = \frac{p}{q}$$

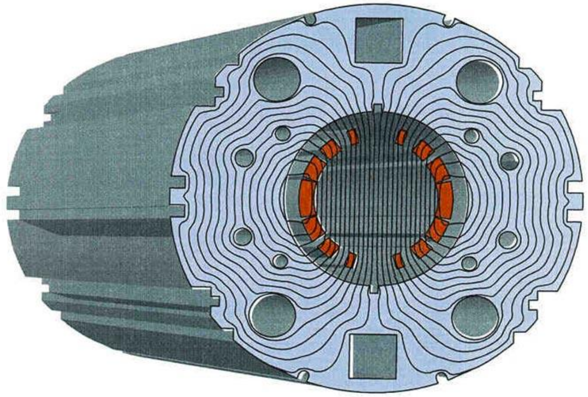
This is true at relativistic speed ($p = \gamma m_0 \beta c$)

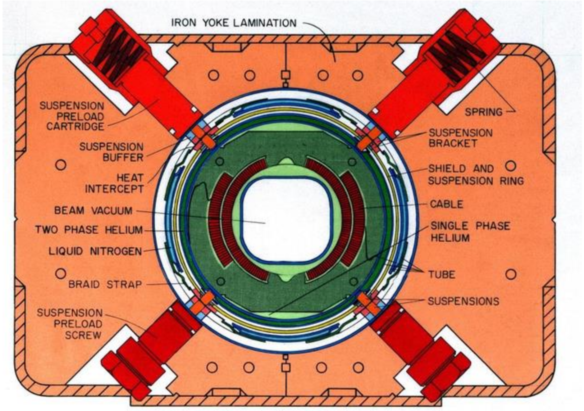
Fridge magnet ~10 mT

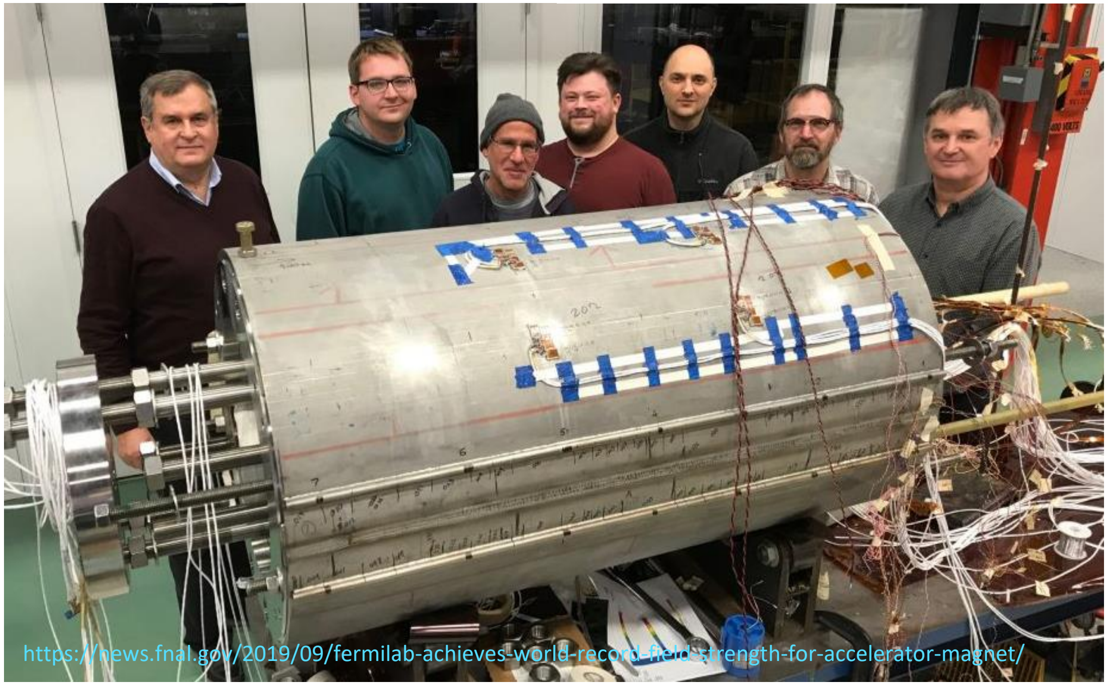
Next generation accelerator dipoles ~15 T

Field needs to be stable, ‘clean’, repeatable

Very high current power supplies, also not easy!



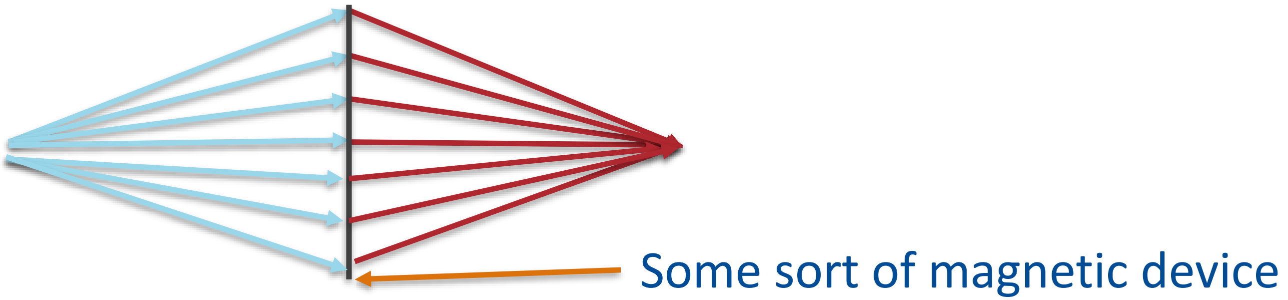




Fermilab

What about focusing?

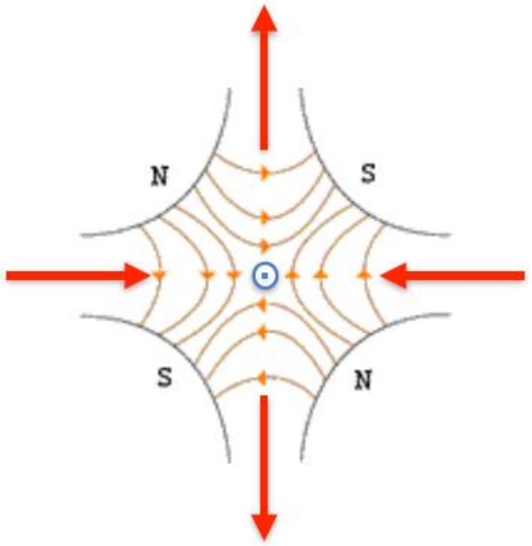
- Now that we can manipulate the average, bend it around, etc., what about focusing the particles back towards the ideal particle?

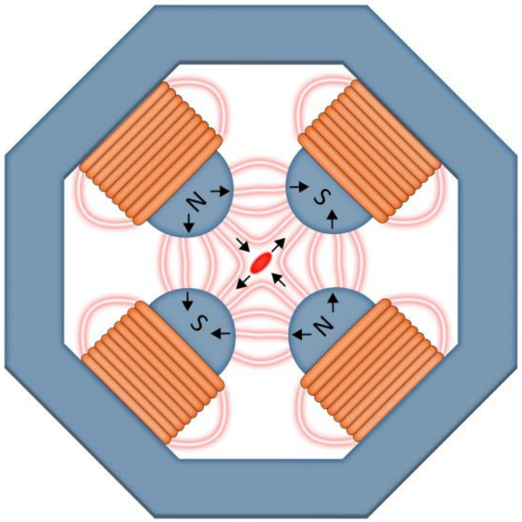


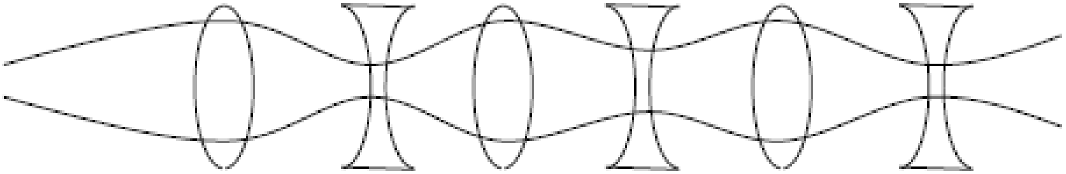
1. Needs a strong enough magnetic field to bend errant particles back on track
2. Stronger as it goes away from the center, but zero in the center
3. Change sign going from one side to the other

(Not quite) Ideal Focusing Element

- Unfortunately, we must obey Maxwell's Equations, and the best we can do it make N-pole magnets (dipole = 2 pole, one N, one S)
- Next option is Quadrupole magnets (4 pole)
- Gives us what we want… in one plane
- Focusing in one plane, defocusing in the other
- Fortunately, we can alternate them, and get a stable solution



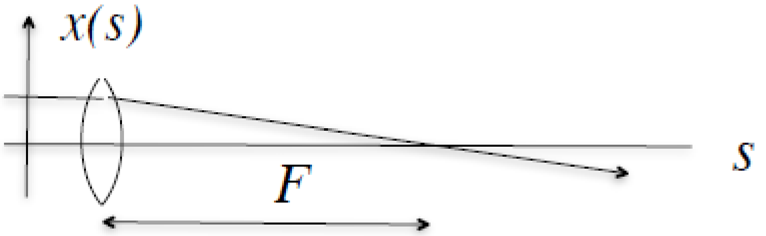




https://news.fnal.gov/2020/03/the-power-of-attraction-the-use-of-magnets-in-particle-accelerators/
http://nicadd.niu.edu/~syphers/uspas/2018w

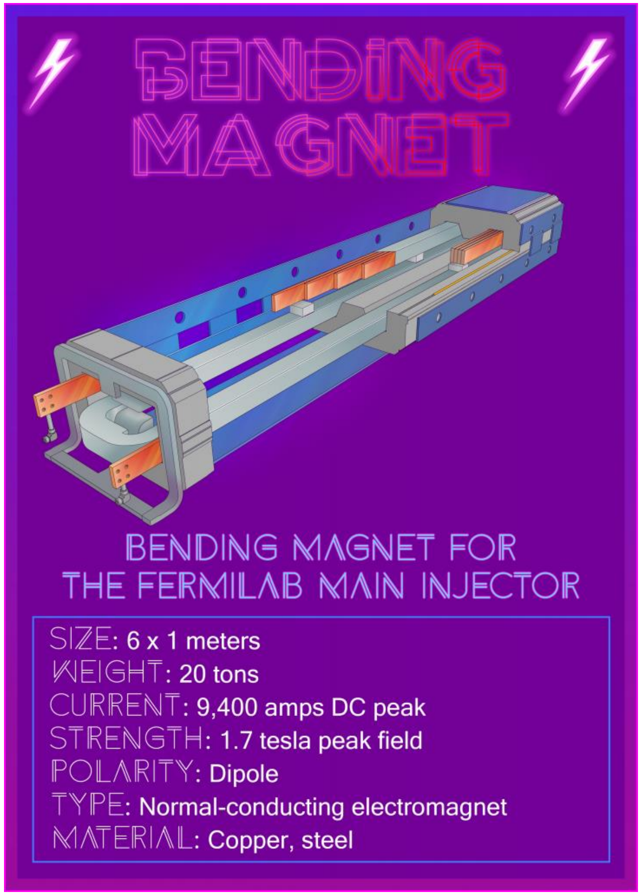
Little bit deeper dive into focusing magnets

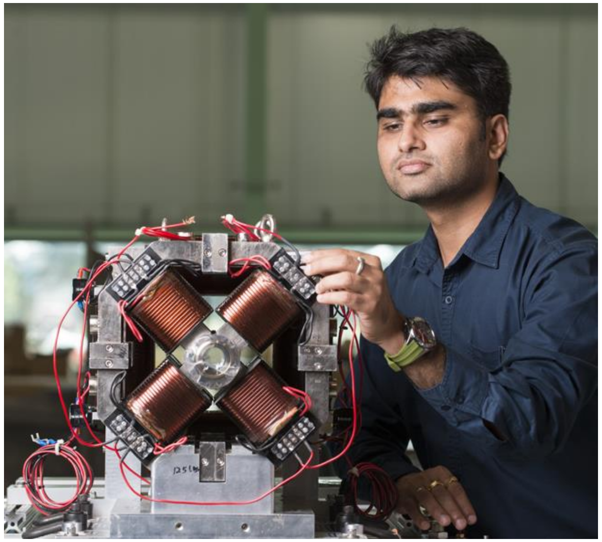
- If we assume the quads aren't very long, and they don't bend the particles too much, we can treat them like thin optical lenses
- $B' \equiv \frac{\partial B}{\partial x}; \frac{B'L}{B\rho} = \frac{1}{F}\ for\ F \gg L$

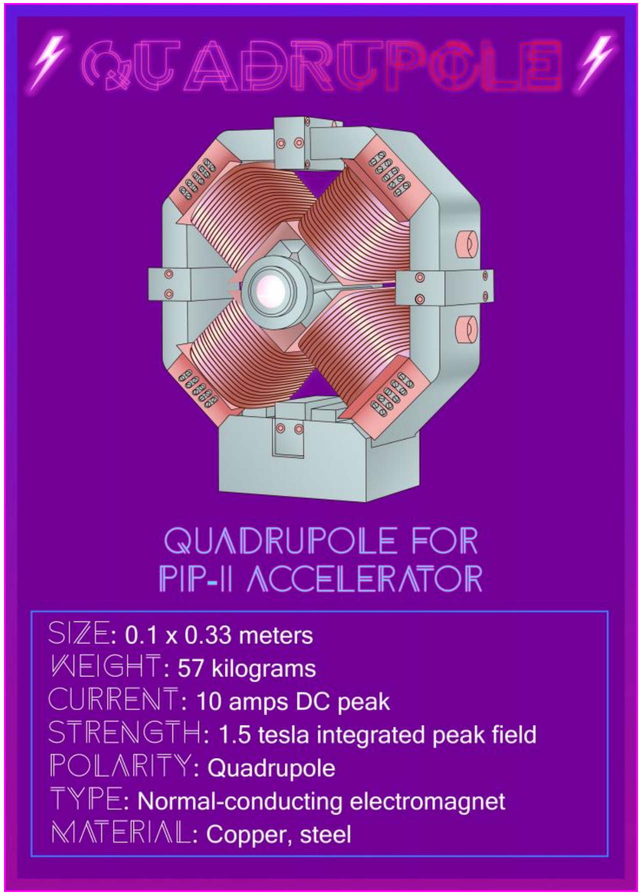


- We can relatively simply build a model of a full machine, treating each magnet as a thin lens, using linear algebra to solve for all the parameters
- CAVEAT: Errors, end effects, and higher-order effects are a huge deal. Ideal magnets don't exist.

Fermilab Magnet Examples, big and small



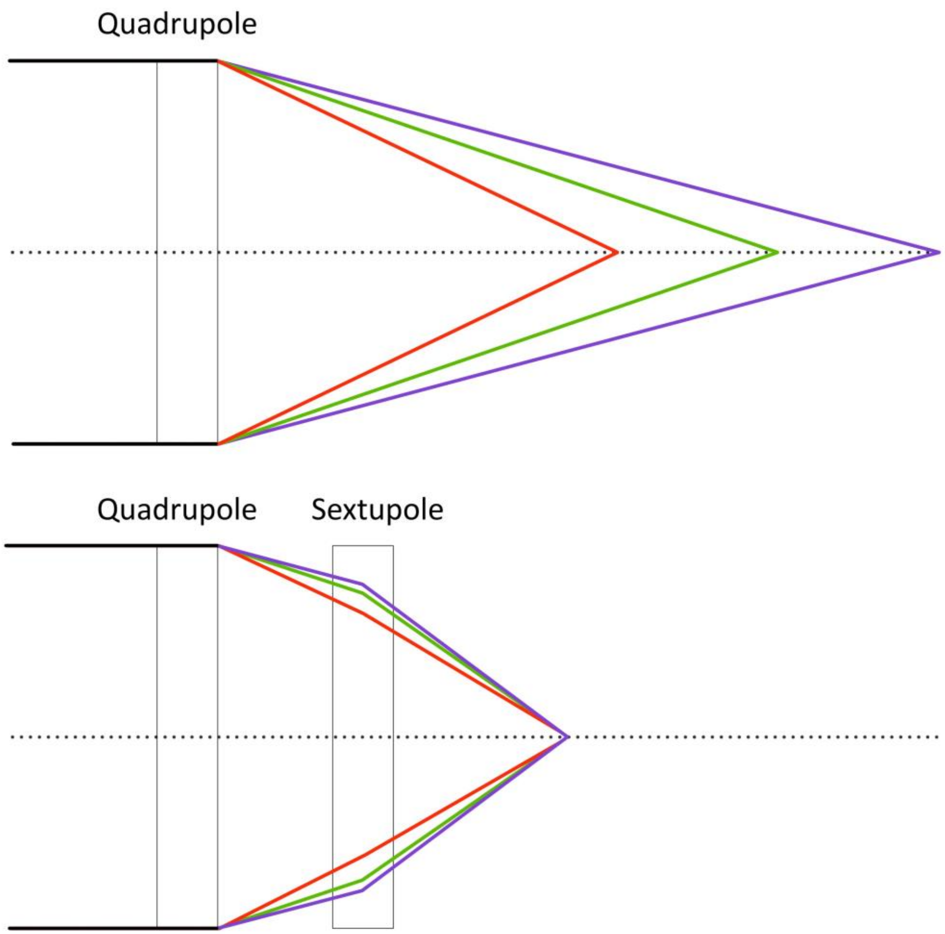




https://news.fnal.gov/2020/03/fermilab-presents-march-magnets/

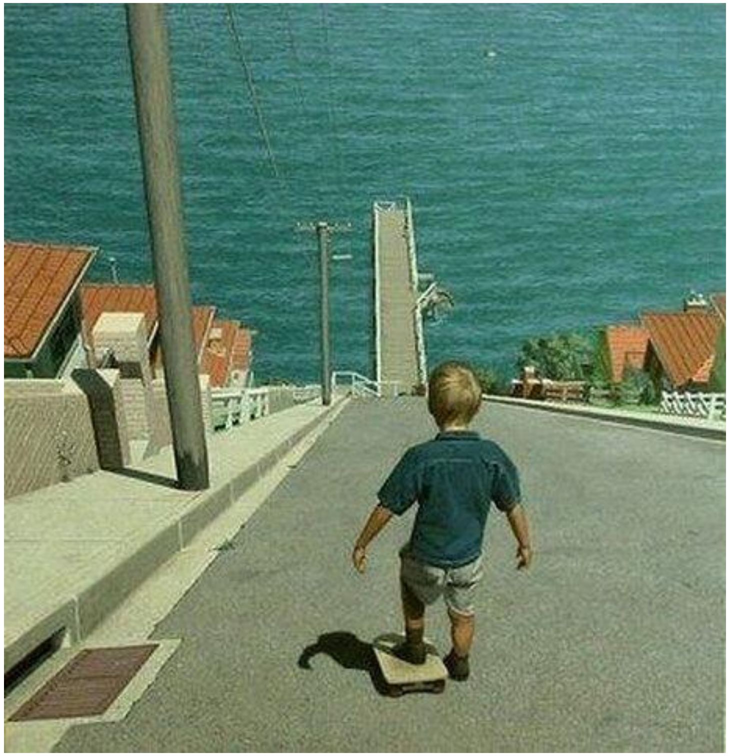
One more thing…

- When the energy isn't uniform (i.e. all the time), you need a sextupole magnet to correct it, for instance.
- Here, red is too low energy, purple is too high (green is ideal)
- The sextupole field distribution corrects the focusing error due to off energy particles



https://news.fnal.gov/2020/03/the-power-of-attraction-the-use-of-magnets-in-particle-accelerators/

3) Always More Energy!



Electrostatic is limited, like trying to just use a big hill to speed up, the hill can only get so tall (and you can only use it once!)

If we use waves (time varying forces) we can ride the wave as long as we want, limited by other practical concerns

We need fancy microwaves!

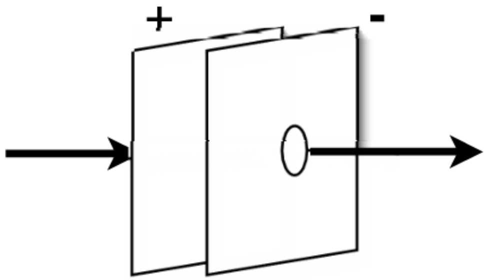
- Takes power from the wall, makes high energy waves (microwaves, RF)
- Directs that power to the 'box' of the microwave
- Accelerates (heats) up the particles in the food
- Control system, timer, power setting, interlocks, etc.

Only problem: *Food isn't moving, our particles are flying by at a giant speed, so we must synchronize with them*

The Benefits of Radio Frequency Fields

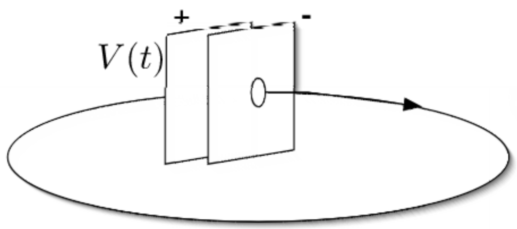
- The Need for AC Systems

$$\text{energy gain} = q \cdot V$$

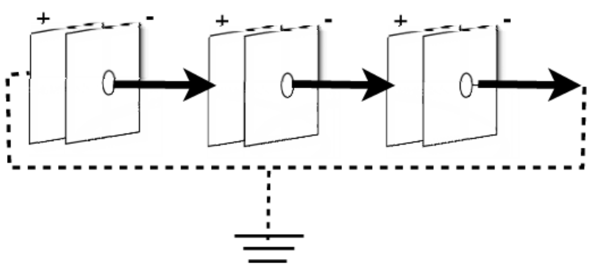


DC systems limited to a few MV

Circular Accelerator



Linear Accelerator



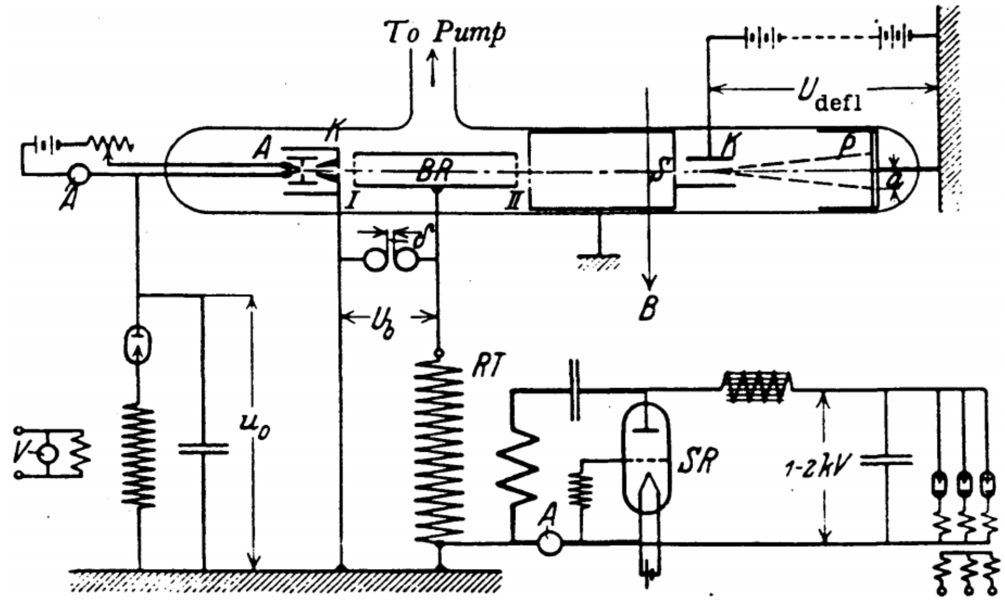
$$\oint (q\vec{E}) \cdot d\vec{s} = work = \Delta(energy)$$

To gain energy, a time-varying field is required:

$$\oint \vec{E} \cdot d\vec{s} = -\frac{\partial}{\partial t} \oint \vec{B} \cdot d\vec{A}$$

Wideroe Drift Tube Linac

- First RF accelerator conceived and demonstrated by Wideroe in 1927 in Aachen, Germany
- RF voltage of 25 kV from 1 MHz oscillator was applied to single electrode between two ground planes
- Accelerated potassium ions to 50 keV, two gaps for twice the voltage
- Sloan and Lawrence built one of these style linacs with 30 electrodes, applying 42 kV to get mercury ions up to 1.36 MeV



Wideroe's Device (from his thesis)

A Digression - Radio Frequency Resonators

- Useful to remember:
  - $\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$
  - Magnetic Fields do no work
  - Opposites Attract

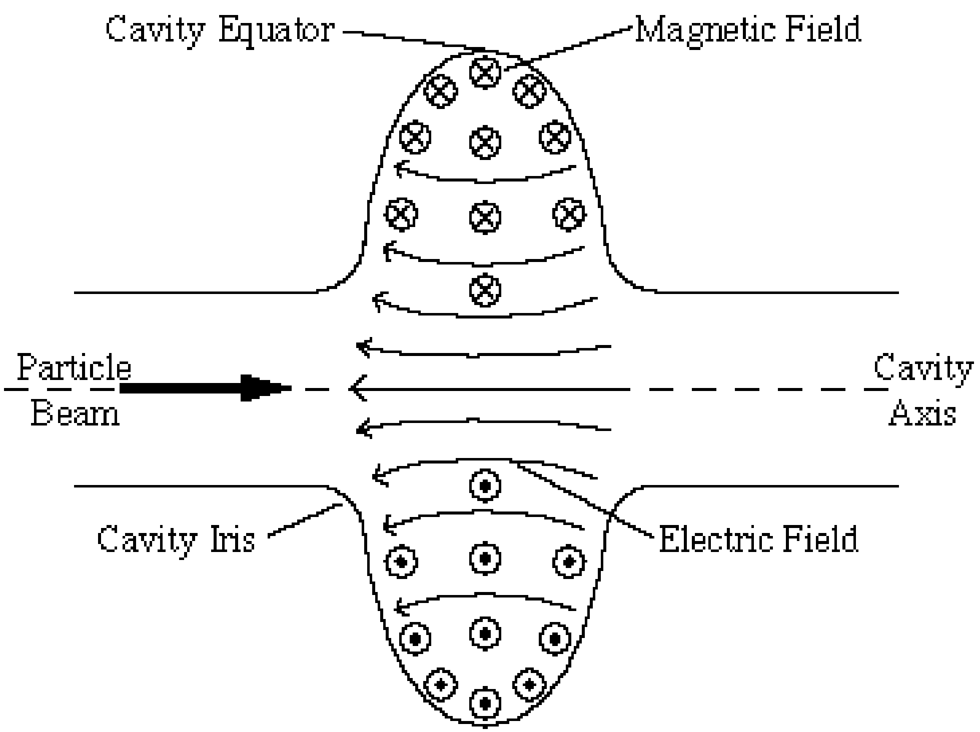
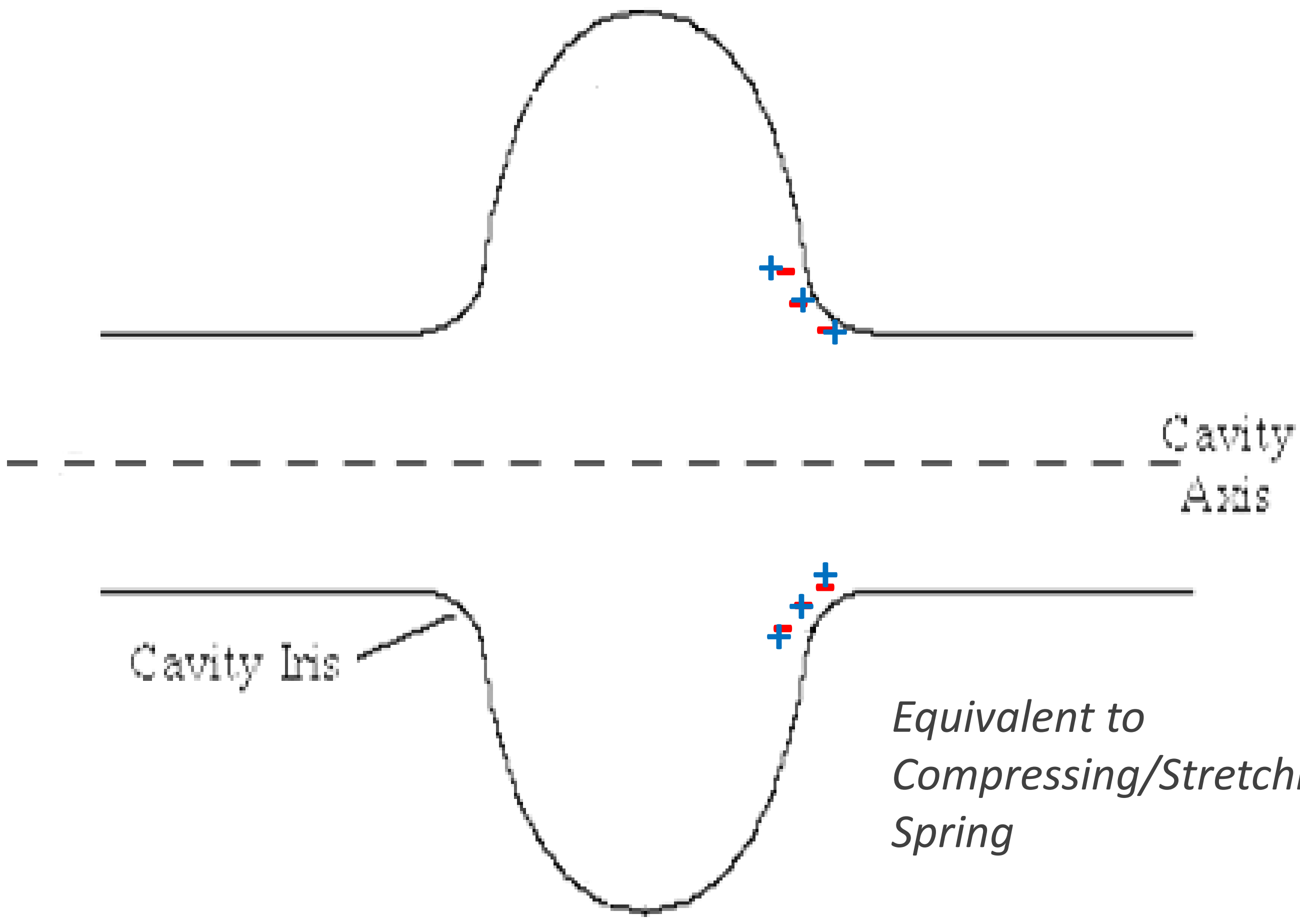


Diagram courtesy of LEPP

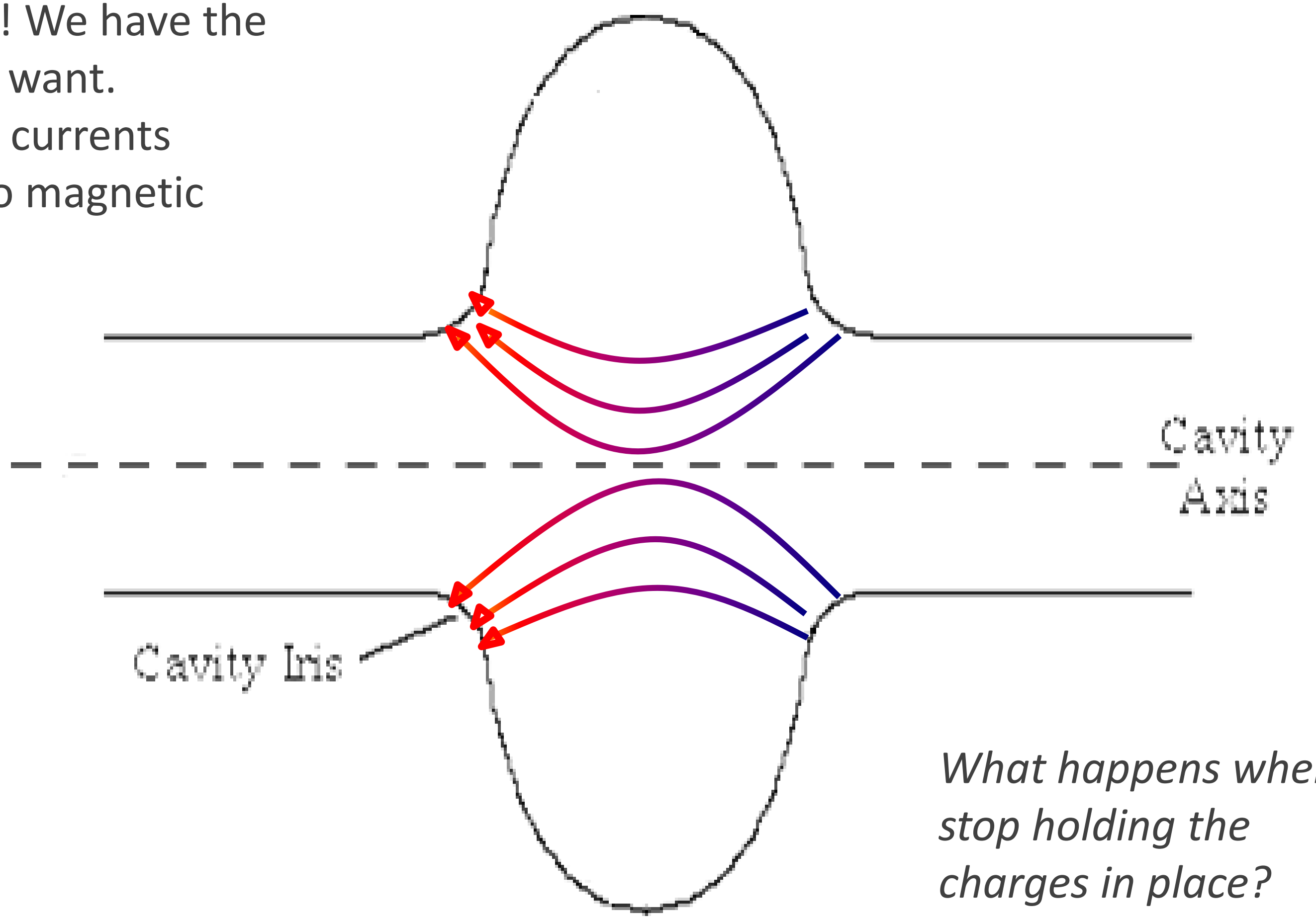
RF Cavity Resonance - Test Charges



Equivalent to Compressing/Stretching Spring

Resulting Electric Fields

Excellent! We have the fields we want.
Note: No currents means no magnetic fields

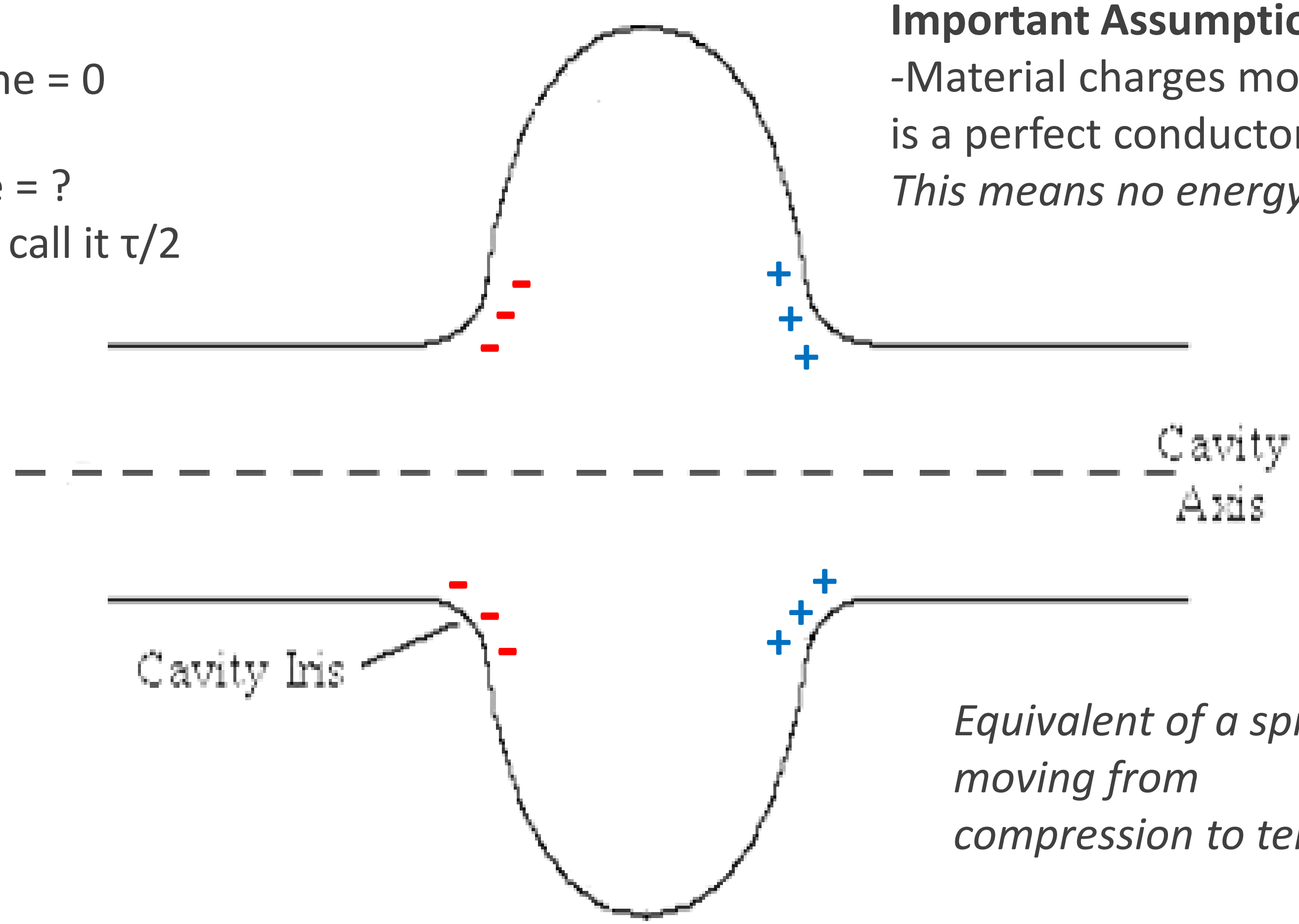


What happens when we stop holding the charges in place?

Releasing the Spring

Time = 0

Time = ?
Let's call it τ/2



Important Assumption:
-Material charges move through is a perfect conductor.
This means no energy is lost.

Equivalent of a spring moving from compression to tension

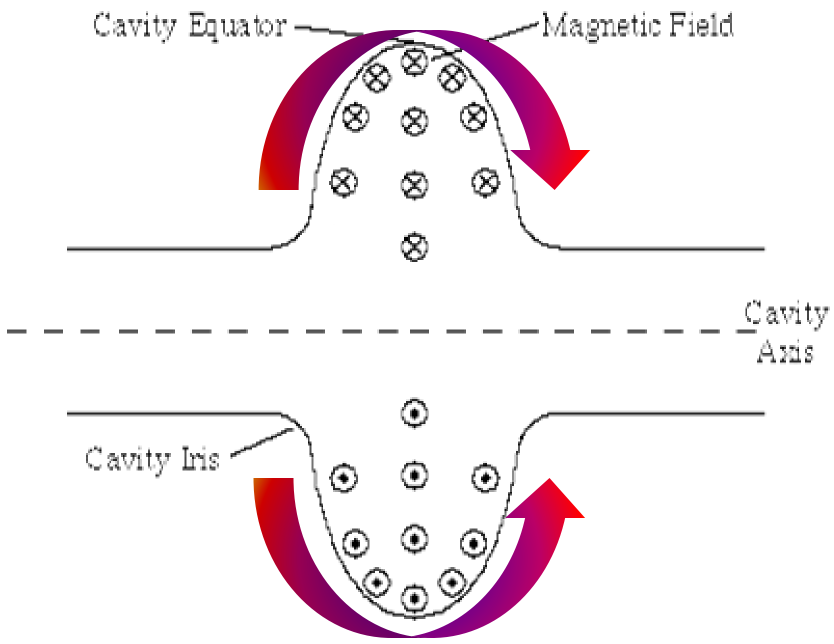
Resonant Behavior

- In τ/2 time, the electric fields reversed themselves
- Symmetry says that in another τ/2, the fields will return to their original position
- Do the Math:
- $\vec{E}(\vec{r},t) = \vec{E}(\vec{r},0)\cos(\omega t)$
- Where $\omega = \frac{2\pi}{\tau}$

- Monopole Mode:
  - One strong electric field region centered on the beam axis
  - Electric field in the direction the beam is traveling

Magnetic Fields

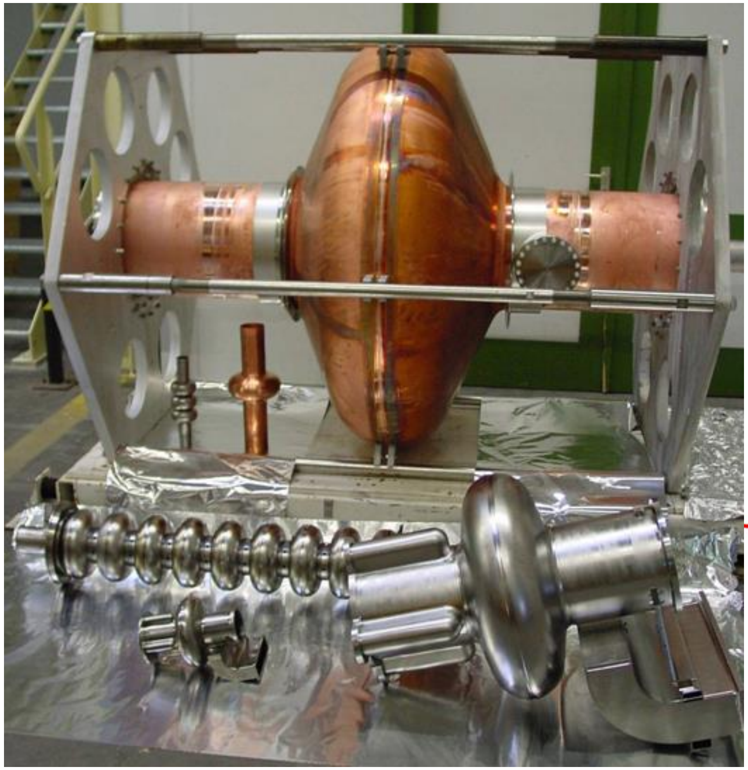
- At t = τ/4, all electric fields are gone, replaced by magnetic fields
- The moving charges act as currents, creating the magnetic fields around the cavity equator
- Remember Maxwell:
- $\nabla \times \vec{B} = \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$ (in vacuum)

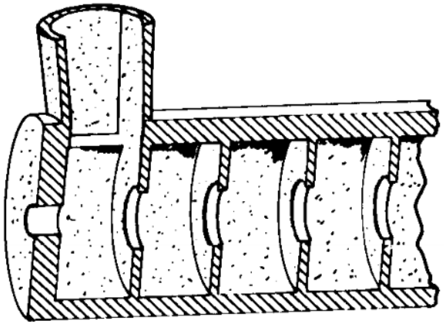


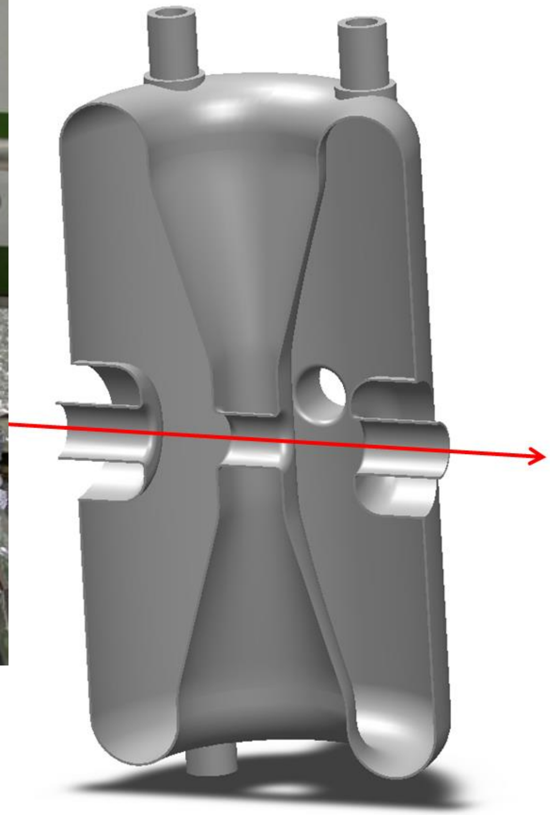
Flowing Charge
= Currents

How do we create V(t)?

- What do we need?
  - Correct Frequency
  - Accelerating fields that are easy to access
  - “Clean” accelerating field distribution
  - Reasonable mechanical properties
  - Efficiency energy storage







How are these cavities judged?

$$\Delta W = q \times V_0 \times TTF(\beta) \times \cos(\phi)$$

Charge

Maximum Accelerating Voltage

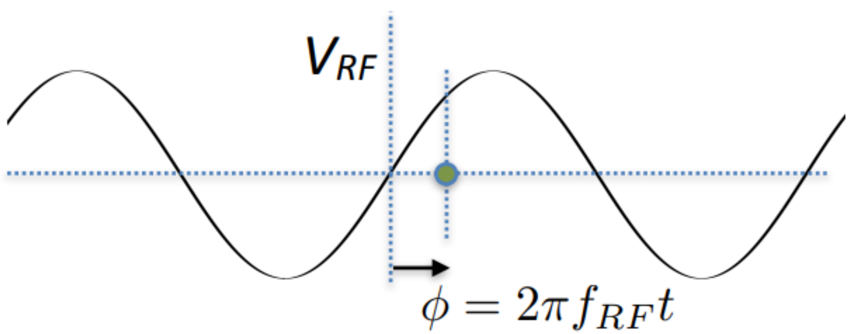
Transit Time Factor

Longitudinal Focusing Term

- R/Q
  - Measure efficiency of transferring energy to the beam

- Geometry Factor
  - Measure of efficiency of energy storage in the cavity

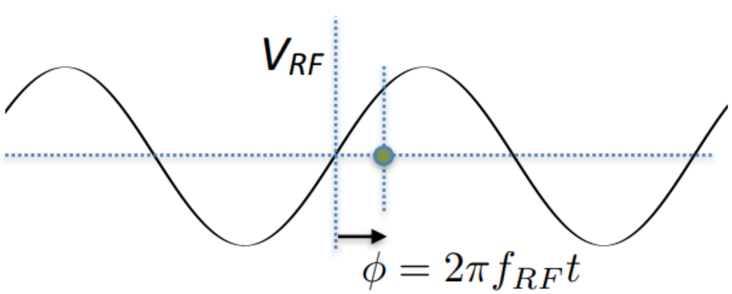
$$R/Q = \frac{V_{acc}^2}{\omega U}$$

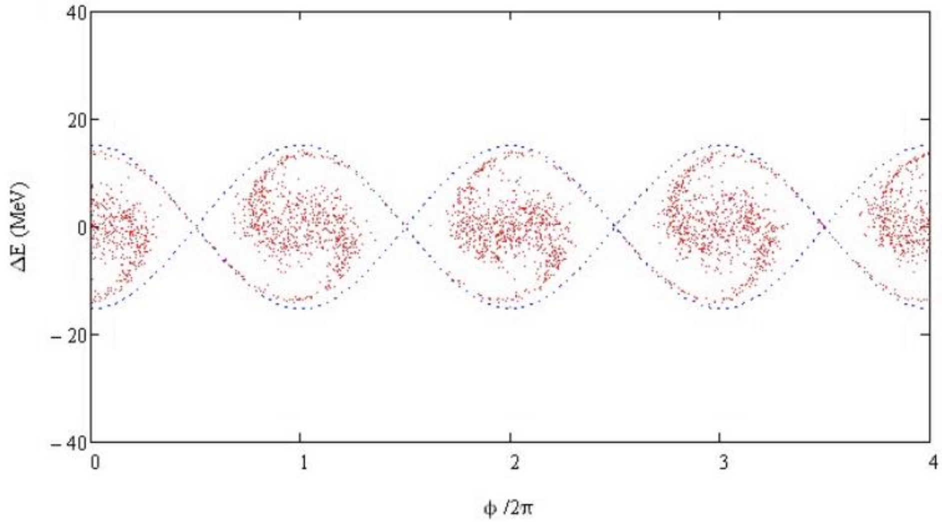


$$G = \frac{\omega U}{P_d / R_s}$$

One last piece… longitudinal focusing

- Quads etc. focus the transverse directions, but what about the direction of travel? Any energy spread means that particles will drift apart from each other.
- Sort of glossed over it, but if you use RF, you can't have a continuous beam of particles, you have to bunch them into packets
- Faster particles get less energy, slower ones get more

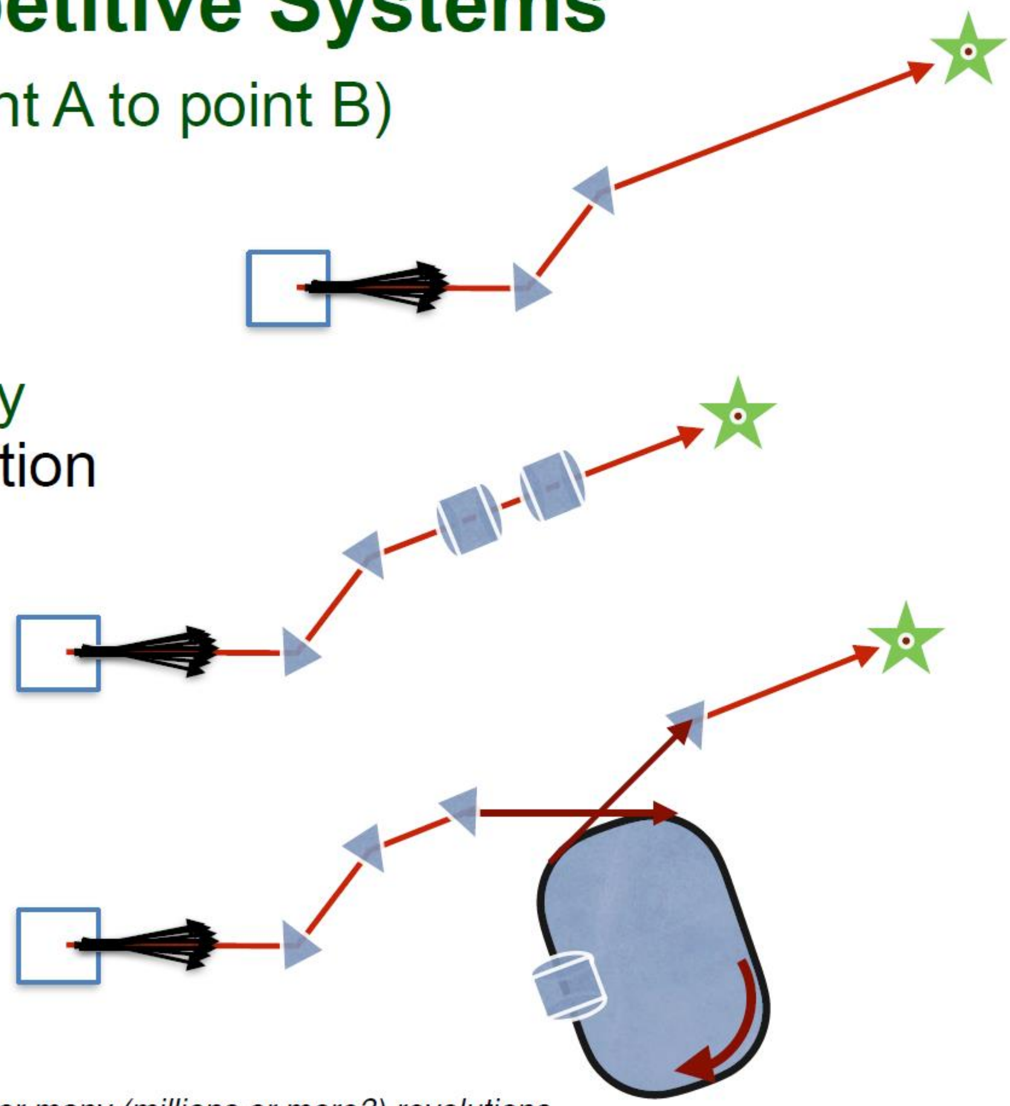




Single-Pass vs. Repetitive Systems

- Beam Transport (from point A to point B)

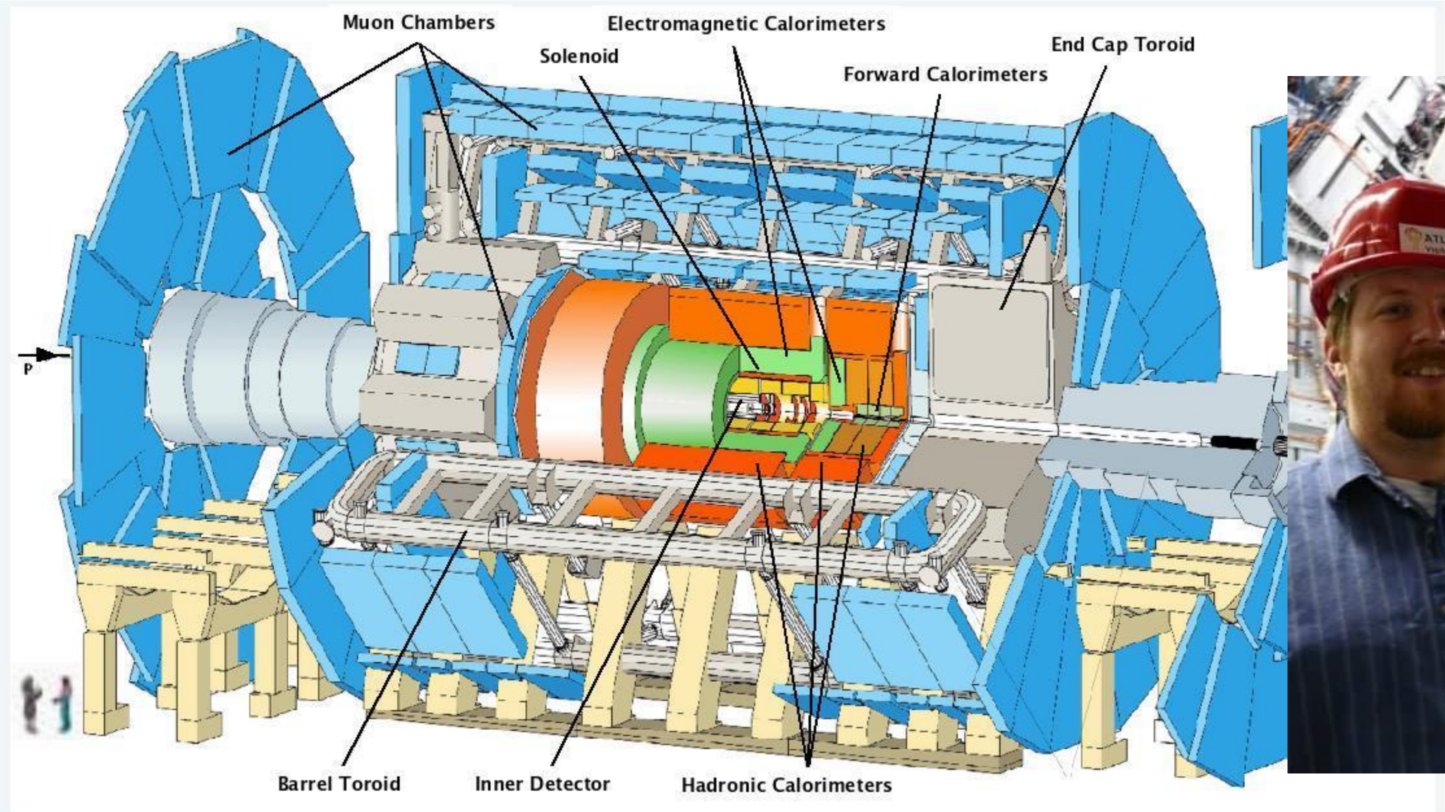
- Acceleration along the way
  - single-pass with acceleration
  - multi-pass acceleration



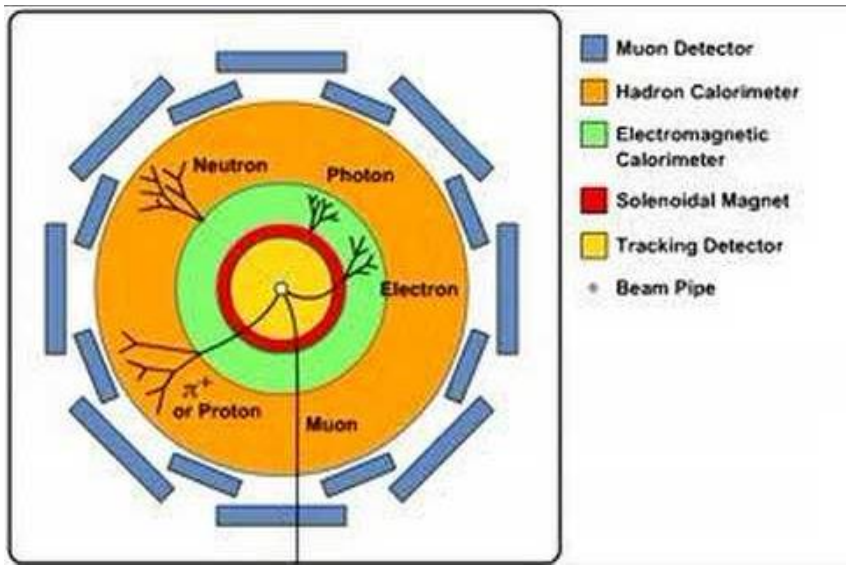
may need motion in such a system to be stable for many (millions or more?) revolutions

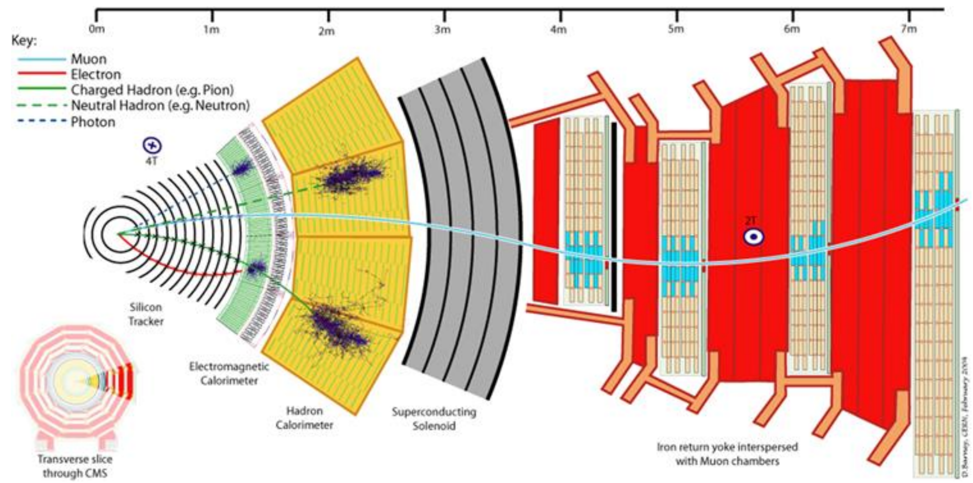
4) Detectors and Cameras

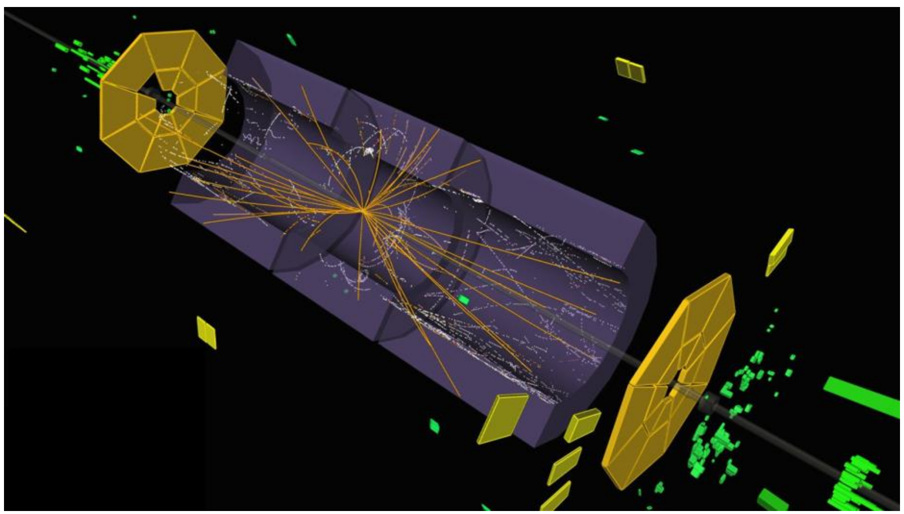
- GIGANTIC topic I can't do justice to (next week's topic)
- The highest energy targets need massive detectors
- Particles collide in the middle, generating lots of things the detector records

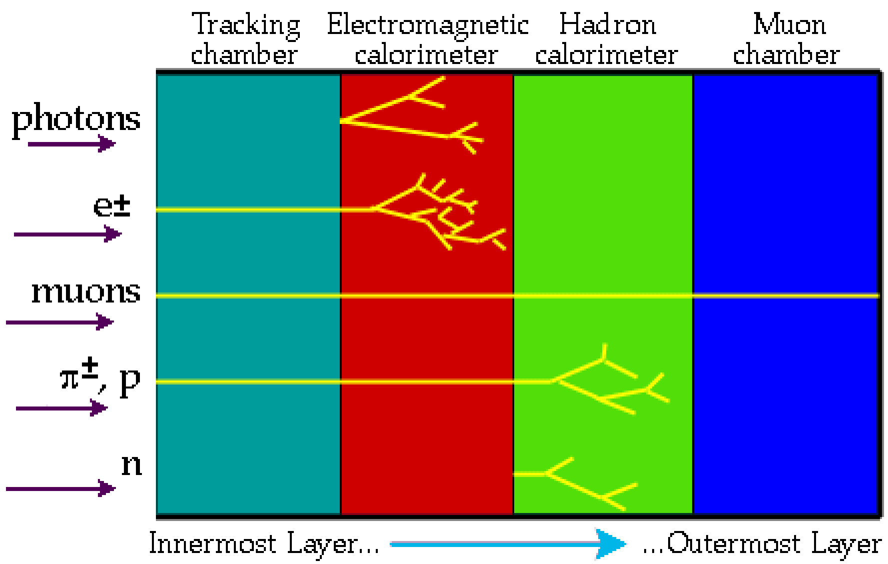


HEP Detector Analysis is a HUGE deal



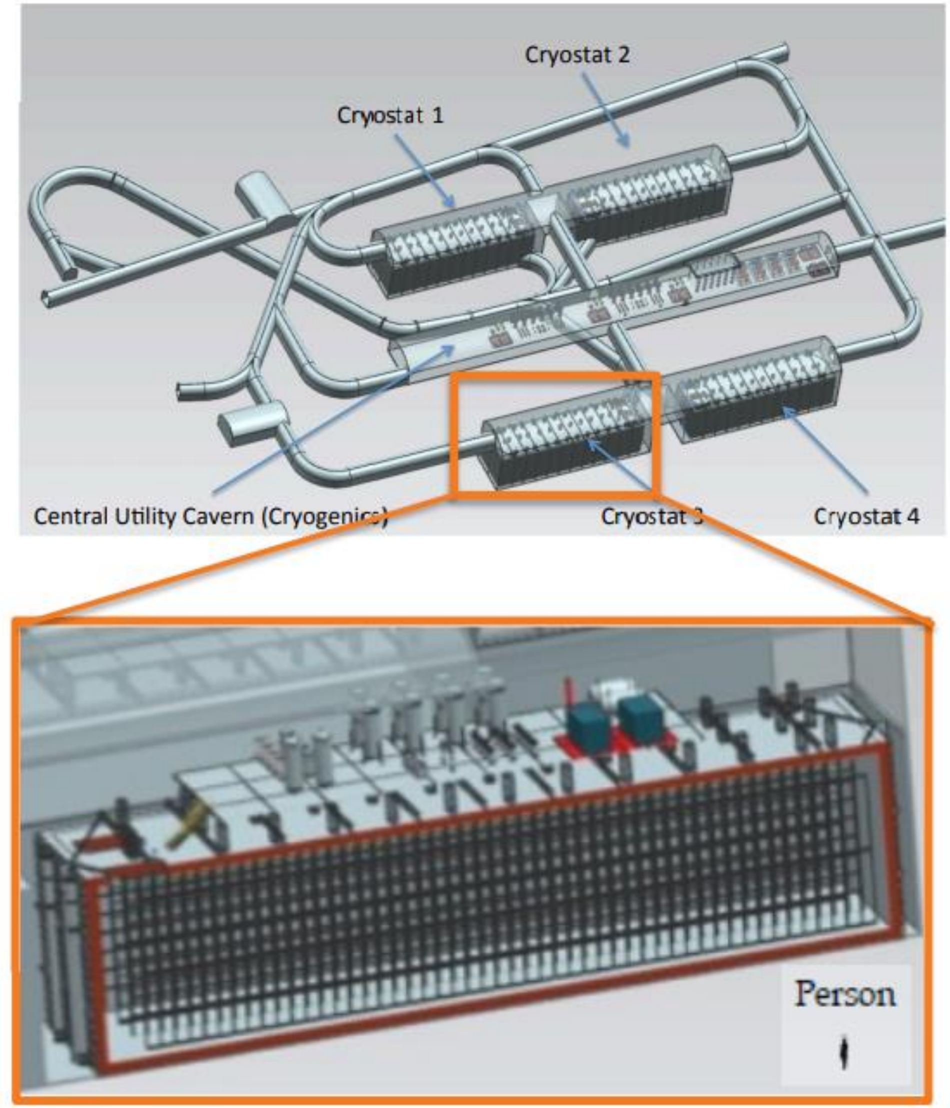


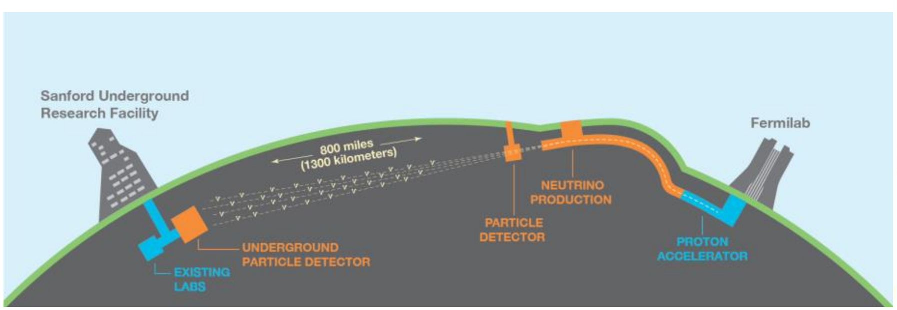




Precision Physics Detectors

- Sometimes you just need LOTS of data, which means huge detectors
- LBNF is a big expansion to the FNAL complex to generate massive number of neutrinos
- DUNE is a detector complex in South Dakota to see them





Long story short

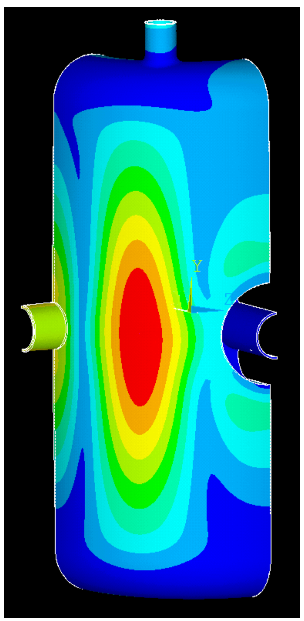
- All topics covered today are things you could spend your whole career on
  - Engineering of all kinds
  - Scientists of most kinds (Physics, materials, etc.)
  - Technical specialists
  - Drafters, machinists, etc.
  - Operations experts
- Lots of variety in education level, experience, and interests
  - uspas.fnal.gov <- US Particle Accelerator School
- Generate, confine, direct, and accelerate particles, delivering them to the experiment as needed
  - Always need of new particle beams

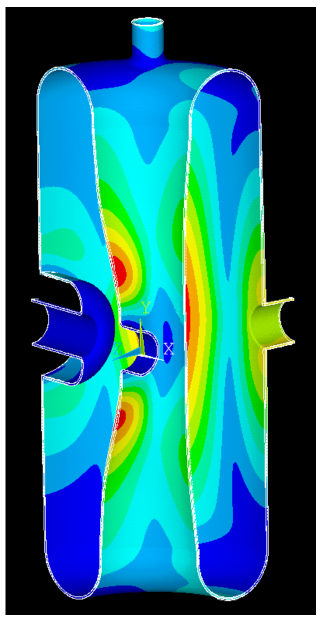
Thanks! Questions?

Backup Slides

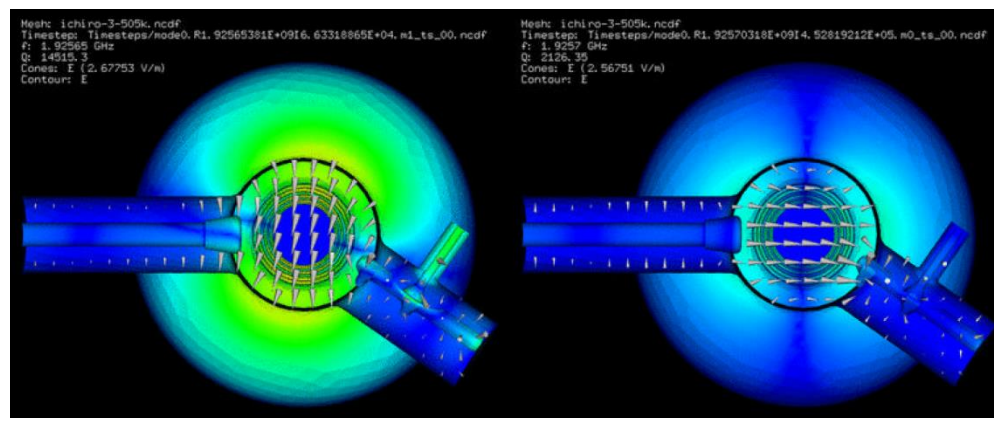
Other Design Considerations

- Mechanical Issues
  - In operation, a cavity is exposed to many different pressures that deform their shape
  - How this deformation changes the cavity frequency and performance must be well understood





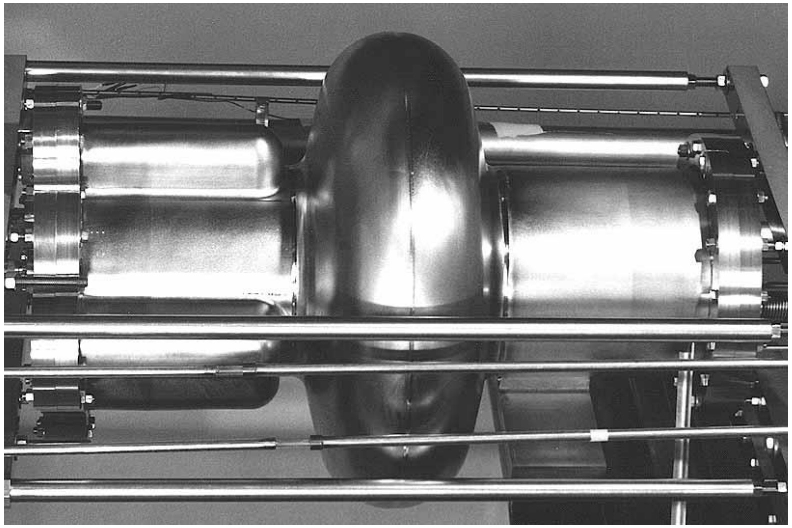
- Higher Order Modes
  - As the beam passes through the cavity, it can excite ALL cavity modes
  - Strong beam asymmetry or offset increases the strength of this coupling
  - These modes must be strongly damped or they can cause emittance growth or beam breakup… in some cases

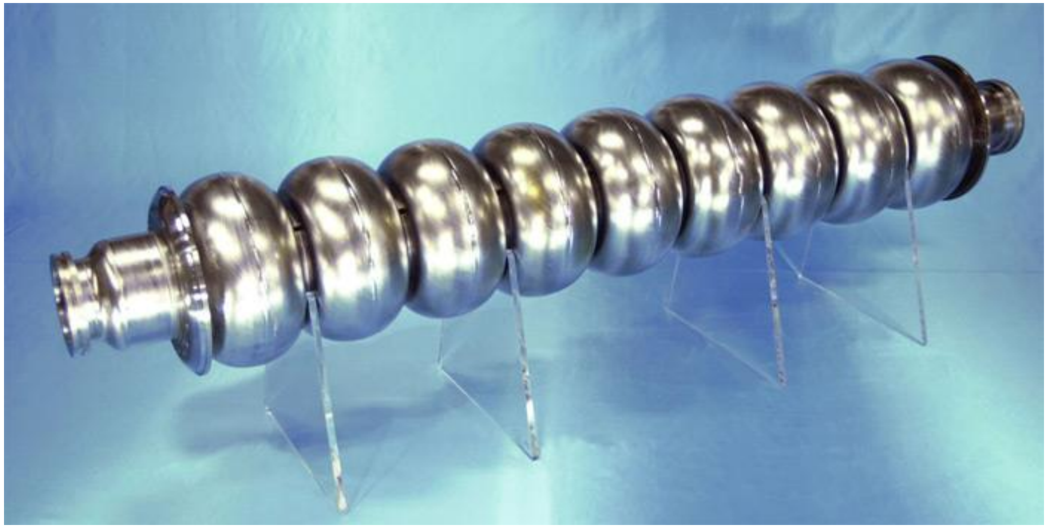


Cavity Design for Different Accelerators

- Synchrotrons (Ring Machines)
  - The beam sees the cavity MANY times, low gradient is typical
  - Field must be very clean and stable
  - Very heavy higher order mode damping
  - Very large aperture
  - Acceleration and bunching

- Linacs (Linear Accelerators)
  - Single (or low #) pass machine
  - High Gradient is KEY (reduces # of cavities needed, therefore $$$)
  - Reliability and ease of fabrication is very important (many cavities)
  - Efficiency of operation also important





Basic Equations

- Maxwell's Equations are very general, govern all classical electromagnetic interactions

- $\vec{\nabla} \cdot \vec{D} = \rho$
- $\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$
- $\vec{\nabla} \cdot \vec{B} = 0$
- $\vec{\nabla} \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$

Where $\vec{\mathrm{D}} = \epsilon_0 \vec{E}$ and $\vec{\mathrm{B}} = \mu_0 \vec{H}$

- Lorentz Force
- Stored Energy density in EM fields
- Poynting Vector is useful conceptual tool (direction of energy flow in EM fields)

- $\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$
- $u = \frac{1}{2}\left(\epsilon_0 \vec{E}^2 + \frac{1}{\mu_0} \vec{B}^2\right)$ in vacuum
- $\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$ in vacuum