Introduction to Accelerators Overview

Saturday Morning Physics
Fermilab – October 18th

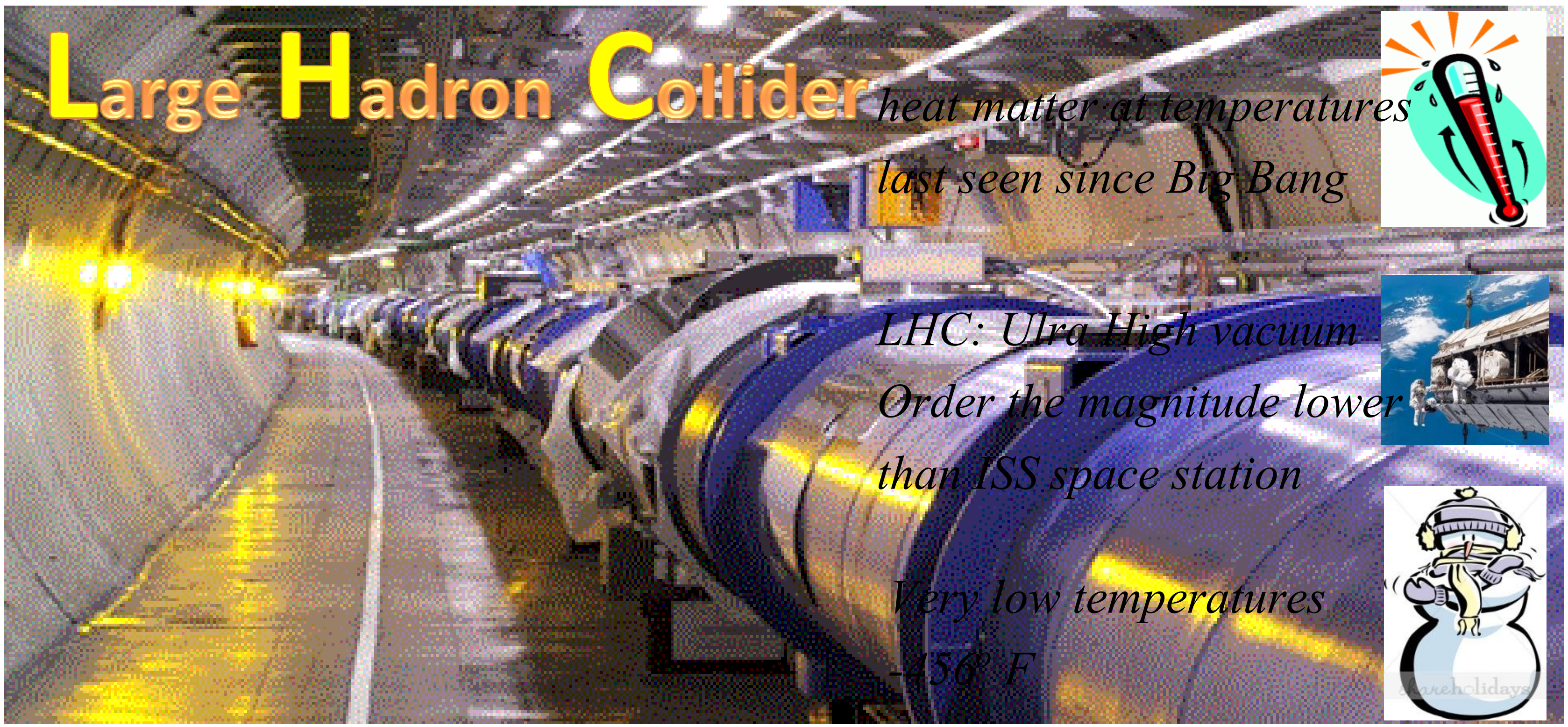
Particle accelerators

Particle accelerator is a device that uses electrostatic force to accelerate and electromagnetic fields to bend charge particles to high speeds and energy

What is a particle accelerator?

Does anyone knows what the name of this machine is?

- *World's biggest particle accelerator*
- *7 TeV energy , 17 miles (27 km) in circumference*
- *574 ft (~180 m) buried underground between the border of France and Switzerland*



How many accelerators are there?

There are > 15,000 particle accelerators around the world

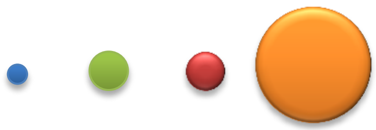
Only research particle accelerators are shown here.
Data: ELSA [http://www-elsa.physik.uni-bonn.de/accelerator_list.html]

How do they work?

Which of these particles you cannot put into an accelerator?

Required elements to make an accelerator

Particles | *Energy* | *Control* | *Collision* | *Detector*

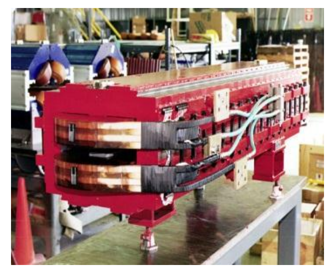


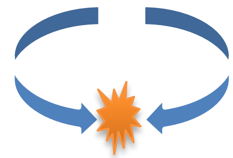
e*lectron*

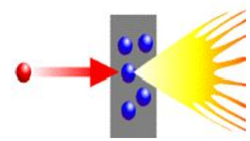
n*eutron*

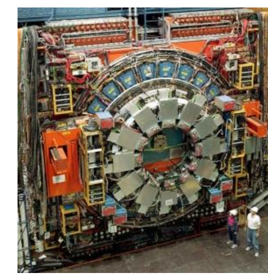
p*roton*

gold atom

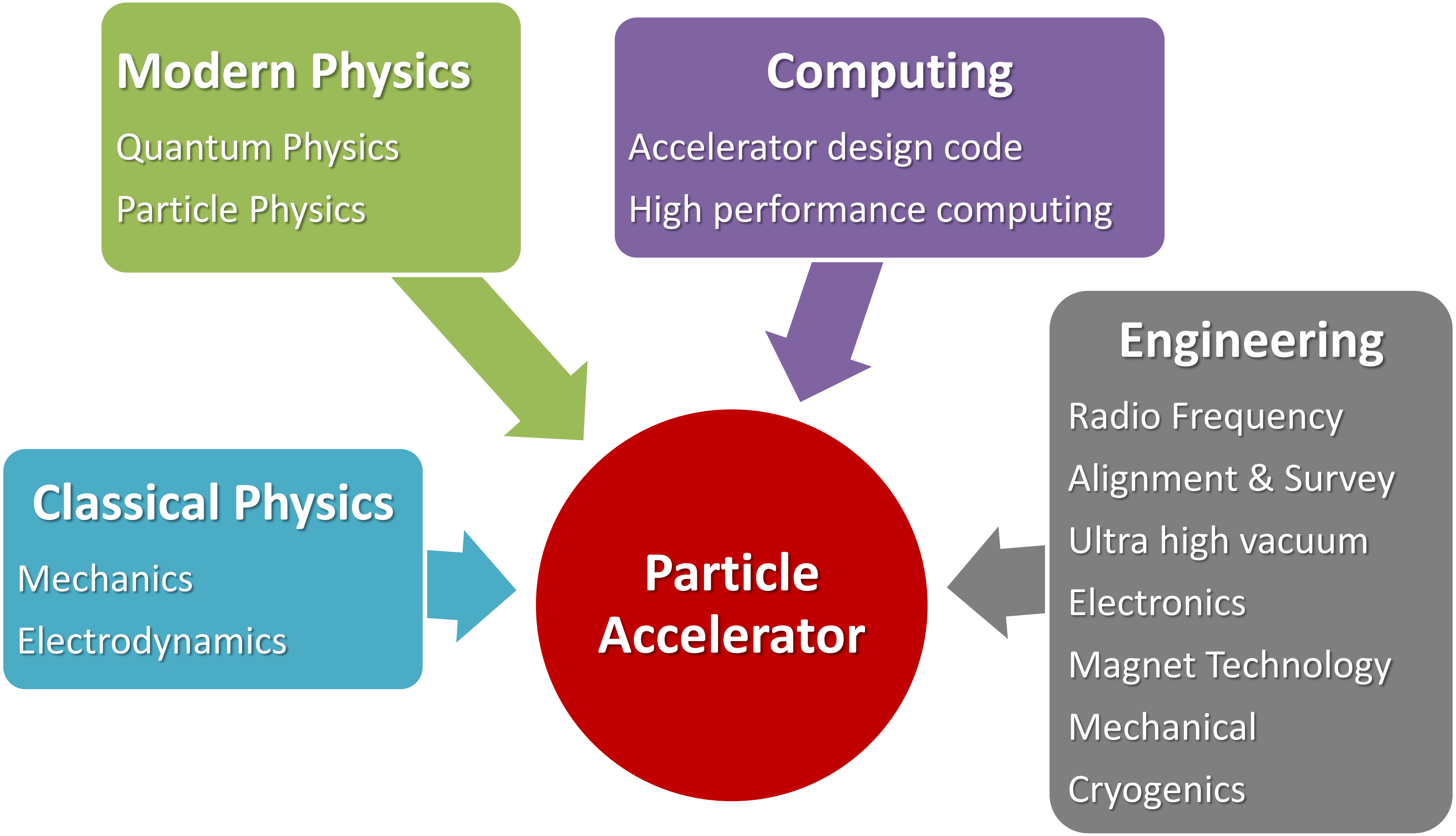




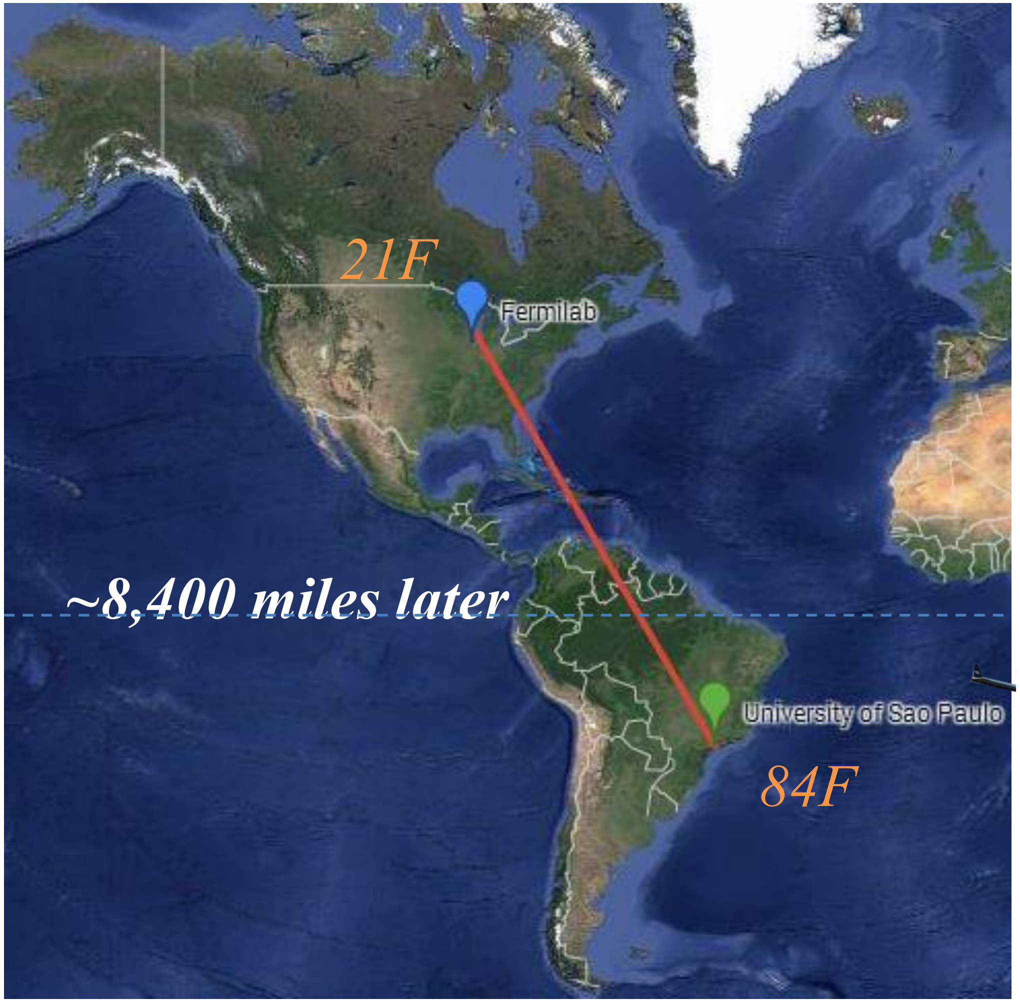




Particle accelerators



A little bit about me…



2001 - Post Doc in RPD

Joined the MiniBooNE exp.

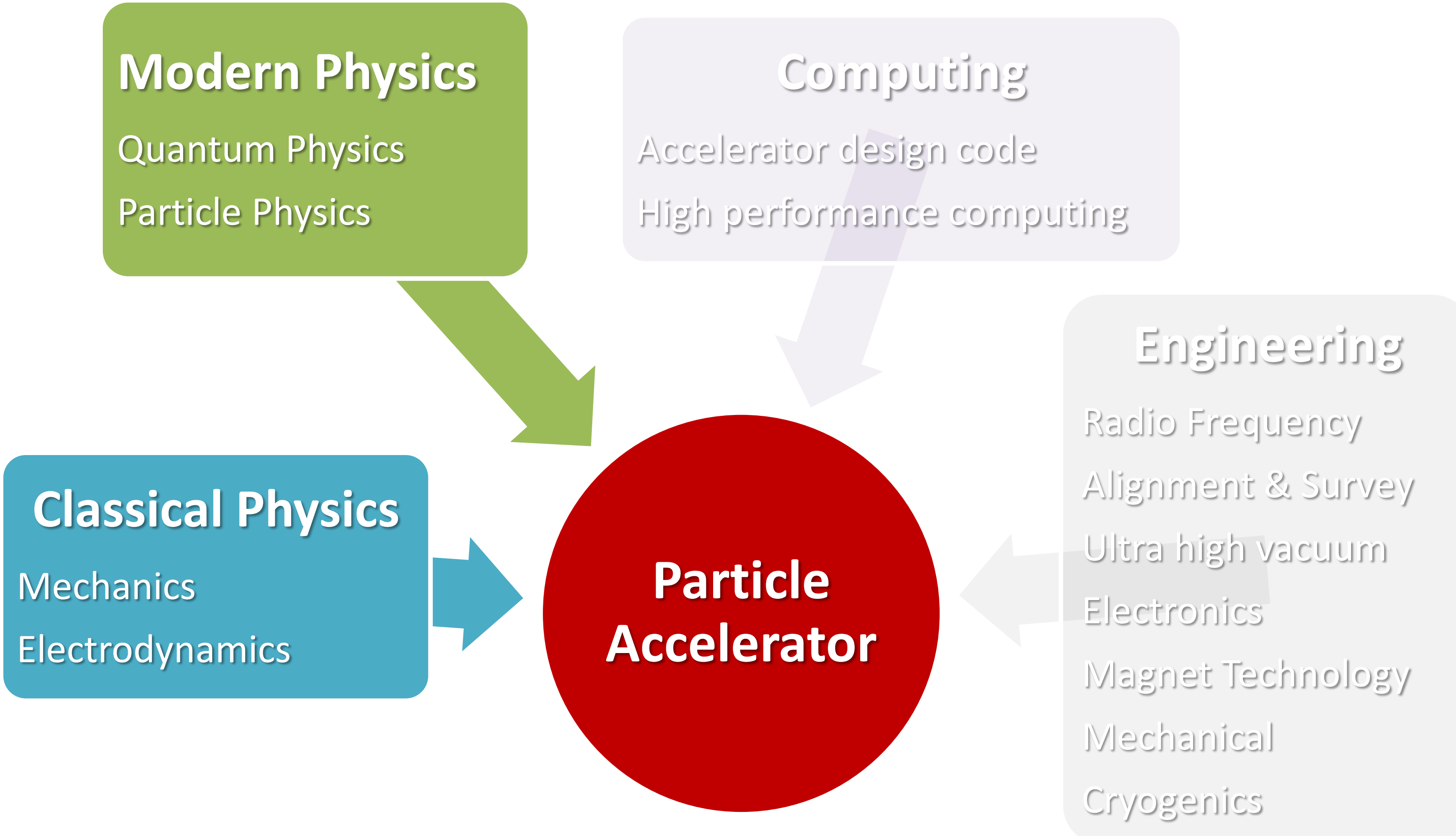
- *Responsible for detector setup, Head of detector installation, commissioning, operations*

2004- Joined Acc. Div. 2004

- *Proton Source (physicist for Booster transfer line)*
- *2008 – Head of the Linac Group*

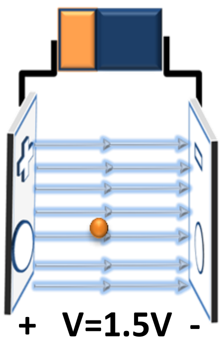
Outline

Particle accelerators



Units

- *Energy is measured in units of* ***electron volt (eV)***
  - ***1 eV*** *: kinetic energy gained (or lost) by a unit charged particle after crossing an electrical potential of one volt*
    - *However, 1V = 1 J/C , so 1eV = $(1.602x10^{-19}$ C)*1 J/C*



$$\Delta E = qV$$

elementary particle

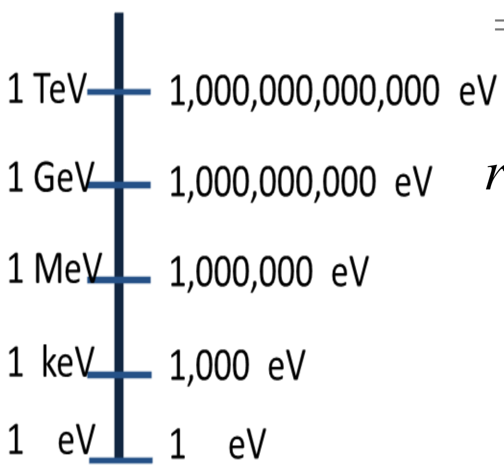
How fast is the particle moving?

$$E = \frac{1}{2}mv^2 \text{ , so } v = \sqrt{2E/m}$$

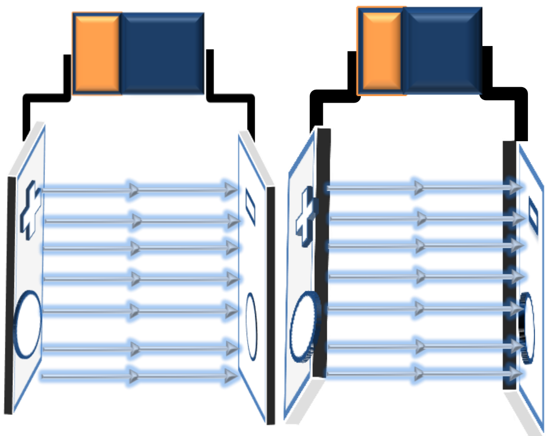
$$= \sqrt{2x1.5x(1.6x10^{-19}J)/(1.67x10^{-27}kg)} \cong 1.7x10^4\ m/s$$

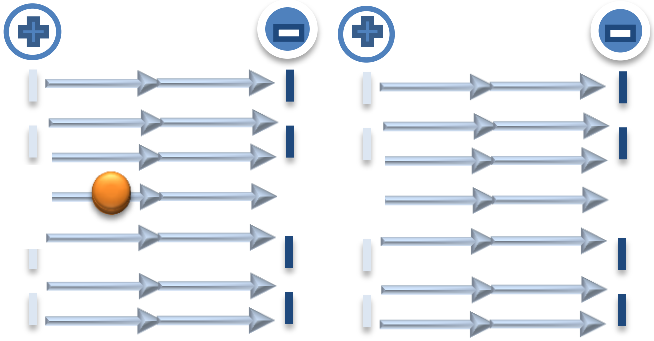
remember that velocity of light is $3x10^8$ m/s

this is only 0.006 of speed of light!!!



Electrostatic





The force from the electrical field will pull the particle and make it move increasing its speed until it moves really fast.

How many batteries would take to create a LHC accelerator?

x 5 Trillion

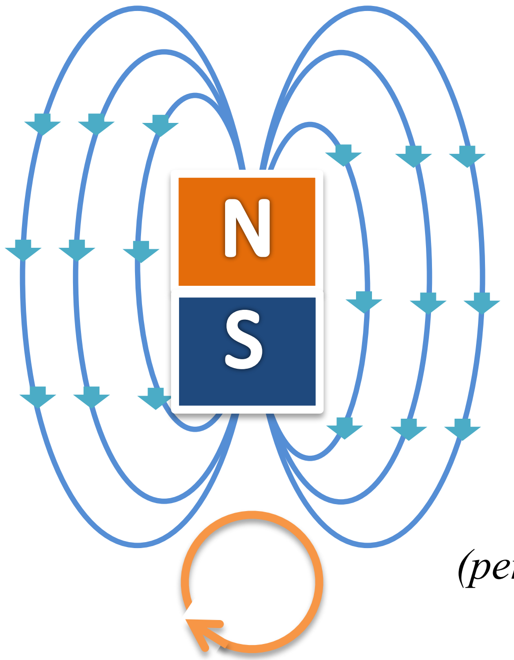
Not very practical, is it?

So…does it mean that particles will be moving at

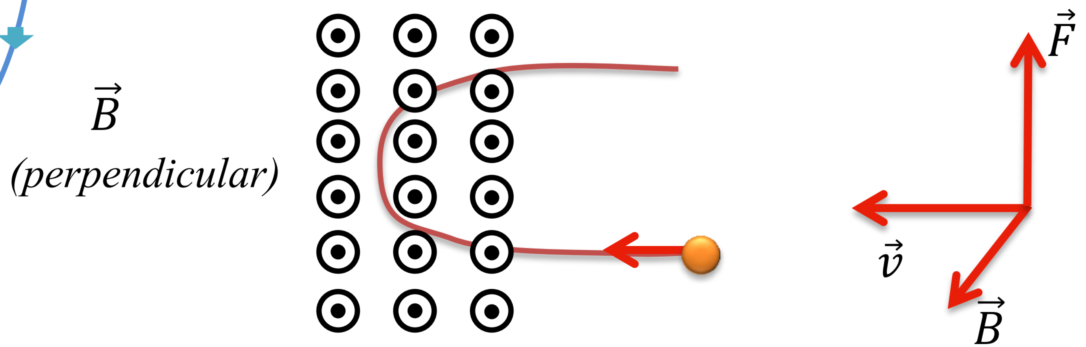
$$\sqrt{\frac{7x10^{12}}{1.5}} \simeq 4{,}000c???$$

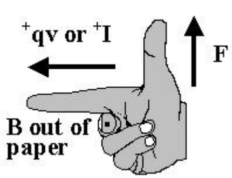
NO! relativistic effects has to be considered (more later…)

Electromagnetism



When a charge particle is placed in a magnetic field, it experiences a magnetic force when the charge is moving relative to the magnetic field

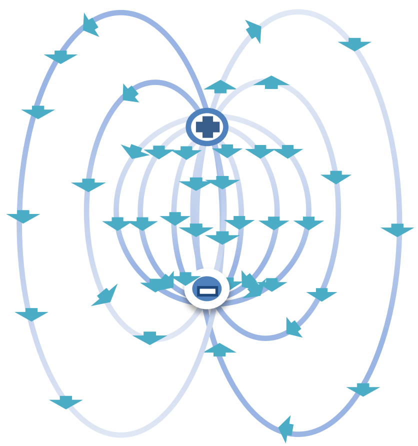




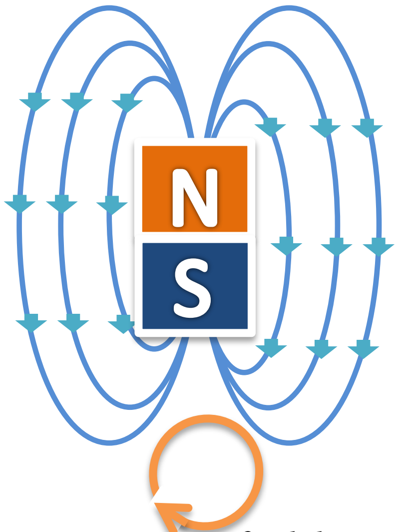
Magnetic field make particles to move on a circular path

Electrostatic & Electromagnetism

INTRODUCTION



While electric fields change the energy of the particles, making the particles move faster ….

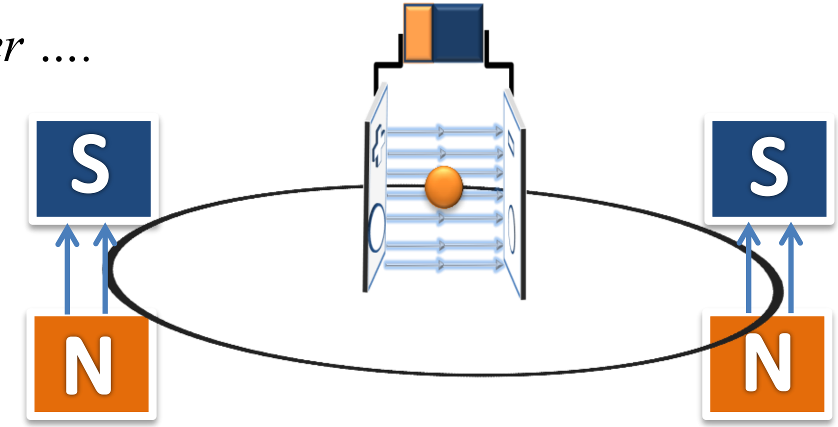


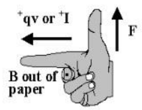
Magnetics fields make them follow a circular path

Lorentz

Equation of motion under Lorentz force

$$\vec{F} = \frac{d\vec{p}}{dt} = q(\vec{E} + \vec{v} \, x\vec{B})$$





Relativity: momentum & energy

INTRODUCTION

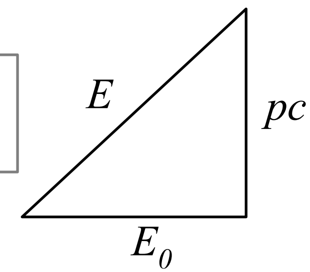
Einstein's relativity formula $E = mc^2$

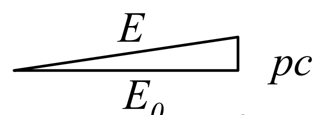
Rest energy	$E_0 = m_0 c^2$
Lorentz factor	$\gamma = \frac{E}{E_0}$
mass of a moving particle	$m = \gamma m_0$
Normal velocity	$\beta = \frac{v}{c}$

When particles are accelerated close to speed of light, relativistic effects start counting…

Total Energy

$$E^2 = E_{kin}^2 + m_0c^2 = \sqrt{(m_0c^2)^2 + (pc^2)^2}$$





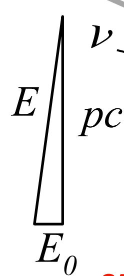
$v << c$

$$p = mv = m_0 c\beta\gamma$$

*momentum and energy are **not** equal*

Non-relativistic $p = m_0 v$

$v \to c$



momentum and energy become closer

High relativistic $p = m_0 c\gamma = E/c$

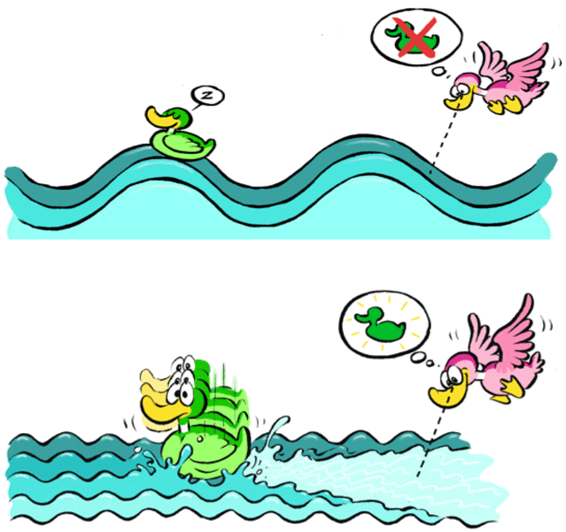
Length scale …why accelerators?

INTRODUCTION

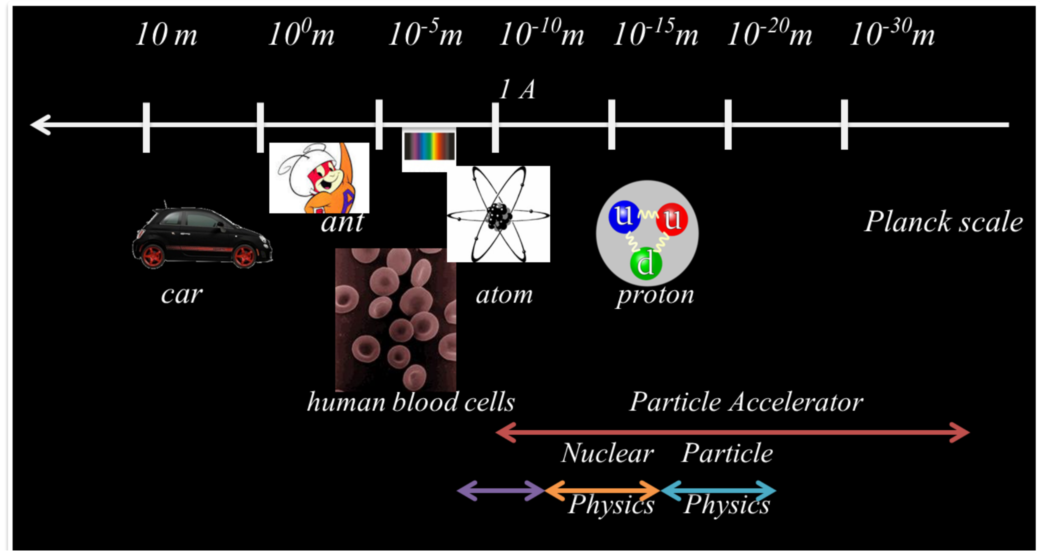
In order to study small objects, the higher the energy of the probe one needs to use it

De Broglie's wavelength $\lambda = \frac{h}{p}$ *Planck constant* $h = 6.63x10^{-34} J.s$

$= 4.14x\ 10^{-15} eV.s$

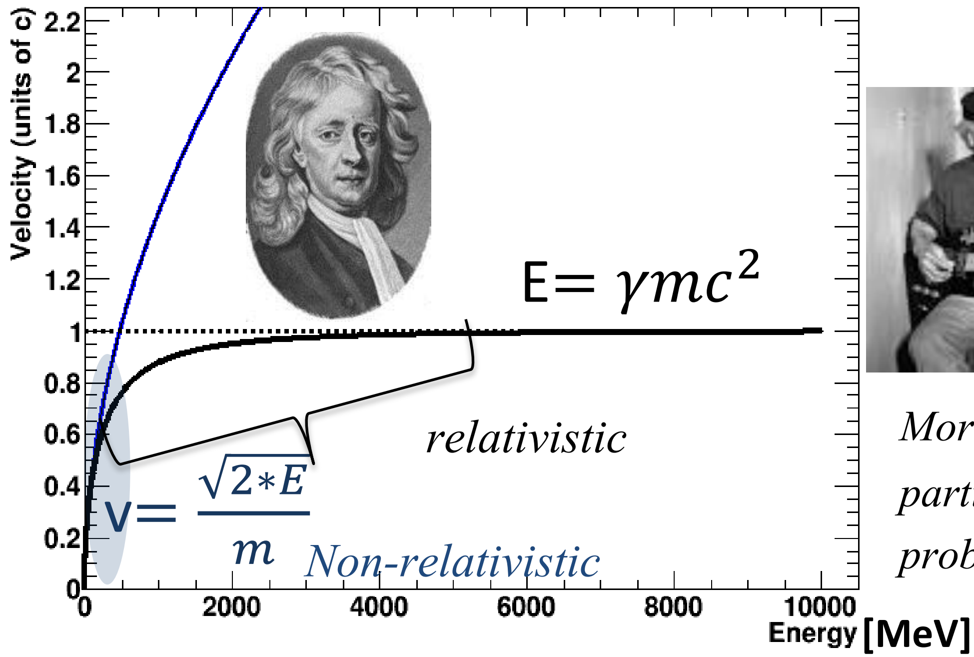


Picture from http://www.clab.edc.uoc.gr/materials/pc/surf/accelerators_intro.html

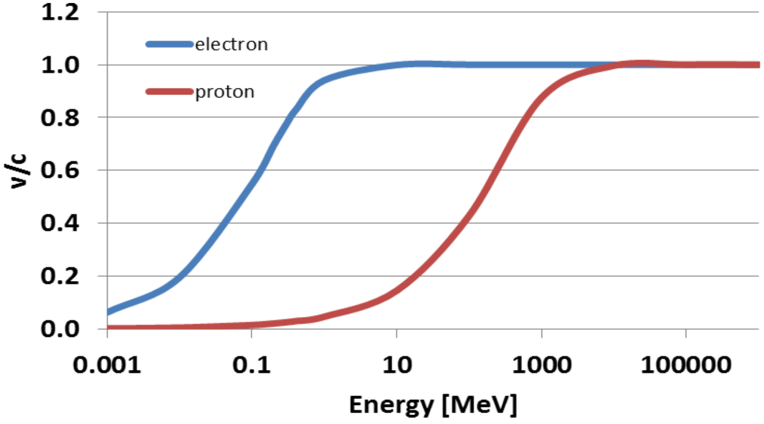


Velocity as function of energy

INTRODUCTION

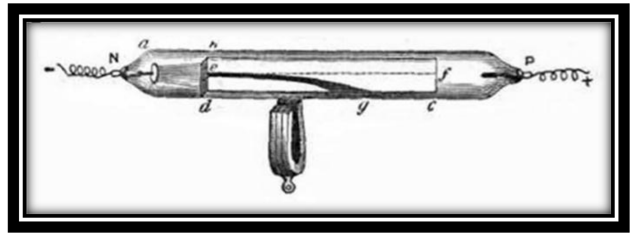


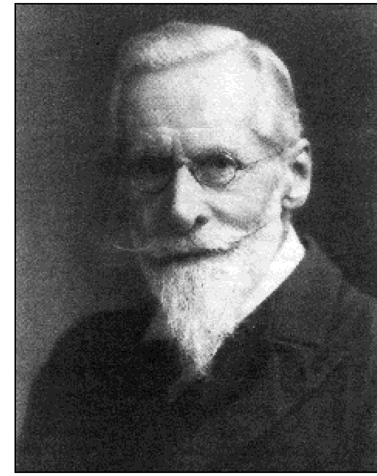
More energy can be poured into the particles, giving a shorter λ so that it probes deeper into the sub-atomic world



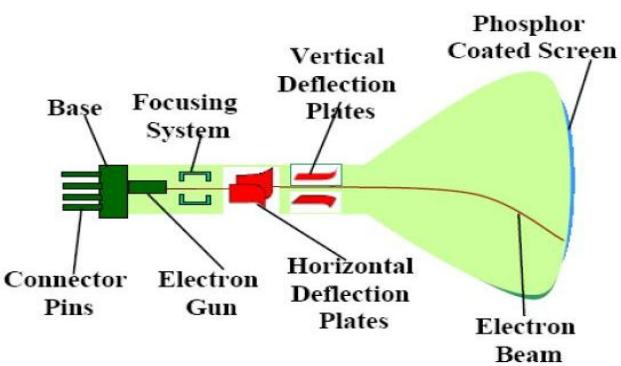
Early days…

- *1870 Discovery of Cathode Rays Tube (CRT) by William Crookes*
  - *Propagation of electrons from the cathode to the anode*





William Crookes



Electrons are emitted from a heated element (cathode) which resides inside glass tube under vacuum. Electrons are attracted to the anode and strike a flat screen coated with phosphor which glows when struck by the beam of electrons

Where was it used for?

Typical energies of about tens of thousands of eV

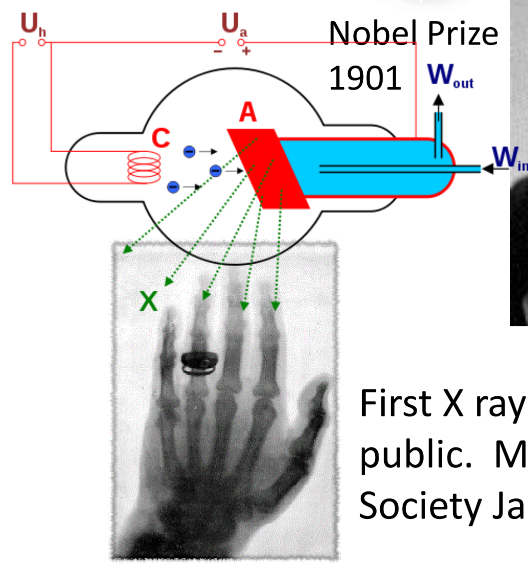
Early days…

- *1895 Discover of X-Rays*
  - *X-rays are produced as the result of changes in the positions of the electrons orbiting the nucleus*

An X-ray tube: *electrons are accelerated by electrical field and generate X-rays when they hit a target.*

Nobel Prize 1901

Wilhelm Rontgen



First X ray made in public. Medical Society Jan 1896

- *1897 – Cavendish Laboratory*
  - *Demonstrates that cathode rays are made of particles*
    - *measured the mass to charge ratio,*
    - *1,800 x lighter than hydrogen atom*
  - *Discovery of the first elementary particle electron*

Nobel Prize 1906

J.J. Thompson

Timeline

1890

Rutherford develops the theory of atomic scattering using alpha-particles

Rutherford need a more powerful source to continue his research

1900

Direct-Voltage accelerators
Cockcroft & Walton & Van de Graaf electrostatic generator

1928 Gurney and Gamov predicted tunneling & Cockcroft-Walton start designing 800kW

1930

1927: "It has been my ambition to have available for study a ***copious supply*** *of atoms and electrons which have an individual* ***energy far transcending that of alpha*** *and beta particles from radioactive bodies. I am hopeful that I may yet have my wish fulfilled."*

1940

Cockcroft-Walton accelerator

- *1928-1930 Rutherford's Laboratory*
  - *Voltage multiplier by using a stack of capacitors and switch diodes*

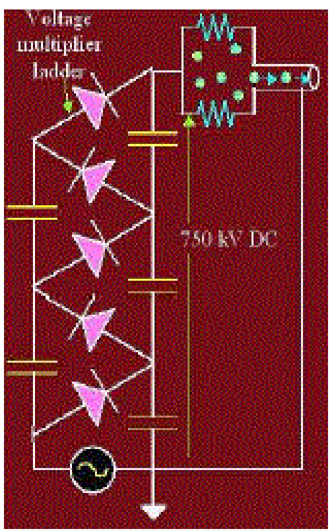
Nobel Prize 1951

John Cockcroft E.T..S. Walton

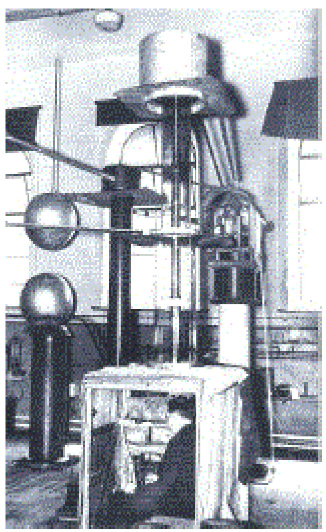
Design for 800 kV, but reached 700kV

Lithium atoms split with only 400 kV protons!

First device to produce an artificial nuclear disintegration



Concept design



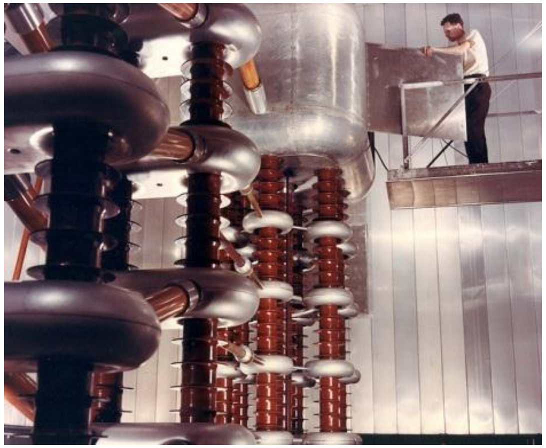
First accelerator

John Cockcroft , Ernest Rutherford, E.T..S. Walton

Main limitation

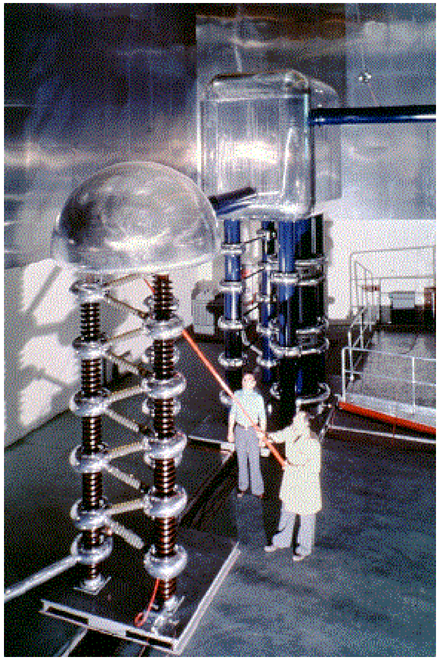
Hard to reach ~1MV due to discharges through air and along material surfaces.

Examples of C-W accelerators



BNL (USA) 1971-1988

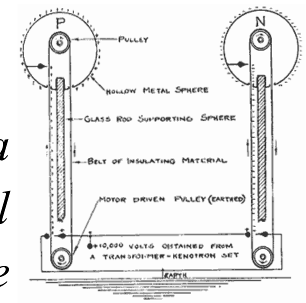
FNAL (USA) 1969-2012



CERN (CH-F) 1959-1993

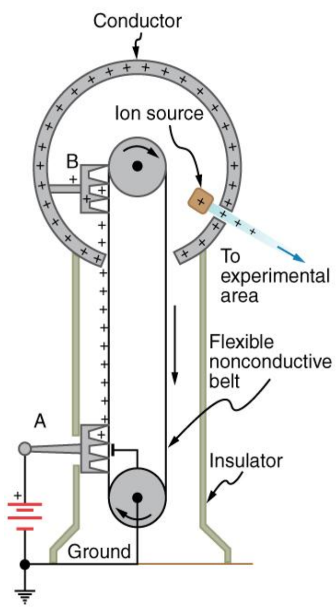
The Van de Graaf generator

- *1929-1933 VDG*
  - *Belt of insulating material carries electricity from a point source to a large insulated spherical conductor. Another belt delivers electricity of the opposite charge to another sphere*



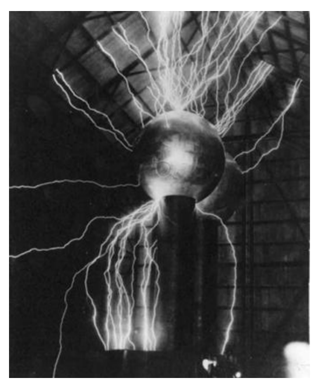
Concept design

R. J. Van de Graaff

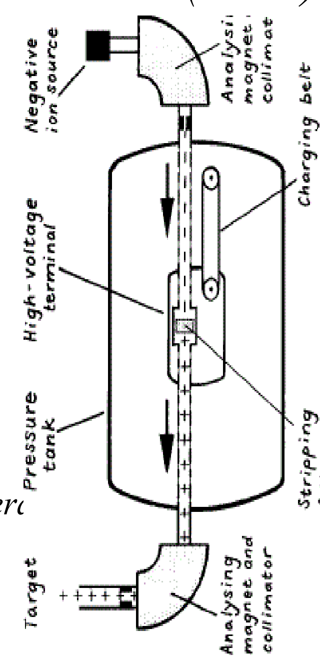


Main limitation

Van de Graaf cannot go much beyond 10-20 MV. Electric breakdown was a fundamental limitation.



- *Tandem Graaf Accelerator (1950)*
  - *Negative ions are accelerate towards a positive terminal located in the center of a pressure tank*
  - *The negative ions pass through a foil the electrons are stripped, producing a positive-ion beam*
  - *The beam is then accelera away from the positive terminal*

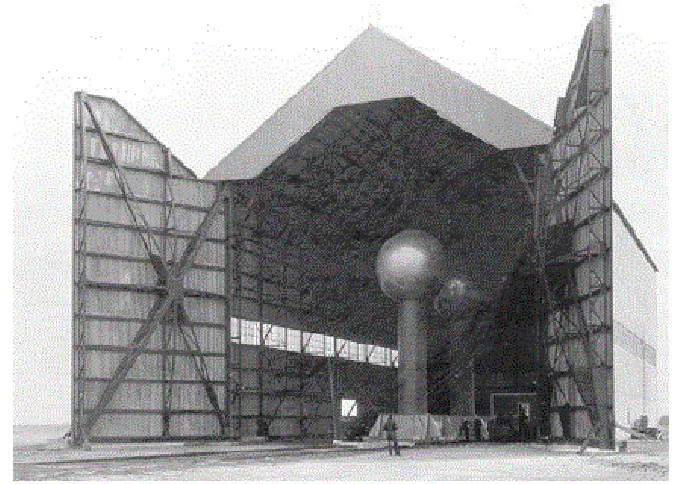


Examples of VDG & Tandem generators

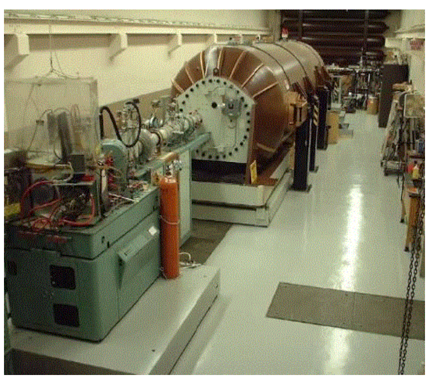
INTRODUCTION

Daresbury (UK) 20MeV 1981

14UD 15MV ANU (Australia)
Operational since 1973

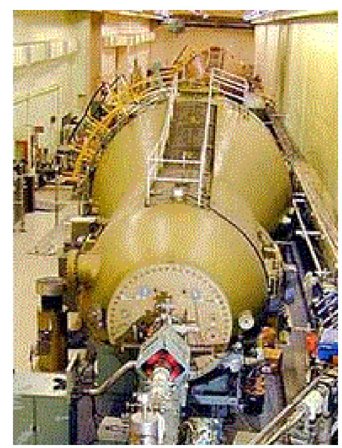


MIT (USA) 5MV generator 1933



Michigan (USA) 6MV Tandem

22.4 MV Tandem



BNL (USA) 15MV

Fermilab (USA)
4.4 MV Pelletron

Timeline

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Rutherford develops the theory of atomic scattering

Rutherford need a more powerful source to continue his research.

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Direct-Voltage accelerators
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1928 Gurney and Gamov predicted tunneling & Cockcroft-Walton start designing 800 kW

1930

Time-varying fields resonant acceleration

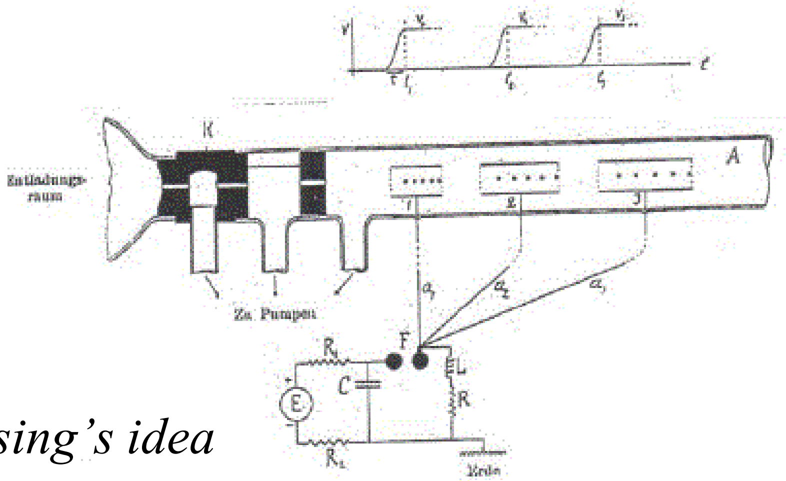
1924 Ising proposes time-varying fields across drift-tubes
1928 Wideroe demonstrates Ising's principle
1929 Lawrence creates cyclotron

1940

Application of time-varying fields

- *1924 Gustav Ising, (Sweden)*
  - *proposes applying much smaller voltage in an linear accelerator by using time-varying fields*

G. Ising



Ising's idea

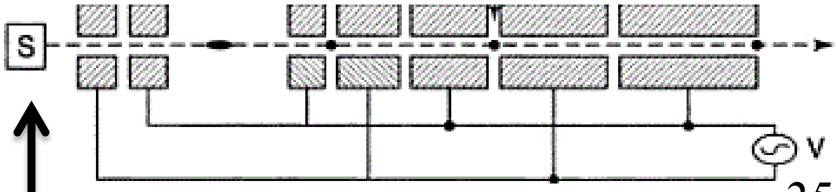
Ising was unable to demonstrate the concept

Particles would be accelerated by using alternating electric fields, with "drift tubes" positioned at appropriate intervals to shield the particles during the half-cycle when the field is in the wrong direction for acceleration

Wideröe first linear accelerator

- *1927 Wideröe (Aachen, Germany) built first linac*
  - *Influenced by Ising's 1924 paper*
  - *Particles acquire small energy increment with by repeatedly transverse the same accelerating field*


R. Wideröe



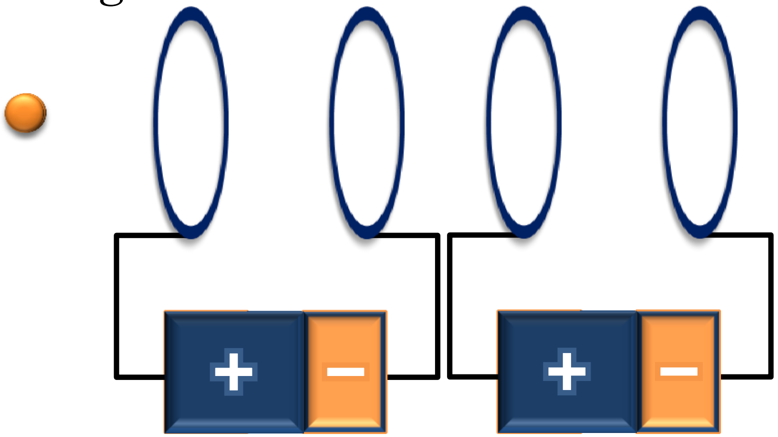
Beam accelerated to 50 keV

Potassium source

25 kV, 1MHZ AC voltage

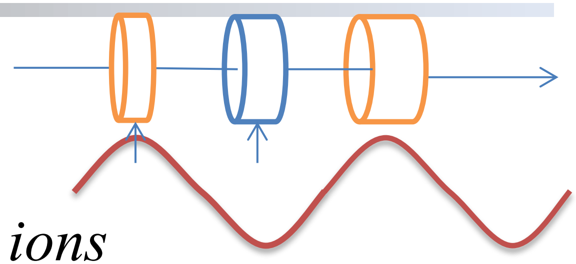
Resonance Acceleration crucial technology

Note: *The drift tube length has to increase because particles are not yet relativistic. Particle has to travel more in the shielded region to be in phase with the accelerating field*



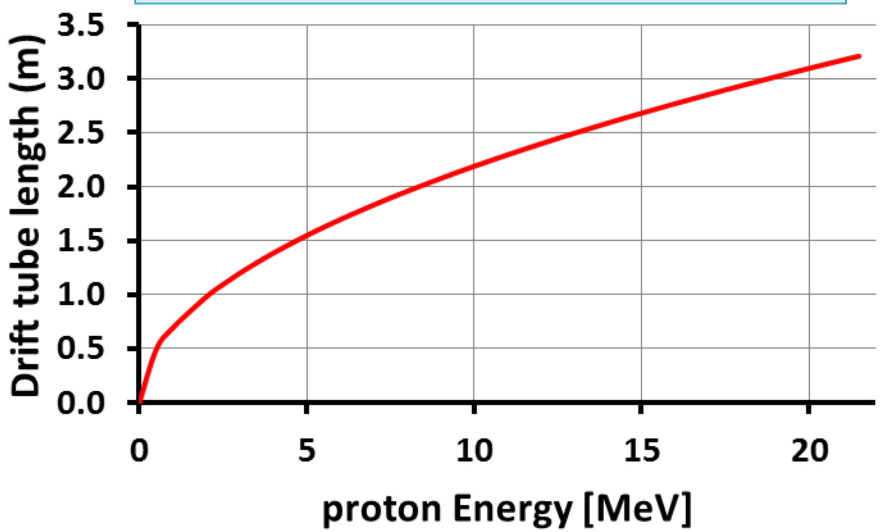
Wideröe linear accelerator…BUT

INTRODUCTION



- *Period length increase with velocity* $l = \frac{v}{2f}$
- *Wideröe linac was good for low-energy heavy ions*
- *When using low frequency, the length of the drift tube becomes prohibited for high energies*
- *Higher frequency power sources were unavailable until after WWII*

e. g. 10 MHz proton accelerator



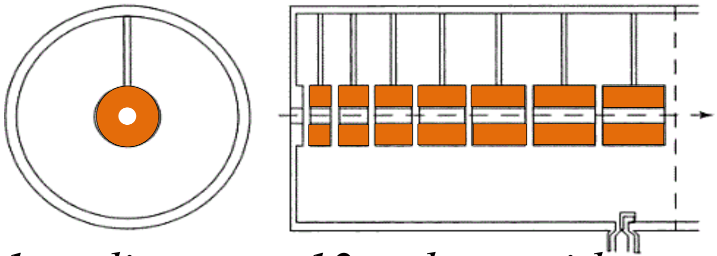
Main limitations

At higher energy, the drift tube length is too long

High RF frequency > 10 MHz higher power loss

Alvarez drift tube linac

- *1947 Alvarez (USA-Berkeley) built first proton drift tube linac*

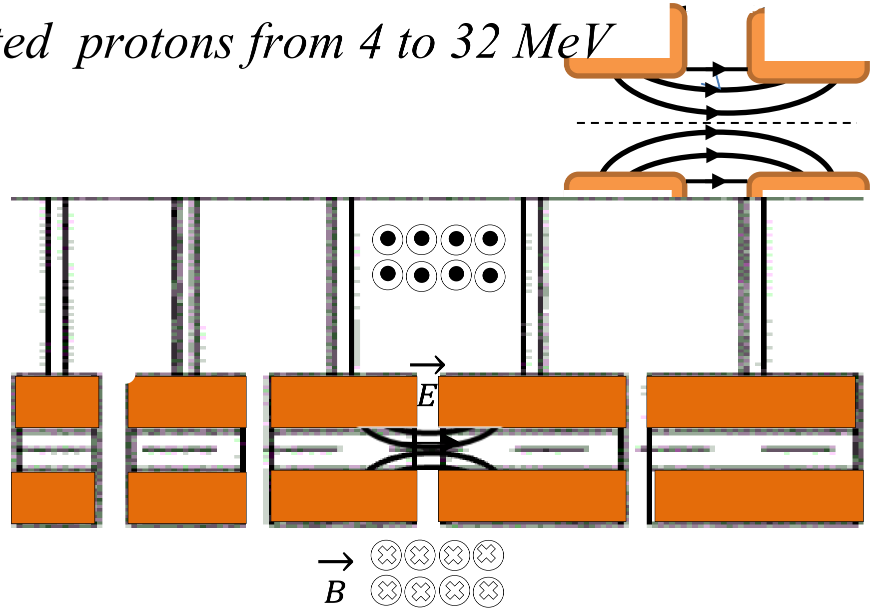


L. W. Alvarez

The drift tubes are enclosed inside a copper resonant cavity with a high frequency power generators

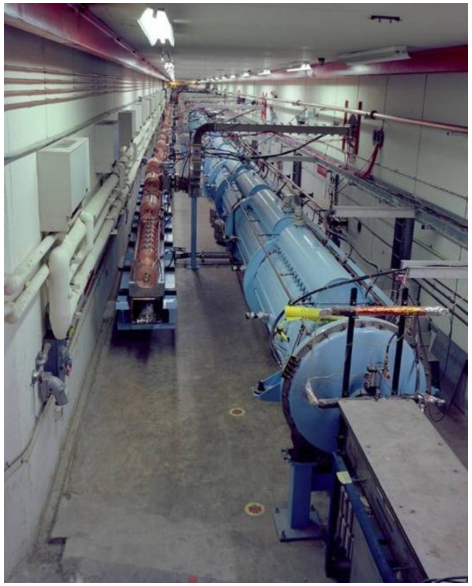
1-m diameter, 12-m long with a resonant frequency of 201.25 MHz which accelerated protons from 4 to 32 MeV

The drift tubes are supported on stems from which current for the quadrupoles (located inside the drift tube) and the cooling water are supplied.



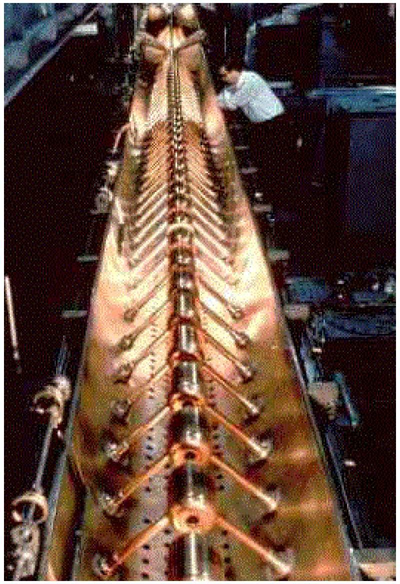
Examples of Alvarez DTL linac

INTRODUCTION



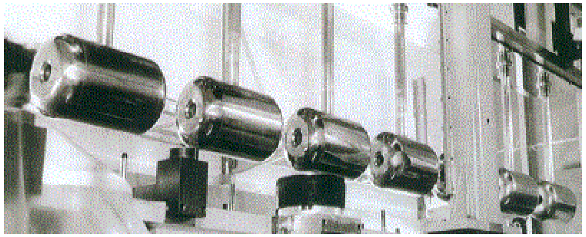
FNAL Linac 400 MeV 200 MHz

(40+ years of Operation)



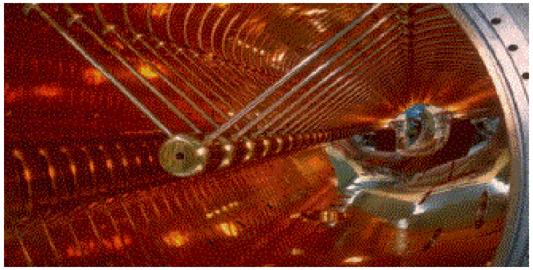
CERN Linac 1 50 MeV

(33 years operational retired in 1992)



DESI 988 MeV LINAC III

(Germany)



GSI LINAC (Germany)

Cyclotron accelerator

INTRODUCTION

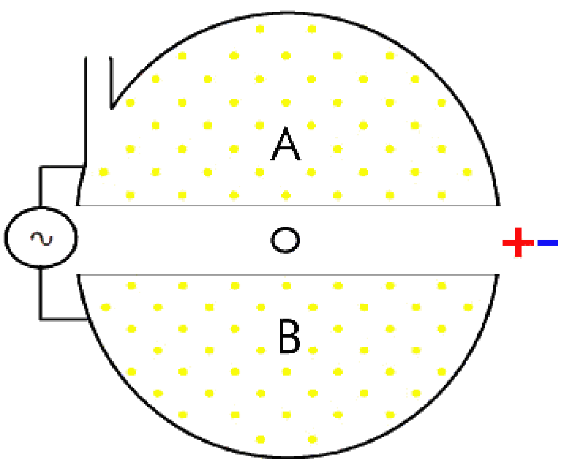
- *1930 Berkeley*
  - *particles circulate in a static magnetic field which held the particles to a spiral trajectory and pass one and the same accelerating gap several times*

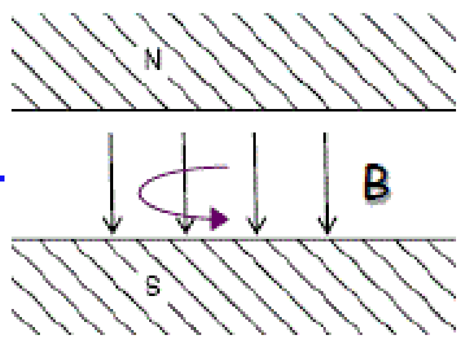
First original cyclotron

Nobel Prize 1939

E. O. Lawrence

Typical max energy : *20 MeV (proton)*



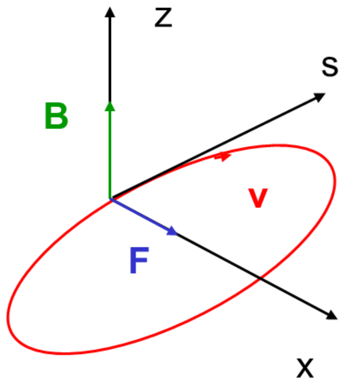


Animation from AIP

> ***Main limitation***
>
> *Does not work with relativistic particles*
>
> *Magnetic field at large radius not vertical*

Cyclotron principle

INTRODUCTION



- *For a particle that moves perpendicular to the magnetic field*

$$F = m\boldsymbol{a} = q\boldsymbol{v}\boldsymbol{B}$$

- *Non-relativistic uniform circular motion is maintained via centripetal acceleration* $\frac{mv^2}{r} = qvB$
- *Radius is* $r = \frac{mv}{qB}$
- *Revolution period is given by* $T = \frac{2\pi r}{v} = \frac{2\pi m}{qB}$
- *Revolution angular frequency is* $\omega = \frac{2\pi}{T} = \frac{qB}{m}$

The **ω** ***is independent of speed and energy of the particle***

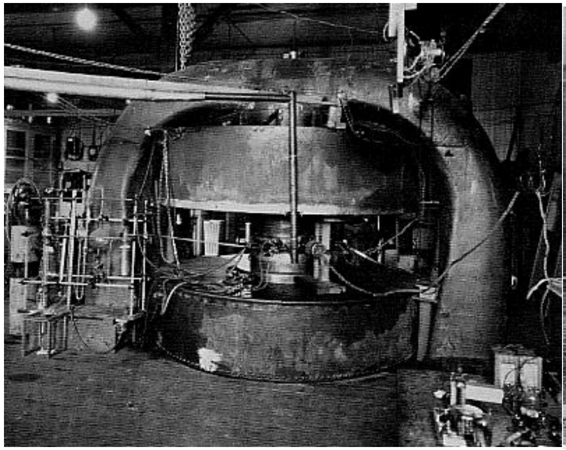
When the particle E & v ↑ *they travel with a larger radius in the magnetic field*

What is the radius of revolution for a 100 GeV proton in a B=2T field?

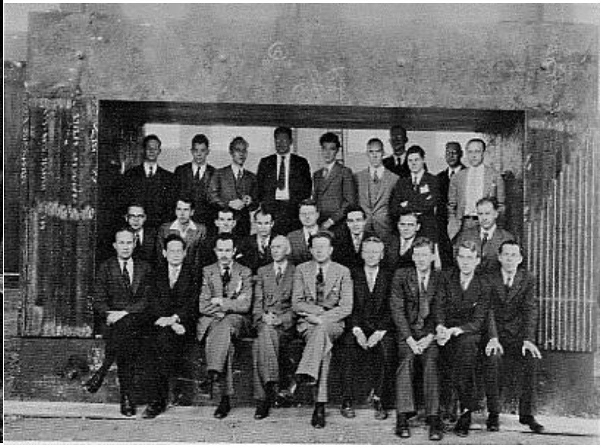
$$K_{max} = \frac{mv^2}{2} = \frac{R^2 q^2 B^2}{2m} \quad R_{max} = \sqrt{\frac{2m\,K_{max}}{q^2 B^2}} = \sqrt{\frac{2\ x\ 1.66x10^{-27}\ x\ \ 1x10^{-8}}{(1.6x10^{-19})^2\ x\ 4}} = 18\ \text{m}$$

Very costly to build a magnet of this extend…
for higher energy the radius would be in km!!

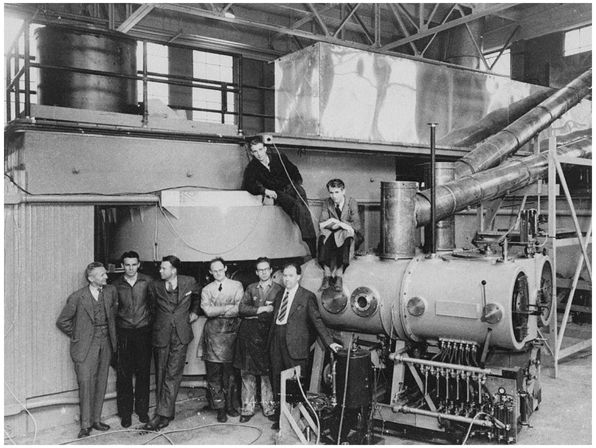
Examples of cyclotron accelerator



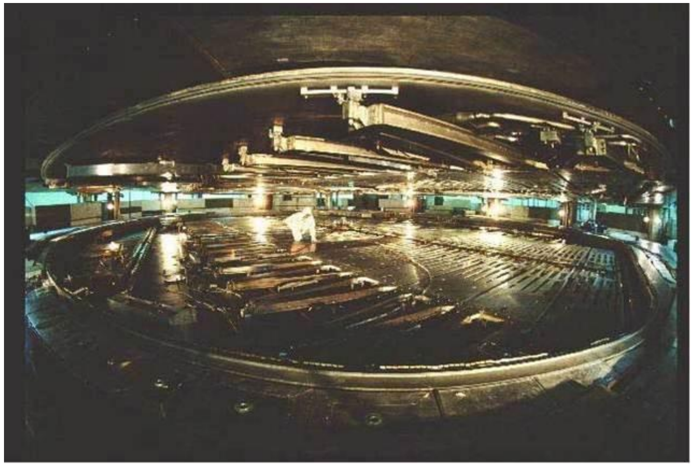
Berkeley (USA) 11-inch – 1.1 MeV



“The Crock” 60-inch Berkeley



60-inch cyclotron - Berkeley



TRIUMP (Canada) 520 MeV (rare isotope)

Timeline

1890

1900

1930

1940

Rutherford develops the theory of atomic scattering

Rutherford need a more powerful source to continue his research.

1927: "It has been my ambition to have available for study a copious supply of atoms and electrons which have an individual energy far transcending that of alpha and beta particles from radioactive bodies. I am hopeful that I may yet have my with fulfilled."

Direct-Voltage accelerators
Cockcroft & Walton & Van de Graaf electrostatic generator

1928 Gurney and Gamov predicted tunneling & Cockcroft-Walton start designing 800 kW

Time-varying fields resonant acceleration

1924 Ising proposes time-varying fields across drift-tubes
1928 Wideroe demonstrates Ising's principle
1929 Lawrence creates cyclotron

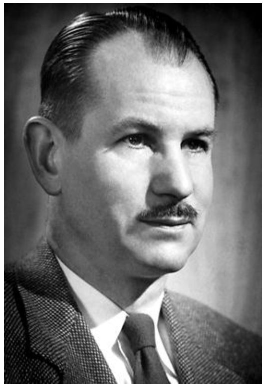
1945 McMillan and Veksler Phase stability

1952 Courant, Livingston and Snyder propose strong focusing

Principle of phase stability

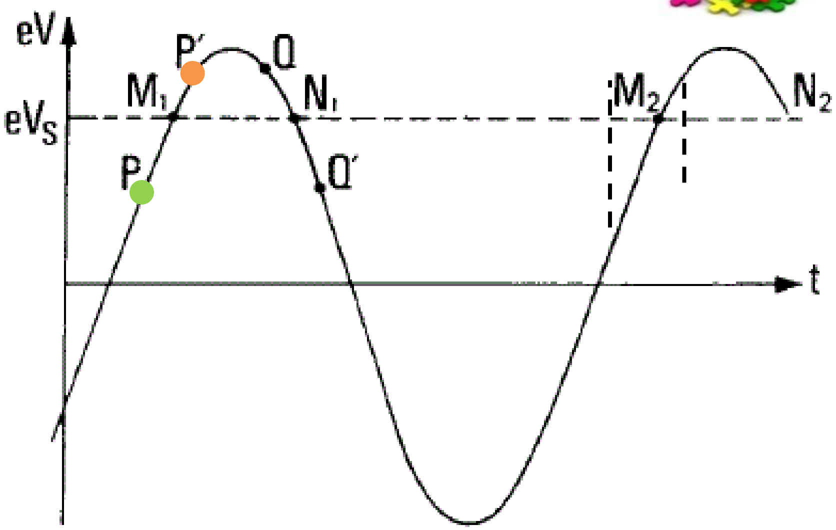
- *1945 McMillan and Veksler independent discovered the principle of phase stability*
  - *adjusting the frequency of the applied voltage, particles were possible to accelerate to several hundred of MeV*
  - *these machines can only accelerate a single bunch of particles*

V. Veksler



E. McMillan

How does phase stability work?

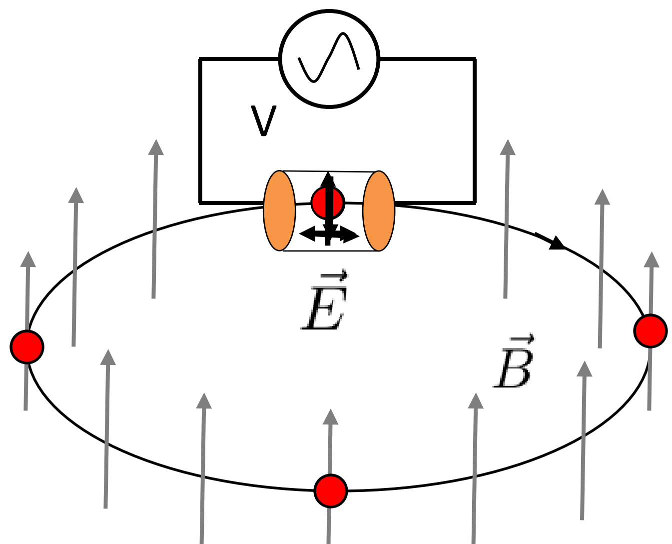


Particle P arrives in a gap in advance as compared to M1 will get less energy and its velocity will be smaller, so it will take more time to travel.

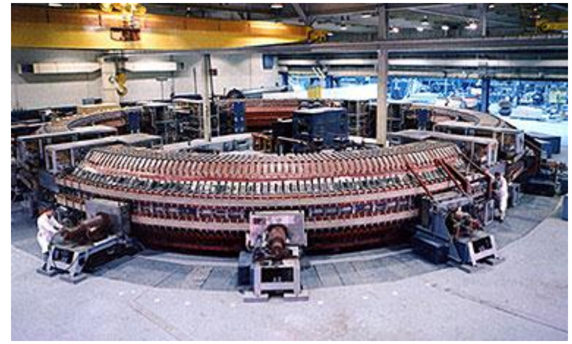
Particle P' arrives late in a gap compared to M1 will get more energy and its velocity will be larger so it will take less time to travel.

The synchrotron accelerator

- *The synchrotron is a synchronous accelerator since there is a synchronous phase for which the energy gain fits the increase in magnetic field at each turn*



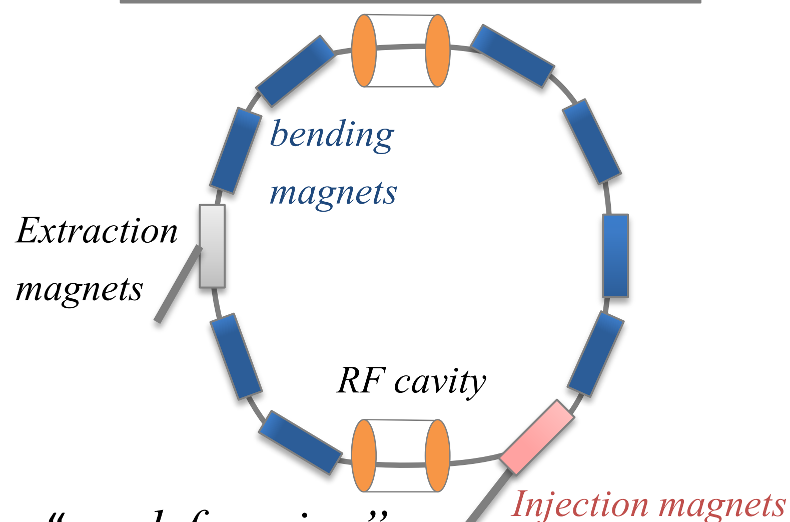
- *In a synchrotron the bending magnetic field is time-dependent.*
  - *As particles accelerate, the B field and the frequency of the RF has to vary proportionally*



1952 - First synchrotron
3-GeV BNL Cosmotron

L. Oliphant

Components of a Synchrotron

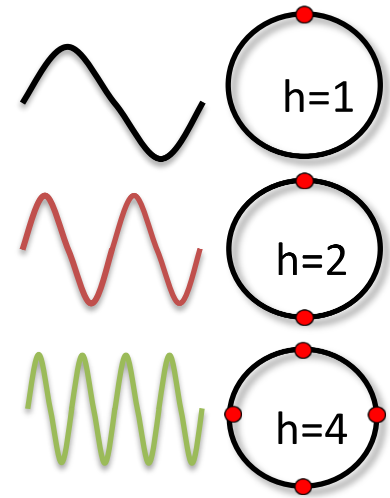


"weak focusing"

Harmonic number & circumference

ring circumference: λ_s

length of the RF bucket: λ_{RF}



- *the accelerating gap is shorter than the distance traveled by the particle during one RF period* T_{RF} $\quad g \ll vT_{RF} = v\frac{\lambda_{RF}}{c} = \beta\lambda_{RF}$
- *the RF angular frequency is an integer multiple of the angular revolution frequency* $\omega_{RF} = h\omega_s \rightarrow f_{RF} = hf_s$

$$\rightarrow \frac{c}{\lambda_{RF}} = \frac{hc}{\lambda_s} \rightarrow \lambda_s = h\lambda_{RF}$$

Hmm….I see…what is it again?

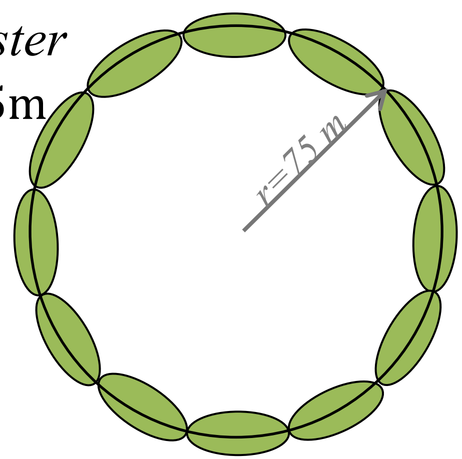
Let's take a look at the FNAL/Booster

Parameters: $f_{RF} = 53MHz, \mathrm{r} = 75\mathrm{m}$

$$\lambda_{RF} = \frac{3x10^8\ m/s}{53x10^6\ 1/s} = 5.66\ m$$

$$\lambda_s = 2.\pi.r = 471.23\ m$$

$$so\ h = \frac{\lambda_s}{\lambda_{RF}} = 84$$



Impress your friends

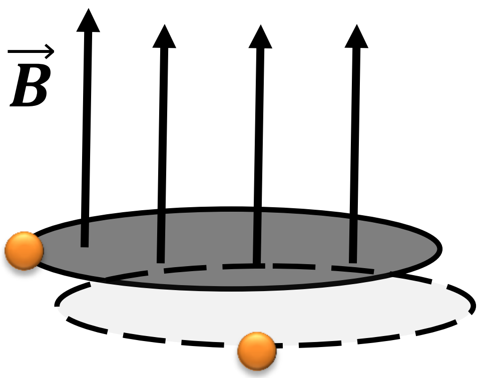
*- **Bucket** is a RF structure without beam*

*- **Bunch** is a RF bucket with beam*

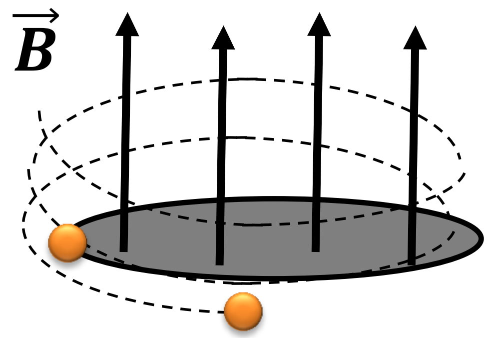
*- **Batch** is a multiple # of bunches*

If life was that easy…

- *In an ideal world, a particle in an accelerator would happily circulate on axis of the machine forever*
  - *what happens if the particle is deflected on the H/V plane?*



Horizontal plane remains stable



Vertical plane spirals away

Possible causes:

Machine misalignment, error in magnet strength, energy error of particles, etc…

If life was that easy…

- *Most of the particles in the beam are not ideal particles*
  - *Sooner or later these particles will hit the walls of the vacuum chamber and be lost*

  sort likely a flashlight beam, spreading out away from the source

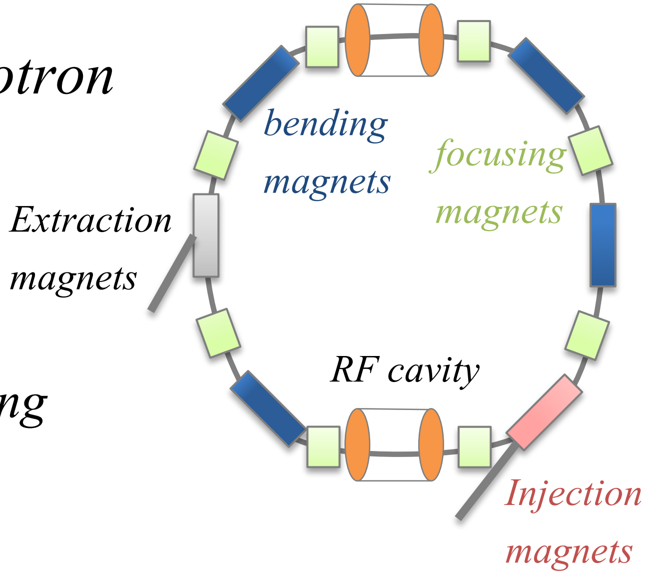
How can we keep these particles within the vacuum chambers?

Alternate gradient focusing

- *1952 strong focusing was proposed by Courant, Livingston and Snyder which revolutionized synchrotron design*
  - *A way of increasing the energy without increasing the size of the machine*
  - *Consist of an array of magnets with alternating focusing to give stability to the particle beam*
- *First applied to 1.2 GeV electron synchrotron at Cornell University in 1954*
  - *Modern application used separated-function magnets*
  - *"Optical" magnetic elements provides focusing (later…)*

E. Courant (left)
M. Livingston,
H. Snyder

Components of a Synchrotron



Example of synchrotron accelerator

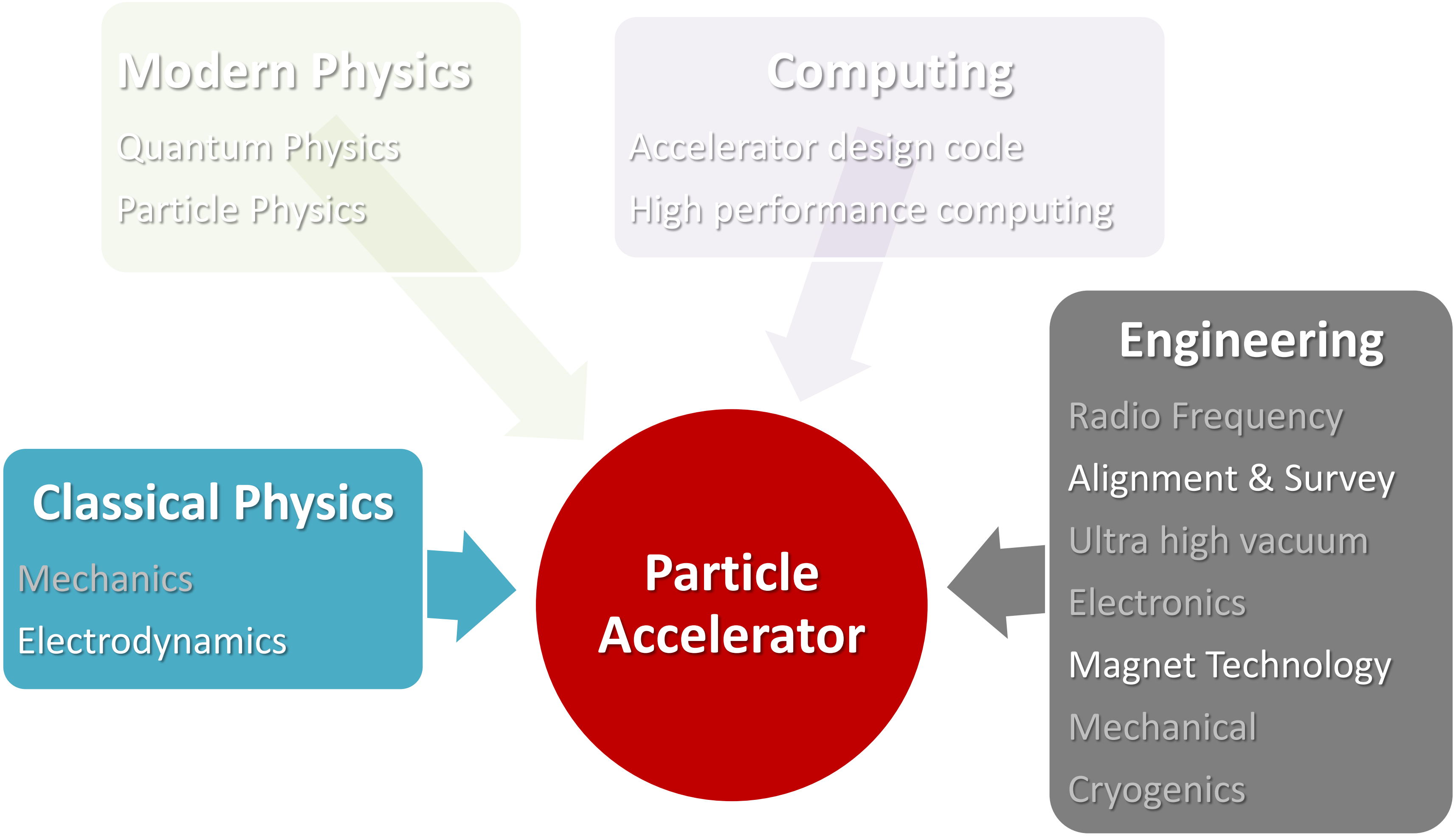
FNAL/Booster 8 GeV (1970-present)

FNAL/Main Injector 120 GeV (1998-present)

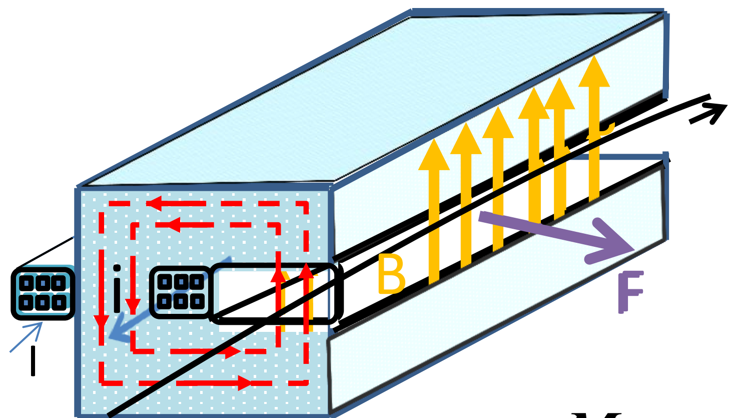
FNAL/Tevatron 980 GeV (1983-2011)

CERN/SPS 450 GeV (1976-present)

Particle accelerators



Dipole magnets

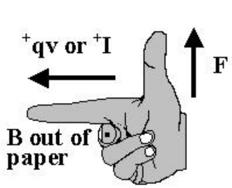


Lorentz Force ***Centripetal Force***

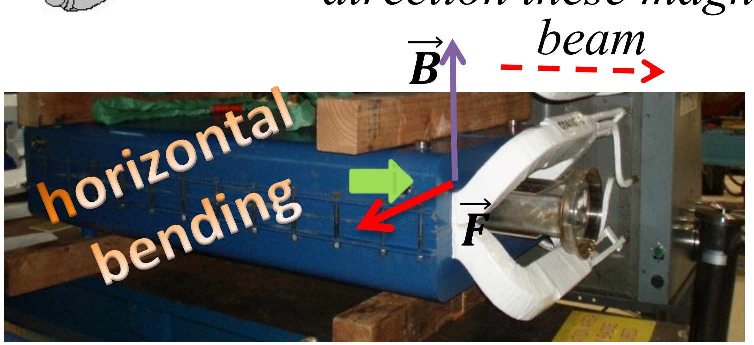
$$evB = \frac{mv^2}{\rho}$$

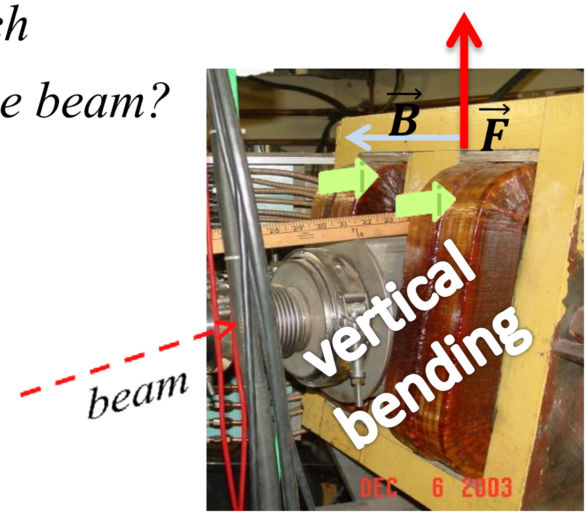
$$B\rho = \frac{mv}{e} = \frac{p}{e}$$

Magnetic rigidity *is the required magnetic bending strength for given radius and energy*



Let’s see if you can tell me which direction these magnets bend the beam?



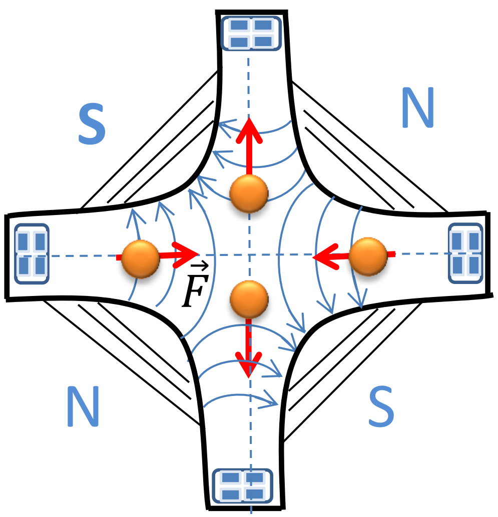


Quadrupole magnets

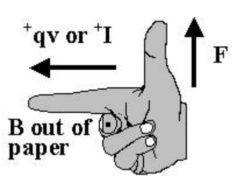
- *In a **quadrupole magnet**, the force increases linearly with displacement*

$$F_x = -gx$$
$$F_y = gy$$

Consider a positive particle traveling into the page



- *The force on a particle on the right side of the magnet is to the left*
- *The force on a particle on the left side of the magnet is to the right*

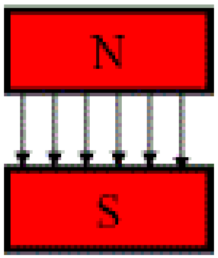


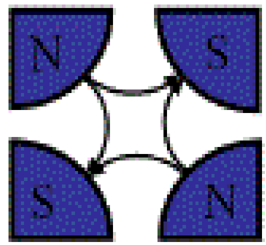
This magnet is horizontally focusing

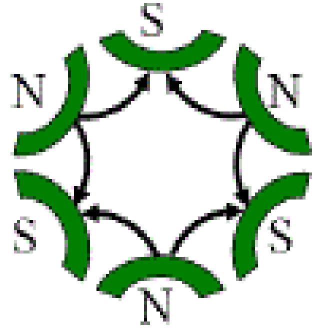
*A distribution of particle would be **focused on the x-plane** and **defocused on the y-plane***

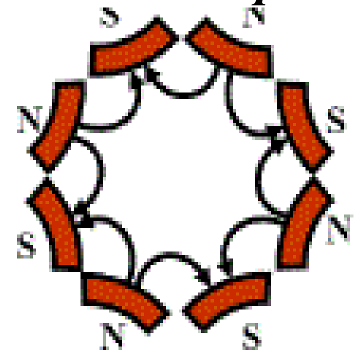
Other n-pole magnets

N=1 Dipole ***N=2 Quadrupole*** ***N=3 Sextupole*** ***N=4 Octupole***





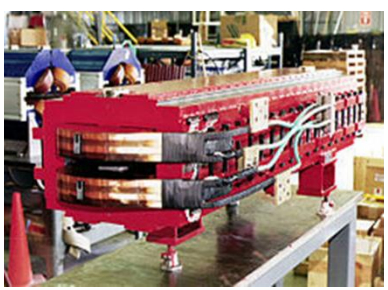




180^0 between poles *90^0 between poles* *60^0 between poles* *45^0 between poles*

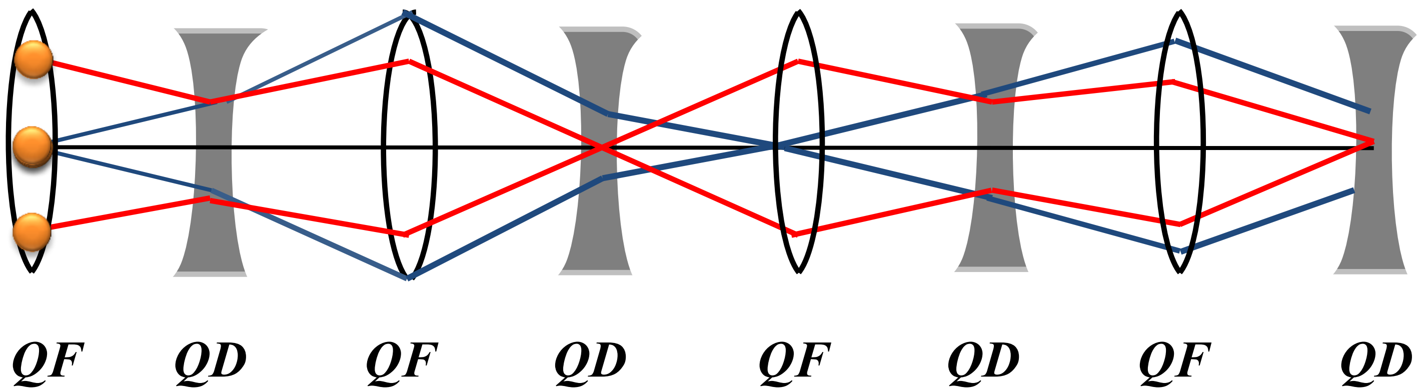
General rule: poles are $360^0/2n$ apart

Bending particles *Focus particles* *Chromaticity compensation* *High-order corrections…*



Alternating gradient focusing

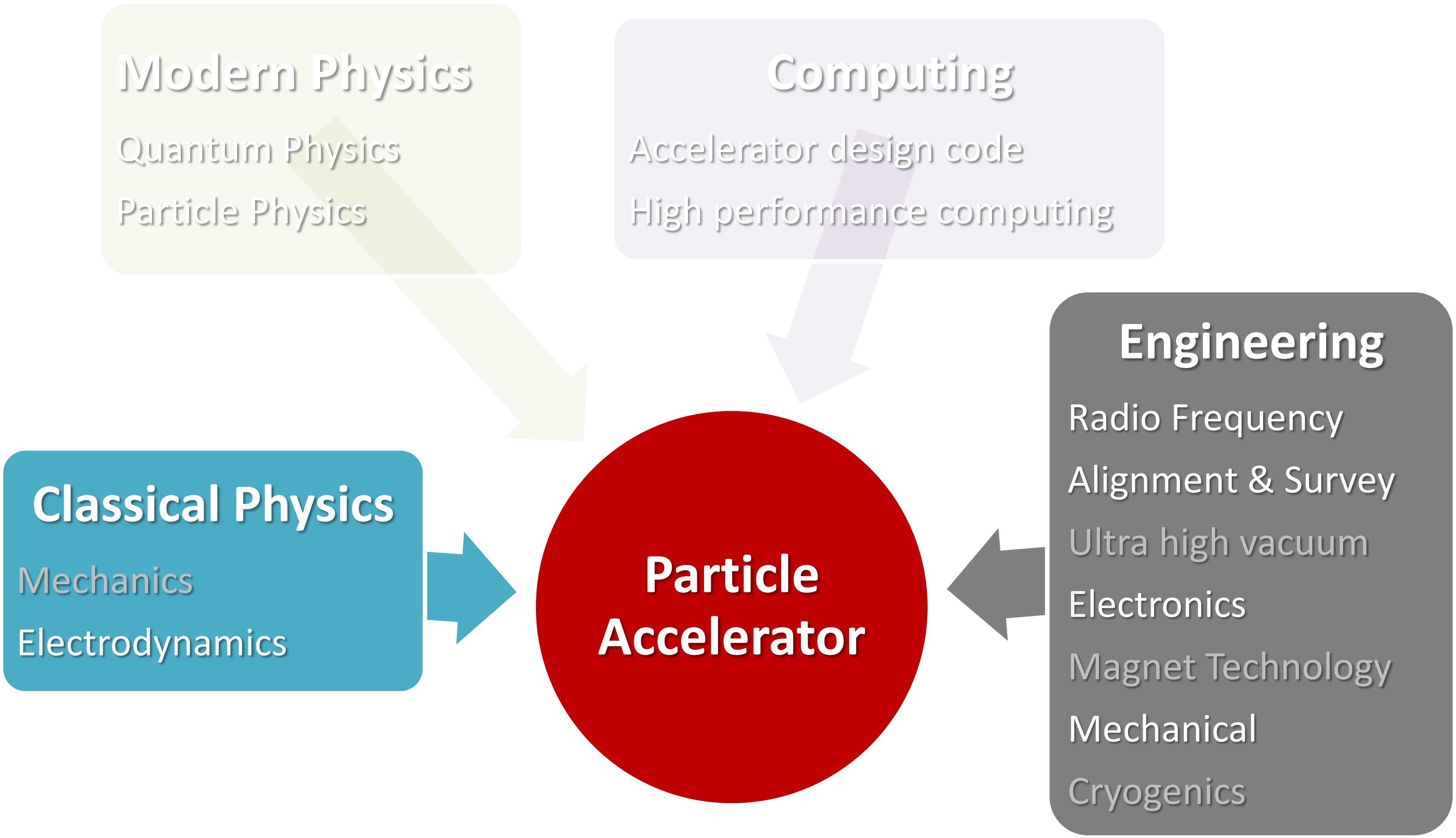
- *Alternate H/V focusing magnets*
- *The accelerator is composed of a **periodic** repetition of **FODO** cells*



- *The ideal particle will follow a **particular** trajectory, which closes on itself after one revolution*

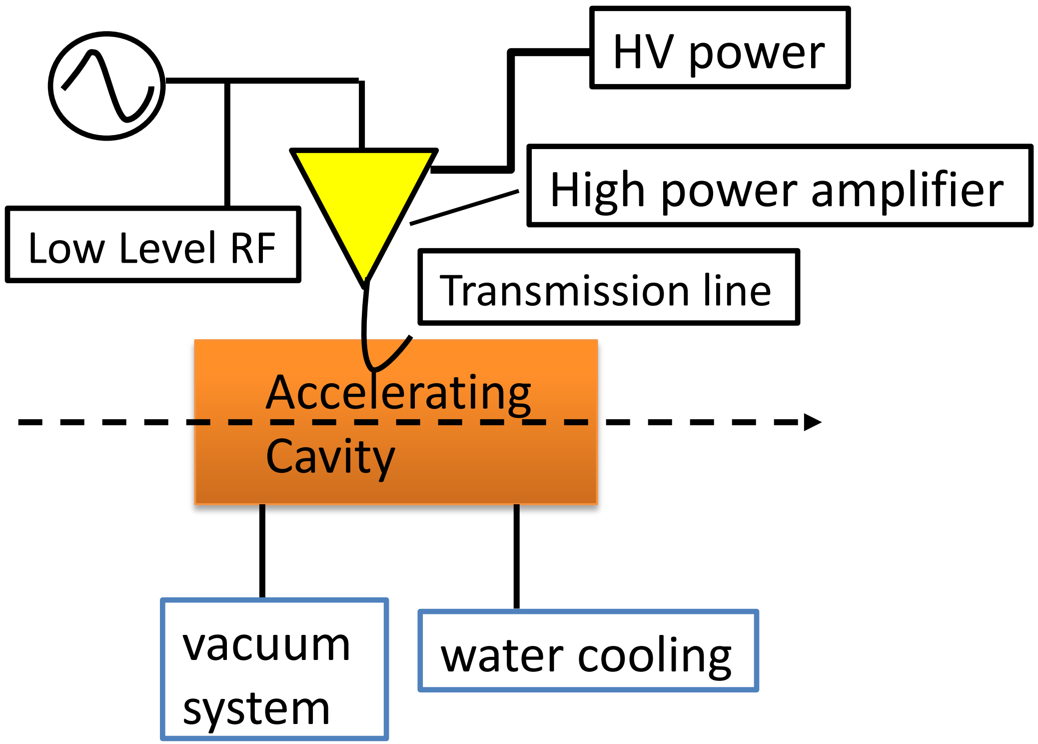
- *The real particles will perform oscillations **around the ideal orbit***

Particle accelerators



What is an RF system?

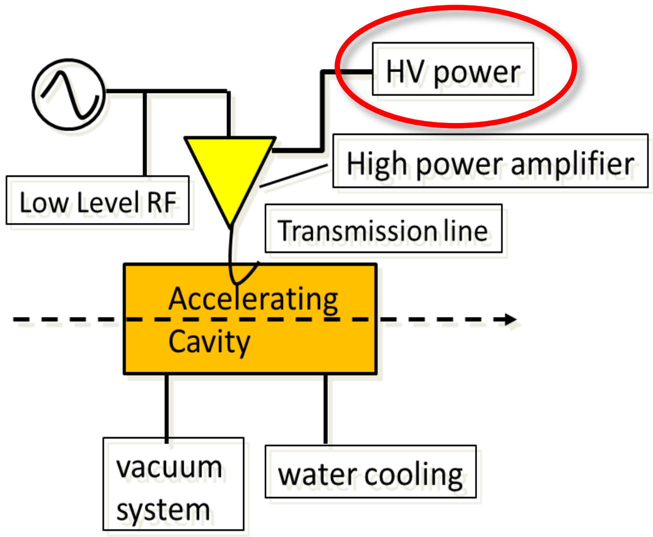
- ***Radio-Frequency*** *in a particle accelerator is a system intended to transfer energy to a beam of charged particles by interaction with an electric field oscillating at RF frequency*



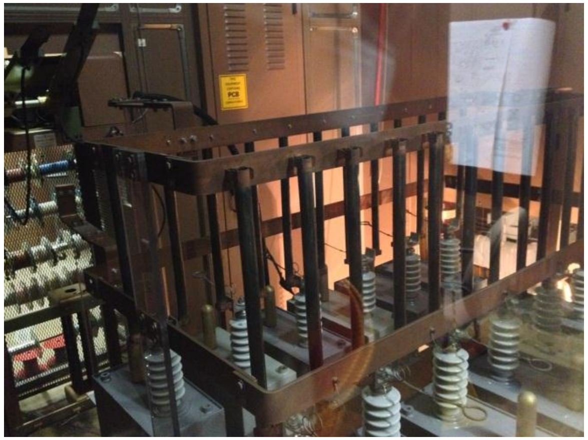
Radio-Frequency building blocks

- *power amplifier*
- *high voltage power*
- *accelerating cavity*
- *low level RF system*
- *auxiliary equipment*

What is an RF system? (2)

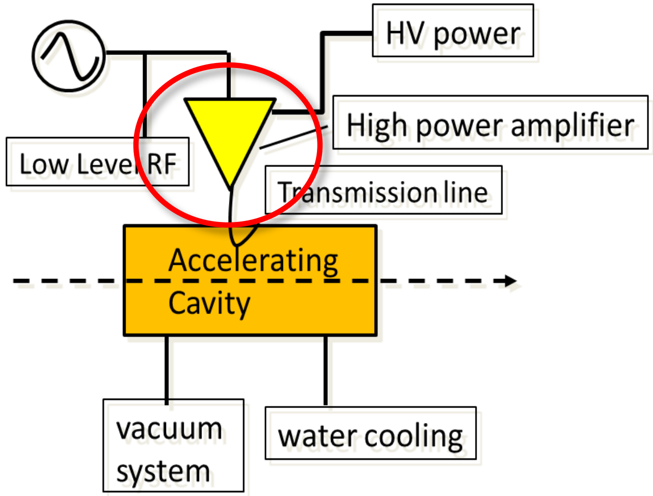


- ***HV Power** is an essential part for the RF system*
  - *Many components such as HV transformer, capacitor bank, called "Modulator"*



FNAL 200MHZ Linac Modulator

What is an RF system? (3)

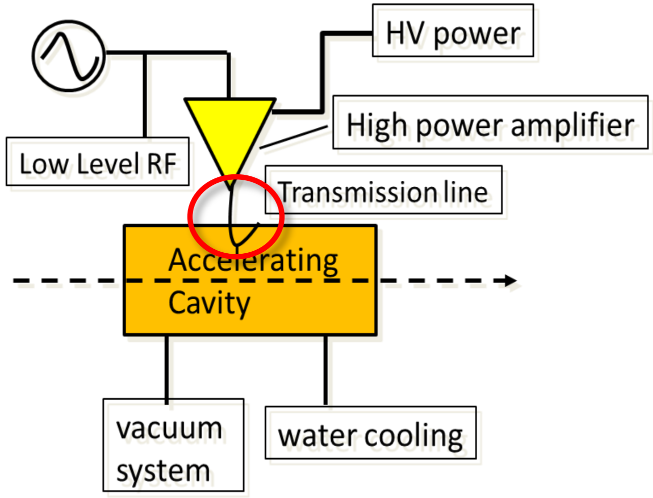


- ***High Power Amplifier*** *device that provides the RF power: RF tube (tetrode or triode) or a klystron*

FNAL/Linac 800 MHz 7MW Klystron RF system

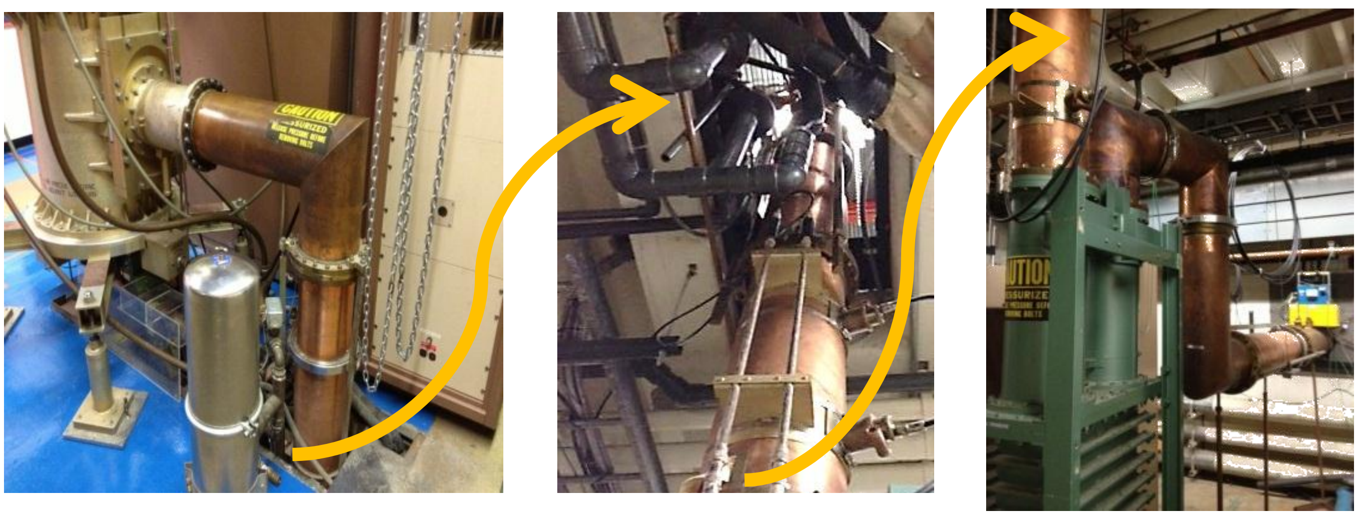
FNAL/Linac 200 MHz 5 MW Triode Power Amplifier

What is an RF system? (4)

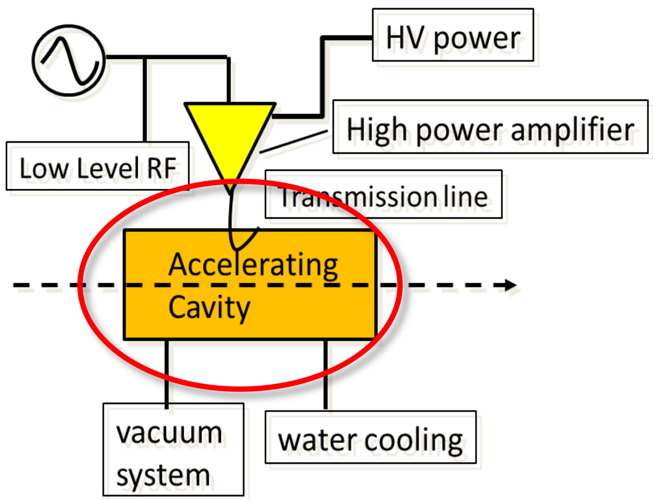


- ***Transmission line*** *RF power is transported from the amplifier to the cavity with no reflection and minimum loss.*

FNAL/Linac 200 MHz coax line (≅ 40ft long)



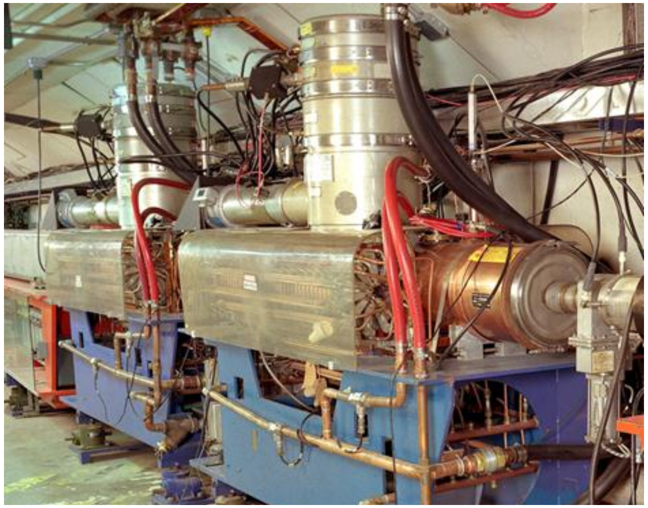
What is an RF system? (5)



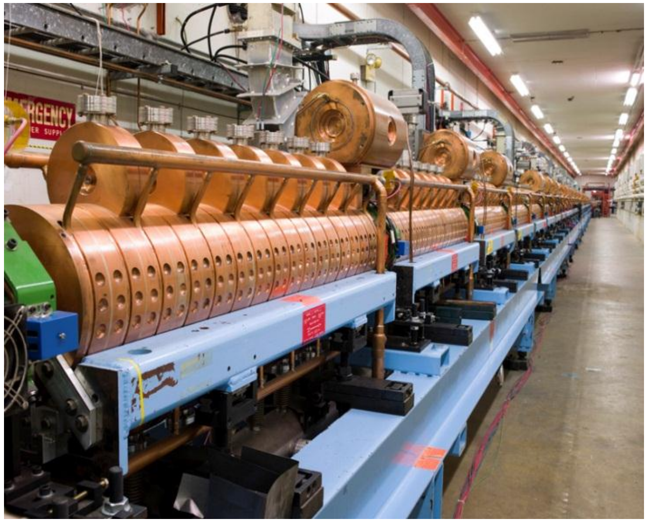
- ***Accelerating cavity***

crème de la crème

accumulates electric energy in a series of gaps with a minimum power loss



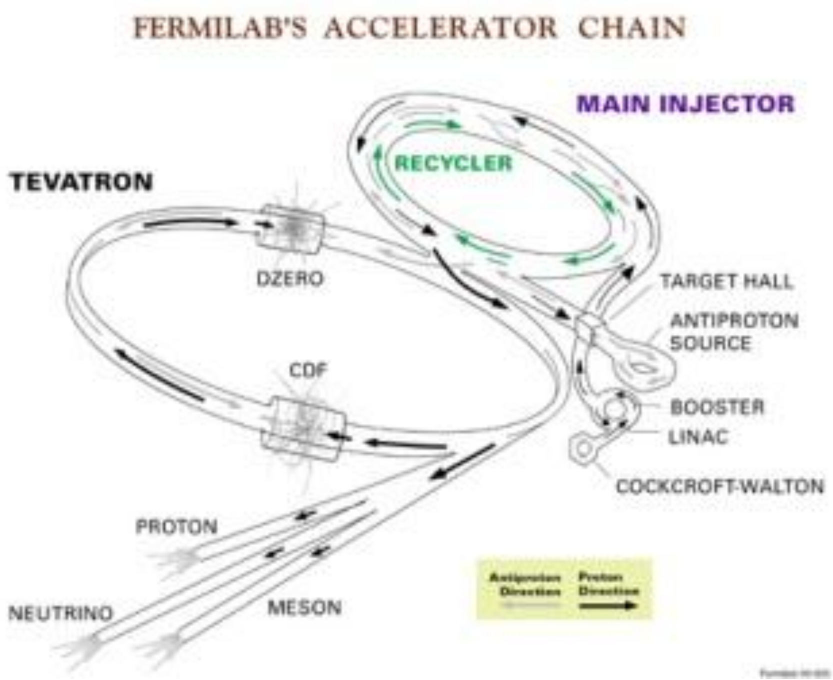
FNAL Booster cavity



FNAL Linac side-couple cavity

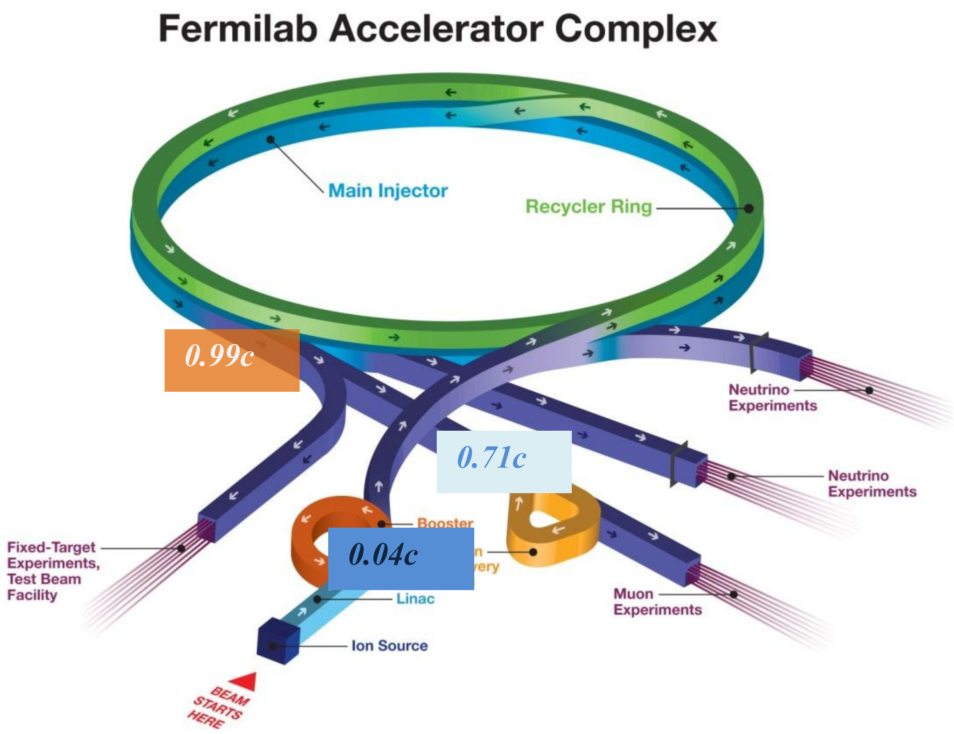
Fermilab Accelerator Chain

Fermilab accelerator chain (until 2011)



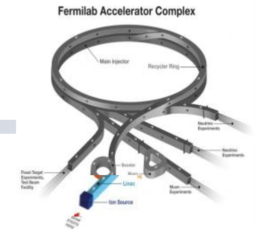
	Machine	Energies
Injector	*Cockcroft-Walton*	*750 keV*
Linac	*DTL + SCC*	*400 MeV*
Booster	*Synchrotron*	*8 GeV*
Main Injector	*Synchrotron*	*120 GeV*
Recycler	*Synchotron*	*8 GeV*
Electron Cooling	*Pelletron*	
Pbar rings	*Synchrotron*	*8 GeV*
Tevatron	*Synchotron*	*1 TeV*

Fermilab accelerator chain (after 2012)

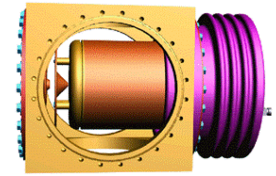


	Machine	Energy
Injector	*RFQ*	*750 keV*
Linac	*DTL + SCC*	*400 MeV*
Booster	*Synchrotron*	*8 GeV*
Main Injector	*Synchrotron*	*120 GeV*
Recycler	*Synchotron*	*8 GeV*
Muon Campus	*Synchrotron*	*8 GeV*

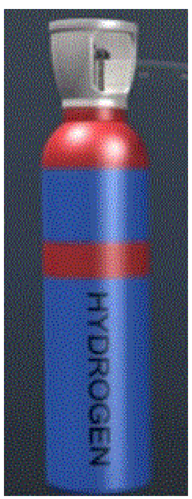
Ion Source

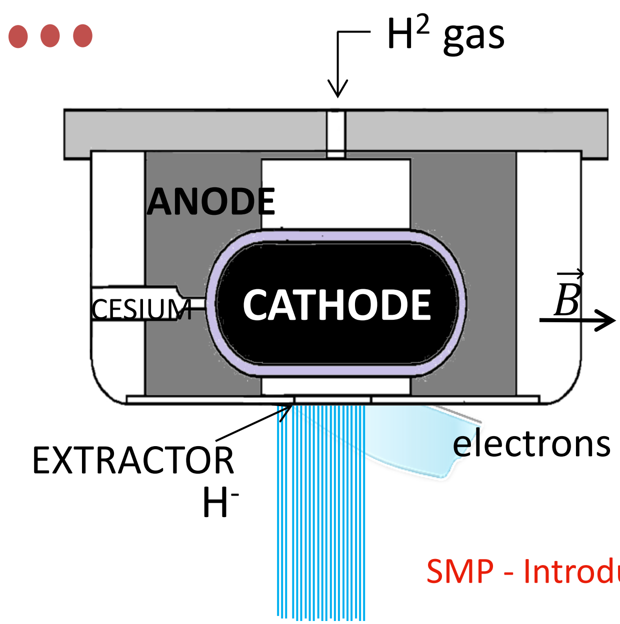


All starts with a simple bottle of hydrogen gas …

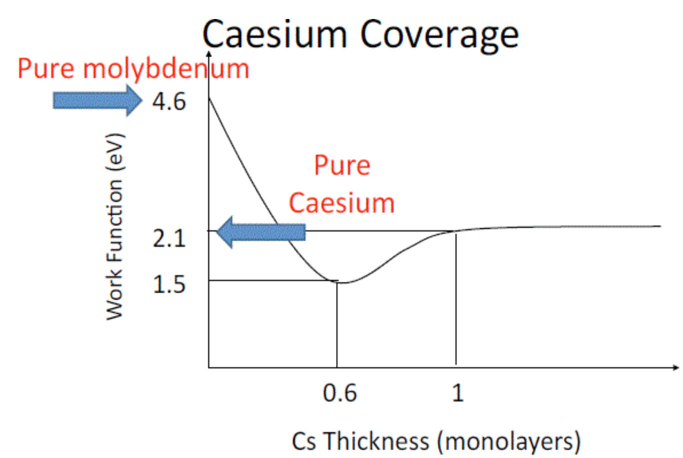


- *The H_2 gas is fed precisely into the volume between the electrodes*
  - *a parallel magnetic field is applied to the cathode surface*
  - *an arc is applied between the electrodes*
    - *e^- in the arc efficiently ionize the gas to form a plasma of H^+/e^-*
    - *These ions strike the cathode and capture electrons which are repealed from the cathode*



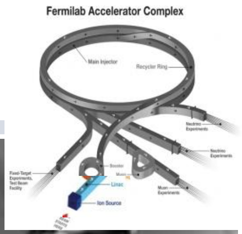


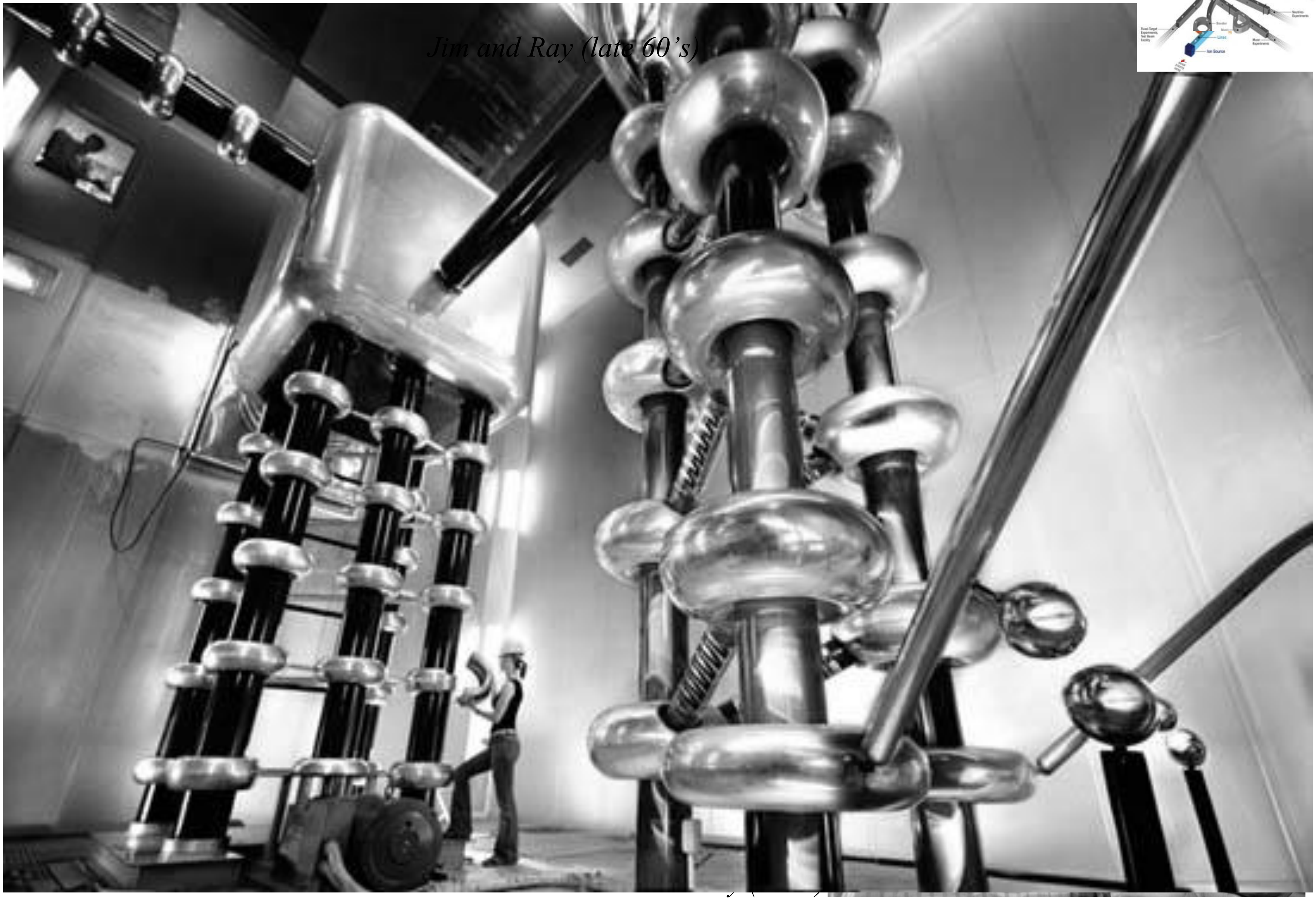
Cs^+ ions on metal increase yield of sputtered negative ions



Pre-Accelerator (1968-2012)

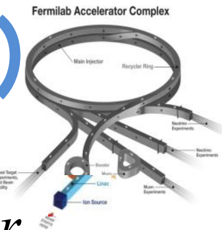
ACCELERATOR CHAIN – PRE-ACCELERATOR

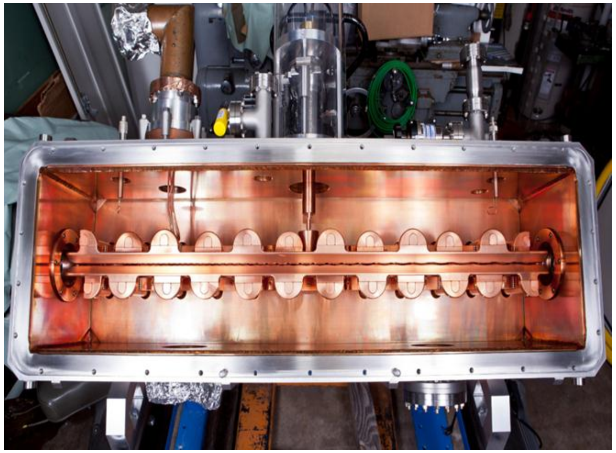




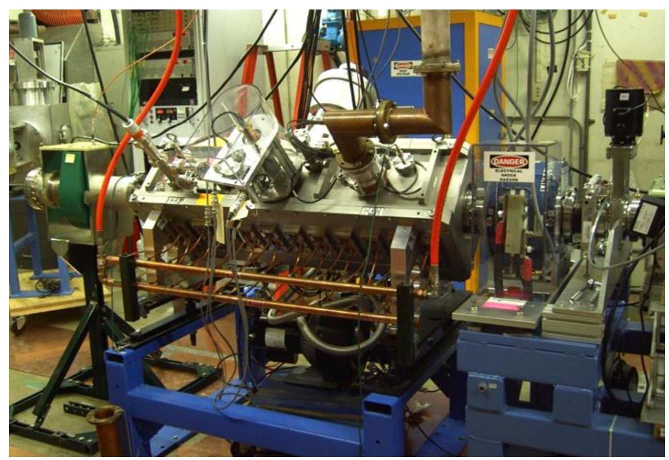
Jim and Ray (late 60's)

RFQ Injector Line (2012-present)



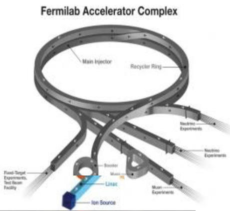


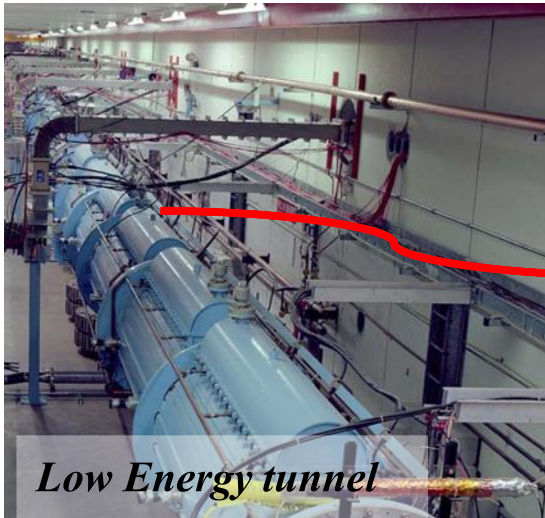
- *RFQ is a relatively new type of linear accelerator for very low velocity region*
  - *With the vanes provide the unique function of both focusing and accelerating in a remarkably compact structure*
  - *Beam is accelerated by longitudinal fields and focused by RF electric quadrupole fields determined by geometry of the structure*



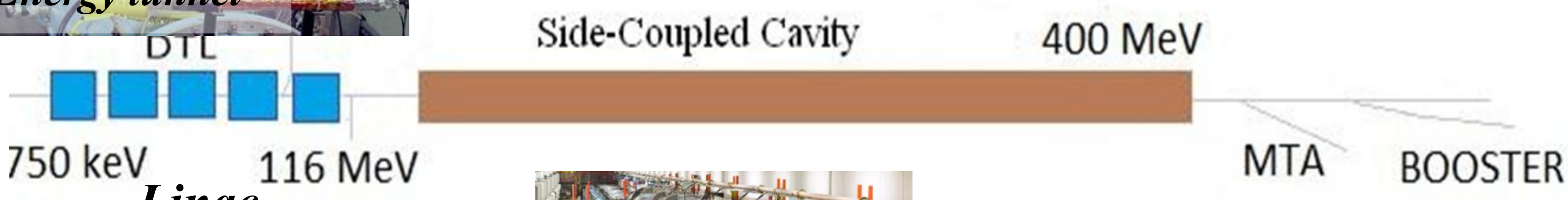
Linac (1970-present)

ACCELERATOR CHAIN – LNAC




Low Energy tunnel


200MHz PA



Linac

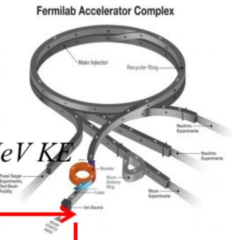
Length (m)	*200 m*
Pulse Frequency	*15 Hz*
Kinetic Energy	*0.750 400 MeV*
Frequency	*201/804 MHz*
Current	*33ma*
Nº of Cavities	*5 DTLs, 7 SCC*


High Energy tunnel


High Energy Linac Gallery

Booster (1970-present)

ACCELERATOR CHAIN – BOOSTER



Injection Energy : 400 MeV

Extraction Energy: 8 GeV

~0.3 miles circumference

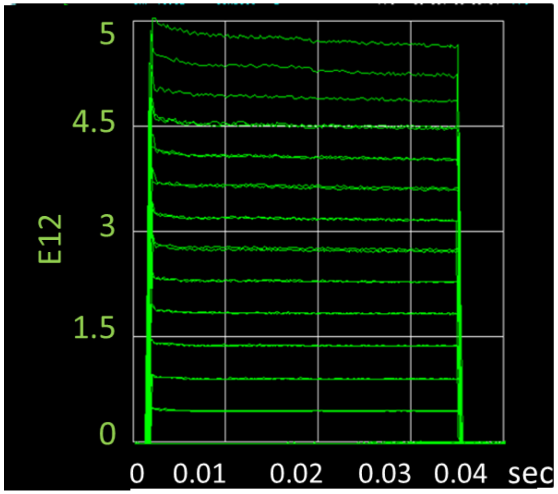
Beam throughput
7.5Hz → 15Hz
(now → future)

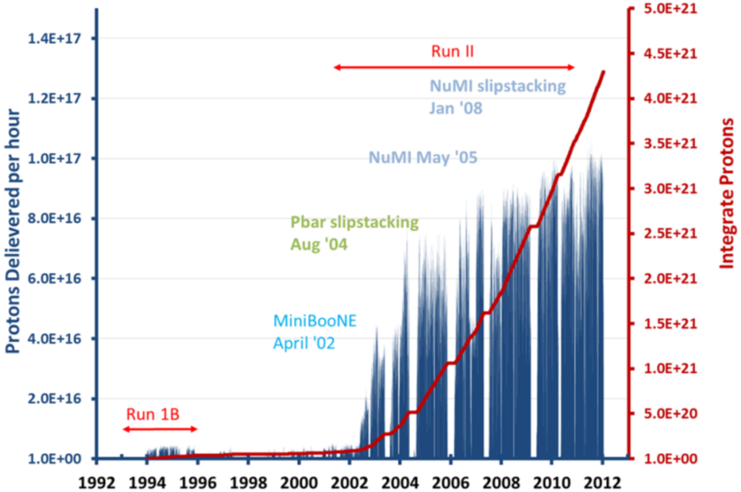
- *Protons to Booster Neutrino Experiment (BNB)* *MiniBooNE, SciBooNE,* *MicroBooNE*
- *Protons to support 120 GeV program* *Protons to support Muon Campus program (later)*

- ~4.5x10^{12} *ppp* ~1.1x10^{17} → 2.2$10^{17}$ *pph*
- *Beam Power = energy/time* *44 kW→ ~90 kW*

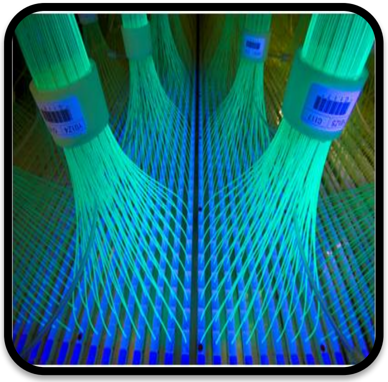
Beam gain 7,600 MeV KE in 0.033 sec !!!

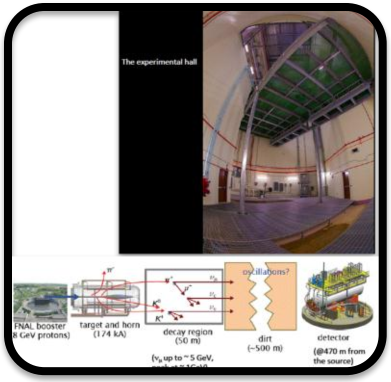
injection *extraction*





8 GeV Program - BNB & Muon Campus





***MiniBooNE Experiment* (2000-2012)**

ν –oscillations

Single detector to check LSND result

SciBooNE Experiment

(2007-2009)

dedicated σ_υ measurements

MicroBooNE Experiment

(start ~ 2015)

Short-baseline

ν-oscillations

Muon Campus Experiments

(start ~ 2016)

g-2 experiment

Mu2eexperiment

Main Injector (1996-present)

ACCELERATOR CHAIN – MAIN INJECTOR

Injection Energy : 8 GeV

Ext. Energy: 120 GeV

~ 2 miles circumference

Beam throughput

ramp 2.2sec→ 1.7 sec

(now → future)

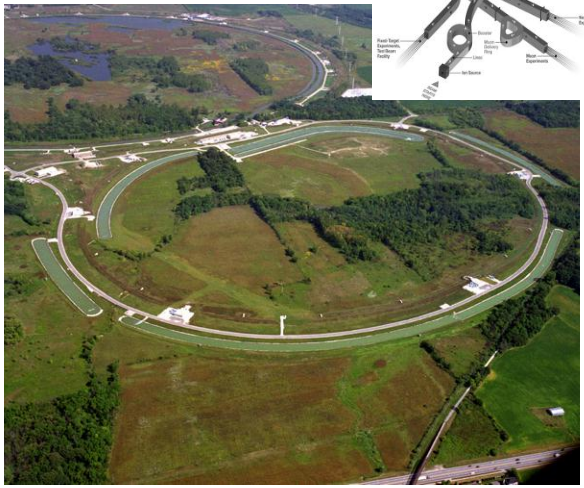
- *Successful supported*
  - *$\bar{p}$ production*
  - *$\bar{p}$ transfer into Recycler storage*
  - *Provide $p/\bar{p}$ for Tevatron*
- *Continue support*
  - *p for Test beam area*
  - *p for 120 GeV Neutrino program*
  - *- MINOS, NOvA,*
  - *- LBNE (future)*

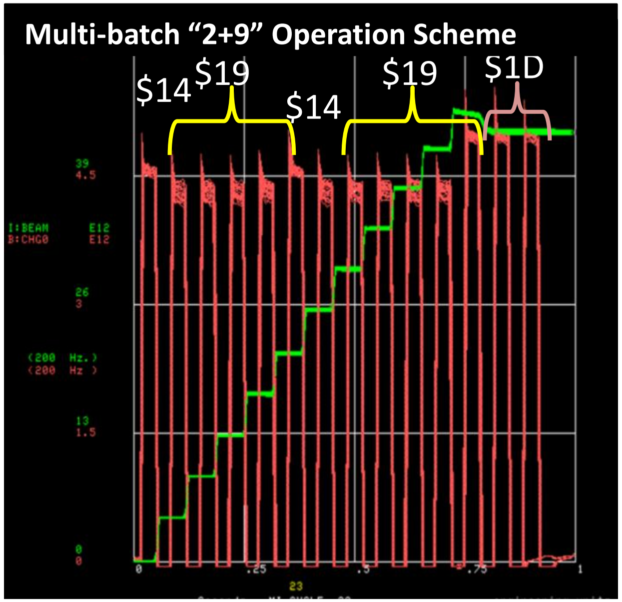
- 12 *batches of* ~4.5x10^{12} *ppp*

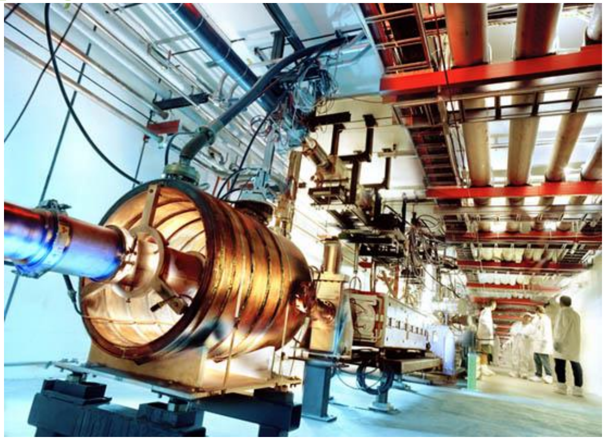
- *Beam Power =*

energy/time

400 kW→ ~700 kW

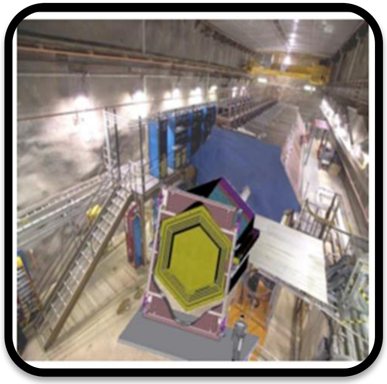


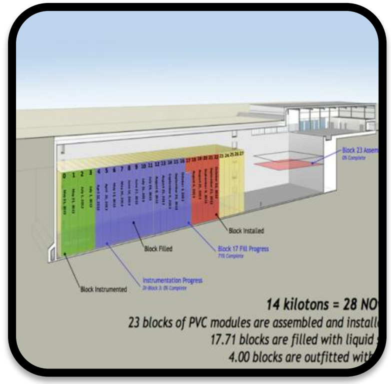




120 GeV - Long Baseline ν experiment

ACCELERATOR EXPERIMENTS





Minos Experiment

(2006-present)

ν physics

Start pushing for beam power

~400 kW

Minerva Experiment

(2009-present)

dedicated σ_ν measurements

NOvA Experiment

(2014-200?)

ν physics

requires higher beam power than Minos

~700 kW

LBNE Experiment

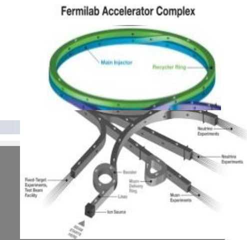
(start ~ 2025)

ν physics

requires higher beam power than NOvA

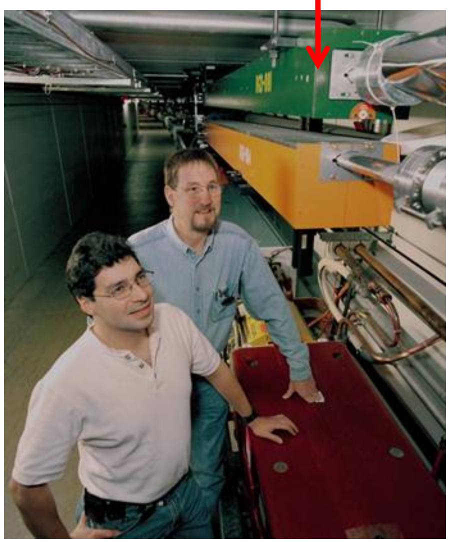
~1-2 MW (Project X)

Recycler & Electron Cooling



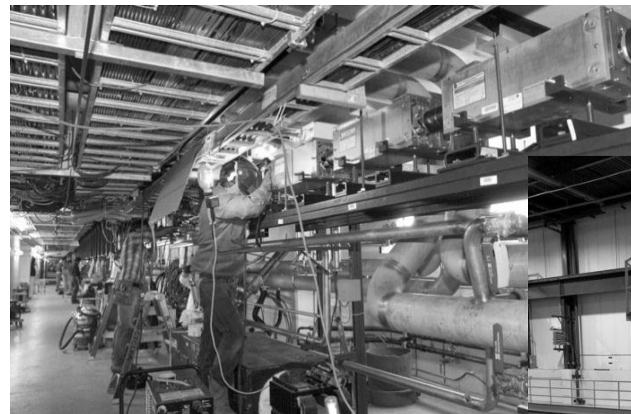
Recycler Energy: 8 GeV (1998-present) 2 miles circumference	Electron Cooling Energy: 3.5 MeV (2005- 2011) 25-foot-high Pelletron

- *Recycler resides inside the Main Injector tunnel (above MI)*
- *Stored antiprotons prior to injection into the Tevatron*



- *Current it has been retrofitted to run in proton mode to assist MI in achieving higher beam power*

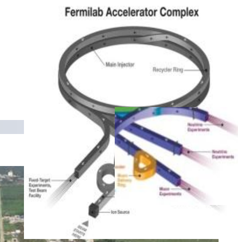
- *Electron Cooling condensate the beam to make easier to manipulate and accelerate*



- *Provided additional cooling beyond that implemented in the Accumulator*

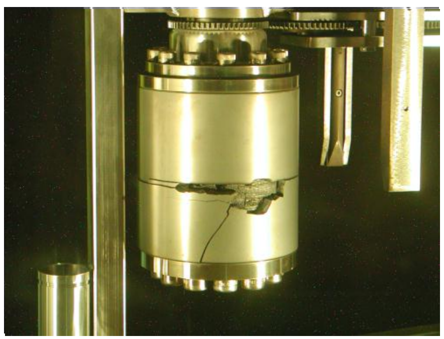
FNAL/Pelletron

Pbar-rings 1986



Energy 8 GeV *~ 0.3 miles circumference*	*Beam parameters* *pulse rate ~2 sec*

- *120 GeV protons strike a target to produce lots of* $\bar{p}$



- *2 batches of* $\sim 4.5x10^{12}$ *ppp*

In ~ 10 hrs. yield ~ 1-2 $x10^{12}$ $\bar{p}$ *!!*

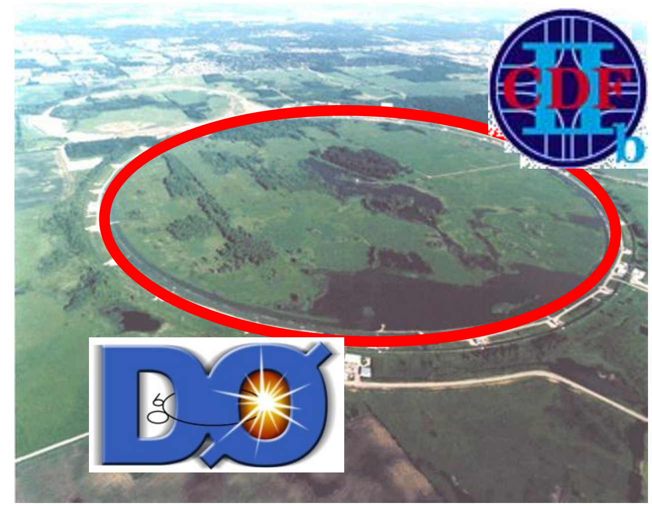
So, ~10^5 *proton on target produced 2* $\bar{p}$

$\bar{p}$ *target design evolved over the course of the years different materials were used with the most common being inconel (Ni,Cr,Fe) 600*
Typical lifetime: 4.14E19 pot

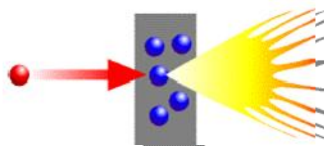
Current being modified to be used as a proton machine for the Muon campus program

Tevatron (1983)

For 28 years the World's Highest particle accelerator Energy 1 TeV
4 miles circumference

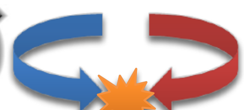


- *1983 Tevatron began operations as a 400 GeV to provide fixed target machine*



1984 reached 800 GeV

- *1986 Begin of collider era at Fermilab by accelerating protons and antiprotons and colliding them at two collision points*

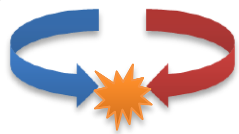
&  *experiments*

- *Beam is accelerated by using 8 RF cavities which occupies ~ 0.3% of tunnel.*
  The rest of the tunnel is lined with superconducting magnets and instrumentation.

Tevatron (1983-2011)

ACCELERATOR CHAIN – TEVATRON

Major engineering achievements



Accelerators

- *First major superconducting synchrotron*
- *First electron cooling system developed for use with high-energy beam*
- *Tevatron cryogenic system named International Historic Mechanical Engineer Landmark by ASMS in 1993*
- *Tevatron antiproton source is the most intense source of antiprotons in the world and enabled the first* $\mathrm{p}-\bar{\mathrm{p}}$ *research in the TeV range*

Fore more info about TeVatron history: http://www.fnal.gov/pub/tevatron/media.html

Major scientific contributions

1,000 PhD degrees

Discover:

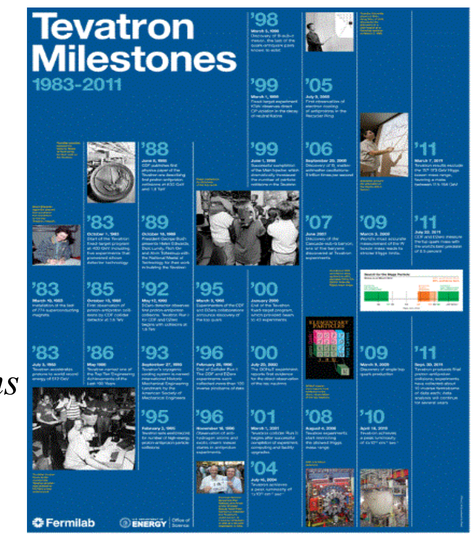
- *Top quark and determined its mass to high precision*
- *production mechanism for the top quark: pair and single production*
- B_c *meson and* B_s *oscillations*
- *Y(4140), quark structure*

Observed:

- ✓ *strongest evidence for violation of matter-antimatter symmetry in particles containing b-quark*
- ✓ *Evidence for* $\not{C}\not{P}$ *in neutral B mesons*

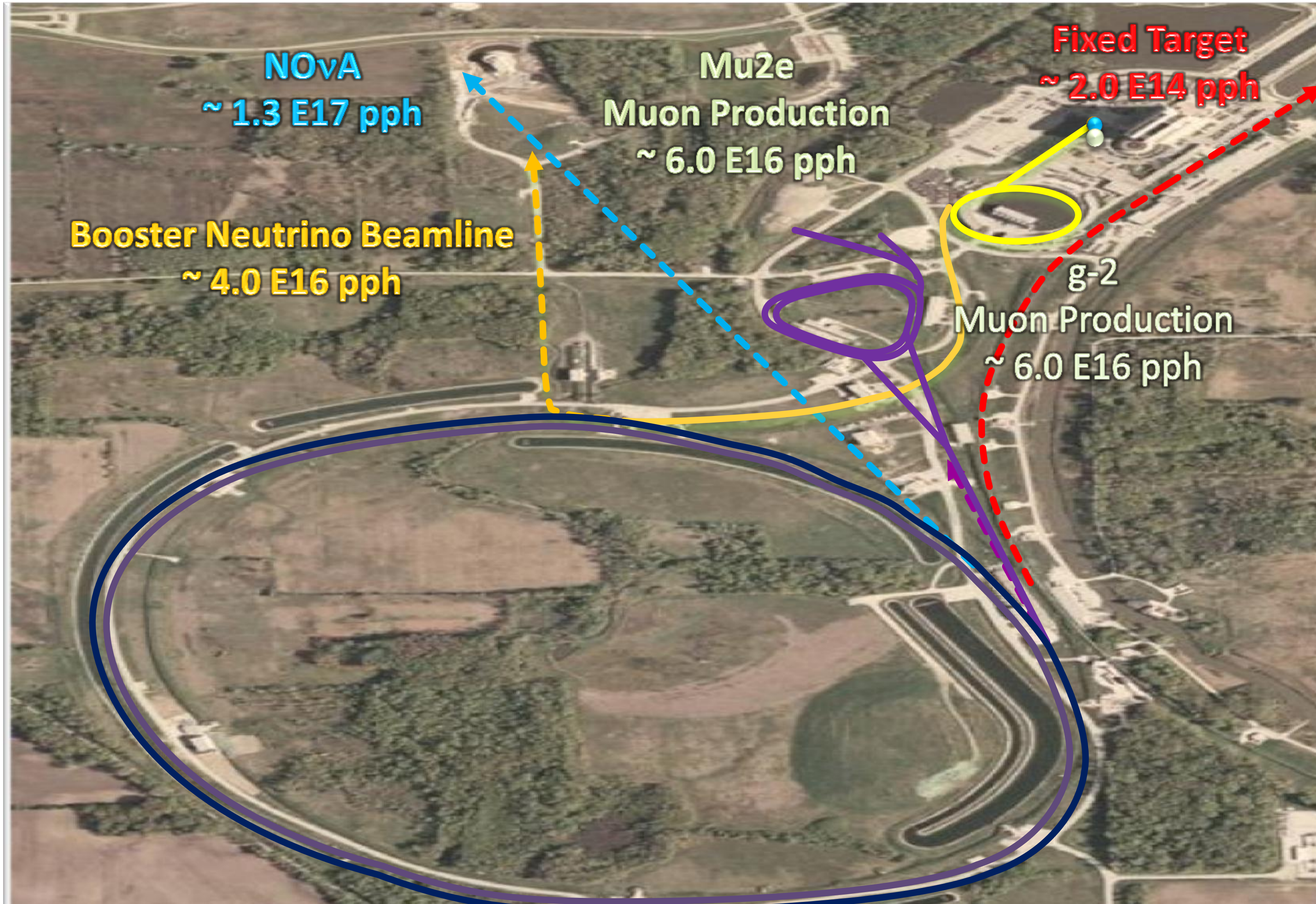
Measured:

- *bottom quark and properties*
- *Precise lifetimes of charm particles*
- *Leading constraints on Higgs boson*
- *Most precise measurement of W boson mass*



Protons demand going forward

ACCELERATOR CHAIN



Beam diagnostic

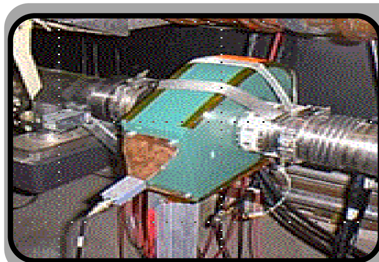
- *Beam diagnostic instruments are essential for monitoring and assessing beam quality*

Diagnostic devices and quantity measured

Instrument	***Physical Effect***	***Measured Quantity***	***Effect on beam***
Current transformer	*Magnetic field*	*Intensity*	*Non-destructive*
Beam position monitor	*Electric/Magnet field*	*Position*	*Non-destructive*
Wire Scanner	*Secondary particle creation*	*Transverse size/shape*	*Slightly destructive*
Beam loss Monitor	*Ionization*	*Intensity*	*Non-destructive*

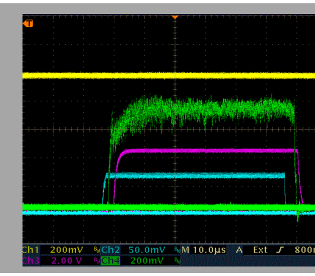
Beam diagnostic (1)

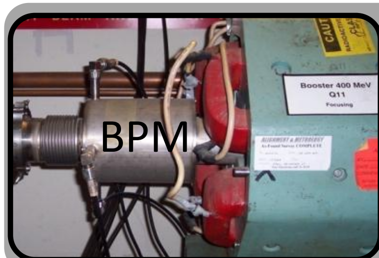
ACCELERATOR CHAIN



Toroid

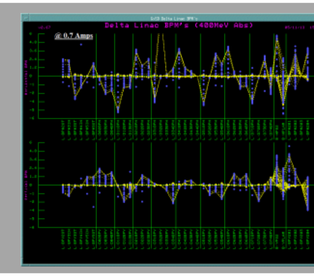
Intensity devices used to measure a pulse beam current

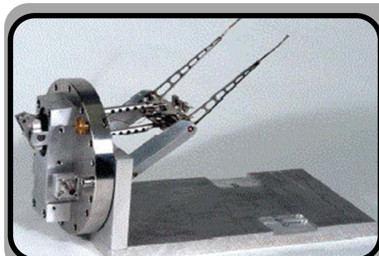




Beam Position Monitor

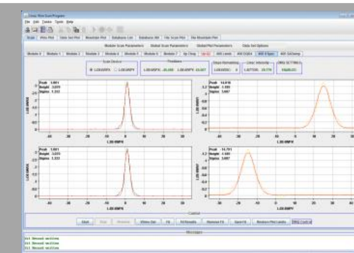
Measure the center of the mass of the beam





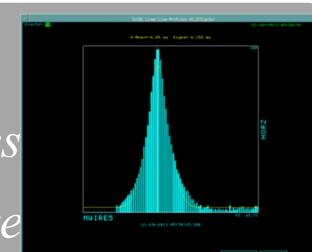
Wire Scanner

A thin wire is quickly moved across the beam



Multi Wire

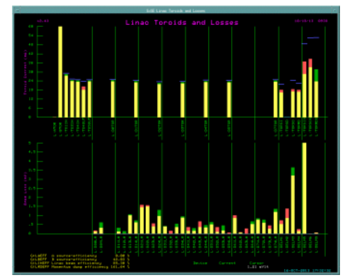
A vacuum chamber houses a paddle with wires which are kept under tension and high voltage

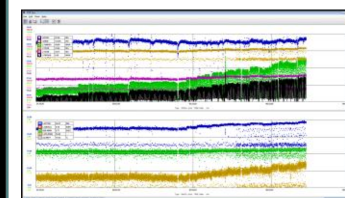


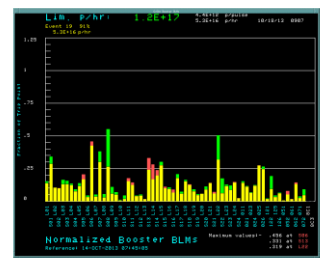
Running the machines

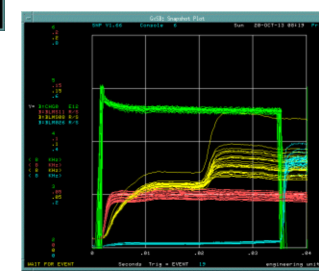
ACCELERATOR CHAIN

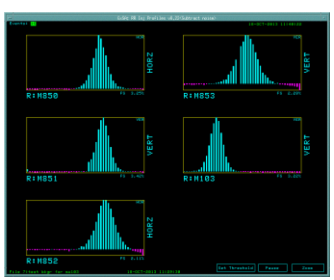
- *Monitoring and Control*
  - *Main Control Room (MCR) staffed 24/7/365*
  - *> 200k devices monitored/controlled through Accelerator Control Network (ACNET)*
  - *Respond and resolve alarms*
    - *minor and major*
  - *Tuning accelerators/beamlines for efficiency*
  - *Route/provide beam to desired/scheduled experiment/studies*
  - *Record events in electronic log book*

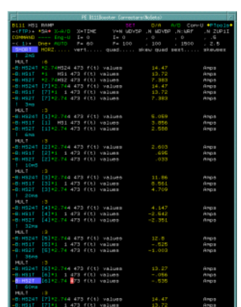






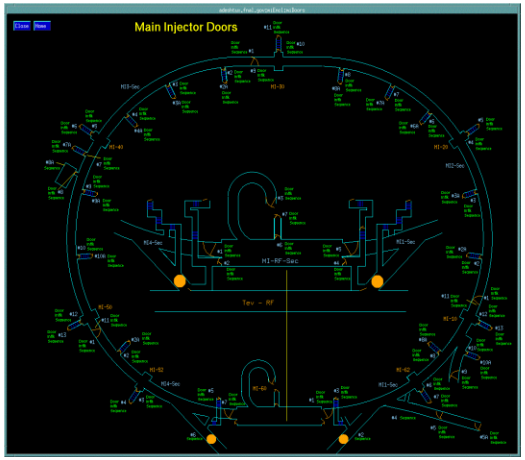


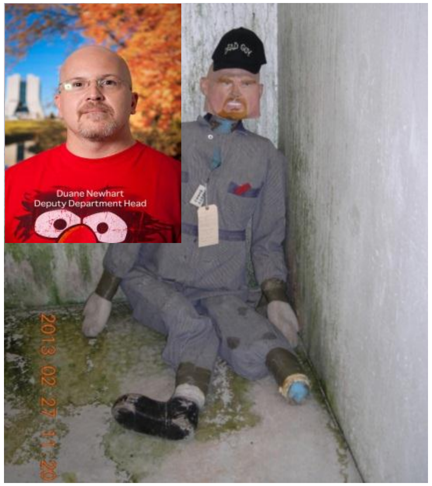




Running the machines (1)

- *Access Control*
  - *turn off and on each accelerator & beamline for enclosure access*
  - *Provide a single point LOTO in most cases*
  - *Issue enclosure access keys*
    - *search and secure enclosures in preparation to resume beam when needed*

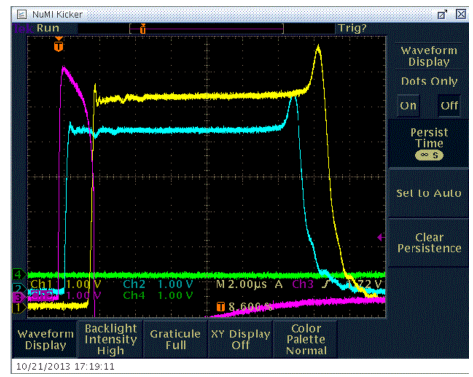


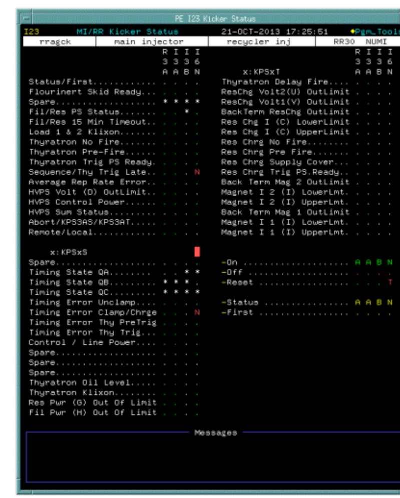


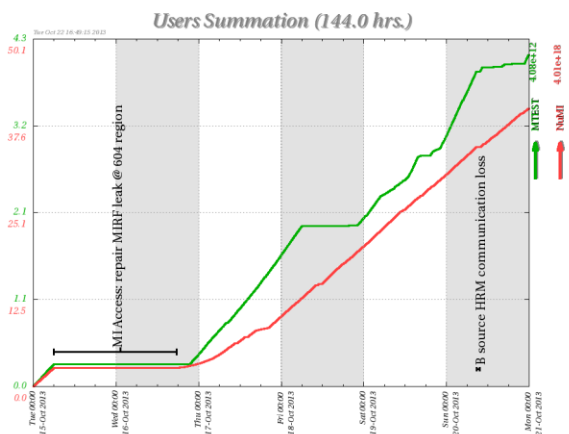
Running the machines (2)

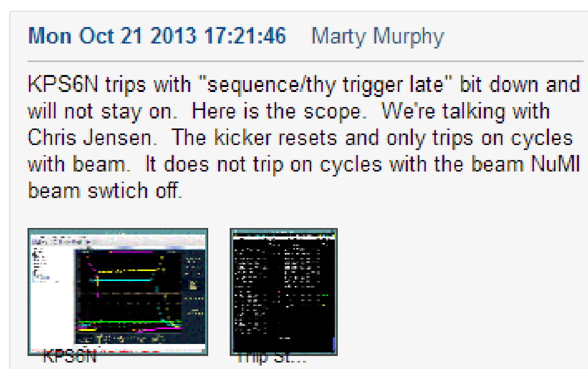
ACCELERATOR CHAIN

- *First responders*
  - *fire alarm & ODH alarms*
  - *equipment failure*
- *Troubleshooting*
  - *system and component*
    - *expert contact when needed*
- *Daily Schedule*
  - *maintain beam delivery*
    - *adjust on the fly*







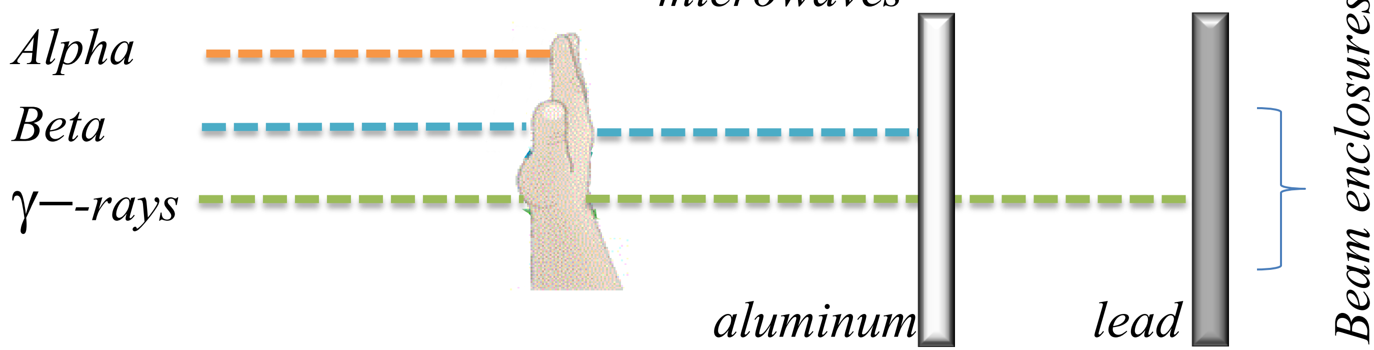


A taste of what looks like to be in the Main Control Room

Radiation at a glance

- ***Radiation*** *is energy that is transmitted in the form of waves of stream of particles.* ***It is present everywhere!!***

Radiation
- ***Ionizing*** *comes from both natural and man-made*
- ***Non-ionizing*** *lower radiation such as radio waves, microwaves*



Can you give me an example of something you know that is radioactive?

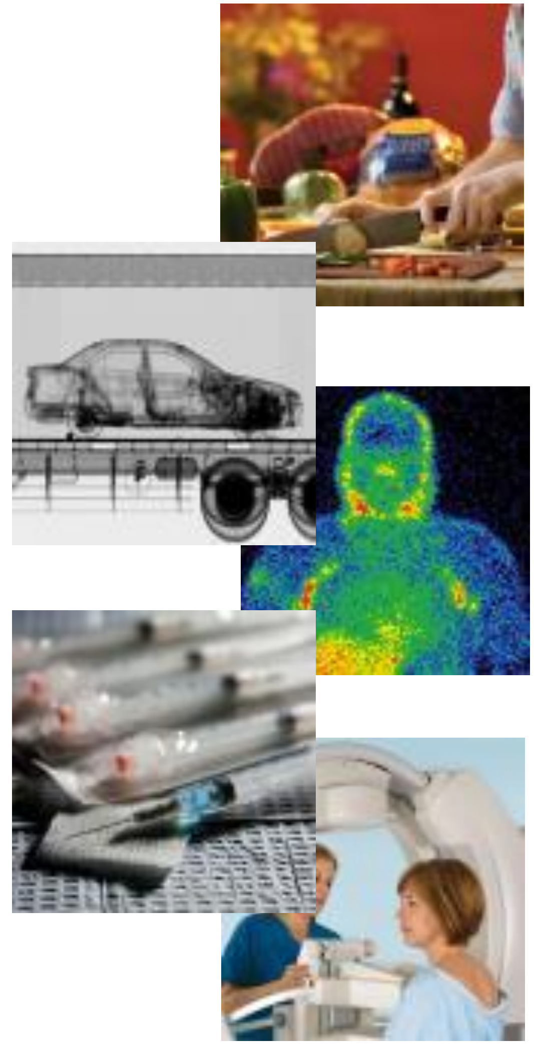
Application of accelerators

Three main applications:

1) Scientific research
2) Medical applications
3) Industrial uses

CATEGORY OF ACCELERATORS	*# IN USE*
Nuclear/High-Energy Accelerators	*120*
Synchrotron radiation sources	*100*
Medical radioisotope production	*1,000*
Radiation therapy	*5,000*
Research accelerators (non-nuclear research)	*1,000*
Industrial processing and research	*1,500*
Ion implanters	*7,000*
TOTAL	*> 15,000*

Data collected by W. Scarf & W. Wiesczycka (U.Amaldi Europhysics News, June 2000)



Application of accelerators (2)

- ***Irradiation pasteurization*** *is the process used on food irradiation*
  - *Food irradiation is the process of using ionizing radiation to kill harmful micro-organisms to reduce food spoilage and mildew development*

Radiant energy
- e^- *beam generator (10 MeV)*
- γ-rays Co^{60}
- *X-rays (max 5 MeV)*

US labeling for irradiated foods

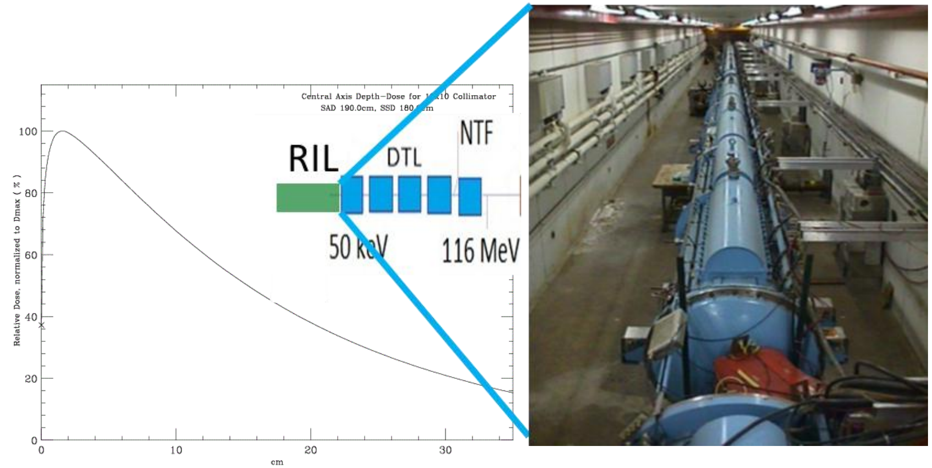



Lower dose → ***Higher dose***

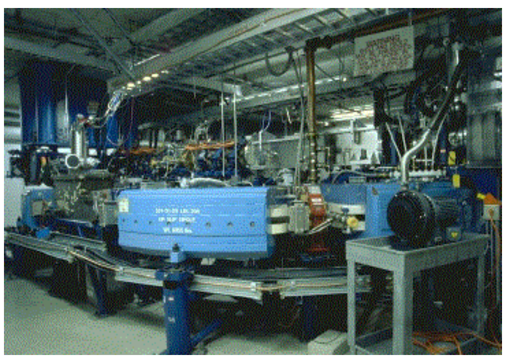
Application of accelerators (3)

- ***Medical therapy***

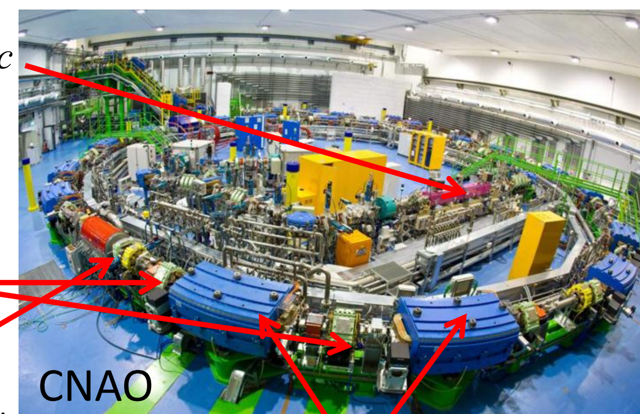
electron linacs for conventional radiation therapy



Low-energy hadron therapy (66 MeV)
Neutron therapy (NTF)/FNAL



Medium-energy cyclotrons and synchrotrons for hadron therapy with protons (250MeV)



Injector linac

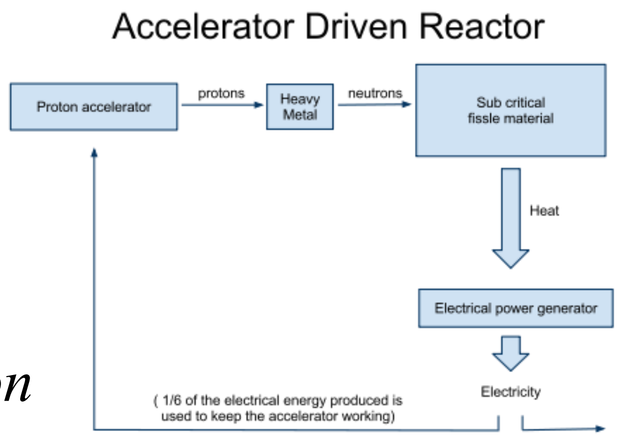
Quadrupole magnets

RF cavity

Dipole magnets

Application of accelerators (4)

- ***Accelerator Driven System (ADS)***
  - *proton accelerator at low energy & high beam power*
  - *aim these protons to a heavy metal target and create lots of neutrons*
  - *These neutrons can drive the reaction in the reactor*
    - *Continue to drive the reactor,*
  - *Twofold application: generate energy & nuclear waste transmutation*



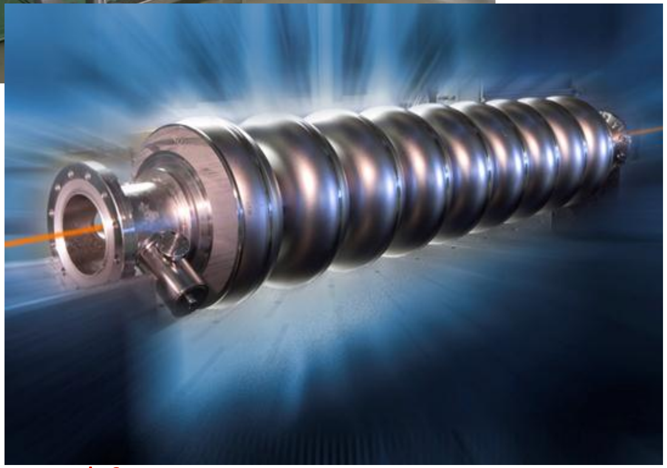
Picture taken from wikipedia

Superconducting RF R&D

- *Fermilab is the lead on SRF R&D Program*
  - *Fermilab has been developing the infrastructure and skill set to be a key player in superconducting RF technology applications*
  - *NML facility – propose site for ASTA*

(Advanced Superconducting Test Accelerator)

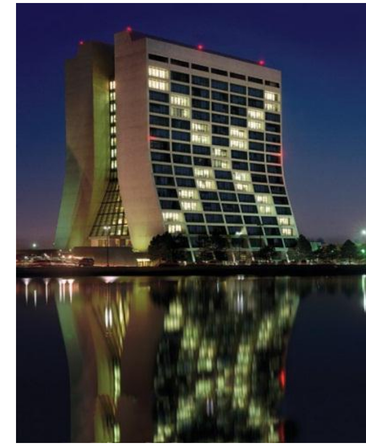
- *SRF technology is a highly efficient way to accelerate beams of particles*
  - *Several strings, or cavities are nestle in a vessel called a cryomodule, which bathes them in liquid helium and keeps them at the ultra cold temperature*
- *Future accelerators design involves SRF accelerator elements*

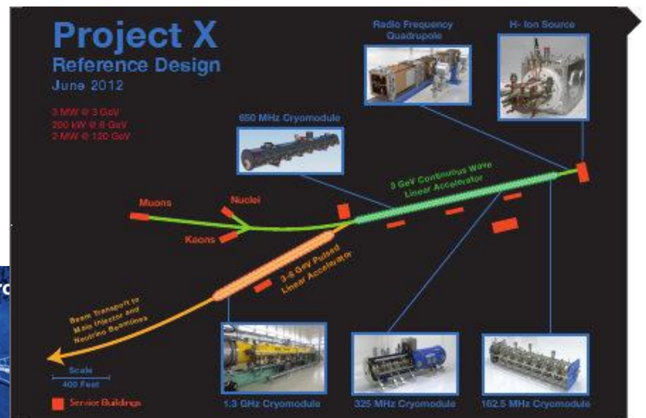


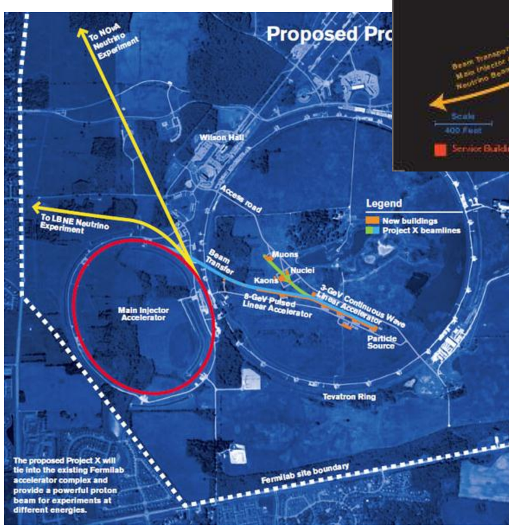
Future Accelerators

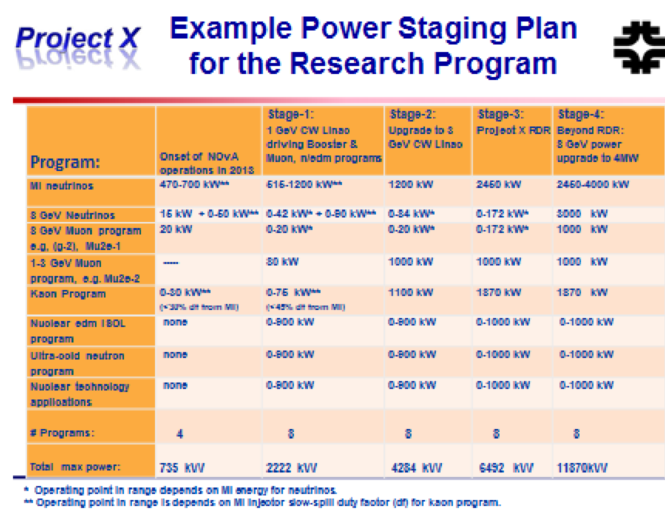
- ***PIP-II*** *(former Project-X), a high-power proton facility*

Provide MW beam power to ν experiments & simultaneously multi-GeV beam for other experiments









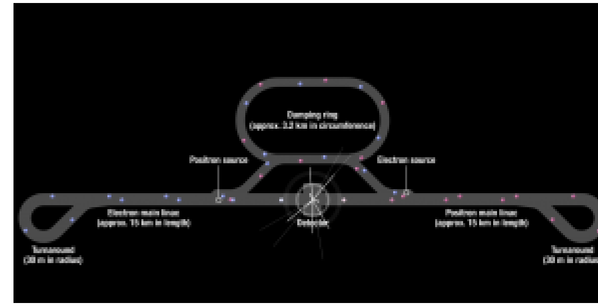
Project X — Example Power Staging Plan for the Research Program

Program:	Onset of NOvA operations in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g. (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

* Operating point in range depends on MI energy for neutrinos.
** Operating point in range is depends on MI injector slow-spill duty factor (df) for kaon program.

Future Accelerators (2)

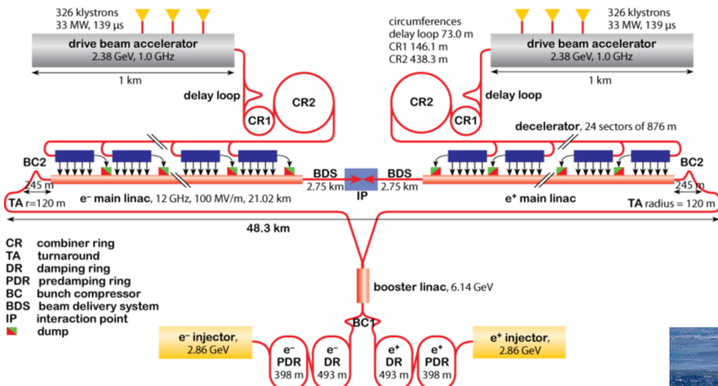
- ***I**nternational **L**inear **C**ollider (ILC)*



***Site:** Japan*

***Energy:** 1TeV cm*

***Technology:** Superconduct Linac*



- ***C**ompact **L**inear **C**ollider (CLIC)*

***Site :** Europe*

***Energy:** 3 TeV*

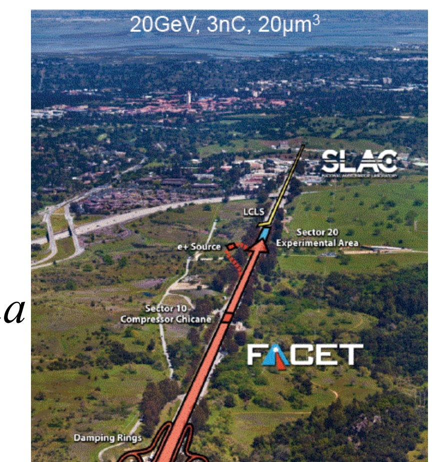
***Technology**; standard accelerator technology*

- ***Plasma Accelerator***

SLAC has been building

Facilities to demonstrate plasma

accelerators



Summary

Sometimes pretty crazy ideas are surprisingly good ones to make the world a better place

Particles accelerators are not only used for research

cancer treatment

killing bacteria in food

nuclear transmutation

(and so many other applications that were not covered here…)

Wherever life takes you, find something you think is important

Do it because you are passionate about it, that you believe is worthwhile

Challenge yourself

Believe in yourself

&

Dig Deep!

Books, Webs and Lectures

1) USPAS Accelerator Schools [http://uspas.fnal.gov/]
2) Previous SMP accelerator lectures (thanks for sharing the material)
3) Connexions web site [http://cnx.org]
4) [http://cas.webhttp://www.clab.edc.uoc.gr/materials/pc/surf/ACCELERATORS_INTRO.HTML]
5) Food irradiation [http://www.epa.gov/radiation/sources/food_irrad.html]
6) CERN Accelerator Schools.cern.ch/cas
7) RF Linear Accelerators, 2nd edition, Thomas P. Wrangler, Wiley-VCH
8) Enertial of Modern Physics, T.R. Sandin, Addison-Wesley
9) … and I would like to thank many other outstanding references available online which helped formulate this lecture