Accelerators: Fermilab & Elsewhere

***Tevatron was* the world's highest energy accelerator**

Peter H. Garbincius – Fermilab – since 1976

Ask-a-Scientist – July 13, 2008 revised Sept 8, 2019

What are accelerators?
Fermilab's accelerators
What do we use them for?
What we've learned
What we don't know
What's happened over last 11 yrs?
What we're planning, thinking about

general particle physics reference:
http://www.particleadventure.org
http://www.fnal.gov
http://www.linearcollider.org

What is the universe made of and how does it work?

What is this made of, Daddy?

What's inside of that?

What's that made of?

What inside of that?

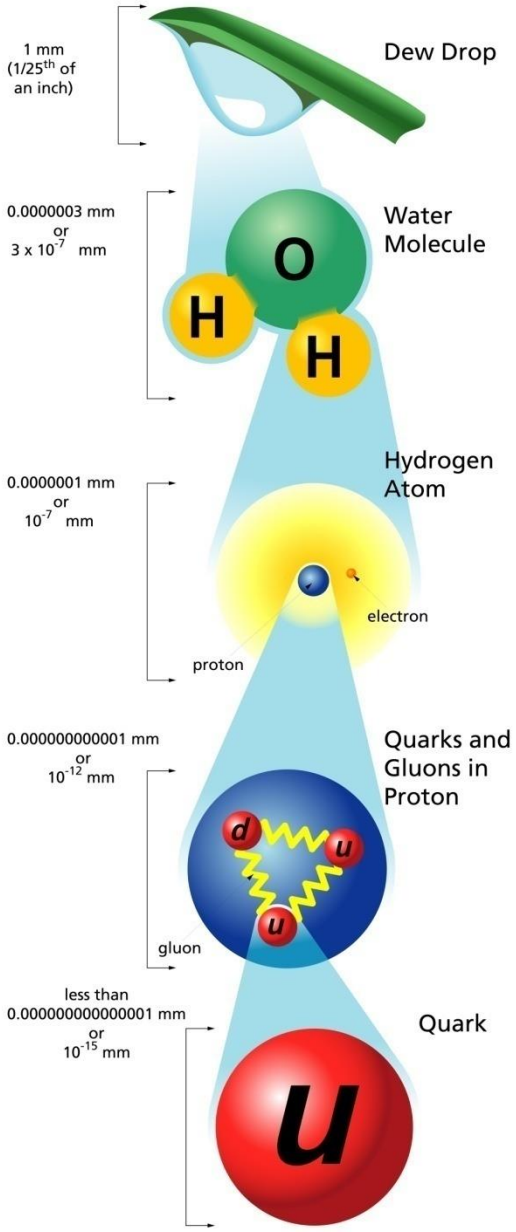
. . . .

Questions of

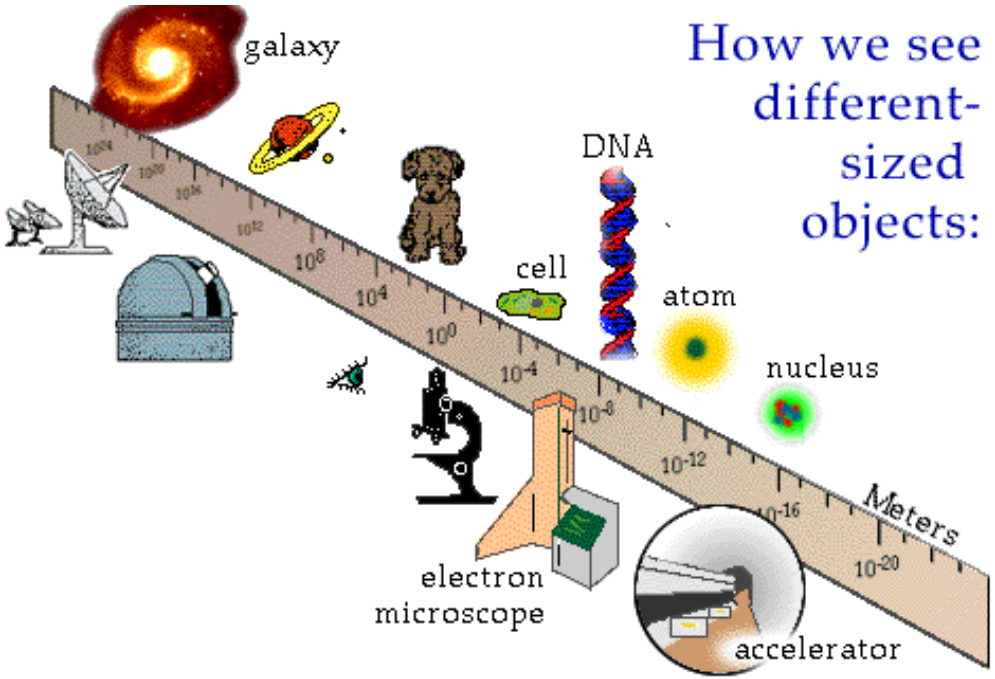
little children →

ancient Greeks (atoms) →

today's physicists

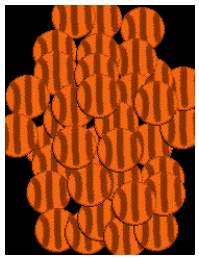


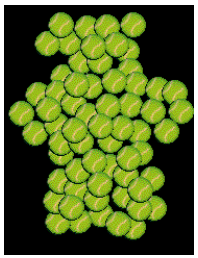
Wave-Particle Duality of Nature

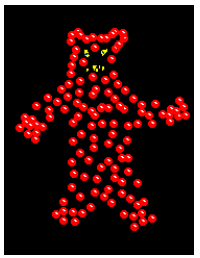


DeBroglie said moving particles have an equivalent wavelength,

$$\lambda \propto \frac{1}{p}$$







as size of probe decreases (energy goes up) => resolution improves

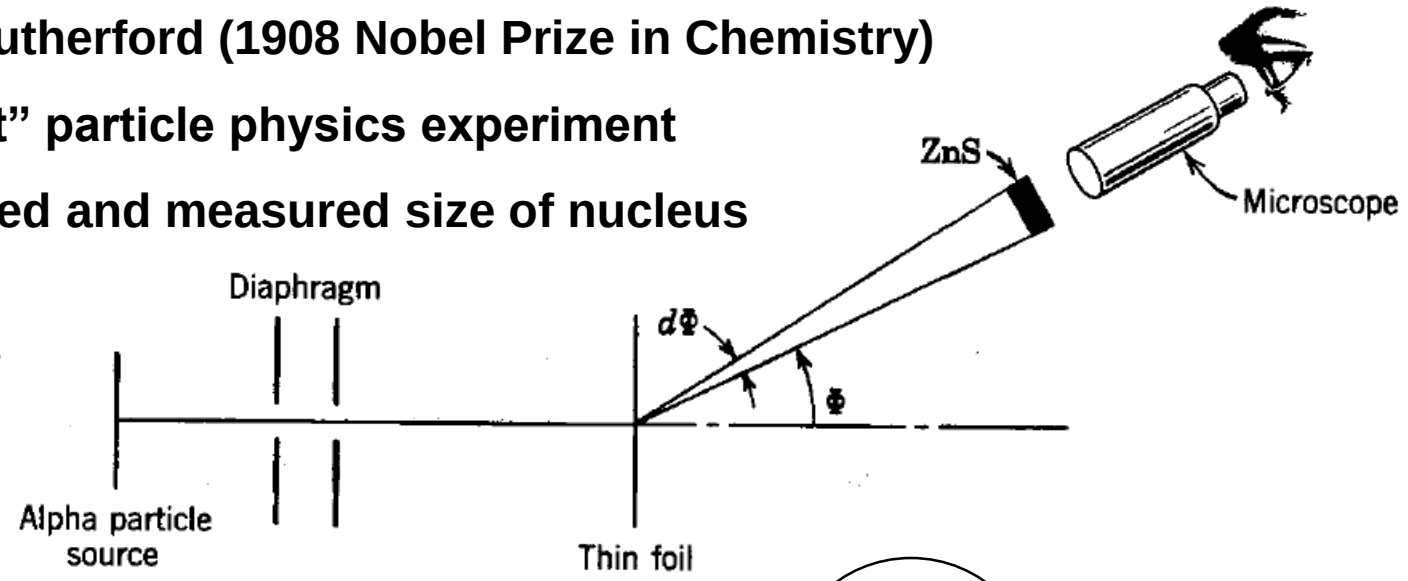
basketball **tennis ball** **pea**

How do we measure the very small?

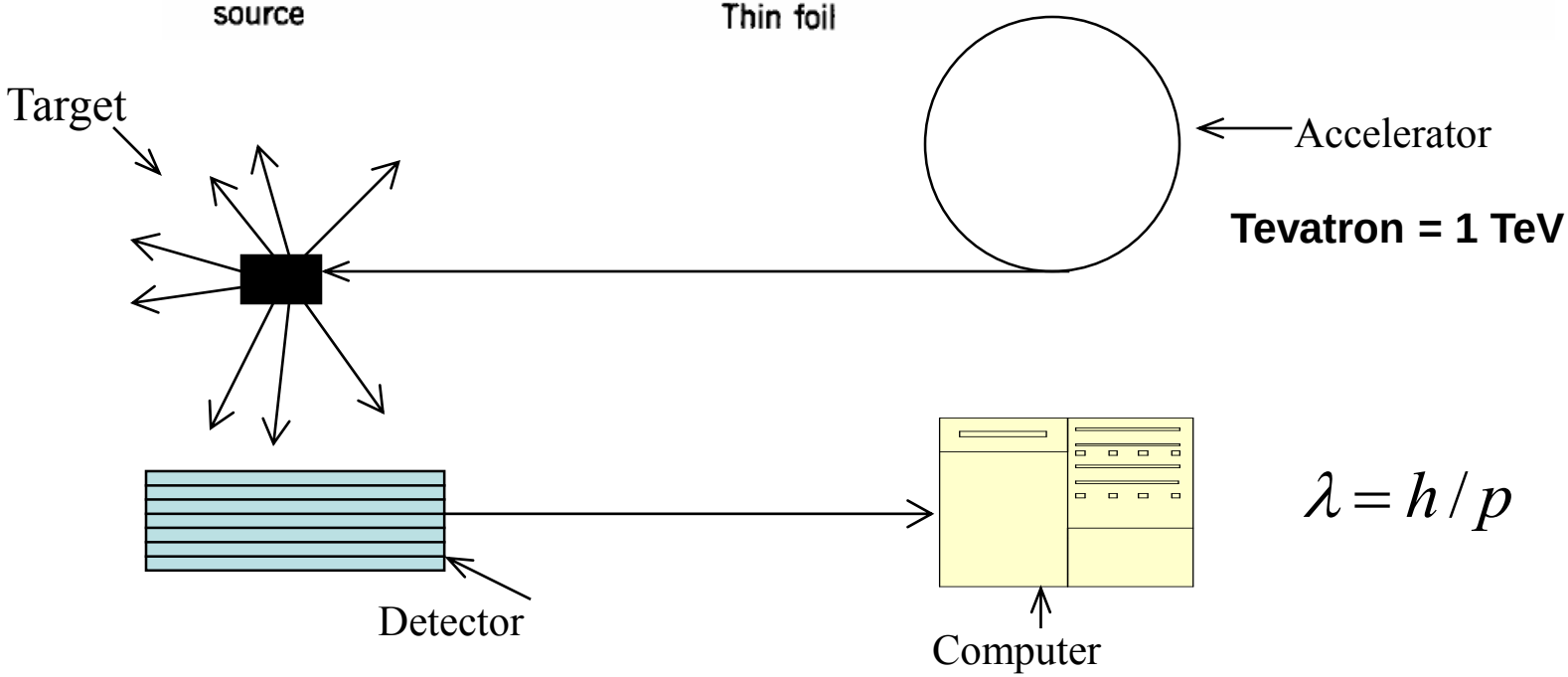
Ernest Rutherford (1908 Nobel Prize in Chemistry)

The "first" particle physics experiment

Discovered and measured size of nucleus



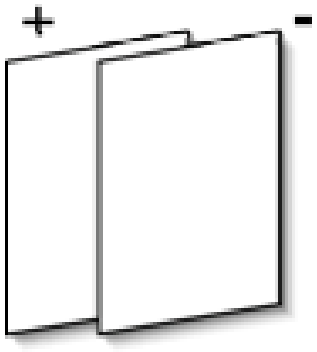
radioactive source a few MeV



Tevatron = 1 TeV

$$\lambda = h / p$$

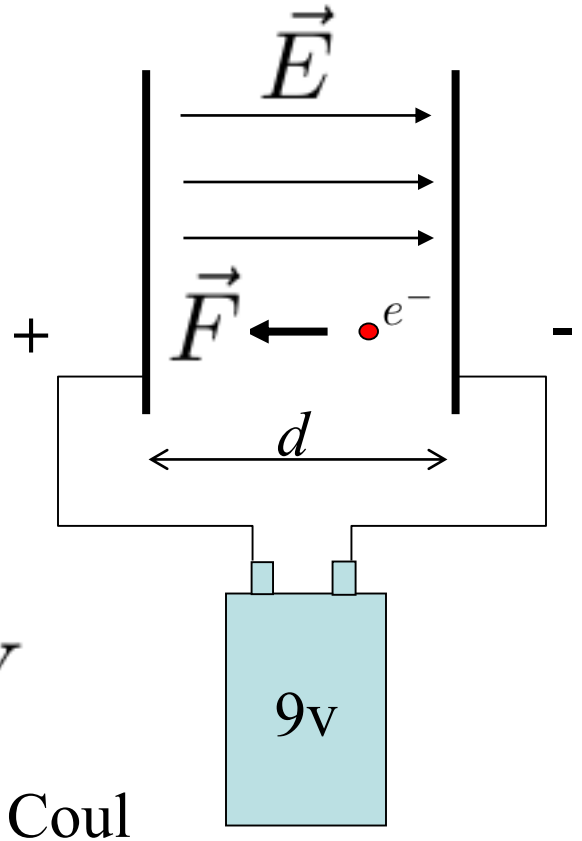
How to Accelerate Charged Particles



$$|\vec{E}| = V/d$$

$$|\vec{F}| = q|\vec{E}| = qV/d$$

E = electric field



As the electron accelerates from the right-hand plate to the left, the change in energy is the work done,

different *E*!

$$\Delta E = F \times d = qV$$

E = kinetic energy of particle

The charge on an electron is $q = -e = -1.6 \times 10^{-19}$ Coul

(on a proton, $+1.6 \times 10^{-19}$ Coul $= +e$)

So, we say that an electron/proton accelerated through 1 volt gains an amount of energy $\Delta E = 1$ eV (1 **electron volt**) ($= 1.6 \times 10^{-19}$ J)

In example above, the electron would gain energy of amount 9 eV.

The energies we talk about:

- meV = milli- (1/1000th) electron Volt

40 meV ~ K.E. of gas molecules at room temp.

- eV = electron Volt = visable light, chem, bio
- KeV = Kilo- (1000) electron Volts = *x-rays*
- MeV = Million electron Volts = nucl. reactors
  nuclear decays
- GeV = (Giga-) Billion electron Volts
- TeV = Trillion electron Volts

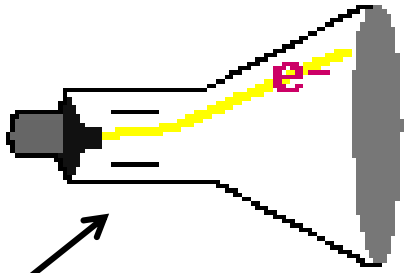
Let’s have a show of hands:

How many of you have a particle accelerator at home?

the “classic” cathode ray tube television is

both an accelerator and detector!

heated *filament*, electron source (cathode)



phosphorescent screen which lights up when struck by e^-’s

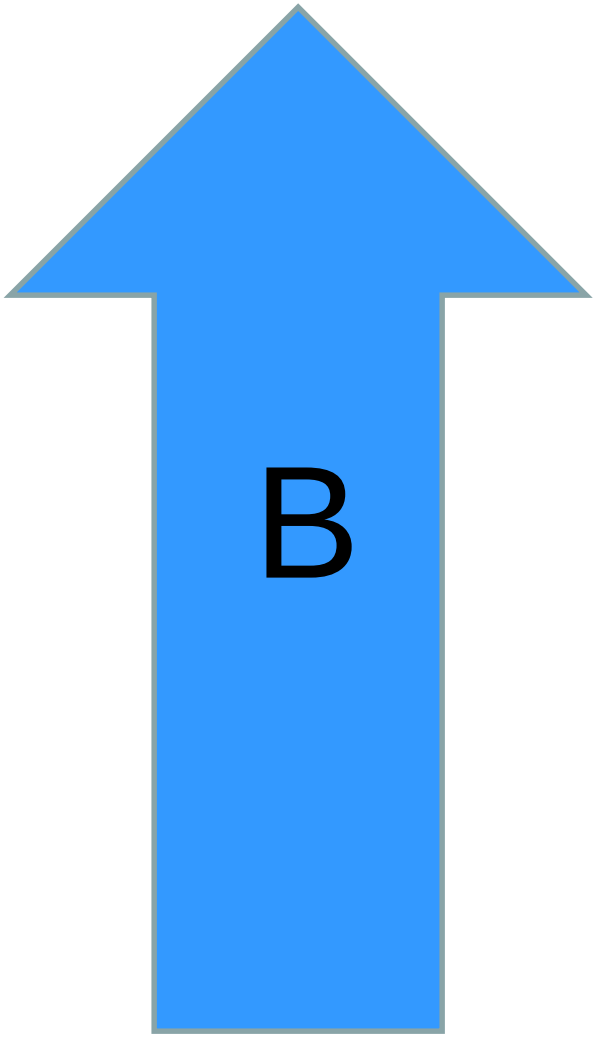
electromagentic fields to ***accelerate*** and steer the electron beam (ray)

evacuated glass container (tube)

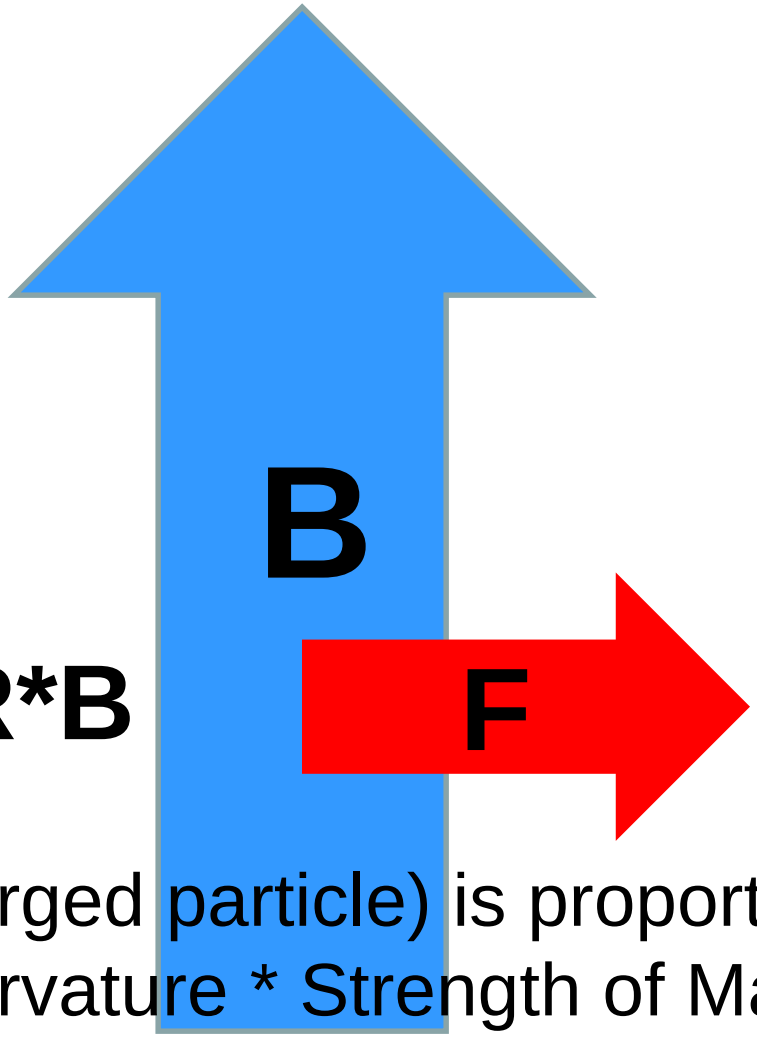
OK, so it’s a *little* more than that…
but not much! *Really*!

Note: voltages encountered are a few tens of thousands of volts, therefore particle energies of about **10 keV**, say!

Magnetic Field



Magnetic Fields bend moving charged particles

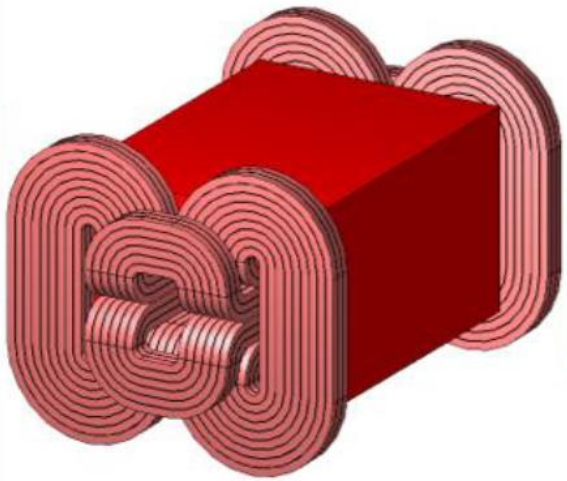


p = m*v α R*B

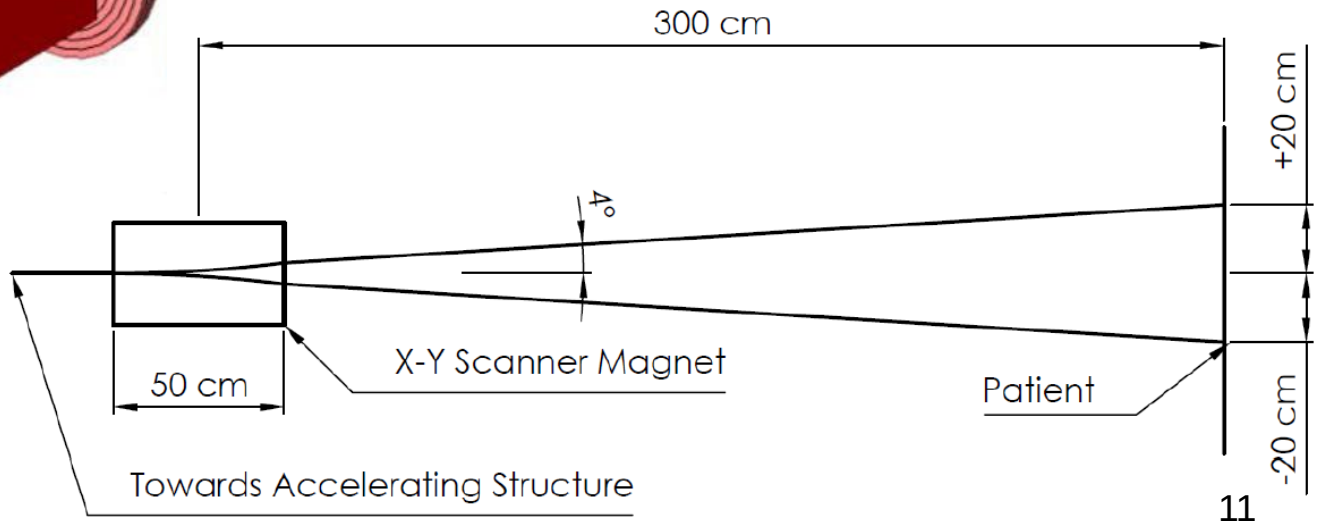
Momentum (of charged particle) is proportional to
Radius of Curvature * Strength of Magnetic Field

Analysis of an X-Y Scanner Magnet for Use in Cancer Radio Therapy Treatment

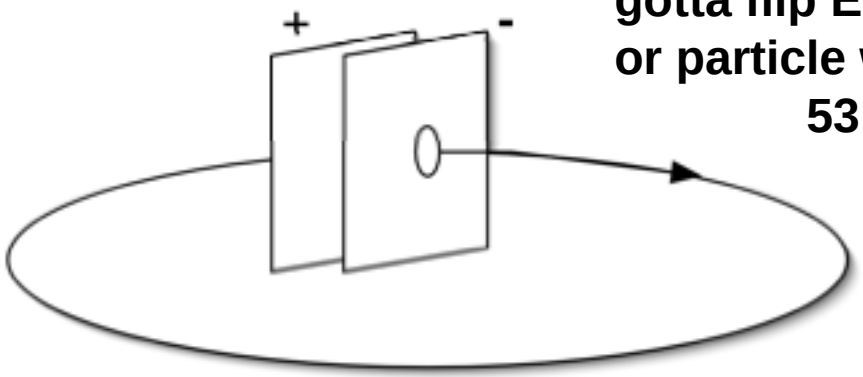
Jackson P. Morgan
Lee Teng Undergraduate Intern – Summer 2019
Argonne Nat. Lab & Oregon Institute of Technology



Magnet deflects beam either vertically or horizontally, or both simultaneously



Let's re-use (recycle) the E-field!



gotta flip E-field when particle outside of plates or particle will be decelerated – RF voltages

53 MHz = TV Ch2

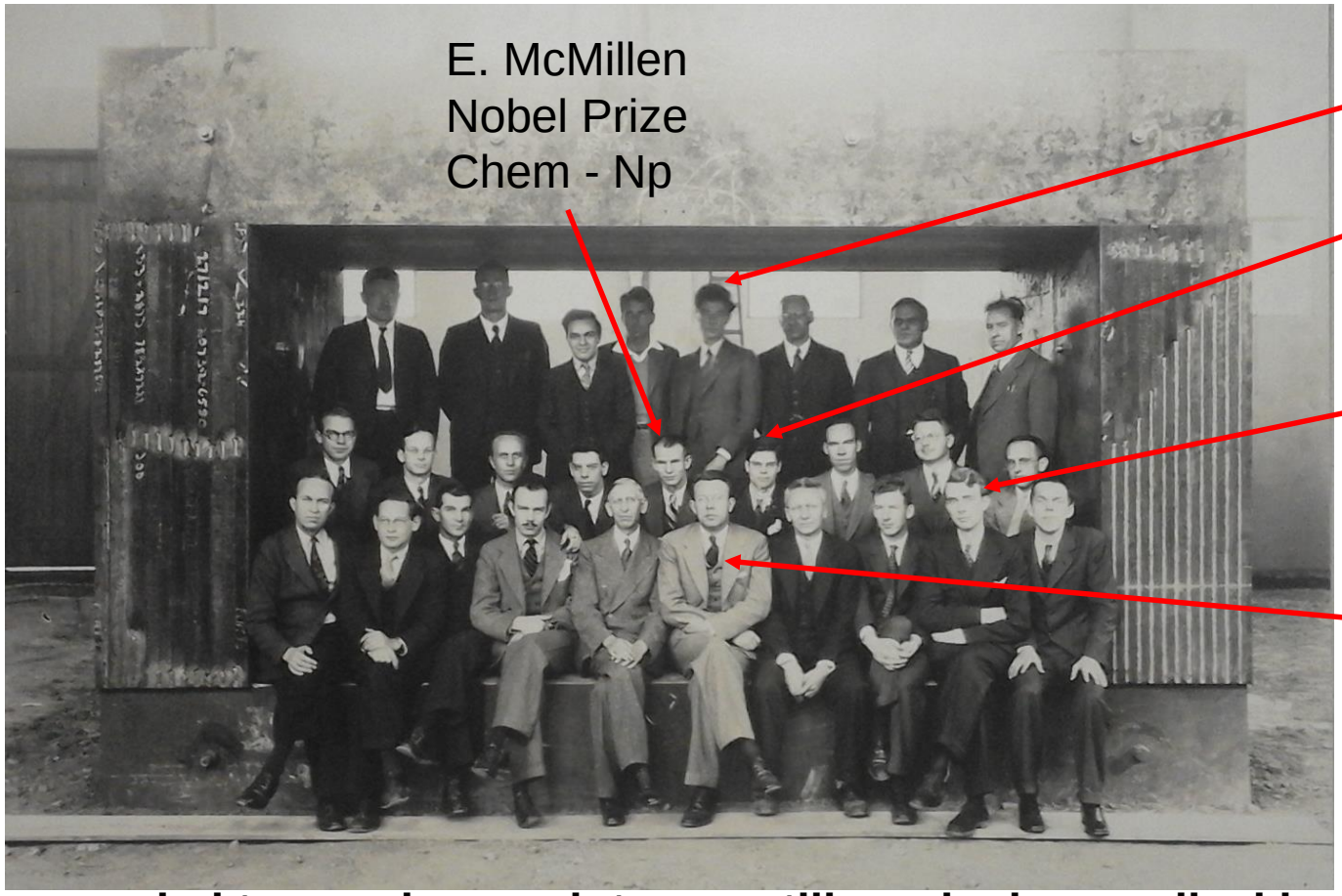
bend particles with magnetic field

1st Cyclotron - Ernest Lawrence - Berkeley - 1932

1.22 MeV Kinetic Energy protons

Bigger magnets, to contain entire cyclotron, get prohibitively expensive very quickly as E ↑

building 16 MeV (60 inch) cyclotron at Berkeley, 1939



upgraded to synchro-cyclotron – still producing medical isotopes at UC-Davis

Solution:

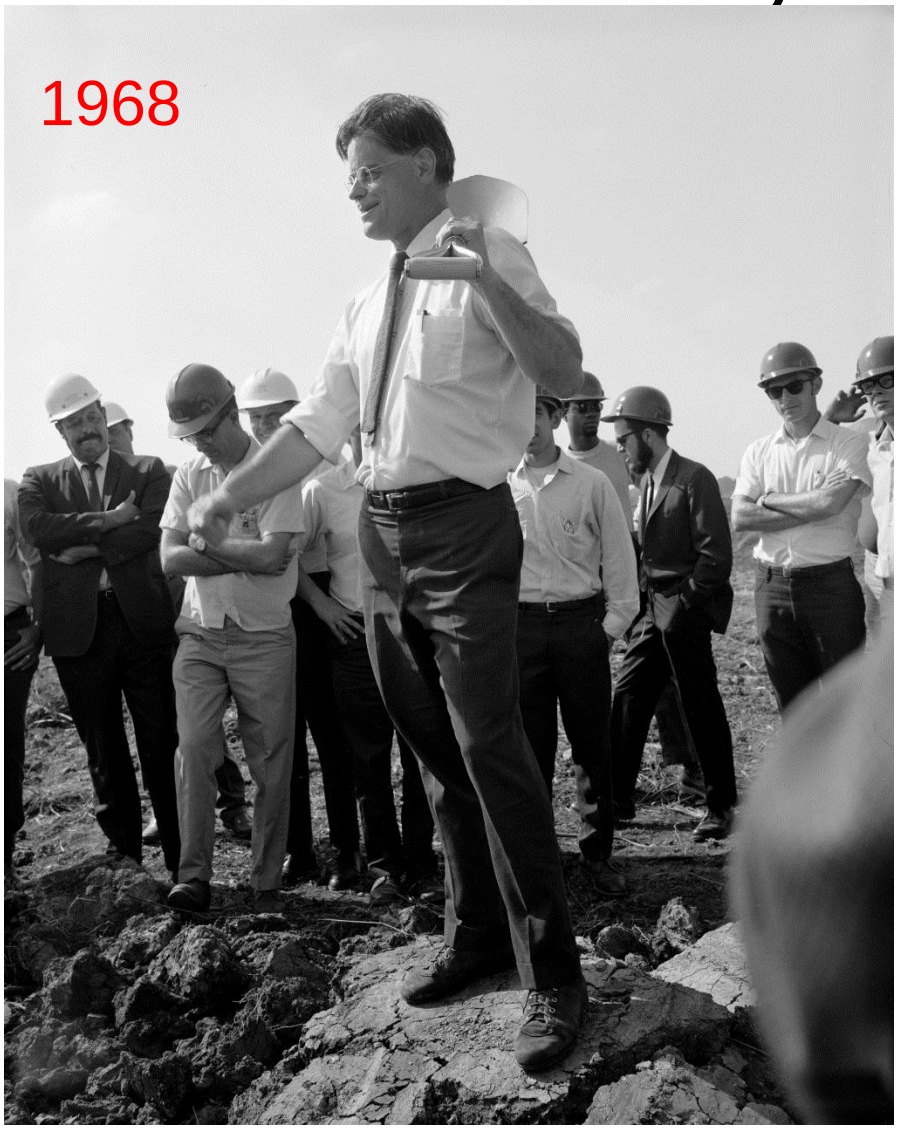
Ring of smaller magnets, like a donut, whose magnetic field increases in synchronization with particles increasing energy to maintain constant orbit radius, hence the term

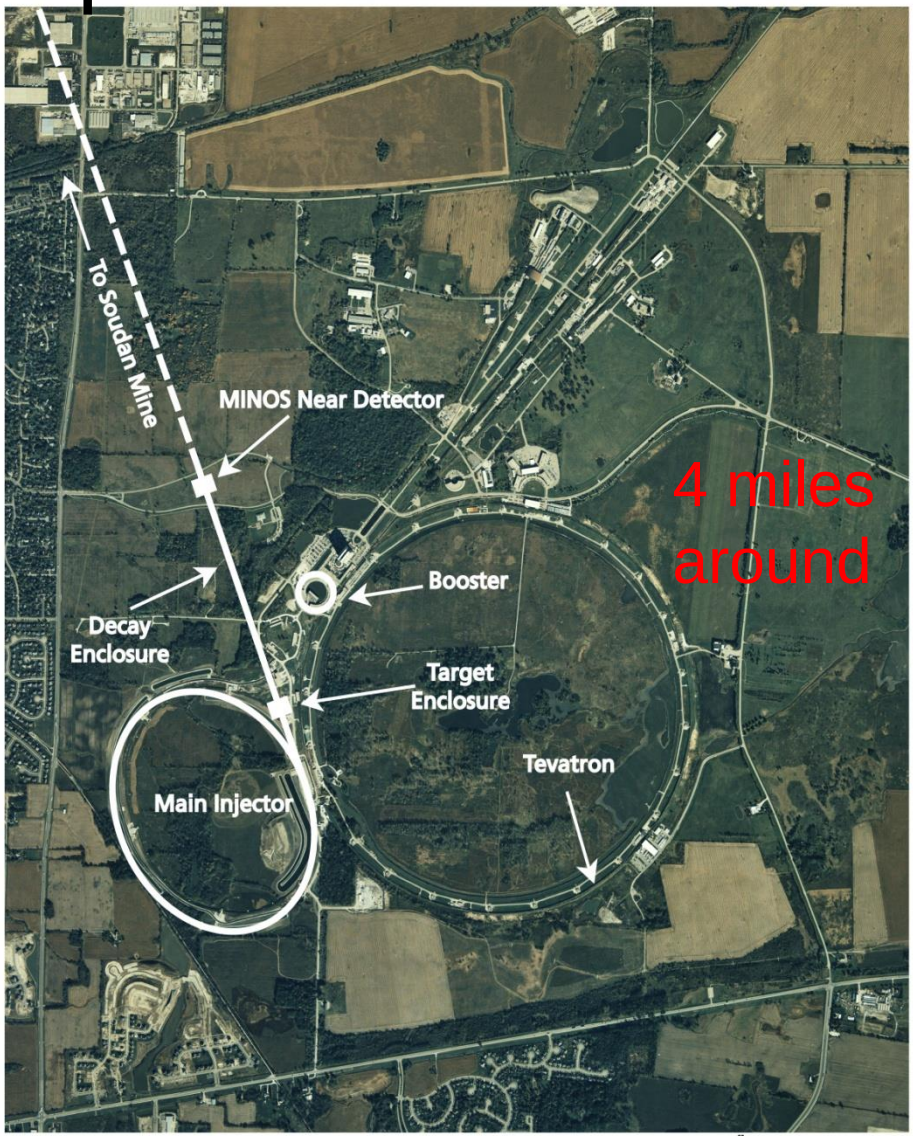
"synchrotron"

-tron seems to be attached to circular proton accelerators: Bevatron, Cosmotron, Tevatron

but betatron refers to electron synchrotons…

You need *big* machines to study *small* particles!





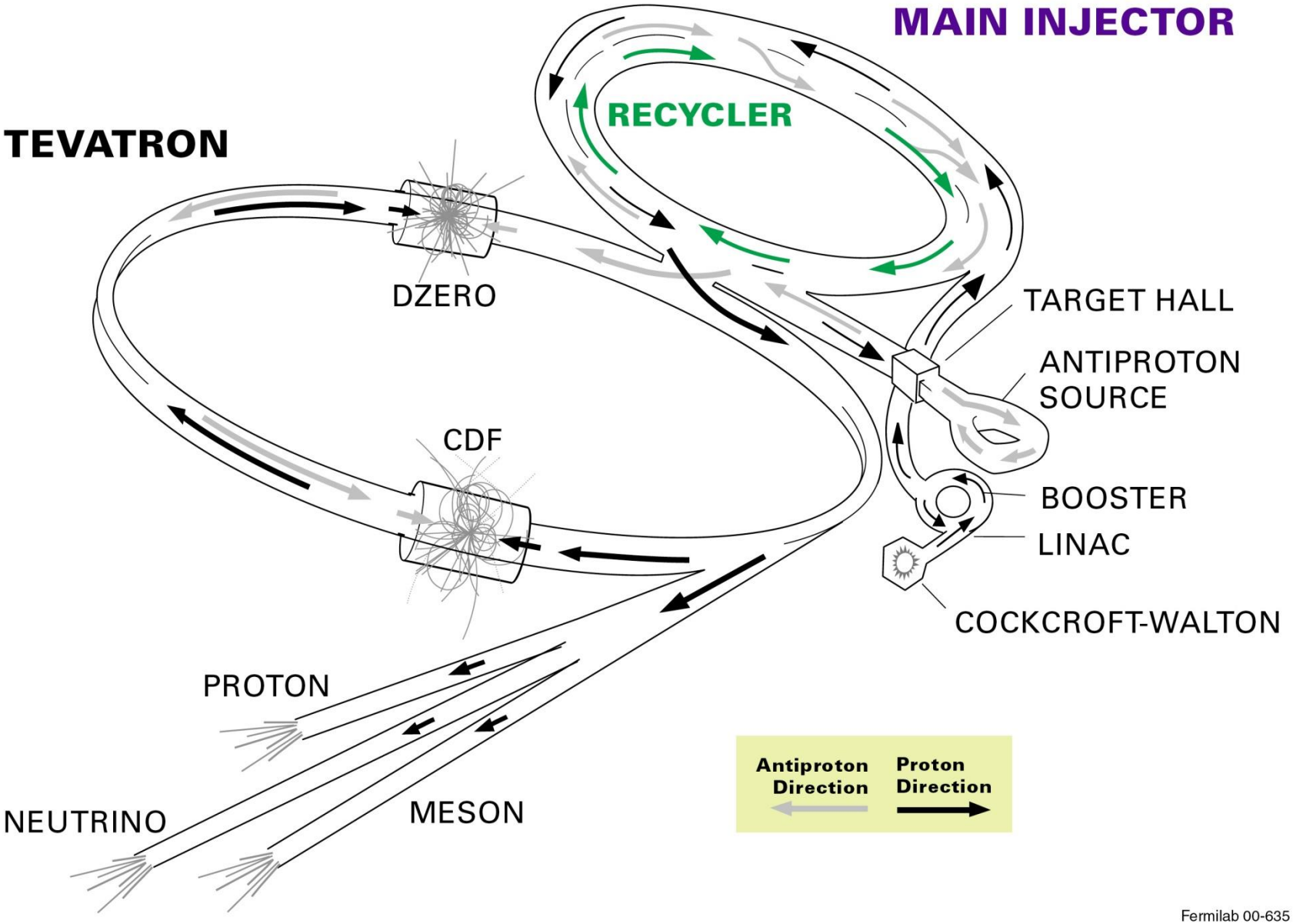
Fermilab Accelerator Complex

- **Complex Accelerator Systems**
  - **Fermilab - currently 9 separate machines**

    with upgrades from 2008
    - **Cockcroft- Walton (2) → RadioFrequency Quadrupole**
    - **Linac (operational since '72) → to be replaced by PIP-II**
    - **Booster (still going strong, upgraded for higher intensity**
    - **Main Injector (fed Tevatron) → high intensity neutrino source**
    - **Recyler (cool anti-p) → slip-stacking inject into Main Injector**
    - **Pelletron (electron cooling of antiprotons) → scavenge parts**
    - **Antiproton Debuncher → removed from ring**
    - **Antiproton Accumulator → Muon Delivery Ring (g-2 & Mu2e)**
    - **Tevatron → decommissioned in 9/2011 – RIP: rusting in place**
    - **Accelerator R&D facilities:**
      Fermilab NICADD Photo Injector Laboratory (FNPL)
      FAST (ILC cryomodule 250 MeV) & IOTA storage Ring

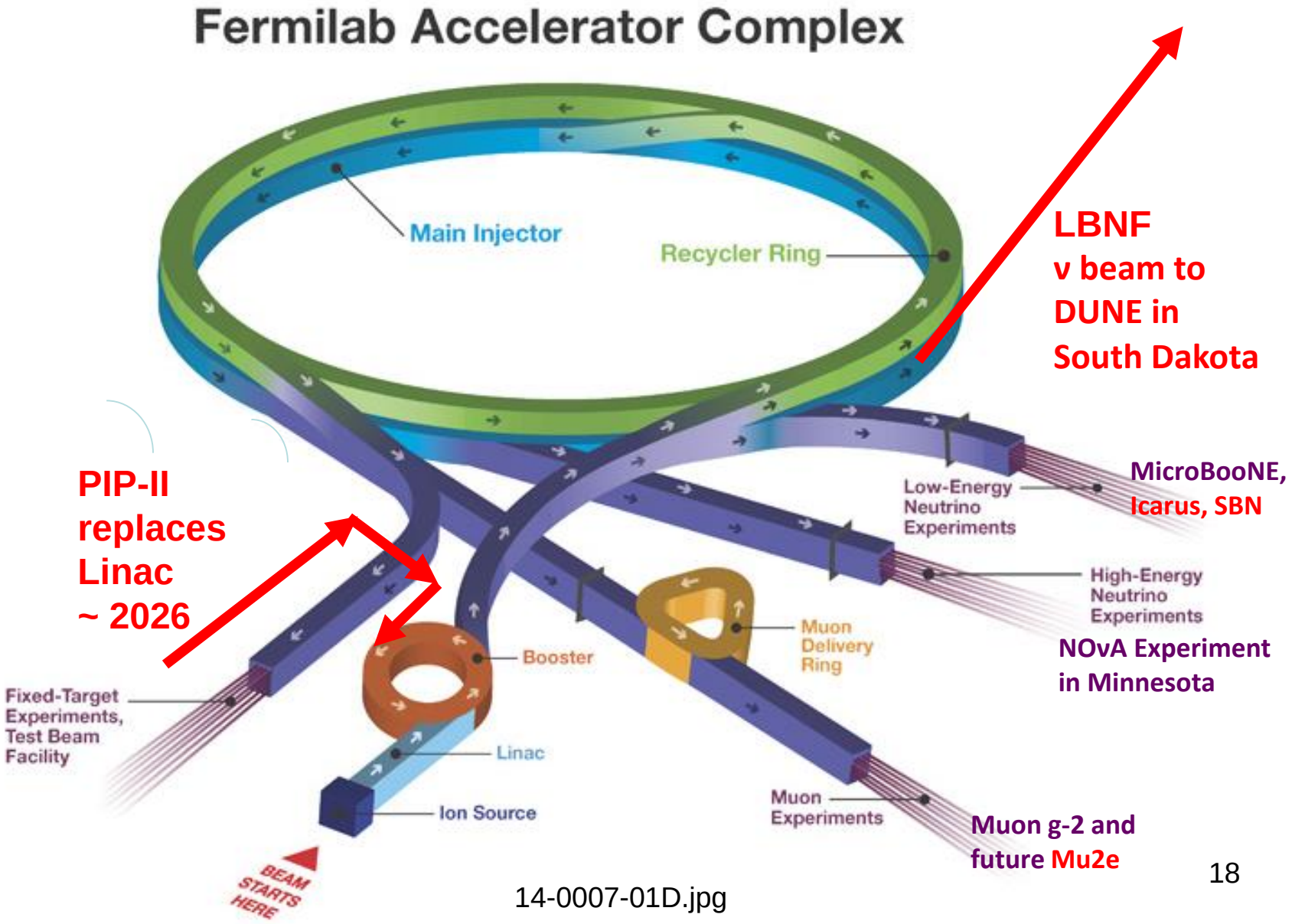
FERMILAB'S ACCELERATOR CHAIN

collider - circa 2008



Fermilab 00-635

Current, and Future Facilities



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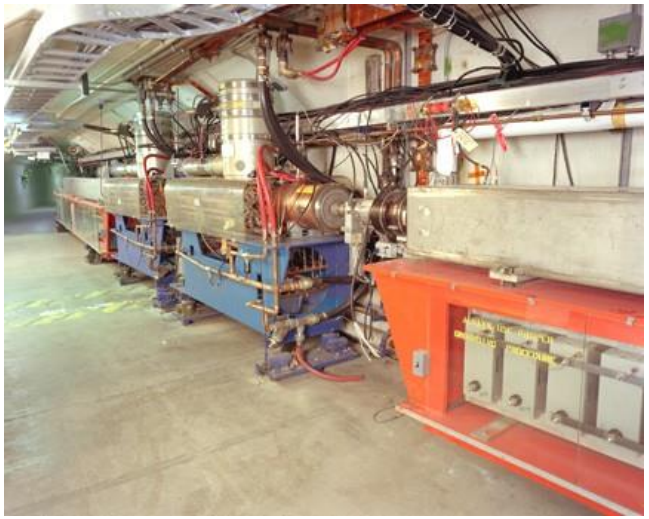
2012 replaced 750 KeV Cockcroft-Walton electrostatic accelerator with Radio Frequency Quadrupole (RFQ)

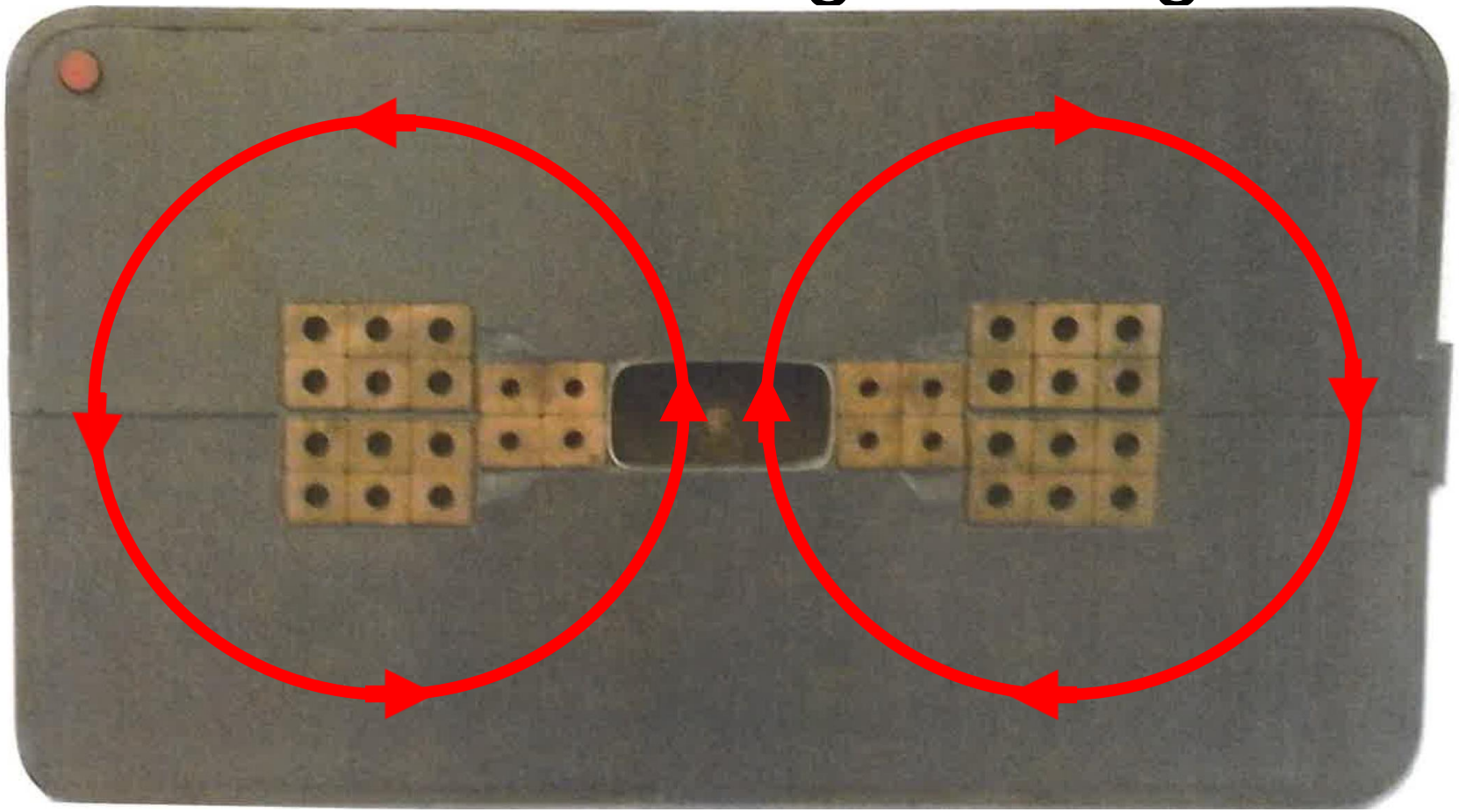


Radio Freq. Quad 750 KeV *velocity = 0* → *0.04 c* **LINAC 400 MeV** → *0.71 c* **Booster 8 GeV** → *0.994 c*

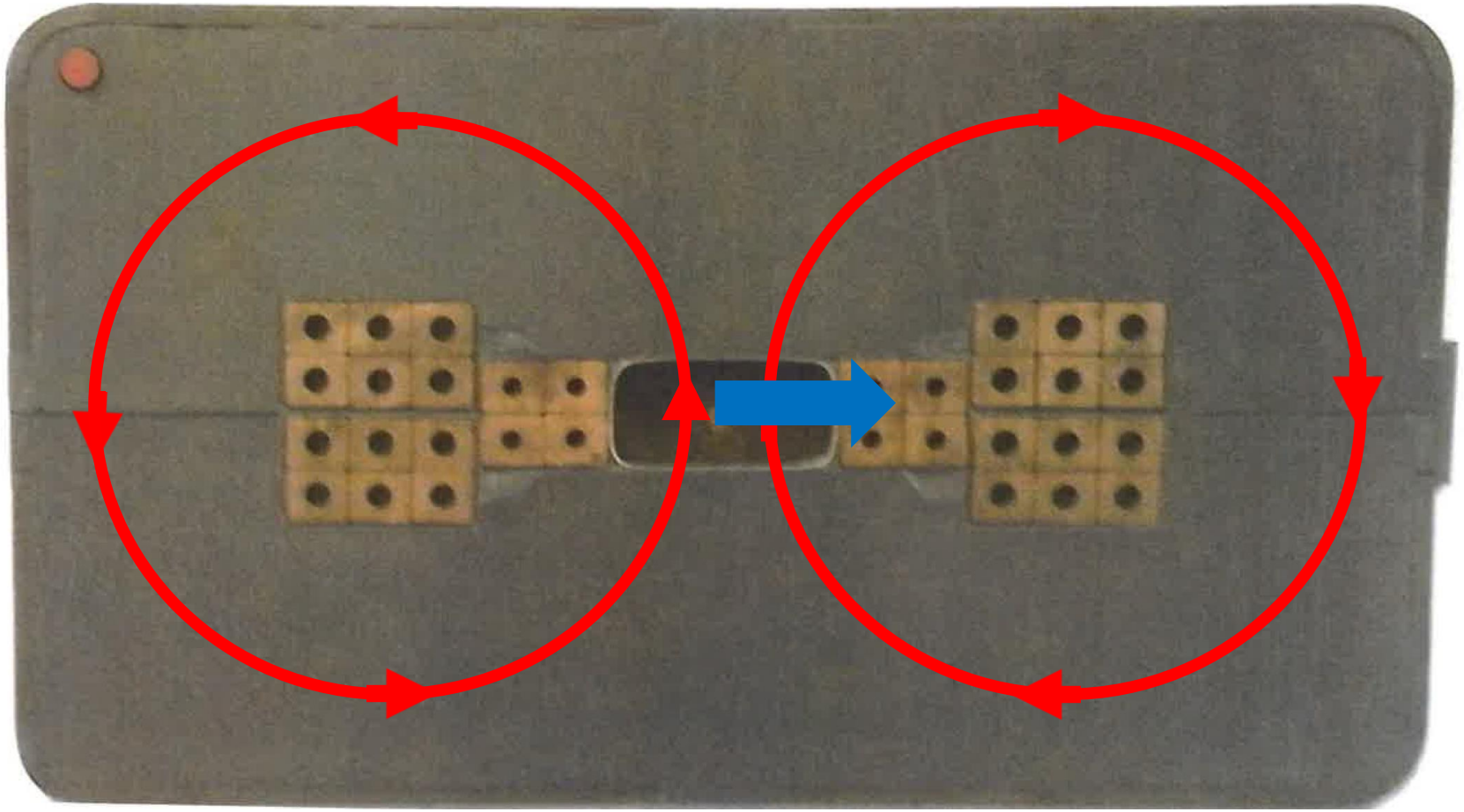
Recycler Ring – 8 GeV permanent magnets

Main Injector 120 GeV *0.994 c* → *0.99997 c* **Muon Delivery Ring** *previously antiproton "bottle"* **Tevatron 1000 GeV = 1 TeV** *0.99998 c* → *0.9999995 c*

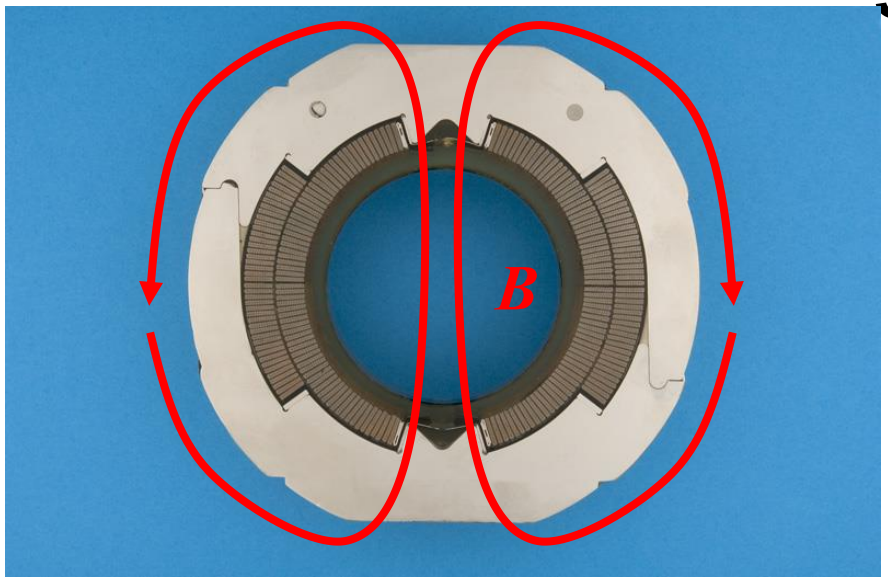
How a conventional electromagnet works this is a Main Ring B2 magnet

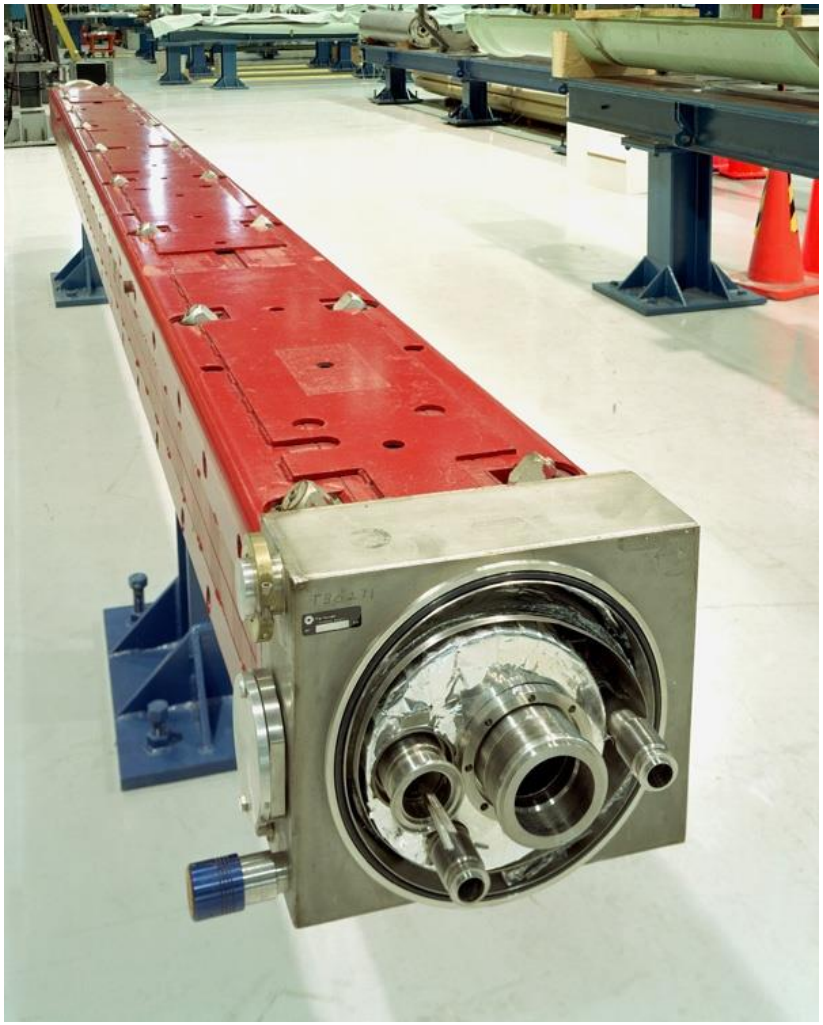


A positive particle moving away will be deflected to right by upward B



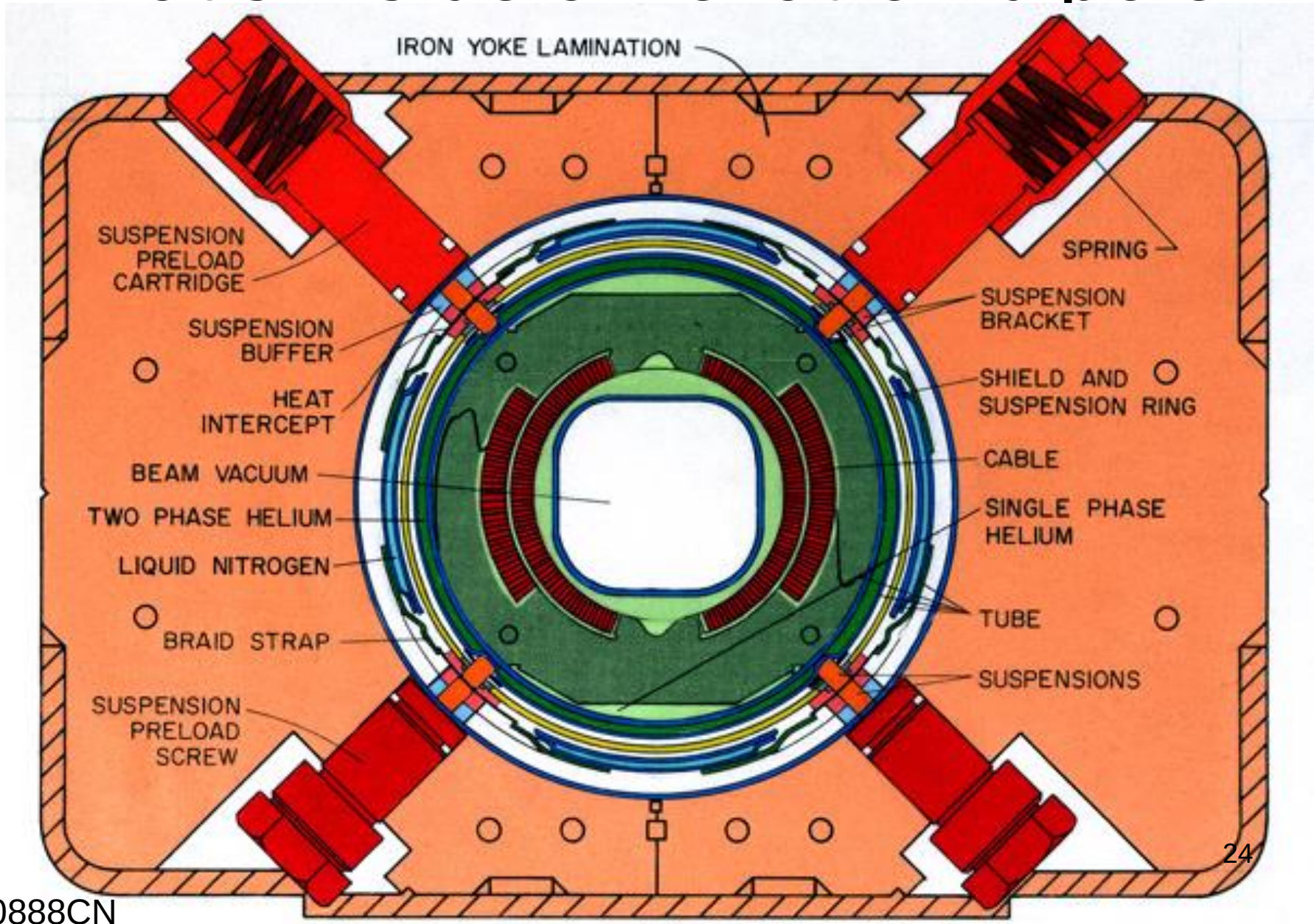
Superconducting Tevatron Magnet





- Outside is at room temperature; inside is at 4°K = - 452°F!
- Field is 4.4 Tesla @ ~4,000 A
- Each magnet is ~20 ft long, and weighs about 4 tons
- ~1000 magnets in the Tevatron (~800 dipoles, ~200 quadrupoles)

What's inside a Tevatron dipole?



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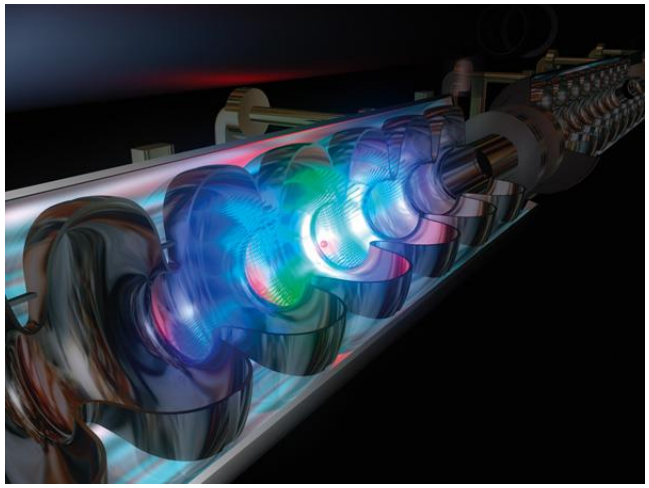
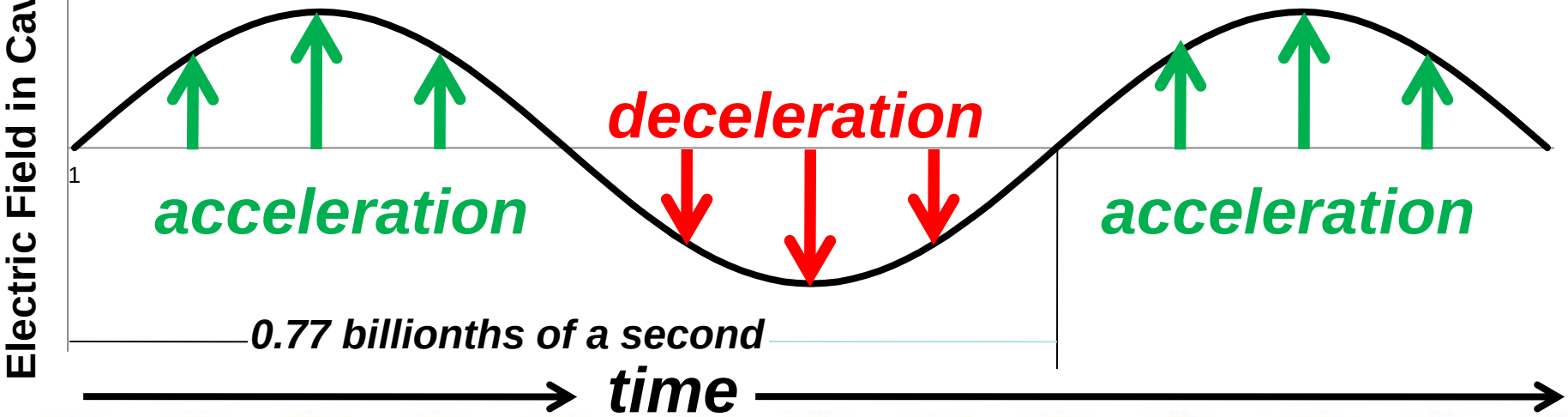
SC RF cavities, EXFEL, PIP-II

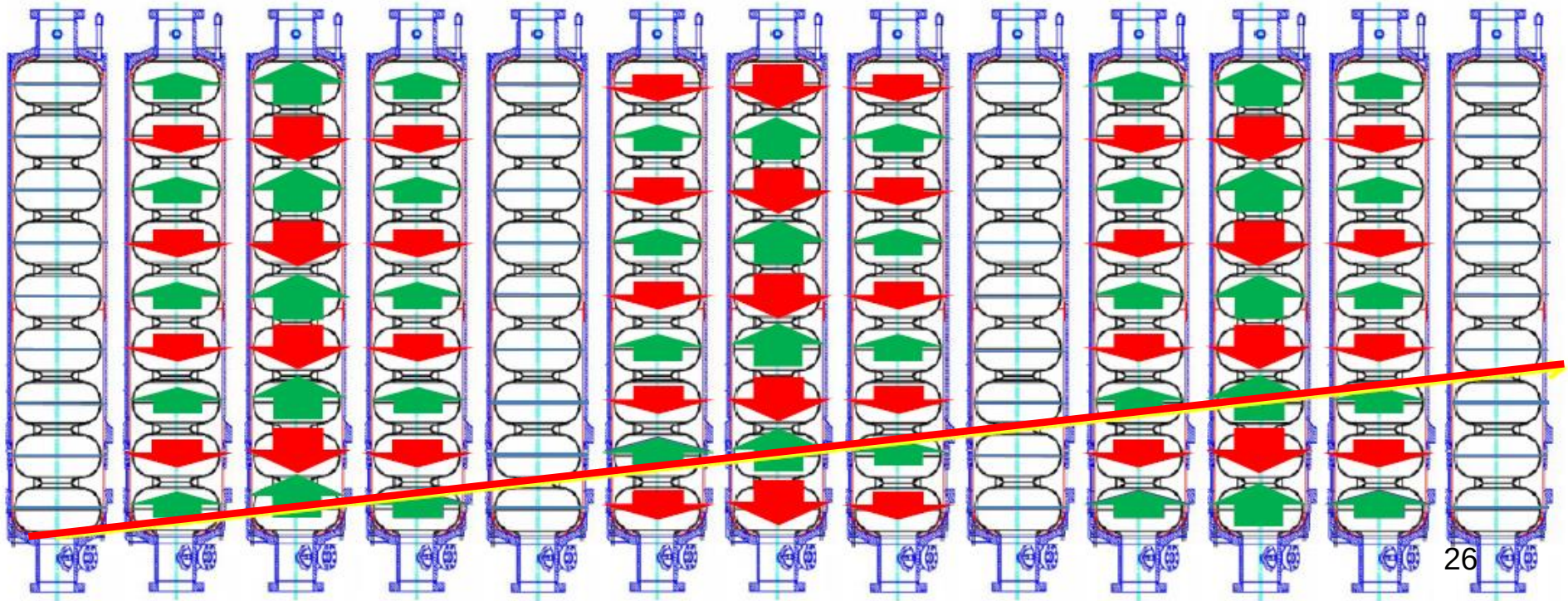
below is first Fermilab Cryomodule

8 cavities, 12 m long x 1 m dia.



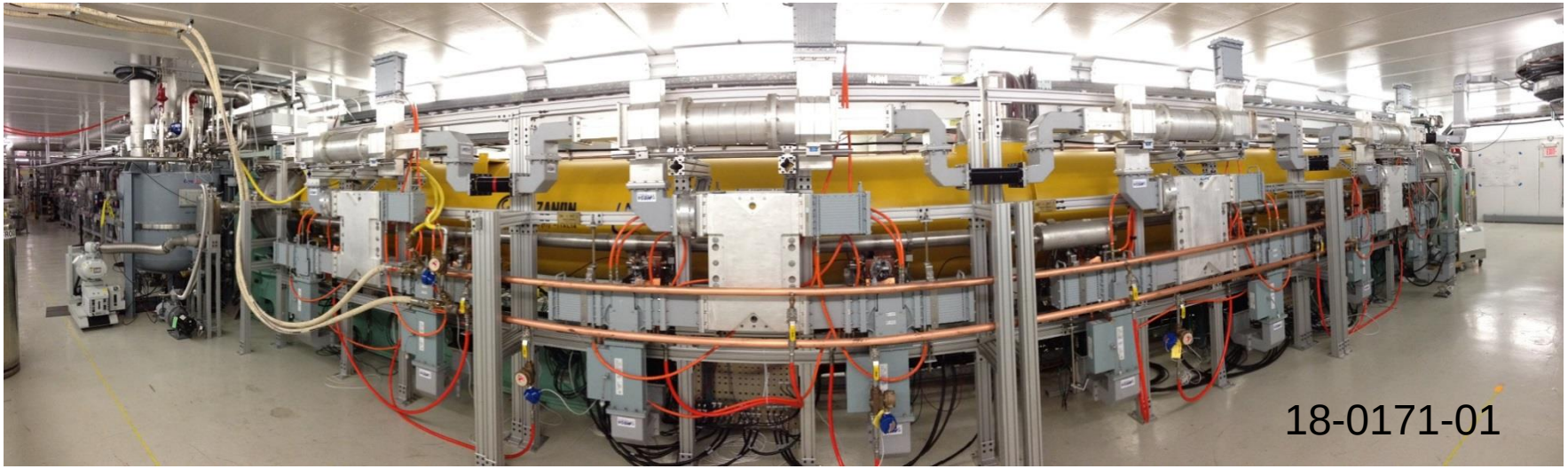
RF Cavity Operations – 1.3 GHz

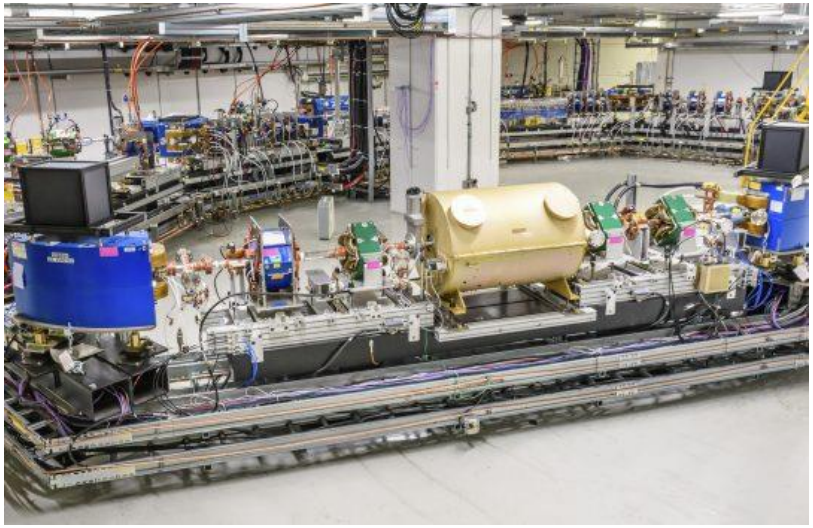


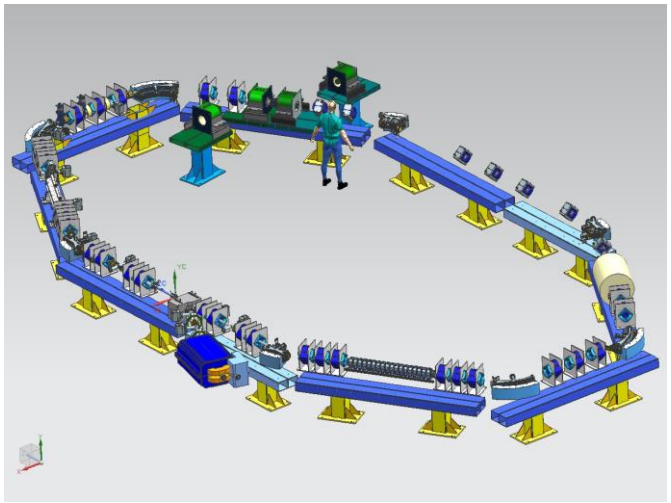


FAST-IOTA

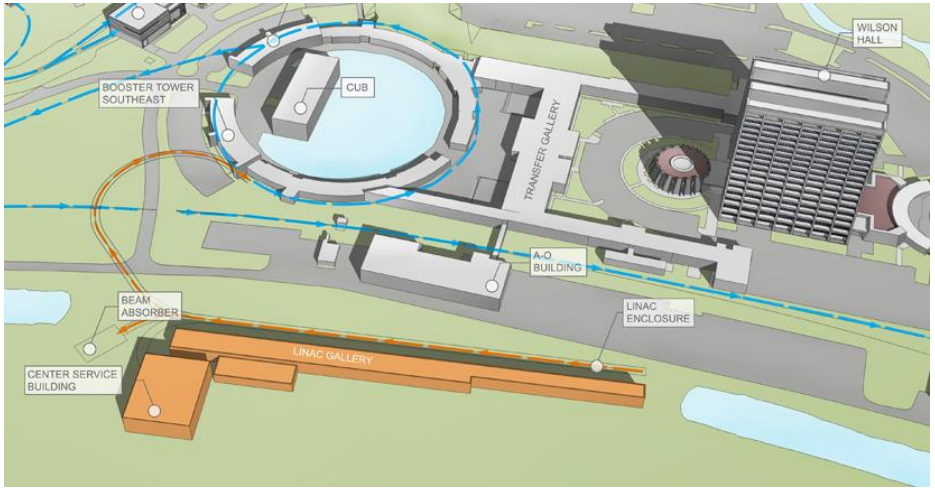
FAST: record 250 MeV electrons in 1 CM







PIP-II: 800 MeV superconducting replacement for Linac , startup ~ 2026



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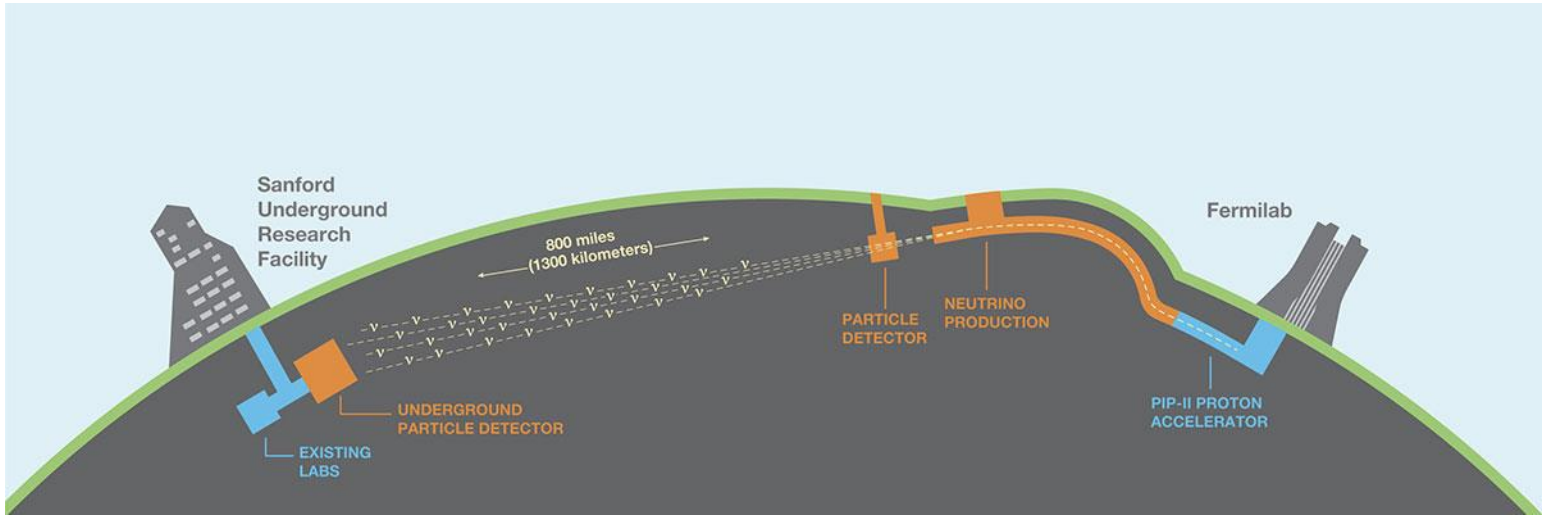
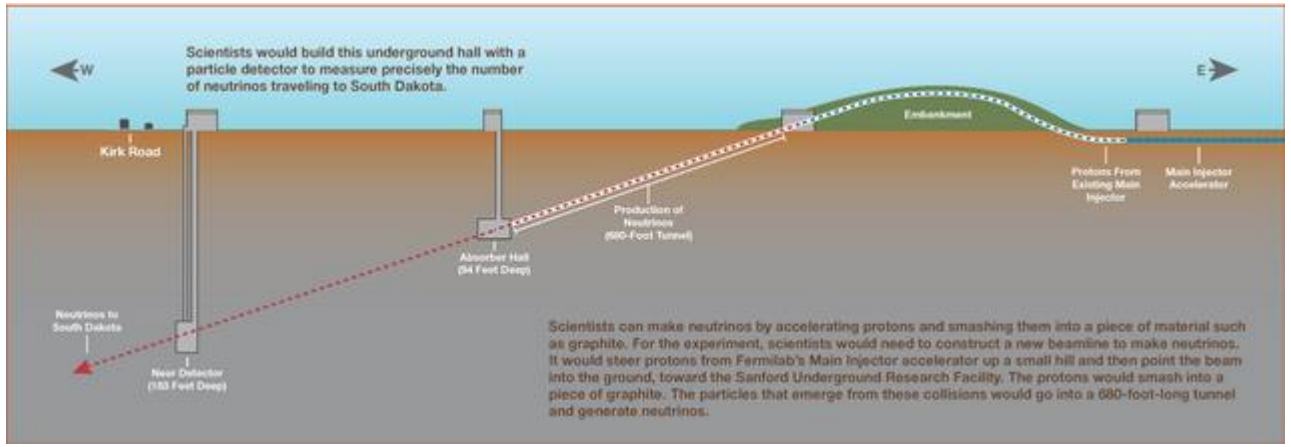
LBNF/DUNE
Long baseline – 1300 KM
FNAL → Leeds, South Dakota
ν oscillation experiment
start-up w PIP-II & LBNF
in ~ 2026





Fermilab Main Control Room

From here, control and monitor properties of all accelerators

around the clock operation, 24/7 all year

shut down periods occur, for maintenance

-- *now, for instance!*

crews of 5-6 Accelerator Operators and Crew Chief

In 2008:

- Running Fermilab Tevatron: 2 Tev p-pbar
  - Discovered top quark, searching for Higgs boson
- Fermilab MI ν to MINOS @ Sudan, MN
  - 1st long baseline ν oscillations, ν_μ disappearance
- BaBaR and Belle at e+e- *b*-quark factories
- CERN was building LHC
  - Expecting to discover Higgs boson
  - hoping for SUSY, extra dimensions, dark matter
- Proposed 500 GeV e+e- ILC, wait on approval

In the meantime:

- LHC started-up in 2008
- Tevatron shutdown, Sept 30, 2011
  - Fermilab to continue as high intensity ν lab
- CMS & ATLAS @ CERN LHC discover Higgs
  - announced July 4, 2012, Nobel Prize in 2013
- Fermilab builds NOvA exp. in Ash River, MN
  - observes electron neutrino appearance.
- European XFEL starts 2018 at DESY
  - Based on TESLA/ILC technology
  - Apply at SLAC LCLS-II and Fermilab PIP-II

In the meantime (continued):

- FNAL proposes Project X (renamed PIP-II)
  - Descoped from 8 GeV (Booster replacement) to 800 MeV (just LINAC replacement) will still need to replace Booster Later
- US HEPAP P5 (10 yr plan 2014) recommends:
  - Global: Continue US involvement in LHC upgrades
  - LBNF/DUNE & short-baseline ν exps @ Fermilab
  - PIP-II (800 MeV replacement for LINAC) needed for high-intensity ν program
  - Complete Muon g-2 and Mu2e exps @ Fermilab
  - Discontinue R&D on Muon Collider

Upcoming future choices, esp. European Strategy for post-LHC

- High Luminosity LHC – happening now
- ***Still waiting*** on decision on ILC 250 GeV
- High Energy LHC (27 TeV w 16 T magnets)
- FCC (CERN): 250 GeV e+e- → $H^0 + Z^0$

  100 TeV p p → *discovery*
- CEPC: Chinese electron positron Collider

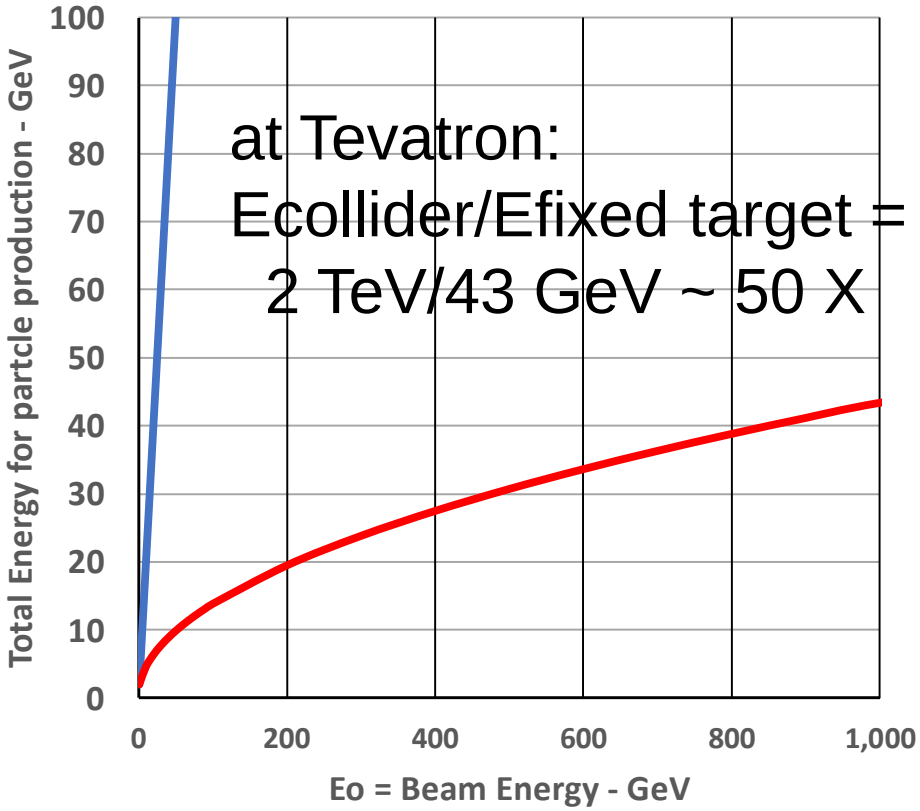
  initially 250 Gev e+e- → $H^0 + Z^0$

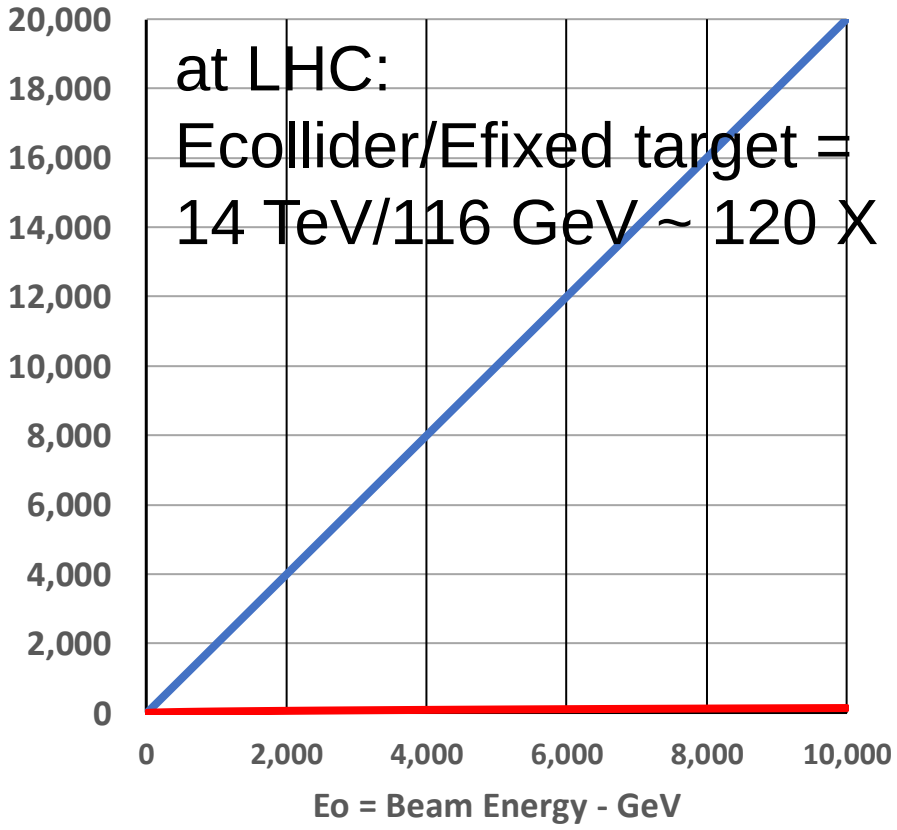
  followed by SPPC: 100 TeV p p

Why Colliders?
Energy Available for Particle Production

$$\textbf{Collider:} \quad E = 2\,Eo$$

$$\textbf{Fixed Target:} \quad E = \sqrt{2\,M\,Eo}$$



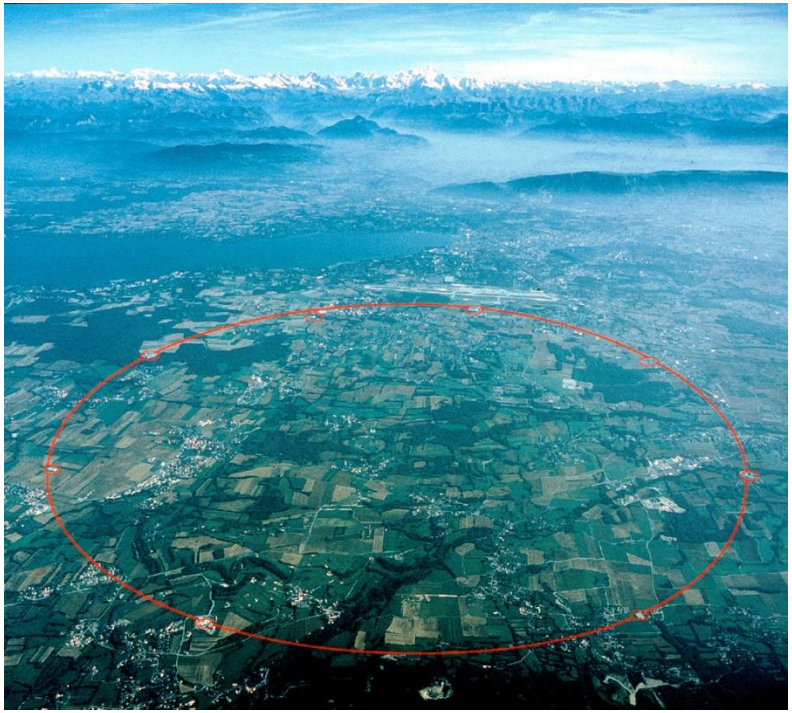


Fermilab: 2 TeV proton-antiproton collider

6 km circumference, 4.4 Tesla magnets, 1986-2011

CERN built the LHC, a 14 TeV p-p collider

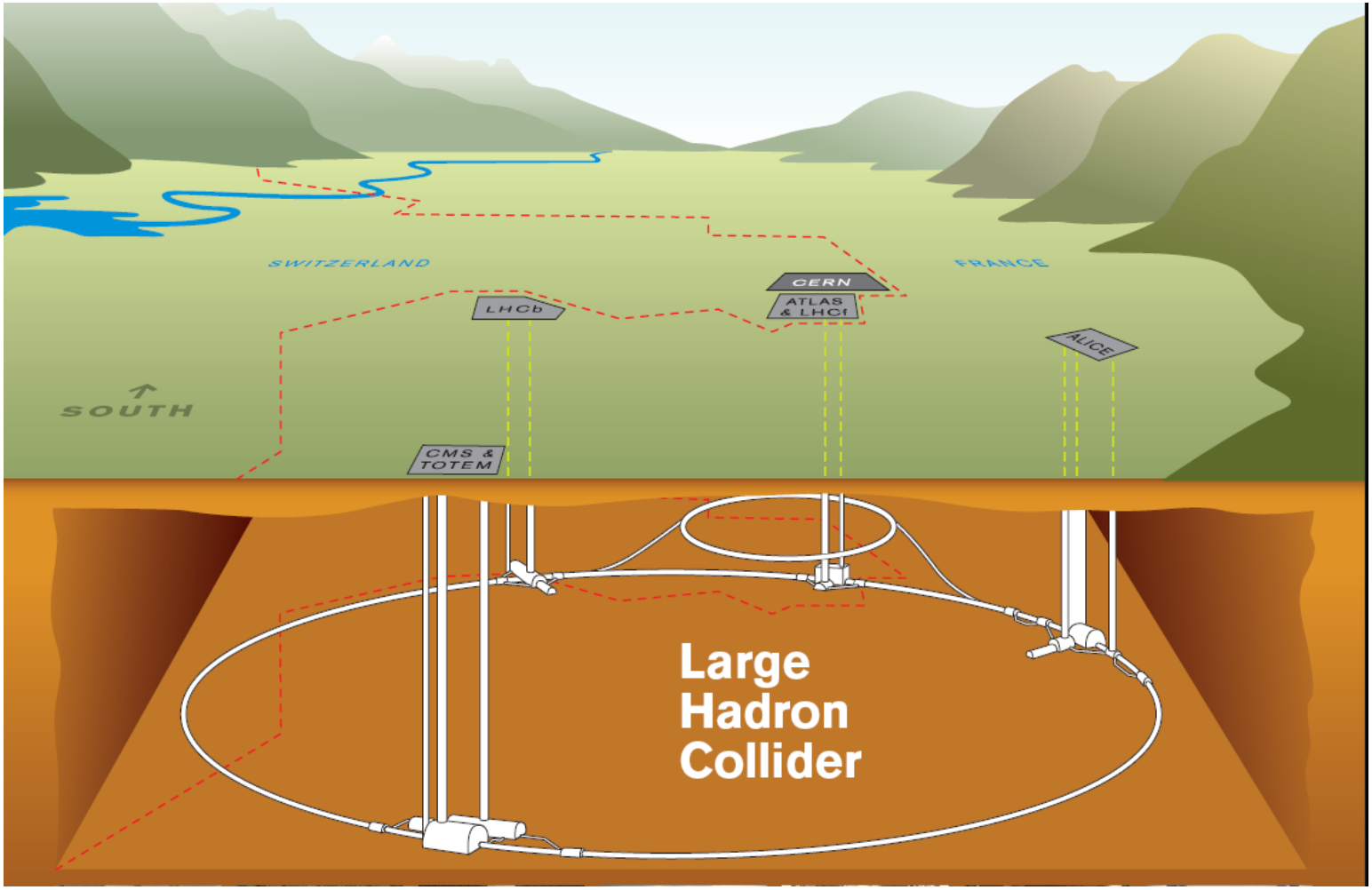
in a 27 km tunnel, 8.33 Tesla magnets, start-up in 2008



chicagotribune.com
Chicago Tribune Web Edition

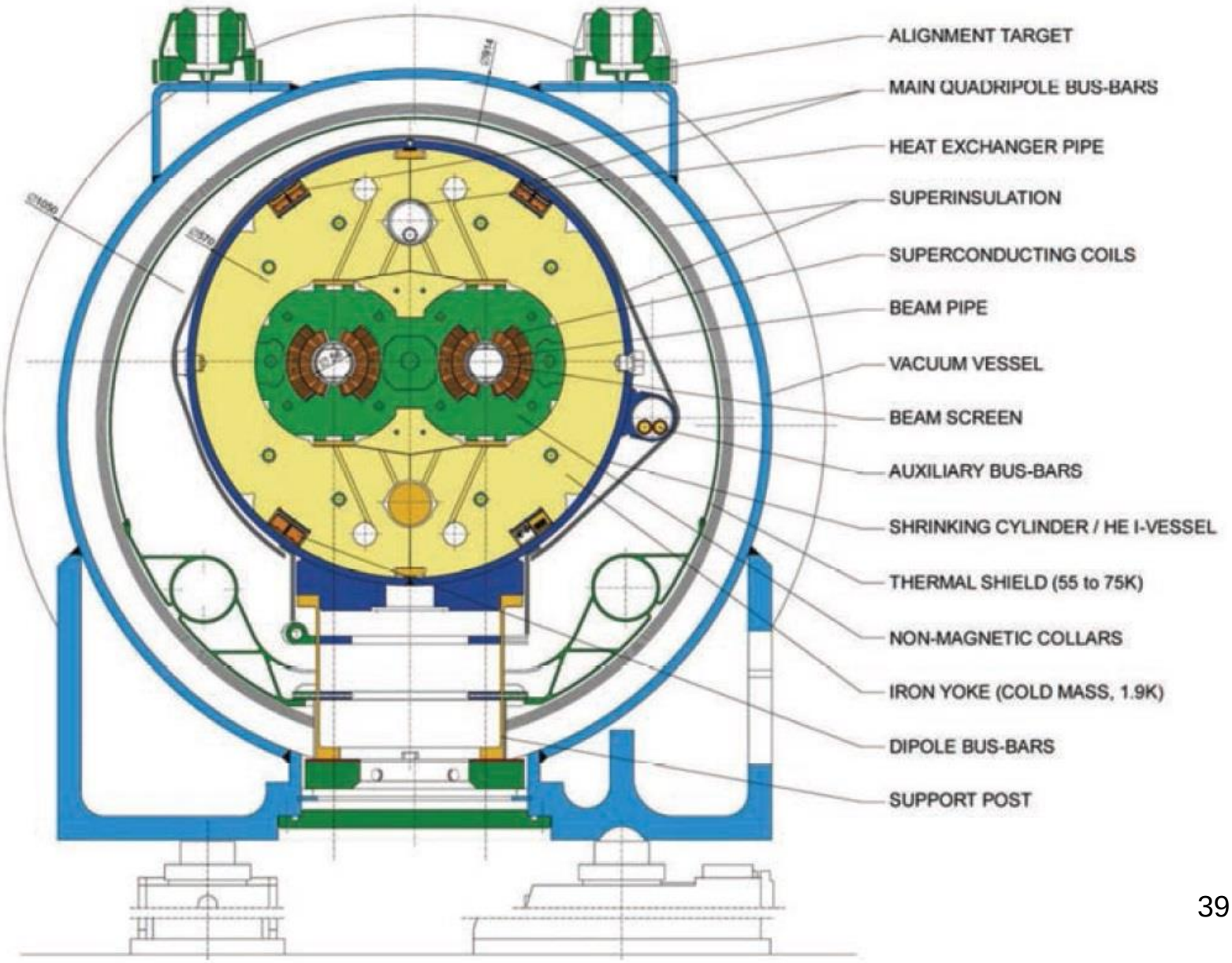
September 5, 2007

We've been on top for 25 years, now it's CERN's turn!

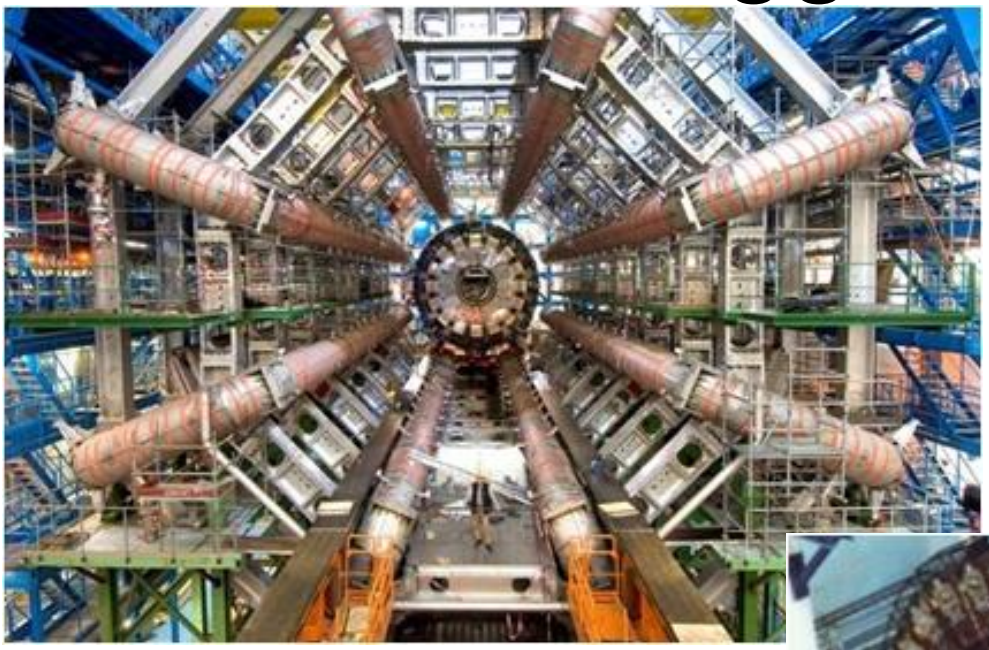


CERN's LHC has
4.25 x circumference, 1.65 x stronger magnets,
7 x more energy, and 33 x event rate,
than Fermilab's Tevatron Collider

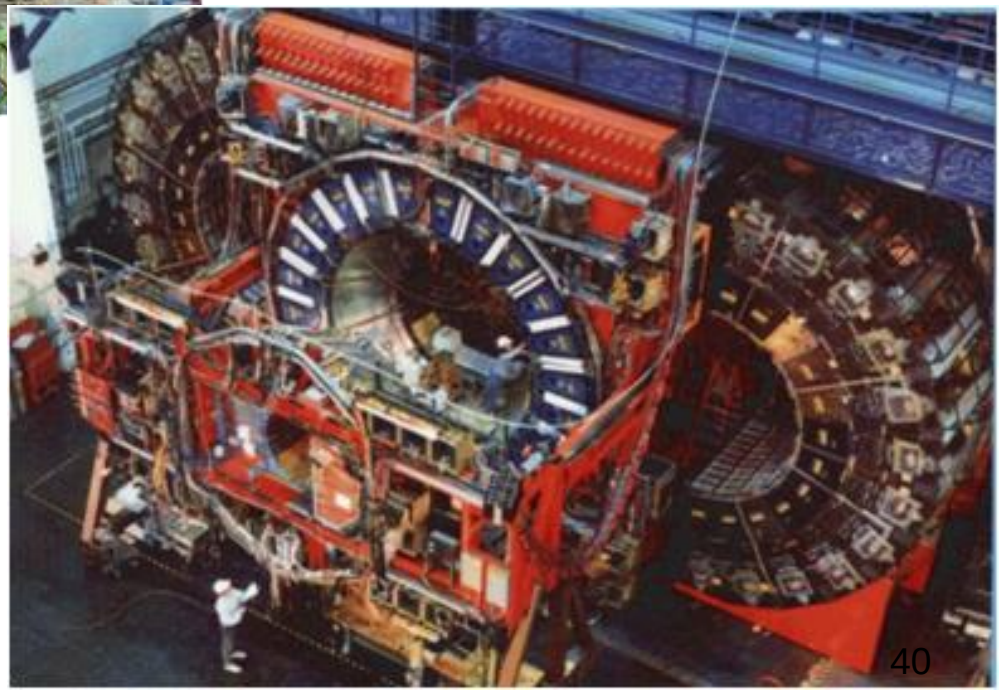
LHC dipole magnets 8.33 T @ 7 + 7 TeV



And Much Bigger Experiments!

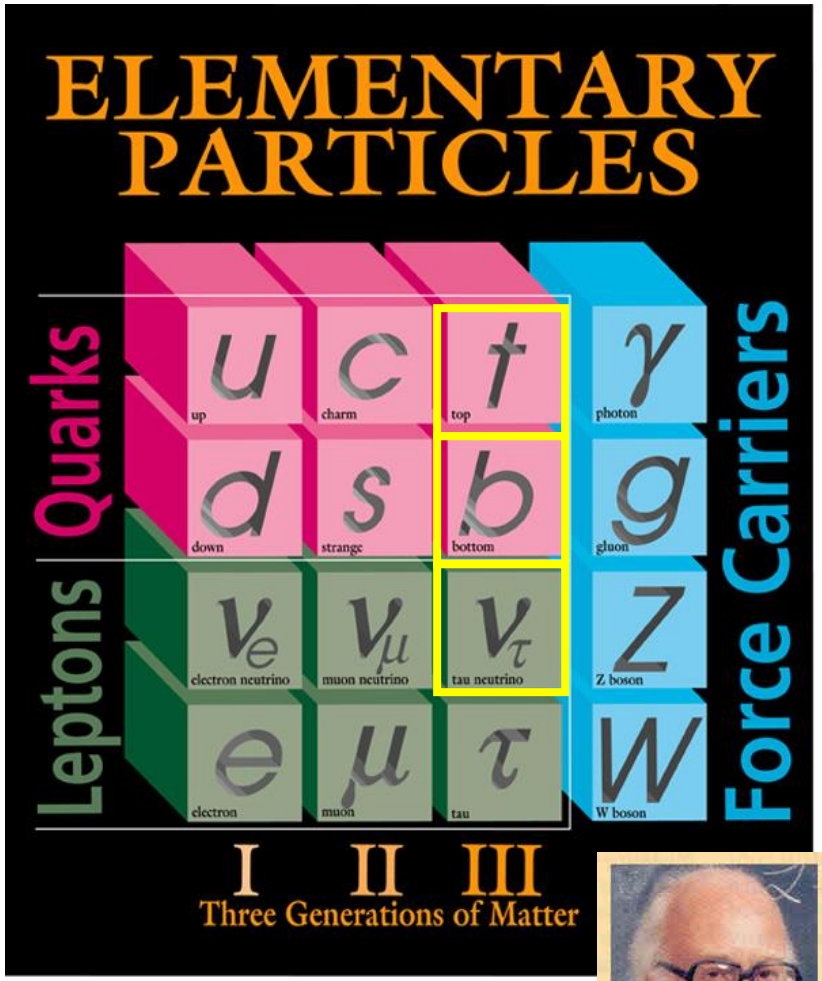


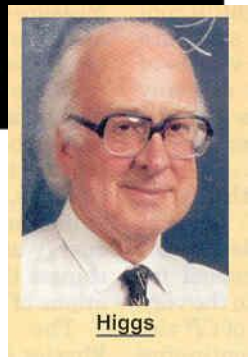
ATLAS at CERN



CDF at Fermilab

Our "Periodic Table"





Quarks, Leptons, & Forces

b, t, ν_τ discovered at FNAL

Electromagnetism
Strong Nuclear Force
Weak Nuclear Force
(radioactive decay)
Gravity is too weak
for Fermilab to study

fundamental particles
no size – without parts
can't break them apart
(at least with today's accelerators)

Higgs boson discovered at CERN
announced July 4, 2012
Higgs field gives all the other particles their mass

Some of today's *hot* physics topics:

What causes *mass*? *Properties of* the *Higgs boson*
Why are there different types of quarks & leptons?
Very curious *neutrinos*! (weak force)
Why does the universe seem to be "*matter*",
rather than a balance of matter and anti-matter?
Is there anything *inside* quarks & leptons?
Are there any *other types* of particles or forces?
Are there more than 4 *dimensions* (x, y, z, t)?
How does *gravity* fit in to the picture?
What is "*dark matter*" and "*dark energy*"?
***experimental astrophysics* questions**
not only high energy or particle physics,

Accelerator Uses

- **Fundamental Research into Nature**
  - **Particle Physics and Nuclear Physics**

  } **~100 accelerators**
- **Light sources:** **e.g. Advanced Photon Source @ ANL**
  - **Condensed Matter Physics**
  - **Chemistry**
  - **Biology**
  - **Archeology**
- **Medicine (~ 5000 accelerators)**
  - **X-rays**
  - **Particle therapy:** **neutrons, Fermilab synchrotron for Loma Linda, NW Medicine Chicago Proton Center**
  - **Production of Radioactive Isotopes:** **FNAL PET RFQ → Louisiana**
- **Industrial Applications (~ 4900 accelerators)**
  - **Semiconductor Fabrication**
  - **Electron Beam Welding and Furnaces**
- **(old-fashioned) Televisions!**

Modern Accelerator Technologies

- RFQ: now everywhere now, Fermilab PET
- Superconducting Synchrotrons:
  - Fermilab Tevatron, HERA proton ring @ DESY, Relativistic Heavy Iron Collider (RHIC) @ BNL, Large Hadron Collider (LHC) @ CERN
- Superconducting RF Cavities (SRF):
  - ATLAS (heavy ion Linac) @ ANL, J-Lab e-beam, Spallation Neutron Source (SNS) @ ORNL, FLASH & EXFEL @ DESY => FAST @ FNAL

  → LCLS-II @ SLAC (construct @ FNAL & J-Lab),

  → PIP-II Linac at Fermilab

End of my Presentation
Thank you for coming!

http://www.fnal.gov
http://www.fnal.gov/pub/today/
http://www.linearcollider.org
http://www.symmetrymagazine.org
http://www.particleadventure.org
https://ed.fnal.gov/programs/tours/ask-a-scientist-archive.shtml

- **I'll be happy to continue discussion:**
  - **Benefits of Research in Particle Physics**
  - **More on what we don't know about nature**
  - **Seeing particles**
  - **Neutrino Physics (beams to MN & SD)**

Don Lincoln's accelerator u-tube videos

https://www.youtube.com/playlist?list=PLCfRa7MXBEsoJuAM8s6D8oKDPyBepBosS

(numbers, as of 6sept2019, may change)

7: How PIP-II will take Fermilab to the next level

10: Everything you ever wanted to know about Fermilab

37: Future Circular Colliders

39: Accelerator Science: Why RF?

41: Accelerator Science: Circular vs. Linear

42: Accelerator Science: Proton vs. Electron

43: Accelerator Science: Luminosity vs. Energy

44: Accelerator Science: Collider vs. Fixed Target

67: LHC: The Large Hadron Collider

Ask-a-Scientist

https://ed.fnal.gov/programs/tours/ask-a-scientist.shtml

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Ask-a-Scientist

Attend a free lecture, talk to scientists and tour Fermilab.

Program: Take science questions straight to experts. Physicists answer questions and explain everything from the Big Bang to how a particle accelerator works. A Spanish version of Ask-a-Scientist (Pregunte a un CientÃfico) is available twice a year.

When: 1 PM to 4 PM on the first Sunday of the month (except holiday weekends when we delay by one week and the month of the Family Open House).

Where: Wilson Hall, Fermilab (Directions to Fermilab)

Suggested audience: adults and students with a keen interest in science! The presentation and tone is set for high school seniors - college freshman. **Students 10 to 14 years old can attend, but must be accompanied by an adult. The minimum age for the tour is 10 years old. No exceptions.**

Registration: Reservations are required and space is limited. To register for this event, go to the Special Events Calendar or the Online Registration. Click the pencil icon next to the event.

Contact: Lederman Science Center, Education Office
P.O. Box 500
Batavia, IL 60510-0500
(630) 840-5588, edreg@fnal.gov

Related Links:

Archive of Ask-a-Scientist Lectures
Special Events Calendar
Online Registration

Neutrino physicist Herman White talking to visitor

Backup materials

- Accelerator Technology
- Experimental Physics incl. Neutrinos
- ILC

Benefits of Fermilab Research

- **increase our understanding of nature and how it works – just part of being human**

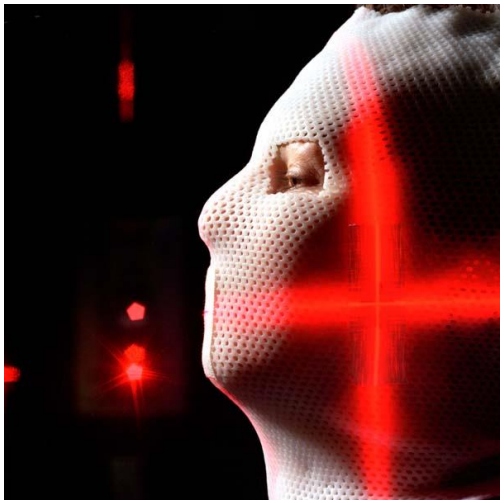
- **technological spin-offs – often far in future**
  much of today's economy based on research in the late 1800's – early 1900's

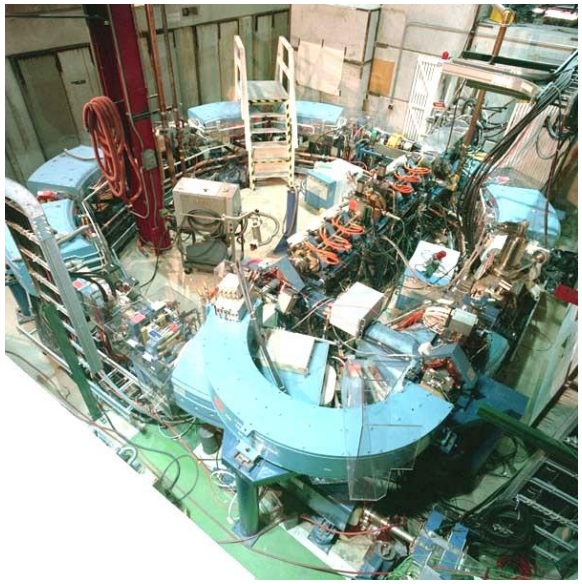
electron → TV (accelerator) & communications

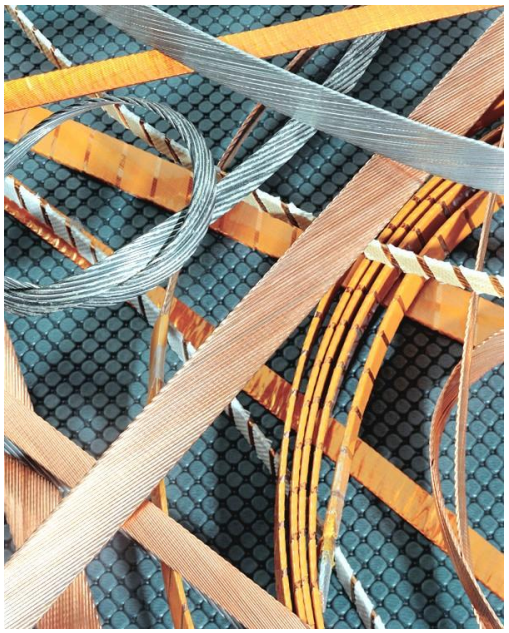
- **some examples from Fermilab & HEP**

Neutron Therapy Facility at Fermilab – R. R. Wilson

Proton Accelerators for Medicine – Loma Linda & PET







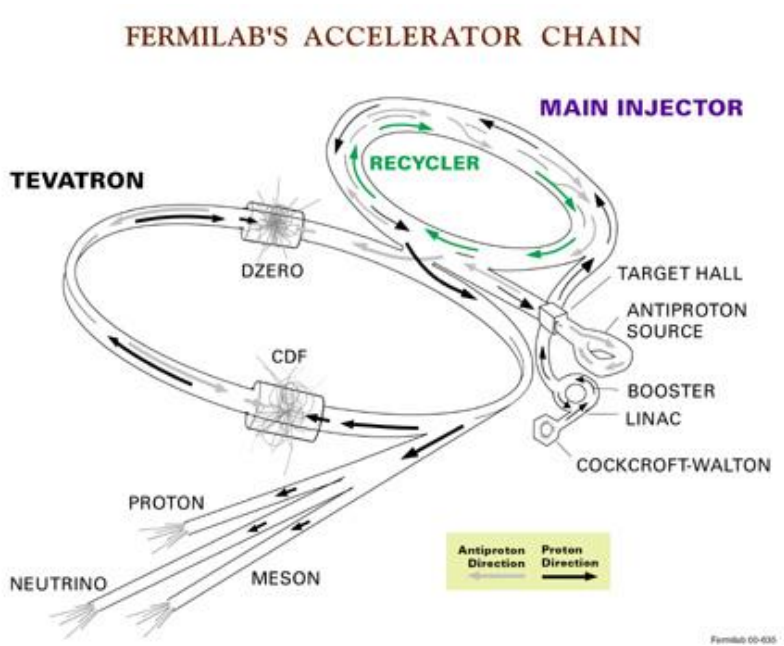
SC wire – Tevatron → practical MRI (medical diagnostic)

WWW – invented @ CERN by Tim Berners-Lee

Accelerator Technology

Fermilab Accelerator Complex

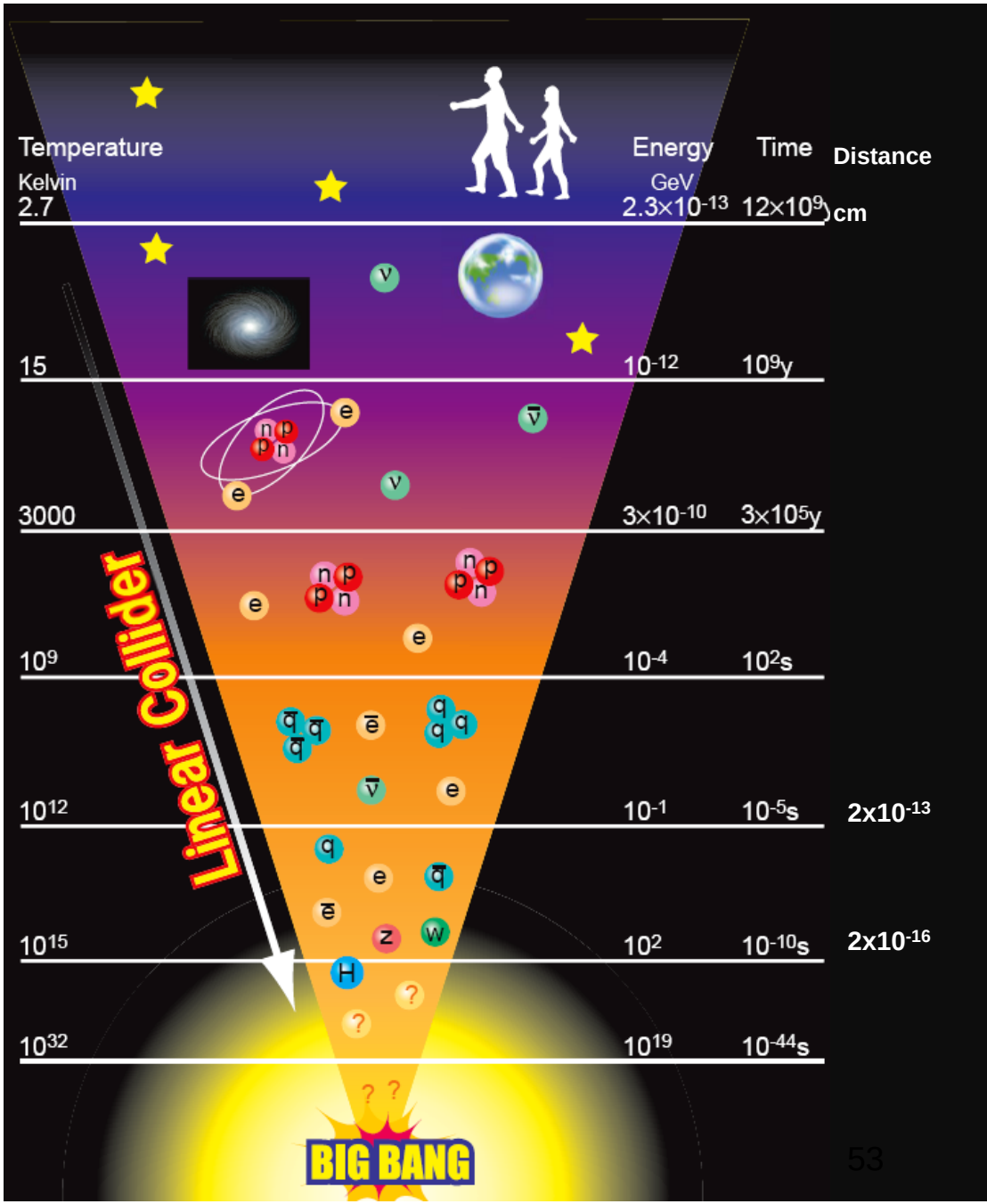
http://www-bd.fnal.gov/public/



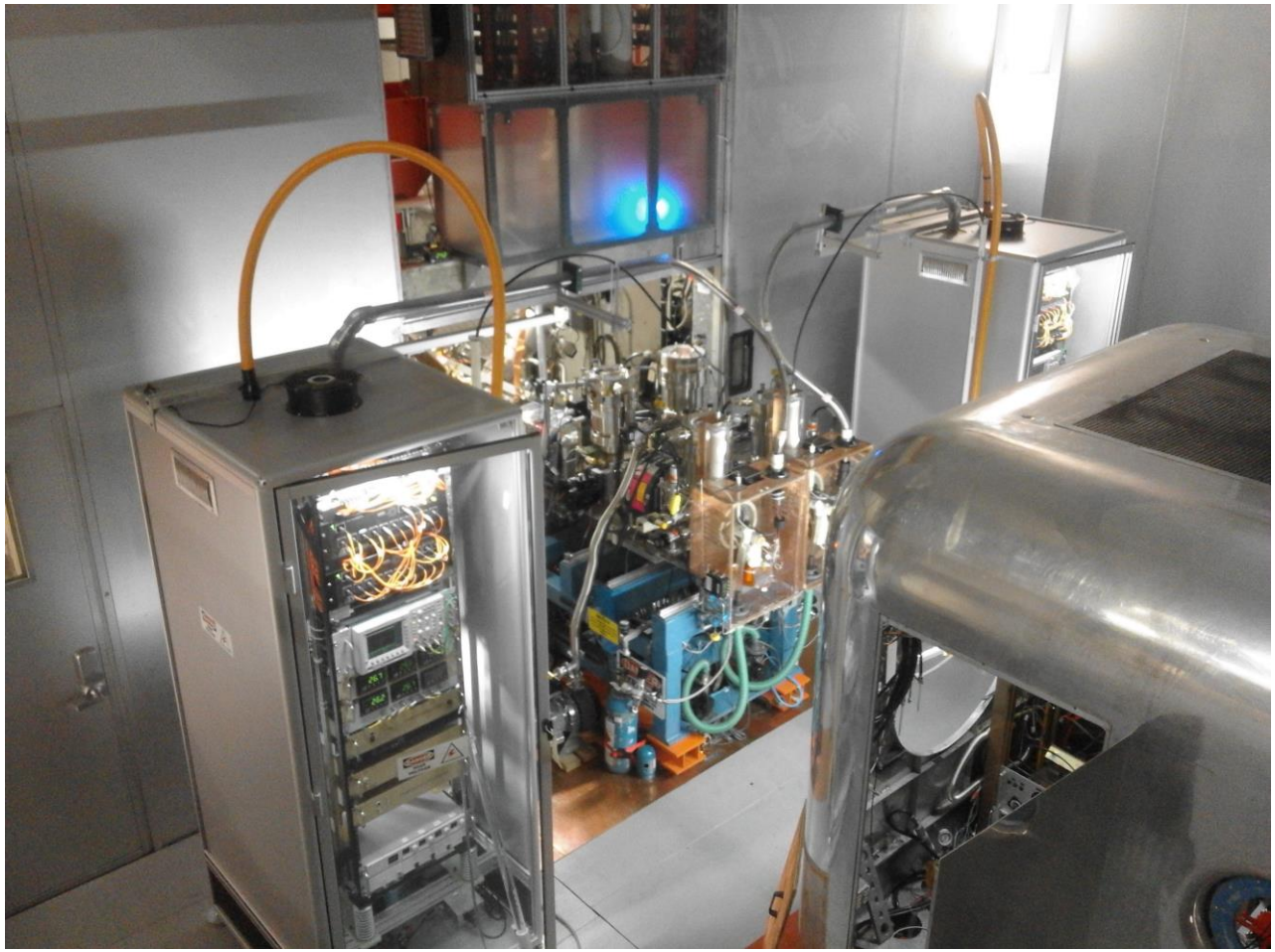
You need big machines to study small particles!

Accelerators are like ***microscopes:*** Energy => 1/distance and like ***time machines:*** Energy => 1/time

also Energy => ***Temperature***

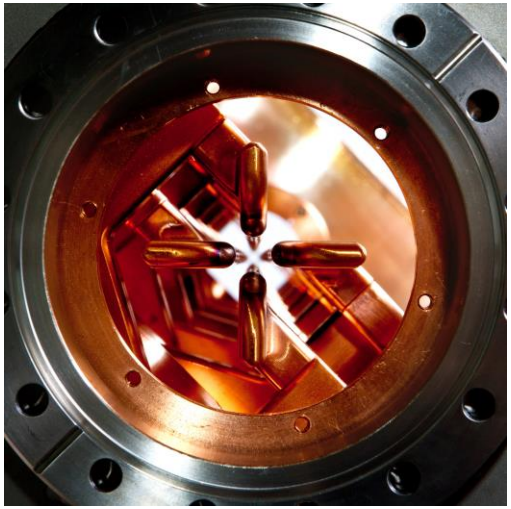


H^- source

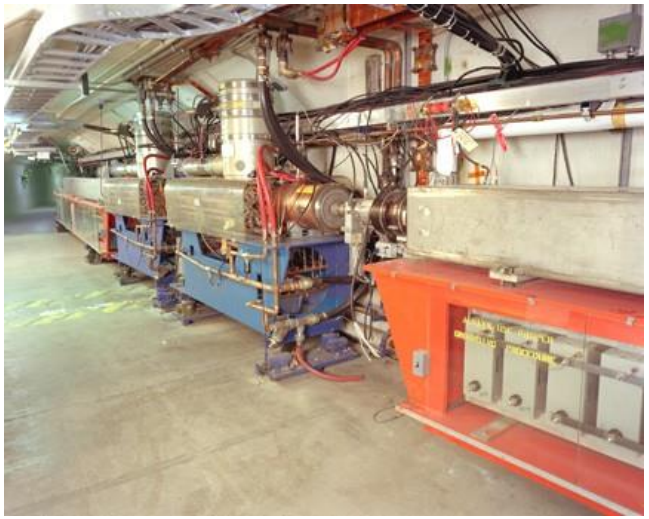


How an RFQ works – CY Tan

Radio Frequency Quadrupole



Tevatron dipole & quadrupole cross sections w/cryo lines



Cockcroft-Walton 750 KeV — ***velocity = 0*** → ***0.04 c***

LINAC 400 MeV — ***0.71 c*** →

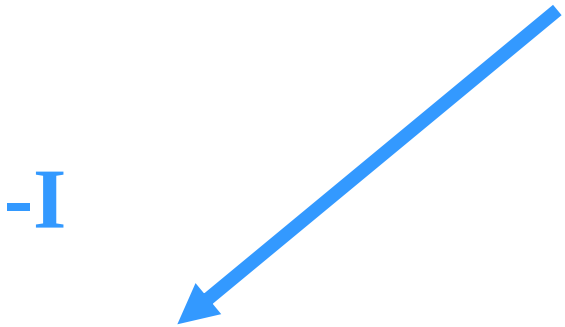
Booster 8 GeV — ***0.994 c***

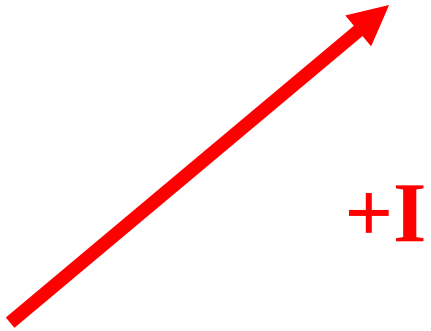
Main Injector 150 GeV — ***0.994 c*** → ***0.99998 c***

Antiproton "Bottle" — ***@ 8 GeV***

Tevatron 1000 GeV = 1 TeV — ***0.99998 c*** → ***0.9999995 c***

particles moving in magnetic field

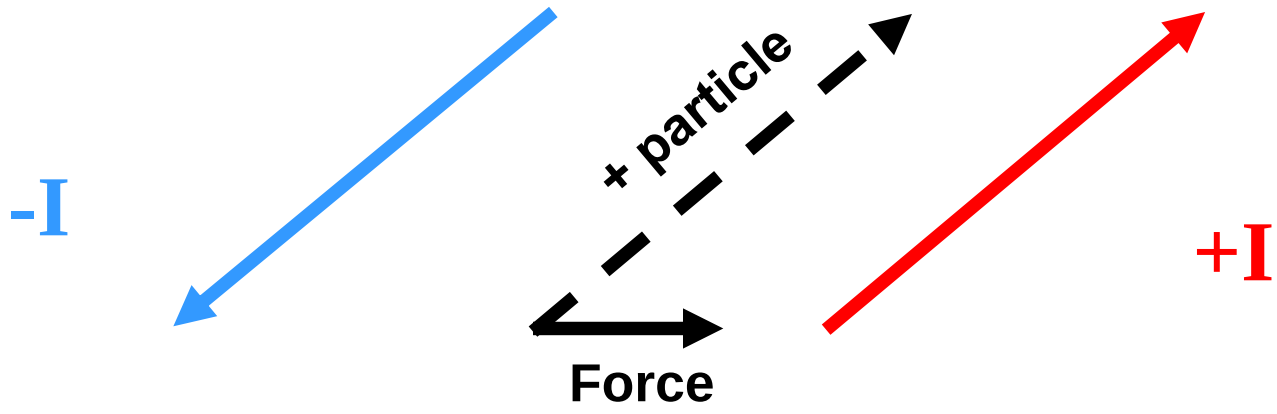




electric current moving towards produces counter-clockwise magnetic field

electric current moving away produces clockwise magnetic field

particles moving in magnetic field



positively charged particle moving away, feels force from vertical magnetic field bending particle toward right

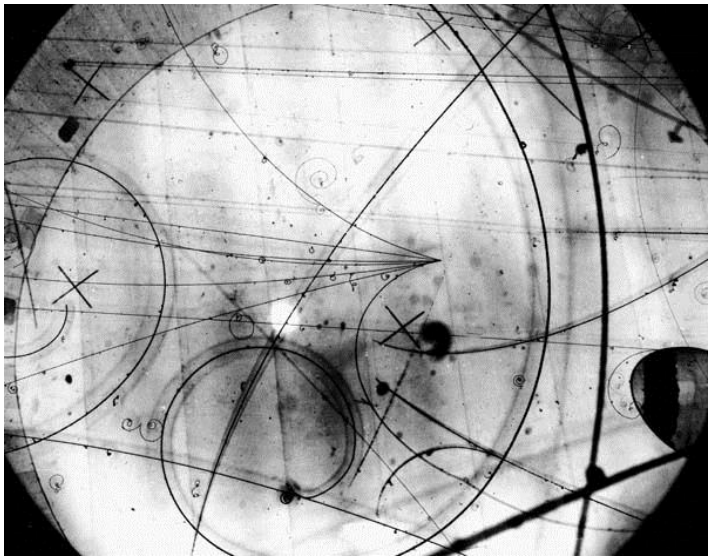
opposite currents attract ….

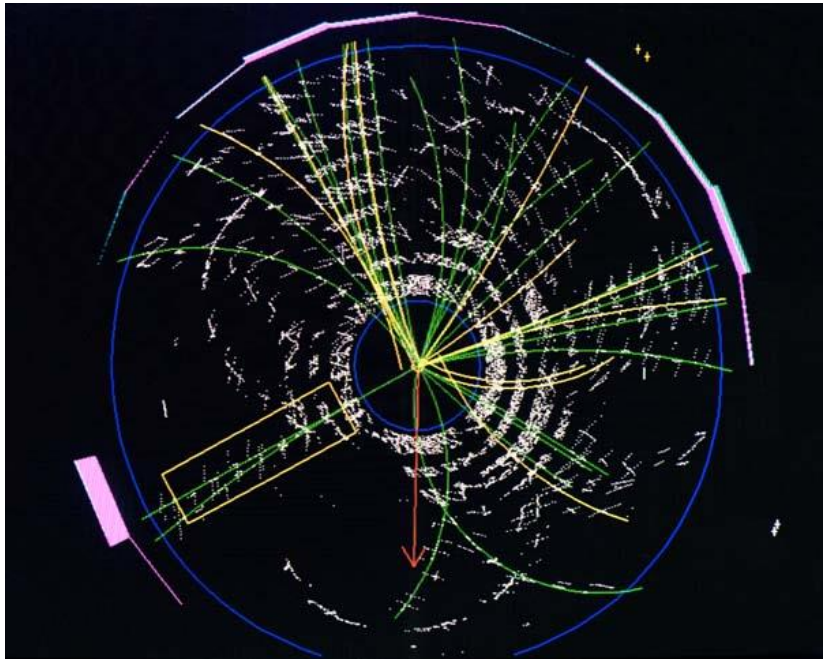
electric current moving towards produces counter-clockwise magnetic field

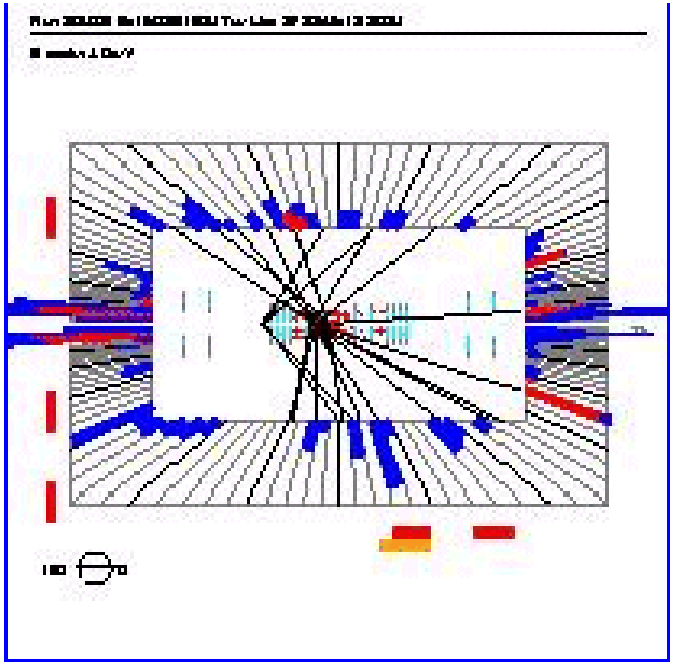
electric current moving away produces clockwise magnetic field

Seeing Particles

Seeing particles - indirectly

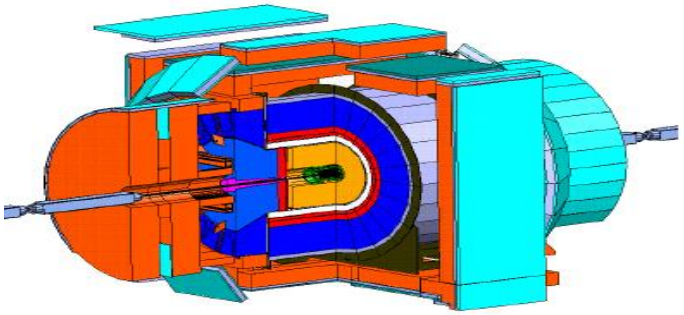




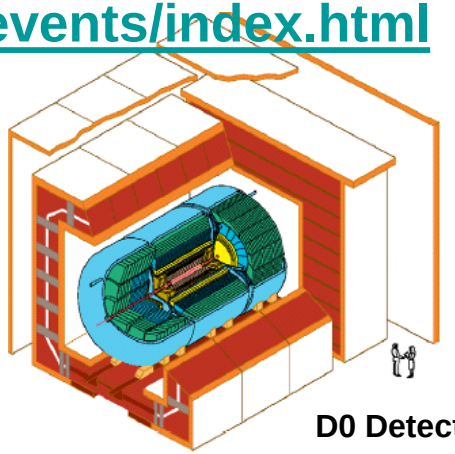


CDF & D-Zero Experiments

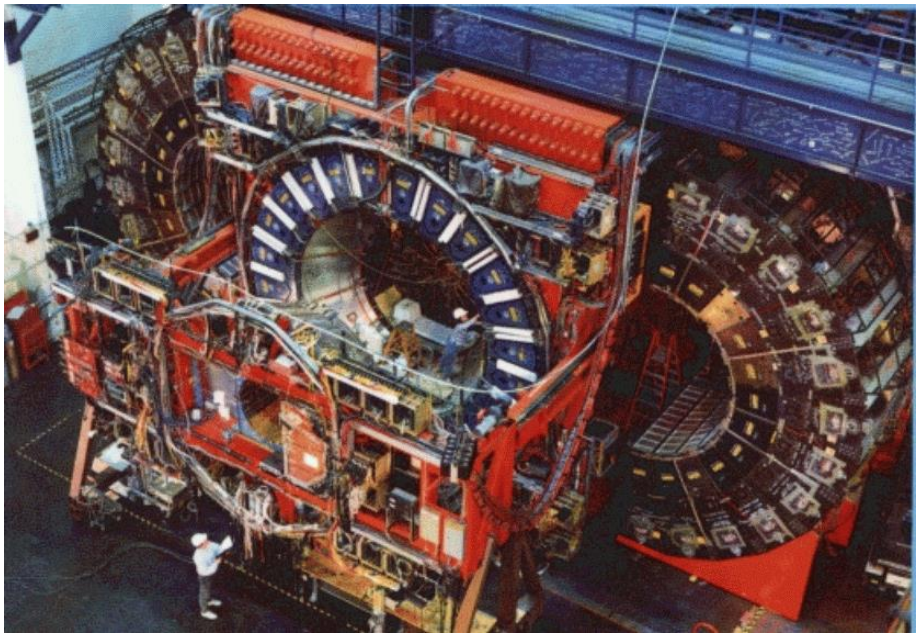
http://www.fnal.gov/pub/now/live_events/index.html



CDF Detector

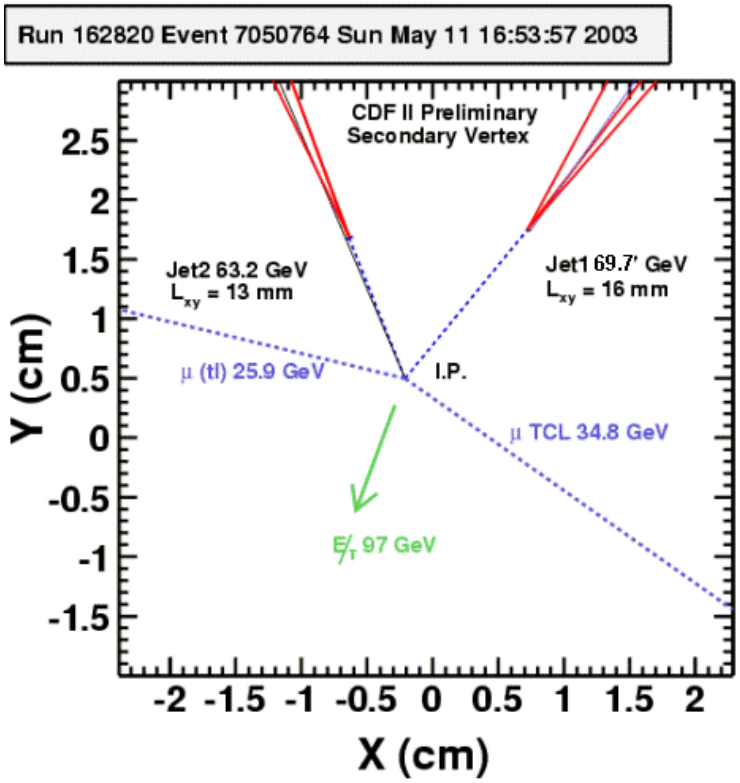


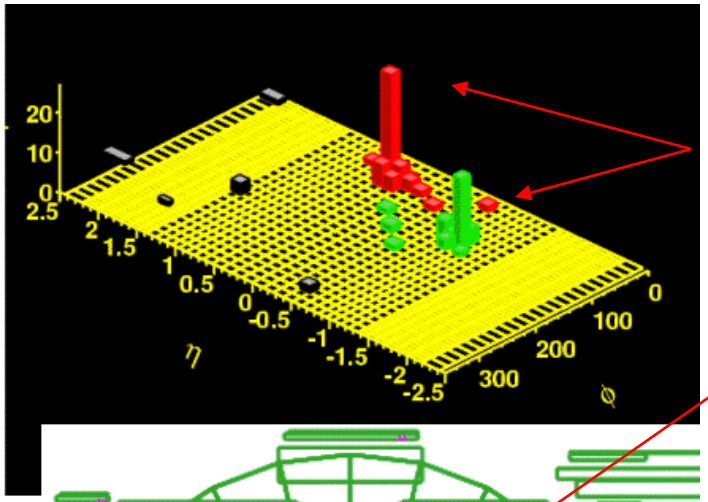
D0 Detector

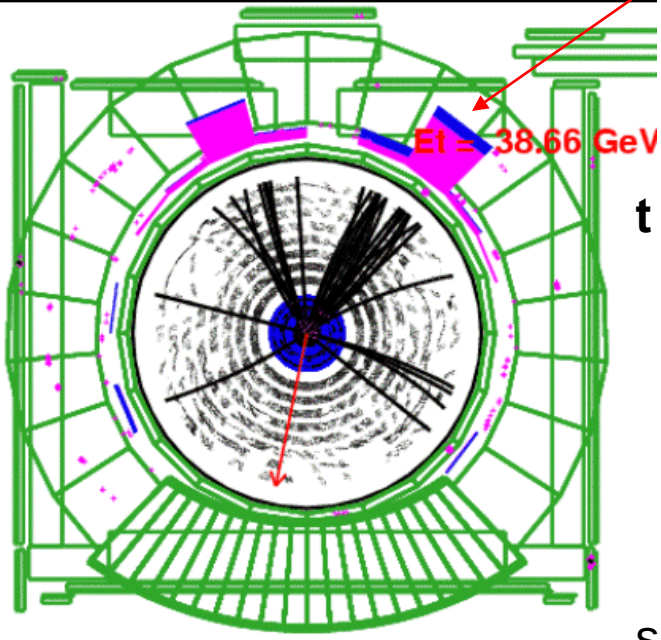


Observation of top-quark pair production at Fermilab

Double b-tagged dilepton event @ CDF







$E = mc^2$

Jets or sprays of particles from bottom quarks

$t \rightarrow W + b$

$\downarrow \quad \downarrow$

$\nu + \mu \quad$ jet

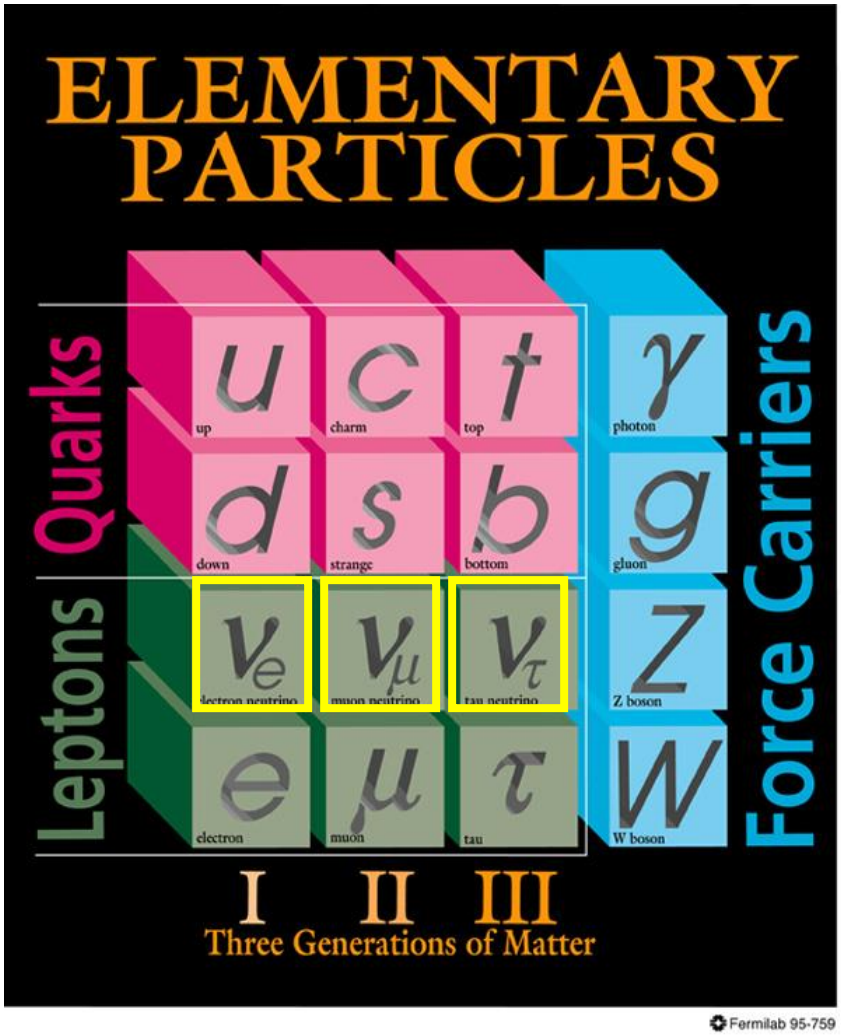
$\downarrow \quad \downarrow$

missing energy — multi-particles

similar for decay for **t-bar**

ZOOM IN : silicon microstrip detector

Experiments incl Neutrinos



***Curious neutrinos*!**

only *Weak* force

do ν have any *mass*?

if so, one kind of ν

could change

into another

kind of ν and

back again!

oscillations…

$\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$

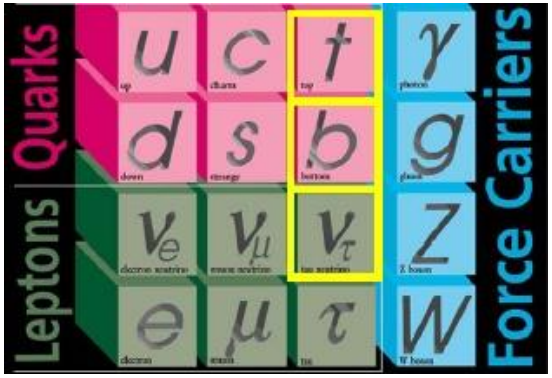
Is There a New Symmetry in Nature?

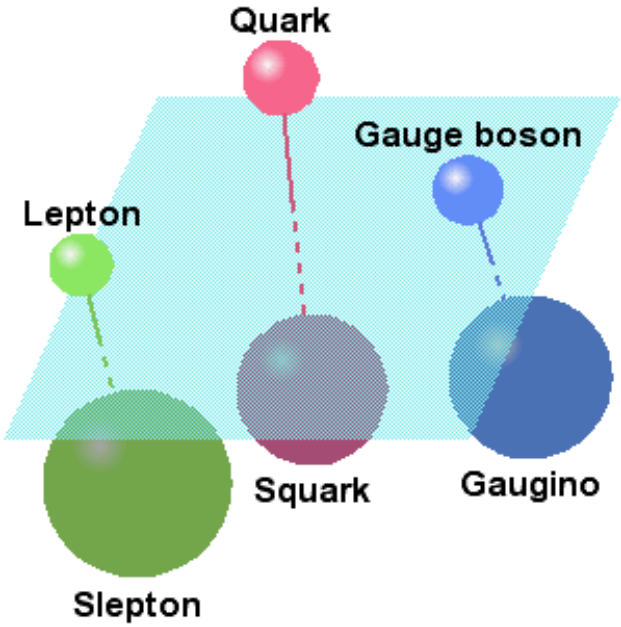
Supersymmetry

Bosons ⟷ **Fermions**

Particles

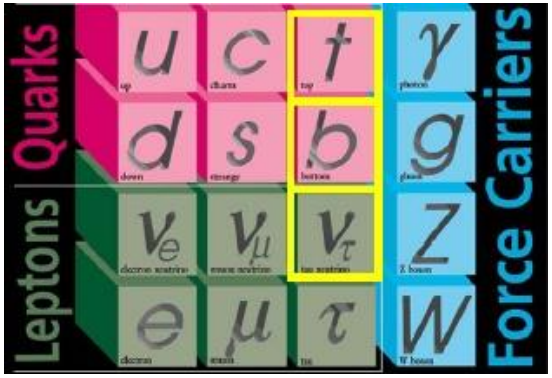
S = ½ S = 1





SUSY Sparticles

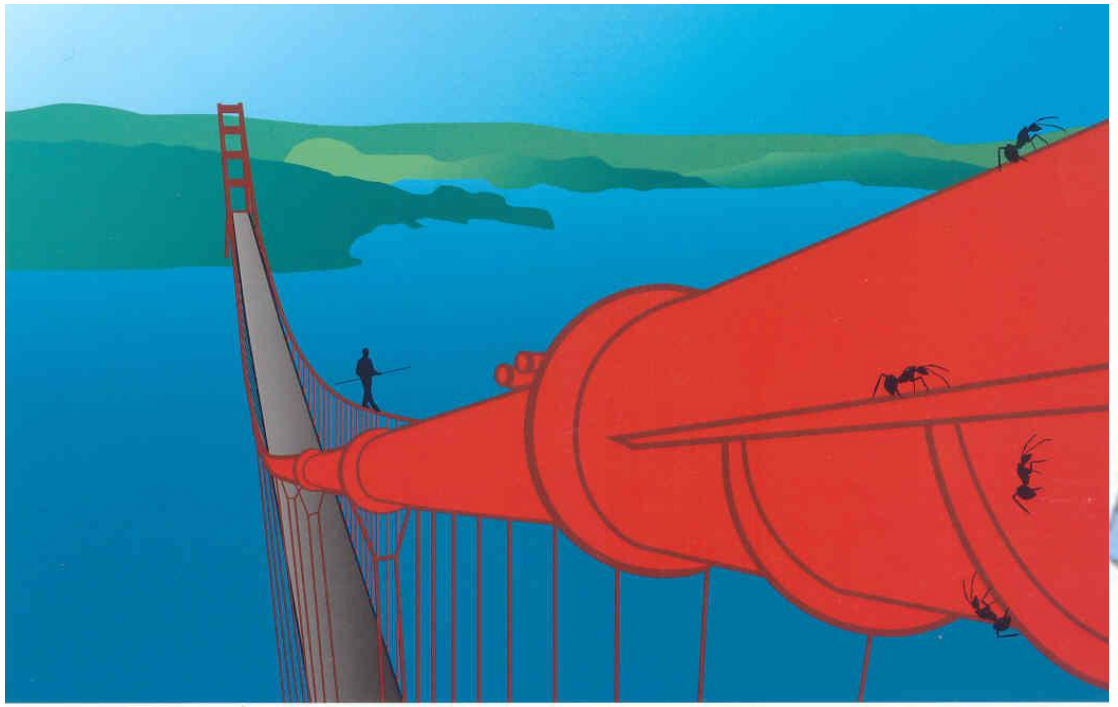
S = 0,1 S = 1/2

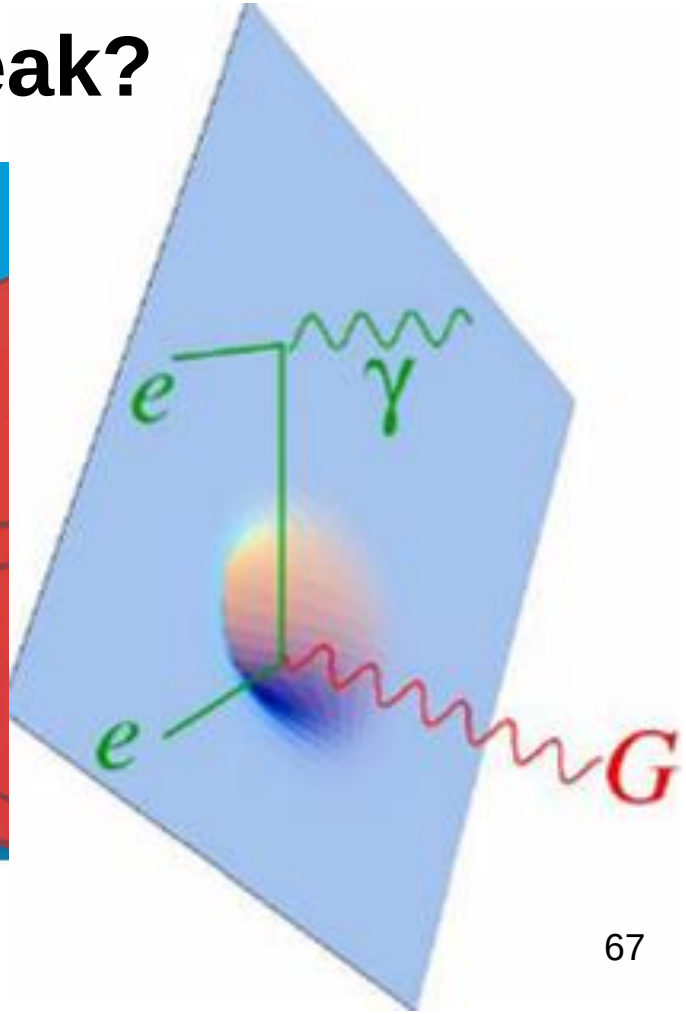


Example of a curled-up (invisible) extra dimension

How can we observe it?

Is that why gravity is so weak?





The mass-energy of Universe consists of 25 % dark matter & 70% dark energy

"dark" => doesn't emit or absorb starlight

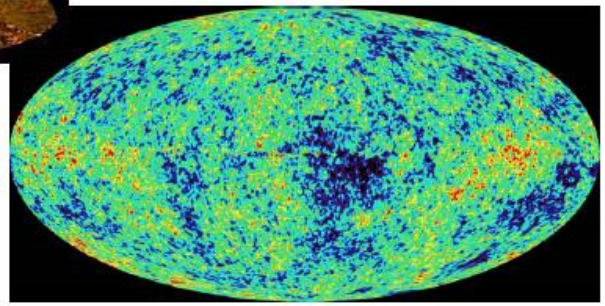
Rotational speed of galaxies

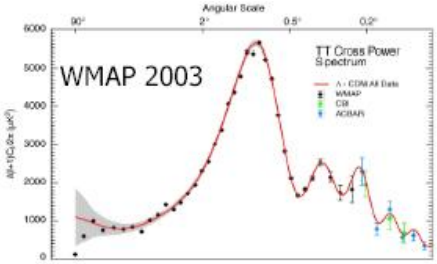
Clumpiness of cosmic microwave background radiation

M81 galaxy &

WMAP satellite

About six to seven times more mass in the universe (27±4%) than there is baryonic matter (4.4±0.4%)





What is this stuff? How can we get a firmer understanding of it?

Accelerators

The rate of expansion of universe seems to be *increasing!*

Much more mass-energy than (known) quarks & leptons!

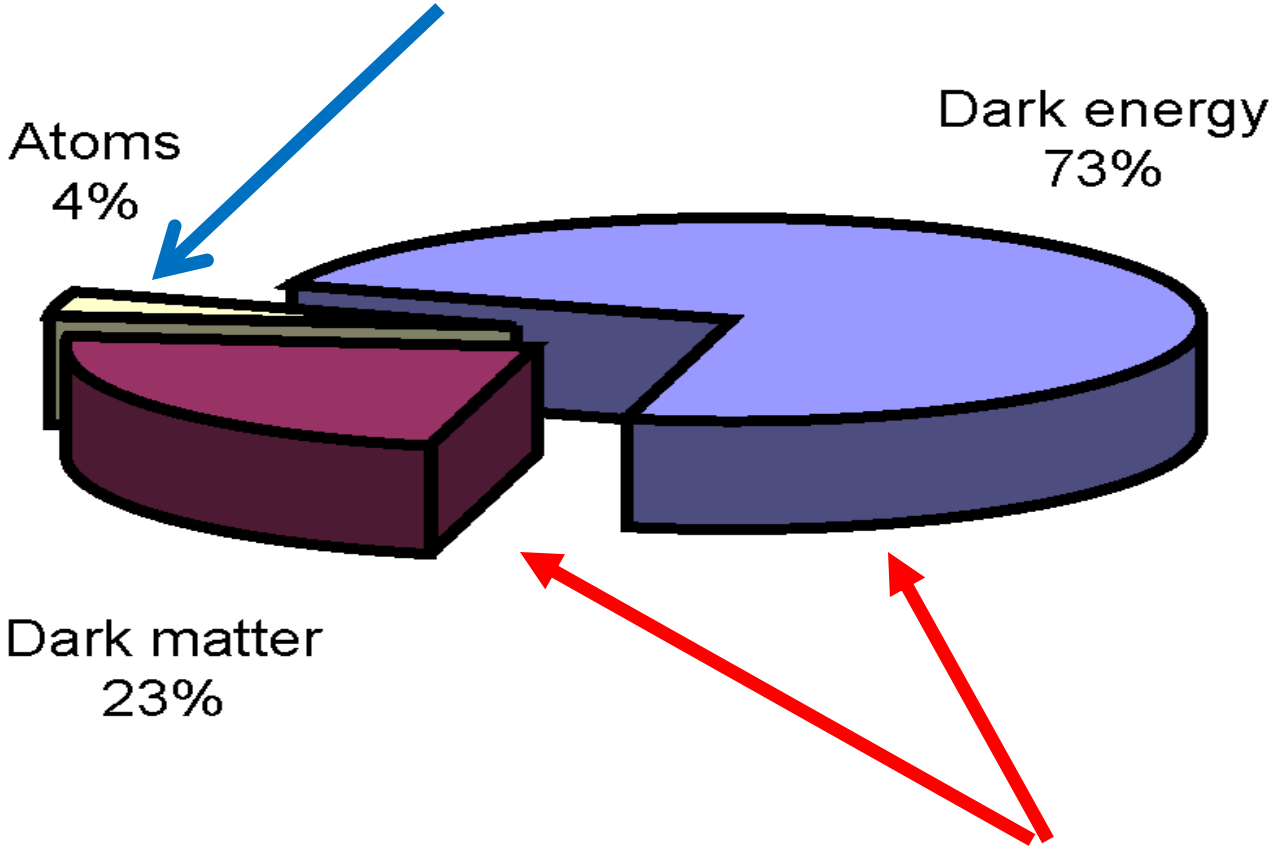
We only know (understand?) ~ 5% of the universe!!!

Colliding galaxy clusters 1E0757-558

Luminous normal matter (pink): hot gas - Chandra X-rays

Total mass (blue): optical (gravitation lensing) – Hubble

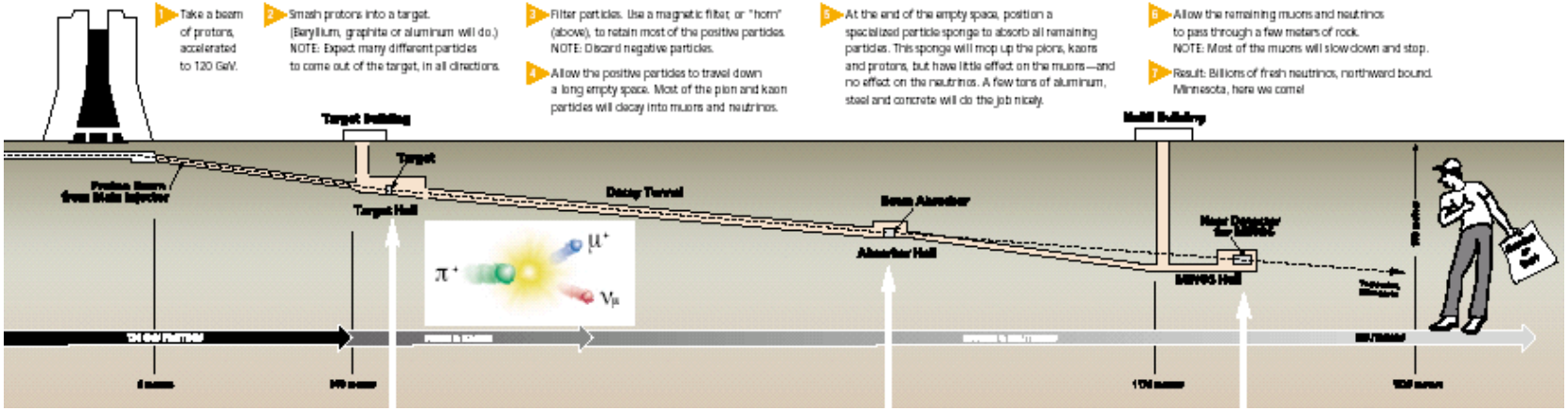
quarks, leptons, stars, plasma….

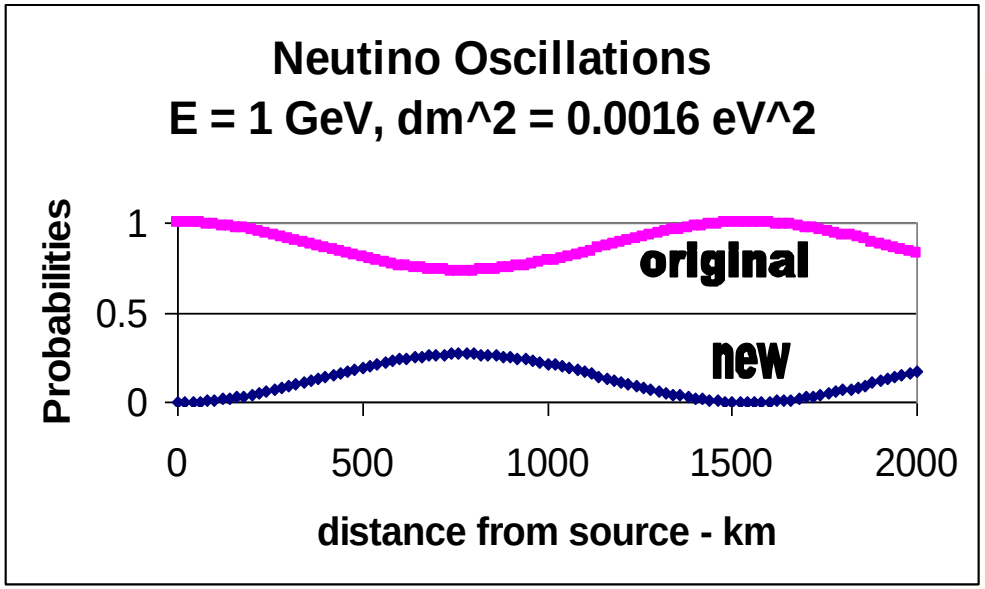


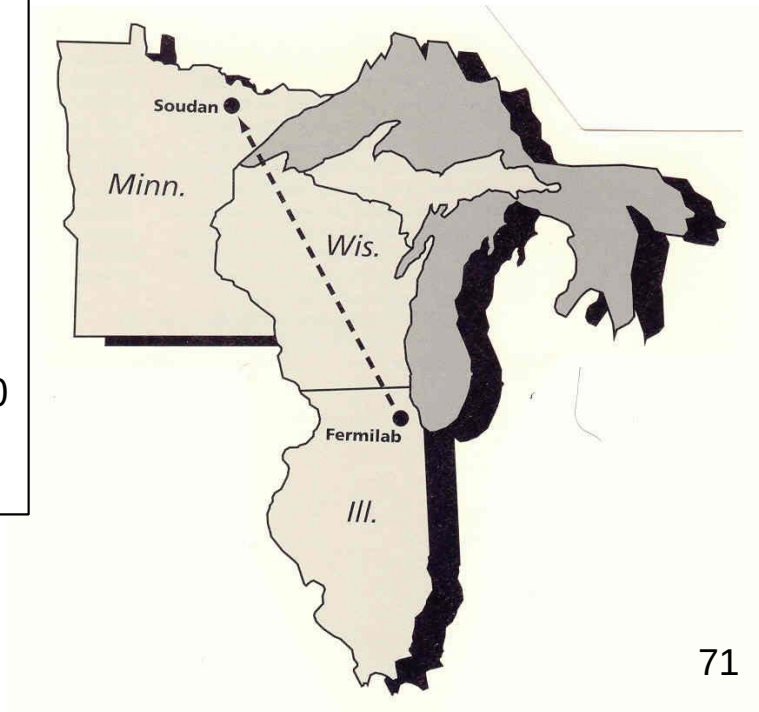
So what is all of this "stuff"?

I thought we knew
what the universe is all about!

NUMI – Neutrinos at the Main Injector







a 735 km long beam, right thru the earth! 10 km deep

Neutrino Interactions

- ν's interact very weakly (the weak force!)
- total νp cross section (interaction probability)

  $\sigma(\nu p) = 6.7 \times 10^{-39}$ cm^2 at 1 GeV

  $\sigma(pp) = 2.2 \times 10^{-26}$ cm^2 (strong force)

  $\sigma(\gamma p) = 2 \times 10^{-28}$ cm^2 (E.M. force - photons)
- EM force/Gravitation $\approx 10^{36}$ between 2 protons
- only 650 out of 1 billion ν's interact before reaching Soudan (735 km earth)
- only 40 out of 1 trillion ν's interact in detector

phenomonology of ν oscillations

for two neutrinos $\nu_\mu \rightarrow \nu_x \rightarrow \nu_\mu$ … *etc.*
exactly same for 3 ν, math more complicated
by quantum interference of two states $\nu_\mu - \nu_x$

ν_μ disappearance → oscillate into ν_x

Starting out with a pure ν_μ beam, the probability of seeing ν_μ as a function of Energy & Distance:

$$P\nu_\mu(E,L) = 1 - \sin^2(2\theta_{\mu x}) \sin^2(1.27\, \Delta m^2_{\mu x}\, L/E)$$

where ***L*** = distance in km, ***E*** = energy in GeV,

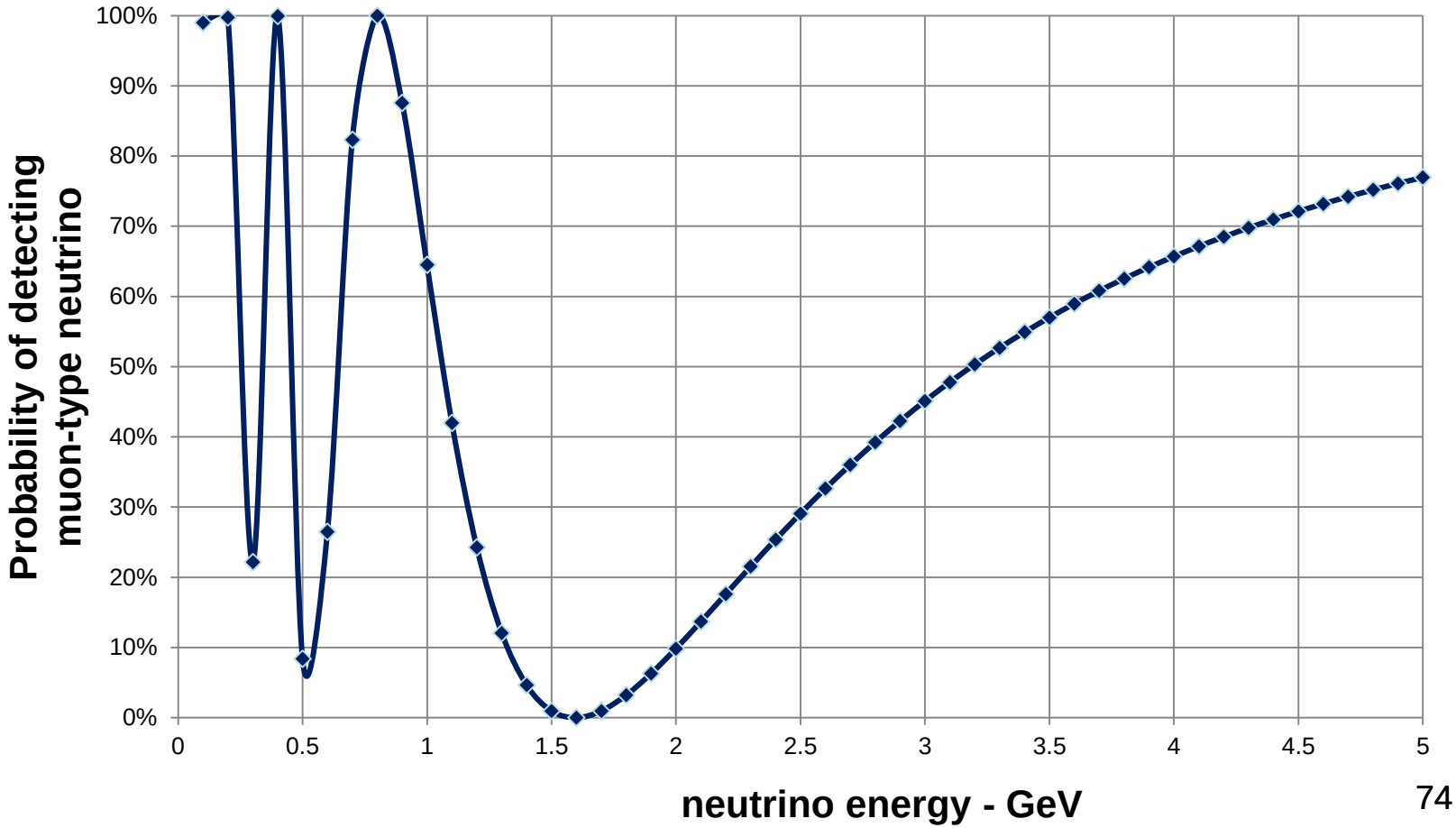
$\Delta m^2_{\mu x} = m^2(\nu_\mu) - m^2(\nu_x)$ (note ***square***!)

$\sin^2(2\theta_{\mu x})$ = coupling strength $\nu_\mu \leftrightarrow \nu_x$

Neutrino Oscillation $\nu_\mu \Rightarrow \nu_x$

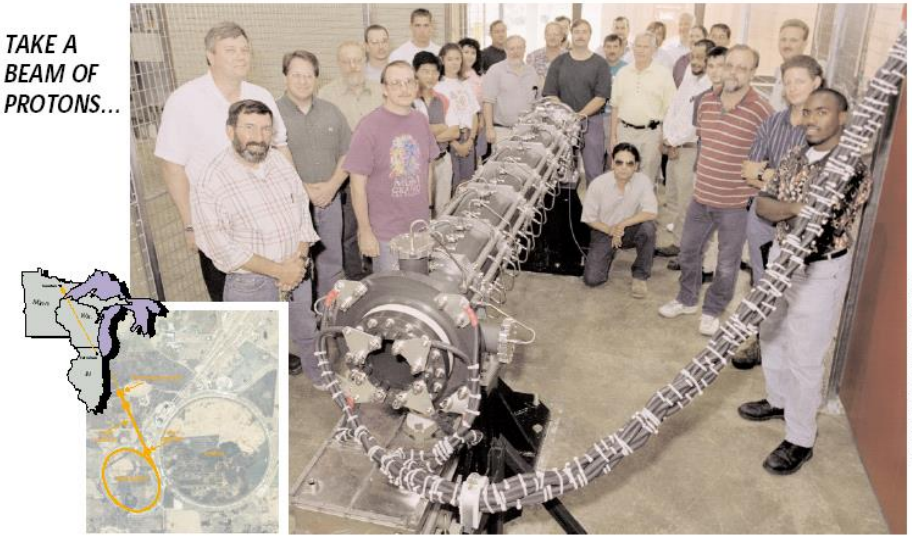
Oscillation function – disappearance

L = 730 km $\delta m^2 = 0.0027\ eV^2$ $\sin^2(2\theta) = 1.0$

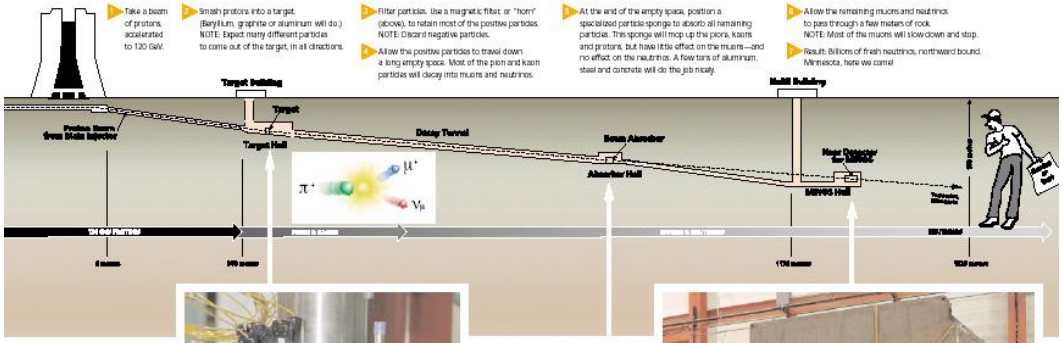


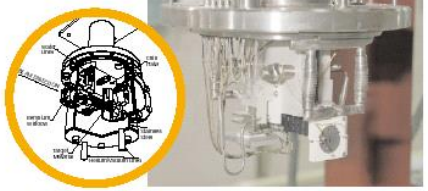
How to MAKE a Neutrino Beam

TAKE A BEAM OF PROTONS...



The first of two horns (magnetic filters) that align the positively charged particles produced in the target, posed with the team that built it. Current pulses of 200,000 amps are applied to the horn for a thousandth of a second at the same time as the proton beam strikes the target.





A prototype of the MINOS target. 4 x 10^{13} protons, accelerated to 120 GeV, will strike the black graphite fins of the target every 1.9 seconds. Water cooling keeps the target from melting.

The near detector, located at Fermilab, is a smaller version of the main MINOS detector at Soudan, Minnesota. The near detector is used to verify the flavor of the neutrino beam at the source. The detector is smaller because the neutrino beam hasn't yet spread out very much.

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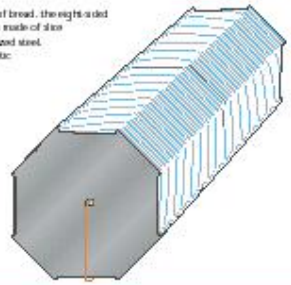
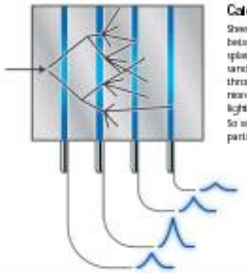
How to DETECT a Neutrino

The MINOS collaboration poses for a photo in front of a steel plane of the MINOS detector. Eventually the detector will be 90 feet long and 24 feet in diameter, made of 486 layers of these eight-sided steel plates. Even with 5,000 tons of steel, only a few in 10 billion neutrinos coming from Fermilab will interact in the MINOS detector.

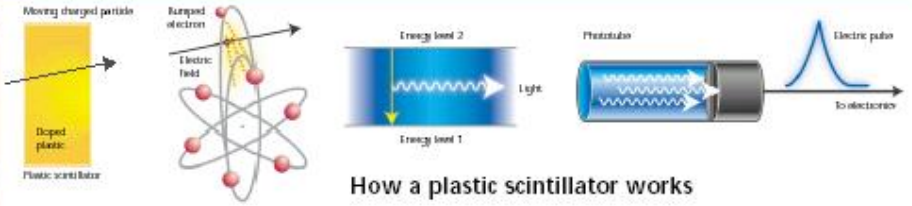
Like a 5000-ton loaf of bread, the eight-sided MINOS far detector is made of slice after slice of magnetized steel, sandwiched with plastic scintillator. When a neutrino collides with an iron nucleus, it produces a splash of particles. Charged particles passing through the scintillator produce light, which is then converted to an electronic signal for the watching experimenters.



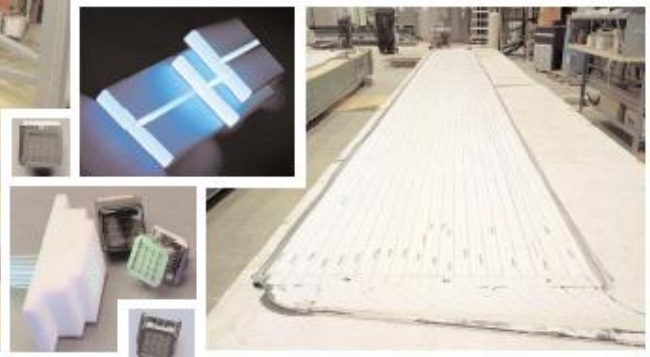


Calorimeter Sandwich Detector

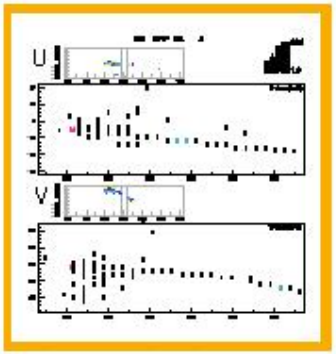
Sheets of plastic scintillator are placed between the steel plates. The particle splash is quickly absorbed in the calorimeter sandwich. Each charged particle passing through the scintillator creates light. The more particles, the more light. The more light the bigger the electronic signal. So we can measure the energy of the particles by adding up the electronic signals.



How a plastic scintillator works



Plastic scintillator strips 24 feet long and about 1-5/8" by 3/8" are assembled into modules of 20 or 28 strips wide. Eight modules are assembled to make one plane of 192 strips, which is sandwiched between the steel plates. Each strip has a light fiber glued along its center to bring the light to a phototube. Each phototube receives the light from 128 fibers.



A picture of a typical interaction of a muon-flavor neutrino. The muon produced in the interaction (the long track in the picture) is gradually losing energy as it goes through the steel plates. The magnetic field present in the steel causes the muon to bend. The amount of bending gives a measurement of the muon energy.

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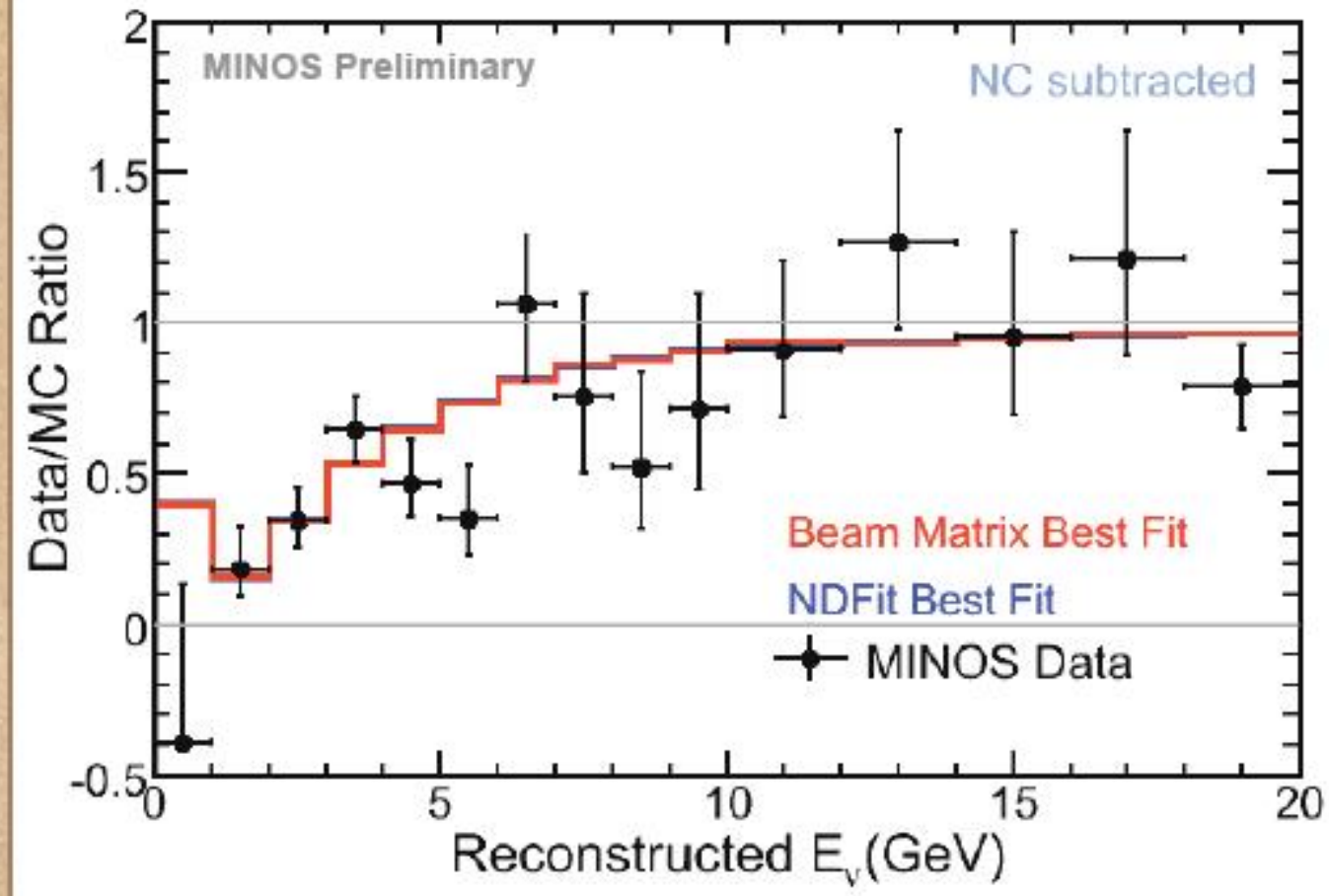
NuMI installation in Minnesota mine

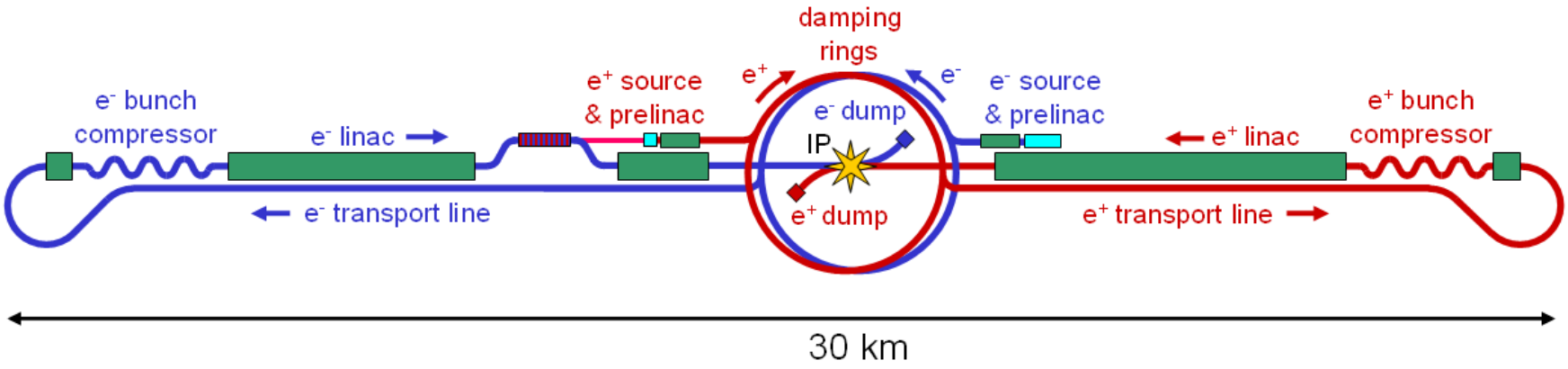
first NuMI results – July 31, 2006



$$|\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26}(stat + syst) \times 10^{-3} eV^2$$

$$sin^2(2\theta_{23}) = 1.00_{-0.13}(stat + syst)$$

The International Linear Collider



a 250 GeV x 250 GeV e^+e^- collider

~ 31 km long!

The Reference Design Report (RDR) for the ILC
including cost and labor estimates
was released in August, 2007