



# Welcome to Fermilab!

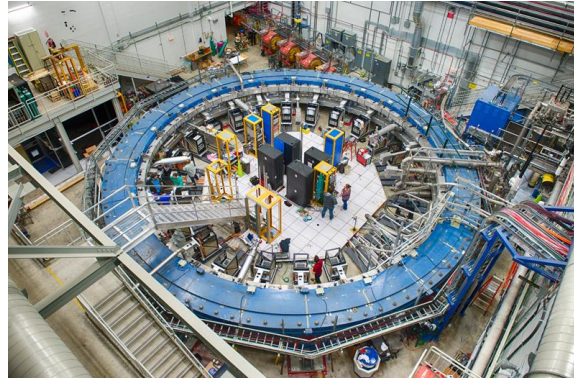
Sergei Nagaitsev (Fermilab and UChicago)  
20 July 2017



# Fermilab-at-a-Glance



6,800 acres = 27 sq. km  
~\$400M operating budget



1,793 FTEs  
3,245 facility users



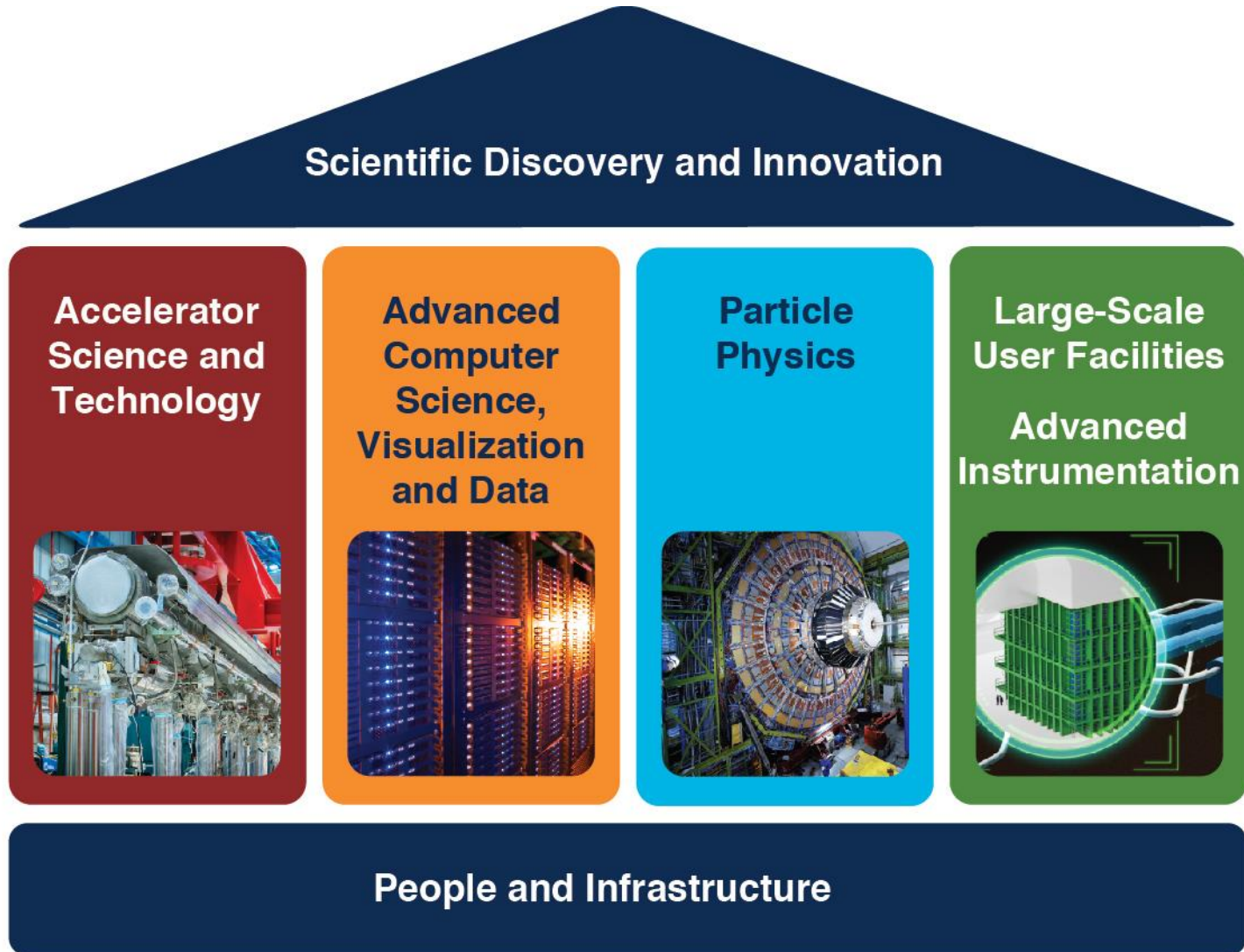
Unique natural area,  
prairie, wetlands, wildlife

**Fermilab celebrates 50 years at the forefront of discovery in 2017 (top & bottom quarks, tau neutrino, ...)**

As we move into the next 50 years, our vision remains to solve the mysteries of matter, energy, space, and time for the benefit of all. We strive to:

- Lead the world in neutrino science with particle accelerators
- Lead the nation in the development of particle accelerators and colliders, and their use for scientific discovery
- Advance particle physics through measurements of the cosmos

# Fermilab's Core Capabilities



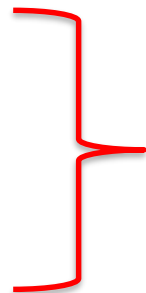
# Accelerator Science and Technology



# Accelerator Science

- Accelerator science is a branch of applied science, concerned with designing, building and operating particle accelerators. As such, it can be described as the study of motion, manipulation and observation of charged particle beams and their interaction with accelerator structures by electromagnetic fields.
- Applied science is a discipline of science that applies existing scientific knowledge to develop more practical applications, like technology or inventions.

Maxwell's equations  
EM forces  
Superconductivity  
Quantum mechanics  
Special Relativity...



Accelerator Physics



Accelerator  
technology

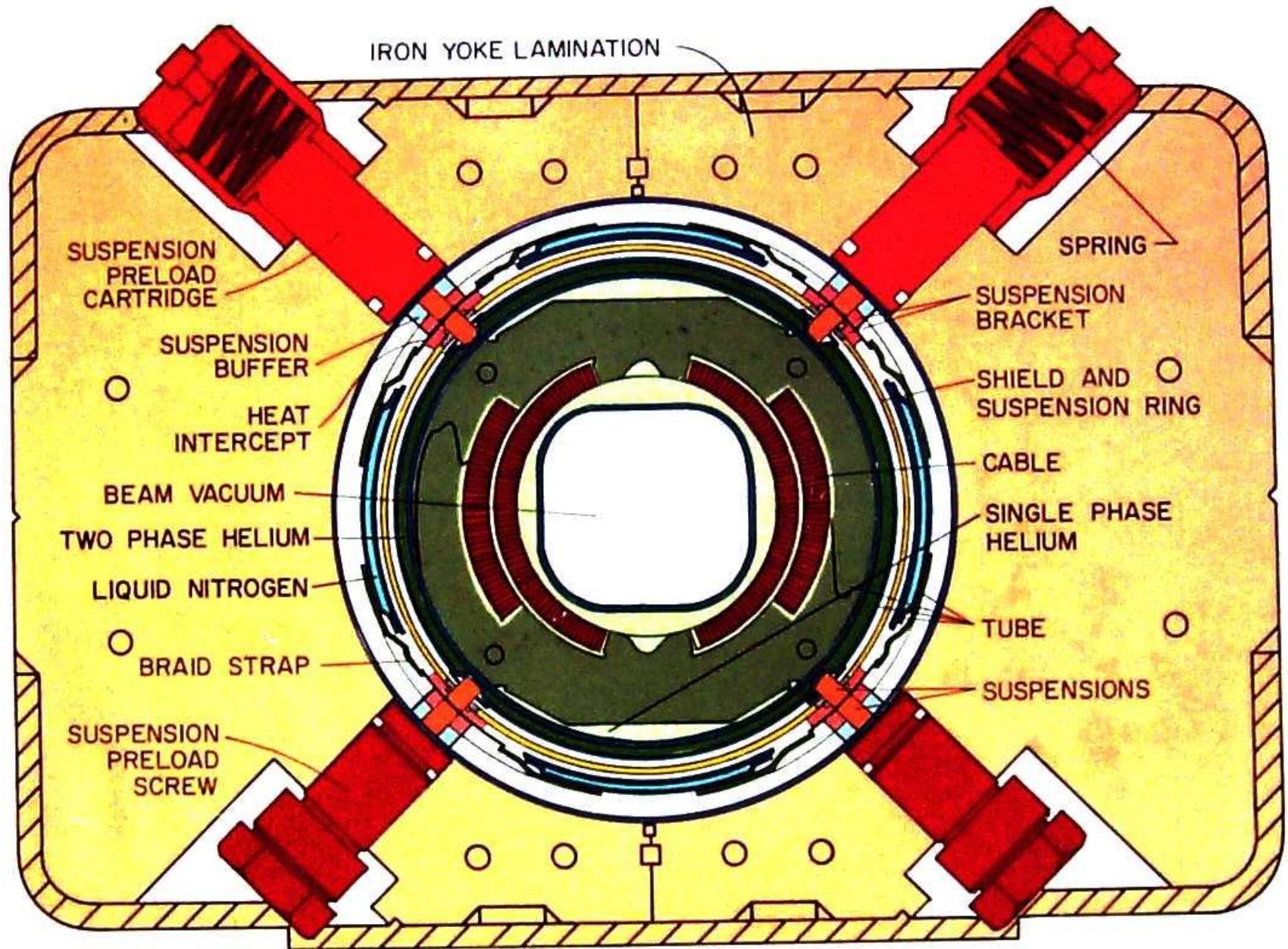
# What do Accelerator Scientists and Engineers do?

- We study human-made objects (beams of charged particles, accelerators and various accelerator-related systems).
- We design, construct, and operate accelerators.

# What is Fermilab known for?

(if you were to ask an accelerator scientist or engineer...)

# Technology: 4.5T SC Magnets



This is not the Tevatron!  
-remnants of the Main Ring  
(first separated-function  
synchrotron ever built)

This is the Tevatron!

C=6.28km, ~800 SC magnets @ 4.2 K,

# 1989 NATIONAL MEDAL OF TECHNOLOGY



HELEN EDWARDS  
RICHARD A. LUNDY  
J. RICHIE ORR  
ALVIN TOLLESTRUP

For their contributions to the design, construction and initial operation of the TEVATRON particle accelerator. The scientific instrument was designed to explore the fundamental properties of matter. The innovative design and successful operation of the TEVATRON has been crucial to the design of the Superconducting Super Collider, the planned next generation particle accelerator.

# State of the Art SC Magnets: 3 Decades

**4.5T**

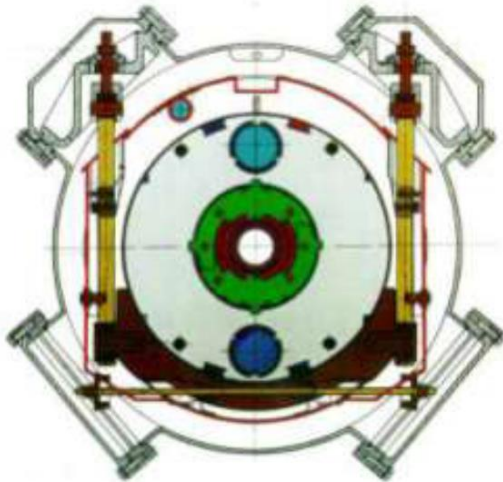
Tevatron,  
6 m, 76 mm  
774 dipoles



4.5 K He, NbTi  
+ warm iron  
small He-plant

**5.3T**

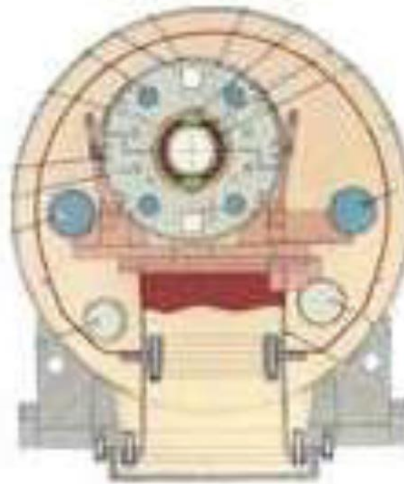
HERA,  
9 m, 75 mm  
416 dipoles



NbTi cable  
cold iron  
Al collar

**3.5T**

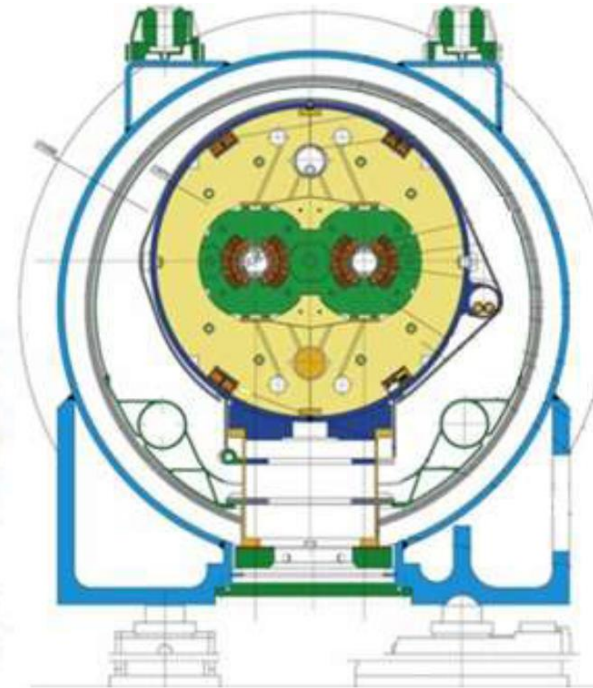
RHIC,  
9 m, 80 mm  
264 dipoles



NbTi cable  
simple &  
cheap

**8.3T**

LHC,  
15 m, 56 mm  
1276 dipoles



NbTi cable  
2K He  
two bores

# Accomplishment: IEEE Milestone Award

- IEEE Board of Directors has approved a Milestone Award for the superconducting magnet system of the Tevatron
  - “The IEEE Milestones program honors significant technical achievements in all areas associated with IEEE...Milestones recognize the technological innovation and excellence for the benefit of humanity found in unique products, services, seminal papers and patents.”
- Ceremony at Fermilab planned for November 2017

## **Superconducting Magnet System for the Fermilab Tevatron Accelerator/Collider, 1983-1985**

**The first large-scale use of superconducting magnets enabled the construction of the Tevatron. By 1985, the Tevatron achieved energy above 1 Tera electron-volt (TeV) in proton-antiproton collisions, making it the most powerful particle collider in the world until 2009. The Tevatron construction established the superconducting wire manufacturing infrastructure that made applications such as Magnetic Resonance Imaging (MRI) viable.**

# Present: Fermilab SRF science and technology

- R&D program is world leader in SRF science; pursuing fundamental understanding and “materials science” of SRF surfaces
- Pioneered the most important latest advances in SRF technology such as N doping, N infusion, Magnetic Flux expulsion/retention
- Great partnerships with other lab and university groups around the world
  - Partner lab in the LCLS-II project at SLAC



CM03 at CMTS

# What are accelerators used for?

## Discovery Science

- Particle and Nuclear Physics
- Materials science, chemistry, biology, ...

## Medicine

- Cancer therapy
- Medical radioisotopes



## Accelerators and Beams

## Energy and Environment

- accelerator-driven reactors (future)
- Inertial confinement fusion with heavy-ions (future)
- Flue-gas treatment



## National Security

- Cargo screening
- Active interrogation
- Radiography



## Industry

- Electron processing
- Sterilization
- Ion implantation

# Accelerators by the Numbers

Application	Systems (thru 2008)
Ion Implantation	10,000
Electron beam modification	7,000
Electron and X-ray irradiators	2,000
Ion beam analysis and AMS	200
Radioisotope production	600
High energy x-ray inspection	750
Neutron generators	2000
Radiotherapy	8000
Hadrontherapy	25
Photon Sources (synchrotron radiation, ...)	80
Nuclear and Particle Physics Research	110
Total	~30,000

The most well known category of accelerators – particle physics research accelerators – is one of the smallest in number. The technology for other types of accelerators was born from these machines.

# Nuclear and Particle Physics

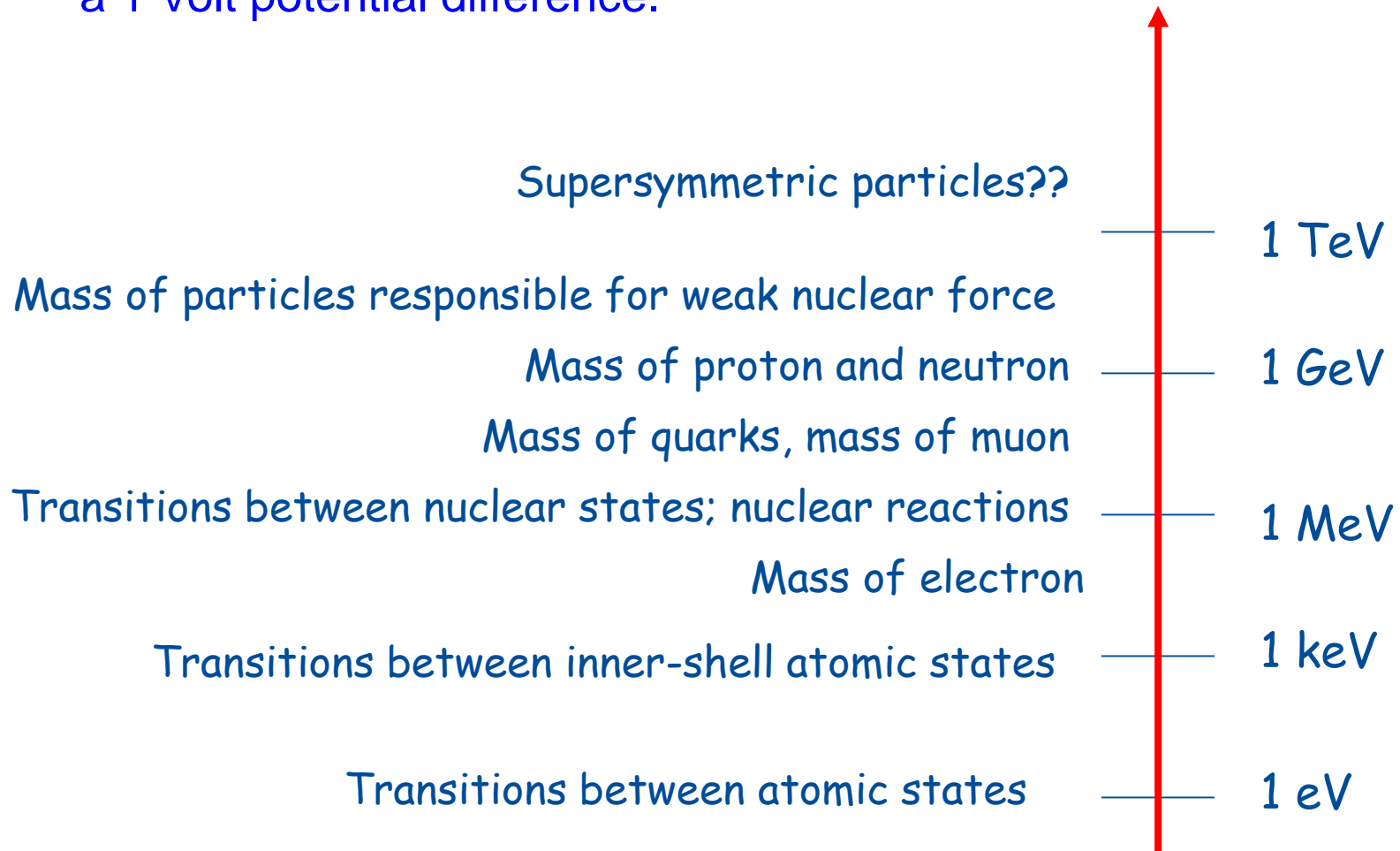
- Much of what we know about the subatomic world is from experiments enabled by particle accelerators.
- The first “high-energy” accelerator, made by Cockcroft and Walton, was immediately used to understand the atomic nucleus. They made the first artificially produced nuclear reaction:



- Early accelerator developments were driven by the quest for higher and higher particle energies, which in turn was driven by developments in nuclear physics (through the 1960s) and then elementary particle physics (1960s-onward)
- The largest accelerator is at CERN. It collides two proton beams of energy 7 TeV each.

# Energies in the atomic and subatomic world

- Energies are measured in electron-volts:  $\text{eV}$   
And  $\text{eV}$  is the amount gained by an electron accelerated across a 1 Volt potential difference.



# Creation of new particles

- Einstein's famous equation:  $E=mc^2$  puts mass and energy on an equal footing.
  - An energetic particle has total relativistic energy  $E = T + m_0c^2$ ,
- One particle colliding with its antimatter partner can annihilate and produces pairs of other particles.
- Example:

$$e^- + e^+ \rightarrow B^+ B^-$$

	Rest Mass Energy [MeV]	Kinetic Energy [MeV]
$e^+, e^-$	0.511	5290
$B^+, B^-$	5279	11.5

# Types of particle accelerators

- A wide variety of particle accelerators are in use today. The types of machines are distinguished more by the velocity of particles that are accelerated than by the mass of particle accelerated.
- **Accelerators for electrons generally “look” different from accelerators for protons or heavy ions.**

## Example:

- Compare velocities of particles generated at 100 keV kinetic energy:
  - Electrons:  $v/c = 0.55$
  - Protons:  $v/c = 0.015$
  - $\text{Au}^{1+}$ :  $v/c = 0.001$
- This has important implications for the type of acceleration scheme that is appropriate, as we will see throughout this course.

# How to build a particle accelerator

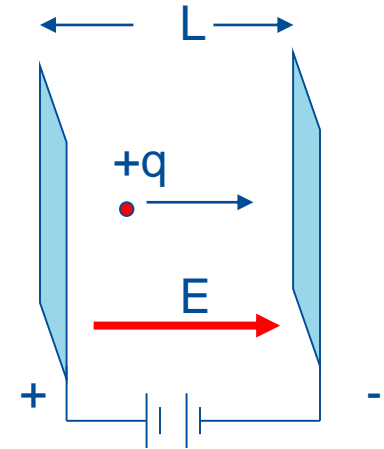
- In two easy steps
  - First, one needs acceleration
  - Second, one needs focusing

# Potential-Drop Accelerators

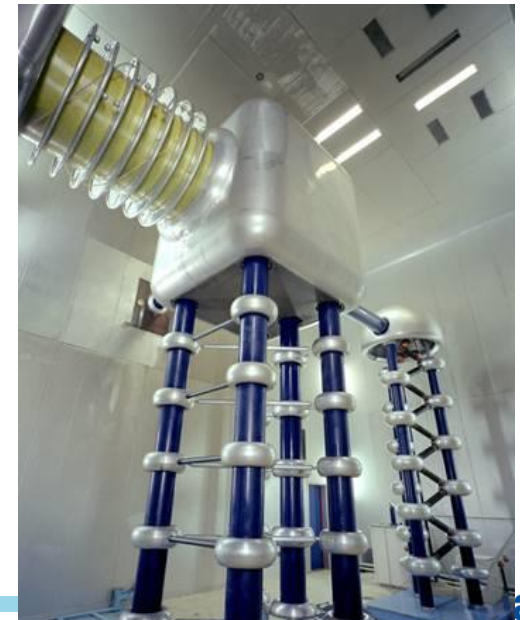
- These accelerators use at static, DC, potential difference between two conductors to impart a kinetic energy

$$\Delta W = qV_0$$

- Earliest particle accelerators were the Cockcroft-Walton generator and the Van de Graaff generator
- Highest voltage achieved is 25 MV
- It is difficult to establish and maintain a static DC field of 20+ MV



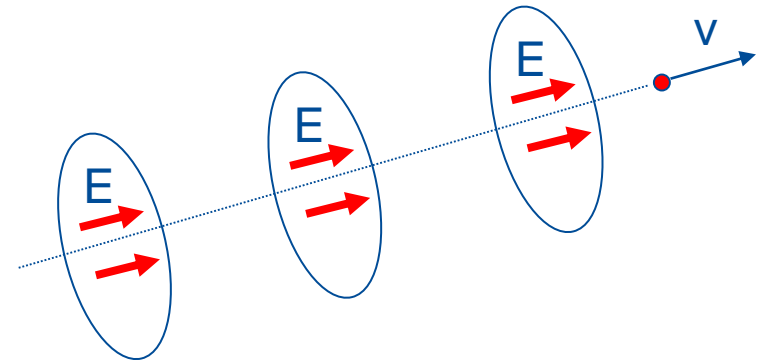
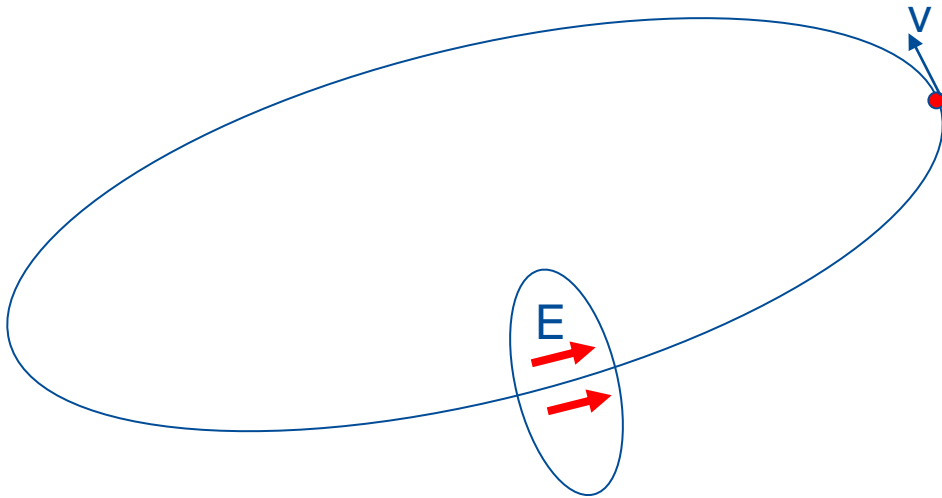
Van de Graaff generator



Cockcroft-Walton generator

# Acceleration by repeated application of time-varying accelerating fields

Two approaches for accelerating with time-varying fields



## ***Circular Accelerators***

Use one or a small number of Radio-frequency accelerating cavities and make use of repeated passage through them. This approach is realized in circular accelerators: Cyclotrons, synchrotrons and their variants

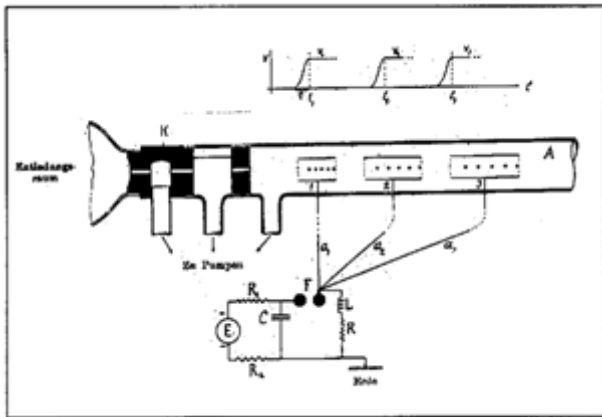
## ***Linear Accelerators***

Use many accelerating cavities through which the particle beam passes once:

These are linear accelerators

# Linear Accelerators

- Ising and Wideroe suggested to repeatedly apply a small voltage in a linear accelerator by using time-varying fields
- In this way, a high particle beam energy could be attained by repeatedly applying voltage “kicks”



Ising's idea



R. Wideroe

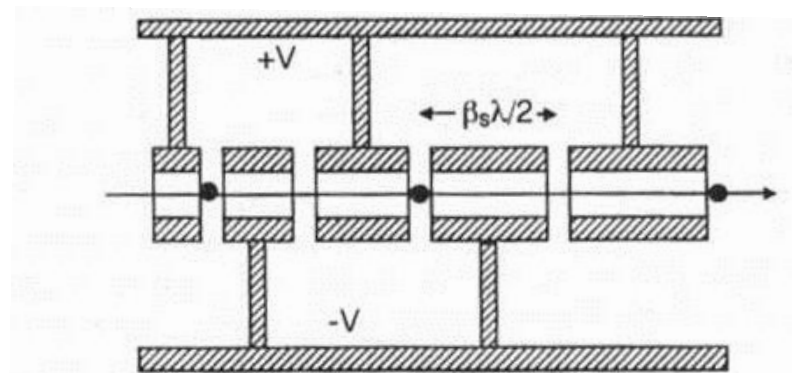
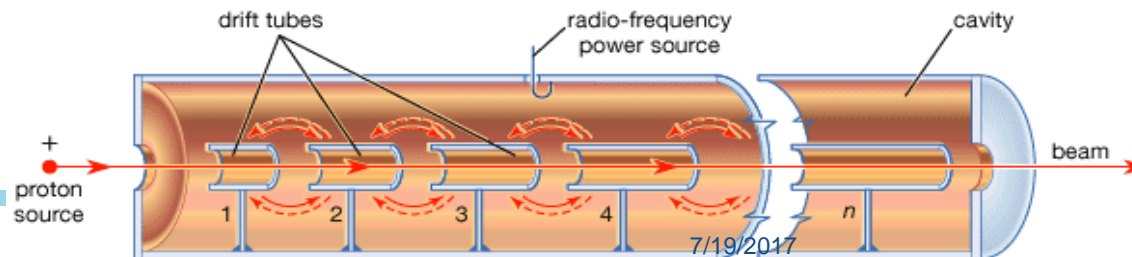
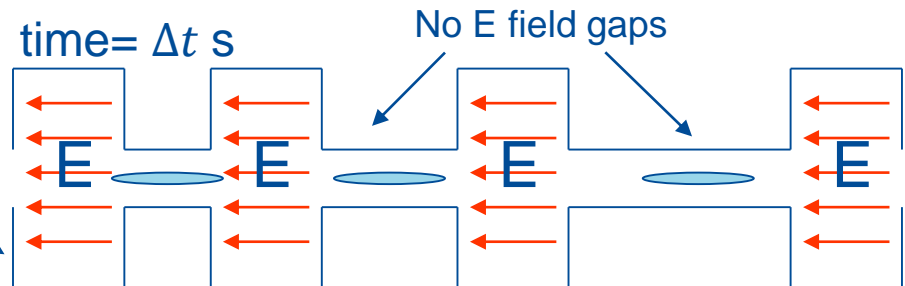
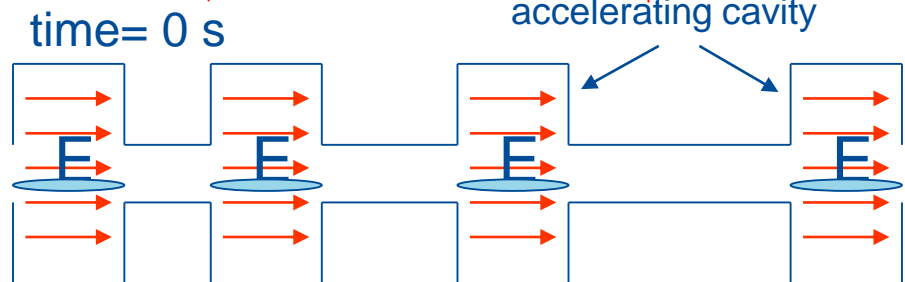
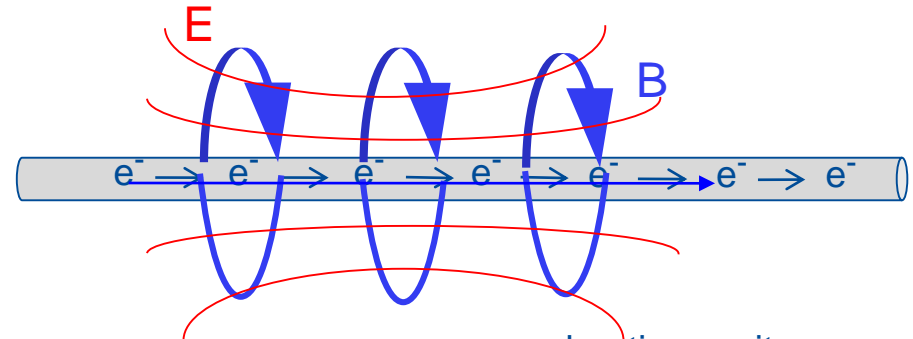
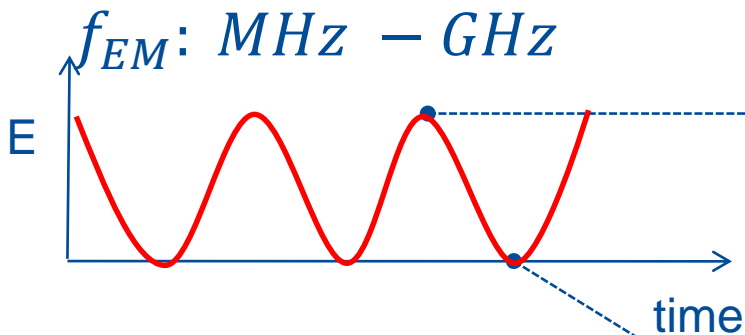


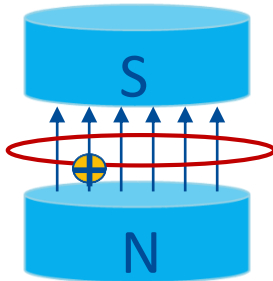
Figure 4.4 Wideroe or Sloan-Lawrence or interdigital structure.

# Time Varying RF Fields

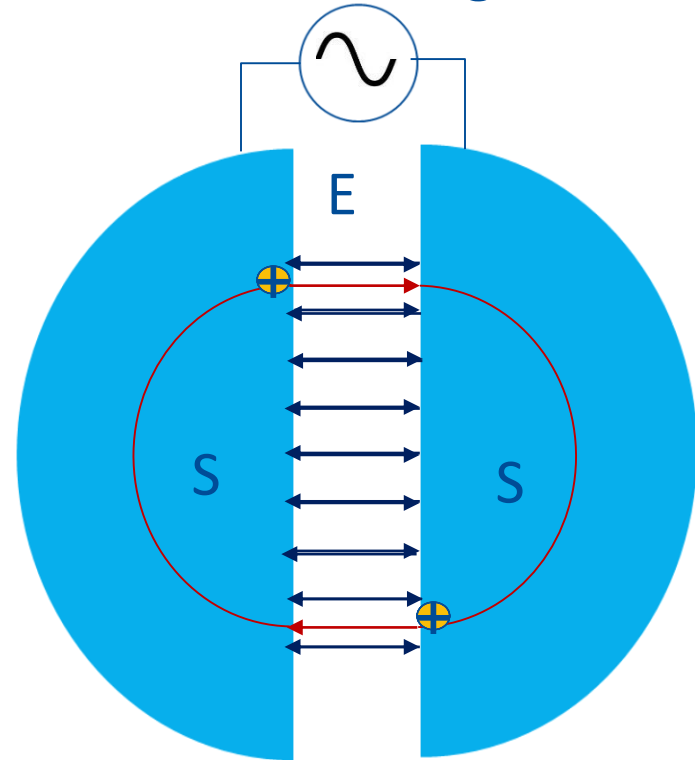
Generating a time varying electromagnetic field.



# The Cyclotron Concept



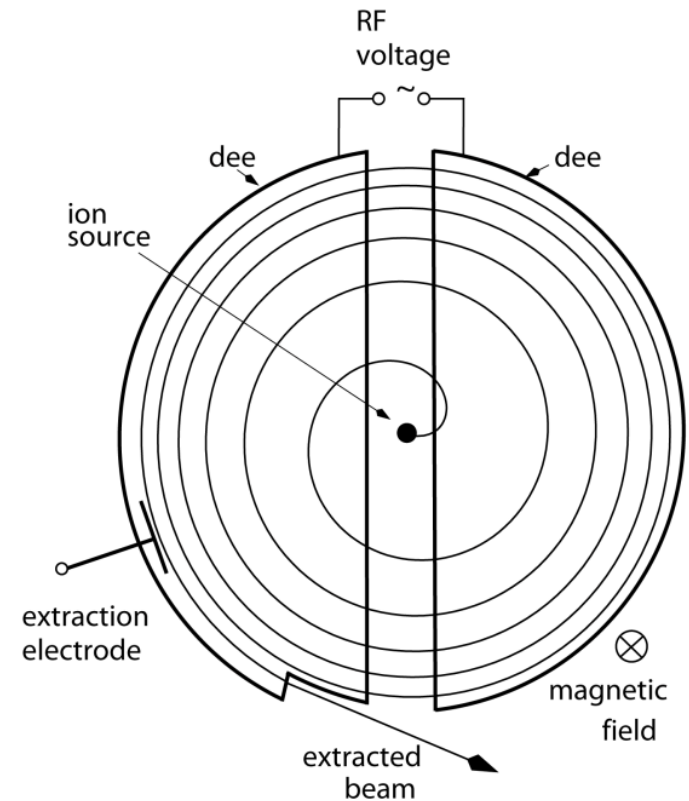
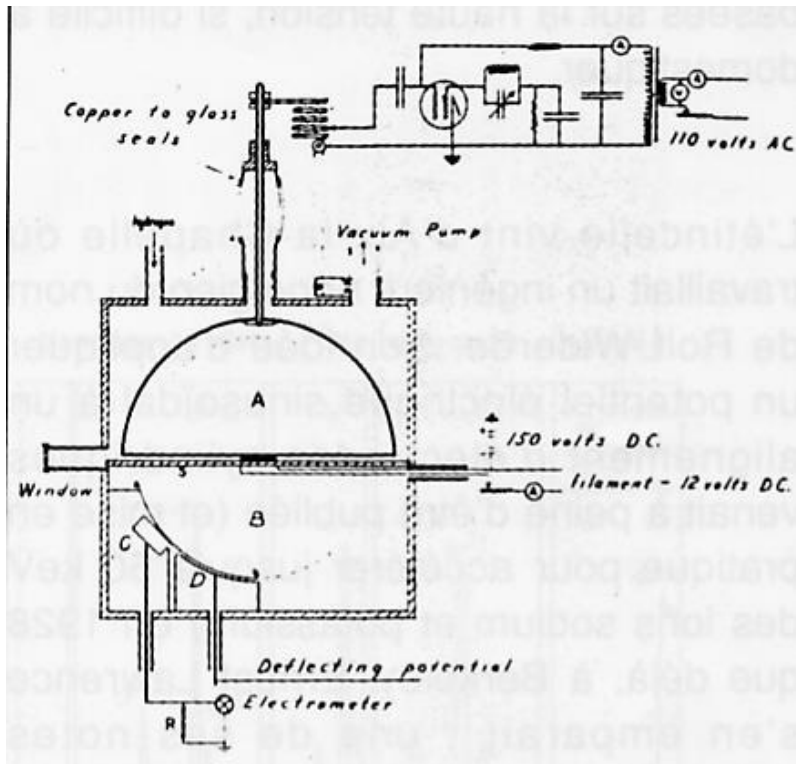
Sinusoidal voltage source



## The Recipe:

1. A magnetic field to bend a particle around.
2. An sinusoidally varying electric field.

# The First Cyclotron

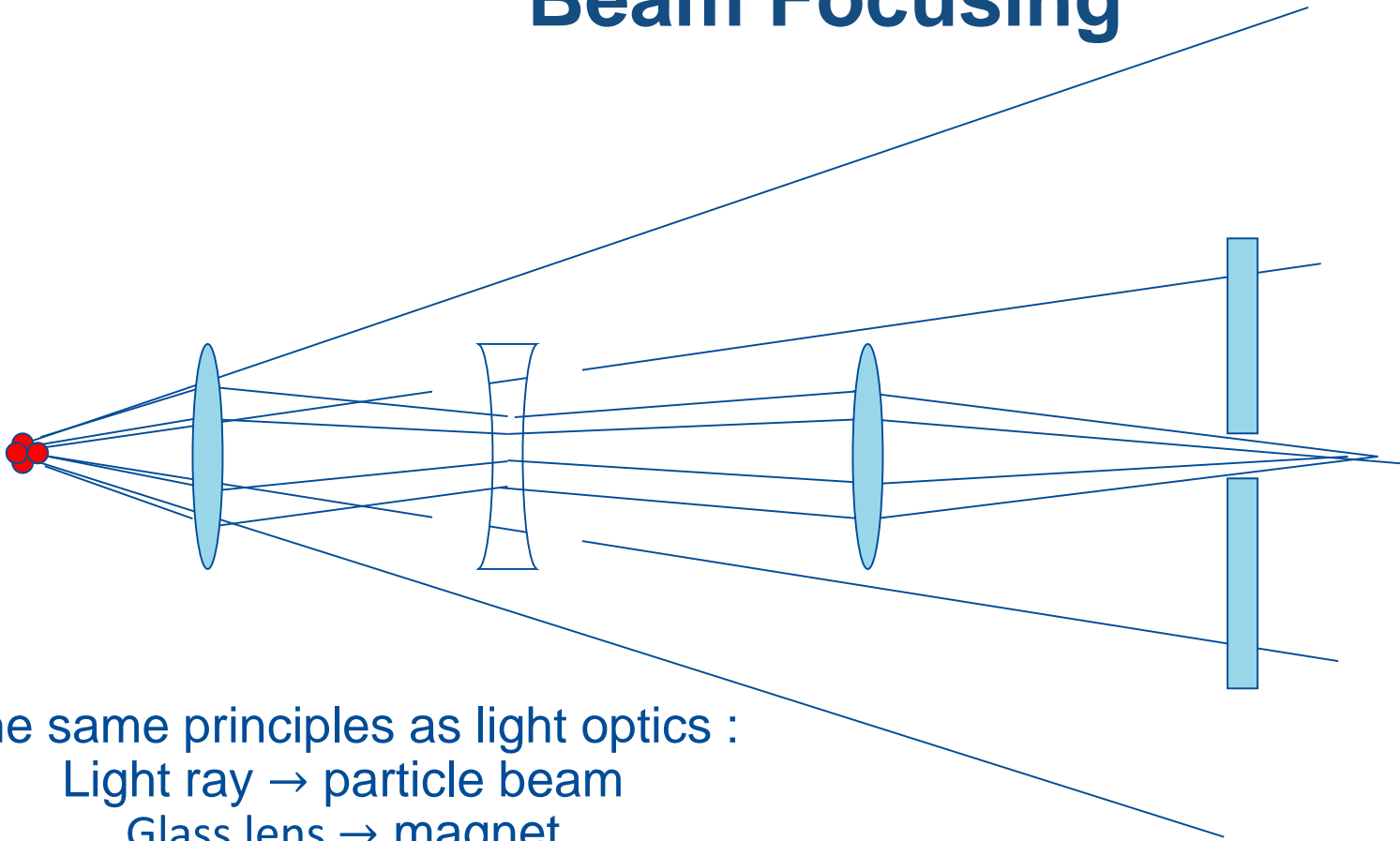


## First cyclotron (1931):

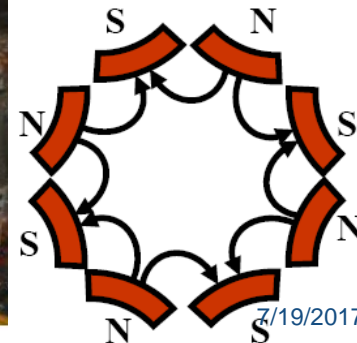
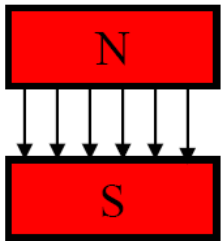
- 1 kV gap voltage
- 80 kV protons
- 4.5" in diameter



# Beam Focusing

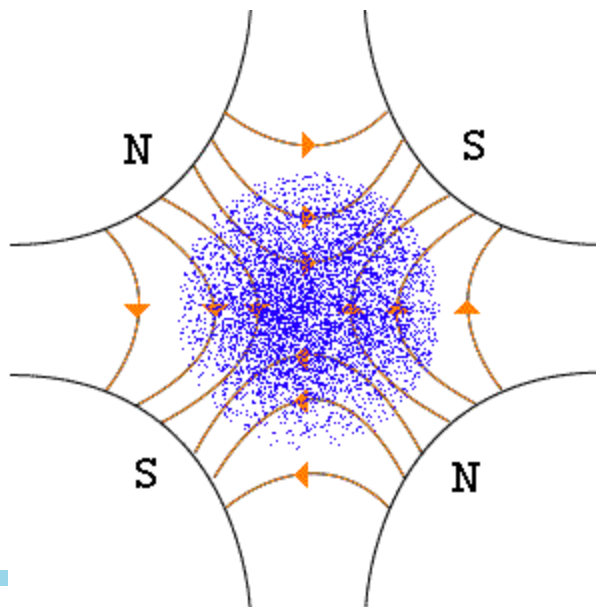
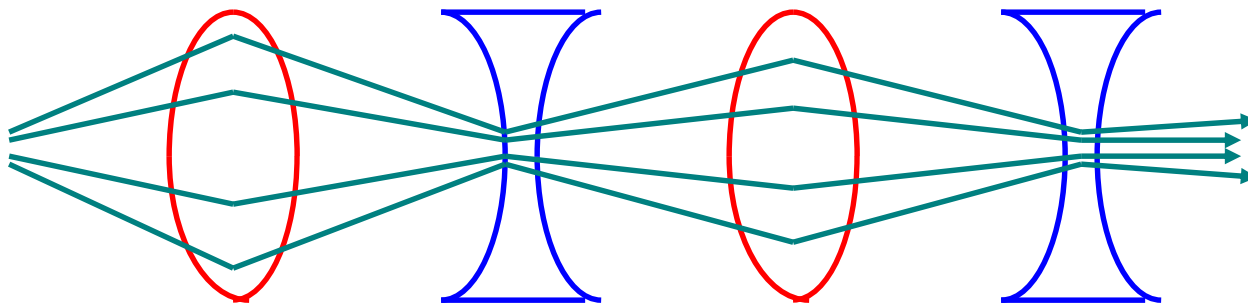


The same principles as light optics :  
Light ray  $\rightarrow$  particle beam  
Glass lens  $\rightarrow$  magnet

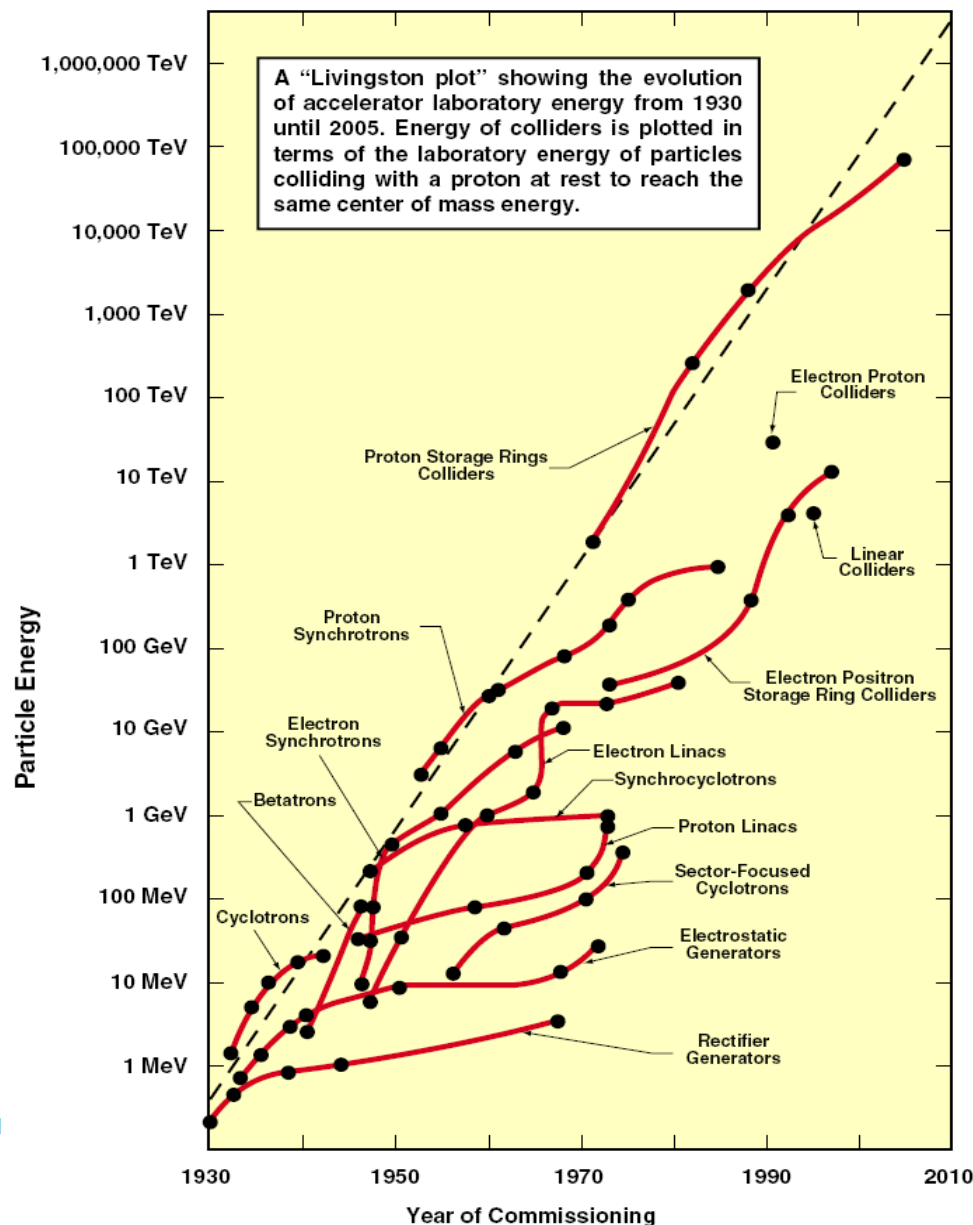


# How To Get Net-Focusing from Quadrupoles???

The key is to alternate focusing and defocusing quadrupoles. This is called a FODO lattice (Focus-Drift-Defocus-Drift). :



# Energy Evolution



- Exponential growth of energy with time
- Increase of the energy by an order of magnitude every 6-10 years
- Each generation replaces previous one to get even higher energies
- The process continues...
- Energy is not the only interesting parameter
  - Intensity
  - Size of the beam
  - Luminosity

# 90 Years of Accelerator Evolution...

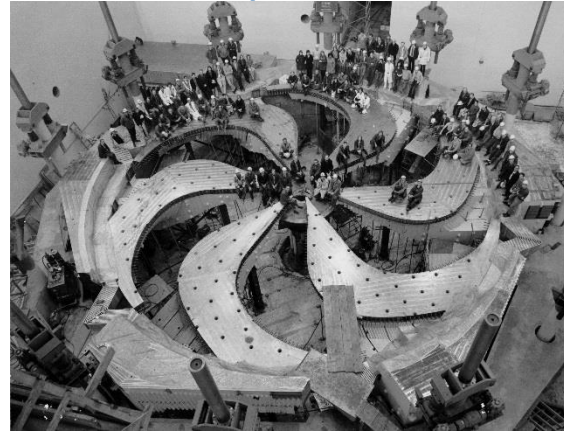
**1931:**

Person holds a cyclotron



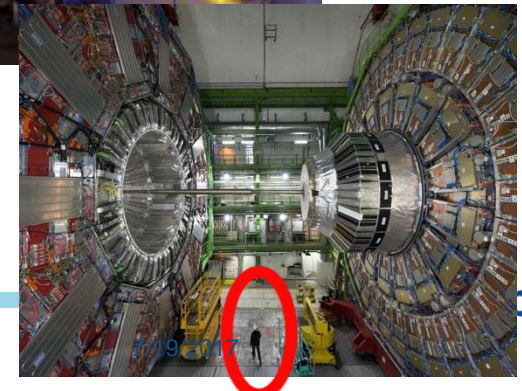
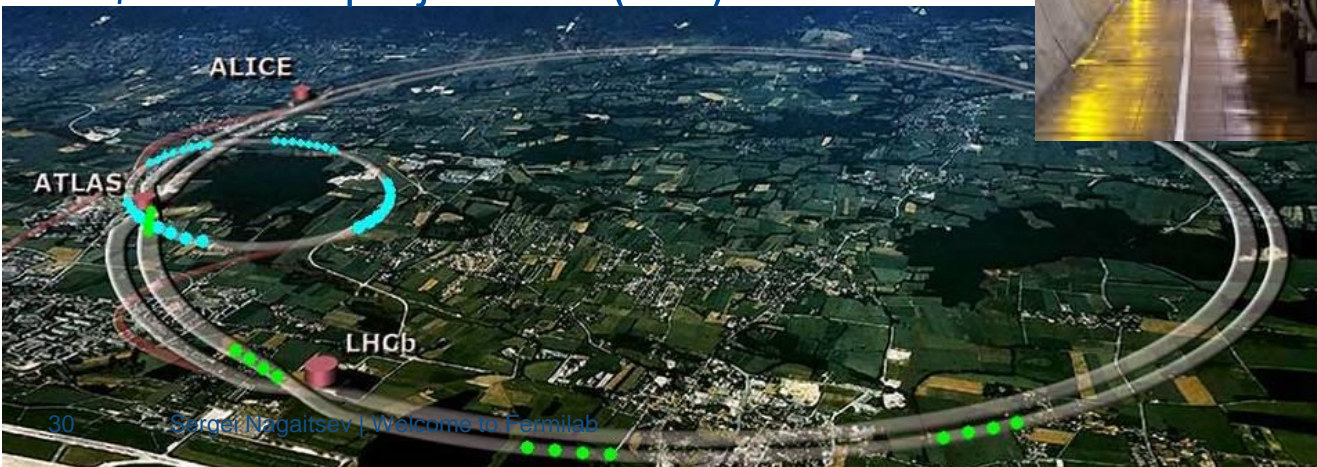
**Today:**

Cyclotron holds a person



**Today's Scales:**

- Miles long.
- 99% the speed of light
- Thousands of magnets + cavities
- Complex technologies.
- ~\$10B total project cost (LHC)



# Secondary Particle Beams

- Beams of accelerated particles can be used to produce beams of secondary particles:
  - Photons (x-rays, gamma-rays, visible light) are generated from beams of electrons (light sources)
  - Neutrons, kaons, pions, antiprotons, muons, neutrinos are generated from beams of protons
- These secondary particle beams are in turn used to do science
  - Materials science, particle, atomic physics

# Colliders : 1964

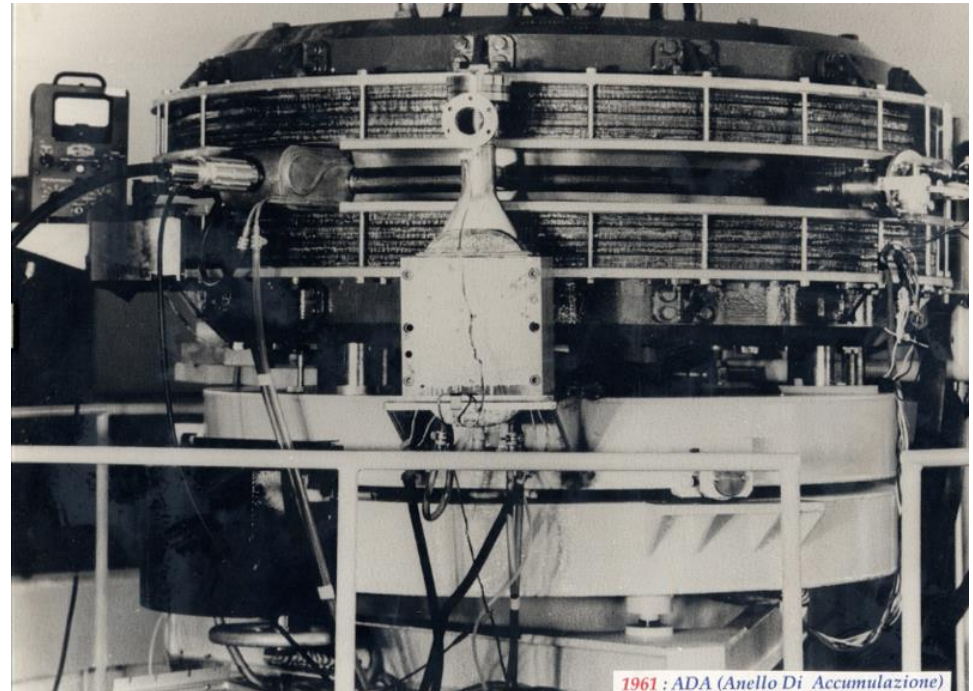


It's easier to collide  $e^+$  /  $e^-$ , because synchrotron radiation naturally “cools” the beam to smaller size.

- VEP-1 (*Встречные Электронные Пучки*) at Novosibirsk, USSR
  - 130 MeV  $e^-$  x 130 MeV  $e^-$
- ADA (Anello Di Accumulazione) at INFN, Frascati, Italy
  - 250 MeV  $e^+$  x 250 MeV  $e^-$



- 1963: Construction Finished
- May 19, 1964: Luminosity

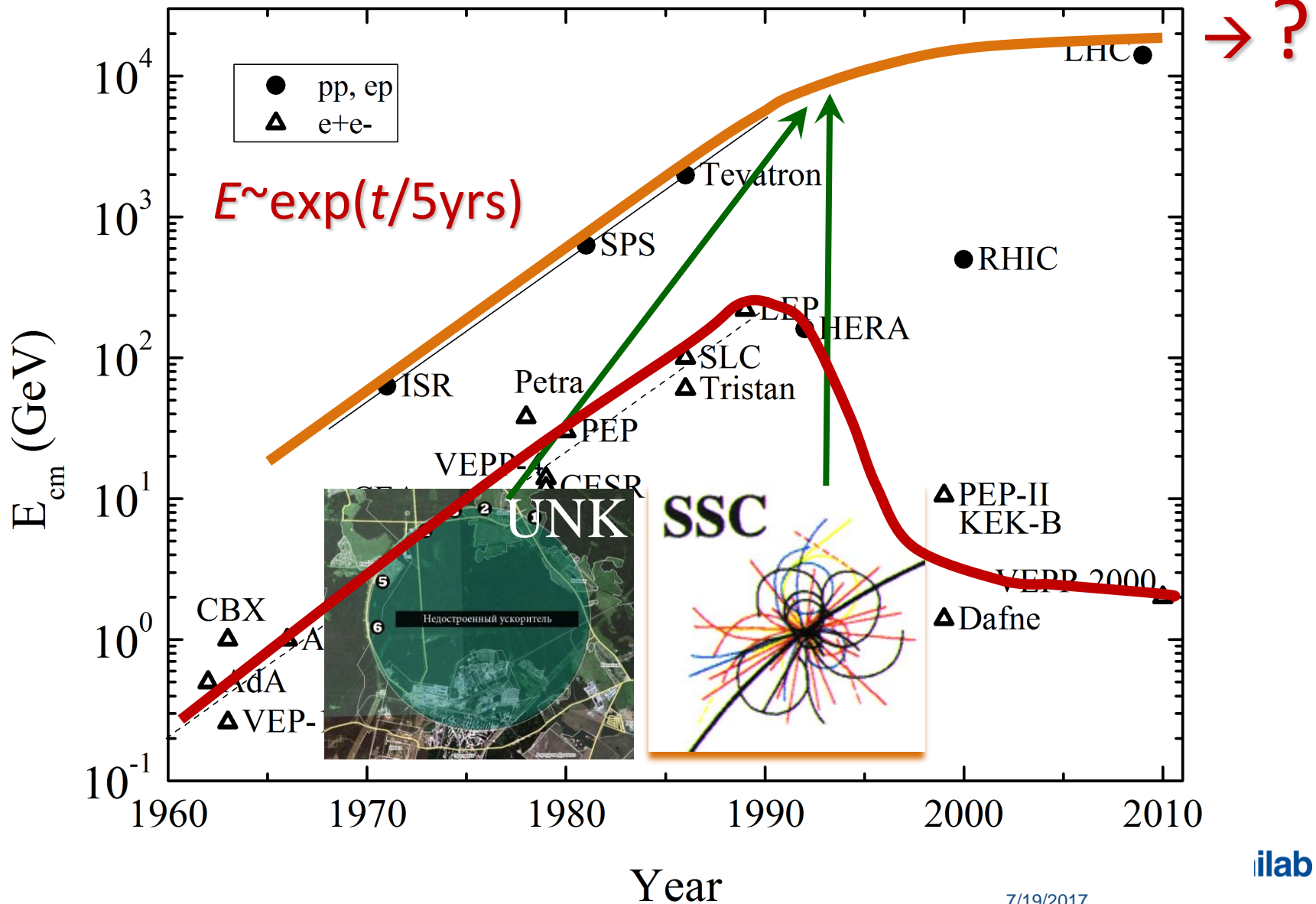


- 1961 : Construction Finished
- ~ May-June 1964: Luminosity Detected

# Colliders: 29 Built... 7 in Operation



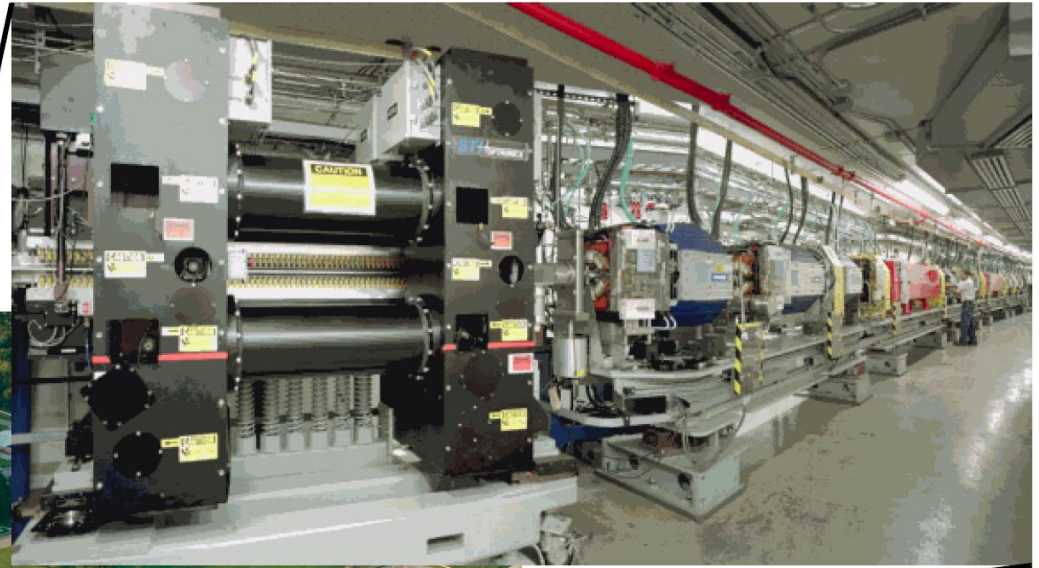
# Colliders: Glorious Past



# Great Accelerators near Chicago

# Advanced Photon Source @ ANL

$C=1100$  m,  $e^- E=7$  GeV  
Serves a community of  
>5,000 unique users  
per year

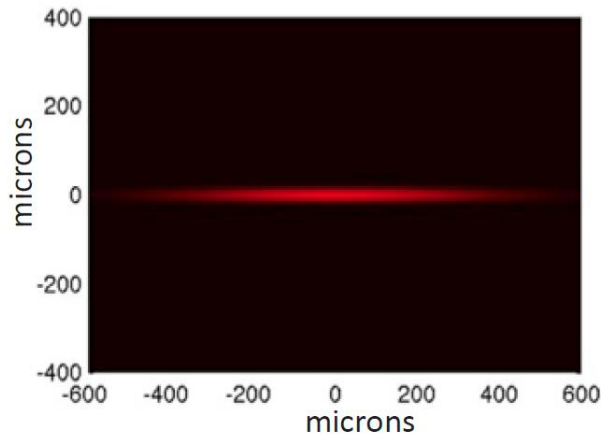


World's brightest  
storage ring light  
source, photon  
energy  $> 4$  keV

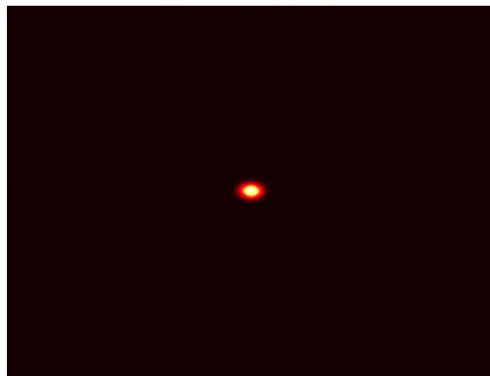
Started a 734M\$  
upgrade, by 2024

# APS Upgrade: 2-3 orders in Brightness

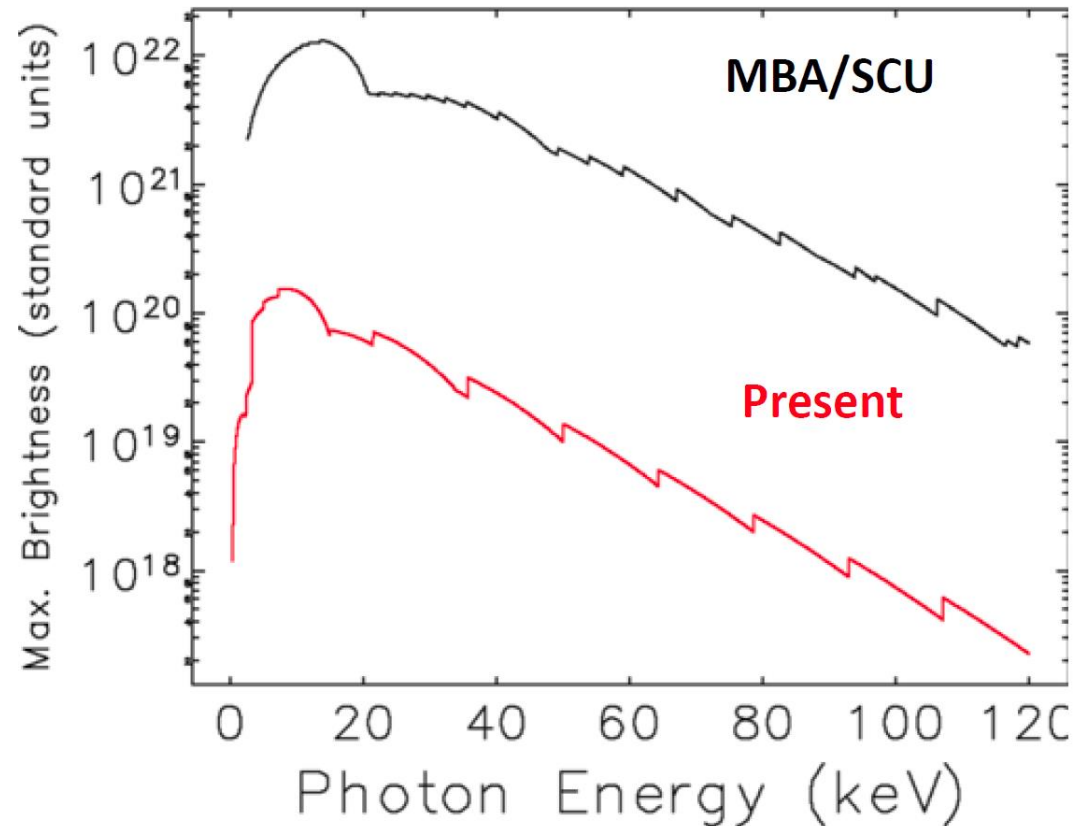
APS Now



APS MBA



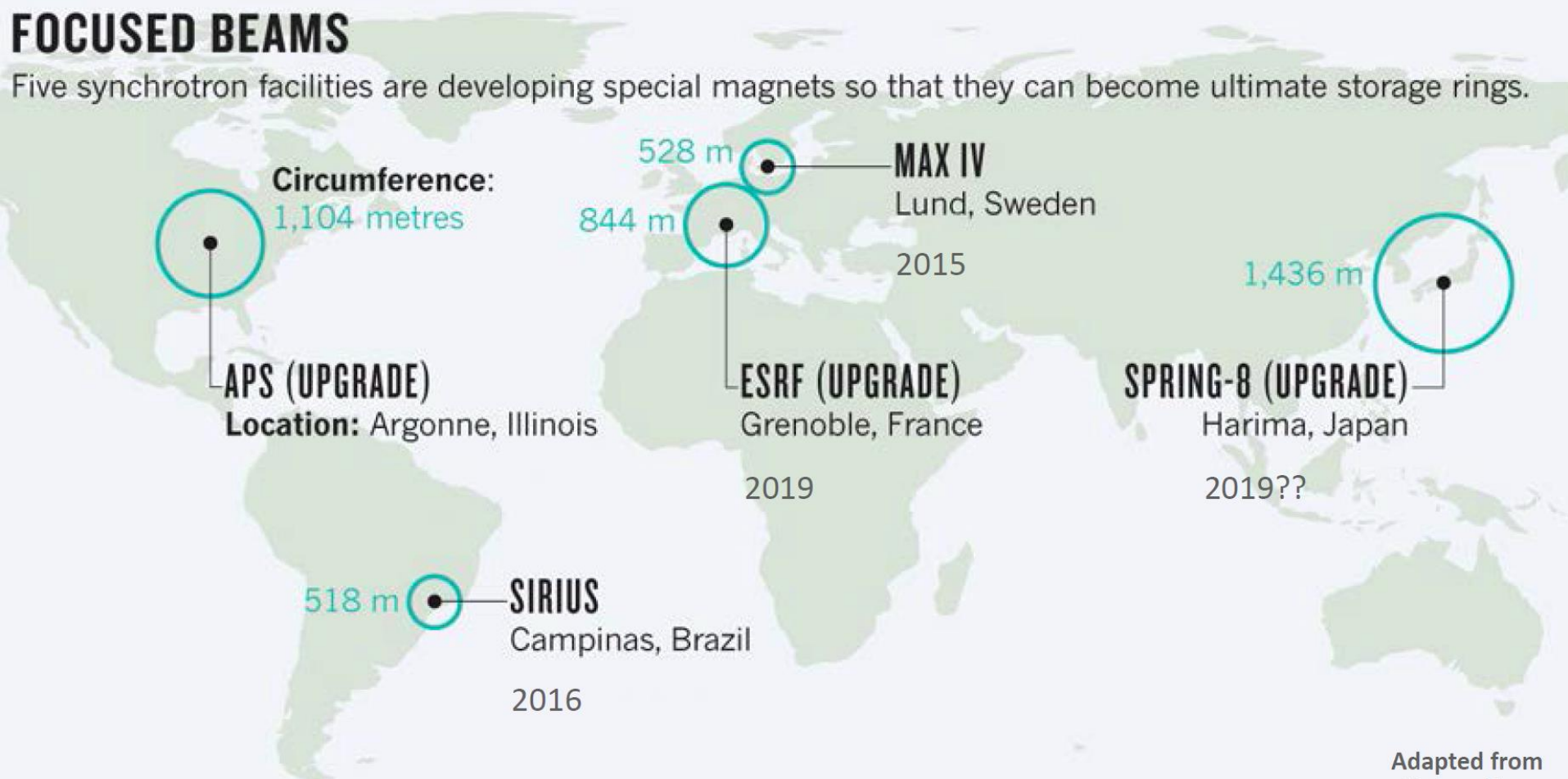
1 mm



# APS will maintain US leadership in Photon Science

## FOCUSED BEAMS

Five synchrotron facilities are developing special magnets so that they can become ultimate storage rings.



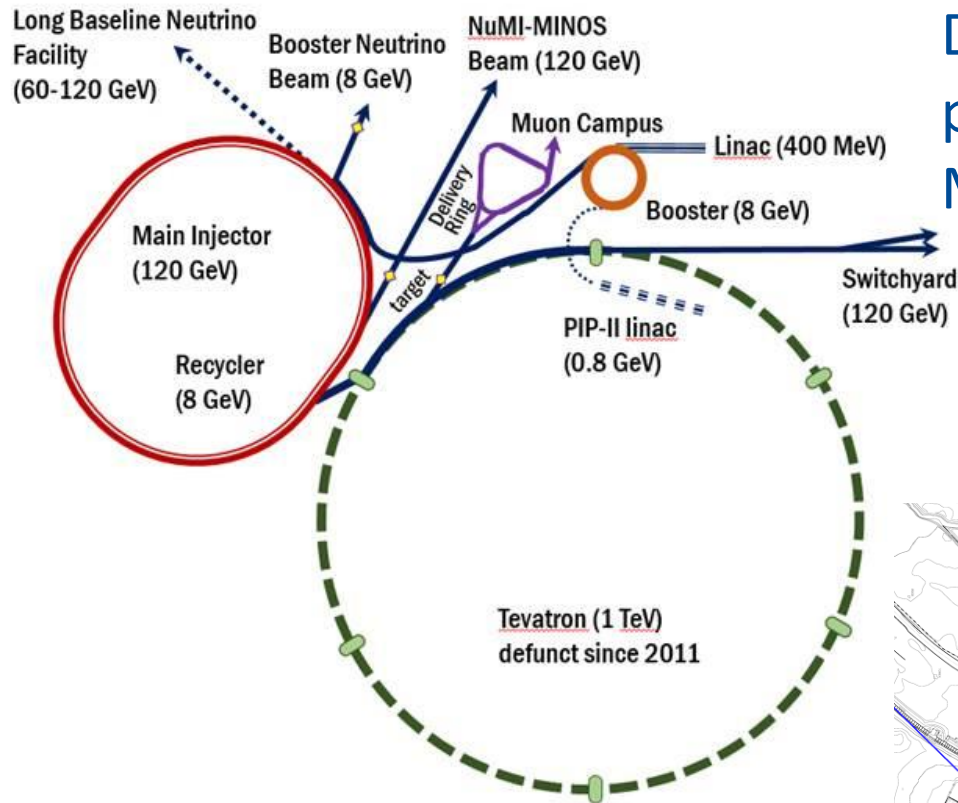
APS, Advanced Photon Source; ESRF, European Synchrotron Radiation Facility.

Adapted from  
*Nature News*  
Sep 10, 2013

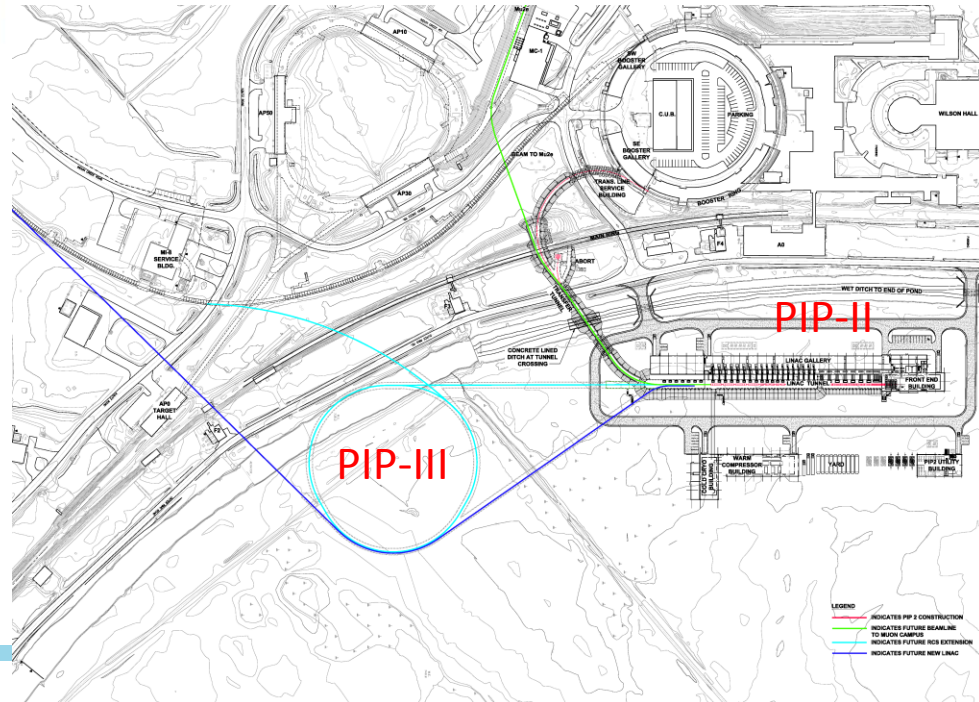
Fermilab Complex : 16 km of accelerators and beamlines, two high power targets, several low power target stations...



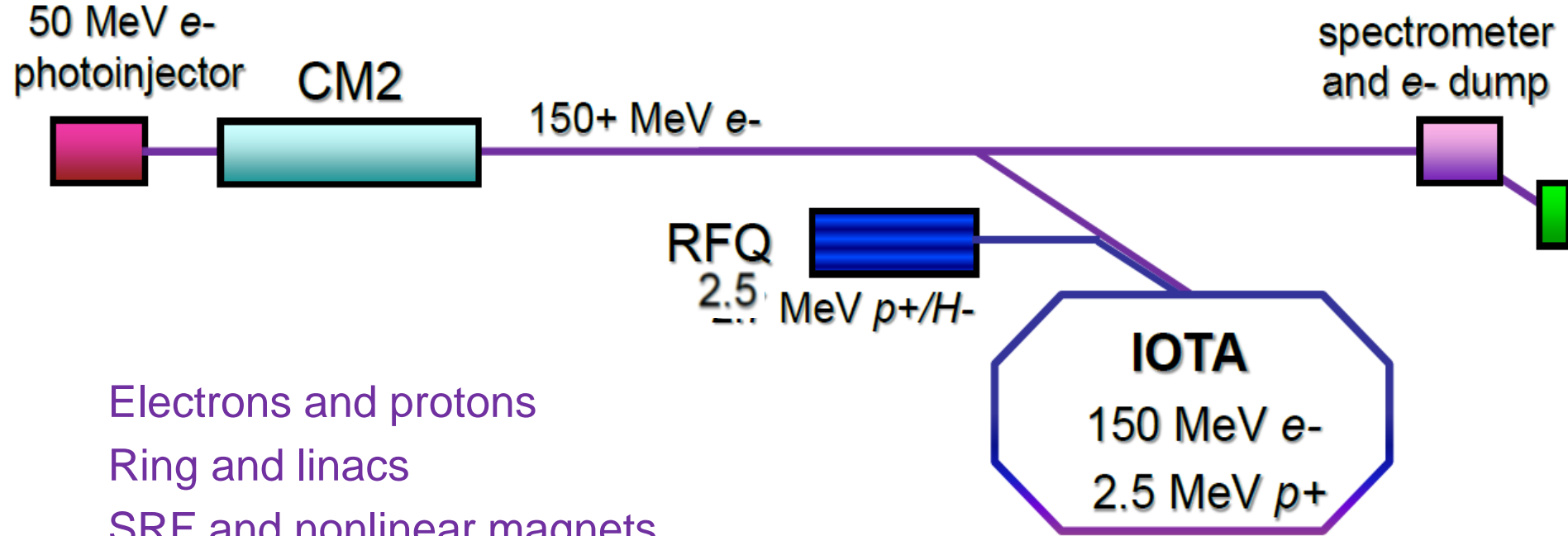
# Fermilab accelerators



Delivering 8 GeV and 120 GeV protons for neutrino experiments  
Muon beams to the g-2 experiment



# FAST/IOTA at Fermilab



Electrons and protons

Ring and linacs

SRF and nonlinear magnets

Accelerator Science topics:

Nonlinear beam dynamics

Space-charge compensation with electron lenses and electron columns

Optical stochastic cooling

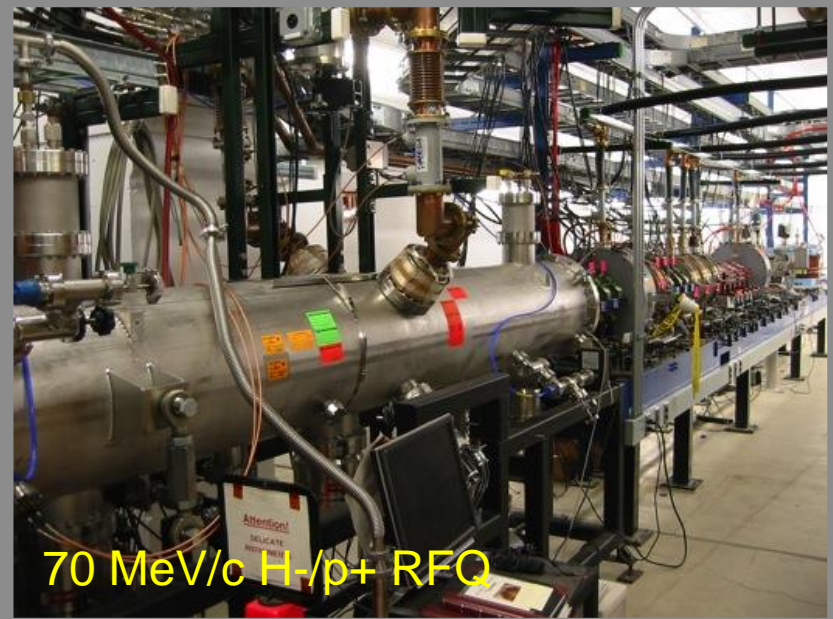
Radiation and phase-space manipulation in dense electron bunches

Laser plasma wakefield injector for IOTA

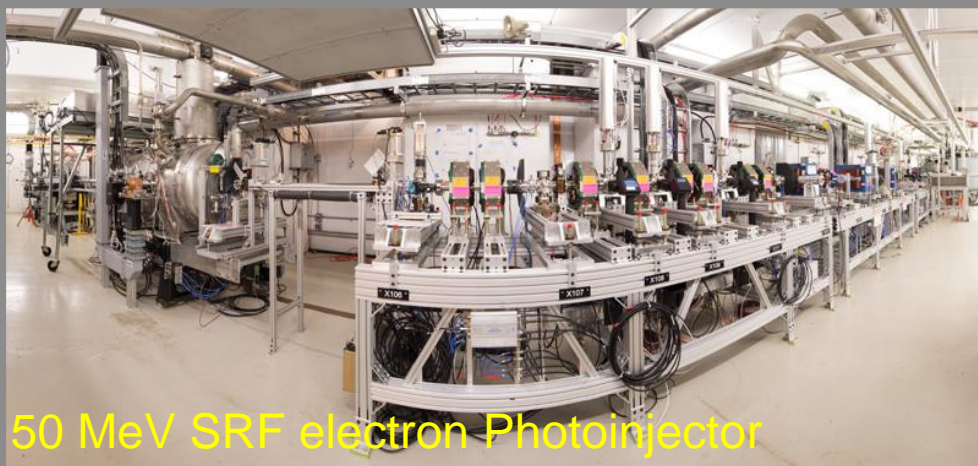
record gradient **31.5 MV/m**  
achieved in CM2



1.3 GHz SRF Cryomodule



70 MeV/c H-/p+ RFQ



50 MeV SRF electron Photoinjector

IOTA Ring Hall



# Great Universities in Chicago area: (with PhD programs in Accelerator Science)

- The University of Chicago, IIT, NIU
  - ...And a little farther away: MSU and Indiana University
- At UChicago, we currently have 3 graduate students and 2 incoming students in accelerator science.
- See: <http://beamscience.uchicago.edu/>
- We currently have openings for graduate students in the area of accelerator science.



# Welcome to Fermilab!