# hi

Day 14, 22.02.2018

Particle Accelerators

Special Relativity

# housekeeping


Lectures forever now: Gotta come to class

Anyone have trouble with the videos inside Lesson 13?

> I extended the HW to Sunday and added direct links to the videos in the Lesson

I think MasteringAstronomy is screwed up. I fixed it

> question about *anything*? I'll make a movie for you:

Midterm…before Spring Break

# February 2018

| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
|---|---|---|---|---|---|---|
| 28 | 29 | 30 | 31 | 1 | 2 | 3 |
| 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| 25 | 26 | 27 | 28 | 1 | 2 | 3 |

yadda yadda yadda

yadda yadda yadda

HW5

HW6

today

lesson 12

HW5 due

HW7

lecture

lecture

HW6 due

midterm

HW8

lecture

lecture

HW7 due

Eastern Time Time Zone

Page 1/1

HW8 due 3/16

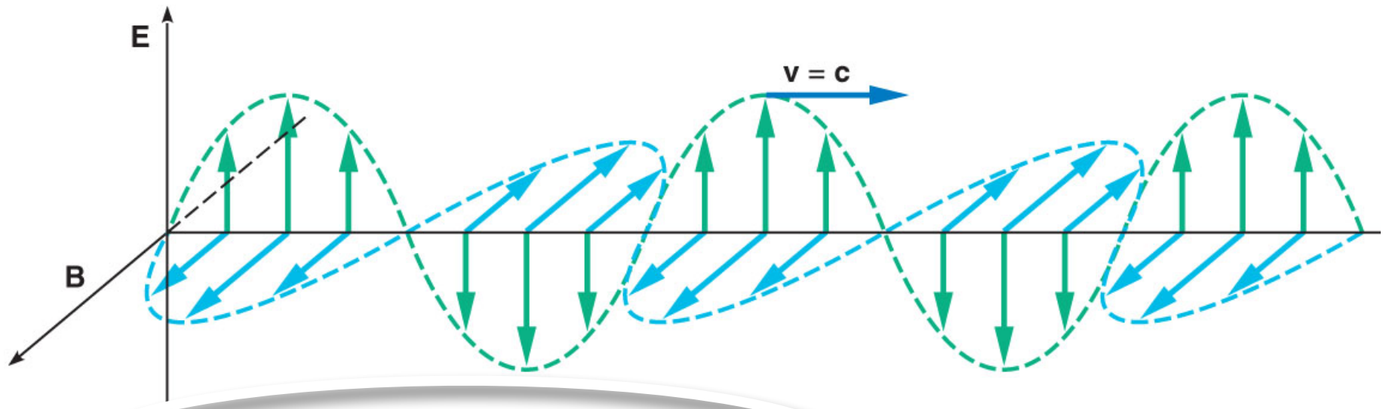
You might want to remember this:

**a changing B field creates an E field**

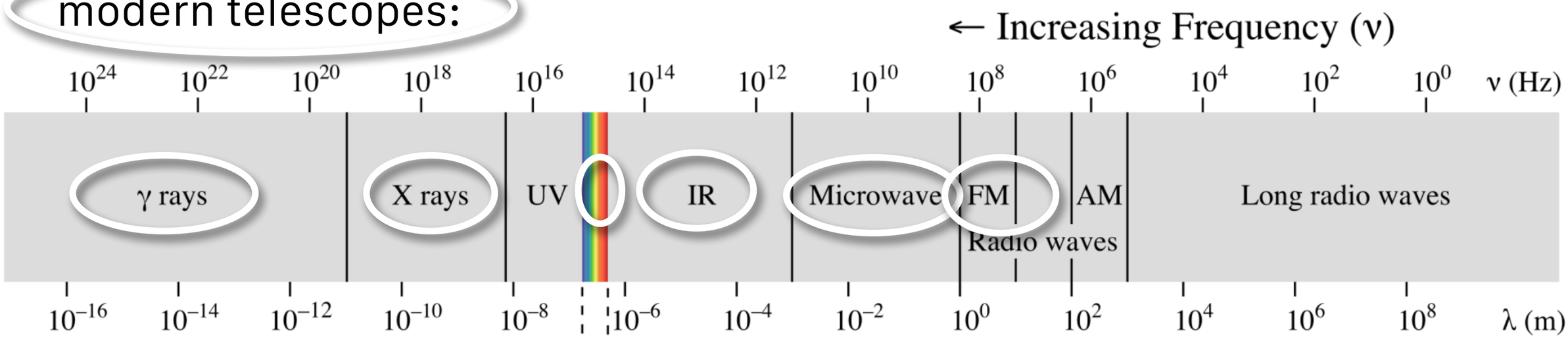
**a changing E field creates a B field**

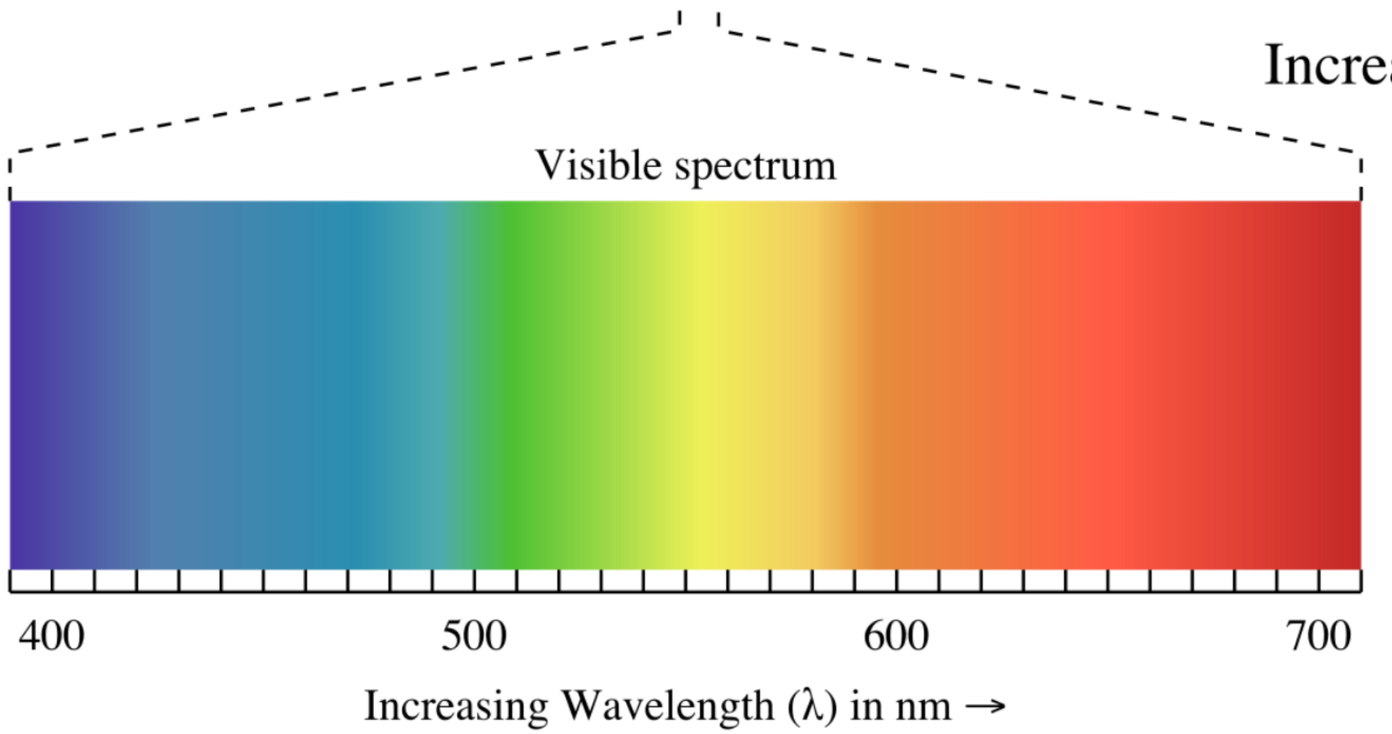
**accelerated charges produce electromagnetic radiation**

# Modern Electromagnetic Spectrum

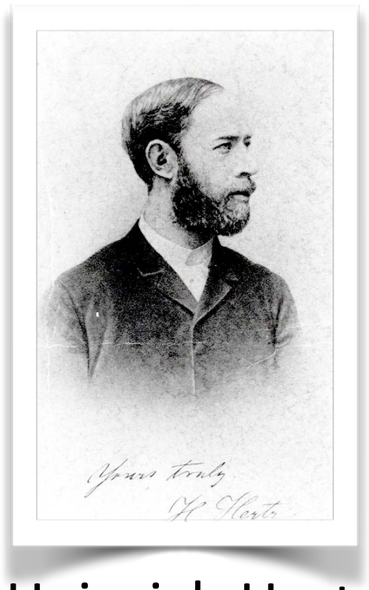



modern telescopes:




all travel at $c$ = 3 x $10^8$ m/s




Heinrich Hertz

1857 – 1 January 1894

# what's a particle accelerator?

a device designed to:

**accelerate** elementary particles to interesting energies

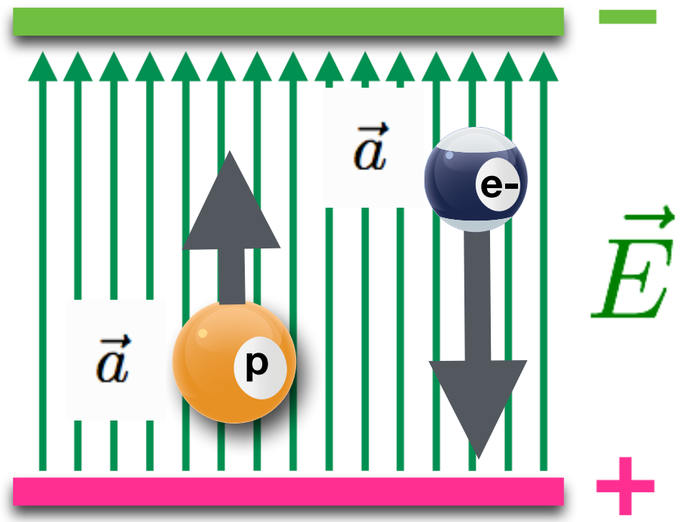
&

**bend** them where you want them to go

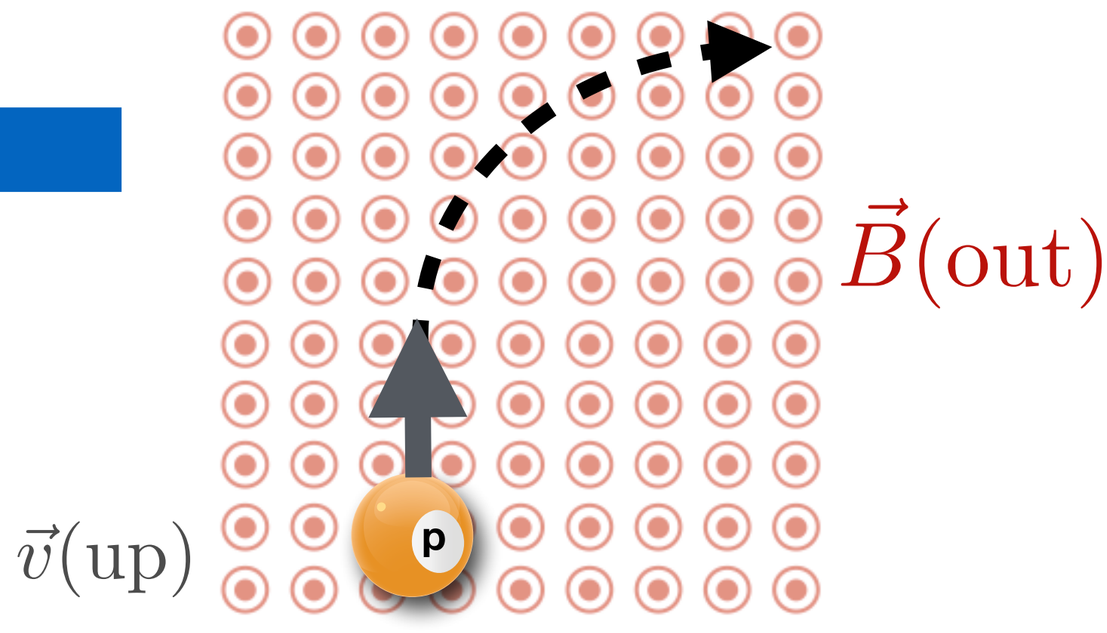
# Accelerator ingredients: E and B

for two configurations of charges and currents

**Electric Fields**
**accelerate**




**Magnetic Fields**
**bend**



# 4 kinds of accelerators

in particle and nuclear physics:

Cockcroft-Walton accelerator

Linear accelerators

Synchrotron accelerators

*by themselves, or coupled together*

Cyclotron

## what's a particle accelerator?

a device designed to:

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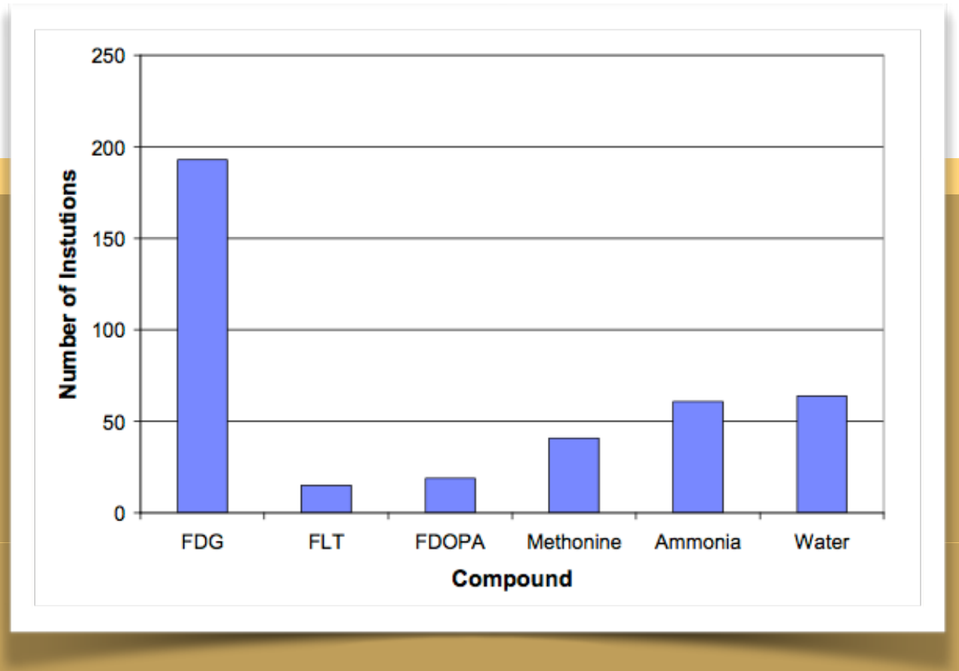
&

**bend** them where you want them to go

40 nations for medical radioisotope production




beam:

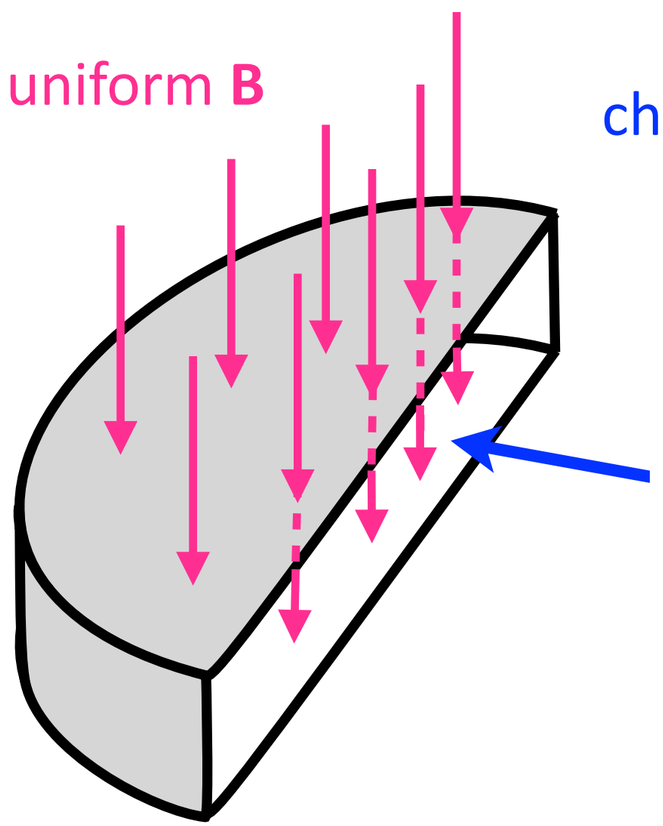
# cyclotron

| | |
|---|---|
| beam: | nuclei |
| source: | ion source |
| acceleration: | electrostatic |
| energy: | few 100 MeV/nucleon |
| location: | physics research: MSU, Canada, Germany, Japan, Britain, France |

NSCL, superconducting cyclotron

"cyclotrons" were the first

for Nuclear Physics…creating rare nuclei and studying them



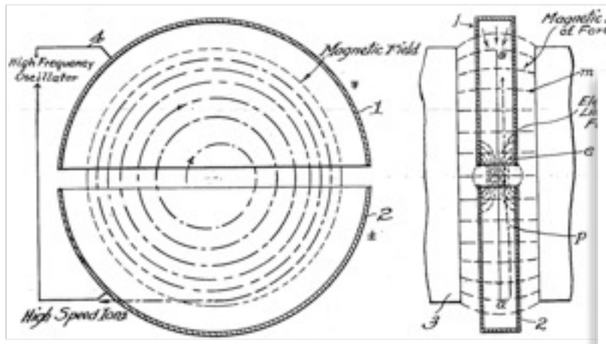

"Dees" ...think of them as metal cans, open across a diameter

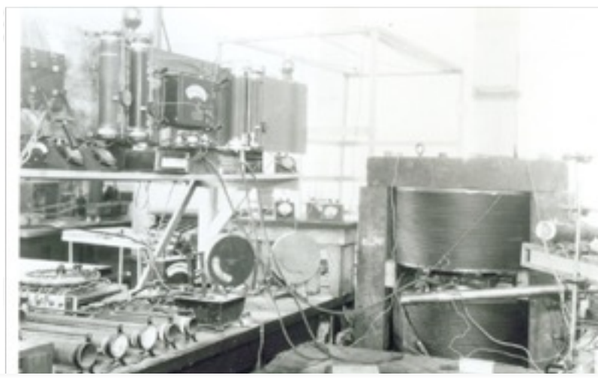
Higher energy beams...need larger and larger **B** fields.

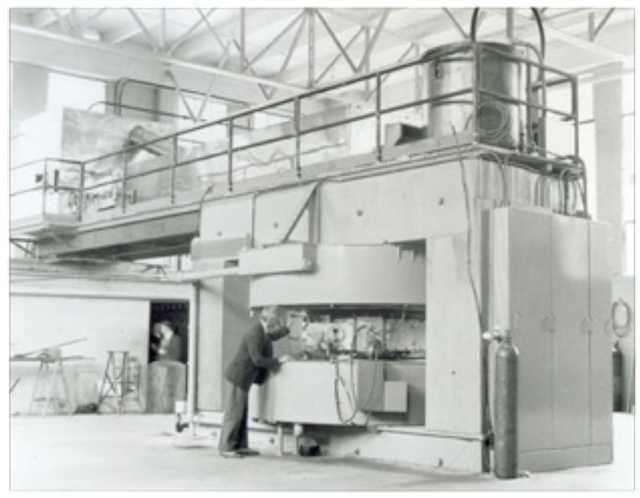
Conventional technology reached an endpoint...that's where MSU dominated: the first superconducting cyclotron 1981

# invented 1929

Ernest Lawrence at University of California, Berkeley






# 1939 Nobel

**The Nobel Prize in Physics 1939**
Ernest Lawrence

*Share this:*

# The Nobel Prize in Physics 1939

**Ernest Orlando Lawrence**

**Prize share:** 1/1

**The Nobel Prize in Physics 1939 was awarded to Ernest Lawrence *"for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements".***

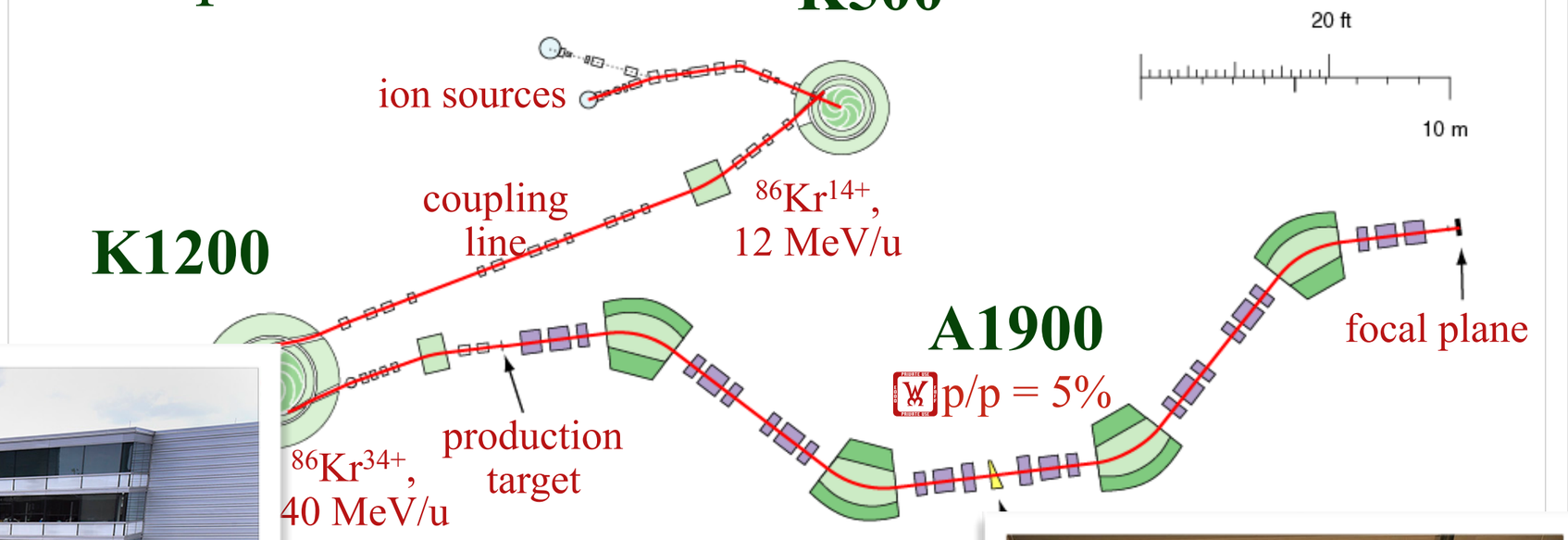


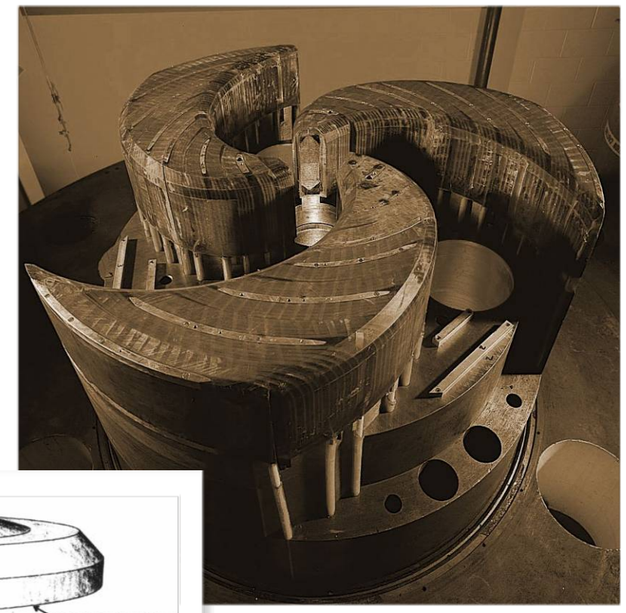
*e this:*

**is page**
"The Nobel Prize in Physics 1939". *Nobelprize.org.* Nobel Media AB 2014. Web. 9 F
http://www.nobelprize.org/nobel_prizes/physics/laureates/1939/>

# NSCL

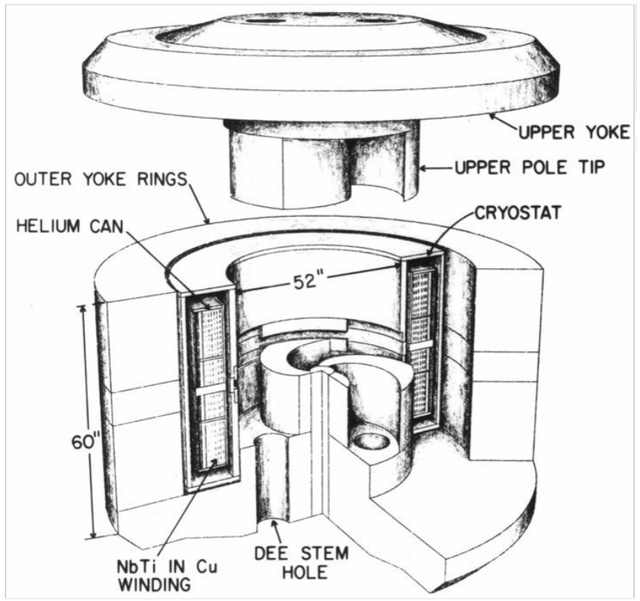
## Example: $^{86}Kr \rightarrow {}^{78}Ni$



K500

K1200



beam:

# linear accelerator aka “LINAC”

| | |
|---|---|
| beam: | *e or p* |
| source: | pre-accelerator (C-W) |
| acceleration: | RF |
| energy: | 10’s  GeV beam energy |
| location: | Fermilab, CERN, SLAC |

# accelerate and bend

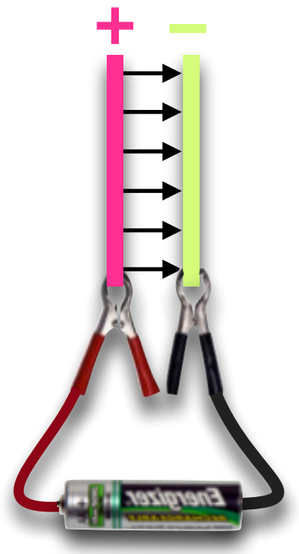
## what's a particle accelerator?

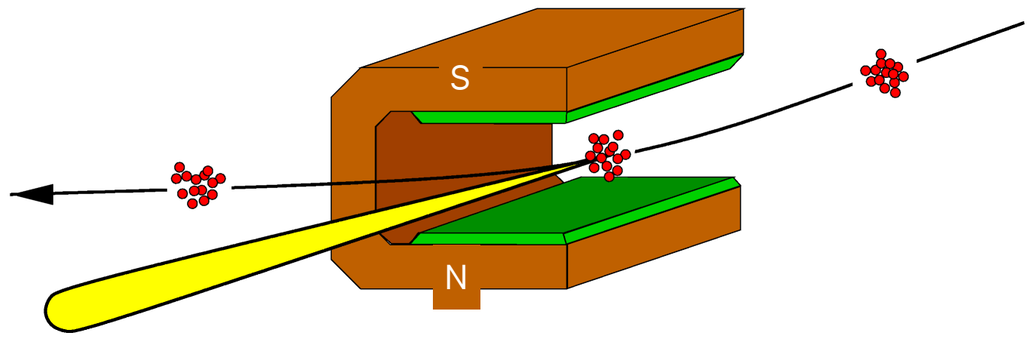
a device designed to:

**accelerate** elementary particles to interesting energies

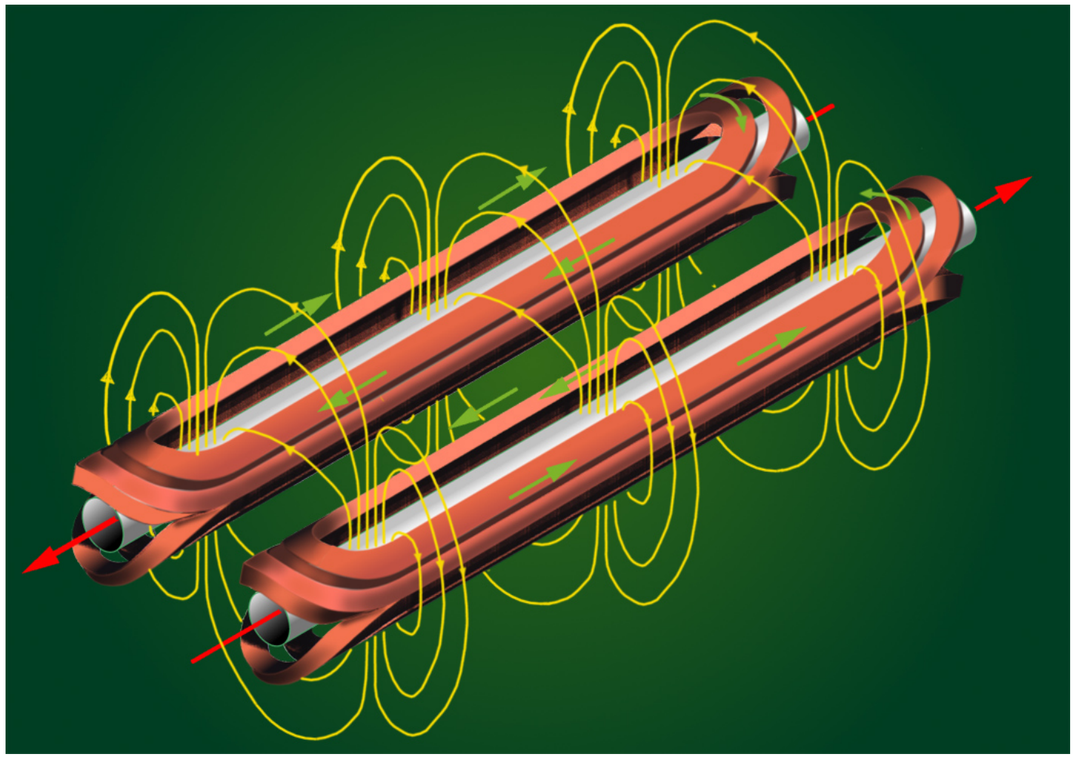
&

**bend** them where you want them to go




permanent magnet dipole



LHC superconducting current dipole

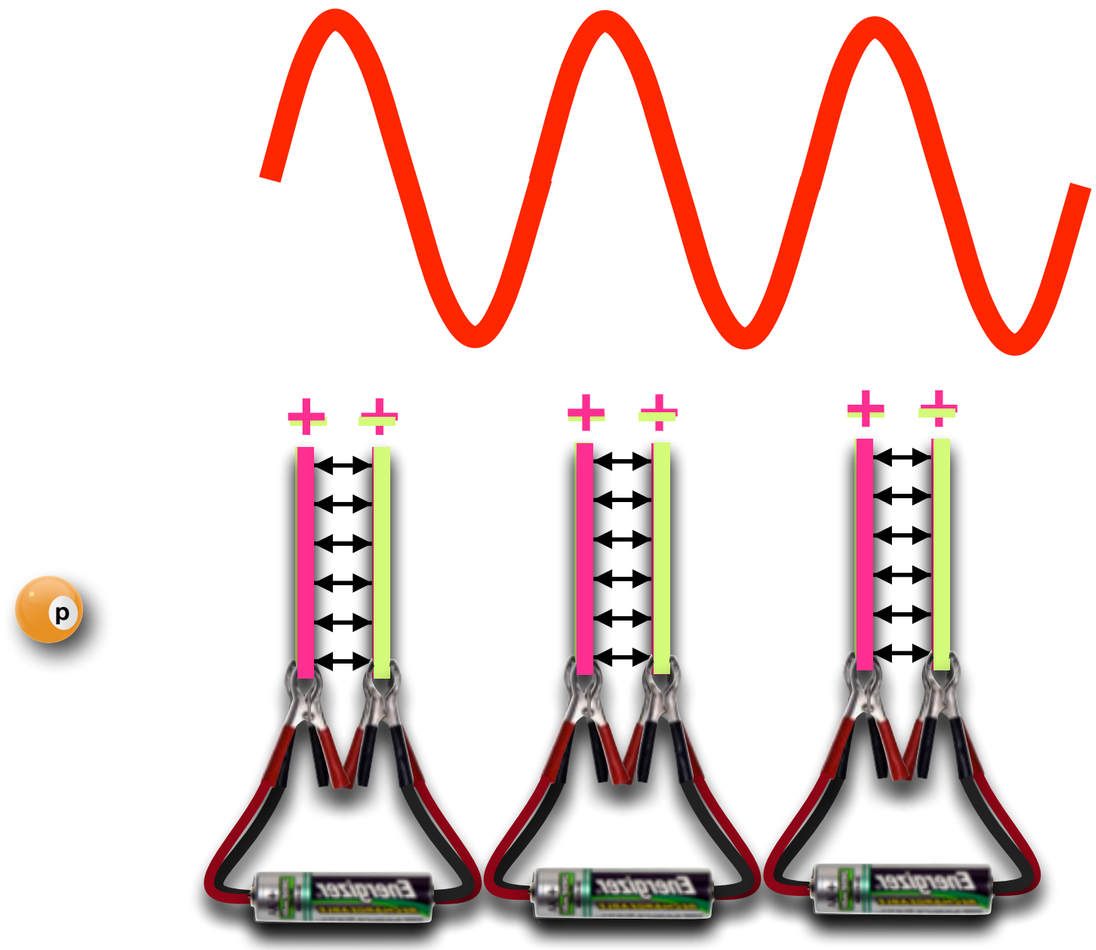
familiar principle now?

use Radio Frequency (RF) "cavities"

synchronized pushes to charged particles

*by changing the E Field direction*

# How particles are accelerated:



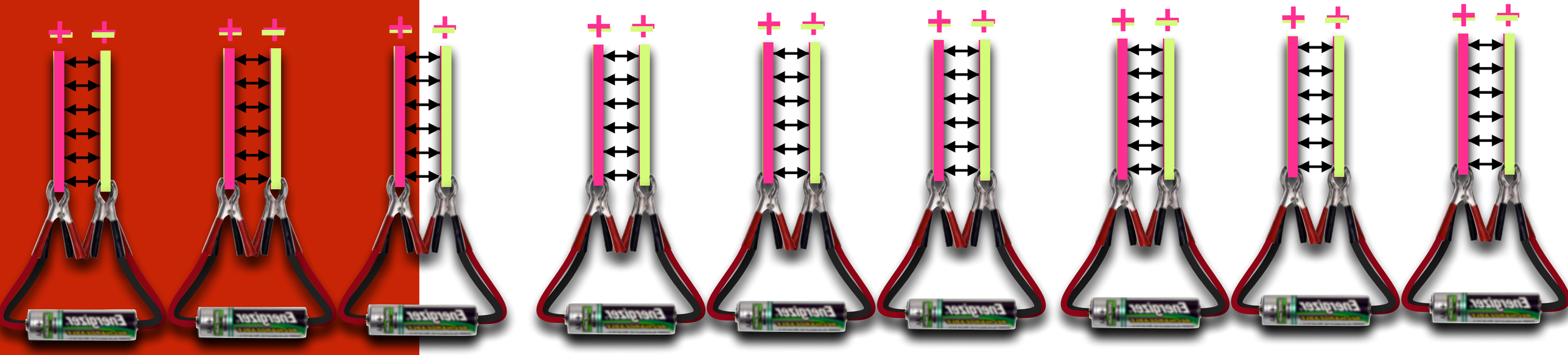
of course, acceleration of negative particles is the same...just the opposite phase.

There are many geometrical configurations that make use of RF cavity acceleration.

# ‘‘LINAC’’

## stand-alone accelerators
## stager for other accelerators

4 of the 330 RF cavities for FRIB

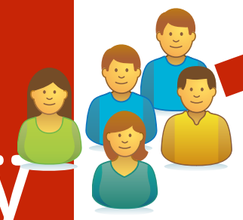


# Facility for Rare Isotope Beams

"FRIB"

major event in the history of MSU

you are here



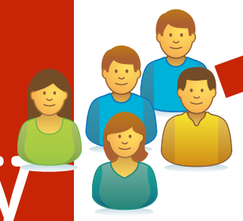
you are here

will be a linear accelerator of heavy ions

# Facility for Rare Isotope Beams

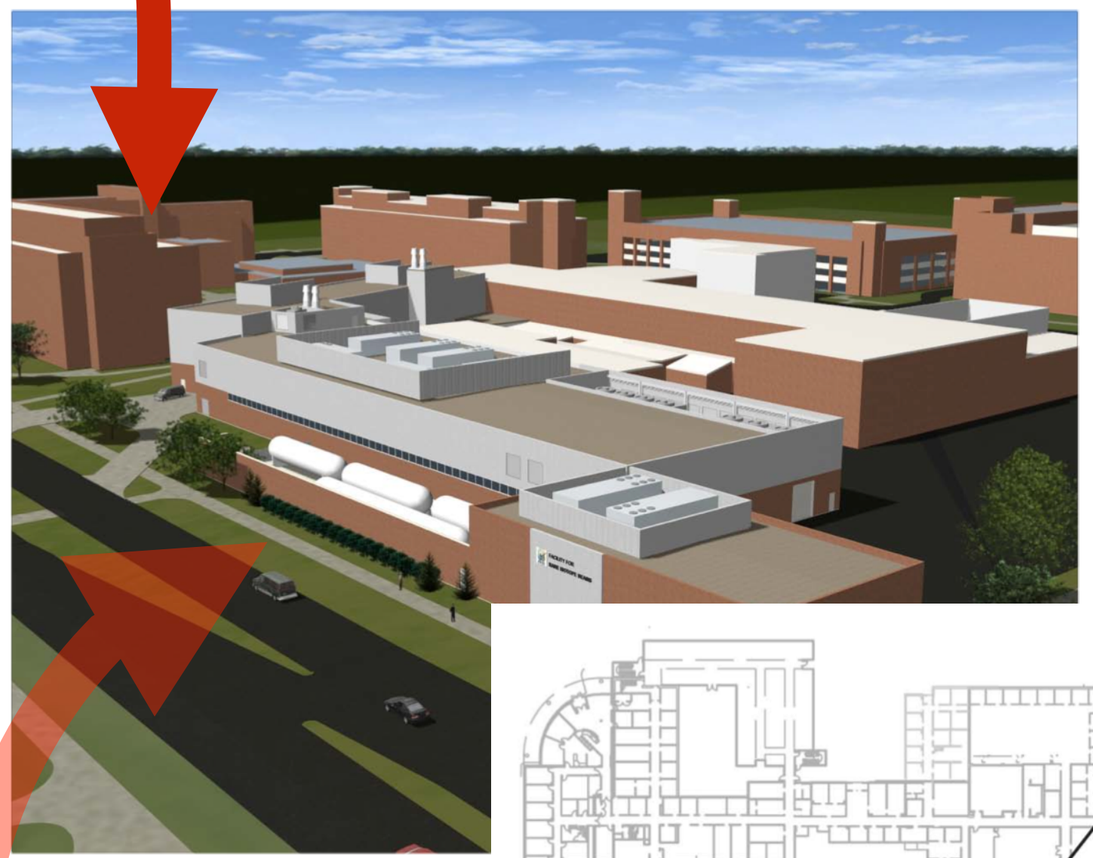
"FRIB"

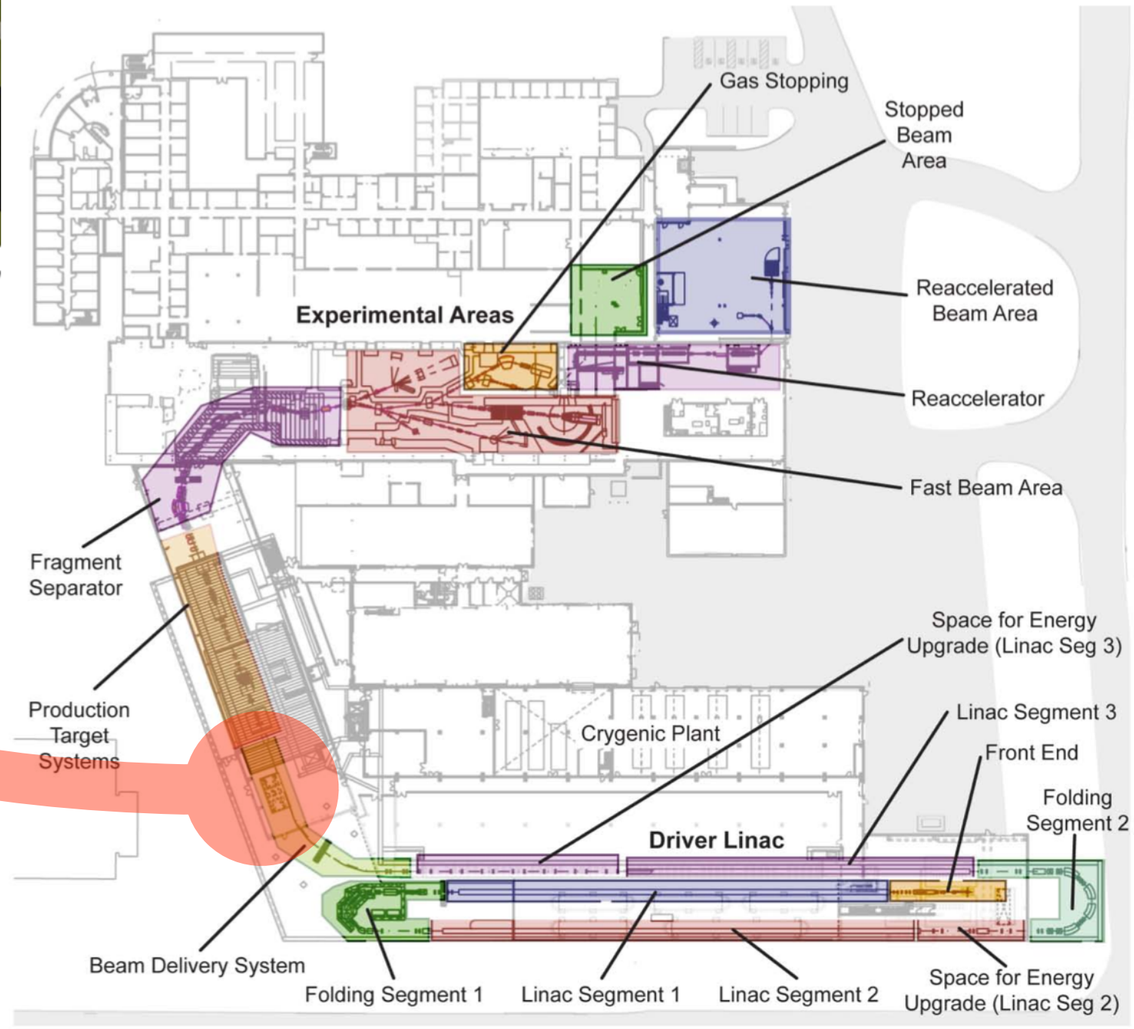
major event in the history of MSU



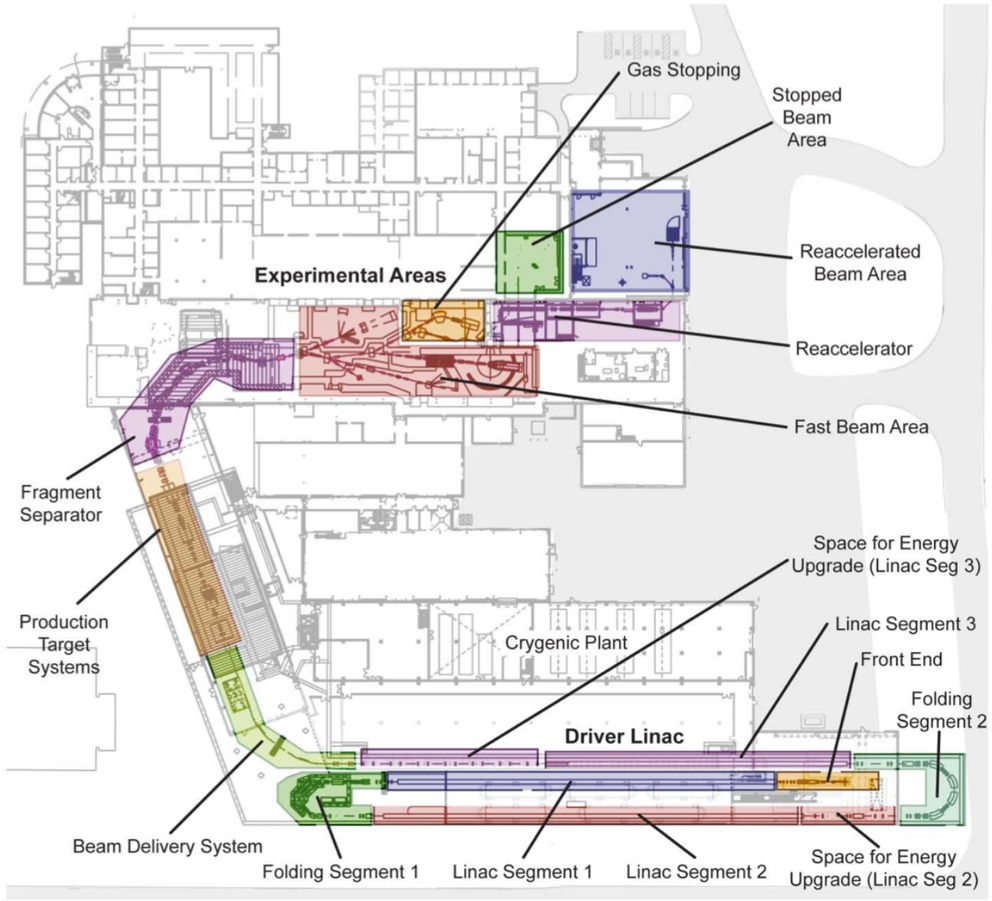
you are here

**will be a linear accelerator of heavy ions**



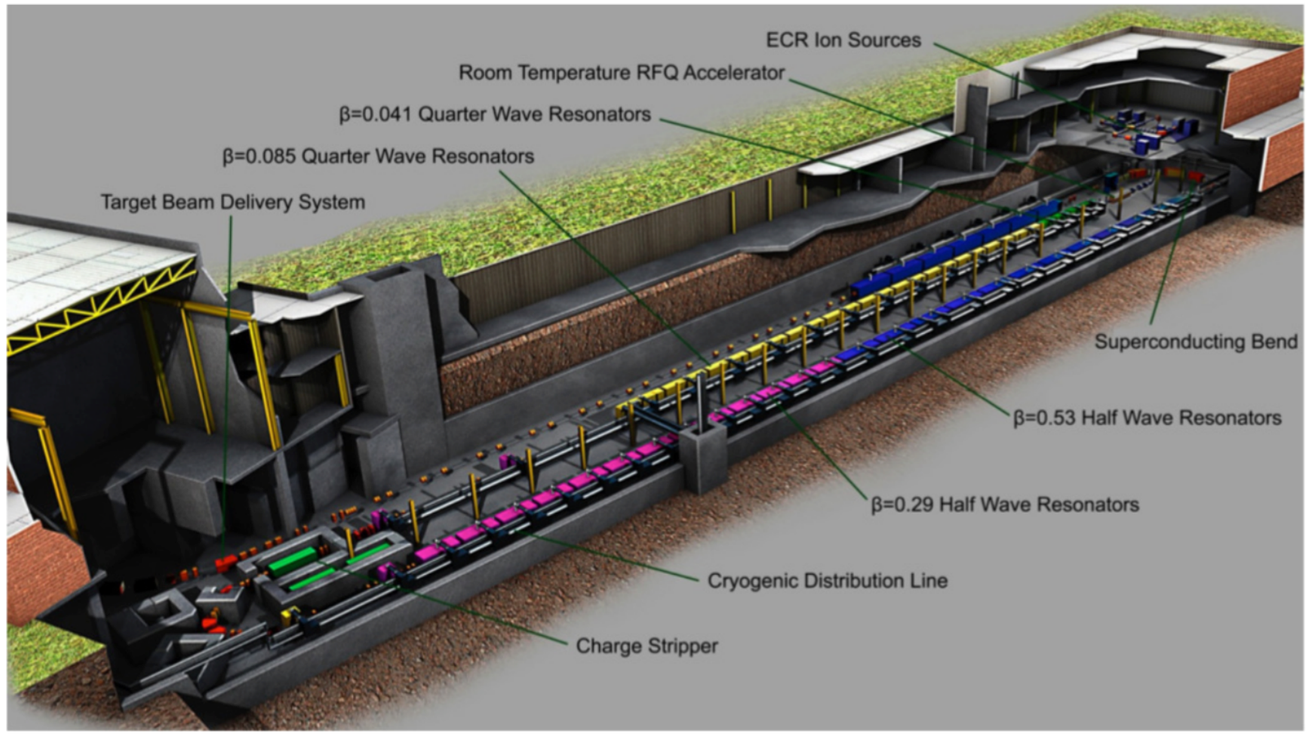


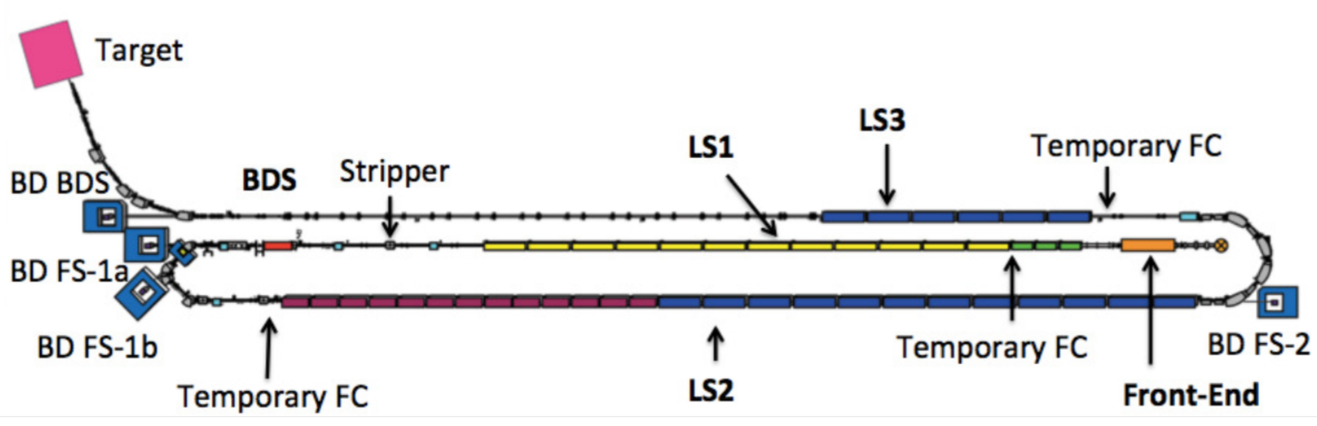

**a "folded" linear accelerator of heavy ions**




3 linear accelerators

superconducting and very complex



## what's a particle accelerator?

a device designed to:

**accelerate** elementary particles to interesting energies

&

**bend** them where you want them to go

beam: **synchrotron**

beam: *e, p, $\bar{p}$, heavy nuclei, or $\mu$*

source: LINACs

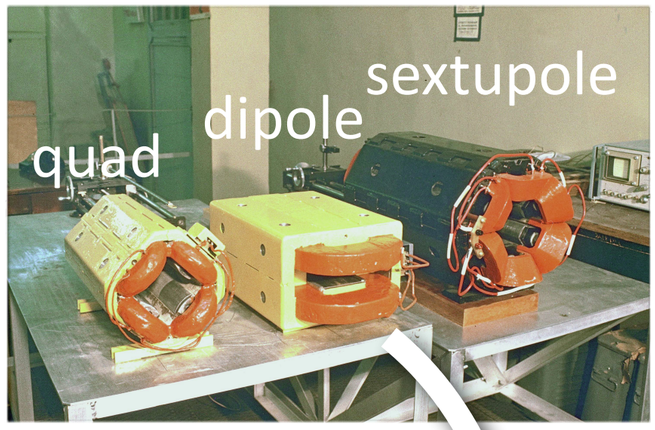
acceleration: RF

energy: 10's GeV - few TeV beam energy

location: CERN (p, Nuclei), Fermilab($\mu$), SLAC (e), other US and international labs

# cartoon of a synchrotron

quadrupole: focus
392, LHC




dipole: bend
1232 LHC, 15m long

R = 2.8 km, LHC

LHC dipole

cutaways of:

dipole: bend

RF: accelerate

dipole: bend

dipole: bend

quadrupole: focus

final focus

final focus

# particle physics accelerators

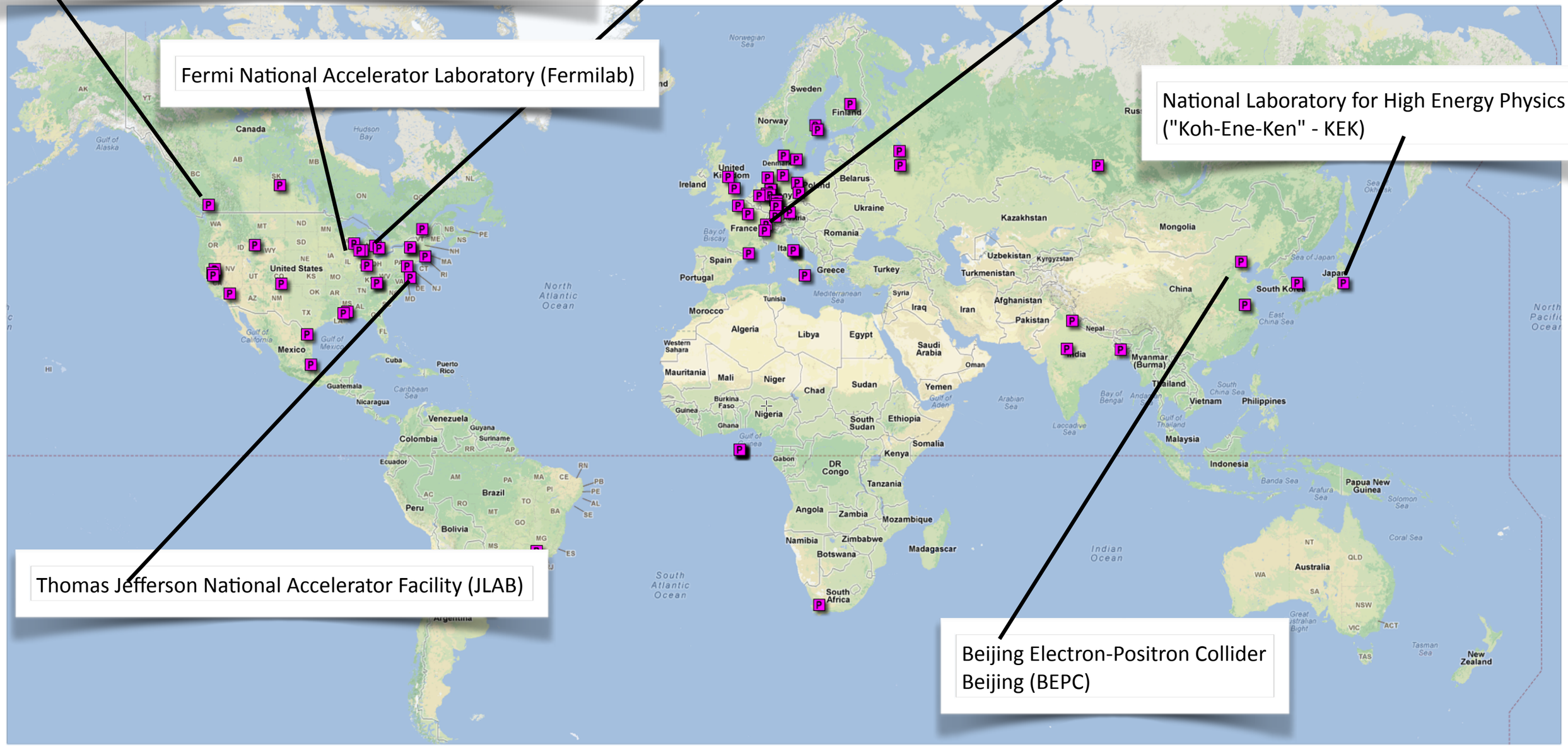
National Superconducting Cyclotron Laboratory (NSCL)
soon...Facility for Rare Isotope Beams (FRIB)

National Laboratory for Particle and Nuclear Physics (TRIUMF)

European Centre for Particle Physics (CERN)

Fermi National Accelerator Laboratory (Fermilab)

National Laboratory for High Energy Physics
("Koh-Ene-Ken" - KEK)




Thomas Jefferson National Accelerator Facility (JLAB)

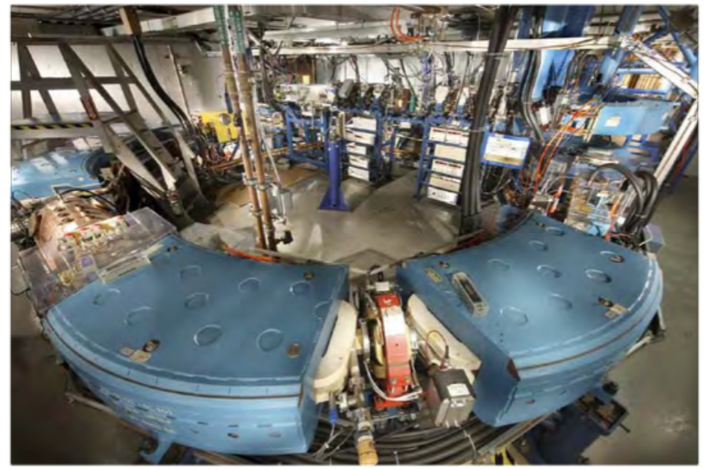
Beijing Electron-Positron Collider
Beijing (BEPC)

http://find.mapmuse.com/map/particle-accelerators

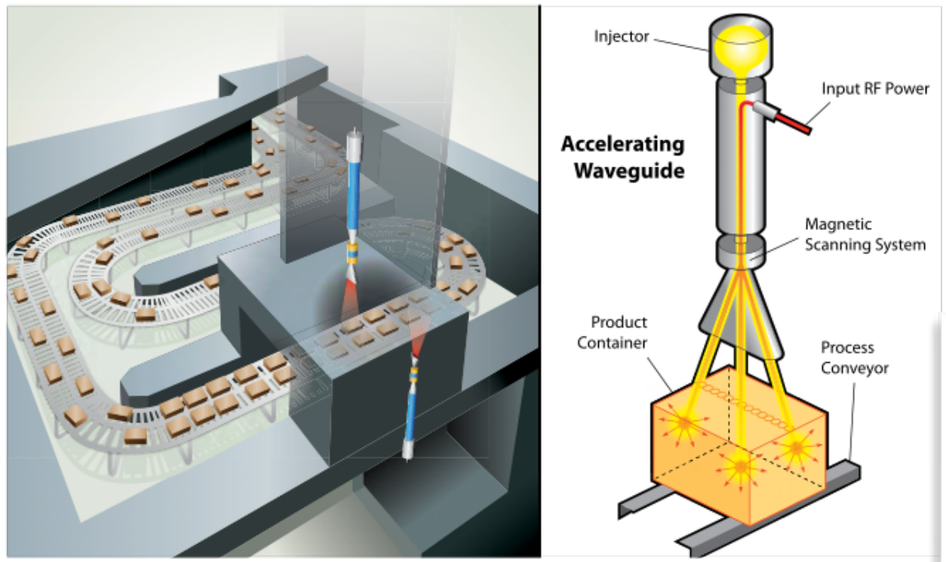
# particle accelerators

medicine

The Loma Linda Proton Treatment Center

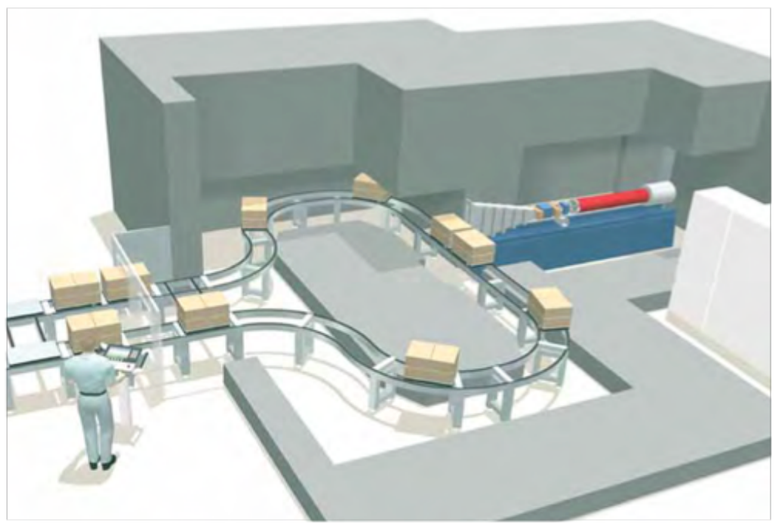


sterilization




electron beams making X-rays

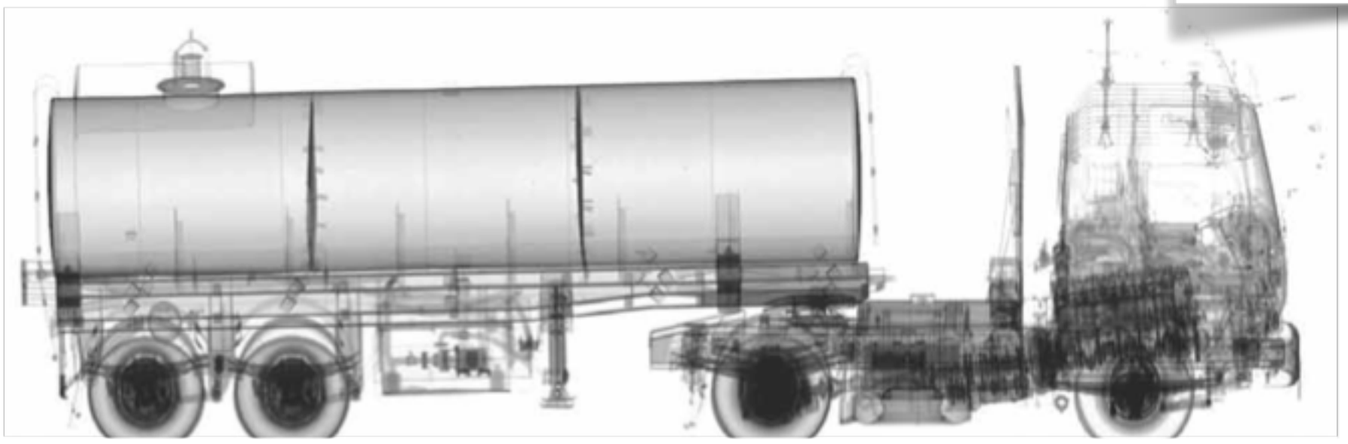
The international Radura symbol indicates food has been irradiated.

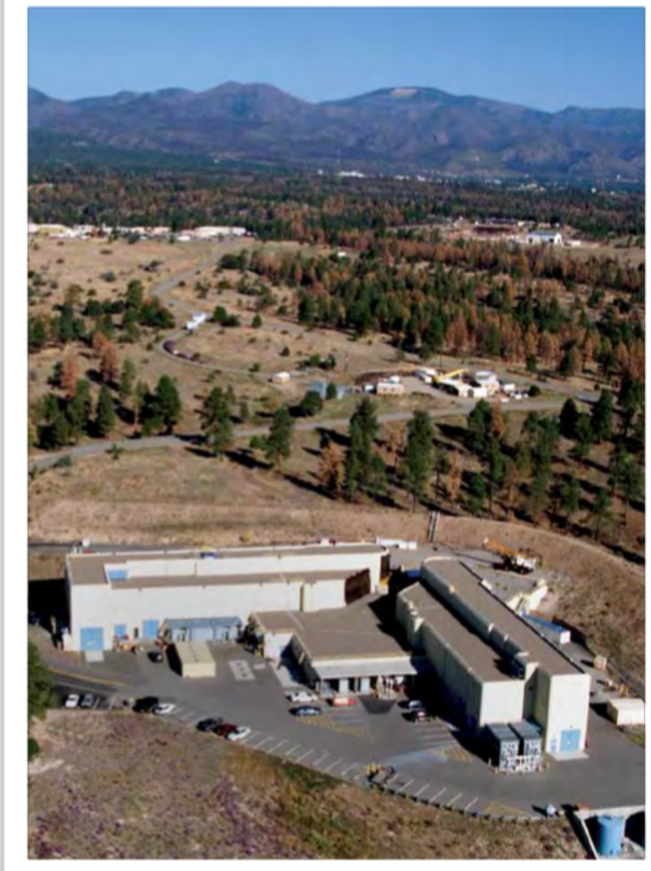


Electron beams irradiate whole boxes of band-aids, blood platelets, skin grafts...eliminating bacteria

# particle accelerators

Security

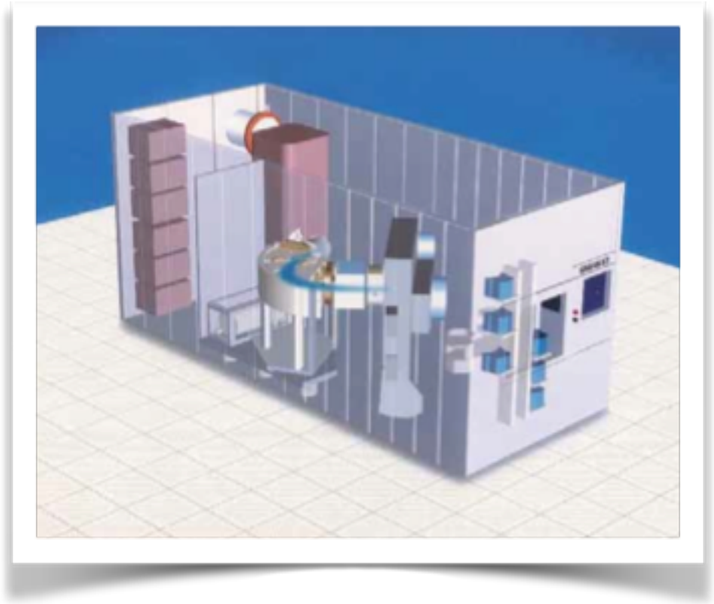




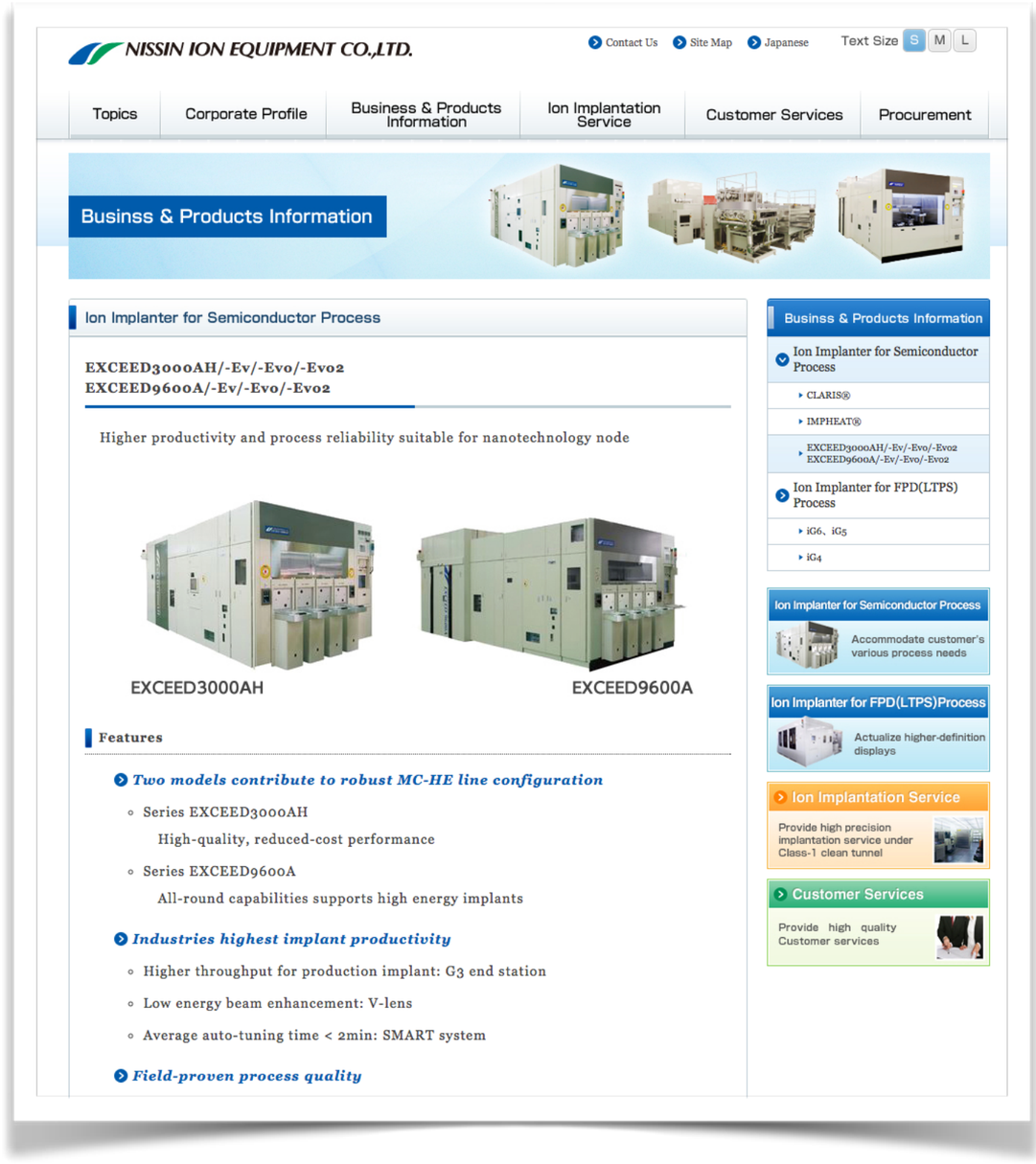
Nuclear weapon “Stockpile Stewardship”
Los Alamos National Laboratory: Dual-Axis Radiographic Hydrodynamic Test Facility, or DARHT Facility

# particle accelerators

manufacturing



ion implantation to harden tools

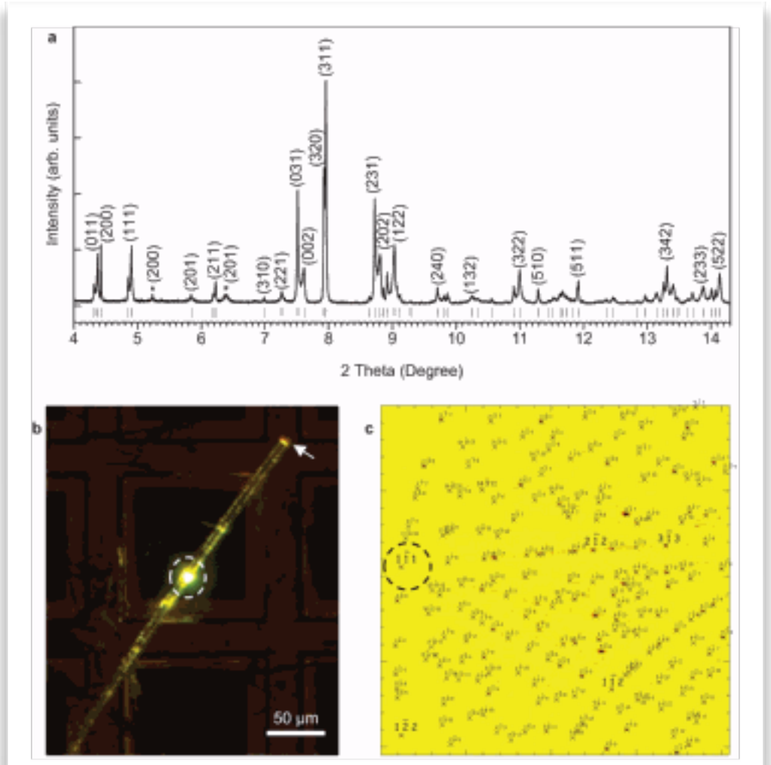


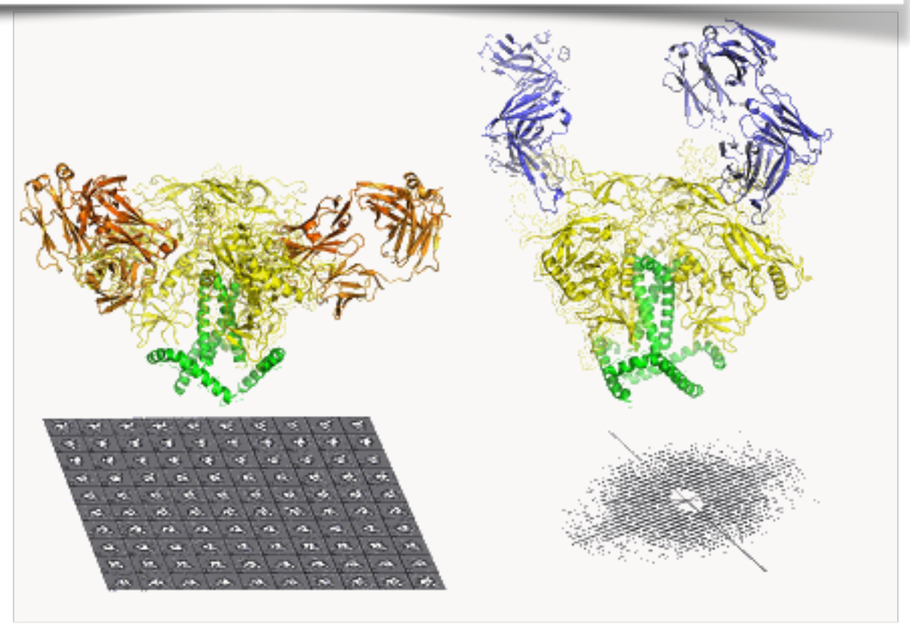

ion implantation for semiconductor manufacturing

# particle accelerators

Basic scientific research


The Advanced Photon Source (APS) at the U.S. Department of Energy's Argonne National LaboratoryLight beams for studies of materials



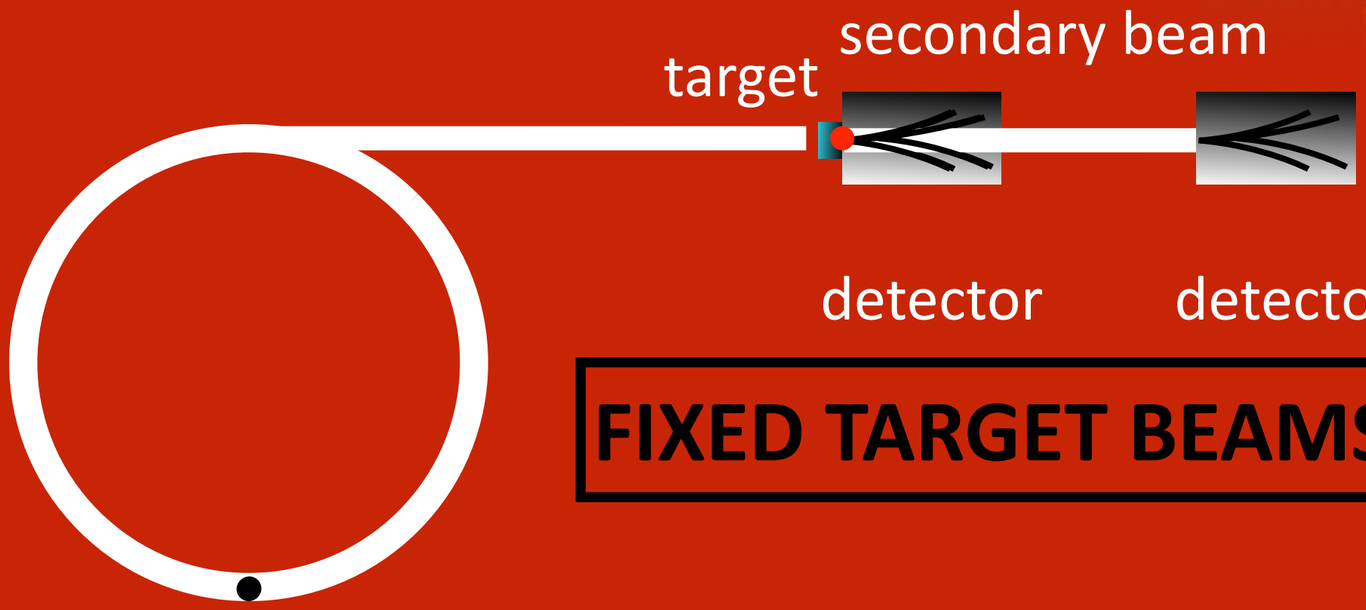
The structure of the human immunodeficiency virus envelope protein

Synchrotron x-ray diffraction measurements of $Ba_{0.93}Eu_{0.07}Al_2O_4$ phosphor.

# two basic kinds of arrangements:

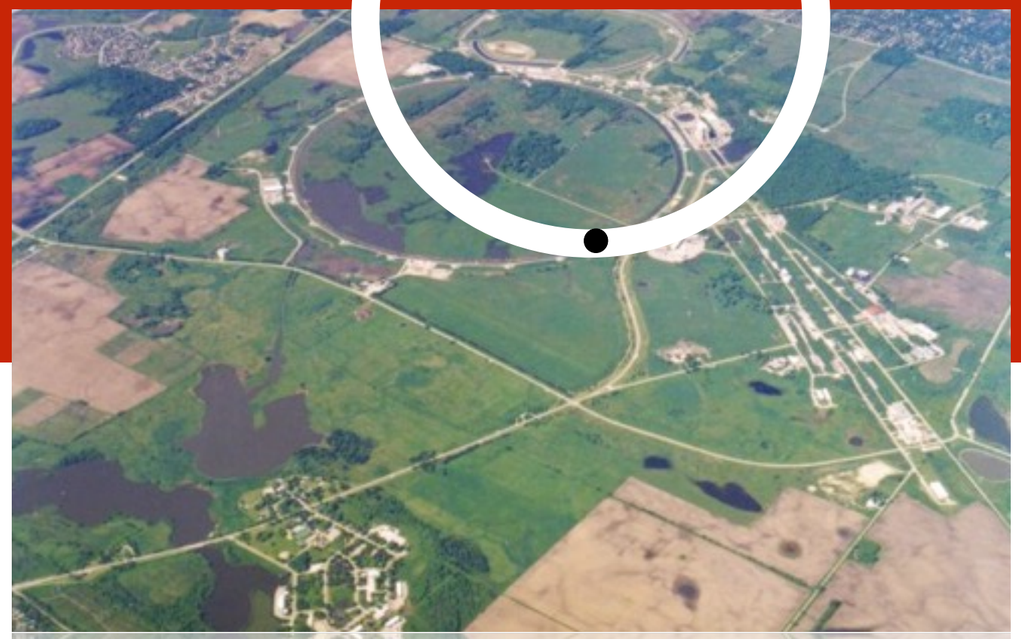
Fixed Target Beams
and Colliding Beams


CERN LHC




**FIXED TARGET BEAMS**


**COLLIDING BEAMS**



Fermi National Accelerator Laboratory
Batavia, IL

jargon alert: **fixed target experiment (aka "FT")**

refers to: a beam of particles impinges on a stationary target

entomology: obvious

example: SLAC fixed target experiments, all neutrino experiments

jargon alert: **colliding beam facility (aka “collider”)**

refers to: two beams are brought to head-on collisions

entomology: obvious

example: Fermilab Tevatron, LHC, SLAC colliders

# 3 kinds of accelerators

in particle physics:

Particle sources: e.g., Cockcroft-Walton accelerator

Linear accelerators

Synchrotron accelerators

*by themselves, or coupled together*

# 1932: John Cockroft & Ernest Walton

took on the task of making a proton accelerator

the 800 pound Gorilla: Ernest Rutherford

They made a “voltage multiplier” and used it to accelerate protons

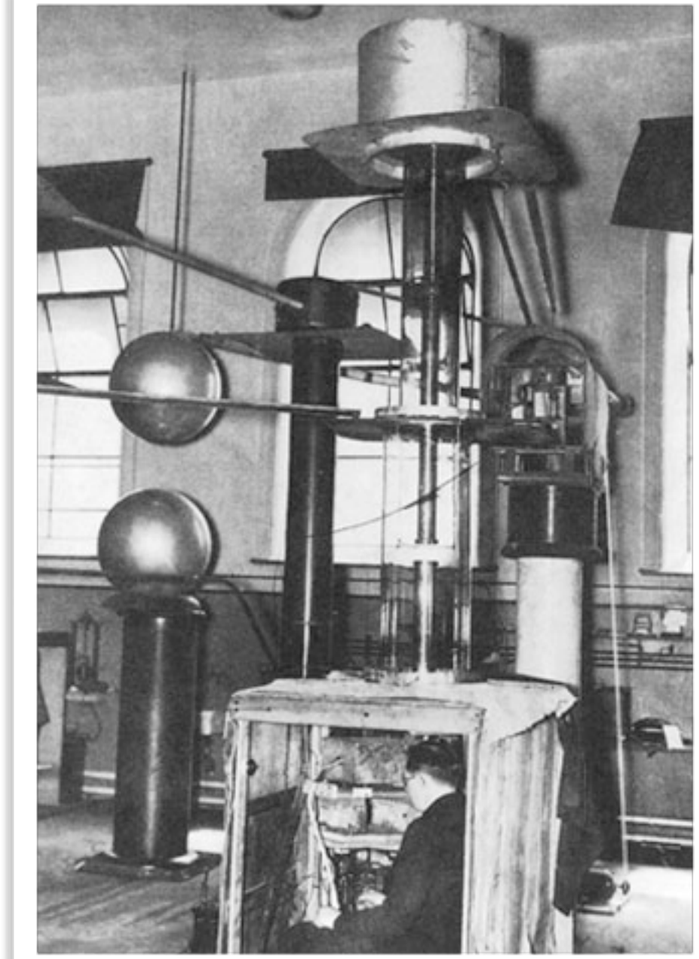
beam:

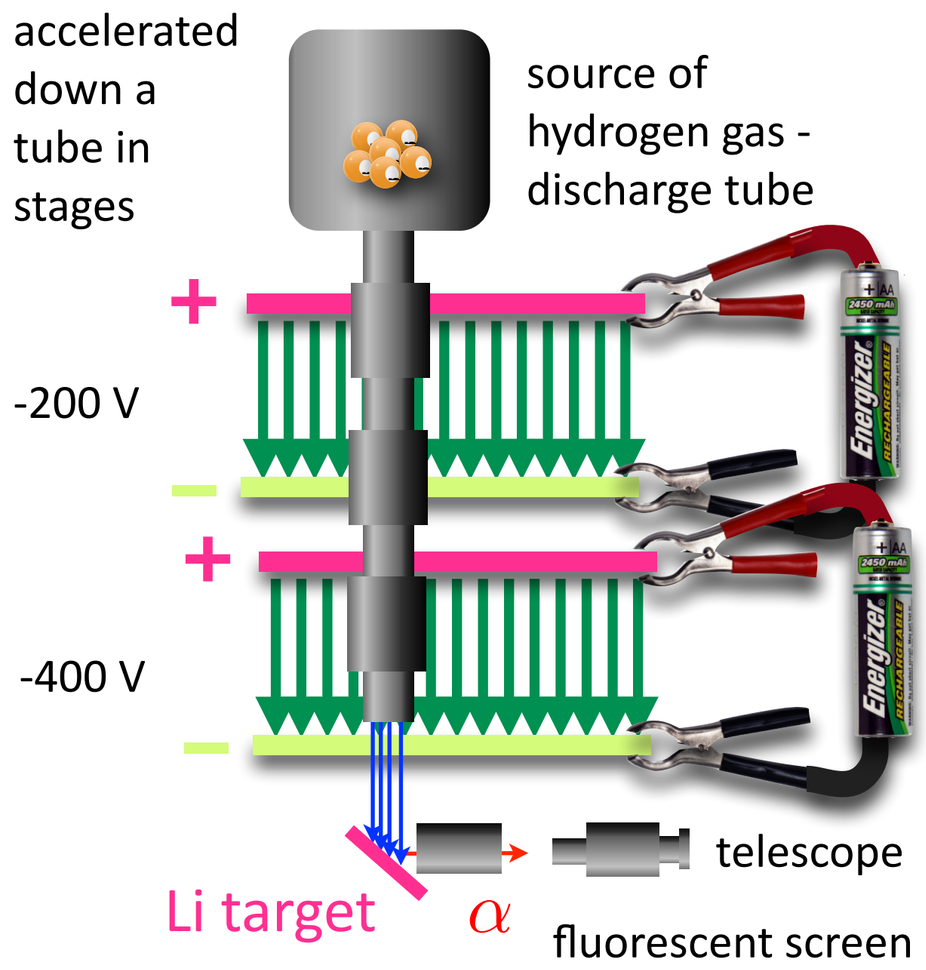
# Cockcroft-Walton Accelerator

| | |
|---|---|
| beam: | protons |
| source: | hydrogen |
| acceleration: | electrostatic |
| energy: | few 100 - 1000 keV |
| location: | most proton syncrotrons |

# Cockloft-Walton Accelerator 1932

invented it and then did "award-winning" experiments





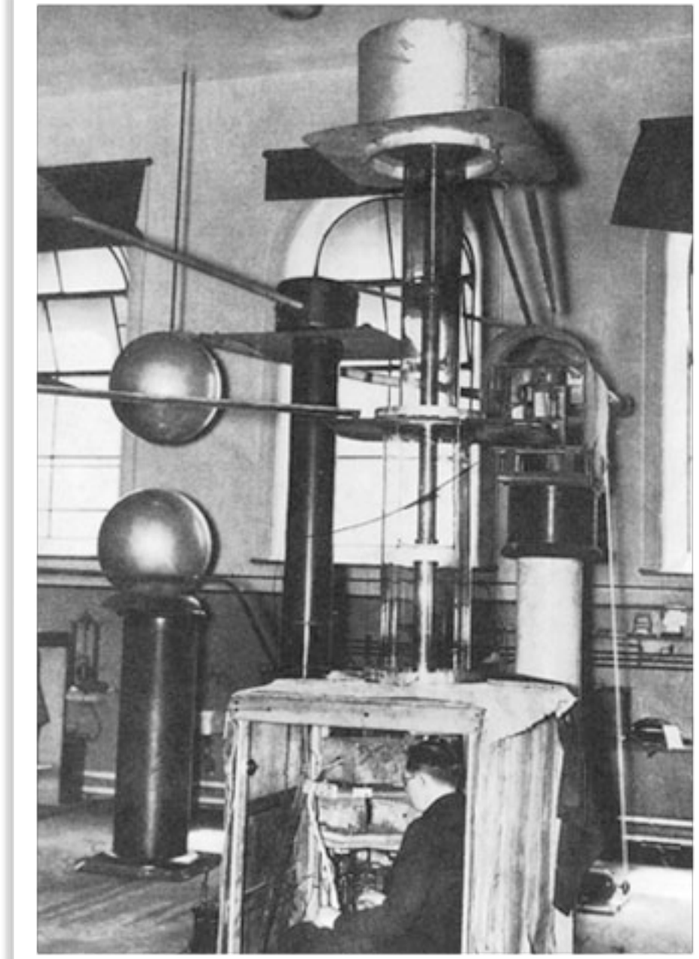

Their voltage multiplication circuit became a standard way to accelerate electrons/protons - in a TV

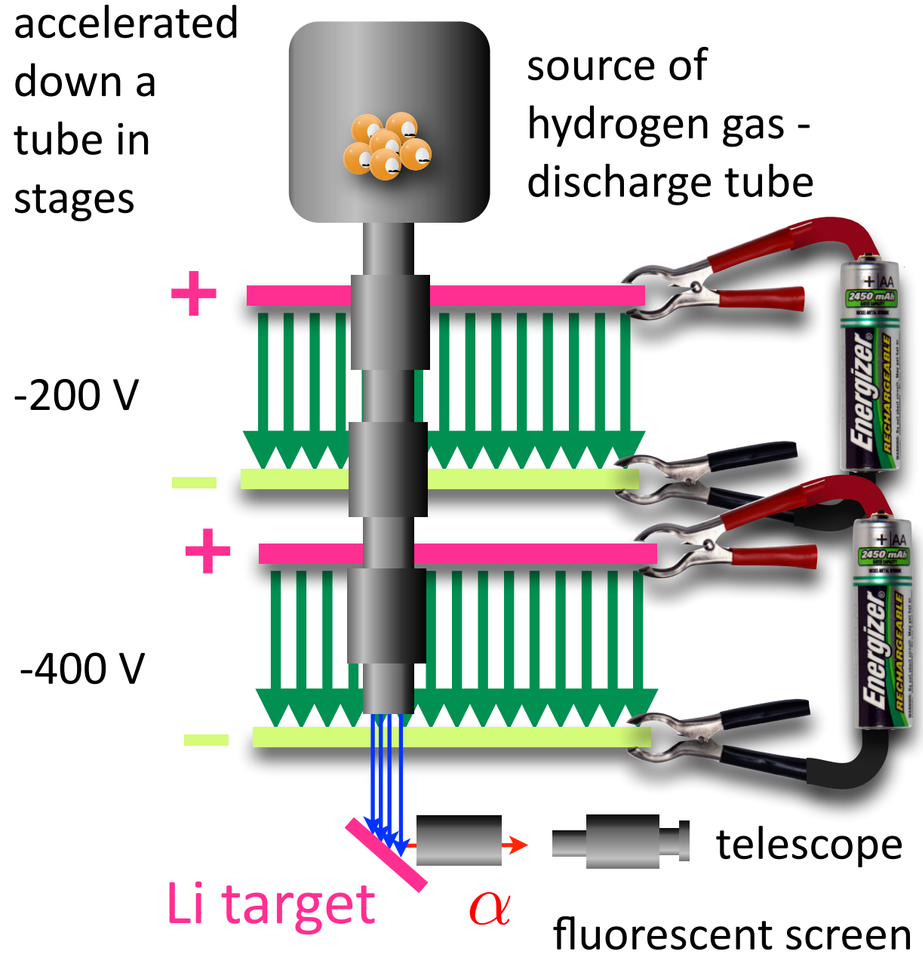
at first, a slow beam, then a medium beam, then a high beam

they could produce beams of **micro-**Amps

# Cockloft-Walton Accelerator 1932

invented it and then did "award-winning" experiments






Their voltage multiplication circuit became a standard way to accelerate electrons/protons - in a TV

at first, a slow beam, then a medium beam, then a high beam

they could produce beams of micro-Amps…

$6.5 \times 10^{12}$ protons/second

6,500,000,000,000 protons/second

# 1951 Nobels

**The Nobel Prize in Physics 1951**
John Cockcroft, Ernest T.S. Walton

*Share this:*

## John Cockcroft - Biographical

**John Douglas Cockcroft** was born at Todmorden, England, on May 27th, 1897. His family had for several generations been cotton manufacturers.

He was educated at Todmorden Secondary School and studied mathematics at Manchester University under Horace Lamb in 1914-1915. After serving in the First World War in the Royal Field Artillery he returned to Manchester to study electrical engineering at the College of Technology under Miles Walker. After two years apprenticeship with Metropolitan Vickers Electrical Company he went to St. John's College, Cambridge, and took the Mathematical Tripos in 1924. He then worked under Lord Rutherford in the Cavendish Laboratory.

He first collaborated with P. Kapitsa in the production of intense magnetic fields and low temperatures. In 1928 he turned to work on the acceleration of protons by high voltages and was soon joined in this work by E.T.S. Walton. In 1932 they succeeded in transmuting lithium and boron by high energy protons. In 1933 artificial radioactivity was produced by protons and a wide variety of transmutations produced by protons and deuterons was studied. In 1934 he took charge of the Royal Society Mond Laboratory in Cambridge.

In 1929 he was elected to a Fellowship in St. John's College and became successively University demonstrator, lecturer and in 1939 Jacksonian Professor of Natural Philosophy.

In September 1939 he took up a war-time appointment as Assistant Director of Scientific Research in the Ministry of Supply and started to work on the application of radar to coast and air defence problems. He was a member of the Tizard Mission to the United States in the autumn of 1940. After this he was appointed Head of the Air Defence Research and Development Establishment. In 1944 he went to Canada to take charge of the Canadian Atomic Energy project and became Director of the Montreal and Chalk River ...s until 1946 when he returned to England as Director of the ...esearch Establishment, Harwell.

...59 he was scientific research member of the U.K. ...and has since continued this function on a part time ...Churchill College, Cambridge, followed in October ...ncellor of the Australian National University, ...dent of the Institute of Physics, the Physical Society ...sh Association for the Advancement of Science

...doctorates from some 19 universities and is a ...ber of many of the principal scientific societies. In ...nours and awards have also been bestowed upon him.


**The Nobel Prize in Physics 1951**
John Cockcroft, Ernest T.S. Walton

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## Ernest T.S. Walton - Facts

**Ernest Thomas Sinton Walton**

**Born:** 6 October 1903, Dungarvan, Ireland

**Died:** 25 June 1995, Belfast, Northern Ireland

**Affiliation at the time of the award:** Trinity College, Dublin, Ireland

**Prize motivation:** "for their pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles"

**Field:** accelerator physics, nuclear physics

**Prize share:** 1/2

### Split the Atom for the First Time

Ernest Rutherford used alpha particles from radioactive elements to study nuclear reactions and managed to convert nitrogen to oxygen. However, only very few reactions could be achieved with alpha particles from radioactive elements. Ernest Walton and John Cockcroft developed a device, an accelerator, to make more penetrating radiation. Using an electric field, protons were accelerated to high velocities. In 1932 they bombarded lithium with protons and the lithium nucleus broke-up and two alpha particles were produced.

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16. <http...lerize.org/nobel_prizes/physics/laureates/1951/walton-facts.html>

laboratory: **European Organization for Nuclear Research (CERN*)**

location: Geneva, Switzerland

established: 1954

notable directors: Edoardo Amaldi, Felix Bloch**, Victor Weisskopf, John Adams, Leon van Hove, Carlo Rubbia**, Chris Llewellyn Smith, Luciano Maiani, Rolf Heuer

type of lab: fixed target: neutrinos, hadrons

collider: p-$\overline{p}$, e-$\overline{e}$, p-p, heavy ions

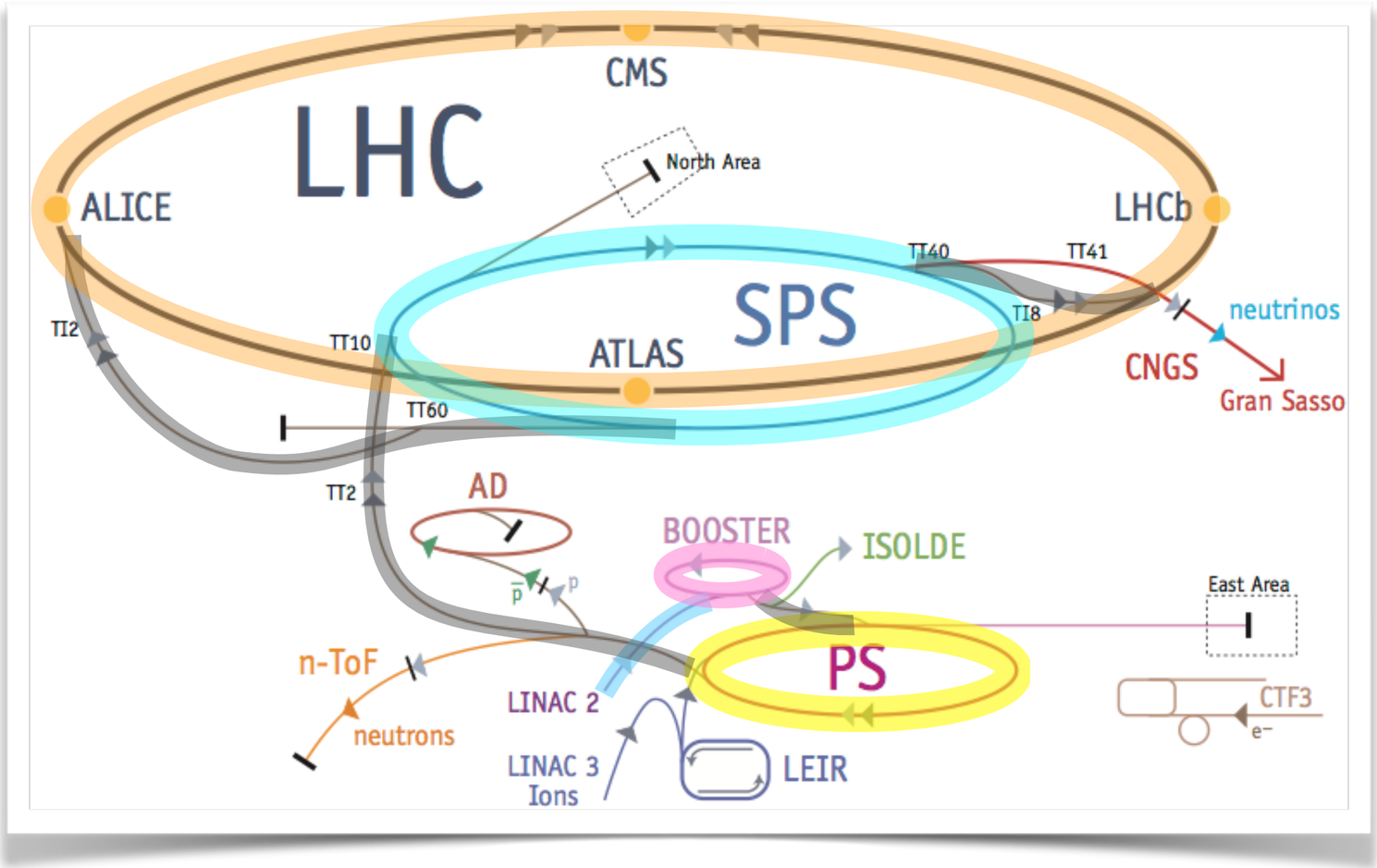
* originally: *Conseil Européen pour la Recherche Nucléaire*

** Nobel Prize

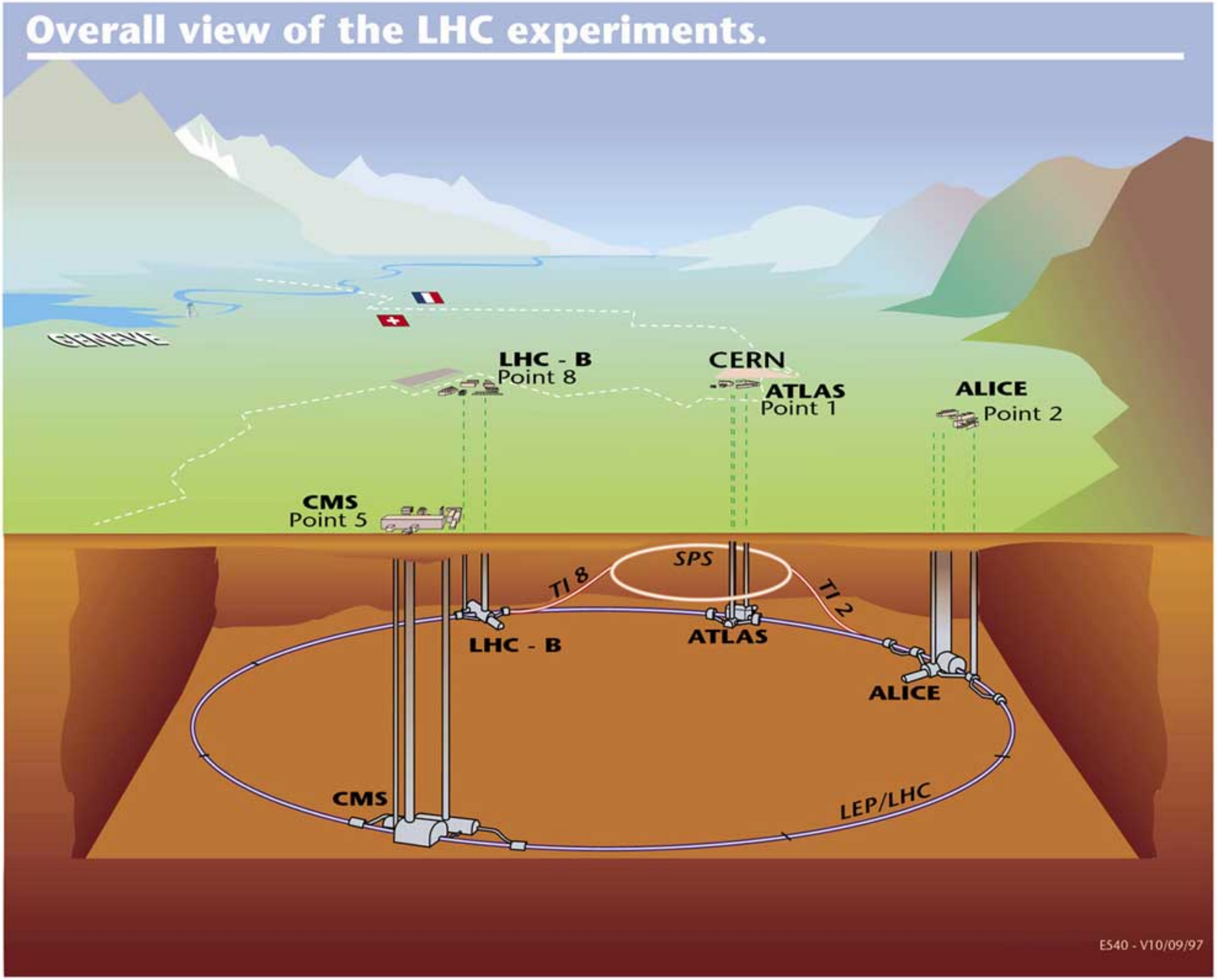
# CERN



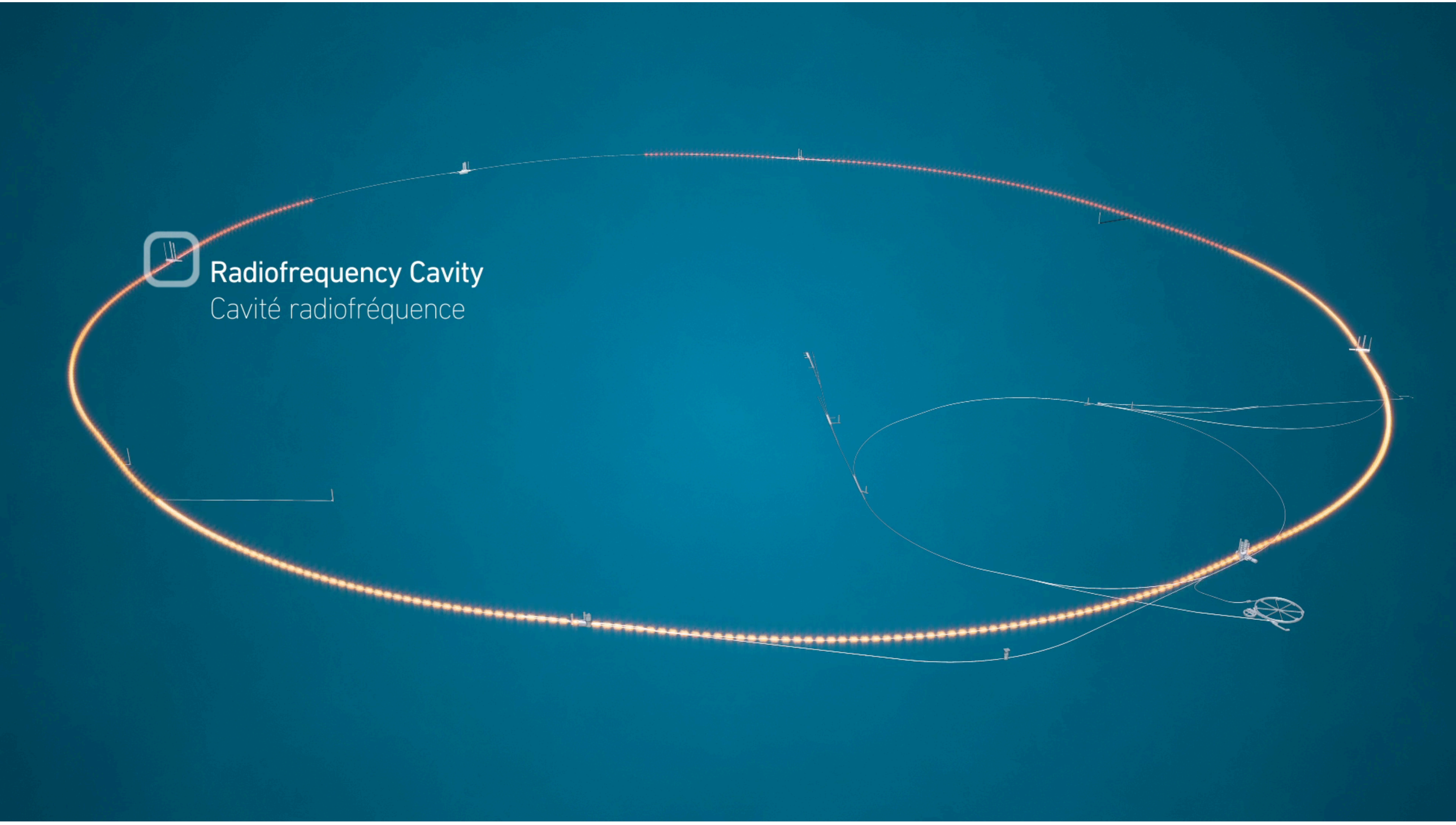

# LHC complex


CMS
LHC
North Area
ALICE
LHCb
TT40
TT41
TI8
SPS
neutrinos
TI2
TT10
ATLAS
CNGS
Gran Sasso
TT60
TT2
AD
BOOSTER
ISOLDE
East Area
n-ToF
PS
CTF3
LINAC 2
neutrons
LINAC 3
Ions
LEIR

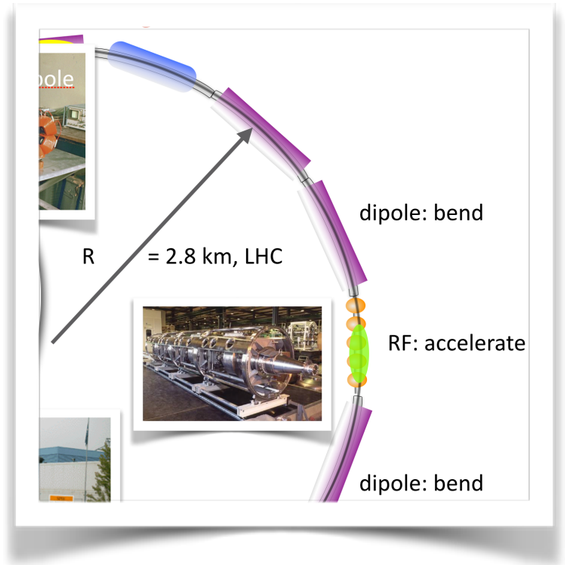
# Overall view of the LHC experiments.



# ‘‘RF’’ and ‘‘dipoles’’



# “buckets” of protons




E field @400 MHz frequency...?

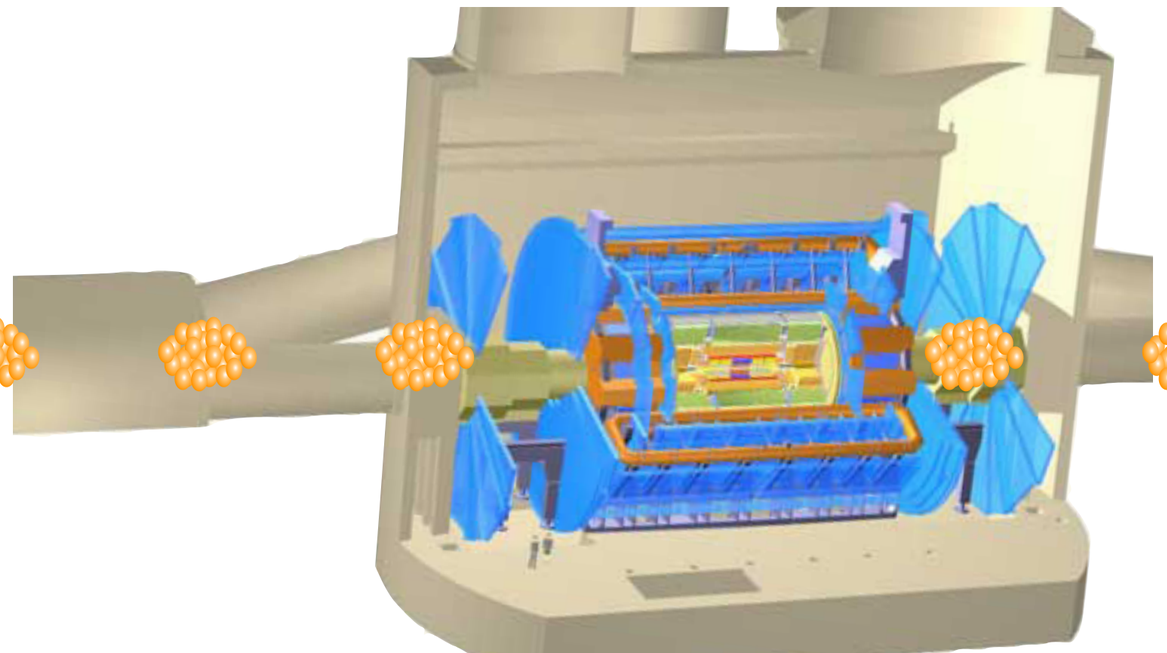
400 MHz means 400 x $10^6$ cycles per second

or a E-field push every $\dfrac{1}{400 \times 10^6} = 0.25 \times 10^{-8} = 2.5$ nanoseconds

about every 10th bucket is filled

25 nsec

2.5 nsec



# ‘‘RF’’ and ‘‘dipoles’’

# LHC dipole magnets

HUGE

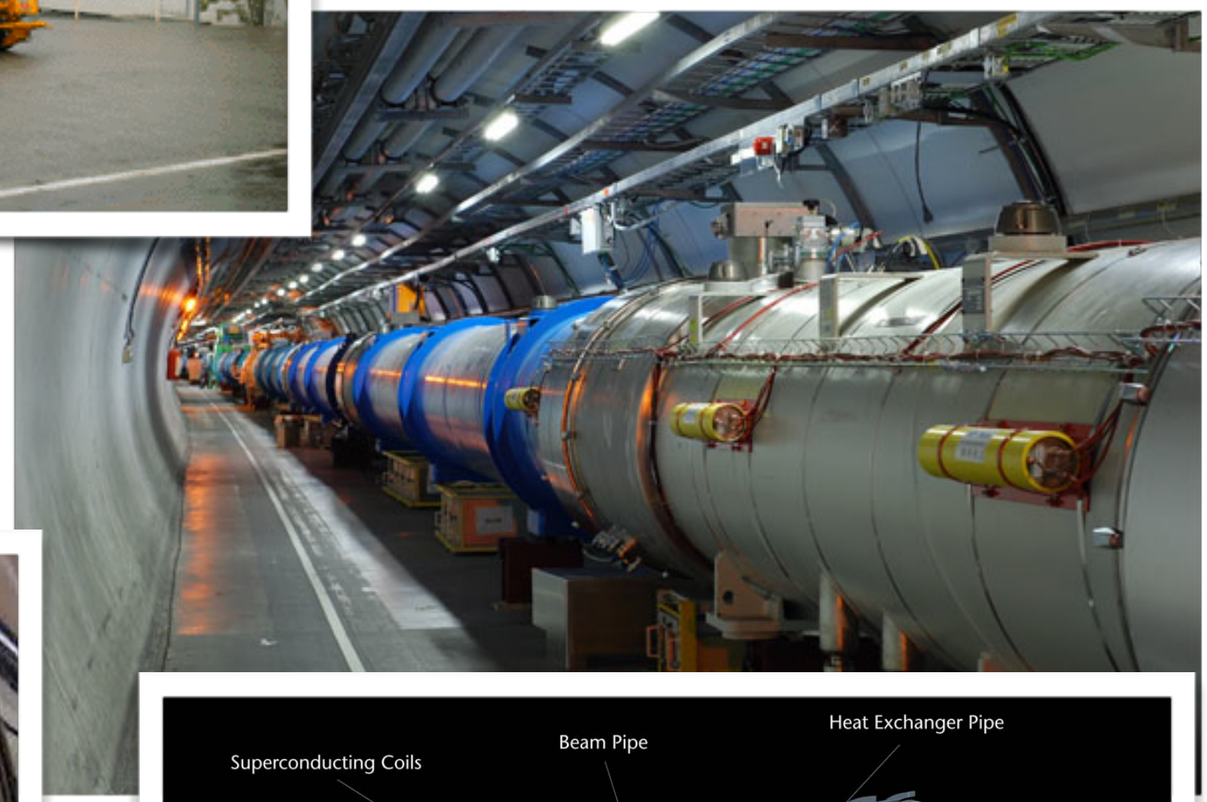
50 tons

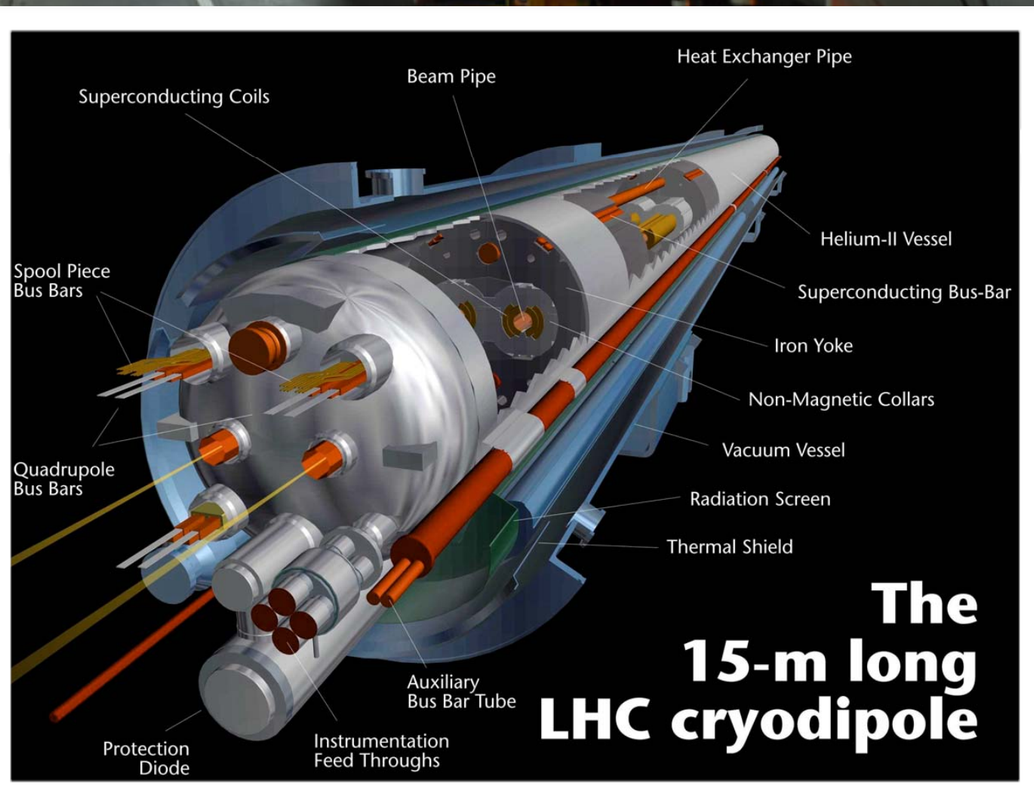
30 feet long

*superconducting, operating at 3C above absolute zero

LHC has 9000 magnets overall

1232 dipoles





laboratory: **Fermi National Accelerator Laboratory**

| | |
|---|---|
| location: | Batavia, IL |
| established: | 1967 |
| notable directors: | Bob Wilson, Leon Lederman*, John Peoples, Mike Witherell, Pier Oddone |
| type of lab: | fixed target: neutrinos, hadrons<br>collider: proton-antiproton |

* Nobel Prize

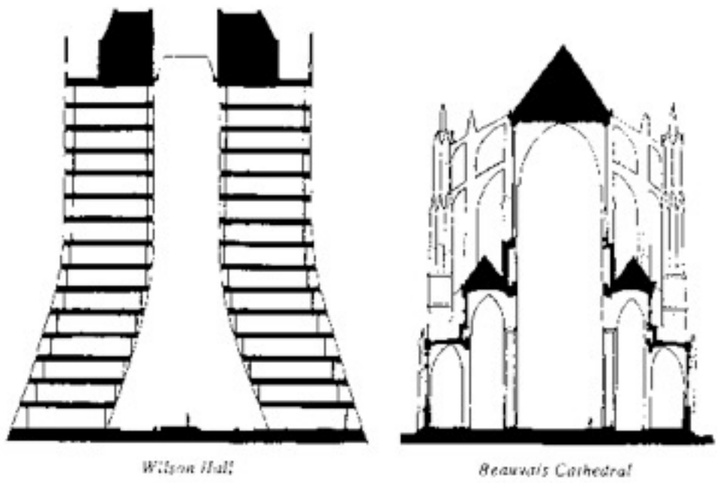
beam: **proton-antiproton collider**

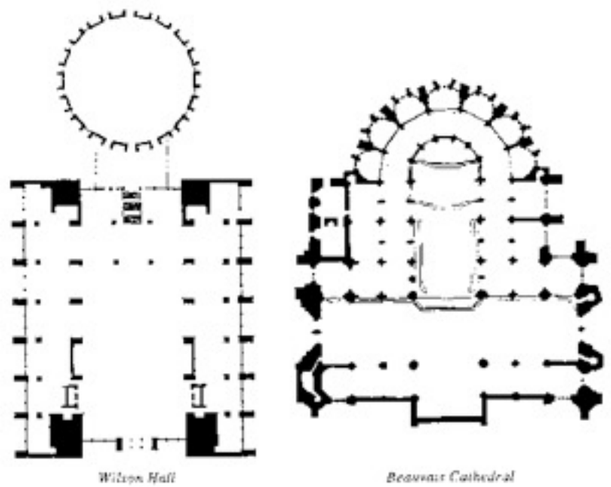
| | |
|---|---|
| beam: | protons and antiprotons |
| source: | hydrogen and secondary targets |
| acceleration: | electrostatic + RF |
| energy: | CERN SppS: 540, 630, 900 GeV cms |
| location: | Fermilab: 1960 GeV cms |
| | CERN: Geneva, Switzerland |

# Fermilab's my particle physics home

I've worked there since 1975

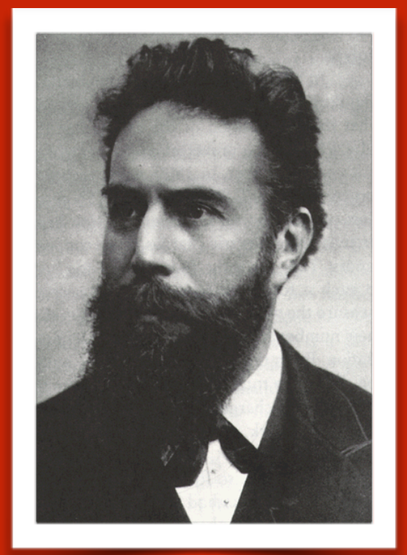
Batavia was in my high school athletic conference!

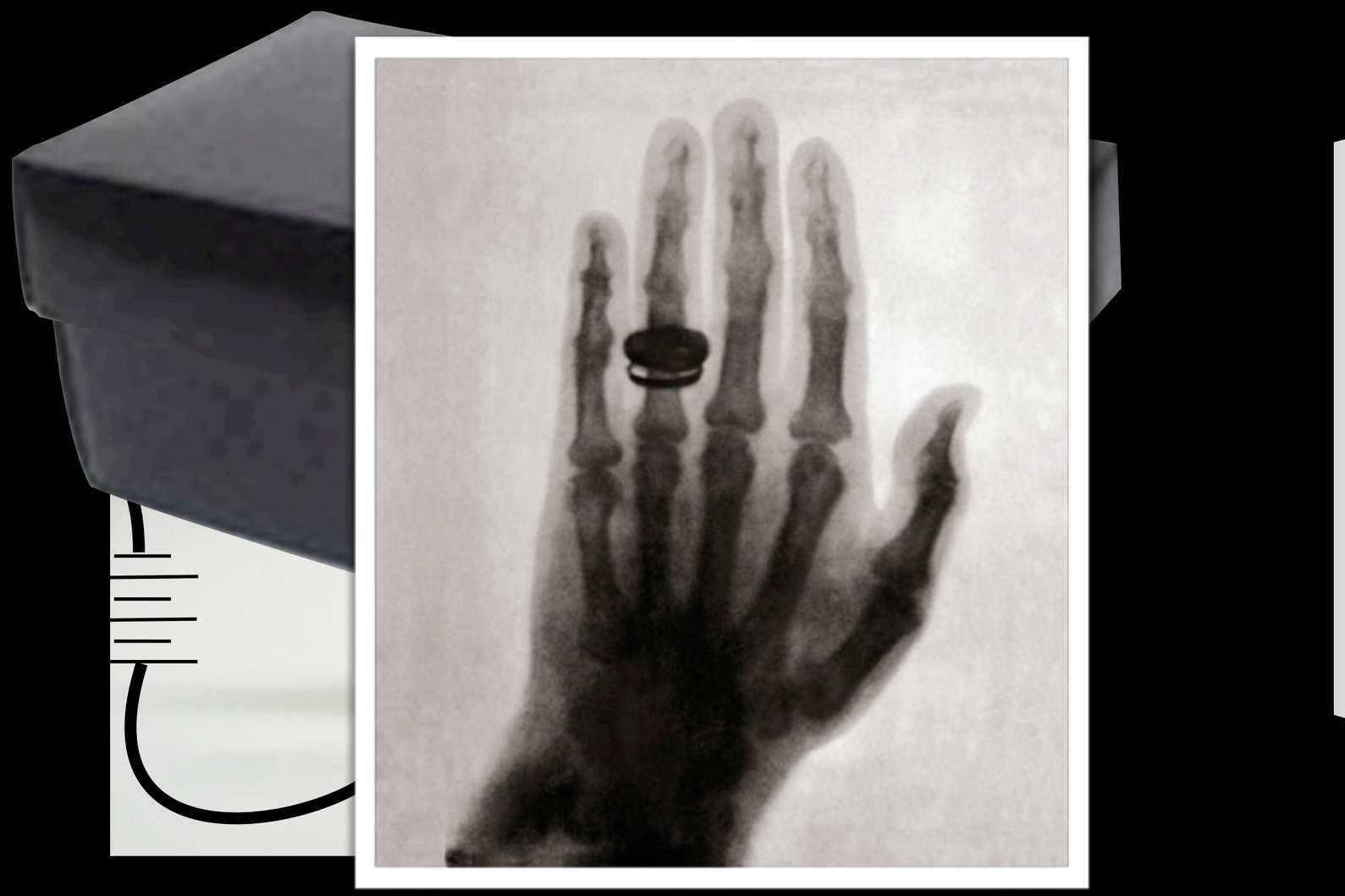


# 1895 Wilhelm Roentgen

1845-1923

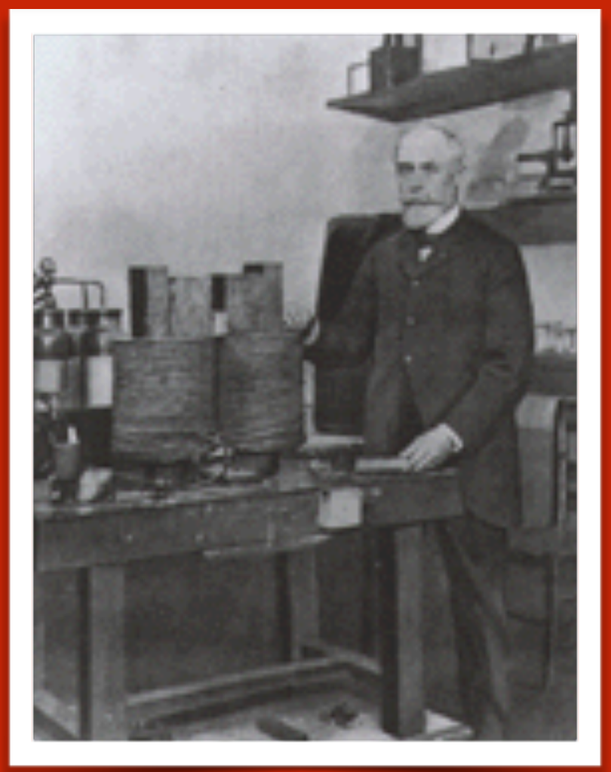




# then it got strange

# 1896 Antoine-Henri Becquerel

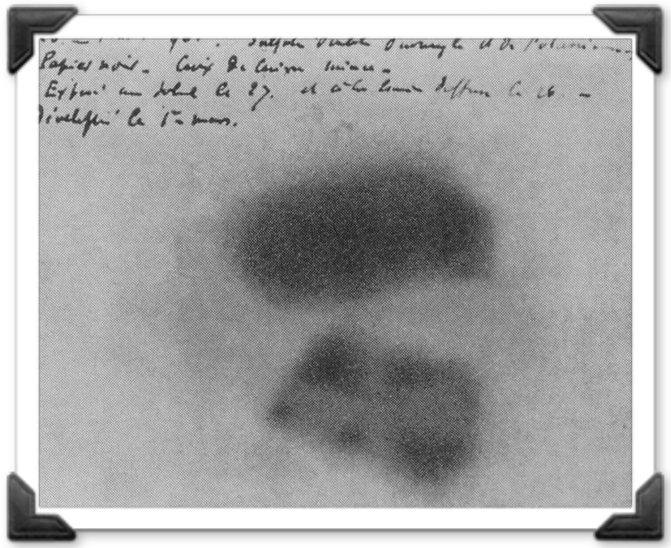
1852-1908



In the audience when X-rays were announced...

Expert in phosphorescence...thought X-rays were phosphorescence. wrong.

Wrapped up piece of Uranium when it got cloudy in Paris. When he unwrapped it:



**Energy created out of nothing?**

“Becquerel Rays”...didn’t catch on.

But: the idea of matter spontaneously emitting energy did!

He studied it and found the emanations ionized air and could be deflected by a magnet...so, it consisted of charged particles & not X-rays

# then it got strange

1898

Marie

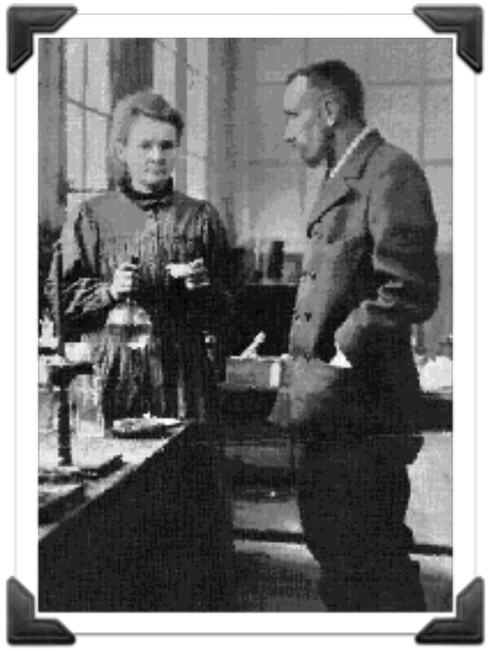
Skodowska

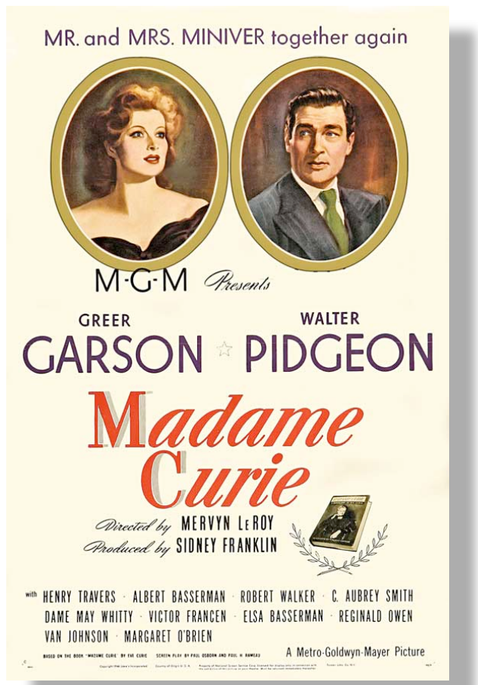
Curie

1857-1934

# believe it or not

true-love stories in physics are rare!





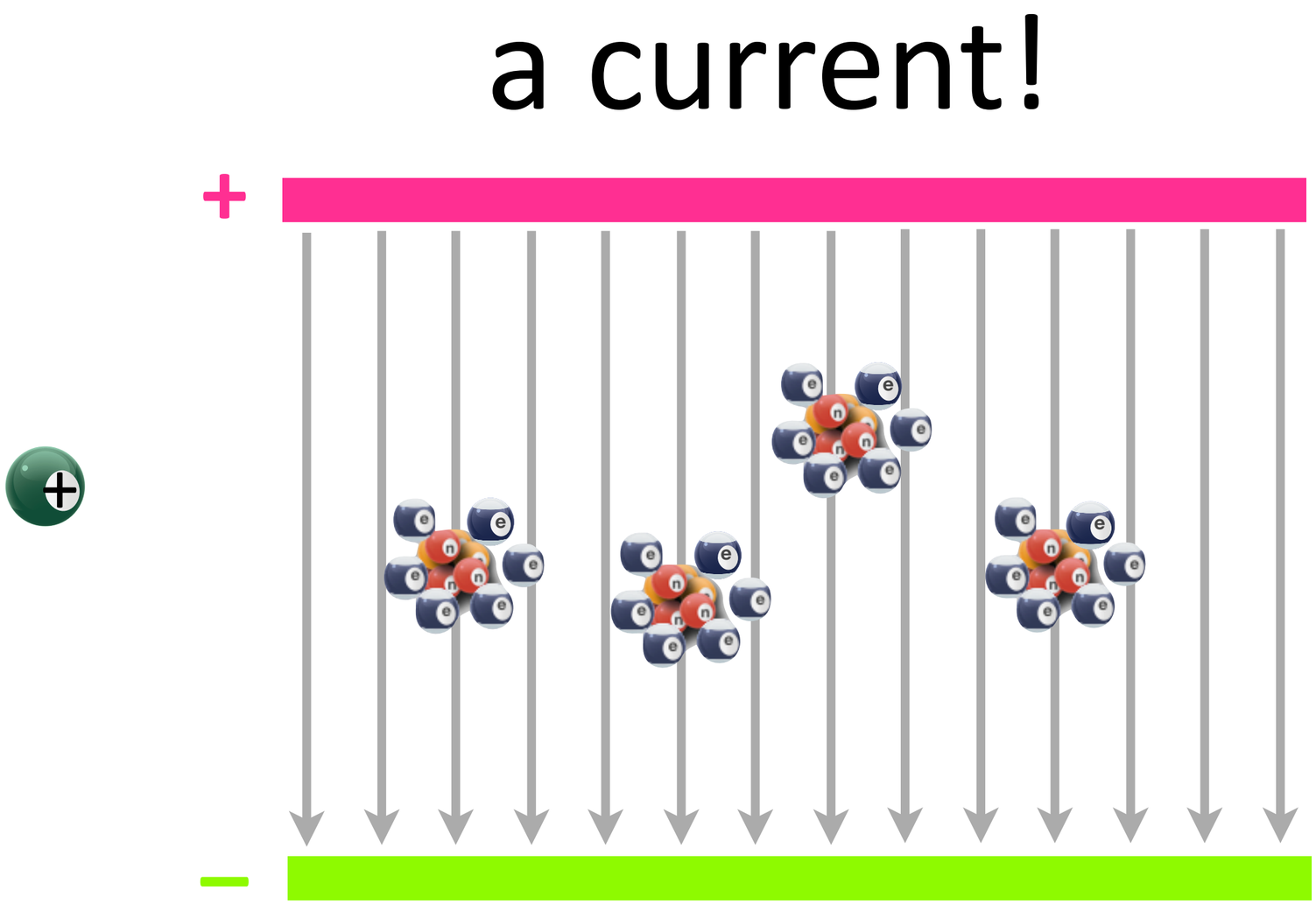
# set out to quantify

Becquerel rays

Marie built a new kind of apparatus for her PhD thesis

Ionizing radiation: Becquerel had found that the phenomenon of Uranium emissions would cause air to become **ionized**.

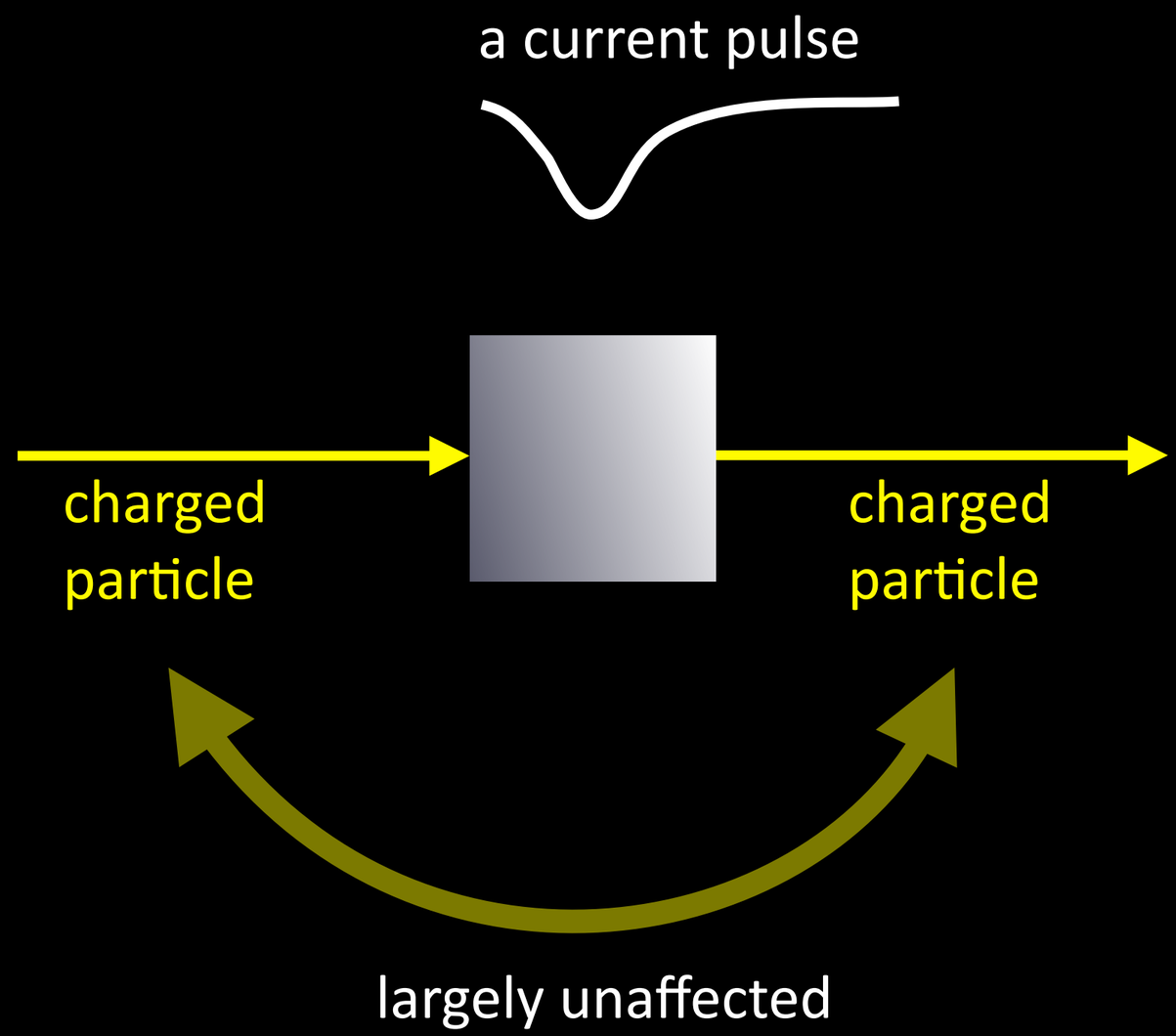
Madame Curie used that idea:



# our first detector

**Ionization Detector**

*indicates the **location** and **time** of passage of a charged particle*



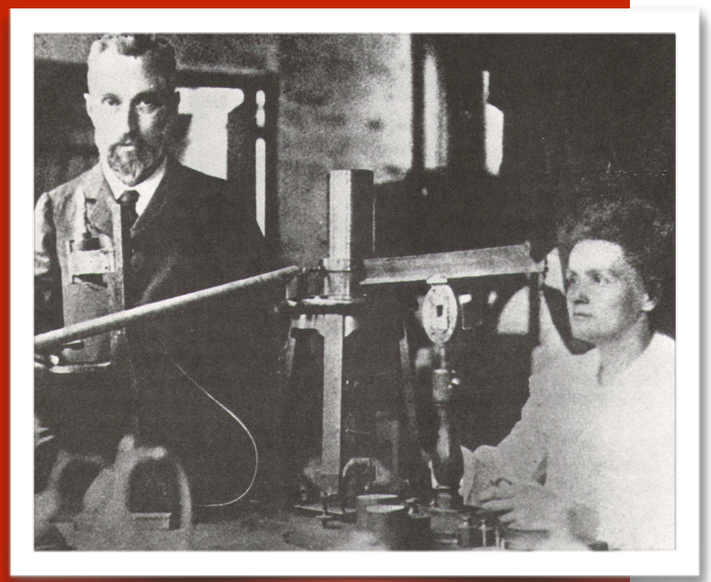

WARNING

# piezo electricity

apply a force to some crystals

get a voltage

Discovered by Pierre Curie and his brother



balance is created by adjusting the weight

piezo electric crystal - & a weight

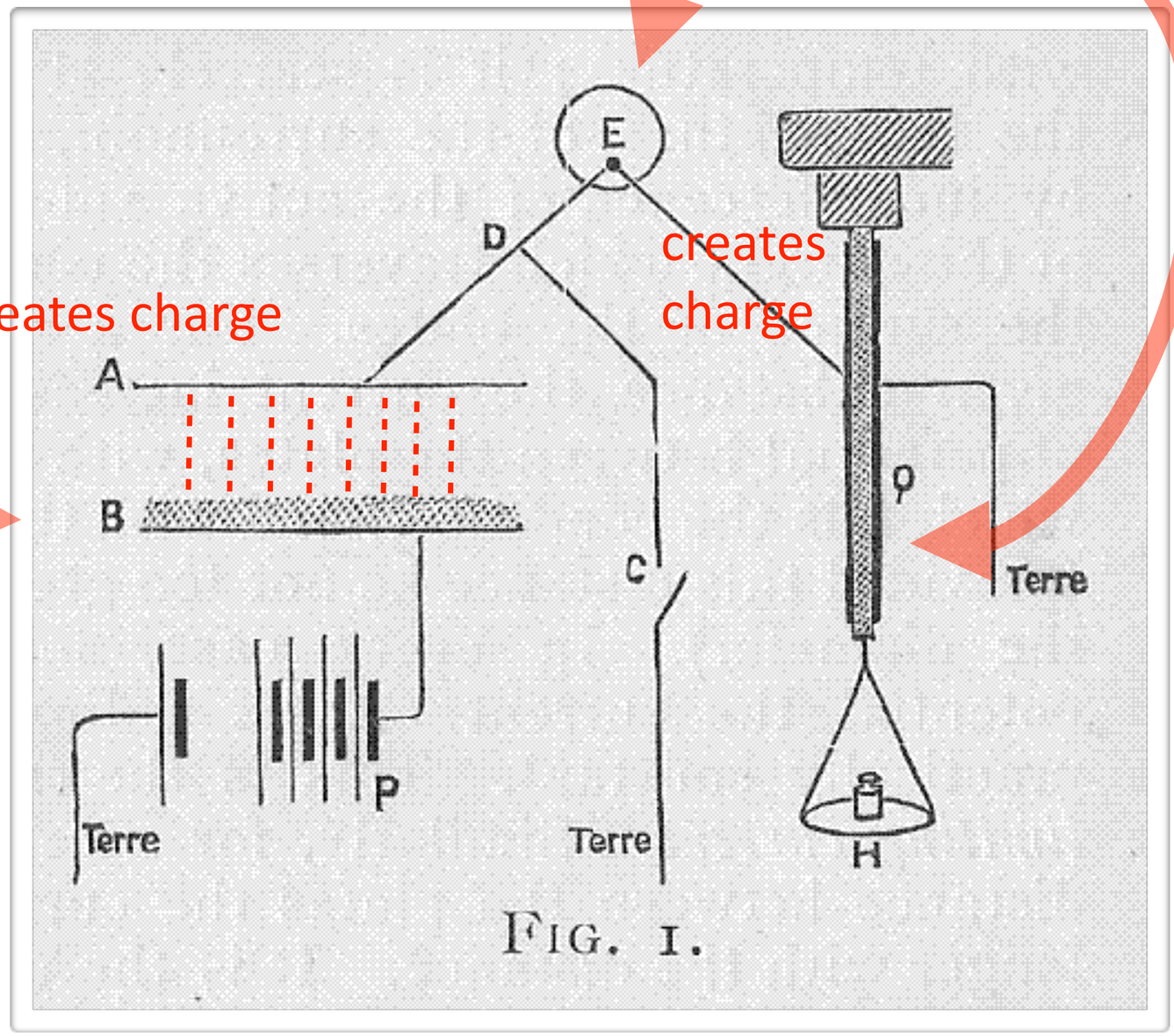


FIG. 1.

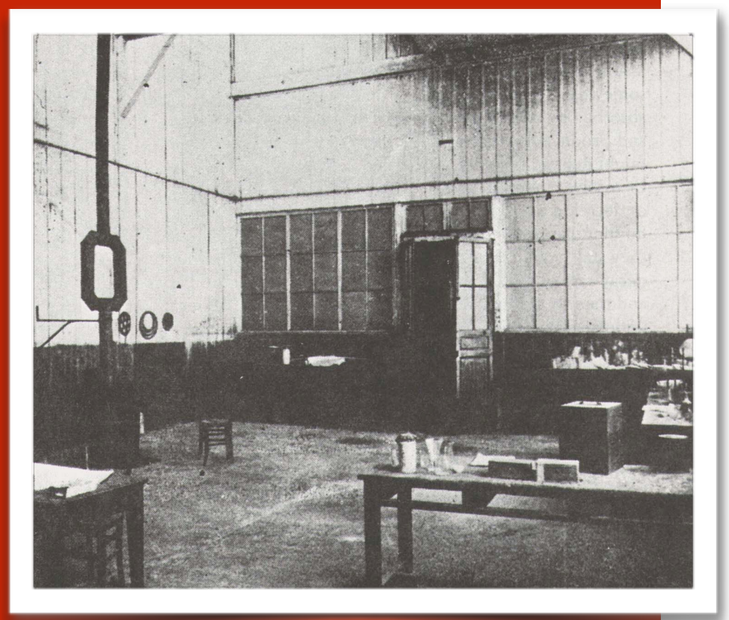
a radioactive substance inside of a parallel-plate capacitor

# they found something else

They found a surprising thing:
**pitchblend**…an ore which contains concentrations of $UO_2$
was *more radioactive than uranium by itself*

"This fact is a very remarkable and leads one to believe that these minerals contain an element which is much more active than uranium."

She and Pierre began the systematic study of the relative radioactivity of whatever they could chemically isolate in the pitchblend



Announced the discovery of Po (Polonium) and Ra (Radium).
Then...they had to find it.

1900, 3 years later:

# Nobel 1903

tragically Pierre kille a street accident 1

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## The Nobel Prize in Chemistry 1911
Marie Curie

The Nobel Prize in Chemistry 1911
Marie Curie

### Marie Curie, née Sklodowska

The Nobel Prize in Chemistry 1911 was awarded to
*her services to the advancement of chemistry by th*
*radium and polonium, by the isolation of radium and*
*compounds of this remarkable element".*

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## The Nobel Prize in Physics 1903
Henri Becquerel, Pierre Curie, Marie Curie

- The Nobel Prize in Physics 1903
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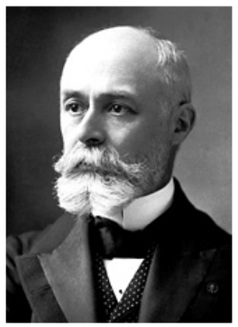
- Pierre Curie
- Marie Curie



### Antoine Henri Becquerel

### Pierre Curie

### Marie Curie, née Sklodowska

The Nobel Prize in Physics 1903 was divided, one half awarded to Antoine Henri Becquerel *"in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity"*,the other half jointly to Pierre Curie and Marie Curie, née Sklodowska *"in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel"*.

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their daughter also…

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## The Nobel Prize in Chemistry 1935
Frédéric Joliot, Irène Joliot-Curie

- **The Nobel Prize in Chemistry 1935**
- Frédéric Joliot
- Irène Joliot-Curie

Frédéric Joliot

Irène Joliot-Curie

The Nobel Prize in Chemistry 1935 was awarded jointly to Frédéric Joliot and Irène Joliot-Curie *"in recognition of their synthesis of new radioactive elements"*

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part of Paris still