Accelerator Physics, Introduction
Notes Adapted from Mike Syphers, USPAS

Steve Lund and Yue Hao
Physics and Astronomy Department
Facility for Rare Isotope Beams (FRIB)
Michigan State University (MSU)

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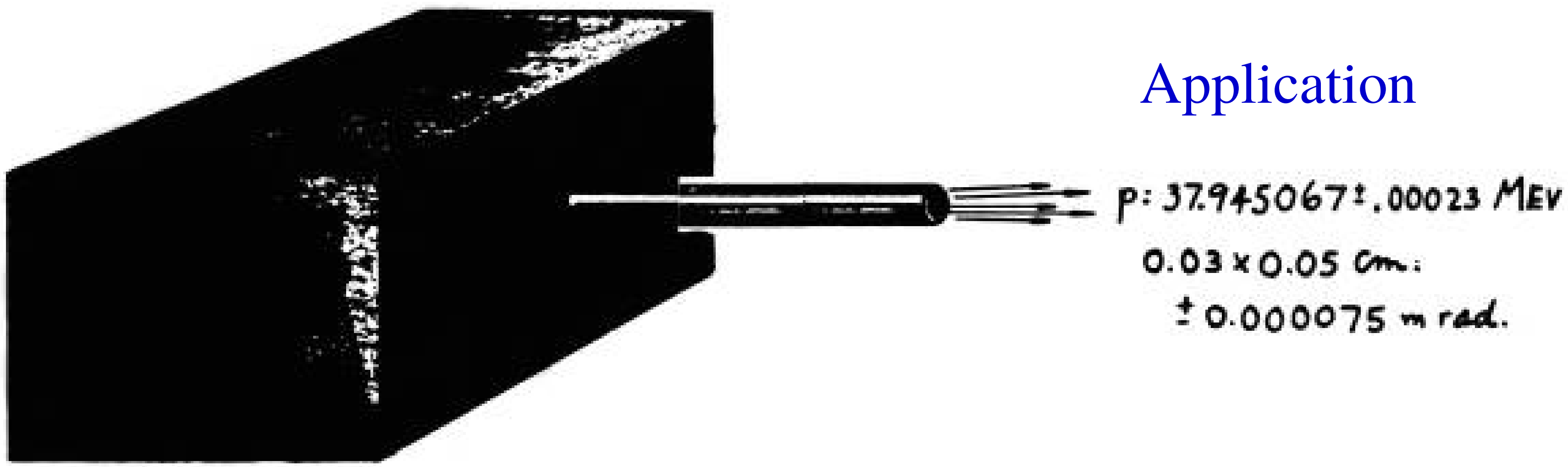
Overview

Accelerators tend to be viewed by specialists in other fields as a "black box" producing particles with some parameters

Accelerator

Application



But accelerator science and technology is a highly developed field enabling a broad range of discovery science and industry

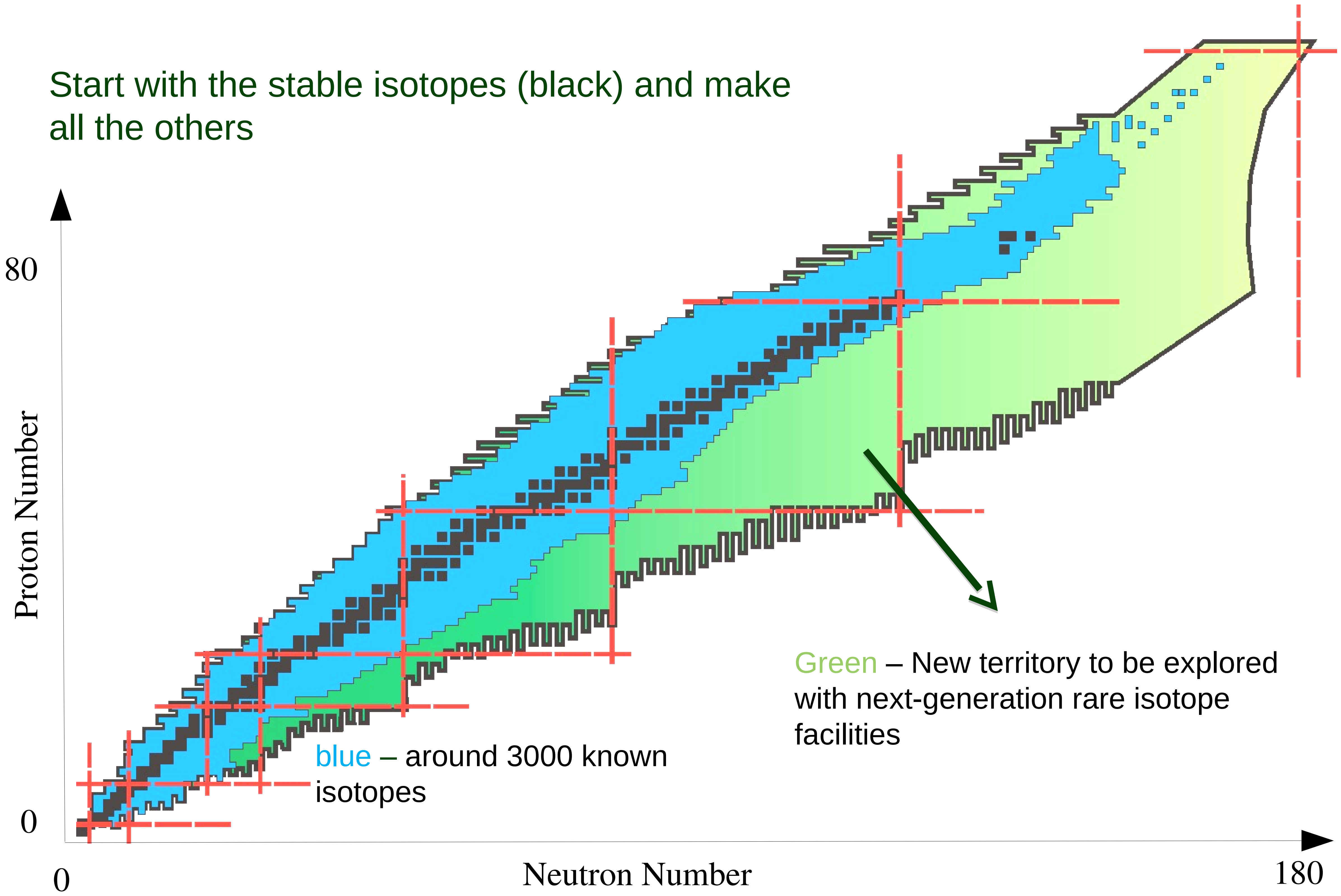
- Discovery Science:
  - High Energy (Colliders) and Nuclear Physics (Cyclotrons, Rings, Linacs)
  - Materials Science (Light Sources)
- Industrial: Semiconductor Processing, Material Processing, Welding
- Medical: X-Rays, Tumor Therapy, Sterilization

Modern, large-scale accelerator facilities are a monument to modern technology and take a large number of specialists working effectively together to develop and maintain

- Only briefly survey a small part of linear optics in this lecture …. much much more !

In nuclear physics, accelerators are used to produce beams of important rare isotopes

Start with the stable isotopes (black) and make all the others



Accelerators for rare isotope production

- The particle accelerator used for production is called the "driver"
- Types
  - Cyclotron NSCL (USA; MSU), GANIL (France), TRIUMF (proton; Canada), HRIBF (proton; USA ORNL), RIKEN RIBF (Japan)
  - Synchroton GSI, FAIR-GSI (Germany); IMP (China)
  - LINAC (LINear ACcelerator) FRIB (USA; MSU), ATLAS (USA; ANL), RAON (Korea)
  - Others like FFAGs (Fixed-Field Alternating Gradient) not currently used but considered
- Main Parameters
  - Max Kinetic Energy (e.g. FRIB will have 200 MeV/u uranium ions)
  - Particle Range (TRIUMF cyclotron accelerates hydrogen, used for spallation)
  - Intensity or Beam Power (e.g. 400 kW = $8 \times 6 \times 10^{12}$/s x 50GeV
  - Power = pμA x Beam Energy (GeV) (1pμA = 6×10^{12} /s)

A Little Accelerator History

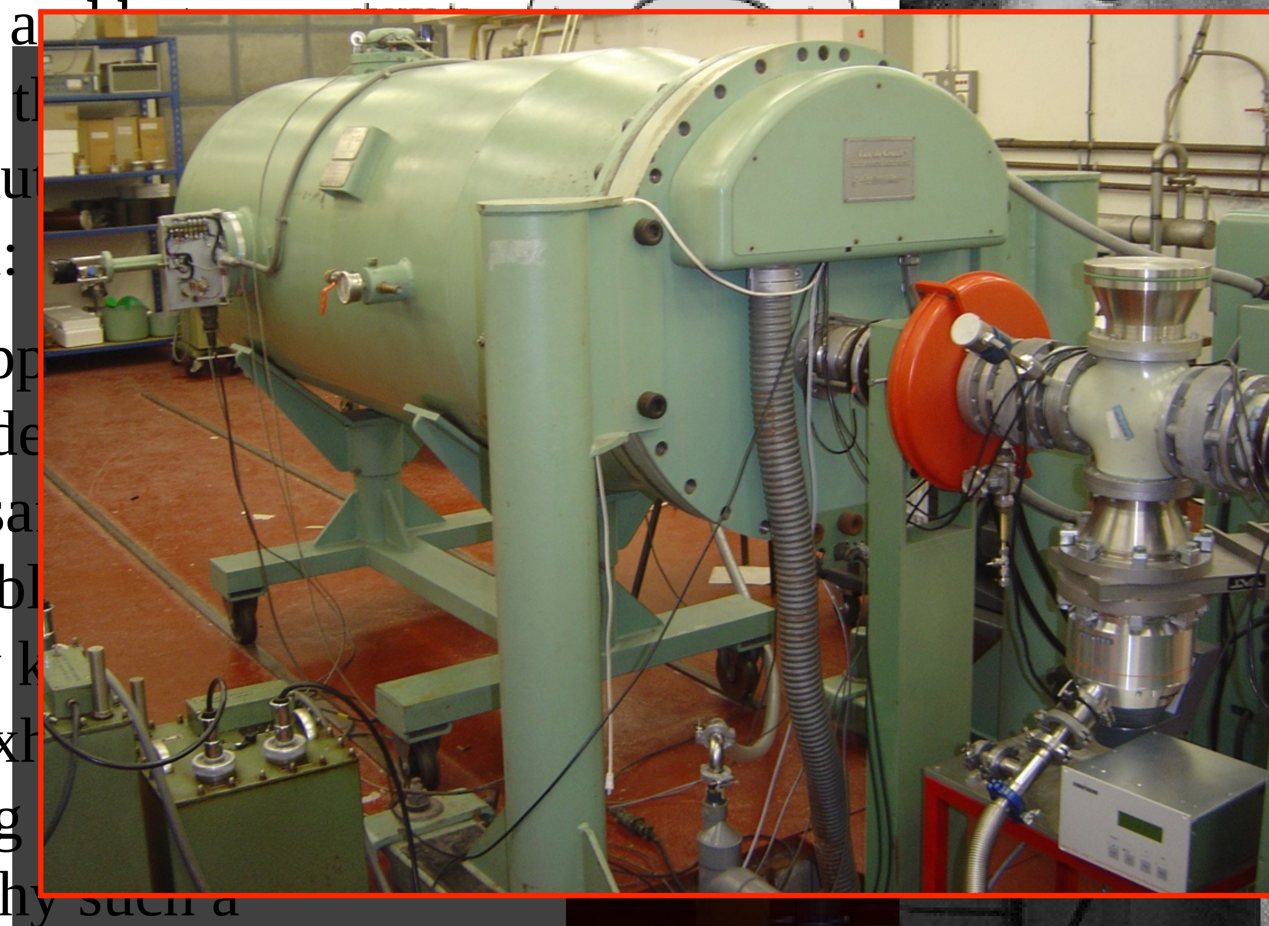
- DC Acceleration

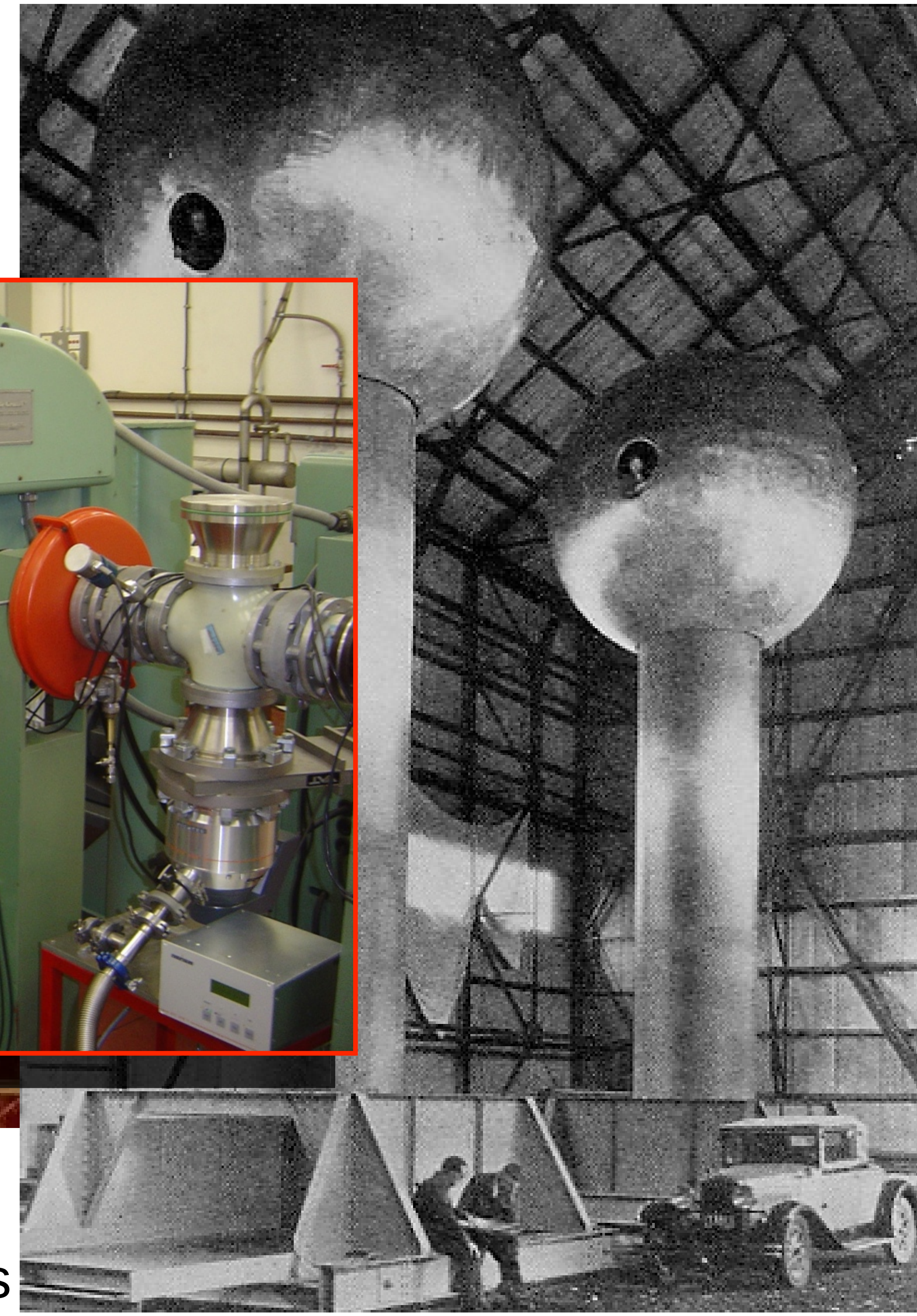
1927: Lord Rutherford requested a "copious supply" of projectiles more energetic than natural alpha a
particles. At the opening of t
High Tension Laboratory, Ru
went on to reiterate the goal:

"What we require is an app
give us a potential of the orde
million volts which can be sa
accommodated in a reasonabl
room and operated by a few k
power. We require too an exh
tube capable of withstanding
voltage… I see no reason why such a requirement cannot be made practical."

Van de Graaff

(1929)





MIT, c.1940s

Cockcroft and Walton

- Voltage Multiplier

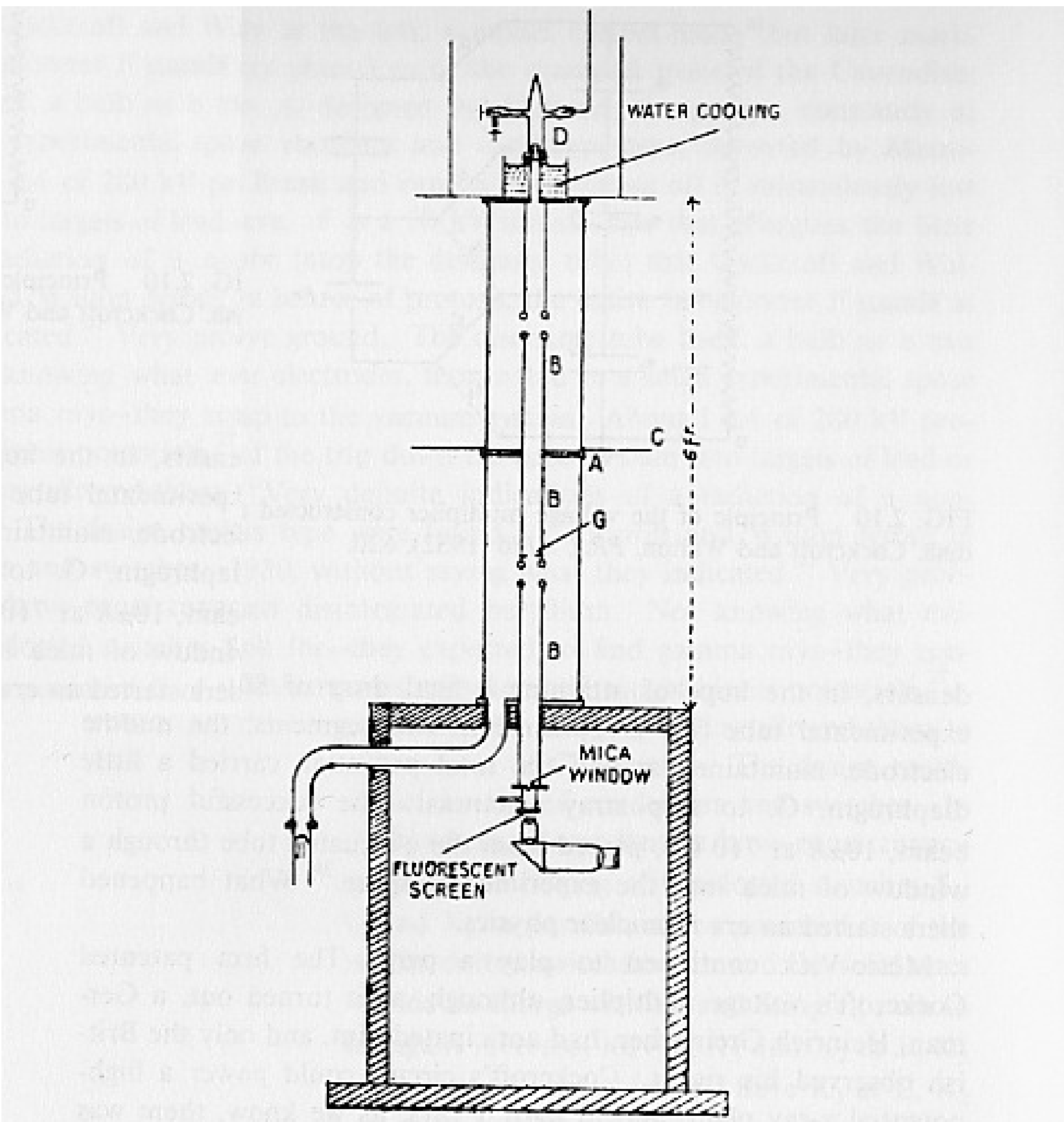
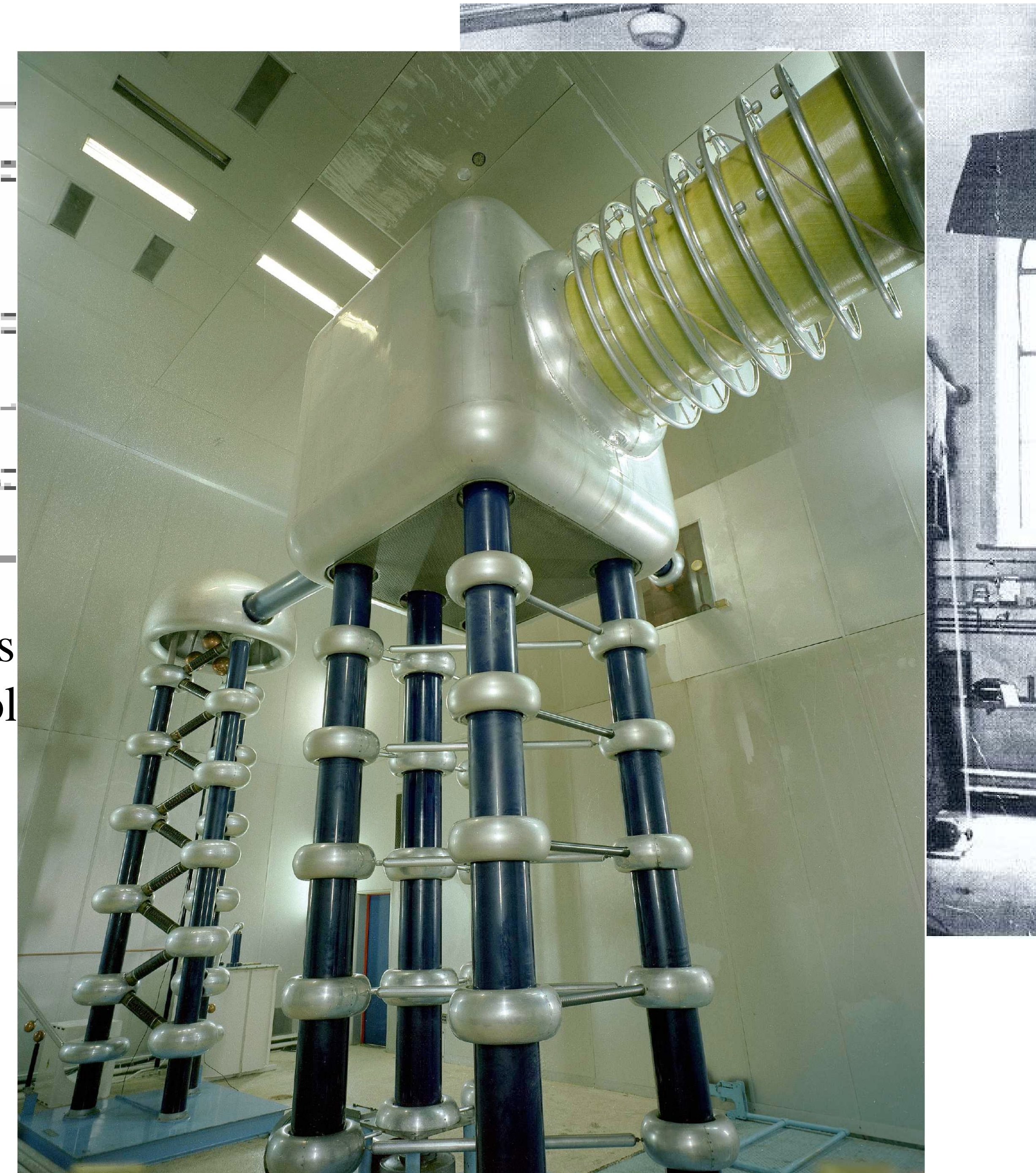


FIG. 2.11 Accelerating tube and target arrangement of the Cockcroft-Walton machine. The source is at D; C is a metallic ring joint between the two sections of the constantly pumped tube. The mica window closes the evacuated space. Cockcroft and Walton, *PRS, A136* (1932), 626.

Converts
DC vol

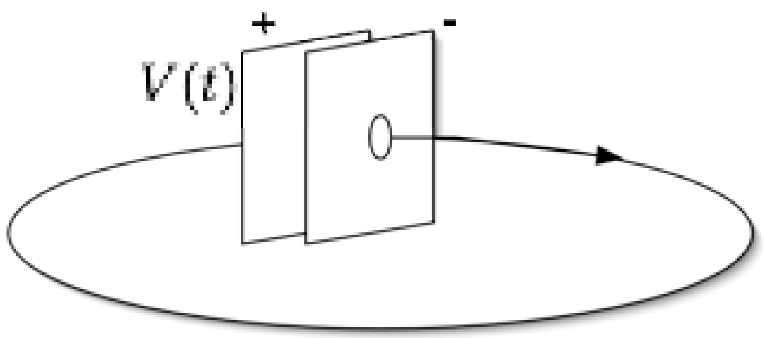


Fermilab (recently decommissioned)

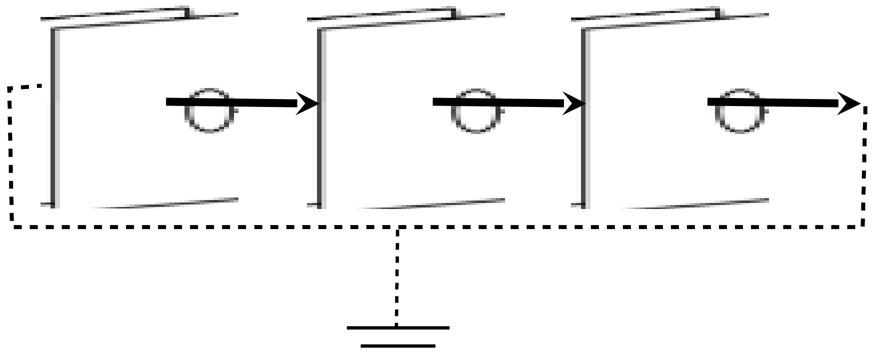
The Route to Higher Energies

- The Need for AC Systems…

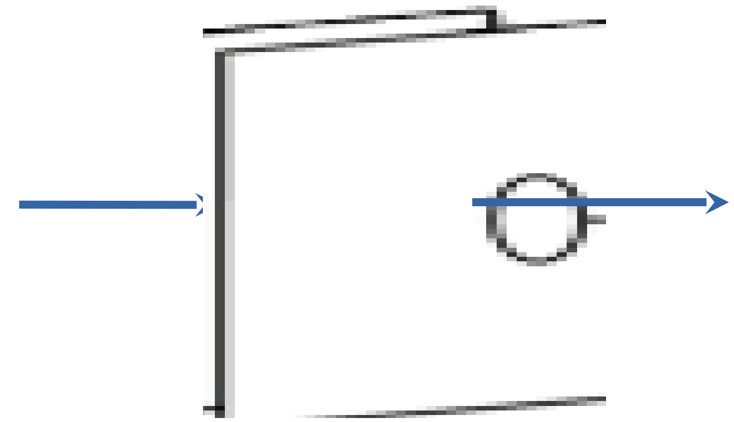
Circular Accelerator



Linear Accelerator



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



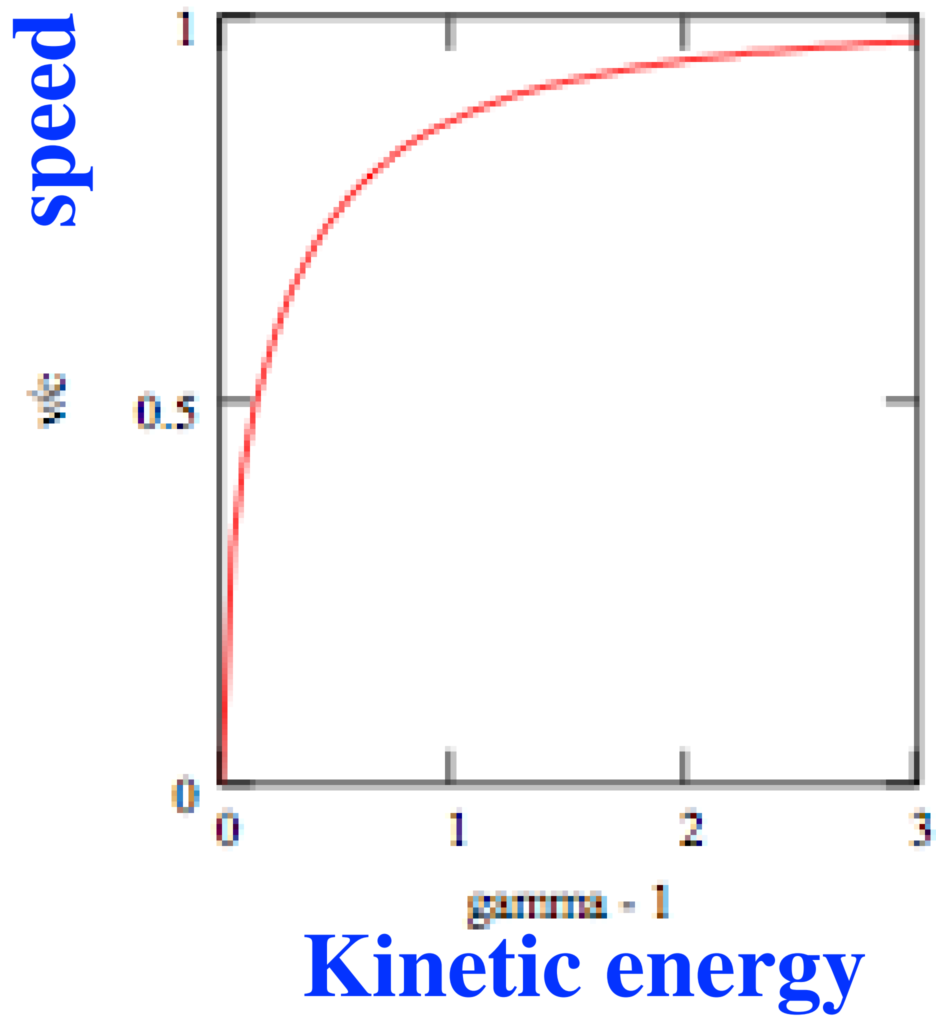
DC systems limited to a few MV

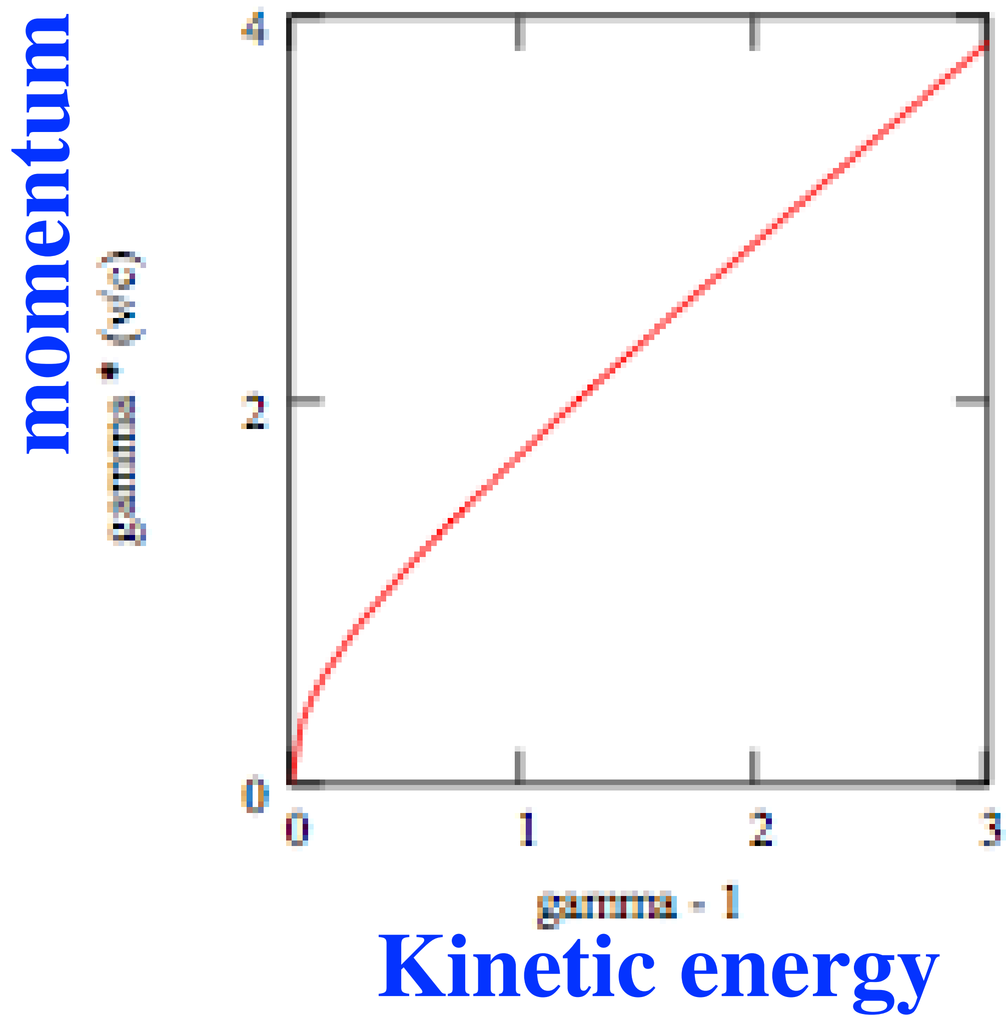
$$\oint (q\vec{E}) \cdot d\vec{s} = work = \Delta(energy)$$

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

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

Speed, Momentum vs. Energy





Electron:	0	0.5	1.0	1.5	MeV
Proton:	0	1000	2000	3000	MeV

$$\text{gamma} = \frac{1}{\sqrt{1-(v/c)^2}}$$

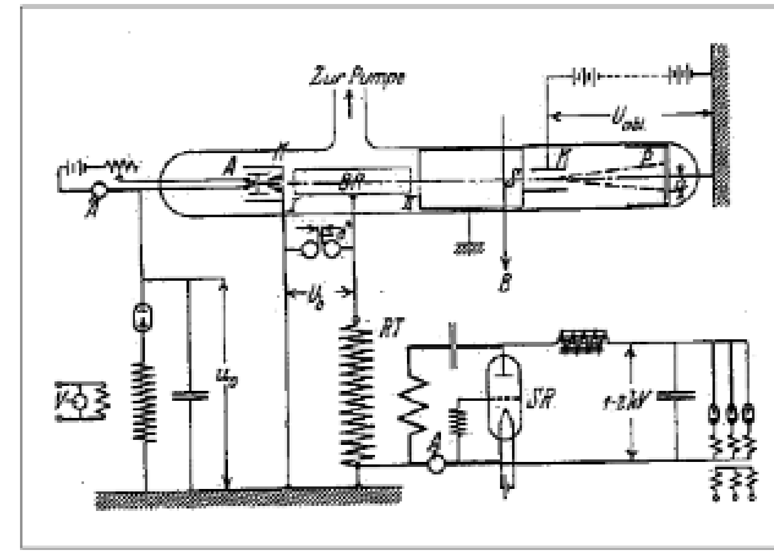
rest energy, mc^2:

e-	0.5 MeV
p	938 MeV

Oscillating Fields

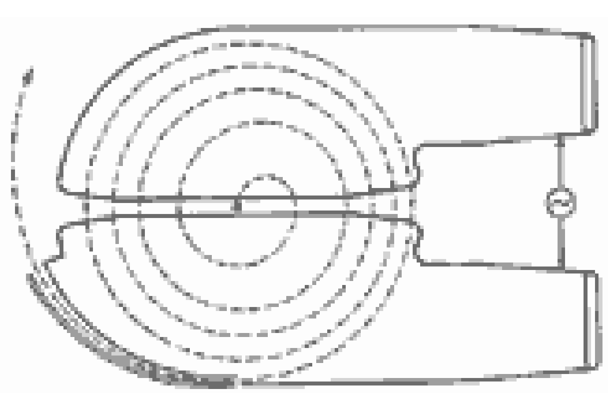
➡The linear accelerator (linac) -- 1928-29

- Wideroe (U. Aachen; grad student!)
  - Dreamt up concept of "Ray Transformer" (later, called the "Betatron"); thesis advisor said was "sure to fail," and was rejected as a PhD project. Not deterred, illustrated the principle with a "linear" device, which he made to work -- got his PhD in engineering
- 50 keV; accelerated heavy ions (K+, Na+)
- utilized oscillating voltage of 25 kV @ 1 MHz



➡The Cyclotron -- 1930's, Lawrence (U. California)

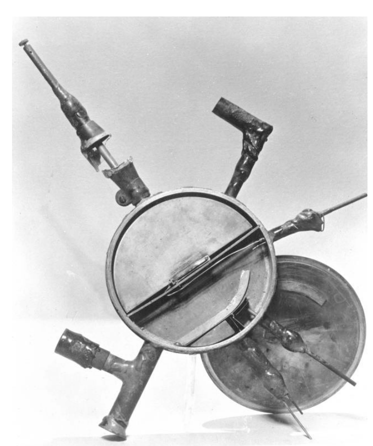
- read Wideroe's paper (actually, looked at the pictures!)
- an extended "linac" unappealing -- make it more compact:



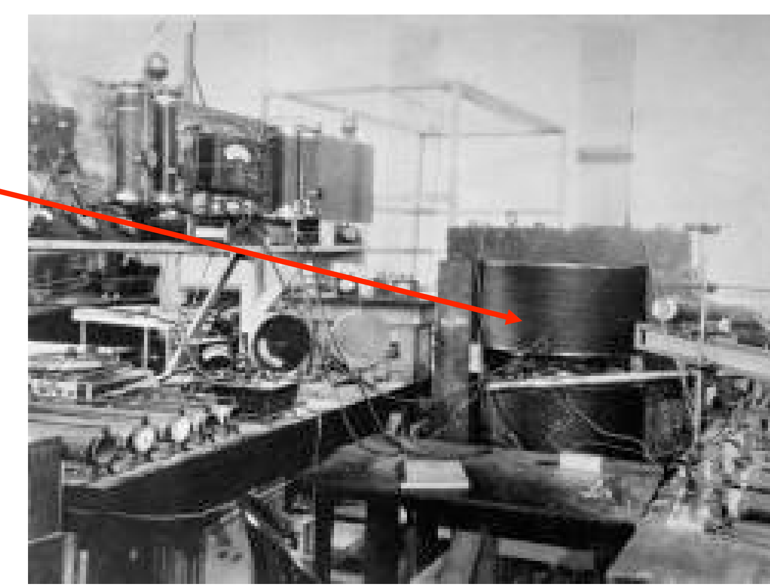
V

$$\frac{1}{T} = \frac{q \cdot B}{2\pi m}$$

4.5 inch diameter!



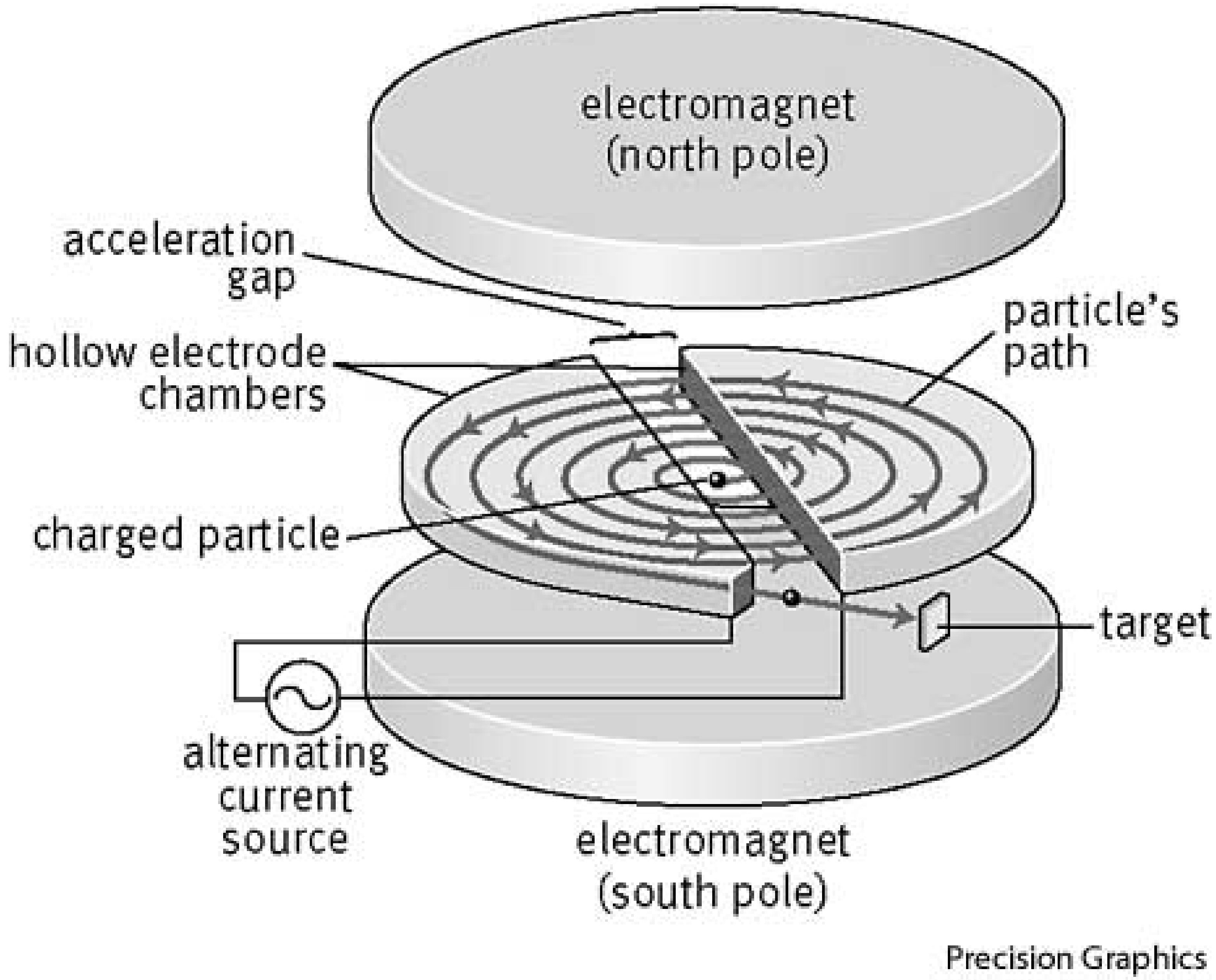
11 inch diameter



Cyclotrons

Continuous train of particle bunches injected from center and spiral outward on RF acceleration over many laps. Exits machine on last lap to impinge on target.

- Relatively easy to operate and tune (few parts)
- Used for isotope production and applications where reliable and reproducible operation are important (medical)
- Intensity low (but continuous train of bunches) due to limited transverse focusing, acceleration efficiency is high, cost low
- Relativity limits energy gain, so energy is limited to a few hundred MeV/u.
- State of art for heavy ions: RIKEN (Japan) Superconducting Cyclotron 350 MeV/u

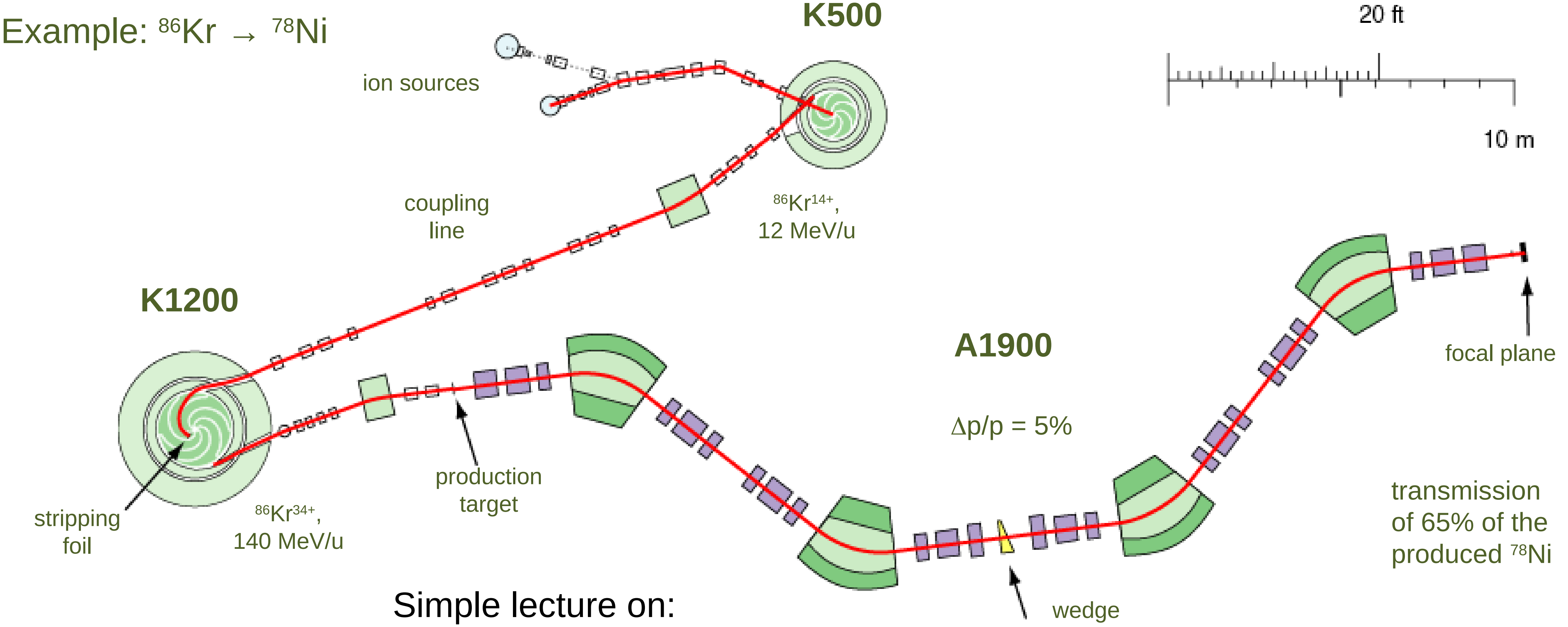


http://images.yourdictionary.com/cyclotron

Cyclotron example: NSCL's coupled cyclotron facility

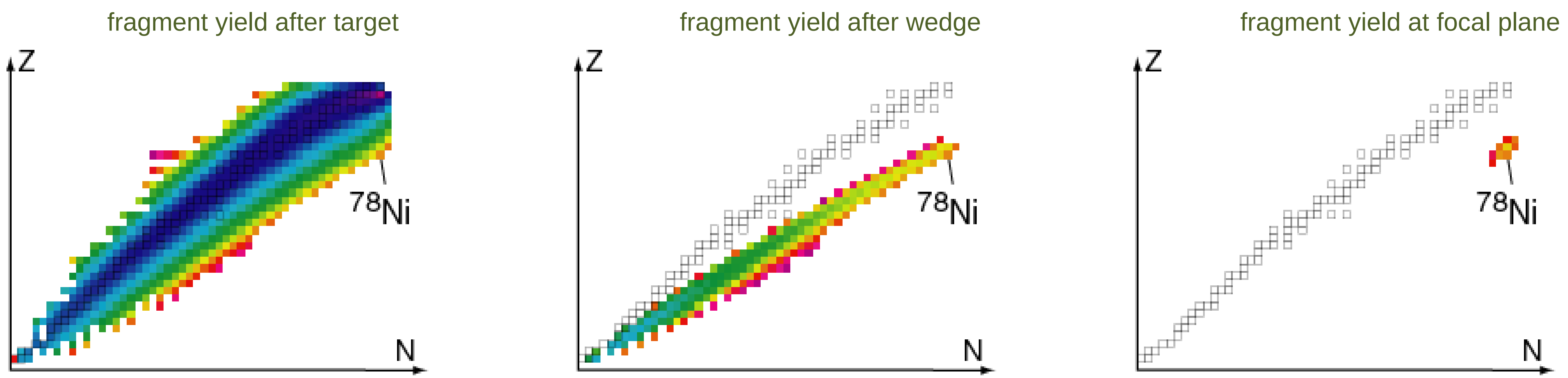
D.J. Morrissey, B.M. Sherrill, Philos. Trans. R. Soc. Lond. Ser. A. Math. Phys. Eng. Sci. 356 (1998) 1985.

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



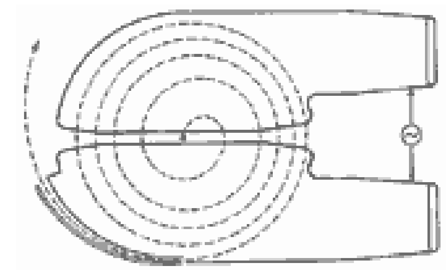
transmission of 65% of the produced ^{78}Ni

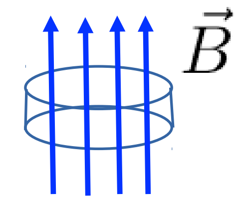
Simple lecture on:
https://people.nscl.msu.edu/~lund/ebss/ebss_2016/

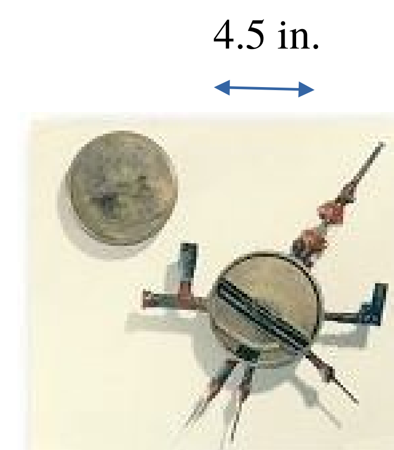


The Cyclotron

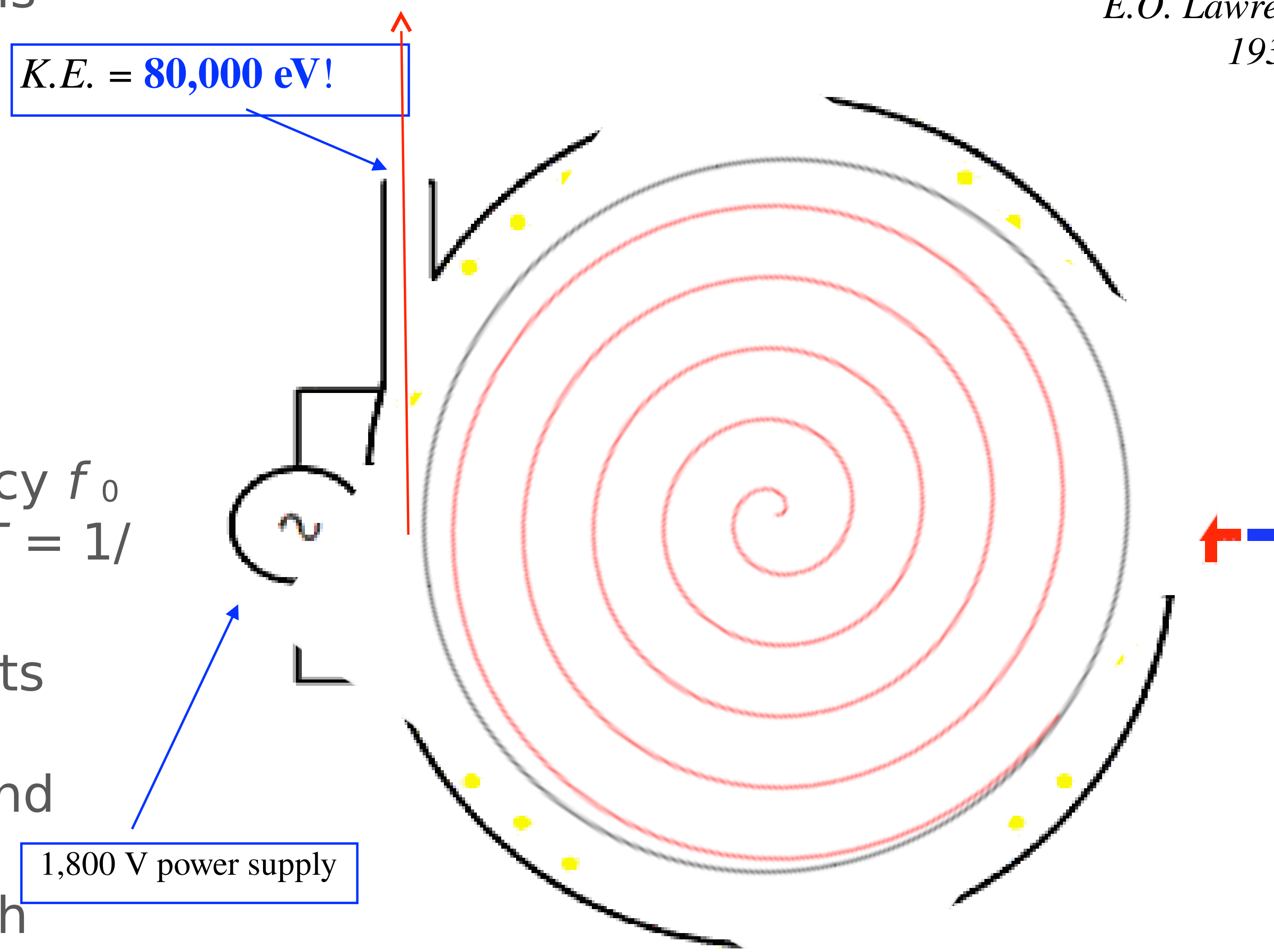
- A charged particle in a magnetic field, B, moves in a circular path of radius r at a speed v. The time to orbit once is
  $T = 2\pi r/v$.
- The force due to the magnetic field is
  $F = qvB = mv^2/r$
- thus, $r/v = m/qB$
- and so, $T = 2\pi m / qB = const$
- Oscillate the voltage with a frequency f_0 and adjust the magnetic field until $T = 1/f_0$.
- As the particle passes the gap, it gets accelerated, circulates on a slightly larger orbit, but the time to go around remains fixed.
- Eventually, the orbit gets big enough that the particle leaves the device.







E.O. Lawrence, 1931

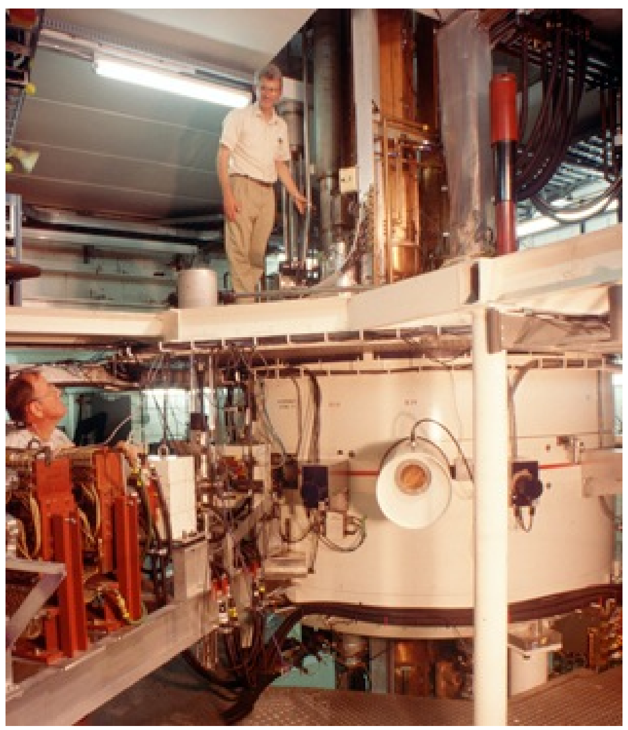


60-inch Cyclotron, Berkeley -- 1930’s

184-inch Cyclotron, Berkeley -- 1940’s

National Superconducting Cyclotron Lab

- First use of superconducting magnet technology in a major particle accelerator — K500; next was K1200

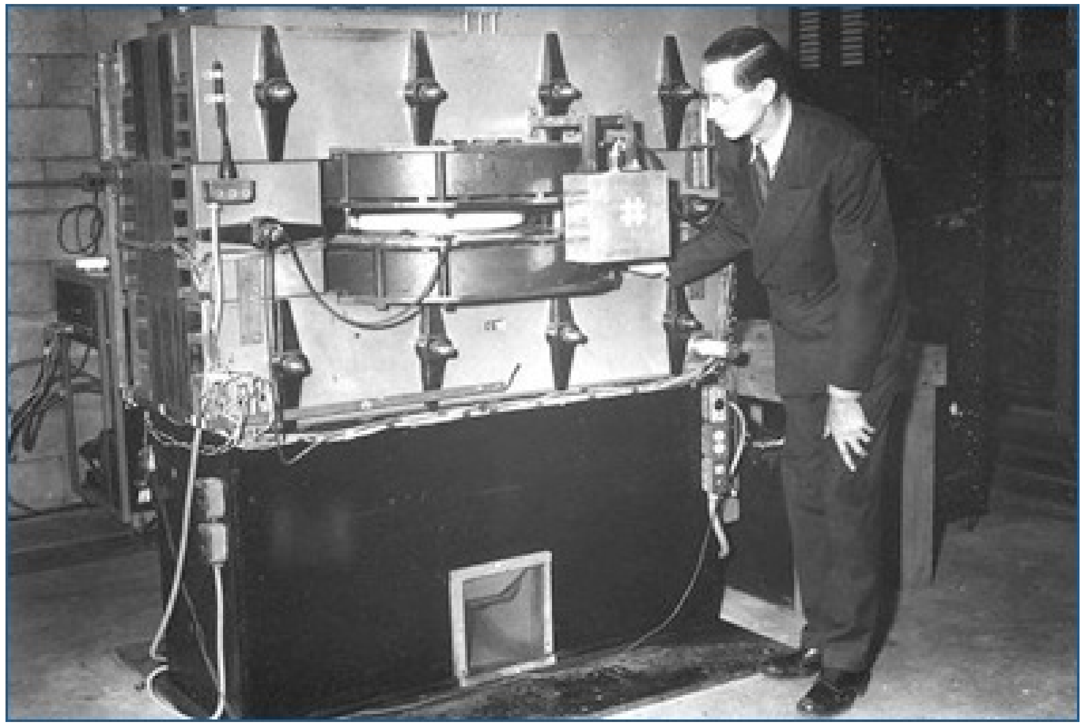


The K500 superconducting cyclotron, early-1980’s;
Note the compact size compared to earlier picture of 184” cyclotron(!), which was of comparable energy

Accelerating “dees” of the K1200 cyclotron

Meeting up with Relativity

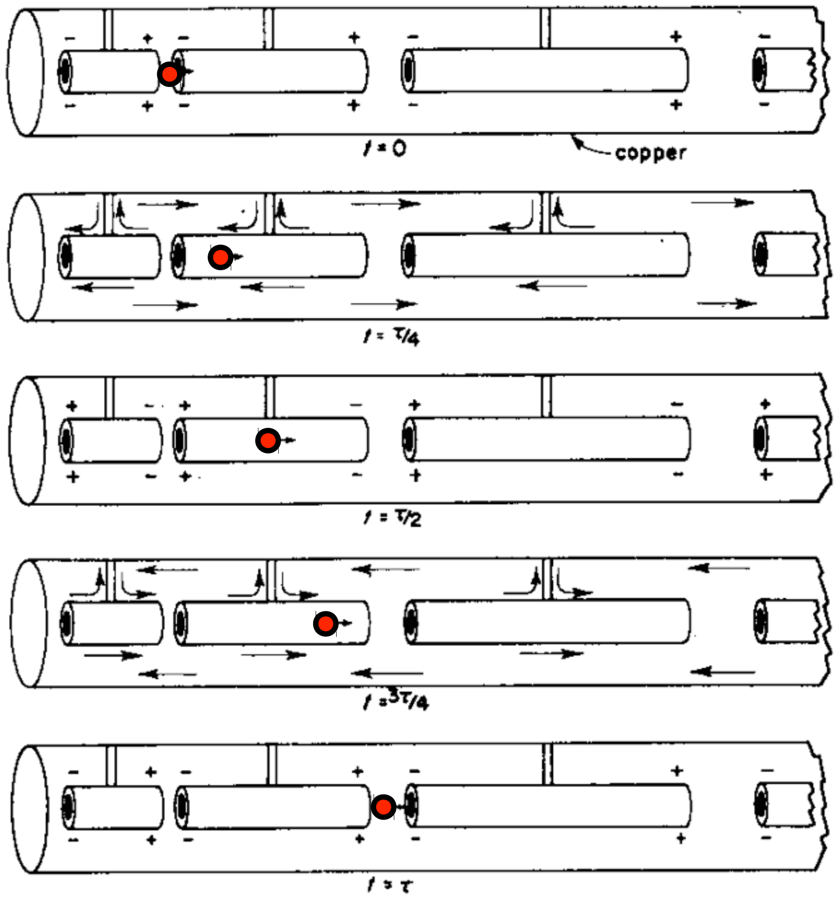
- The Synchrocyclotron (FM cyclotron) -- 1940's
  - beams became relativistic (esp. e^-) --> oscillation frequency no longer independent of momentum; cyclotron condition no longer held throughout process; thus, modulate freq.
- The Betatron -- 1940, Kerst (U. Illinois)
  - induction accelerator
    - $$\oint \vec{E} \cdot d\vec{s} = -\frac{\partial}{\partial t} \oint \vec{B} \cdot d\vec{A}$$
    - used for electrons
    - beam dynamics heavily studied
      - » “betatron oscillations”



~ 2 MeV; later models --> 300 MeV

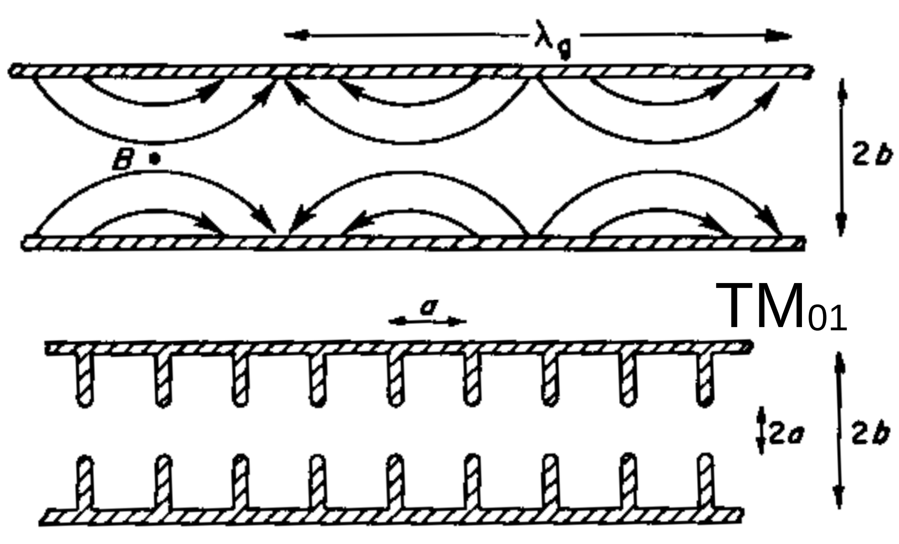
- The Microtron --1944, Veksler (Russia)
  - use one cavity with one frequency, but vary path length each “revolution” as function of particle speed

The “Modern” Linear Accelerator

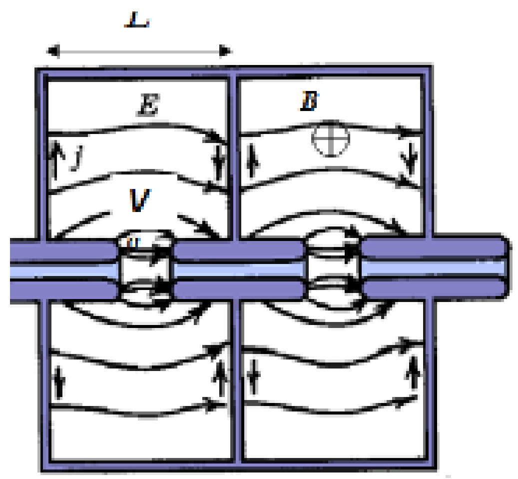


- Alvarez -- 1946 (U. California)
  - cylindrical cavity with drift tubes
  - particles “shielded” as fields change sign
  - most practical for protons, ions
  - GI surplus equip. from WWII Radar technology

- Traveling-Wave Electron Accelerator -- c.1950 (Stanford, + Europe)
  - TM_{01} waveguide arrangement
  - iris-loaded cylindrical waveguide
    - match phase velocity w/ particle velocity...

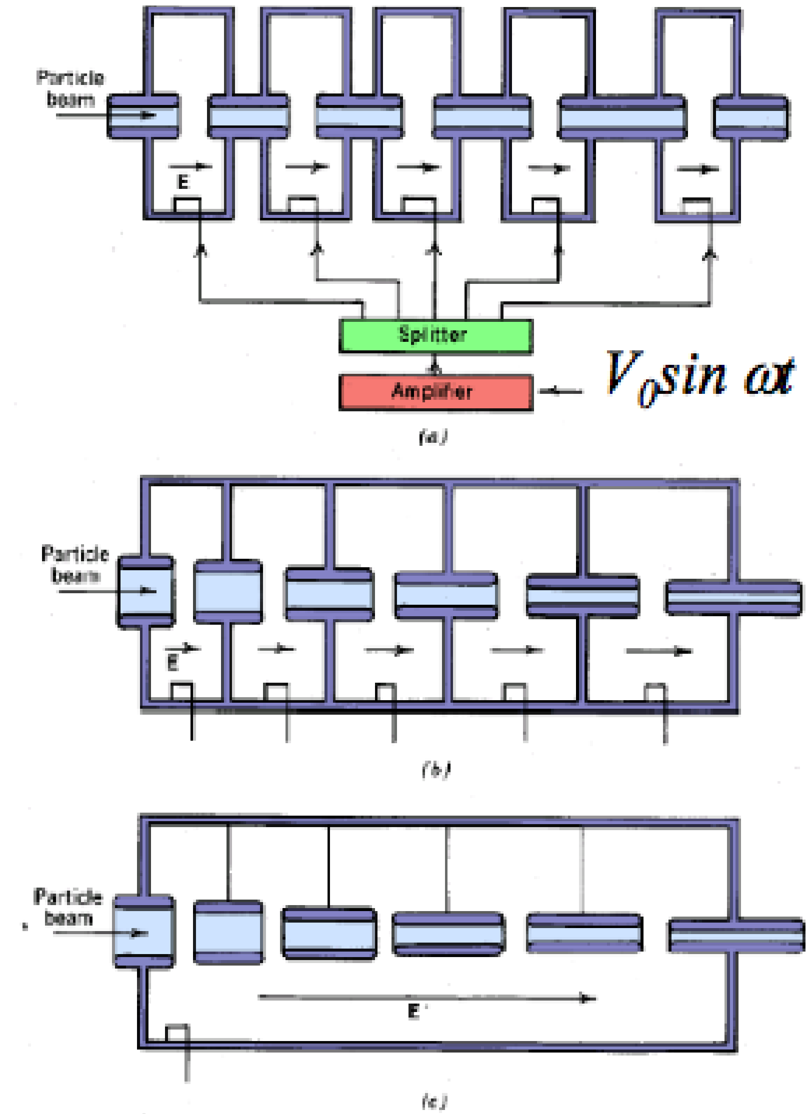


Radio-frequency Resonant Cavities



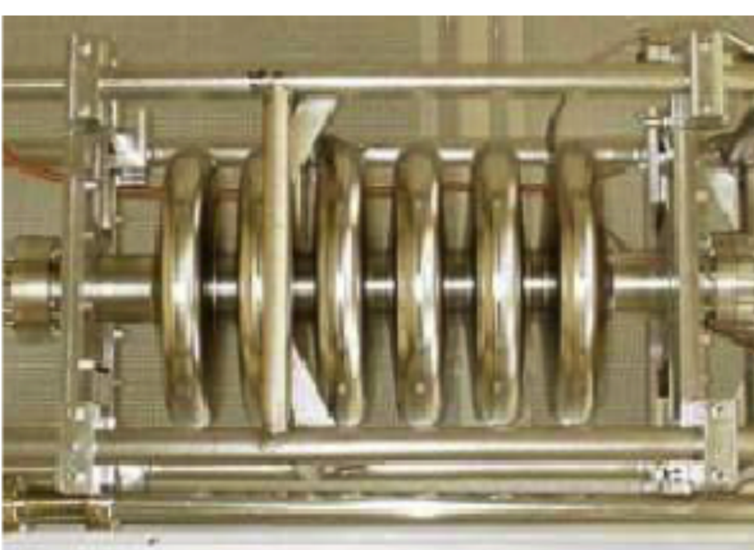
$$\oint \vec{E} \cdot d\vec{r} = -\frac{d\Phi_B}{dt}$$

Time varying: we can use many cavities in series!



- *Resonant cavities reduce rf power consumption, increase gradient and efficiency*
- *Long cavities (with many gaps) are generally more efficient*

Accelerating field	$E_a = V_g/L$
Stored EM energy	$U \propto E_a^2$
Quality Factor	$Q = \omega U/P = \Gamma/R_s$



A. Facco –FRIB and INFN *SRF Low-beta Accelerating Cavities for FRIB* *MSU 4/10/2011*

Normal vs. Superconducting Cavities

DTL tank - Fermilab

Normal conducting

Cu cavity @ 300K

$R_s \sim 10^{-3}\ \Omega$

$Q \sim 10^4$

Superconducting

Nb Cavity @ 4.2K

$R_s \sim 10^{-8}\ \Omega$

$Q \sim 10^9$

LNL PIAVE 80 MHz, β =0.047 QWR

Superconductivity allows

- *great reduction of rf power consumption even considering cryogenics (1W at 4.2K ~ 300W at 300K)*
- *the use of short cavities with wide velocity acceptance*

Superconducting Cavities

- Can use regularly spaced cavities when particle velocity is not changing much -- i.e., when *v* ~ *c*

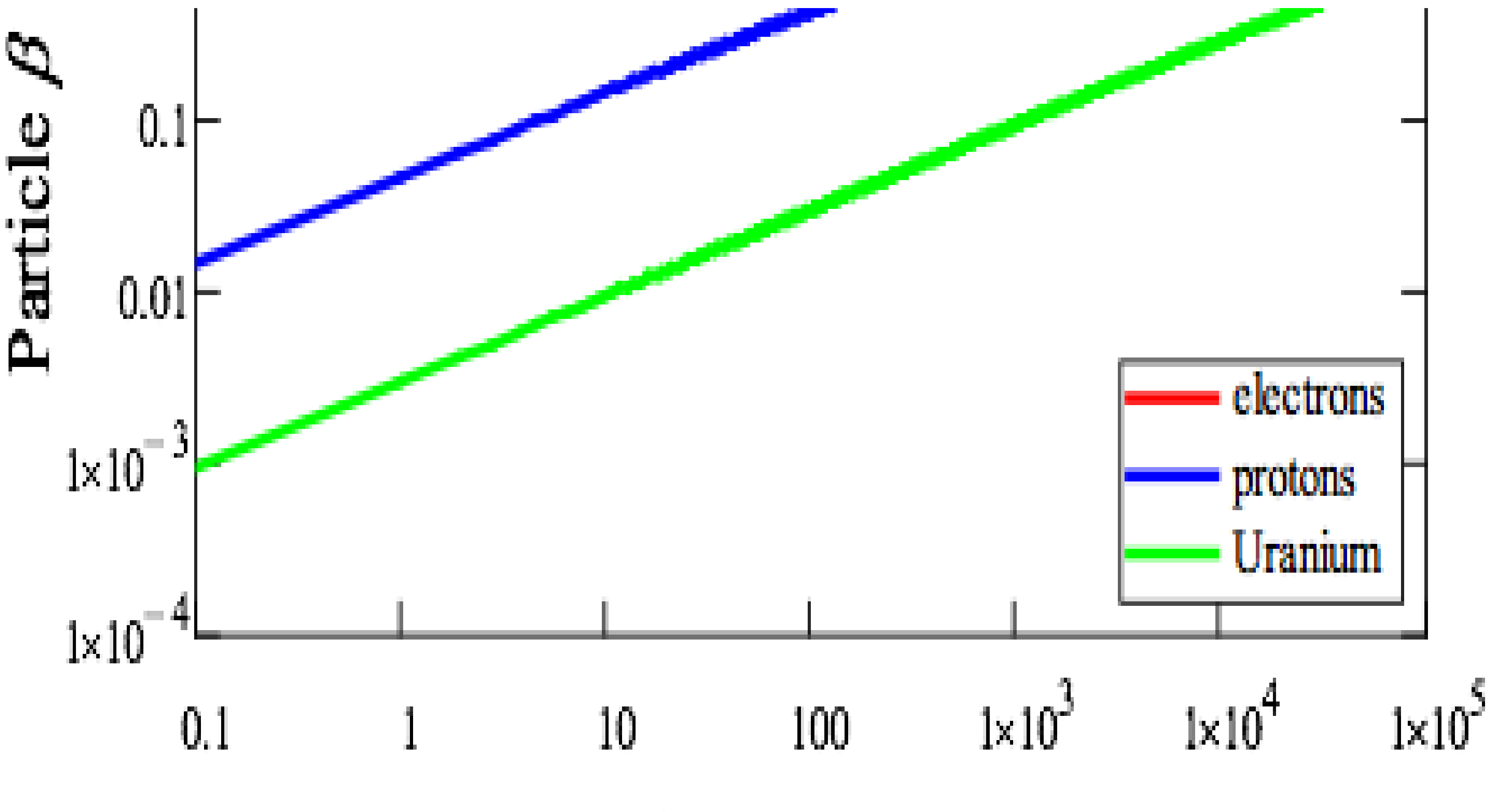
- For "slow" particles, in which velocity changes are dramatic between accelerating gaps, various solutions/designs...

A. Facco

Different Arrangements for Different Particles

- Accelerating system used will depend upon the evolution of the particle velocity along the system
  - electrons reach a constant velocity at relatively low energy
    - thus, can use one type of resonator
  - heavy particles reach a constant velocity only at very high energy
    - thus, may need different types of resonators, optimized for different velocities

- *e* 0.511 *MeV*
- *p* 938 *MeV*
- ^{239}U ~220000 *MeV*



Center of Mass Energy

Relativistic Review

$p_\mu = (\mathcal{E}/c, \vec{p}) =$ Energy-Momentum 4-vector

particle mass m in motion

$\mathcal{E} = \gamma m c^2$, $\vec{p} = \gamma m \frac{d\vec{x}}{dt}$

$\gamma = (1 - \vec{v}^2/c^2)^{-1/2}$

Transforms under Lorentz Transform as usual

A contraction of a 4-vector generates a Lorentz scalar that is invariant under Lorentz transforms:

$$p_\mu p^\mu = m^2 c^2 = \text{const} \quad \text{(trivial: evaluate in rest frame)}$$

$$= \frac{\mathcal{E}^2}{c^2} - \vec{p}^2 = m^2 c^2$$

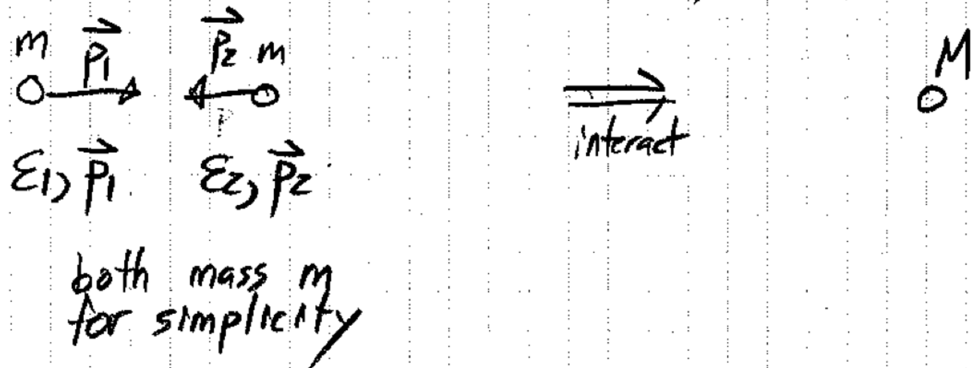
—or—

$$\boxed{\sqrt{\mathcal{E}^2 - \vec{p}^2 c^2} = m c^2}$$

Collisions

In elementary particle physics, accelerate particles at target (or another beam: collider) to generate other particles. Illustrate point in idealized form:

Two particles (beams or beam-stationary) interact head-on to make a massive particle M



$$p_\mu = \left(\frac{\mathcal{E}_1}{c} + \frac{\mathcal{E}_2}{c}, \vec{p}_1 + \vec{p}_2\right)$$

$$p_\mu p^\mu = M^2 c^2 = \left(\frac{\mathcal{E}_1}{c} + \frac{\mathcal{E}_2}{c}\right)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

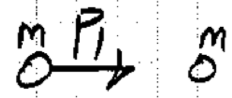
$$\boxed{Mc^2 = \sqrt{(\mathcal{E}_1 + \mathcal{E}_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}}$$

Contrast energy needed in 2 situations:

1) Fixed Target

$\vec{p}_2 = 0$

$\mathcal{E}_2 = mc^2$



$$\sqrt{(\mathcal{E}_1 + mc^2)^2 - \vec{p}_1^{\,2} c^2} = Mc^2$$

$$\sqrt{\underbrace{\mathcal{E}_1^2 - \vec{p}_1^{\,2} c^2}_{m^2c^4} + m^2c^4 + 2\mathcal{E}_1 mc^2} = Mc^2$$

$$\sqrt{2m^2c^4 + 2\mathcal{E}_1 mc^2} = Mc^2$$

$\mathcal{E}_1 \gg mc^2$

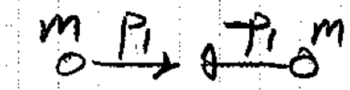
$$\sqrt{2\mathcal{E}_1 mc^2} = Mc^2$$

$$\mathcal{E}_1 = \left(\frac{M}{2m}\right) Mc^2$$

2) Collider

$\vec{p}_1 + \vec{p}_2 = 0$

$\mathcal{E}_1 = \mathcal{E}_2$



$$\sqrt{(\mathcal{E}_1 + \underset{\mathcal{E}_1}{\mathcal{E}_2}) - \cancelto{0}{(\vec{p}_1 + \vec{p}_2)^2}} = Mc^2$$

$$\sqrt{(2\mathcal{E}_1)^2} = Mc^2$$

$$\mathcal{E}_1 = \frac{Mc^2}{2}$$

Much less energy required in collider case!

Why ever fixed targets?

Depends on what doing. Precision tests of products easy to make ....

Types of particles can matter too .... quantum # conservations

$p\,p$ collider CERN

$p\,\bar{p}$ collider Tevatron

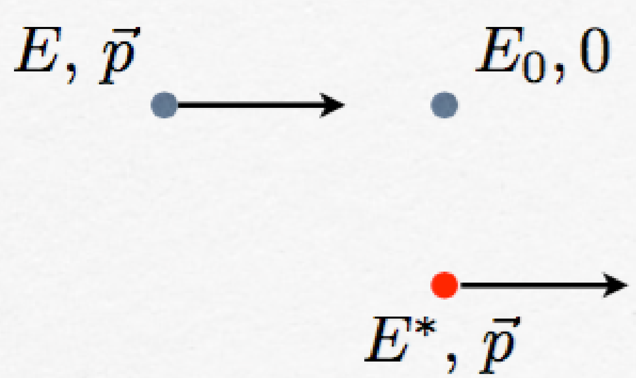
$e\,\bar{e}$ colliders SLAC, KEKb, NLC

FRIB production of rare isotopes essentially $\propto$ power on target.

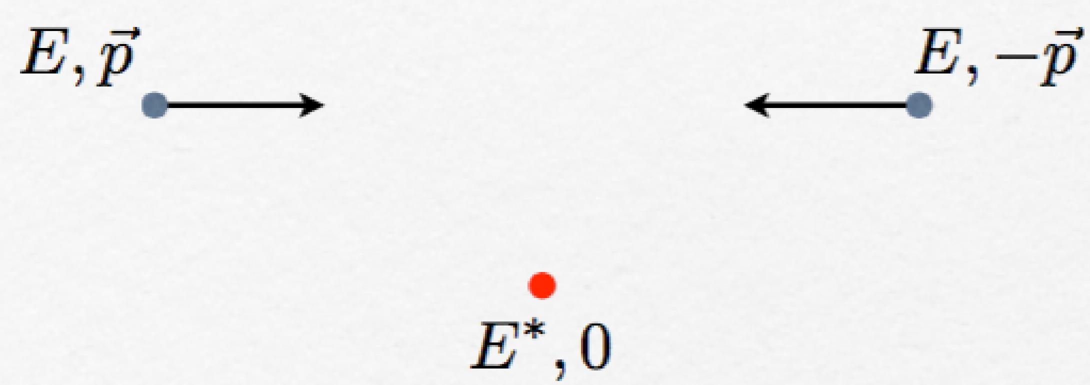
Fixed Target Energy vs. Collider Energy

- Beam/target particles: $E_0 \equiv mc^2$

Fixed Target



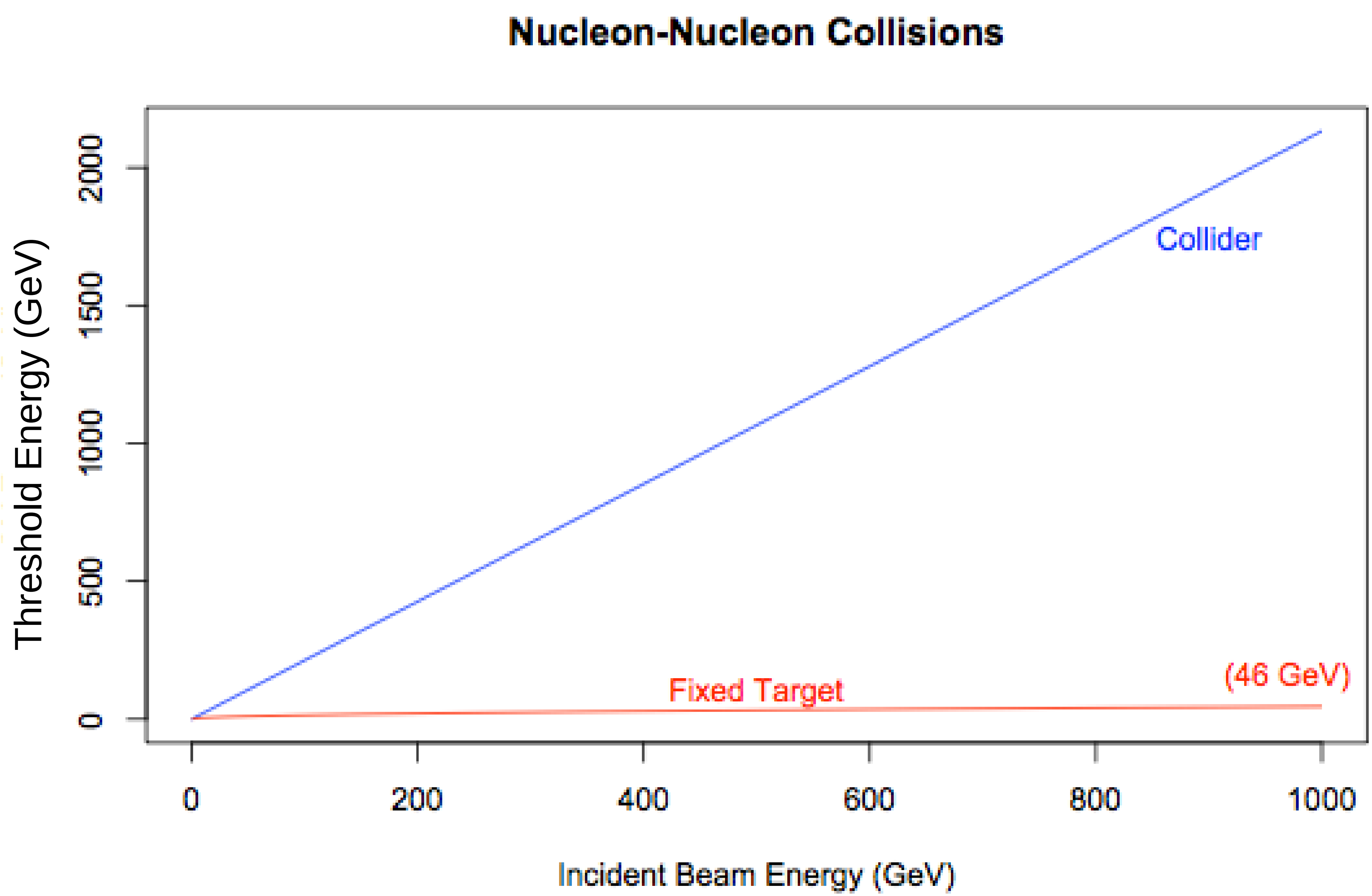
Collider



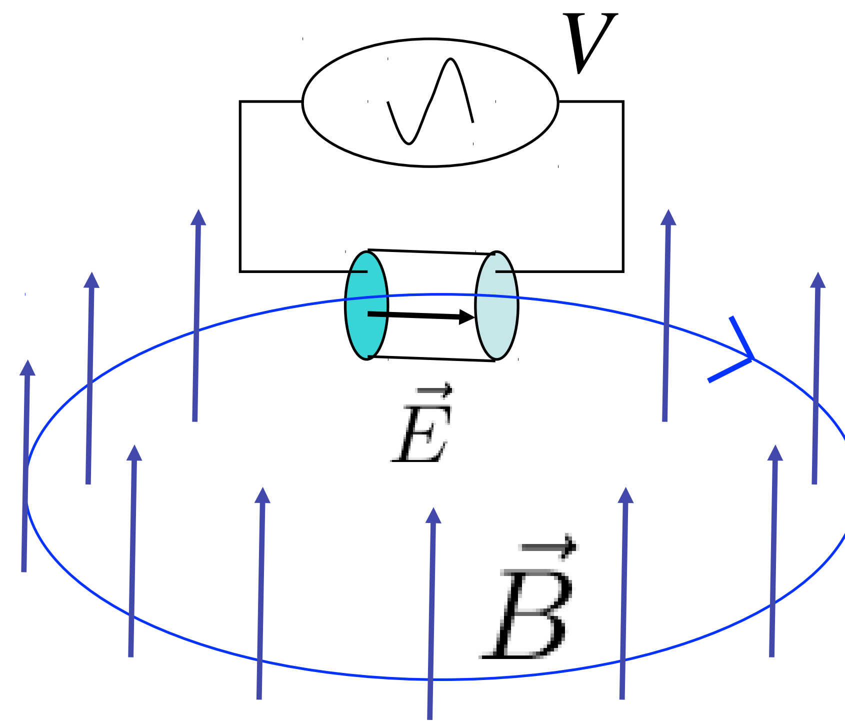
$$
\begin{aligned}
E^{*2} = (m^*c^2)^2 + (pc)^2 &= [\,E_0 + E\,]^2 \\
&= E_0^2 + 2E_0E + (E_0^2 + (pc)^2) \\
m^*c^2 &= \sqrt{2}\,E_0\,[1 + \gamma_{FT}]^{1/2}
\end{aligned}
$$

$$
\begin{aligned}
m^*c^2 &= 2E \\
&= 2E_0\gamma_{coll}
\end{aligned}
$$

Fixed Target Energy vs. Collider

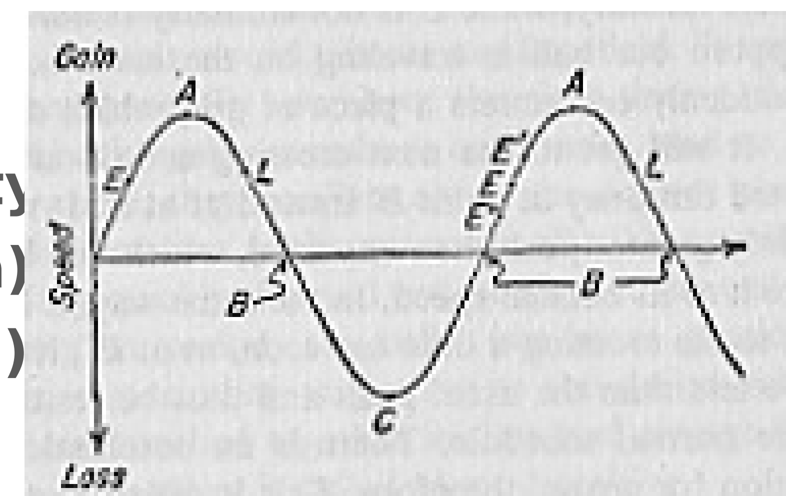


For Highest Elementary Particle Energies…



- … the **Synchrotron** -- late 1940's
  - RF powered cavity(ies); Radar power sources
  - keep R = const.;   increase B (= p/eR)
  - 1st in U.S. was at G.E. research lab, 70 MeV

- principal of phase stability
  - McMillan (U. California)
  - …   and Veksler (again)

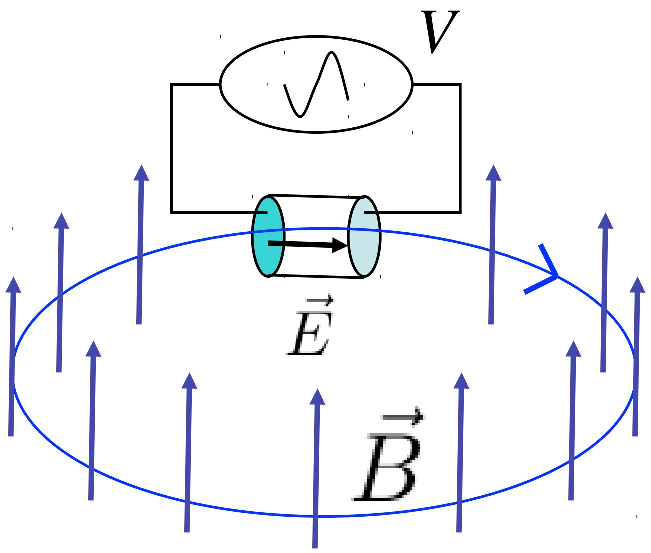


  - arrive late, gain energy;   arrive early, get less   --
    - *restoring force* -> energy oscillation
  - as strength of B raised adiabatically, the oscillations will continue about the "synchronous" momentum, defined by $p/e = B.R$ for constant R :

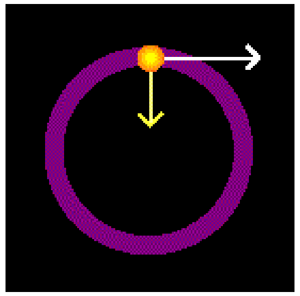
Synchrotron Oscillations

Synchrotron (cont'd)

- As the electromagnet fields are slowly increased, the particle will be accelerated by the cavity enough to keep its momentum in step with the magnetic field and keep the orbit radius constant:



$$mv^2/R = evB \quad \Longrightarrow R = mv / eB$$
$$= p / eB$$



The quantity "$B \cdot \rho$" is called the *magnetic rigidity*.

$$B\rho = p/q \quad \approx \frac{10}{3} \text{ T-m} \cdot p_{[\text{GeV}/c]}$$

for a particle of charge e; divide by Q if charge is Qe.

What frequencies do we need?
Let's say v ~ c,
and say R = 1 m
then,
$f = v / 2\pi R$
$= (3 \times 10^8 \text{ m/s}) / (2\pi \ 1\text{m})$
$= 5 \times 10^7 / \text{s} = 50 \text{ MHz}$

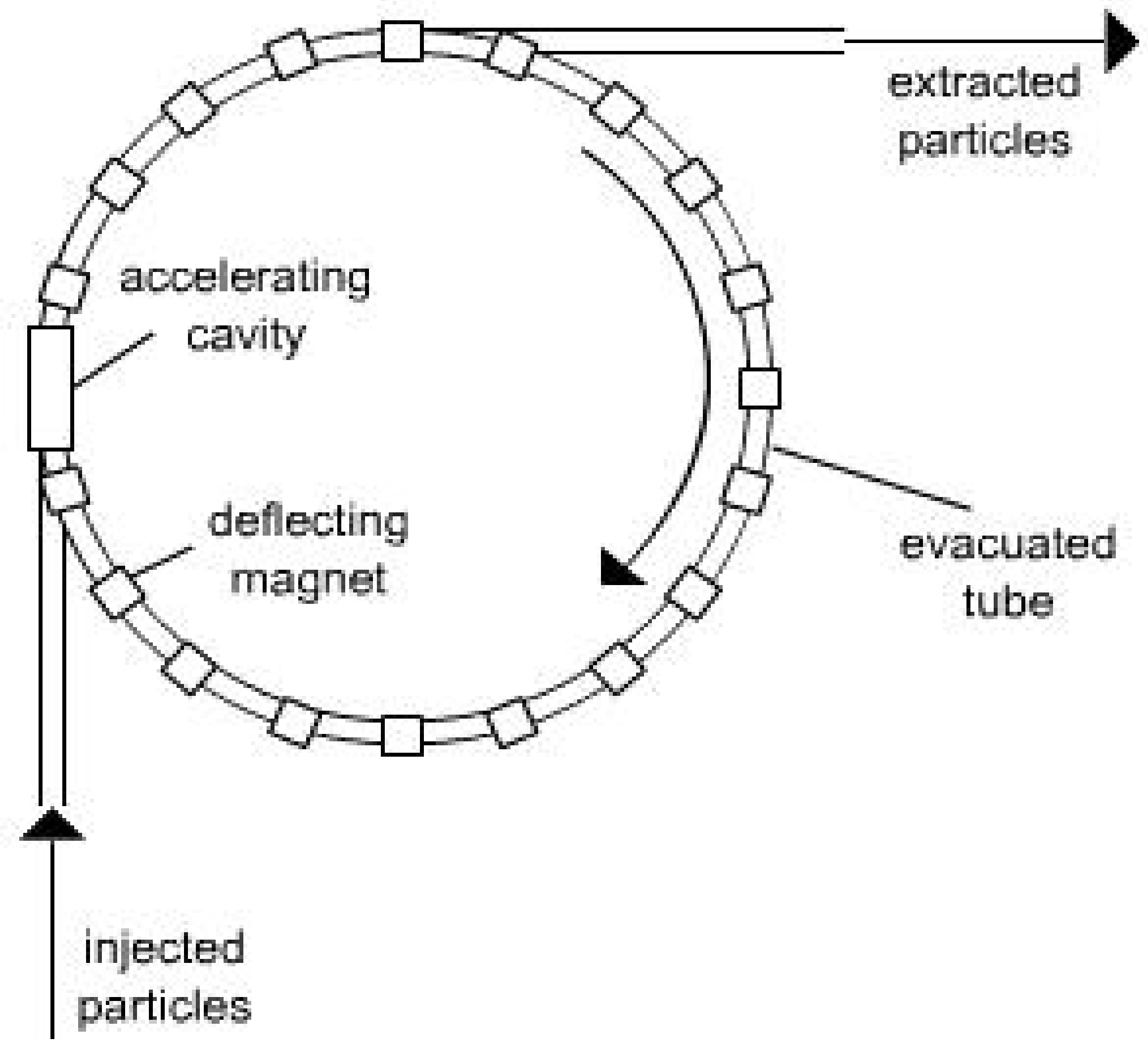
FM Radio Stations: 88 - 108 MHz!
thus, we use RF cavities and power sources

Synchrotrons

A "train" of bunches injected to fill ring and then bunches in ring accelerated while bending and focusing rise synchronously. At max energy bunch train is kicked out of ring and impinges on target. Then next cycle is loaded.

- Can achieve high energy at modest cost – tend to be used to deliver the highest energies
- Intensity is limited by the Coulomb force of particles within bunches (Space Charge)
- The magnets (bend and focus) must rapidly ramp and this can be difficult to do for superconducting magnets
- Machine must be refilled for next operating cycle giving up average intensity due to overall duty factor
- State of the art for heavy ions now under construction: FAIR (Germany) and IMP/Lanzhou

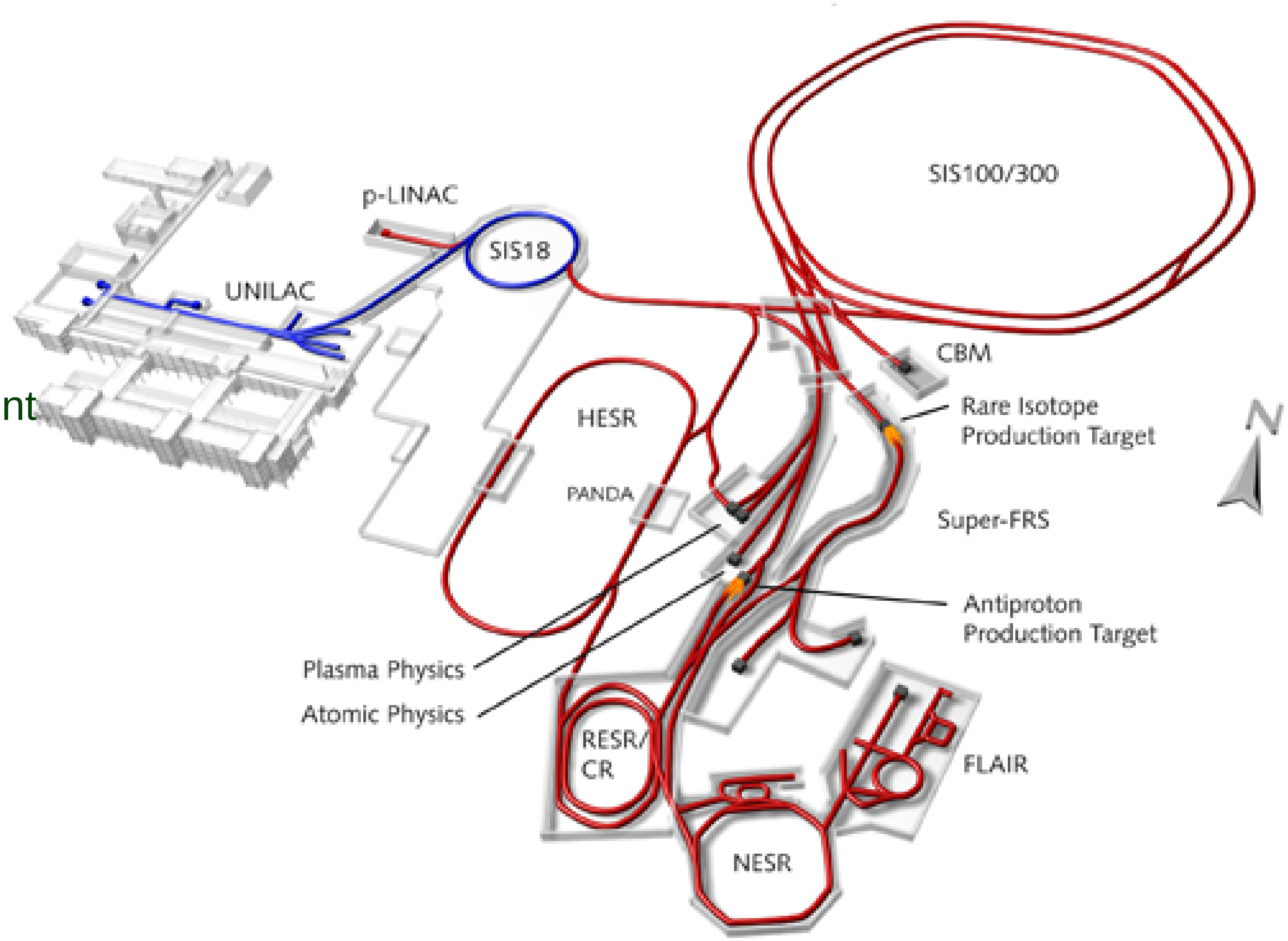
  + CERN LHC for p-p (Higgs)



http://universe-review.ca/R15-20-accelerators.htm

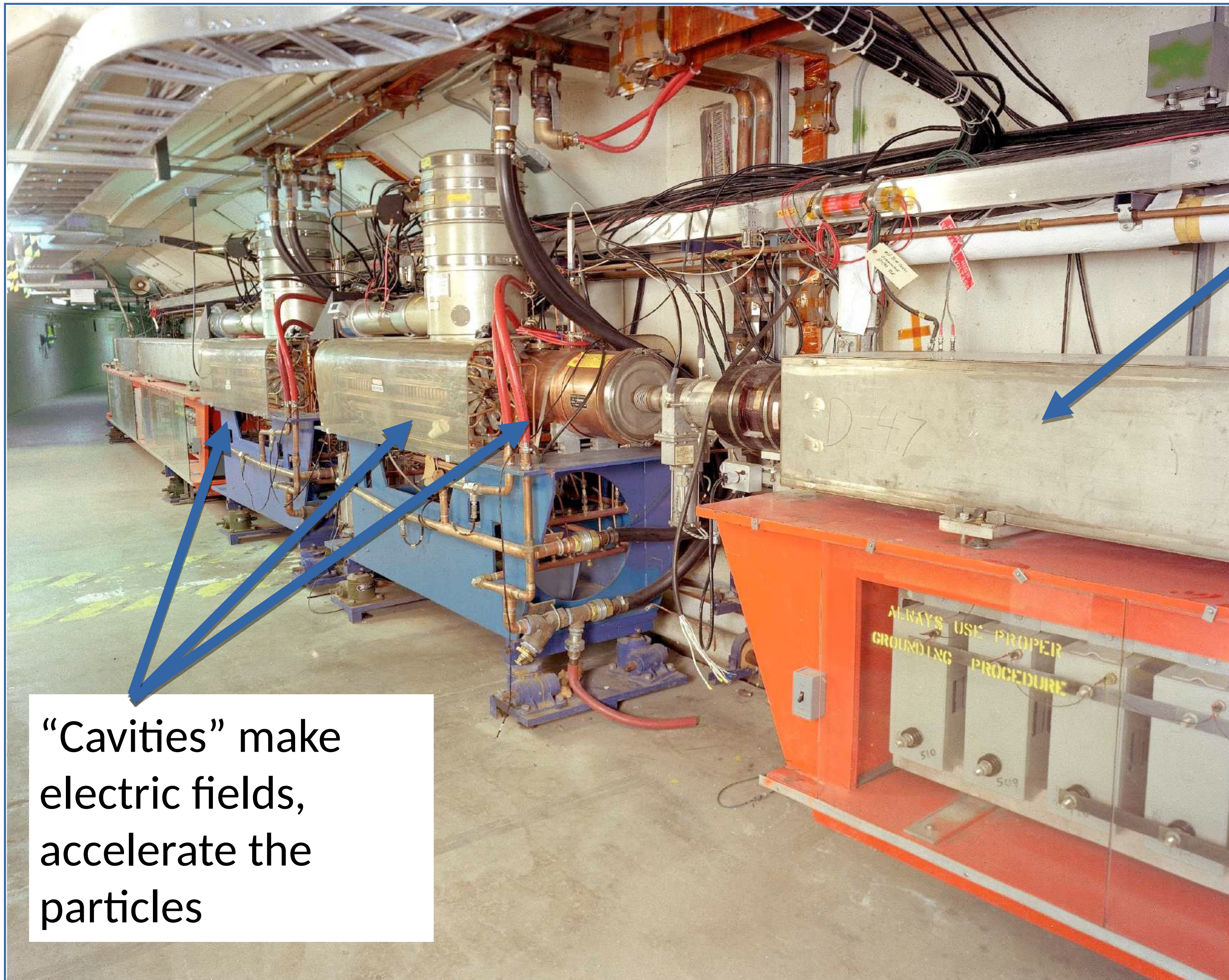
Example synchrotron: Facility for Antiproton and Ion Research (FAIR), GSI Germany

- Beams at 1.5 GeV/u
- 10^{12}/s Uranium
- Research
  - Rare isotopes
  - Antiproton
  - Atomic physics
  - Compressed matter
  - Plasma physics
- Under construction now with front end working/upgraded



http://www.fair-center.de/index.php?id=1

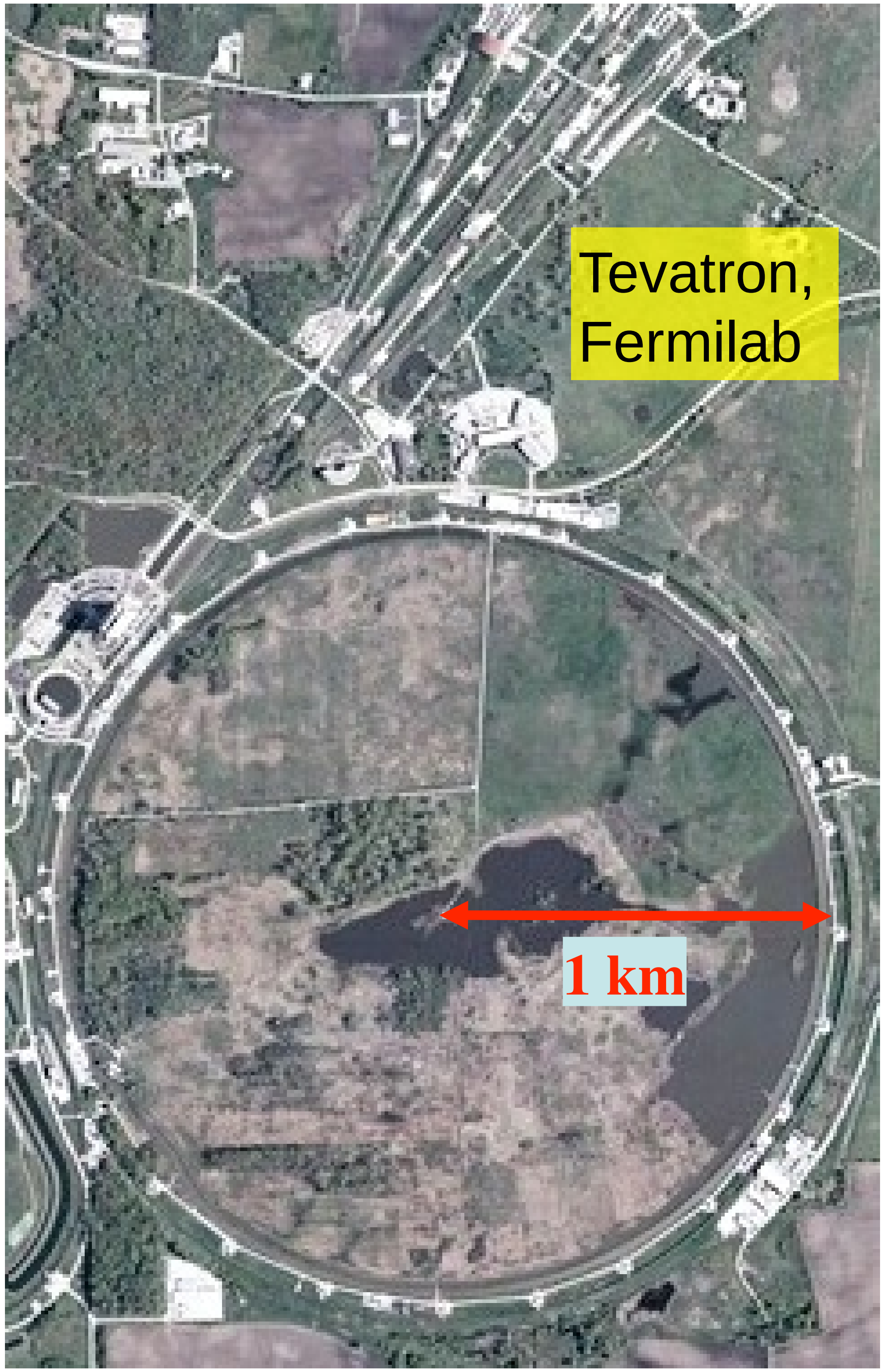
A Synchrotron

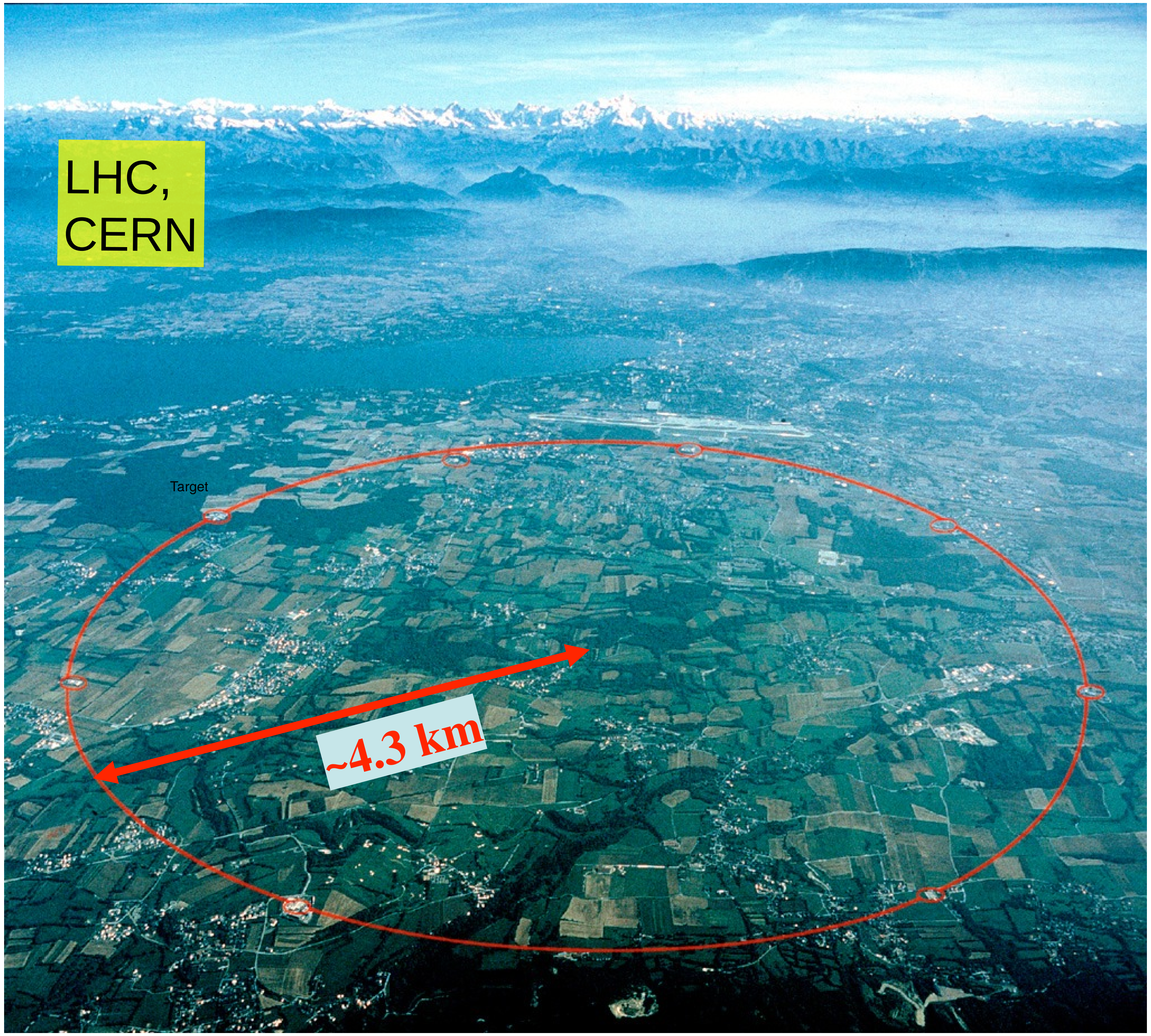


Magnets steer the particles in a circle

Booster Synchrotron, Fermilab (Batavia, IL)

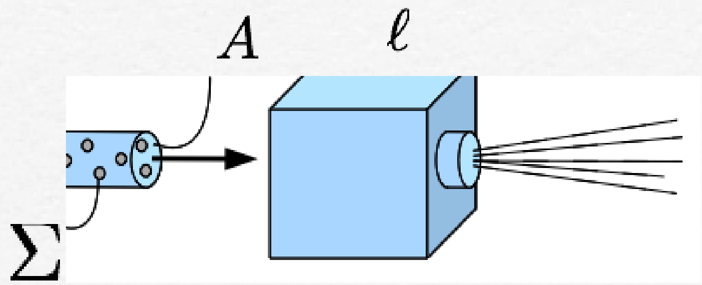
The Large Colliders





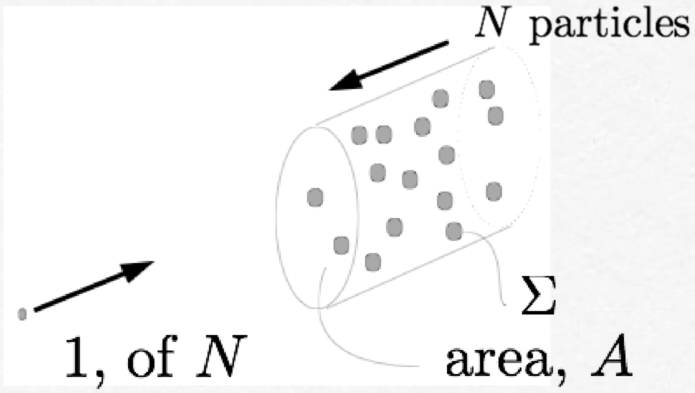
Luminosity

- Experiments want "collisions/events" -- rate?
- Fixed Target Experiment: $$\begin{aligned}\mathcal{R} &= \left(\frac{\Sigma}{A}\right)\cdot\rho\cdot A\cdot\ell\cdot N_A\cdot\dot{N}_{beam}\\ &= \rho N_A \ell \dot{N}_{beam}\cdot\Sigma\\ &\equiv \mathcal{L}\cdot\Sigma\end{aligned}$$



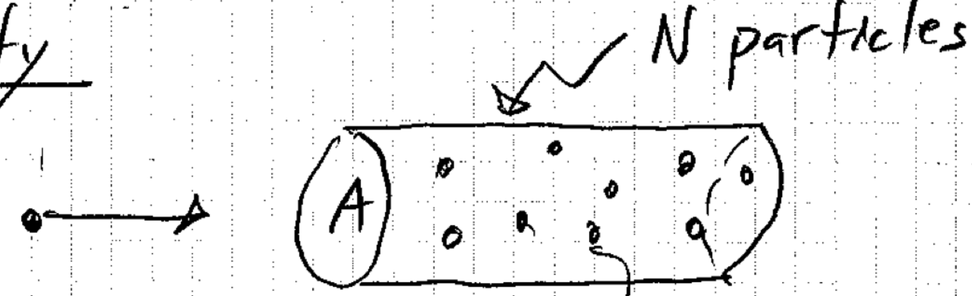
ex.: $\mathcal{L} = \rho N_A \ell \dot{N}_{beam} = 10^{24}/\mathrm{cm}^3\cdot 100\ \mathrm{cm}\cdot 10^{13}/\mathrm{sec} = 10^{39}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$

- Bunched-Beam Collider: $$\begin{aligned}\mathcal{R} &= \left(\frac{\Sigma}{A}\right)\cdot N\cdot(f\cdot N)\\ &= \frac{f\ N^2}{A}\cdot\Sigma\\ \mathcal{L} &\equiv \frac{f\ N^2}{A}\end{aligned}$$



($10^{34}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ for LHC)

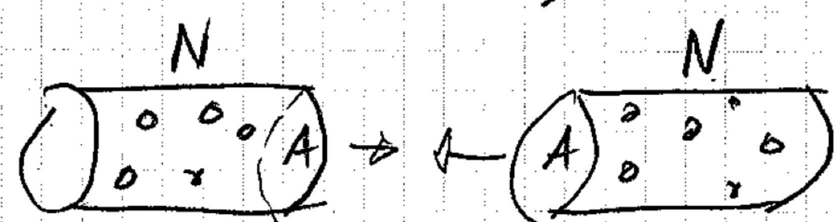
Luminosity



Σ = total overlap of 2 colliding particles

$[\Sigma] = \text{Area}$ given in cm^2 typically

1 particle sees $\left(\frac{N}{A}\right)\Sigma$ obscured.



$\Rightarrow \quad N\left(\frac{N}{A}\right)\Sigma$ events

Assume a collider ring with bunch cycling frequency f_0 and B bunches.
Then the rate of events is:

$$\frac{d\,\text{Events}}{dt} \equiv \mathcal{R} = f_0 \cdot B \; N\left(\frac{N}{A}\right)\Sigma$$

Define a normalized event rate as Luminosity

$$\boxed{\text{Luminosity} \equiv \mathcal{L} = \frac{\mathcal{R}}{\Sigma} = \frac{f_0 B N^2}{A}}$$

Actual beams have more Gaussian profiles:

$$dn(r) = \frac{N}{\sigma^2} e^{-r^2/(2\sigma^2)}\, r\,dr \qquad \langle r^2 \rangle = \sigma^2 \quad \text{rms radius of beam}$$

Accounting for this in the luminosity calculation leads to:

$$\boxed{\mathcal{L} = \frac{f_0 B N^2}{4\pi\sigma^2}}$$

Formulas straightforward to adapt for linear colliders

Some numbers

$$\mathcal{L} \approx \frac{10^{30}}{cm^2\,sec} \quad \text{Fermilab } p\bar{p} \ (1990s)$$

$$\frac{10^{34}}{cm^2\,sec} \quad \text{LHC } pp \ (2016)$$

$$\frac{10^{34}}{cm^2\,sec} \quad \text{KEKB } e\bar{e} \ (2009)$$

total cross sections $\Sigma \sim 100$ mb

(1 mb $= 1$ milli-barn $= 10^{-27}\,cm^2$)

$\Rightarrow R \approx \mathcal{L}\Sigma \sim \frac{10^9}{sec}$ large for

But cross sections of interest may be $\sim 10^8$ or more smaller. event discrimination challenging.

Simple picture above is not fully accurate for rings: Synchrotrons bring filled and brought up to energy and then particles collide till bunches decay away:

$$B\dot{N} = -\mathcal{L}\Sigma n \qquad n = \#\text{ detectors luminosity delivered to.}$$

$$\dot{N} = -f_0 \frac{BN^2}{A} \Sigma n$$

Solve this system:

$$\frac{dN}{N^2} = -\frac{f_0}{A}\Sigma n\,dt \quad\Rightarrow\quad -\frac{1}{N} = -\frac{f_0}{A}\Sigma n t + \text{const}$$

$N_0 \equiv N(t=0)$

$$\frac{1}{N} = \frac{1}{N_0} + \frac{f_0}{A}\Sigma n t \quad\Rightarrow\quad N = \frac{N_0}{1+\frac{f_0 N_0}{A}\Sigma n t}$$

Denote $\mathcal{L}_0 = \frac{f_0 B N_0^2}{A}$

$$\mathcal{L} \equiv \frac{f_0 B N^2}{A} = \frac{f_0 B N_0^2/A}{\left(1+\frac{f_0 N_0}{A}\Sigma n t\right)^2} \Rightarrow \boxed{\mathcal{L} = \frac{\mathcal{L}_0}{\left(1+\frac{n\mathcal{L}_0\Sigma t}{BN_0}\right)^2}}$$

$\mathcal{L}(t)$ Luminosity decays in time t over machine cycle.

Number of events:

$$R = \mathcal{L}\Sigma = \frac{d\,\text{Events}}{dt} \Rightarrow \text{Events} = \int_0^T \mathcal{L}(t)\,\Sigma\,dt$$

Store/Interaction time T

$$\boxed{I(t) = \text{Integrated Luminosity} \equiv \int_0^t \mathcal{L}(\tilde{t})\,d\tilde{t} = \frac{\mathcal{L}_0 t}{1+\mathcal{L}_0 t\frac{n\Sigma}{BN_0}}}$$

$$\text{"} \frac{\text{Events}}{\Sigma}$$

$$= I_0 \frac{\mathcal{L}_0 t/I_0}{1+\mathcal{L}_0 t/I_0}$$

$I(t)$ Integrated luminosity rises in time reaching a limiting value of

$$I_0 = \frac{BN_0}{n\Sigma}$$

as $t \to \infty$.

Many other factors to really account for:

* Evolution of beam size.
* Crossing angle of beams
* Structure of beam overlap over bunches.

..... Formulas get complicated.

See Syphers plots for example evolution

Integrated Luminosity

- Bunched beam is natural in collider that "accelerates" (more later)

$$\mathcal{L} = \frac{f_0 B N^2}{A}$$

$f_0 = \text{rev. frequency}$
$B = \text{no. bunches}$

- In ideal case, particles are "lost" only due to "collisions":

$$B\dot{N} = -\mathcal{L}\,\Sigma\,n$$

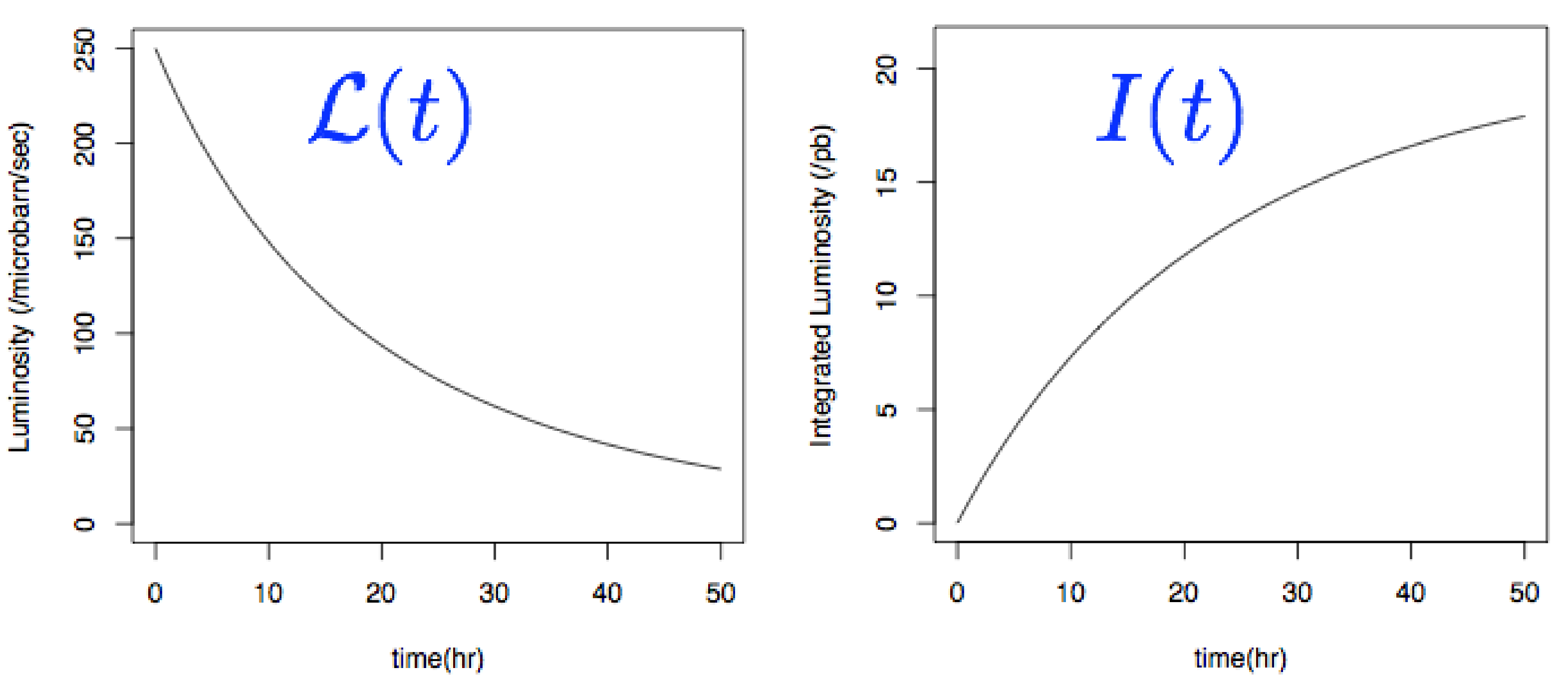
(n = no. of detectors receiving luminosity $\mathcal{L}$)

- So, in this ideal case, $$\mathcal{L}(t) = \frac{\mathcal{L}_0}{\left[1 + \left(\frac{n\mathcal{L}_0\Sigma}{BN_0}\right)t\right]^2}$$

Ultimate Number of Collisions

- Since $\mathcal{R} = \mathcal{L} \cdot \Sigma$ then, #events = $\int \mathcal{L}(t)dt \cdot \Sigma$
- So, our integrated luminosity is

$$I(T) \equiv \int_0^T \mathcal{L}(t)dt = \frac{\mathcal{L}_0 T}{1 + \mathcal{L}_0 T(n\Sigma/BN_0)} = I_0 \cdot \frac{\mathcal{L}_0 T/I_0}{1 + \mathcal{L}_0 T/I_0}$$



asymptotic limit:

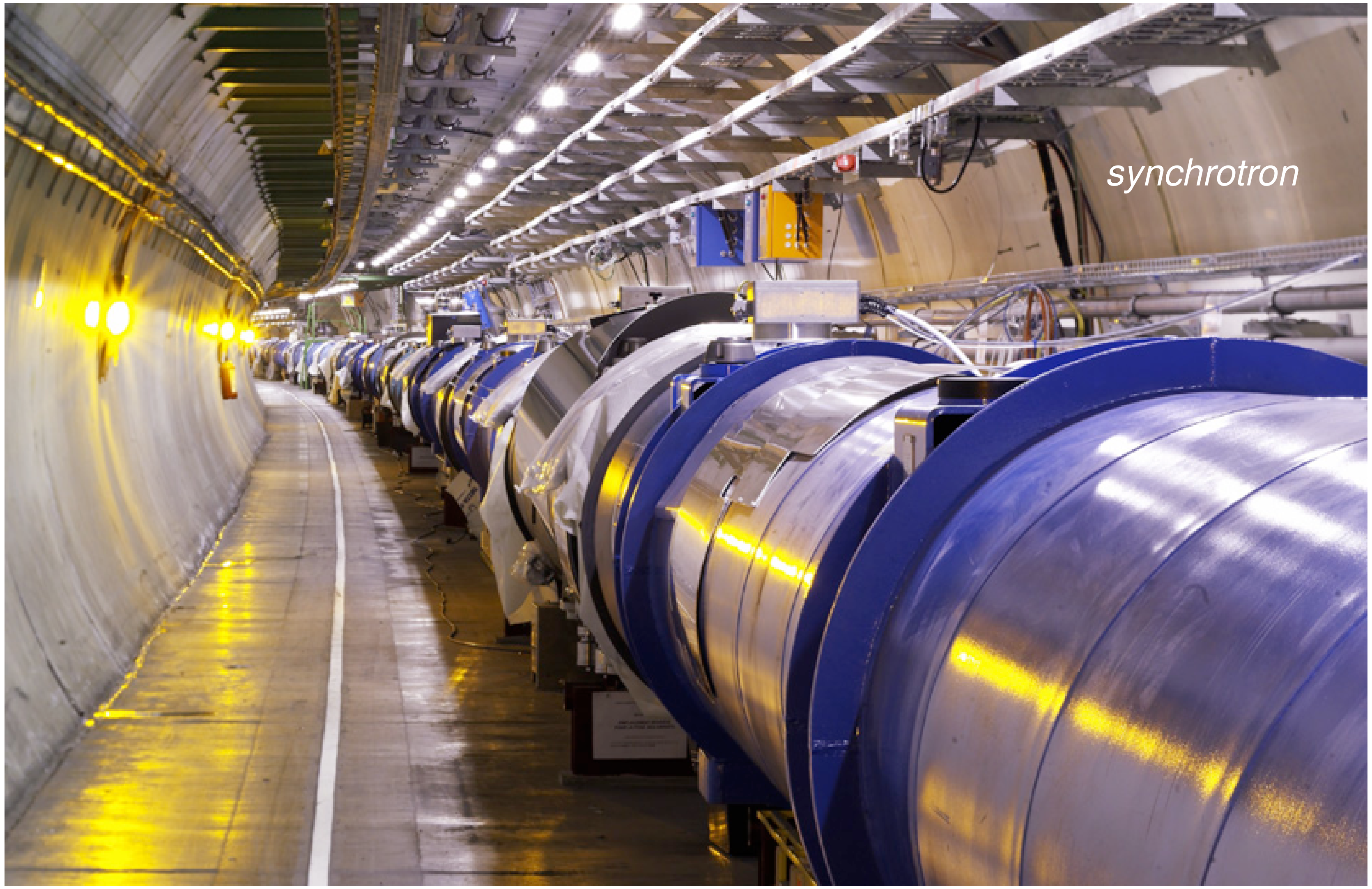
$$I_0 \equiv \frac{BN_0}{n\Sigma}$$

so, ...

$$\mathcal{L} = \frac{f_0 B N^2}{A}$$

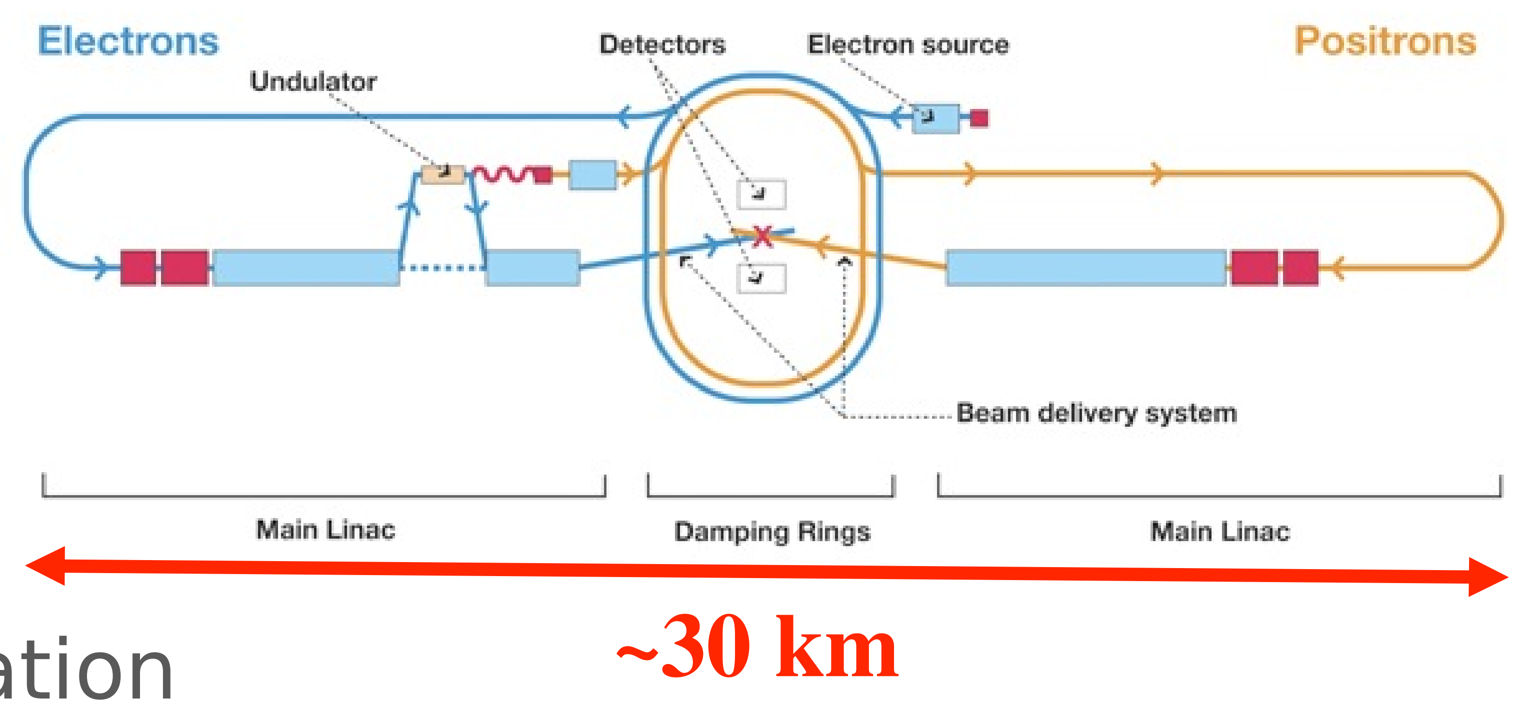
Recent Large-Scale Accelerators

Large Hadron Collider (LHC)



Spallation Neutron Source (SNS)

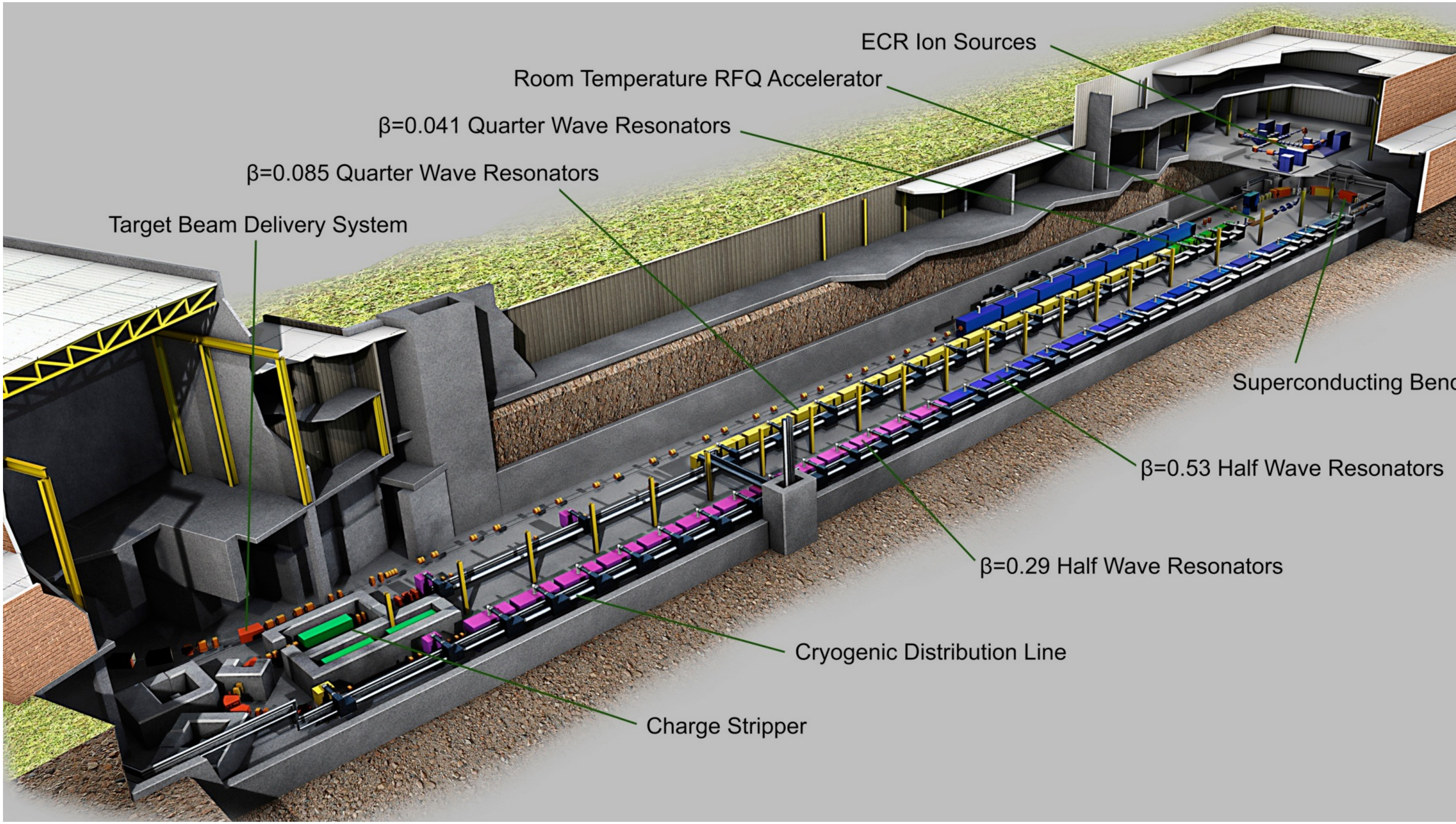
The Linac -- Again



- Linacs for e+/-
  - ILC, CLIC
  - avoid synchrotron radiation
  - damping rings produce very small beams at interaction points

- Resurgent use of Linacs for large *p* and ion accelerators...
  - SNS; FRIB, ESS
  - high current/intensity/power for use in high rate/statistical experiments
- For flexible program at FRIB --> Superconducting CW Linac
  - very unique features -- low velocities, large range of particle species, high current via multiple charge state acceleration, challenging charge stripping,...

MSU’s Facility for Rare Isotope Beams (FRIB)

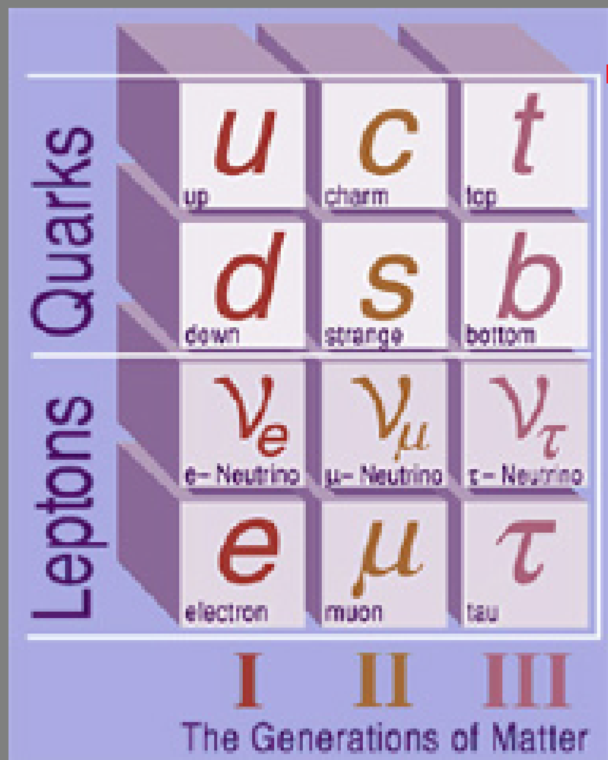


Modern Accelerators

- The High Energy Physics (HEP) era -- SLAC, CESR, Tevatron, LEP, KEKb, PEP II, SSC, LHC, ...
- Also, modern-day Nuclear Physics -- NSCL, RIKEN, ATLAS, CEBAF, RHIC, FRIB, ...
- Emergence of other interests -- medicine, defense, industry -- light sources, neutron spallation sources, medical cyclotrons (proton therapy, etc), ...
- Someone did a better job ...
  - where do those 1 Joule cosmic rays come from?

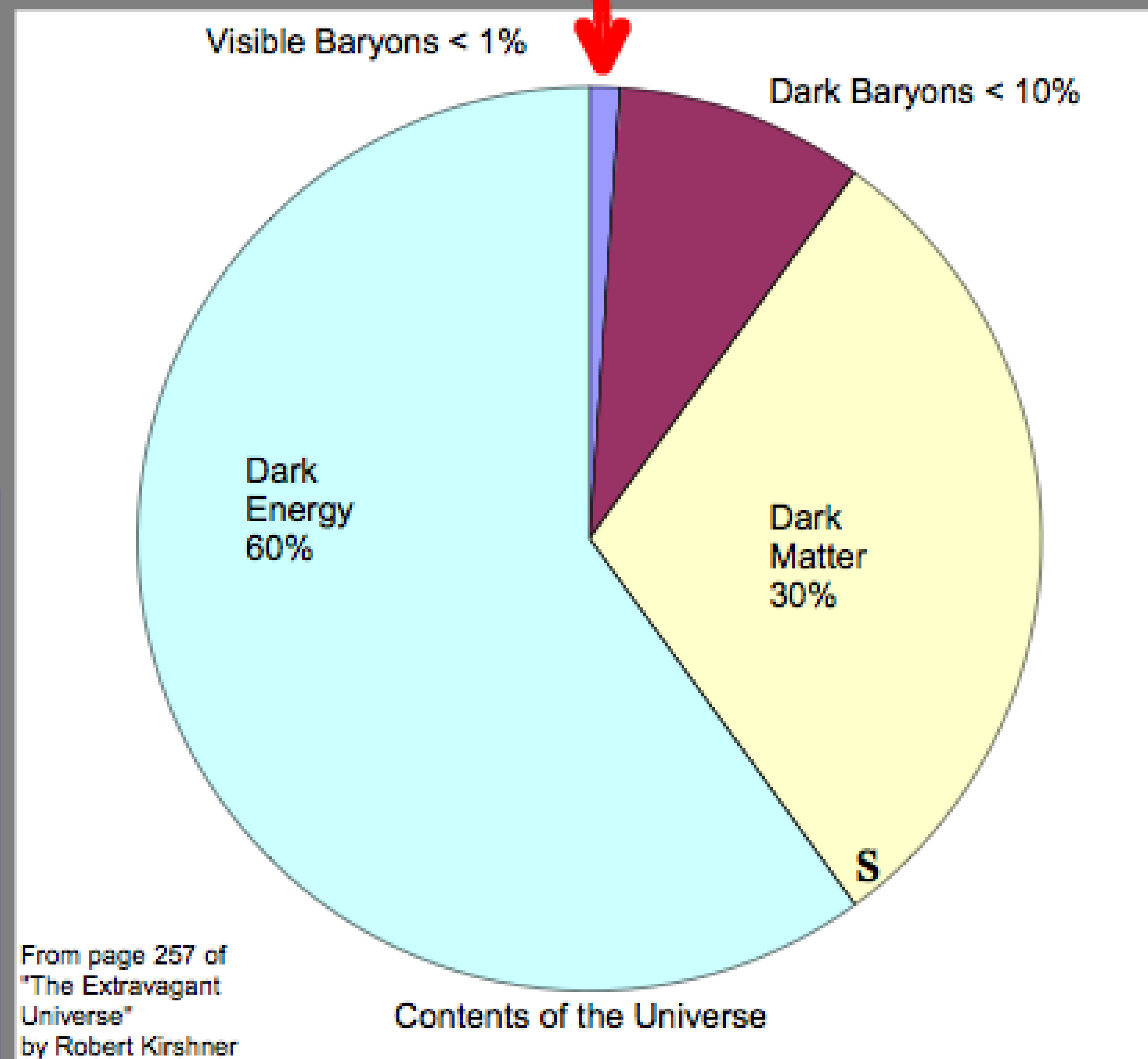
Is it almost all figured out??

(yes, ~ every 100 years!)



The Universal Pie.

Although we can be proud that we have filled up the diagram above, the biggest slice of energy-density in the universe is dark energy, which we don't understand, and the next biggest is dark matter, which we don't understand. There is ***plenty*** more work to be done.



Measurements suggest equivalent density of universe is about 6 protons/m^3

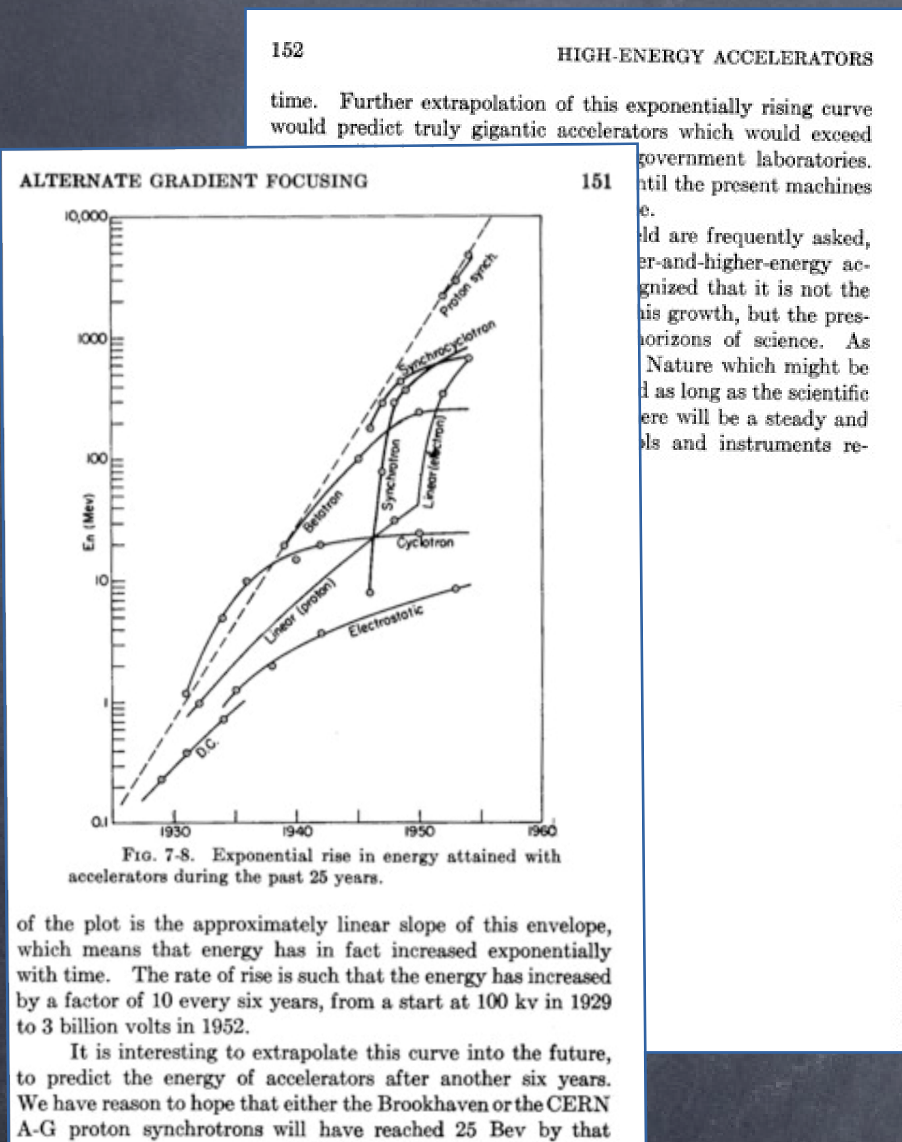
However, baryonic matter can only account for about 1 proton per 4 m^3

Note: inter-stellar space, within local galaxy, is about 1 million protons per m^3

Why go through all this?

- Accelerators are used to probe the universe, with obvious spin-offs for other applications
- Future large-scale accelerators may/will be used to probe deeper into space and time
- Energy, mass, (gravity?,) other fundamental properties are somehow intimately related

The Livingston Plot (1954)



152 HIGH-ENERGY ACCELERATORS

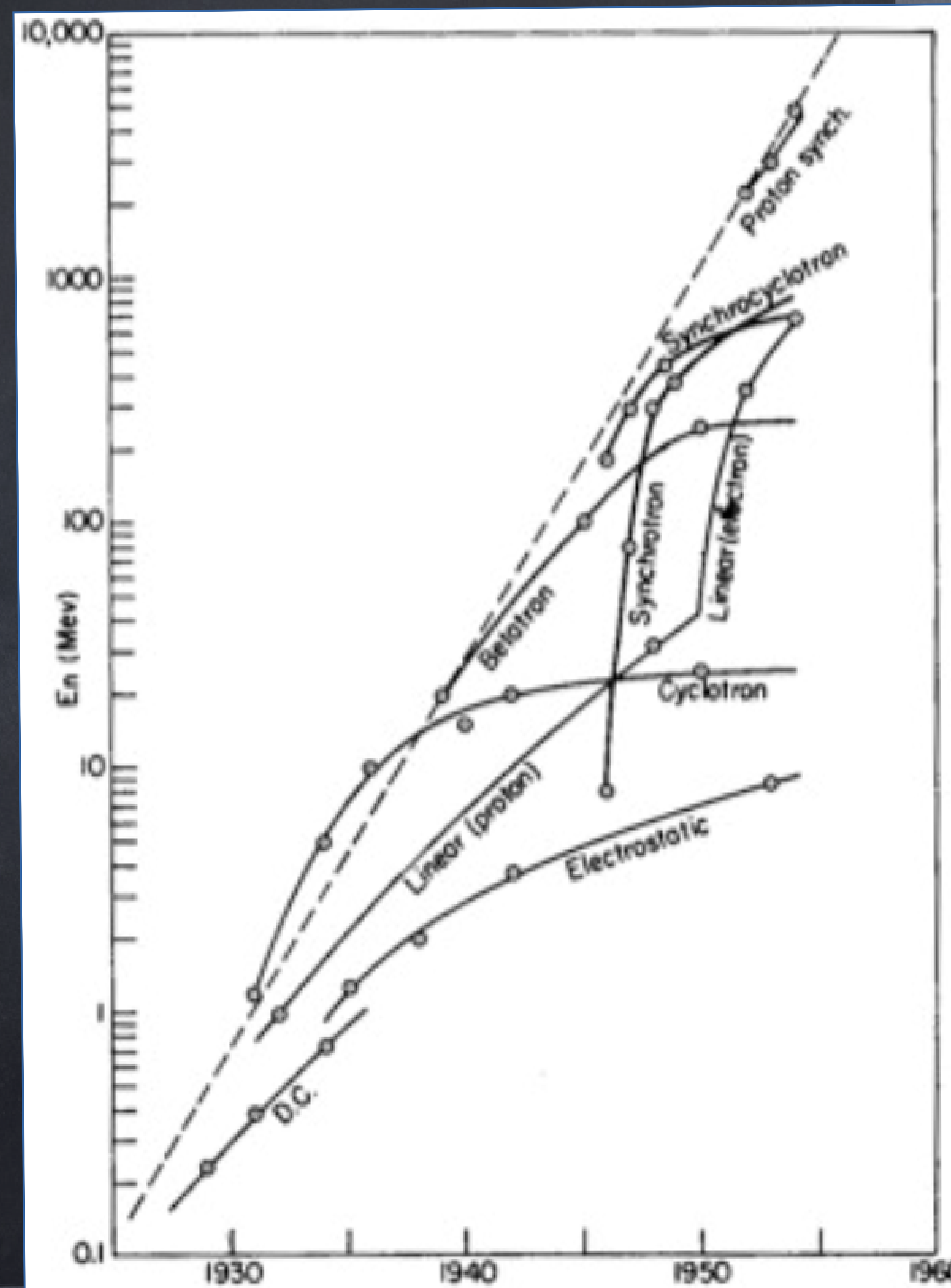
time. Further extrapolation of this exponentially rising curve
would predict truly gigantic accelerators which would exceed
government laboratories.
ntil the present machines
e.
ld are frequently asked,
er-and-higher-energy ac-
gnized that it is not the
is growth, but the pres-
horizons of science. As
Nature which might be
d as long as the scientific
ere will be a steady and
ls and instruments re-

ALTERNATE GRADIENT FOCUSING 151

FIG. 7-8. Exponential rise in energy attained with accelerators during the past 25 years.

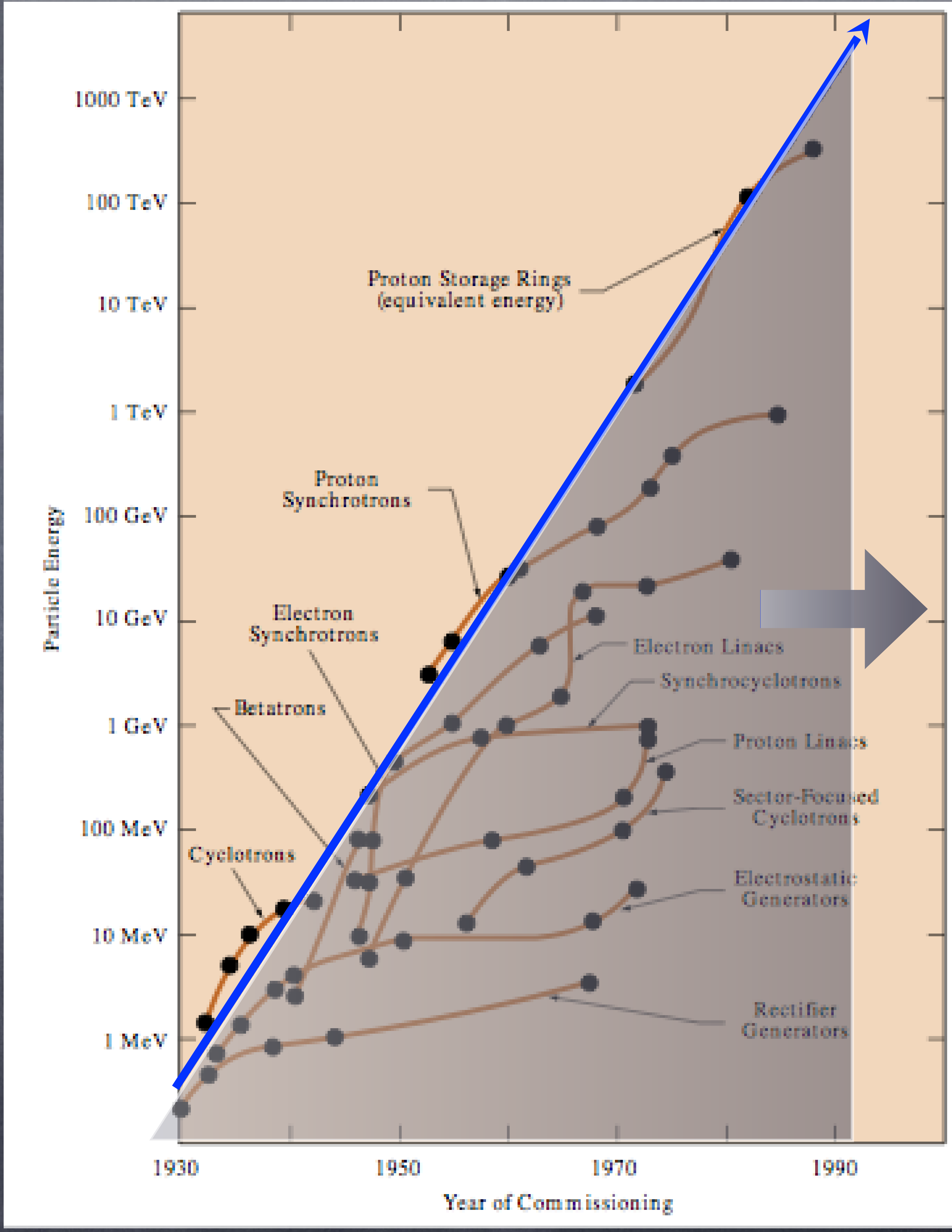
of the plot is the approximately linear slope of this envelope, which means that energy has in fact increased exponentially with time. The rate of rise is such that the energy has increased by a factor of 10 every six years, from a start at 100 kv in 1929 to 3 billion volts in 1952.

It is interesting to extrapolate this curve into the future, to predict the energy of accelerators after another six years. We have reason to hope that either the Brookhaven or the CERN A-G proton synchrotrons will have reached 25 Bev by that



Livingston Plot

- Evolution of (human-controlled) Particle energies (per nucleon):
  - pre-electricity -- 10^3 m/s --> W = 5 meV
  - circa 1900 -- W = 100 keV
  - circa 2000 -- W = 10,000 GeV
  - circa 2100 -- W -- > 10^{12} GeV ?
  - 2200 -- E_{Planck} ?? (10^{19} GeV)
- need BREAKTHROUGH!



What are the Next Steps?

Example: Lawrence Berkeley Lab —
Laser Wakefield Acceleration

RESEARCH NEWS
BERKELEY LAB

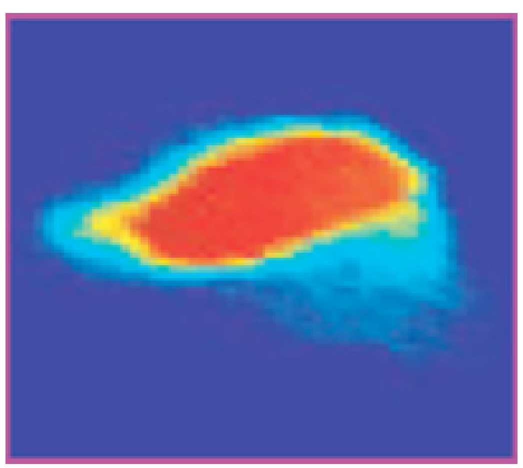
lab a-z index | phone book
search: go

September 25, 2006 news releases | receive our news releases by email | science@berkeley lab

From Zero to a Billion Electron Volts in 3.3 Centimeters
Highest Energies Yet From Laser Wakefield Acceleration

Contact: Paul Preuss, (510) 486-6249, paul_preuss@lbl.gov

BERKELEY, CA — In a precedent-shattering demonstration of the potential of laser-wakefield acceleration, scientists at the Department of Energy's Lawrence Berkeley National Laboratory, working with colleagues at the University of Oxford, have accelerated electron beams to energies exceeding a billion electron volts (1 GeV) in a distance of just 3.3 centimeters. The researchers report their results in the October issue of *Nature Physics*.

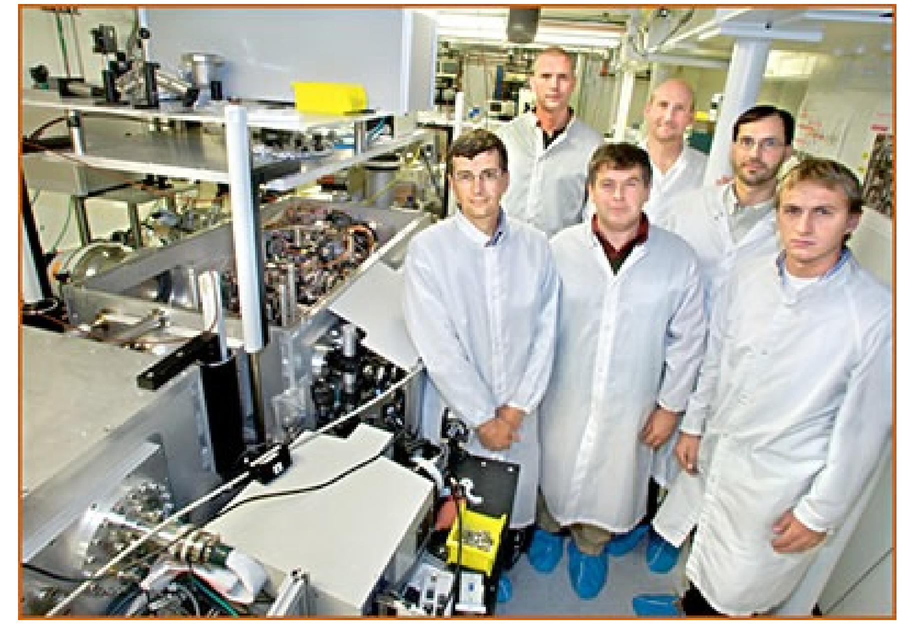


Billion-electron-volt, high-quality electron beams have been produced with laser wakefield acceleration in recent experiments by Berkeley Lab's LOASIS group, in collaboration with scientists from Oxford University.

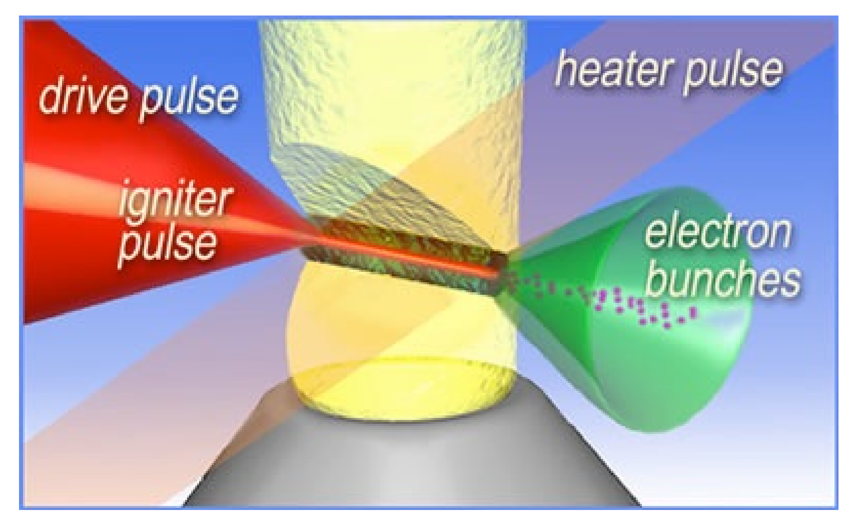
By comparison, SLAC, the Stanford Linear Accelerator Center, boosts electrons to 50 GeV over a distance of two miles (3.2 kilometers) with radiofrequency cavities whose accelerating electric fields are limited to about 20 million volts per meter.

The electric field of a plasma wave driven by a laser pulse can reach 100 *billion* volts per meter, however, which has made it possible for the Berkeley Lab group and their Oxford collaborators to achieve a 50th of SLAC's beam energy in just one-100,000th of SLAC's length.

This is only the first step, says Wim Leemans of Berkeley Lab's Accelerator and Fusion Research Division (AFRD). "Billion-electron-volt beams from laser-wakefield accelerators open the way to very compact high-energy experiments and superbright free-electron lasers."



- 30 GeV/m, compared to 30 MeV/m in present SRF cavity designs
- ... and, small momentum spread (2-5%) as well



Future High Energy Facilities

- Groups around the world are looking into the next steps toward even larger accelerators for fundamental physics research
- Next-generation Hadron collider
- Next-generation Lepton collider

view from France into Switzerland, showing existing LHC complex (orange) and a possible 100 TeV collider ring (yellow)
photo courtesy J. Wenninger (CERN)

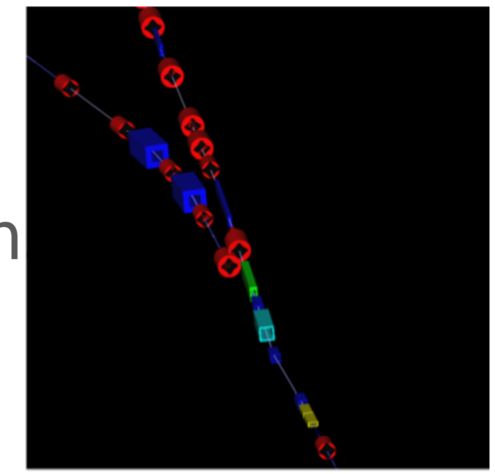
Higher Energy is not the Only Game in Town

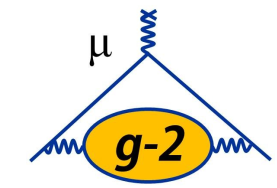
- Many processes to be studied or utilized are not necessarily at the highest energies, but rather are rare events thus requiring high beam intensity/current/power on target
- Many modern large-scale accelerators are moving toward ***intense beams*** rather than just pushing the energy frontier
  - LHC: 7 TeV x 3×10^{14} = 340 MJ stored energy
    - but power in the collisions is “only” ~1.3 kW
  - SNS: 1 GeV proton beam @ 1 mA beam current = 1 MW
  - FRIB: 200 MeV/u uranium beam @ 0.65 mA beam current, but 238 u and Q=78/particle --> 0.40 MW

Beams & Rings for Precision Measurements

- Magnetic Dipole Moment of Muon E989 (Fermilab)
  - creation of highly-polarized high-purity muon beam
  - inject into precision storage ring, monitor precession of spin direction (as muons decay)
  - past MDM measurement, theory disagree at ~3σ sigma level

3-D design of 3.1 GeV muon beam transport system

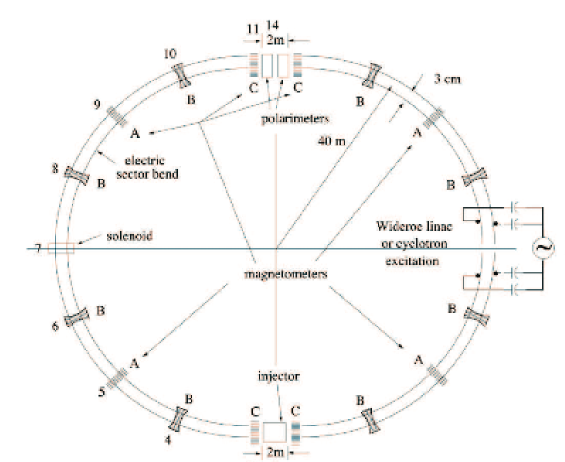




Ring arrives at Fermilab from NY

“g-2” storage ring as assembled at Brookhaven National Lab (NY)

- Electric Dipole Moments
  - investigating designs of all-electric storage rings for storing elementary particles or ions for detection of weak EDM signals (non-zero value would imply new physics)



Wait, There's More!

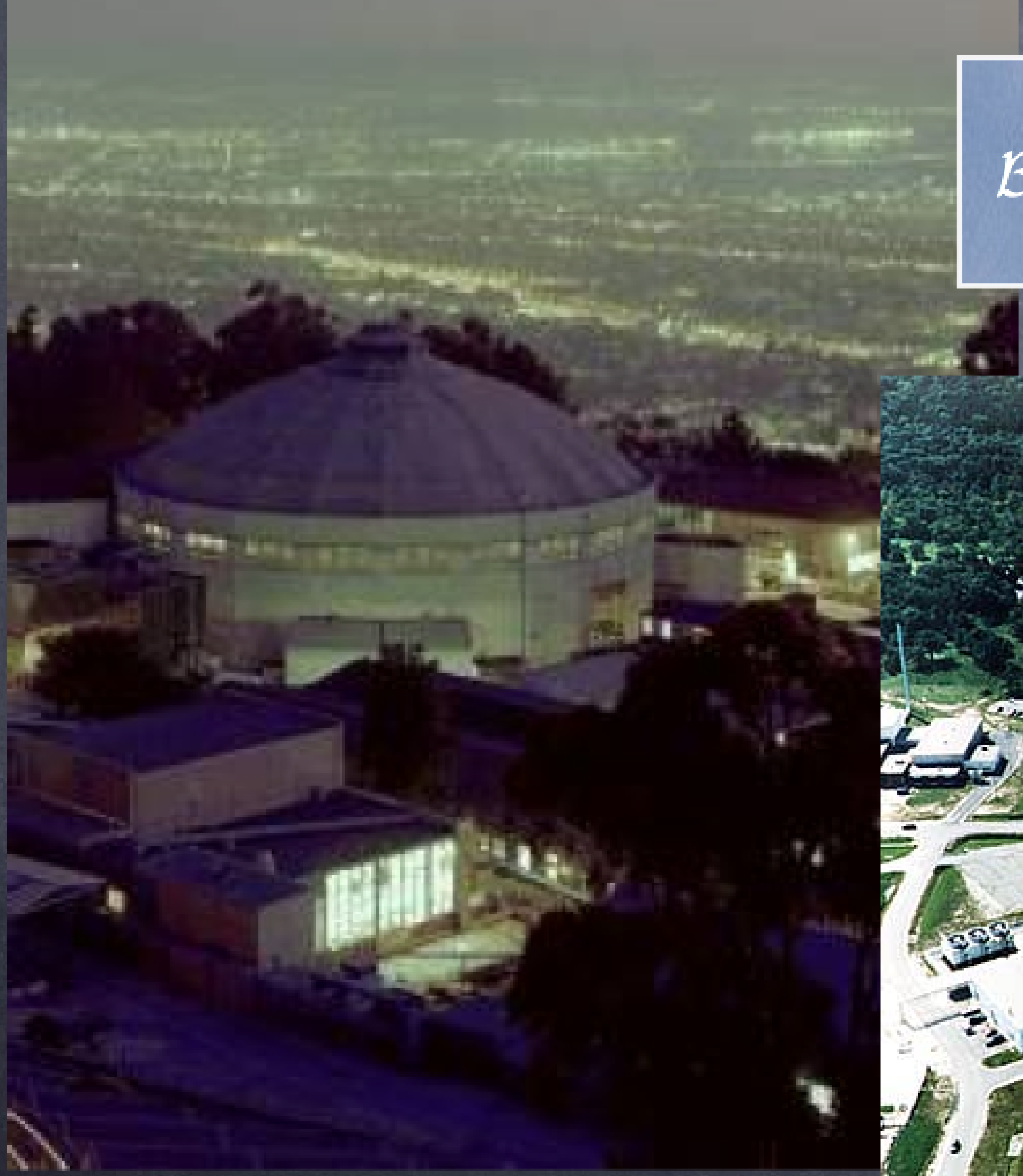
- And, of course, not all applications are in high energy or nuclear physics!
- Basic energy sciences as well as industrial applications make up the bulk of our field, in terms of number of accelerators and arguably their direct impact on society
  - ~26,000 accelerators worldwide*
  - ~1% are research machines with energies above 1 GeV; of the rest, about 44% are for radiotherapy, 41% for ion implantation, 9% for industrial processing and research, and 4% for biomedical and other low-energy research*

*Feder, T. (2010). "Accelerator school travels university circuit". *Physics Today* **63** (2): 20. Bibcode 2010PhT....63b..20F. doi:10.1063/1.3326981

Light Sources

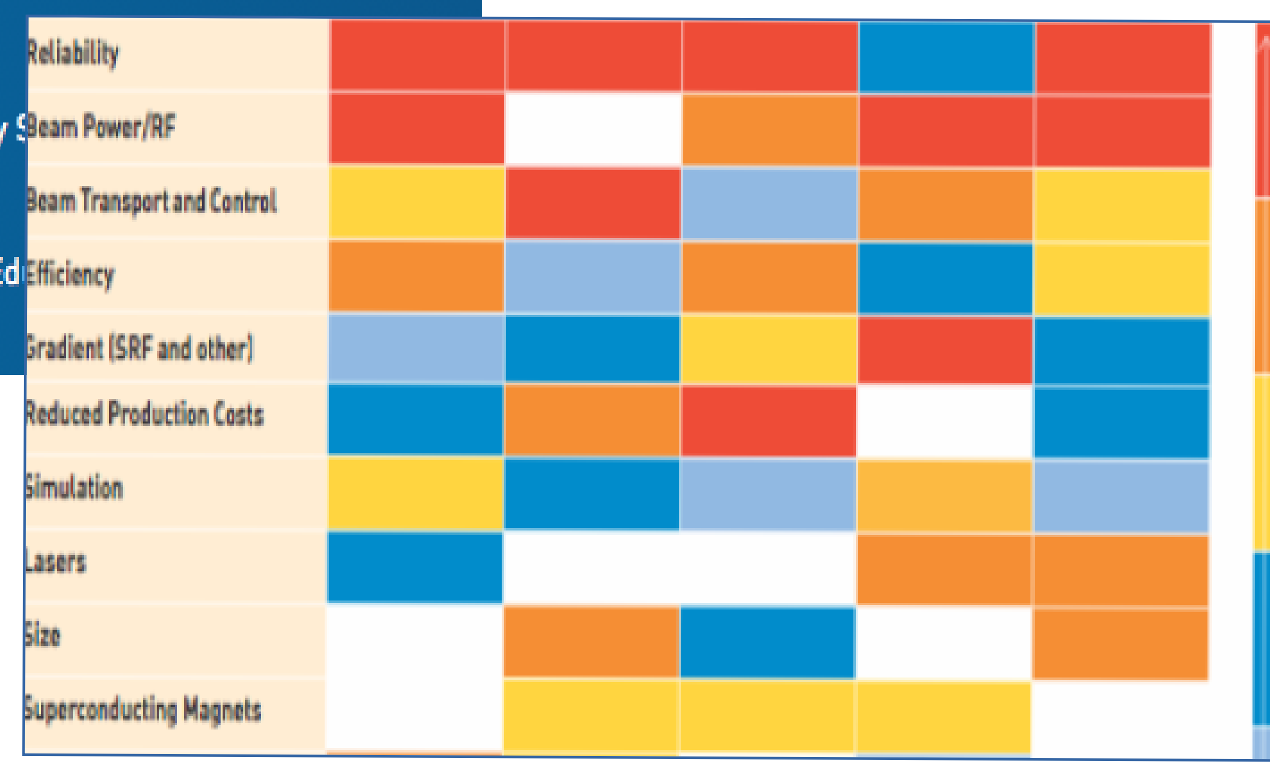
"Brilliance" is the figure of merit
Very similar to luminosity:

$$\mathcal{B} = \frac{\text{photons/sec}}{\text{mm}^2\text{mrad}^2(0.1\%\ \text{BW})}$$



Accelerators for America’s Future

- Symposium and workshop held in Washington, D.C., October 2009
- 100-page Report available at web site



http://www.acceleratorsamerica.org/

Accelerators: Essential Tools in Industry

Ion Implantation

- Accelerators can precisely deposit ions modifying materials and electrical properties

Semi Conductors

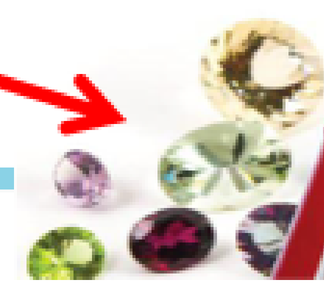
- CMOS transistor fabrication of essentially all IC's
- CCD & CMOS imagers for digital cameras
- Cleaving silicon for photovoltaic solar cells
- Typical IC may have 25 implant steps

Metals

- Harden cutting tools
- Reducing friction
- Biomaterials for implants

Ceramics and Glasses

- Harden surfaces
- Modify optics
- Color in Gem stones!



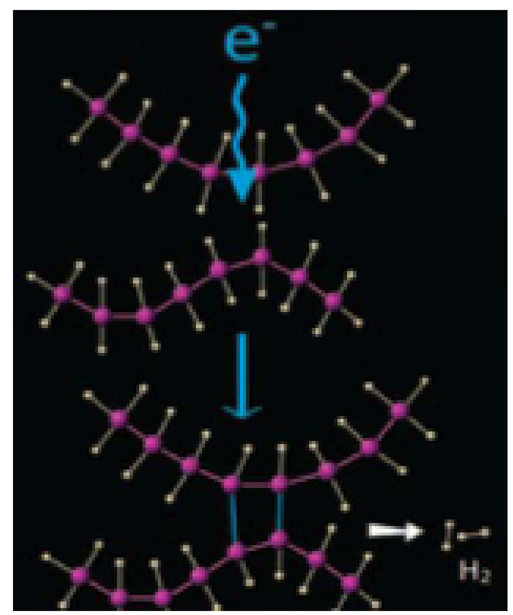
Fermilab

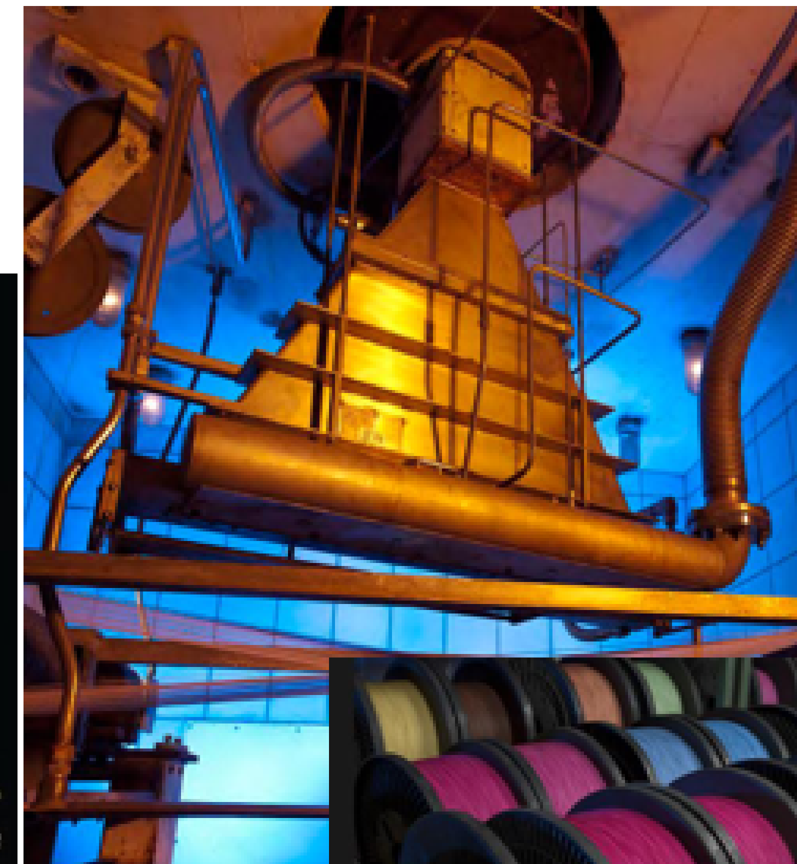
(courtesy R. Kephart)

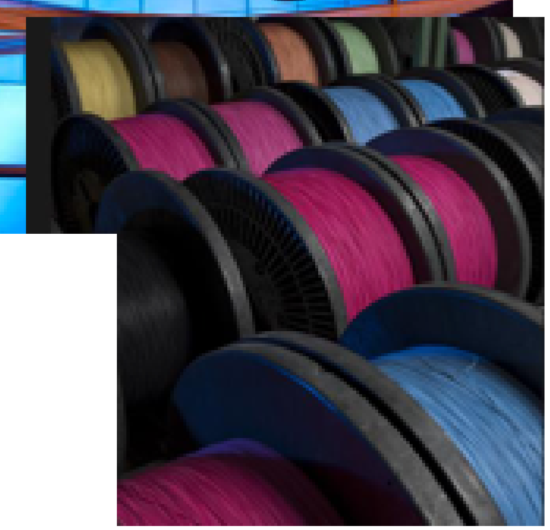
Accelerators: Essential Tools in Industry

A wide-range of industrial applications makes use of low-energy beams of electrons to drive chemistry

- 0.1-10 MeV up to MW beam power electrostatic, linac, betatron accelerators







Electron Beam Irradiation

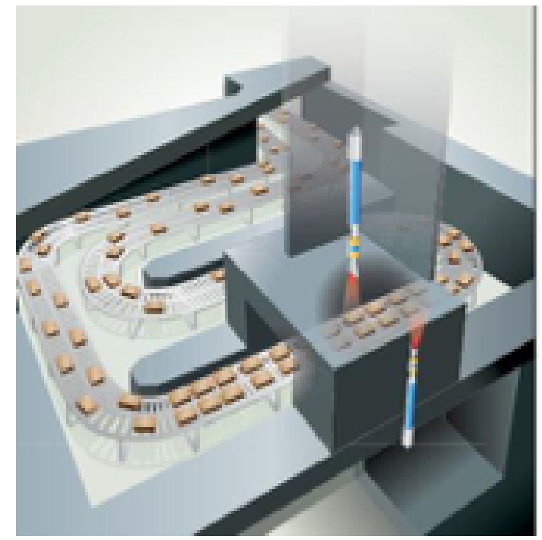
Improved heat resistance of coatings, wire and cable, crosslinking polymers, radial tires, etc)

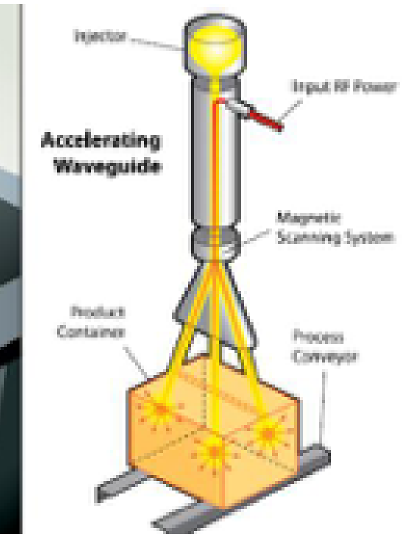
1500 dedicated facilities worldwide

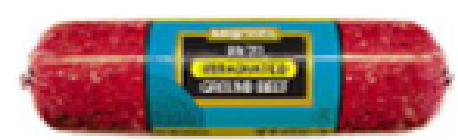
Accelerators: Food Preservation

Low-energy beams of electrons can help beat food-borne Illness

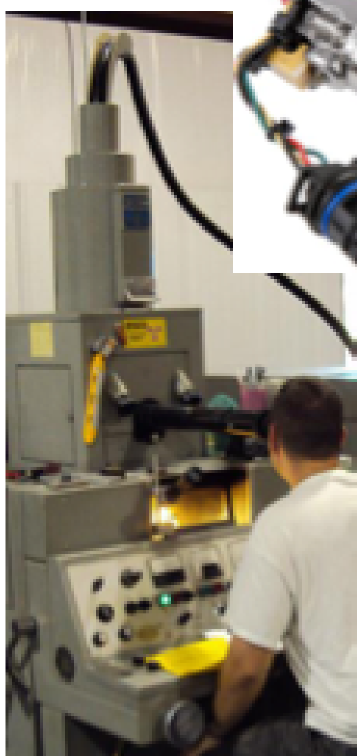
- ~6000 people/week are sickened, and ~100/week die from food-borne illness in the U.S.
- Food poisoning is estimated to cost the US $152 billion a year.
- Electron beams and/or X-rays can kill bacteria like E. coli, Salmonella, and Listeria.
- Currently in use for: Spices, fruit, lettuce, ground beef, milk, juice, military rations…
- Many more opportunities exist
- Barriers = cost & public acceptance



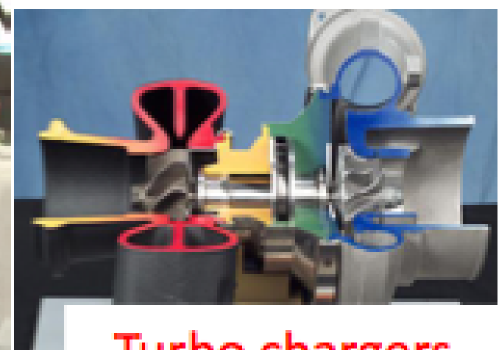




Accelerators for Industrial Processes



Fuel injectors

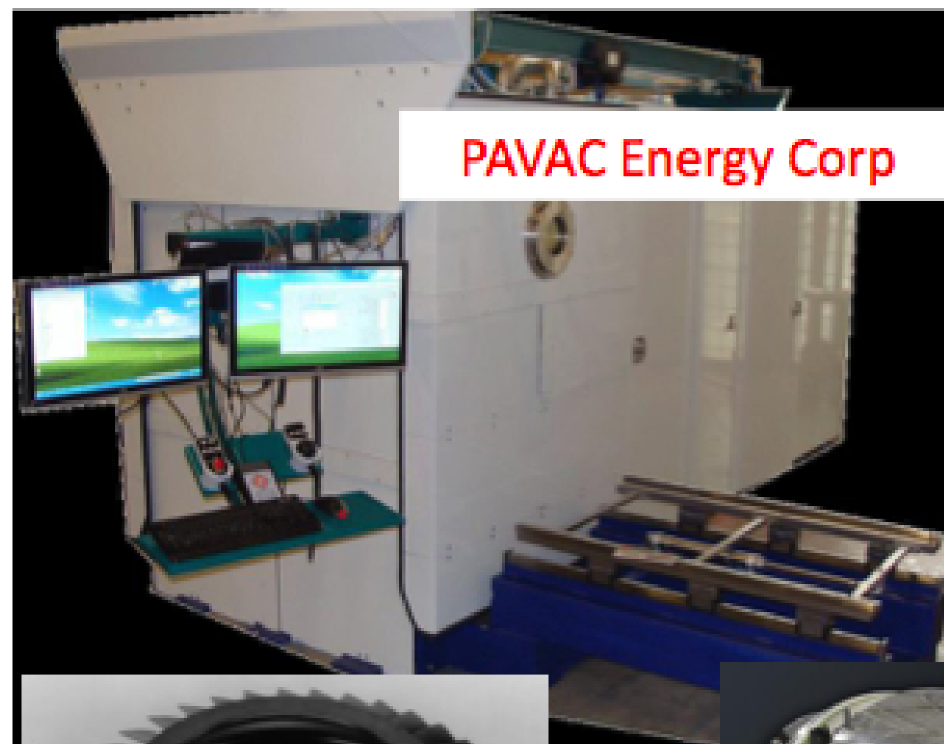


Turbo chargers

Weld gear boxes
Harden gears

Electron Beam Welding and Machining

- Deep welds, low weld shrinkage
- Dissimilar or refractory metals, etc
- Widely used in automotive and aerospace industry
- Drill 3000 holes/sec!

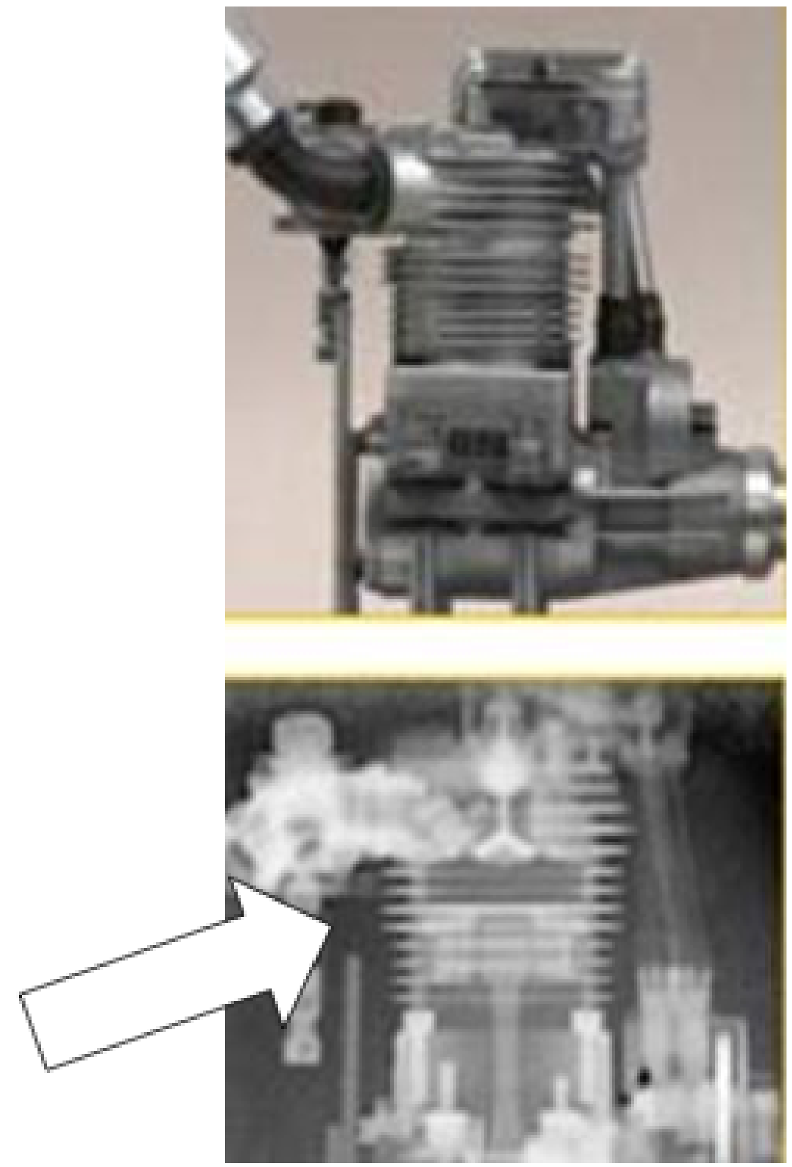


Jet engines & Gas turbines

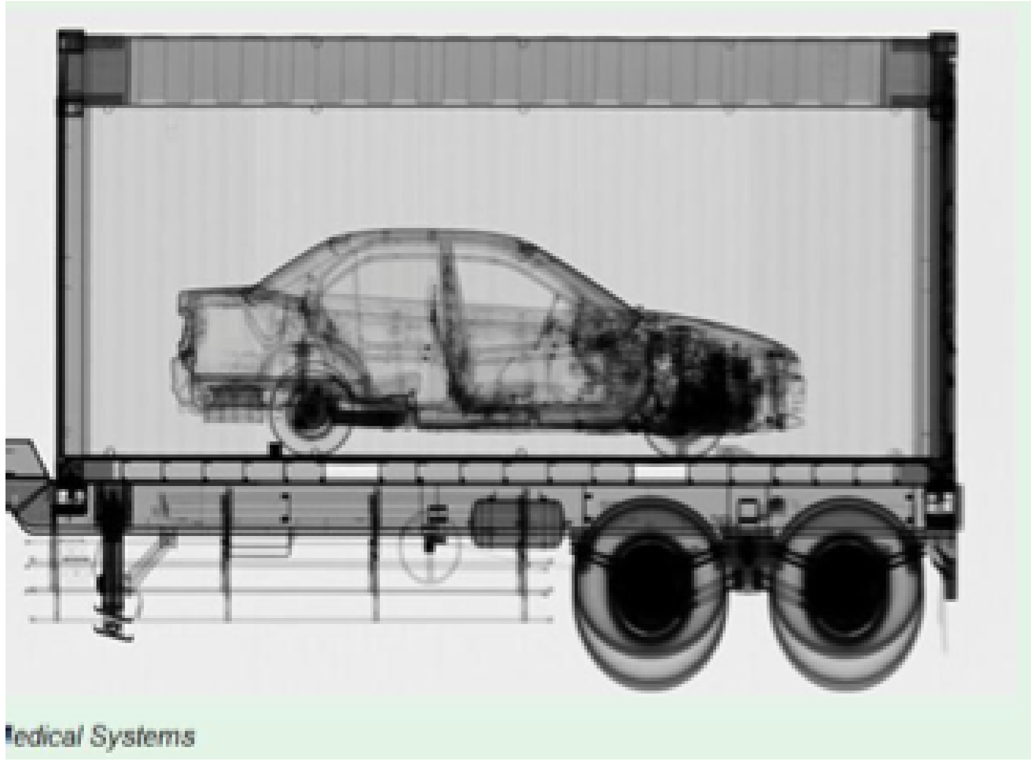
Accelerators for Defense

Dual Axis Radiographic Hydrodynamic Test Facility, Stockpile stewardship Los Alamos Nat. Lab

- Stockpile stewardship
- Materials characterization
- Proton Radiography LANL: Imaging materials in motion using x-ray and particle beams (remarkable capability!)



Accelerators for National Security



- More than two billion tons of cargo pass through U.S. ports and waterways annually.
- Accelerators are used for cargo scanning and “active interrogation” to detect special materials

Fermilab

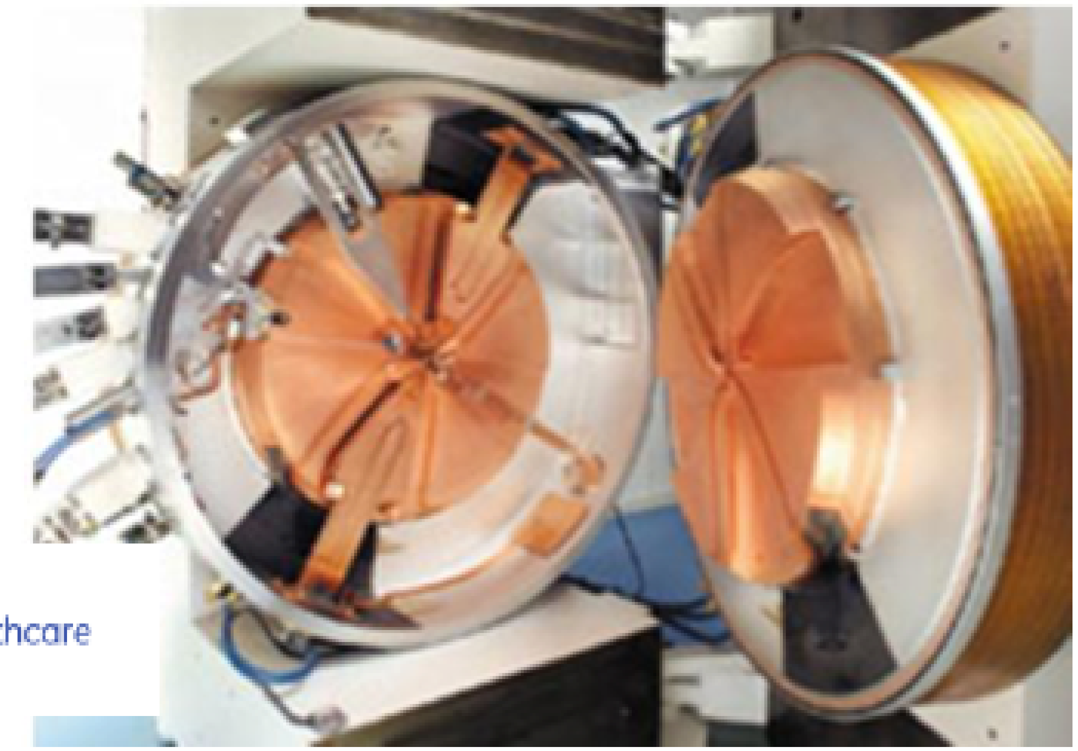
Accelerators in Medicine

Electron accelerator
Based X-Ray facility
For cancer treatment
(Varian Medical systems)

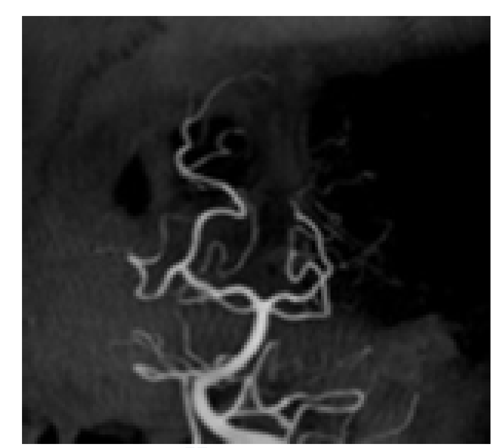
Rhodotron, commercial
electron beam accelerator used
For sterilization of medical devices

Accelerators for the Medical Isotopes

GE Healthcare



- "Turn key" cyclotrons produced by industry are routinely used to produce short lived radio-pharmacy isotopes for molecular imaging (^{18}F, $^{11}CO_2$ $^{11}CH4$, ^{13}N, ^{15}O, etc)
- PET =Positron Emission Tomography



Accelerators in Medicine
Proton Cancer Therapy

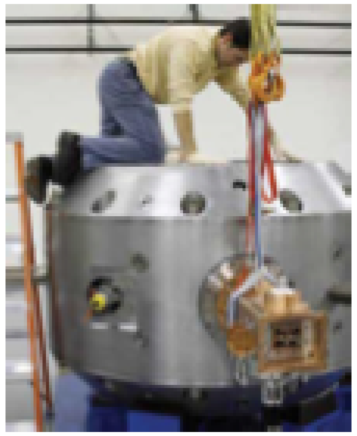
Loma Linda Proton Therapy and Treatment Center

World's 1st proton accelerator built specifically for proton therapy

Designed and built at Fermilab

Technology Demonstration → Industry

New compact SC magnets (another HEP technology!) → smaller size/ costs →



US Particle Accelerator School

- Held twice yearly at venues across the country; offers graduate credit at major universities for courses in accelerator physics and technology

http://uspas.fnal.gov

University-style programs

A complete history of U.S. Particle Accelerator School university credit programs.

Date	Sponsoring University	Courses
June 17-28, 2019	University of New Mexico	Curriculum
January 21-February 1, 2019	Northern Illinois University (held in Knoxville, TN)	Curriculum
June 4-15, 2018	Michigan State University	Curriculum
January 15-26, 2018	Old Dominion University	Curriculum
June 12-23, 2017	Northern Illinois University	Curriculum
January 16-27, 2017	University of California, Davis	Curriculum
June 13-24, 2016	Colorado State University	Curriculum
January 25-February 5, 2016	University of Texas at Austin	Curriculum
June 15-26, 2015	Rutgers University	Curriculum
January 19-30, 2015	Old Dominion University	Curriculum
June 16-27, 2014	University of New Mexico	Curriculum
January 20-31, 2014	University of Tennessee, Knoxville	Curriculum
June 10-21, 2013	Colorado State University	Curriculum
January 14-25, 2013	Duke University	Curriculum
June 18-29, 2012	Michigan State University	Curriculum
January 16-27, 2012	University of Texas at Austin	Curriculum
June 13-24, 2011	Stony Brook University	Curriculum
January 17-28, 2011	Old Dominion University	Curriculum
June 14-25, 2010	Massachusetts Institute of Technology	Curriculum
January 18-29, 2010	University of California, Santa Cruz	Curriculum

The US Particle Accelerator School (USPAS) trains specialist in Accelerator Science and Technology

- **USPAS is recognized as world leading**
  - Formed out of necessity
  - Present format since 1987 (61 Sessions, 621 Courses and counting …)
- **Holds two, two-week intensive school sessions per year:**

  Winter (January)   **Summer** (June)
- **Sessions move around country linked to hosting universities that provide graduate credit**



Most USA specialists in Accelerator Science and Engineering pass through USPAS several times and MSU can send you while in our ASET program

- **Topics covered from basic to advanced specialized courses that cannot be regularly taught at Universities**

Superconducting Magnets	Project Management
RF Cavities	Ion Sources
Software Controls	Cryogenic Engineering
Space-Charge Effects	…. and so much more …

- **A "critical mass" of selected and highly motivated students gather to learn**

Accelerator Field is broad … should be something to fit for most everyone

Particle Accelerators are tools of discovery science and industry with wide ranging and profound impact

High Energy Physics   Materials Science   Medical
Nuclear Physics   Industrial   Military   ….

Accelerator Science & Technology is very broad

Physics   Engineering   Technology   Materials Science
Physics to Design Engineering,   Conceptual to Precise,   Experiment to Modeling to Theory

and many recognized career opportunities exist

Government Labs   Universities   Industry   Medical   ….

that are central to our modern technological society.

We hope this course will provide a solid and systematic introduction to our field.