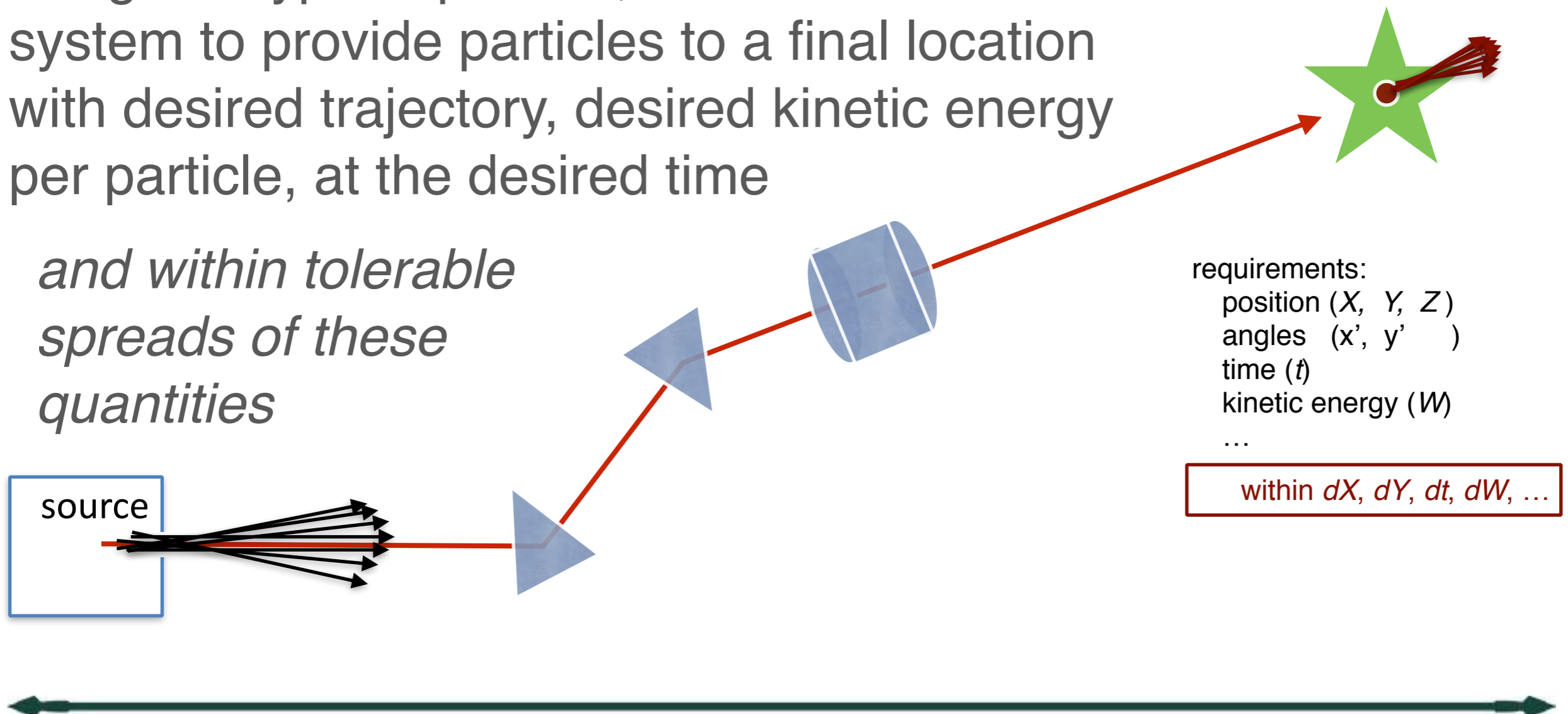# The Problem

- 1927: Lord Rutherford requested a "copious supply" of projectiles "more energetic than natural alpha and beta particles"

- For given type of particle, create an ideal system to provide particles to a final location with desired trajectory, desired kinetic energy per particle, at the desired time

and within tolerable spreads of these quantities

source

requirements:
  position ($X,\ Y,\ Z$)
  angles ($x',\ y'$)
  time (t)
  kinetic energy (W)
  …

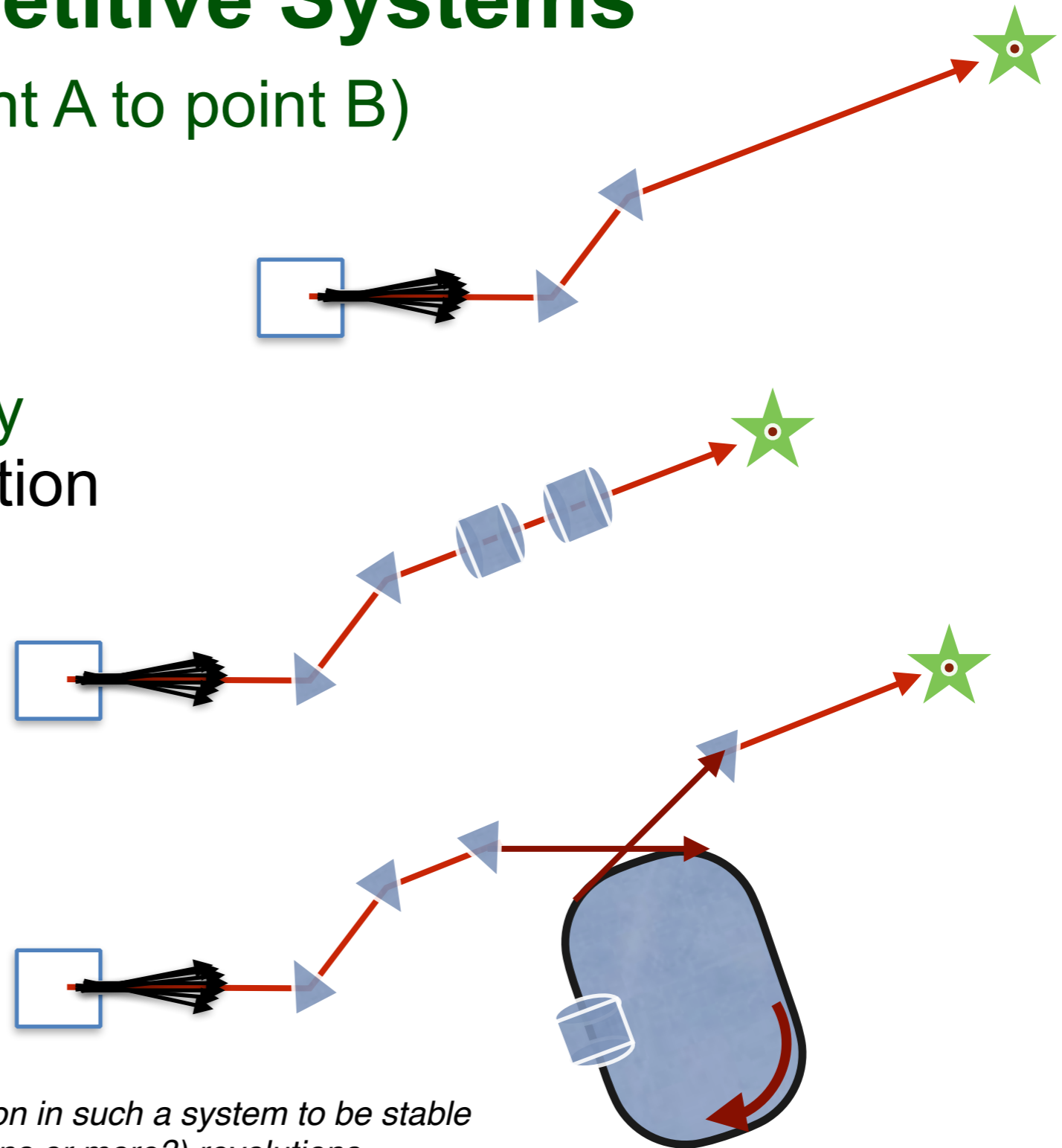within dX, dY, dt, dW, …

Single-Pass vs. Repetitive Systems

- Beam Transport (from point A to point B)

- Acceleration along the way
  - single-pass with acceleration

  - multi-pass acceleration

*may need motion in such a system to be stable
for many (millions or more?) revolutions*

A Few Words on Particle Sources…

- Electrons — relatively easy
  - ‣ filaments; photocathodes, laser driven plasmas,…
- Protons — not "too" hard
  - ‣ ionized hydrogen gas, plasma sources,…
- Ions — similar techniques
  - ‣ ovens, plasma sources, ECRs — plus, separation
- Even more exotic particles: target, separate, collect
  - ‣ heavy ion isotopes
 - ‣ pions, muons, antiprotons, neutrinos,…
- Also polarized sources, …

A Little Accelerator History

- ## DC Acceleration

1927: Lord Rutherford requested a "copious supply" of projectiles more energetic than natural alpha and beta particles. At the opening of t~~~~ resulting High Tension Labor~~~~ Rutherford went on to reitera~~~~

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

Van de Graaff

(1929)

Sharply pointed metal comb at top allows
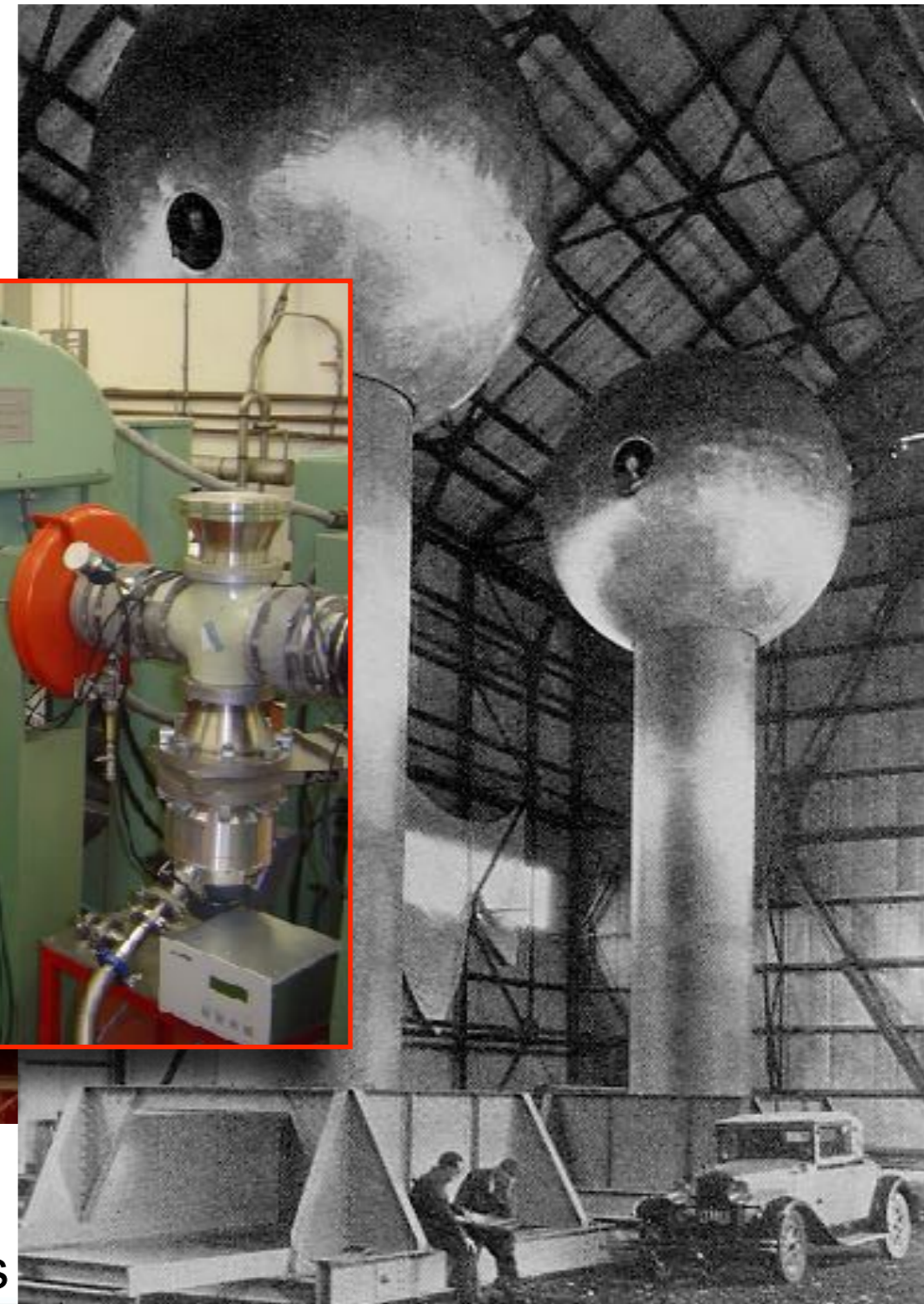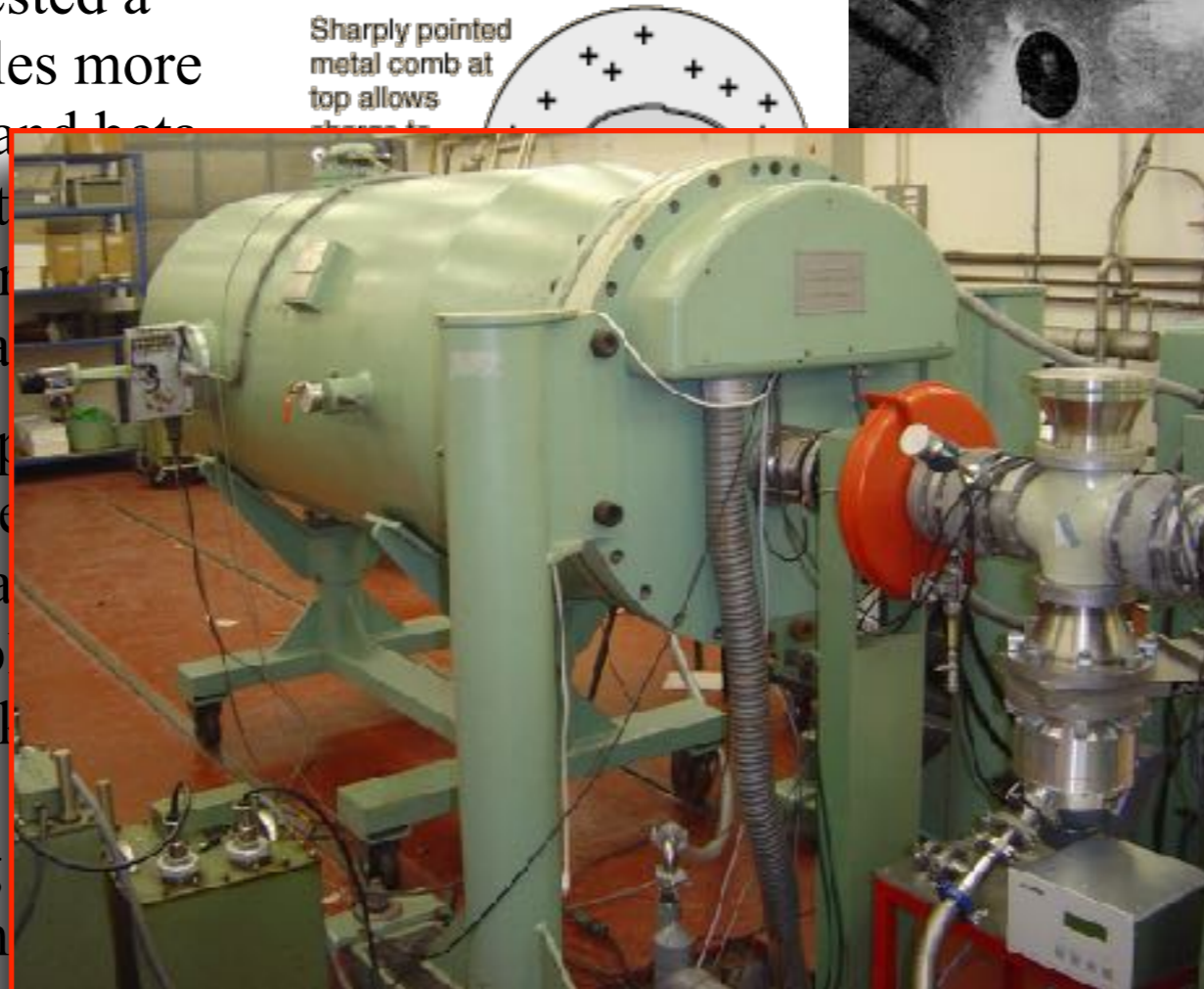
MIT, c.1940s

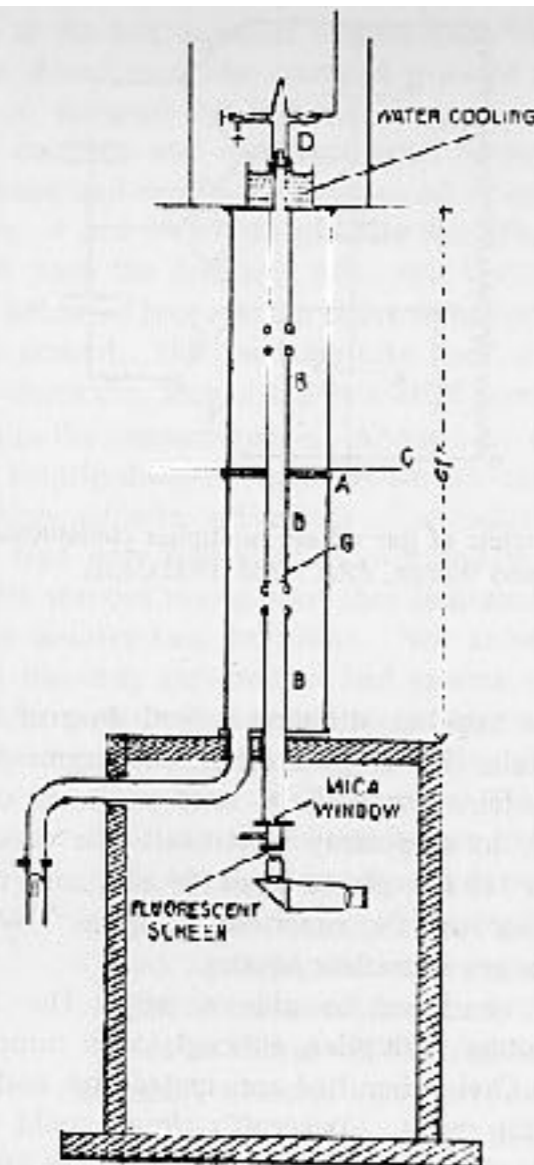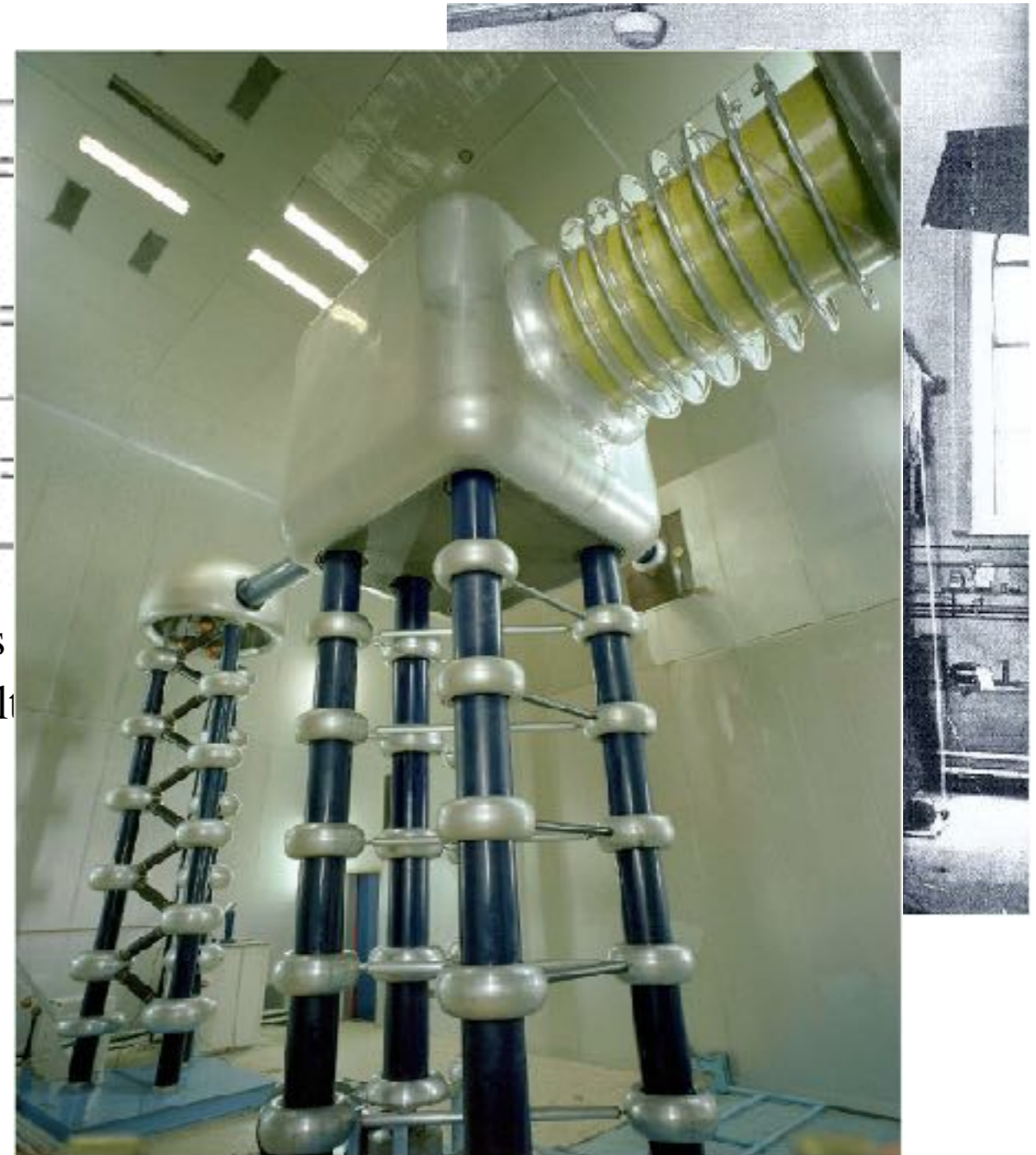# Cockcroft and Walton

- 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.
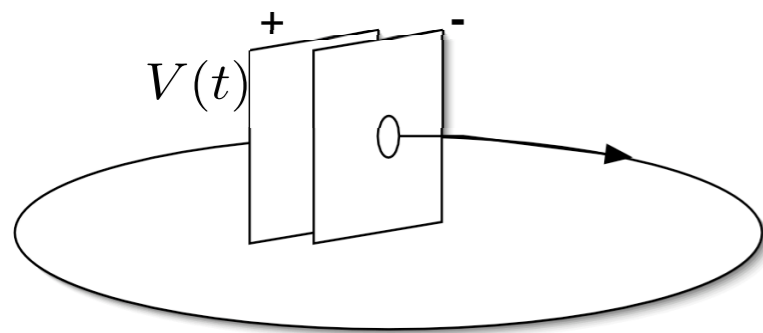
Converts
DC volt

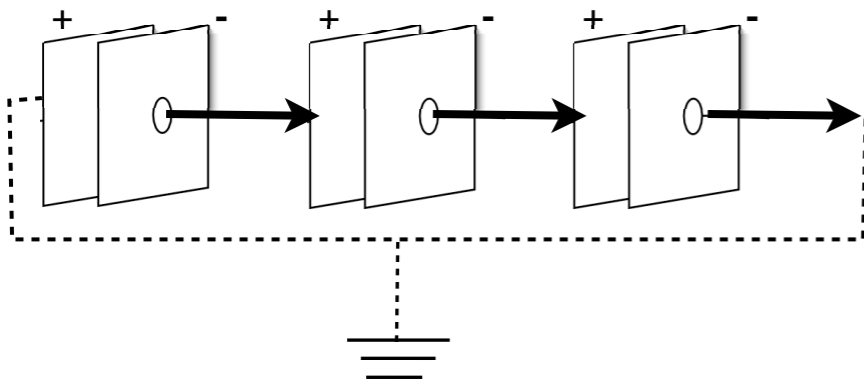
Fermilab (recently decommissioned)

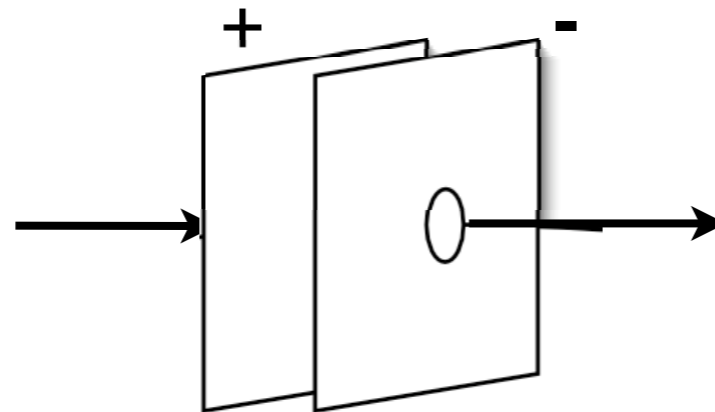# The Route to Higher Energies

■ The Need for
AC Systems…

Circular Accelerator

Linear Accelerator

$$\text{energy gain} = q \cdot V$$
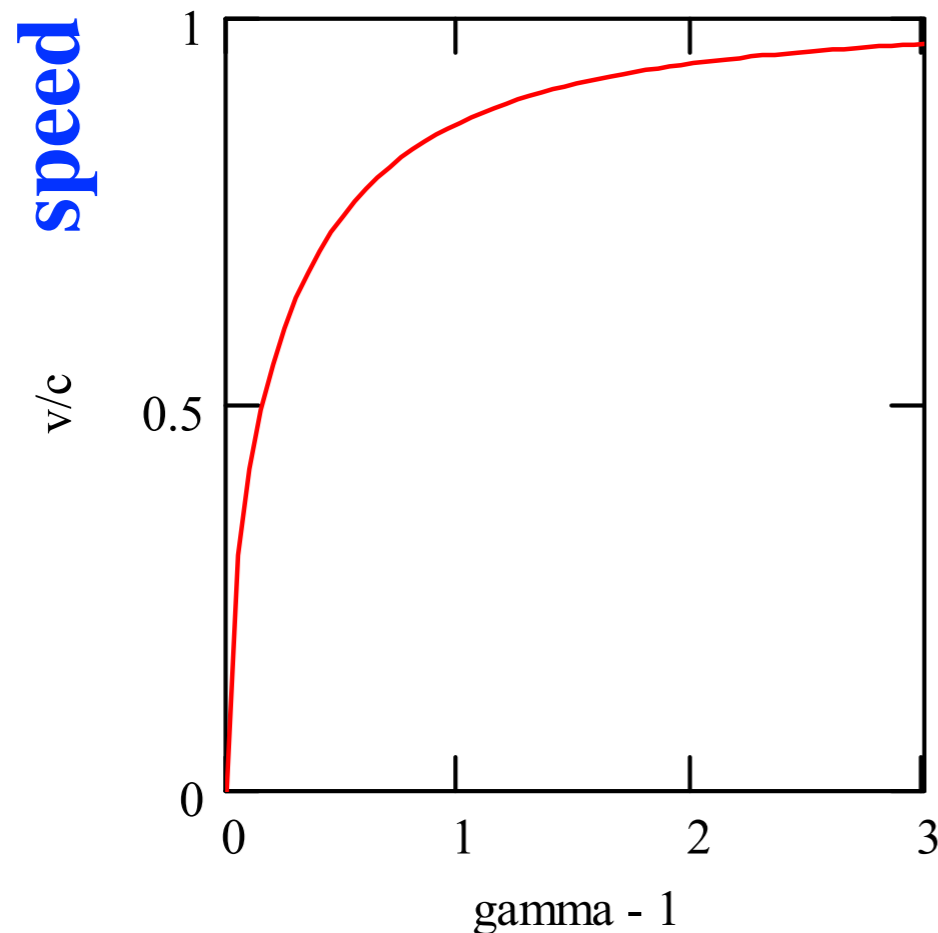
DC systems limited
to a few MV

$$\oint (q\vec{E}) \cdot d\vec{s} = work = \Delta(energy)$$
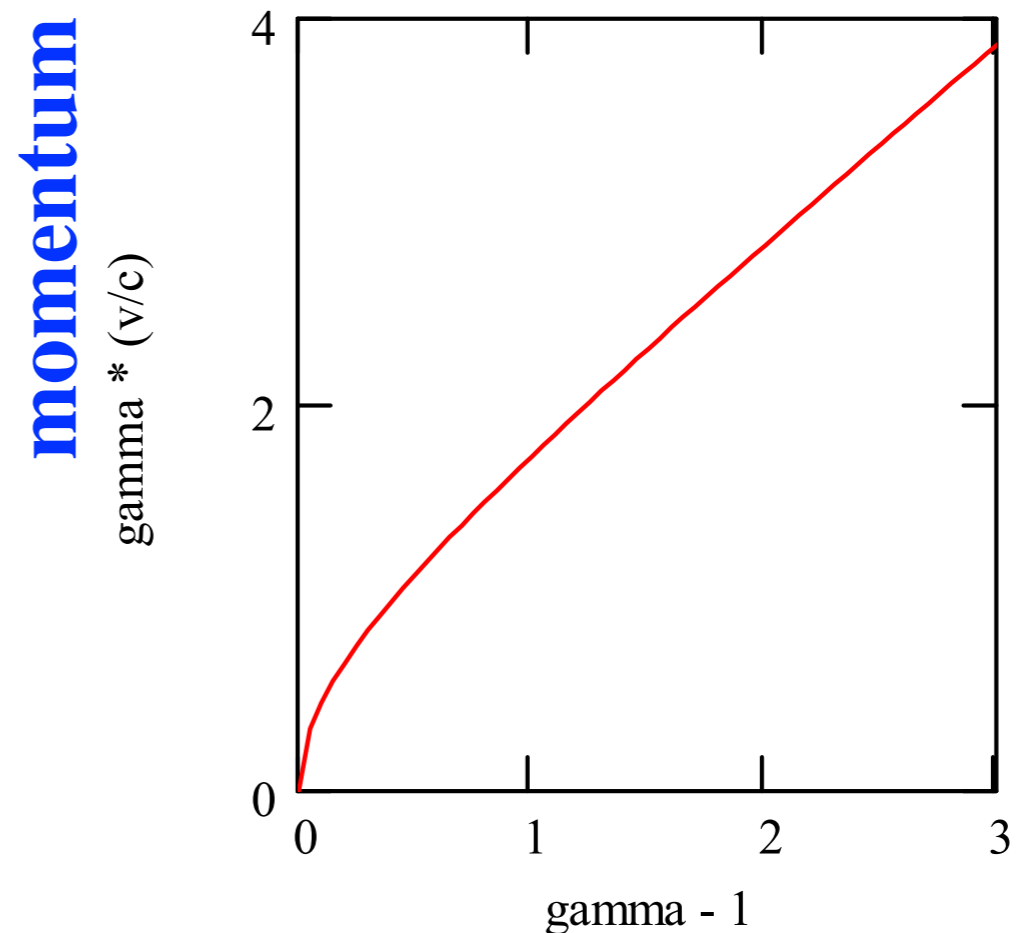
To gain energy, a time-varying field is required:

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

Speed, Momentum vs. Energy

speed (v/c) vs. **Kinetic energy** (gamma - 1)

momentum (gamma * (v/c)) vs. **Kinetic energy** (gamma - 1)

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
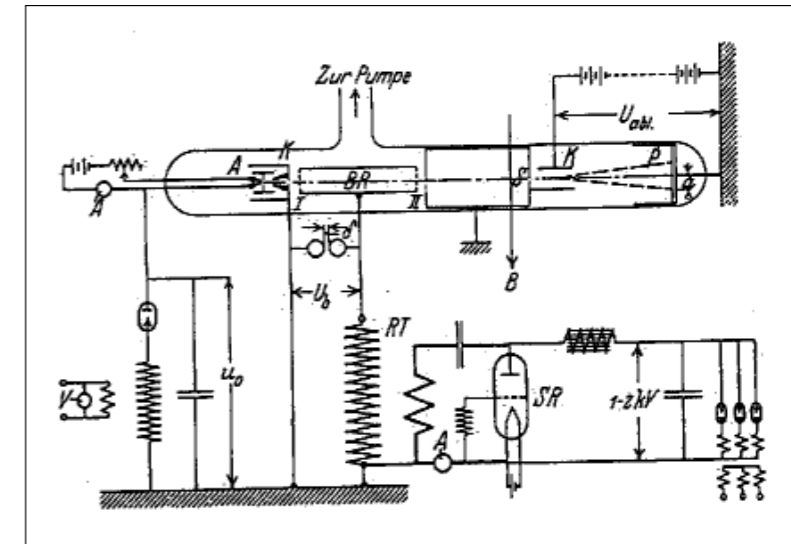
➡️The Cyclotron -- 1930's, Lawrence (U. California)
- read Wideroe's paper (actually, looked at the pictures!)
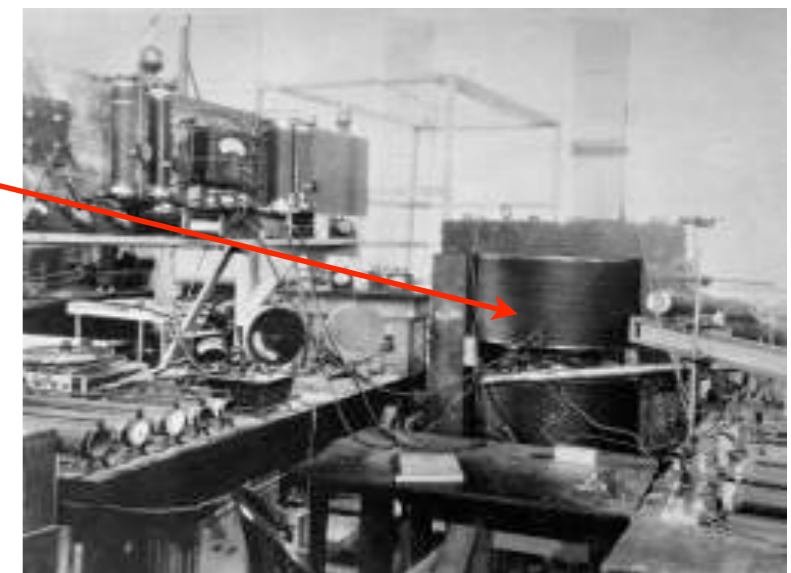- an extended "linac" unappealing -- make it more compact:

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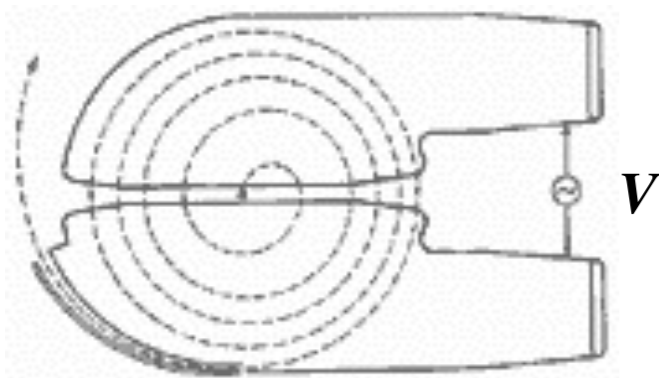
$$\frac{1}{T} = \frac{q \cdot B}{2\pi m}$$

4.5 inch diameter!

11 inch diameter

60-inch Cyclotron, Berkeley -- 1930's

184-inch Cyclotron, Berkeley -- 1940's

2005

Meeting up with Relativity
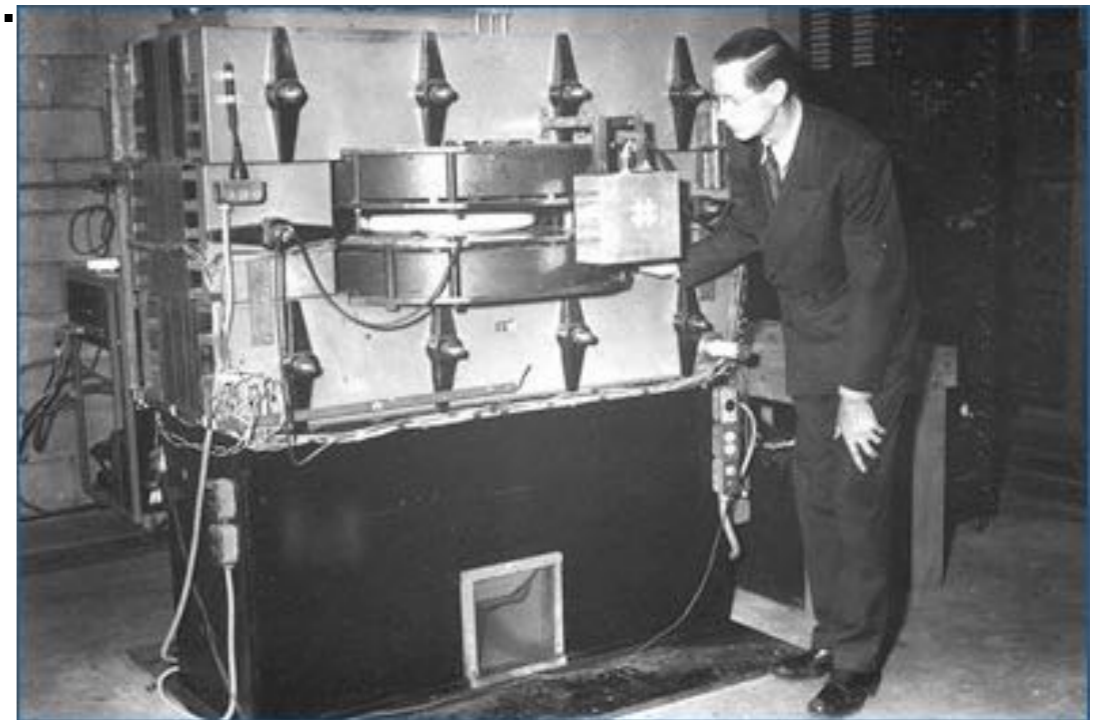
- ## The Synchrocyclotron (FM cyclotron) -- 1940's
    - ‣ beams became relativistic (esp. e⁻) --> oscillation frequency no longer independent of momentum; cyclotron condition no longer held throughout process; thus, modulate freq.

- ## 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
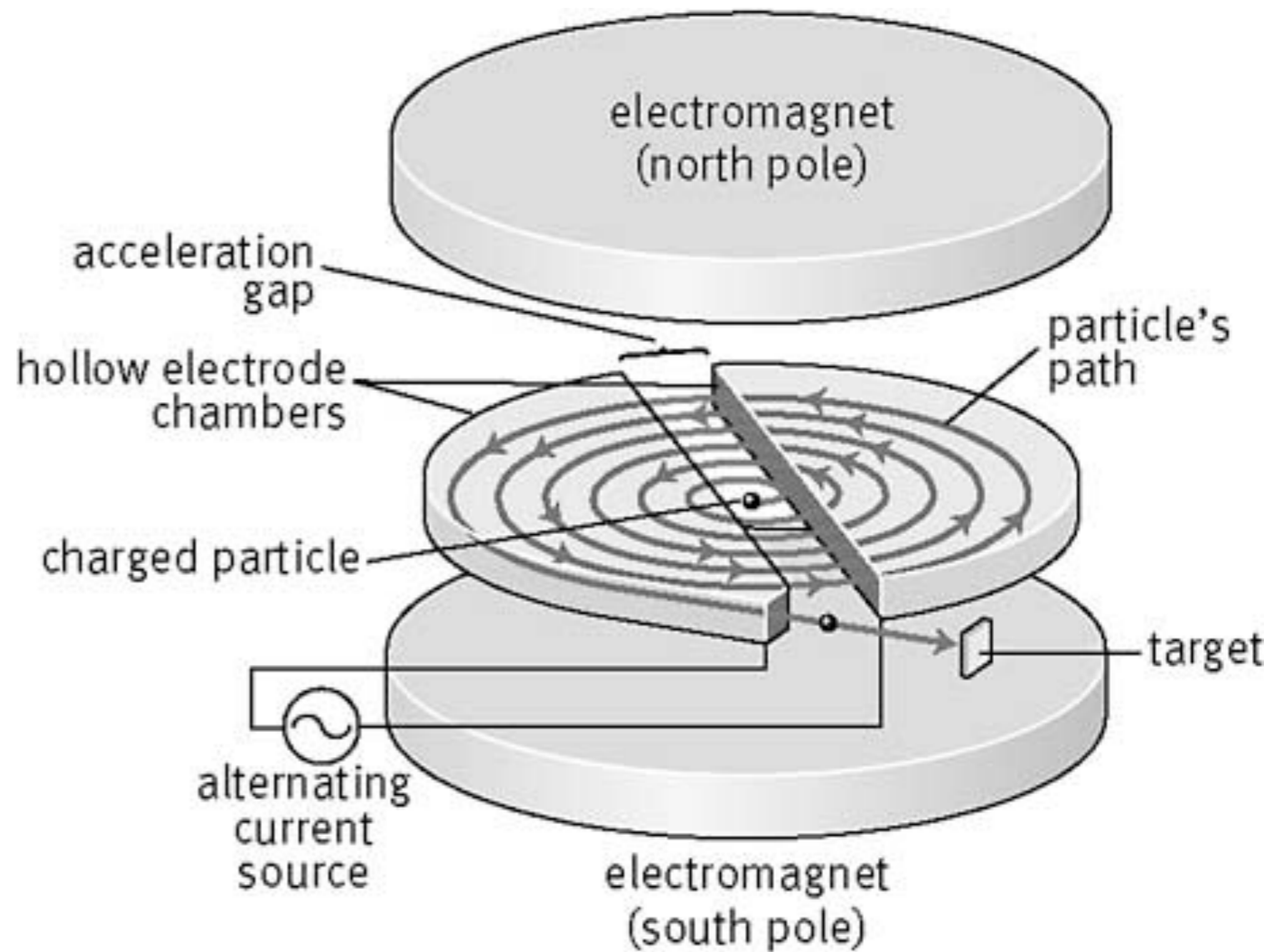   - » "betatron oscillations"

~ 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

Cyclotrons

- Relatively easy to operate and tune (only a few parts).

- Tend to be used for isotope production and places where reliable and reproducible operation are important

- Intensity is moderately high, acceleration efficiency is high, cost low

- Relativity is an issue, so energy is limited to a few hundred MeV/u.

- RIKEN Superconducting Ring Cyclotron 350 MeV/u


electromagnet (north pole)

acceleration gap

hollow electrode chambers

charged particle

particle's path

target

alternating current source

electromagnet (south pole)

Precision Graphics

http://images.yourdictionary.com/cyclotron

The "Modern" Linear Accelerator

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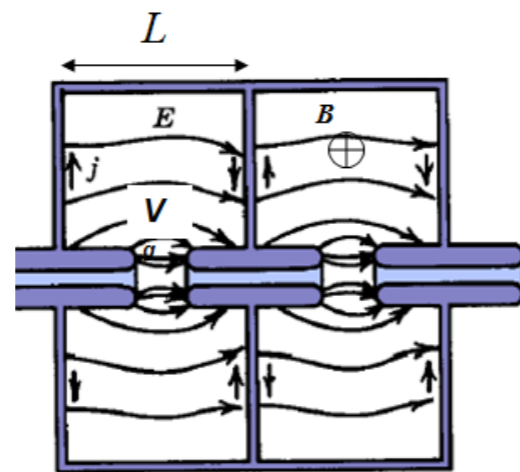   - GI surplus equip. from WWII Radar technology
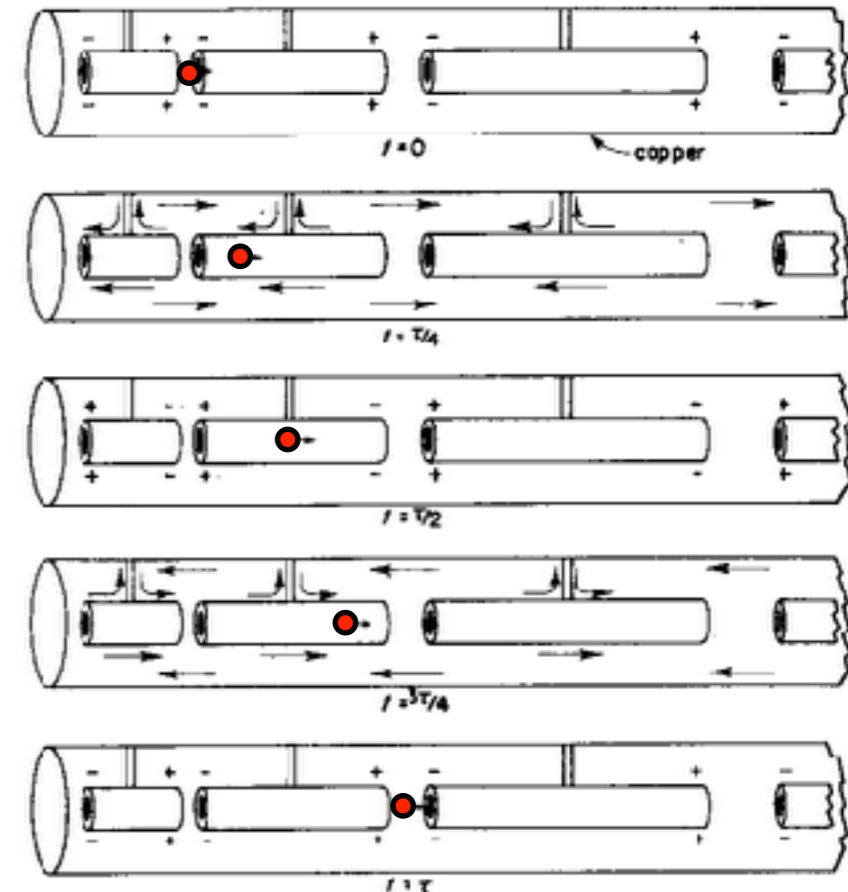
- **Traveling-Wave Electron Accelerator --**

    c.1950 (Stanford, + Europe)

    - TM_{01} waveguide arrangement

    - iris-loaded cylindrical waveguide
        - match phase velocity w/ particle velocity...
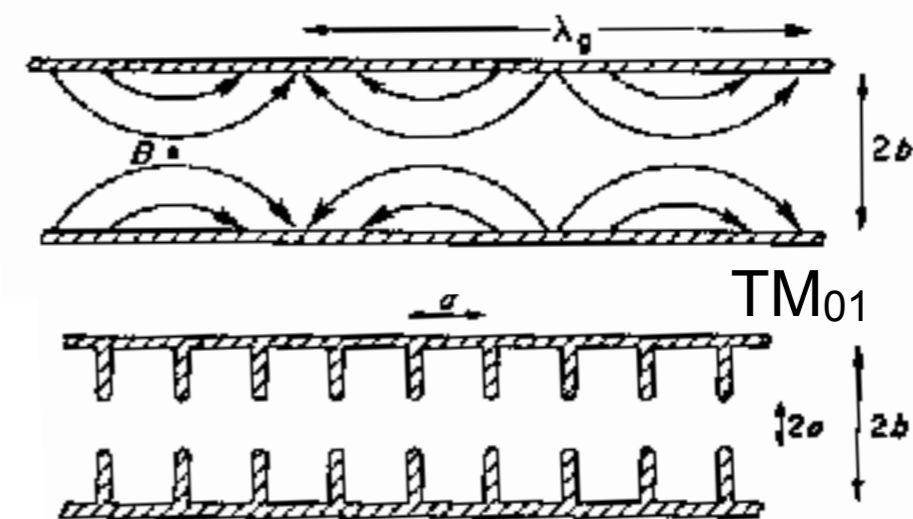
Radio-frequency Resonant Cavities

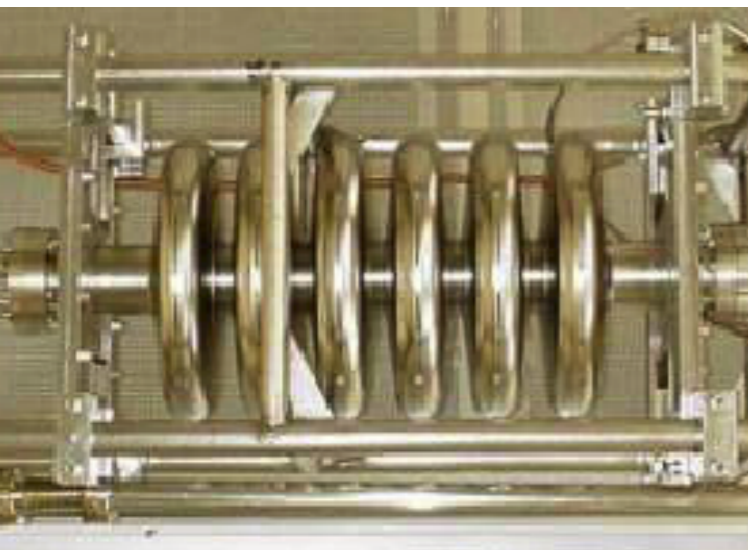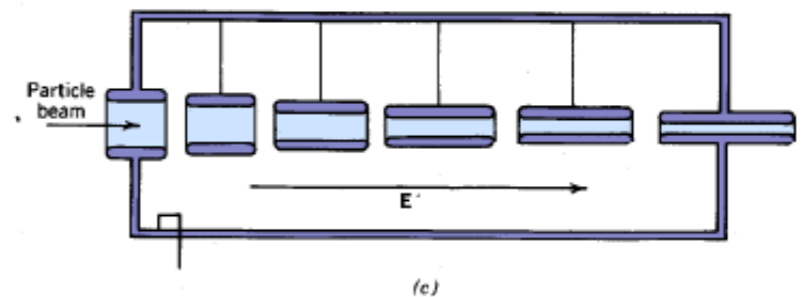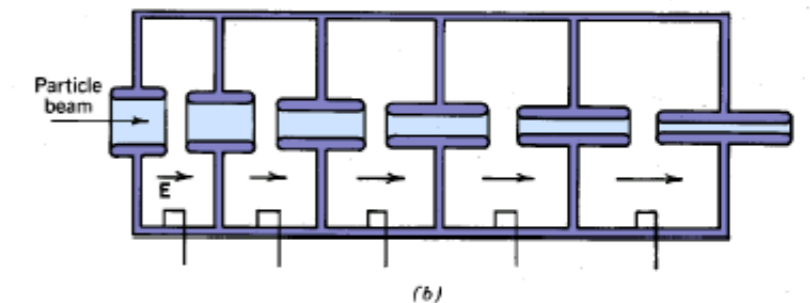$$\oint \vec{E} \cdot d\vec{r} = -\frac{d\Phi_B}{dt}$$
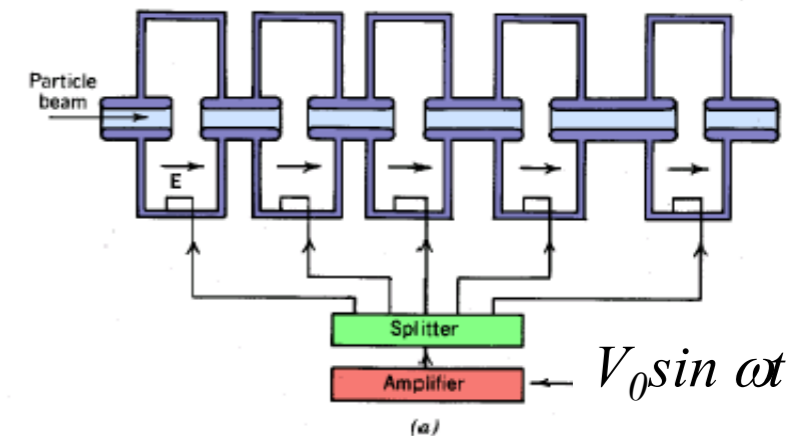
Time varying: we can use many cavities in series!

$V_0 \sin \omega t$

- *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	$Q = \omega U/P = \Gamma/R_s$

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
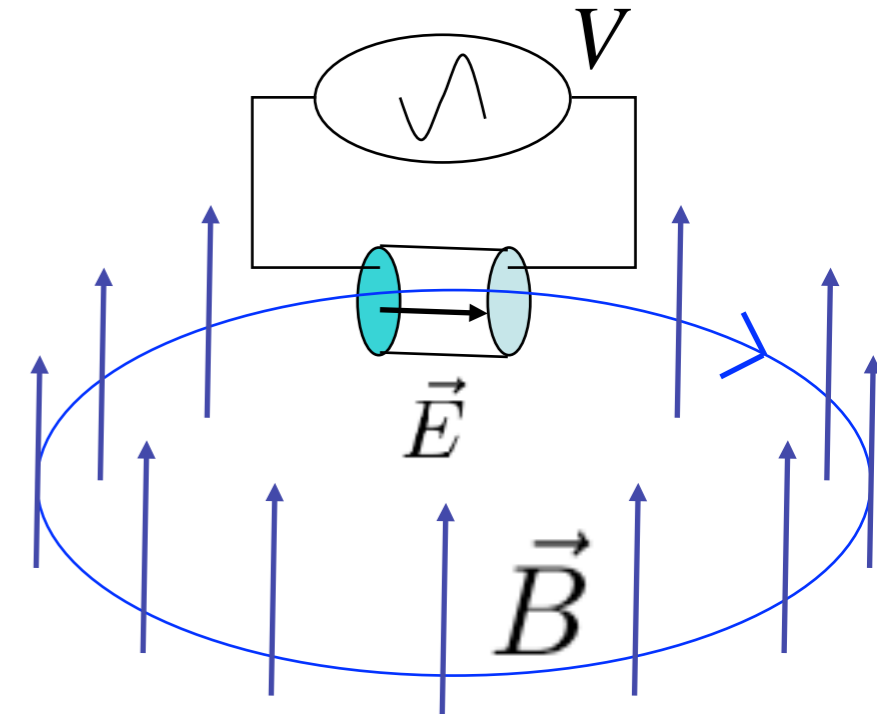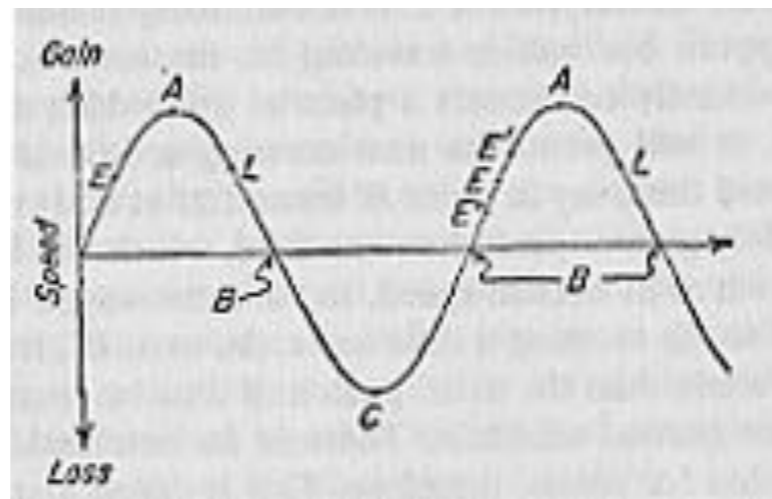
Particles rest mass:

- e *0.511 MeV*
- p *938 MeV*
- ^{239}U *~220000 MeV*
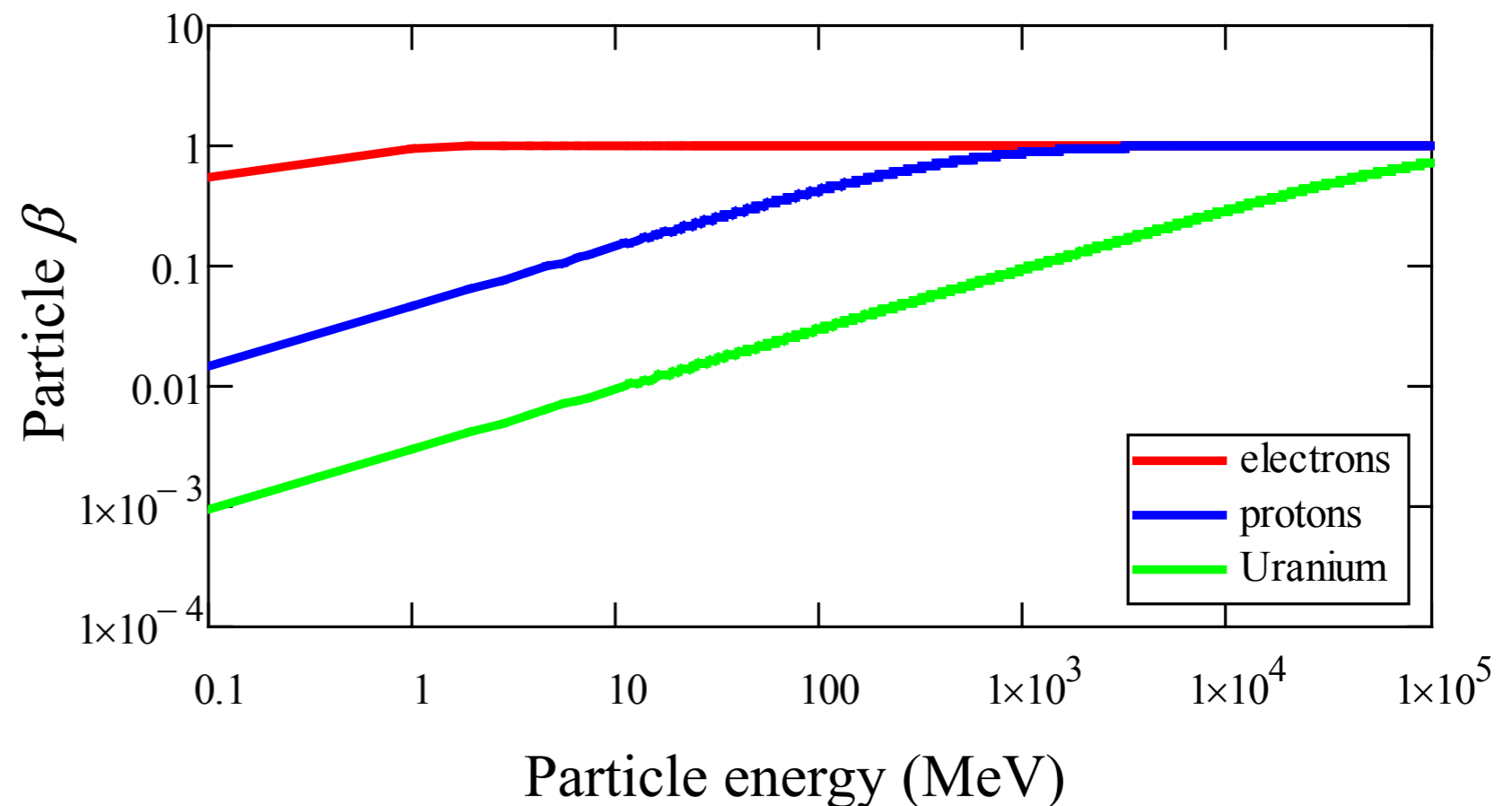
For Highest Elementary Particle Energies...

- ... 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

A Synchrotron
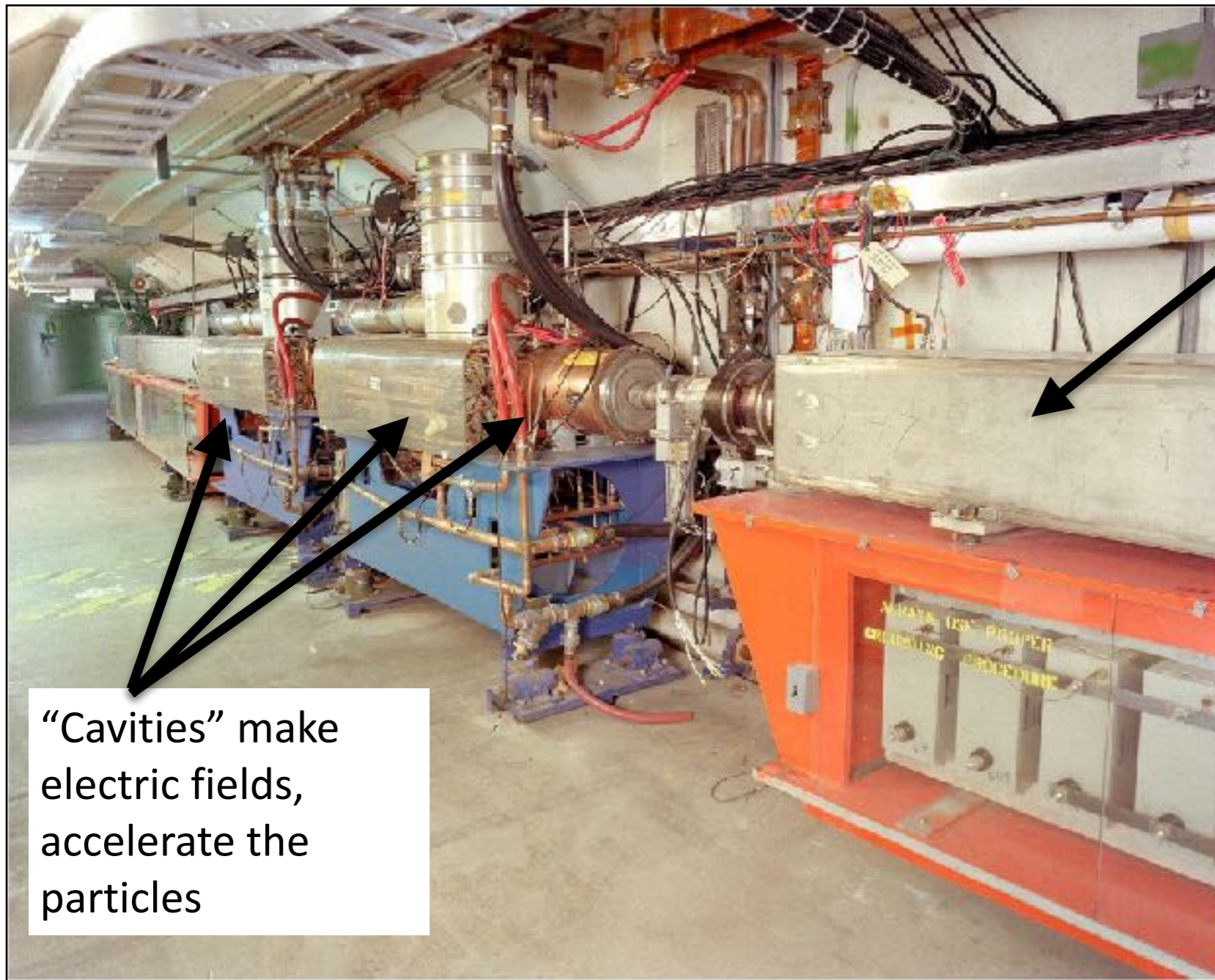
Magnets steer the particles in a circle

"Cavities" make electric fields, accelerate the particles

Booster Synchrotron, Fermilab (Batavia, IL)

The Large Colliders

Tevatron, Fermilab
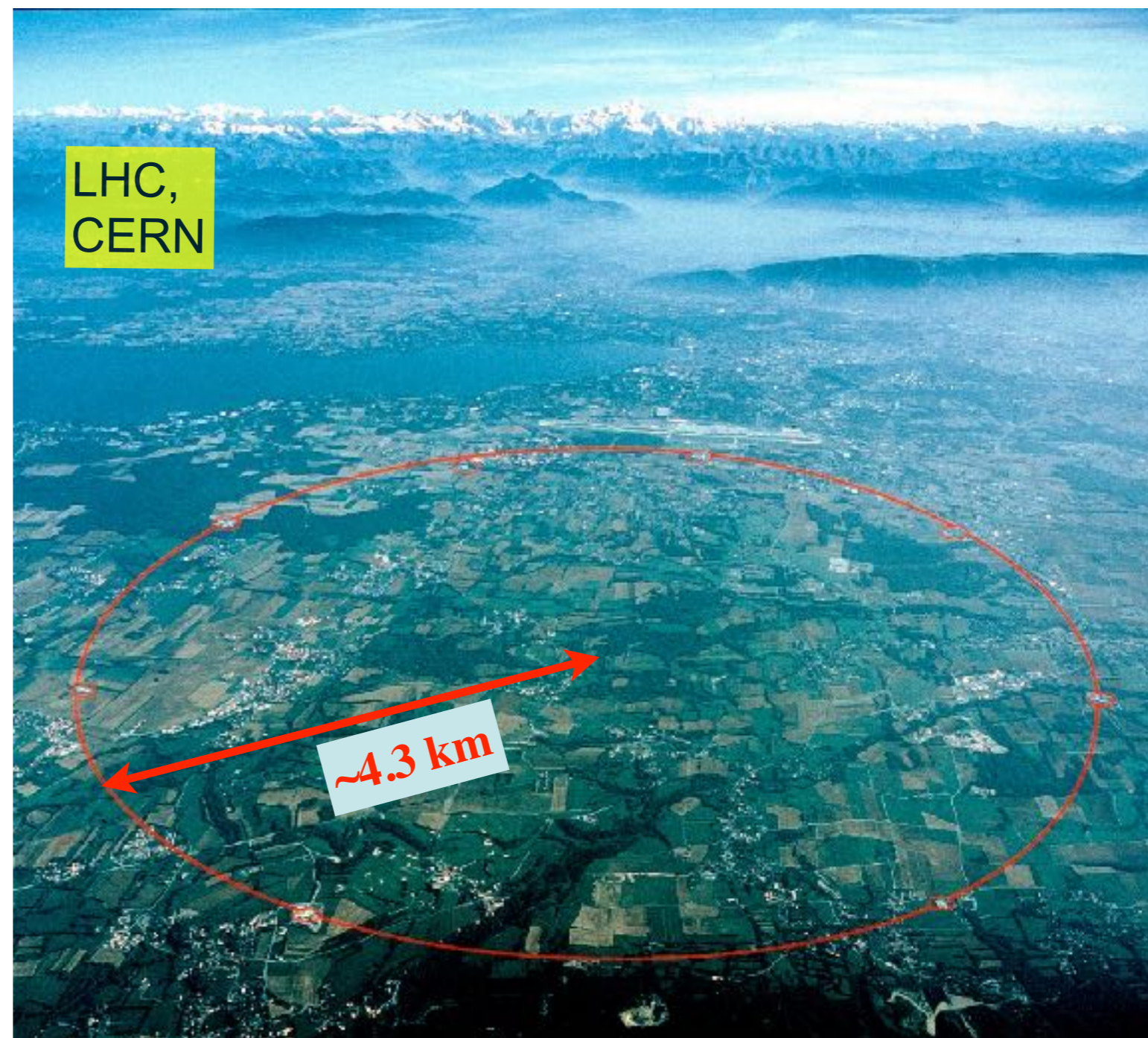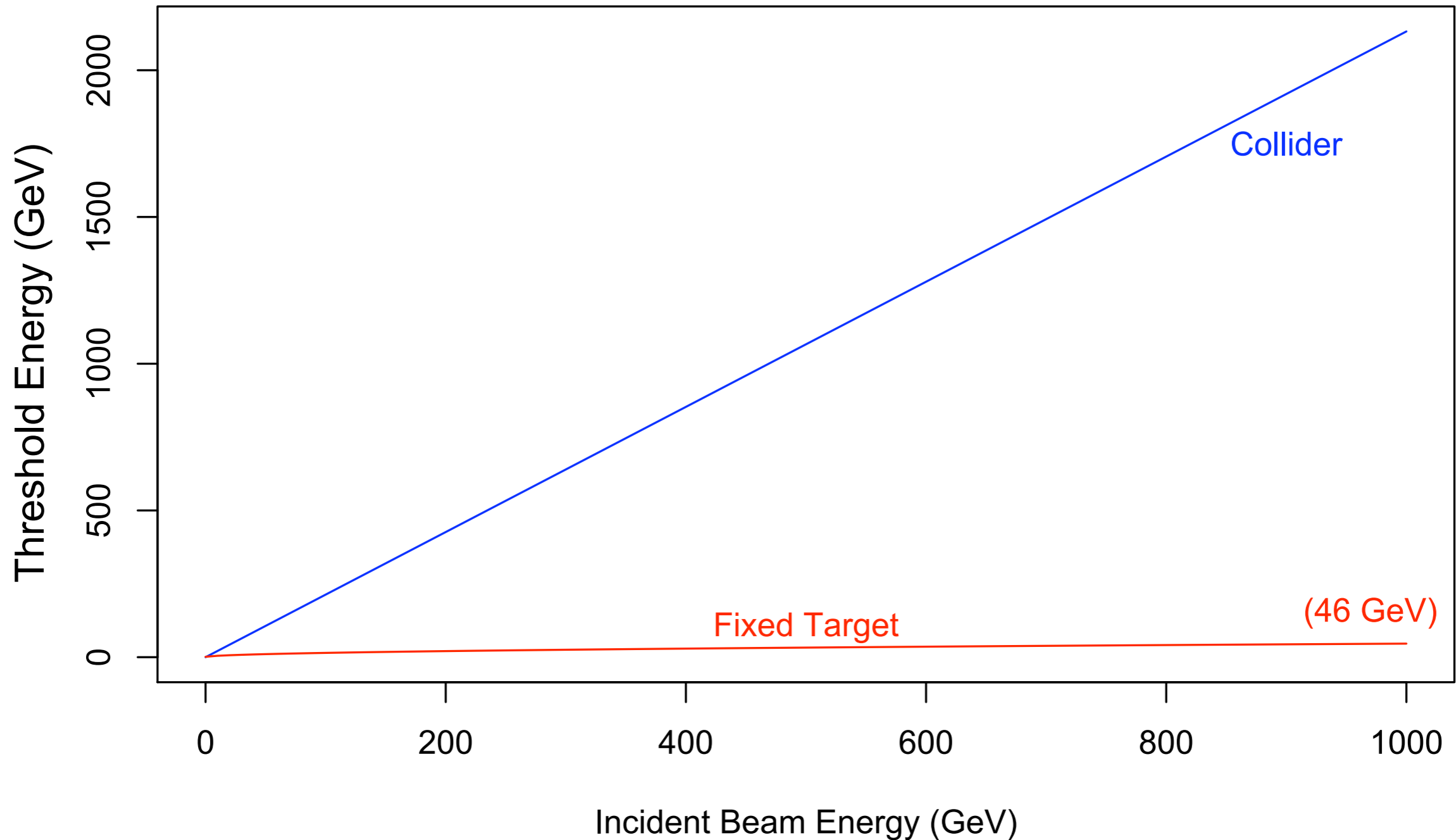
1 km

LHC, CERN

~4.3 km

Fixed Target Energy vs. Collider Energy
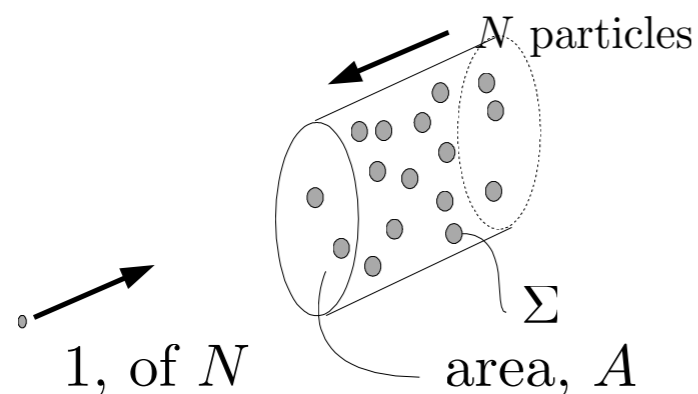
-

Nucleon-Nucleon Collisions

Luminosity

- Experiments want "collisions/events" -- rate?

- Fixed Target Experiment:

$$
\begin{aligned}
\mathcal{R} &= \left(\frac{\Sigma}{A}\right) \cdot \rho \cdot A \cdot \ell \cdot N_A \cdot \dot{N}_{beam} \\
&= \rho N_A \ell \dot{N}_{beam} \cdot \Sigma \\
&\equiv \mathcal{L} \cdot \Sigma
\end{aligned}
$$

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

- Bunched-Beam Collider:

$$
\begin{aligned}
\mathcal{R} &= \left(\frac{\Sigma}{A}\right) \cdot N \cdot (f \cdot N) \\
&= \frac{f \, N^2}{A} \cdot \Sigma \\
\mathcal{L} &\equiv \frac{f \, N^2}{A} \qquad \boxed{(10^{34}\mathrm{cm}^{-2}\mathrm{sec}^{-1} \text{ for LHC})}
\end{aligned}
$$

Integrated Luminosity

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

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

$f_0 =$ rev. frequency
$B =$ no. bunches

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

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

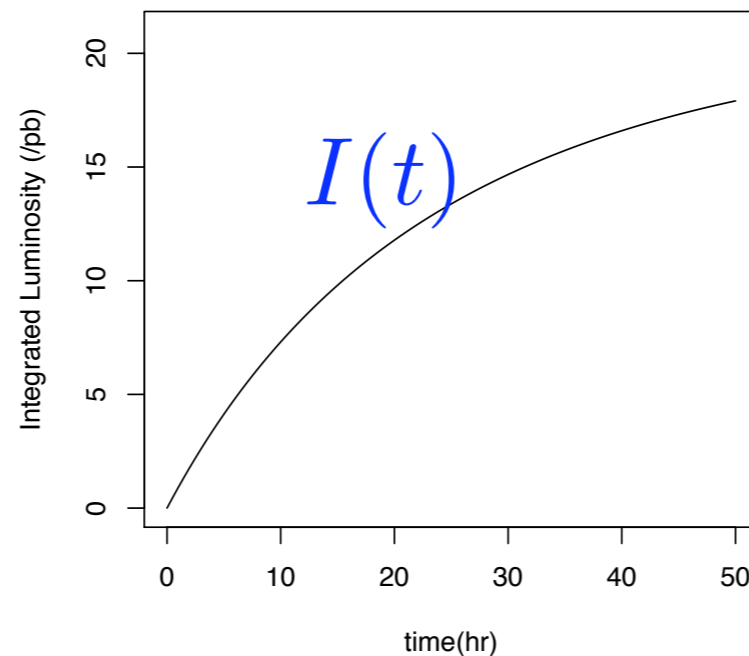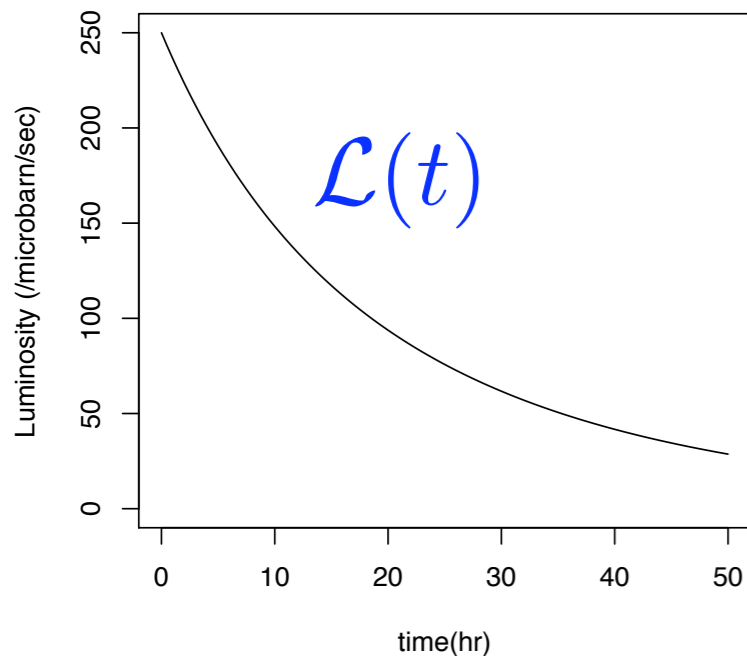($n =$ no. of detectors receiving luminosity $\mathcal{L}$)

- 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 = $\displaystyle\int \mathcal{L}(t)dt \cdot \Sigma$
- So, our integrated luminosity is

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

$\mathcal{L}(t)$

$I(t)$

asymptotic limit:

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

so, ...

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

Recent Large-Scale Accelerators

Large Hadron Collider (LHC)

synchrotron
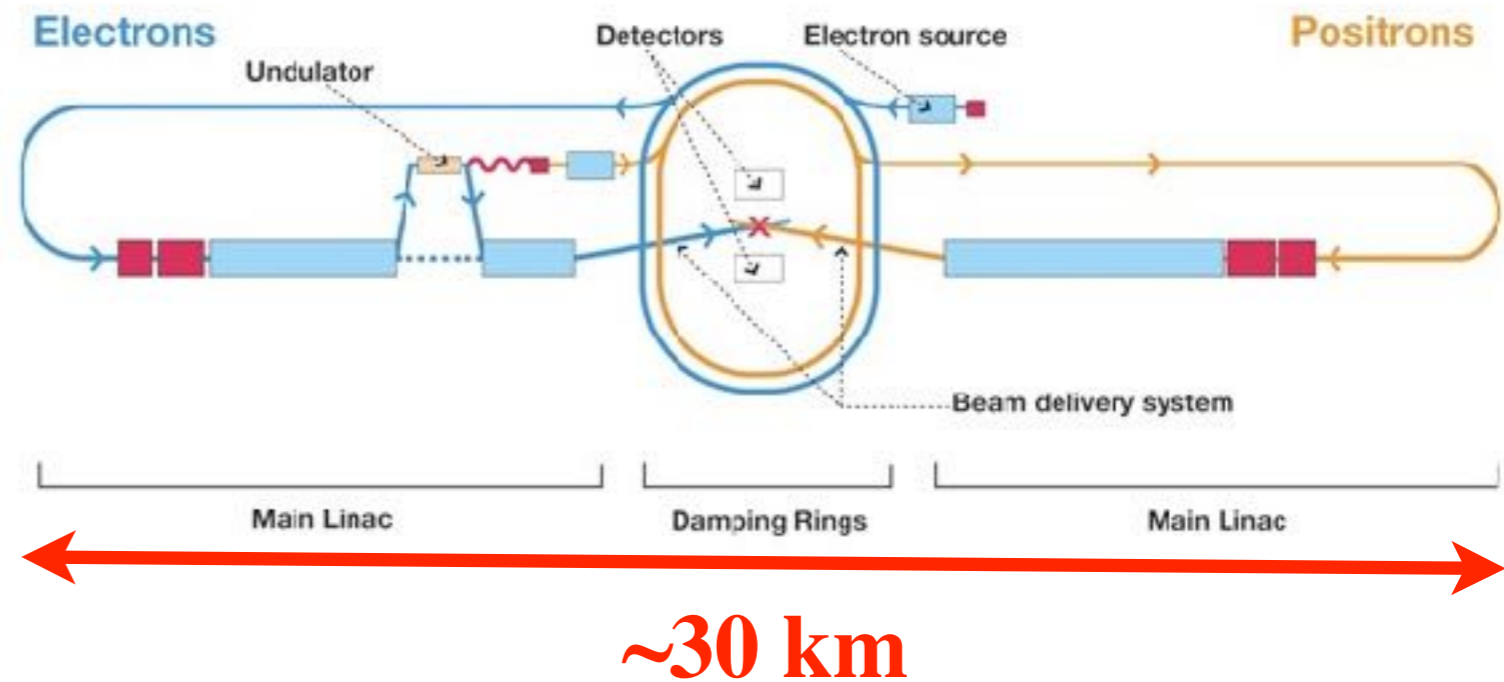

linac

Spallation Neutron Source (SNS)

The Linac -- Again

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

~30 km

- **Resurgent use of Linacs for large *p*, *N* accelerators...**
  - SNS; FRIB, ESS, neutrino sources
  - 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)
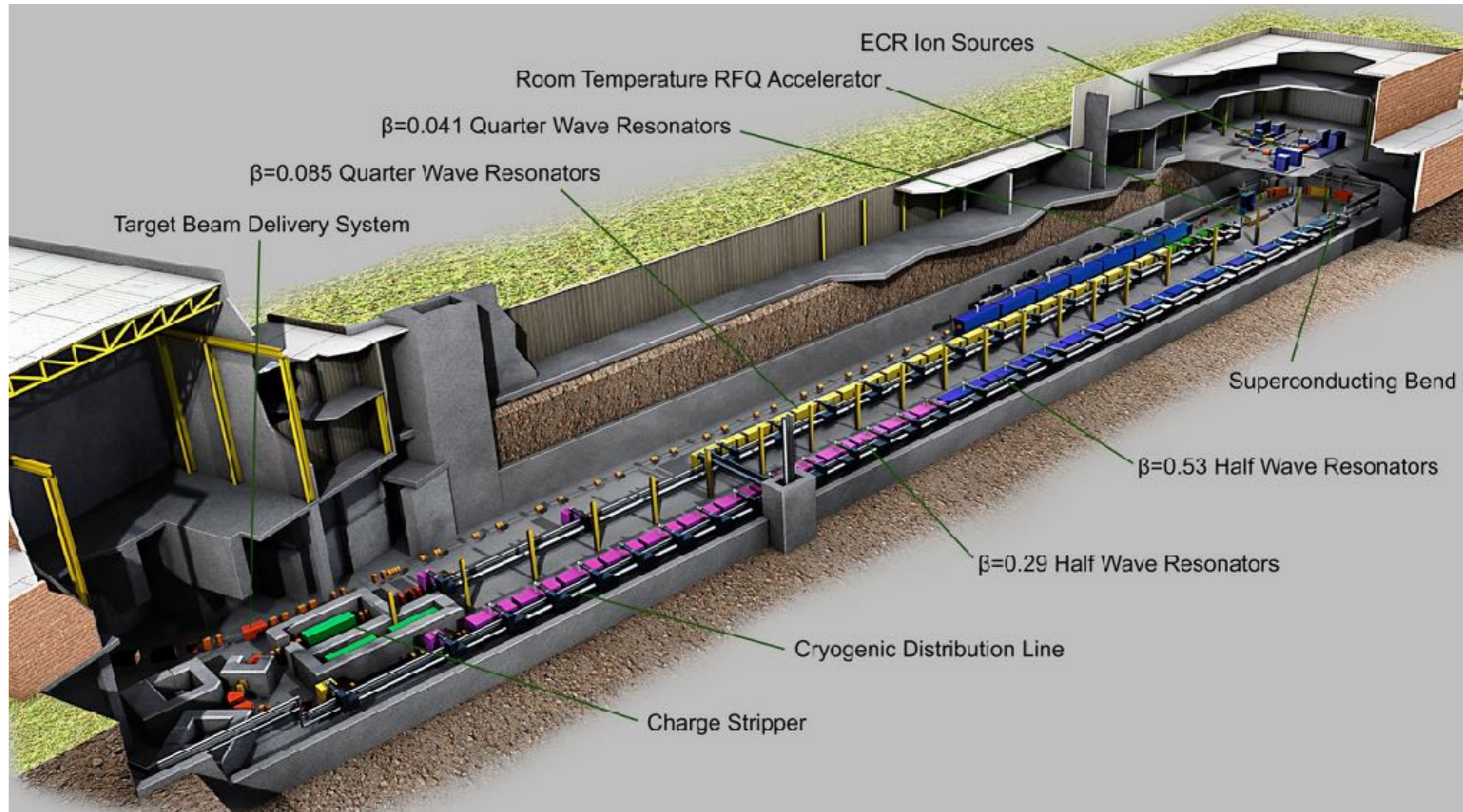
Modern Accelerators

- 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), ...

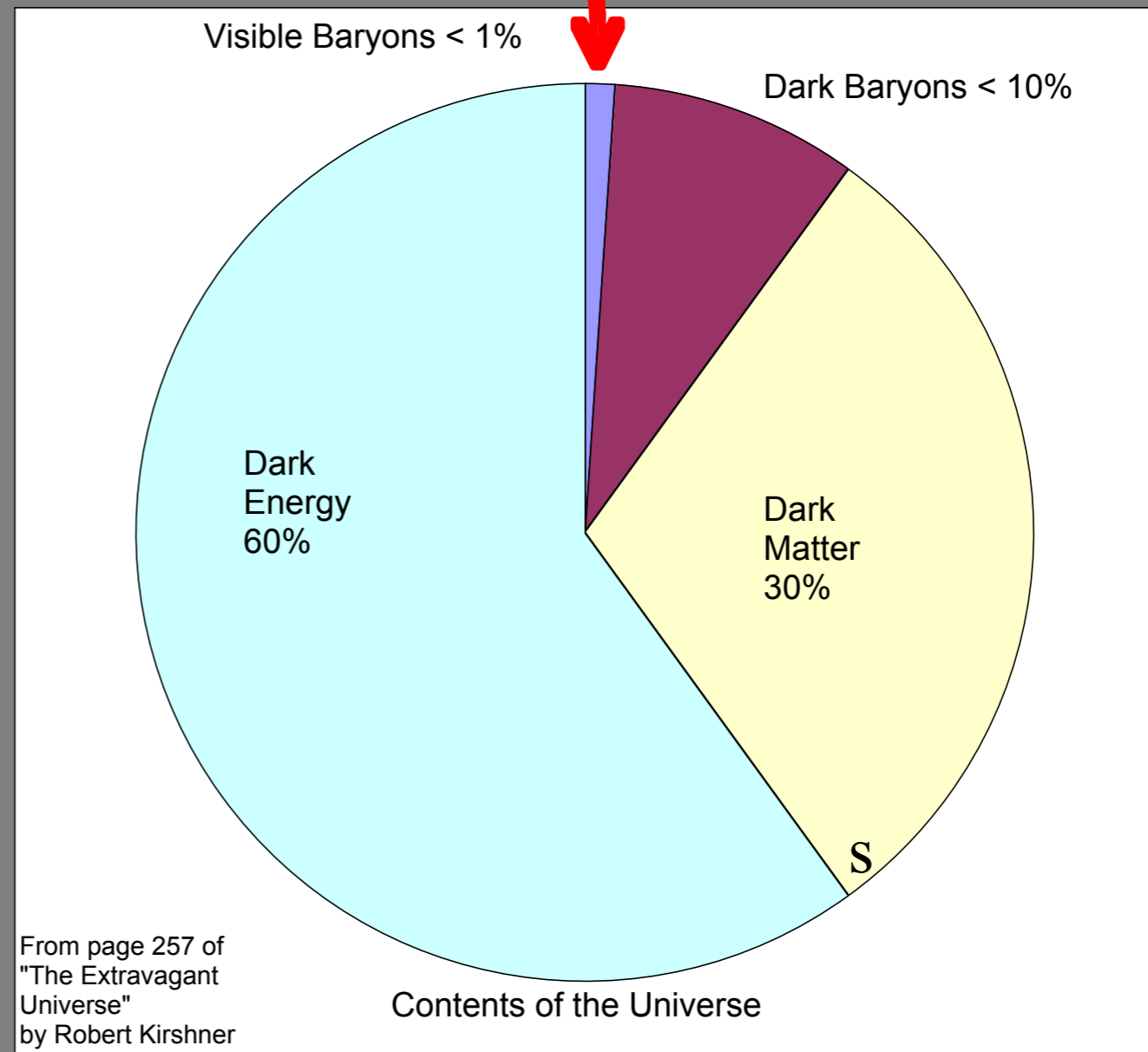- Someone did a better job ...

  - 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.

Contents of the Universe

- Visible Baryons < 1%
- Dark Baryons < 10%
- Dark Matter 30%
- Dark Energy 60%
- S

From page 257 of "The Extravagant Universe" by Robert Kirshner

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

But 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

Accelerators
for America's
Future

U.S. DEPARTMENT OF
ENERGY

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

http://www.acceleratorsamerica.org/

Areas of R&D identified by each working group. All areas are of importance to each working group. Color coding indicates areas with greatest impact.

R&D Need	Energy & Environment	Medicine	Industry	Security & Defense	Discovery Science
Reliability					
Beam Power/RF					
Beam Transport and Control					
Efficiency					
Gradient (SRF and other)					
Reduced Production Costs					
Simulation					
Lasers					
Size					
Superconducting Magnets					
Targetry					
Particle Sources					

Color code: Increased priority