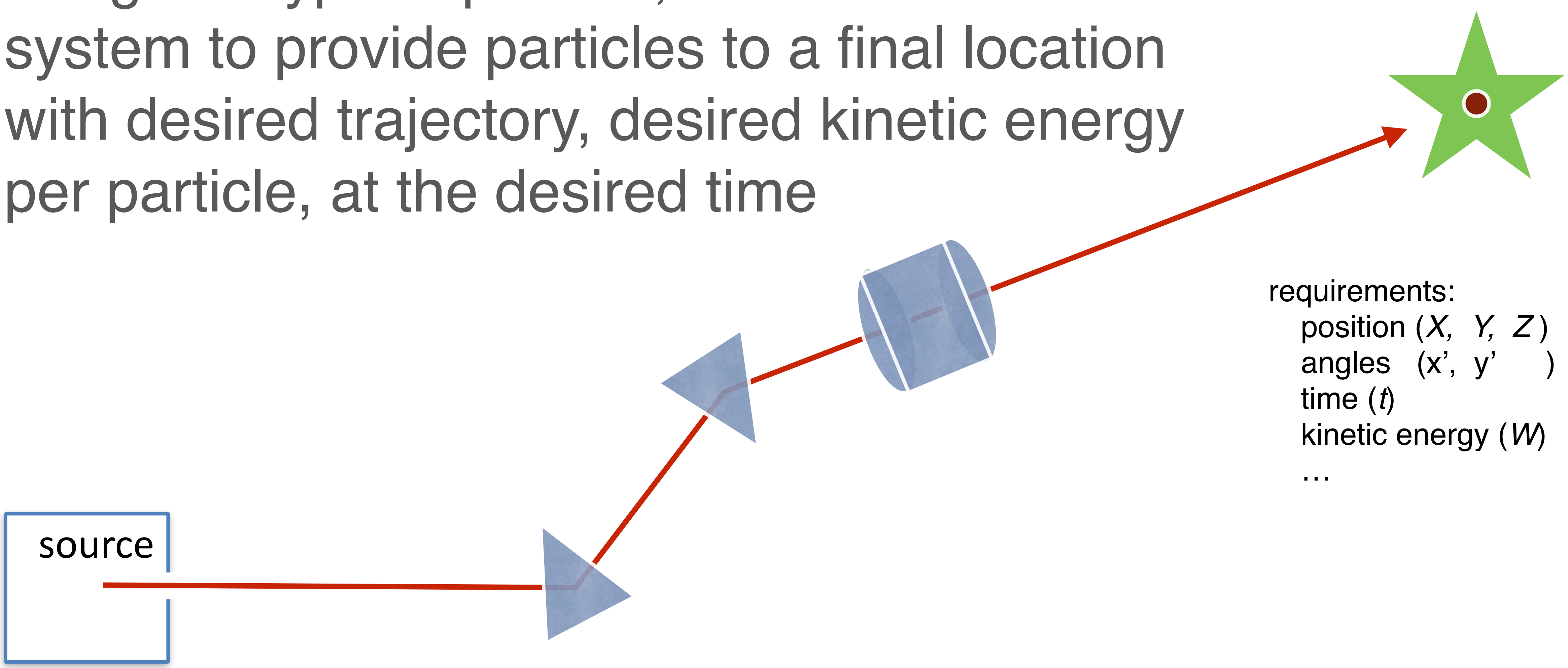
The Problem

Northern Illinois University

- 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



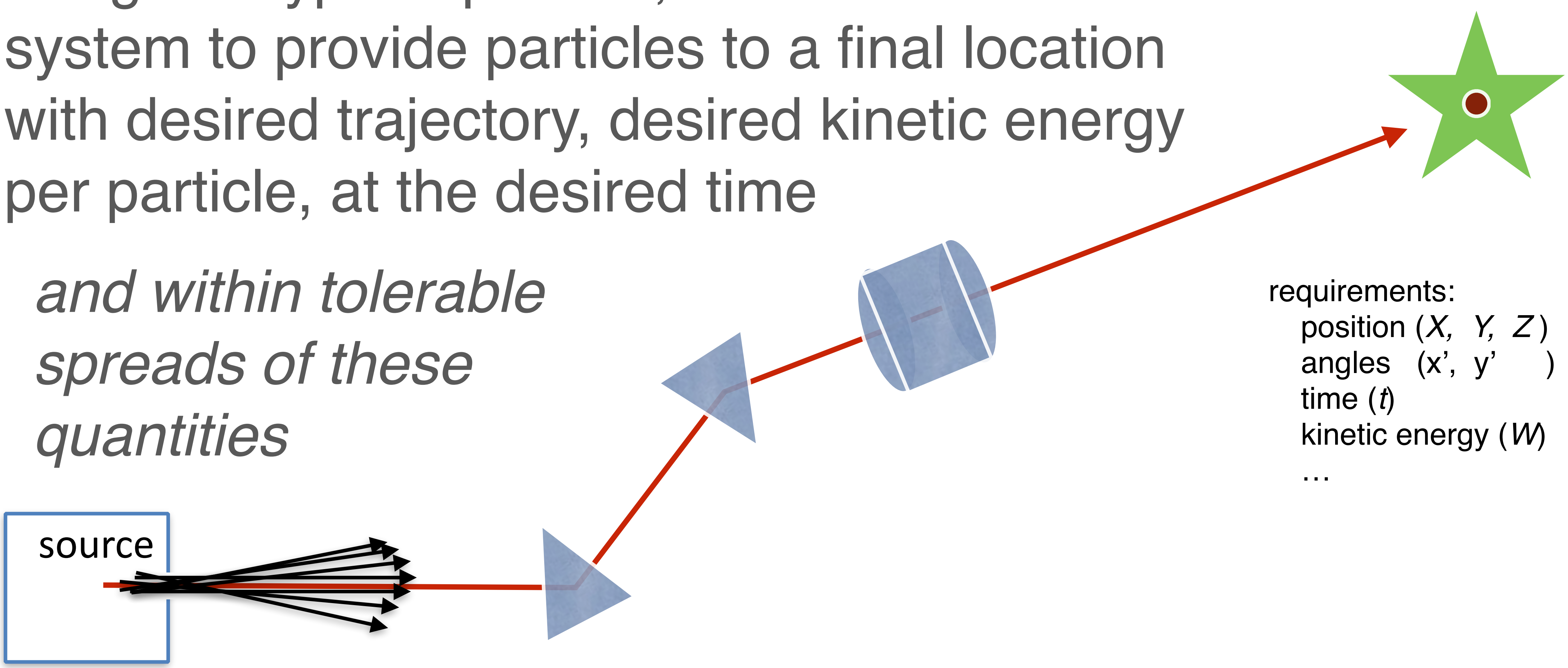
The Problem

Northern Illinois University

- 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



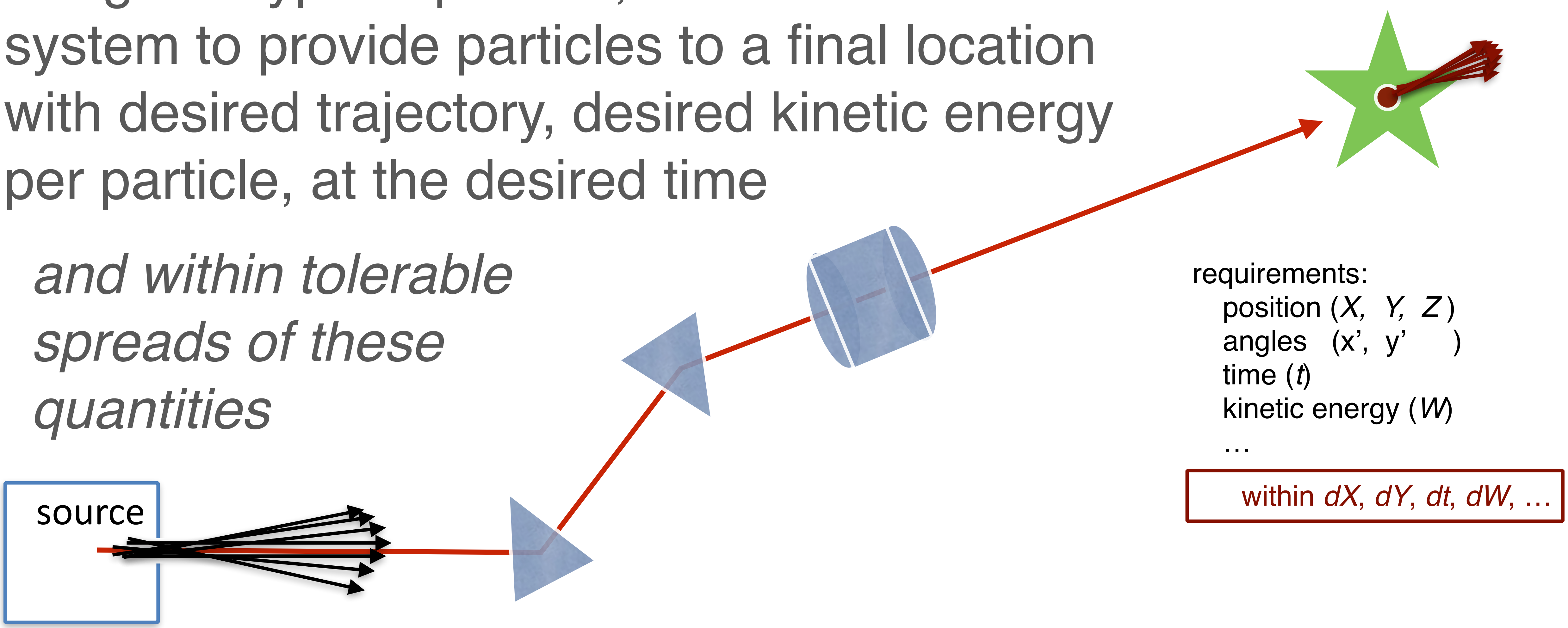
requirements:
- position (X, Y, Z)
- angles (x', y')
- time (t)
- kinetic energy (W)
- …

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



A Few Words on Particle Sources…

Northern Illinois University

- 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 the resulting High Tension Laboratory, Rutherford went on to reiterate the goal:

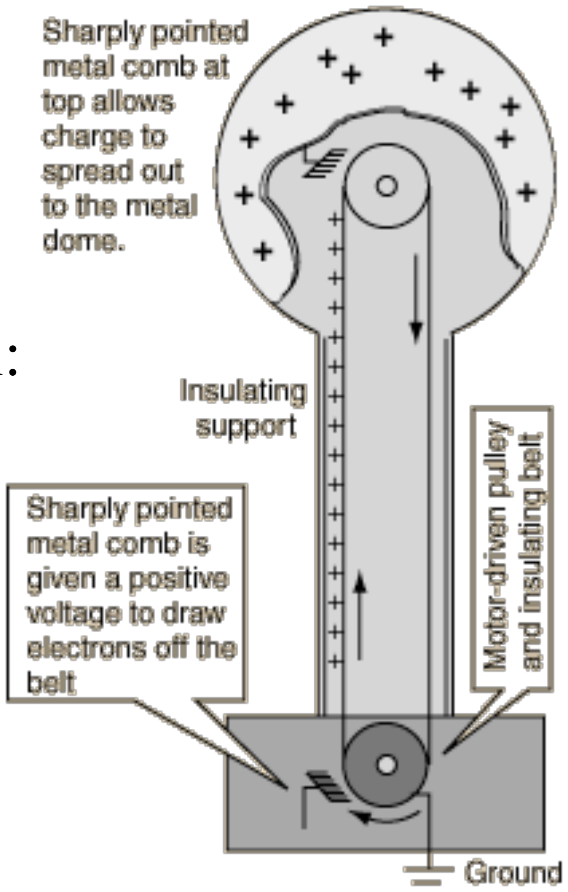
"What we require is an apparatus to give us a potential of the order of 10 million volts which can be safely accommodated in a reasonably sized room and operated by a few kilowatts of power. We require too an exhausted tube capable of withstanding this voltage… I see no reason why such a requirement cannot be made practical."

A Little Accelerator History

- DC Acceleration

Van de Graaff

(1929)



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

"What we require is an apparatus to give us a potential of the order of 10 million volts which can be safely accommodated in a reasonably sized room and operated by a few kilowatts of power. We require too an exhausted tube capable of withstanding this voltage… I see no reason why such a requirement cannot be made practical."

A Little Accelerator History

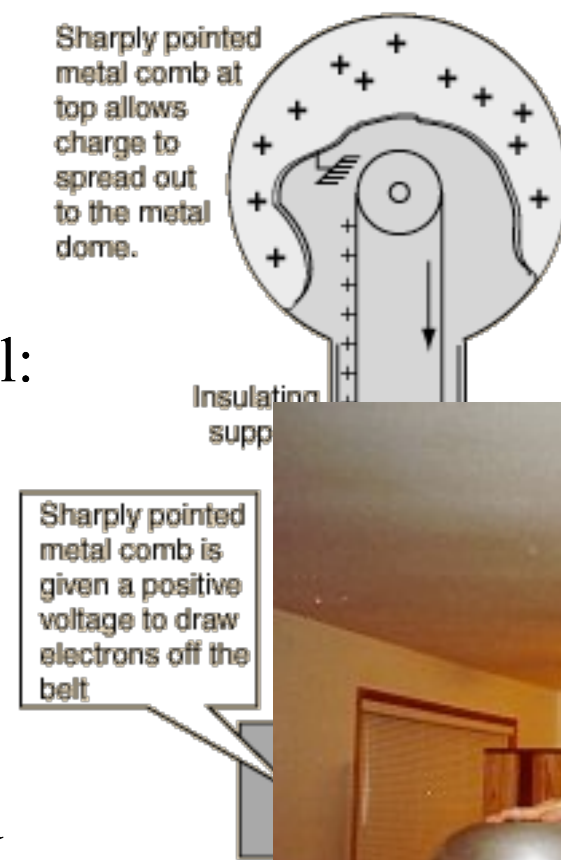
- DC Acceleration

Van de Graaff

(1929)

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

"What we require is an apparatus to give us a potential of the order of 10 million volts which can be safely accommodated in a reasonably sized room and operated by a few kilowatts of power. We require too an exhausted tube capable of withstanding this voltage… I see no reason why such a requirement cannot be made practical."



A Little Accelerator History

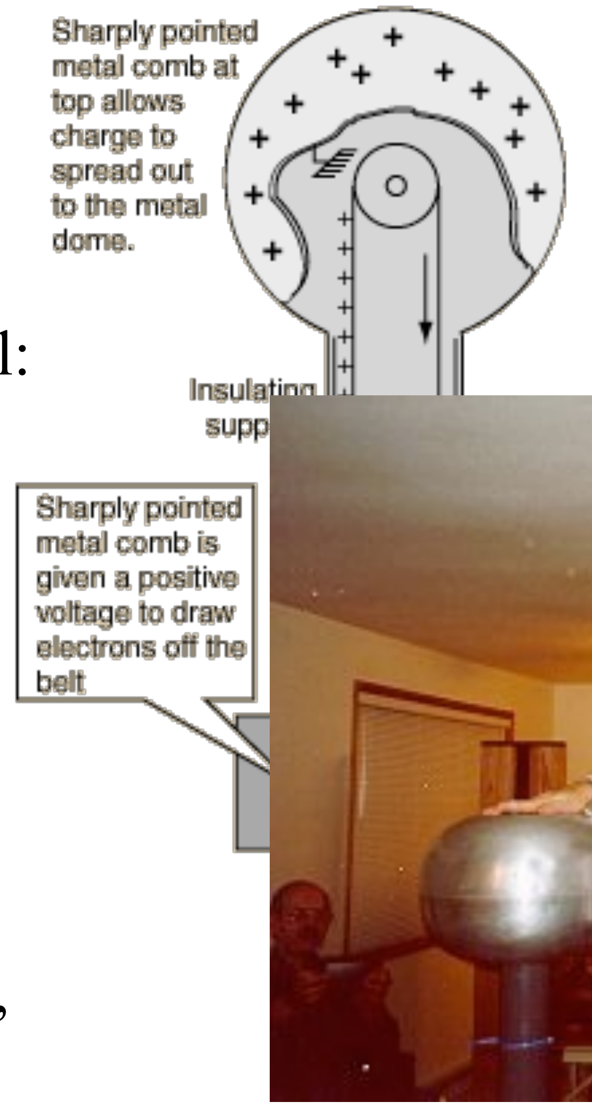
- DC Acceleration

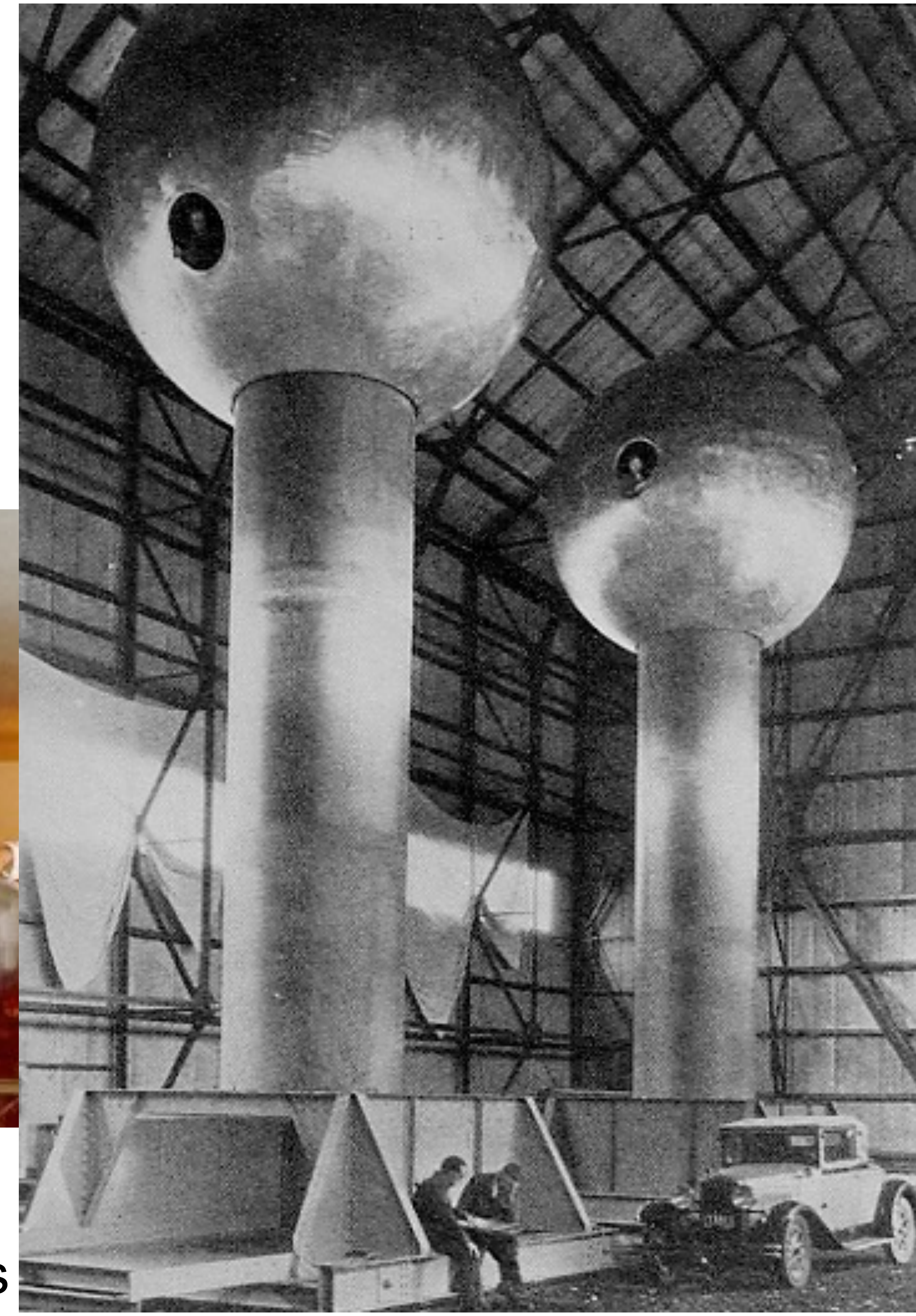
1927: Lord Rutherford requested a "copious supply" of projectiles more energetic than natural alpha and beta particles. At the opening of the resulting High Tension Laboratory, Rutherford went on to reiterate the goal:

"What we require is an apparatus to give us a potential of the order of 10 million volts which can be safely accommodated in a reasonably sized room and operated by a few kilowatts of power. We require too an exhausted tube capable of withstanding this voltage… I see no reason why such a requirement cannot be made practical."

Van de Graaff

(1929)





MIT, c.1940s

A Little Accelerator History

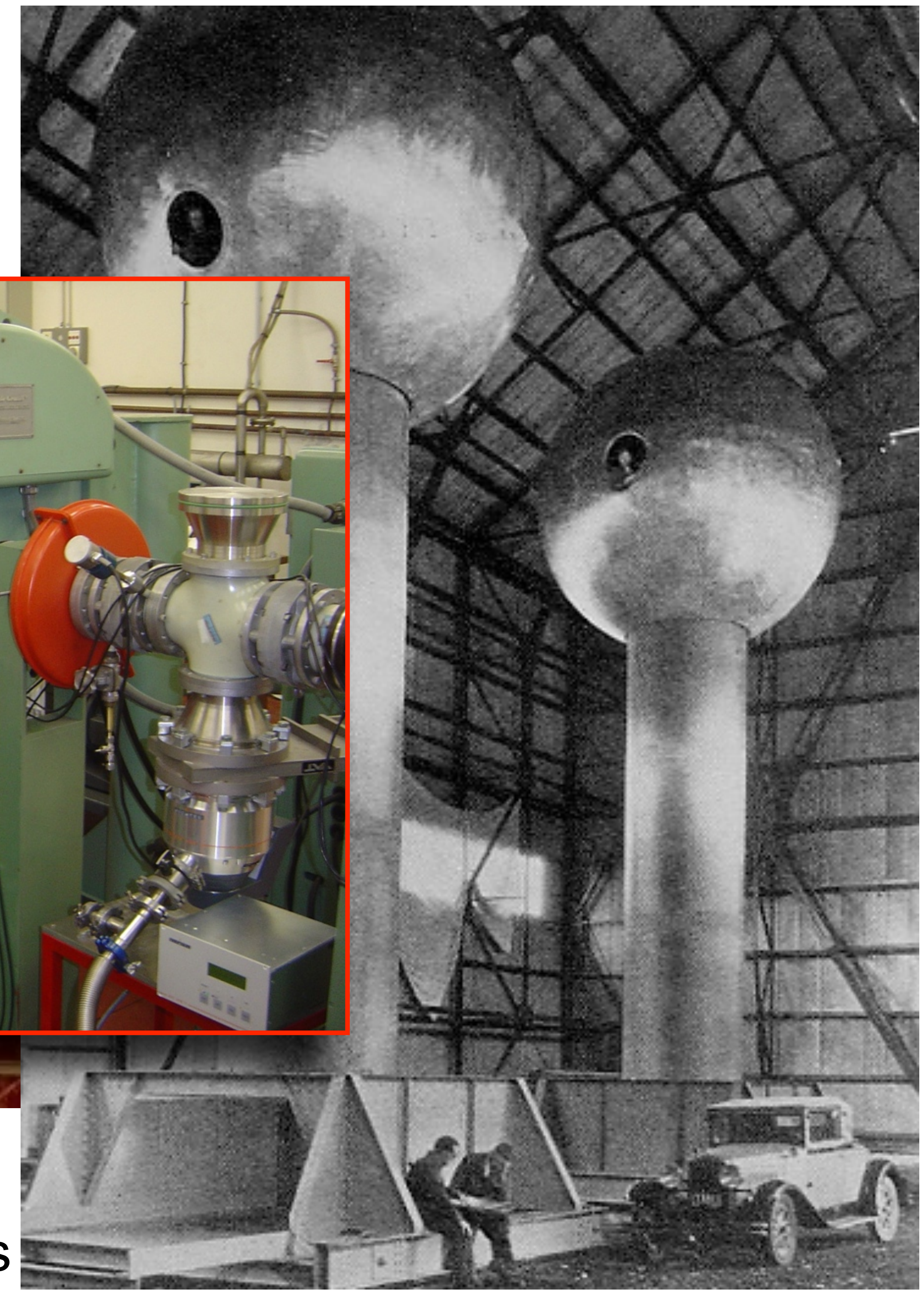
- DC Acceleration

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 k
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)



MIT, c.1940s

Cockcroft and Walton

- Voltage Multiplier

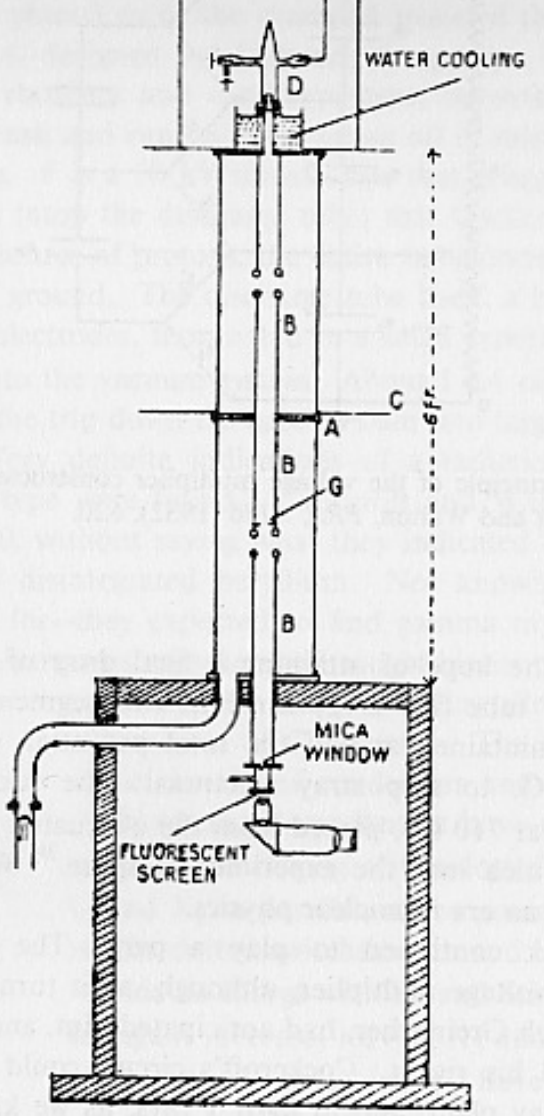


FIG. 2.11 Accelerating tube and target arrangement of the Cockcroft-Walton machine. The source is at D; C is a metallic ring joint between the two sections of the constantly pumped tube. The mica window closes the evacuated space. Cockcroft and Walton, *PRS, A136* (1932), 626.

Cockcroft and Walton

- Voltage Multiplier

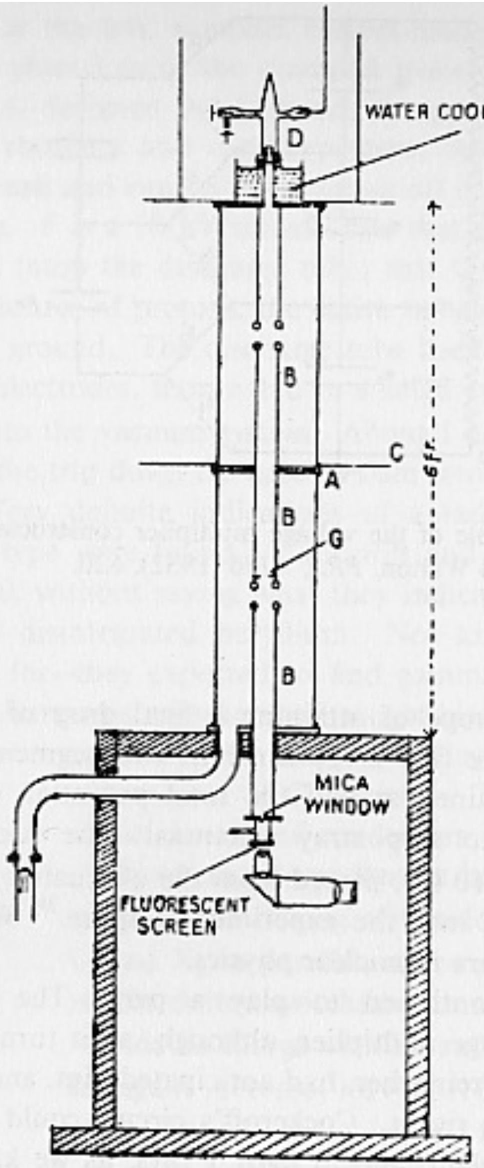
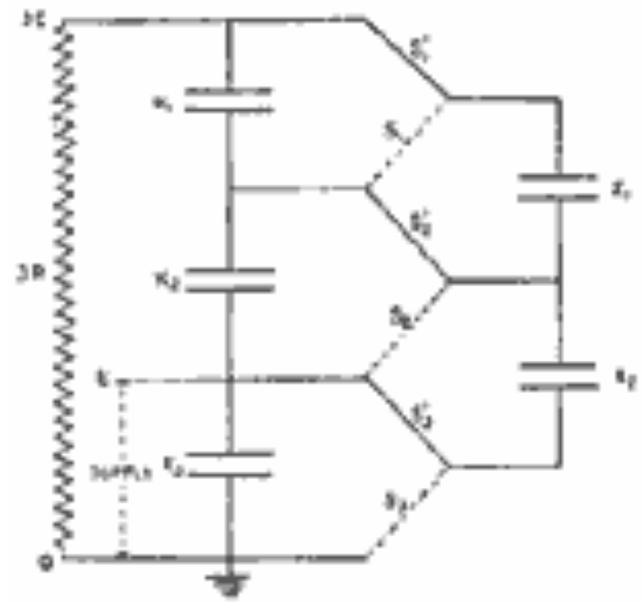
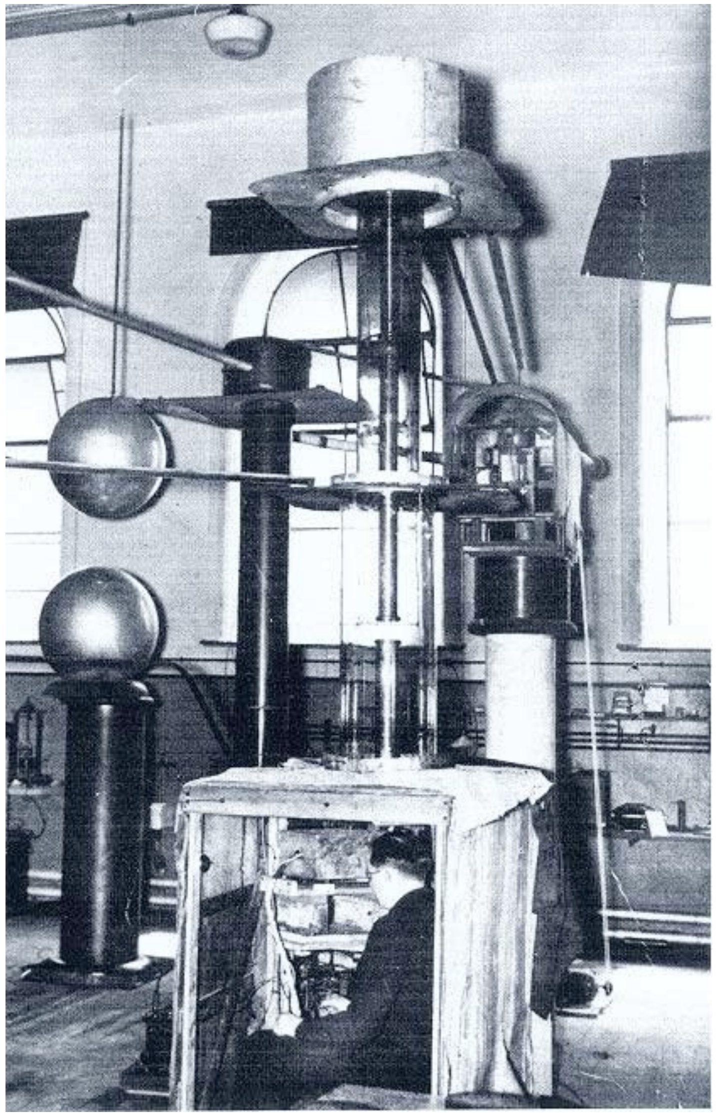


FIG. 2.11 Accelerating tube and target arrangement of the Cockcroft-Walton machine. The source is at D; C is a metallic ring joint between the two sections of the constantly pumped tube. The mica window closes the evacuated space. Cockcroft and Walton, *PRS, A136* (1932), 626.



Converts AC voltage V to DC voltage n x V



Cockcroft and Walton

- Voltage Multiplier

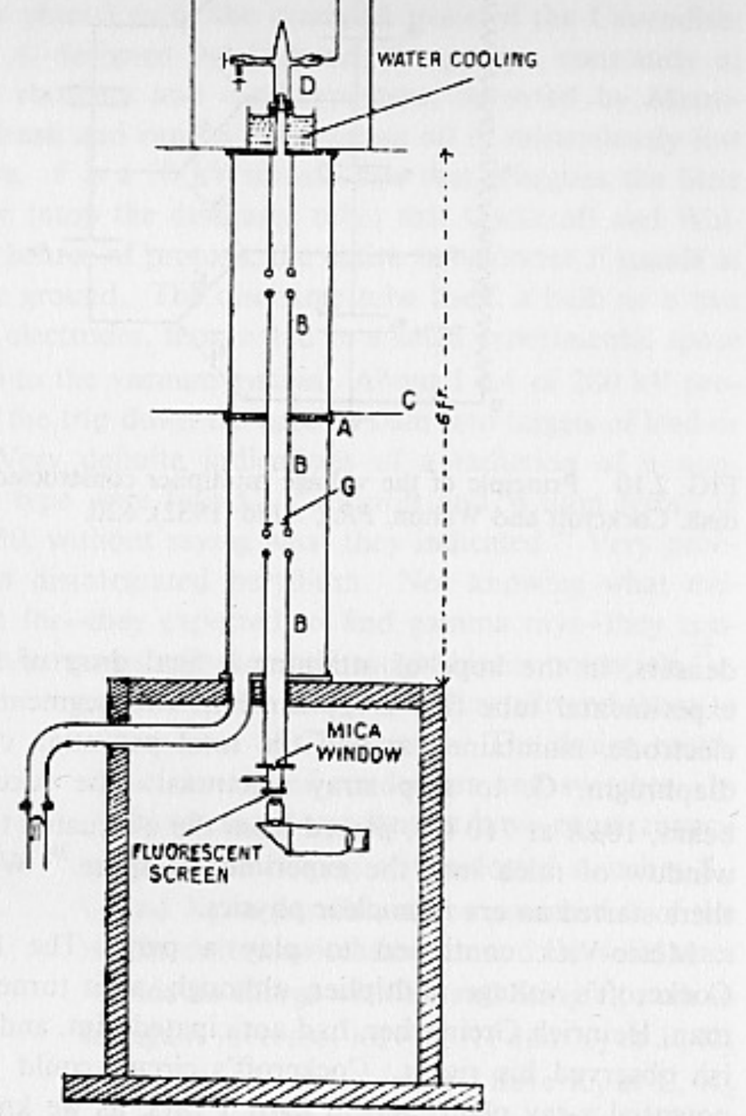
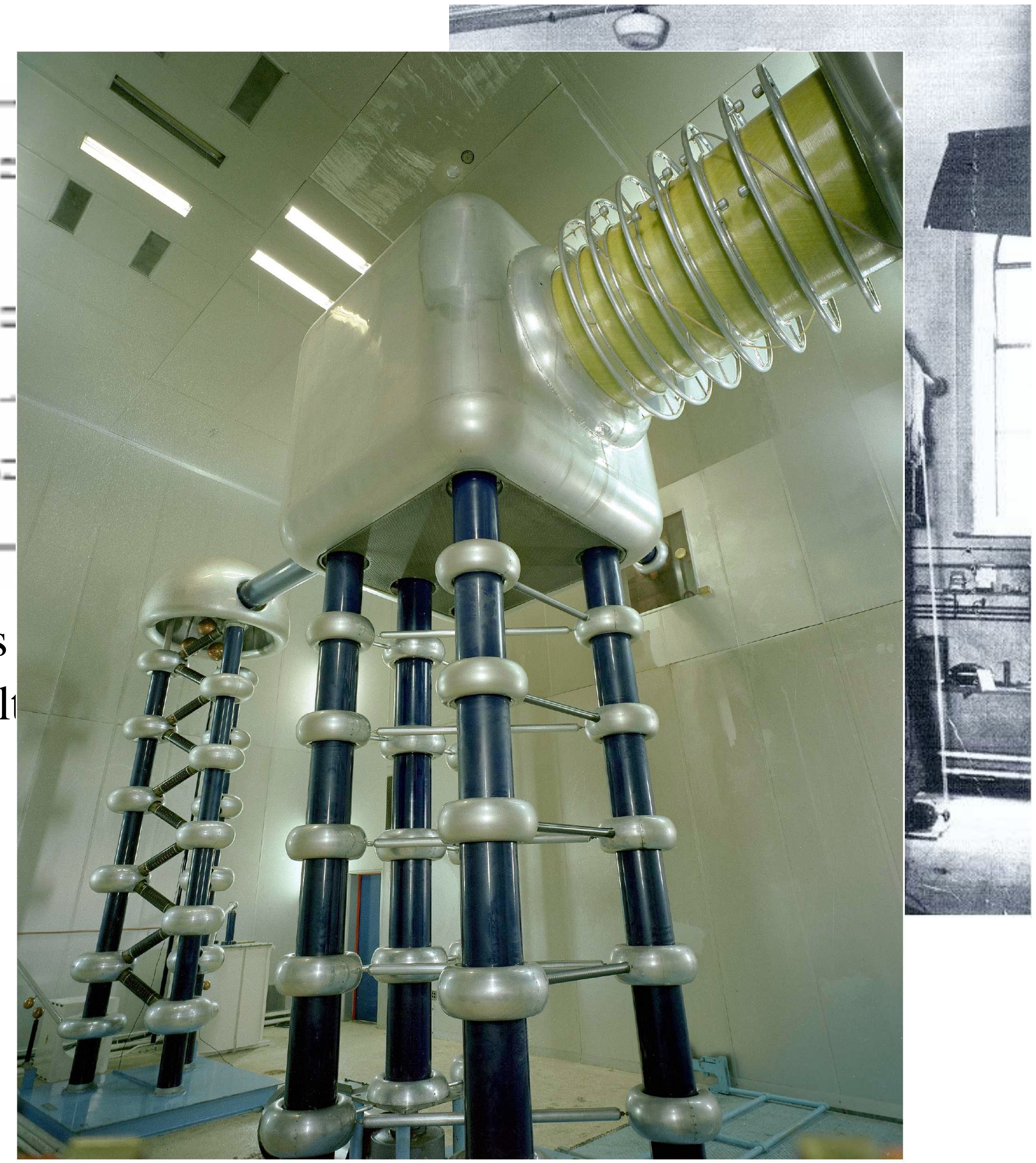


FIG. 2.11 Accelerating tube and target arrangement of the Cockcroft-Walton machine. The source is at D; C is a metallic ring joint between the two sections of the constantly pumped tube. The mica window closes the evacuated space. Cockcroft and Walton, *PRS, A136* (1932), 626.

Converts
DC volt



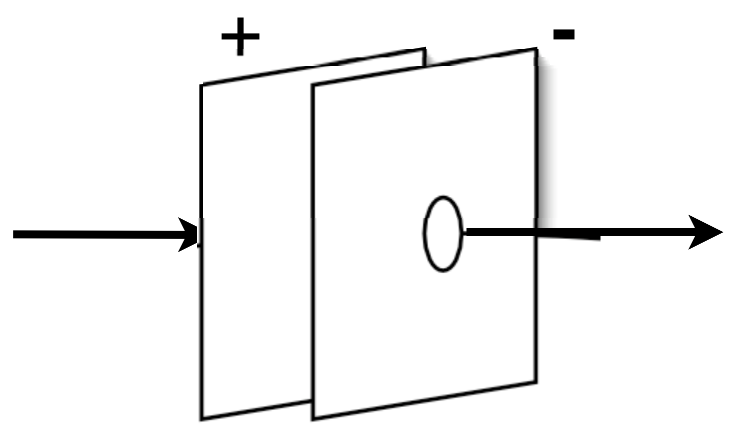
Fermilab (recently decommissioned)

The Route to Higher Energies

- The need for AC systems

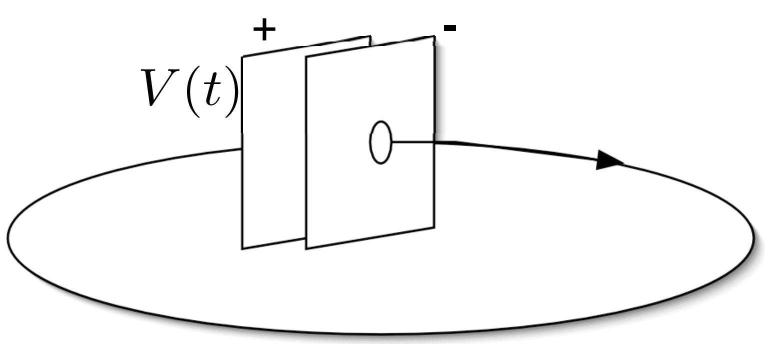
- The Need for AC Systems…

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



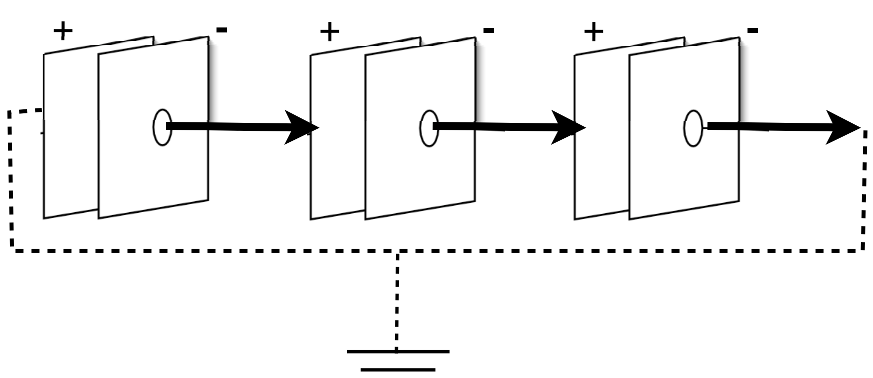
DC systems limited to a few MV

Circular Accelerator



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

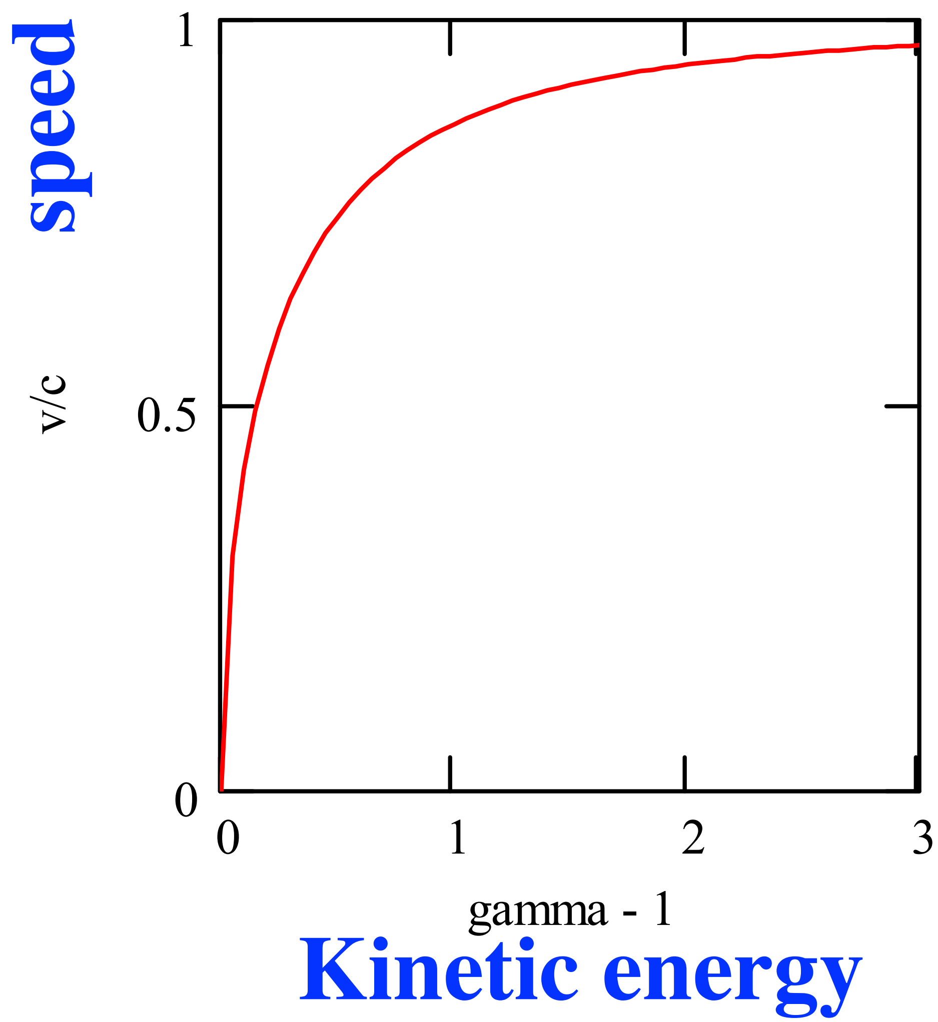
Linear Accelerator

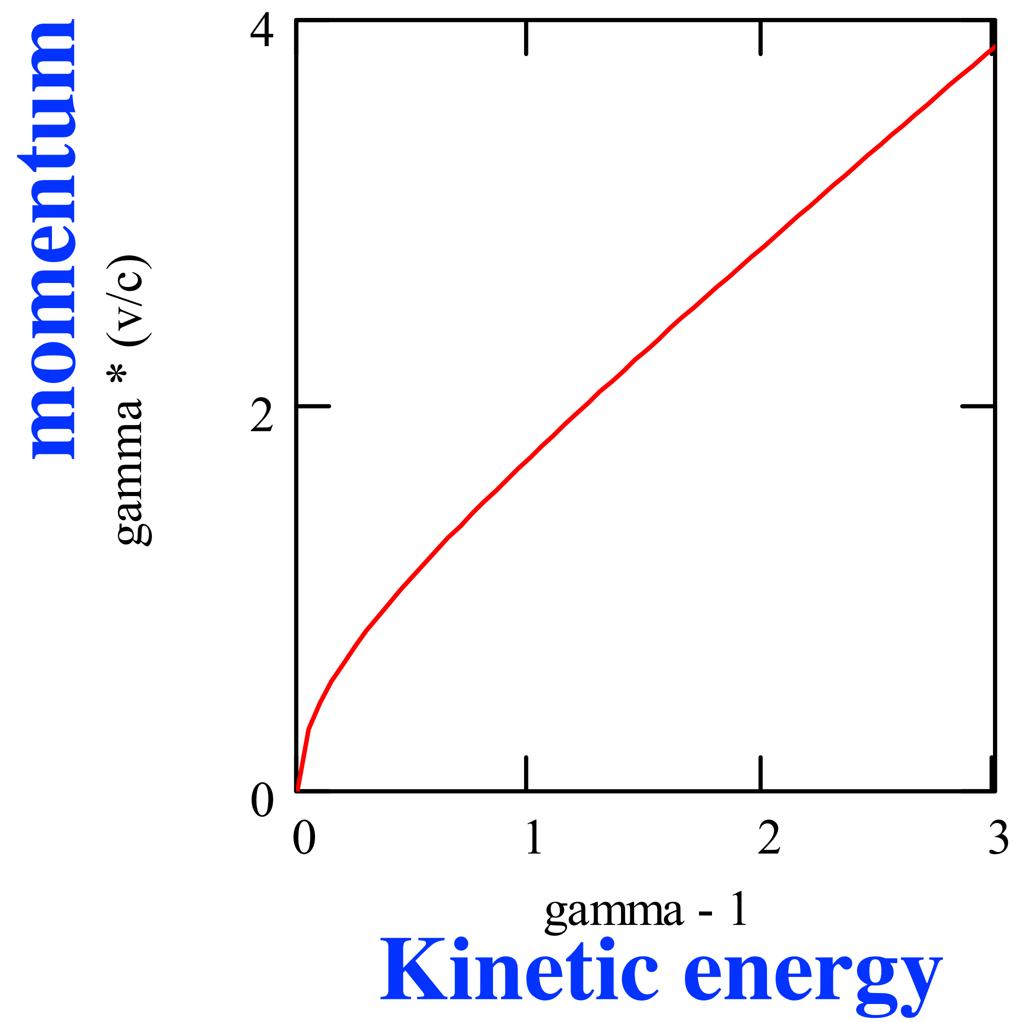


To gain energy, a time-varying field is required:

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

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:

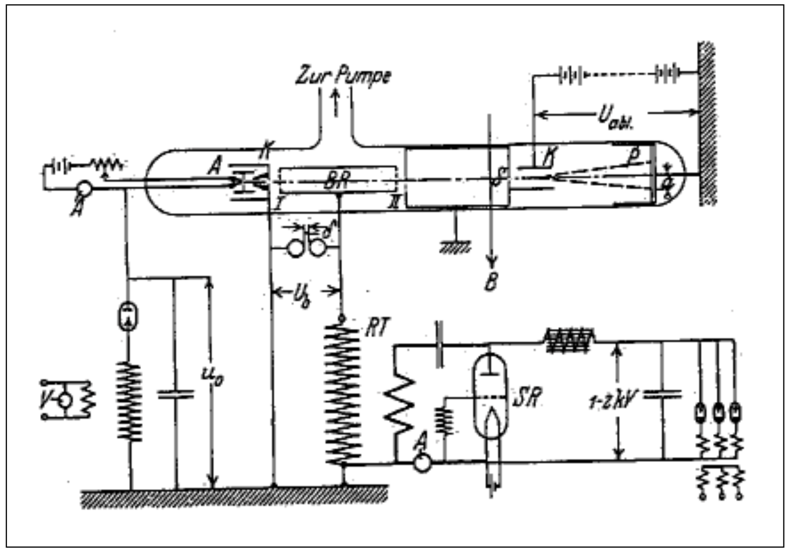
e-	0.5 MeV
p	938 MeV

Oscillating Fields

Oscillating Fields

Northern Illinois University

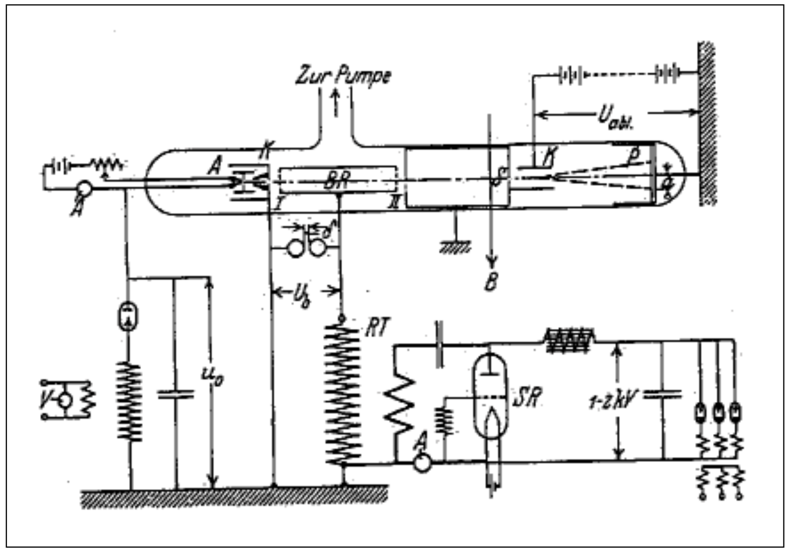
➡ The linear accelerator (linac) -- 1928-29
- Wideroe (U. Aachen; grad student!)
  - Dreamt up concept of “Ray Transformer” (later, called the “Betatron”); thesis advisor said was “sure to fail,” and was rejected as a PhD project. Not deterred, illustrated the principle with a “linear” device, which he made to work -- got his PhD in engineering
- 50 keV; accelerated heavy ions (K+, Na+)
- utilized oscillating voltage of 25 kV @ 1 MHz



Oscillating Fields

Northern Illinois University

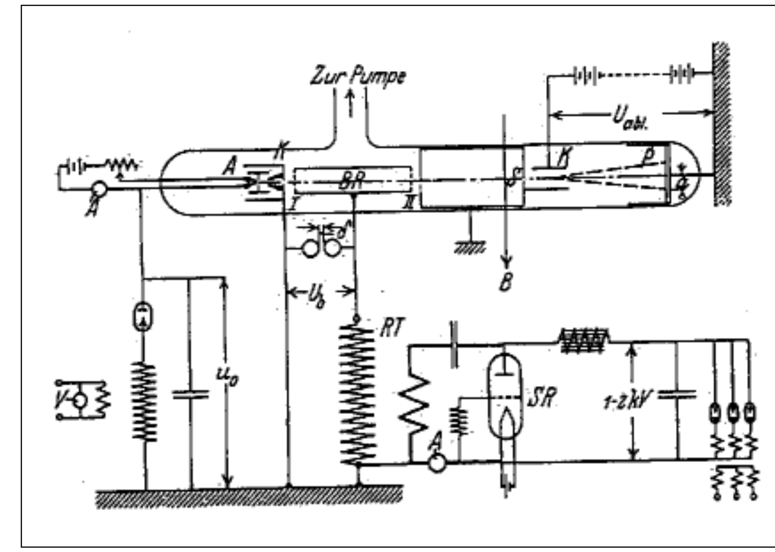
➡The linear accelerator (linac) -- 1928-29
- Wideroe (U. Aachen; grad student!)
  - Dreamt up concept of “Ray Transformer” (later, called the “Betatron”); thesis advisor said was “sure to fail,” and was rejected as a PhD project. Not deterred, illustrated the principle with a “linear” device, which he made to work -- got his PhD in engineering
- 50 keV; accelerated heavy ions (K+, Na+)
- utilized oscillating voltage of 25 kV @ 1 MHz



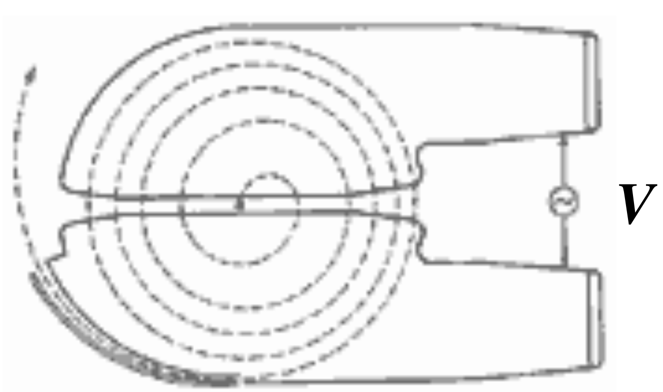
➡The Cyclotron -- 1930's, Lawrence (U. California)
- read Wideroe’s paper (actually, looked at the pictures!)
- an extended “linac” unappealing -- make it more compact:

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:



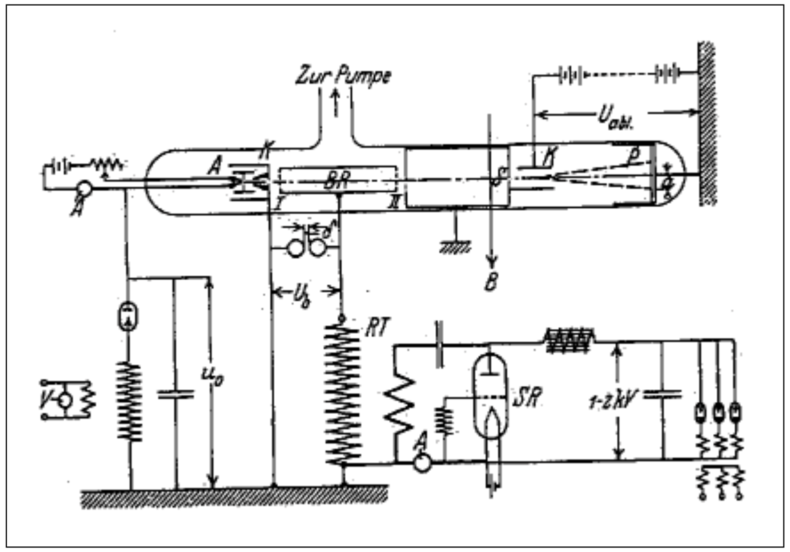
$$\frac{1}{T} = \frac{q \cdot B}{2\pi m}$$

Oscillating Fields

Northern Illinois University

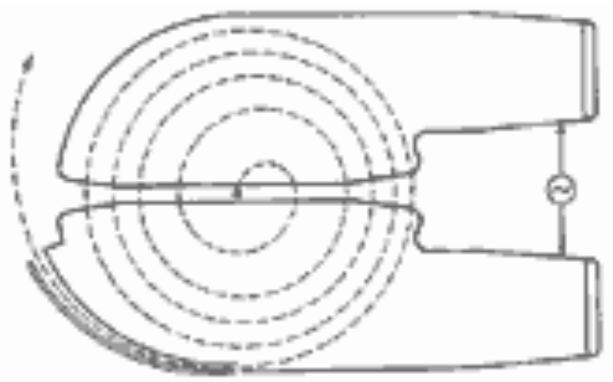
➡ The linear accelerator (linac) -- 1928-29

- 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)

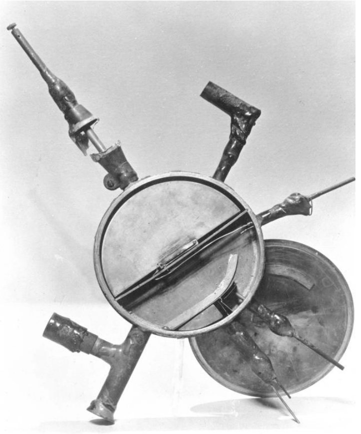
- read Wideroe’s paper (actually, looked at the pictures!)
- an extended “linac” unappealing -- make it more compact:



V

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

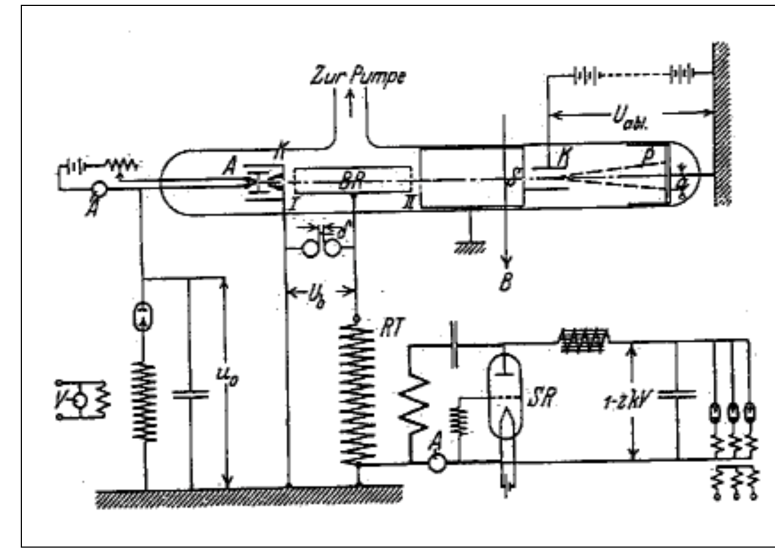
4.5 inch diameter!



Oscillating Fields

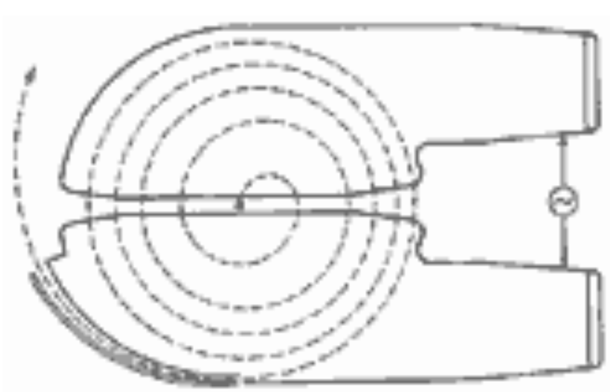
➡The linear accelerator (linac) -- 1928-29

- 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)

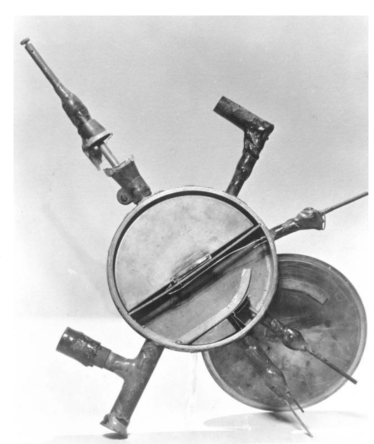
- read Wideroe’s paper (actually, looked at the pictures!)
- an extended “linac” unappealing -- make it more compact:



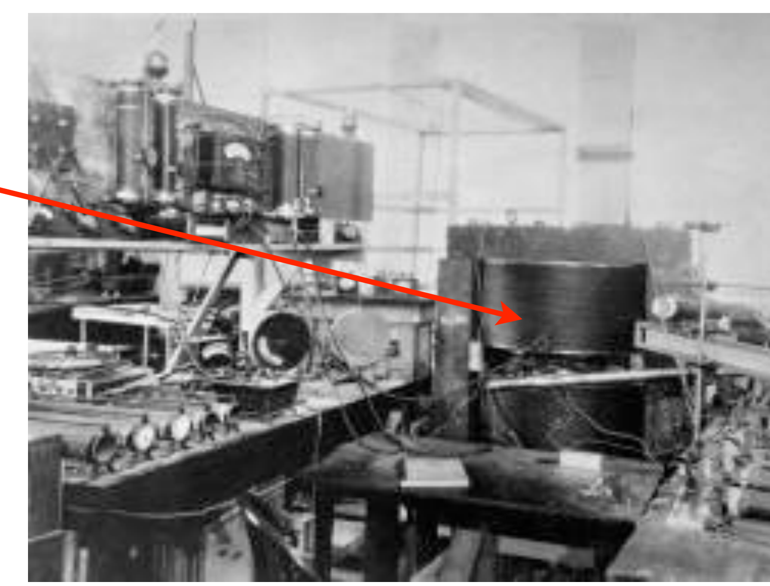
V

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

4.5 inch diameter!



11 inch diameter



60-inch Cyclotron, Berkeley -- 1930's

184-inch Cyclotron, Berkeley -- 1940's

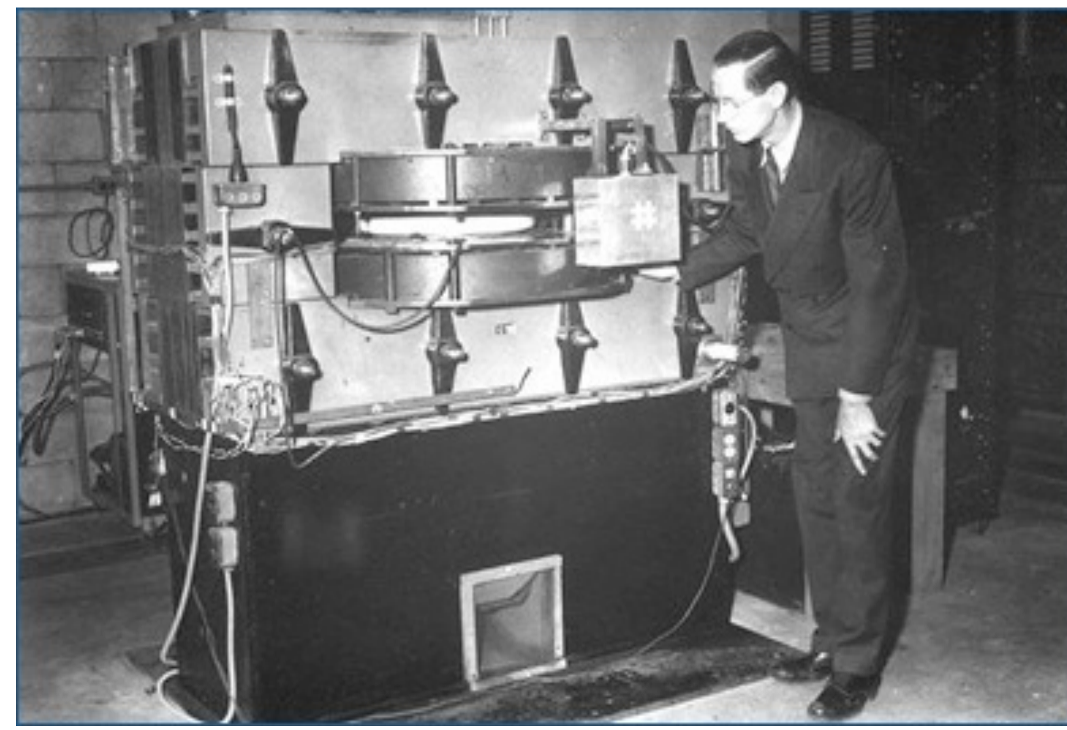
Northern Illinois University

184-inch Cyclotron, Berkeley -- 1940's

Northern Illinois University

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"

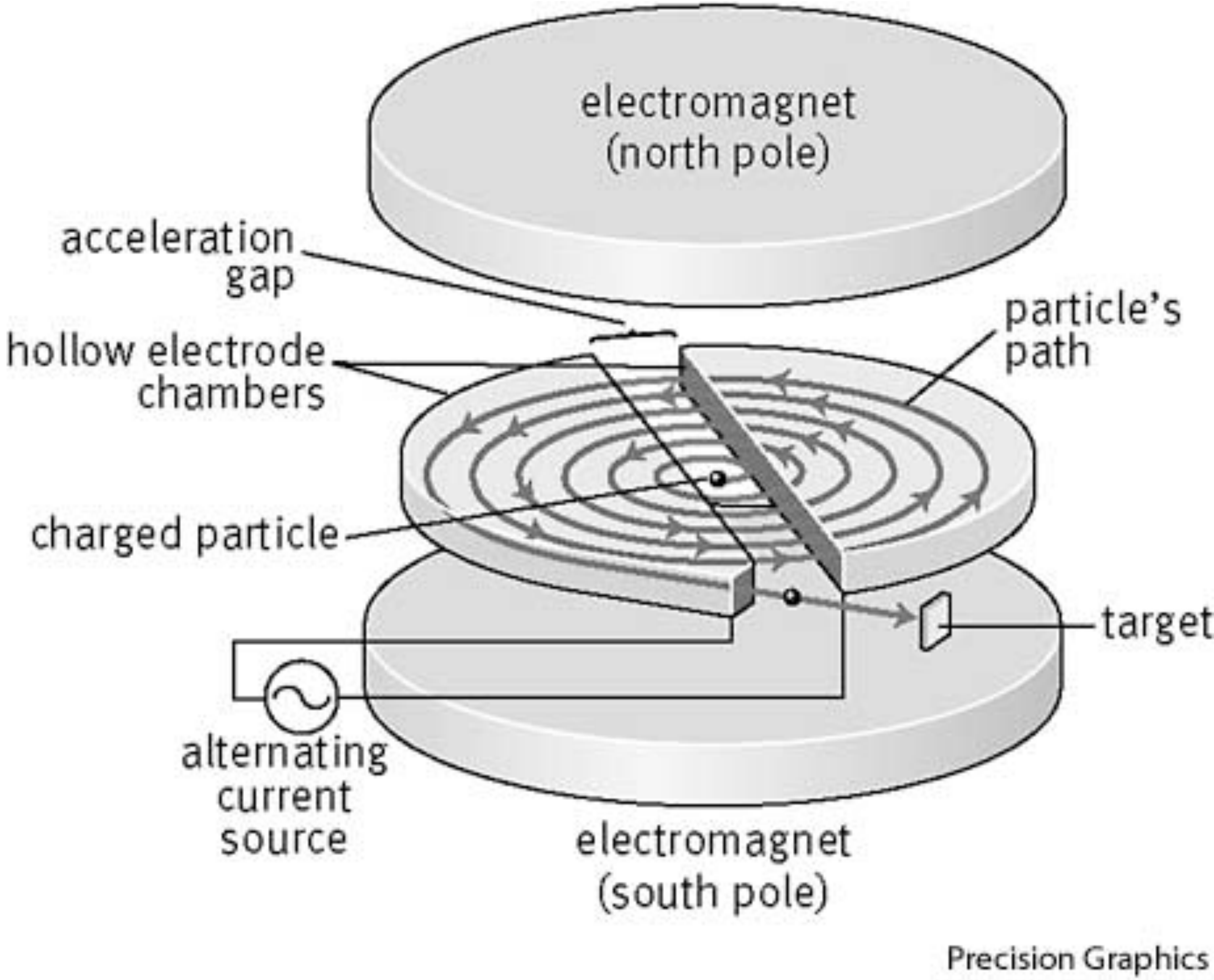


~ 2 MeV; later models --> 300 MeV

- 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

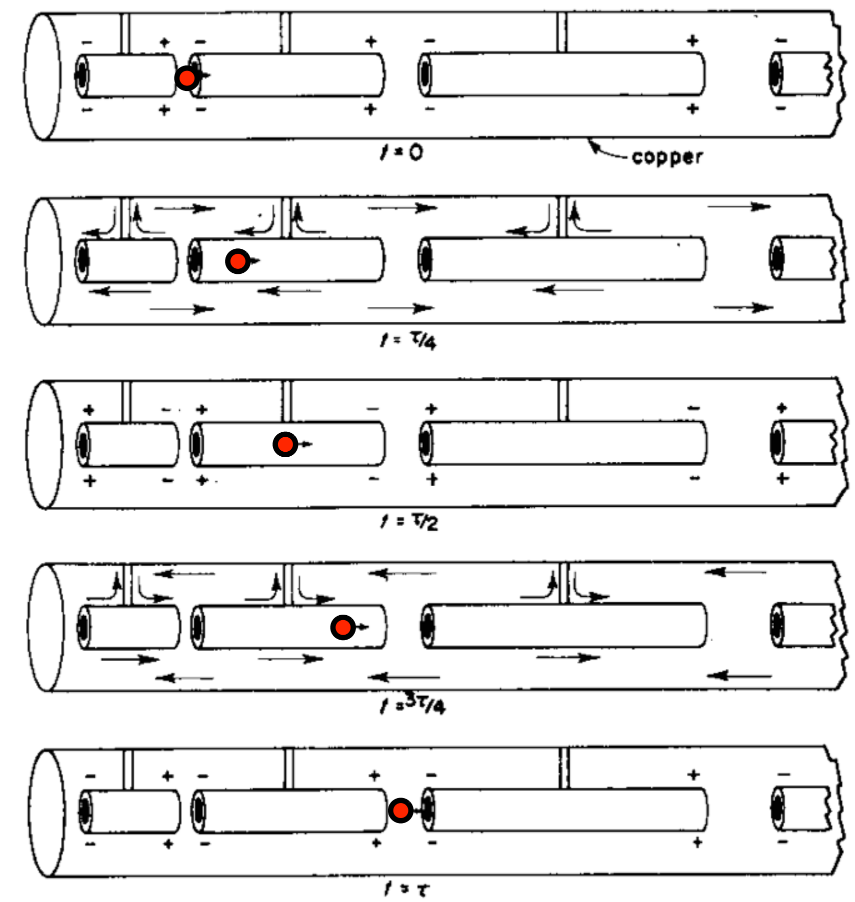


http://images.yourdictionary.com/cyclotron

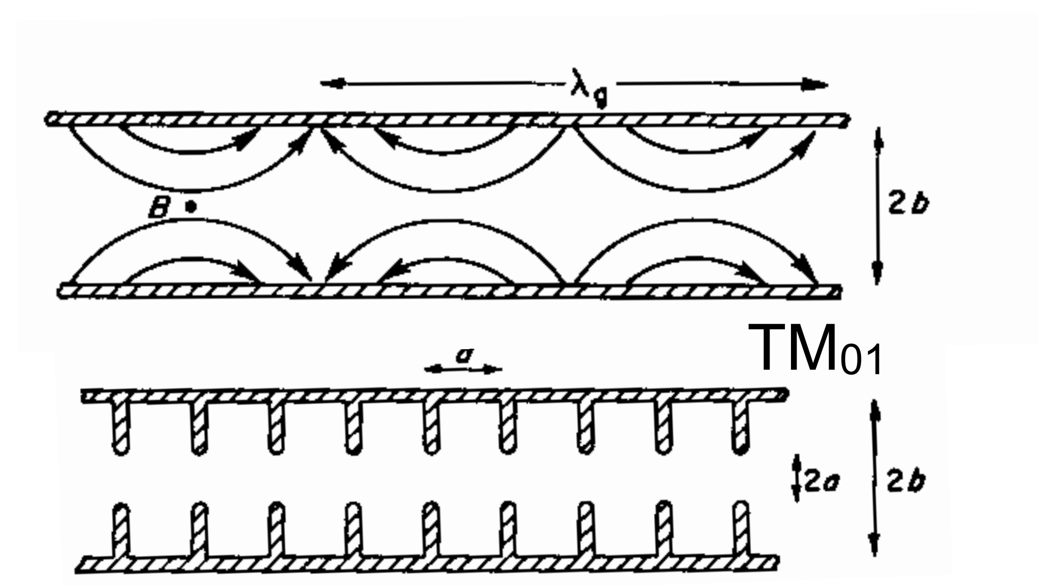
The “Modern” Linear Accelerator

Northern Illinois University

- 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

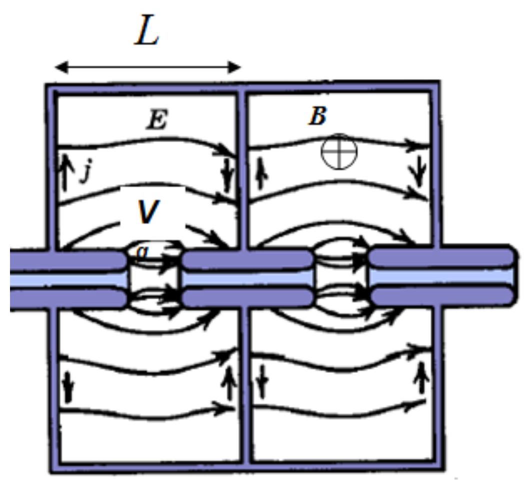


- Traveling-Wave Electron Accelerator -- c.1950 (Stanford, + Europe)
  - TM_{01} waveguide arrangement
  - iris-loaded cylindrical waveguide
    - » match phase velocity w/ particle velocity...



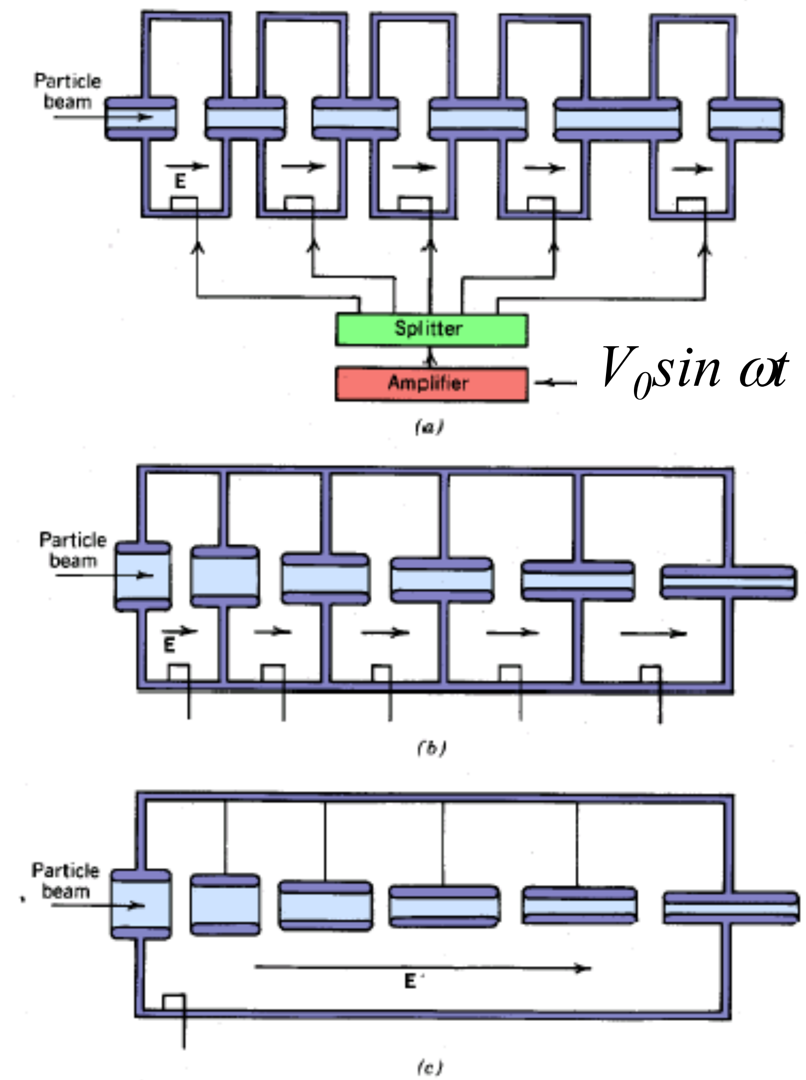
Radio-frequency Resonant Cavities

Northern Illinois University



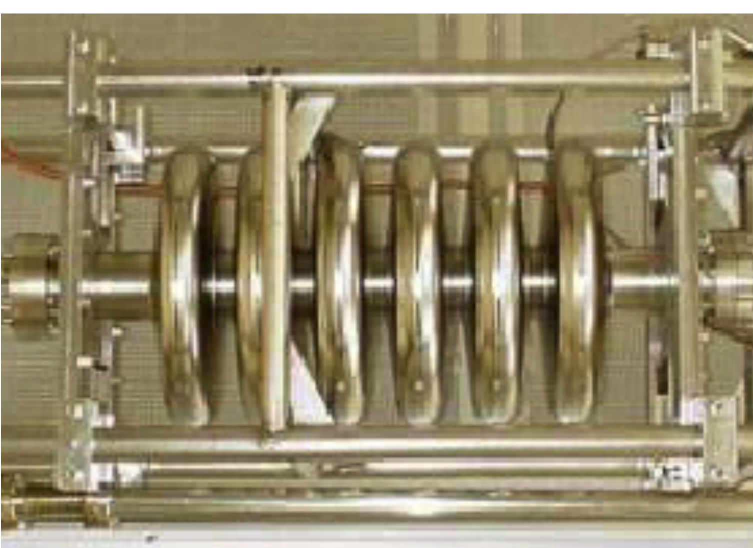
$$\oint \vec{E} \cdot d\vec{r} = -\frac{d\Phi_B}{dt}$$

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

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

Different Arrangements for Different Particles

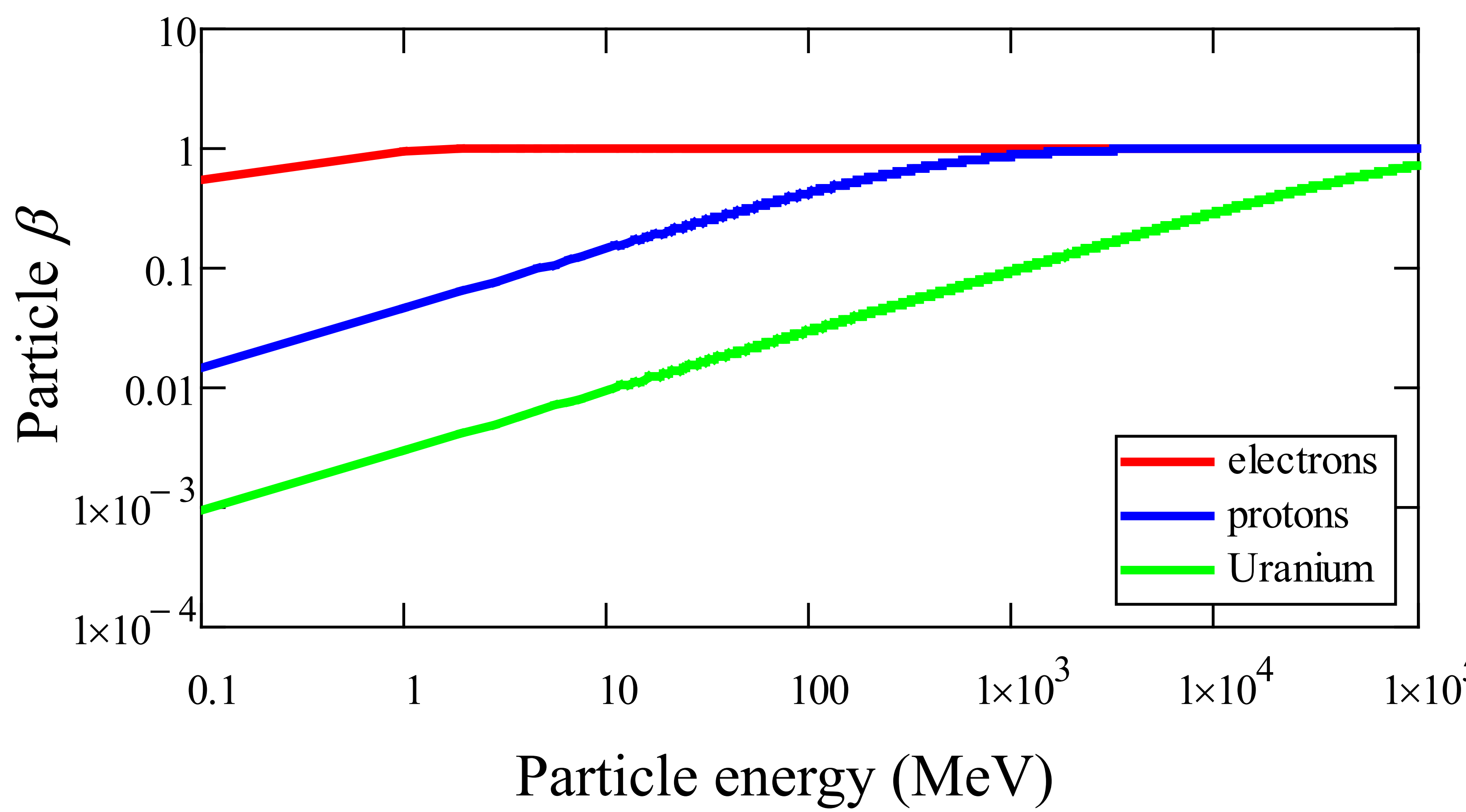
- Accelerating system used will depend upon the evolution of the particle velocity along the system
  - electrons reach a constant velocity at relatively low energy
    - » thus, can use one type of resonator
  - heavy particles reach a constant velocity only at very high energy
    - » thus, may need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

Particles rest mass:

•e 0.511 MeV

•p 938 MeV

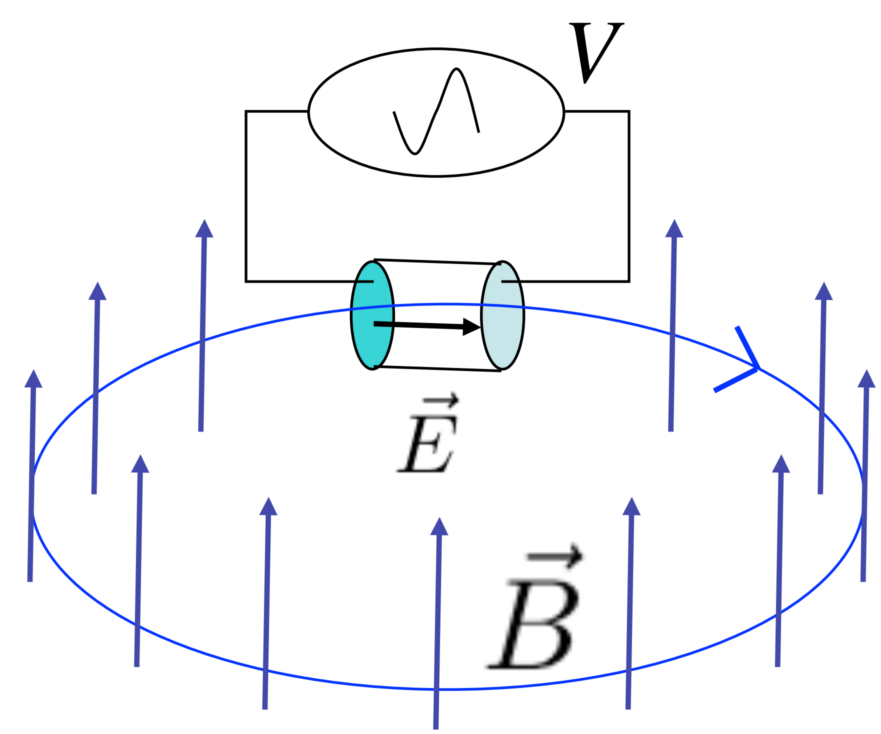
•^{239}U ~220000 MeV



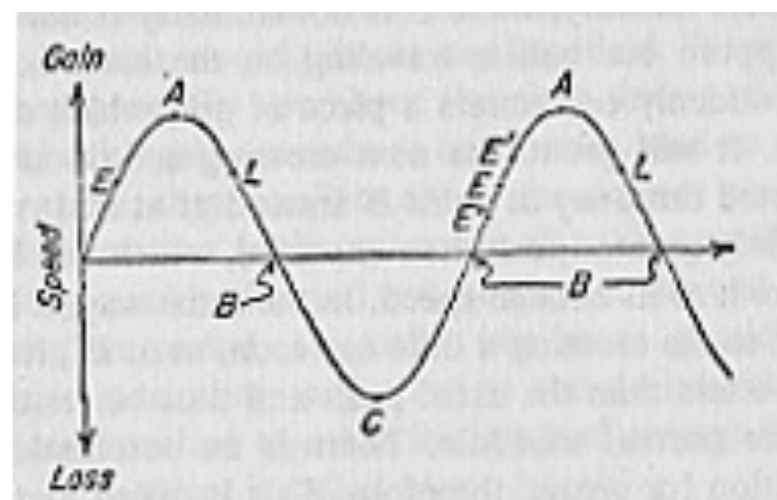
For Highest Elementary Particle Energies...

Northern Illinois University

- ... 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)



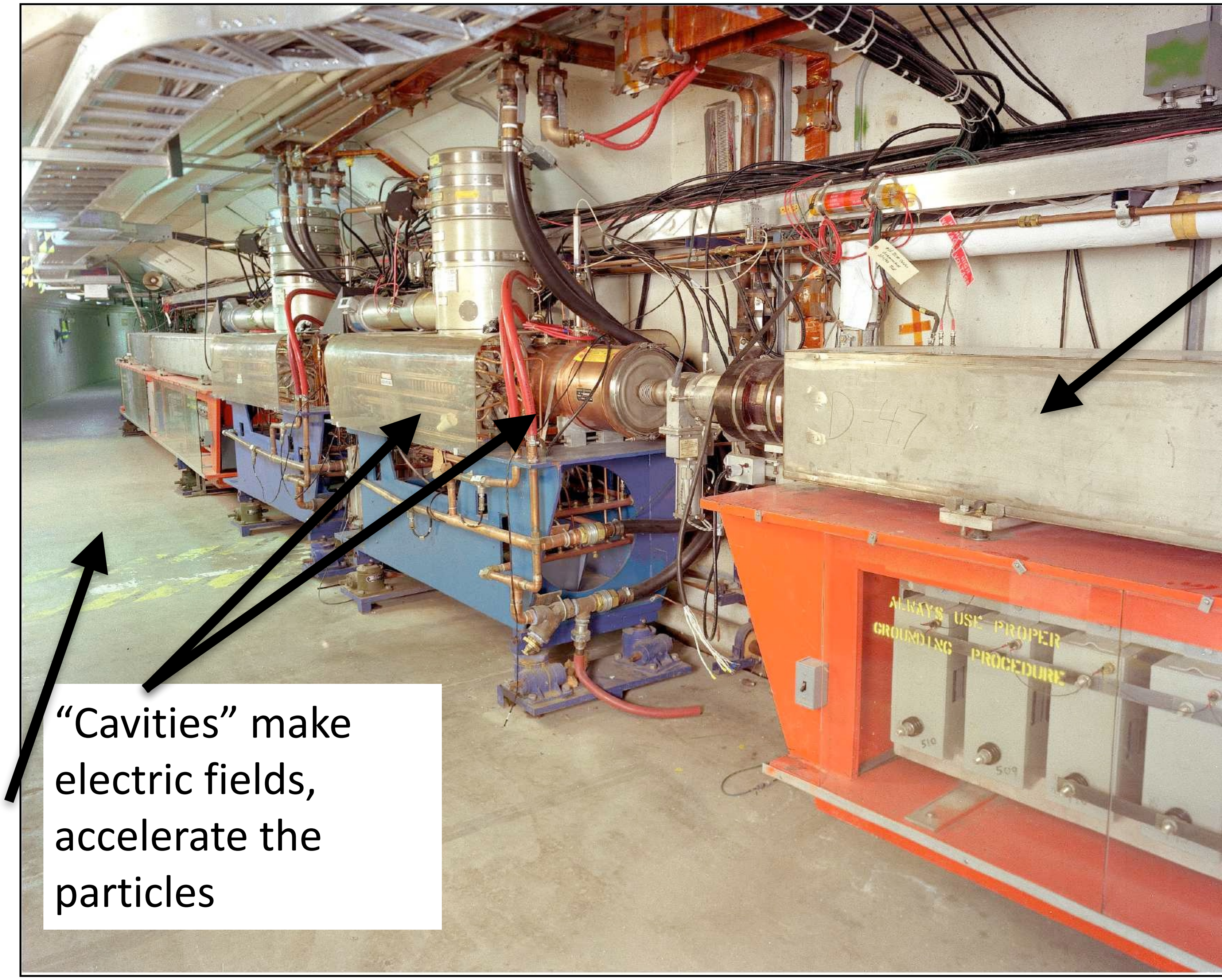
- arrive late, gain energy;   arrive early, get less   --
  - » *restoring force -> energy oscillation*
- as strength of *B* raised adiabatically, the oscillations will continue about the "*synchronous*" momentum, defined by $p/e = B \cdot R$ for constant *R* :

Synchrotron Oscillations

A Synchrotron

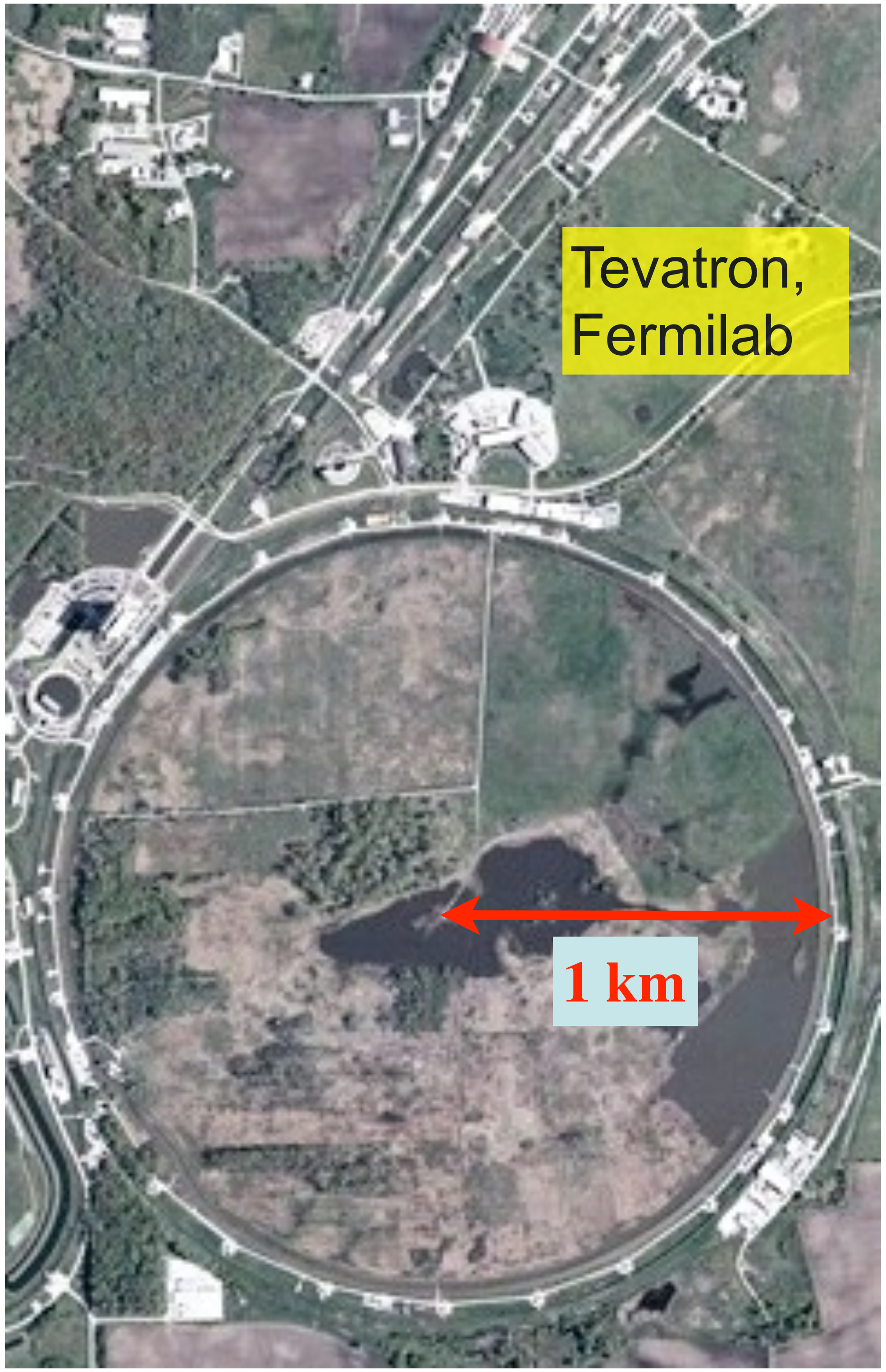
Northern Illinois University

Magnets steer the particles in a circle



Booster Synchrotron, Fermilab (Batavia, IL)

The Large Colliders



Fixed Target Energy vs. Collider Energy

Northern Illinois University

- Beam/target particles:

$$E_0 \equiv mc^2$$

before

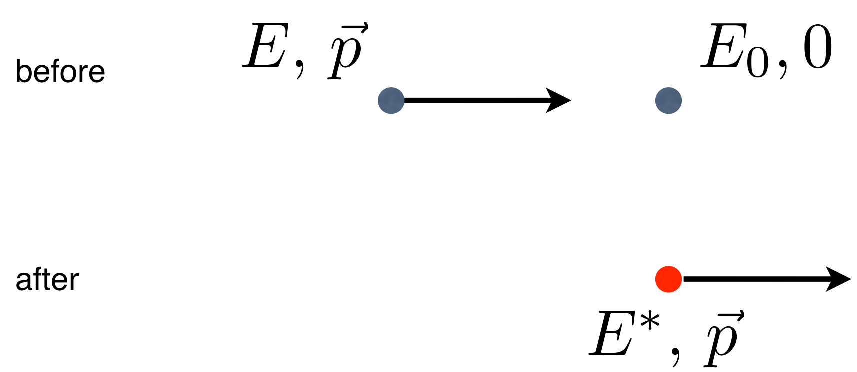
after

Fixed Target Energy vs. Collider Energy

- Beam/target particles:

$$E_0 \equiv mc^2$$

Fixed Target



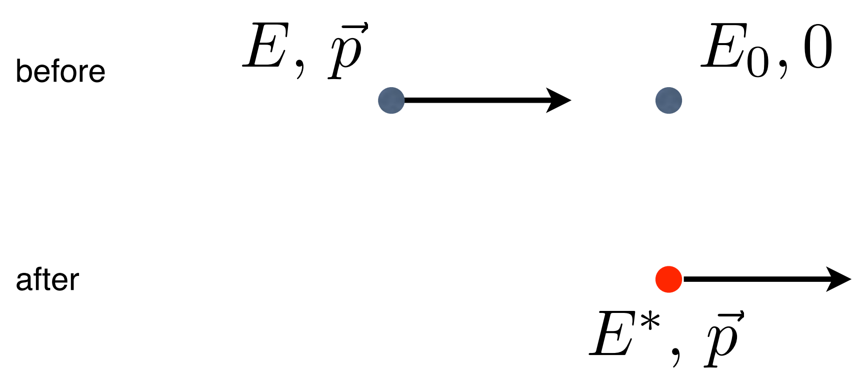
Fixed Target Energy vs. Collider Energy

Northern Illinois University

- Beam/target particles:

$$E_0 \equiv mc^2$$

__Fixed Target__

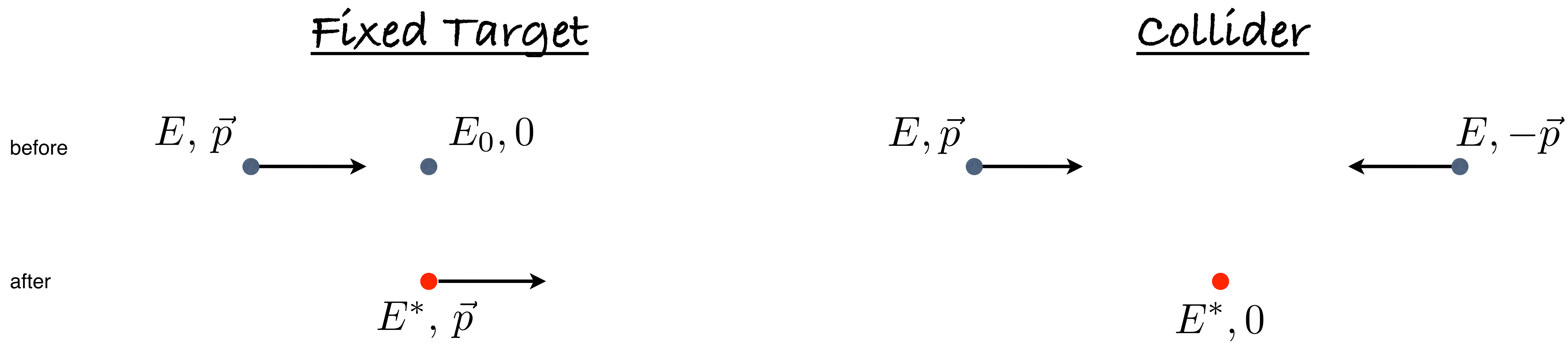


$$\begin{aligned} E^{*2} = (m^* c^2)^2 + (pc)^2 &= [\ E_0 + E\ ]^2 \\ &= E_0^2 + 2E_0 E + (E_0^2 + (pc)^2) \\ m^* c^2 &= \sqrt{2}\ E_0\ [1 + \gamma_{FT}]^{1/2} \end{aligned}$$

Fixed Target Energy vs. Collider Energy

- Beam/target particles:

$$E_0 \equiv mc^2$$



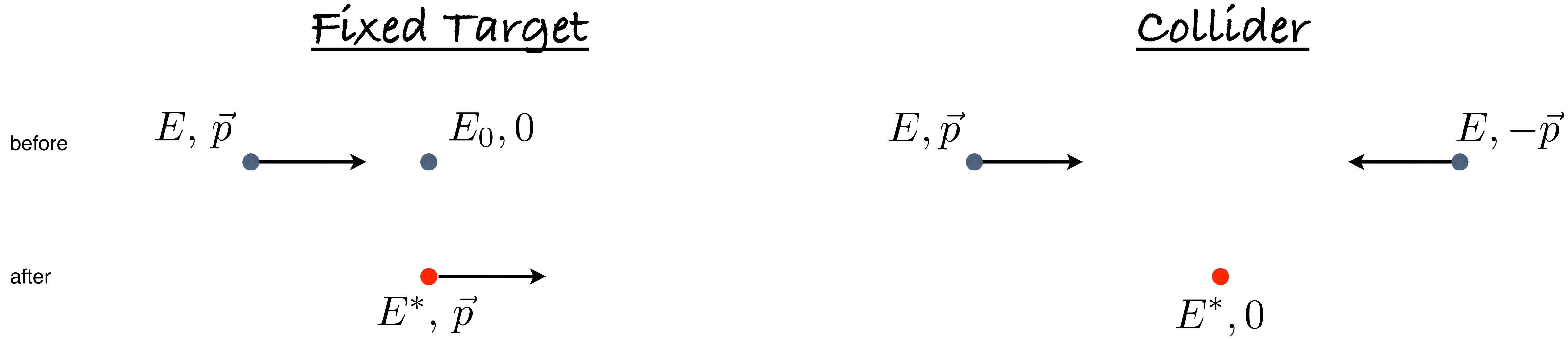
$$\begin{aligned}
E^{*2} = (m^* c^2)^2 + (pc)^2 &= [\ E_0 + E\ ]^2 \\
&= E_0^2 + 2E_0 E + (E_0^2 + (pc)^2) \\
m^* c^2 &= \sqrt{2}\ E_0\ [1 + \gamma_{FT}]^{1/2}
\end{aligned}$$

Fixed Target Energy vs. Collider Energy

Northern Illinois University

- Beam/target particles:

$$E_0 \equiv mc^2$$



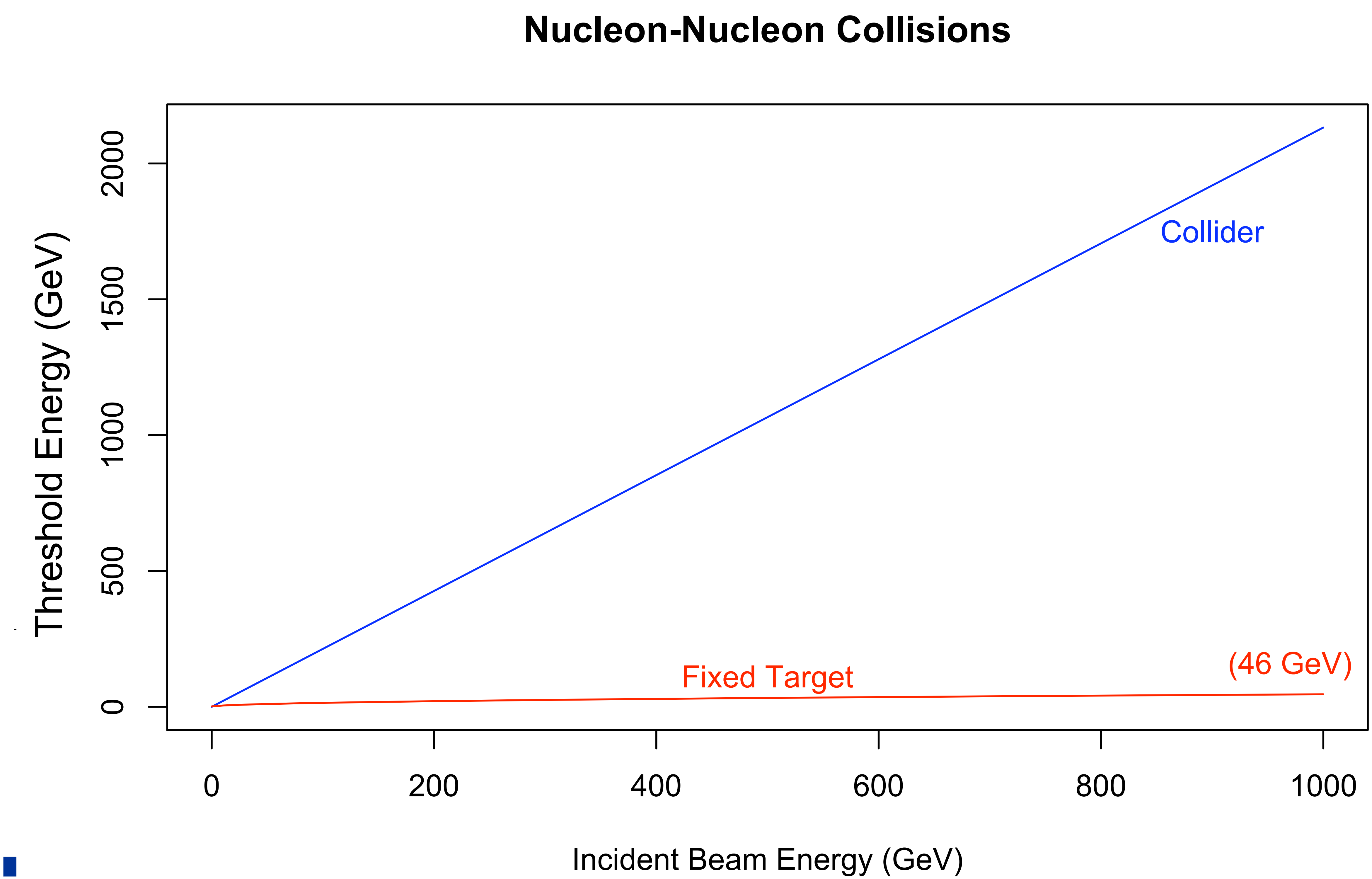
$$\begin{aligned} E^{*2} = (m^*c^2)^2 + (pc)^2 &= [\ E_0 + E\ ]^2 \\ &= E_0^2 + 2E_0E + (E_0^2 + (pc)^2) \\ m^*c^2 &= \sqrt{2}\ E_0\ [1 + \gamma_{FT}]^{1/2} \end{aligned}$$

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

Fixed Target Energy vs. Collider Energy

Northern Illinois University

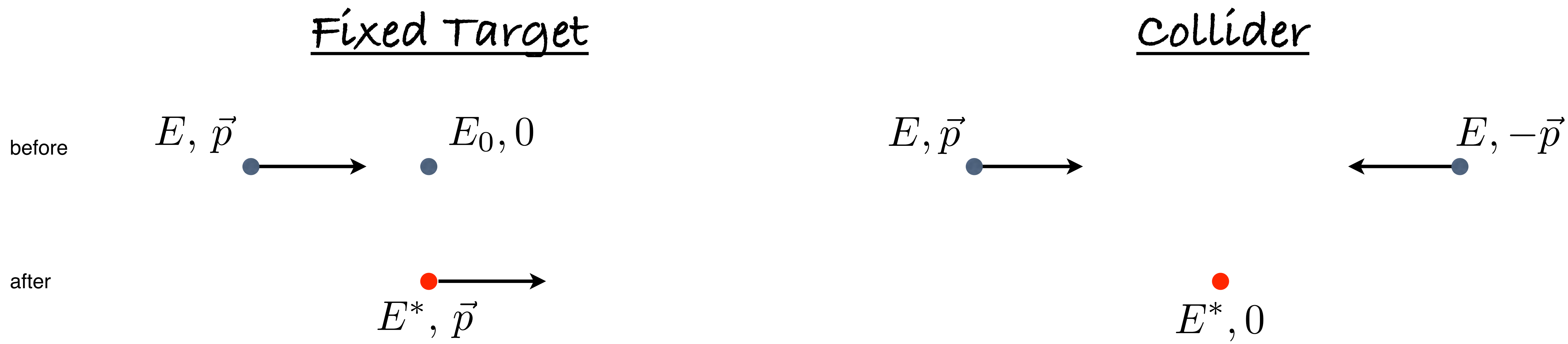
•



Fixed Target Energy vs. Collider Energy

- Beam/target particles:

$$E_0 \equiv mc^2$$



Fixed Target:

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

Collider:

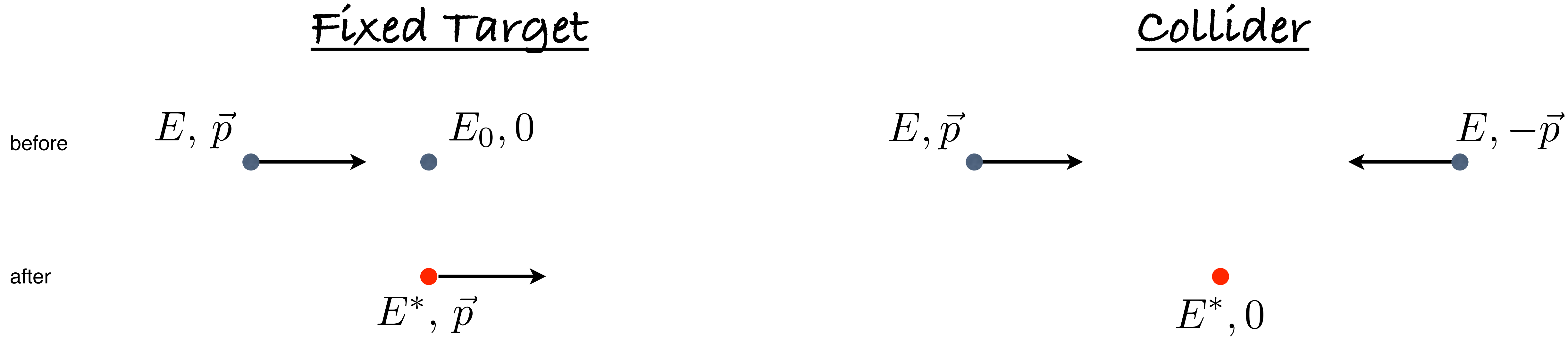
$$\begin{aligned} m^*c^2 &= 2E \\ &= 2E_0\gamma_{coll} \end{aligned}$$

Fixed Target Energy vs. Collider Energy

Northern Illinois University

- Beam/target particles:

$$E_0 \equiv mc^2$$



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

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

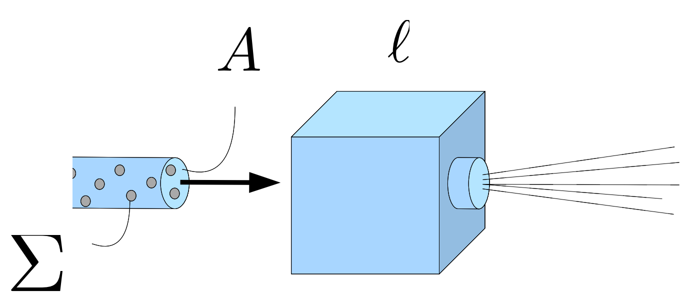
100,000 TeV FT synch. == 14 TeV LHC

Luminosity

Northern Illinois University

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

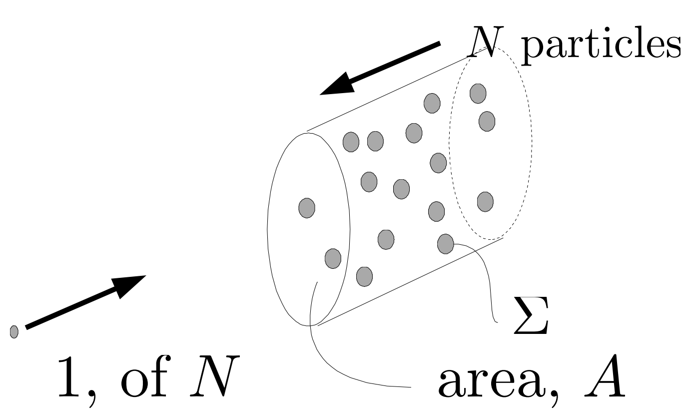
- Fixed Target Experiment:



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

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

- Bunched-Beam Collider:

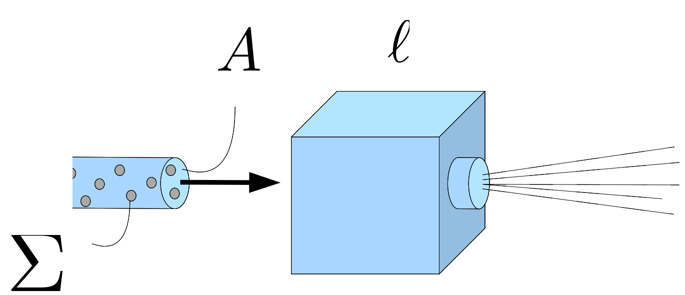


$$\begin{aligned}\mathcal{R} &= \left(\frac{\Sigma}{A}\right) \cdot N \cdot (f \cdot N) \\ &= \frac{f\ N^2}{A} \cdot \Sigma \\ \mathcal{L} &\equiv \frac{f\ N^2}{A} \qquad (10^{34}\mathrm{cm}^{-2}\mathrm{sec}^{-1} \text{ for LHC})\end{aligned}$$

Luminosity

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

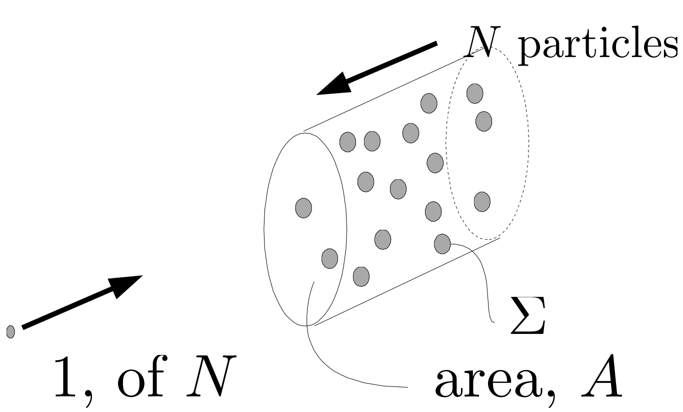
- Fixed Target Experiment:



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

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

- Bunched-Beam Collider:



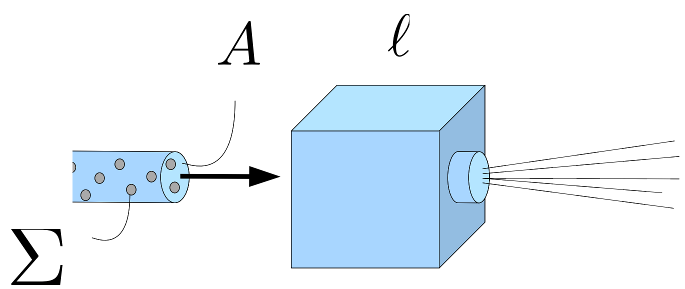
$$\begin{aligned}\mathcal{R} &= \left(\frac{\Sigma}{A}\right)\cdot N\cdot(f\cdot N)\\ &= \frac{f\ N^2}{A}\cdot\Sigma\\ \mathcal{L} &\equiv \frac{f\ N^2}{A}\end{aligned}$$

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

Luminosity

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

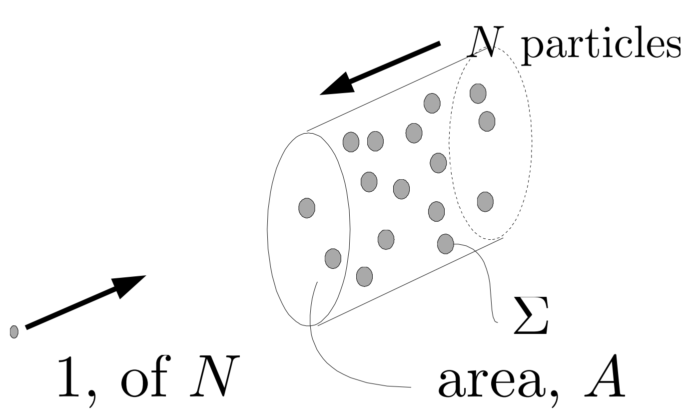
- Fixed Target Experiment:



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

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

- Bunched-Beam Collider:



$$\mathcal{R} = \left(\frac{\Sigma}{A}\right) \cdot N \cdot (f \cdot N)$$
$$= \frac{f\ N^2}{A} \cdot \Sigma$$
$$\mathcal{L} \equiv \frac{f\ N^2}{A}$$

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

Integrated Luminosity

Northern Illinois University

- 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 $\mathcal{L}$)

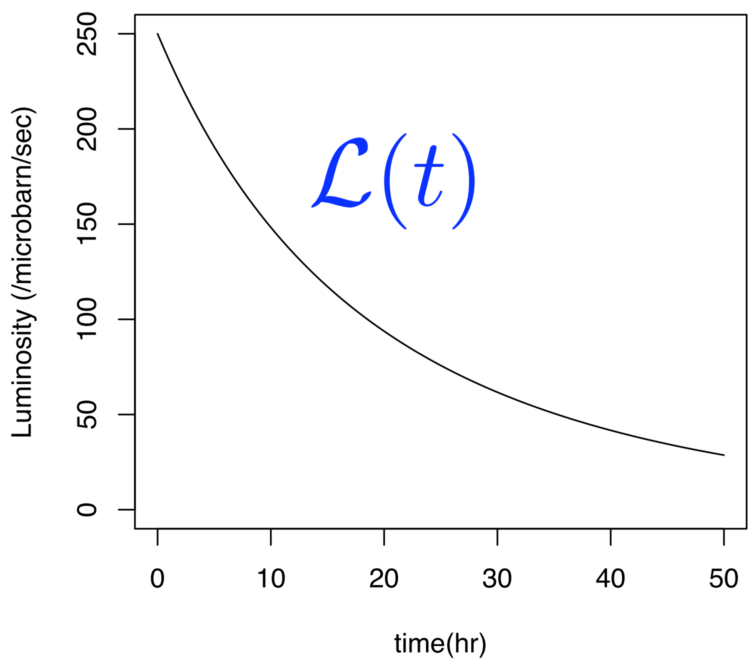
- So, in this ideal case,

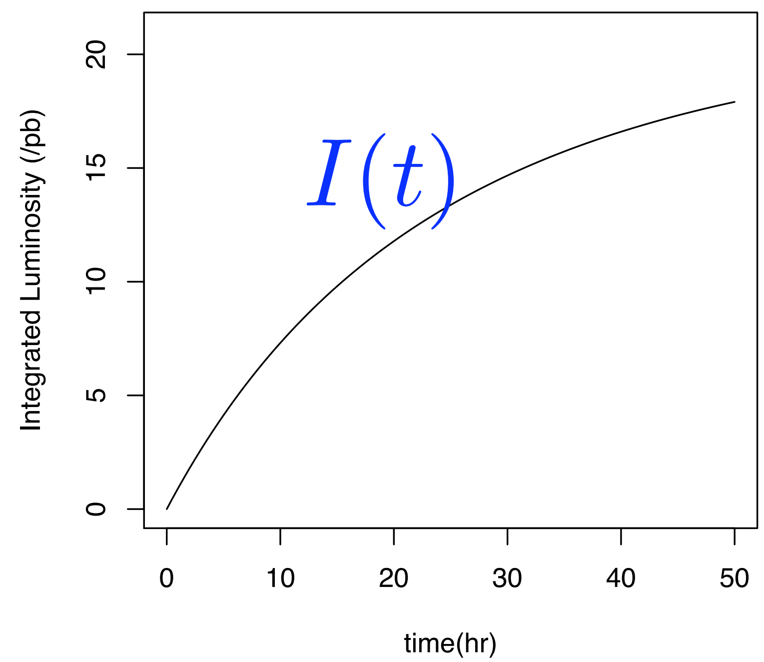
$$\mathcal{L}(t) = \frac{\mathcal{L}_0}{\left[1 + \left(\frac{n\mathcal{L}_0\Sigma}{BN_0}\right)t\right]^2}$$

Ultimate Number of Collisions

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

$$I(T) \equiv \int_0^T \mathcal{L}(t)dt = \frac{\mathcal{L}_0 T}{1 + \mathcal{L}_0 T (n\Sigma / B N_0)} = I_0 \cdot \frac{\mathcal{L}_0 T / I_0}{1 + \mathcal{L}_0 T / I_0}$$





asymptotic limit:

$$I_0 \equiv \frac{B N_0}{n\Sigma}$$

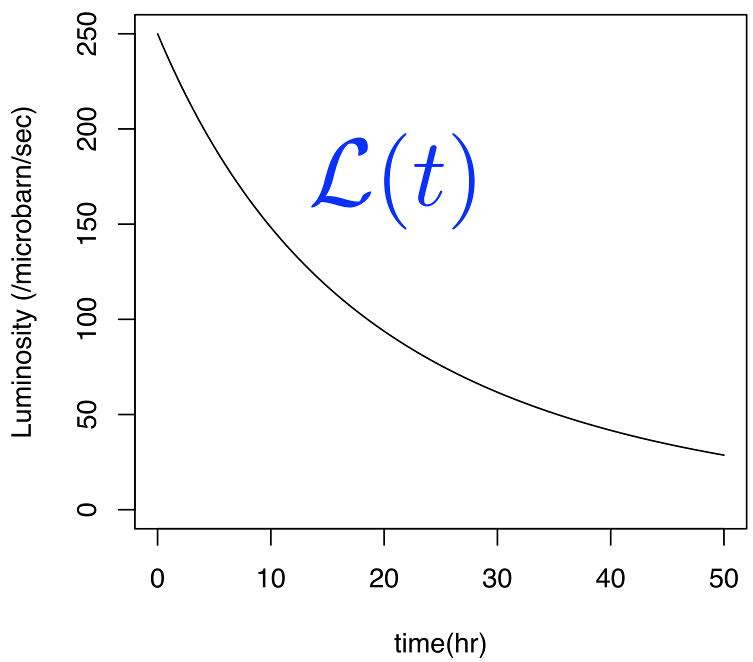
so, ...

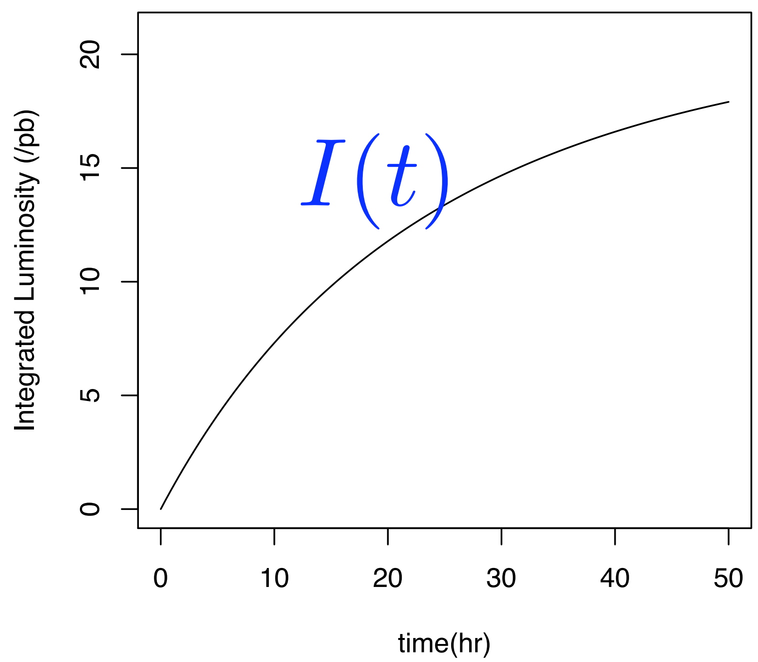
$$\mathcal{L} = \frac{f_0 B N^2}{A}$$

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:

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

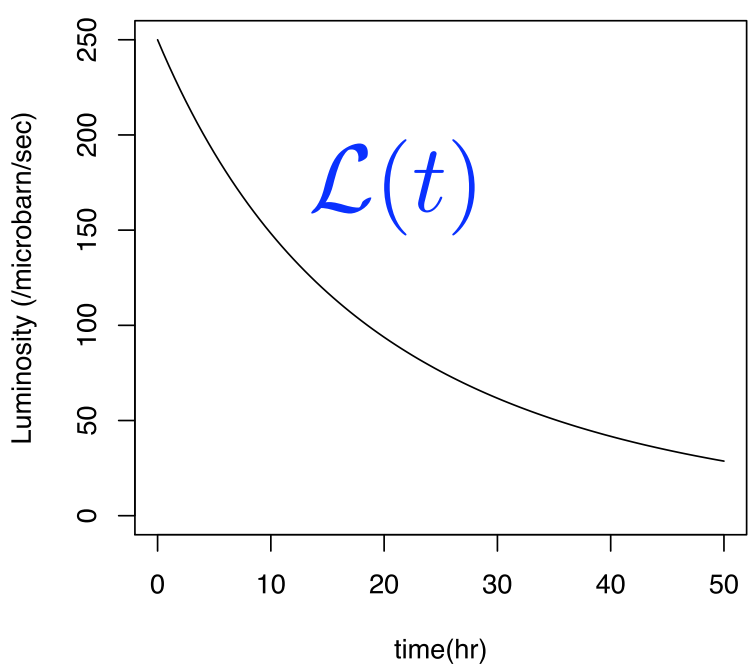
so, ...

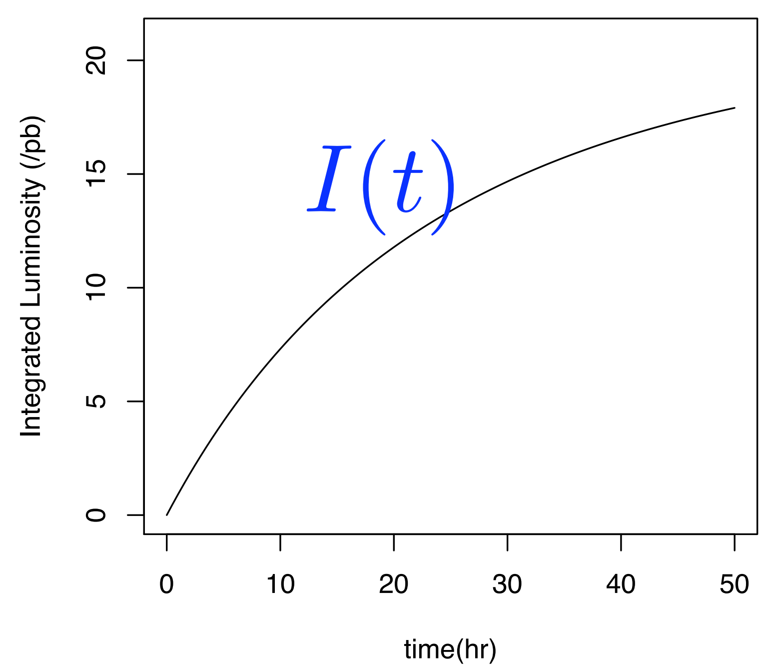
$$\mathcal{L} = \frac{f_0 B N^2}{A}$$

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

$$I(T) \equiv \int_0^T \mathcal{L}(t)dt = \frac{\mathcal{L}_0 T}{1 + \mathcal{L}_0 T (n\Sigma / B N_0)} = I_0 \cdot \frac{\mathcal{L}_0 T / I_0}{1 + \mathcal{L}_0 T / I_0}$$





asymptotic limit:

$$I_0 \equiv \frac{B N_0}{n\Sigma}$$

so, ...

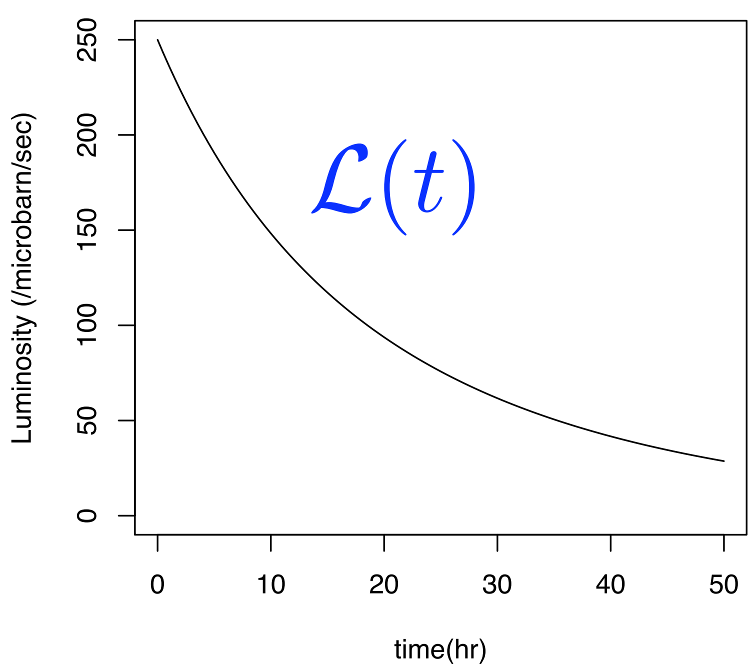
$$\mathcal{L} = \frac{f_0 B N^2}{A}$$

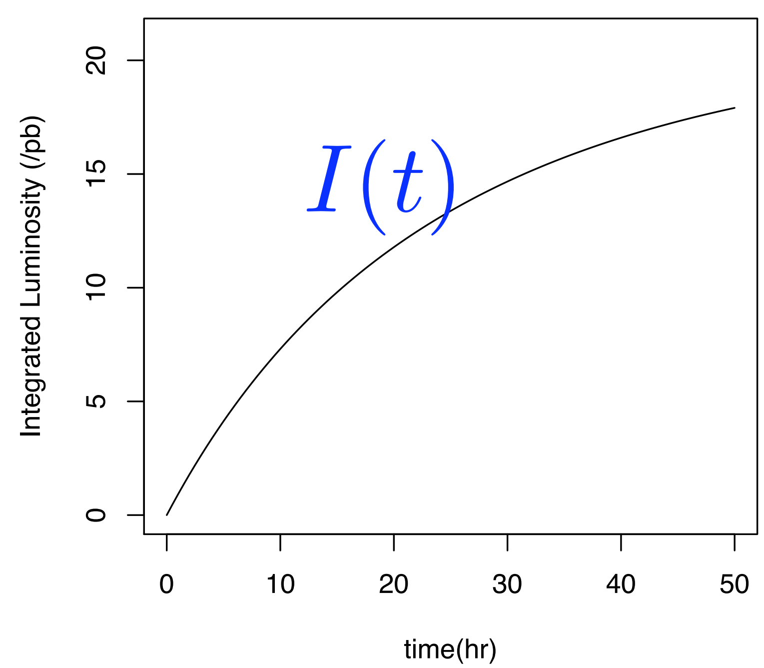
Ultimate Number of Collisions

Northern Illinois University

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

$$I(T) \equiv \int_0^T \mathcal{L}(t)dt = \frac{\mathcal{L}_0 T}{1 + \mathcal{L}_0 T (n\Sigma / B N_0)} = I_0 \cdot \frac{\mathcal{L}_0 T / I_0}{1 + \mathcal{L}_0 T / I_0}$$





asymptotic limit:

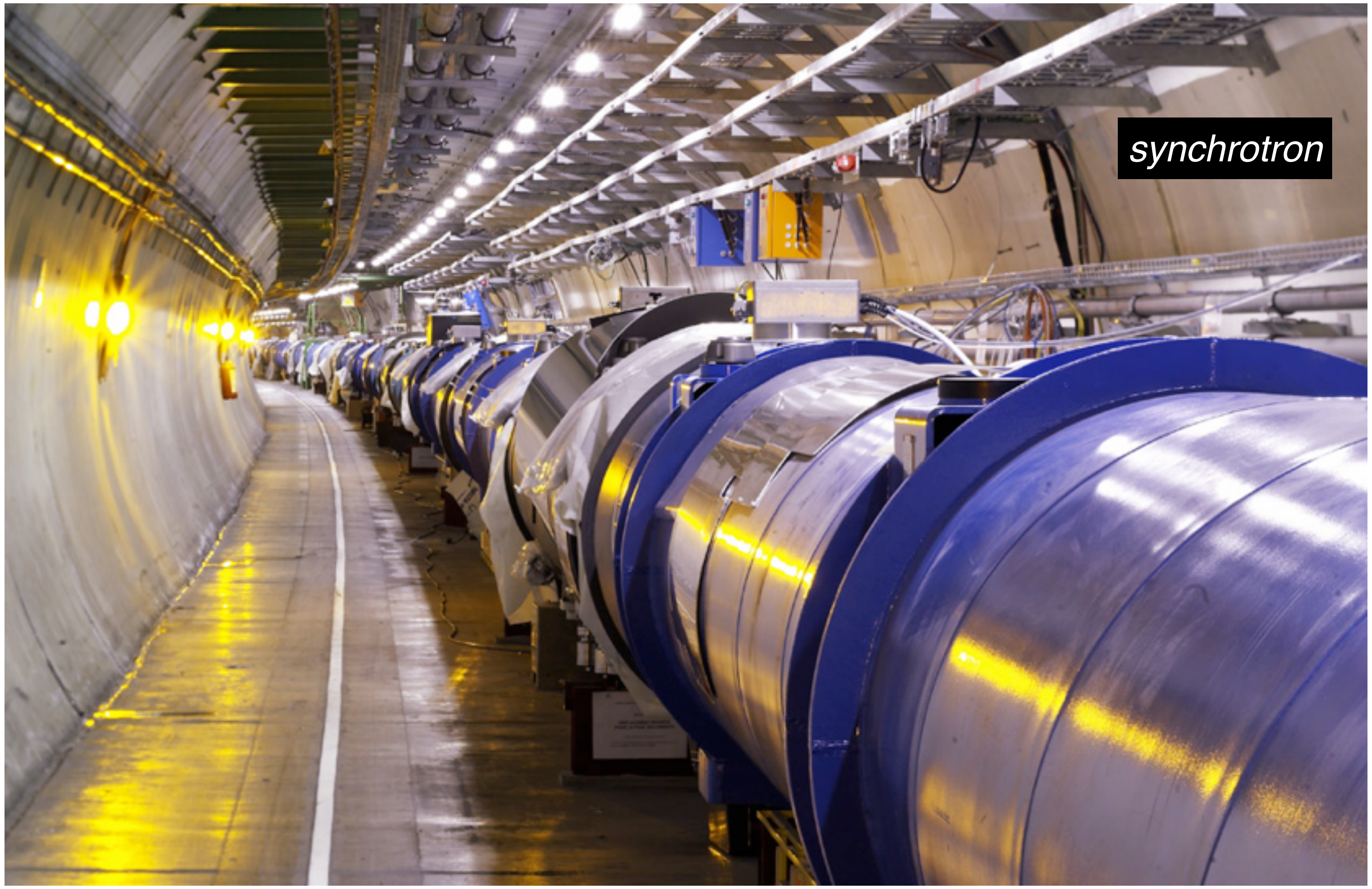
$$I_0 \equiv \frac{B N_0}{n\Sigma}$$

so, ...

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

Recent Large-Scale Accelerators

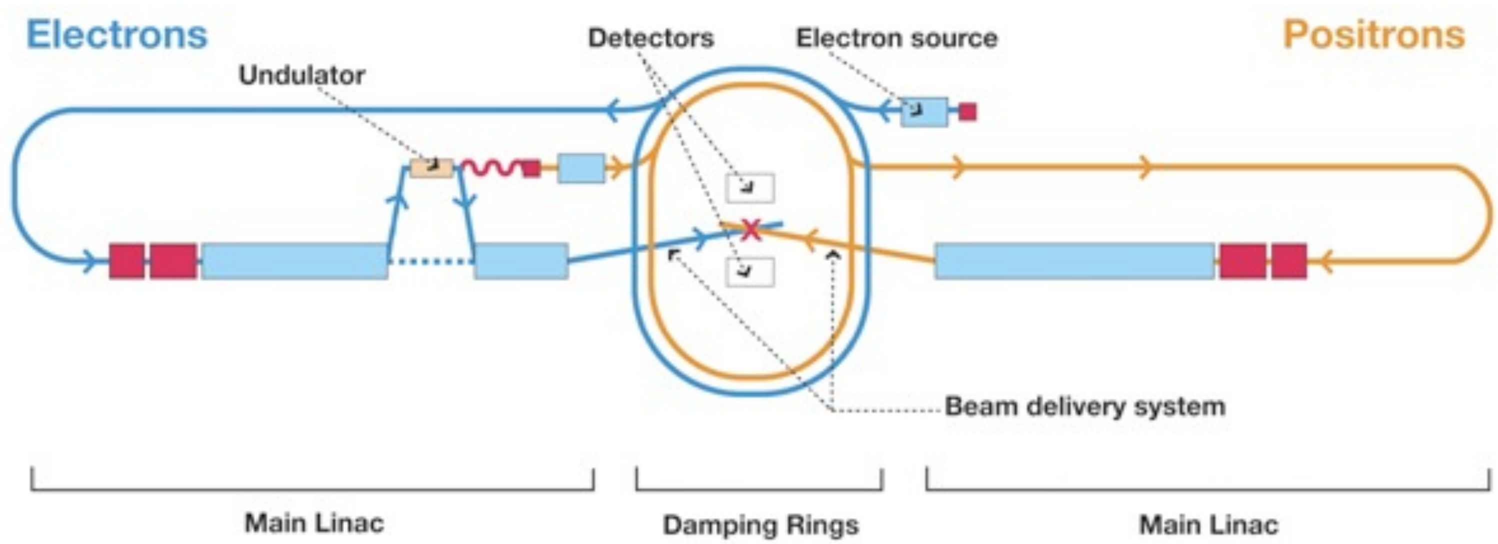
Large Hadron Collider (LHC)



Spallation Neutron Source (SNS)

The Linac -- Again

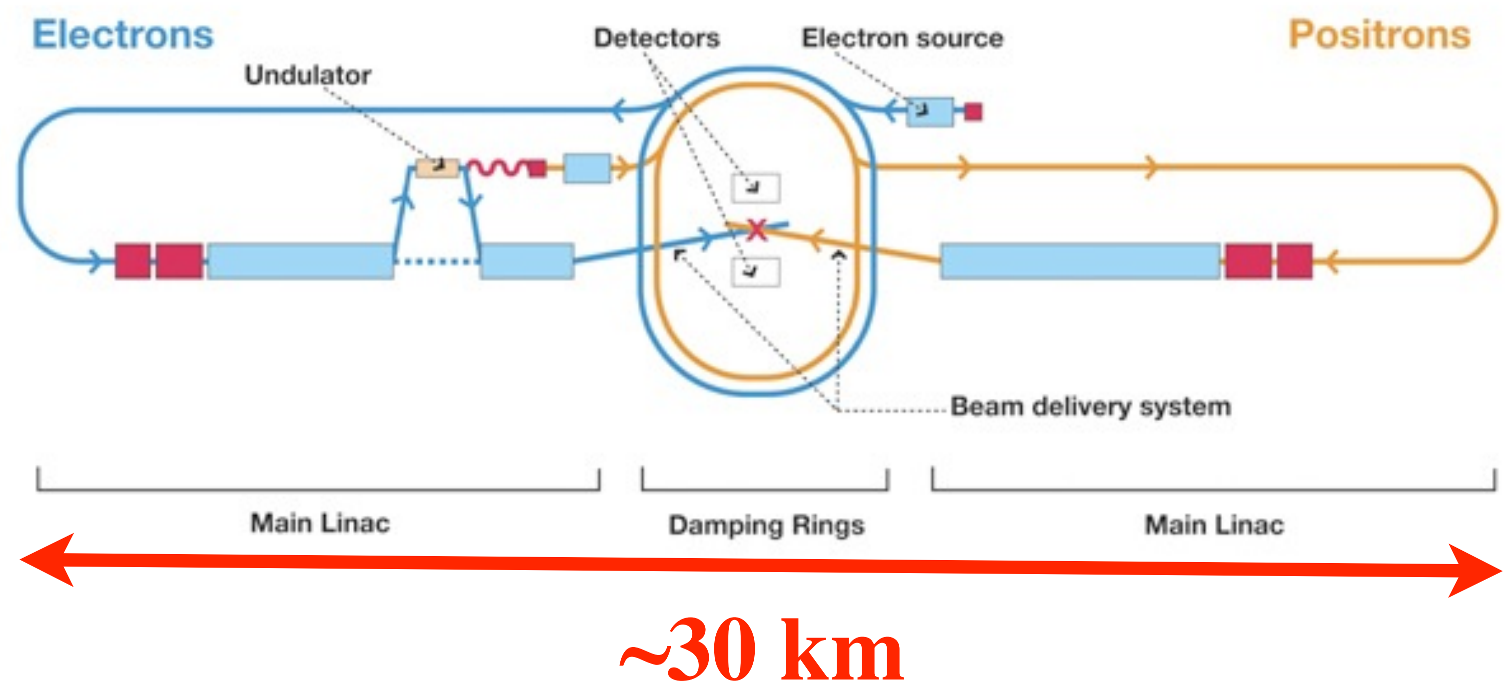
- Linacs for e+/-
  - ILC, CLIC
  - avoid synchrotron radiation
  - damping rings produce very small beams at interaction points



- Resurgent use of Linacs for large *p*, *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,...

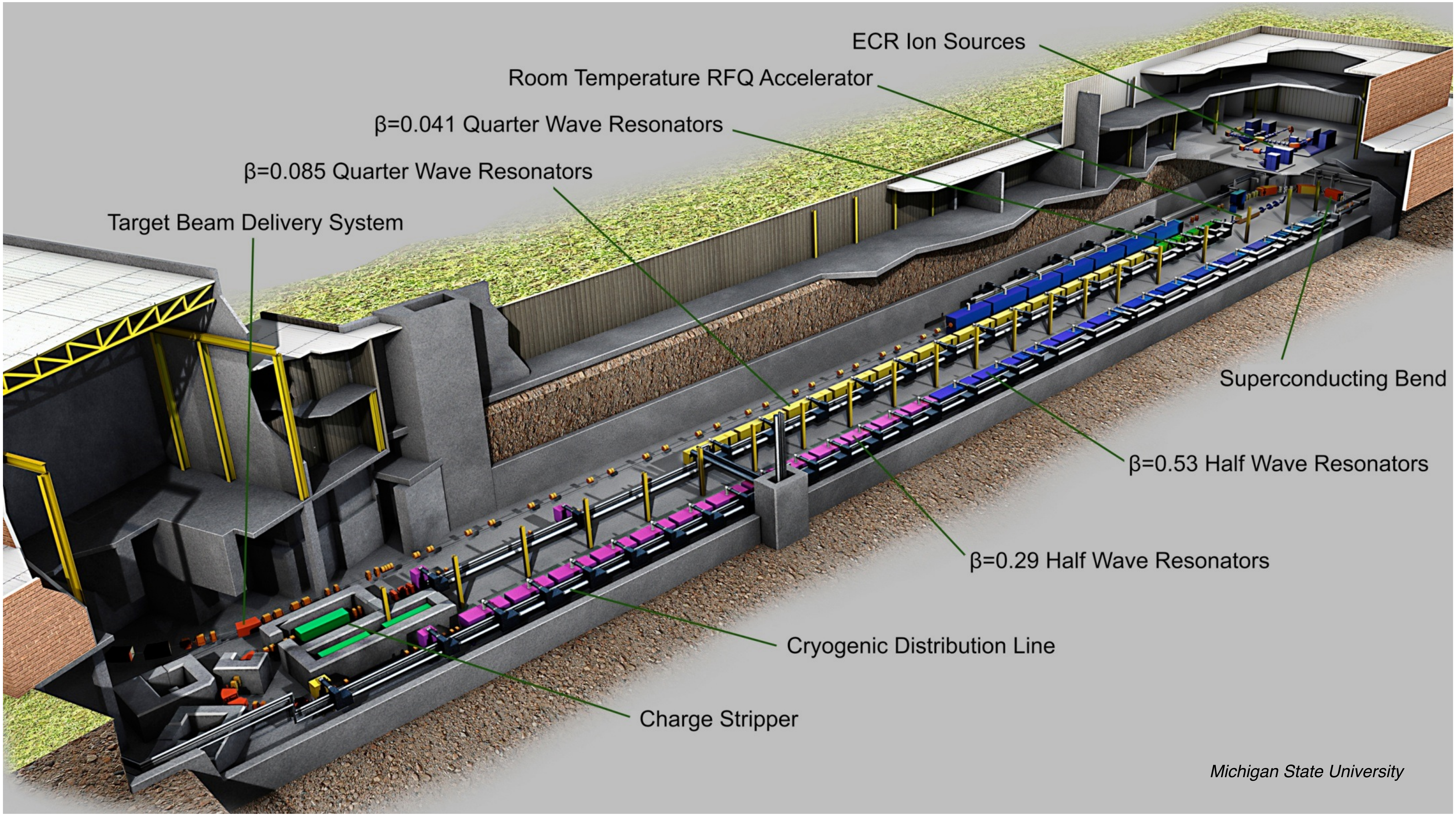
The Linac -- Again

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



- Resurgent use of Linacs for large *p*, *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,...

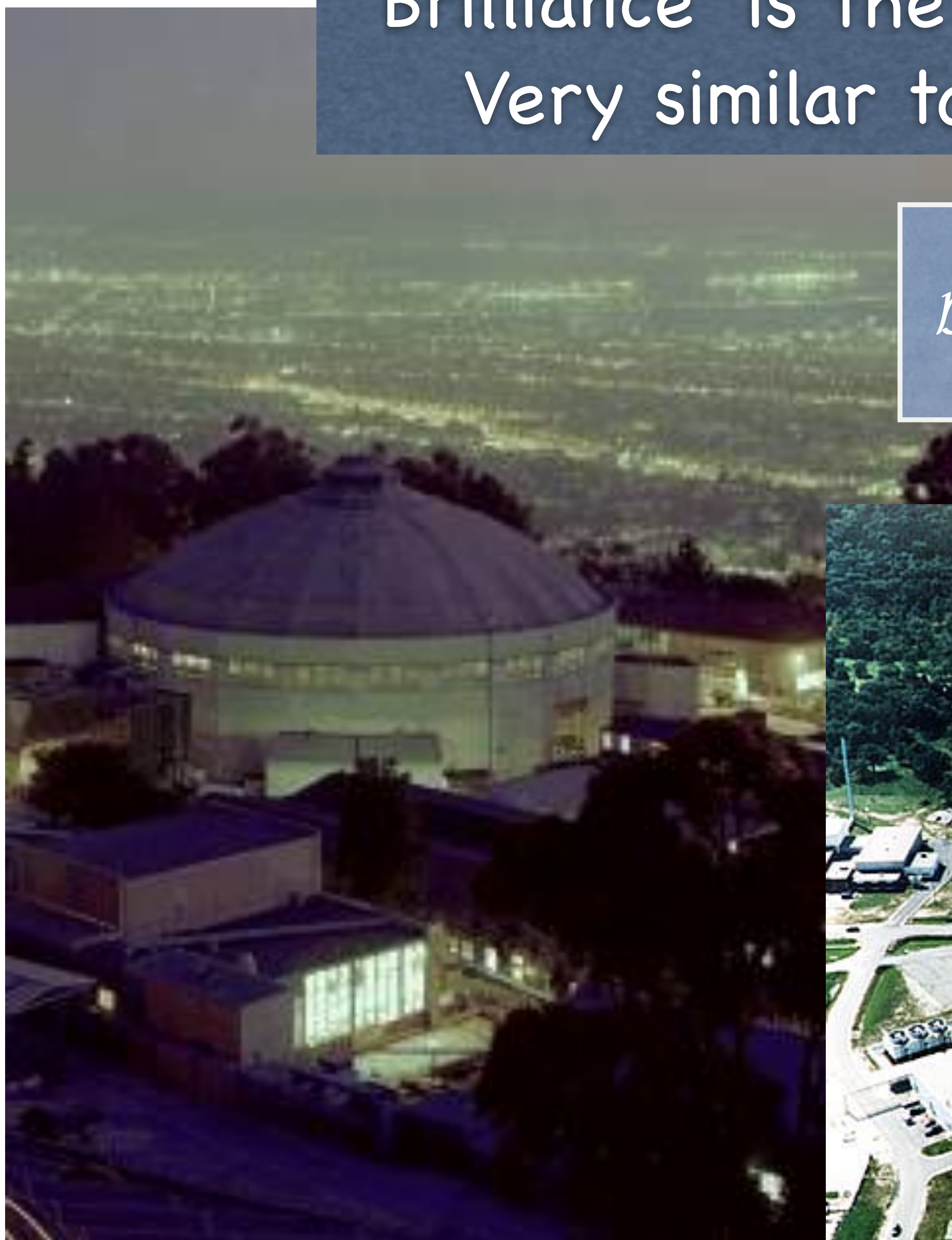
Facility for Rare Isotope Beams (FRIB)



Light Sources

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

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



But Wait, There's More!

Northern Illinois University

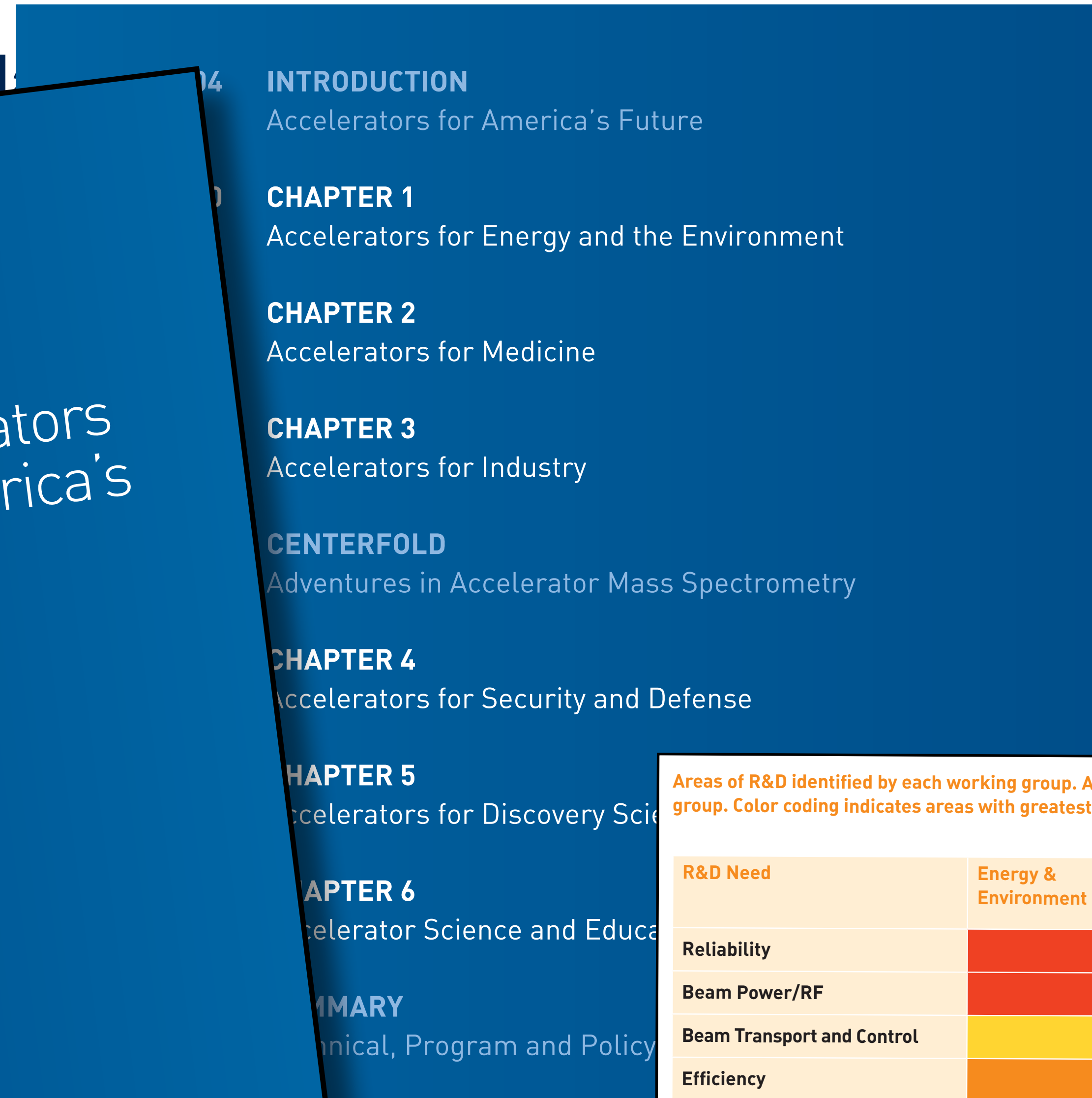
- And, of course, not all applications are in high energy or nuclear physics!
- Basic energy sciences as well as industrial applications make up the bulk of our field, in terms of number of accelerators and arguably their direct impact on society
  - ~26,000 accelerators worldwide*
  - ~1% are research 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*

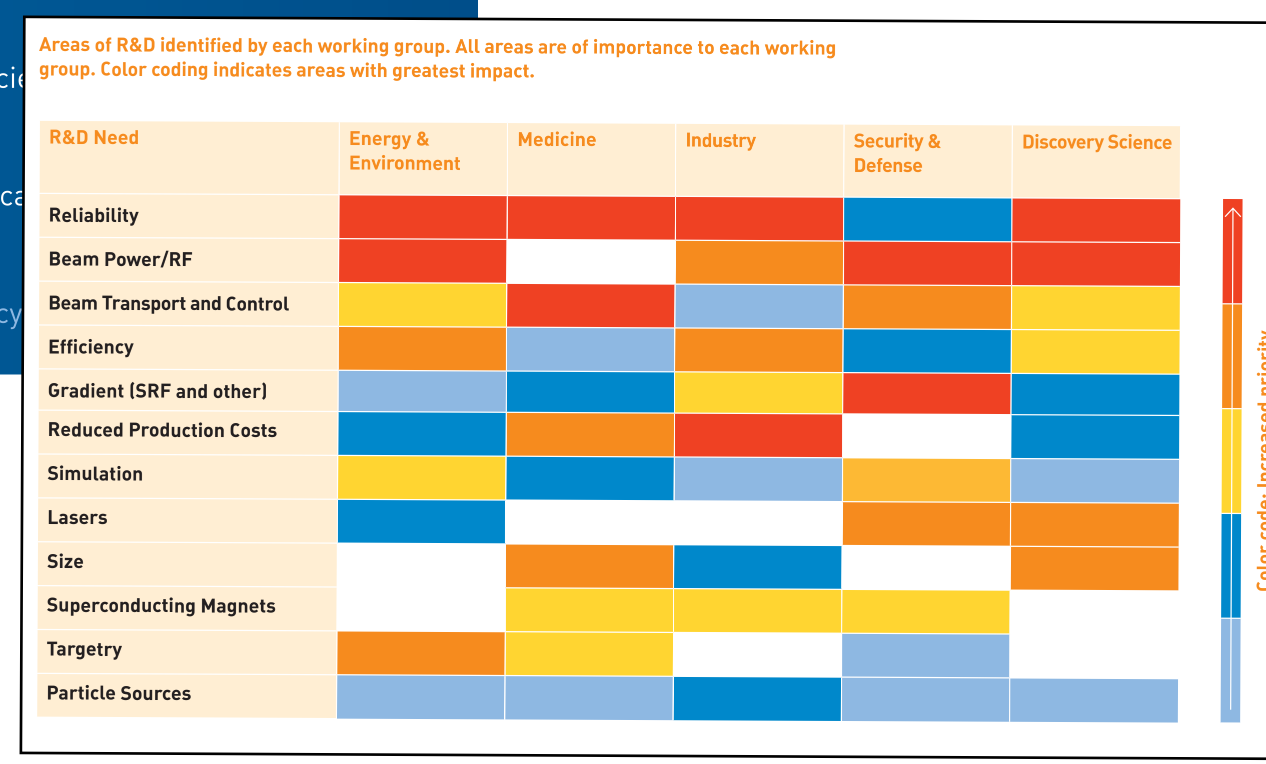
*Feder, T. (2010). "Accelerator school travels university circuit". *Physics Today* **63** (2): 20. Bibcode 2010PhT....63b..20F. doi:10.1063/1.3326981

Accelerators for America's Future

Northern Illinois University

- Symposium and workshop held in Washington, D.C., October 2009
- 100-page Report avail





http://www.acceleratorsamerica.org/