# Lecture Notes From: Fundamentals of Particle Accelerators

U.S. Particle Accelerator School
Old Dominion University, Winter 2015

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## A Little Accelerator History

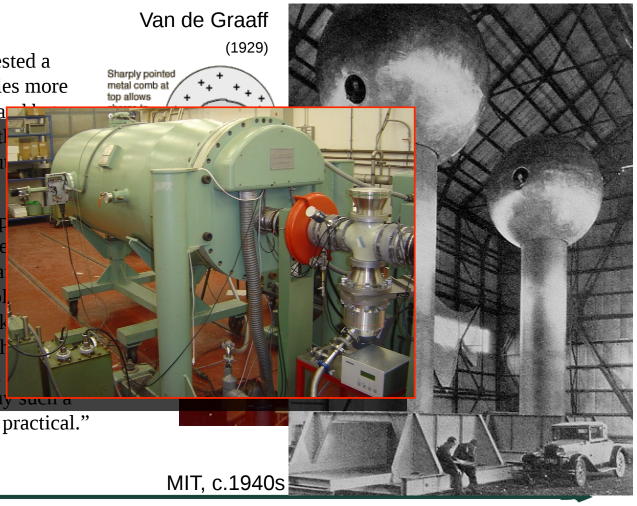
- DC Acceleration

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 ex tube capable of withstanding voltage… I see no reason why such a requirement cannot be made practical.”

Van de Graaff

(1929)



MIT, c.1940s

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## Cockcroft and Walton

- Voltage Multiplier

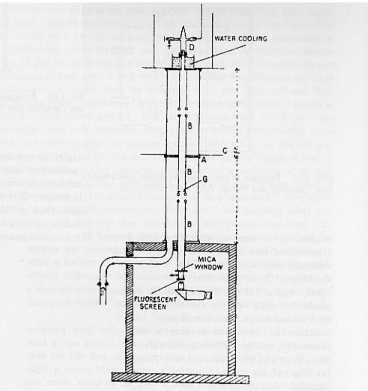
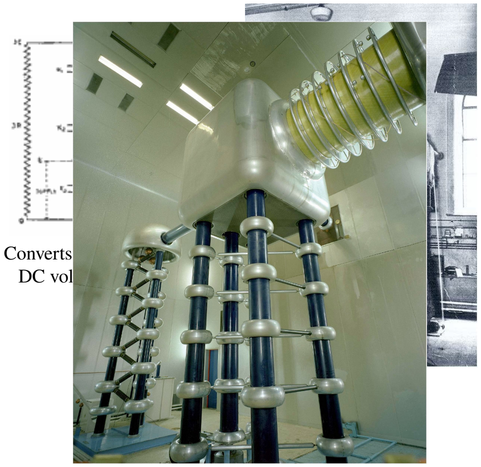


FIG. 2.11 Accelerating tube and target arrangement of the Cockcroft-Walton machine. The source is at D; C is a metallic ring joint between the two sections of the constantly pumped tube. The mica window closes the evacuated space. Cockcroft and Walton, *PRS, A136* (1932), 626.

Converts
DC vol



*Fermilab (recently decommissioned)*

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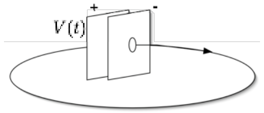
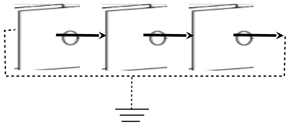
## The Route to Higher Energies

- The Need for AC Systems…

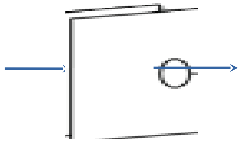
*Circular Accelerator*



*Linear Accelerator*



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



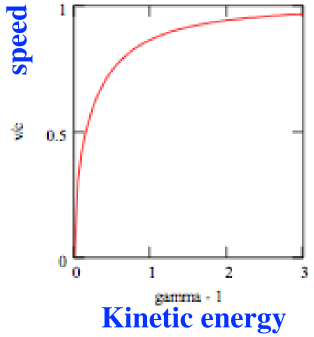
DC systems limited to a few MV

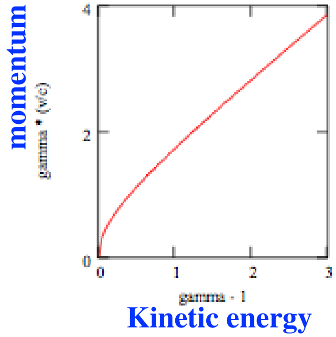
$$\oint (q\vec{E}) \cdot d\vec{s} = work = \Delta(energy)$$

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 |

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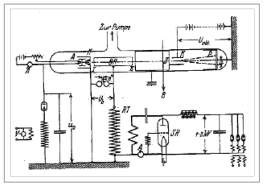
# Oscillating Fields

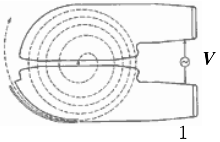


➡The linear accelerator (linac) -- 1928-29

- 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

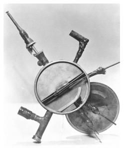
➡The Cyclotron -- 1930's, Lawrence (U. California)

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

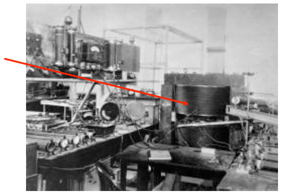


$$\frac{1}{T} = \frac{q \cdot B}{2\pi m}$$

4.5 inch diameter!



11 inch diameter



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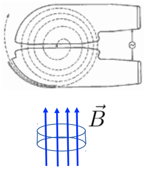
# The Cyclotron

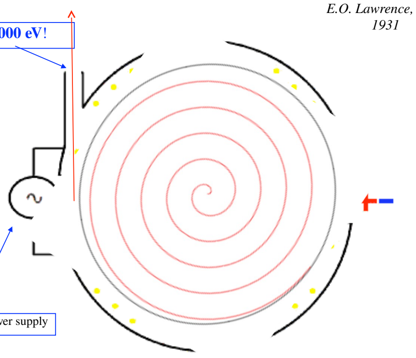


4.5 in.

*E.O. Lawrence, 1931*

- 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* = 2π*r*/*v*.
- The force due to the magnetic field is
  *F* = *evB* = *mv*²/*r*
- thus, *r*/*v* = *m*/*eB*
- and so, *T* = 2*πm* / *eB*
- 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.

K.E. = **80,000 eV!**



1,800 V power supply

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# 60-inch Cyclotron, Berkeley -- 1930's

# 184-inch Cyclotron, Berkeley -- 1940's

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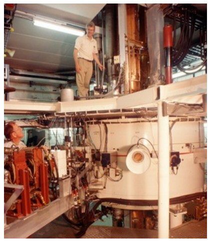
# National Superconducting Cyclotron Lab

(**MSU**)

- 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

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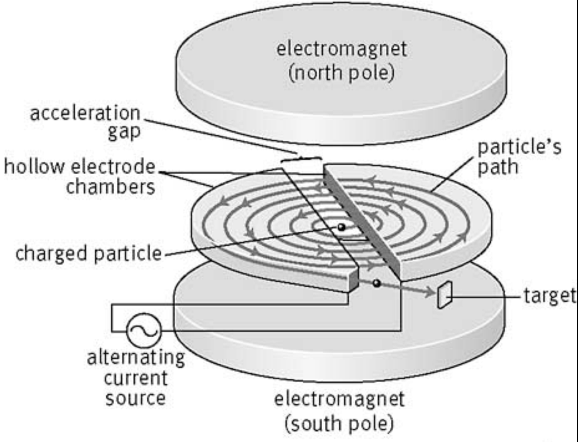
# Cyclotrons

- 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



Precision Graphics

http://images.yourdictionary.com/cyclotron

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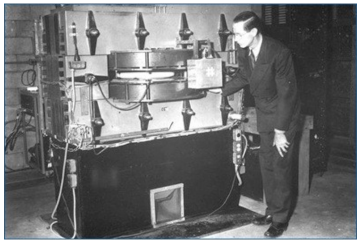
# Meeting up with Relativity

- 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"

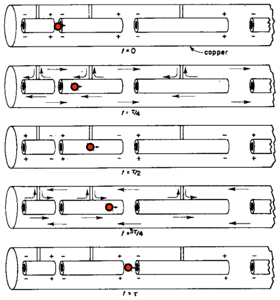


~ 2 MeV; later models --> 300 MeV

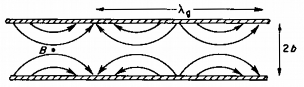
- The Microtron --1944, Veksler (Russia)
  - use one cavity with one frequency, but vary path length each "revolution" as function of particle speed

# The “Modern” Linear Accelerator

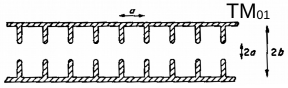
- Alvarez -- 1946 (U. California)
  - cylindrical cavity with drift tubes
  - particles “shielded” as fields change sign
  - most practical for protons, ions
  - GI surplus equip. from WWII Radar technology



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



$TM_{01}$



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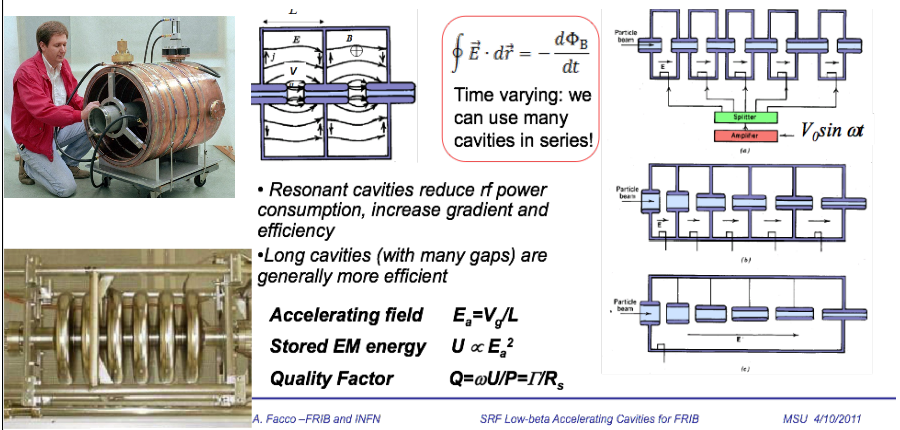
# Radio-frequency Resonant Cavities



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

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*

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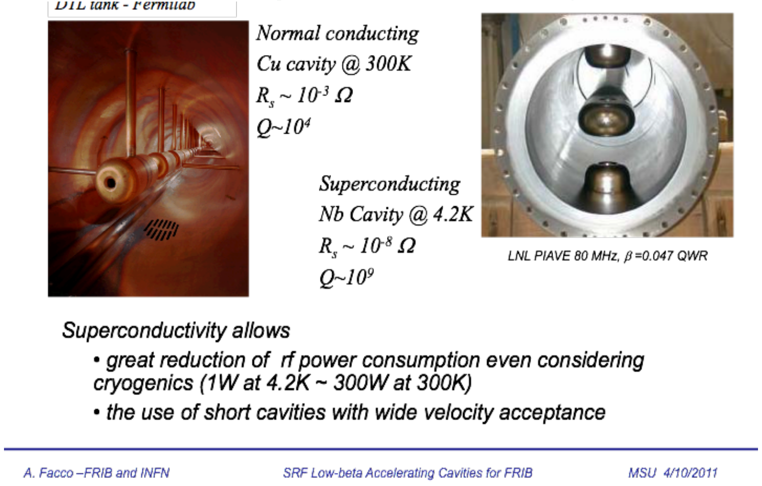
# Normal vs. Superconducting Cavities



*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*

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

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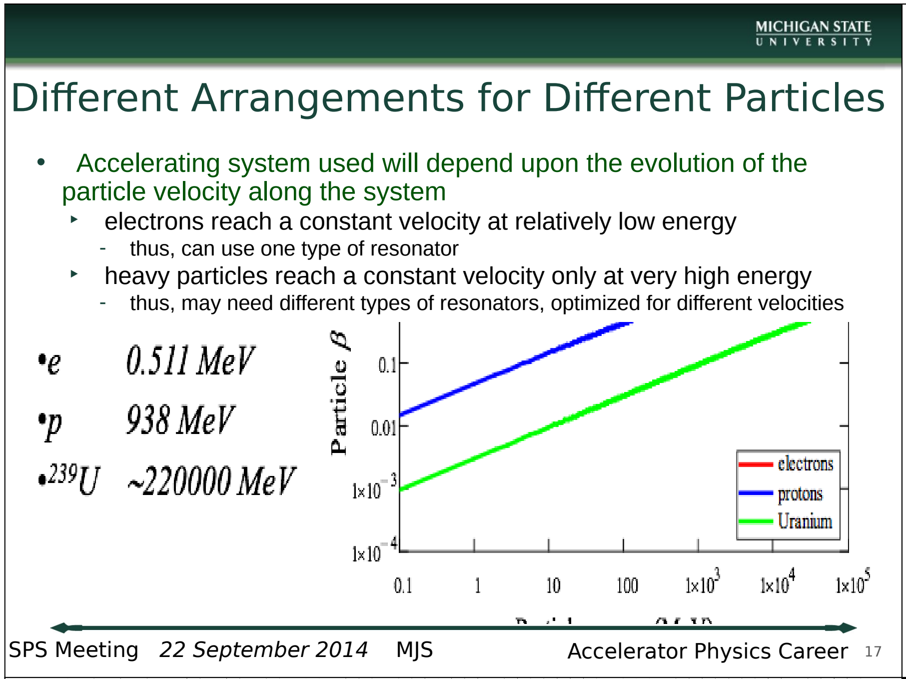
# Superconducting Cavities

- 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

SPS Meeting 22 September 2014 MJS Accelerator Physics Career 17

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## Center of Mass Energy

### Relativistic Review

$p_\nu = (\mathcal{E}/c, \vec{p})$ = 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:

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

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

—or— $\boxed{\sqrt{\mathcal{E}^2 - \vec{p}^2c^2} = mc^2}$

### 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 $M$

$\overset{m}{\circ}\xrightarrow{\vec{p}_1}\quad\xleftarrow{\vec{p}_2}\overset{m}{\circ}\quad\xRightarrow[\text{interact}]{}\quad\overset{M}{\circ}$

$\mathcal{E}_1, \vec{p}_1 \qquad \mathcal{E}_2, \vec{p}_2$

both mass $m$ for simplicity

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

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

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

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Contrast energy needed in 2 situations:

### 1) Fixed Target

$\vec{p}_2 = 0$

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

$\overset{m}{\circ}\xrightarrow{\vec{p}_1}\quad\overset{m}{\circ}$

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

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

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

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

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

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

### 2) Collider

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

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

$\overset{m}{\circ}\xrightarrow{\vec{p}_1}\quad\xleftarrow{-\vec{p}_1}\overset{m}{\circ}$

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

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

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

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.

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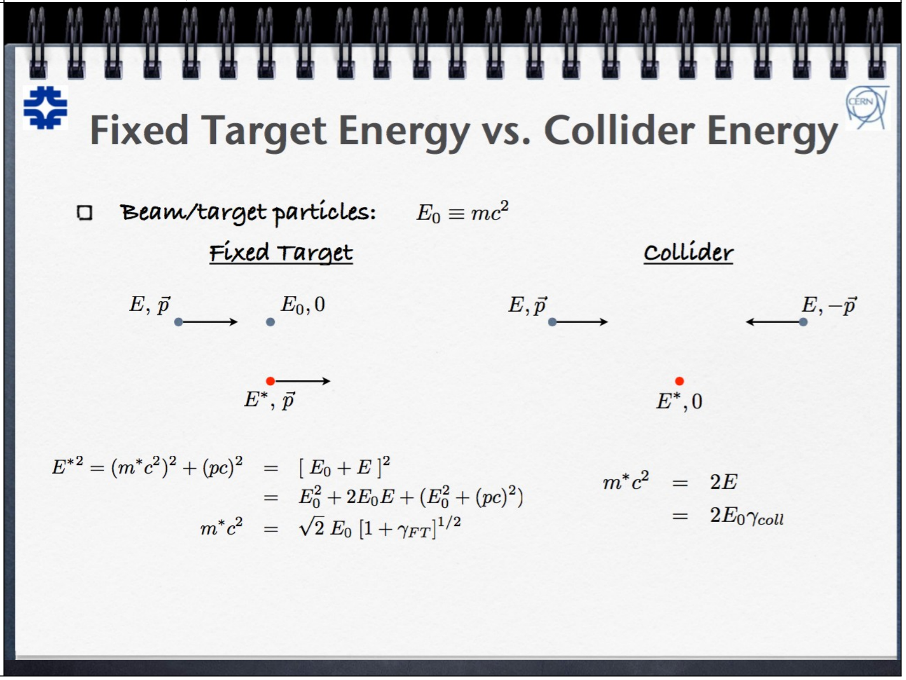


# Fixed Target Energy vs. Collider Energy

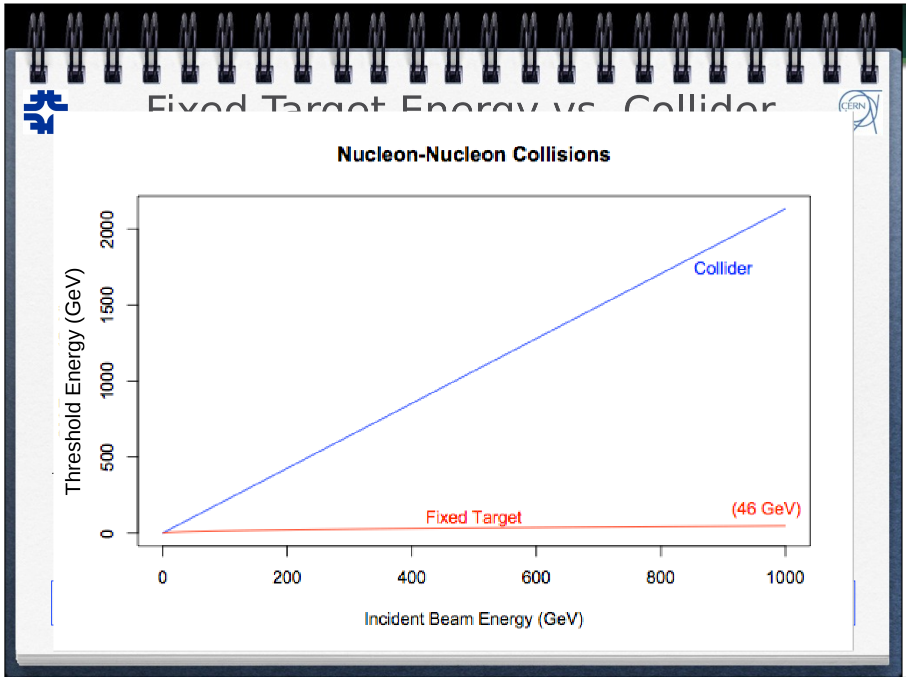
☐ **Beam/target particles:** $E_0 \equiv mc^2$

**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

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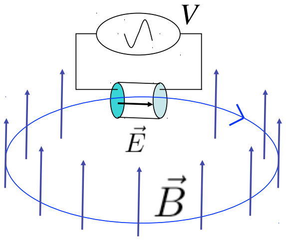
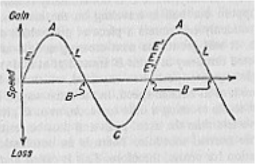
# For Highest Elementary Particle Energies...

- **... the Synchrotron -- late 1940's**
  - **RF powered cavity(ies); Radar power sources**
  - **keep *R* = const.;    increase *B*  ( = *p/eR* )**
  - **$1^{st}$ 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***

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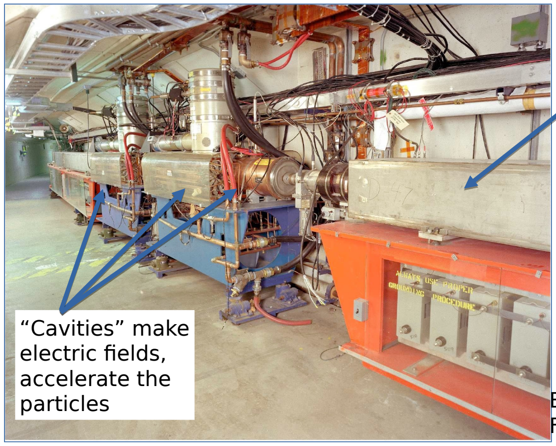
# A Synchrotron



"Cavities" make electric fields, accelerate the particles

Magnets steer the particles in a circle

Booster Synchrotron, Fermilab (Batavia, IL)

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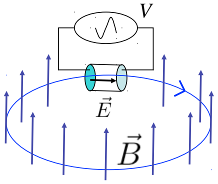
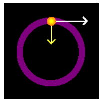
# Synchrotron (cont'd)

- 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:



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

$= p / eB$



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

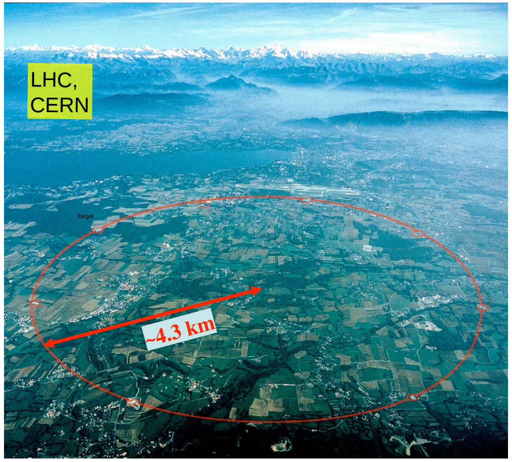
$$B\rho = p/q \quad \approx \tfrac{10}{3}\ \text{T-m} \cdot p_{[\mathrm{GeV}/c]}$$

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

# The Large Colliders



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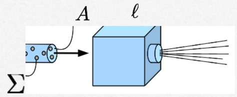
# Luminosity

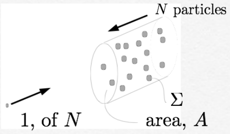
- Experiments want "collisions/events" -- rate?
- Fixed Target Experiment: $\mathcal{R} = \left(\frac{\Sigma}{A}\right) \cdot \rho \cdot A \cdot \ell \cdot N_A \cdot \dot{N}_{beam}$



$$= \rho N_A \ell \dot{N}_{beam} \cdot \Sigma$$
$$\equiv \mathcal{L} \cdot \Sigma$$

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

- Bunched-Beam Collider: $\mathcal{R} = \left(\frac{\Sigma}{A}\right) \cdot N \cdot (f \cdot N)$



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

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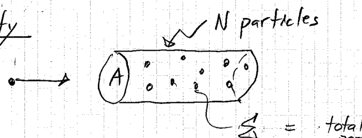
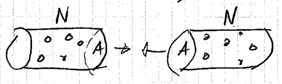
## Luminosity



$\Sigma$ = total overlap of 2 colliding particles

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

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



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

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

---

2/

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

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

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

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

total cross sections $\Sigma \sim 100$ mb

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

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

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

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

3/

Solve this system:

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

$$N_0 \equiv N(t=0) \qquad \frac{1}{N} = \frac{1}{N_0} + \frac{f_0}{A}\Sigma n t \quad \Rightarrow \quad N = \frac{N_0}{1 + \frac{f_0 N_0}{A}\Sigma n t}$$

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

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

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

Number of events:

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

Store/Interaction time $T$

$$I(t) = \text{Integrated Luminosity} \equiv \int_0^t \mathcal{L}(\tilde{t})\,d\tilde{t} = \frac{\mathcal{L}_0 t}{1 + \mathcal{L}_0 t \frac{n\Sigma}{B N_0}} = I_0 \frac{\mathcal{L}_0 t/I_0}{1 + \mathcal{L}_0 t/I_0}$$

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

$I(t)$ Integrated luminosity rises in time reaching a limiting value of $I_0 = \frac{B N_0}{n \Sigma}$ 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)

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

$f_0$ = 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 $\mathcal{L}$)

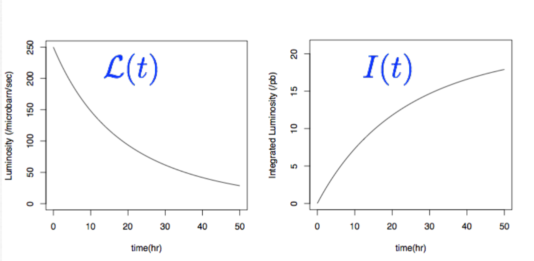
- So, in this ideal case, $\mathcal{L}(t) = \dfrac{\mathcal{L}_0}{\left[1 + \left(\frac{n\mathcal{L}_0\Sigma}{BN_0}\right)t\right]^2}$

---

# 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:

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

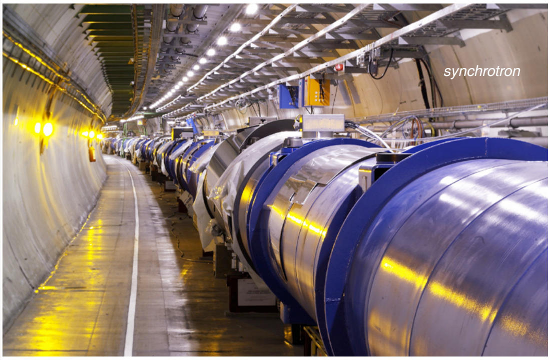
so, ...

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

---

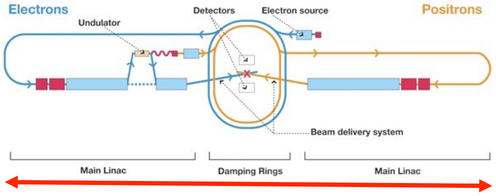
# Recent Large-Scale Accelerators

Large Hadron Collider (LHC)



Spallation Neutron Source (S

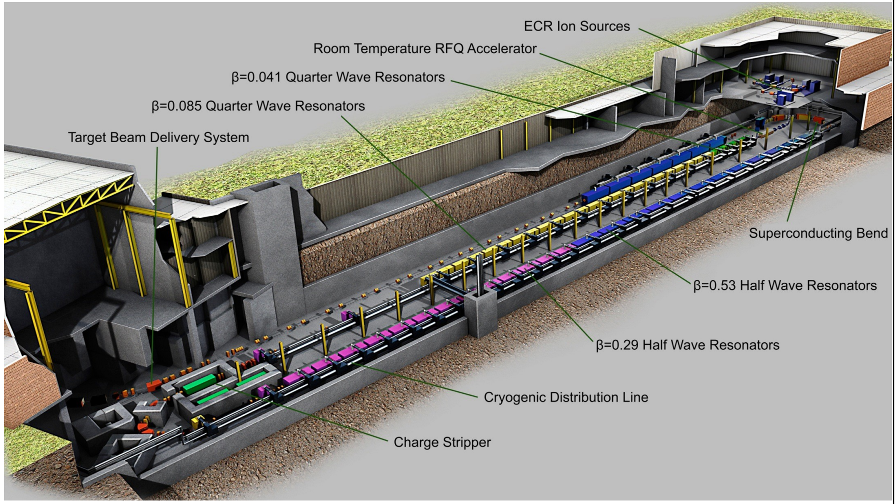
# The Linac -- Again



- 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)



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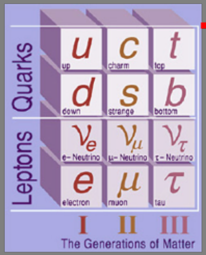
# Modern Accelerators

- 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?

---

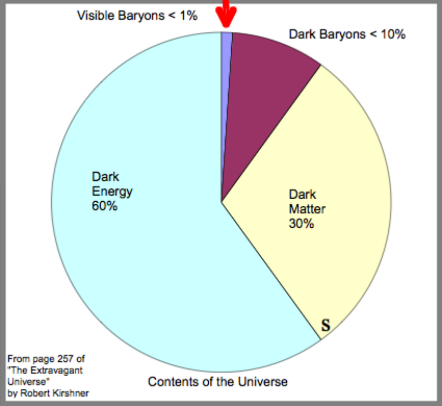
# Is it almost all figured out??

*(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.



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

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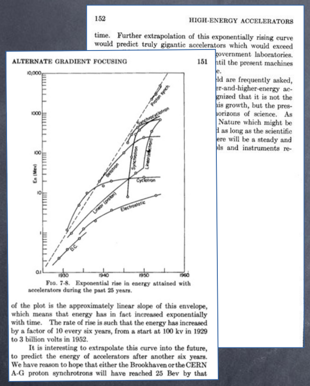
# The Livingston Plot (1954)



152 HIGH-ENERGY ACCELERATORS

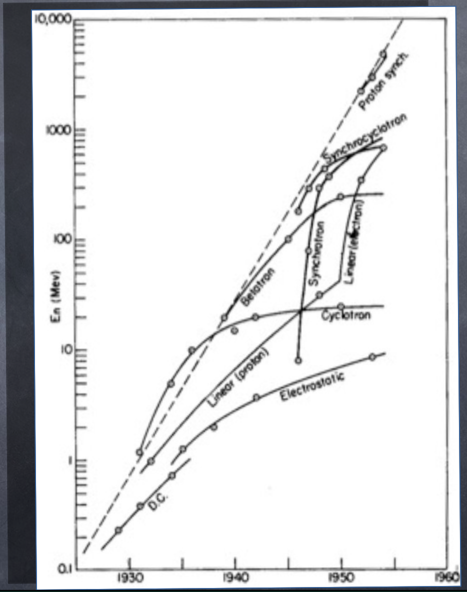
time. Further extrapolation of this exponentially rising curve
would predict truly gigantic accelerators which would exceed
government laboratories.
ntil the present machines
e.
ld are frequently asked,
er-and-higher-energy ac-
gnized that it is not the
his growth, but the pres-
horizons of science. As
Nature which might be
l 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



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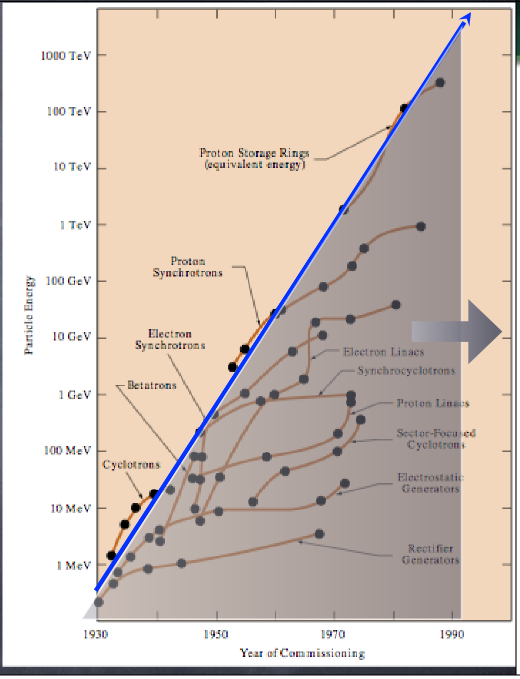
# Livingston Plot

- 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 -- $E_{\text{Planck}}$ ?? ($10^{19}$ GeV)
- need BREAKTHROUGH!



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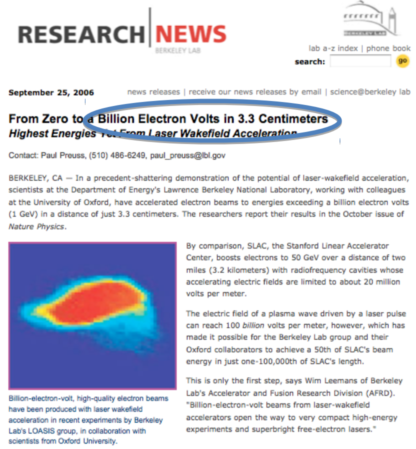
# What are the Next Steps?

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*.

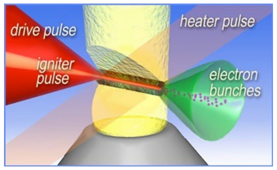
Billion-electron-volt, high-quality electron beams have been produced with laser wakefield acceleration in recent experiments by Berkeley Lab's LOASIS group, in collaboration with scientists from Oxford University.

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)*

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# Higher Energy is not the Only Game in Town

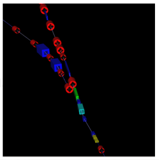
- Many processes that wish to be studied or utilized are not necessarily at the highest energies, but rather are rare events thus requiring high beam intensity/current/power
- Many modern large-scale accelerators are moving toward intense beams rather than just pushing the energy envelope
  - LHC: 7 TeV x $3\text{x}10^{14}$ = 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

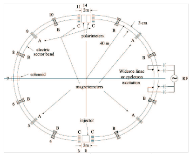
*3-D design of 3.1 GeV muon beam transport system*



*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)



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# Wait, There’s More!

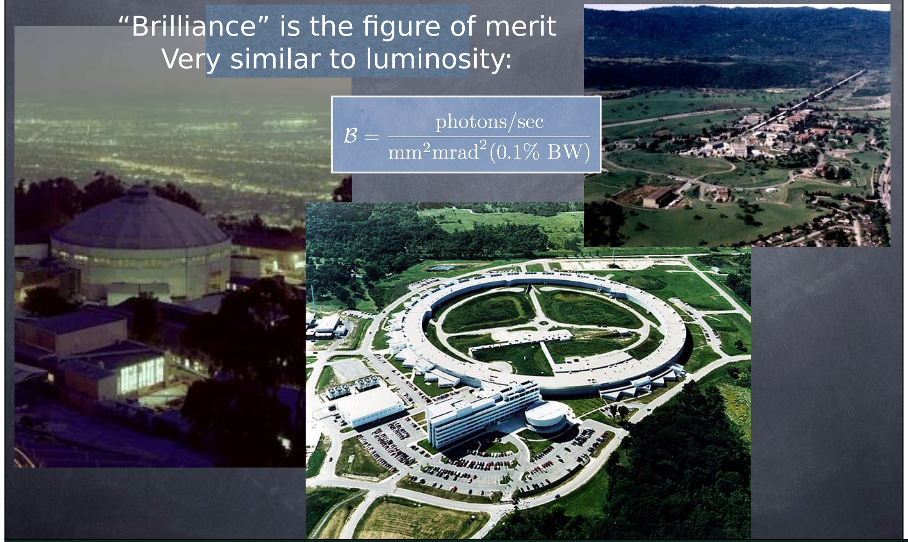
- And, of course, not all applications are in high energy or nuclear physics!
- Basic energy sciences as well as industrial applications make up the bulk of our field, in terms of number of accelerators and arguably their direct impact on society
  - ~26,000 accelerators worldwide*
  - ~1% are research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

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



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# Accelerators for America's Future

Accelerators for America's Future

**CHAPTER 1**
Accelerators for Energy and the Environment

**CHAPTER 2**
Accelerators for Medicine

**CHAPTER 3**
Accelerators for Industry

**CENTERFOLD**
Adventures in Accelerator Mass Spectrometry

**CHAPTER 4**
ccelerators for Security and Defense

**HAPTER 5**
celerators for Discovery S

**APTER 6**
elerator Science and Ed

| | | | | | |
|---|---|---|---|---|---|
| Reliability | 🟥 | 🟥 | 🟥 | 🟦 | 🟥 |
| Beam Power/RF | 🟥 | | 🟧 | 🟥 | 🟥 |
| Beam Transport and Control | 🟨 | 🟥 | ▨ | 🟧 | 🟨 |
| Efficiency | 🟧 | ▨ | 🟧 | 🟦 | 🟨 |
| Gradient (SRF and other) | ▨ | 🟦 | 🟨 | 🟥 | 🟦 |
| Reduced Production Costs | 🟦 | 🟧 | 🟥 | | 🟦 |
| Simulation | 🟨 | 🟦 | ▨ | 🟨 | ▨ |
| Lasers | 🟦 | | | 🟧 | 🟧 |
| Size | | 🟧 | 🟦 | | 🟧 |
| Superconducting Magnets | | 🟨 | 🟨 | 🟨 | |

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

http://www.acceleratorsamerica.org/

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# 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

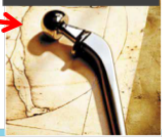
- Harden cutting tools
- Reducing friction
- Biomaterials for implants

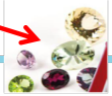
Ceramics and Glasses

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

Applied Materials, Inc.

N2 ions reduce wear and corrosion in this artificial femur





Fermilab (courtesy R. Kephart)

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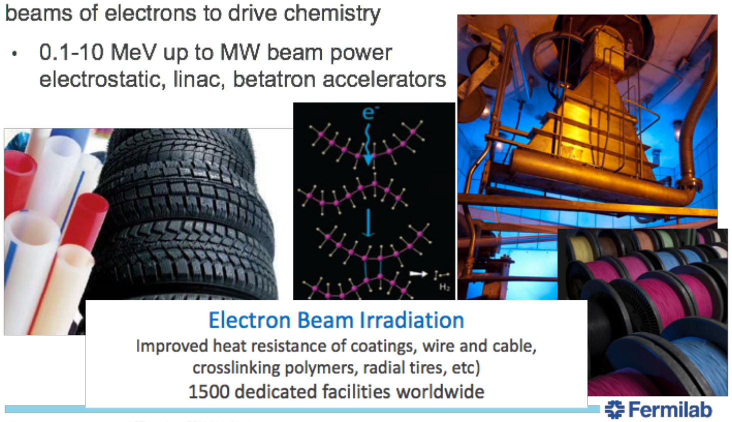
# Accelerators: Essential Tools in Industry

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



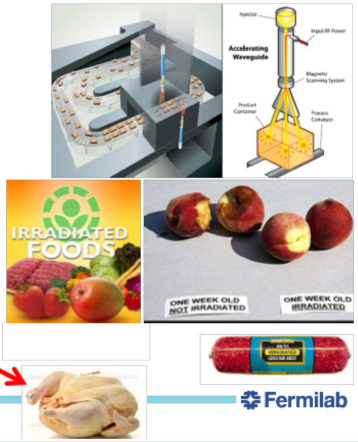
**Electron Beam Irradiation**
Improved heat resistance of coatings, wire and cable, crosslinking polymers, radial tires, etc)
1500 dedicated facilities worldwide

Fermilab

# 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



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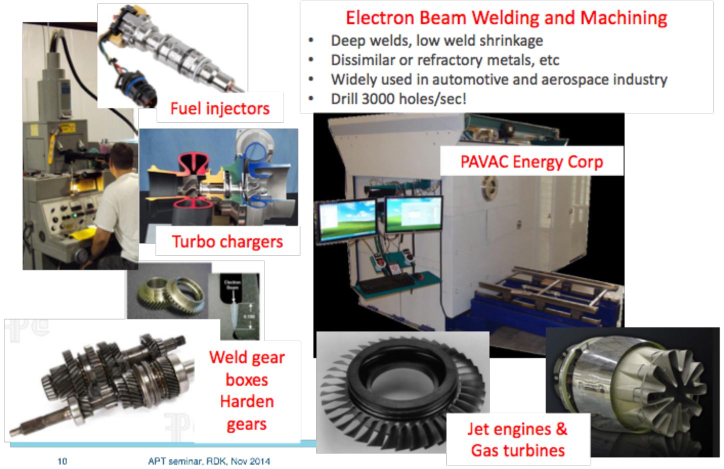
# Accelerators for Industrial Processes

**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!



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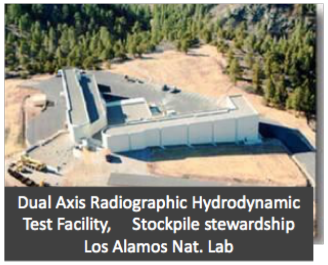
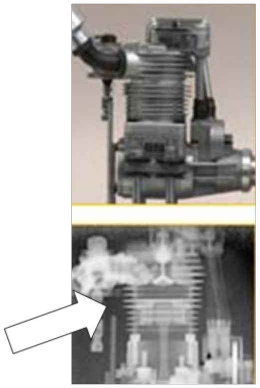
# Accelerators for Defense



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!)



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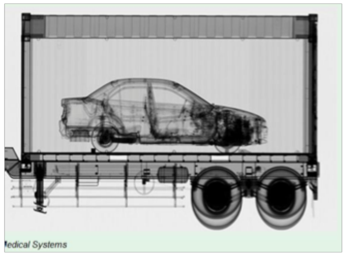
# Accelerators for National Security



- 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

# 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

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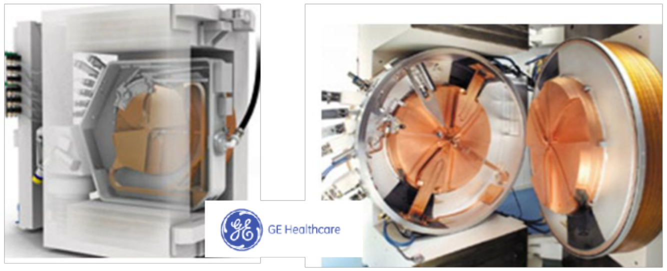
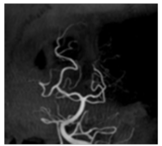
# Accelerators for the Medical Isotopes



- "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



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# 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 ⇒

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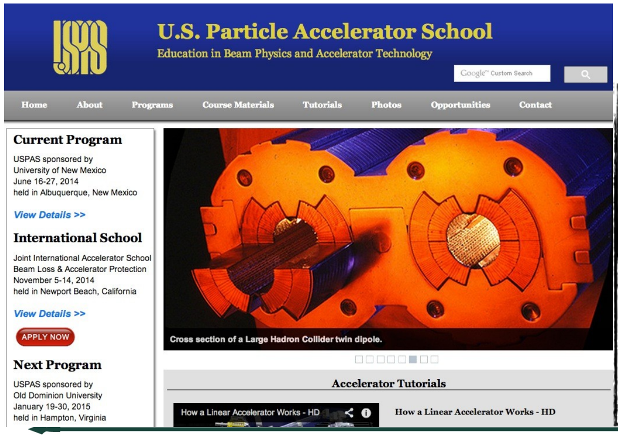
which brings us to ...

# 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



**U.S. Particle Accelerator School**
Education in Beam Physics and Accelerator Technology

**Current Program**
USPAS sponsored by
University of New Mexico
June 16-27, 2014
held in Albuquerque, New Mexico
*View Details >>*

**International School**
Joint International Accelerator School
Beam Loss & Accelerator Protection
November 5-14, 2014
held in Newport Beach, California
*View Details >>*

**Next Program**
USPAS sponsored by
Old Dominion University
January 19-30, 2015
held in Hampton, Virginia

Cross section of a Large Hadron Collider twin dipole.

**Accelerator Tutorials**

How a Linear Accelerator Works - HD

http://uspas.fnal.gov

**Past USPAS University Programs**

A complete history of USPAS university credit programs.

| Date | Sponsoring University |
|---|---|
| January 20-31, 2014 | University of Tennessee |
| June 10-21, 2013 | Colorado State University |
| January 14-25, 2013 | Duke University |
| June 18-29, 2012 | Michigan State University |
| January 16-27, 2012 | University of Texas at Austin |
| June 13-24, 2011 | Stony Brook University |
| January 17-28, 2011 | Old Dominion University |
| June 14-25, 2010 | Massachusetts Institute of Technology |
| January 18-29, 2010 | University of California, Santa Cruz |
| June 15-26, 2009 | University of New Mexico |
| January 12-23, 2009 | Vanderbilt University |
| June 16-27, 2008 | University of Maryland |
| January 14-25, 2008 | University of California, Santa Cruz |
| June 4-15, 2007 | Michigan State University |
| January 15-26, 2007 | Texas A&M University |
| June 12-23, 2006 | Boston University |
| January 16-27, 2006 | Arizona State University |
| June 20 - July 1, 2005 | Cornell University |
| January 10-21, 2005 | University of California, Berkeley |
| June 21 - July 2, 2004 | University of Wisconsin - Madison |
| January 19-30, 2004 | College of William and Mary |
| June 16-27, 2003 | University of California, Santa Barbara |
| January 6-17, 2003 | Indiana University (held in Baton Rouge, LA) |
| June 10-21, 2002 | Yale University |

## 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 (60 Sessions, ~570 Courses)
- **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**

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## Most USA specialists in Accelerator Science and Engineering pass through USPAS several times

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

  Superconducting Magnets
  RF Cavities
  Software Controls
  Space-Charge Effects
  Project Management
  Ion Sources
  Cryogenic Engineering
  …. and so much more …
- **A “critical mass” of selected and highly motivated students gather to learn**