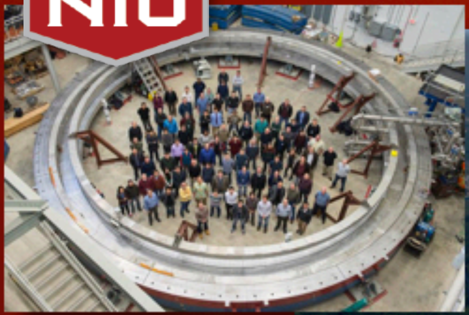
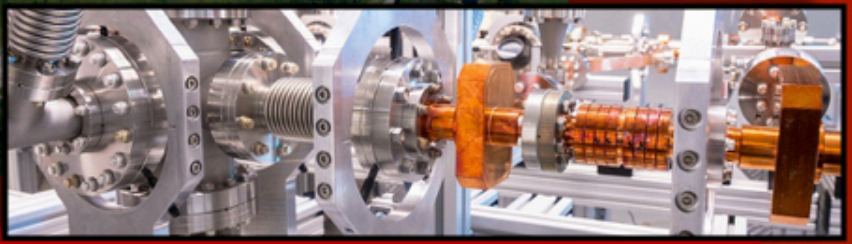
Accelerator Science at NIU





Accelerator and Beam Physics

Northern Illinois University

Mike Syphers
Research Professor
Dep. Dir., *NICADD*

Accelerator Science

- Among the largest and most expensive of all scientific instruments, particle accelerators have impacts in many fields of science and society. The theory behind their operation, developments of their technical design, and the understanding of their performance require a host of tools and methods ranging from applied physics and engineering to pure mathematics.
- For more information on this rapidly growing discipline, please visit:
  - Accelerators for America's Future
  - Accelerators and Beams, Tools of Discovery and Innovation
  - Resources -- APS Division of Physics of Beams

The Livingston Plot

- In 1954, M. Stanley Livingston produced a curve in his book High Energy Accelerators, indicating exponential growth in particle beam energies over "past" ~25 years;
  - the 33 "Bev" (GeV) AGS at Brookhaven and 28 GeV PS at CERN were underway, and kept up the trend
- The advent of Strong Focusing (A-G focusing) was key to keeping this trend going…

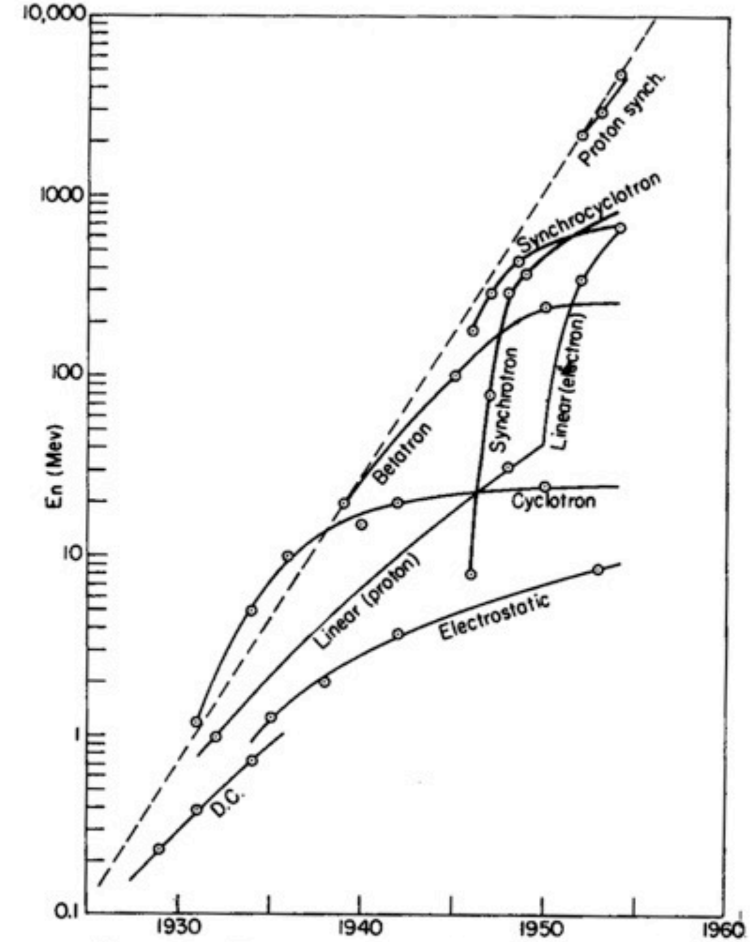


FIG. 7-8. Exponential rise in energy attained with accelerators during the past 25 years.

The Past 40 Years

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."

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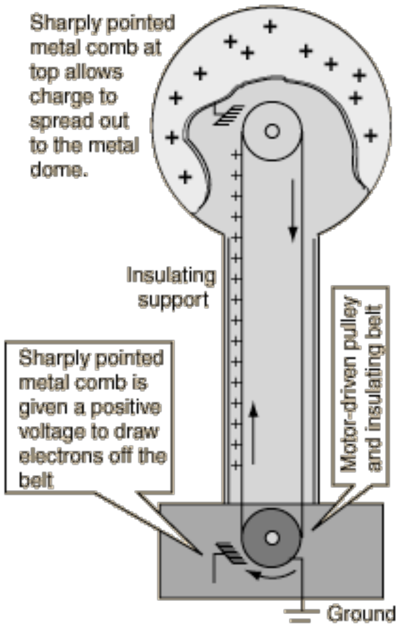
(1929)



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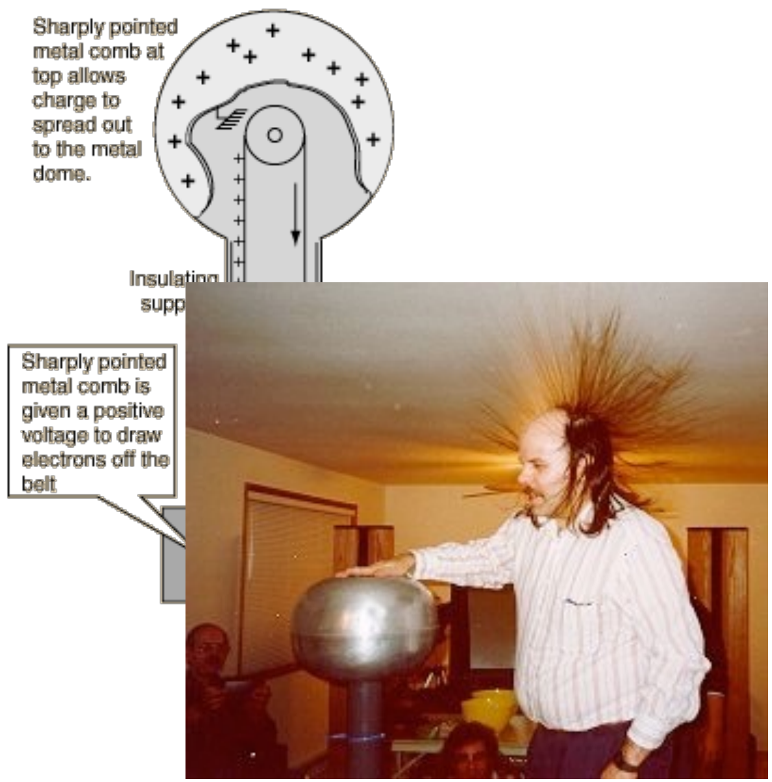

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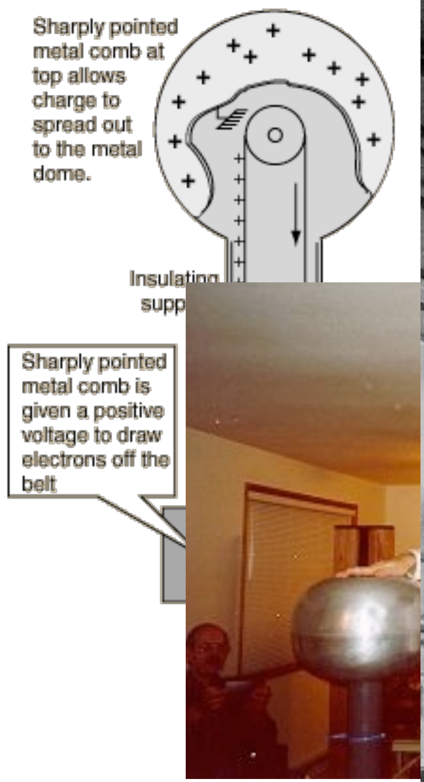

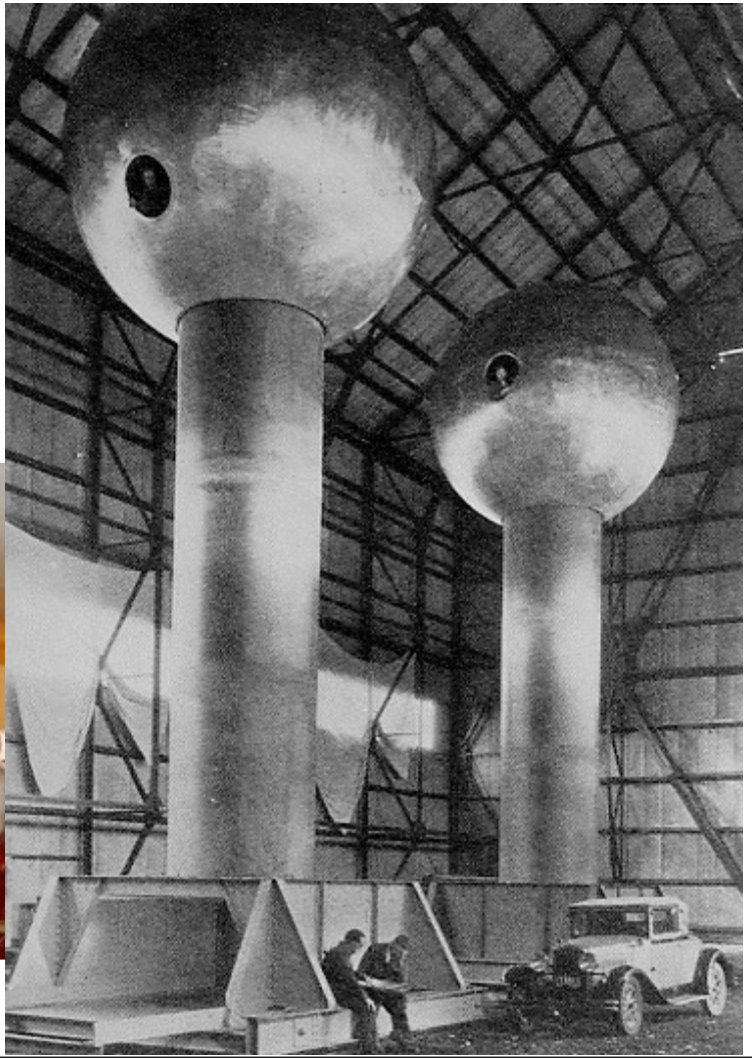

MIT, c.1940s

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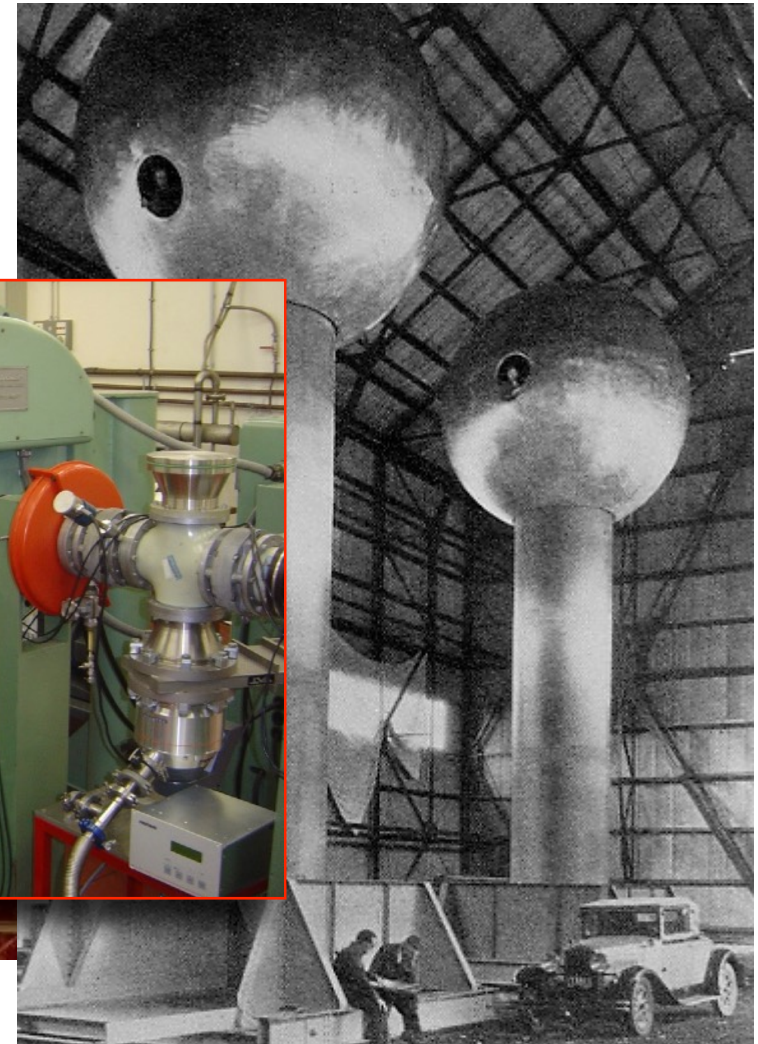

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Cockcroft and Walton

- **Voltage Multiplier**

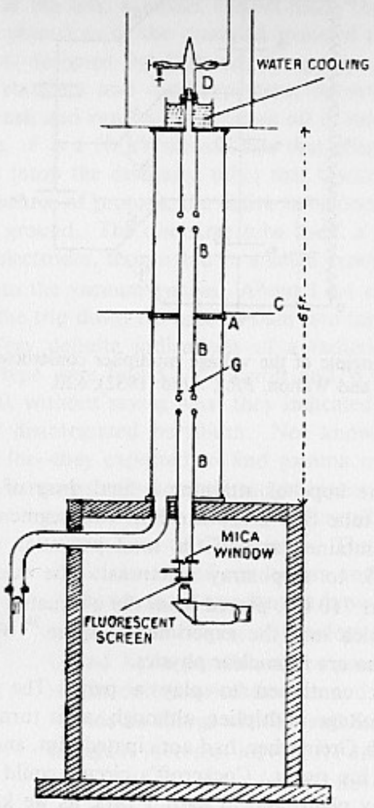

FIG. 2.11 Accelerating tube and target arrangement of the Cockcroft-Walton machine. The source is at D; C is a metallic ring joint between the two sections of the constantly pumped tube. The mica window closes the evacuated space. Cockcroft and Walton, *PRS, A136* (1932), 626.

Cockcroft and Walton

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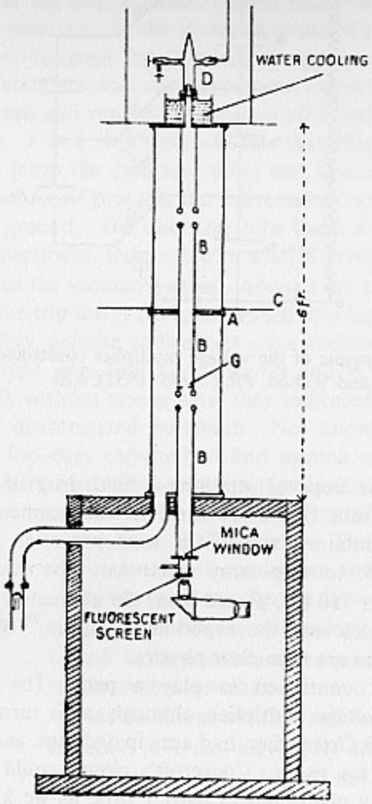

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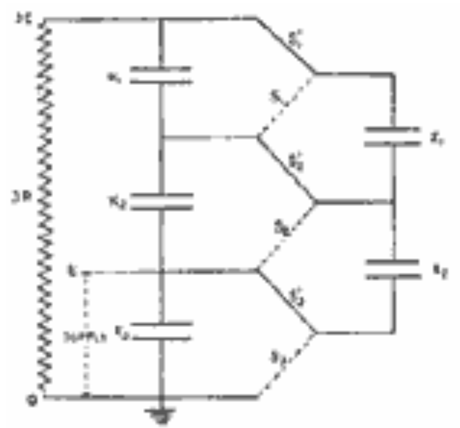
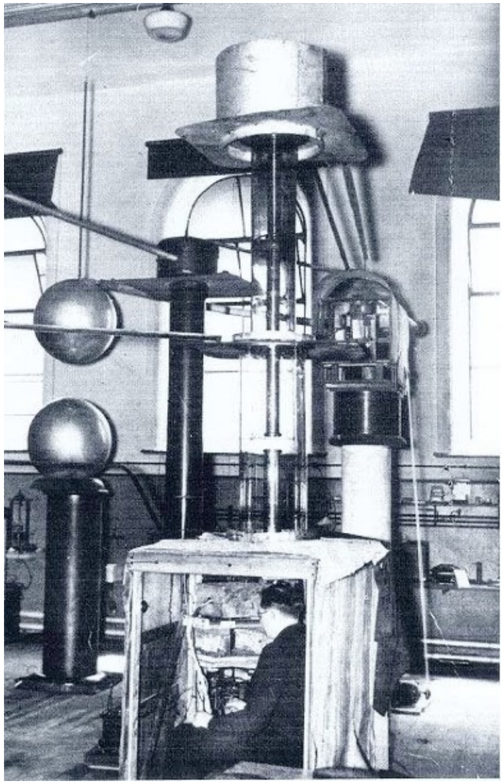


Converts AC voltage V to
DC voltage n x V



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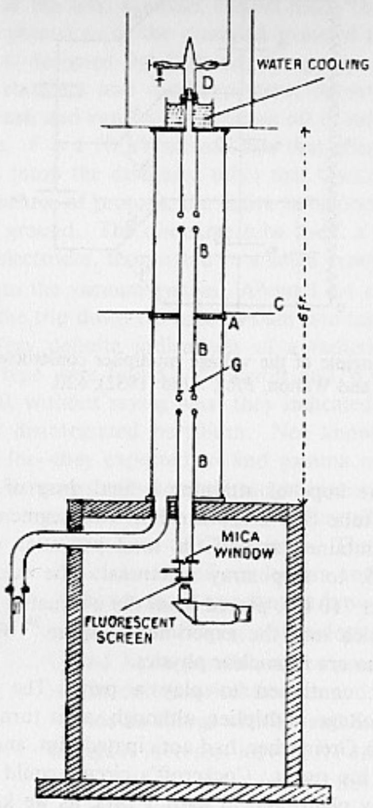

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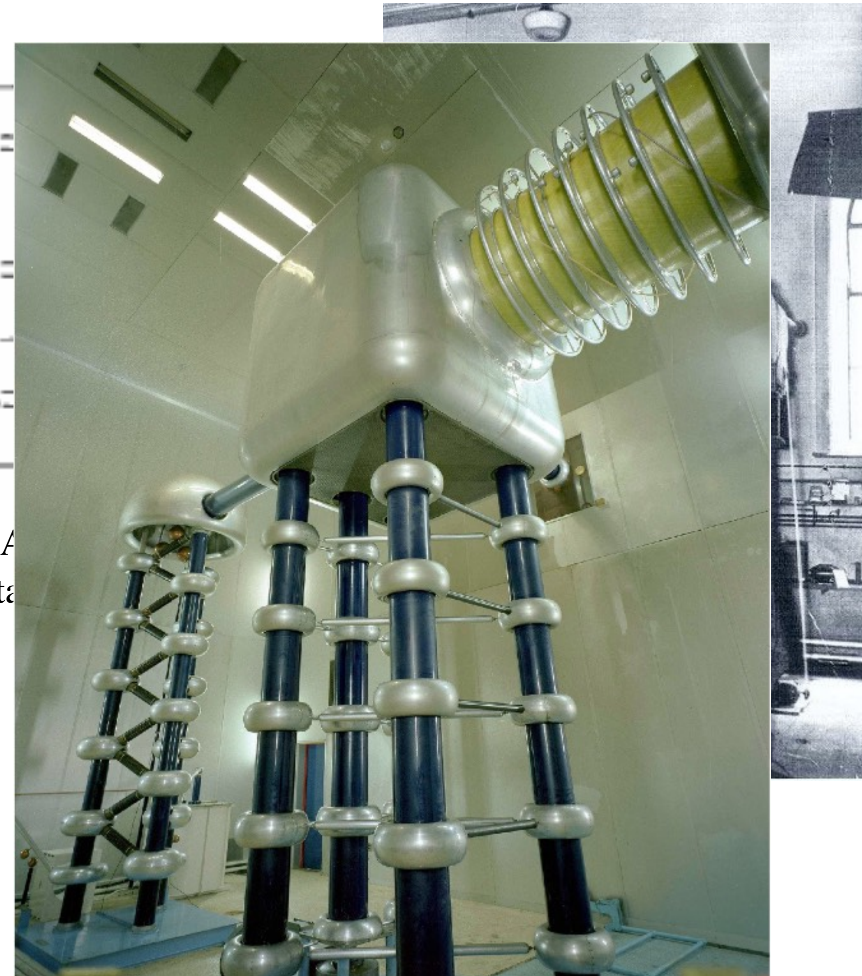
Converts A
DC volta

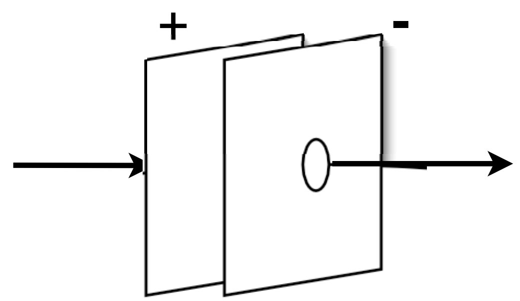


Fermilab (recently decommissioned)

The Route to Higher Energies

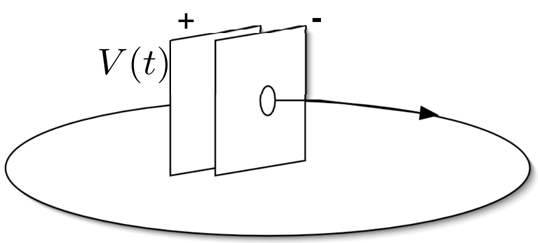
- The Need for AC Systems…

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



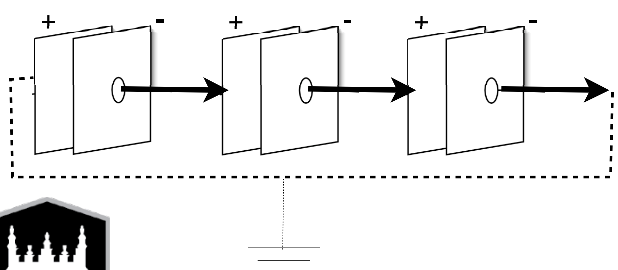
DC systems limited to a few MV

Circular Accelerator



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

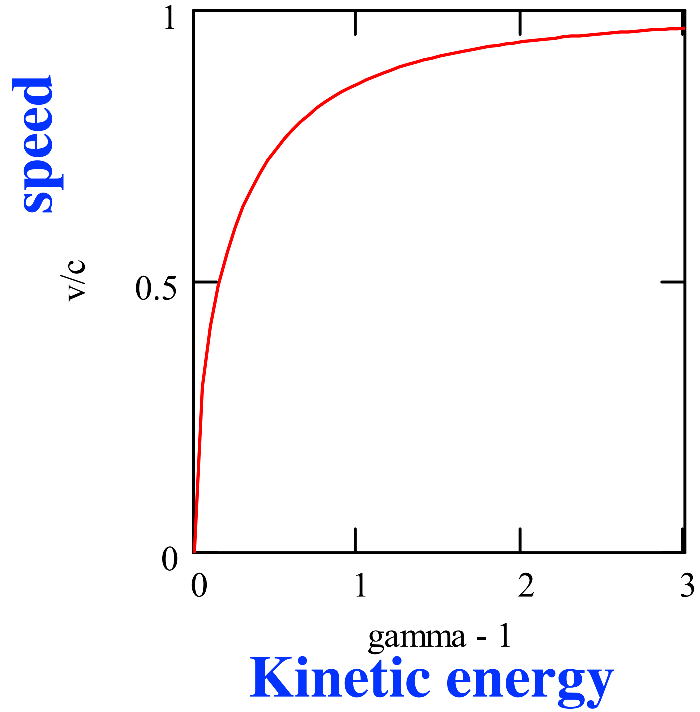
Linear Accelerator

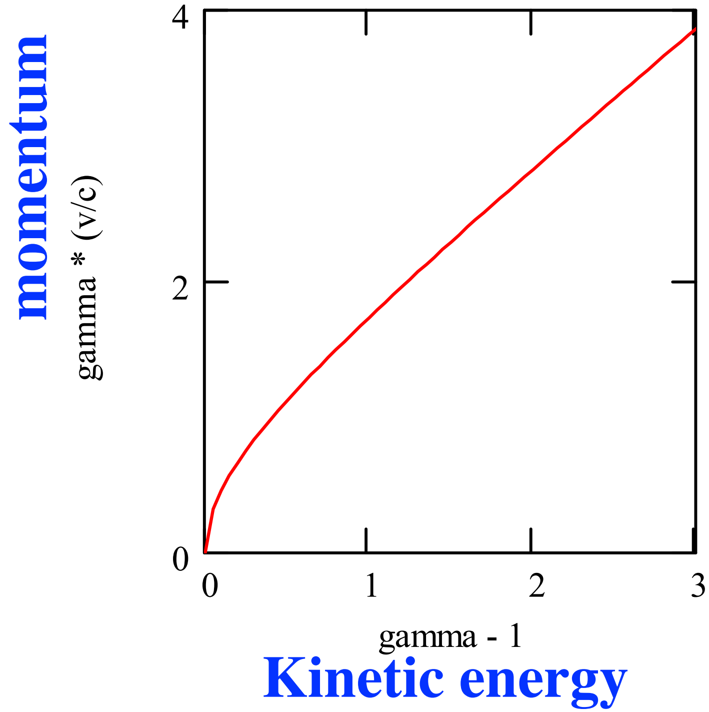


To gain energy, a time-varying field is required:

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

Speed, Momentum vs. Energy





e:	0	0.5	1.0	1.5	MeV
p:	0	1000	2000	3000	MeV

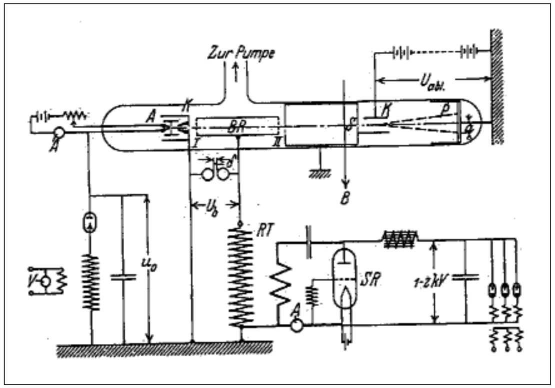
$$\text{gamma} = \frac{1}{\sqrt{1-(v/c)^2}}$$

rest energy, mc^2:

e-	0.5 MeV
p	938 MeV

Oscillating Fields

Oscillating Fields



➡ **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

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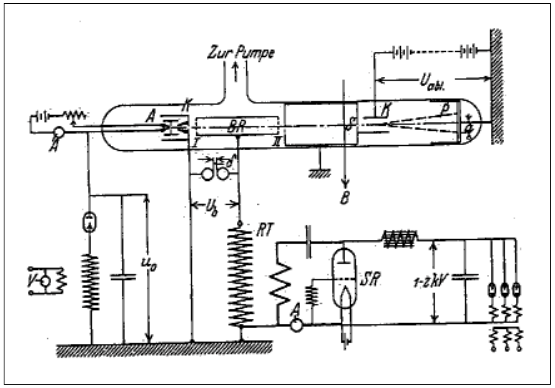

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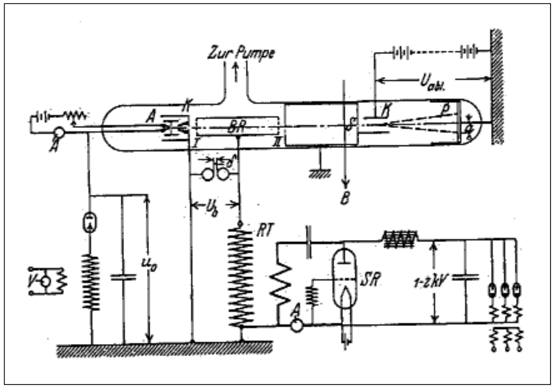

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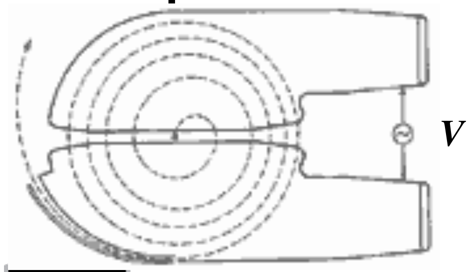
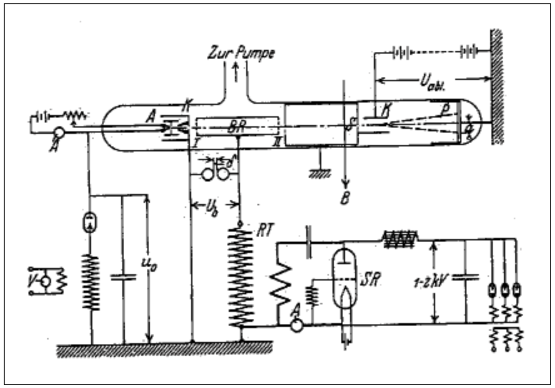


$$\frac{1}{T} = \frac{q \cdot B}{2\pi m}$$

Oscillating Fields



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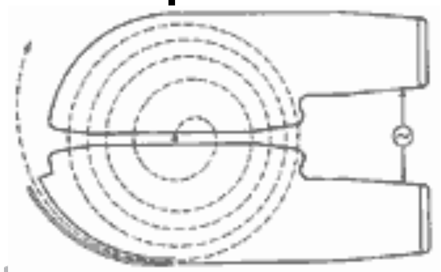
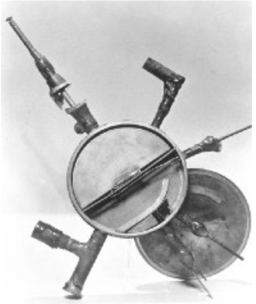


V

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

4.5 inch diameter!



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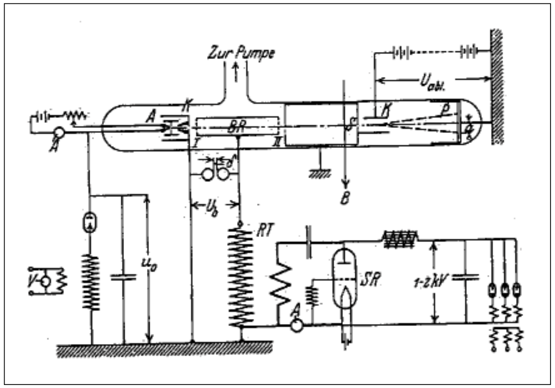

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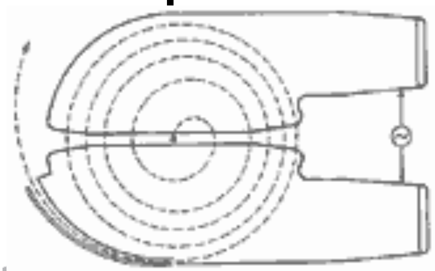

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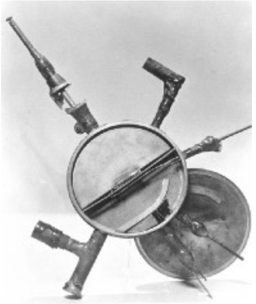
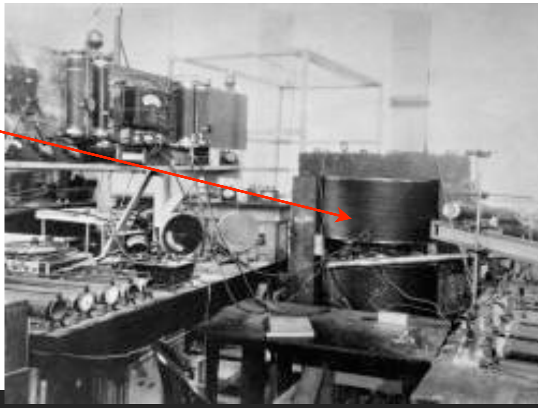


11 inch diameter



60-inch Cyclotron, Berkeley -- 1930's

184-inch Cyclotron, Berkeley -- 1940's

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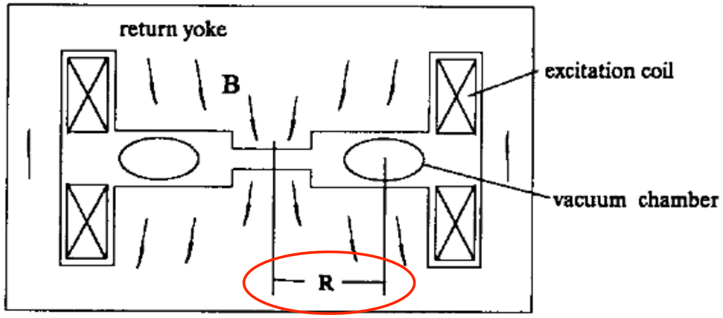
Meeting up with Relativity

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

field on orbit of radius *R*

$$\boxed{\frac{d\Phi}{dt} = 2(\pi R^2)\frac{dB_z}{dt}}$$



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)**
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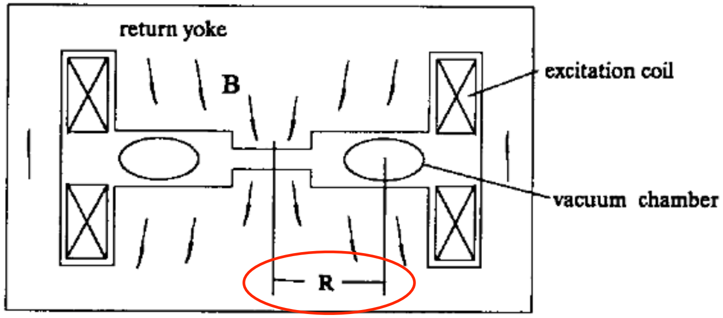

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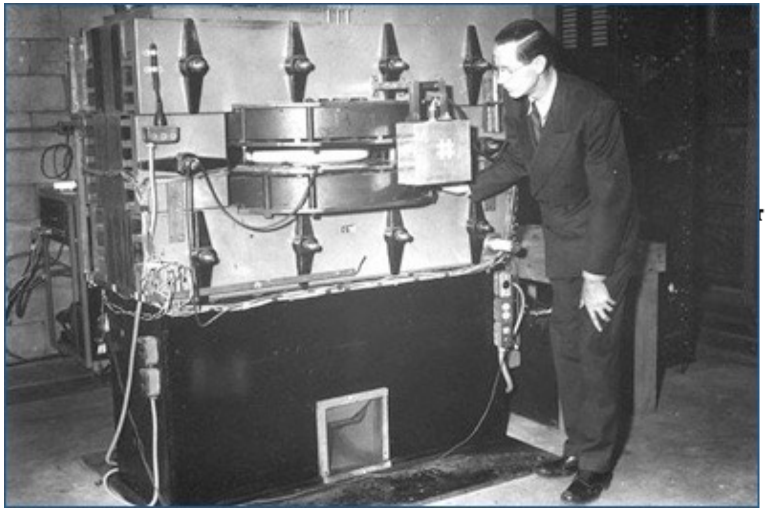

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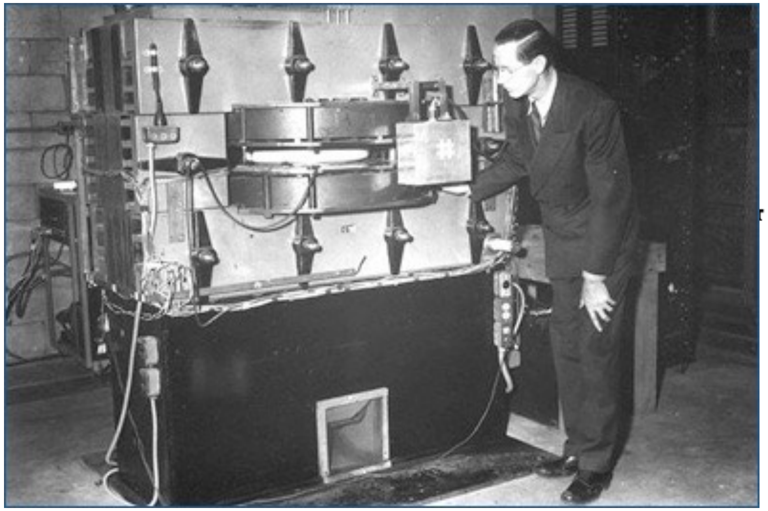

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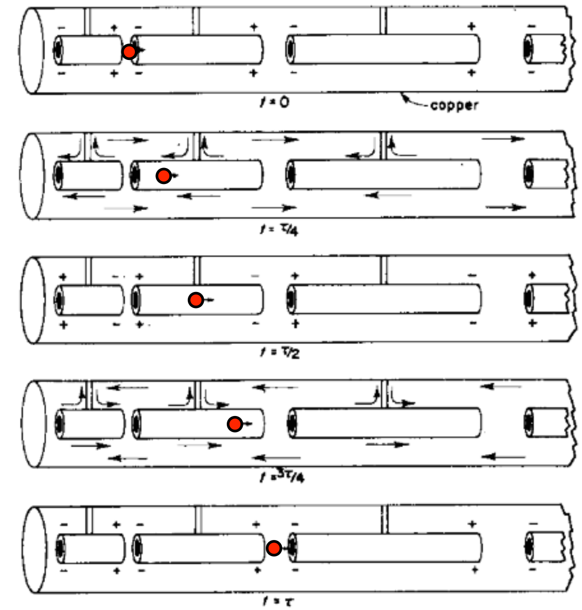
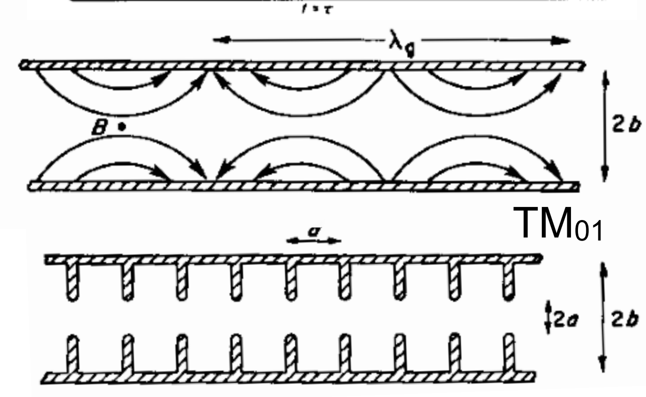
    - “betatron oscillations”
- **The Microtron --1944, Veksler (Russia)**
  - **use one cavity with one frequency, but vary path length each “revolution” as function of particle speed**

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

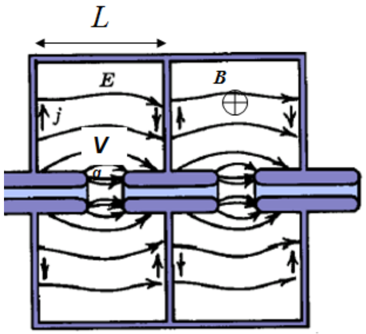


- **Traveling-Wave Electron Accelerator -- c.1950 (Stanford, + Europe)**
  - TM_{01} waveguide arrangement
  - iris-loaded cylindrical waveguide
    - match phase velocity w/ particle velocity...



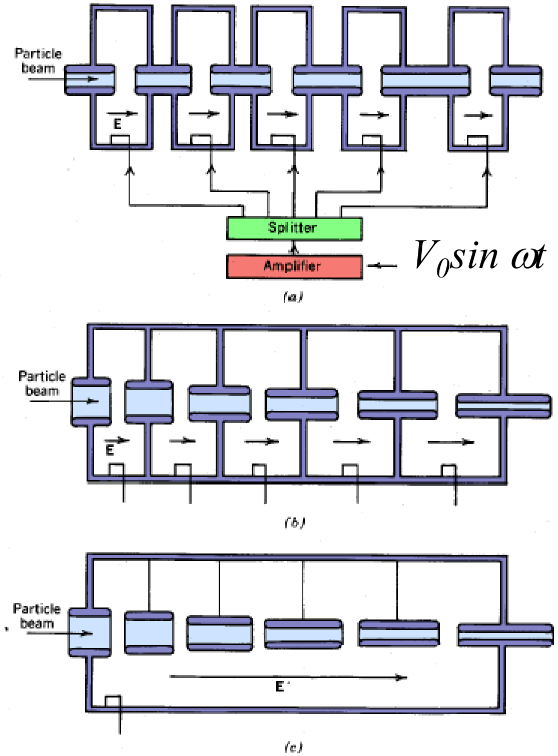
TM_{01}

Radio-frequency Resonant Cavities

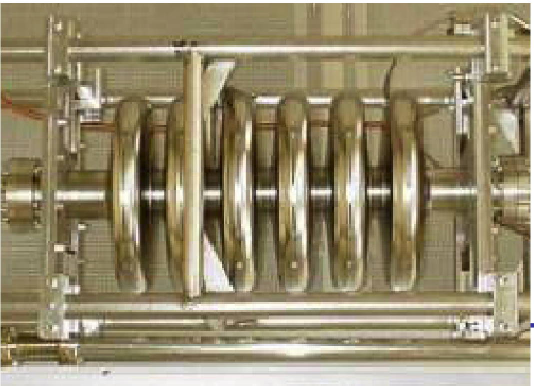


$$\oint \vec{E} \cdot d\vec{r} = -\frac{d\Phi_B}{dt}$$

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

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

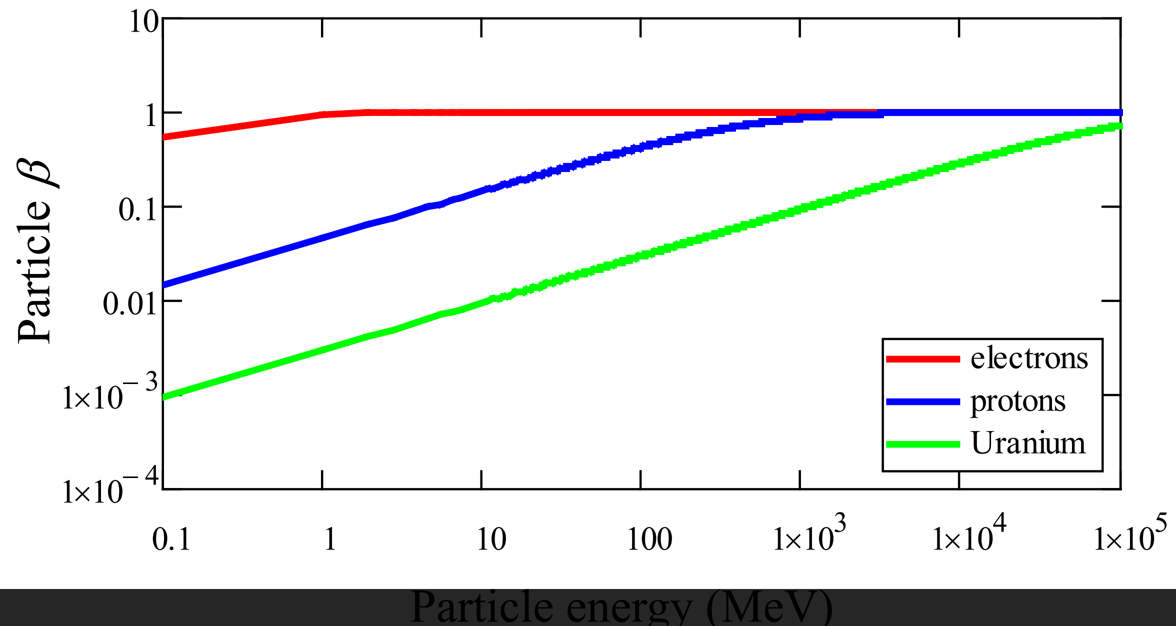
- *great reduction of rf power consumption even considering cryogenics (1W at 4.2K ~ 300W at 300K)*
- *the use of short cavities with wide velocity acceptance*

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*



Low-β Superconducting Cavities

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

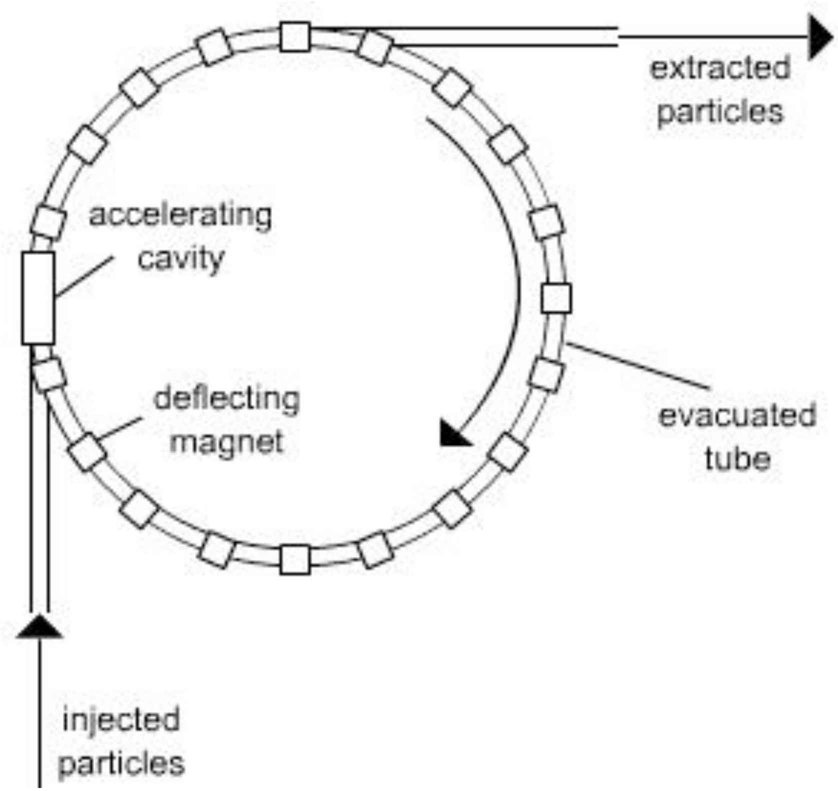
- For “slow” particles, in which velocity changes are dramatic between accelerating gaps, various solutions/designs...

β<1 resonators, from very low (β~0.03) to intermediate (β~0.5): many different shapes and sizes

A. Facco

Back to Circles: The Synchrotron

- **Can achieve high energy at modest cost – tend to be used to deliver the highest energies**
- **Beam is accelerated in bunches, using RF cavities**
- **Beam is accelerated internally and then ejected**
- **Intensity can be limited by the Coulomb force of particles within a bunch (Space Charge)**
- **The magnets must ramp, and this can be difficult to do quickly for superconducting magnets**

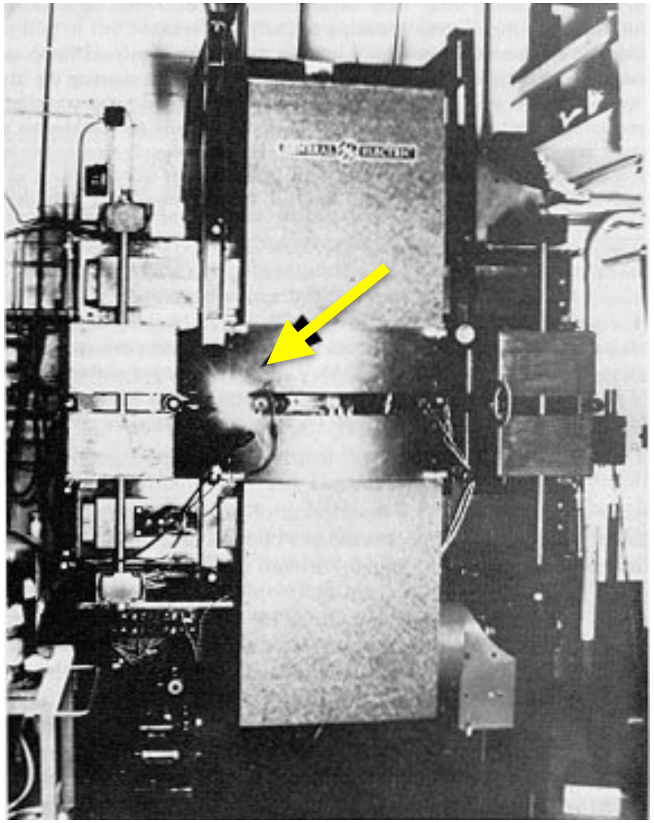


http://universe-review.ca/R15-20-accelerators.htm

The Synchrotron

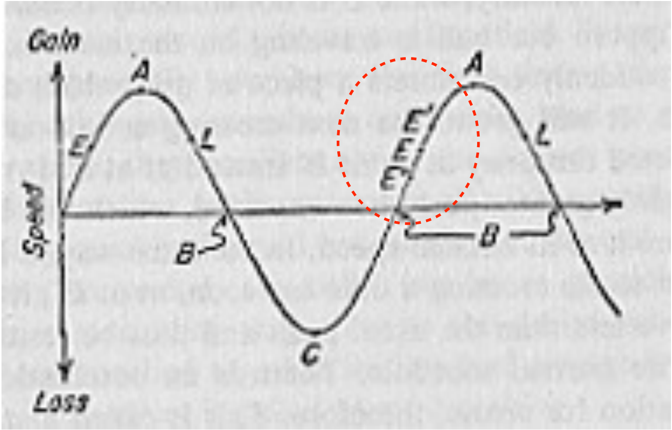
- 1^{st} in U.S. was at G.E. research lab, late 1940's -- 70 MeV electron beam

Notice the "light" being emitted at the location of the arrow — this is called "synchrotron radiation", and is the radiation given off by the accelerated electrons; at this energy it is visible light. Today, we operate "light sources" which are higher-energy electron synchrotrons which produce X-rays for scientific studies in materials science, biology, etc.



RF Systems

- For power efficiency, use a resonant system whereby the accelerating field is generated within "cavities" being driven by a power source
  - high power radio sources come to mind -- MHz frequencies ("RF")

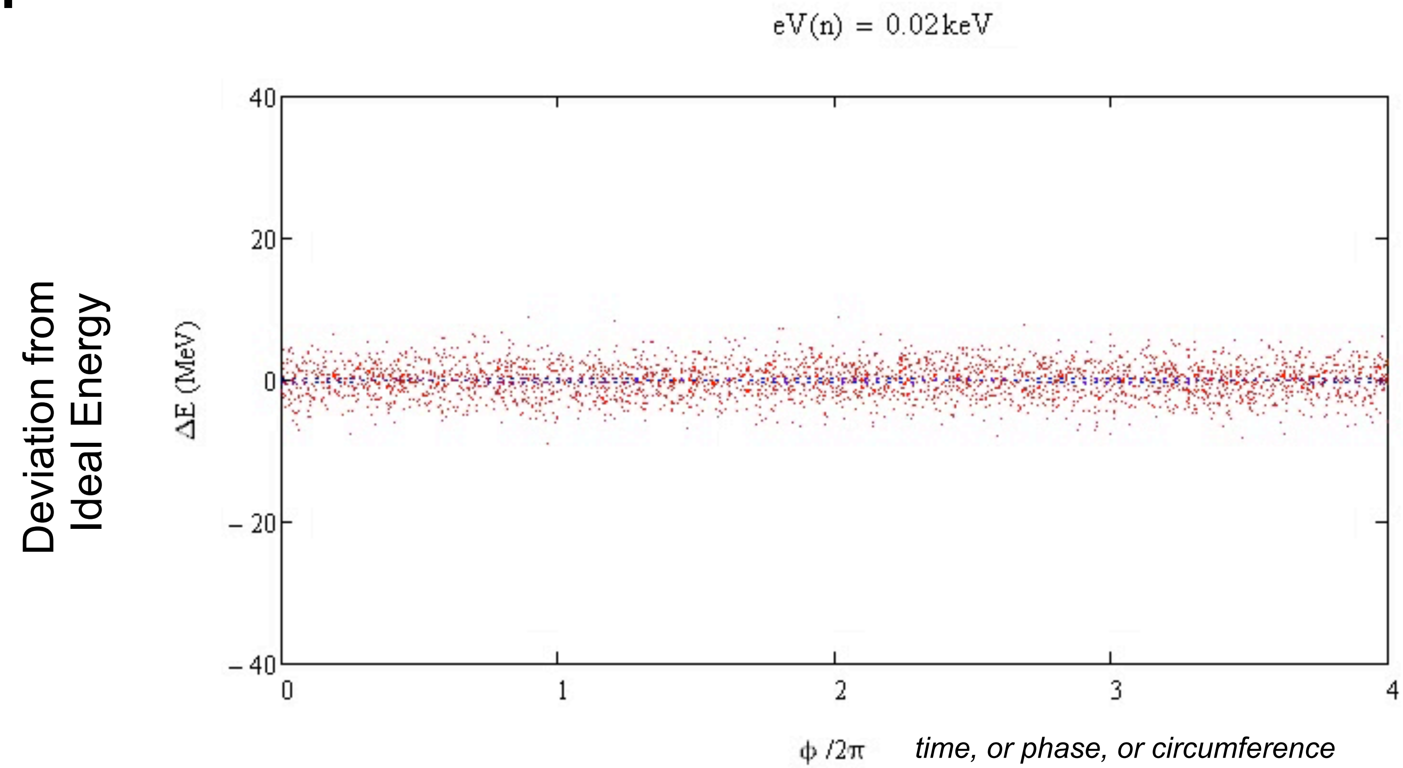


Here, ideal particle has energy E

- Using a sinusoidal voltage for acceleration introduces a restoring force on the energy oscillations about the ideal accelerating energy
  - First studied by McMillan (U. Cal), and Veksler (Russia)

Creating a Bunched Beam

- **Example: Fill a circular accelerator with particles, uniformly about the circumference; will have a natural spread in energies (~ < 1%, say)**
- **Adiabatically raise the voltage in an accelerating cavity; bunches will form**



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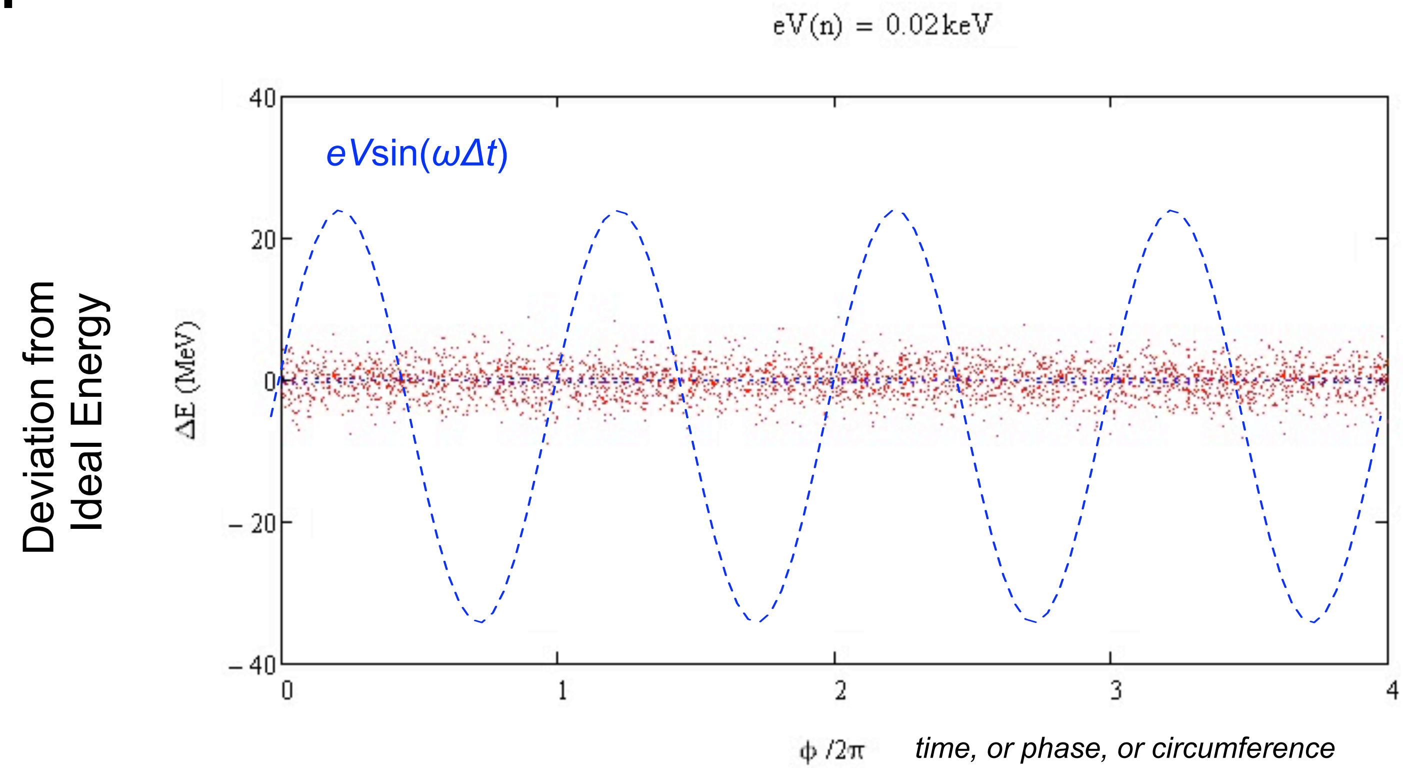

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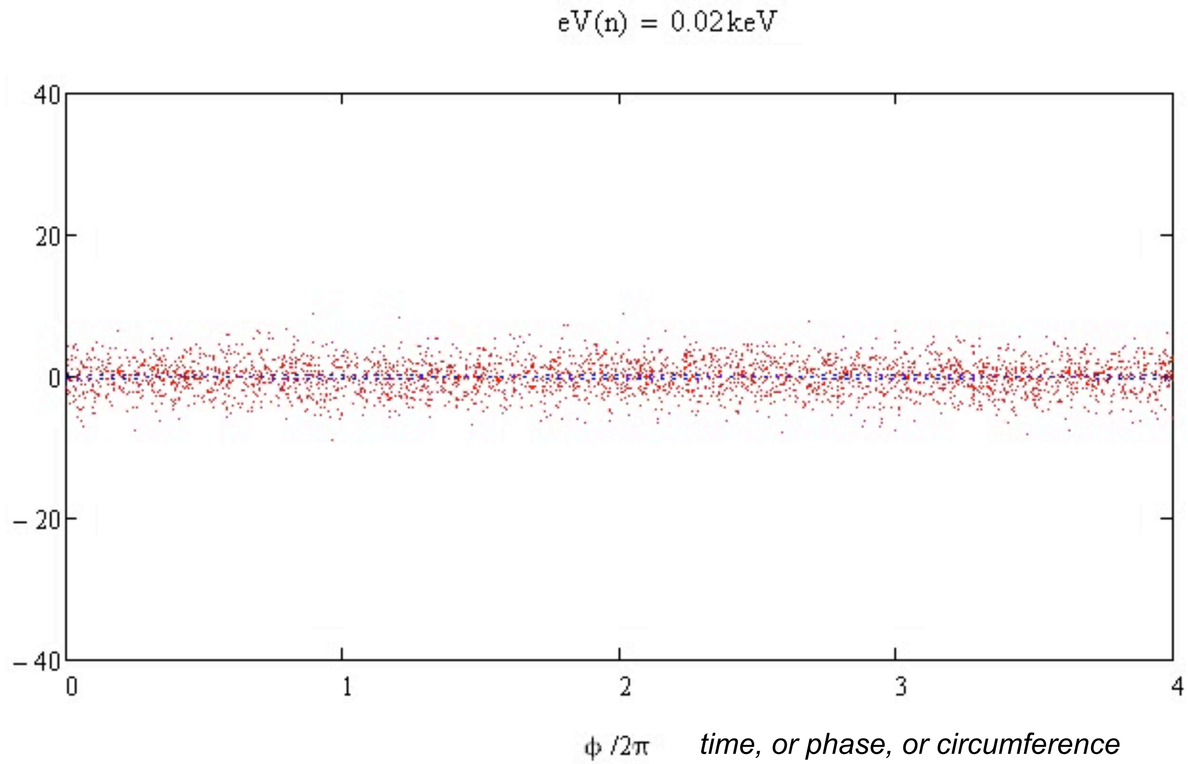


Deviation from Ideal Energy

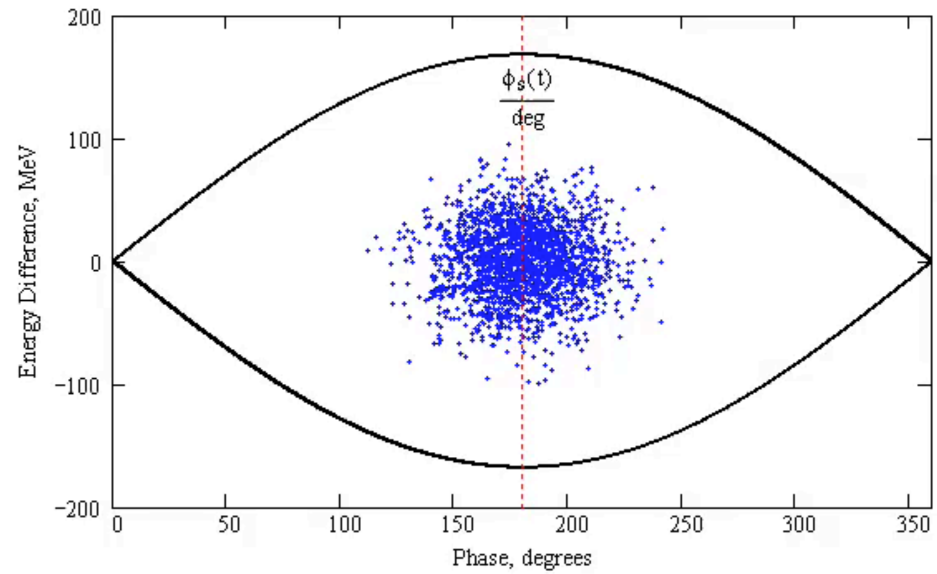
time, or phase, or circumference

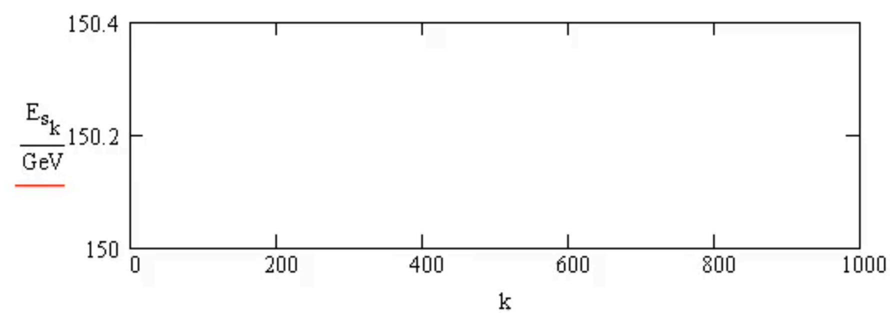
Acceleration through RF systems

If ideal particle has energy E_s and arrives at phase φ_s …

- **particles arriving nearby in phase, and nearby in energy will oscillate about this ideal condition**
  - **$E = E_s + \Delta E$**

- **If increase of the central particle energy is adiabatic (on scale of energy oscillation period), then particles nearby in energy and phase will oscillate about that ideal energy and follow along (E-t canonical variables)**





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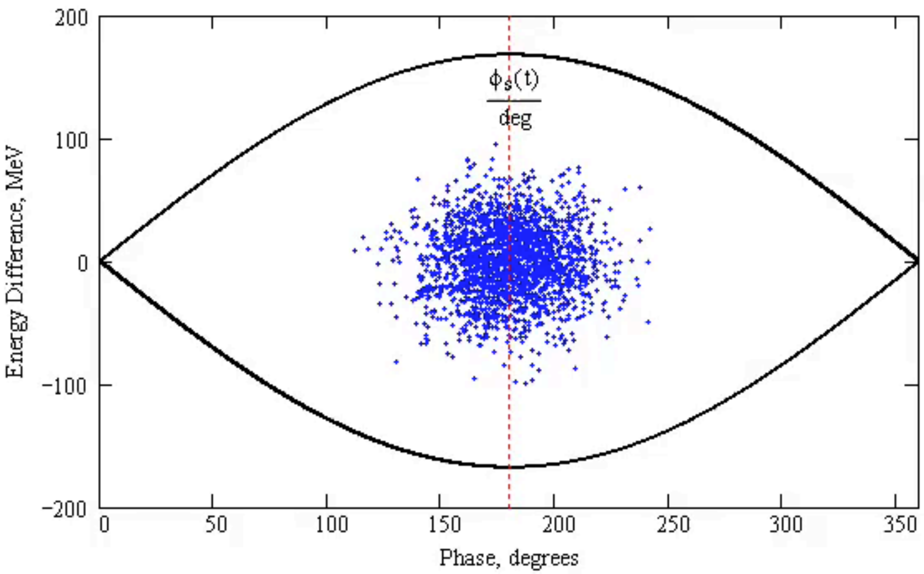
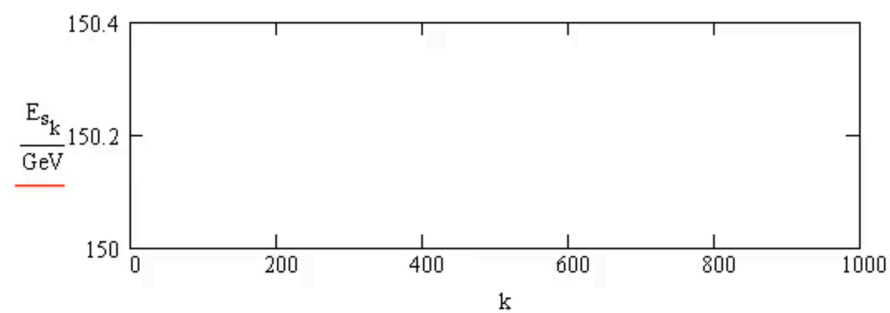




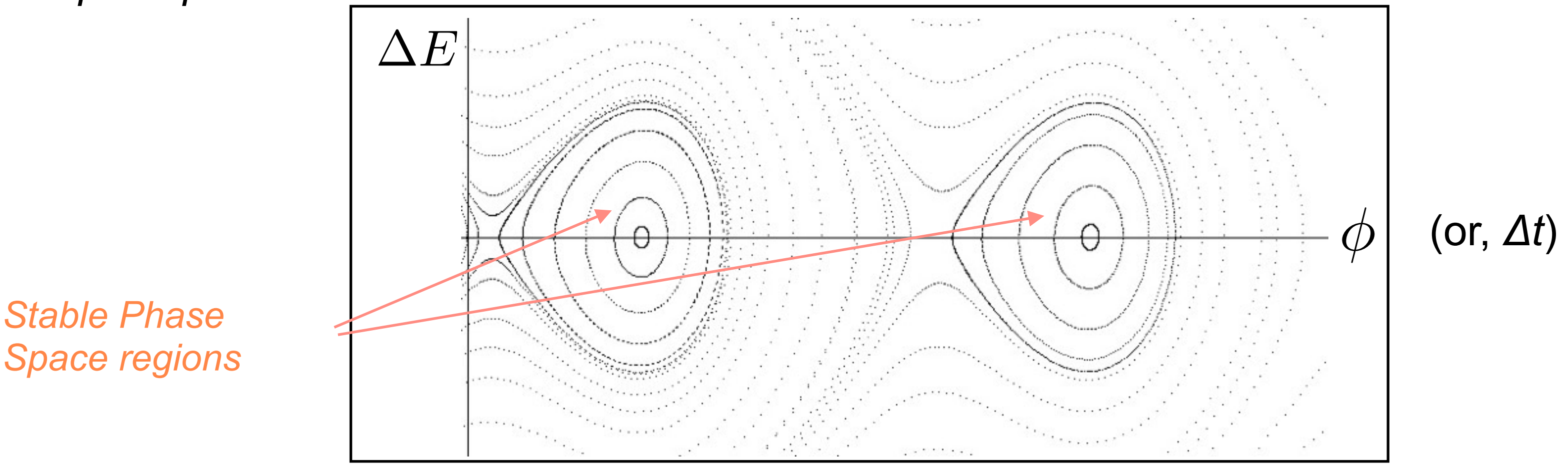
Stability of Longitudinal Motion

- **If increase of the central particle energy is adiabatic (on scale of energy oscillation period), then particles nearby in energy/phase will oscillate about that ideal energy and follow along (E-t canonical variables)**

If *ideal* particle has energy E_s and arrives at phase φ_s ...

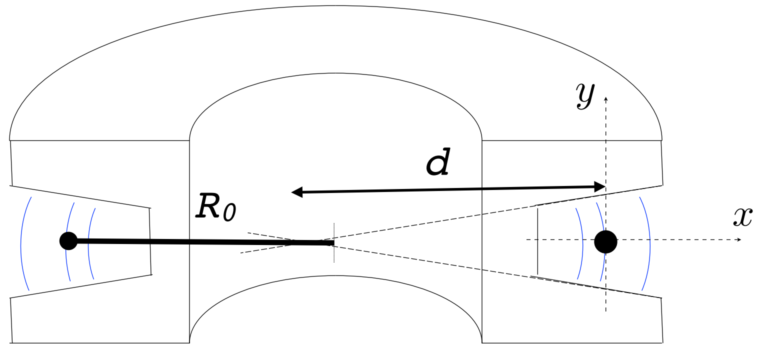
particles arriving nearby in phase, and nearby in energy $E = E_s + \Delta E$ will oscillate about this ideal condition

Phase Space plot:



How to Keep the Beam Focused

- **In addition to increasing the particle's energy, must keep the beam focused transversely along its journey**
- **Early accelerators employed what is now called "weak focusing"**



$$B = B_0 \left(\frac{R_0}{r}\right)^n$$

$$n \approx \frac{R_0}{d}$$

must have
$0 \leq n \leq 1$
for stability

n is determined by adjusting the opening angle between the poles

$$d = \infty,\ n = 0$$

$$d = R_0,\ n = 1$$

Room for improvement...

- **With weak focusing, for a given transverse angular deflection,** $x_{max} \sim \frac{R_0}{\sqrt{n}}\,\theta$
- **Thus, aperture ~ radius ~ energy**

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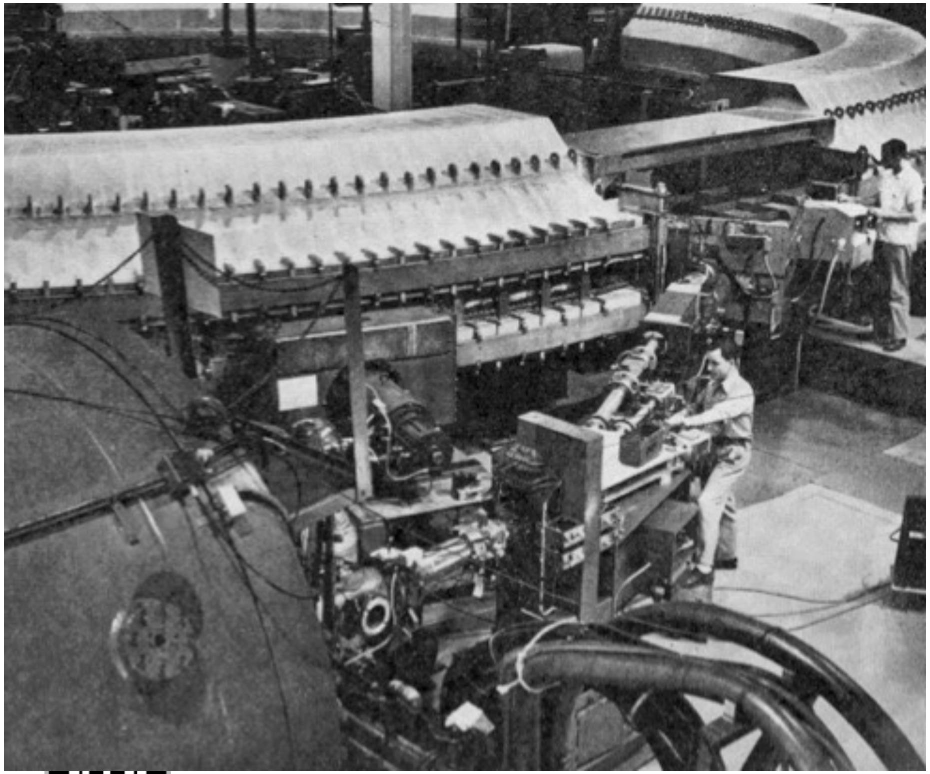
(3.3 GeV)



Cosmotron (1952)

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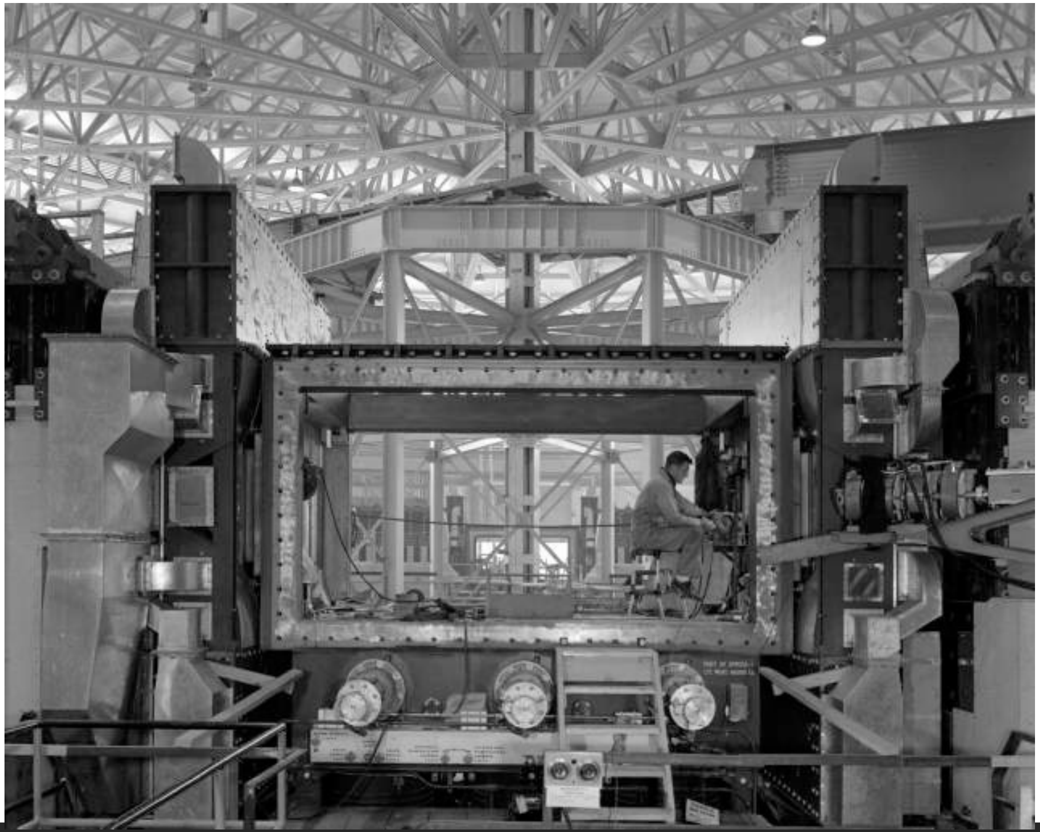
(6 GeV)

Bevatron (1954)



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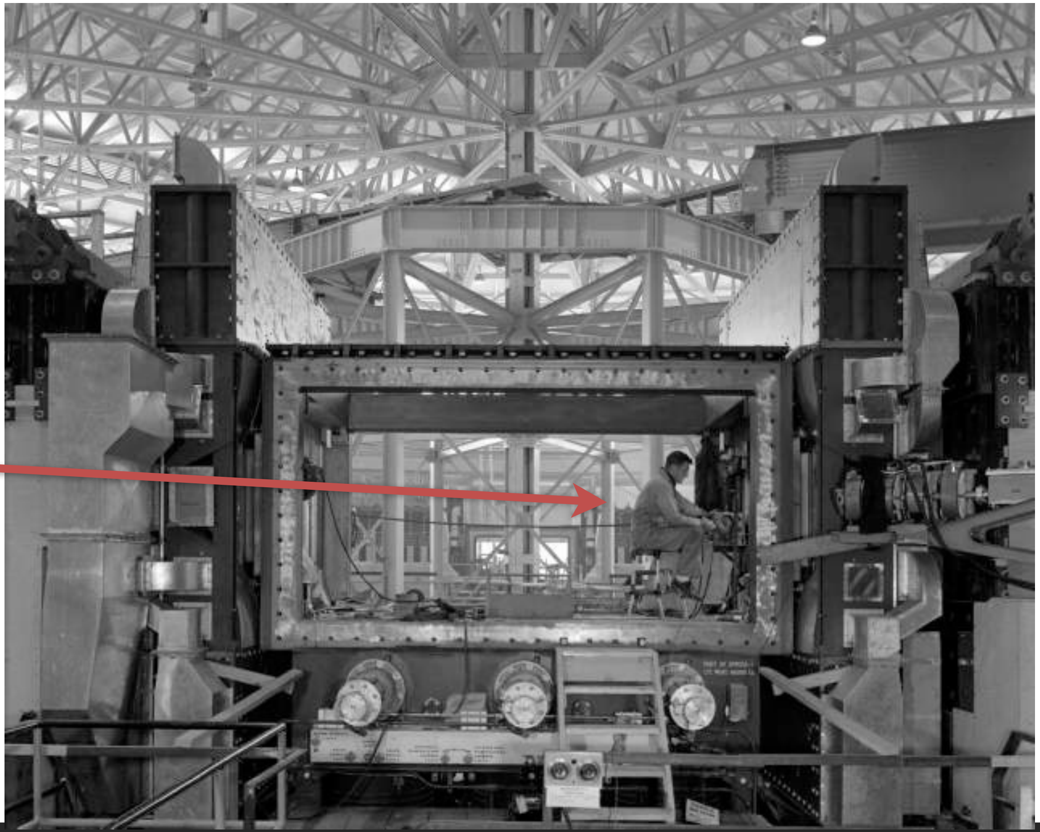
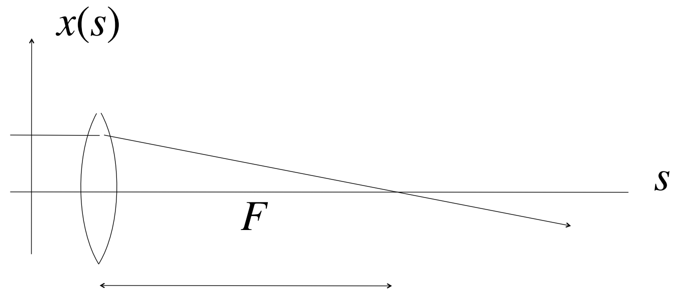


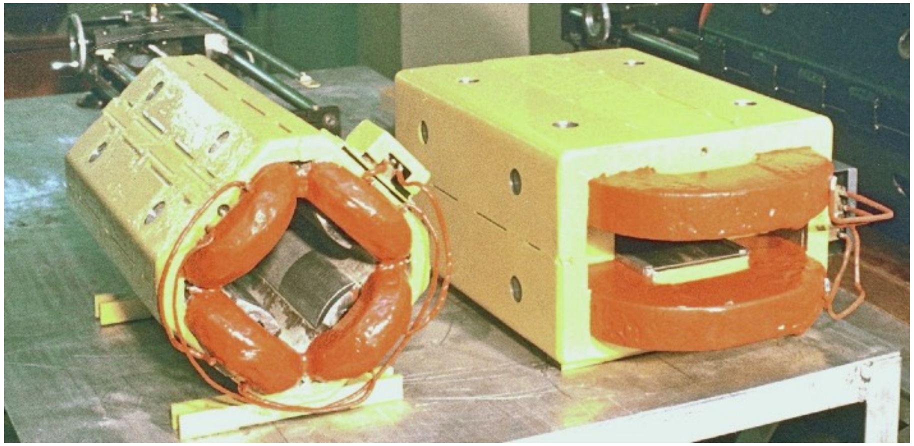
Could actually sit inside the vacuum chamber!!

Separated Function

- Until late 60's, early accelerator magnets (wedge-shaped variety) both focused and steered the particles in a circle. ("combined function")
- Now, use "dipole" magnets to steer, and use "quadrupole" magnets to focus
- Quadrupole magnets, with alternating field gradients, "focus" particles about the central trajectory -- act like lenses
  - Thin lens focal length:

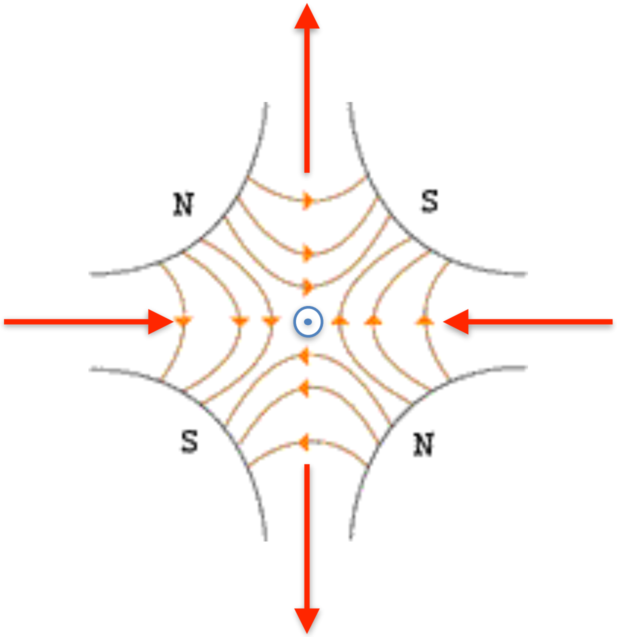
$$\Delta x' = eB_y\ell/p = (eB'\ell/p)\,x \rightarrow 1/F = eB'\ell/p$$





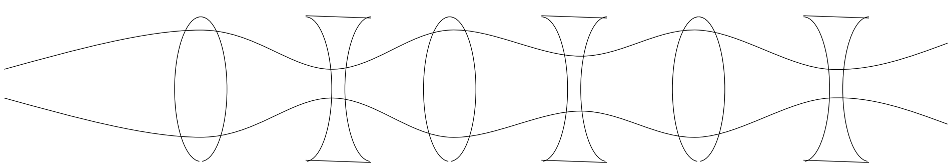
Strong Focusing

Think of standard focusing scheme as alternating system of focusing and defocusing lenses (today, use quadrupole magnets)



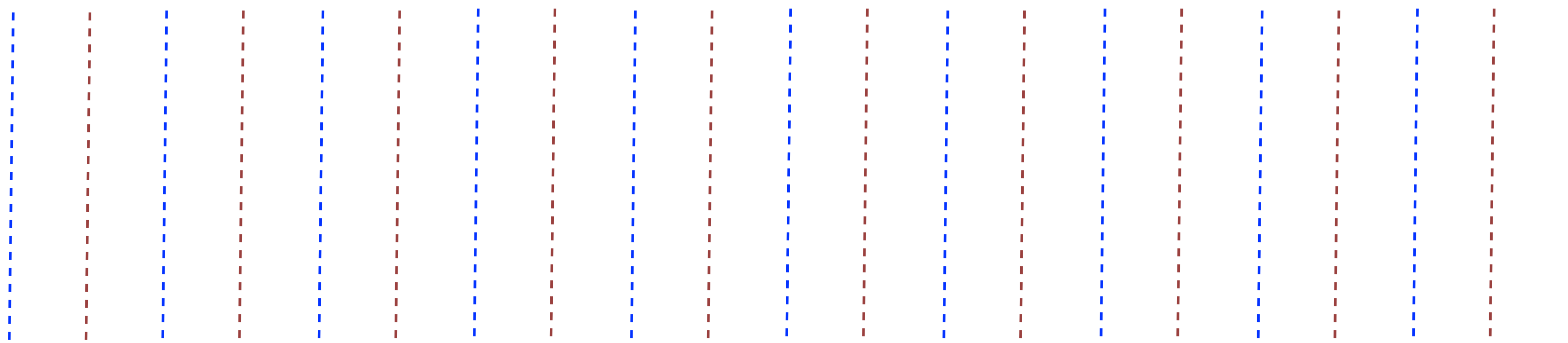
Quadrupole will focus in one transverse plane, but defocus in other; if alternate, can have net focusing in both

alternating gradients:



Particle Trajectories

F/D “cells”



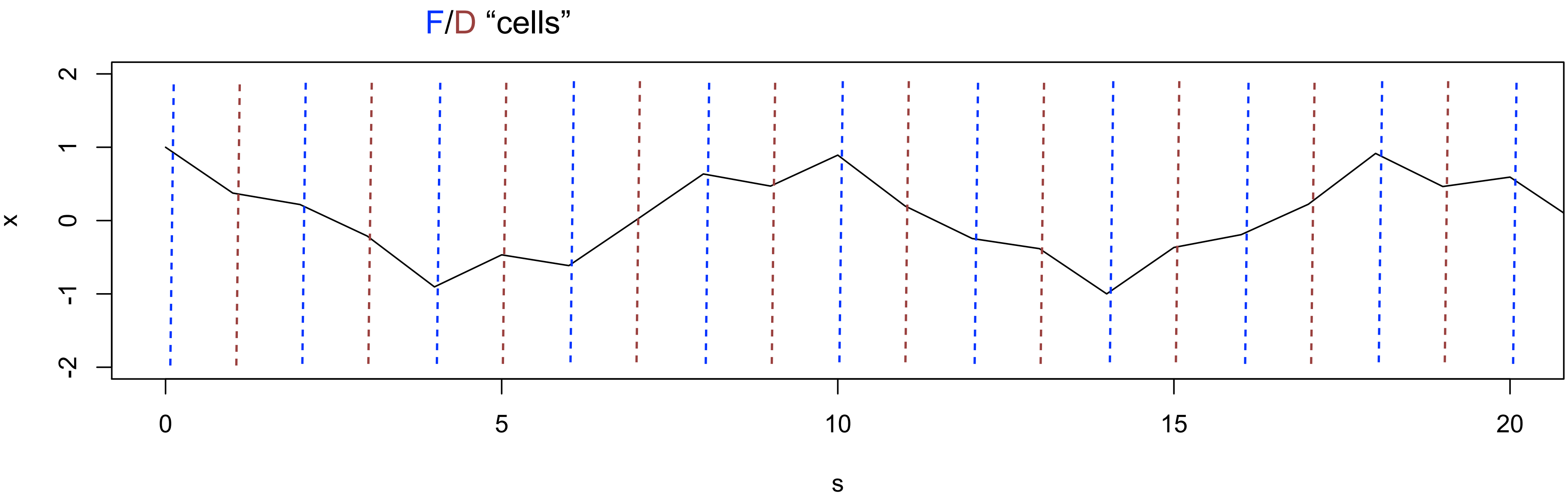
$$\frac{dx'}{ds} = \frac{d^2x}{ds^2} = -\frac{eB'(s)}{p}x$$

(Hill’s Equation)

$$\boxed{x'' + K(s)x = 0}$$

$$\left[K(s) = \frac{e}{p}\frac{\partial B_y}{\partial x}(s)\right]$$

Particle Trajectories



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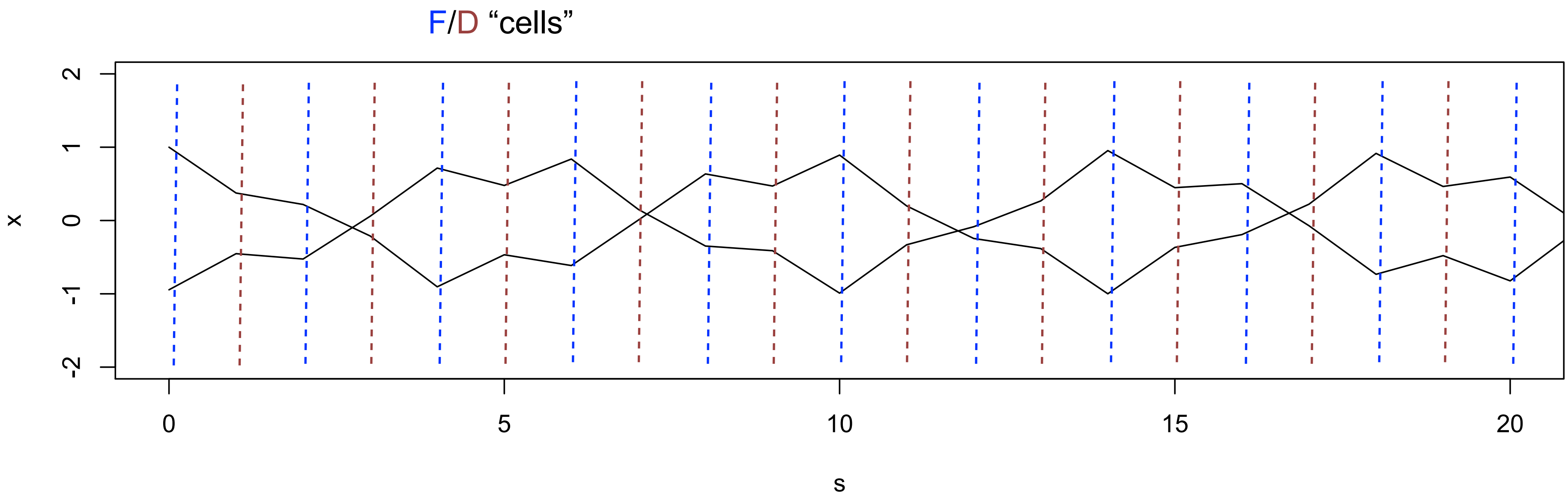

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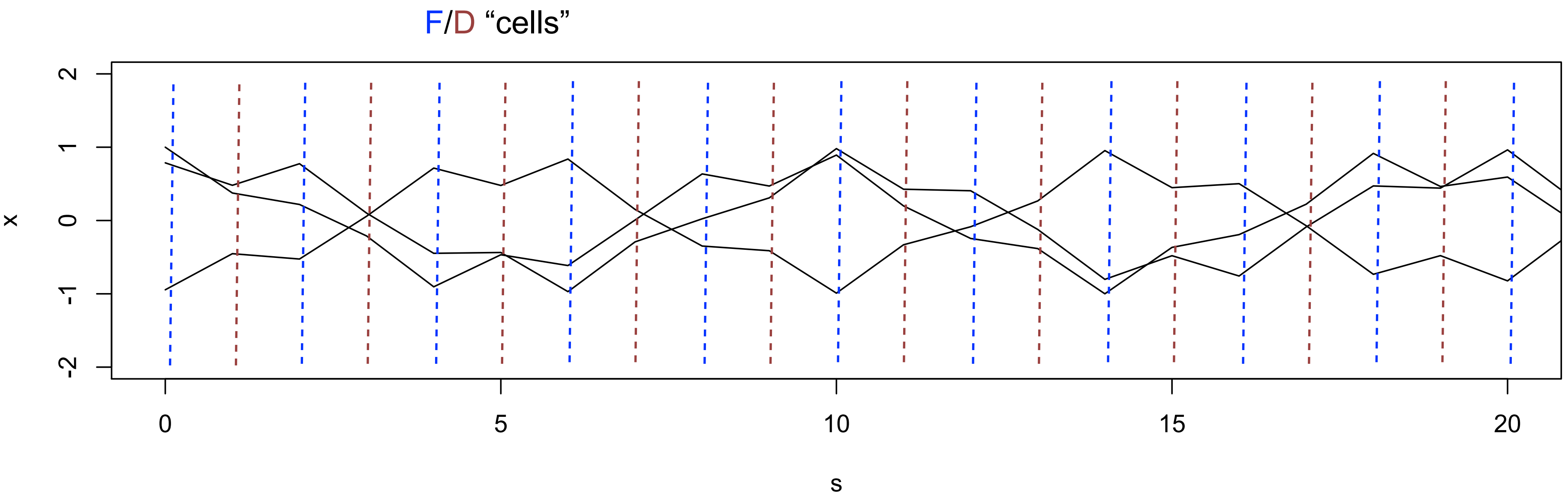

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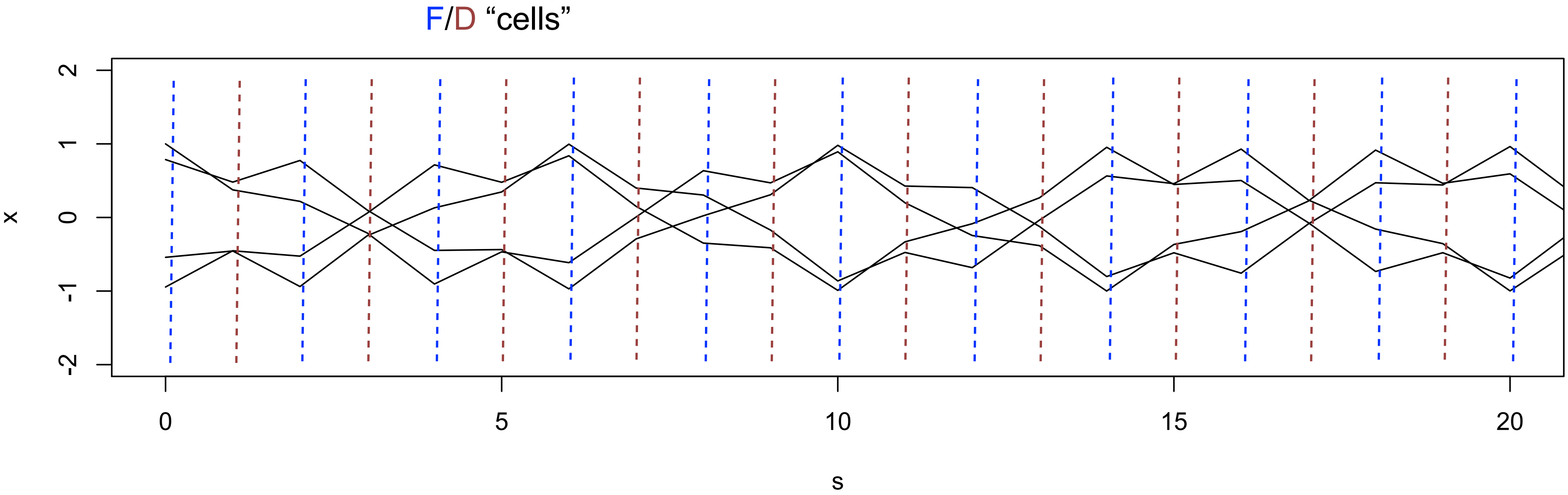

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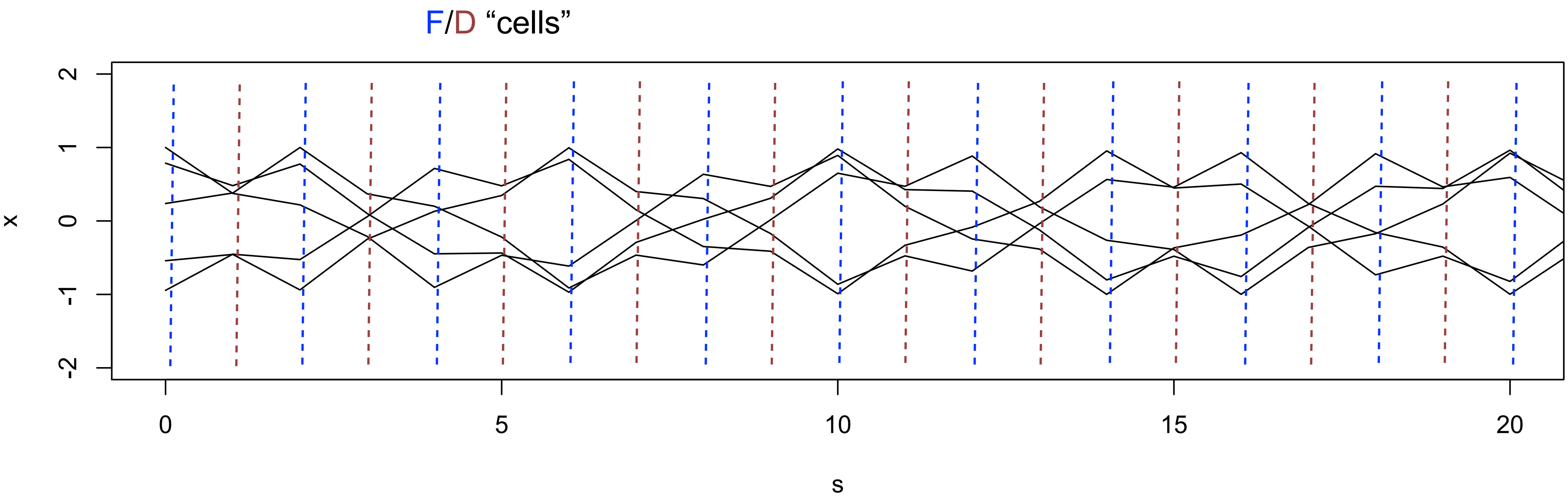

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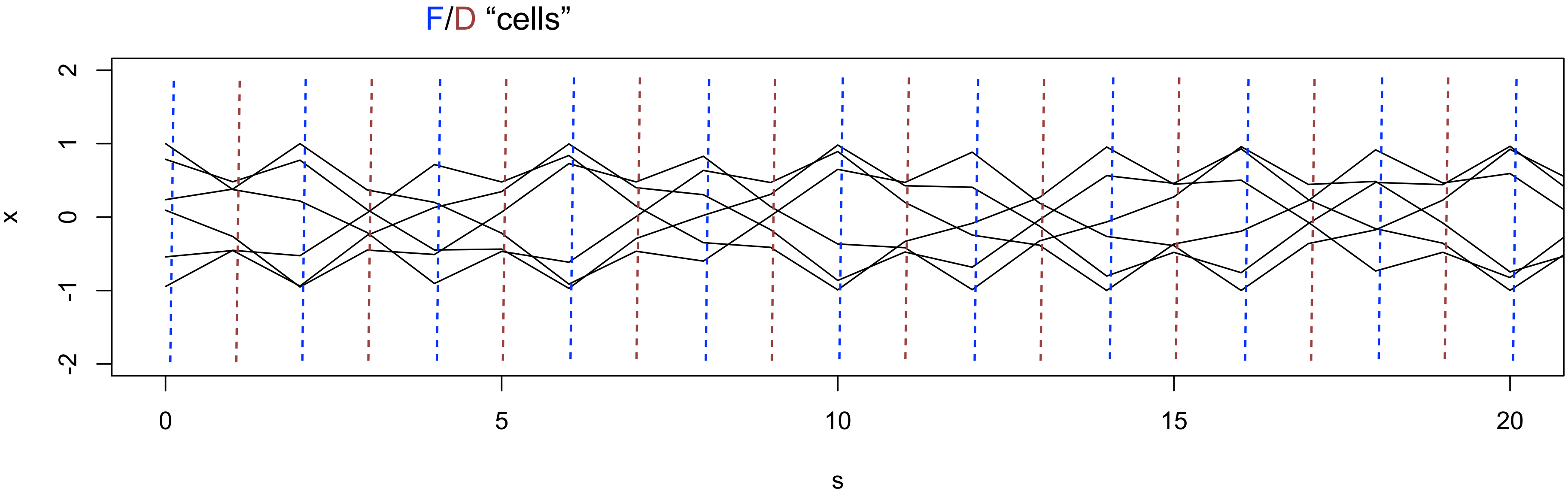

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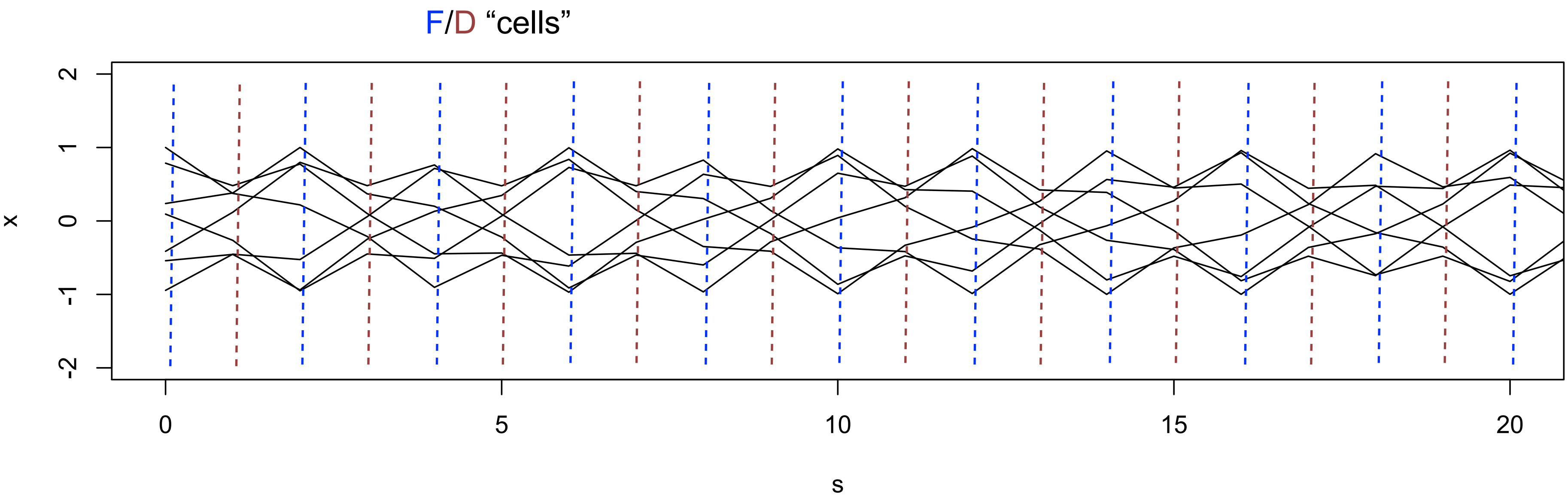

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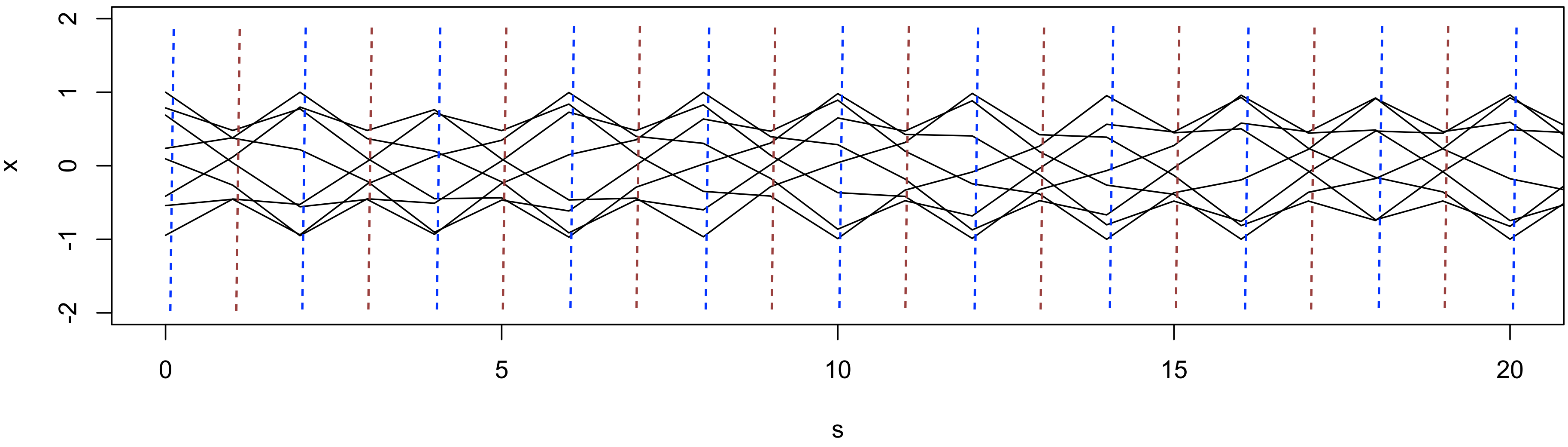

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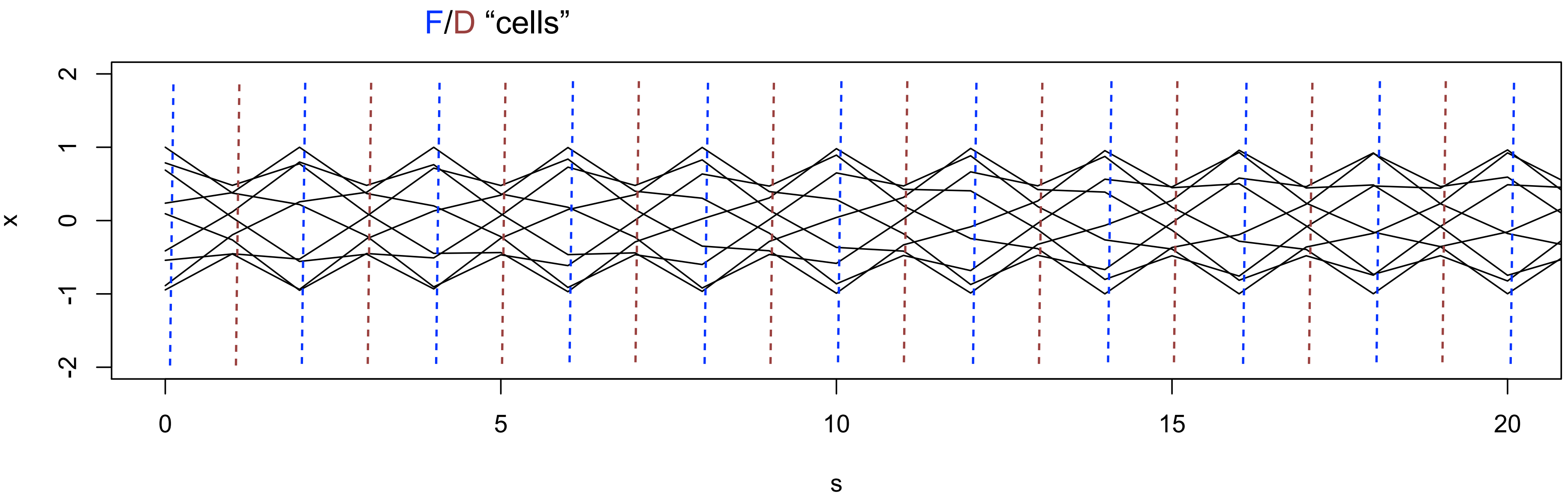

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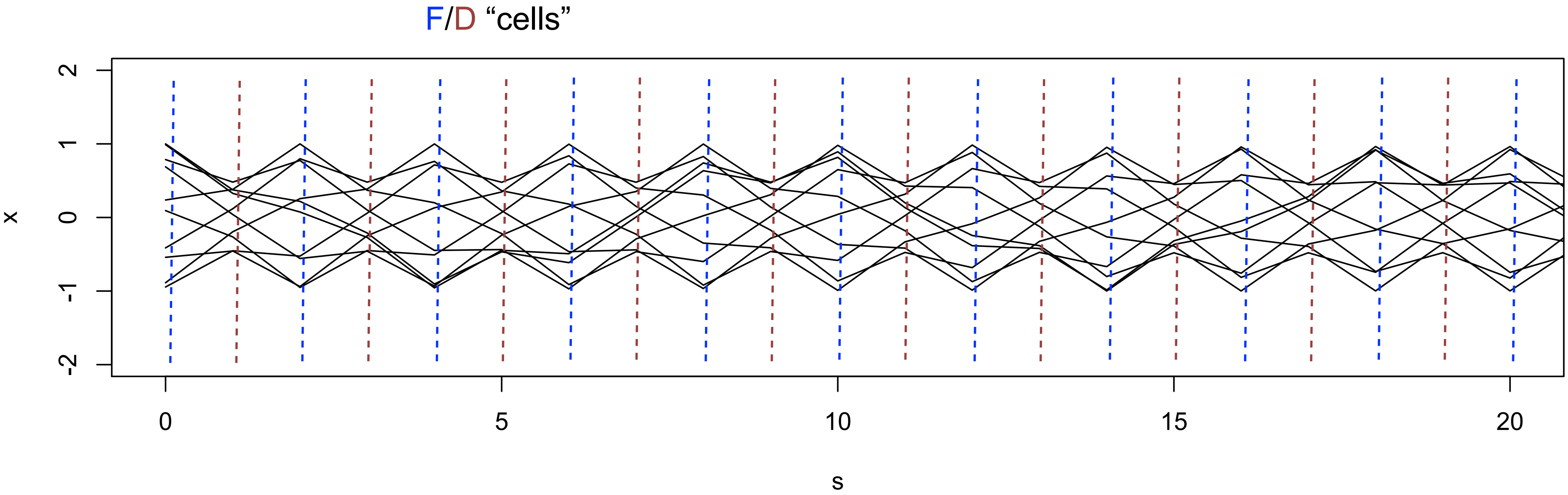

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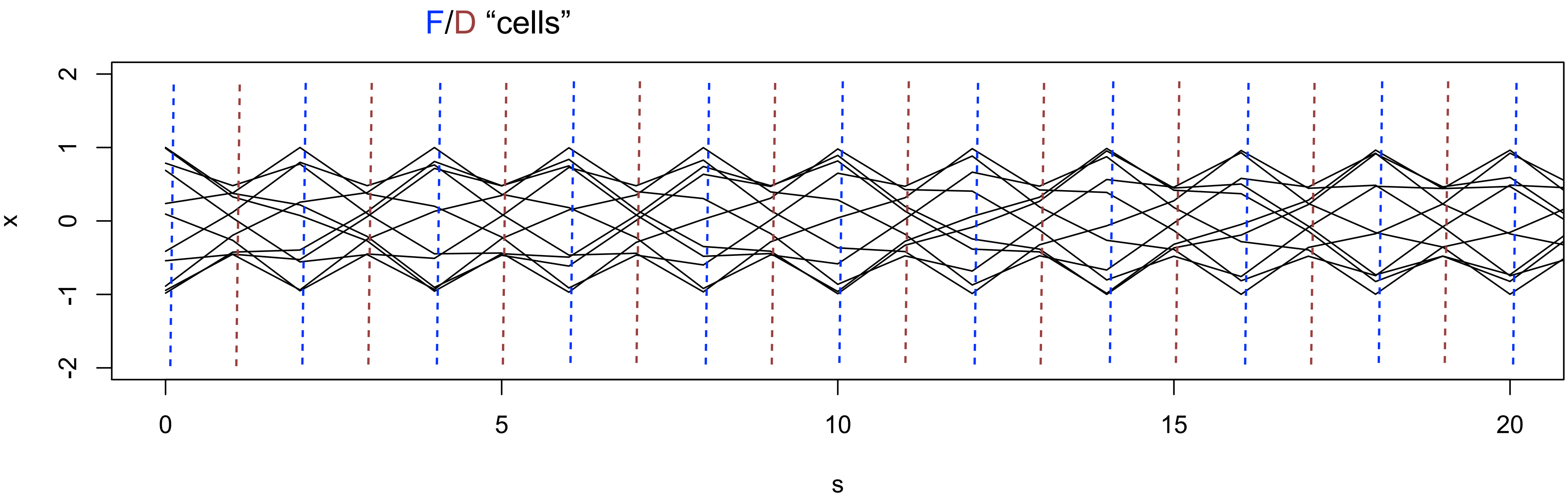

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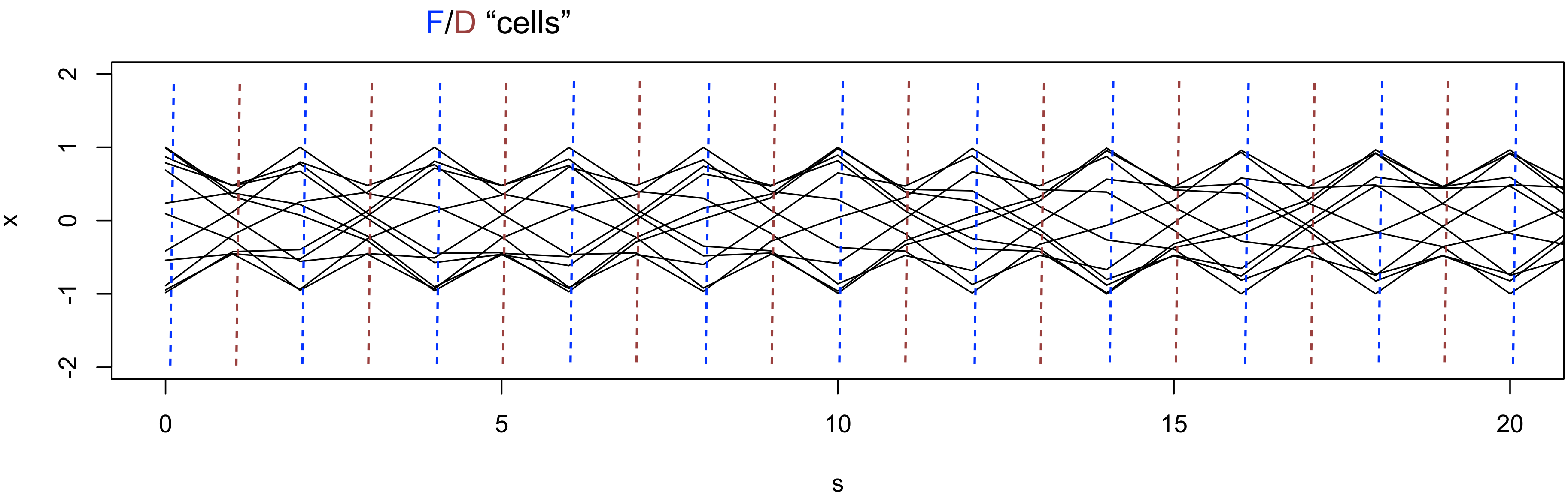

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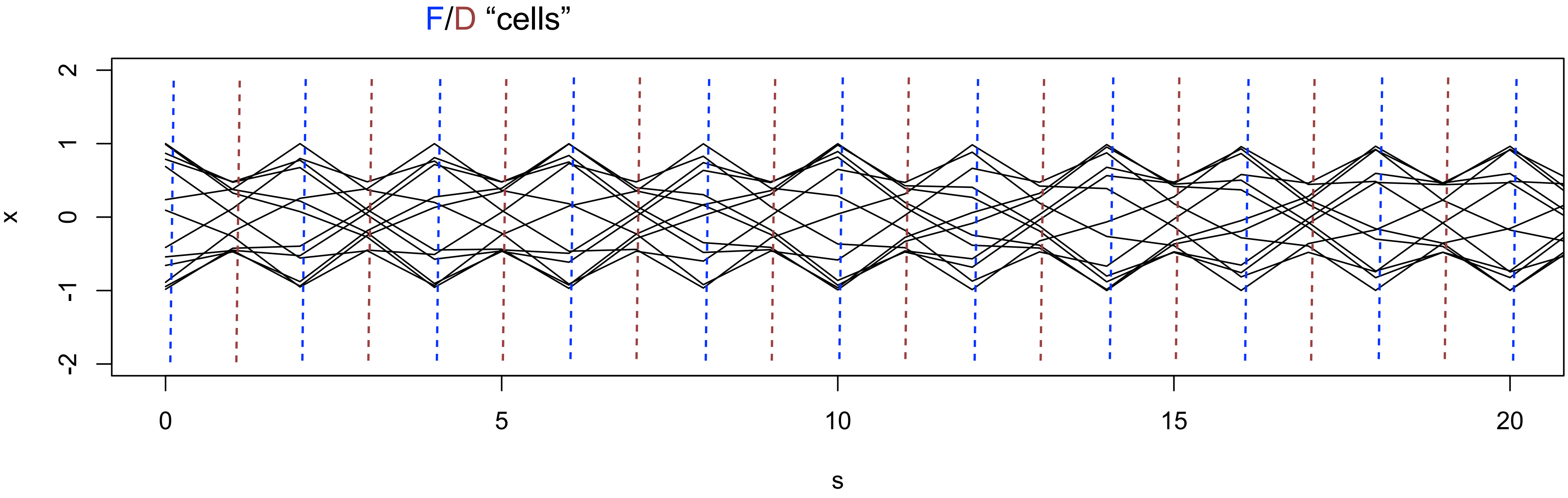

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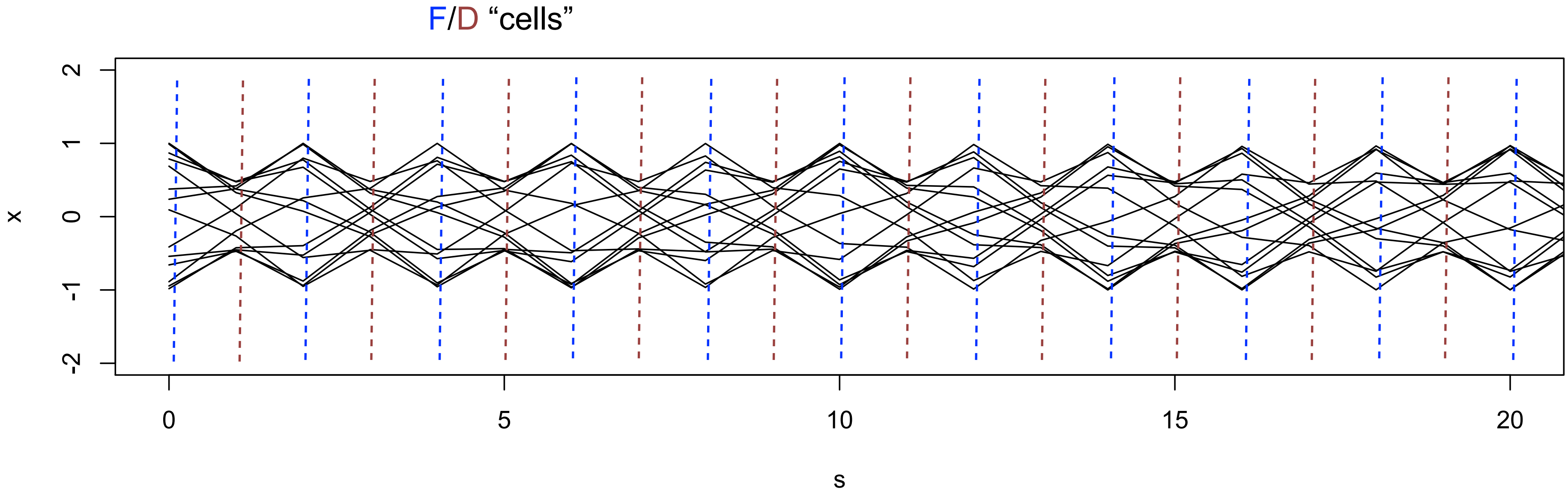

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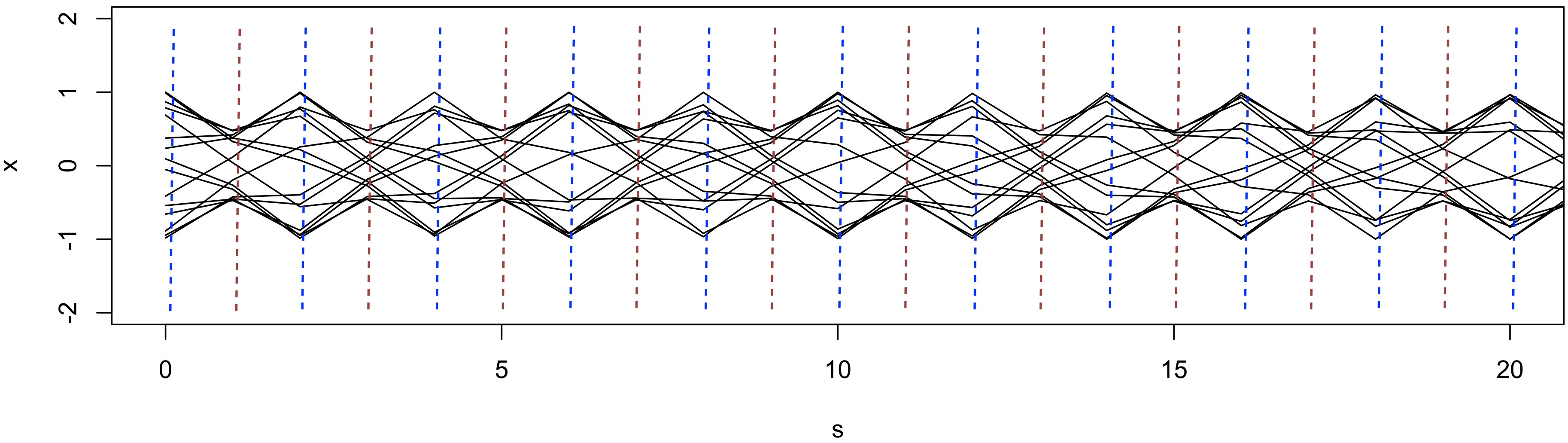

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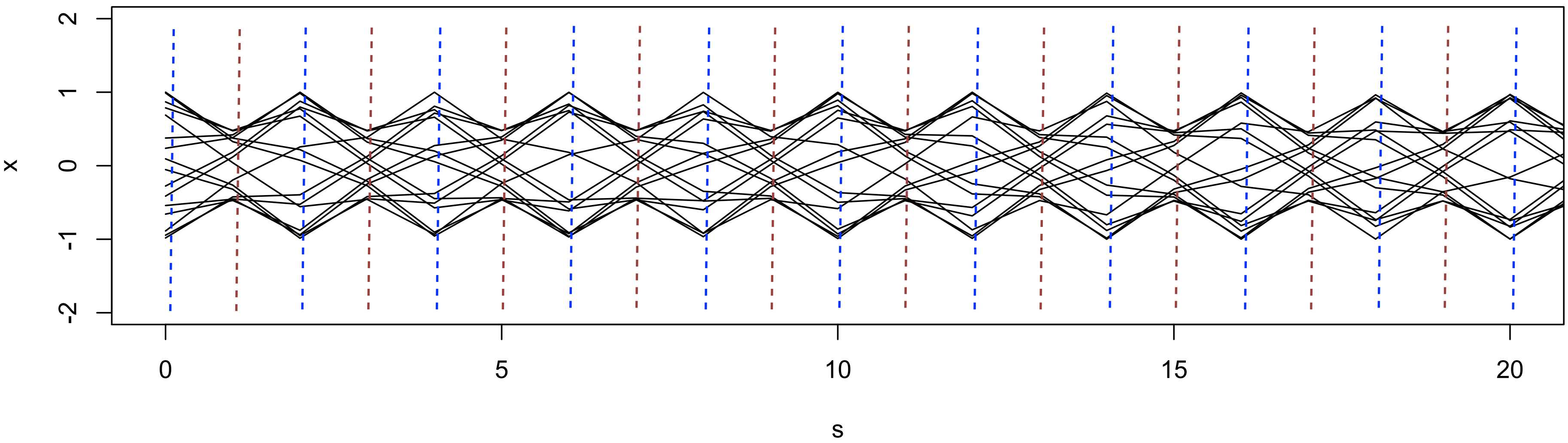

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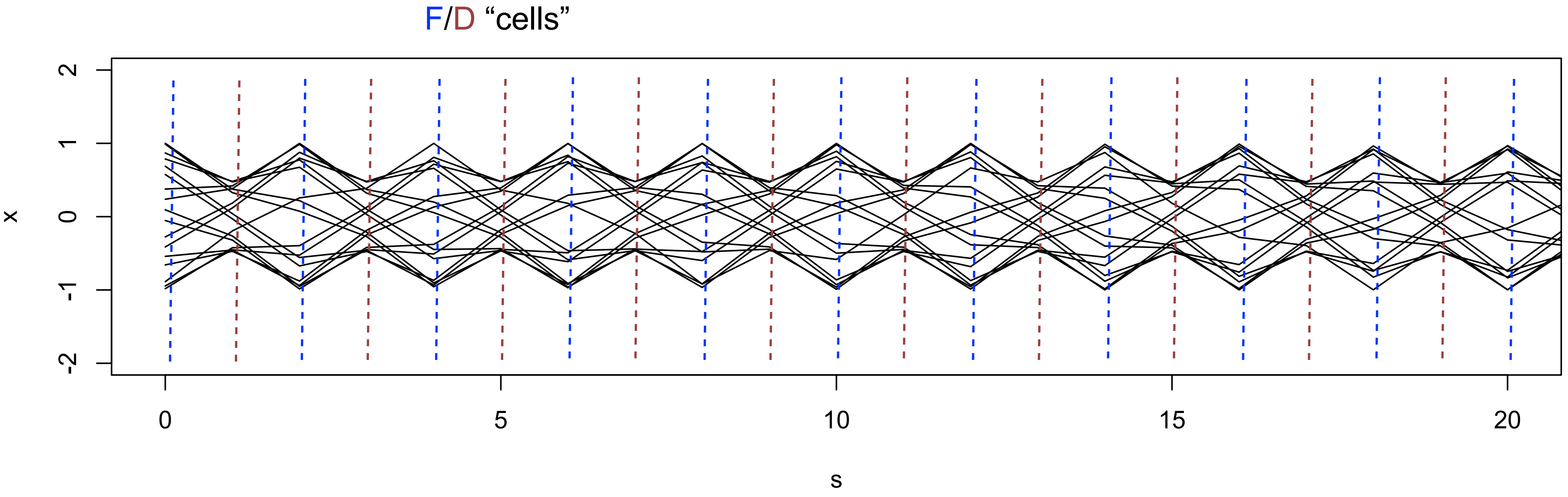

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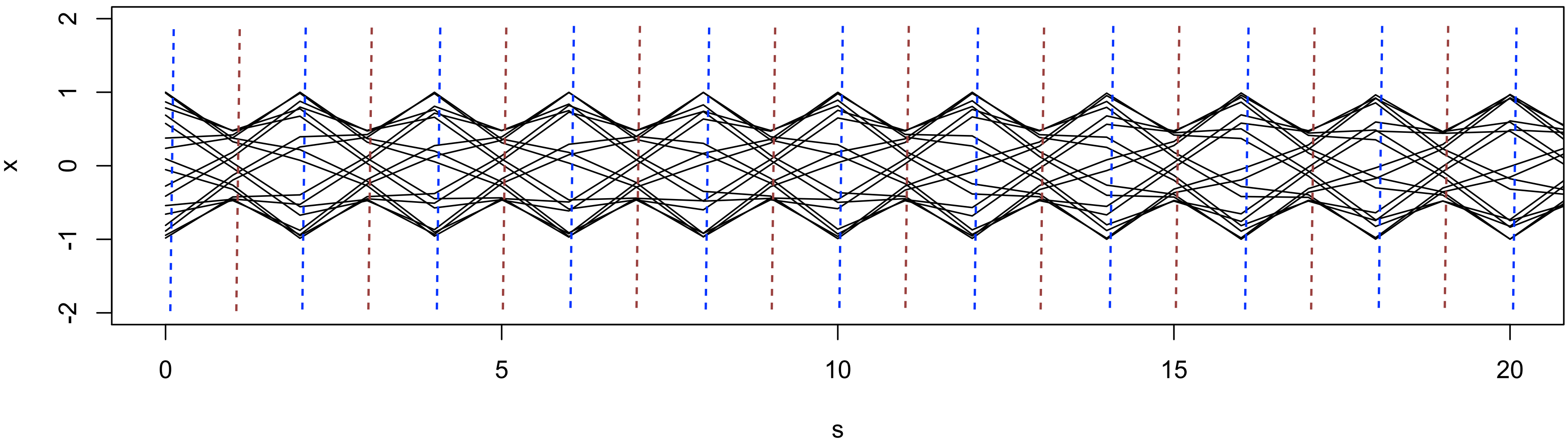

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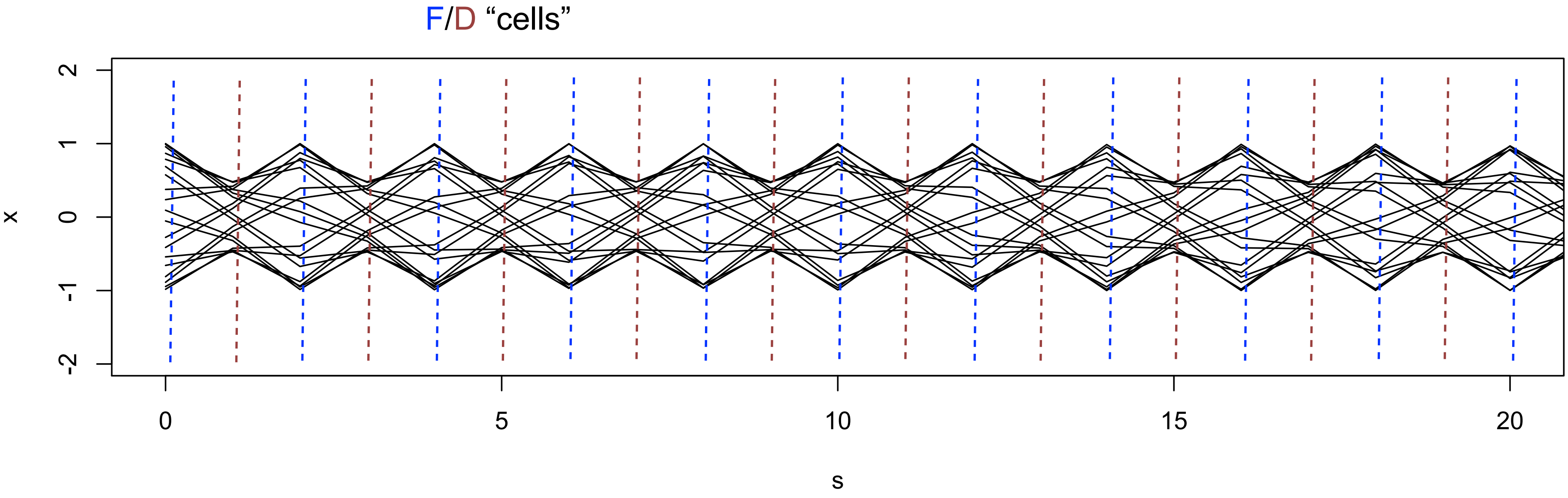

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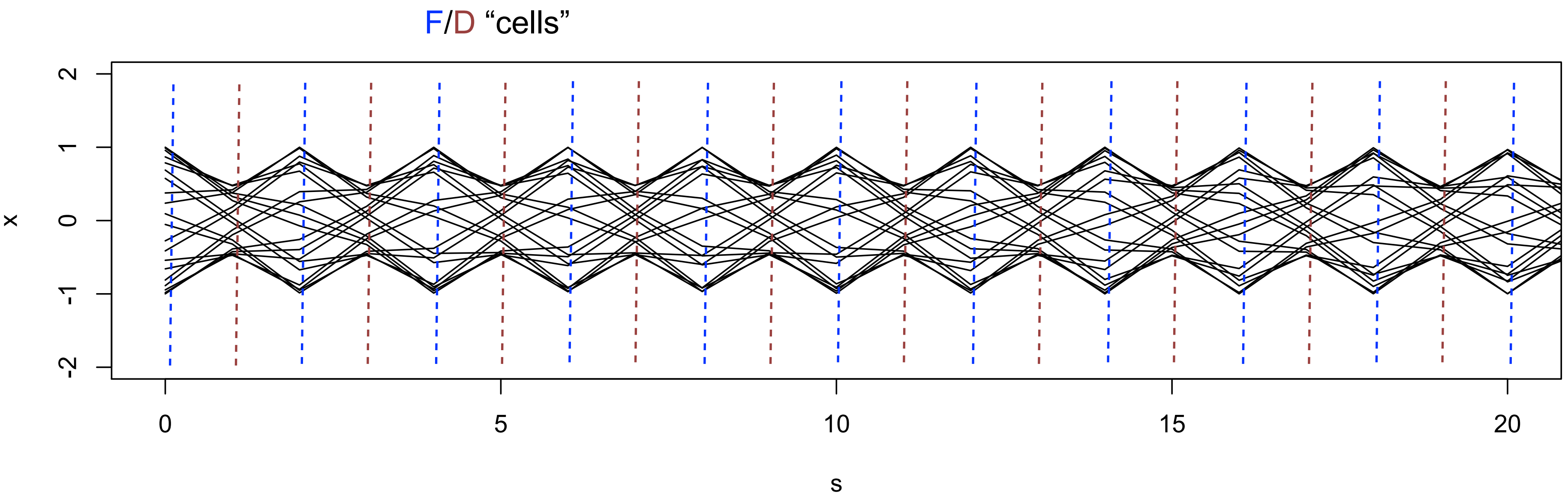

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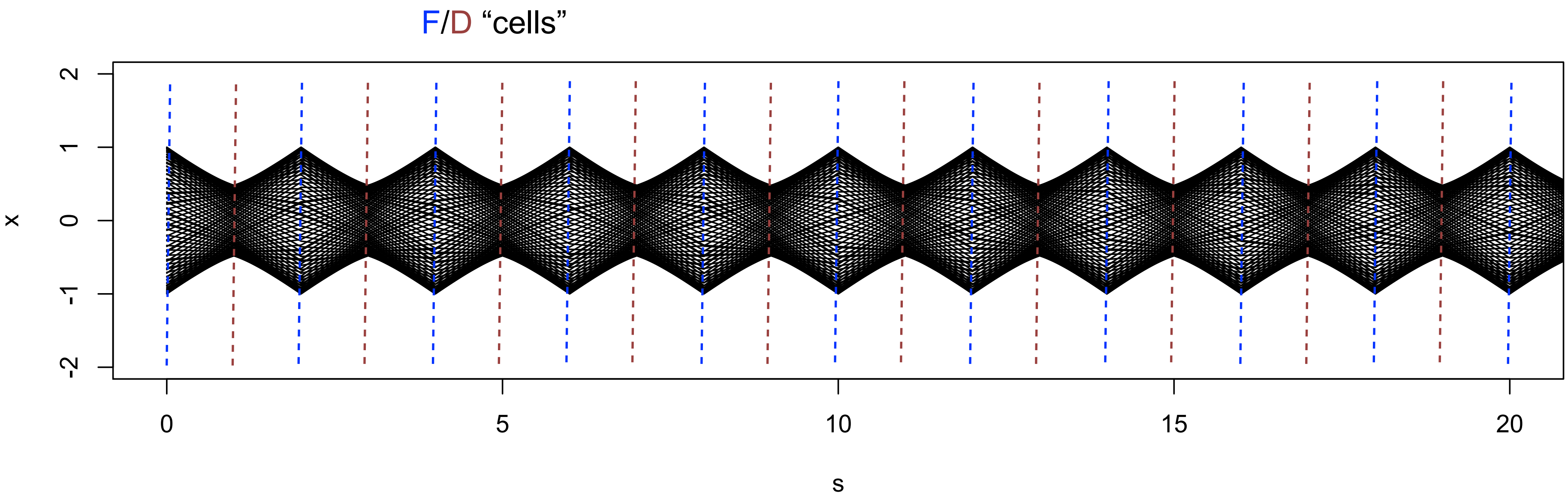

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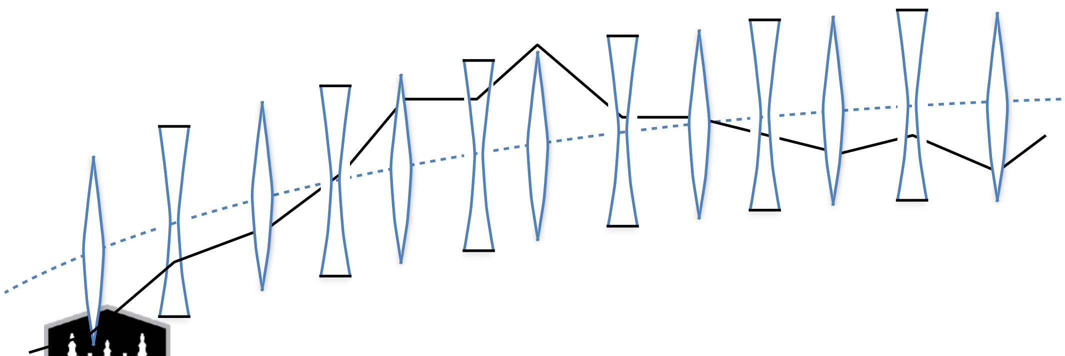
Strong Focusing -- what it means

- **Essentially, if focus (positive gradient, say), and then defocus (negative gradient), with appropriate "lens" spacing, then can control beam size over great distances**
- **Ex: simple system of lenses, spaced by d:**

$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

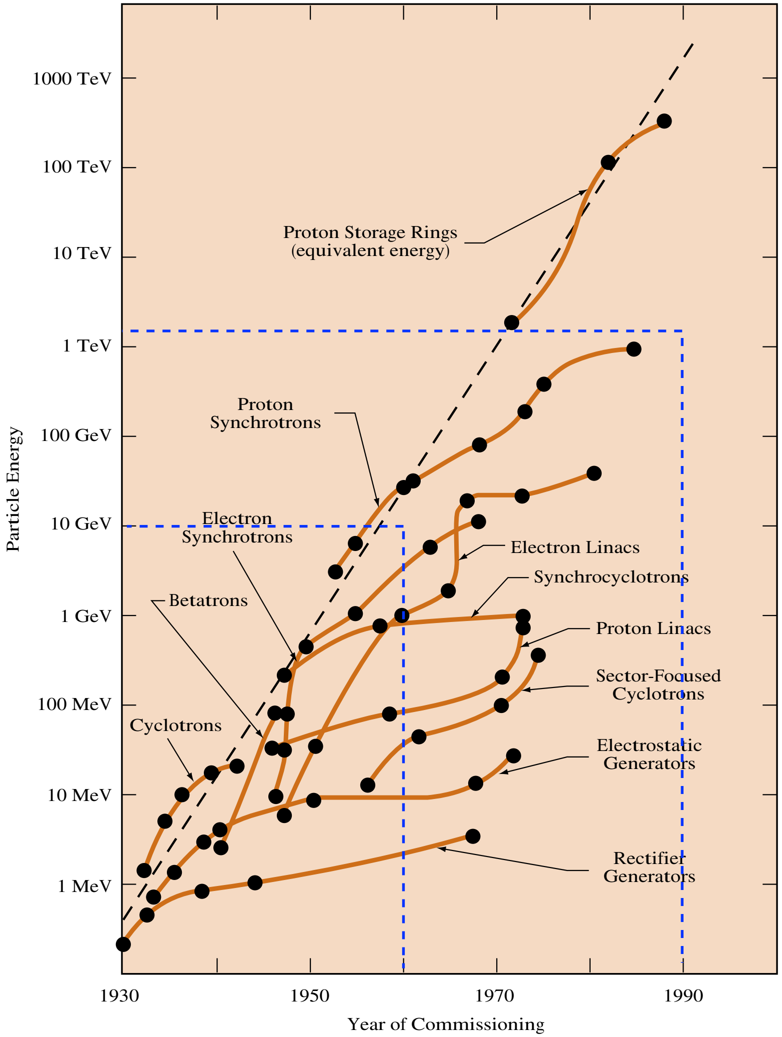
$$f_2 = -f_1 \quad \longrightarrow \quad F = \frac{f_1^2}{d} > 0$$

So, can in principle generate arbitrarily long focusing system:

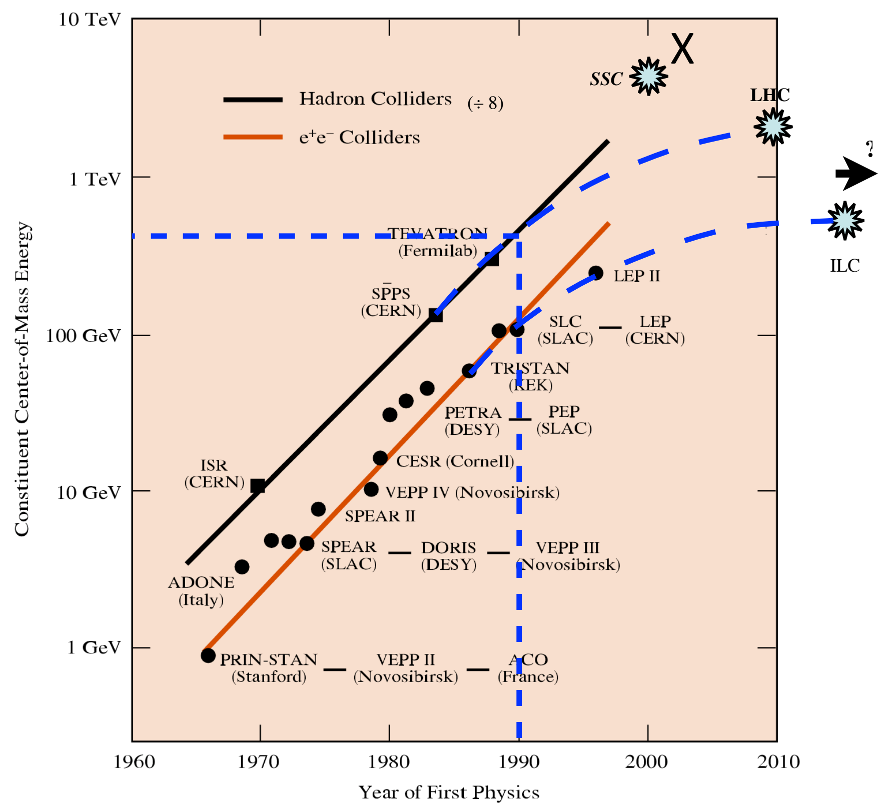


AGS construction, Brookhaven, New York

Livingston Revisited



adapted from W. Panofsky. *Beam Line* (SLAC) 1997



Fermilab Rings for the *Intensity* Frontier

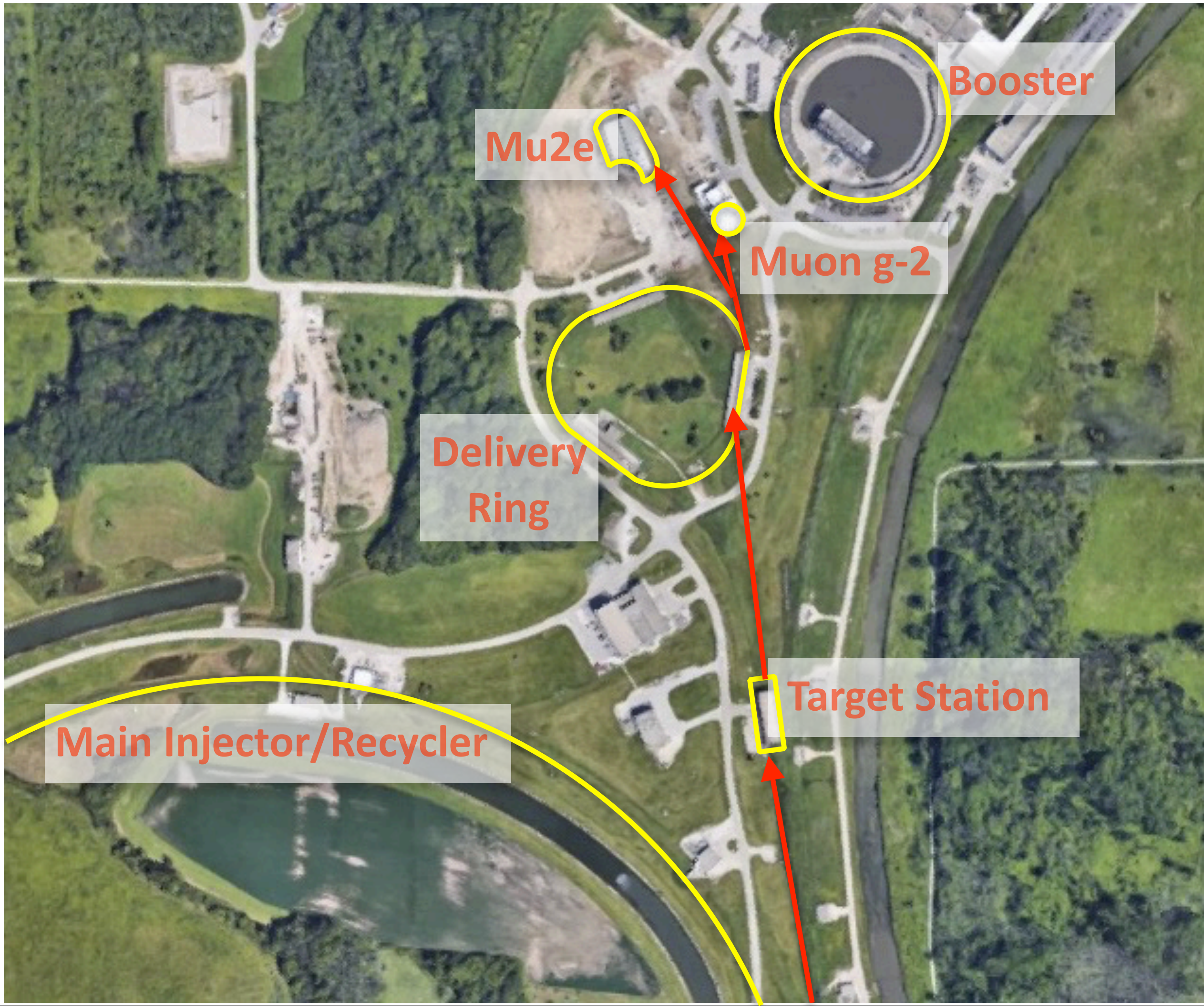
Fermilab Rings for the *Intensity* Frontier

Fermilab Rings for the *Intensity* Frontier

kinetic energies indicated here

The Muon Campus

- Delivery Ring has same circumference (slightly larger) than Booster
  - ~500 m
- 8 GeV protons from Booster to Recycler/Main Injector; manipulate bunches to create time structure appropriate for g-2, Mu2e
- Use (not use) target station for g-2 (Mu2e)
- Fast extract (g-2) or slow spill (Mu2e) particles from DR to experiments

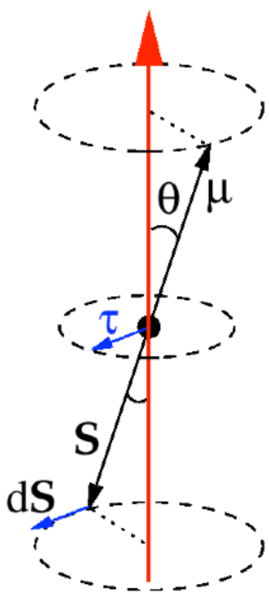


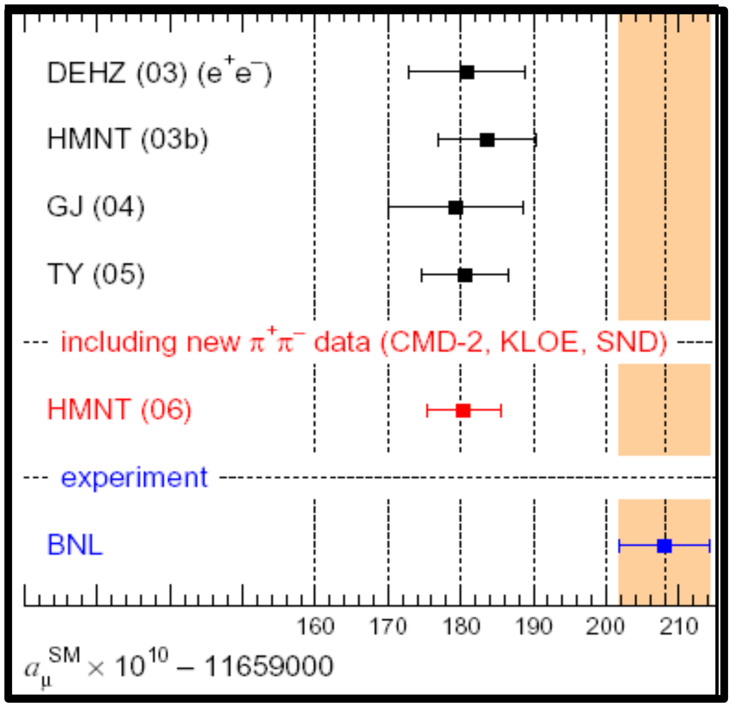
The Muon *g*-2 Experiment

- Theory and most recent measurement disagree by a “few sigma”

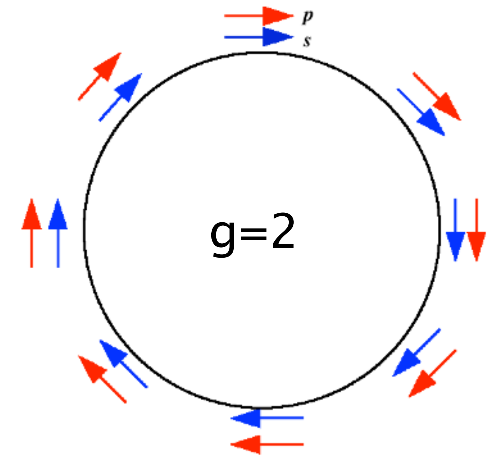
magnetic dipole moment:

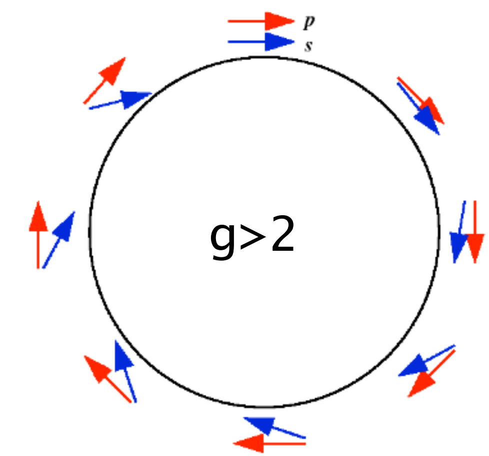
$$\mu = (g/2)\mu_B$$





K. Hagiwara, A.D. Martin, Daisuke Nomura, T. Teubner

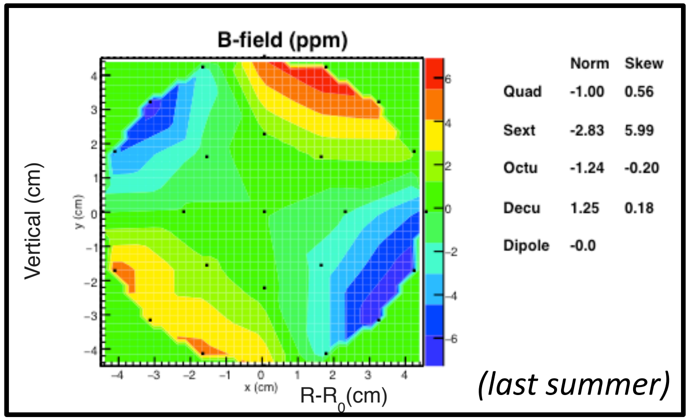


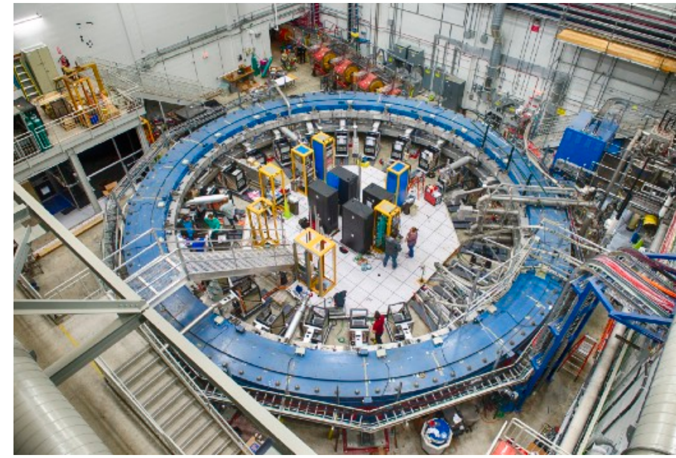


$$\omega_a = \omega_s - \omega_c = -\frac{g-2}{2} \cdot \frac{QeB}{m} \equiv -a\,\frac{QeB}{m}$$

Muon Beams for g-2 Measurement

- Precision Field



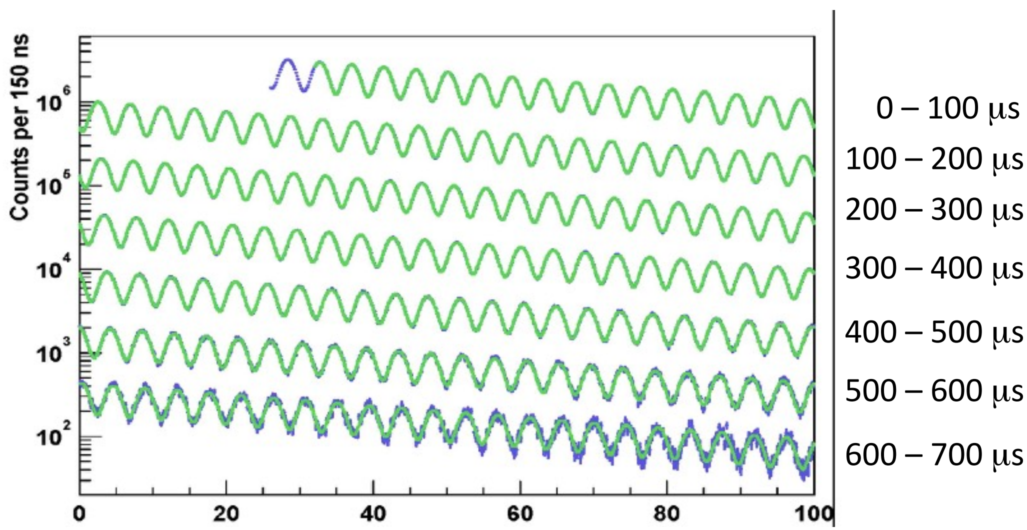


- Precision Spin Precession

$$f(t) \simeq N_0 e^{-\lambda t}[1 + A\cos\omega_a t + \phi)]$$

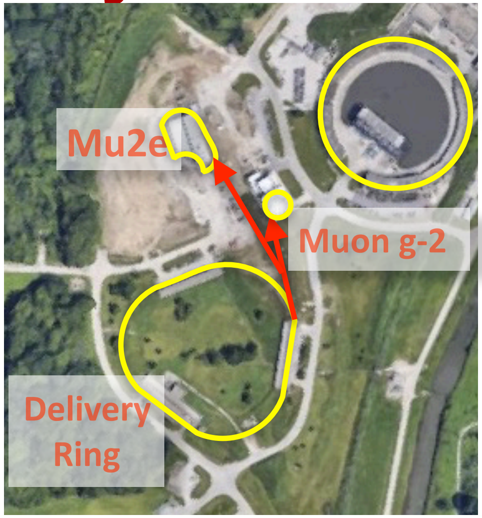
$$\omega_a = \omega_s - \omega_c = -\frac{g-2}{2} \cdot \frac{QeB}{m} \equiv -a\,\frac{QeB}{m}$$

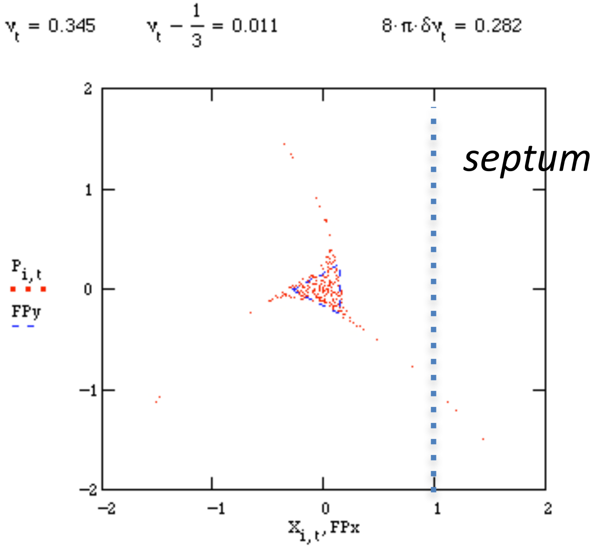
from BNL Exp. E821



Beam Production for Mu2e and Beyond

- Proton beams for muon production for Mu2e
  - generation of desired particle species
    - » use 8 GeV protons onto target, collect muons
  - generation of desired particle rates
    - » want roughly 35x10^6 protons on target per measurement
  - generation of desired time structure
    - » measurements separated by >1.5 μsec
    - » circulation time in DR = 1.69 μsec
  - slow spill
    - » create 0.15 μsec beam bunch, 10^{12} p
    - » use slow resonant extraction to extract
    - » pulses will emerge every 1.69 μsec
  - create extinction system
    - » ensure no particles reach target between pulses

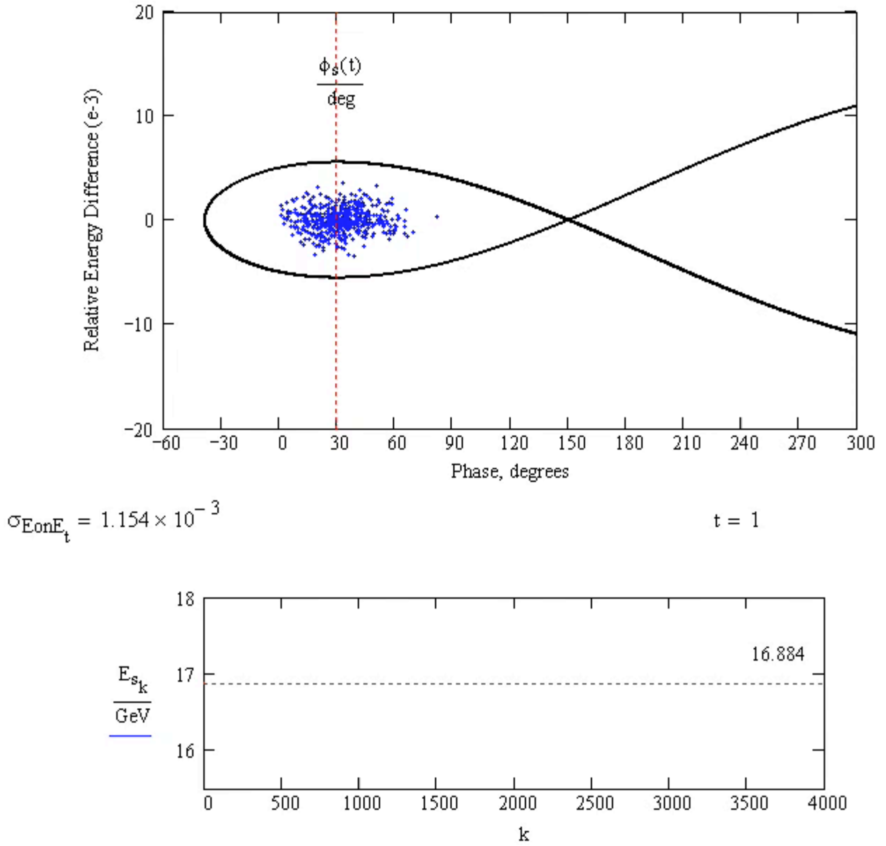




NICADD members have been very involved with development of extinction monitoring

Beam Production for Mu2e and Beyond

- Proton beams at intermediate energies
  - If could add deceleration capabilities to the DR, then creates new program at Fermilab with beams at intermediate energies
    - » REDTOP, Mu2e calibrations, g-2 tuning, lower-energy test beams, uSR?



- Rare Eta Decays with a TPC for Optical Photons (REDTOP) (Blazey, Syphers, Zutshi, Chintalapati)
  - Delivery Ring requirements
    - » use ~"g-2"-momentum proton beam
    - » use resonant extraction system, similar as for Mu2e
    - » add deceleration
      - alter the ***transition energy*** in the DR
        - » energy where *dt/t* independent of *dp/p*
        - » *see J. Johnstone and M.J. Syphers, proc. NA-PAC 2016, Chicago (2016).*

Beam Production for Mu2e and Beyond

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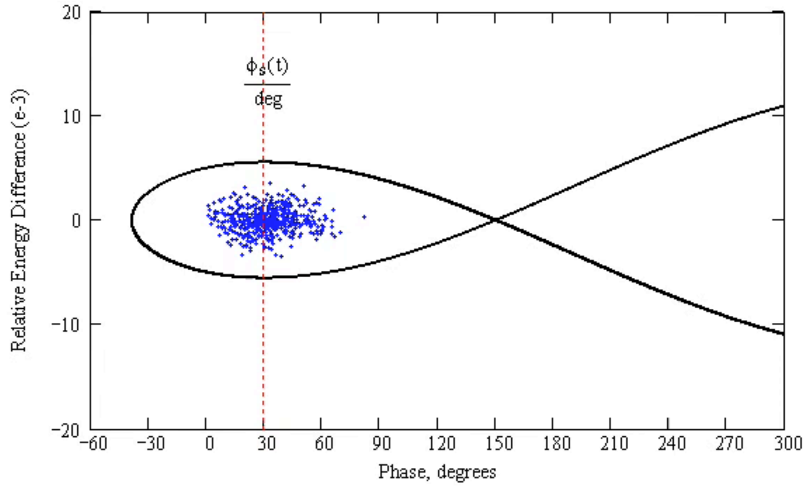
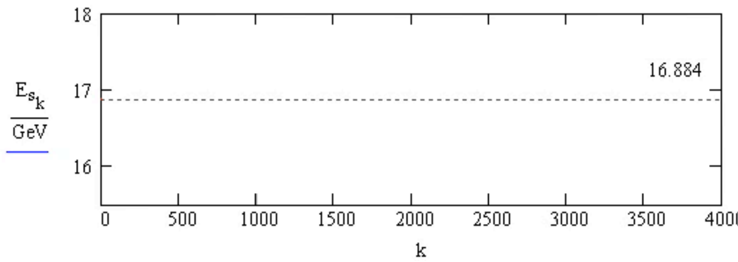


$\sigma_{EonE_t} = 1.154 \times 10^{-3}$ $t = 1$



Further Beyond: The EDM Landscape

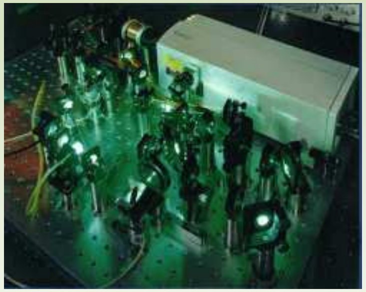
- Magnetic and electric dipole moments (MDMs and EDMs):

$$\mathcal{H} = -(\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}) \qquad \vec{\tau} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

- Standard Model predicts η = 0 (or very close to it!); a non-zero EDM would be new physics; a possible ~*5* σ difference in muon MDM is tantalizing, and generates interest in enhanced EDM searches in the muon and other systems

particle	limit [e · cm]	system	SM [e · cm]	New Physics [e · cm]
electron	1.9×10^{-27}	^{205}Tl atom	$\sim 10^{-38}$	10^{-27}
muon	9.3×10^{-19}	rest frame E fi eld	$\sim 10^{-35}$	10^{-22}
tau	2.5×10^{-17}	$(e^+e^- \to \tau^+\tau^-\gamma^*)$	$\sim 10^{-34}$	10^{-20}
proton	5.4×10^{-24}	^{199}Hg atom	$\sim 10^{-31}$	5×10^{-26}
neutron	7.4×10^{-26}	ultra cold neutrons	$\sim 10^{-31}$	5×10^{-26}
^{199}Hg	2.1×10^{-28}	^{199}Hg atom	$\sim 10^{-33}$	10^{-28}





Gerco Onderwater, KVI talk given at NuFACT05

EDM searches using Storage Rings

- Thomas-BMT again, with "Electric Dipole Moment" included:

$$
\begin{aligned}
\Delta\vec{\omega} &= \vec{\omega_a} + \vec{\omega_e} \\
&\equiv -\frac{e}{m}\left[a\,\vec{B} - a\,\left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] \\
&\quad -\frac{\eta}{2}\frac{e}{m}\left[\frac{\vec{E}}{c} - \frac{\gamma}{\gamma+1}(\vec{\beta}\cdot\vec{E}/c)\vec{\beta} + \vec{\beta}\times\vec{B}\right]
\end{aligned}
$$

$$
\mu = (g/2)\mu_B
$$

$$
d = (\eta/2)(\mu_B/c)
$$

- use only electric fields in a storage ring?

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\end{aligned}
$$

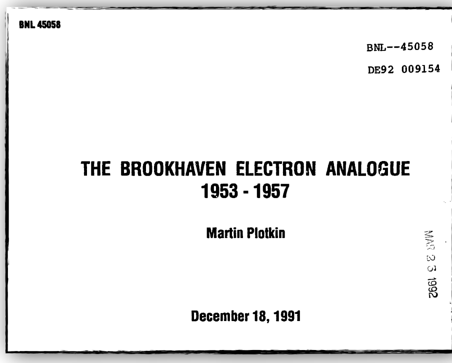
dominant term

$$
\mu = (g/2)\mu_B
$$
$$
d = (\eta/2)(\mu_B/c)
$$

- use only electric fields in a storage ring?

EDM searches using Storage Rings

- Use all-electric rings!
  - new research area; NSF grant for design studies! (Syphers and Narayanan)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THE BROOKHAVEN ELECTRON ANALOGUE
1953 - 1957

Martin Plotkin

December 18, 1991

MAR 2 3 1992

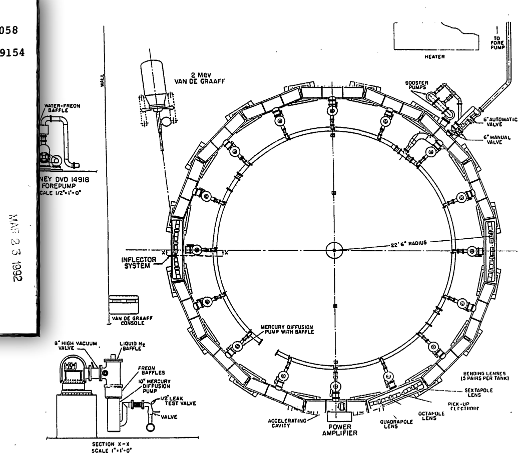
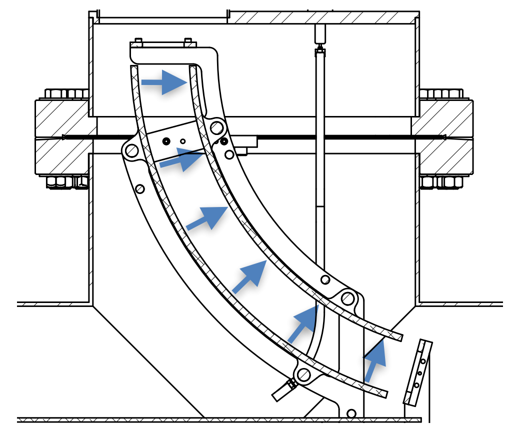


Fig. 22 Vacuum system layout.

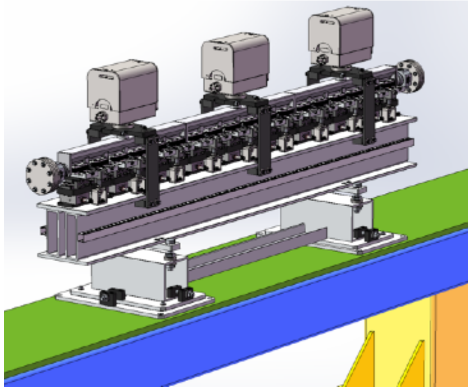
	mc^2	a	g	p_{magic}	KE_{magic}	E_0	ρ	f	C
	MeV			MeV/c	MeV	MV/m	m		m
μ	105.66	0.001166	2.00233	3094.4	2990.5	8	386.57	0.75	3238.56
e	0.511	0.001160	2.00232	15.0	14.5	8	1.875	0.75	15.70
p	938	1.792	5.58560	700.54642	232.73024	8	52.400	0.75	438.98

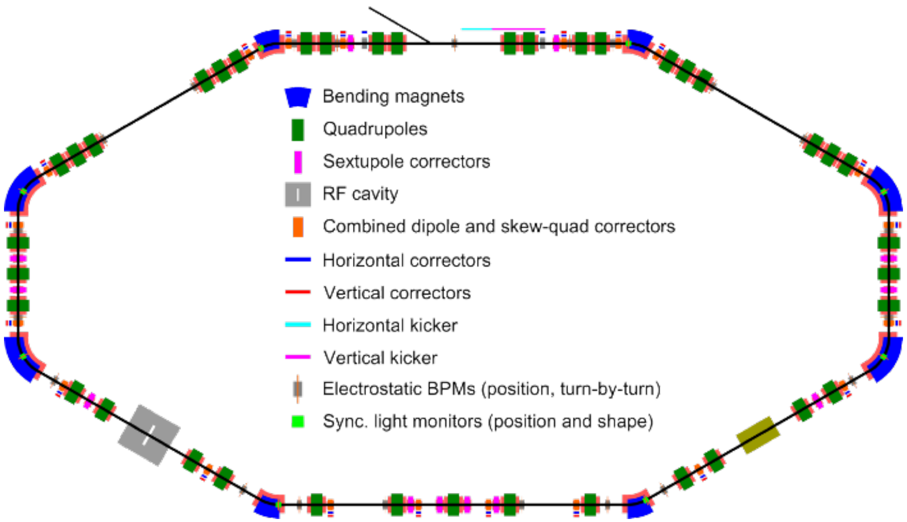


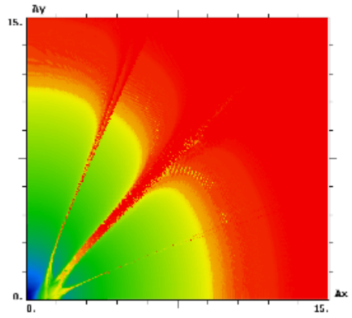
- can we use a combination of E-B fields?
  - deuteron, for instance, has $a < 0$

On to Higher Intensities

- Yet another ring is on the Fermilab horizon: Integrable Optics Test Accelerator (Freemire, Szustkowski w/ Prof. Chattopadhyay, ...)
  - beam dynamics investigations toward higher intensity beams
  - strongly non-linear focusing system
  - applications for high-intensity linacs and synchrotrons, beam-beam colliders, or other high-current devices where coherent effects may be of concern



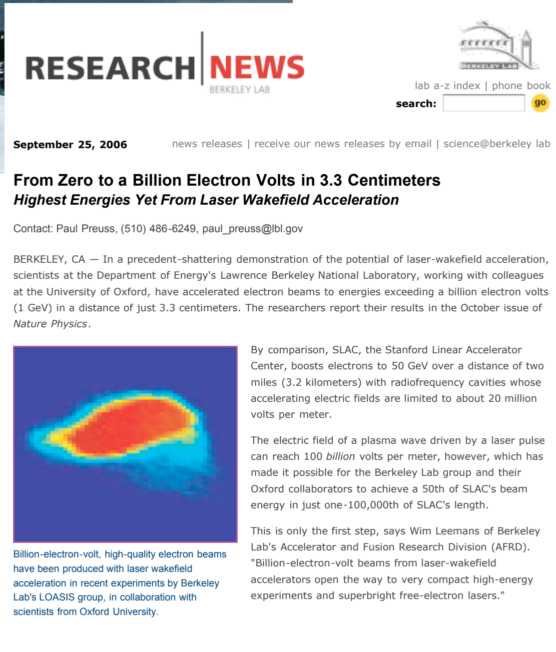




Future of the Energy Frontier?

More of the same? 100-km-scale Colliders?

New technologies? Table-top TeV??



RESEARCH NEWS
BERKELEY LAB

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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

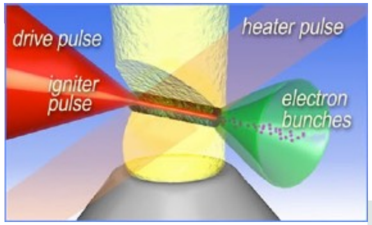
BERKELEY, CA — In a precedent-shattering demonstration of the potential of laser-wakefield acceleration, scientists at the Department of Energy's Lawrence Berkeley National Laboratory, working with colleagues at the University of Oxford, have accelerated electron beams to energies exceeding a billion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

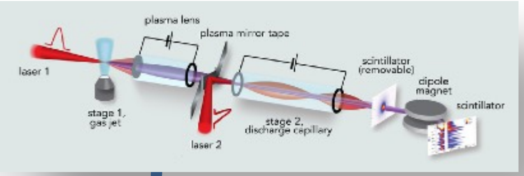
Billion-electron-volt, high-quality electron beams have been produced with laser wakefield acceleration in recent experiments by Berkeley Lab's LOASIS group, in collaboration with scientists from Oxford University.

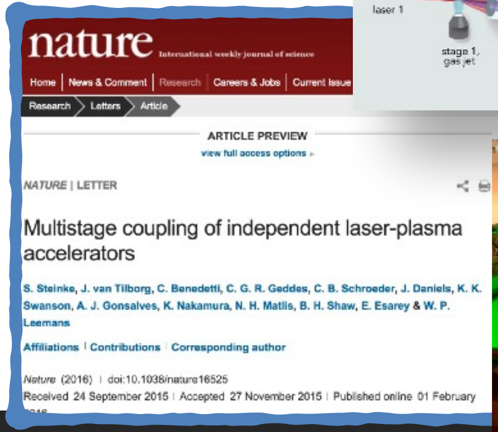
By comparison, SLAC, the Stanford Linear Accelerator Center, boosts electrons to 50 GeV over a distance of two miles (3.2 kilometers) with radiofrequency cavities whose accelerating electric fields are limited to about 20 million volts per meter.

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."







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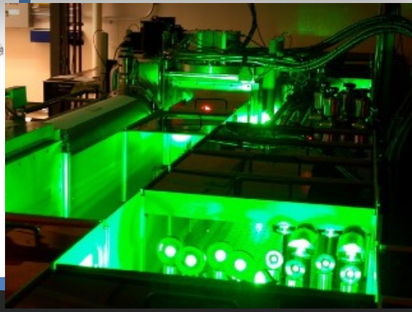
NATURE | LETTER

Multistage coupling of independent laser-plasma accelerators

S. Steinke, J. van Tilborg, C. Benedetti, C. G. R. Geddes, C. B. Schroeder, J. Daniels, K. K. Swanson, A. J. Gonsalves, K. Nakamura, N. H. Matlis, B. H. Shaw, E. Esarey & W. P. Leemans

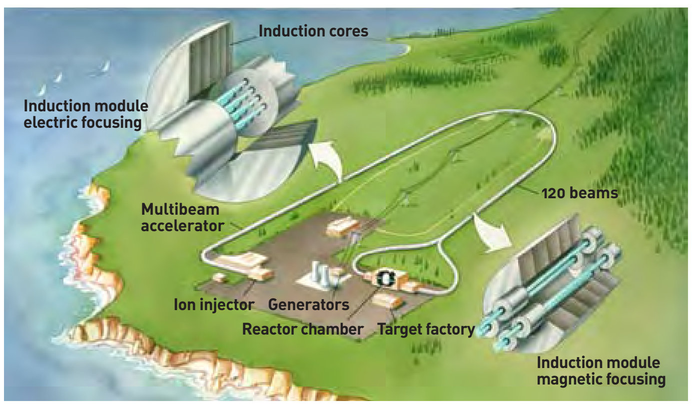
Affiliations | Contributions | Corresponding author

Nature (2016) | doi:10.1038/nature16525
Received 24 September 2015 | Accepted 27 November 2015 | Published online 01 February

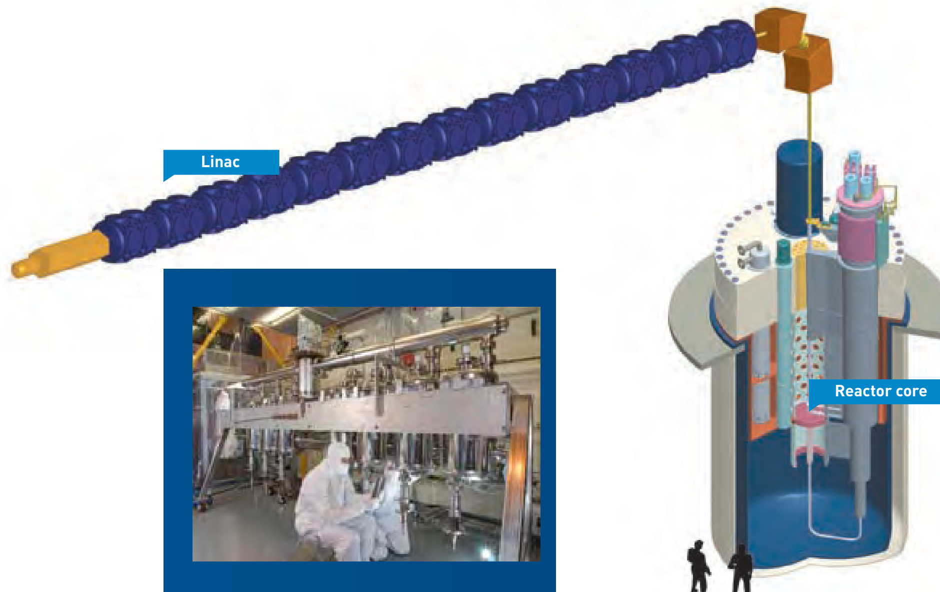


Industry and Others

- **Besides basic physics research, accelerator science has reached out into medicine, food industry, national security, materials, …**
  - **~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***
- **Many Concepts for the Future**



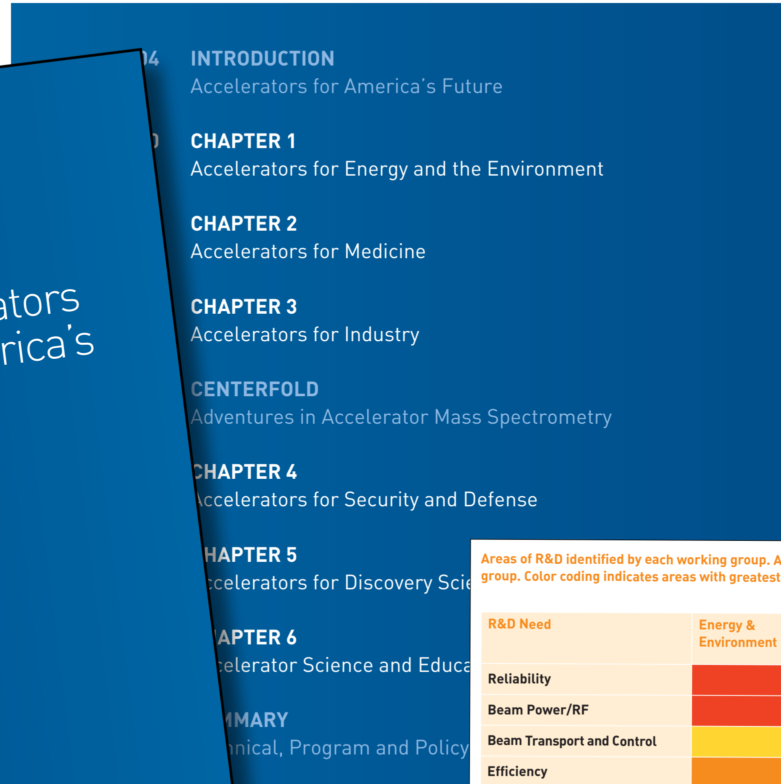
Concept of an inertial-fusion power plant based on a heavy-ion induction linear accelerator
Image courtesy of Lawrence Berkeley National Laboratory



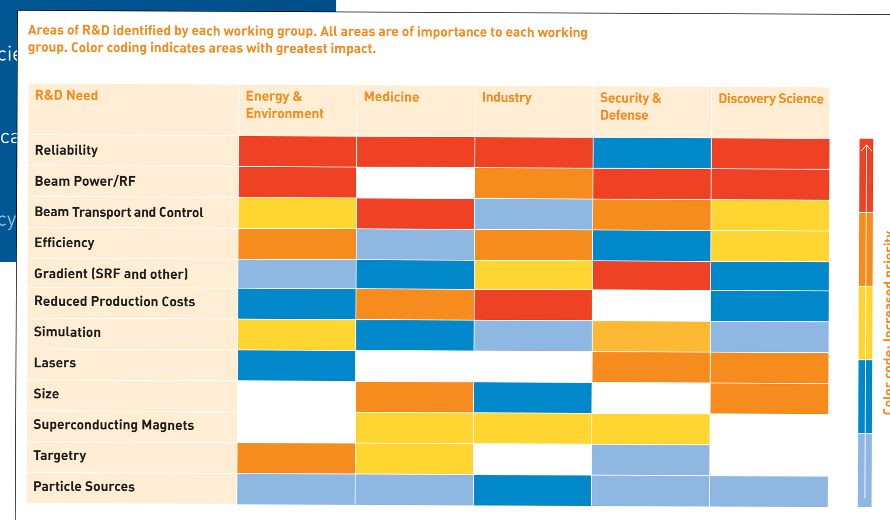
Assembly of a superconducting accelerator section for production of ion beams
Photo courtesy of J. Nolen, Argonne National Laboratory

*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



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


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					

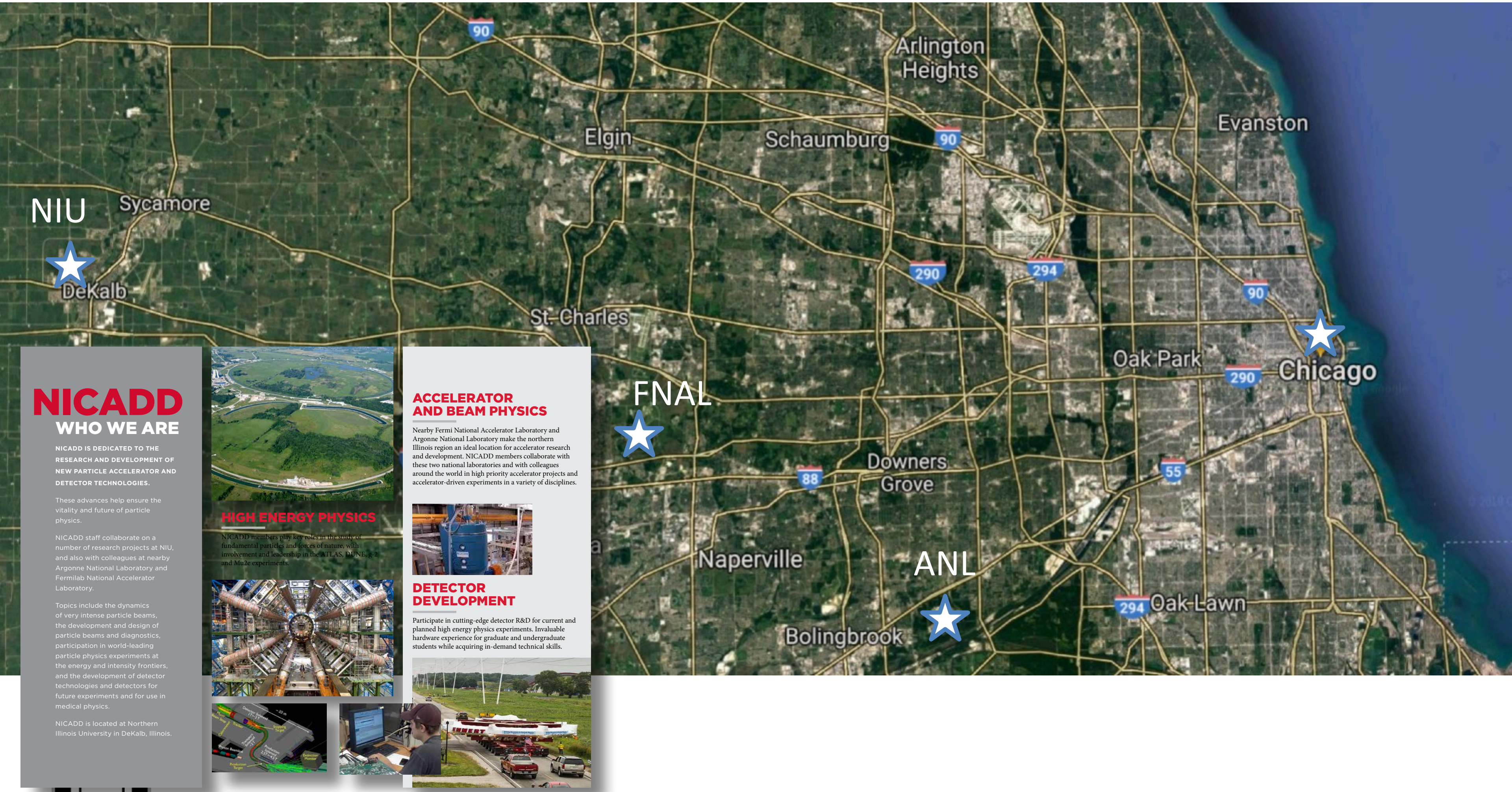
Color code: Increased priority

http://www.acceleratorsamerica.org/

Accelerator and Beam Physics

- NIU offers MS and PhD degrees in Physics with specialties in Accelerator and Beam Physics.
  - A premier university accelerator physics program in the U.S., leveraging and enhancing the major accelerator research facilities at nearby Fermi National Accelerator Laboratory (FNAL) and Argonne National Laboratory (ANL).
  - The confluence of these two national facilities makes northern Illinois an ideal location for accelerator research and development.
  - Faculty members collaborate with these two national laboratories and with colleagues around the world in high-priority accelerator projects and accelerator-driven experiments in a variety of disciplines.

Accelerator and Beam Physics



NICADD

WHO WE ARE

NICADD IS DEDICATED TO THE RESEARCH AND DEVELOPMENT OF NEW PARTICLE ACCELERATOR AND DETECTOR TECHNOLOGIES.

These advances help ensure the vitality and future of particle physics.

NICADD staff collaborate on a number of research projects at NIU, and also with colleagues at nearby Argonne National Laboratory and Fermilab National Accelerator Laboratory.

Topics include the dynamics of very intense particle beams, the development and design of particle beams and diagnostics, participation in world-leading particle physics experiments at the energy and intensity frontiers, and the development of detector technologies and detectors for future experiments and for use in medical physics.

NICADD is located at Northern Illinois University in DeKalb, Illinois.

HIGH ENERGY PHYSICS

NICADD members play key roles in the study of fundamental particles and forces of nature, with involvement and leadership in the ATLAS, DUNE, g-2 and Mu2e experiments.

ACCELERATOR AND BEAM PHYSICS

Nearby Fermi National Accelerator Laboratory and Argonne National Laboratory make the northern Illinois region an ideal location for accelerator research and development. NICADD members collaborate with these two national laboratories and with colleagues around the world in high priority accelerator projects and accelerator-driven experiments in a variety of disciplines.

DETECTOR DEVELOPMENT

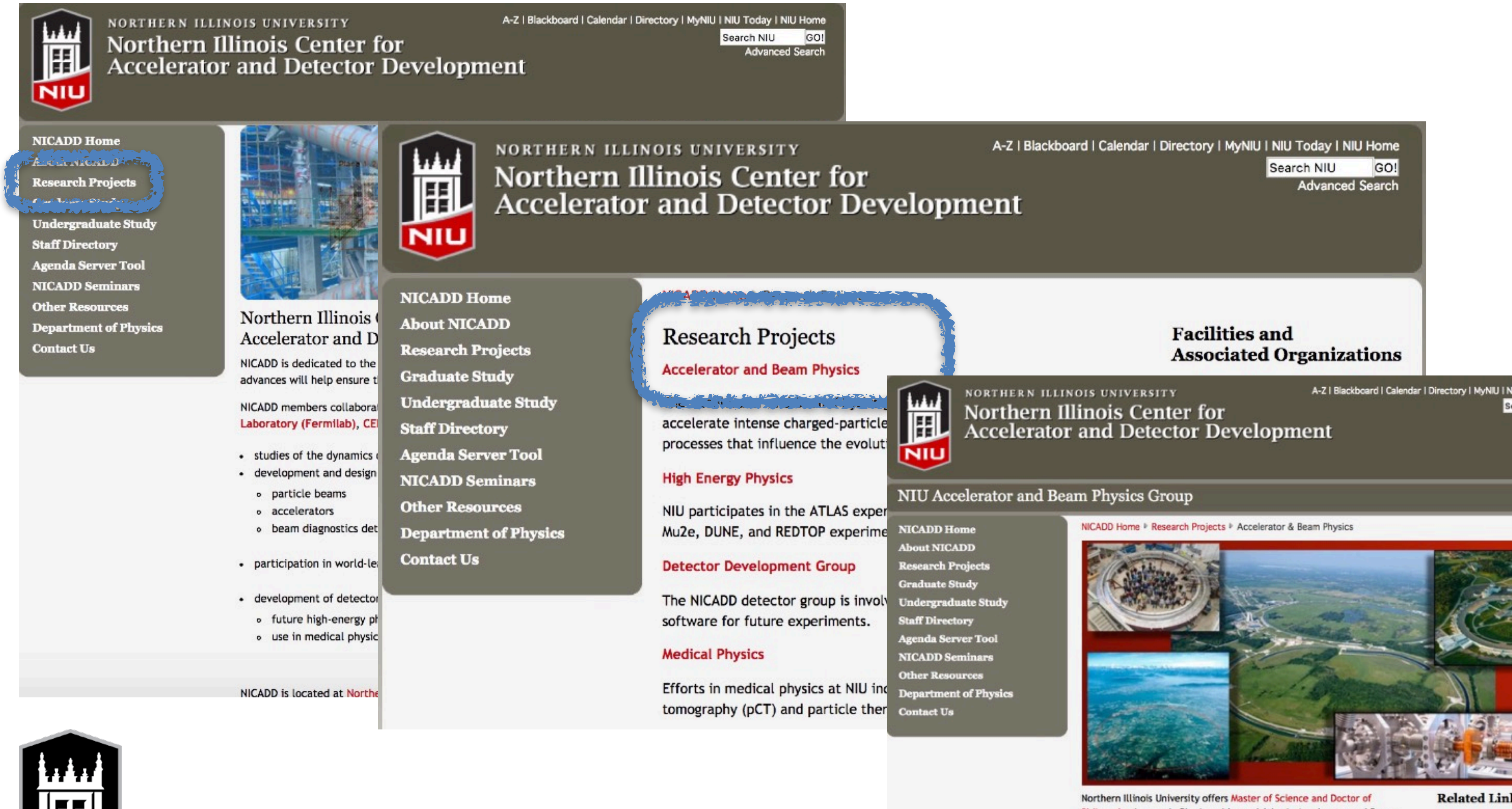
Participate in cutting-edge detector R&D for current and planned high energy physics experiments. Invaluable hardware experience for graduate and undergraduate students while acquiring in-demand technical skills.

Accelerator Physics at NIU

- Within Northern Illinois University
  - 4 Faculty in PHYS, looking to become 6 in next ~12-24 mos.
  - fairly large number of physics graduate students (~10-15)
  - Physics connections to Engineering, Math, Computer Science, …
    - high power, rf engineering, controls, etc.; computational math
- Fermilab / Argonne
  - several faculty members have joint appointments at U.S. Nat'l Labs
  - also several adjunct professors, from Fermilab in particular
- US Particle Accelerator School
  - instructors, Curriculum Committee
  - many students attend from NIU
  - NIU "hosted" USPAS session in June 2017, and upcoming January 2018
- The Larger Accelerator Physics Community
  - faculty are active on national and international advisory boards, editorial boards, APS/IEEE service, conference program committees, journal reviews, etc.

NICADD Web Site

http://nicadd.niu.edu



Accelerator and Beam Physics Faculty

	Faculty	Research Topics
Swapan Chattopadhyay schaterji at niu.edu La Tourette 230a		nonlinear beam dynamics, microwave superconductivity, colliders/ accelerators, free electron lasers, Terahertz sources, quantum optics/ electronics, meta-materials/photonic structures
Bela Erdelyi erdelyi at nicadd.niu.edu La Tourette 225		Beam physics, accelerator theory and design, nonlinear dynamics, applications of symplectic geometry in - and numerical methods for - Hamiltonian dynamics, medical physics and imaging, high performance computing
Philippe Piot piot at nicadd.niu.edu La Tourette 220		high-brightness electron beams, advanced acceleration concepts, compact coherent radiation source
Mike Syphers msyphers at niu.edu La Tourette 204		particle beam transport and focusing, beam optics design and analysis, nonlinear particle beam dynamics, systems of polarized particle beams, accelerators for medical therapy and research, Muon g-2, FCC, srEDM, REDTOP

ABP Research Activities at NIU

- Accelerator and Beam Physics group has diverse research in theoretical, computational and experimental particle beam physics.
  - Nonlinear particle dynamics including applications of symplectic geometry in - and numerical methods for - Hamiltonian dynamics leading to experimental verification
  - Advanced developments in particle beam optics and transport, accelerator and collider design and advanced acceleration concepts
  - Development of coherent microwave radiation sources, beam-wave interaction dynamics in meta-materials, high-brightness electron beams and compact coherent radiation sources
  - Applications of particle beam and accelerator systems for high-energy and nuclear experiments, basic energy science, medical use and industrial demands

Degree Program

- **Candidates for the degrees Master of Science in Physics and Doctor of Philosophy in Physics with an Accelerator and Beam Physics emphasis must meet the general requirements set forth by the Department of Physics for these degrees but are expected to take accelerator/beam-related course work as a major part of their electives.**
- **Additionally, students in the Accelerator and Beam Physics program often attend the U.S. Particle Accelerator School, held twice annually, which offers many higher-level graduate physics courses in the discipline. NIU credit for participation in USPAS courses can be arranged through the Department of Physics with sufficient notice.**

US Particle Accelerator School

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

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

Google Search

Home | About | Programs | Course Materials | Tutorials | Photos | Opportunities | Contact

Current Program
USPAS sponsored by
Michigan State University
June 4-15, 2018
held in East Lansing, Michigan

View Details >>

APPLY NOW

Next Program
USPAS sponsored by
Northern Illinois University
and UT Battelle
Jan 21 – Feb 1, 2019
held in Knoxville, Tennessee

Details coming soon

Hot Topics
- A series of student tutorials will precede the 9th International Particle

Accelerator Tutorials
LHC Superconducting Ma...

LHC Superconducting Magnets

Watch this first video, in a sequence of three, explain the

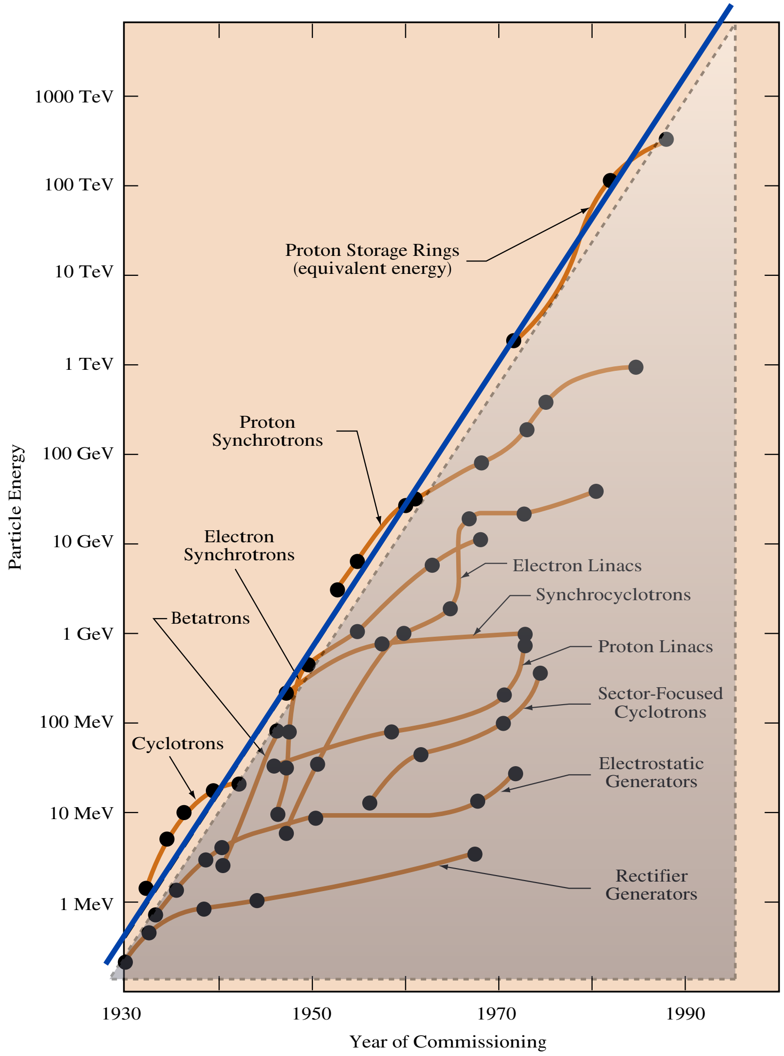
http://uspas.fnal.gov

Past USPAS University Programs
A complete history of U.S. Particle Accelerator School university credit programs

Date	Sponsoring University
January 15-26, 2018	Old Dominion Univeristy
June 12-23, 2017	Northern Illinois University
January 16-27, 2017	University of California, Davis
June 13-24, 2016	Colorado State University
January 25-February 5, 2016	University of Texas at Austin
June 15-26, 2015	Rutgers University
January 19-30, 2015	Old Dominion University
June 16-27, 2014	University of New Mexico
January 20-31, 2014	University of Tennessee, Knoxville
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

Looking Below the Curve

- **Accelerator Facilities, and the need for scientists to develop, build, commission, operate, improve them have seen an enormous growth over the decades**
- **While peak accelerator energies continue to drive particle physics, much work to do and applications to develop at lower energies**
- **Many, many facilities and industrial uses are not shown here, but flood the area "below the curve"**



Some Present Major Facilities

http://www-elsa.physik.uni-bonn.de/accelerator_list.html

Particle Accelerators Around the World

Please note that this list does not include accelerators which are used for medical or industrial purposes only.

Please visit also the WWW Virtual library of Beam Physics and Accelerator Technology, the Division of Physics of Beams of the American Physical Society, and the Los Alamos Accelerator Code Group.

Sorted by Location

Europe

AGOR	Accelerateur Groningen-ORsay, KVI Groningen, Netherl...
ALBA	Synchrotron Light Facility...
ANKA	Ångströmquelle Karlsruhe... Synchrotronstrahlung (FG...
BESSY	Berliner Elektronenspeiche...
CEMHTI	Conditions Extrêmes et Ma... France
CERN	Centre Europeen de Re... SL-Division)
CMAM	Centro de Microanálisis de M...
COSY	Cooler Synchrotron, IKP, F...
CYCLONE	Cyclotron of Louvain la Neuv...
DELTA	Dortmunder ELekTronenspei... der Technischen Universität D... Germany
DESY	Deutsches Elektronen Synchrotron, Hamburg, Germany (XFEL, PETRA III, FLASH, ILC, PITZ)
ELBE	ELectron source with high Brilliance and low Emittance, Forschungszentrum Dresden - Rossendorf e.V. (FZD), Germany
ELETTRA	AREA Science Park, Trieste, Italy
ELSA	Electron Stretcher Accelerator, Bonn University, Germany (ELSA status)
ESRF	European Synchrotron Radiation Facility, Grenoble, France
GANIL	Grand Accélérateur National d'Ions Lourds, Caen, France (GANIL, SPIRAL2)
GSI	Gesellschaft für Schwerionenforschung, Darmstadt, Germany

North America

88" Cycl.	88-Inch Cyclotron, Lawrence Berkeley Laboratory (LBL), Berkeley, CA
ALS	Advanced Light Source, Lawrence Berkeley Laboratory (LBL), Berkeley, CA (ALS Status)
ANL	Argonne National Laboratory, Chicago, IL (Advanced Photon Source APS, Argonne Tandem Linac Accelerator System ATLAS)
BATES	Bates Linear Accelerator Center, Massachusetts Institute of Technology, USA
BNL	Brookhaven National Laboratory, Upton, NY (AGS, ATF, NSLS, RHIC)

CAMD	Center for Advanced Microstructures and Devices, Louisiana State University
CENPA	Center for Experimental Nuclear Physics and Astrophysics, University of Washington, USA
CESR	Cornell Electron-positron Storage Ring, Cornell University, Ithaca, NY
CHESS	Cornell High Energy Synchrotron Source, Cornell University, Ithaca, NY
CLS	Canadian Light Source, U of Saskatchewan, Saskatoon, Canada
CNL	Crocker Nuclear Laboratory, University of California Davis, CA
FNAL	Fermi National Accelerator Laboratory , Batavia, IL (Tevatron)
	John D. Fox Superconducting Accelerator Laboratory, Florida State University, USA
IAC	Idaho accelerator center, Pocatello, Idaho
ININ	National Institute for Nuclear Research, Mexico
ISNAP	Institute for Structure and Nuclear Astrophysics, Notre Dame University, USA
IUCF	Indiana University Cyclotron Facility, Bloomington, Indiana
JLab	aka TJNAF, Thomas Jefferson National Accelerator Facility (formerly known as CEBAF), Newport News, VA
	...Center, U of Louisiana at Lafayette, Louisiana
	...boratory
	...oratory, University of Michigan
	...g Cyclotron Laboratory, Michigan State University
	...ratory Oak Ridge, Tennessee
	...ator Laboratory, Ohio University, USA
	...b (Neptune-Laboratory, PEGASUS - Photoelectron ...ntaneous Radition Source)
	...r Center, (SLC - SLAC Linear electron positron ... SSRL - Stanford Synchrotron Radiation Laboratory)
SNS	Spallation Neutron Source, Oak Ridge, Tennessee
SRC	Synchrotron Radiation Center, U of Wisconsin - Madison
SURF III	Synchrotron Ultraviolet Radiation Facility, National Institute of Standards and Technology (NIST), Gaithersburg, Maryland
TAMU	Cyclotron Institute, Texas A&M University, USA
TRIUMF	Canada's National Laboratory for Particle and Nuclear Physics, Vancouver, BC (Canada)
TUNL	Triangle Universities Nuclear Laboratory, USA
UMASS	University of Massachusetts Lowell Radiation Laboratory, USA
UNAM	Universidad Nacional Autónoma de México, Mexico
WMU	Van de Graaff Accelerator at the Physics Department of the Western Michigan University...

Professional Organizations and Journals

- American Physical Society (APS)
  - Division of Physics of Beams (DPB)
- Institute of Electrical and Electronics Engineers (IEEE)
- Physical Review Accelerators and Beams (PRAB)
  - previously called PR Special Topics —AB
  - prominent peer-reviewed journal for the field
- Nuclear Instruments and Methods - A (NIM-A)
  - many peer-reviewed accelerator articles
- Joint Accelerator Conferences Website (JACoW)
  - on-line proceedings of major accelerator conferences

Summary

- NIU Accelerator and Beam Physics group brings leading researchers and connections to world-class facilities and technologies to NIU students
- Significant MS and PhD degree program in ABP with wide range of research topics and opportunities available to students
- NICADD perpetuates the integration of HEP and accelerator technologies, personnel, and facilities for outstanding graduate school experience

A "Final" word… from 1954…

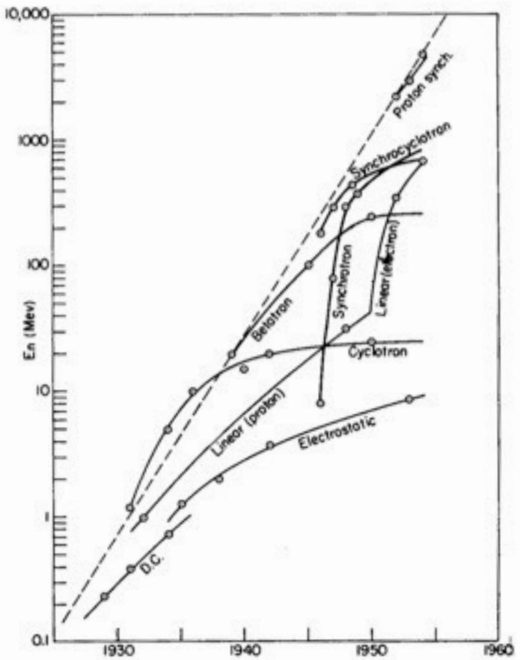


FIG. 7-8. Exponential rise in energy attained with accelerators during the past 25 years.

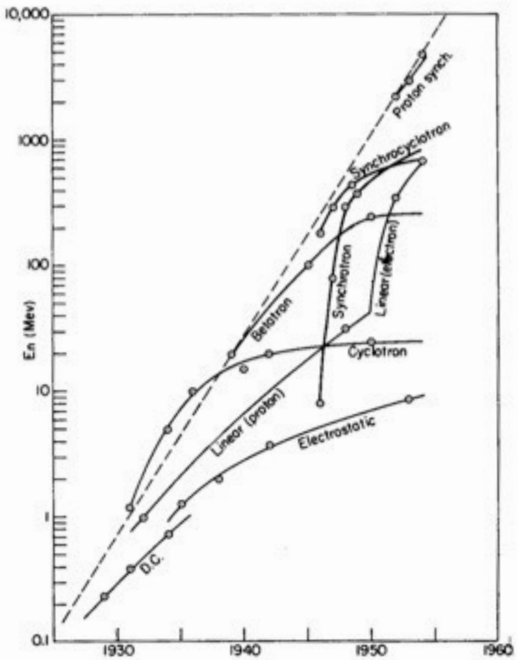
of the plot is the approximately linear slope of this envelope, which means that energy has in fact increased exponentially with time. The rate of rise is such that the energy has increased by a factor of 10 every six years, from a start at 100 kv in 1929 to 3 billion volts in 1952.

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

time. Further extrapolation of this exponentially rising curve would predict truly gigantic accelerators which would exceed any possible budgets, even those of government laboratories. So we will postpone such speculation until the present machines can demonstrate their value to science.

Those of us in the accelerator field are frequently asked, "When will this development of higher-and-higher-energy accelerators stop?" Yet it must be recognized that it is not the urge to higher voltage which inspires this growth, but the pressure of the continuously expanding horizons of science. As long as there are unsolved problems in Nature which might be answered by higher-energy particles, and as long as the scientific urge to know the answers continues, there will be a steady and persistent demand to develop the tools and instruments required.

A “Final” word… from 1954…



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M. Stanley Livingston, 1954

THANKS!

Mike Syphers

msyphers@niu

Further reading:

D. A. Edwards and M. J. Syphers, *An Introduction to the Physics of High Energy Accelerators*, John Wiley & Sons (1993)

T. Wangler, *RF Linear Accelerators*, John Wiley & Sons (1998)

H. Padamsee, J. Knobloch, T. Hays, *RF Superconductivity for Accelerators*, John Wiley & Sons (1998)

S. Y. Lee, *Accelerator Physics*, World Scientific (1999)

and many others…

Conference Proceedings --

Particle Accelerator Conference (2013, 2011, 2009, …)

International Particle Accelerator Conference (2014, 2013, …)

visit http://www.jacow.org