Jefferson Lab GSPDA Summer Lecture Series

Introduction to Accelerators (and Applied Relativity and E&M)

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Summer Lecture Series

Summer Lecture Series 2015

Date	Time	Speaker	Talk	Room #
June 4	11:00AM	Rolf Ent	Introduction to Nuclear Physics	AUD
June 9	11:00AM	Todd Satogata	Introduction to Accelerators	AUD
June 11	11:00AM	Howard Fenker	Introduction to Detectors for Nuclear Physics	AUD
June 16	11:00AM	Mike Spata	Overview of CEBAF Accelerator	AUD
June 18	11:00AM	Drew Weisenberger	Guesstimation: Approximate answers to any question	AUD
June 23	11:00AM	Eugene Chudakov	Calorimetry	F113
June 25	11:00AM	Larry Weinstein	Guesstimation: Approximate answers to any question	F113
June 30	11:00AM	Grigory Eremeev	SRF Science and Technology	F113
July 2	11:00AM	Gail Dodge	Ethics in Research	F113
July 7	11:00AM	Elton Smith	Scintillator and Photomultipliers	F113
July 9	11:00AM	Joe Grames	Polarized Electron Source	F113
July 14	11:00AM	Mark Ito	Kinematic Fitting	F113
July 16	11:00AM	Graham Heyes	Data Acquisition Systems	AUD
July 21	11:00AM	Cynthia Keppel	Medical Applications of Nuclear Physics	AUD
July 23	11:00AM	Mac Mestayer	Discovery of the Quark	F113
July 28	11:00AM	Doug Higinbotham	Nuclear Physics Experiment, an example	AUD
July 30	11:00AM	Marcy Stutzman	Extreme High Vacuum	AUD

History: Jean-Antoine Nollet

In 1746 he gathered about **two hundred monks** into a circle over a mile in circumference, with pieces of iron wire connecting them. He then discharged a battery of Leyden jars through the human chain and observed that **each man reacted at substantially the same time to the electric shock**, showing that the speed of electricity's propagation was very high.

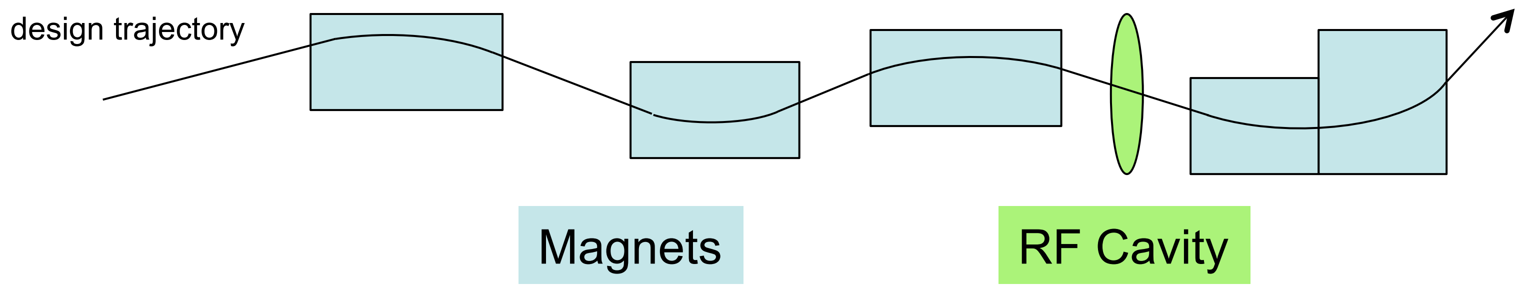
The Monkotron

- Nollet had
  - lots of charged particles
  - moving in a confined 2km ring (!)
  - at very high velocities
  - accelerated by high voltage

- Nollet didn't have
  - controlled magnets
  - controlled acceleration
  - proper instrumentation
  - many friends after this experiment

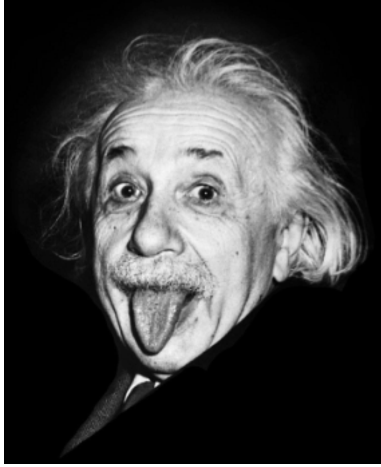
http://www.yproductions.com/writing/archives/twitch_token_of_such_things.html

Simplified Particle Motion



- Design trajectory and perturbation theory
  - Particle motion is perturbatively expanded around a **design trajectory** or **orbit**
  - This orbit can be over 10^{10} km in a storage ring
- Separation of fields: Lorentz force $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$
  - Magnetic fields from static or slowly-changing magnets
    - (usually) transverse to design trajectory
  - Electric fields from high-frequency resonators (RF cavities)
    - (usually) in direction of design trajectory
- (very) Relativistic charged particle velocities

Applied Special Relativity



- Accelerators: applied special relativity
  - Subatomic particles traveling near light speed
  - Kinetic energy >> rest mass energy
- Relativistic parameters:

$$\beta \equiv \frac{v}{c} \qquad \gamma \equiv \frac{1}{\sqrt{1-\beta^2}} \qquad \beta = \sqrt{1-1/\gamma^2}$$

  - γ =1 (classical mechanics) to ~2.05x10^5 (to date) (where??)

    v=0.99999999997 c

- Total energy U, momentum p, and kinetic energy W

$$U = \gamma m c^2 \qquad p = (\beta\gamma) m c = \beta \left(\frac{U}{c}\right) \qquad W = (\gamma - 1)\, m c^2$$

Relative Relativity

WolframAlp

LEP energy

Input interpretation:

LEP (Large Electron Positron Collider) | ce

Result:

208 GeV (gigaelectronvolts)

Unit conversions:

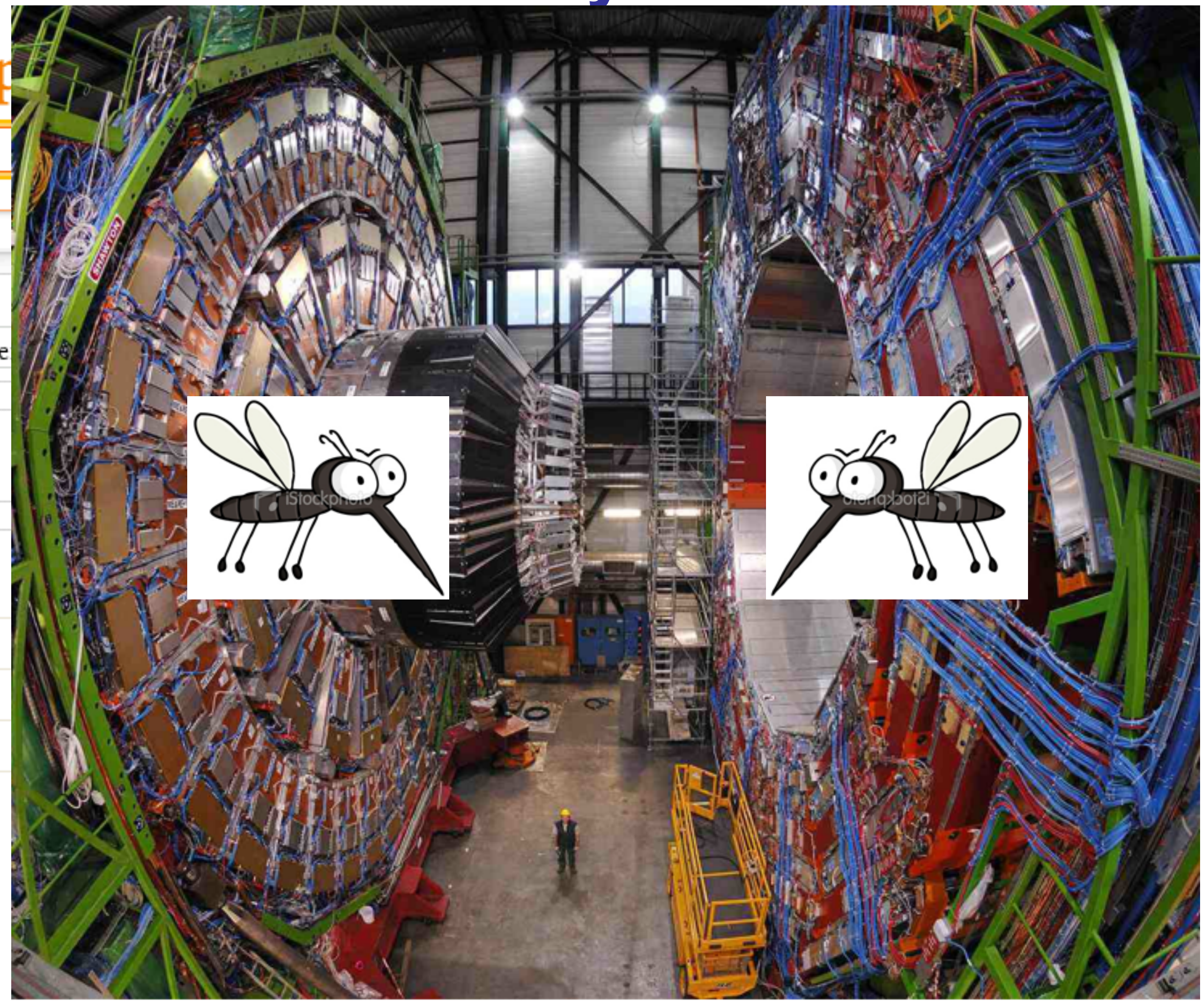
0.208 TeV (teraelectronvolts)

2.08×10^{11} eV (electronvolts)

0.03333 μJ (microjoules)

3.333×10^{-8} J (joules)

0.3333 ergs
(unit officially deprecated)



Comparisons as energy:

≈ (0.21 ≈ 1/5) ×
approximate kinetic energy of a flying mosquito ($\approx 1.6 \times 10^{-7}$ J)

≈ 2.2 × mass-energy equivalent of a Z boson ($\approx 1.5 \times 10^{-8}$ J)

"Convenient" Units

$$1\,\text{eV} = (1.602 \times 10^{-19}\,\text{C})(1\,\text{V}) = 1.602 \times 10^{-19}\,\text{J}$$

$$1\,\text{MeV} = 1.602 \times 10^{-13}\,\text{J}$$

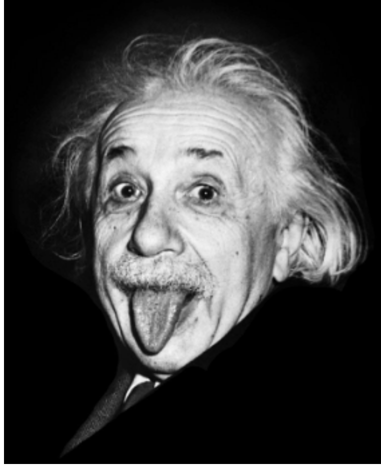
$$1\,\text{GeV} = 1.602 \times 10^{-10}\,\text{J}$$

- How much is a TeV?
  - Energy to raise 1g about 16 um against gravity
  - Energy to power 100W light bulb 1.6 ns
- But many accelerators have $10^{10\text{-}12}$ particles
  - Single bunch "instantaneous power" of tens of **Tera**watts
- Highest energy observed cosmic ray
  - ~300 EeV ($3\text{x}10^{20}$ eV or $3\text{x}10^{8}$ TeV!)

(125 g hamster at 100 km/hr)

OMG particle

Applied Special Relativity



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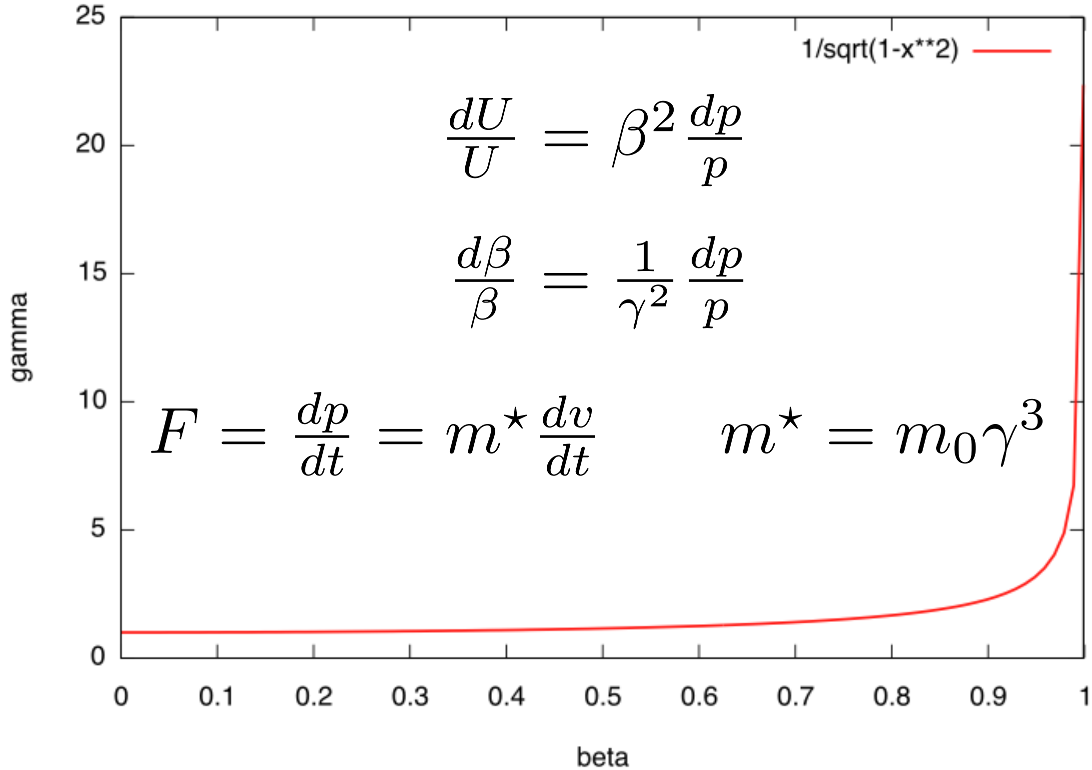
  - γ=1 (classical mechanics) to ~2.05x10^5 (to date) (at LEP)

    v=0.99999999997 c

- Total energy U, momentum p, and kinetic energy W

$$U = \gamma m c^2 \qquad p = (\beta\gamma) mc = \beta\left(\frac{U}{c}\right) \qquad W = (\gamma - 1)\, mc^2$$

Convenient Relativity Relations



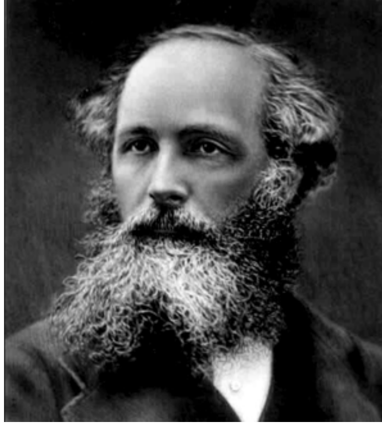
$$\frac{dU}{U} = \beta^2 \frac{dp}{p}$$

$$\frac{d\beta}{\beta} = \frac{1}{\gamma^2} \frac{dp}{p}$$

$$F = \frac{dp}{dt} = m^\star \frac{dv}{dt} \qquad m^\star = m_0 \gamma^3$$

- In “ultra” relativistic limit $\beta \approx 1$
  - Usually must be careful below $\gamma \approx 5$ or $U \approx 5\ mc^2$
  - Many accelerator physics phenomena scale with γ^k or $(\beta\gamma)^k$
  - Electrons are light: they are ultrarelativistic above a few MeV

Applied Electricity and Magnetism



- Accelerators: applied E&M
  - Charged subatomic particles affected by controlled electric and magnetic fields
- Lorentz force: forces from **fields** on a charged particle

$$\vec{F} = \frac{d\vec{p}}{dt} = \frac{d(\gamma m \vec{v})}{dt} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

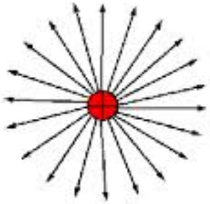
  - True even for relativistically-moving particles

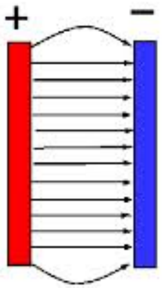
$$\vec{E} : \text{Electric field}$$

$$\vec{B} : \text{Magnetic (Induction) field}$$

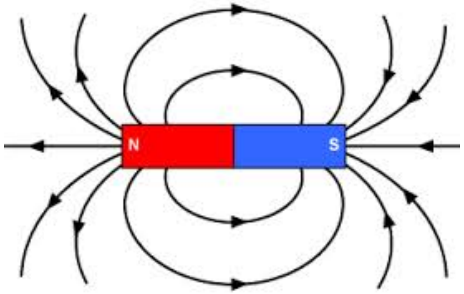
  - Only electric fields can change particle speed!
    - Magnetic fields only change particle direction

Electric and Magnetic Fields





- Electric fields
  - Created by distributions of electric charge
  - Measured in Volts/m and proportional to charge
  - ε_0 : "permittivity of free space", 8.854×10^{-12} $C^2/(J\text{-}m)$

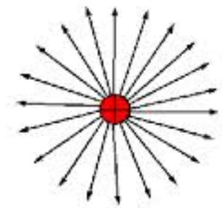


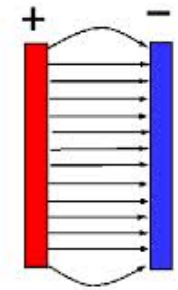
- Magnetic fields
  - Created by moving charges, currents
    - (magnetic dipole moments)
  - Measured in Tesla = 10^4 Gauss = N/(A-m)
  - μ_0 : "permeability of free space", $4\pi \times 10^{-7}$ $N\text{-}s^2/C^2$

- Since Joule=N-m, $1/(\varepsilon_0\mu_0)$ has units of m^2/s^2
  - In fact,

$$1/(\varepsilon_0\mu_0) = c^2$$

Electric and Magnetic Fields





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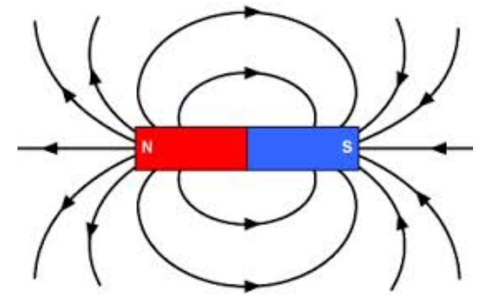

- Magnetic fields
  - Created by moving charges, currents
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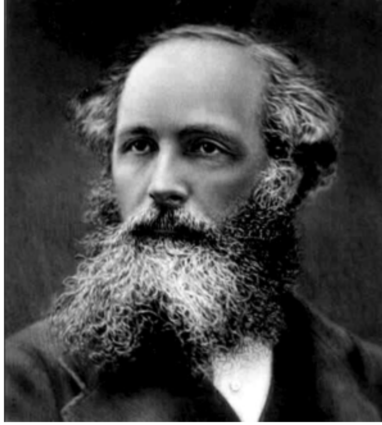
  - Measured in Tesla = 10^4 Gauss = N/(A-m)
  - μ_0 : "permeability of free space", 4p x 10^{-7} $N\text{-}s^2/C^2$
  - (Also a band…)

Maxwell's Equations



- (Vector) EM fields must obey Maxwell's eqns
  - First order linear differential equations

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

Electric field is generated by electric charges

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Changing magnetic fields generate electric fields (Faraday's Law)

$$\vec{\nabla} \cdot \vec{B} = 0$$

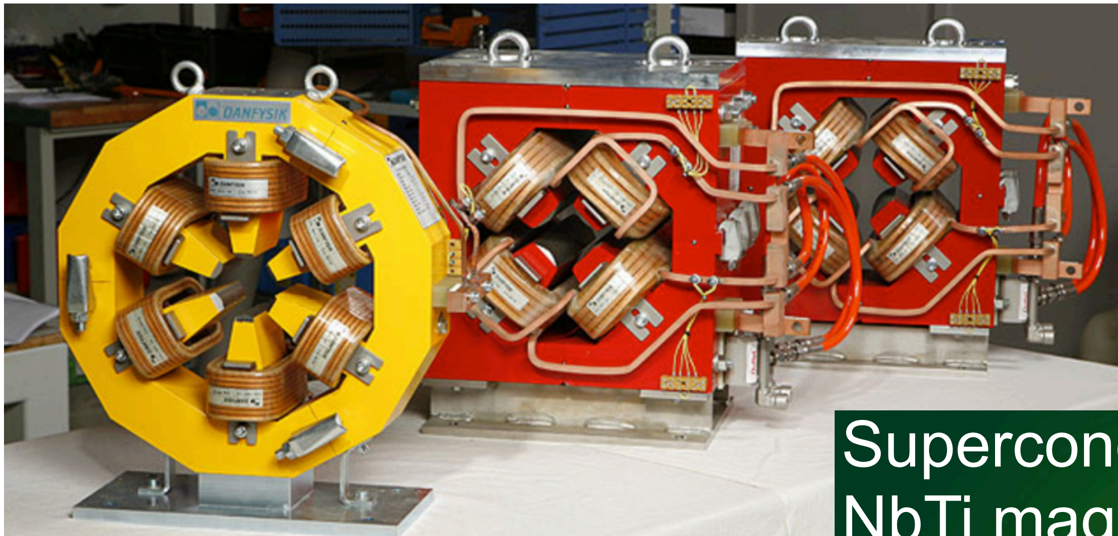
No magnetic charges (monopoles) and magnetic field lines must close

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$$

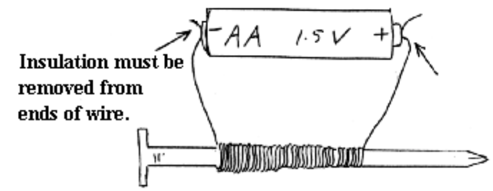
Magnetic fields are generated by moving electric charges (currents) and changing electric fields

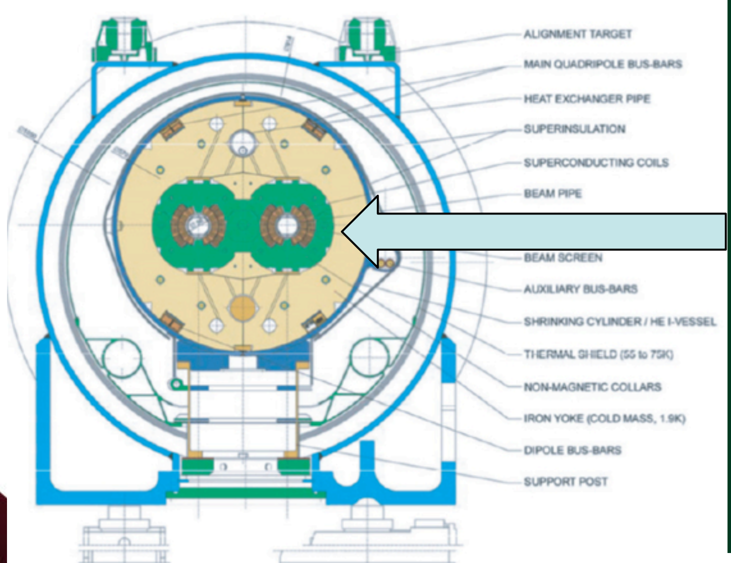
Accelerator Magnet Examples

0.1-15 Tesla!



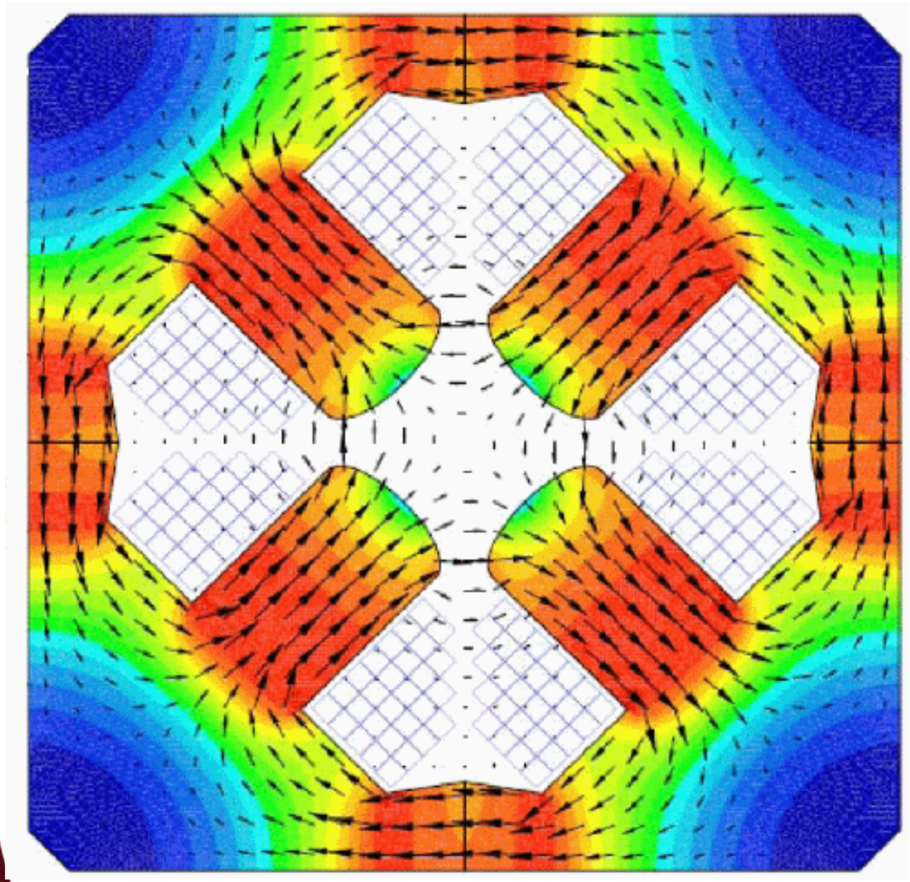
Air-temperature steel magnets (Danfysik)



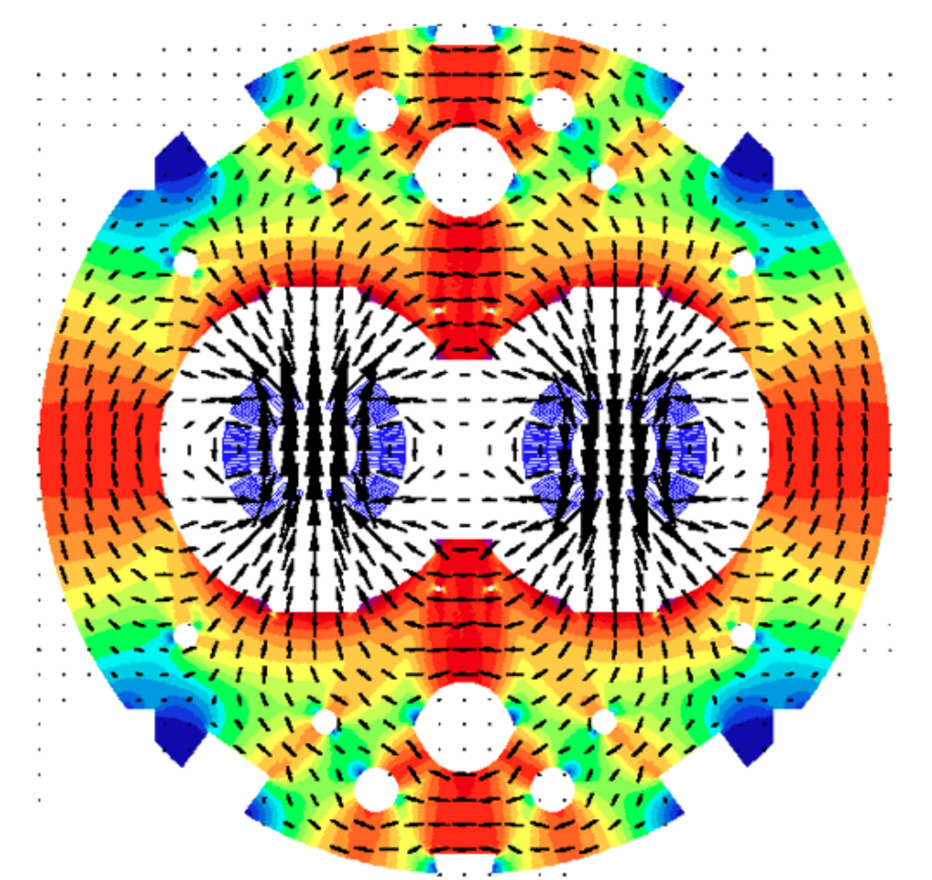


Superconducting NbTi magnets (LHC)

Normal vs Superconducting Magnets



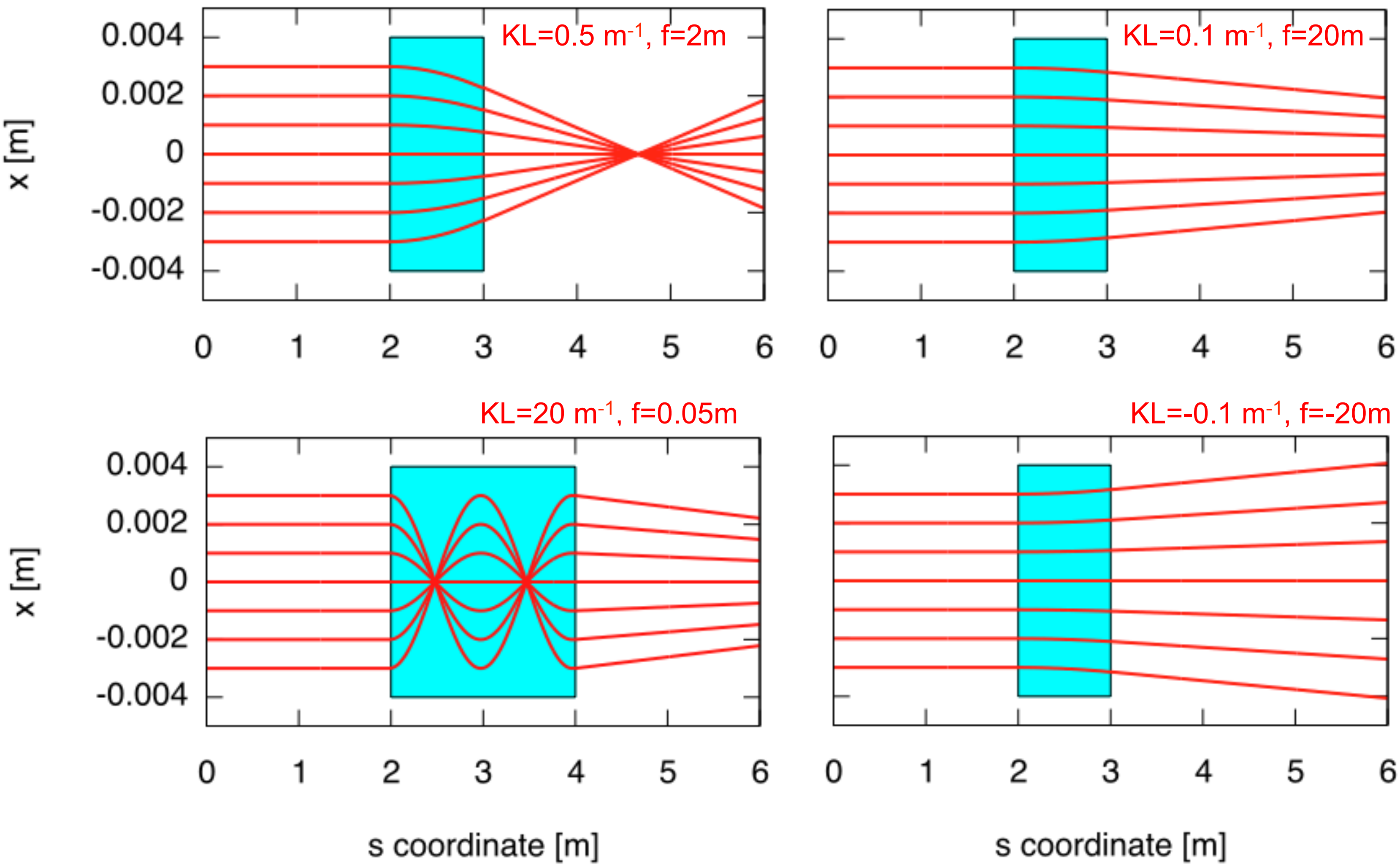
LEP quadrupole magnet (NC)



LHC dipole magnets (SC)

- Note high field strengths (red) where flux lines are densely packed together

Picturing Drift and Quadrupole Motion

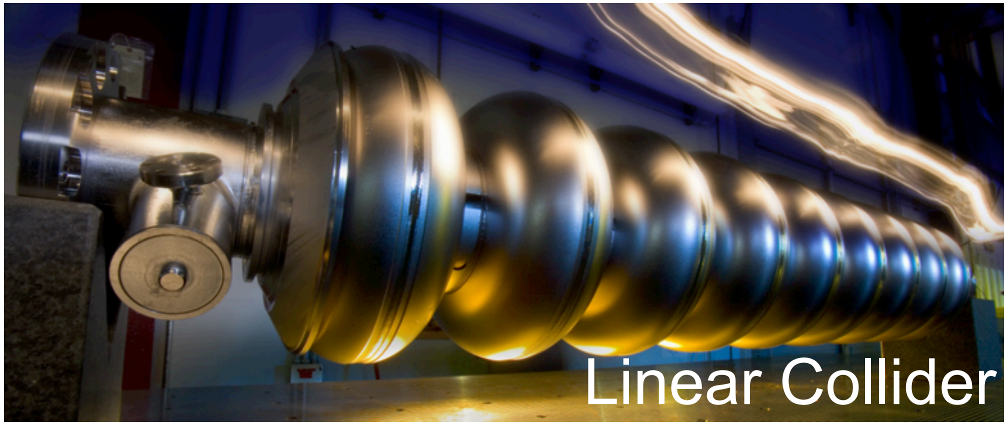


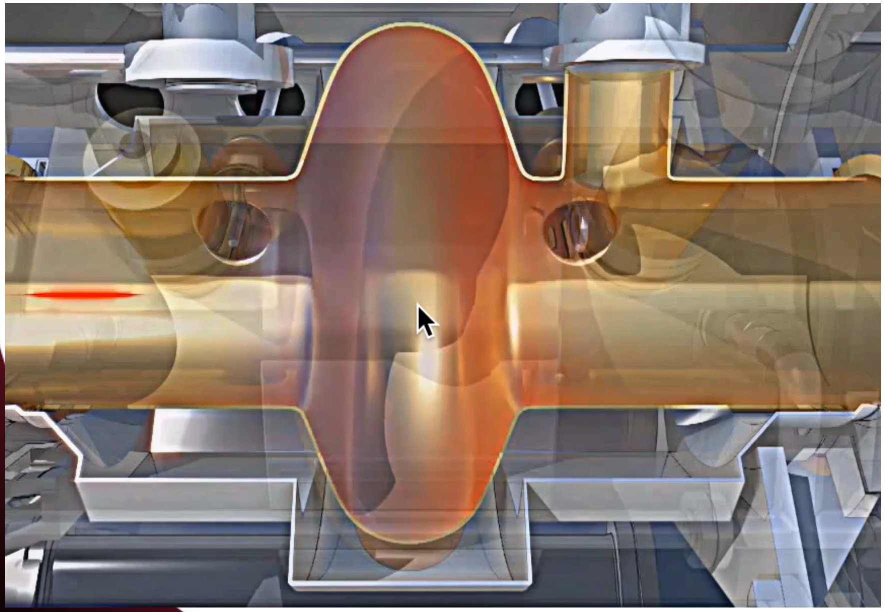
Quadrupoles act **just like** lenses in classical optics

RF Cavity Examples

Tens of Millions of V/m!

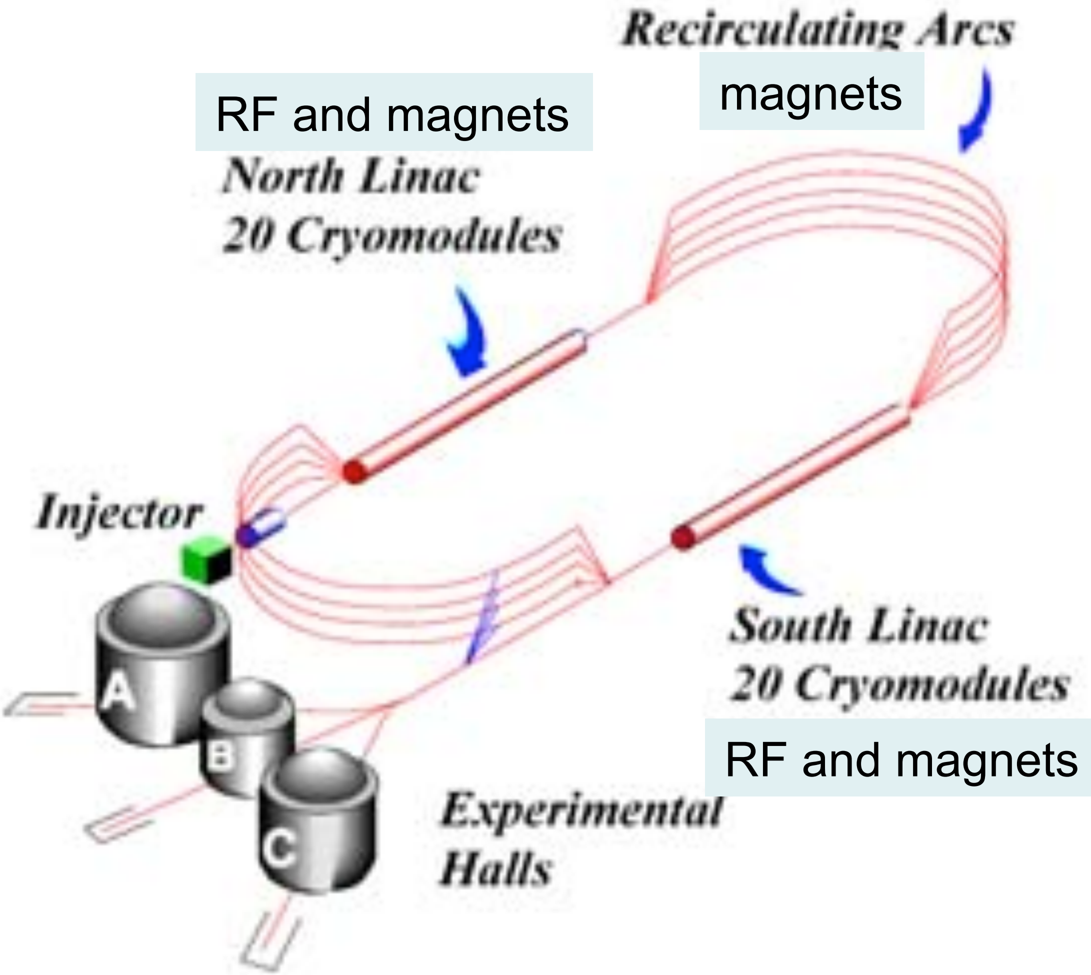
1497 MHz





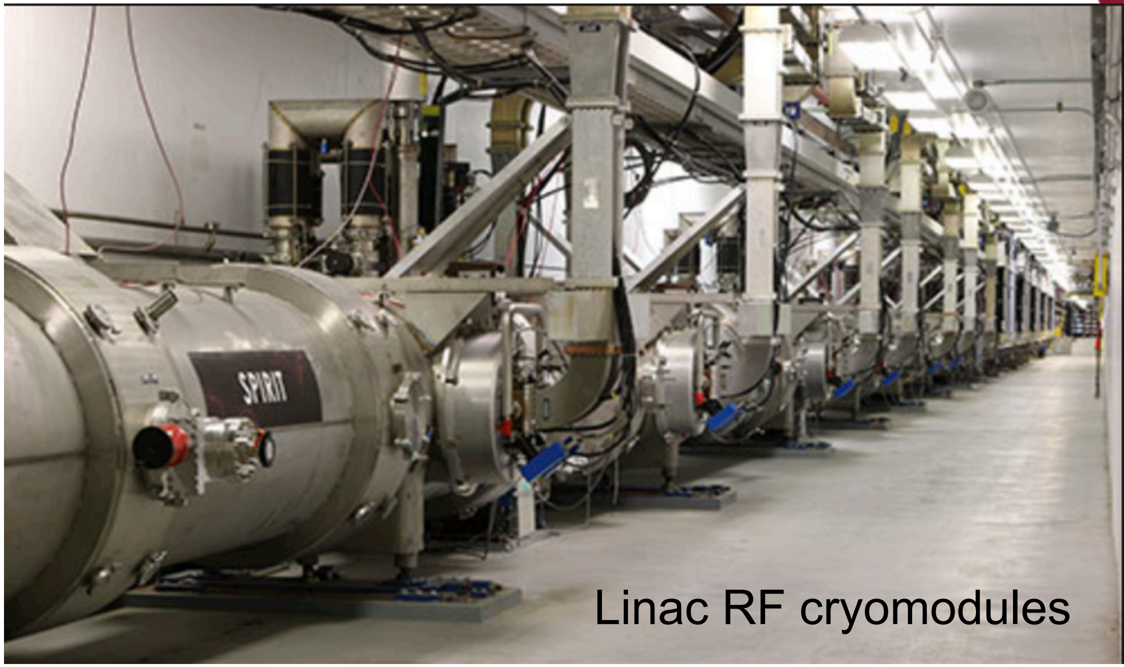
197 MHz

Did Somebody Say CEBAF?



6-12 GeV (~1 MW) polarized electrons
1497 MHz beams
Circumference ~1300m (0.8 miles)
CW recirculating linacs

The CEBAF Tunnel



- Superconducting RF operates at 2K
- High vacuum systems
- Instrumentation/diagnostic systems
- High-power electrical systems
- Control system: 10k+ control points

Why CEBAF?

- Let's say we want to do a diffraction/scattering experiment to get images of atomic nuclei (protons and neutrons)
  - Proton charge radius: ~0.88×10^{-15} m (0.88 fm)
- We also want to measure electroweak interactions
  - So our probe better be EM charged and polarizable (to see asymmetric scattering from weak force parity violation)
- High-energy electrons fit the bill perfectly

$$\lambda_{\mathrm{e}} = 10^{-15}\ \mathrm{m} \quad \Rightarrow \quad E_{\mathrm{e}} = \frac{hc}{\lambda_{\mathrm{e}}} = 1.24\ \mathrm{GeV}$$

  - Higher energies can also excite new nuclear/parton states
  - Polarized beam asymmetries are sensitive to weak interaction currents

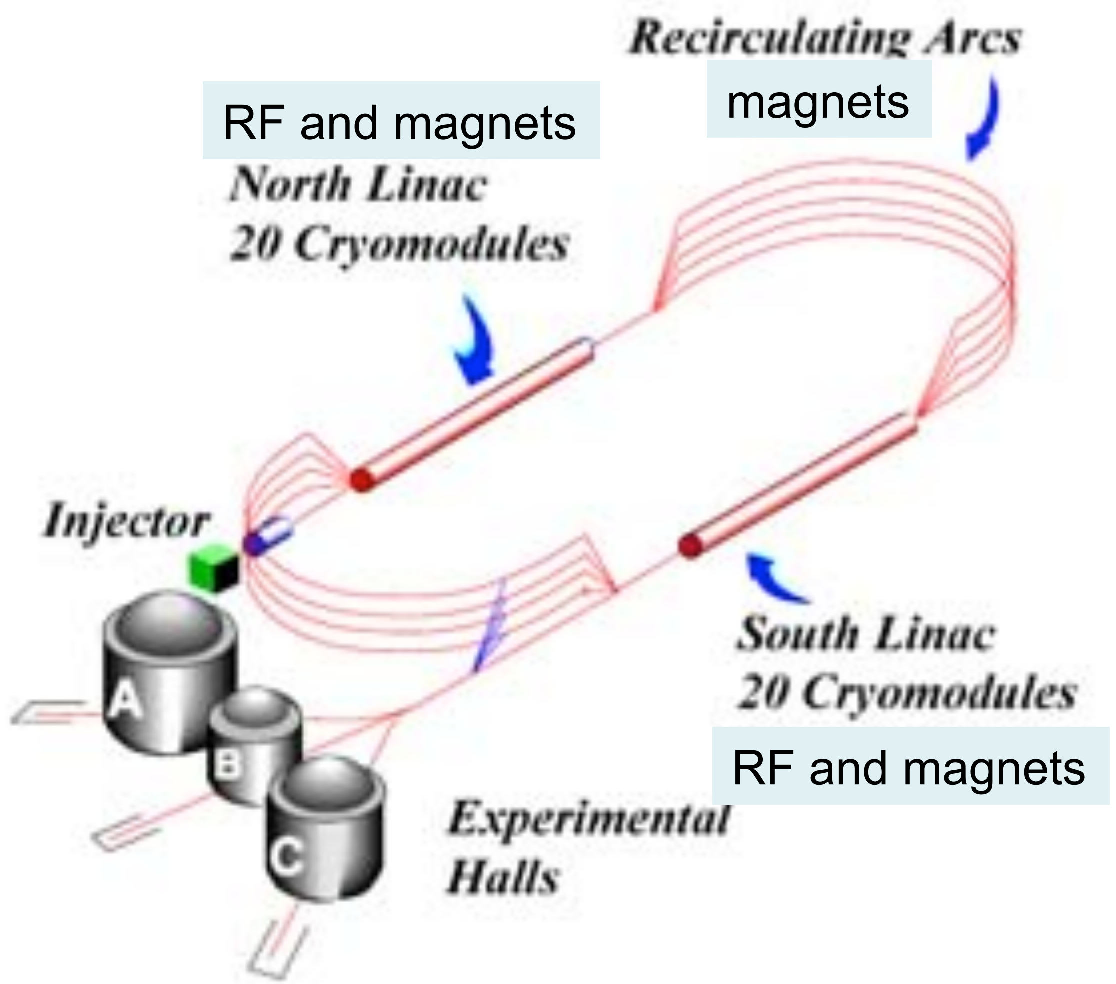
How CEBAF?

- A multi-GeV continuous electron beam is not common!
  - Equivalent to accelerating through GV of potential
  - Far far too large to create with electrostatics

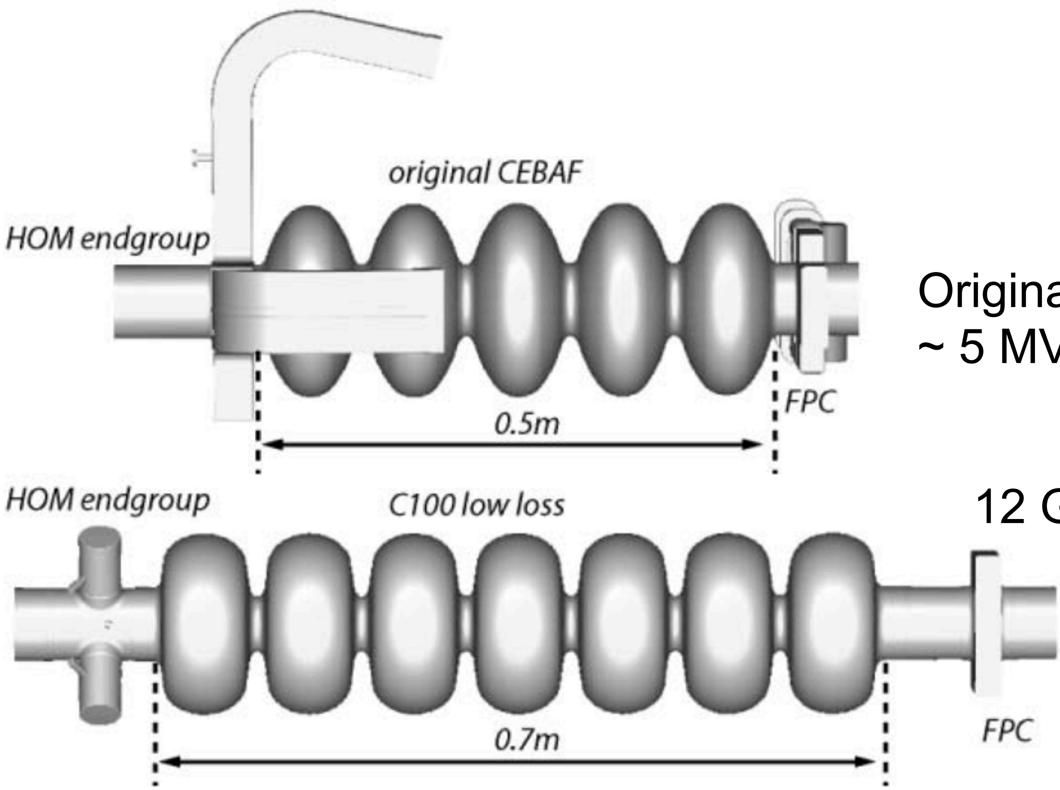
- Regular (non-superconducting) RF cavities?
  - CW state of the art was ~2 MV/m: 2 GeV = 1 km of cavities
  - We want high frequency (100s of MHz): **high Ohmic losses**
  - This implies many 10s of MW of wall plug power!

- Superconducting RF cavities!
  - Requires construction of large 2K (or 4K) cryogenic facility
  - But can achieve high energy, “high current” CW beams
  - Original gradients: ~5 MV/m => E_e ~ 4 GeV
  - The first major superconducting RF facility in the world

CEBAF Reminder



How CEBAF?

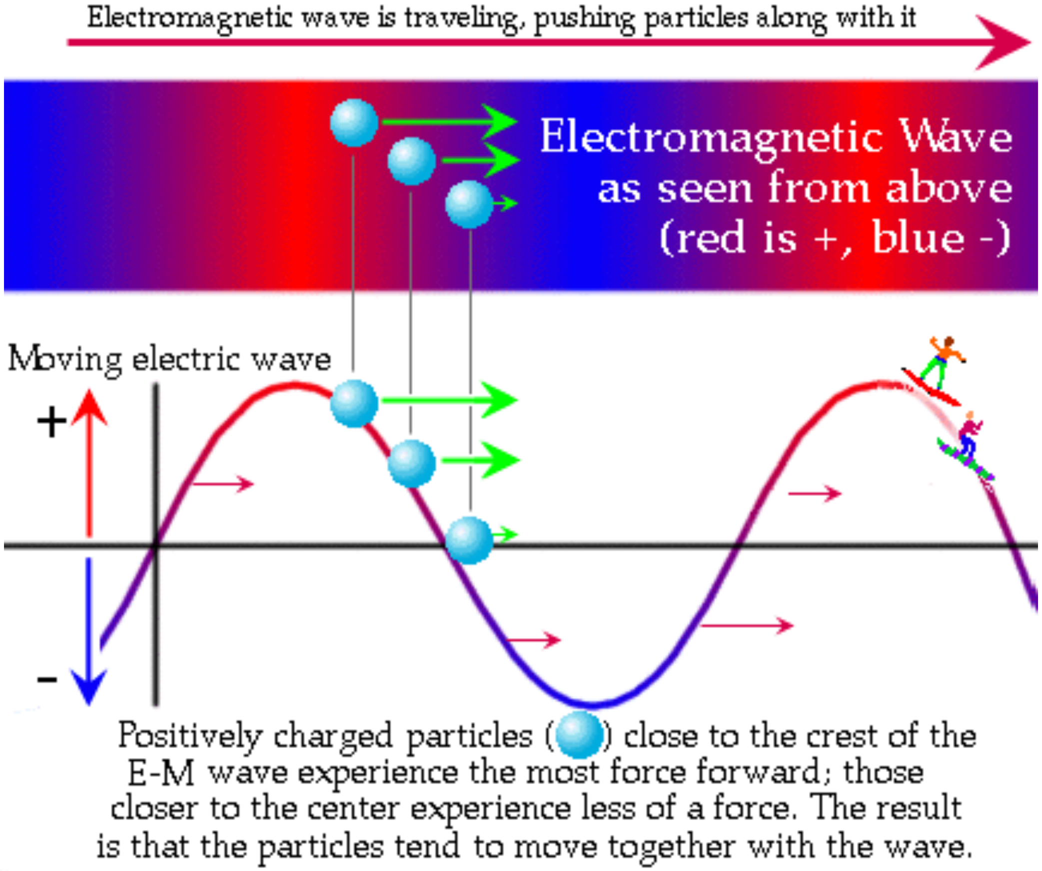


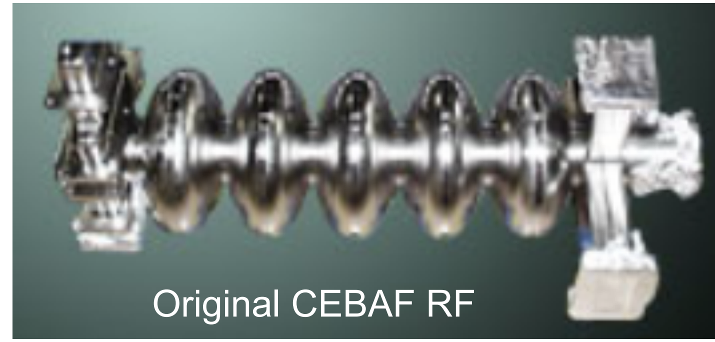
Original RF cavities
~ 5 MV/m

12 GeV RF cavities
~ 20 MV/m

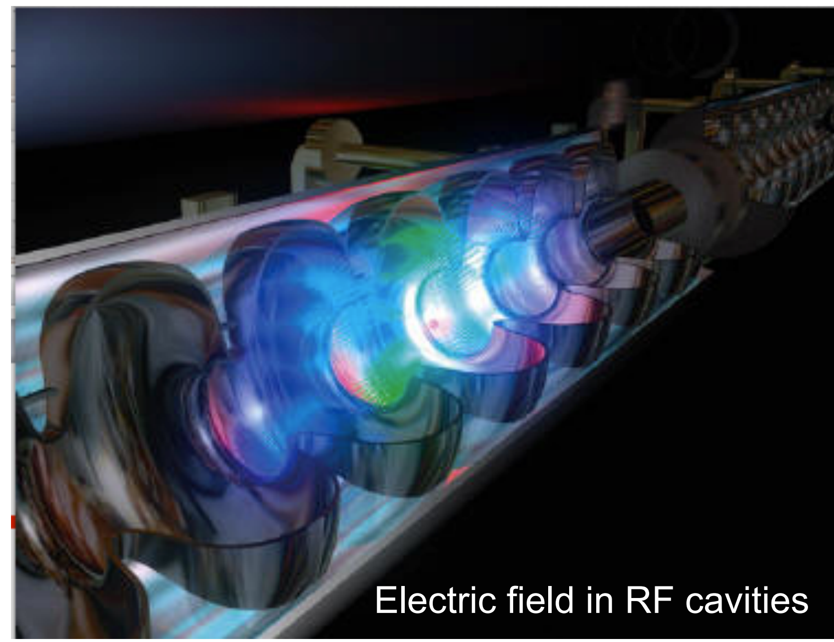
- CEBAF original RF cavities had 5 cavities per "cell"
- RF cavities act like coupled 3D EM harmonic oscillators
  - Higher order modes ("HOMs") can also interact with the beam
  - Q: 1/e resistive damping time in cycles. Here Q=10^9 to 10^{10}!!

Wave Riding in RF Cavities at CEBAF




Original CEBAF RF


12 GeV Upgrade CEBAF RF

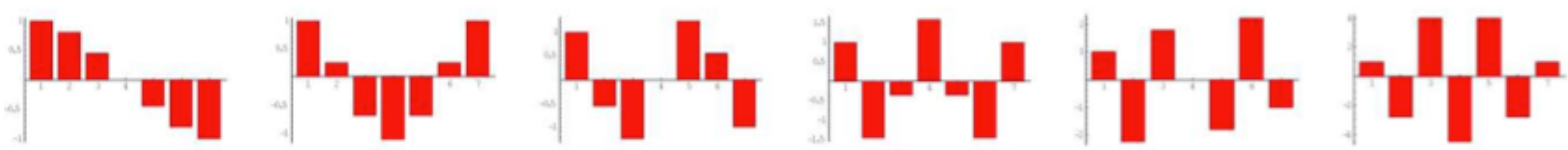

Electric field in RF cavities

RF Cavities: Coupled Harmonic Oscillators

magnetic boundaries (left and right) → no 0-mode

$2\pi/7$ $3\pi/7$ $4\pi/7$ $5\pi/7$ $6\pi/7$ π

electric boundaries (left and right) → no π-mode



$\pi/7$ $2\pi/7$ $3\pi/7$ $4\pi/7$ $5\pi/7$ $6\pi/7$

Pretty visualization at http://www.falstad.com/emwave2/

Numerical Examples

$$\lambda f = c \qquad f = c/\lambda$$

$$f_{CEBAF} = 1497 \text{ MHz} = 1.497\times10^9 \sec^{-1} \rightarrow \lambda_{CEBAF} = 20 \text{ cm}$$

$$I = \frac{P}{A} = \frac{E_x B_y}{\mu_0} = \frac{E_x^2}{\mu_0 c} \text{ or on average } \frac{c\varepsilon_0 E_{x,amp}^2}{2}$$

1. Light Bulb

$10 \text{ W} @ 1 \text{ m} \rightarrow E_{x,amp}$: 24.5 V/m or 12.2 V/m @ 2 m

2. Radio Station

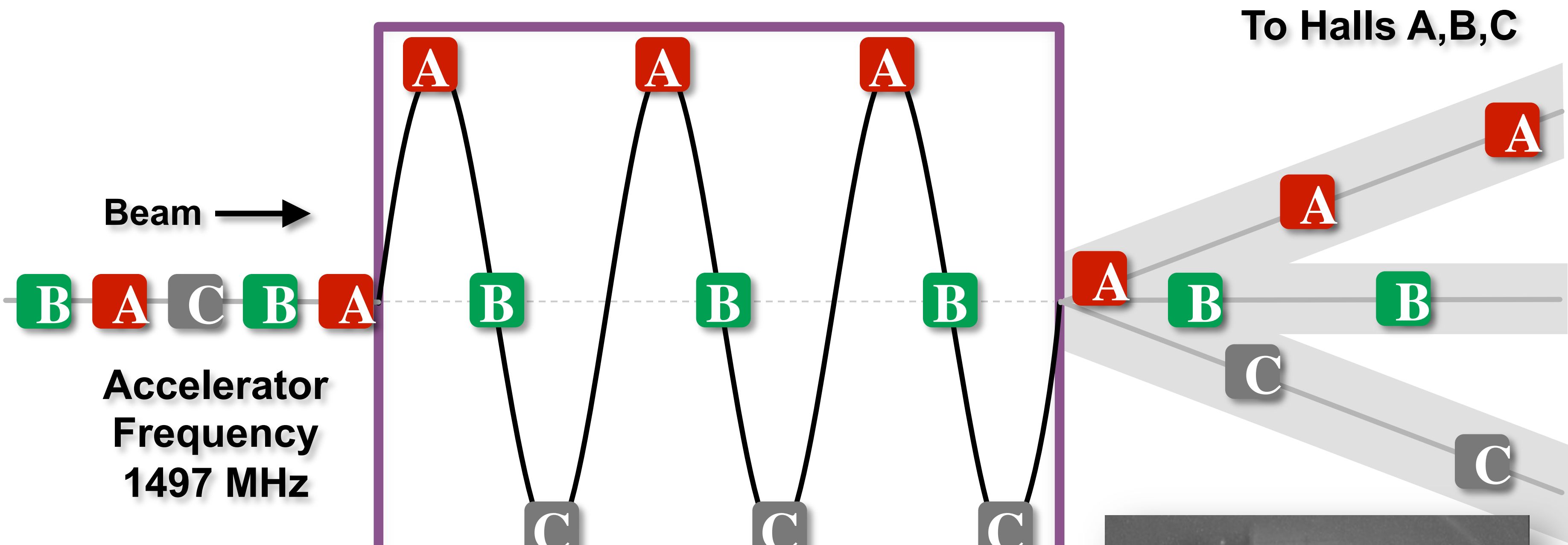
$50 \text{ kW} @ 10{,}000 \text{ m} \rightarrow E_{x,amp}$: 0.17 V/m or 0.09 V/m @ 20 km

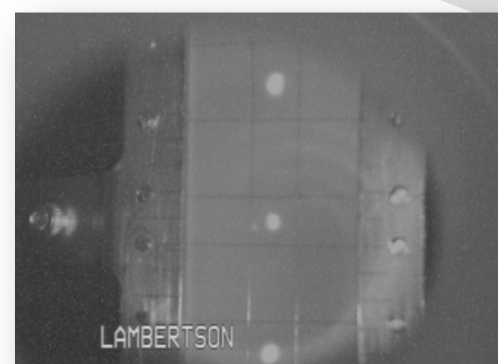
3. CEBAF Waveguide

$400 \text{ W in } .1 \text{ m}\times.2 \text{ m} \rightarrow E_{x,amp}$: 3.9 kV/m

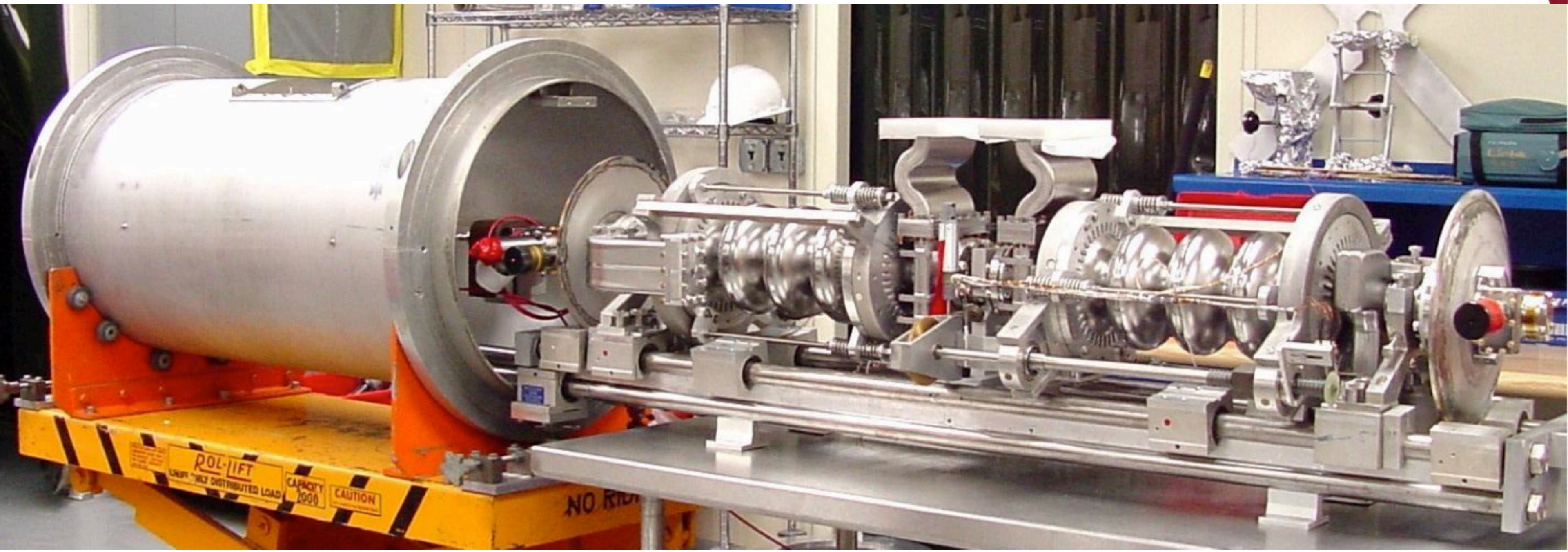
CEBAF 6 GeV 3-Hall Operations

- Beam comes in “bunches” at 1497 MHz
- TM mode cavities split into three 499 MHz beams for 3 halls



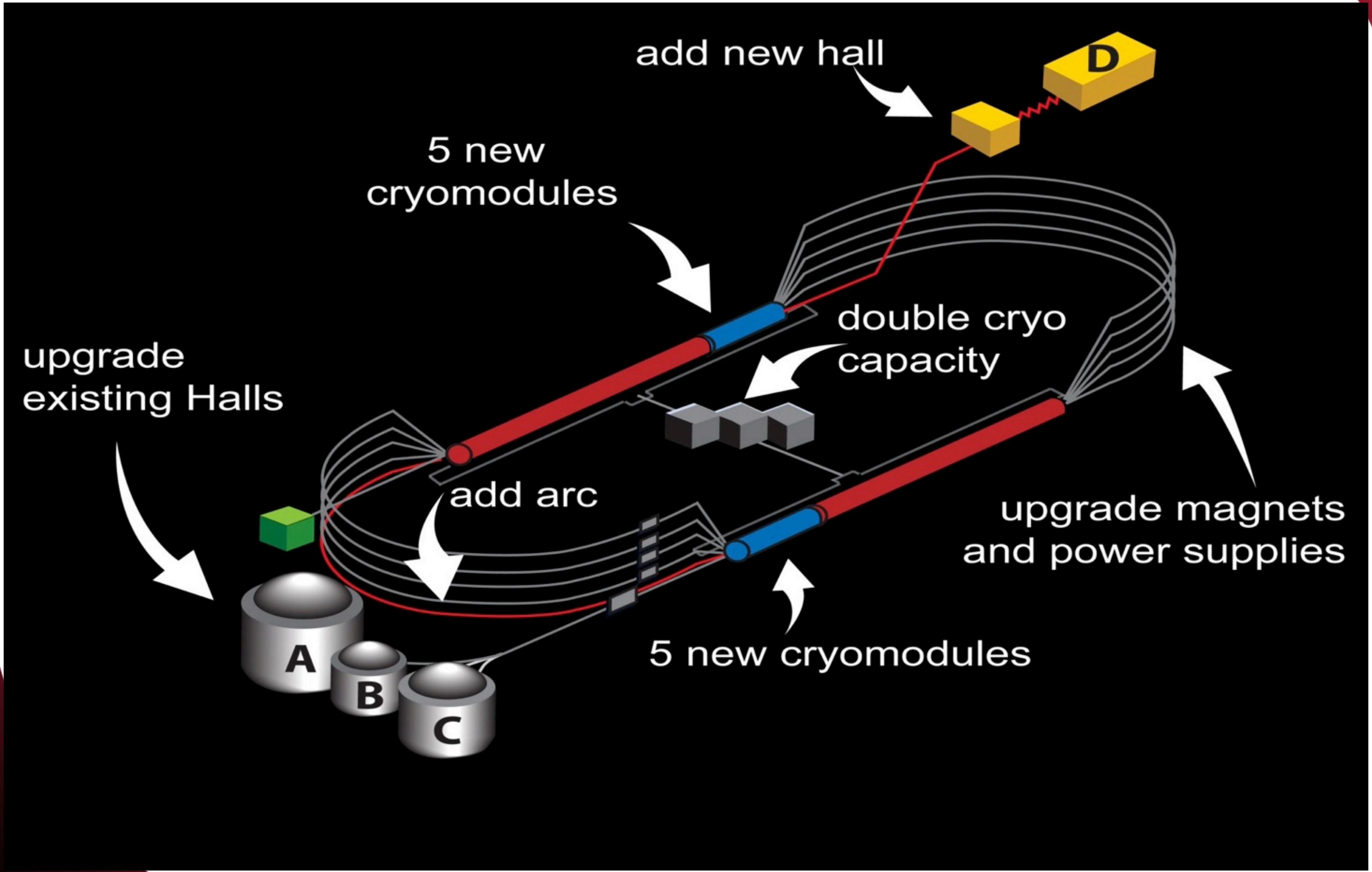


Refurbished CEBAF RF Cavities



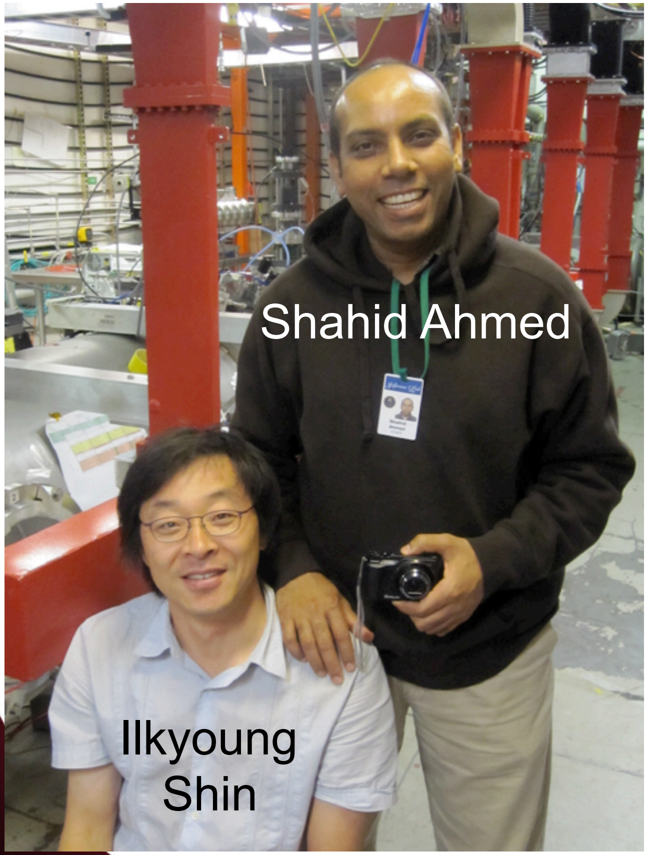
- Made out of very pure large-grain Nb
  - Superconducting RF technology research is a very active area
    - Includes many active control loops for consistent fields
  - Nb RF technology theoretical limit: 55 MV/m
  - Insulating cryomodule layers removed here for visibility

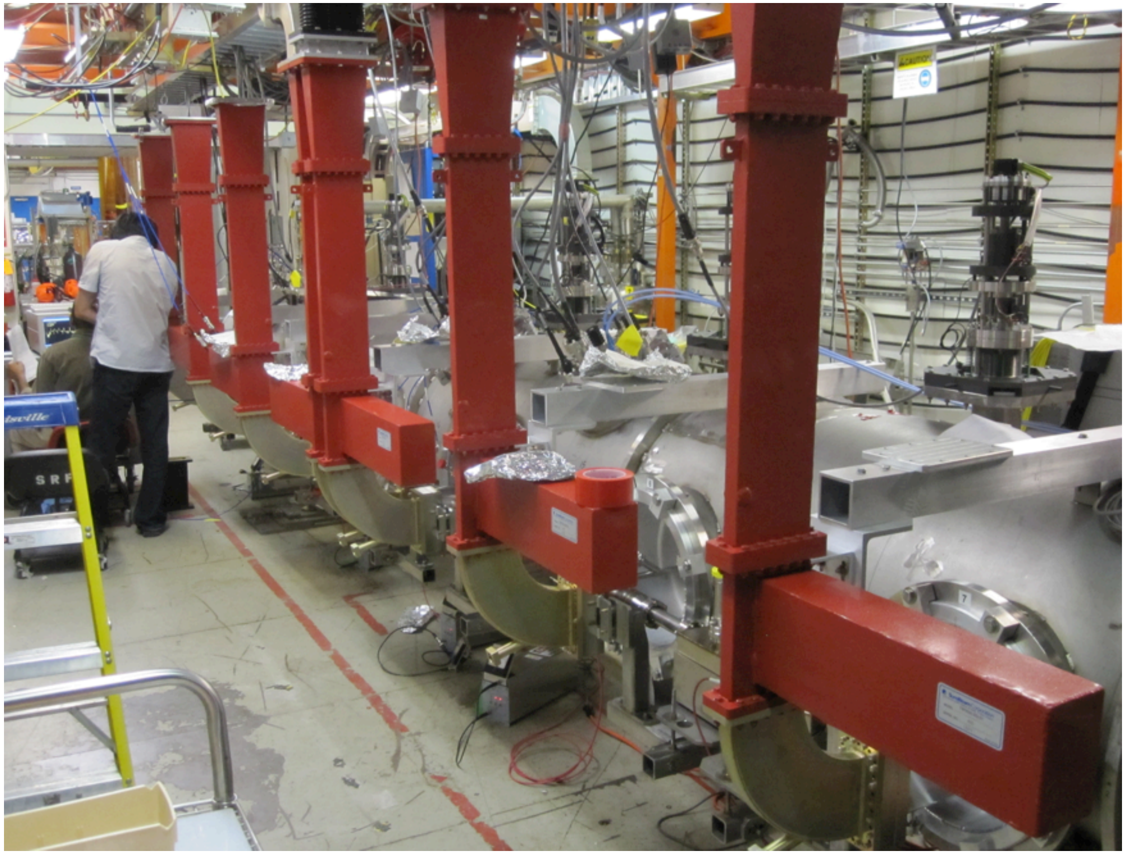
CEBAF: From 6 GeV to 12 GeV



C100 RF

- New RF cryomodules: 4x gradient of old modules
  - Adding 5 new modules doubles energy of accelerator
  - Each module: 20 MV/m, ~100 MeV energy gain/module





A Humorous Interlude Before History Lessons