Beam Physics by Particle Physicists

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Food for Thought, Fermilab, April 10th 2001

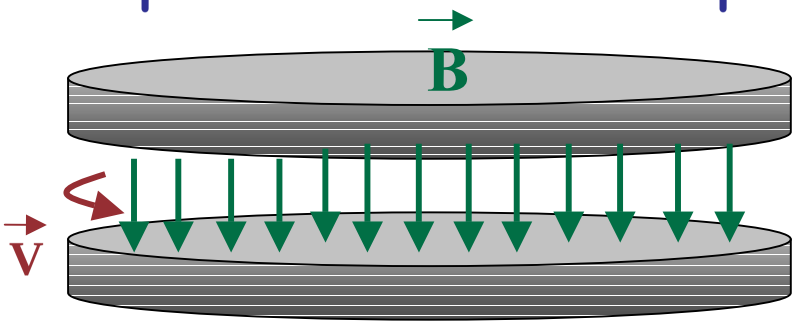
Outline

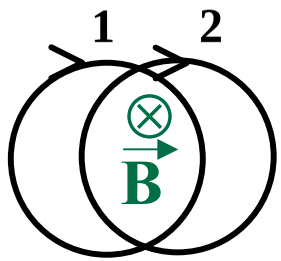
- Basics on beam physics
- Projects and challenges
- How we can contribute to this effort

(From the experience of a particle physicist working on the neutrino source/muon collider project)

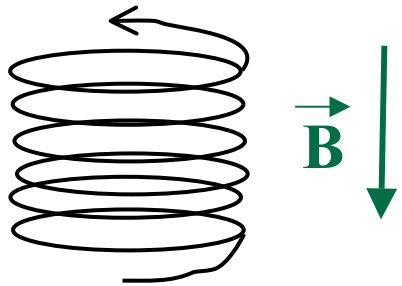
Magnets: dipoles, quadrupoles, solenoids

Basic elements of an accelerator to bend, focus, capture a beam of particles.





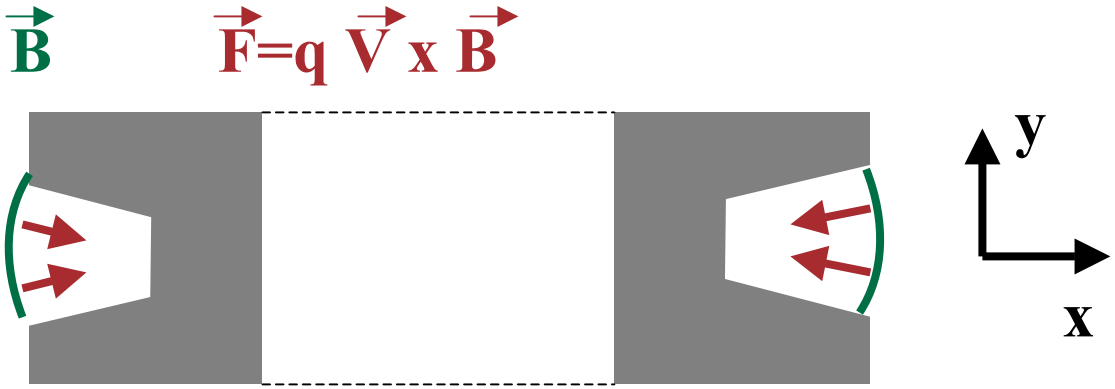
Horizontal



Vertical deflection

Uniform field provides focusing in the horizontal direction but a deflection in the direction of the field would make the particle spiral away

Weak Focusing



$$B_y = \frac{B_0}{r}$$

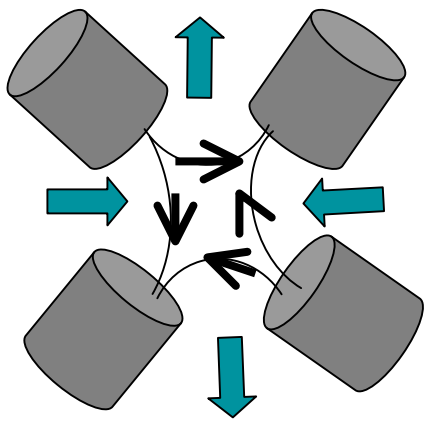
Cross section of a circular accelerator

Particles above (below) midplane experience downward (upward) force → vertical focusing

Focusing is weak because although there is also radial focusing, B_y gets weaker as a function of radius (gaps too large, and lots of iron !)

Strong Focusing

Alternating gradient focusing (1952) by Livingston at BNL → Cosmotron (magnets in a ring)



Quadrupole lens: focus horizontally and defocus vertically or vice-versa

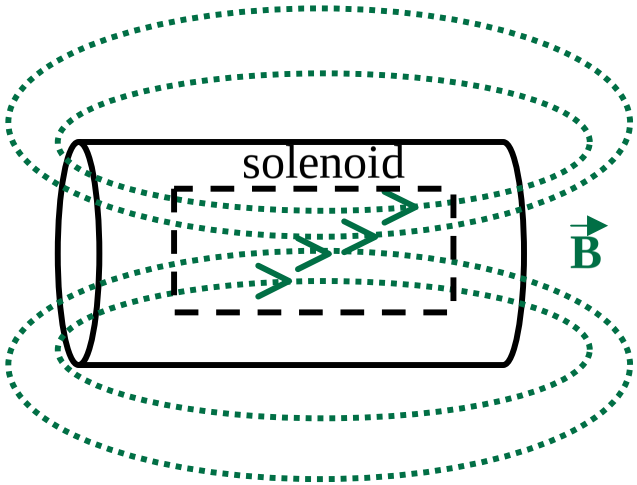
$$B_y = \frac{\partial B_y}{\partial x} x \qquad B_x = \frac{\partial B_x}{\partial y} y \qquad \frac{\partial B_y}{\partial x} = \frac{\partial B_x}{\partial y}$$

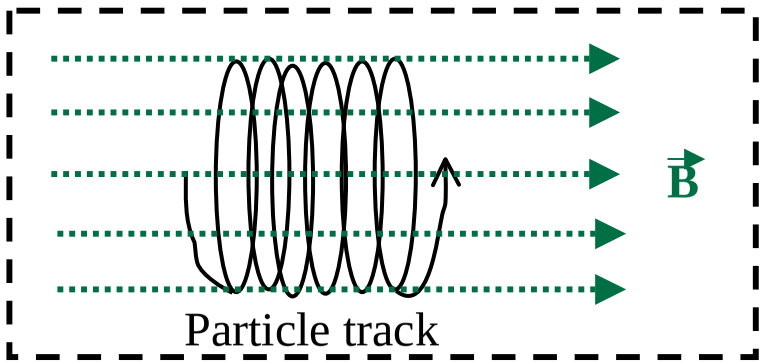
Geometric optics: equal strength convex and concave lenses can produce net focusing (if their distance < focal length)

Solenoid Focusing

Characteristic feature of the Muon Collider/ Neutrino source design. Solenoids focus in two directions simultaneously.

Large beam size ($\sigma_x \sim \sigma_y \sim$1-10 cm), large angles → large aperture, thin lens approximation no longer valid: $B_y = \frac{\partial B_y}{\partial x} x \neq \text{const}$



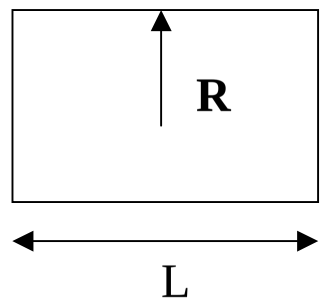


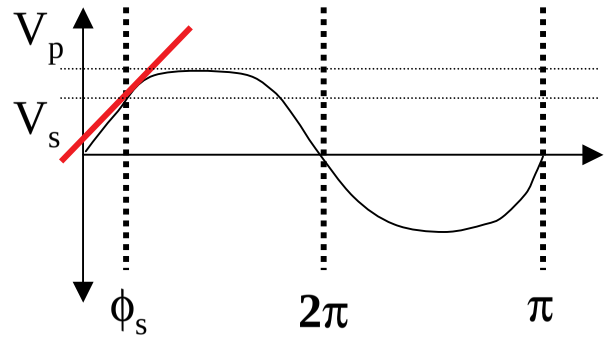
$B_z=f(r,z)$, $B_r=g(r,z)$ → Non-linear equations, horizontal and vertical motion not independent (x-p_y & y-p_x correlations)

Acceleration

Resonant cavities provide both acceleration and focusing in the longitudinal direction

Pillbox cavity





L: cavity length, R: cavity radius V_p: peak voltage ν: frequency ϕ_s: synchronous phase

V_s: synchronous V

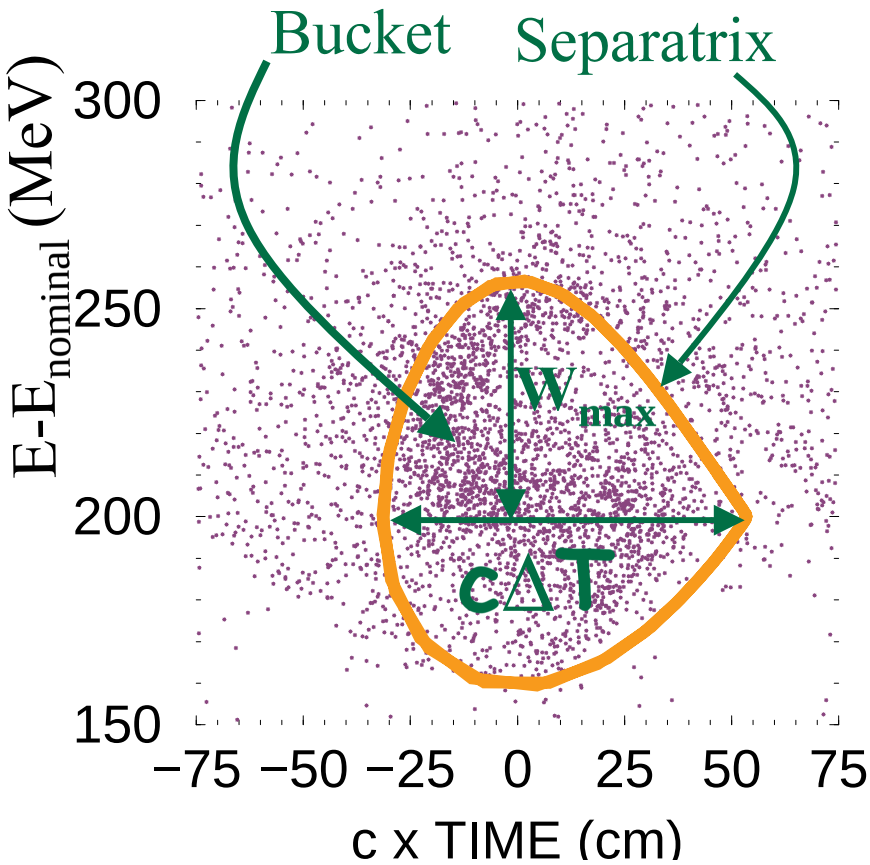
$$E_z = (r,t) = \overbrace{E_0 J_0\left(\frac{2\pi\nu}{c} r\right)}^{V_p} \sin(\varphi_s + 2\pi\nu t)$$

$$\frac{2\pi\nu}{c} R = 2.405$$

Fast particles get a smaller kick than fast particles (longitudinal focusing)

$Ez = 0$ at $r = R$ (ν fixes radius)

L is fixed by V_z, ν, phase advance



Longitudinal phase space distribution of a "bunch" of particles

The separatrix divides the regions of stable (inside the bucket) and unstable motion

$$W_{max} \propto \sqrt{E_{nomi}}$$

$$c\Delta T \approx \frac{3c}{2\pi\nu}\left(\pi - \varphi_s\right)$$

Bucket size depends on the beam energy, and the r.f. frequency and synchronous phase

Example: Enominal=200 MeV

L=32 cm, R=57 cm V_p=16.5 MV/m ν=201.25 MHz ϕ_s= 25.7°

W_{max} ~ 60 MeV CT~80 cm

The Beam

Liouville's theorem: density in phase space of non interactive particles in a conservative system is invariant

Phase space volume enclosed by the separatrix or any given surface is conserved (shape may change), if acceleration is performed adiabatically

Normalized Longitudinal Emittance: $\varepsilon_L = (\sigma_E\, \sigma_{CT})/mc^2$

Normalized Transverse Emittance: $\varepsilon_x = (\sigma_x\, \sigma_{px})/mc^2$

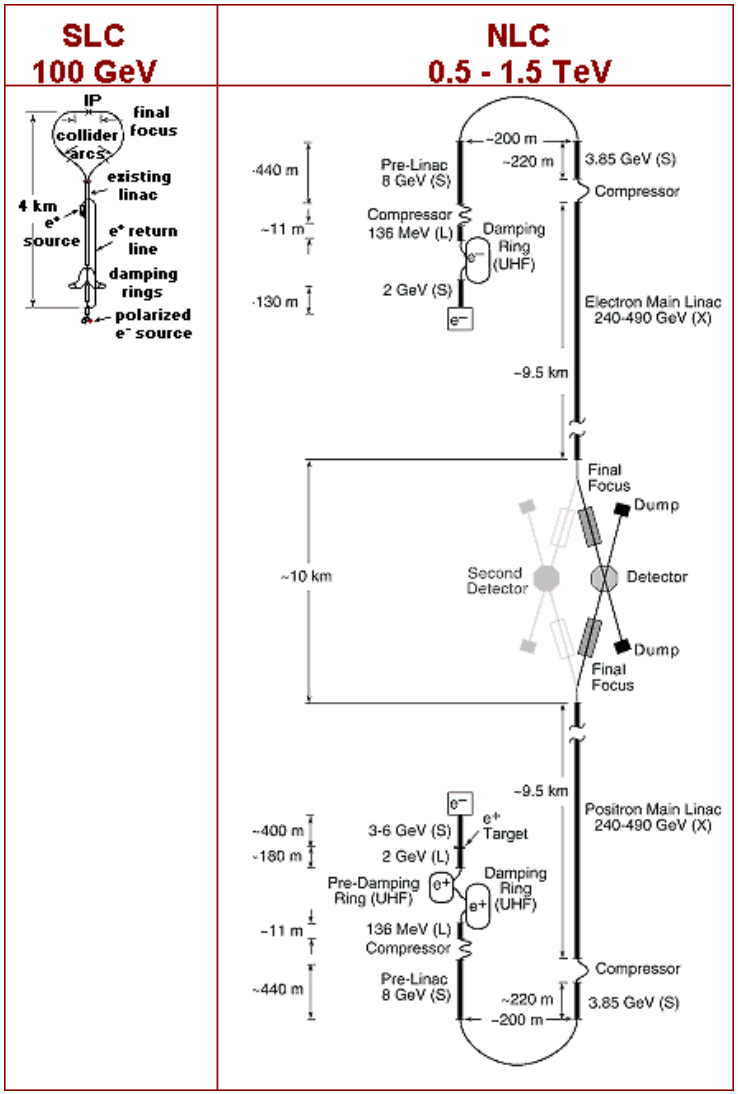
Lorenz invariant

Beta Function, $\beta(s)$ is proportional to beam envelope (amplitud) along its path. It is determined by the accelerator lattice

Examples: $\beta(s) = 2pc/eB_z$ (solenoid) oscillating (FODO)

The NLC

0.5-1.5 TeV e^+-e^- linear collider, $\mathcal{L}=10^{34}$ (~30 Km long)



Challenges:

- accelerator gradient: 50-100 MV/m (NLCTA experiment at SLAC)
- beam size and emittance preservation:
  σ_x~0.3, σ_y~0.005, σ_z~100 μm
  (FFTB experiment at SLAC)
- beam jitter, alignment

The VLHC

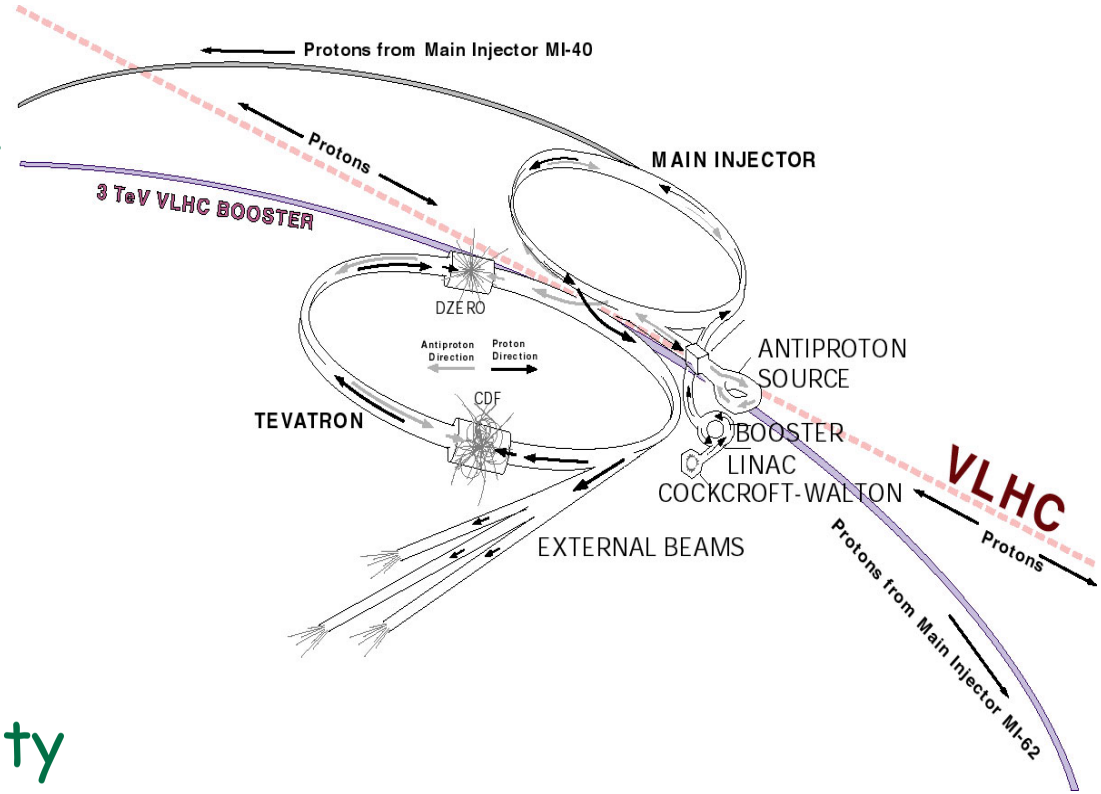
100 TeV p-p collider, $\mathcal{L} = 10^{34} - 10^{36}$

Option 1: 2 Tesla magnets (~500 Km circumference)

Option 2: 10 Tesla magnets (~130 Km circumference)

Challenges:

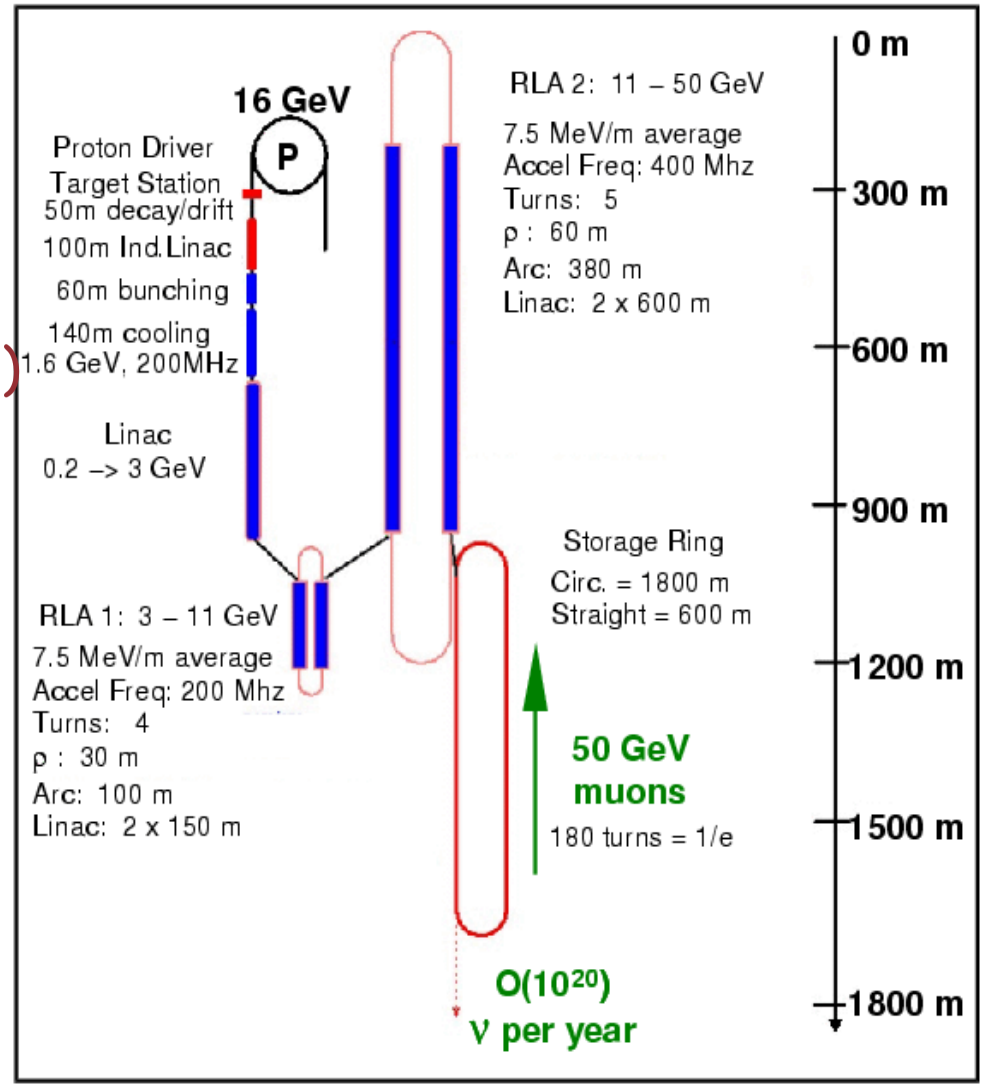
- High field magnets ~10 T
- Synchrotron radiation damping: 5 MW power (effect on beam pipe)
- Beam stability due to collective effects
- Tunnel cost, maintainability



The ν Source

Neutrino beam based on μ storage ring (1.7 km long):

- 16-24 GeV proton driver (1-1.5 MW)
- Carbon target: $p \longrightarrow \pi + \kappa$
- Capture, decay into μ, bunching
- Muon cooling (ε_x~1 cm, factor~10)
- Linac + recirculating linacs
- μ Storage ring (50 GeV), gives 10^{20} neutrinos/year



Challenges:

- target facility
- cooling channel

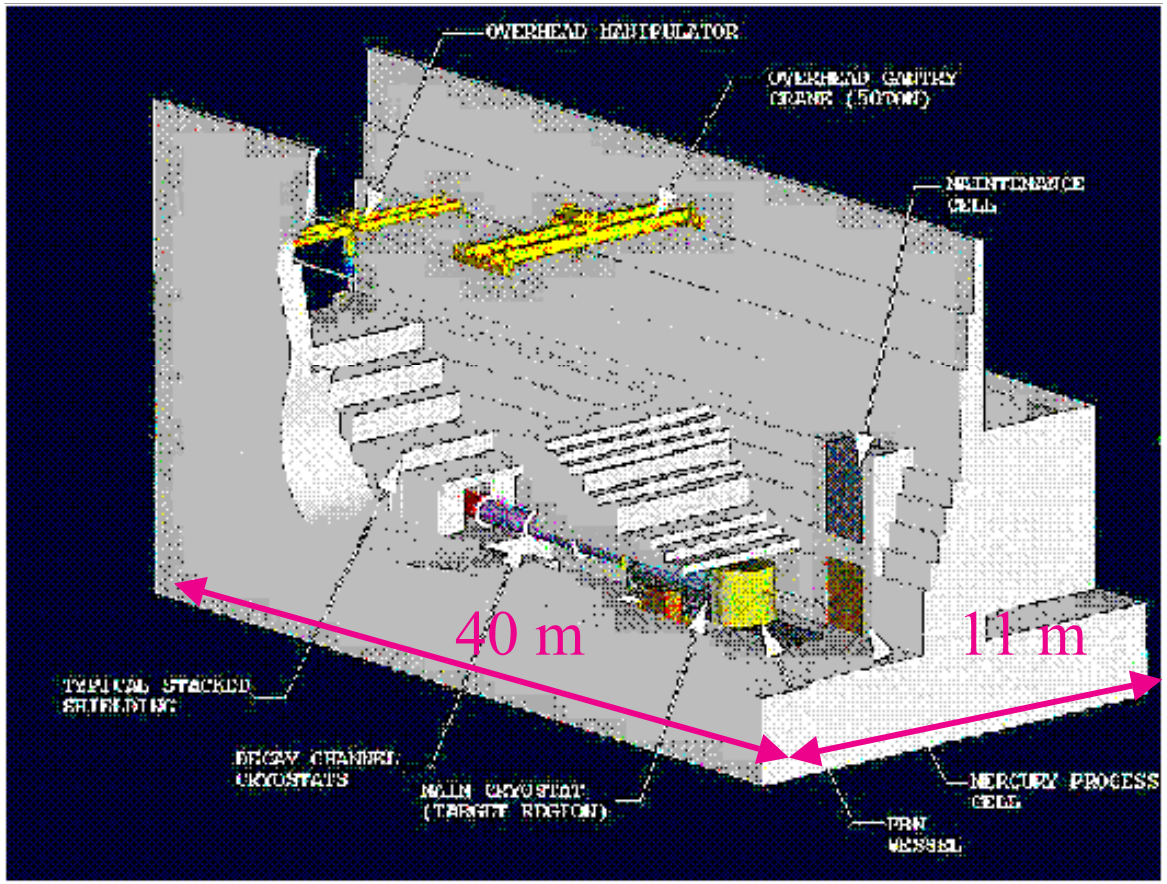
The Target

Carbon or Liquid Mercury jet target

20 Tesla capture solenoid

Issues:

- power dissipation, target durability
- pion yield of solid & liquid target
- performance of capture solenoid in a high radiation environment



Targetry experiments (NHMFL, ORNL, FNAL, BNL)

MC simulations (physics processes, radiation)

The Cooling Channel

ε_x reduced to ~ 1 cm (cooling factor ~ 10) so that:
beam divergence < 1/10 of decay angle ($1/\gamma_\mu$)

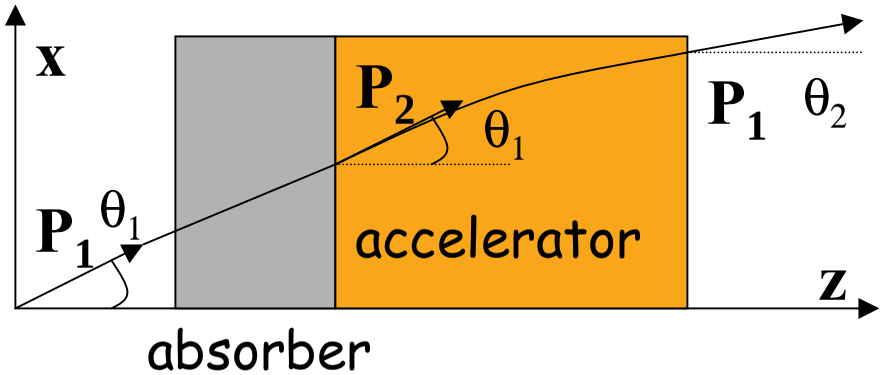
ε_L reduction not critical, just small enough to meet accelerator acceptance.

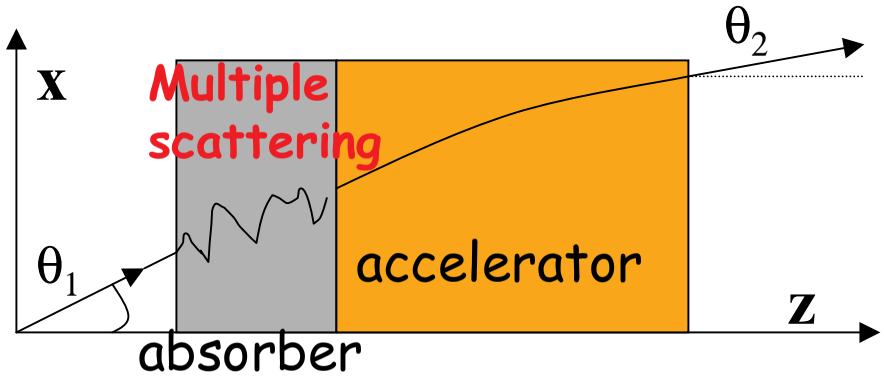
<u>ν source</u> → performance depends on ν flux, number of particles per pulse (does not need longitudinal cooling)

<u>Muon Collider</u> → longitudinal cooling is critical for high luminosity and small energy spread (ε_L)

Longitudinal cooling is the Muon Collider's SHOW STOP. Need ~ 10^6 3D cooling factor

Muon Ionization Cooling





$$\beta = v/c \qquad L_{trans} = \beta^2 E \frac{dz}{dE}$$

$$\beta_\perp = \frac{2pc}{eB} \qquad L_R : \text{radiation length}$$

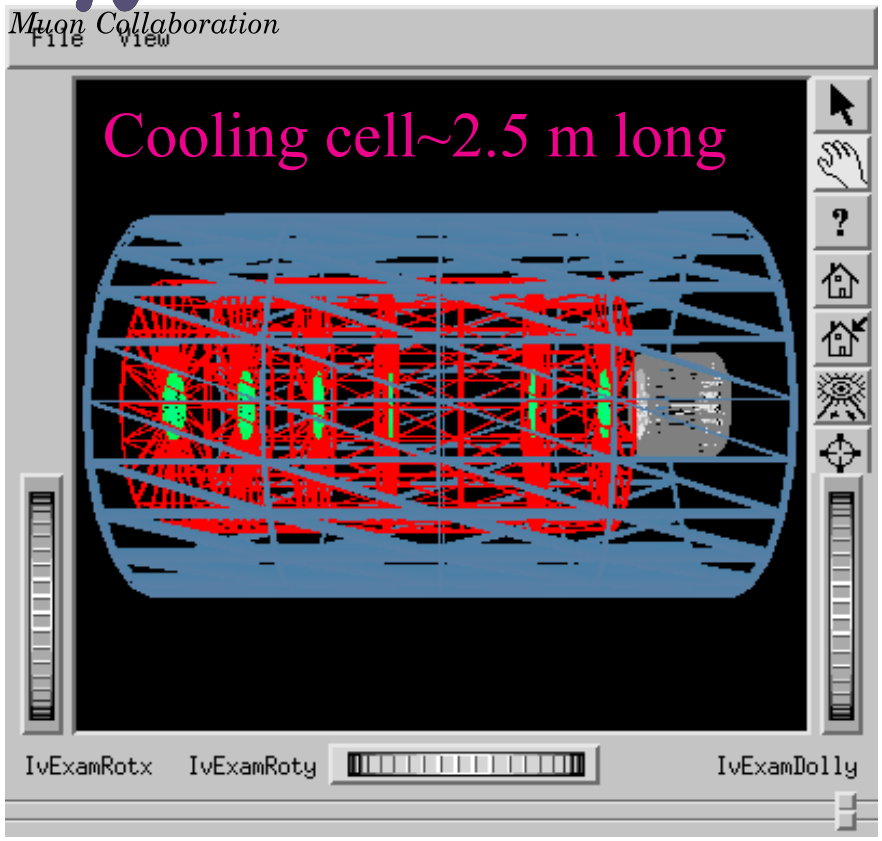
With transverse focussing (solenoid) :

$$\boxed{\frac{d\varepsilon_x}{dz} = -\frac{\varepsilon_x}{L_{trans}} + f\left(\frac{\beta_\perp}{\beta^3 E m_\mu L_R}\right)}$$

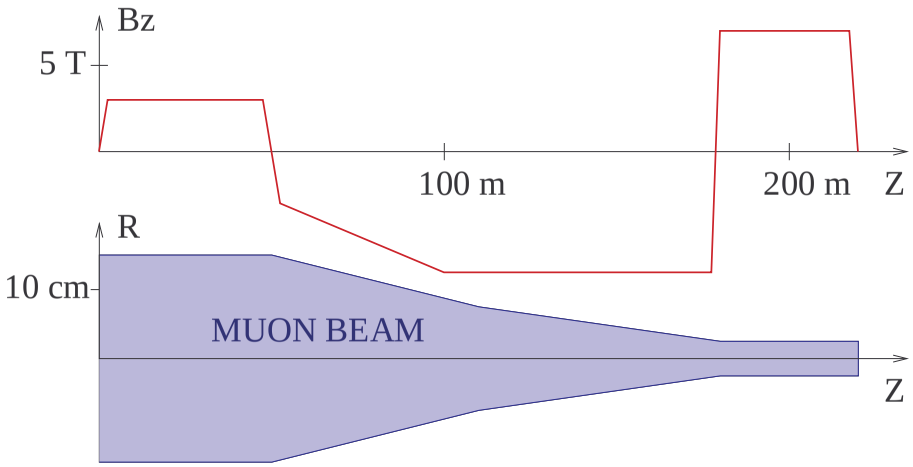
Low $\beta_\perp$ for max. emittance reduction

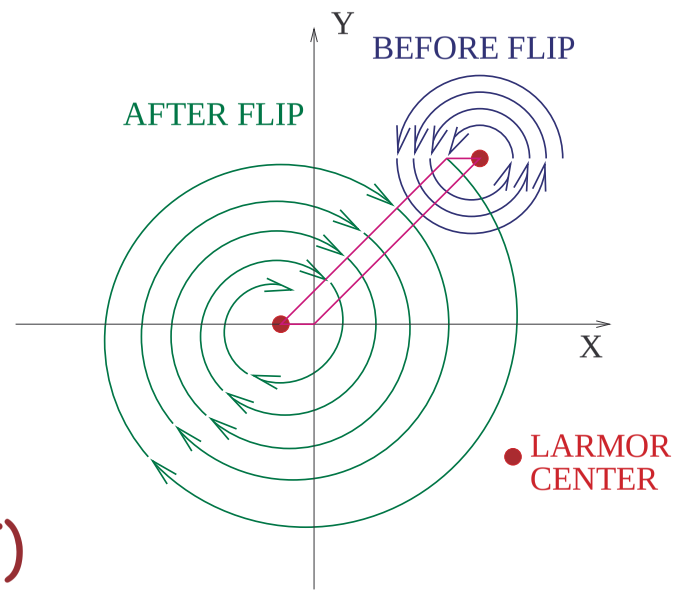
Cooling term + Heating term (Mult.Scatt.)

Example: the Double Flip Channel



220 m long (87 cooling cells), two field flip regions (3T to -3T & -7T to 7T)



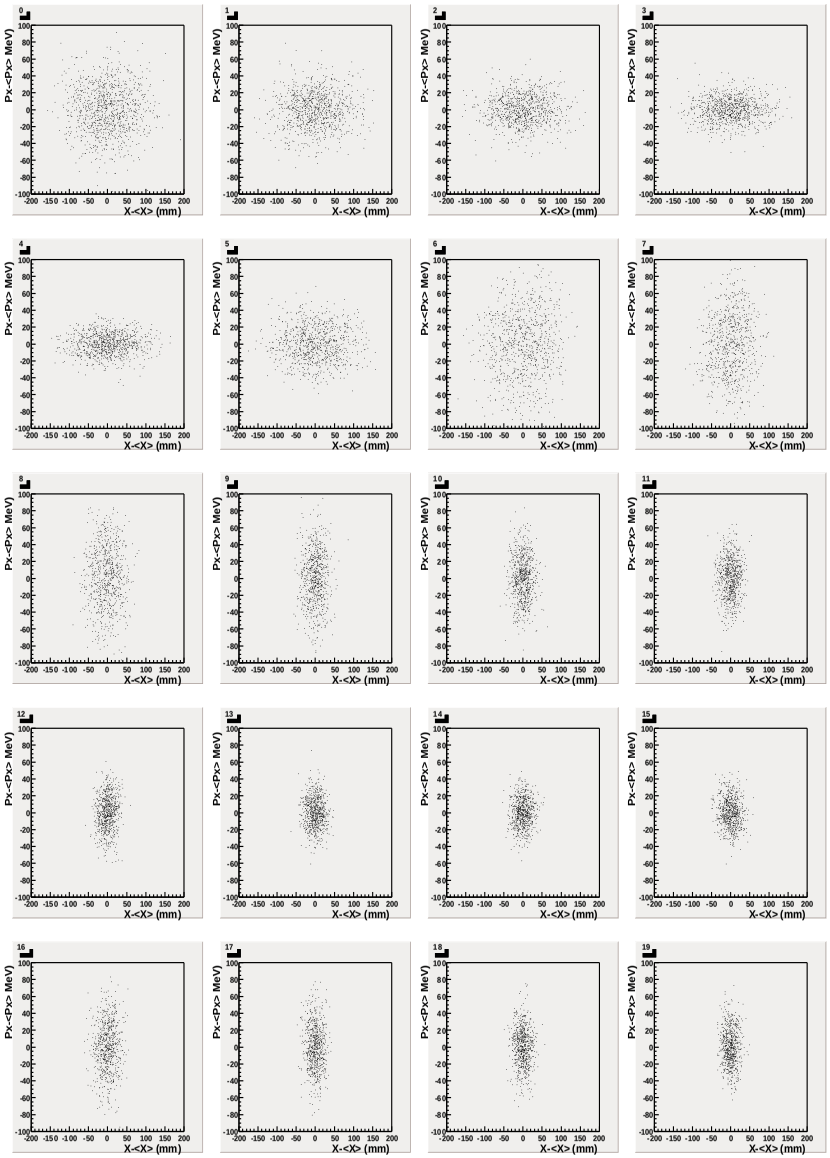


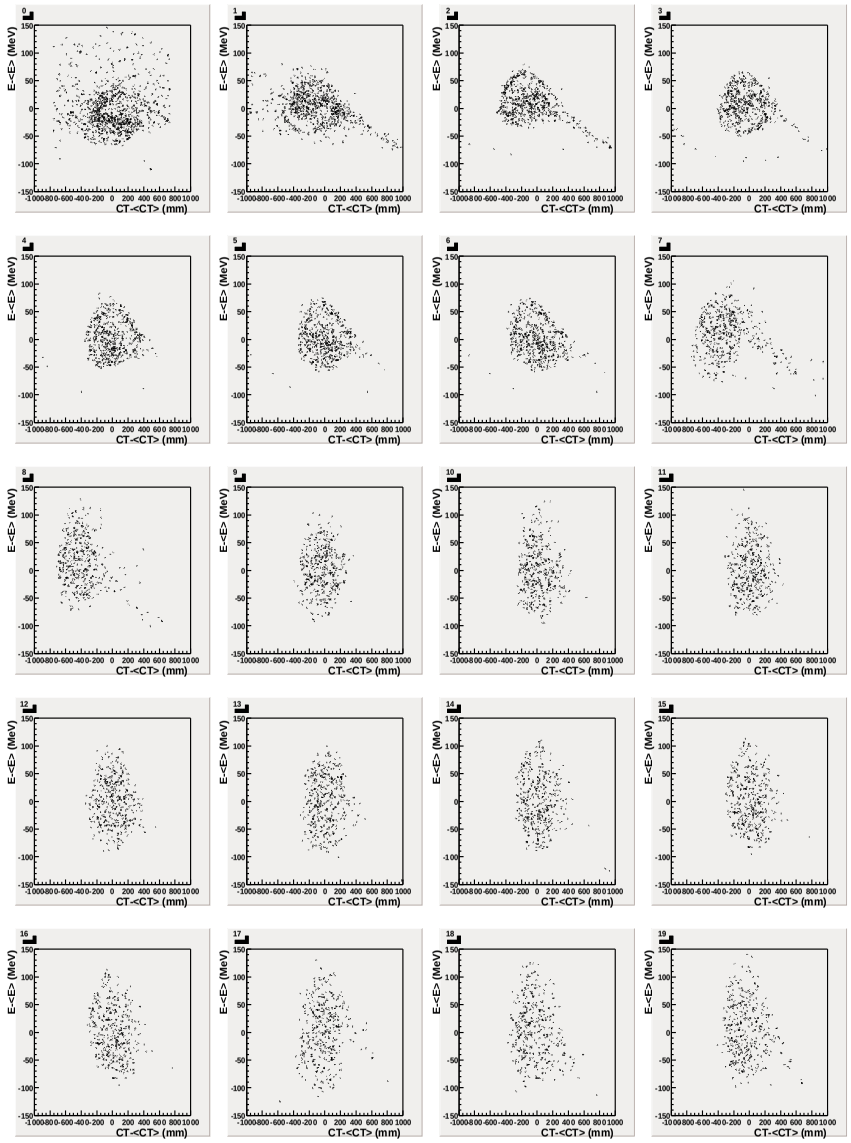
- 6 r.f. cavities, 32 cm long, 201 MHz, $\phi_s = 25.7^o$
- 30-39 cm liquid hydrogen absorbers
- r.f. & abs inside long solenoids (3-7 T)

P_x versus x

GEANT4 Simulation

E versus CT





Final ε_x ~ 2 mm

μ/p yield ~ 0.12

Final ε_L ~ 2 x Initial ε_L

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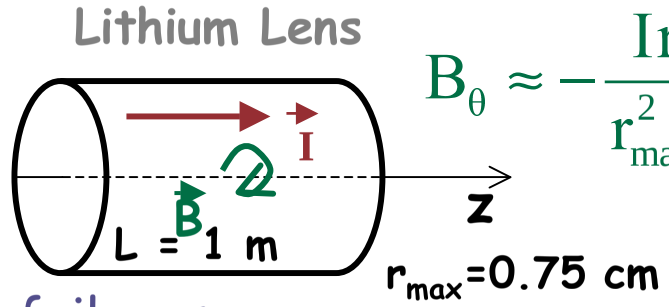
New Ideas for Cooling

Muon Collaboration

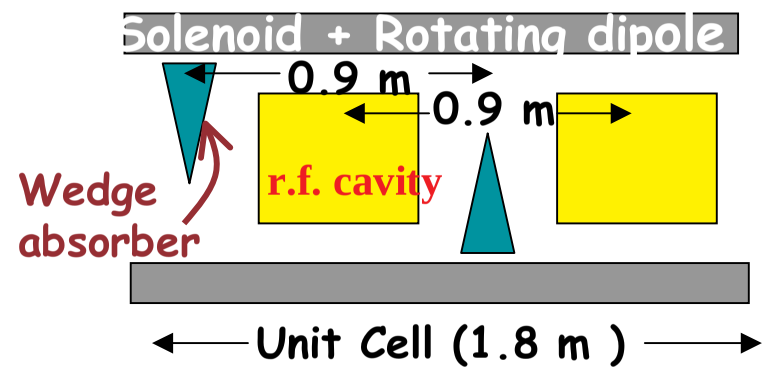
- Use of Lithium Lenses provide strong radial focusing (cooling factor of 1.6 in just 1 m)

  15 HZ pulsed current → mechanical failures



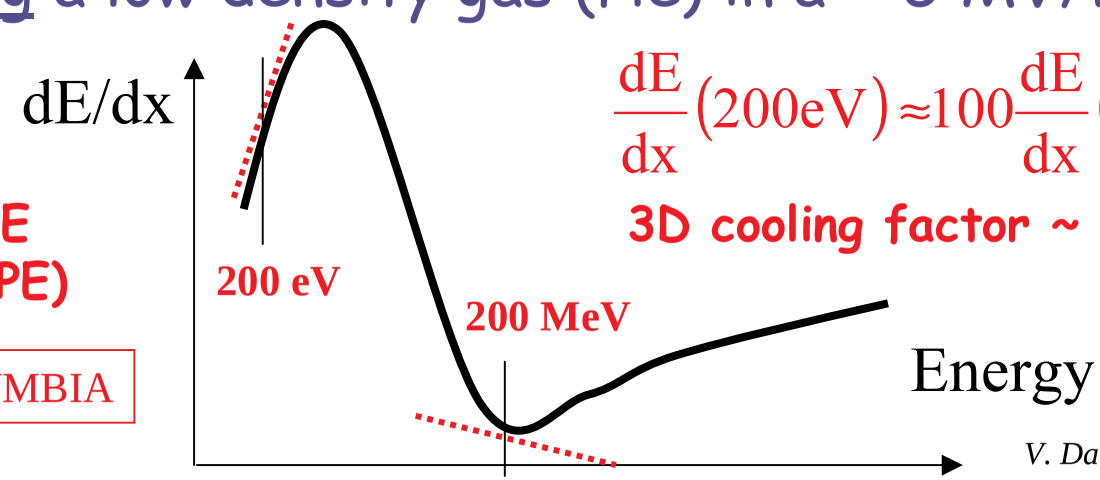
$$B_\theta \approx -\frac{Ir}{r_{max}^2} = 10\,T$$

- Emittance Exchange is based on establishing a correlation between transverse and longitudinal phase space



- Low E μ^+ cooling a low density gas (He) in a ~ 5 MV/m electric field

Cools px, py, and LONG.PHASE SPACE (RIGHT dE/dx SLOPE)



$$\frac{dE}{dx}(200eV) \approx 100\frac{dE}{dx}(200MeV)$$

3D cooling factor ~ 10^7

EXPERIMENT AT COLUMBIA

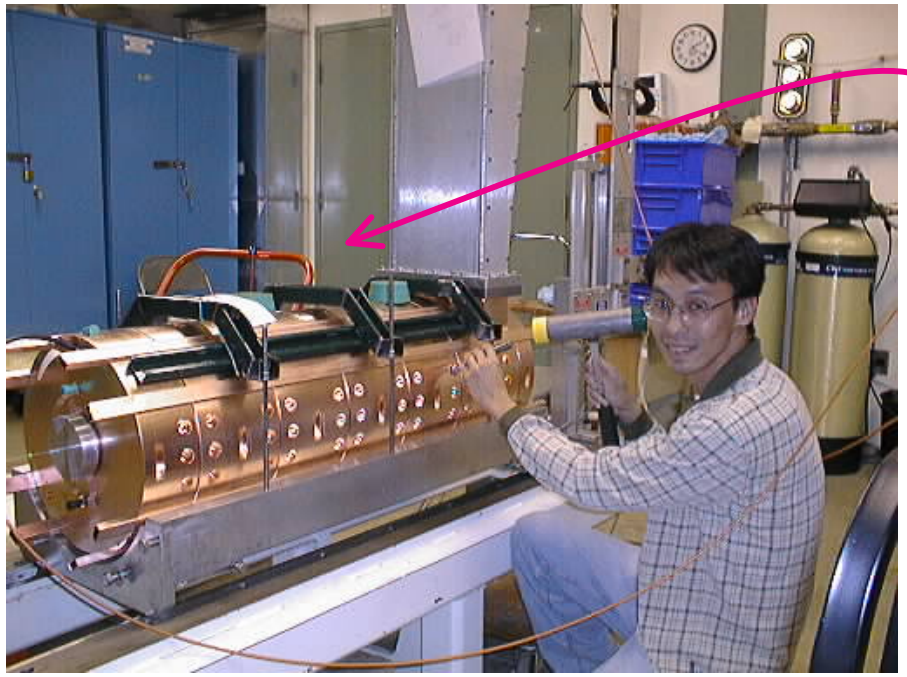
The MuCool Experiment

Design, build and test a cooling device to demonstrate feasibility of the cooling design requirements of the ν factory **ANL, BNL, FNAL, IIT, IU, LBNL, HHMFL, NIU, NWU, Princeton, UC Berkeley, UCLA, UIUC, U Mississippi**

- Test cooling channel components (more or less common to all designs): 5 T solenoid, LH2 absorber, 201 (805) MHz cavities
- Decide on cooling channel design: SFOFO, Double Flip, Ring Cooler, anything else? (In ~ 2 years)
- Build and test a cooling cell followed by a second prototype iteration (In ~ 4 years)
- "String" experiment
- Test beam, and channel experiment

Time scale ~ 10 years

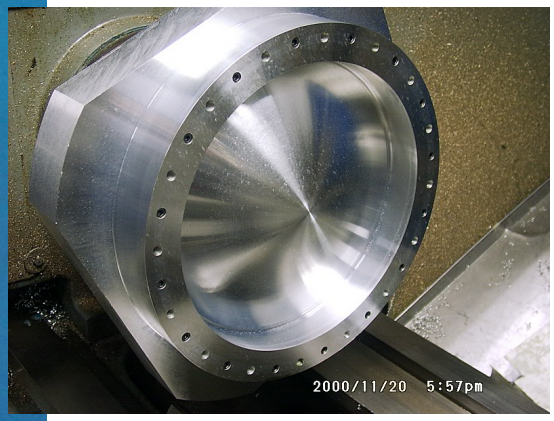
Test area: Lab G



Cavity cell and Be window

- 805 MHz open cavity
  ~ 30 MV/m (Fermilab)
- 201 MHz Be window cavity
  ~ 15 MV/m (Mississippi-BNL)

Be windows → higher gradients (only for μ beams !), r.f. in high B field, multi-pactoring, detector technologies



Absorber Al window

- LH2 abs ~30-40 cm long
- Thin aluminum windows (200-400 μm thick)

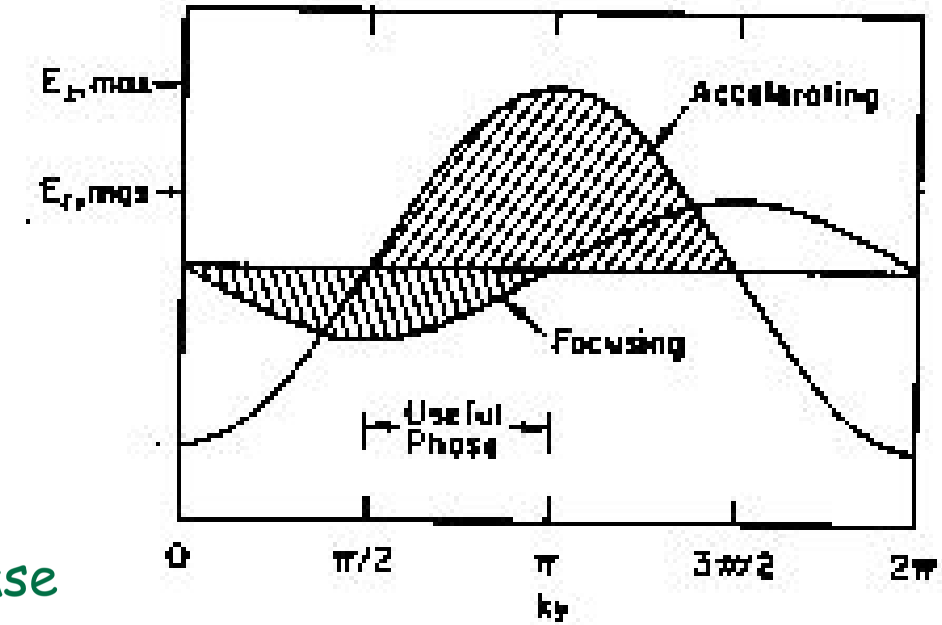
Test absorber inside the magnet, with r.f. & exposed to beam

Accelerator Technology (far future)

Plasma Accelerators

Use a beam driver (PWA) or a laser (LWA) to excite a plasma wave

- longitudinal acceleration
- transverse focusing



~10 GeV/m

Test beam surf-ride on a proper phase of the wave (dashed area)

Crystals Channel Accelerators (for e+)

- strong electrostatic focusing of atomic channels (small emittance in spite of multiple scattering with electrons)
- plasma wave acceleration

10 TeV/m & emittances limited by the uncertainty principle

Physics is Involved in Accelerator Research

- Classical electrodynamics: magnet lenses, resonant cavities, propagation of relativistic charged particles in EM fields, collective effects in high intensity beams,…
- Solid state: beam diagnostic detectors, superconductivity, crystal channels…
- Nuclear and particle physics: nuclear reactions and decay processes at the target and along the channel, multiple scattering
- Plasma: friction cooling at low energies, plasma wave acceleration,….
- Material science: materials have to withstand high, and low temperatures, pressure, EM fields,….

Multidisciplinary field which needs of basic and applied research (theory and experiments)

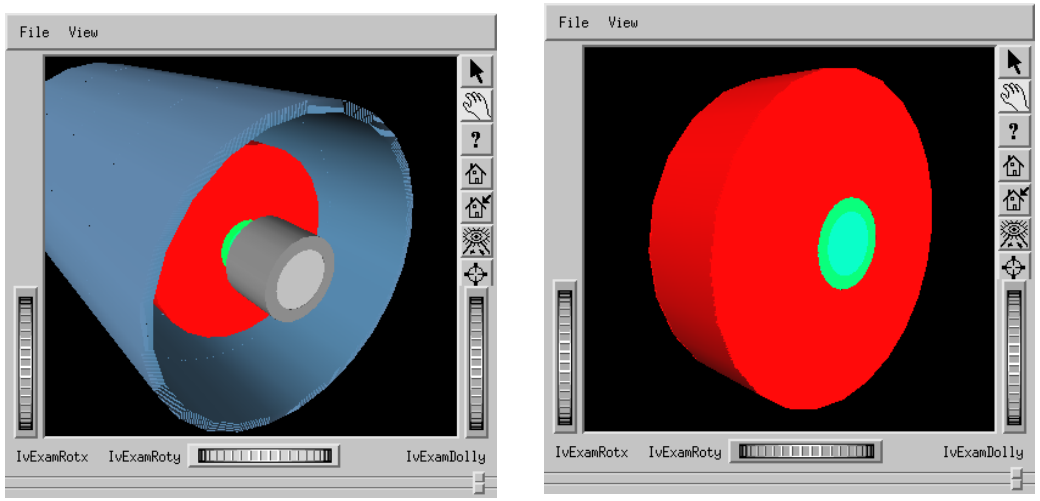
Work Dynamics in a Beam Physics Group

- Concepts (theorists) for example ionization cooling, cooling in a helical field, stochastic cooling, models for collective behavior, plasma acceleration

- Phenomenological Studies (theorists) solving equations for simple systems associated with new physics concepts

- Simulations of realistic accelerator designs (theorists and experimenters) using simple models, accelerator specific packages, HEP tools like GEANT

Simulation of a muon cooling cell and r.f. cavity: computer tools like C++ (programming, GEANT4 (simulation), Open Inventor (visualization), ROOT (analysis)



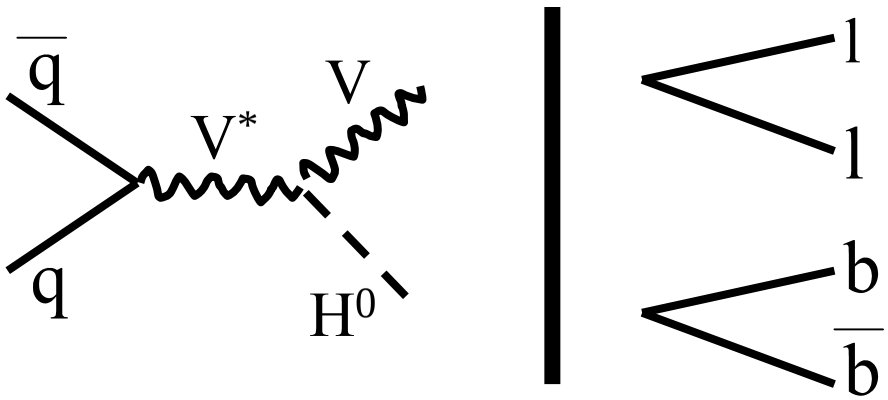
- Experiments like MuCool, NLCTA, FFTB, low ET cooling, targetry
- Machine construction

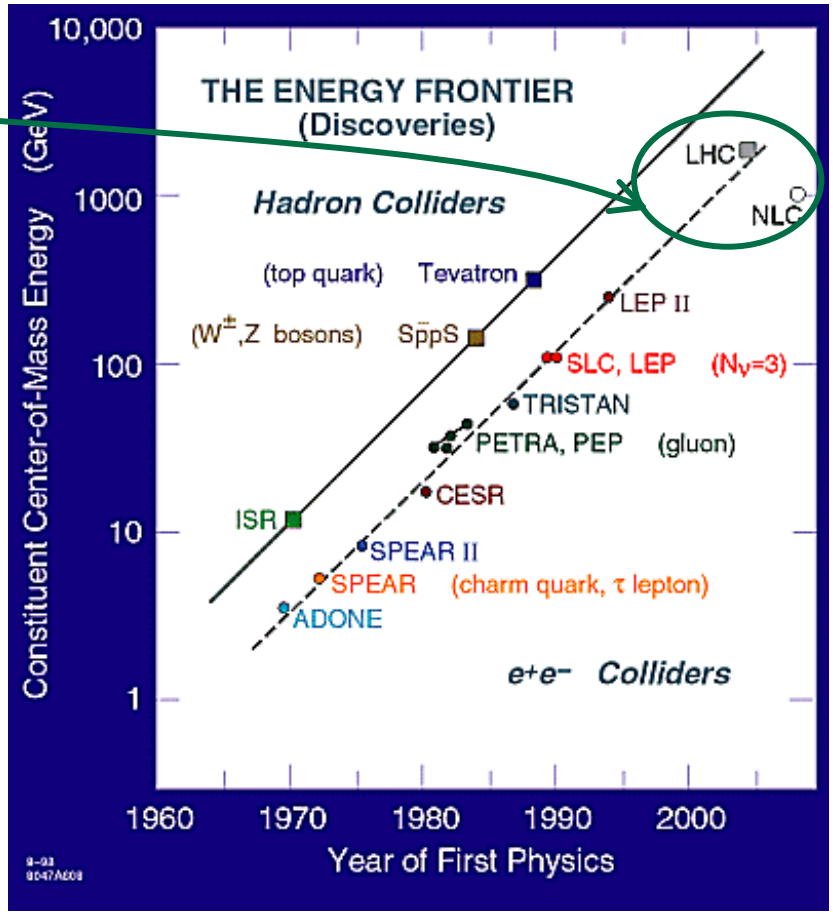
Involves design, construction, data taking and analysis

Summary

- Accelerator research is <u>interesting</u> physics
- Projects are <u>challenging</u>, their resolution <u>necessary</u>:

  We desperately need a breakthrough
- It is as much fun, as much physics, and as much important to contribute to the accelerators as it is to the particle detectors





- More beam/particle physicists interaction is necessary
  We have the skills to make a contribution

Physics Nobel Prizes related to accelerator or detector research

1939-Lawrence, Ernest Orlando, U.S.A.: cyclotron

1948-Blackett, Patrick M. S., Lord, Great Britain: cloud chamber

1950-Powell, Cecil F., Great Britain: photographic emulsions

1951-Cockcroft, John D., Sir, Great Britain, Walton, Ernest T. S., Ireland: Cockroft-Walton accelerator

1958-Cherenkov, Pavel Alekseyevich; Frank, Ilya Mikhailovich; Tamm, Igor Yevgenyevich, USSR: Cherenkov effect

1960-Glaser, Donald A., U.S.A.: bubble chamber

1968-Alvarez, Luis W., U.S.A.,: hydrogen bubble chamber

1984-Rubbia, Carlo , Italy;Van Der Meer, Simon, the Netherlands: colliding beams idea, W and Z discovery