IONIZATION COOLING FOR MUON COLLIDERS

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18 Sep 98

CERN

FORMAT OF TALK

- BRIEF OVERVIEW OF MUON COLLIDE
- Theory of Ionization Cooling
    - Emittances
    - Solenoids/RF
    - Cooling Channel current status
- Ionization Cooling R/D proposal
    - Current Status

A Brief History

- Old idea ... Muon colliders mentioned by Tinlow(1960), Budker(1969), Skrinsky(1971), Neuffer(1979).
- A key concept for a high luminosity muon collider is ionization cooling: Skrinsky & Parkhomchuk (1981).
- The realization that a high luminosity muon collider might be feasible (Neuffer & Palmer) resulted in a series of workshops. After the Sausalito workshop in 1995, Fermilab and BNL joined in an effort to study the concept and publish a report. The collaboration grew -> Muon Collider Collaboration: 19 institutions and ~ 100 physicists.
- -> $\mu^+\mu^-$ Collider: A Feasibility Study, Snowmass (1996); Fermilab-Conf-96/092 -> feasibility of a 2 x 2 TeV Collider.
- Although many questions were left open in the Snowmass report, no show stoppers were identified .... and the muon collider collaboration has therefore continued to develope the study.
- The goal for the next 12 – 18 months is to produce a report on the feasibility of the First Muon Collder (center-of-mass energy 100 – 400 GeV)

Motivation

- Current theoretical prejudice suggests there is new physics to be discovered at or approaching the TeV energy scale.

- If this is so, then sooner or later we will want a multi–TeV lepton collider to make precision measurements of new high–energy phenomena -> multi–TeV muon collider.

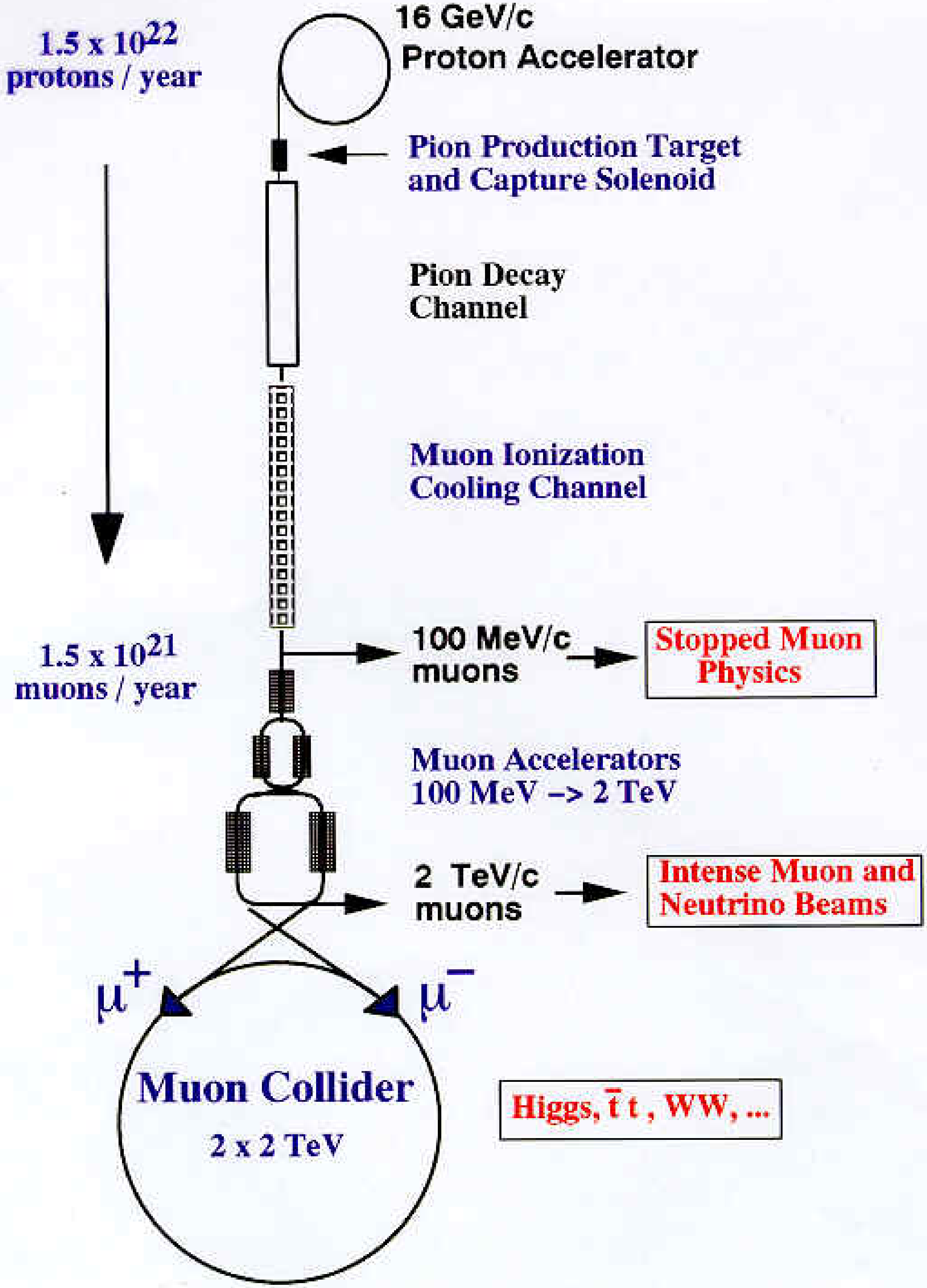
- If feasible, muon colliders have several attractive features ... which are a consequence of the large muon mass ($m_\mu/m_e = 207$)

  - Muons don't radiate as readily as electrons ->

    - Much smaller beam energy spread ($\Delta p/p \sim 0.003$ %) -> precise energy scans and hence precise mass and width measurements.

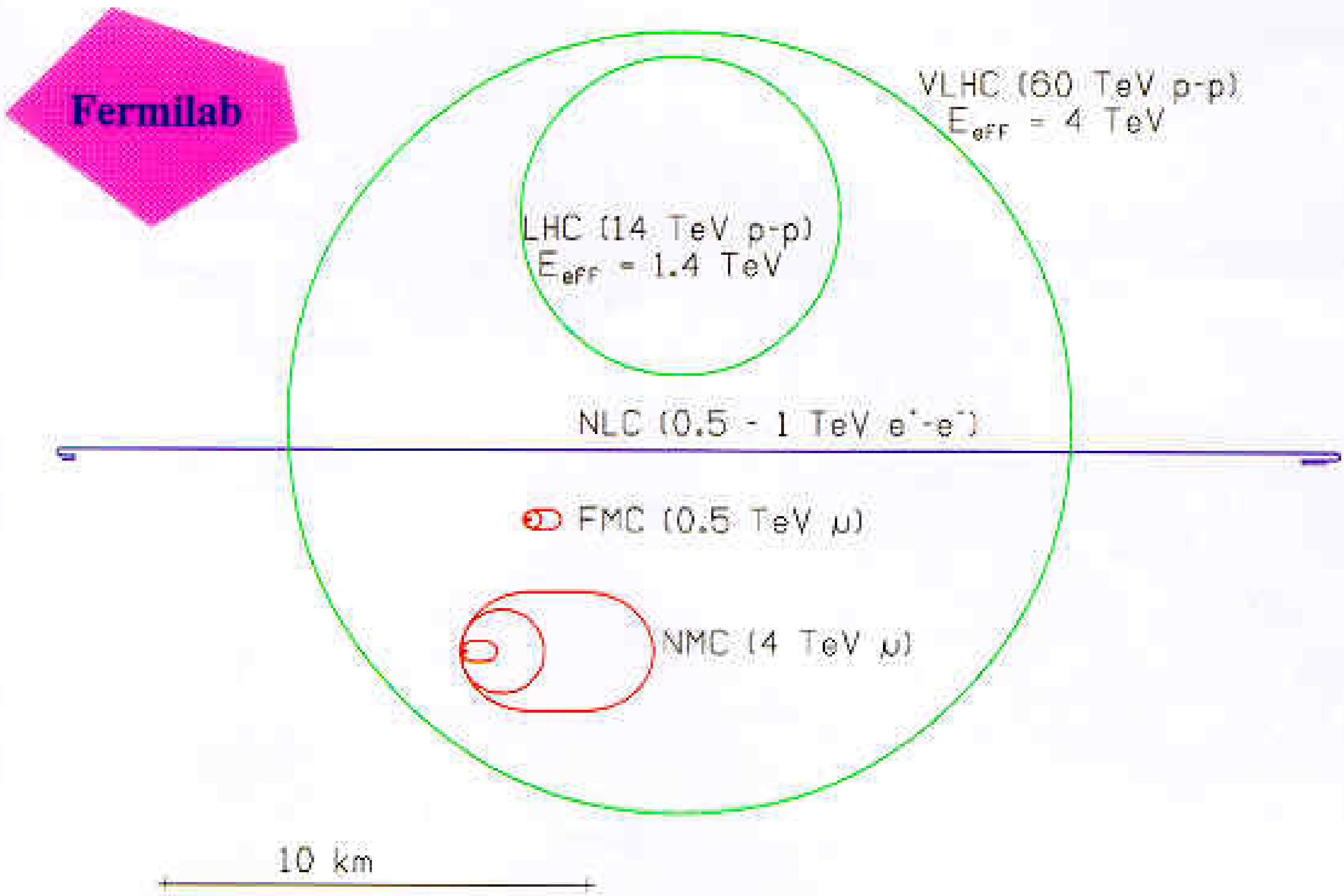
    - Easier to accelerate muons to higher energies -> ultimately much higher energy (multi–TeV) lepton collider possible.

  - Larger coupling to Higgs–like particles -> if $m_h < 2\, m_W$, possibile to study Higgs boson production in the s–channel !


16 GeV/c
Proton Accelerator
1.5 x 10^22
protons / year
Pion Production Target
and Capture Solenoid
Pion Decay
Channel
Muon Ionization
Cooling Channel
1.5 x 10^21
muons / year
100 MeV/c
muons
Stopped Muon
Physics
Muon Accelerators
100 MeV -> 2 TeV
2 TeV/c
muons
Intense Muon and
Neutrino Beams
μ+
μ−
Muon Collider
2 x 2 TeV
Higgs, t̄ t , WW, ...

Muon Colliders can be made very compact

- For example, at least 2 generations of collider would fit on the Fermilab Site:



- A good reason to suspect that if feasible a muon collider will be significantly cheaper than alternative futuristic high energy colliders.

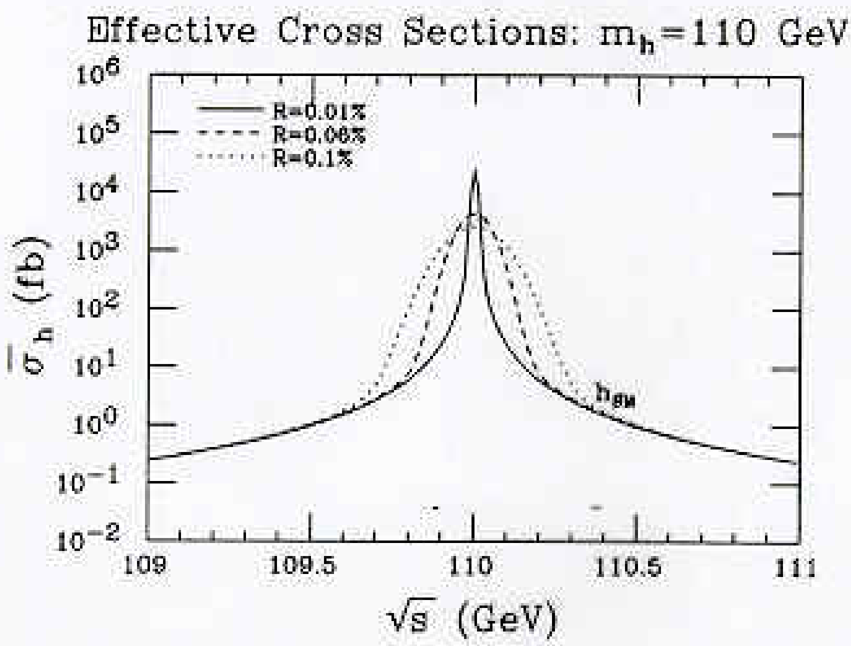
- Most cost in "Front End" ⇒ Proton driver + Cooling

  So can be effectively a search engine 0.5 TeV → 4 TeV in CMS

Light Higgs Resonance Profile

Convolve σ_h with Gaussian spread

$$\bar{\sigma}_h\left(\sqrt{s}\right) = \int \sigma_h\left(\sqrt{\hat{s}}\right) \frac{\exp\left[-\left(\sqrt{\hat{s}}-\sqrt{s}\right)^2\right] d\sqrt{\hat{s}}}{\sqrt{2\pi}\,\sigma_{\sqrt{s}}}$$



Need resolution $\sigma_{\sqrt{s}} \sim \Gamma_h$ to be sensitive to the Higgs width

Light Higgs width

J.G
V.B

$80 \leq m_h \leq 120$ GeV

$\Gamma_h \approx 2$ to 3 MeV if $\tan\beta \sim 1.8$

$\Gamma_h \approx 2$ to 800 MeV if $\tan\beta \sim 20$

→ width sensitive to $\tan\beta$

L [illegible]

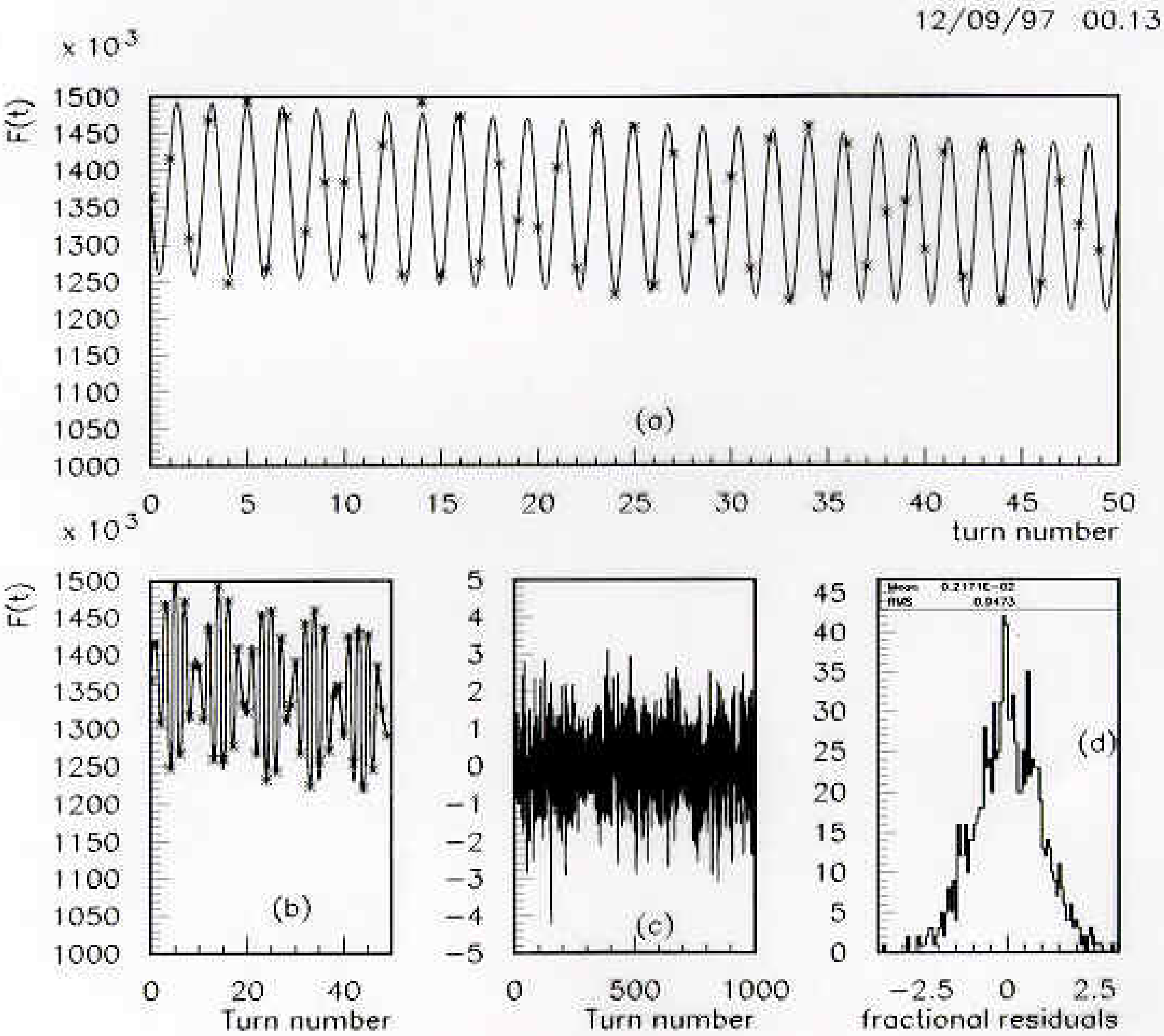
$\frac{h \to WW^*}{h \to b\bar{b}}$; $\frac{h \to c\bar{c}}{h \to b\bar{b}}$; $\frac{h \to WW^*}{h \to \tau\tau}$ $\frac{h \to c\bar{c}}{h \to \tau\tau}$

$> 2\sigma$ deviation from SM predictions

$\Longrightarrow m_{A^0} < 400$ GeV

R. Raja, A. Tollestrup PRD 58 (98) July 1st

Fit to 50 GeV μ^-, P=0.26 $\delta p/p$=0.03E-2



The MUCOOL Collaboration

Fermi National Laboratory
Rockefeller University
Jefferson Laboratory, Newport News, VA
Lawrence Berkeley National Laboratory
Univ. of California Los Angeles
University of Mississippi
Brookhaven National Laboratory
KEK High Energy Research Organization, Japan
Argonne National Laboratory
Princeton University
University of Iowa
Budker Institute of Nuclear Physics, Novosibirsk
Fairfield University
Univ. of California Berkeley
Indiana University

http://www.fnal.gov/projects/muon_collider/cool.html

Cooling R&D: Motivation

- **If a high–luminosity muon collider is to become a reality, we must develop a muon cooling system that can cool the "cloud" of muons coming from a pion decay channel by a factor of $10^5 - 10^6$.**

- **The cooling time must not be long compared to the muon lifetime (2μs) –> new cooling method –> Ionization Cooling** (Skrinsky & Parkhomchuk, 1981).

- **Designing, prototyping and testing the critical components of a muon cooling channel is considered a crucial part of assessing the overall feasibility of building a high luminosity muon collider.**

We propose to conduct a 6 year R&D program to develop and test the critical components needed for a complete ionization cooling channel.

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Emittance Definition

Consider
- Hamiltonian system

i.e no cooling or addition of energy

Then we can define a complete set of 6 variables to describe the motion of a particle as a function of arc length s along the beam

$(x, p_x)\ (y, p_y), (z, p_z)$ or $(x\ p_x), (y\ p_y), (t\ E)$

Conjugate variables

Let us define this set by the vector $X_i\ [i=1,6]$; For an ensemble of particles, define

Define $Y_i \equiv X_i - \langle X_i \rangle$

Then we can define the error matrix

$$E_{ij} = \langle Y_i Y_j \rangle$$ over the ensemble

Then the 6 dimensional Normalized emittance ε_N^6

$$\left(\varepsilon_N^6\right)^2 = \frac{\text{Determinant } E}{(m_\mu c)^6}$$

where m is the mass of particle
c = velocity of light

In a Hamiltonian (conservative) transport system, the vector X' at a later arc length s' is described by a transformation

(Linear system)

$$X' = U X$$

Then

$$E' = U E U^T$$

$$\text{Det } E' = \text{Det } E \quad \text{if} \quad \text{Det } U = 1$$

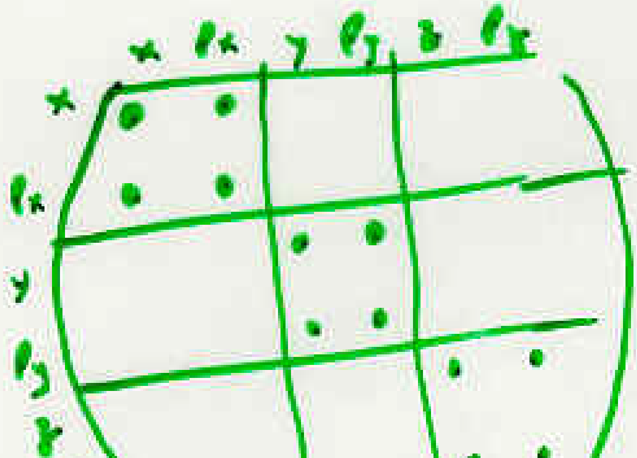
i.e. Emittance is preserved. Liouville's theorem.

"Simplectic transformation"

$E_{ij} \neq 0$ if $i \neq j$; correlations are important.

In the special case when (x, y) (y, z) & $(x\, z)$ correlations are absent, E is block diagonal

E :



Then $\left(\varepsilon_N^6\right)^2 = \left(\varepsilon_N^x\right)^2 \left(\varepsilon_N^y\right)^2 \left(\varepsilon_N^z\right)^2$

transverse — longitudinal

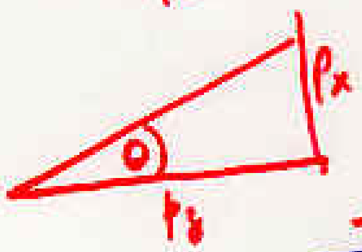
emittances

Consider the expression for ε_N^x; let us assume that $\langle x\rangle = 0$ & $\langle p_x\rangle = 0$ in our co-ordinate system.

Then
$$\left(\varepsilon_N^x\right)^2 = \begin{vmatrix} \langle x^2\rangle & \langle x p_x\rangle \\ \langle x p_x\rangle & \langle p_x^2\rangle \end{vmatrix} \cdot \frac{1}{(m_\mu c)^2}$$

$$= \left\{\langle x^2\rangle\langle p_x^2\rangle - \langle x p_x\rangle^2\right\}\frac{1}{(m_\mu c)^2}$$

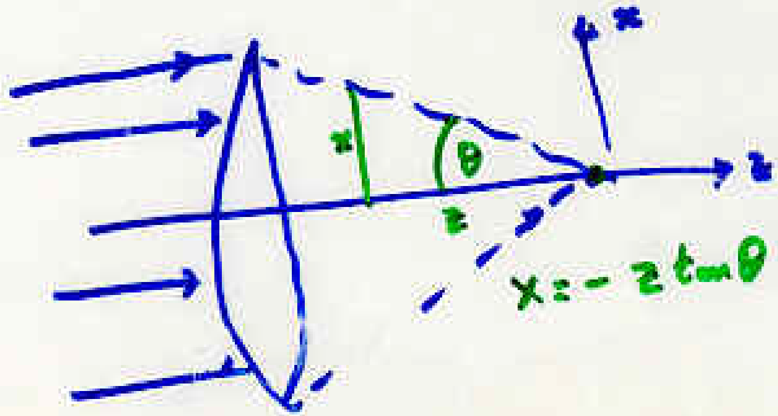
In the approximation $p_z \approx p$ and $p_{x,y} \approx 0$



$$p_x = p_z \tan\theta \approx p\cdot\theta$$

Then
$$\left(\varepsilon_N^x\right)^2 = \left\{\langle x^2\rangle\langle\theta^2\rangle - \langle x\theta\rangle^2\right\}\gamma^2\beta^2$$

ε^x (unnormalized) is without $\gamma\beta$! Factor of π; RMS vs 90%; 95%. ...



$$x = -z\tan\theta \approx -z\theta$$

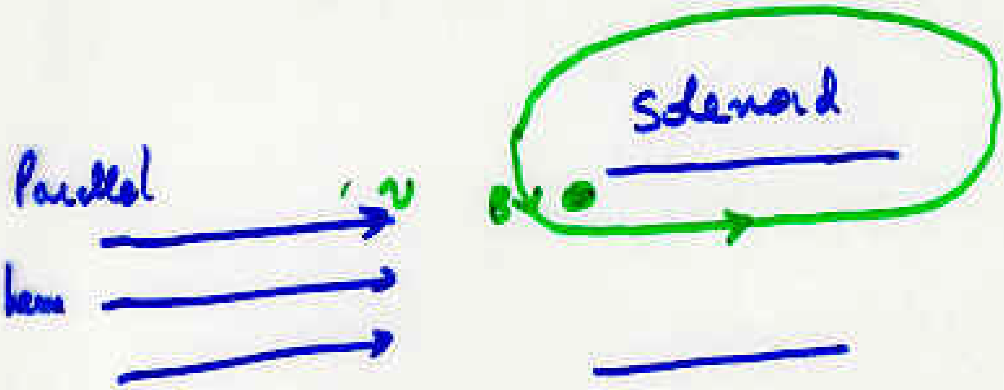
$$\left(\varepsilon_N^x\right)^2 = z^2\gamma^2\beta^2\left\{\langle\theta^2\rangle^2 - \langle\theta^2\rangle^2\right\} = 0$$

for all z.

ε Parallel beam = 0

ε Divergent beam = 0

Solenoids focus!



$\varepsilon_x^N = 0 = \varepsilon_y^N = 0$

Force due to fringe field inb board

Beam Precesses "Larmor" since it is no longer parallel to axis.

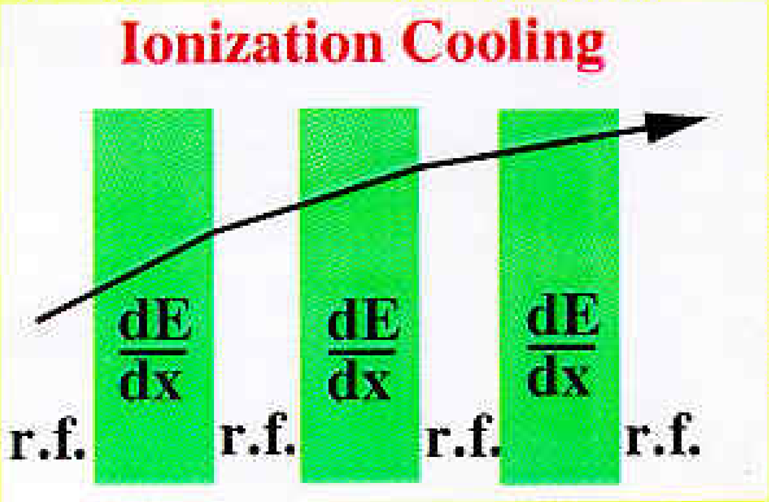
Once it comes out, it must have transverse emittance = 0; So it must focus to a point in the field free region! [or be parallel or be divergent]

Solenoids mix up x & y co-ordinates.
Twisting motion, helical.

focal length of short Solenoid

$$f \approx \frac{4 p^2}{e^2 B^2 L_s}$$

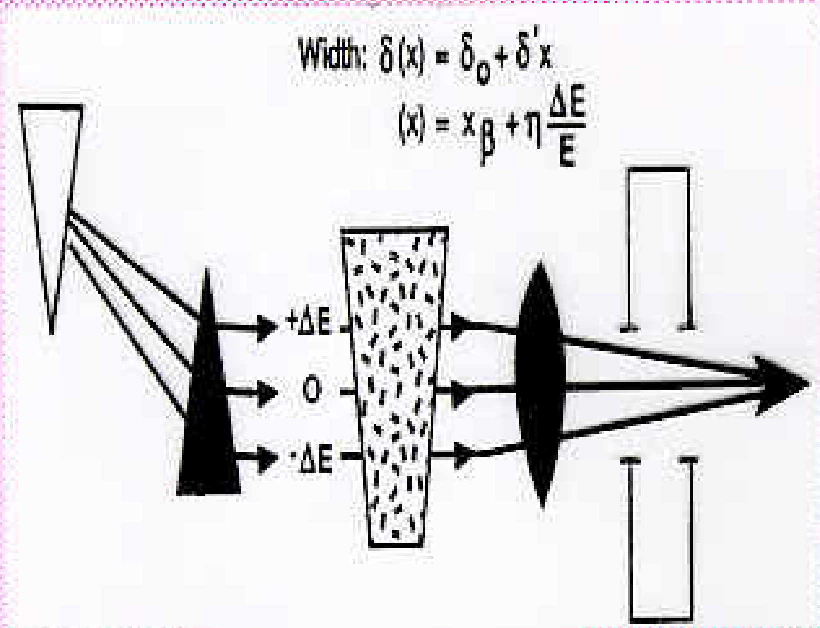
Ionization Cooling



Transverse Cooling

Muons lose energy by dE/dx and long–itudinal momentum replaced by r.f.

- **To Minimize heating from Coulomb Scattering:**
  - ☛ Small $\beta_\perp$ (strong focussing) : High–field solenoids or Lithium Lenses
  - ☛ Large L_R (low–Z absorber) : Liquid H_2



Energy Cooling

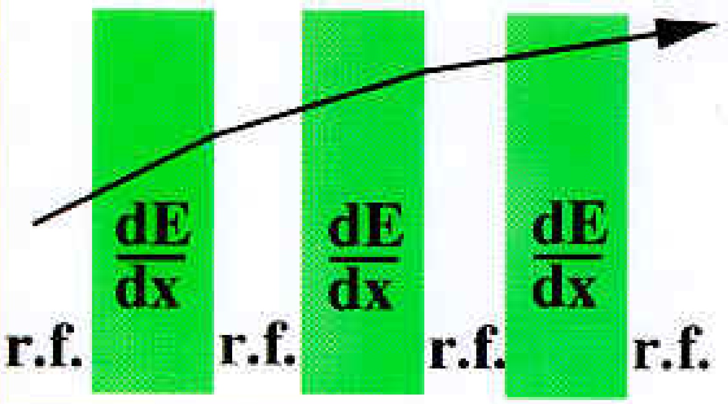
Ionization cooling using a wedge plus dispersion.

Exchanges emitt–ance between transverse & long–itudinal directions

The Cooling System

- Need to reduce the 6–dimensional "beam" phase–space by a factor of ~10^6.

Ionization Cooling



Transverse Cooling

Muons loose energy by dE/dx and long–itudinal momentum replaced by r.f.

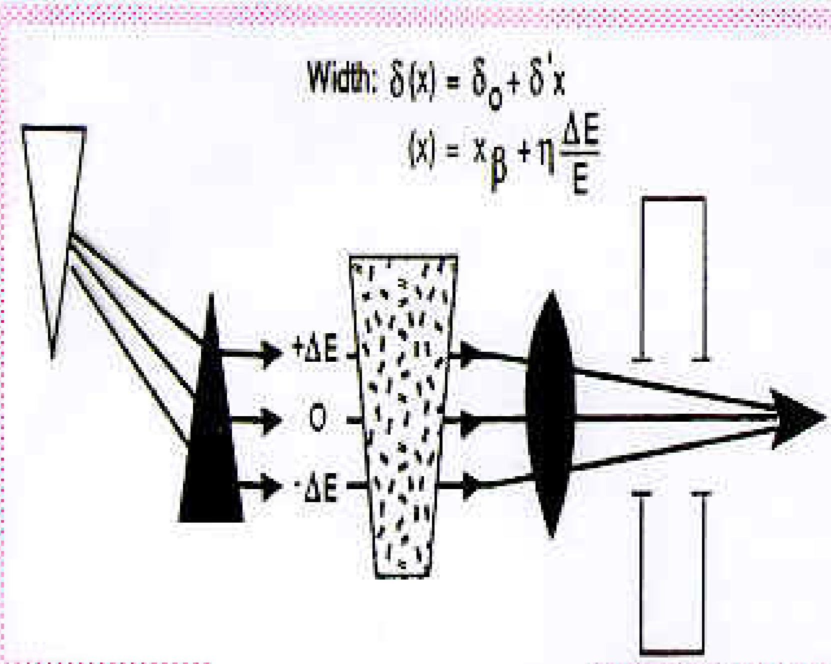
The equation that describes ionization cooling:

$$\frac{d\varepsilon_n}{ds} = -\frac{dE_\mu}{ds}\frac{\varepsilon_n}{E_\mu} + \frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu L_R}$$

coherent cooling | heating due to multiple scattering

- To Minimize the heating term use small $\beta_\perp$ (strong focussing) and large L_R (low–Z absorber).

Longitudinal Cooling



Energy Cooling

Ionization cooling using a wedge plus dispersion.

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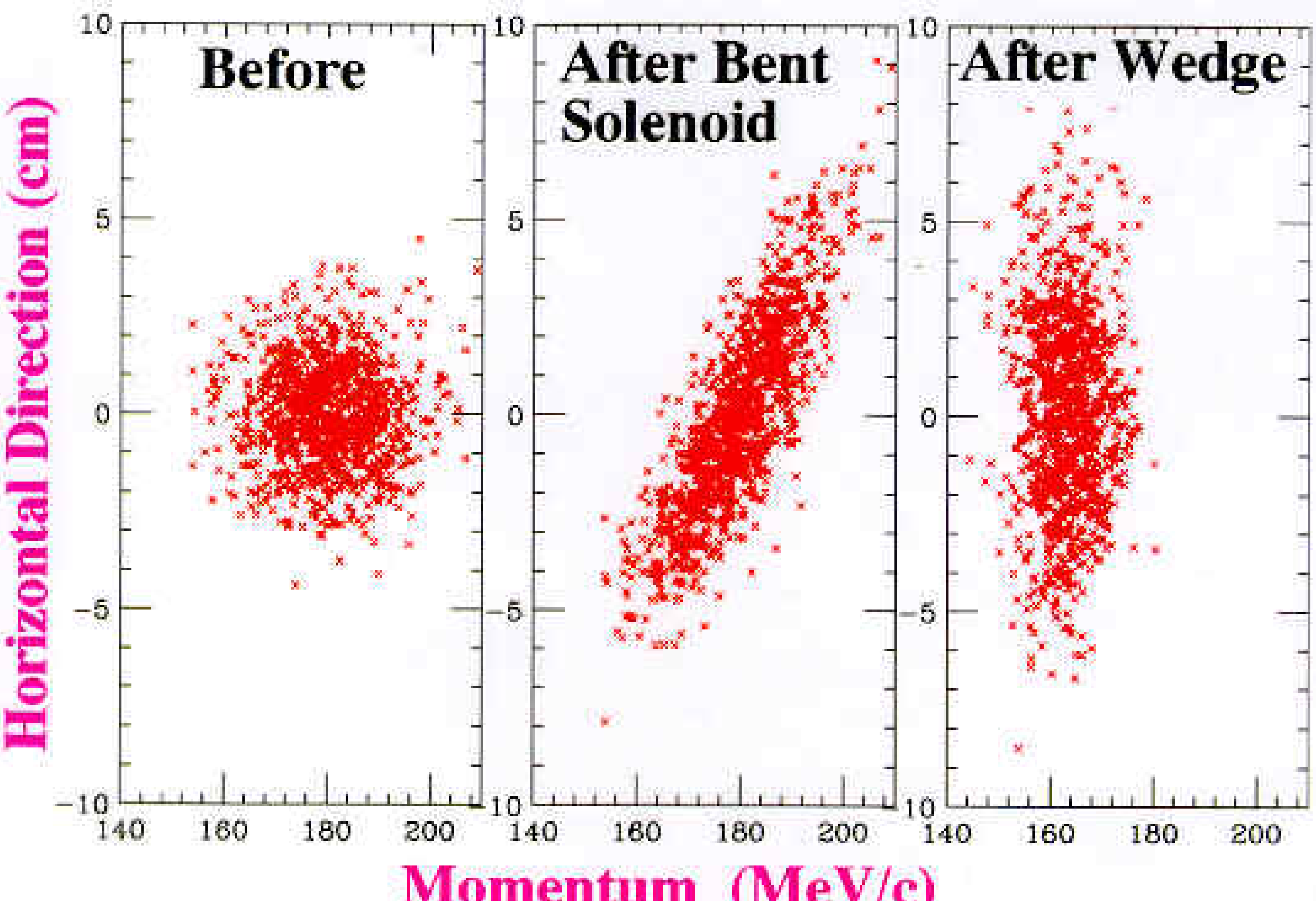
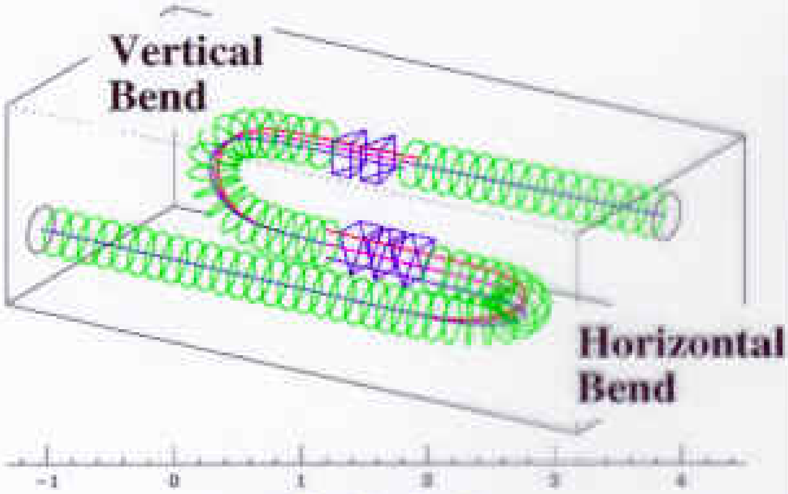


Longitudinal (Wedge) Cooling

Dispersion provided by bent solenoids (curvature drift effect) and momentum spread reduced with liquid H_2 wedges.



At the end of each transverse cooling stage we need a device to reduce the longitudinal emiitance

- Concept exists, initial simulations encouraging. More detailed work in progress.
- Expect to be ready for a detailed design in 2000.
- Estimate 2 years for construction -> beam test in 2003.

Lithium Lens R&D

At the end of the cooling channel, when emitances are small, to continue cooling we require the maximum radial focussing. This could be provided by long (~1m) liquid lithium lenses.

To minimize the final emittances, the maximum radial focussing (surface fields) are needed. It is hoped to raise the surface field to ~ 20 T.

With a muon collider repetition rate of 15 Hz the thermal load would melt a solid lens -> need a liquid lithium lens.

To minimize the absorber-absorber transitions require long (~1m) lenses.

- Short (15cm) liquid lithium lens being developed for antiproton source (FNAL-BINP)
- Need to extend this R&D
- Anticipate first ~1m long lens could be ready for testing in 2001, and a lens-rf-lens system ready for testing in 2003

Cooling Theory

$$\frac{d\varepsilon_x^N}{dz} = \varepsilon_x \frac{d(\beta\gamma)}{dz} + \beta\gamma \frac{d\varepsilon_x}{dz}$$

Cooling term — Heating term

$$\frac{d\varepsilon_x^N}{dz}(\text{cool}) = -\frac{1}{\beta^2}\frac{\varepsilon_x^N}{E}\left|\frac{dE}{dz}\right| \Leftarrow \frac{1}{p}\frac{dp}{dz} = \frac{1}{\beta^2}\frac{1}{E}\frac{dE}{dz}$$

$$\frac{d\varepsilon_x^N}{dz}(\text{heat}) = \frac{\beta\gamma}{2\varepsilon_x}\left[\langle x^2\rangle \frac{d}{dz}\langle\theta^2\rangle + \langle\theta^2\rangle\frac{d}{dz}\langle x^2\rangle - 2\langle x\theta\rangle\frac{d}{dz}\langle x\theta\rangle\right]$$

Assume cooling takes place near a waist; neglect correlations in beam parameters. If focusing is strong, then growth in transverse size is negligible. This will be the case [Fernow & Gallardo]

(a) $\sigma_{x0}^2 \gg \frac{\theta_c^2 L}{2w^2}$; L is length of absorber, w is focusing strength m^{-1}, σ_{x0} is size of beam c. (?) absorber.

$\sigma_{x0}^2 \gg \frac{\theta_c^2}{4w^3}$

θ_c^2 [m^{-1}]; $\theta_c = \frac{E_s}{p c \beta}\frac{1}{\sqrt{L_R}}$; $E_s = 15$ MeV; L_R = rad. length.

$$\frac{d\varepsilon_x^N}{dz}(\text{heat}) \approx \frac{\beta\gamma}{2\varepsilon_x}\langle x^2\rangle \frac{d}{dz}\langle\theta^2\rangle$$

$\langle x^2\rangle = \beta_\perp \varepsilon_x$ where $\beta_\perp$ is the β function.

$$\frac{d\varepsilon_x^N}{dz}(\text{heat}) \approx \beta\gamma\frac{\beta_\perp}{2}\underbrace{\frac{d}{dz}\langle\theta^2\rangle}_{\text{Multiple scattering}}$$

$$\frac{d\varepsilon_x^N}{dz}(\text{heat}) \approx \frac{\beta_\perp}{2}\frac{E_s^2}{E\, mc^2}\frac{1}{L_R}$$

Heating & cooling will be equal when

$$\varepsilon_{x\,\text{minimum}}^N \approx \frac{\beta_\perp E_s^2}{2\beta\, mc^2 L_R \left|\frac{dE}{dz}\right|}$$

$$\frac{d\varepsilon^N}{dz} = \underbrace{-\frac{1}{\beta^2}\frac{\varepsilon^N}{E}\left|\frac{dE}{dz}\right|}_{\text{Cool}} + \underbrace{\frac{\beta_\perp (0.014)^2}{2\beta^3 E m_\mu L_R}}_{\text{HEAT}}$$

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Longitudinal emittance

$$\varepsilon_L^{N\,2} = \frac{1}{m_\mu^2 c^2} \begin{pmatrix} \langle c^2 \Delta t^2 \rangle & 0 \\ 0 & \langle \Delta E^2 \rangle \end{pmatrix} \quad \text{or} \quad \frac{1}{m_\mu^2 c^2} \begin{pmatrix} \langle \delta z^2 \rangle & 0 \\ 0 & \langle \delta p_\delta^2 \rangle \end{pmatrix}$$

$\Downarrow$ $\qquad\qquad$ $\downarrow$

$$\frac{p_\delta^2}{m_\mu^2 c^2} \frac{\delta p_\delta^2}{p_\delta^2} \cdot \sigma_z^2$$

$$\varepsilon_L^{N\,2} = c^2 \Delta t^2 \alpha^2 \gamma^2 ; \quad \alpha = \frac{\Delta E}{E}$$

$$\gamma^2 \beta_\delta^2 \alpha^2 \sigma_z^2 ; \quad \boxed{\alpha = \frac{\delta p_\delta}{p_\delta}}$$

$$\varepsilon_L^N = c \Delta t \cdot \alpha \cdot \gamma$$

$$\therefore \varepsilon_L^N = \gamma \beta_\delta \alpha \sigma_z$$

$$= \frac{\Delta E \ \Delta t}{m_\mu c}$$

RF Acceleration does not change ΔE or Δt; so longitudinal emittance is preserved by RF.

Straggling increases ΔE; so longitudinal emittance grows as transverse cooling takes place.

$\alpha \Delta t$

Emittance exchange

Longitudinal emittance change in absorber

$$\varepsilon_L^N = \gamma \beta_t \alpha \sigma_z \qquad \alpha = \frac{\sigma_{p_z}}{p_z}$$

$$\frac{d\varepsilon_L^N}{dz} = \beta\gamma\alpha \frac{d\sigma_z}{dz} + \beta\gamma\sigma_z \frac{d\alpha}{dz} + \alpha\sigma_z \frac{d(\beta\gamma)}{dz}$$

Assume bunch length change is small. $\frac{d\sigma_z}{dz} \approx 0$

Then

$$\frac{d\varepsilon_L^N}{dz} \propto \frac{\beta\gamma\sigma_z}{p_z} \frac{d}{dz} \sigma_{p_z}$$

$$\frac{d}{dz} \sigma_{p_z} = \frac{\sigma_E}{\beta c} \frac{d}{dE}\left(\frac{dE}{dz}\right)$$

Long. cooling is tiny!

Straggling

$$\frac{d}{dz} \sigma_{p_z} = \frac{k_s}{2\beta c \sigma_z} \gamma^2 \left(1 - \tfrac{1}{2}\beta^2\right)$$

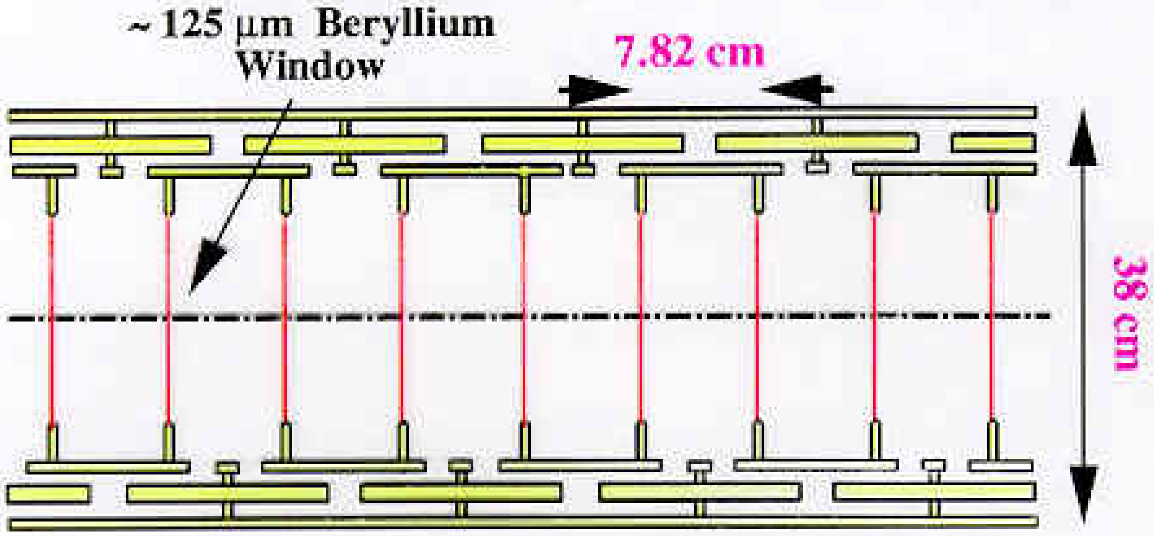
Wedge absorber

$$\frac{d}{dz} \sigma_{p_z} \approx \frac{1}{\beta c} \frac{dE}{dz} \frac{\eta \alpha}{w L_0}$$

where $\eta = \frac{dx}{d\alpha}$; wedge angle $w = \frac{dx}{dz}$ L_0 = Thickness of wedge at $x = 0$
Dispersion

RF Cavities

- **Need the maximum achievable acelerating gradient** –> minimizes length & decay losses.
- Since muons do not interact strongly, can close the aperture in the rf cavity with a thin conductor –> ~ **doubles the accelerating gradient on axis !**



π/2 805 MHz Interleaved Cavity

- Power consumption is an issue .... to ~ halve the power needed, run cavities at liquid N_2 temp.
- **R&D Issues:**
  - Cavity Q, tunability, coupling characteristics at LN_2 temperatures.
  - Be windows: Be properties, mechanical stability.
  - Multipactoring · Presence of Be windows might give rise to electron discharge with resonant feedback
  - Maximum accelerating gradient.

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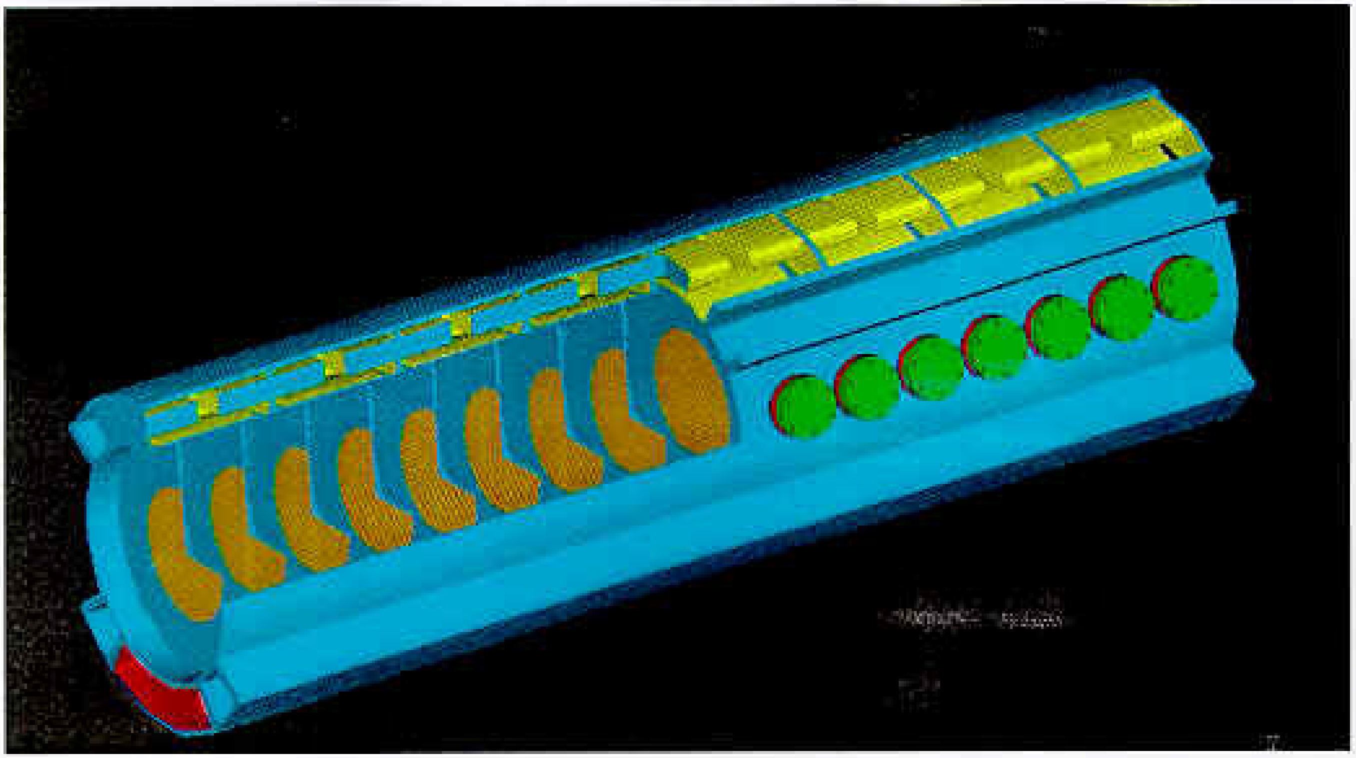
RF Cavity Development

- **Cavity design studies have begun** for a cooling stage towards the end of the Alt. Sol. channel :



- **Cavity parameters:**

RF frequency	805 MHz
Cell length	7.82 cm
Aperture	16 cm
Outer Radius	19 cm
Q/1000	2 x 22
Peak Axial Gradient	30 MV/m
Shunt Impedance	2 x 54 MΩ/m
Z_t^2	2 x 44 MΩ/m
Fill Time	$3\tau = 26\ \mu s$
RF Peak Power	8.3 MW/m
Av. Power (15 Hz)	3.5 kW/m

RF Cavity Goals and Milestones

- **FY98 (funded):**
  - Study Be props at LN_2 temps (BNL,Miss.)
  - Prototype & test Be windows (FNAL)
  - Design 3–cell low power test cavity (LBL)
  - Design 5T solenoid for cavity tests (LBL)
- **FY99:**
  - Construct 3 cell low power test module -> Test at LBL early 1999.
  - Construct 3 cell high power test cavity
- **Early FY2000:**
  - High–power tests at FNAL. Will need a **High Power Cavity Test Setup ...**
  - Shielded x–ray cave (12 x 40) ft^2 x 7.5 ft
  - (Candidate Location: Tagged Photon Lab)

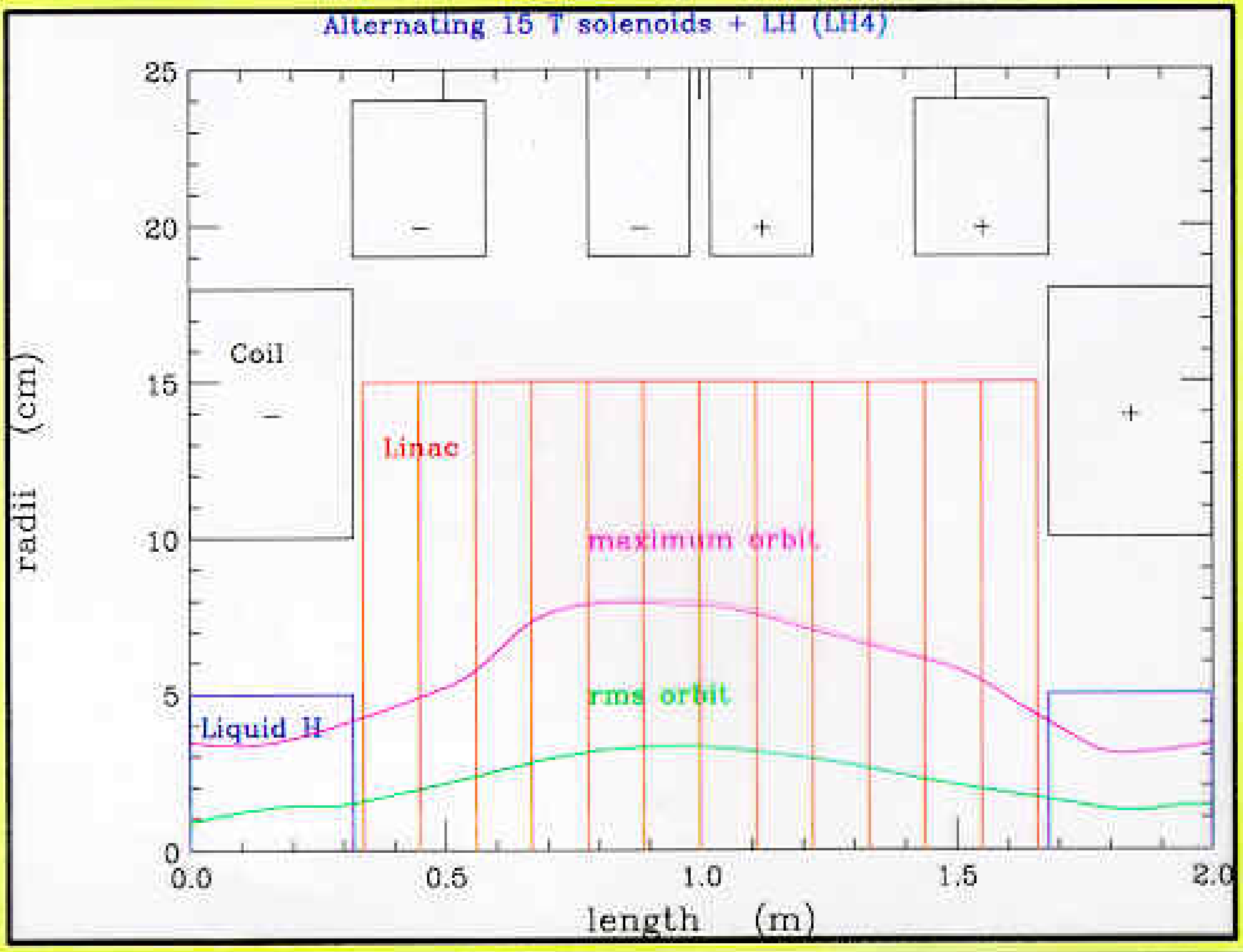
GOAL: In 2 years (Spring 2000) will be ready to begin fabricating the first full 1.3m long RF module for the first 2m long ionization cooling test section.

Alternating Solenoid Transverse Cooling Development

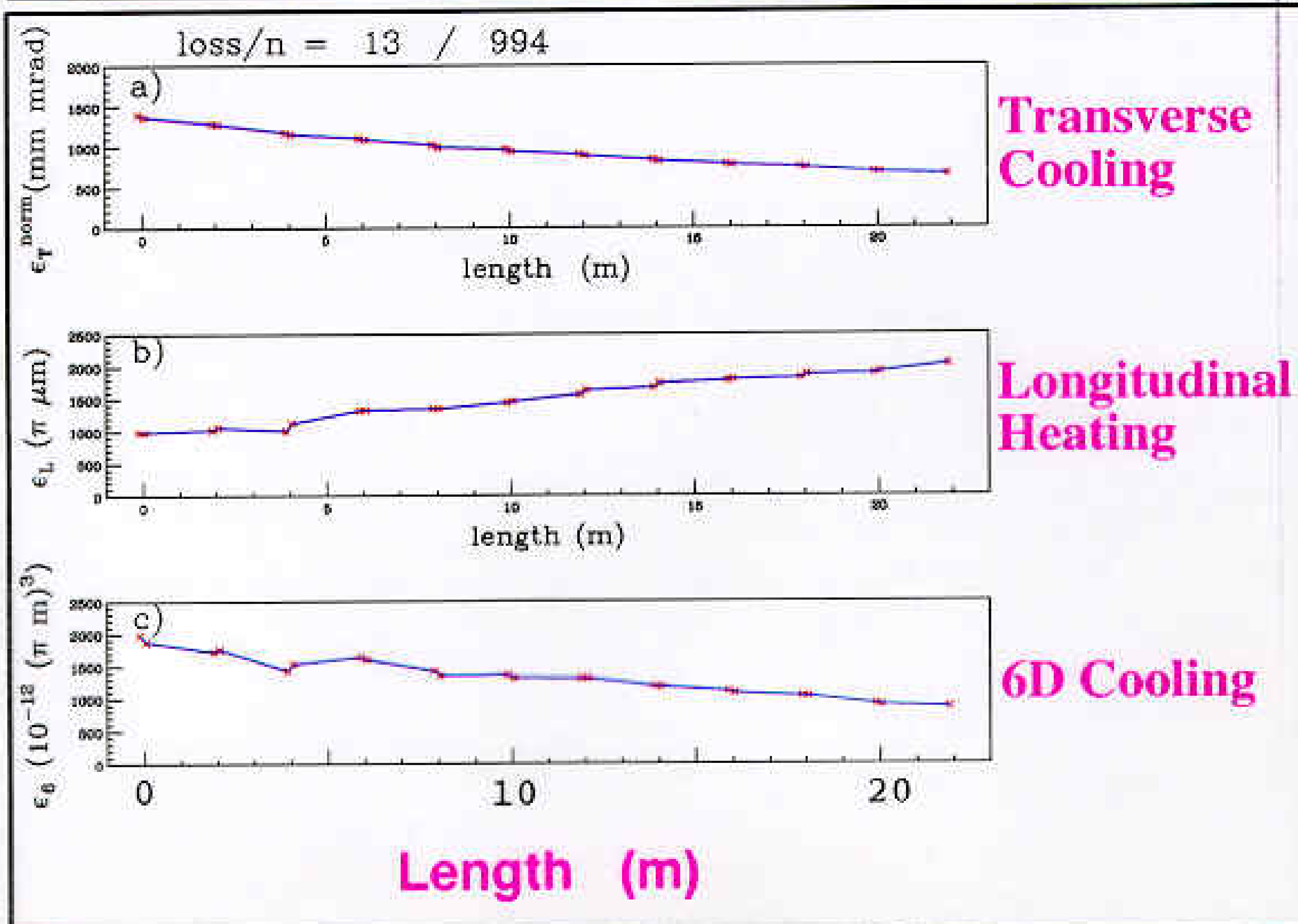
PLAN: Initially construct and test a 2m section (one period) of a transverse cooling channel for a stage towards the end of the alt. sol. channel. Then construct and test a 10m section (half a cooling stage).

One 2m Section of a Transverse Cooling Stage

- Long axial solenoids with alternating field directions.
- Liquid Hydrogen absorbers within the solenoids.
- RF modules between the high field solenoids



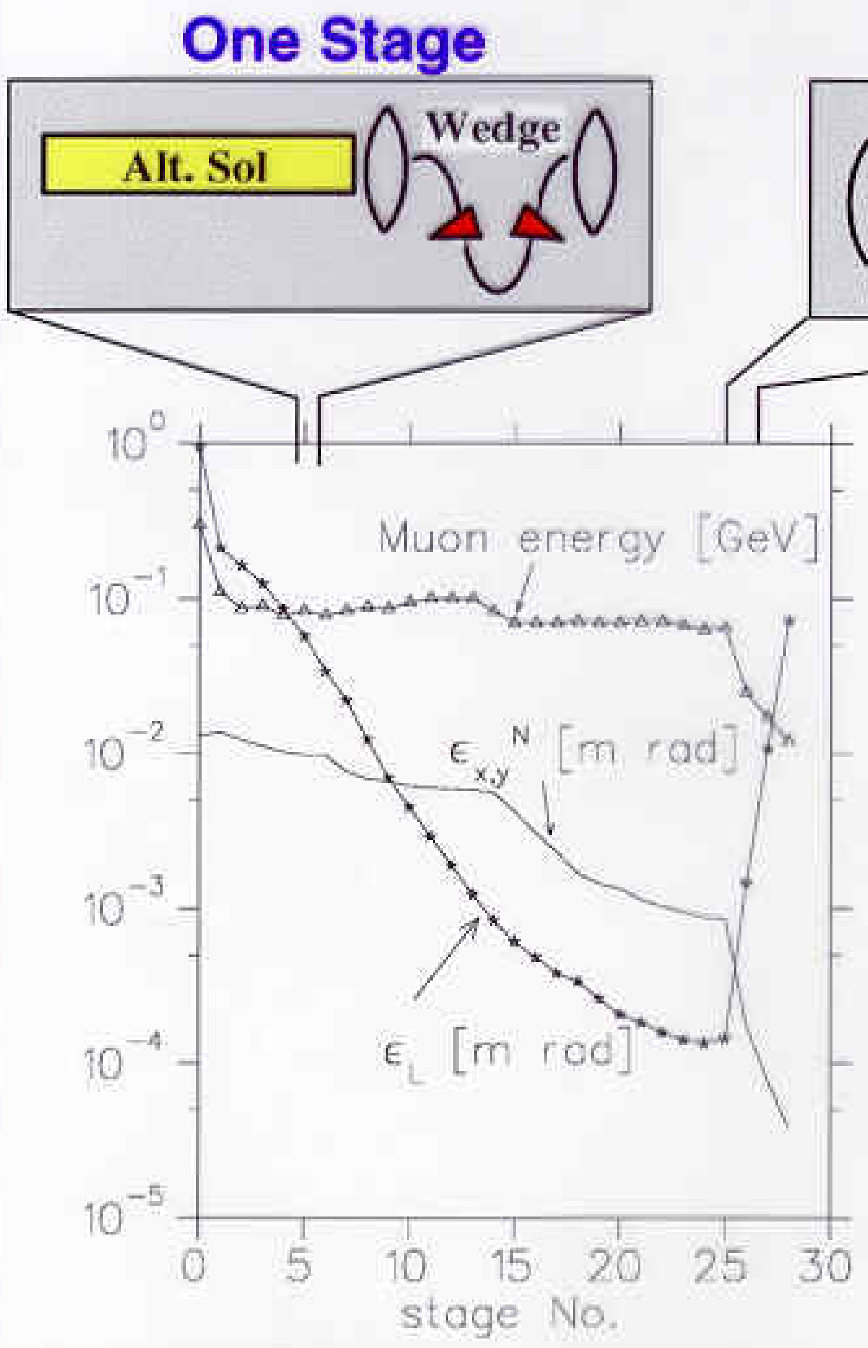
Alternating Solenoid Cooling Stage: Simulation Results



- Single stage gives factor of 2 reduction in 6D phase–space.
- 20 stages required for factor 10^6 ··· length ~ 500m.
- Total cooling channel acceleration = 6 GeV
- Fraction of muons surviving ~ 60%

Ionization Cooling Channel

- A complete cooling channel for a high luminosity muon collider would consist of ~20–30 cooling stages, each ~20m long and each reducing the 6–dimensional phase space by a factor of ~2.



NEED:

- Special RF Modules
- Alternating Solenoid Trans–verse Cooling Stages
- Wedge Cooling Stages
- Lithium Lenses

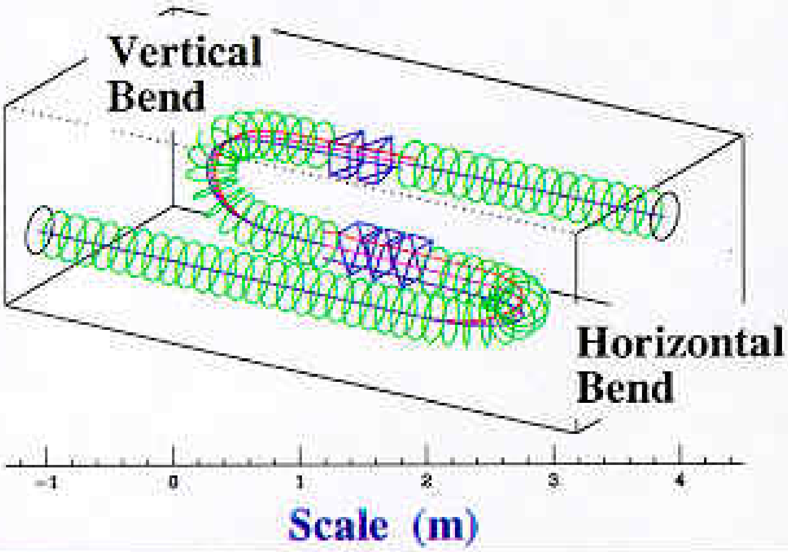
Alt. Sol. Channel: Goals and Milestones

- **FY99:** Design cooling test channel
- **FY00:** Fabricate 2m section
- **FY01:** Bench test 2m section
  Beam test 2m section
  Begin production for 10m section
- **FY02:** Finish 10m construction
  Bench test 10m section
- **FY03:** Beam test 10m section

GOALS: By the end of 2001 to have operated the first 2m long ionization cooling test section in a muon beam, and by the end of 2003 to have measured the performance of a 10m section.

Longitudinal (Wedge) Cooling

Dispersion provided by bent solenoids (curvature drift effect) and momentum spread reduced with liquid H_2 wedges.



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- Short (15cm) liquid lithium lens being developed for antiproton source (FNAL–BINP)
- Need to extend this R&D
- Anticipate first ~1m long lens could be ready for testing in 2001, and a lens–rf–lens system ready for testing in 2003

Ionization Cooling Test Facility

- Need an ionization cooling test facility:
  Muon Beamline + **Exptl Area** + **Instrumentation**

- Propose to measure effect of cooling hardware on individual muons. Would measure the input and output positions of the muons in 6–dimensional phase–space sufficiently well to:

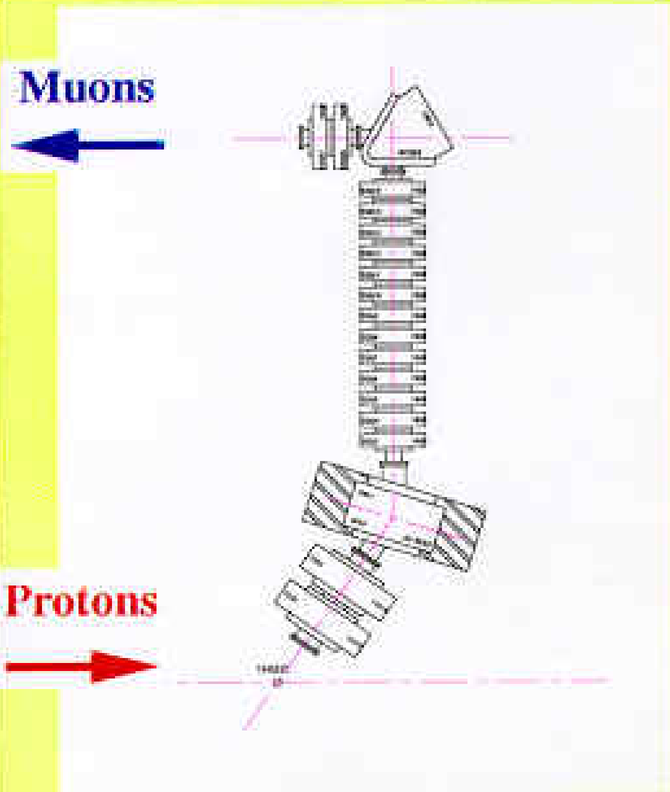
  - Select a population of incident muons corres–ponding to the "ideal bunch".
  - Demonstrate cooling capability of prototypes.
  - Test the cooling calculations (design tools).
  - Study optimization of cooling channel.

Would like to:

- Measure the phase–space volume occupied by the input and output muon populations with a precision of a few %.

- Measure the non–decay loss of muons (~ 1%) with a precision of 10% –> 10,000 muons per measurement within the acceptance of the cooling setup.

Low Energy Muon Beam



Existing low energy muon beamlines consist of a proton source, pion production target, and large aperture quadrupole decay channel with big bends to supress backgrounds.

Need :

- P_{beam} = 100 – 300 MeV/c
- $\Delta P/P \sim 5\%$
- Purity > 99% after tagging
- $\varepsilon_{\perp} \sim 1500\,\pi$ mm–mrad

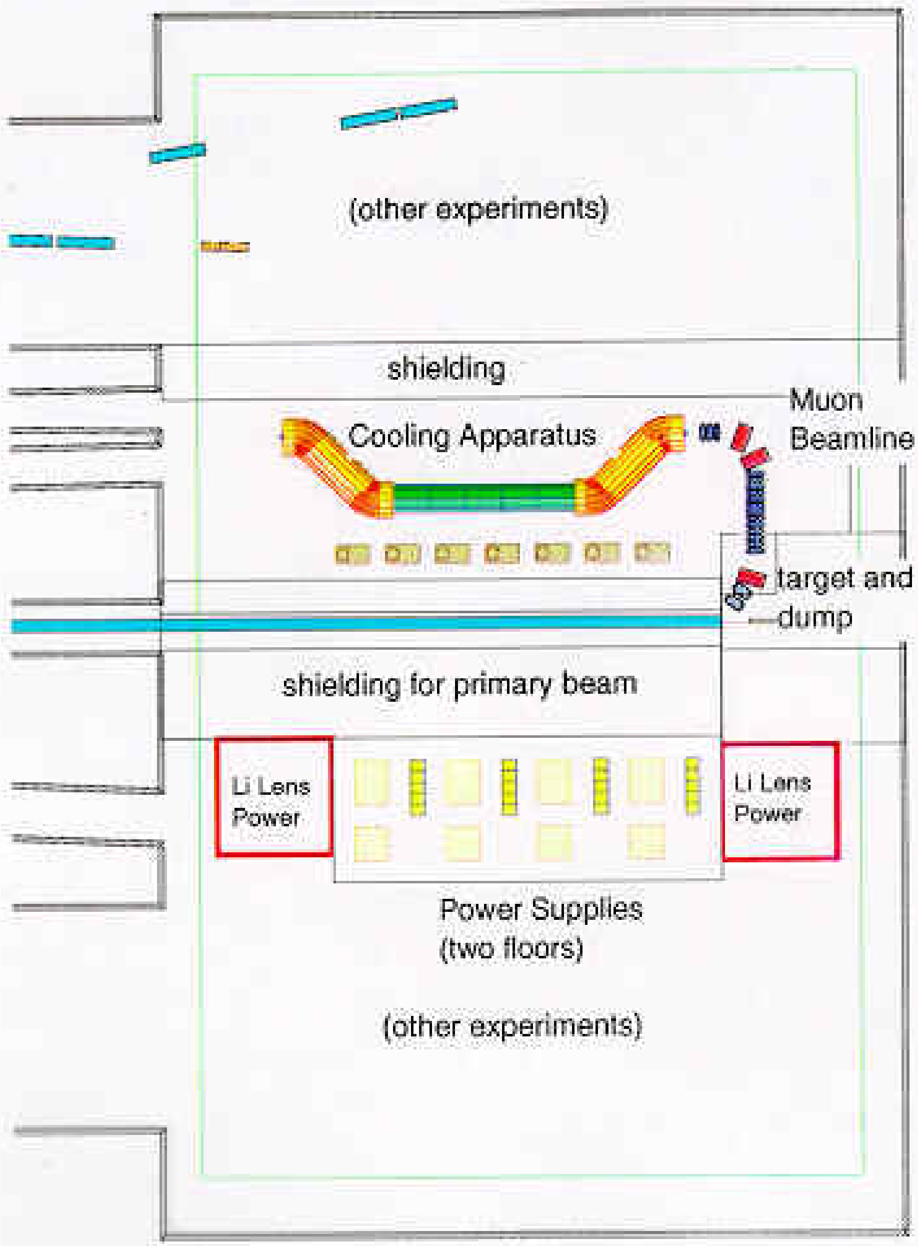
Primary beam requirements & Muon rates.

Initial beam study for 187 MeV/c muon beam:

	MI	Booster
Proton Energy (GeV)	120	8
Protons / spill	5×10^{12}	1×10^{11}
Cu. target length	$1.5\,\lambda$	$0.02\,\lambda$
Muons captured / proton	8.9×10^{-9}	7.9×10^{-12}
Muons / 6μs interval	0.27	0.79
f_{RF}	$2.5 \times 10^{-5(*)}$	0.05
Useful Av. muon rate	0.4 Hz	0.2 Hz

*) More optimal scenario using a ping beam structure under study.

Muon Cooling Beam Test Facility Layout



Example: The MCenter Beamline in the Meson Hall.

Time Measurement

11 cell acceleration Cavity $TM_{0,1,0}$ mode
Peak field 30 MV/m. Cavity will change particles energy by

$$\Delta U = 0.16\,[MeV]\left[\frac{\Delta t}{1\,ps}\right]$$

Since Cavity is phased to give $\Delta U = 0$ for particle in time with the re-acceleration cycle.

This leads to a momentum change

$$\frac{\Delta p}{p} = 0.001\,\frac{\Delta t}{1\,psec}$$

Measure the momentum before & after RF

$$\frac{\sigma_{p}}{p} = \frac{0.008}{\sqrt{2}}$$ to achieve 8 ps time resolution

Momentum measurement

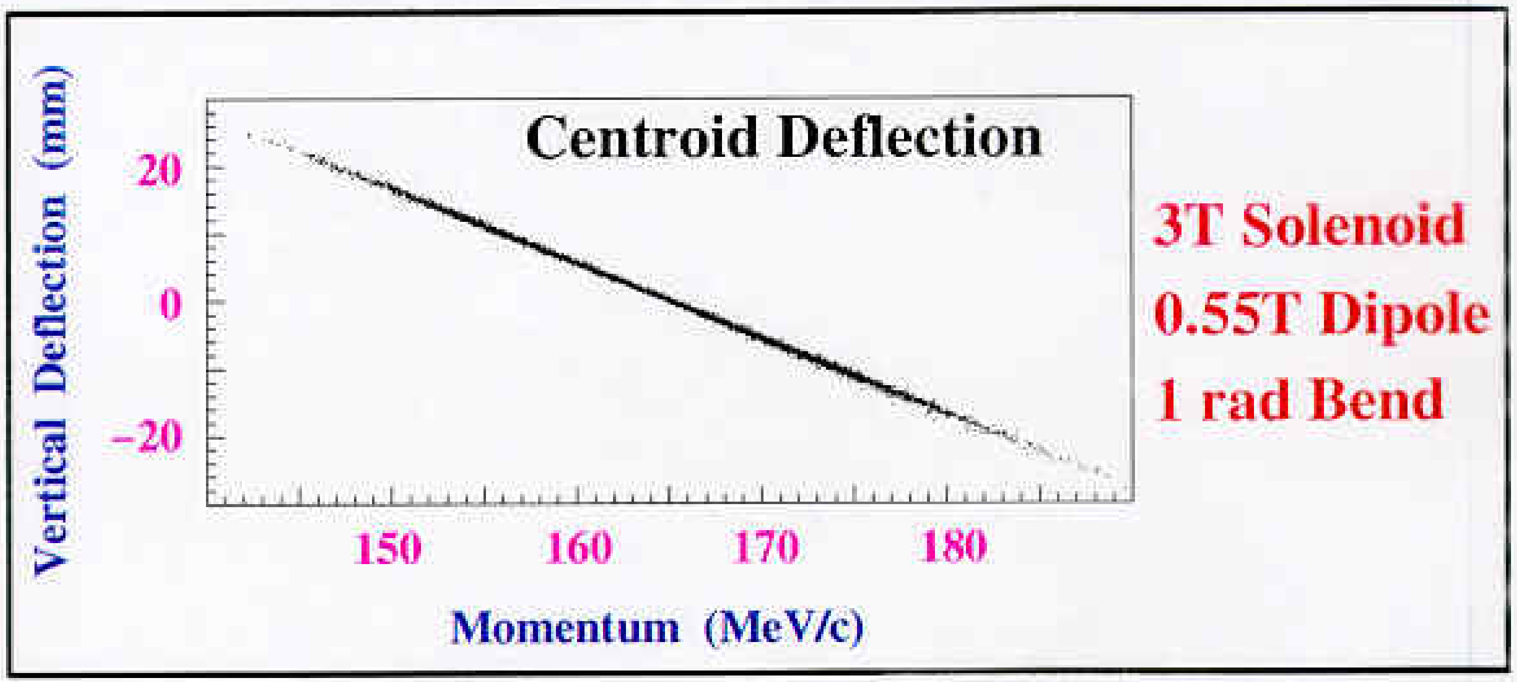
Bent solenoid. Horizontal bend ⟹ vertical displacement.
Use compensating dipole @ 0.55 T. Off momentum muons are displaced by

$$\Delta y \approx \frac{P}{eB_s}\,\frac{\Delta p}{p}\,\Theta_{bend}$$

Use TPC's to measure entrance & exit trajectories

Muon Measuring Systems

- We must measure (x, y, x′, y′, p, t) of the incoming and outgoing muons.
- The large beam phase–space must be confined within the measuring system ... use a solenoidal channel.
- We need a momentum spectrometer within the solenoidal channel. An elegant way to implement this is to use the curvature drift effect within a bent solenoid imbedded in a guiding dipole field:



- **Example:** To measure momentum with a precision of 0.2 MeV/c using a horizontal bend requires the vertical helix deflection to be measured with a precision of 220 μm.

Measurement Requirements

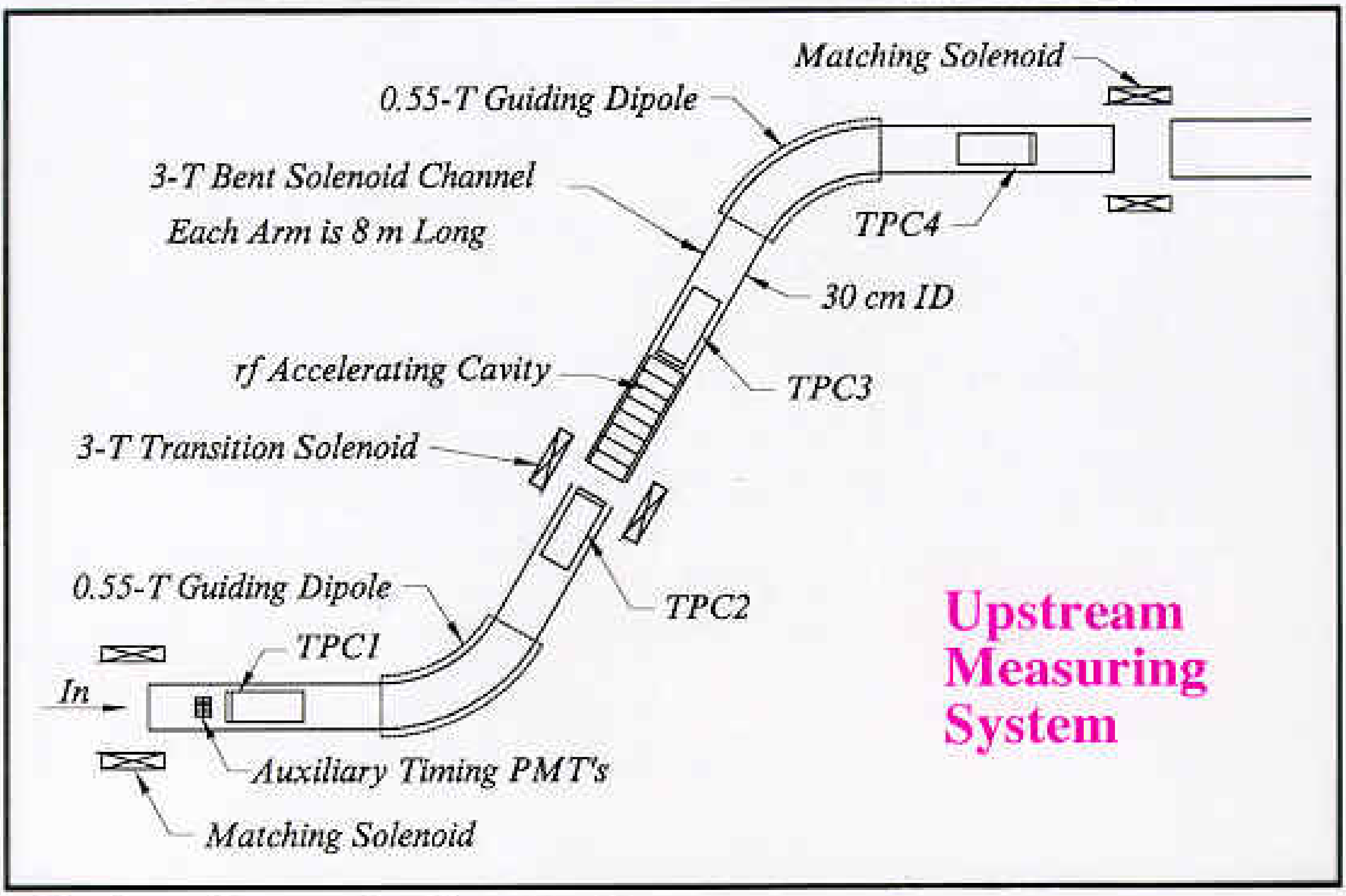
Upstream and Downstream Measuring Systems: Performance required to determine phase–space volume with a precision of a few % :

Variable i	Expected input σ_i	Required σ_{D_i}	Required $\delta\sigma_{D_i}$ [Systematic]
x	24 mm	200 μm	40 μm
y	24 mm	200 μm	40 μm
x′	33 mr	5 mr	1 mr
y′	33 mr	5 mr	1 mr
P	5 MeV/c	0.23 MeV/c	0.05 MeV/c
t	40 ps	8 ps	2 ps

- The most demanding requirement is the measurement of the muon arrival time (with respect to the 805 MHz rf cycle) -> $\sigma_t \sim 8$ ps.

- The best time precision obtained with "conventional" particle detectors is $\sigma_t \sim 30$ ps with a cherenkov detector. We are investigating the feasibility of pushing this technique to obtain a more precise measurement, but we believe the best time precision can be obtained with a momentum–rf–momentum technique ->

Upstream Instrumentation



- Auxiliary timing device
- TPC 1 -> helix before first bend
- Bent Solenoid
- TPC 2 -> helix after first bend

First Momentum Measurment

- rf accelerating cavity

rf

- TPC 3 -> helix before second bend
- Bent Solenoid
- TPC 4 -> helix after second bend

Second Momentum Measurment

Time Measurement with an RF Cavity

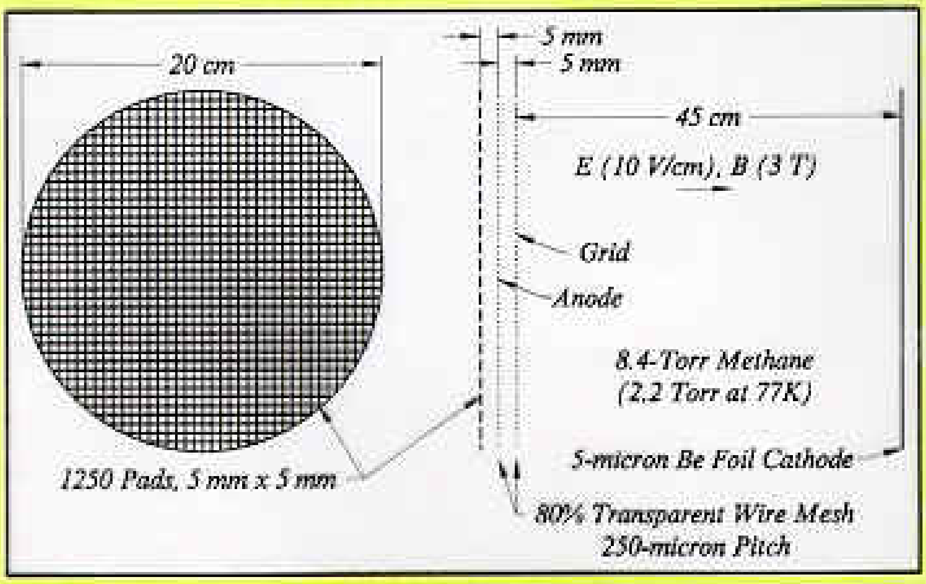
- Need an auxiliary time measurement to locate the muon within 1/4 rf cycle (300 ps).

The rf cavity changes the particles energy:

$$\Delta U = 0.16 \text{ MeV } (\Delta t / 1 \text{ ps})$$

- Need $\sigma_t \sim 8$ ps -> $\sigma_p \sim 1.3$ MeV/c. Must also know time-of-flight over ~4m -> $\sigma_p/p < 0.0014$. This will require a low mass device that can precisely measure the helical trajectories of muons in the 3T solenoidal field.

We are prototyping (Princeton) a low pressure TPC which we plan to test within a 3T solenoid field. The calculated performance of a momentum-rf-momentum system using this TPC is adequate for $\sigma_t \sim 8$ ps.



15 points per track segment

$\sigma_p/p \sim 0.0014$ at 165 MeV/c

$\sigma_\theta \sim 1$ mrad

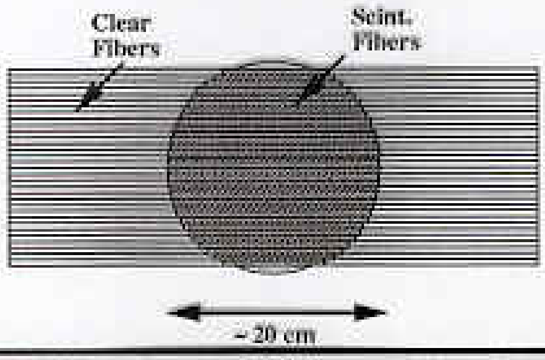
Auxiliary Time Measurement & Particle ID

We need a precise auxiliary time measurement to know arrival time within 1/4 RF cycle. Can use this system to reject incoming π and e by ToF:

ToF Differences (ns) over 3m path

	p (MeV/c)				
	100	187	200	260	300
$\mu - e$	4.5	1.5	1.3	0.80	0.60
$\pi - \mu$	2.6	1.0	0.9	0.56	0.43

We are prototyping a 2 mm diameter scintillating fiber system (UCLA) to measure time to ~100 ps:

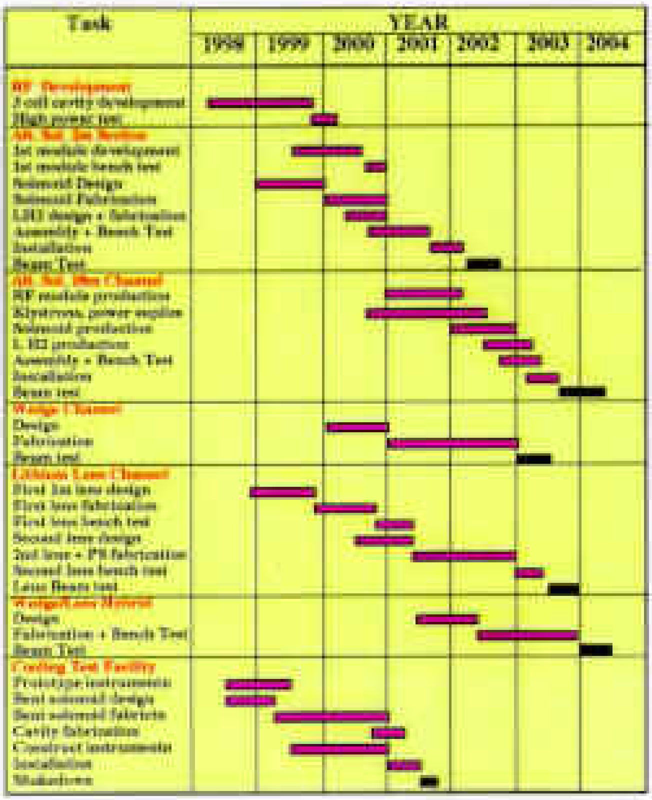


10–15 pe/MIP per fiber end
15 fiber layers
Hamamatsu R5322 PMTs
24 tubes/ timing array

We also plan to prototype a cherenkov detector to reject electrons at end of measuring channel (Mississippi):

Example: Aerogel (0.2 g/cm^3)
Electron threshold: 1.6 MeV/c
Muon threshold: 330 MeV/c

Schedule



Need high power rf test setup late 1999.

Need beam test facility for shake–down mid–2001

Begin beam meas–urements in 2002, continue until mid 2004.

Calendar Year	Funds (M$)
1998	0.7(*)
1999	4.2
2000	8.5
2001	12.0
2002	9.8
2003	1.8
TOTAL	37.0

(*) $570K already funded

Prelim. Funding Profile

No contingency or overhead

RF, Alt. Sol., wedge, Li lens, costs and instrumentation costs included.

Other facility and installation costs not included

Summary

- Muon cooling R&D is on the critical path for determining the feasibility of a muon collider.
- We propose to conduct a 6 year R&D program to develop and test the critical components of an ionization cooling channel.
- The R&D program consists of developing:

RF modules with thin beryllium windows

An alternating solenoid transverse cooling test channel.

Longitudinal (wedge) & liquid lithium lens cooling stages.

- We will need:

A high-power RF test setup in 18 months time (late 1999).

A low energy muon beam test facility starting mid-2001.

Ionization Cooling R+D program

- Develop appropriate rf re-acceleration structure
  3 cell prototype cavity with Beryllium windows
  High power High solenoid field test at liquid N_2 temp.
- Prototype initially a 2m section, then a 10 meter section of alternate solenoid cooling scheme
- Prototype wedge section (Emittance exchange)
- Prototype ~ 1m long liquid Li lenses
- Prototype Liq Li lens – rf – lens system
- Prototype hybrid Li lens / wedge cooling system