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Muon Cooling R&D

- Motivation and Context
- Ionization Cooling
- Cooling R&D
- Summary

Motivation

- There is currently a lot of interest in the possibility of building a multi–TeV muon collider, starting initially with a lower energy demonstration machine (Higgs factory ?).

Muon Collider Collaboration became a formal entity in May 1997 (Spokesperson: R. Palmer) –> ~ 100 physicisits from 27 institutions:

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

- The muon source for a muon collider is envisioned to consist of a proton driver, pion production target within a high field collecting solenoid, and a pion decay channel consisting of a solenoid channel to contain the pions plus rf to keep them bunched –> diffuse muon bunch.

- If a high–luminosity muon collider is to become a reality, we must develope a muon cooling system that can cool the "cloud" of muons coming from the 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).

The MUCOOL Collaboration

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University of Mississippi
Fairfield University
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48 Physicists from 13 Institutions

Why this may be of interest to the JHF community

- The muon source for a muon collider (proton driver + pion target/collection/decay system) is just an example of the next generation of muon sources that are likely to be in operation in a few years time at (for example) the JHF.

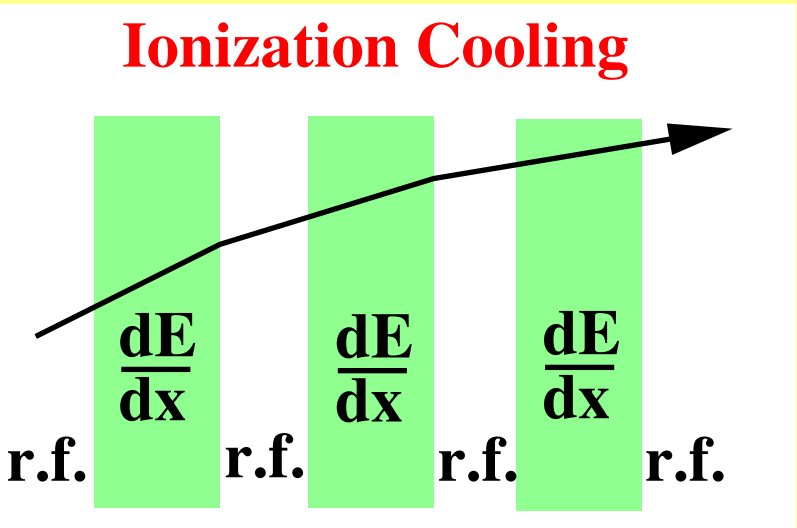
- The cooling channel technology being developed for a muon collider could also be used at the JHF:

  –> Intense cold muon source

  –> Intense flavor–pure neutrino beams

- Ionization cooling R&D will take place in the same time–frame as JHF construction. If successful the resulting technology will redefine the state–of–the art in intense cold muon sources and neutrino beams.

Ionization Cooling



Transverse Cooling

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

The equation that describes ionization cooling:

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

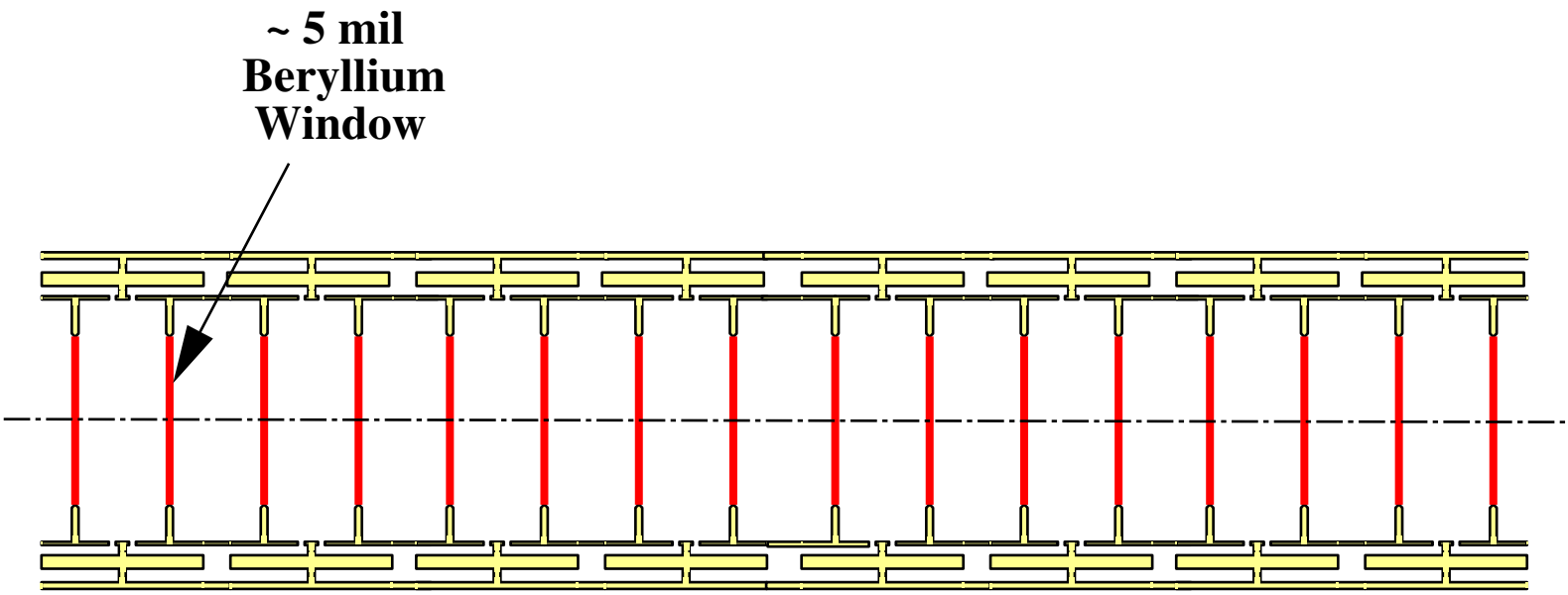
coherent cooling

heating due to multiple scattering

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

RF Cavities

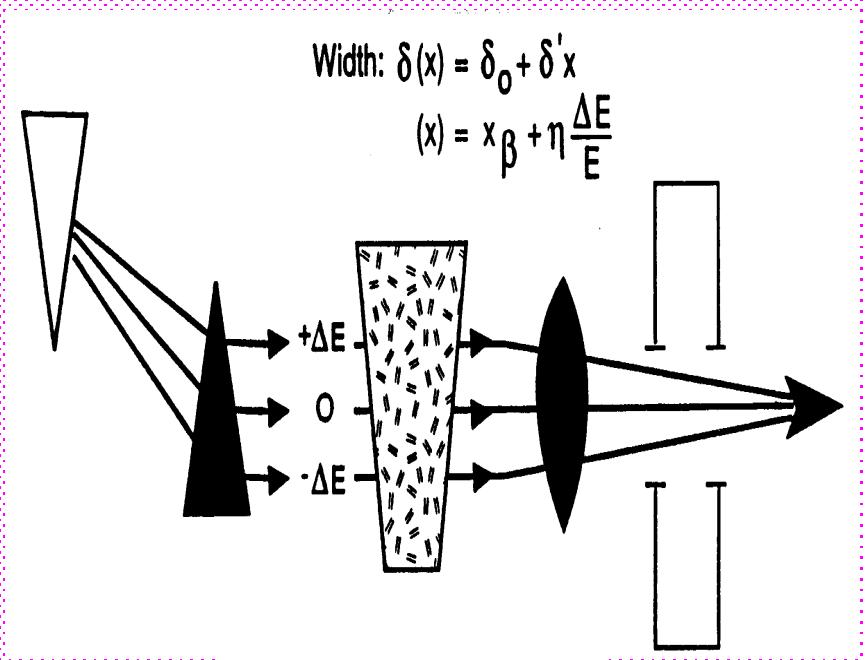
- Since muons do not interact strongly, can close the aperture in the rf cavity with a thin conductor –> ~ doubles the accelerating gradient on axis !



π/2 Interleaved Cavity

- Power consumption is an issue .... to ~ halve the power needed, run cavities at liquid N_2 temp.

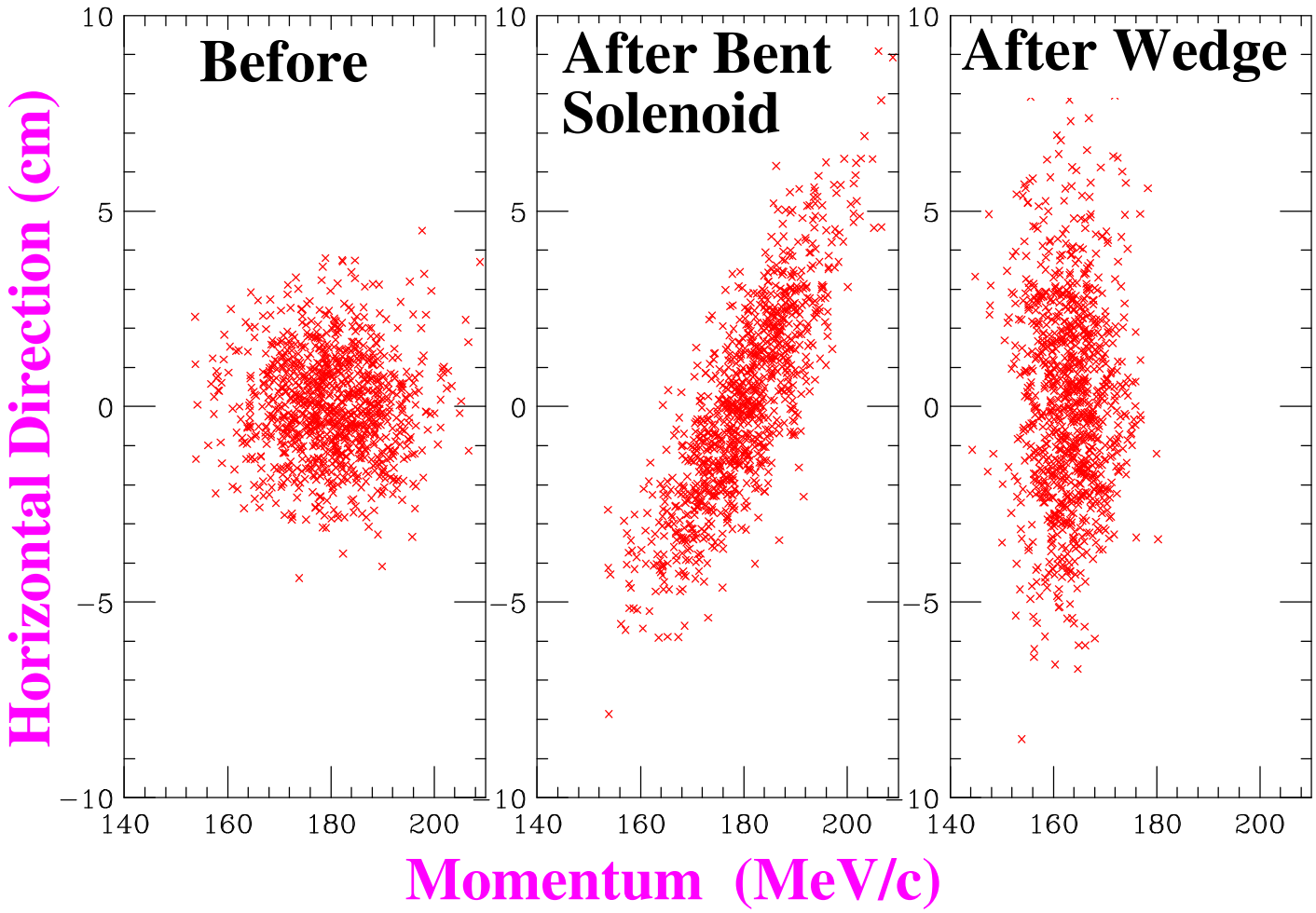
Longitudinal Cooling



Energy Cooling

Ionization cooling using a wedge plus dispersion.

Exchanges emitt–ance between transverse & long–itudinal directions



Simulation Tools

- **Two programs are being developed to simulate the complete target/collection/decay and cooling channel:**

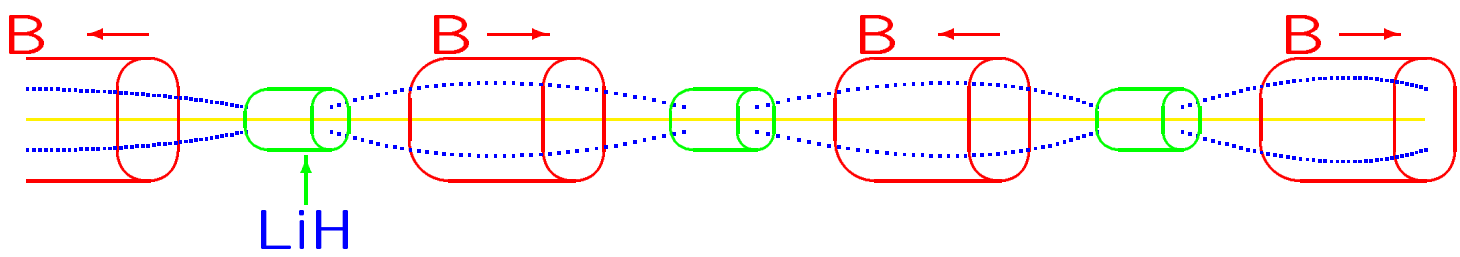
ICOOL (R. Fernow – BNL):
Fast tracking through dipoles, solenoids, rf cavities, absorbers, bent solenoids, etc.

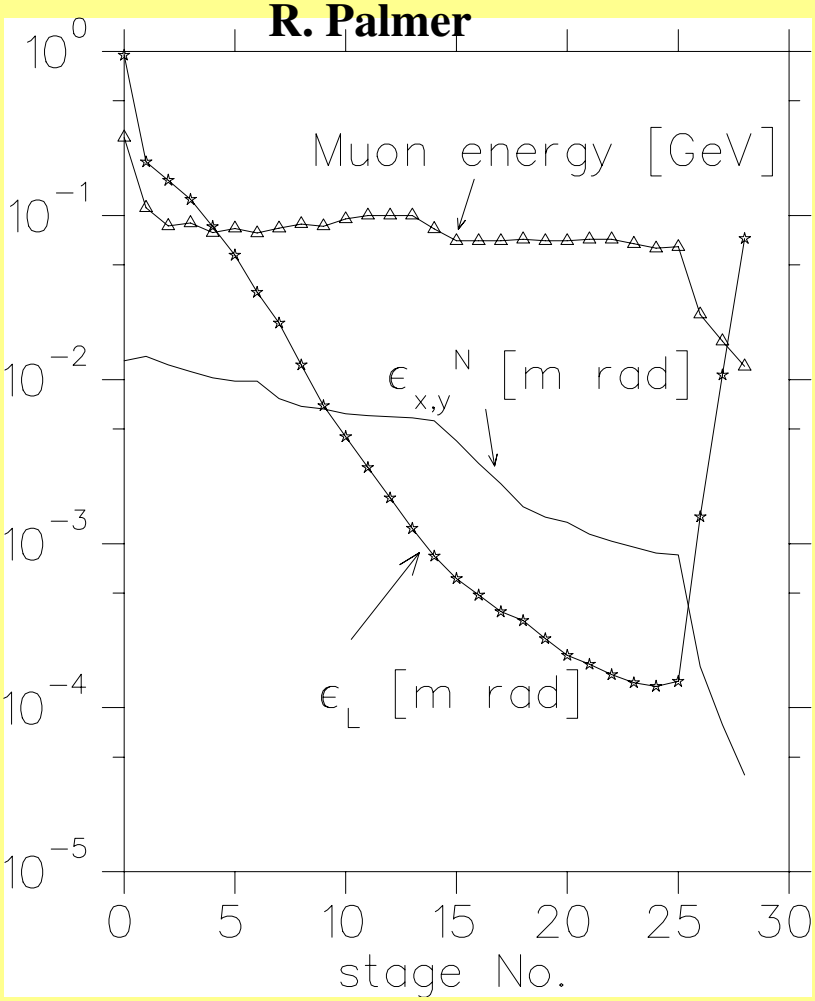
DPGEANT (P. Lebrun – FNAL):
GEANT with douple precision tracking (to supress rounding errors over long tracking distances) and bent solenoids, rf cavities etc added.

- **Potential for wide collaboration on development of these tools.**

Initial Idea: FOFO Scheme

- Short axial solenoids with alternating field directions.
- Li H absorbers between the solenoids.
- Reacceleration linacs within solenoids.
- Last few stages use lithium lenses to maximize radial focussing.





Theoretical studies

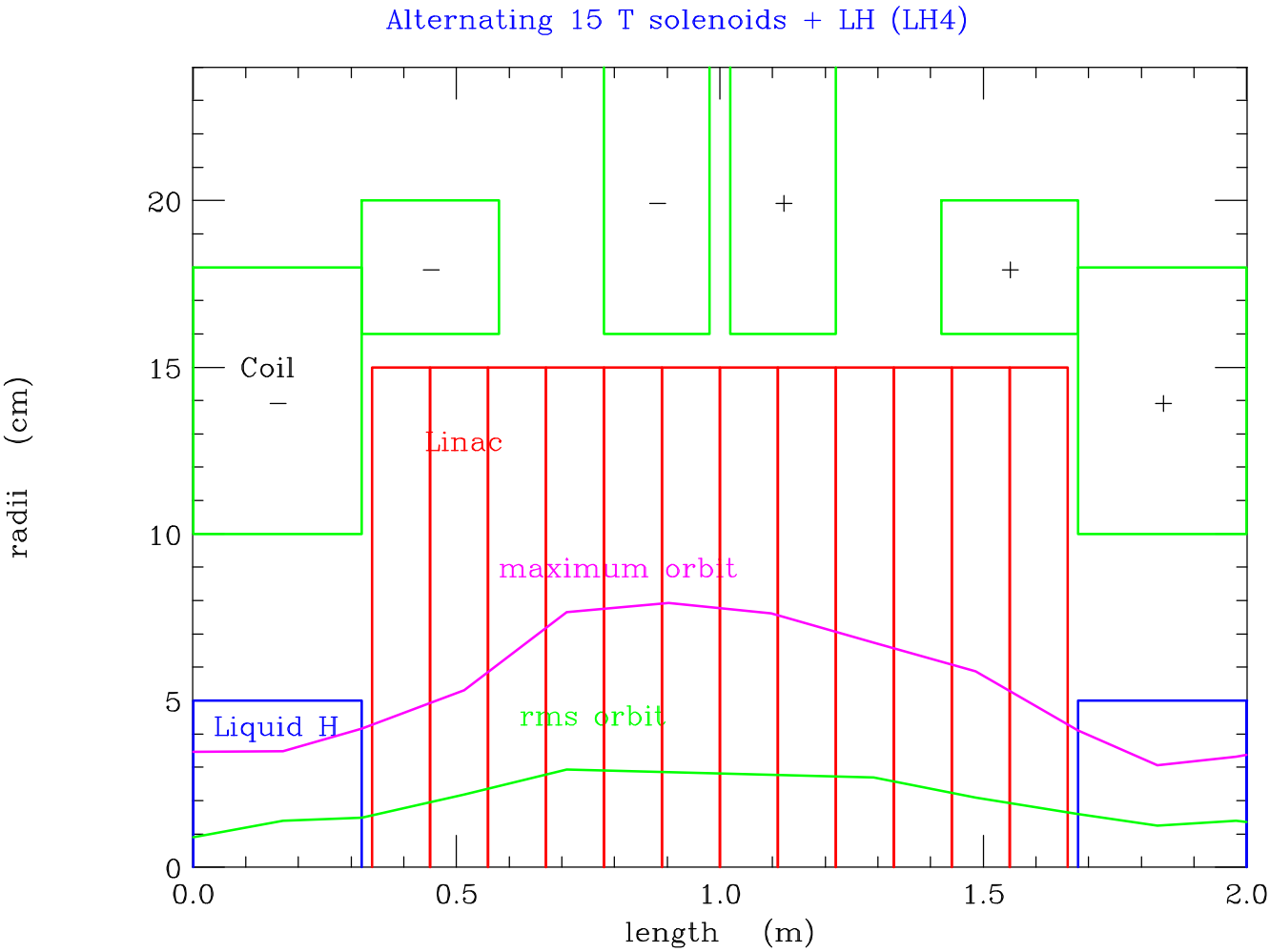
Assume there is a scheme to keep longitudinal emittance under control.

A factor of 10^5 – 10^6 cooling can be obtained from 20 – 30 cooling stages, each stage reducing the 6D phase–space volume by about a factor of 2.

Yields ~10^{21} muons/yr at ~ 200 MeV/c.

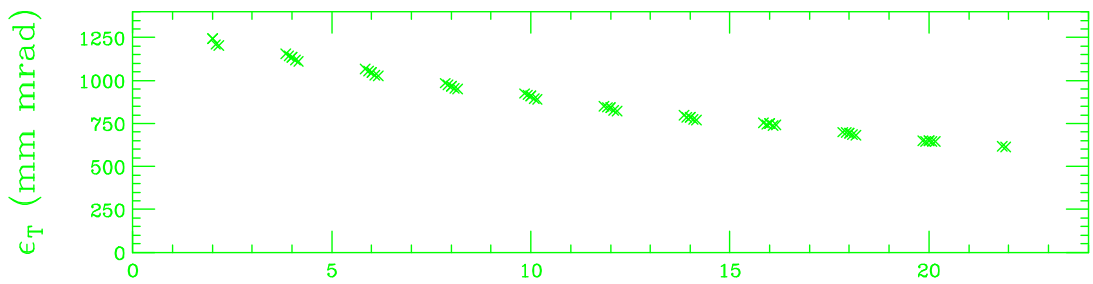
Ionization Cooling Channel: Recent Developments

- Long axial solenoids with alternating field directions.
- Liquid Hydrogen absorbers within the solenoids.
- Reacceleration linacs between solenoids.
- Last few stages use either very high–field solenoids (30 Tesla) or lithium lenses to maximize radial focussing.

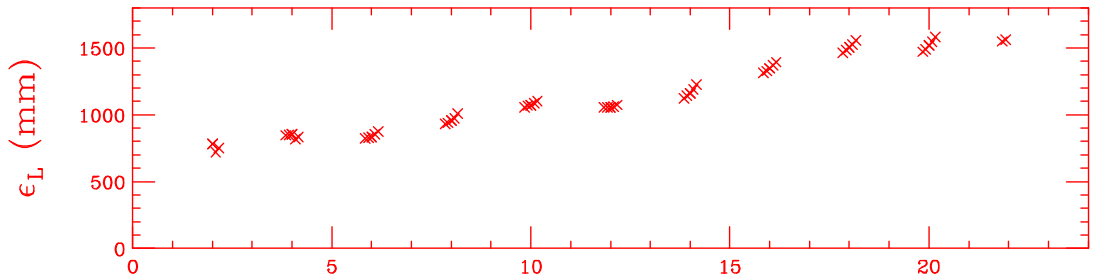


Alternating Solenoid Scheme

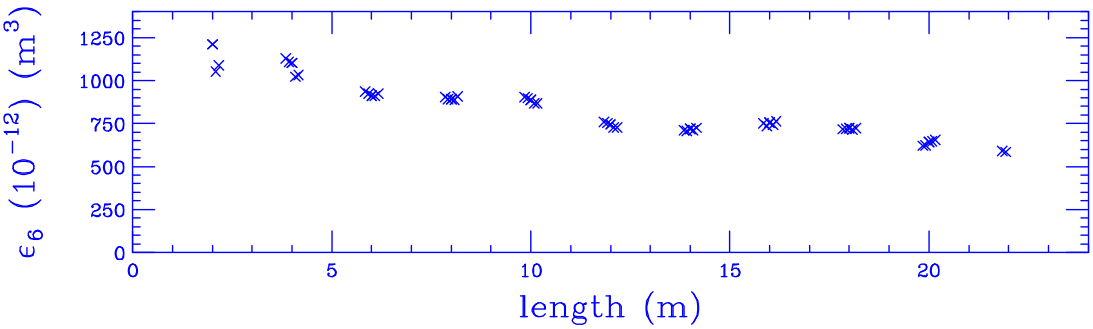
Theoretical studies:
R. Palmer



Transverse Cooling



Longitudinal Heating



6D Cooling

- **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%**

Cooling R&D

- **Ionization cooling is conceptually simple but has never been done before and developing the hard–ware will be challenging.**
- **Need to:**

  Develope a complete simulation of the whole cooling channel, from beginning to end –> complete specification of the performance required for each of the components. This appears to be well advanced.

  Prototype each of the cooling channel components and bench test them –> confront achievable component parameters with cooling simulations.

  Test a prototype cooling section in a low energy muon beam .... establish operation and study optimization of cooling channel. Experiment needs participation of particle physicists.

Cooling Hardware R&D Program

- **Fabricate a cavity with a beryllium foil, then fabricate 3–cell and/or 6–cell cavities.**
- **Construct 1m long model, test at liq. nitrogen temp, evaluate coupling characteristics, study cavity tuning. Decide on the cavity type (standing or traveling wave).**
- **Construct a 1 m long cavity for high–power rf testing at liquid nitrogen temps and demonstrate operation of this cavity in aa appropriate magnetic field, and in a radiation environment.**
- **Construct a 10 m long prototype cooling section and measure its performance when exposed to muons of the appropriate momentum (164 MeV/c).**
- **Develop and test a prototype wedge cooling section.**
- **Develop and test a prototype lithium lens.**

Lithium Lens Requirements

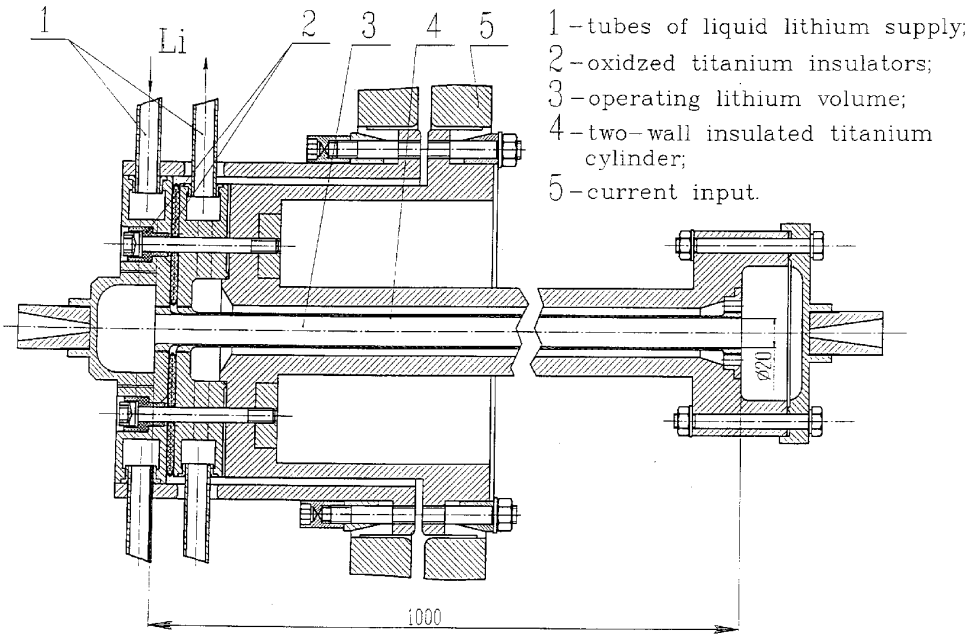
- **Lithium rods with surface fields of 10 T were developed at Novosibirsk and have been operated as focussing elements at CERN and FNAL.**
- **The lithium lenses required for ionization cooling will require the technology to be developed:**
  - **Ionization cooling requires much longer lenses .. of order 1 m to maximize the amount of cooling in a single absorber and minimize the absorber–absorber transitions.**
  - **The muon collider repetition rate will require the lens to operate at up to 15 Hz. The resulting thermal load on a solid lens would melt it –> need a liquid lithium lens.**
  - **To minimize the final emittances, the maximum radial focussing –> maximum surface fields are required. It is hoped to raise the surface field to ~ 20 T.**
- **Parameters of lithium lenses needed for cooling channel**

B (T)	B' (T/m)	radius (cm)	length (m)	I (MA)	τ (μs)
10	1000	1.0	1	0.5	1000
15	3000	0.5	1	0.375	250
20	8000	0.25	1	0.25	63
20	16000	0.125	1	0.125	15
20	40000	0.050	1	0.050	2.2

Lithium Lens R & D

- A contract between Novosibirsk and FNAL exists to develop a high–field liquid lithium lens for anti–proton collection. It is hoped to extend this R&D to produce longer lenses for ionization cooling.

LITHIUM CURRENT CARRYING COOLING ROD

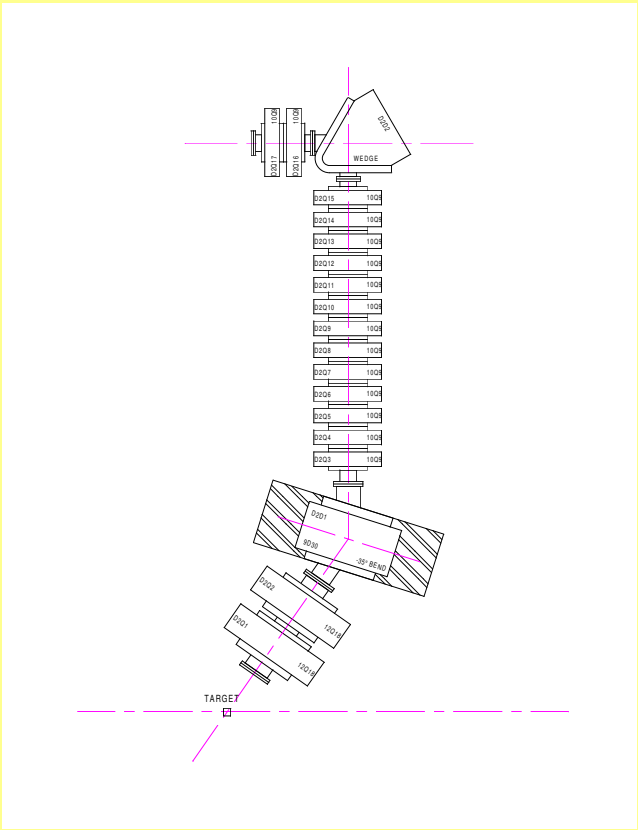


A 1 m long liquid lithium lens has been designed by Silvestrov for muon ionization cooling.

- The proposed liquid lithium lens R & D program :
  - Construct a Silvestrov–type 1 m long lens and measure its performance when exposed to muons in the appropriate momentum range.
  - Construct a second lens and measure the performance of the lens–rf–lens system.
  - Develop and test a lens system for wedge cooling
  - Develop lenses that achieve the highest practical surface fields.

Ionization Cooling Test Facility

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



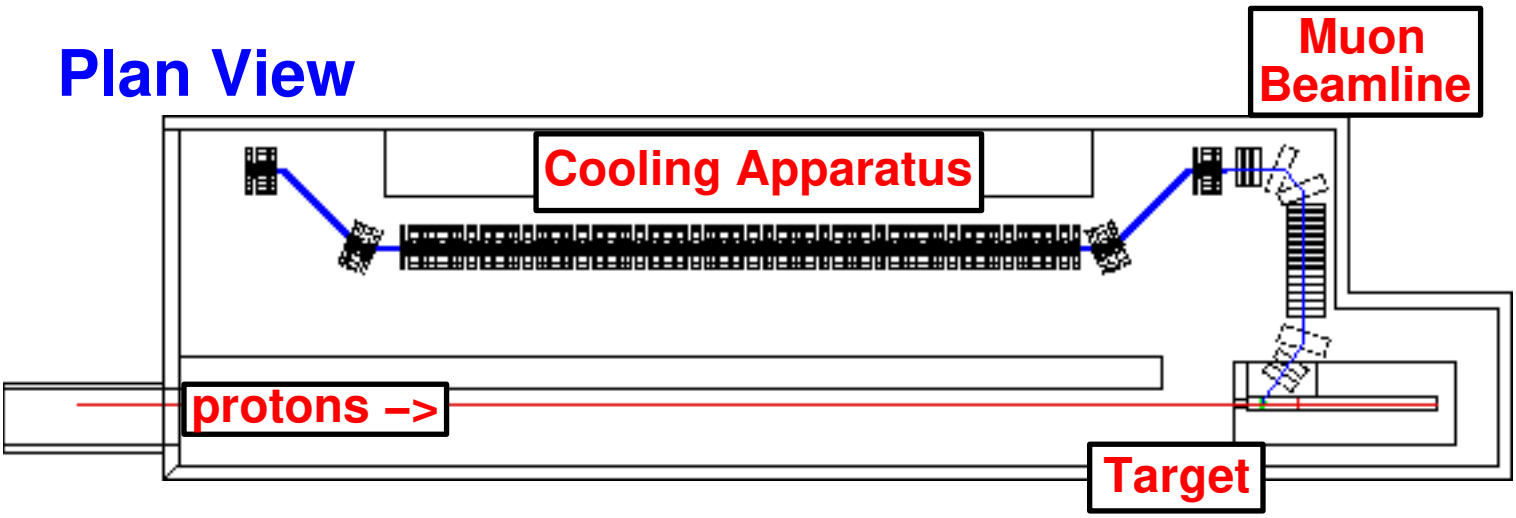
Need :

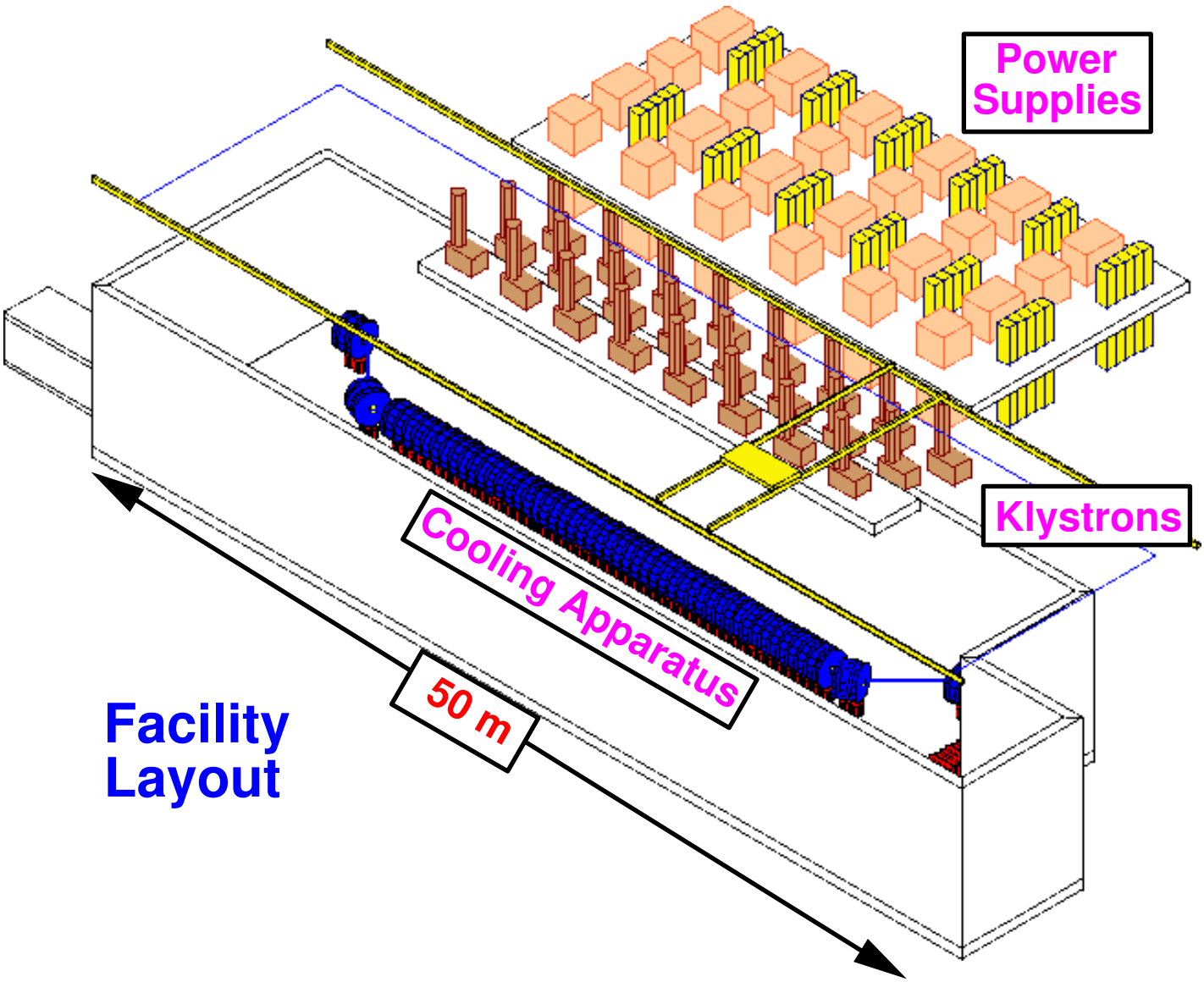
- P_{beam} = 100 – 300 MeV/c
- $\Delta P/P \sim 5\%$
- Purity > 99% after tagging
- $\varepsilon_{\perp} \sim 1500\ \pi$ mm–mrad
- Experimental hall with ~ 50m for experimental setup

- **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:**

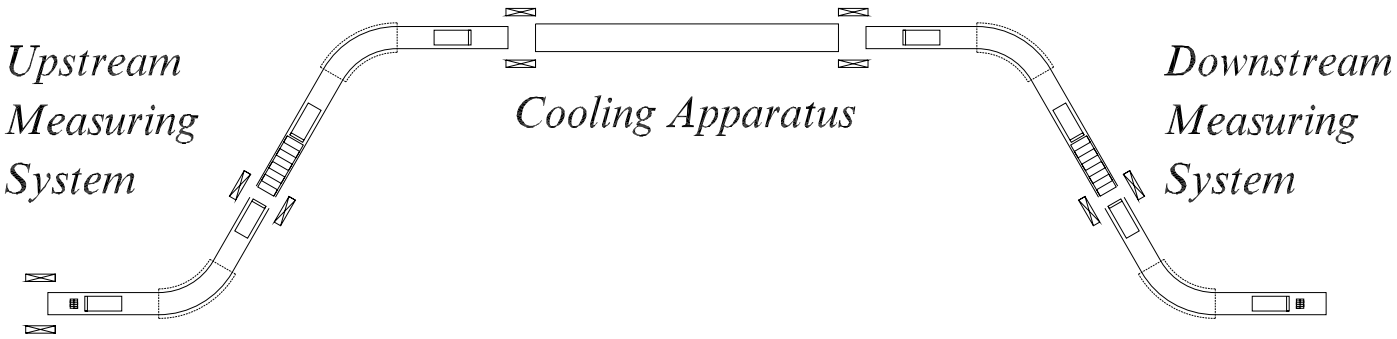
  (i) Select a population of incident muons corres–ponding to the "ideal bunch".
  (ii) Demonstrate cooling.
  (iii) Test the cooling calculations.
  (iv) Study optimization.

Muon Cooling Experimental Facility





Ionization Cooling Test Facility Instrumentation



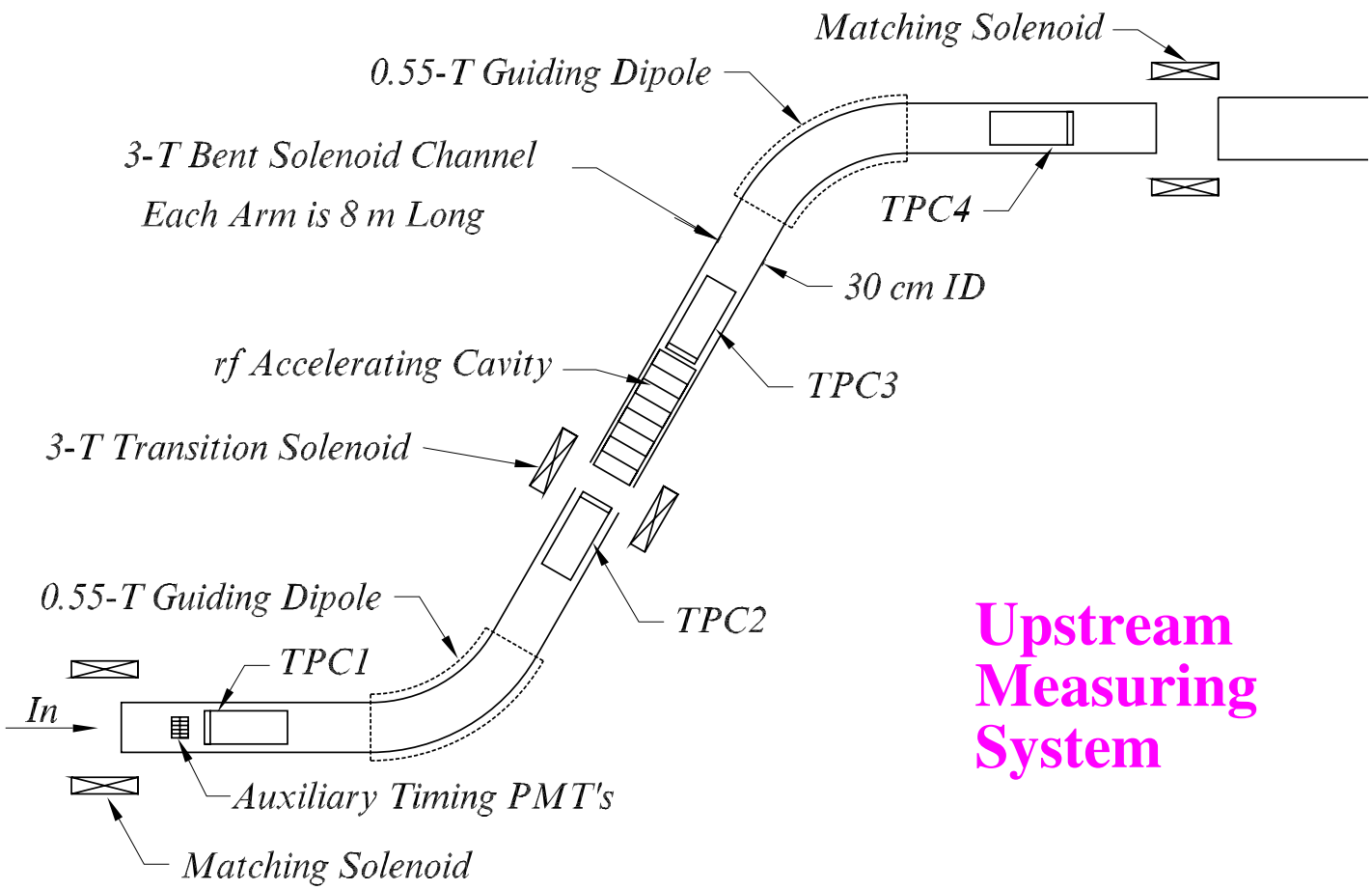
Would like to:

- **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.**

Performance requirements for the upstream and downstream measuring systems

Variable i	Expected input σ_i	Required σ_{D_i}	Required $\delta\sigma_{D_i}$
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

Upstream Instrumentation



Upstream Measuring System

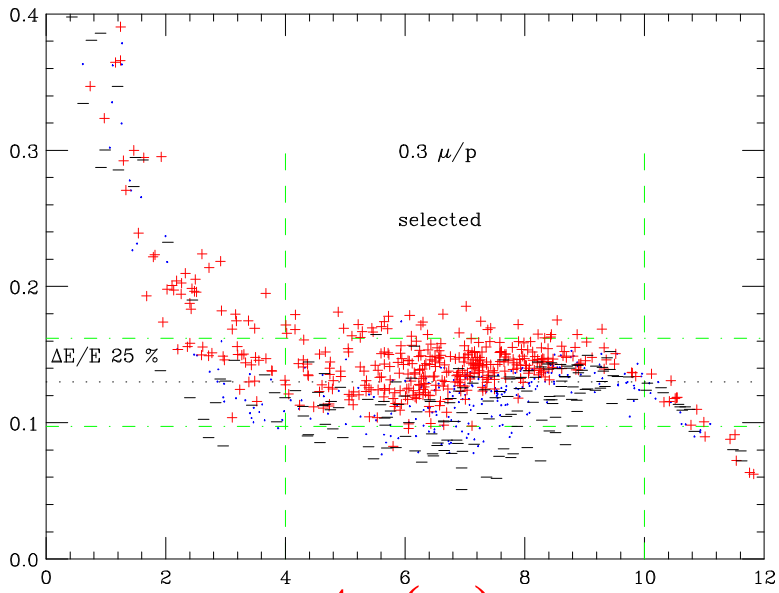
- **Auxiliary timing device**
- **TPC 1 –> helix before first bend**
- **Bent Solenoid**
- **TPC 2 –> helix after first bend**
- **rf accelerating cavity**
- **TPC 3 –> helix before second bend**
- **Bent Solenoid**
- **TPC 4 –> helix after second bend**

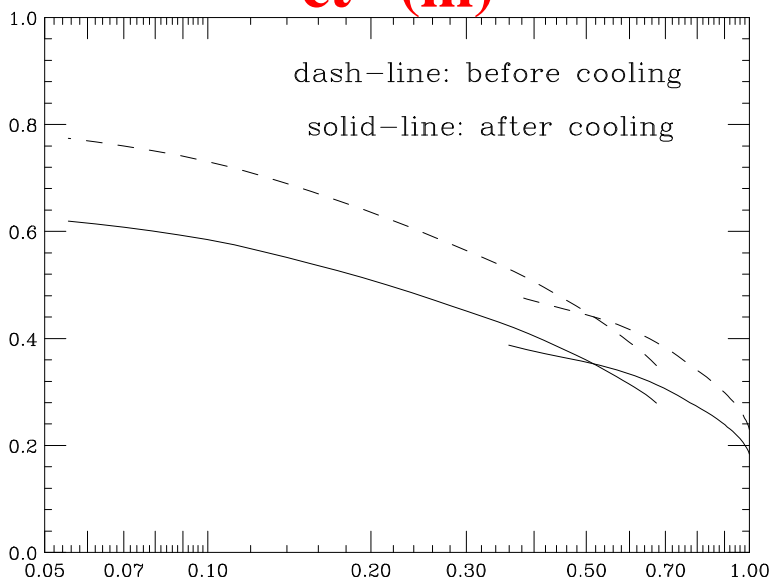
First Momentum Measurment

rf

Second Momentum Measurment

Preservation of Muon Polarization





At the end of the decay channel the average μ polarization depends on energy.

A selection could be made to enhance the muon polarization.

This costs luminosity.

If no selection is made (maximal luminosity) the average polarization is ~20% .. which includes spin flip probability.

If selection made on both beams, luminosity ~ F_{loss}^2

- **During ionization cooling process, spin–flip probability:**

$$P \sim \int \frac{m_e}{m_\mu} \beta^2 \frac{\Delta E}{E} \xrightarrow[\Delta E = 3\ \text{GeV}]{\text{ionization loss}} 10\%$$

- **Fractional polarization loss = 2P ~ 20%**

  Need to develope a more complete understanding of how polarized the muons will be at the end of the cooling channel.

Summary

Ionization cooling is of interest to those people who want to use cold muon beams: muon collider, muon physics, neutrino physics.

- **Muon cooling collaboration exists.**
- **Cooling simulation progressing well .... but lots to do. Potential for collaboration on simulation tools (DPGEANT and ICOOL).**
- **Ready to start hardware development of cooling channel components.**
- **Expect to propose a cooling beam test experiment soon ... it will be like a big fixed target experiment –> needs participation of particle physicists.**

There is lots to do.

Cooling Expt

Physics Program with Cold Muons

Cooling Simulations
(ICOOL & DPGEANT)

Alternative Cooling Ideas

Ionization Cooling Hardware

Please Join Us !