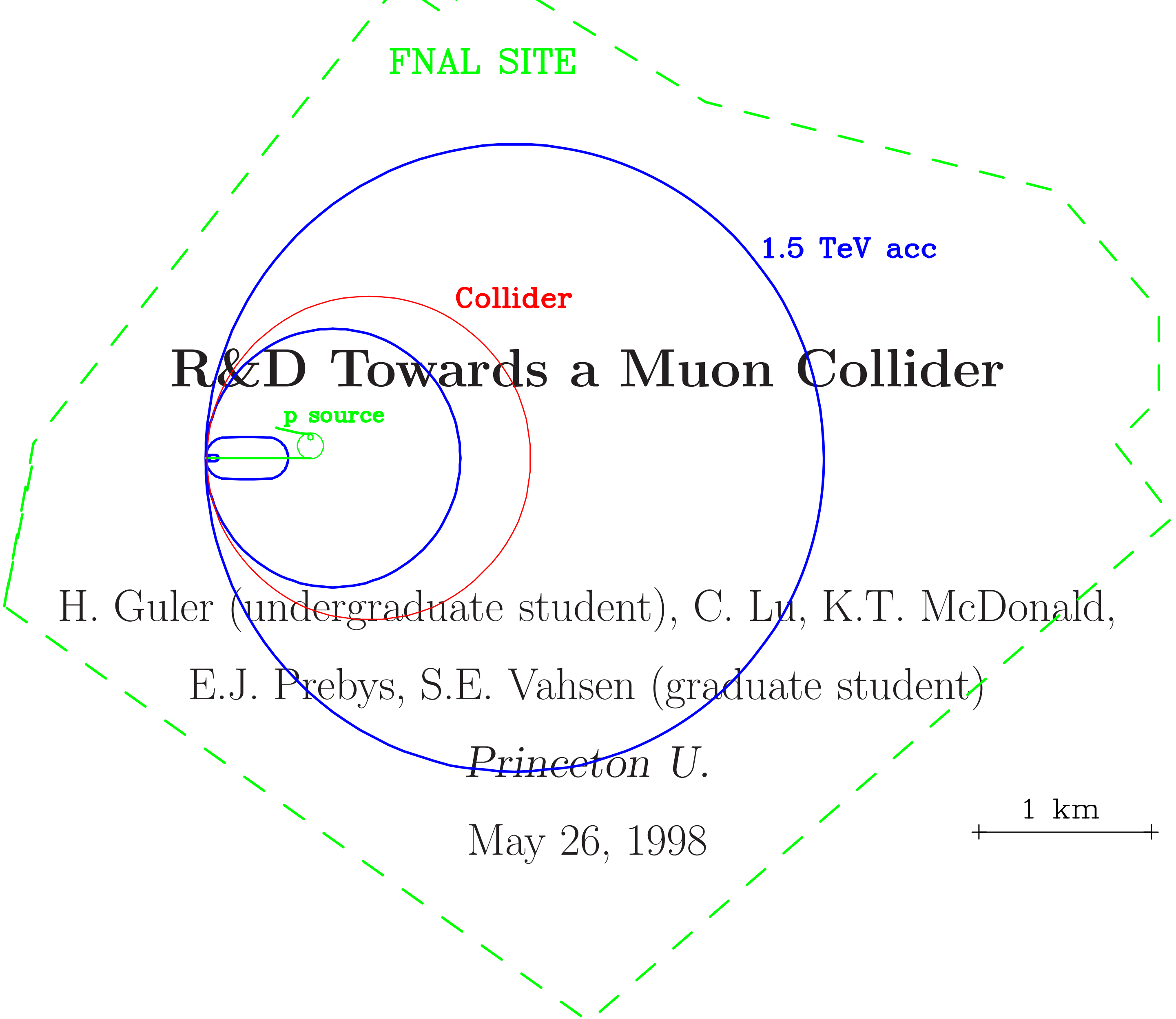


R&D Towards a Muon Collider

H. Guler (undergraduate student), C. Lu, K.T. McDonald,
E.J. Prebys, S.E. Vahsen (graduate student)
Princeton U.

May 26, 1998

Muon Collider main page:

`http://www.cap.bnl.gov/mumu/mu_home_page.html`

Princeton muon collider page:

`http://www.hep.princeton.edu/~mcdonald/mumu`

Options for Future Colliders

- Hadron collider (LHC, SSC): ≈ \$100k/m [superconducting magnets].

  ≈ 2 km per TeV of CM energy.

  Ex: LHC has 14-TeV CM energy, 27 km ring, ≈ \$3B.

- Linear e^+e^- collider (SLAC, NLC(?)): ≈ \$200k/m [rf].

  ≈ 20 km per TeV of CM energy;

  But a lepton colliders needs only ≈ 1/5 the CM energy

  to have equivalent physics reach to a hadron collider.

  Ex: NLC has 3-TeV CM energy, 30 km long, ≈ \$6B (?).

- Muon collider: ≈ \$1B for source/cooler + \$100k/m for rings

  Well-defined leptonic initial state.

  $m_\mu/m_e \approx 200 \Rightarrow$ Little beam radiation.

  $\Rightarrow$ Can use storage rings.

  $\Rightarrow$ Smaller footprint.

  Technology: closer to hadron colliders.

  ≈ 6 km of ring per TeV of CM energy.

  Ex: 3-TeV muon collider ≈ \$3B (?).

The Case for a Muon Collider

- More affordable than an e^+e^- collider at the TeV (LHC) scale.

- More affordable than either a hadron or an e^+e^-collider for (effective) energies beyond the LHC.

- Initial machine could produce light Higgs via s-channel.

  Higgs coupling to μ is $(m_\mu/m_e)^2 \approx 40,000\times$ that to e.

  Beam energy resolution at a muon collider $< 10^{-5}$,

  $\Rightarrow$ Measure Higgs width.

  Add rings to 3 TeV later.

- Neutrino beams from μ decay about 10^4 hotter than present.

Ingredients of a Muon Collider

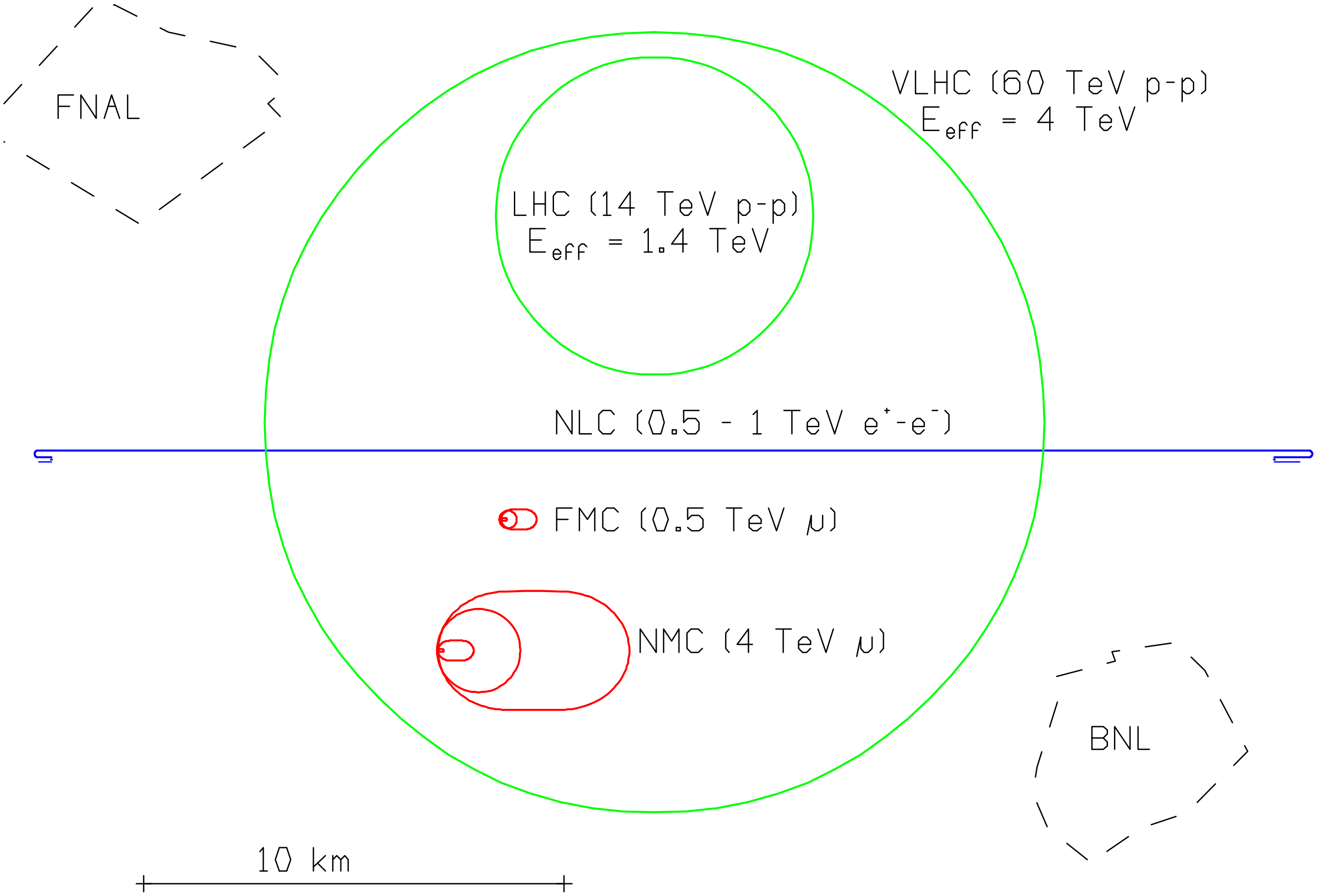
An accelerator complex in which

- Muons (both μ^+ and μ^-) are collected from pion decay following a pN interaction.
- The muon phase volume is reduced by ionization cooling.
- The cooled muons are accelerated and then stored in a ring.
- $\mu^+\mu^-$ collisions are observed over the useful muon life of ≈ 1000 turns at any energy.

Muons decay: $\mu \to e\nu \qquad \Rightarrow$

- Must cool muons quickly (stochastic cooling won't do).
- Detector backgrounds at LHC level.
- Personnel background from ν interactions.

Footprints



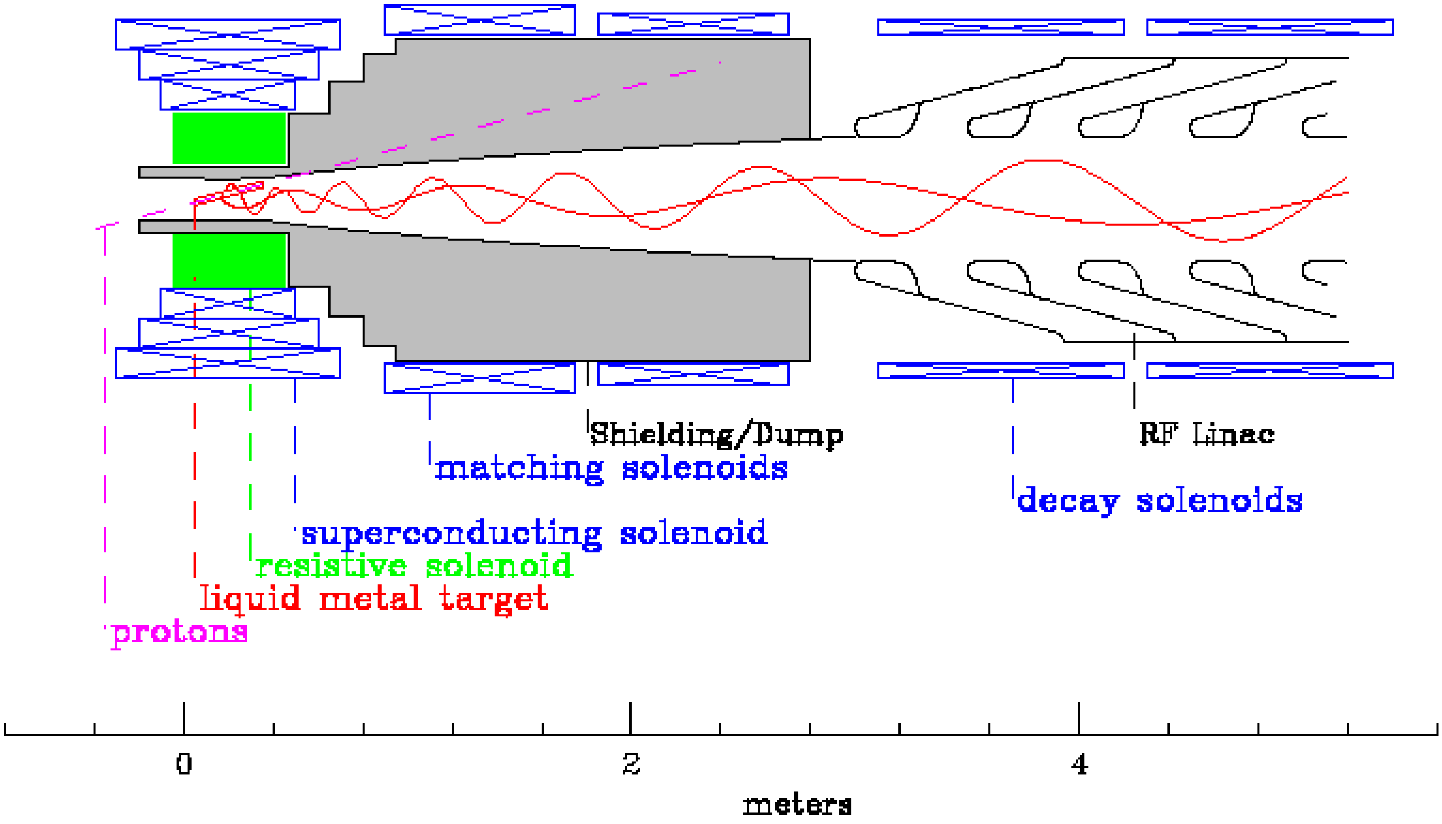
Muon collider:

- Significant base cost (≈ \$1B) at any energy, plus 'modest' cost (≈ \$100k/m) for storage rings.
- Up to 4 TeV on existing sites at cost below LHC.
- Technology path to ≈ 100 TeV before limited by radiation losses.

Technical Challenges

- 16-GeV proton driver, 15 Hz, 4-MW beam power, 1-ns bunch length.
- **Targetry and Capture**
- **Muon Cooling**
- Storage rings have beautiful, highly corrected solutions due to heroic work of Al Garren, Carol Johnstone and Dan Trbojevič.

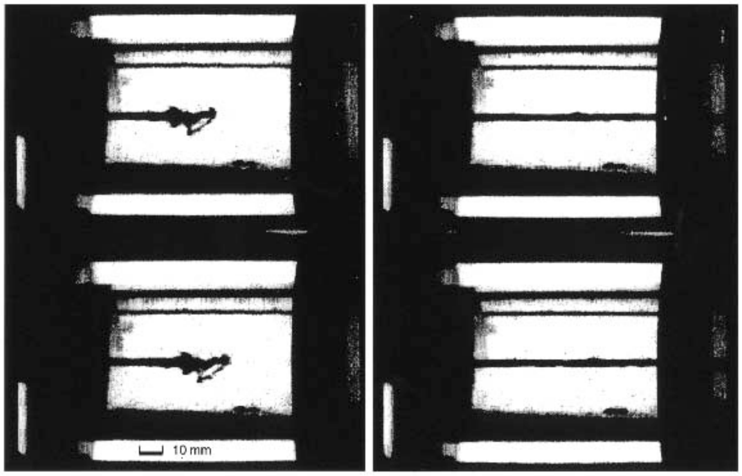
Overview of Targetry for a Muon Collider



- 1.2×10^{14} $\mu^{\pm}$/s via π-decay from 4-MW proton beam.
- Cooling jacket around stationary target would absorb too many pions.
- Liquid metal jet target: Ga, Hg, or solder (Bi/In/Pb/Sn).
- 20-T capture solenoid followed by 1.5-T π-decay channel with phase-rotation via rf (to compress energy of the muon bunch).

Targetry Issues

- 1-ns beam pulse ⇒ shock heating of target.
  - Resulting pressure wave may disperse liquid (or crack solid).
  - Damage to target chamber walls?
  - Magnetic field will damp effects of pressure wave.
- Eddy currents arise as metal jet enters the capture magnet.
  - Jet is retarded and distorted, possible dispersed.
  - Hg jet studied at CERN, but not in beam or magnetic field

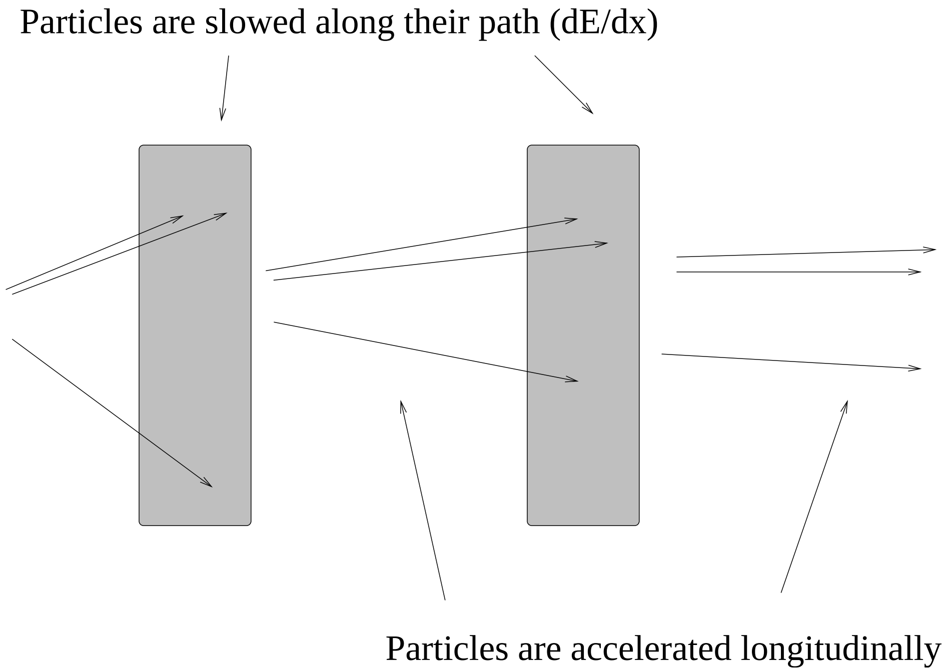


High-speed photographs of mercury jet target for CERN-PS-AA. (laboratory test)
4,000 frames per second, Jet speed: 20 ms^{-1}, diameter: 3 mm, Reynold's Number: >100,000
A. Poncet

- Targetry area also contains beam dump.
  - Need 4 MW of cooling.
  - Harsh radiation environment for magnets and rf.

Ionization Cooling

- Need to reduce 6-D phase volume of muon beam by 10^5-10^6.
- No time for stochastic cooling.
- Ionization: takes momentum away
- RF acceleration: puts momentum back along z axis.
- $\Rightarrow$ Transverse cooling.


Particles are slowed along their path (dE/dx)

Particles are accelerated longitudinally

- Multiple scattering 'heats' the beam.
- If no heating, 'stop' the beam once, and reaccelerate.
- In practice, 'stop' the beam $\approx$ 10 times, $\Rightarrow$ 6-GeV acceleration.

Ionization Cooling Theory

Transverse cooling by ionization, heating by multiple scattering:

$$\frac{d\epsilon_n}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\ \frac{\epsilon_n}{E_\mu}\ +\ \frac{\beta_\perp(0.014)^2}{2\beta^3 E_\mu m_\mu\ L_R},$$

$\epsilon_n = \sigma_x \sigma_{P_x}/m_\mu c$,

$\beta_\perp$ = Betatron function at the absorber,

L_R = Radiation length of absorber.

$$\Rightarrow \text{Equilibrium}\ \ \epsilon_n \propto \frac{\beta_\perp}{\beta L_R(dE_\mu/ds)}.$$

$\Rightarrow$ Low-Z absorber (liquid hydrogen is best),

$\Rightarrow$ Put absorber at low-$\beta_\perp$ (beam-waist),

$\Rightarrow$ Need strong focusing (15-T solenoids, Li lens...),

$\Rightarrow$ Keep $\beta = v/c$ near 1.

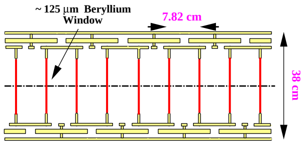
[Economics favor $\beta < 1$ since must restore the beam energy many times,]

Cooling in a Channel of Alternating Solenoids

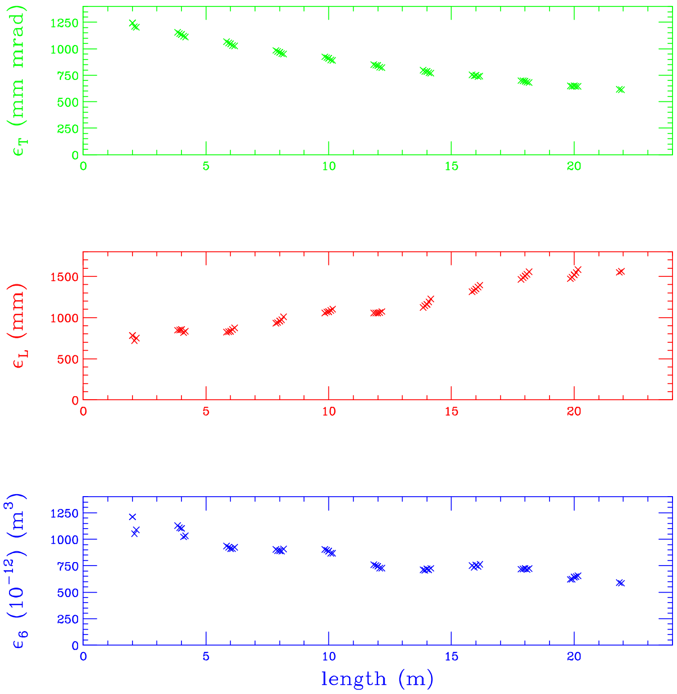
Alternate direction of **B** to avoid buildup of angular momentum.

A cooling **section** contains 10 2-m-long **cells** as above:

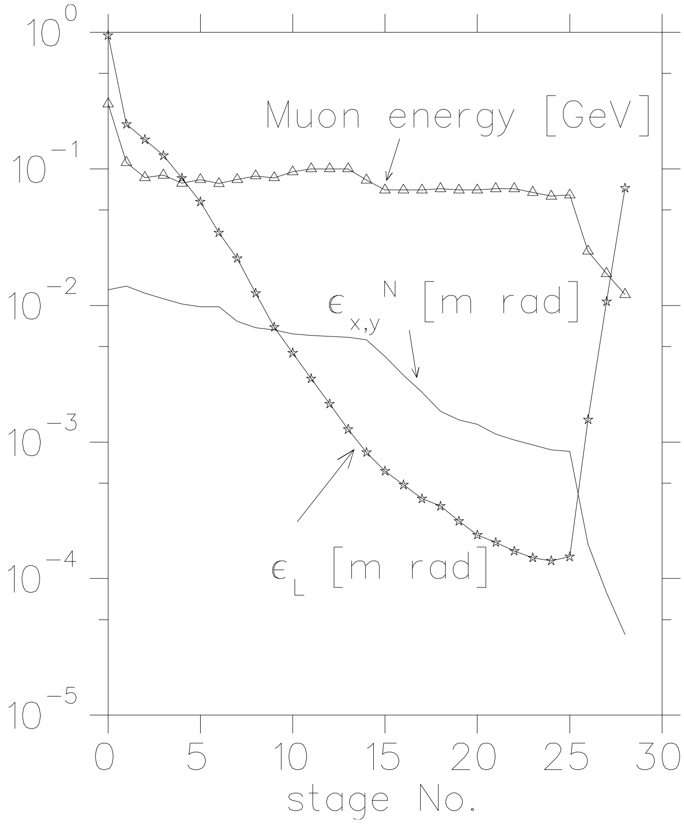
- 64 cm of LH_2 around the low-$\beta_\perp$ point inside a 15-T solenoid,
- 4 lower-field solenoids to flip sign of magnetic field.
- 12 $\pi/2$-mode, interleaved, side-coupled **rf cavities**,
  800-MHz, 5-mil Be windows, 30 MV/m gradient.



Simulated Cooling Performance



Factor of 2 reduction in 6-d emittance in a 20-m stage.



Factor of 10^{-5} reduction in 30 stages.

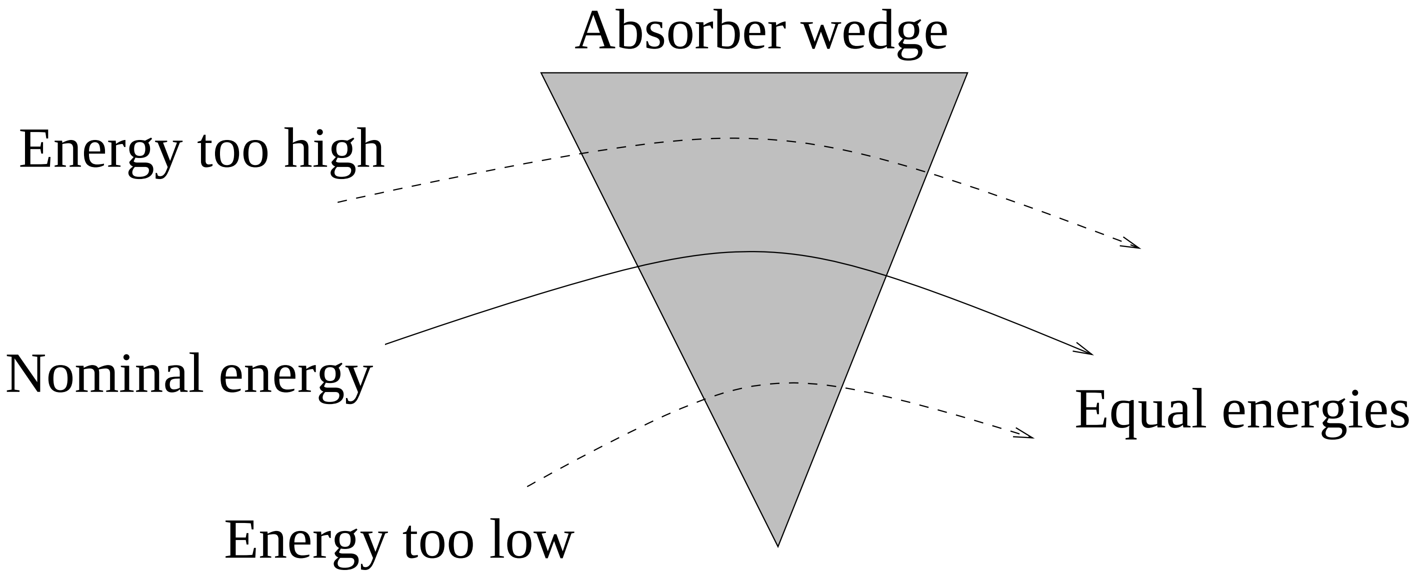
But the **energy spread rises**:

$$\frac{d(\Delta E_\mu)^2}{ds} = -2\,\frac{d\left(\frac{dE_\mu}{ds}\right)}{dE_\mu}(\Delta E_\mu)^2 + \frac{d(\Delta E_\mu)^2_{\rm straggling}}{ds}.$$

Both terms are positive if operate below minimum of dE_μ/ds curve.

$\Rightarrow$ Must exchange longitudinal and transverse emittance frequently to avoid beam loss due to bunch spreading.

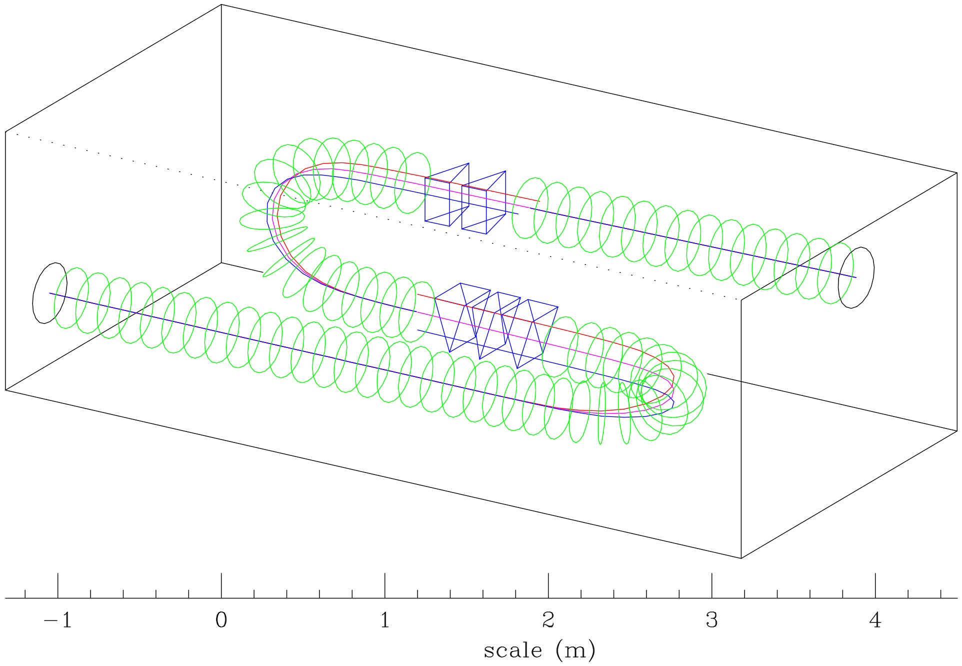
Can reduce energy spread by a wedge absorber at a momentum dispersion point:

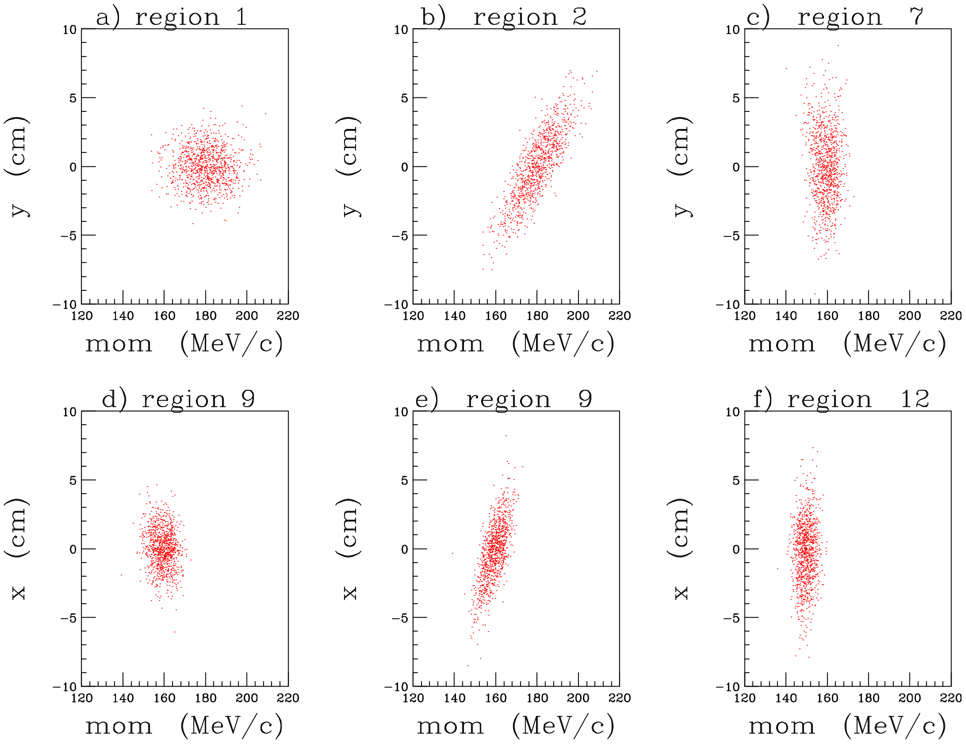


[6-D emittance constant (at best) in this process.]

Emittance Exchange Via Wedges + Bent Solenoids

LONGITUDINAL COOLING

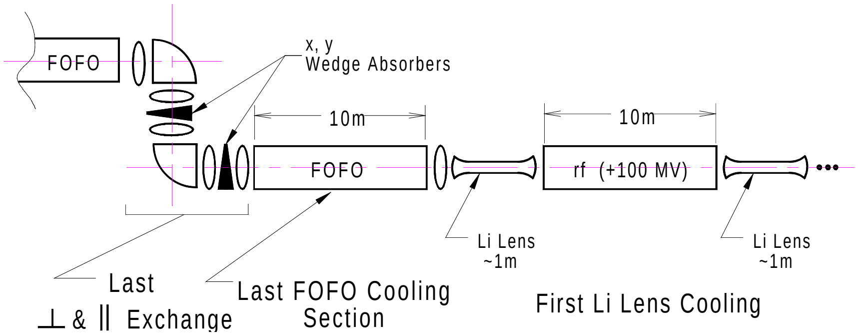


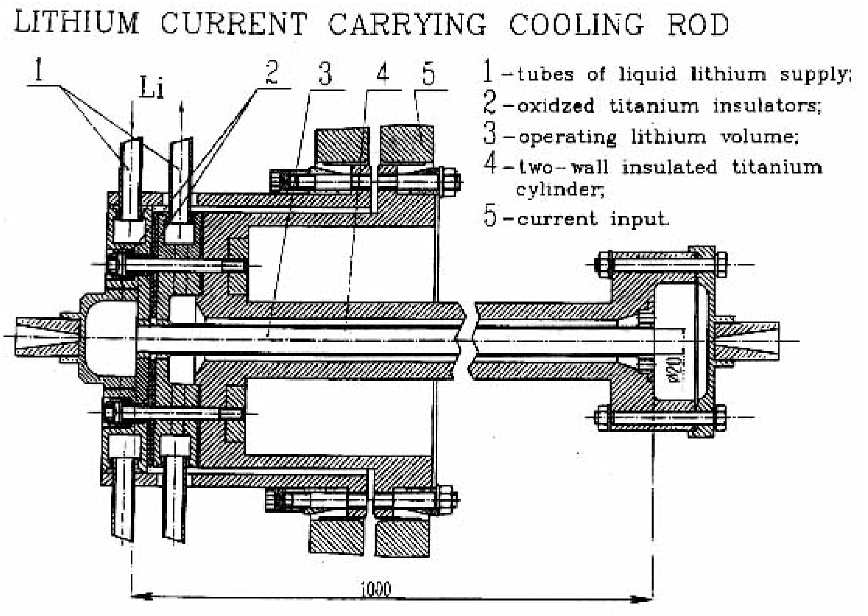


Cooling in Lithium Lenses

Alternating-solenoid scheme becomes difficult after $\approx$ 25 stages.

But more cooling is desirable $\Rightarrow$ use lithium lenses.





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Collaboration Organization

Spokesperson: Bob Palmer (BNL)

Associate Spokesmen: Alvin Tollestrup (FNAL), Andy Sessler (LBNL)

Executive Committee: Bob Palmer, Juan Gallardo (BNL),
Steve Geer, Alvin Tollestrup (FNAL),
Andy Sessler, Jonathan Wurtele (LBNL),
Dave Cline (UCLA), Kirk McDonald (Princeton),
Sasha Skrinsky (BINP), Don Summers (U. Miss)

Technical Committee: Bob Palmer, Rick Fernow (BNL),
Bob Noble (FNAL), Ron Scanlan (LBNL)

Theoretical R&D: Organizer: J. Wurtele

Cooling Experiment: Spokesman: Steve Geer (FNAL),
Coordinators: Rick Fernow (BNL), Bill Turner (LBNL)

Target and Capture Experiment: Spokesmen:
Kirk McDonald (Princeton), Bob Weggel (BNL)

Pulsed Accelerator Magnet: Organizer: Don Summers (U. Miss.)

Superconducting Accelerator Magnet: Organizer: R. Scanlan (LBNL)

BNL E-910 (Pion Production): Spokesman: Harold Kirk (BNL)

FNAL E-932 (Proton Compression): Spokesman: Jim Norem (ANL)

R&D Priorities

- Theoretical Studies:
  - Cooling scenarios (now working 'on paper'!)
  - 4-TeV Collider
  - 'Demonstration' Machines
    - $\approx$ 100-GeV Higgs Factory
    - 200- and 400-GeV Upgrades
- Experimental Programs:
  - Cooling Demonstration
  - Target and RF Capture Demonstration
  - Prototype Superconducting Accelerator Magnets and RF Cavities

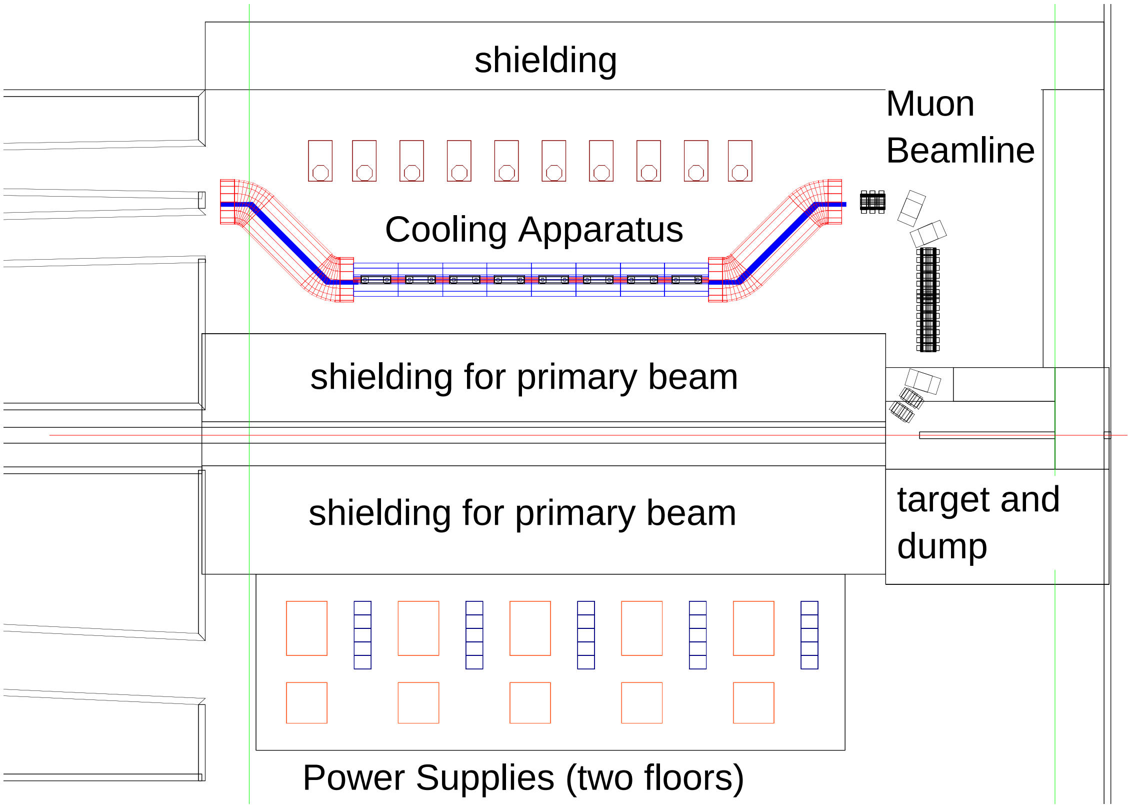
Cooling Demonstration Experiment

Test basic cooling components:

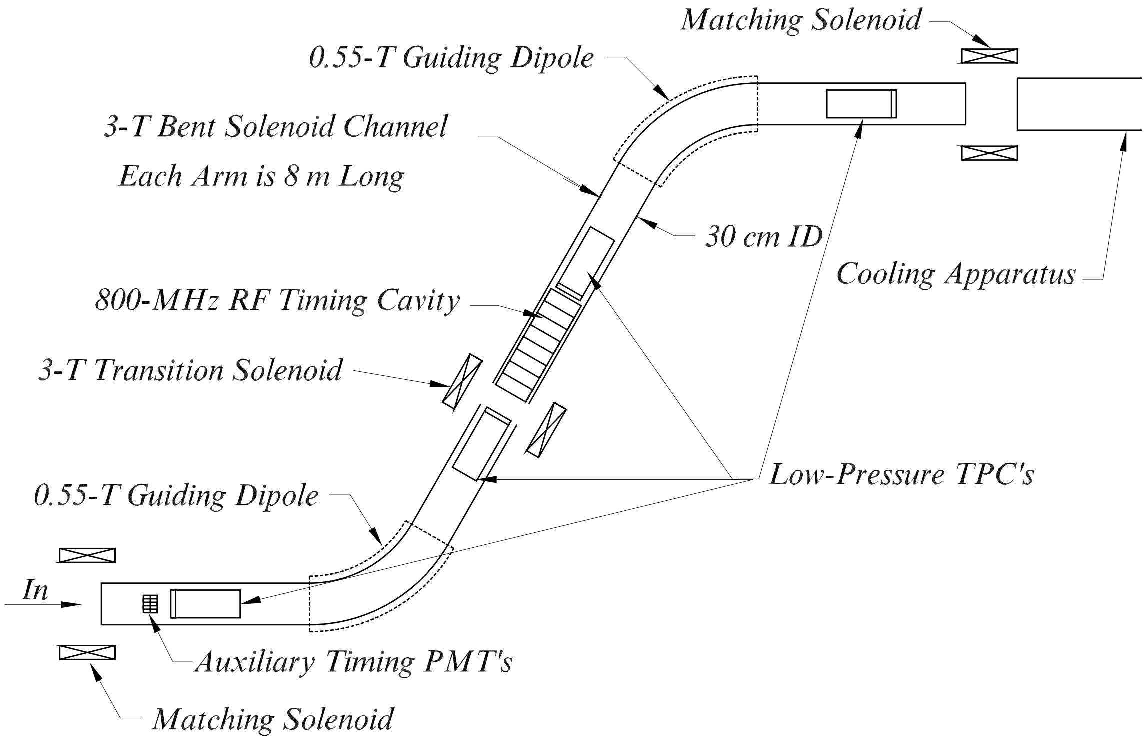
- Alternating solenoid lattice, RF cavities, LH_2 absorber
- Lithium lens (for final cooling)
- Dispersion + wedge absorbers to exchange longitudinal and transverse phase space

Proposal presented to Fermilab PAC on May 15, 1998.

Possible site: Meson Lab at Fermilab:



Measure 6-D Emittance Before and After Cooling



Required detector resolution for a 3% (σ) measurement of the 6-d emittance.

Parameter	Value
$\sigma_{x,D} = \sigma_{y,D}$	200 μm
$\sigma_{x',D} = \sigma_{y',D}$	5 mrad
$\sigma_{P,D}/P$	0.0014
$\sigma_{z,D}$	2 mm
$\sigma_{t,D}$	8 ps

The 8-ps timing requirement is the most stringent.

Overview of Emittance Measurement

Measure muons individually, and form a virtual bunch in software:

$\Rightarrow$ Must know timing to ≈ 8 psec to select muons properly phased to the 800-MHz RF of the cooling apparatus.

$\Rightarrow$ Use RF accelerating cavity to correlate time with momentum.

$\Rightarrow$ Must measure momentum 4 times.

[$\Rightarrow$ Must also have coarse timing ($\lesssim 300$ psec) to remove phase ambiguity.]

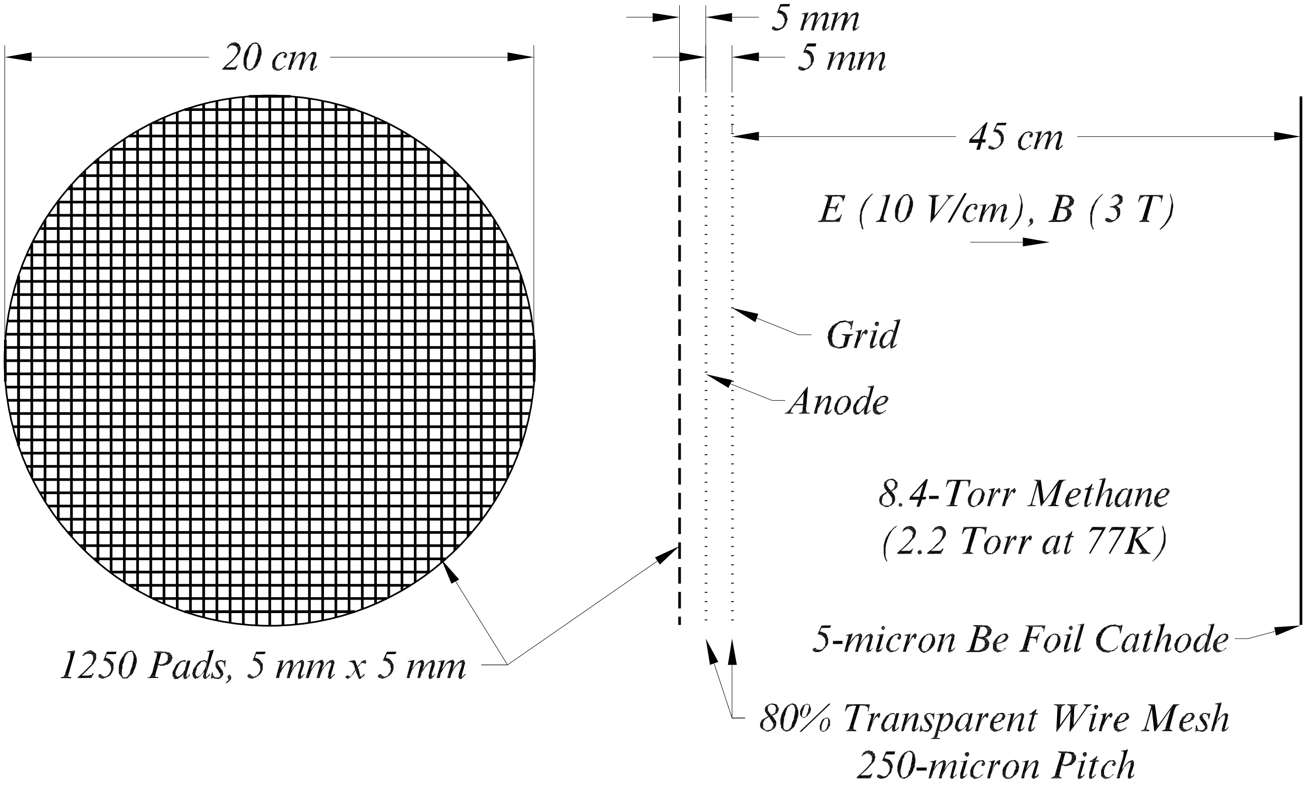
Large transverse emittance, $\epsilon_{N,x} = 1500\pi$ mm-mrad:

$\Rightarrow$ Confine the muon beam in a 3-Tesla solenoid channel.

$\Rightarrow$ Track muons in the 3-T field $\Rightarrow$ **Time projection chamber**.

$\Rightarrow$ Use bent solenoids (toroidal sectors with guiding dipoles) for momentum dispersion.

Time Projection Chamber



- Two TPC's in same pressure vessel for each of 4 momentum spectrometers.
- Low gas pressure ⇒ low operating voltage.
- 1250 cathode pads, 50-MHz timing sampling.
- Analog pipeline via 512-deep switched-capacitor arrays.
- No trigger: capture entire 10 μsec window.
- Could process $\approx$ 10 tracks $\Rightarrow \approx$ 1 MHz rate capability.

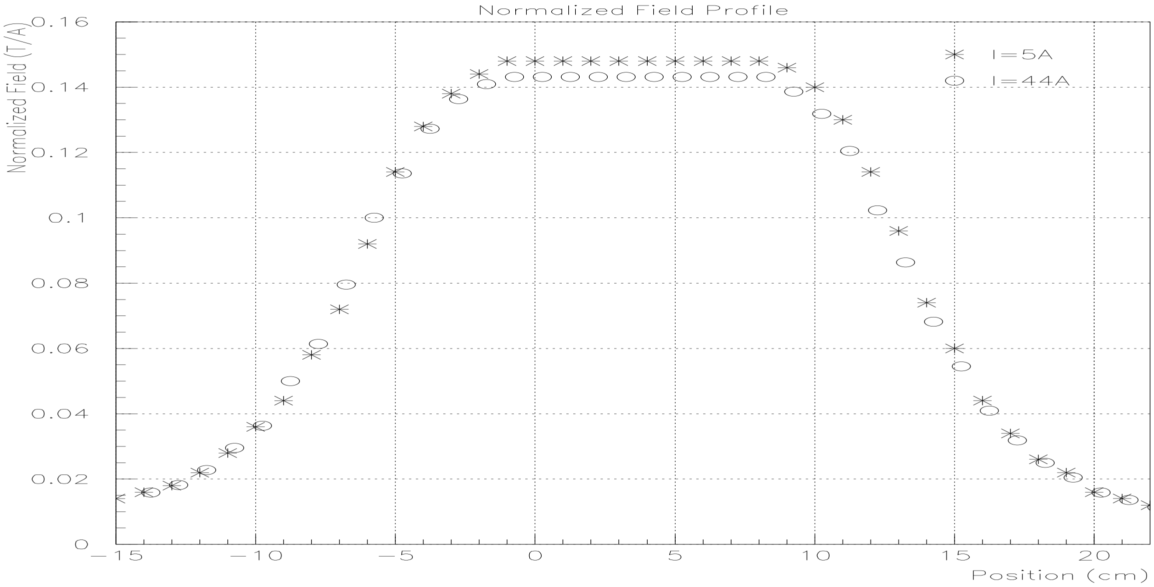
TPC R&D at Princeton

We are now building a small 16-channel low-pressure TPC, which can fit inside an old 6-T magnet that we recently recomissioned.

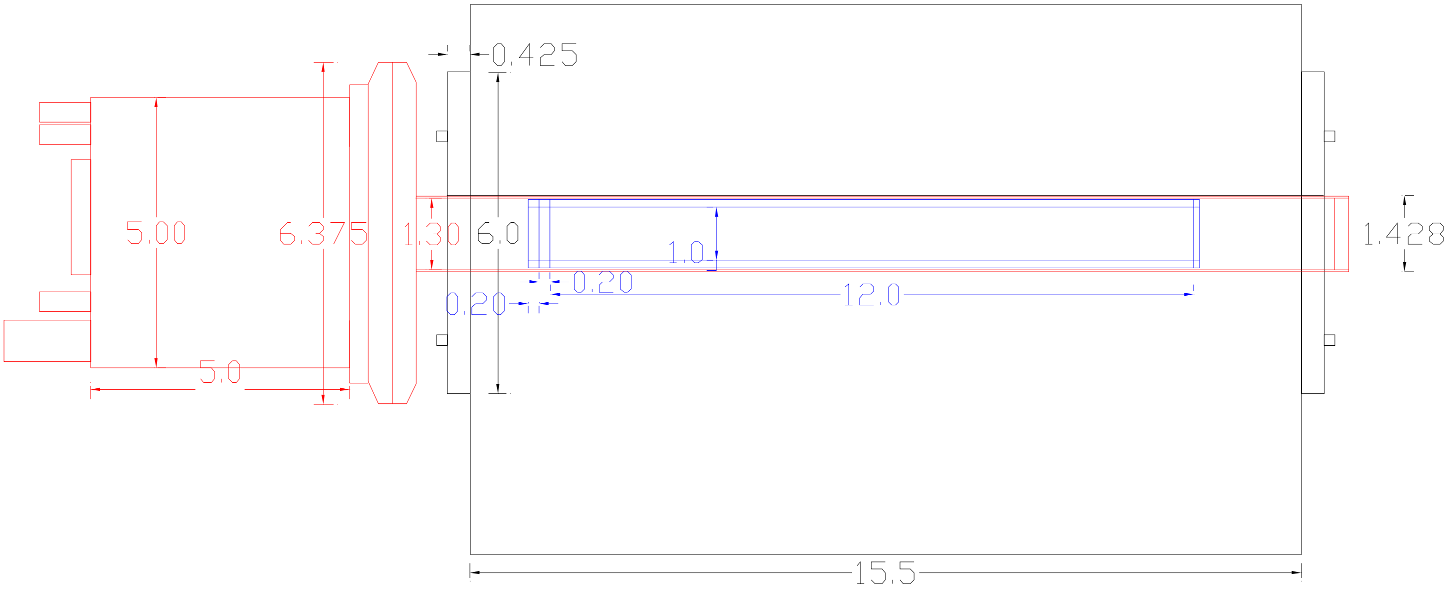
To study:

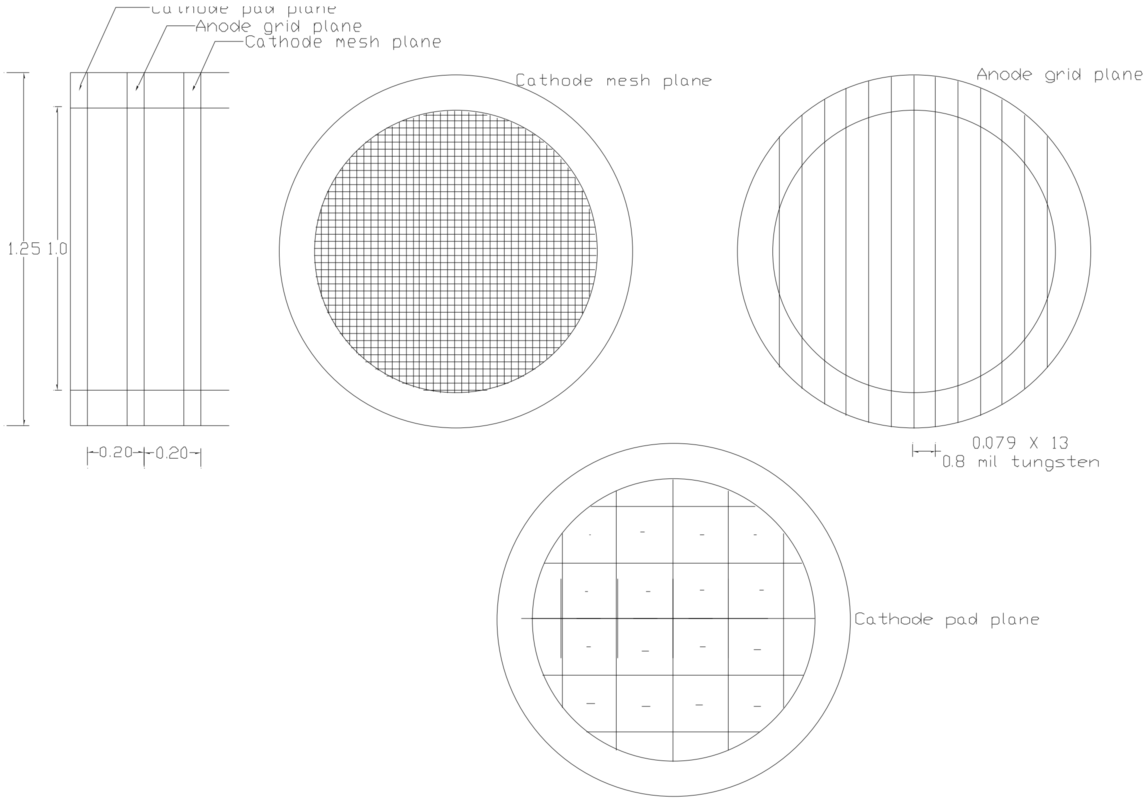
1. Accuracy of time and space interpolation via charge sharing on readout pads.
2. Measurement of gas gain, drift velocity and diffusion at low temperature and pressure for methane and other candidate gases.
3. Verification of detector performance over long drift paths in a strong magnetic field.
4. Viability of placement of readout electronics next to pad plane (inside the magnetic field).
5. Dynamic range the STAR SCA at 50 MHz (somewhat higher than nominal).

6-T, 3.5-cm-Diameter, Warm-Bore Magnet



Prototype TPC Now Under Construction





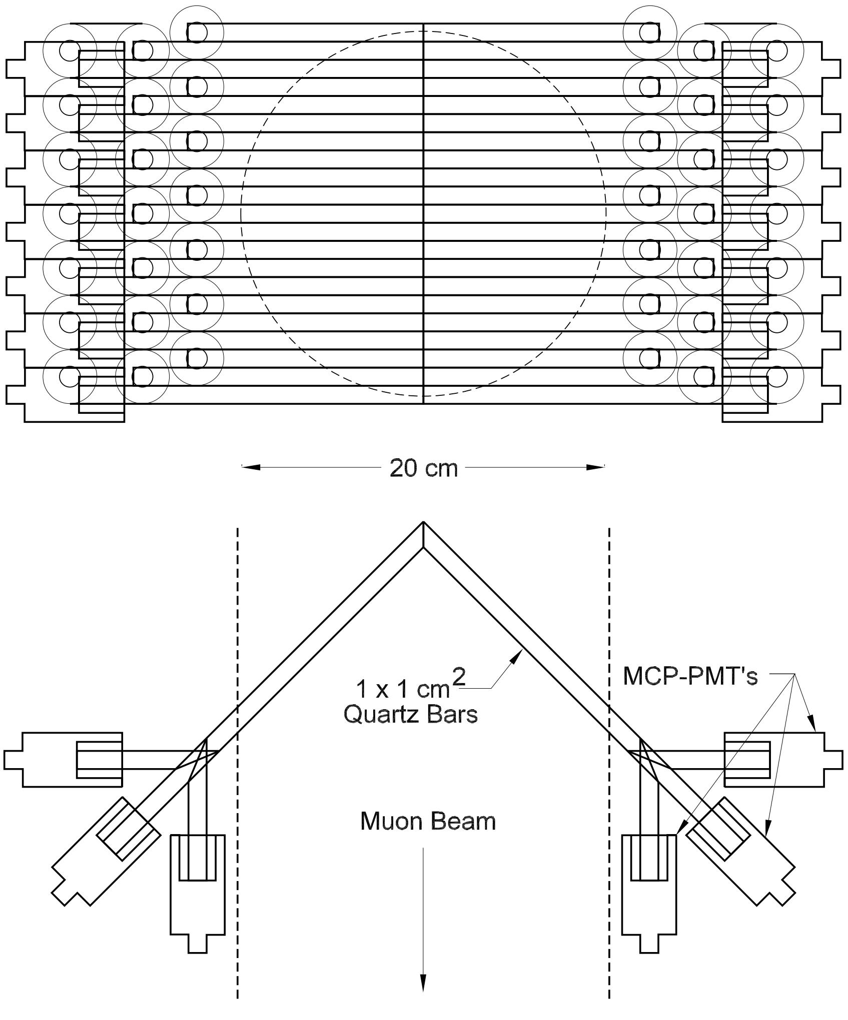
Alternative Timing Scheme

RF timing scheme is expensive.

Consider Čerenkov light viewed by microchannel-plate PMT's.

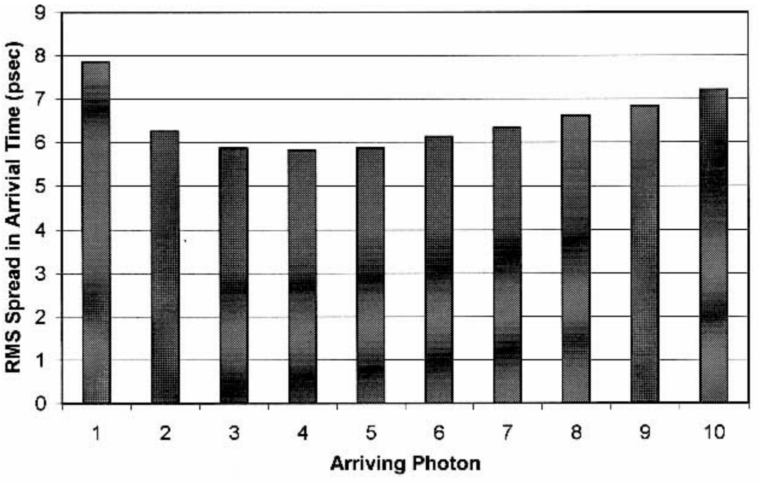
Hamamatsu R3809U claimed to have 11-ps (σ) transit-time jitter.

Couple to quartz bars tilted near the Čerenkov angle:

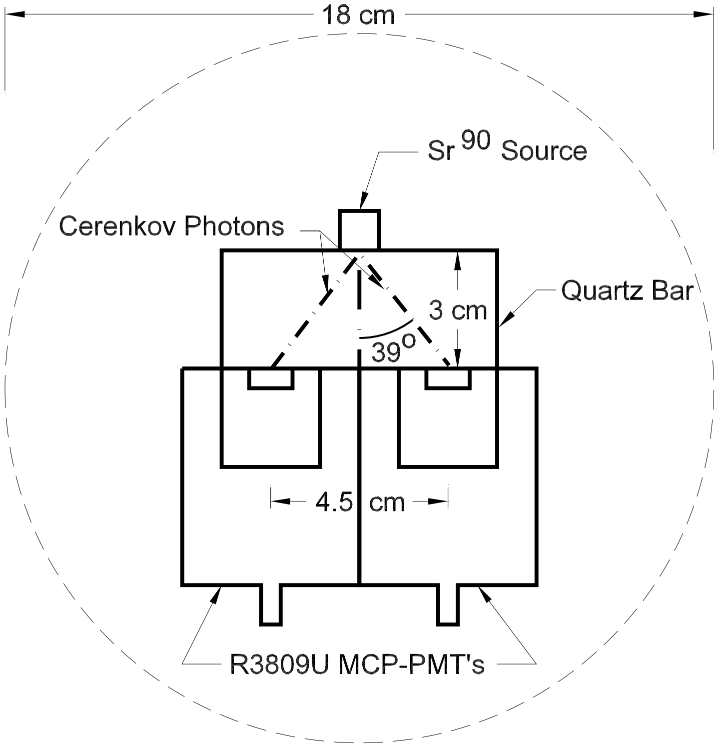


Simulation and Test

Monte Carlo suggests that could achieve $\sigma_t = 6$ps on 4th photon.



Test time resolution and PMT gain in high magnetic fields at FSU National Magnet Laboratory.

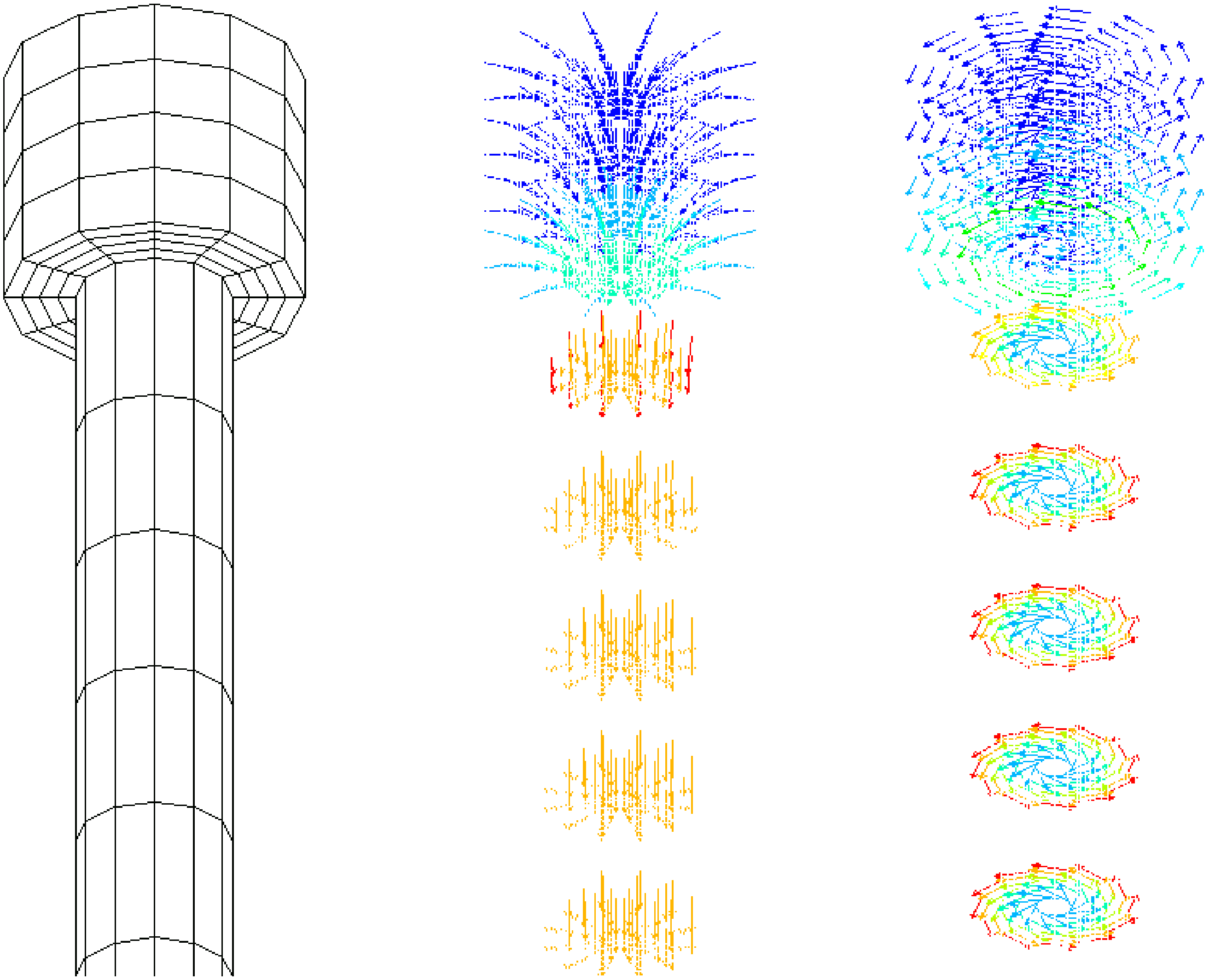


ANSYS Finite Element Analysis

For targetry issues, need simultaneous simulation of thermal, hydrodynamic and electromagnetic effects.

Among commercial codes, ANSYS seems best suited.

Example: current and magnetic field distributions in a lithium lens:

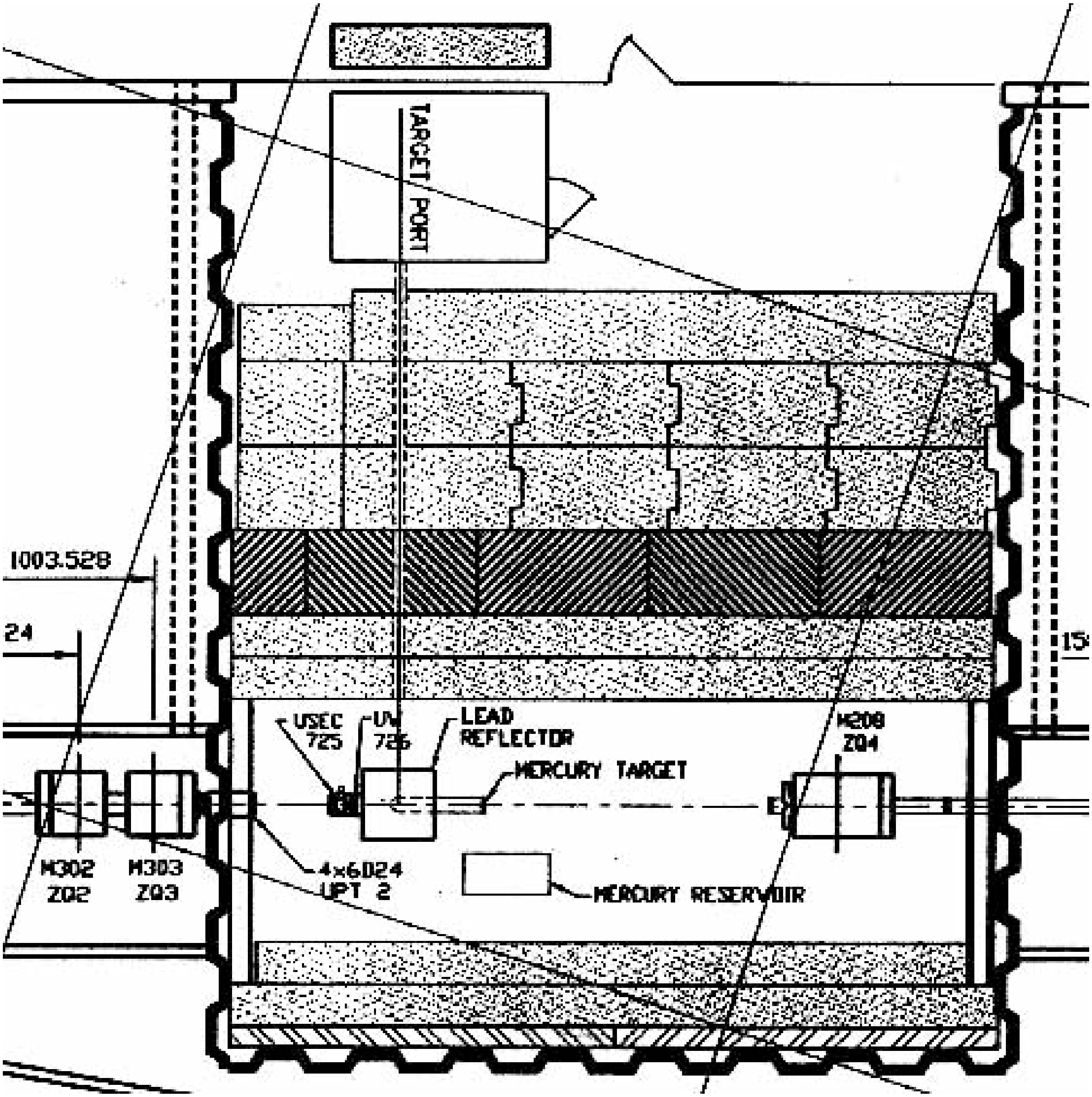


Targetry R&D

- Simulation:
  - Eddy currents in liquid jets: ANSYS: EMAG and FLOTRAN.
  - Shock heating: ANSYS: LSDYNA.
  - Plus research codes at various national labs.
- Lab tests:
  - Expose trough of liquid metal to BNL beam.
  - Squirt liquid jet into 20-T magnet at FSU Magnet lab.
  - Liquid jet + 20-T magnet + proton beam at BNL.
  - (RF cavity + superconducting magnet near target in proton beam.)

Proposals to BNL and FSU in preparation.

Beams Tests in BNL FEB U-Line

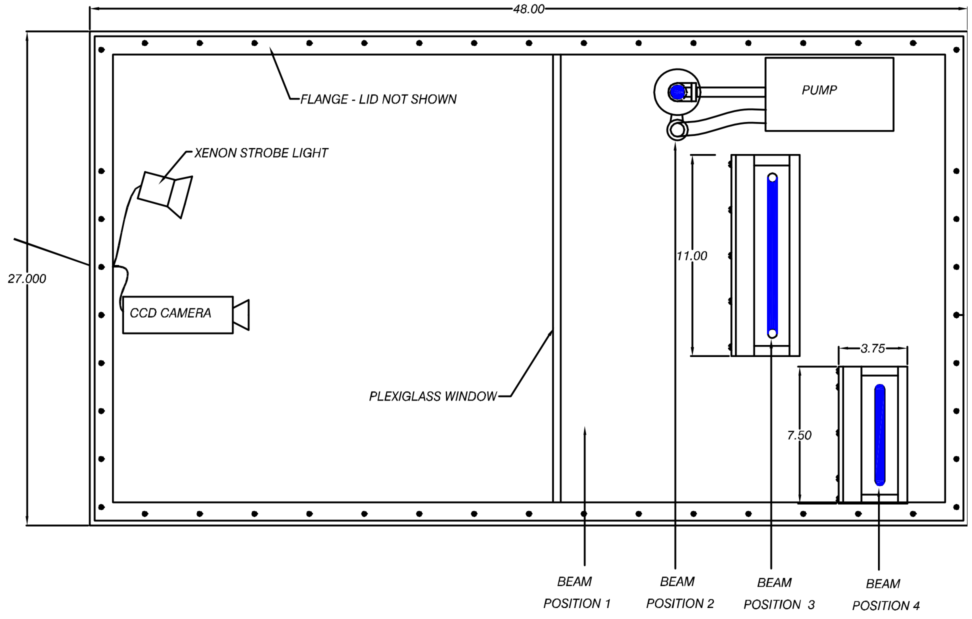


Area previously used by Hg spallation target test.

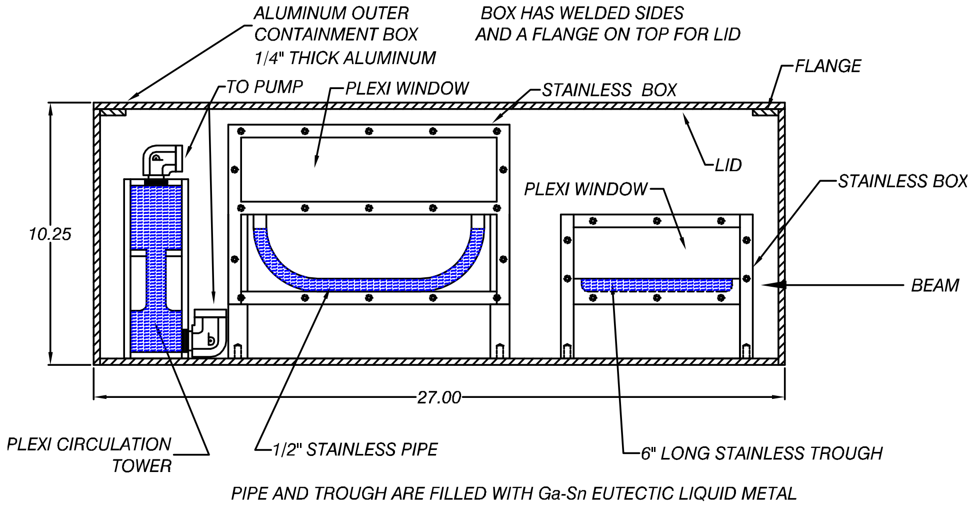
Can target single AGS pulses of 10^{13} protons in 25 ns.

Liquid Metal in a Trough and in a Pipe

TOP VIEW



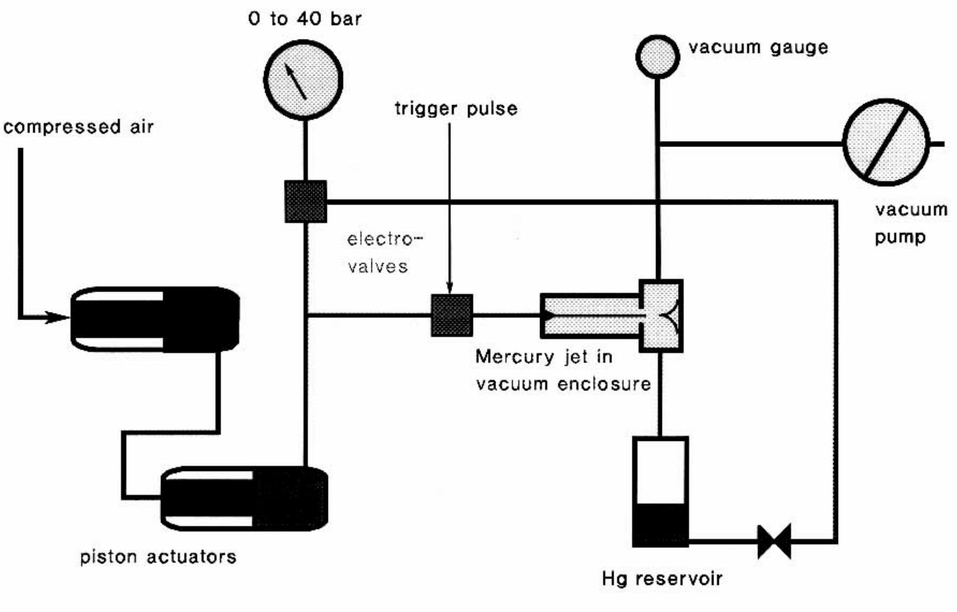
CAMERA VIEW



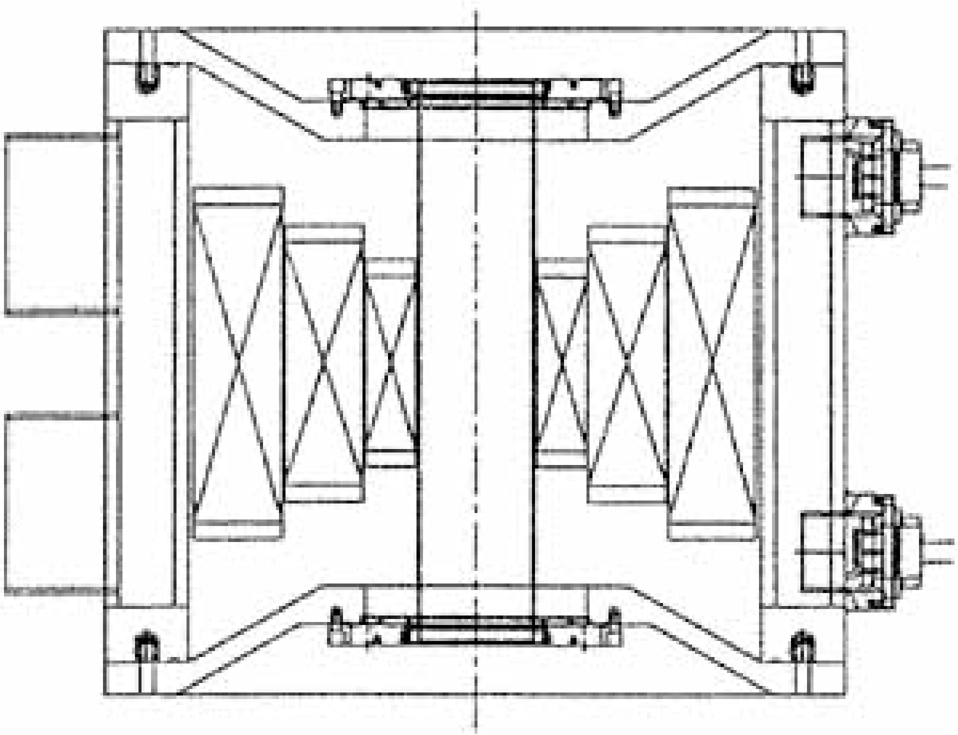
Instrumentation: CCD camera + fiberoptic interferometric strain gauges (from Fiber and Sensor Technologies)

Liquid Jet + 20-T Magnet

Ga-In liquid jet based on CERN (Colin Johnson) design:



Test in new 20-T, 24-MW Bitter magnet at FSU Magnet Lab:



Summary of Muon Collider R&D at Princeton in FY99

- Prototype low-pressure TPC.
- Tests of precision timing via Čerenkov light and MCP-PMT's (with UCLA).
- ANSYS simulations of lithium lens and liquid jet (with BNL + ...)
- Beam test of liquid metal at BNL (with BNL and ORNL).
- Test of liquid metal jet in high-field magnet (with CERN and FSU)