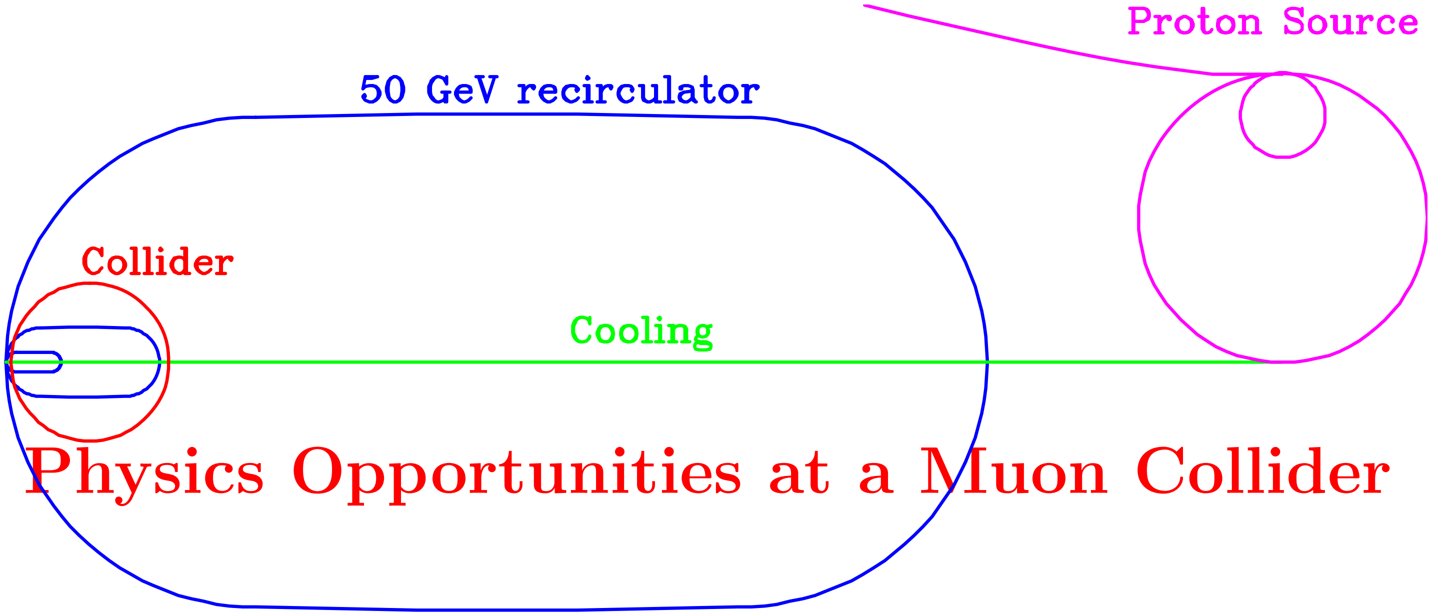

Physics Opportunities at a Muon Collider

Kirk T. McDonald

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February 5, 1999

Seminar at Oak Ridge National Laboratory

Muon Collider main page:

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

Muon Collider R&D Status Report:

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

Princeton Muon Collider page:

`http://puhep1.princeton.edu/mumu/`

AIP Conference Proceedings, Vols. 352, 372, 435 & 441

The Y2K Problem for Particle Physics

- Can elementary particle physics prosper for a 2nd century with laboratory experiments based on innovative particle sources?
- Can a full range of new phenomena be investigated:
  - Neutrino mass ⇒ a 2nd 3×3 (or larger?) mixing matrix.
  - Precision studies of Higgs bosons.
  - A rich supersymmetric sector.
  - ... And more ....
- Will our investment in future accelerators result in more cost-effective technology, that is capable of extension to 10's of TeV of constituent center-of-mass energy?

The Solution...

- A **Muon Collider** is the best option to accomplish the above!

What is a Muon Collider?

An accelerator complex in which

- Muons (both μ^+ and μ^-) are collected from pion decay following a pN interaction.
- Muon phase volume is reduced by 10^6 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.
- Intense neutrino beams and spallation neutron beams are available as byproducts.

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

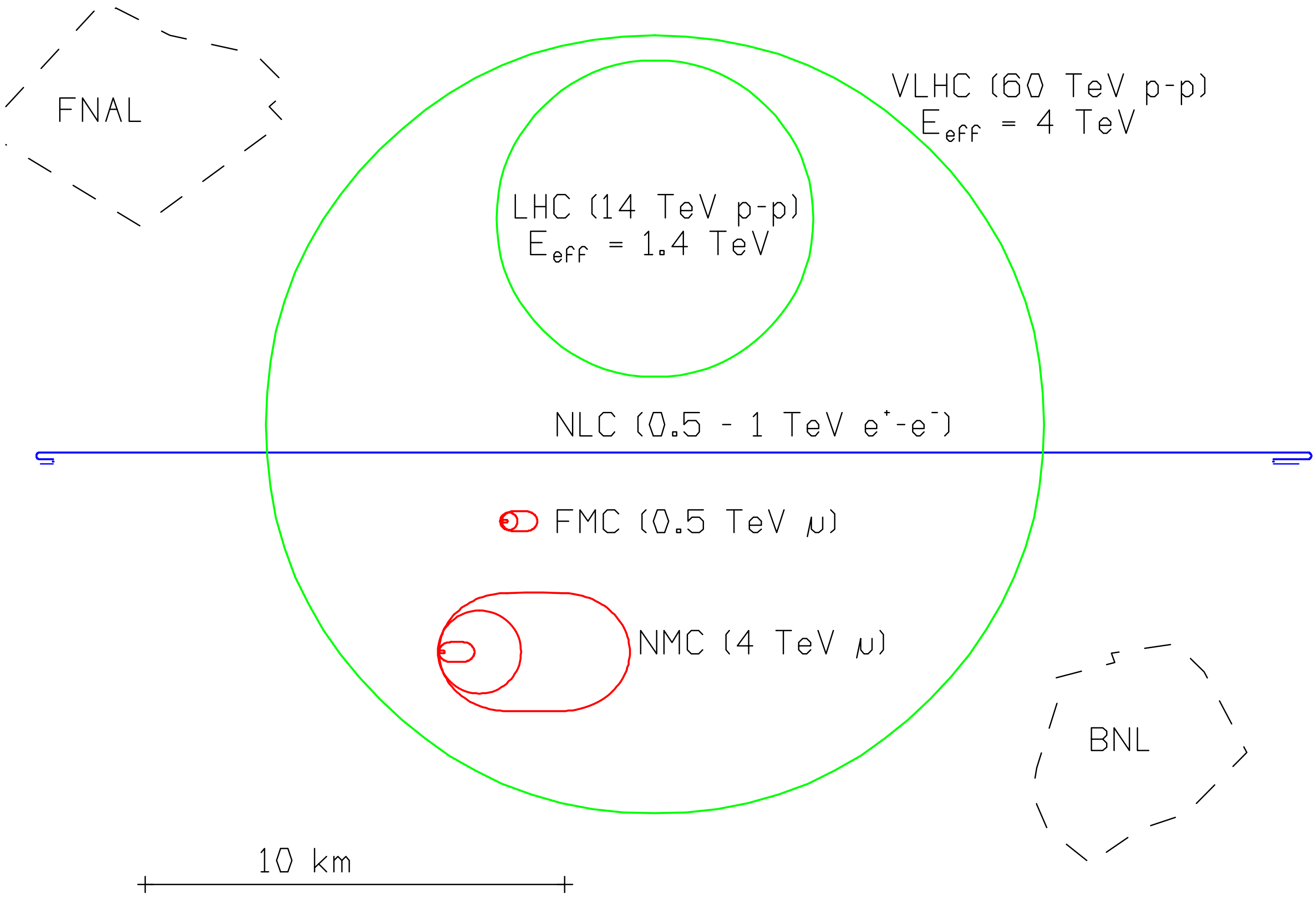
- Must cool muons quickly (stochastic cooling won't do).
- Detector backgrounds at LHC level.
- Potential personnel hazard from ν interactions.

Baseline Parameters

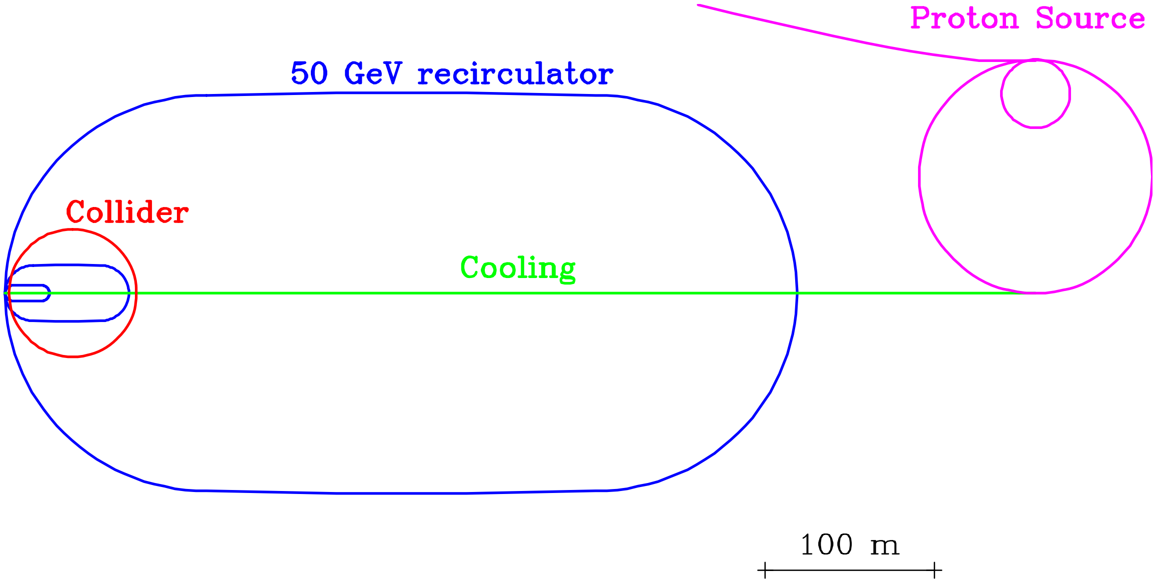
Table 1: Baseline parameters for high- and low-energy muon colliders. Higgs/year assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width $\Gamma = 2.7$ MeV; 1 year = 10^7 s.

CoM energy	TeV	3	0.4		0.1	
p energy	GeV	16	16		16	
p's/bunch		2.5×10^{13}	2.5×10^{13}		5×10^{13}	
Bunches/fill		4	4		2	
Rep. rate	Hz	15	15		15	
p power	MW	4	4		4	
μ/bunch		2×10^{12}	2×10^{12}		4×10^{12}	
μ power	MW	28	4		1	
Wall power	MW	204	120		81	
Collider circum.	m	6000	1000		350	
Ave bending field	T	5.2	4.7		3	
Depth	m	500	100		10	
Rms $\Delta P/P$	%	0.16	0.14	0.12	0.01	0.003
6d ϵ_6	$(\pi \mathrm{m})^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
Rms ϵ_n	π mm-mrad	50	50	85	195	290
β^*	cm	0.3	2.6	4.1	9.4	14.1
σ_z	cm	0.3	2.6	4.1	9.4	14.1
σ_r spot	μm	3.2	26	86	196	294
σ_θ IP	mrad	1.1	1.0	2.1	2.1	2.1
Tune shift		0.044	0.044	0.051	0.022	0.015
n_{turns} (effective)		785	700	450	450	450
Luminosity	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	7×10^{34}	10^{33}	1.2×10^{32}	2.2×10^{31}	10^{31}
Higgs/year				1.9×10^3	4×10^3	3.9×10^3

Footprints



A First Muon Collider to study light-Higgs production:



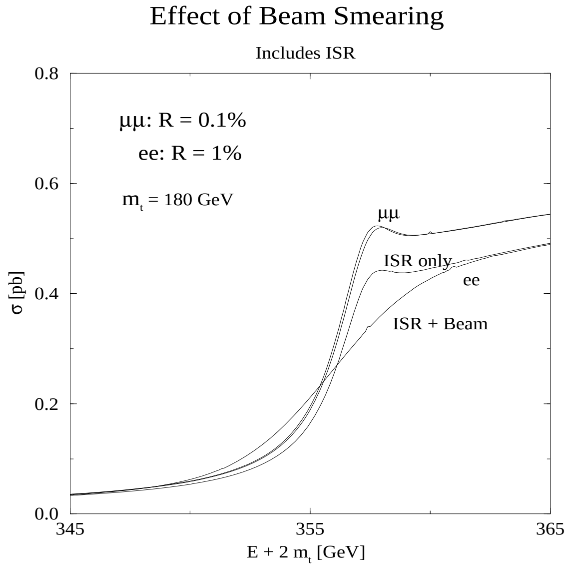
The Case for a Muon Collider

- 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.
- Precision initial state superior even to e^+e^-.

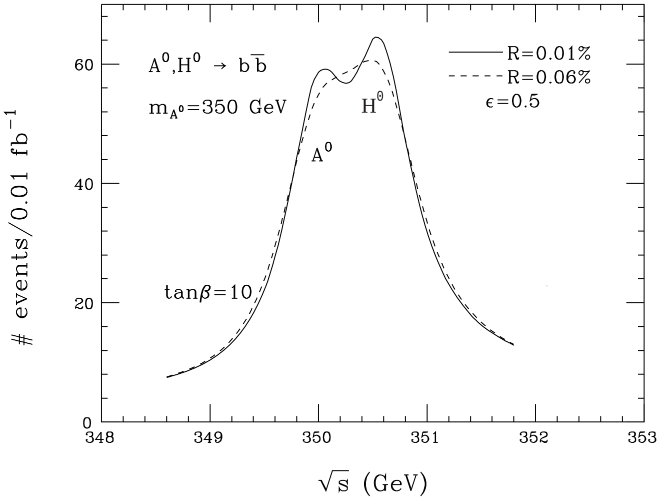
  Muon polarization $\approx 25\%$,

  $\Rightarrow$ Can determine E_{beam} to 10^{-5} via $g-2$ spin precession.

$t\bar{t}$ threshold:



Nearly degenerate A^0 and H^0:



- 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.

  Initial scenario in a low-energy muon storage ring.

  Study CP violation via CP-conjugate initial states:

$$\mu^+ \longrightarrow e^+ \overline{\nu}_\mu \nu_e$$

$$\mu^- \longrightarrow e^- \nu_\mu \overline{\nu}_e$$

Future Frontier Facilities

(A Personal Assessment)

- Hadron collider (LHC, SSC): ≈ \$100k/m [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 collider needs only ≈ 1/10 the CM energy

  to have equivalent physics reach to a hadron collider.

  Ex: NLC, 1.5-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 (?).

HEPAP Subpanel Report on PLANNING FOR THE FUTURE OF U.S. HIGH-ENERGY PHYSICS

February 1998

Recommendation on R&D for a Muon Collider

The Subpanel recommends that an expanded program of R&D be carried out on a muon collider, involving both simulation and experiments. This R&D program should have central project management, involve both laboratory and university groups, and have the aim of resolving the question of whether this machine is feasible to build and operate for exploring the high-energy frontier. The scale and progress of this R&D program should be subject to additional review in about two years.

CERN-EP/98-03
CERN-SL 98-004 (AP)
CERN-TH/98-33

Options for Future Colliders at CERN

J. Ellis, E. Keil, G. Rolandi

January 23, 1998

6 RECOMMENDATIONS

3. CERN should launch technical studies of $\mu^+\mu^-$ colliders, notably in the areas of the source and beam cooling, and should explore the possibility of locating such machines on or in the neighbourhood of the CERN site.

6. These studies should be carried out in collaborations with other laboratories, since most technical problems do not depend on the site. CERN's goal in these collaborations should be to contribute to the global pool of technologies for future collider options. It should confirm its reputation as a valuable and reliable partner in the international collaborations that will form to develop proposals for future collider projects.

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Spokesperson: R.B. Palmer

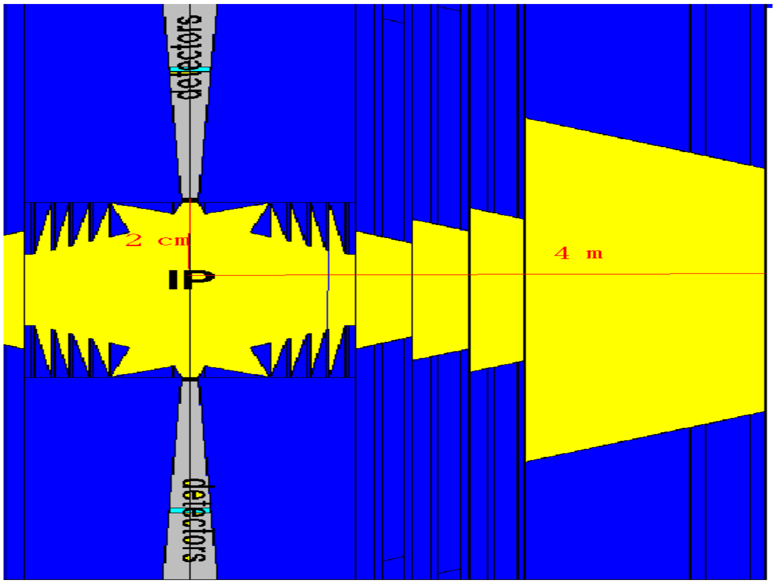
Scheduled Muon Collider Mini-Workshops and Conferences

Subject	Organizer	Place	Date	Additional Information
Expt. rf systems	N. Holtkamp	FNAL	Mar. 18-19, 1999	Contact Norbert Holtkamp (holtkamp@fnal.gov)
Cooling Theory & MUCOOL	R. Fernow and S. Geer	LBNL	April 12-14, 1999	Contact R. Fernow (fernow@bnl.gov) or S. Geer (sgeer@fnal.gov) or John Corlett (jncorlett@LBL.gov
Muon Neutrino Sources	J. Wurtele	LBNL	April 15, 1999	Contact J. Wurtele (wurtele@socrates.berkeley.edu)
Collaboration Meeting	B. Palmer	St. Croix (USVI)	May 20-26, 1999	Contact J. Gallardo (gallardo@bnl.gov)
Neutrino Factories based on Muon Accumulators	B. Autin and A. Blondel	Lyon (France)	July 5-9, 1999	Contacts Autin (Bruno.Autin@cern.ch); J. Wurtele (wurtele@socrates.berkeley.edu) and S. Wojcicki
Muon Colliders at the Highest Energies	C. Johnson, B. King, J. Lykken	Montauk (NY)	Sep 27 - Oct 1, 1999	Contact the organizers (Colin.Johnson@cern.ch;bking@bnl.gov;lykken@fnal
Physics Potential & Development of mu$^+$-mu$^-$ Colliders	D. Cline	Fairmont Hotel San Francisco (CA)	Dec 15 - 17, 1999	Contact Kevin Lee (klee@physics.ucla.edu)

Technical Challenges

- 16-GeV proton driver, 15 Hz, 4-MW beam power, 1-ns bunch length (C. Ankenbrandt, T. Roser...).
- **Targetry and Capture**
- **Muon Cooling**
- Acceleration – more work needed
- Storage rings have beautiful, highly corrected solutions due to heroic work of Al Garren, Carol Johnstone and Dan Trbojevič.
- Interaction region and detector design – more work needed

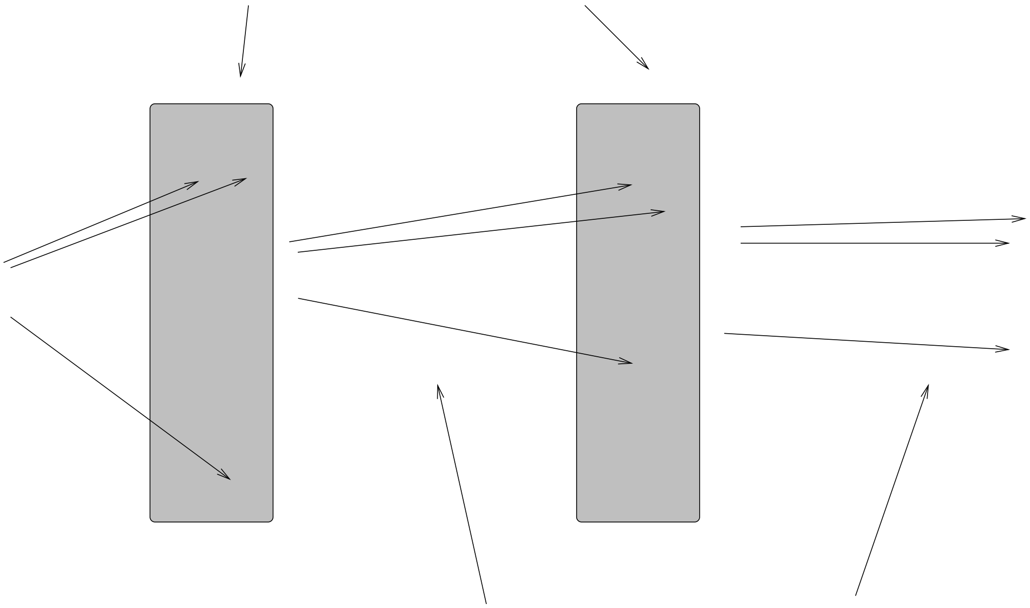
A muon's view of the interaction region:



Ionization Cooling

(An Idea So Simple It Might Just Work)

- Ionization: takes momentum away.
- RF acceleration: puts momentum back along z axis.
- $\Rightarrow$ Transverse "cooling".



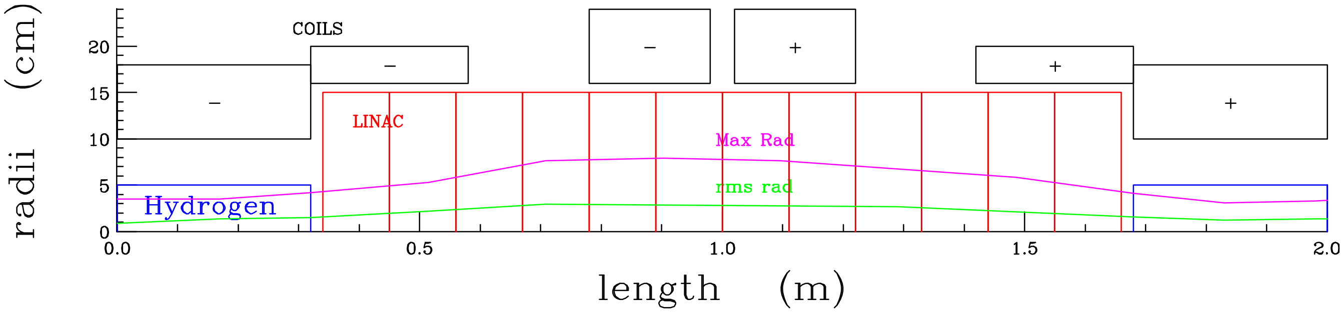
Particles are slowed along their path (dE/dx)

Particles are accelerated longitudinally

- Origin: G.K. O'Neill, Phys. Rev. **102**, 1418 (1956).
- But won't work for electrons or protons.
- So use muons: Balbekov, Budker, Skrinsky, late 1960's.

The Details are Delicate

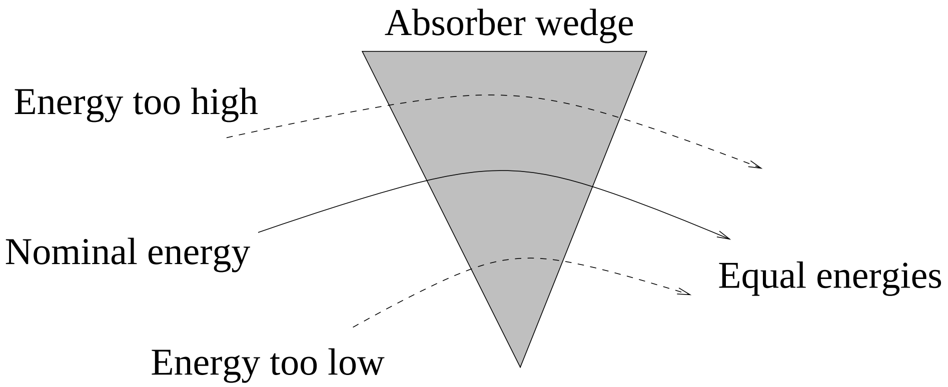
Use channel of LH_2 absorbers, rf cavities and alternating solenoids (to avoid buildup of angular momentum).



The Energy Spread Rises due to “Straggling”

⇒ 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:



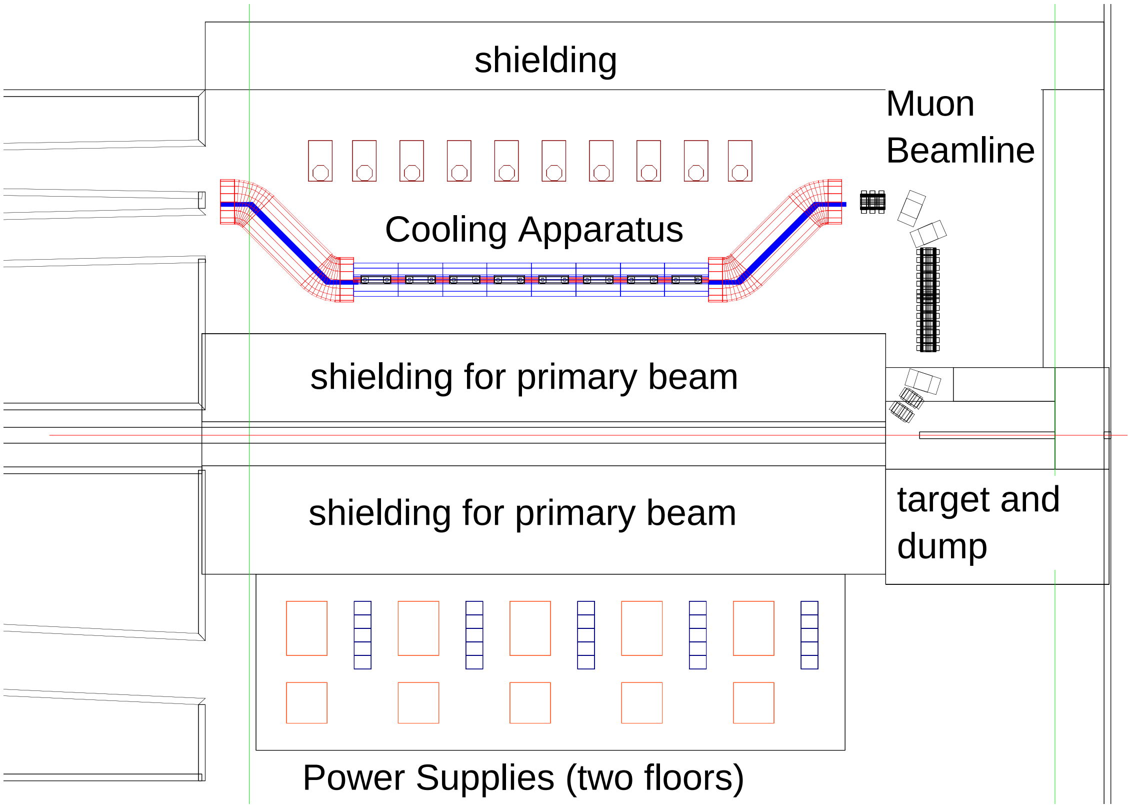
Cooling Demonstration Experiment

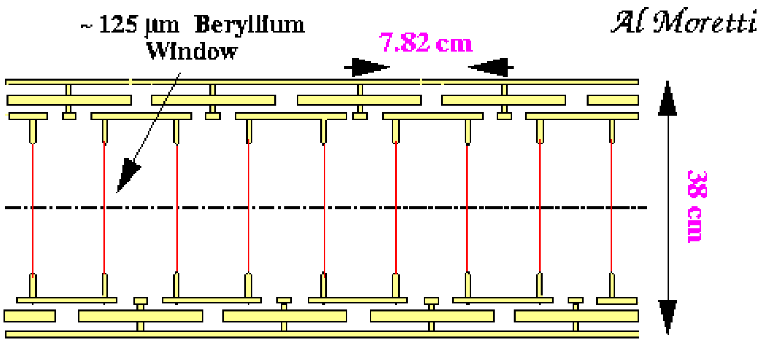
Test basic cooling components:

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

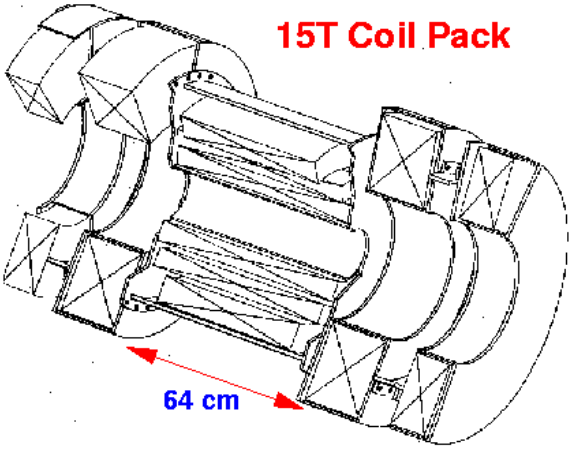
Track individual muons; simulate a bunch in software.

Possible site: Meson Lab at Fermilab:

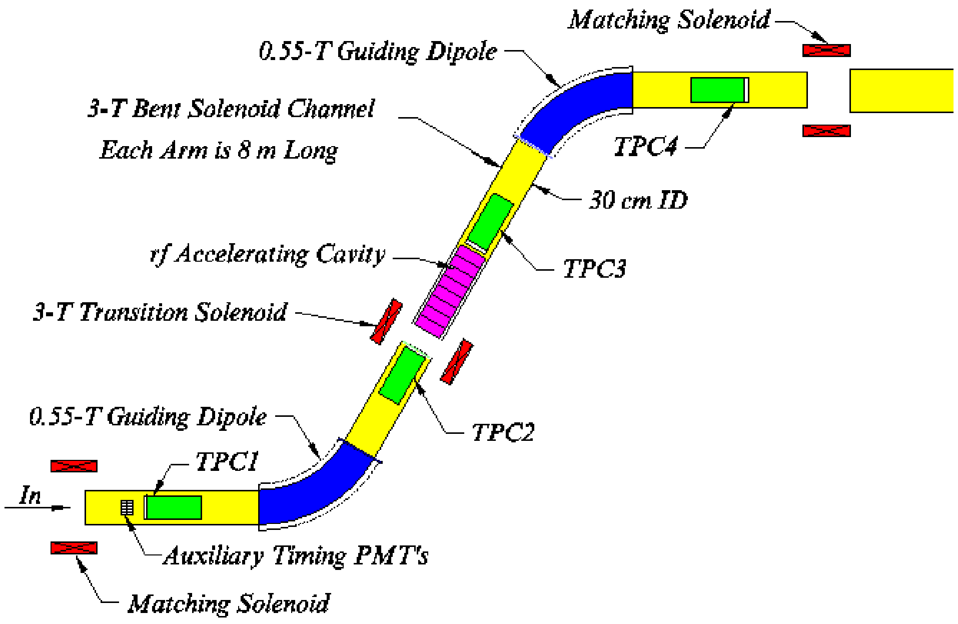




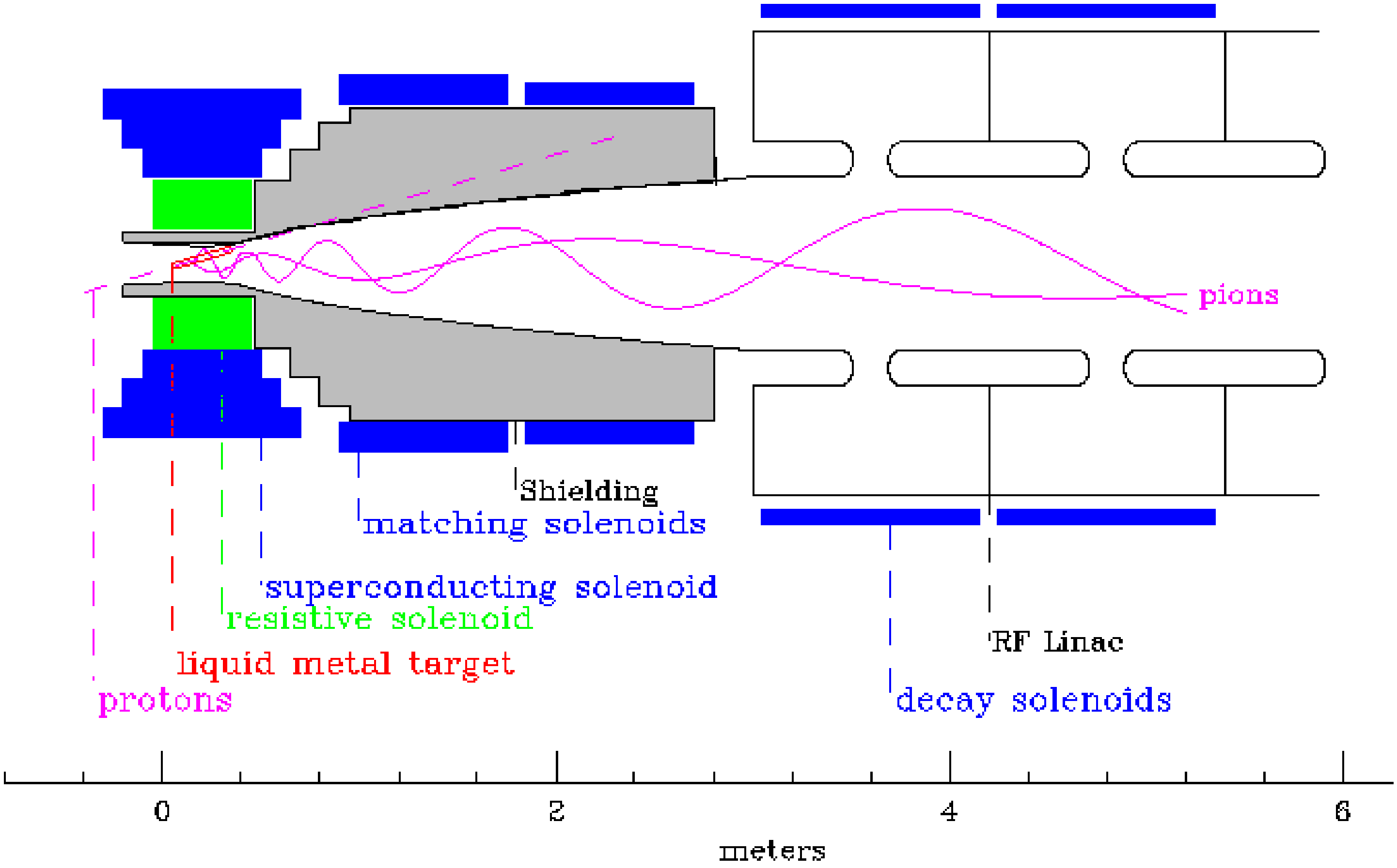
π/2 805 MHz Interleaved Cavity



Detail of the emittance diagnostics:



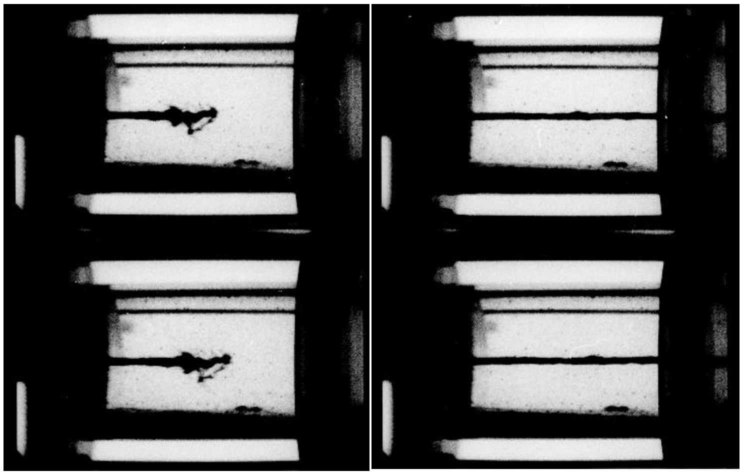
Overview of Targetry for a Muon Collider



- 1.2×10^{14} $\mu^{\pm}$/s via π-decay from a 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 a 1.25-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, possibly 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 tests)

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.

Effect of a Short Beam Pulse on a Liquid?

Will shock heating disperse the target violently?

Simple model to estimate magnitude of shock pressure wave:

Beam energy heats liquid (no heat flow);

Liquid expands causing strain (shock wave);

Liquid 'tears' if pressure exceeds tensile strength.

Fact: tensile strength (T_S) is about $0.002E$ (Young's modulus) in most metals.

$$\Delta U[\mathrm{J/gm}] = C\Delta T = \frac{C}{\alpha}\frac{\Delta l}{l} = \frac{C}{\alpha}\frac{P}{E} \approx 0.002\frac{C}{\alpha},$$

when $P = T_S$:

Ex: Gallium: $\alpha \approx 2 \times 10^{-5}$/K; $C_P \approx 0.3$ J/gm-K, tears when

$$\Delta U \approx (0.002)(0.3)/(2 \times 10^{-5}) \approx 30 \text{ J/gm}.$$

This is roughly the nominal energy deposition in the target!

ISOLDE Liquid Targets Damaged by Short Pulses

Cracks developed at braised joints and lead sprayed out.

Magnetohydrodynamics

Field $\mathbf{E}'$ inside a conductor with velocity $v \ll c$ in field $\mathbf{B}$:

$$\mathbf{E}' = \mathbf{E} + \mathbf{v} \times \mathbf{B}, \qquad \text{(MKSA)}.$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \qquad \nabla \times \mathbf{B} = \mu_0 \mathbf{j}, \qquad \mathbf{j} = \sigma \mathbf{E}' = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}),$$

$$\Rightarrow \qquad \frac{\partial \mathbf{B}}{\partial t} = \frac{\nabla^2 \mathbf{B}}{\mu_0 \sigma} + \nabla \times (\mathbf{v} \times \mathbf{B}).$$

$\Rightarrow$ Field diffusion time into long cylinder: $\tau = \mu_0 \sigma r^2$.

Ex: $\sigma_{\rm Hg} = \sigma_{\rm copper}/50,\ r = 1$ cm,

$\Rightarrow \tau \approx 4\pi \times 10^{-7} \cdot 10^6 \cdot (10^{-2})^2 \approx 10^{-4}$ s.

Magnetic Reynolds number : $\mathcal{R} = \dfrac{\tau v}{D} \approx \dfrac{10^{-4}{\rm s} \cdot 10{\rm m/s}}{0.3{\rm m}} = 0.003,$

for motion through a solenoid of diameter $D = 0.3$ m.

$\Rightarrow$ The liquid is a "poor" conductor, and the field penetrates quickly.

Eddy Current Effects on Conducting Liquid Jets

- In frame of jet, changing magnetic field induces eddy currents.
- Lenz: Forces on eddy current oppose motion of jet.
- Longitudinal drag force $\Rightarrow$ won't penetrate magnet unless jet has a minimum velocity: $\sigma = \sigma_{\rm Cu}/60$, $\rho = 10$ g/cm^3, $\Rightarrow$

$$v_{z,\rm min} \approx \frac{\sigma r^2 B_0^2}{6\rho D} \approx 60 \text{ m/s} \left[\frac{r}{1 \text{ cm}}\right] \left[\frac{r}{D}\right] \left[\frac{B_0}{20 \text{ T}}\right]^2 .$$

  Ex: $B_0 = 20$ T, $r = 1$ cm, $D = 20$ cm, $\Rightarrow v_{\rm min} = 3$m/s.

- Drag force is larger at larger radius $\Rightarrow$ planes deform into cones:

$$\frac{\Delta z(r)}{r} \approx \frac{\sigma r^2 B_0^2 \alpha}{12 \rho v_z} \approx -3\alpha \left[\frac{r}{1 \text{ cm}}\right] \left[\frac{B_0}{20 \text{ T}}\right]^2 \left[\frac{10 \text{ m/s}}{v}\right].$$

  Ex: $\alpha = L/D = 2$, $r = 1$ cm, $v = 10$ m/s $\Rightarrow \Delta z = 6$ cm.

- Radial pressure: compression as jet enters magnet, expansion as it leaves:

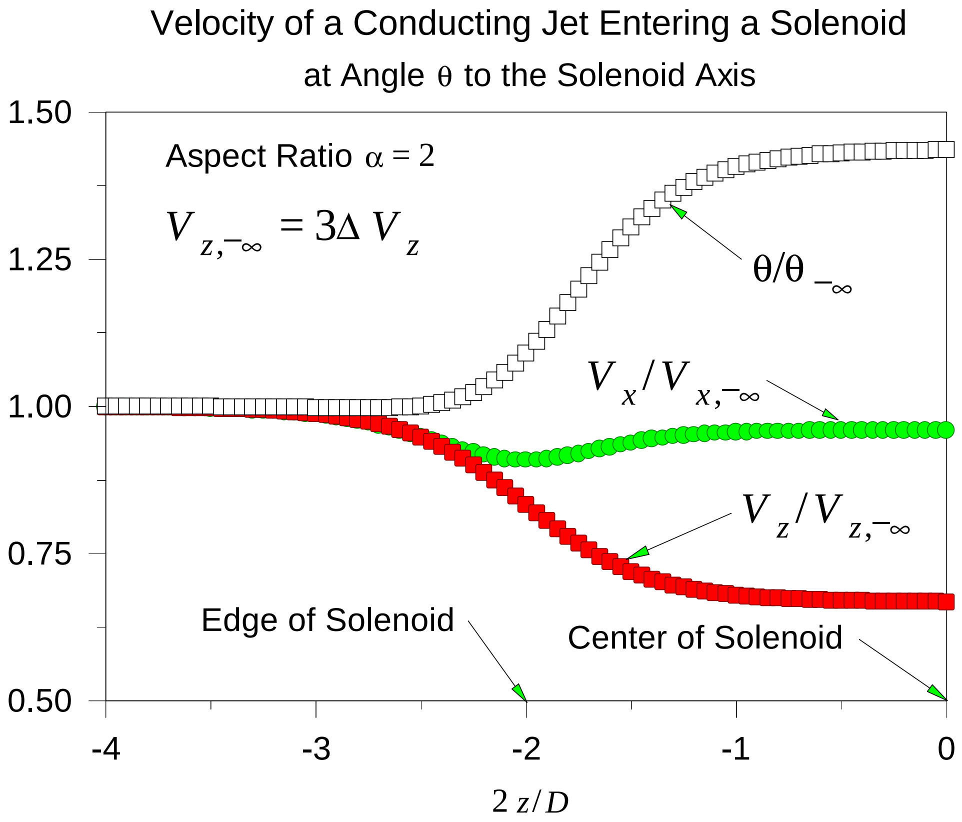
$$P_r \approx \frac{\sigma r^2 B_0^2 v_z}{8D} \approx 50 \text{ atm.} \left[\frac{r}{1 \text{ cm}}\right] \left[\frac{r}{D}\right] \left[\frac{B_0}{20 \text{ T}}\right]^2 \left[\frac{v}{10 \text{ m/s}}\right].$$

  Ex: $P = 2.5$ atm for previous parameters.

- Will the jet break up into droplets?

- Jet at angle θ to magnet axis ⇒ transverse drag.

  But, $\Delta v_x = \Delta v_z/8$.



$\Rightarrow \theta$ increases as jet enters magnet.

Ex: $\alpha = 2,\ v = 3\Delta v_z \Rightarrow \theta_{\rm in} = 1.5\theta_{\rm out}$.

- Drag and shear are smaller for larger initial velocity, but pressure rises with velocity.
- Is there a safe working regime?
- Need both FEA analysis and **lab tests**.

Magnetic Damping of Radial Perturbations

If jet blows apart radially, the flux thru rings of metal changes,

$\Rightarrow$ Eddy current damping.

$$\Rightarrow \qquad \Delta P_{r,\mathrm{damp}} \approx \sigma r v_r B_0^2.$$

Ex: Radial pinch $\Rightarrow v_r \approx \dfrac{\sigma r B_0^2}{4\rho}, \Rightarrow P_{r,\mathrm{damp}} \approx \dfrac{\sigma^2 r^2 B_0^4}{4\rho} \gtrsim P_{r,\mathrm{pinch}}$.

Ex: If beam shock $\Rightarrow v_r \approx 1,000$ m/s,

then $P_{r,\mathrm{damp}} \approx 4$ GPa $\approx T_{S,\mathrm{steel}}$.

Also, a strong magnetic field damps the Rayleigh instability (breakup of a jet into droplets due to surface tension) [Chandrasekhar].

Will test liquid jets in proton beam at Brookhaven National Lab, and in 20-T magnet at National High Magnetic Field Lab.

An R&D Program for Targetry and Capture at a Muon Collider Source

A Proposal to the BNL AGS Division

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R&D Goals

Long Term: Provide a facility to test key components of the front-end of a muon collider in realistic beam conditions.

Near Term (1-2 years): Explore viability of a liquid metal jet target in intense, short proton pulses and (separately) in strong magnetic fields.
(Change target technology if encounter severe difficulties.)

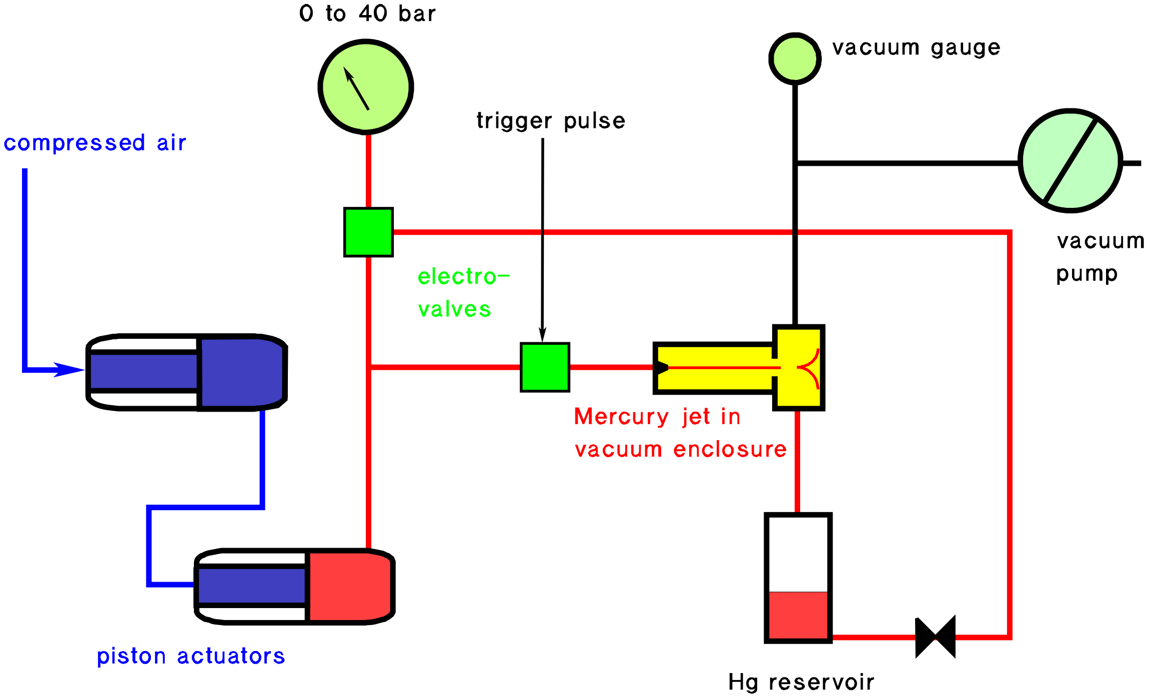
Mid Term (3-4 years): Add 20-T magnet to AGS beam tests;
Test 70-MHz rf cavity (+ 1.25-T magnet) downstream of target;
Characterize pion yield.

Begin with Ga/Sn Liquid-Metal Alloy

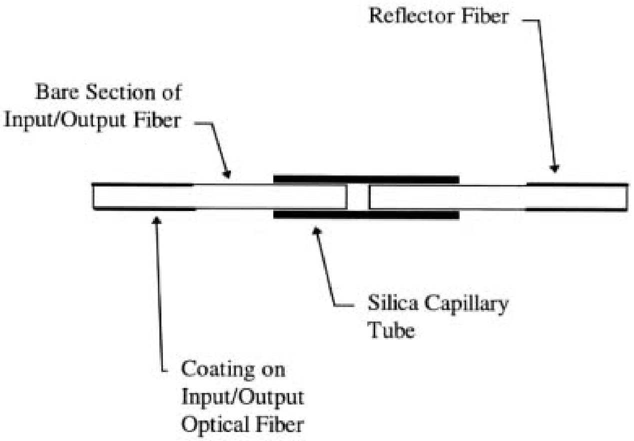
Eutectic Ga/Sn alloy melts at 20C. Density = 6 g/cm^3.

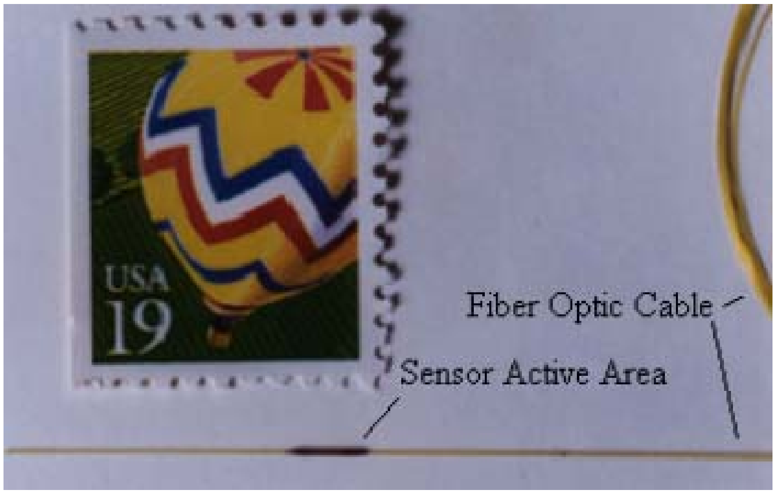
Easy to make and handle; very low viscosity.

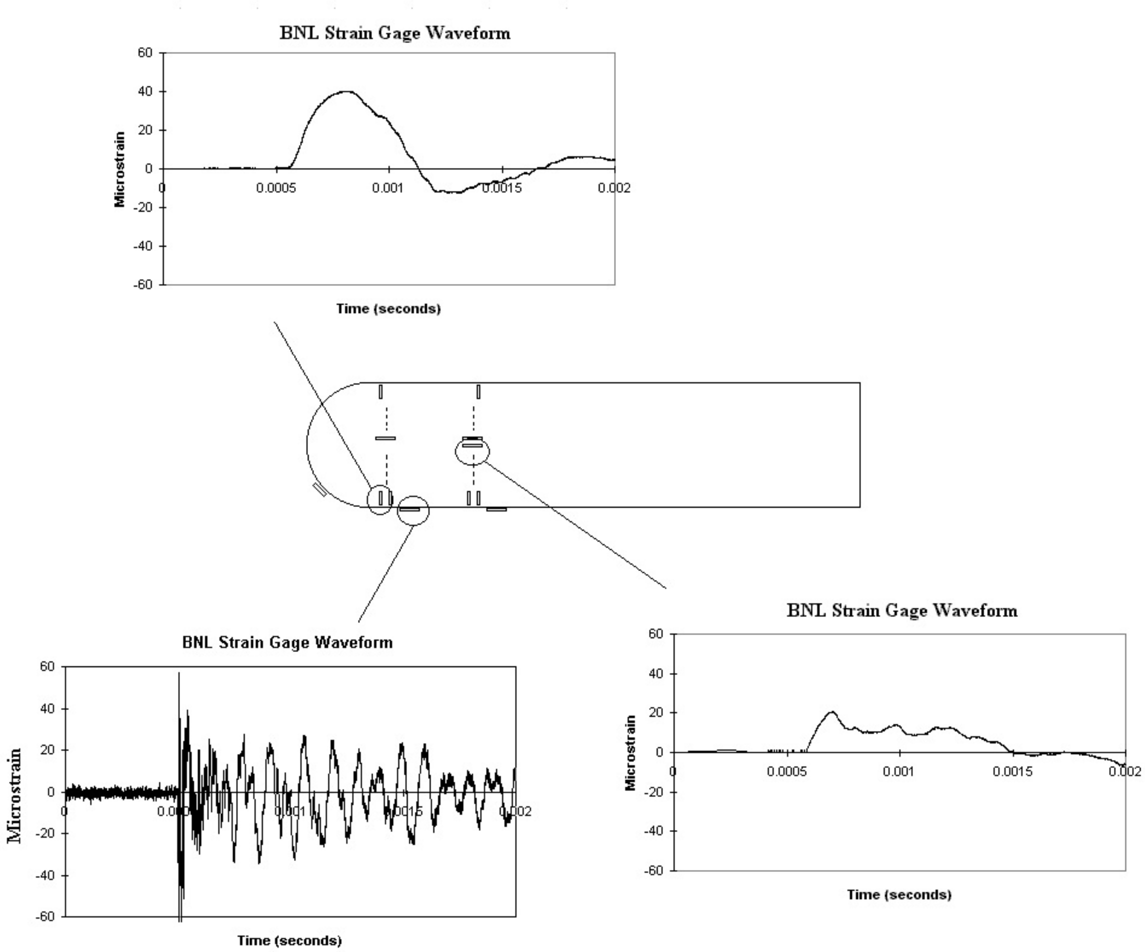
Build pulsed jet following design of C. Johnson:



Fiberoptic Strain Sensors

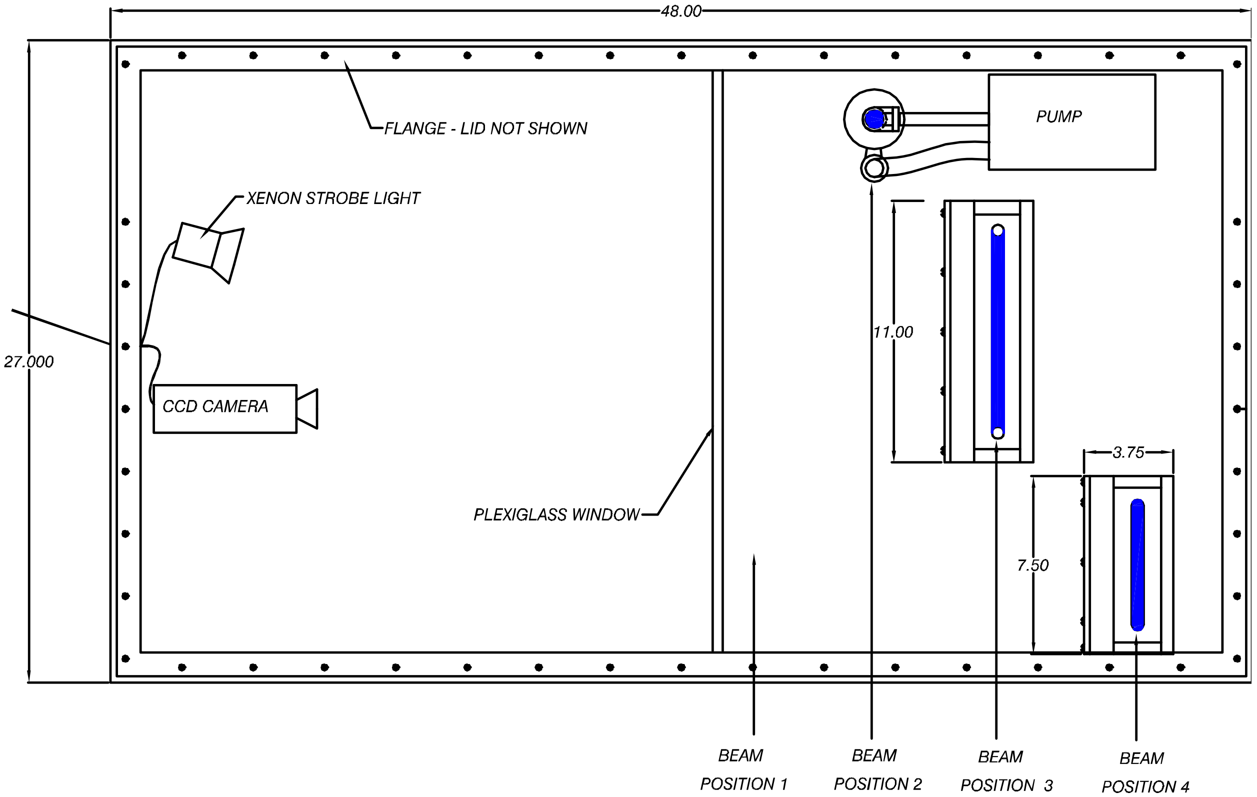




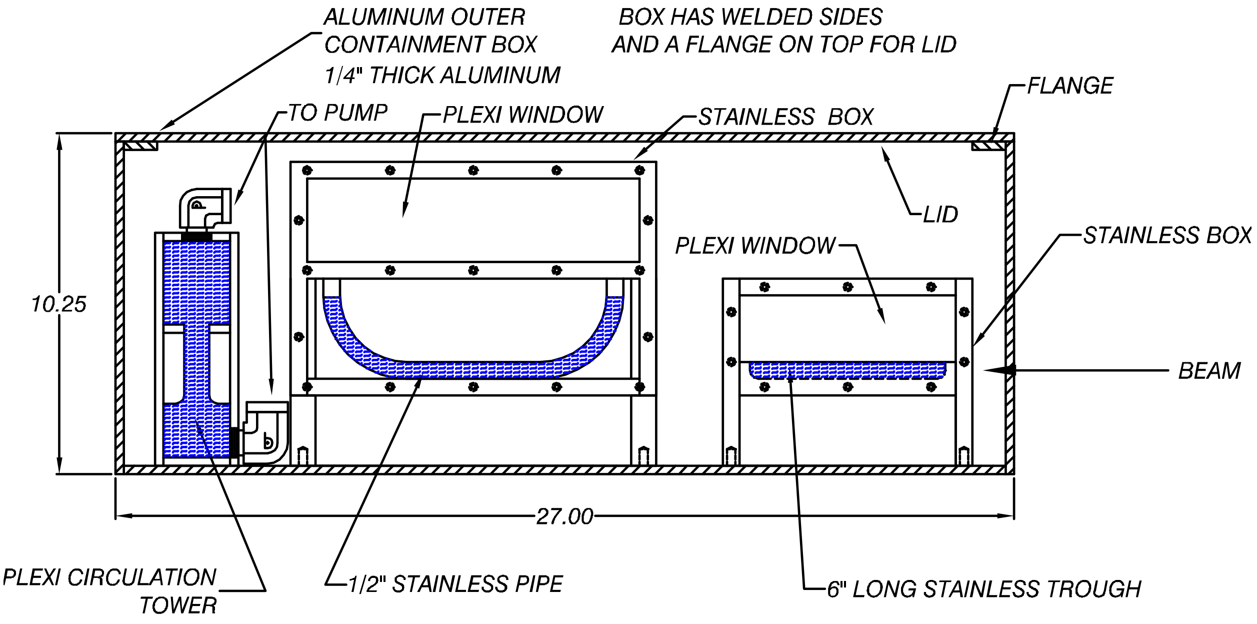


First Test: Liquid Metal in a Trough, a Pipe and Free Flow

TOP VIEW



CAMERA VIEW

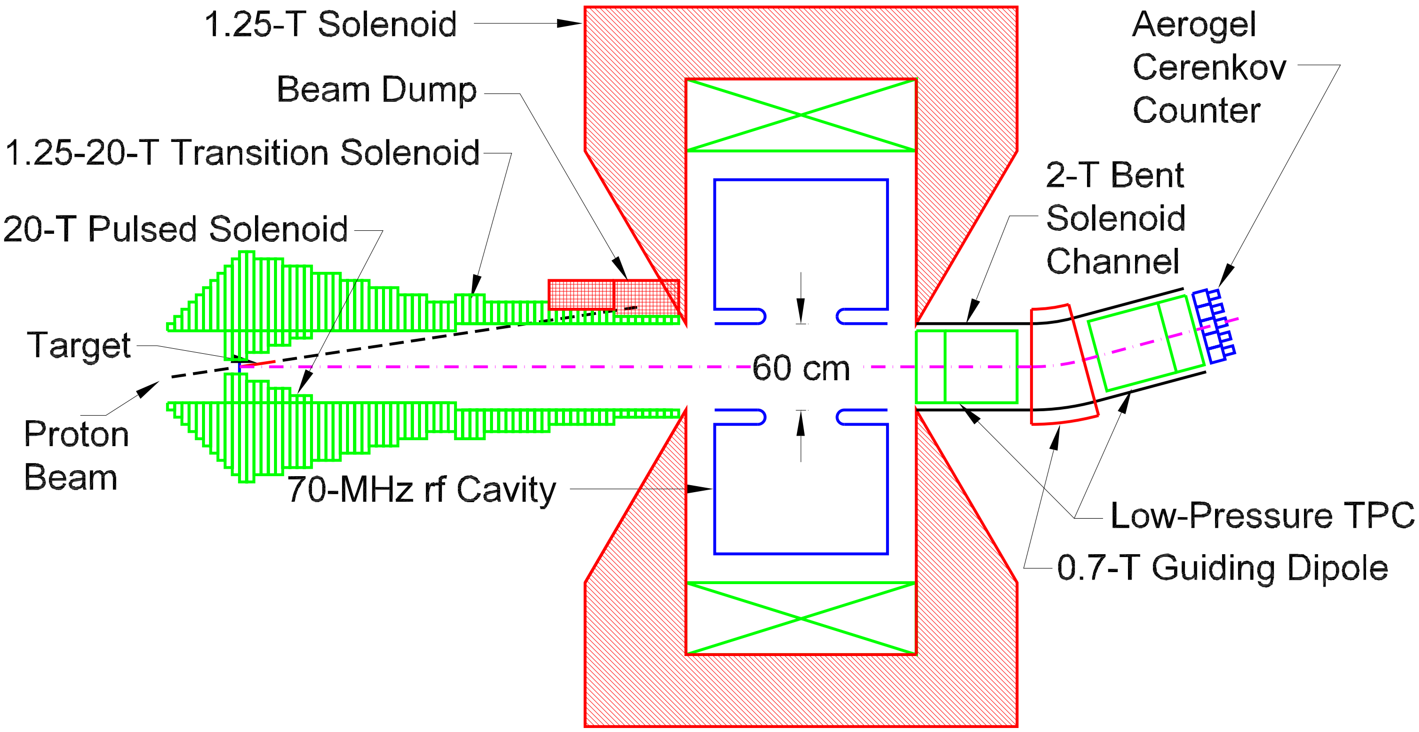


PIPE AND TROUGH ARE FILLED WITH Ga-Sn EUTECTIC LIQUID METAL

The 8 Steps in the R&D Program

1. Simple tests of liquid (Ga-Sn) targets in the AGS FEB U-line.
2. Test of liquid jet entering a 20-T magnet (20-MW cw Bitter magnet at the National High Field Magnet Laboratory).
3. Test of liquid jet in the FEB U-line (without magnet).
4. Add 20-T pulsed magnet (4-MW peak) to the FEB U-line.
5. Add 70-MHz rf cavity downstream of target in FEB U-line.
6. Surround rf cavity with 1.25-T magnet.
7. Characterize pion yield from target + magnet system in FEB U-line.
8. Ongoing simulation of the thermal hydraulics of the liquid-metal target system.

The Targetry and Capture Experiment



Summary

- A muon collider offers the prospect of a more cost-effective technology for high-energy accelerators.
- The concepts of a muon collider are still in a formative stage.
- Cooling the beams is the key.
- Significant technical challenges in producing enough muons.
- ⇒ Join us in exploring the physics opportunities and solving the technical challenges of a muon collider!