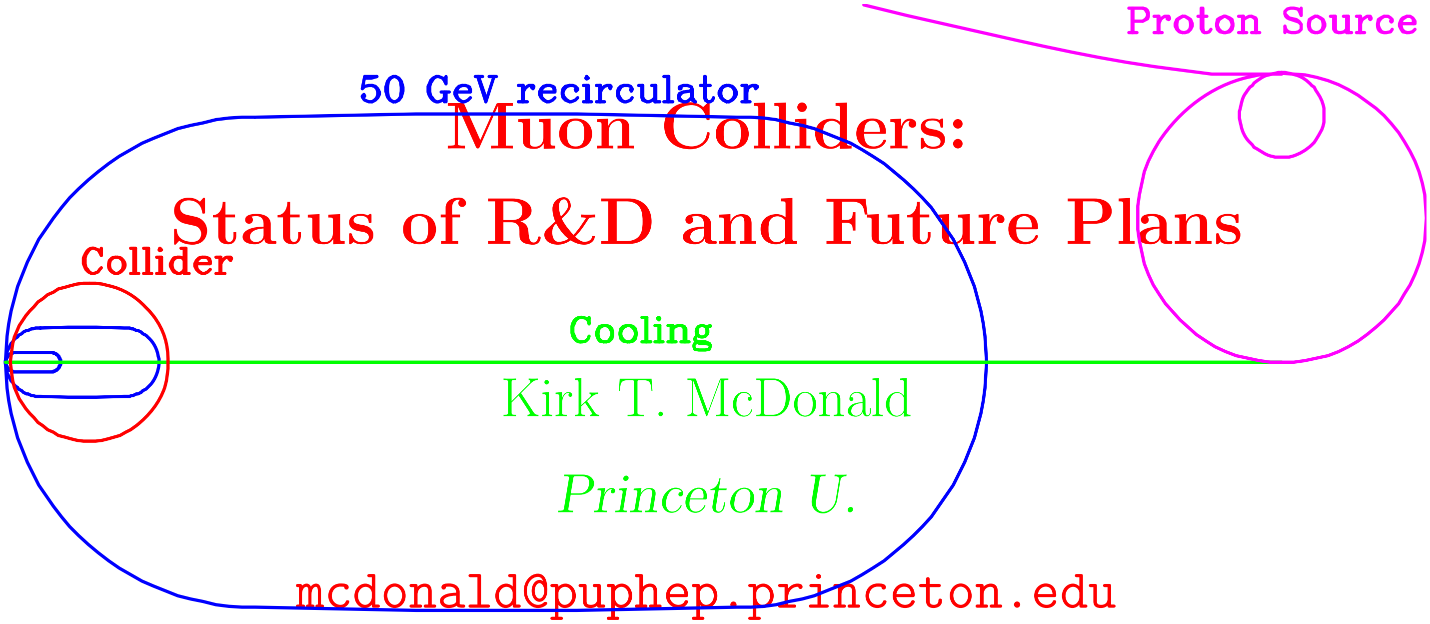

Muon Colliders:
Status of R&D and Future Plans

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[For the Muon Collider Collaboration]

March 31, 1999

PAC'99 Invited Paper WEBR4

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 $\Rightarrow$ a 2nd 3×3 (or larger?) mixing matrix.
  - Precision studies of Higgs bosons.
  - A rich supersymmetric sector (with manifestations of higher dimensions).
  - ... 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.

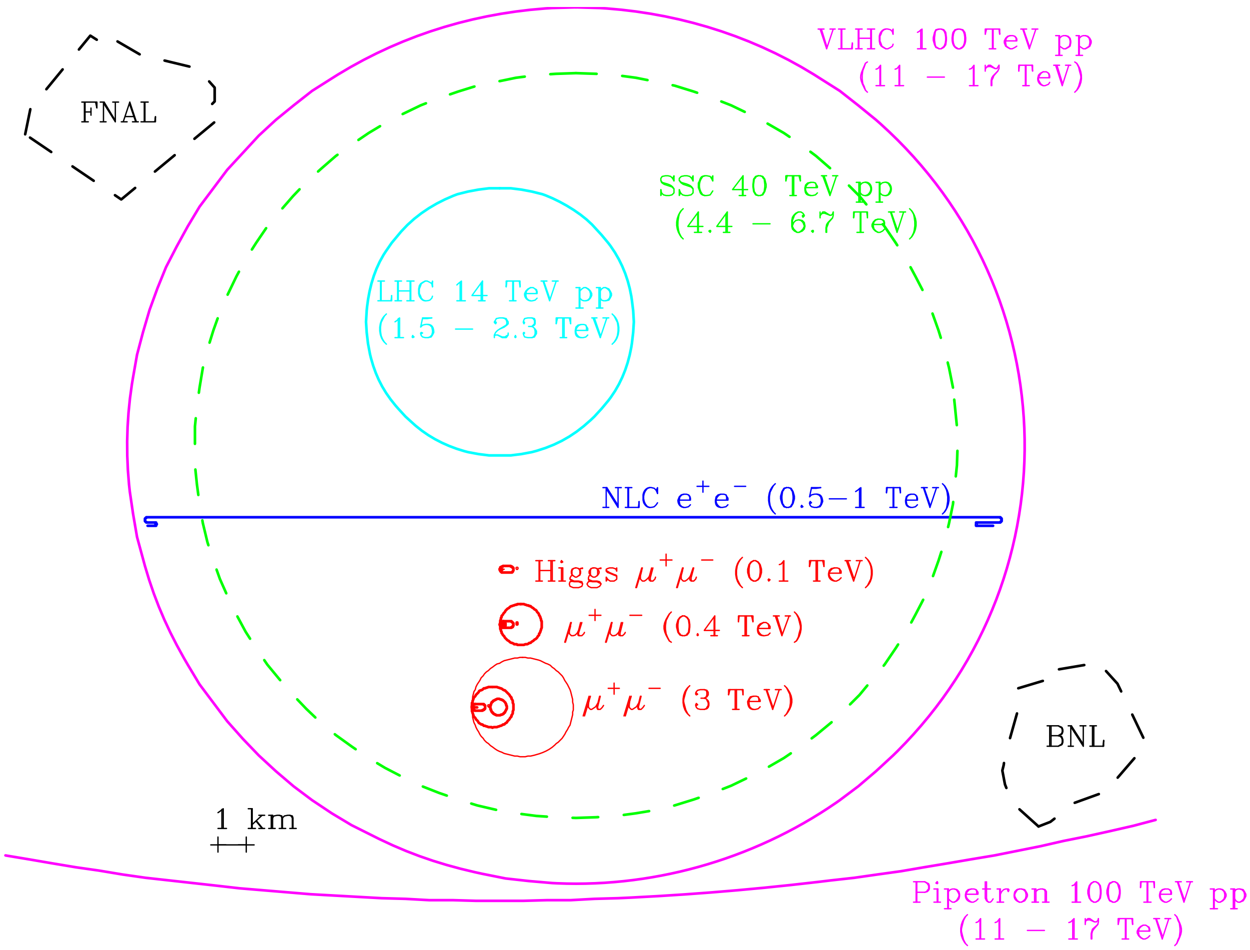
Baseline Parameters

For muon colliders at 3 TeV, 400 GeV (top factory) and 100 GeV (light Higgs factory).

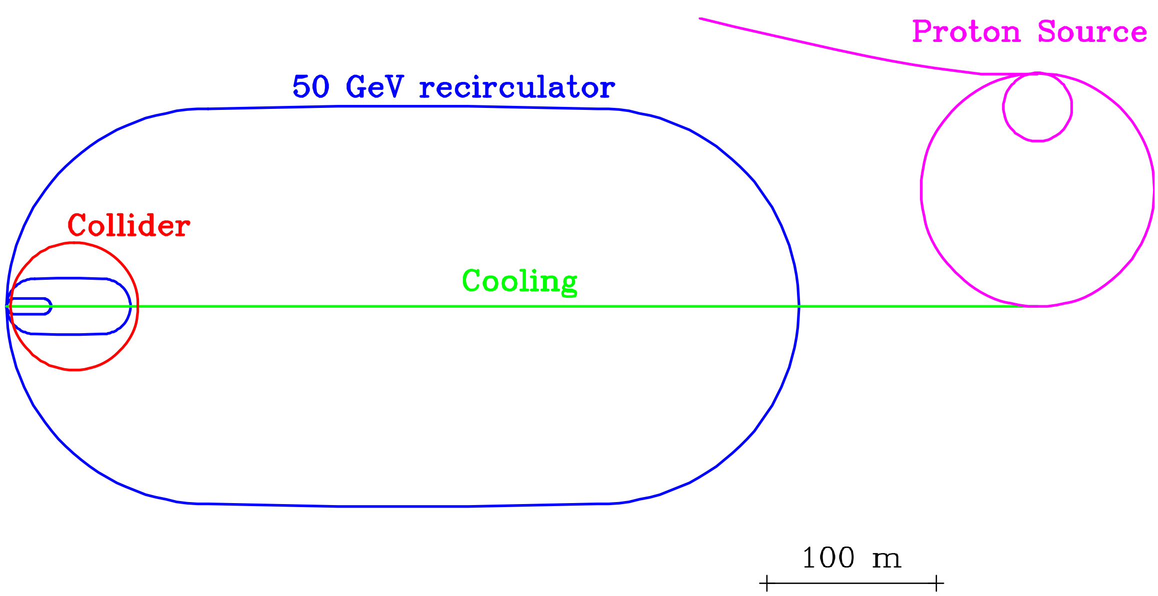
CoM energy (TeV)	3	0.4	0.1
p energy (GeV)	16	16	16
p's/bunch	2.5×10^{13}	2.5×10^{13}	5×10^{13}
Bunches/fill	4	4	2
Rep. rate (Hz)	15	15	15
p power (MW)	4	4	4
μ/bunch	2×10^{12}	2×10^{12}	4×10^{12}
μ power (MW)	28	4	1
Wall power (MW)	204	120	81
Collider circum. (m)	6000	1000	350
Ave. bending field (T)	5.2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

Higgs/year assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width $\Gamma = 2.7$ MeV; 1 year = 10^7 s.

Footprints



A First Muon Collider to study light-Higgs production:



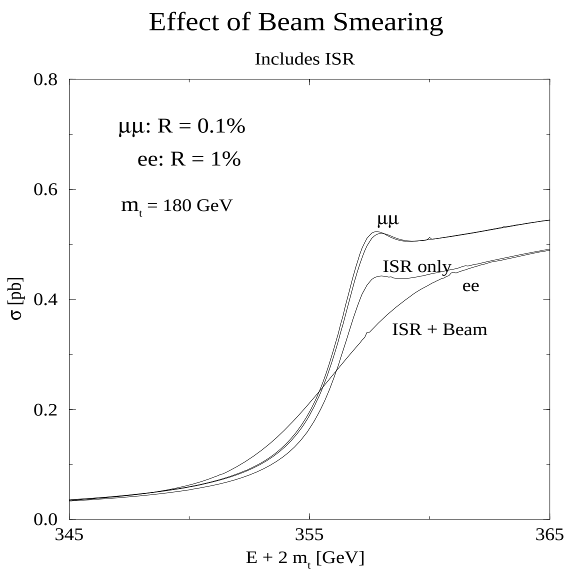
The Case for a Muon Collider

- 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^-.

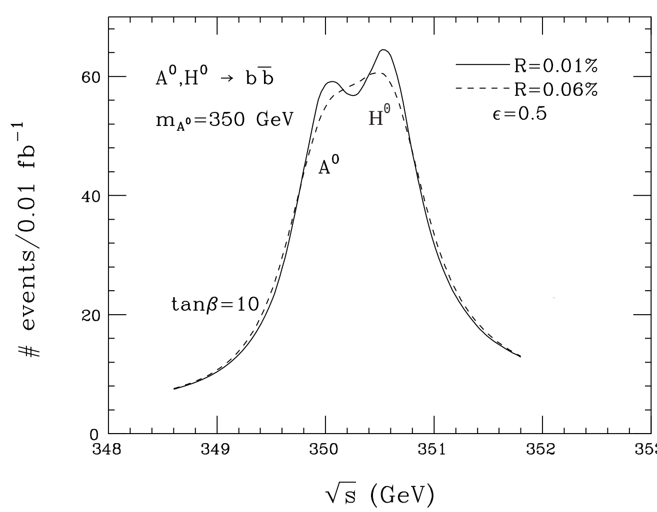
  Muon polarization $\approx 25\%$,

  $\Rightarrow$ 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:

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

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

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.

The Muon Collider Collaboration

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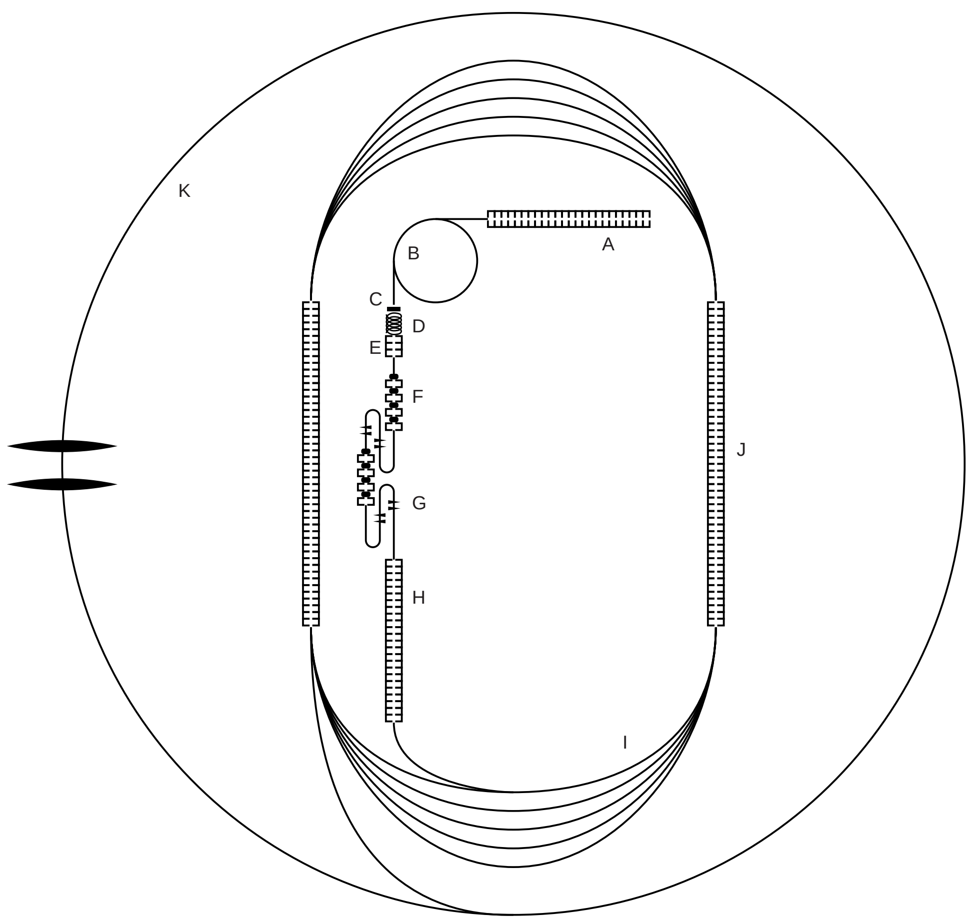
Spokesperson: R.B. Palmer

Scheduled Muon Collider Mini-Workshops and Conferences

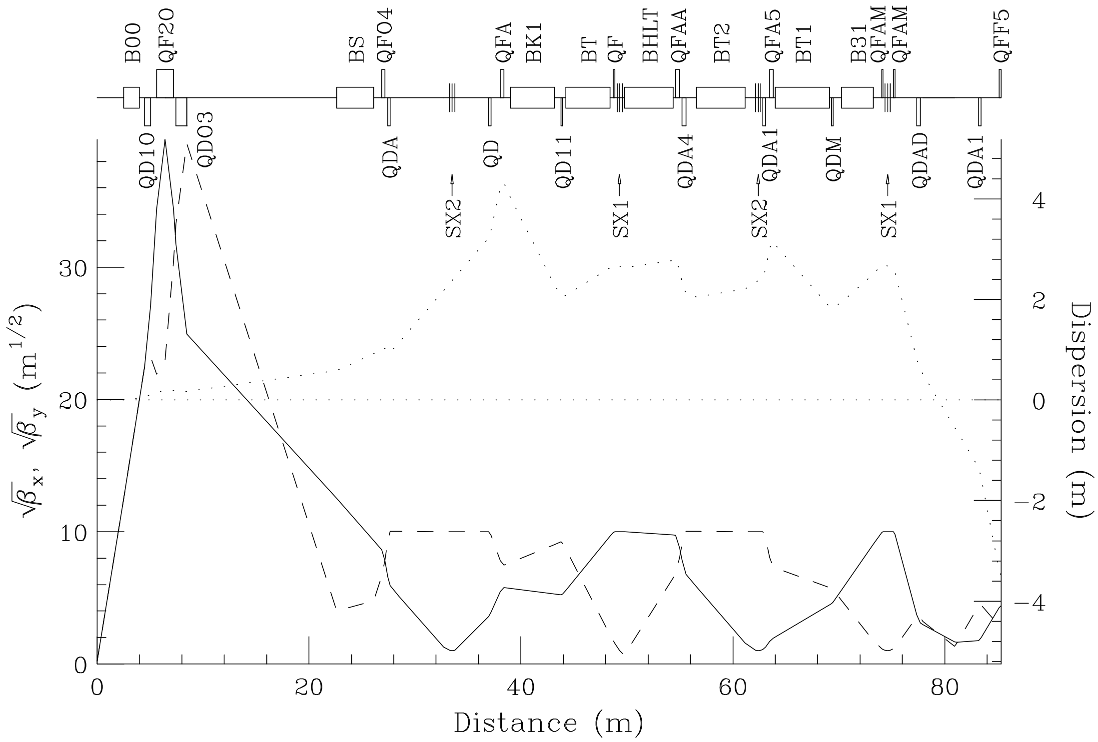
Subject	Organizer	Place	Date	Additional Information
Expt. rf systems	N. Holtkamp	FNAL	Mar. 18-19, 1999	Contact Norbert Holtkamp (holtkamp@fnal.gov)
Cooling Theory & MUCOOL	R. Fernow and S. Geer	LBNL	April 12-14, 1999	Contact R. Fernow (fernow@bnl.gov) or S. Geer (sgeer@fnal.gov) or John Corlett (jncorlett@LBL.gov
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

- Proton Driver, 16-GeV, 15 Hz, 4MW, 1-ns bunch: WEA163
- **Targetry and Capture**: THP34, THP38, THP41, THP55, THP57, THP59
- **Muon Cooling**: MOP98, THA130, THP31, THP33, THP35, THP39, THP40, THP42, THP48, THP54, THP56, THP58, THP60, THP83, THP85, TUA147, TUP101, WEBR5
- Acceleration: MOP86, THP37, THP50, THP86

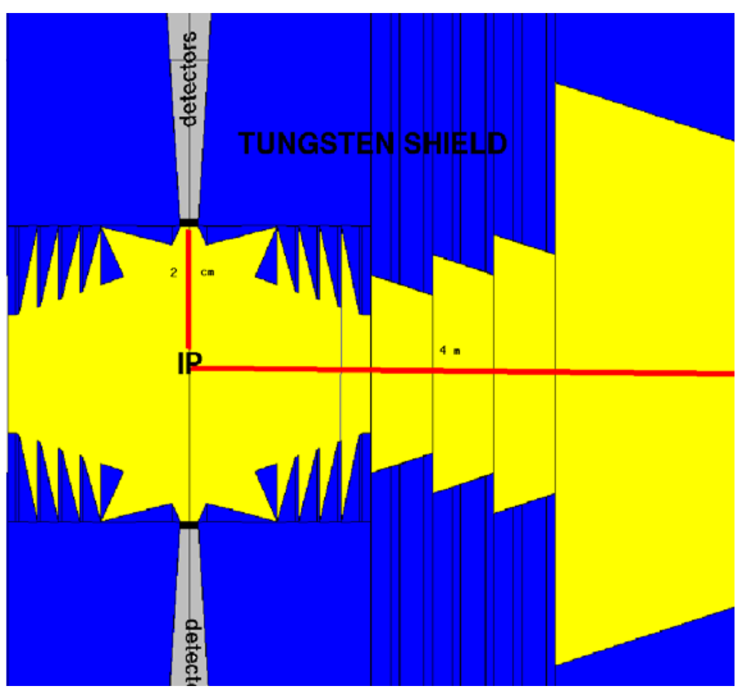


- Storage rings: THP43, THP44, THP45, THP46, THP47, THP49, THP53, TUP129, TUP154

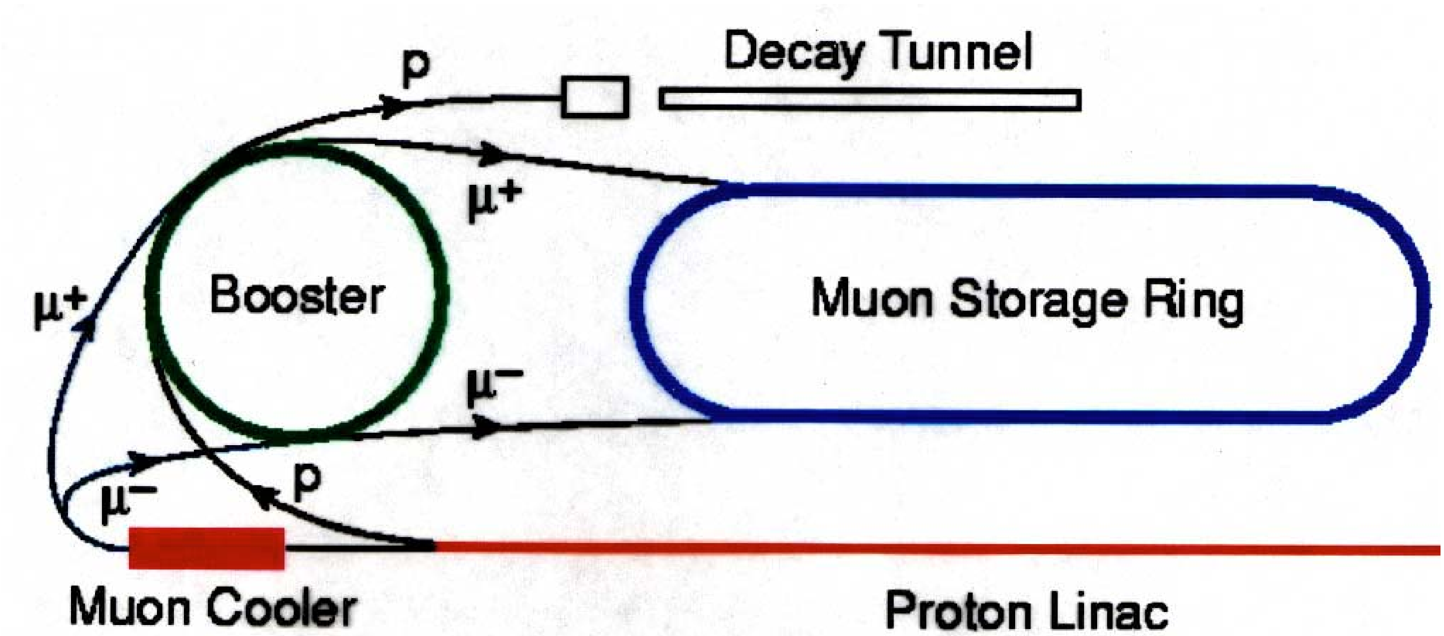


- Interaction region and detector design.

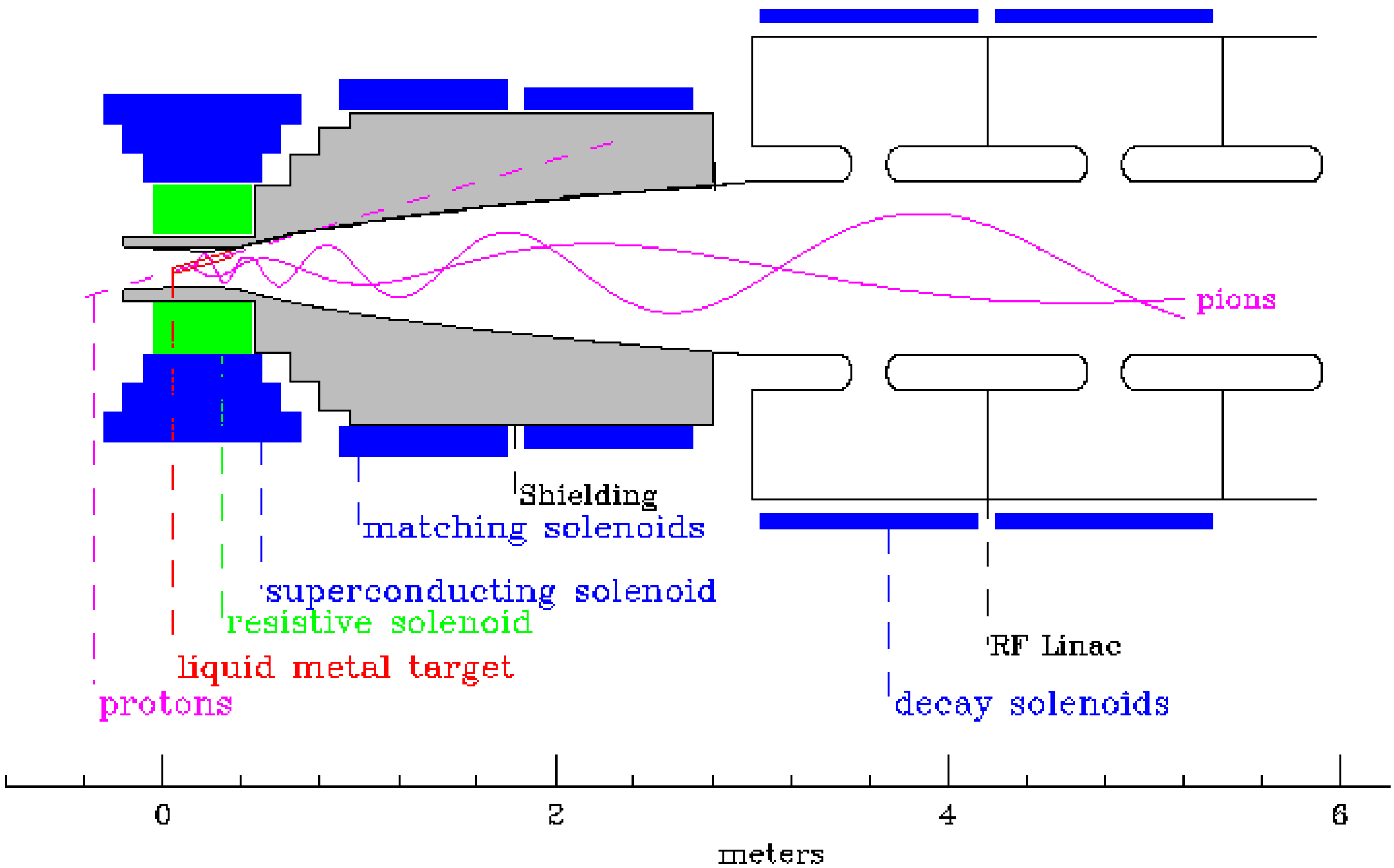
A muon's view of the interaction region:



- Neutrino beams: THP32, THP36, THP51, THP52, WEBR6



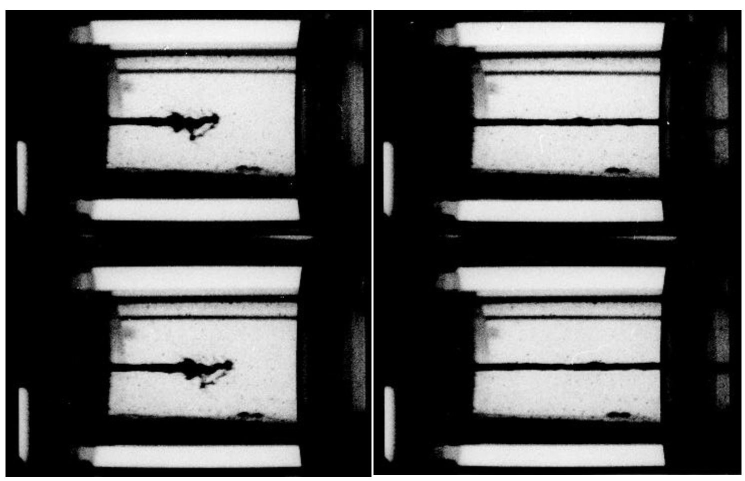
Overview of Targetry for a Muon Collider



- 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

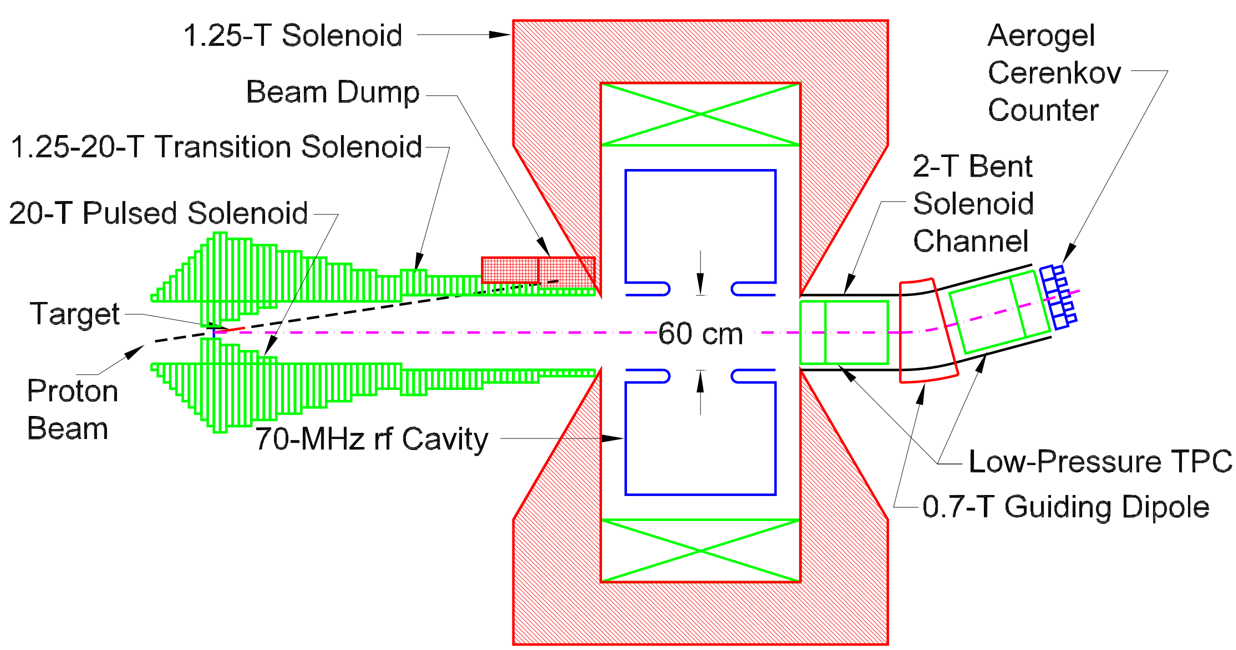
- Targetry area also contains beam dump.
  - Need 4 MW of cooling.
  - Harsh radiation environment for magnets and rf.

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.)

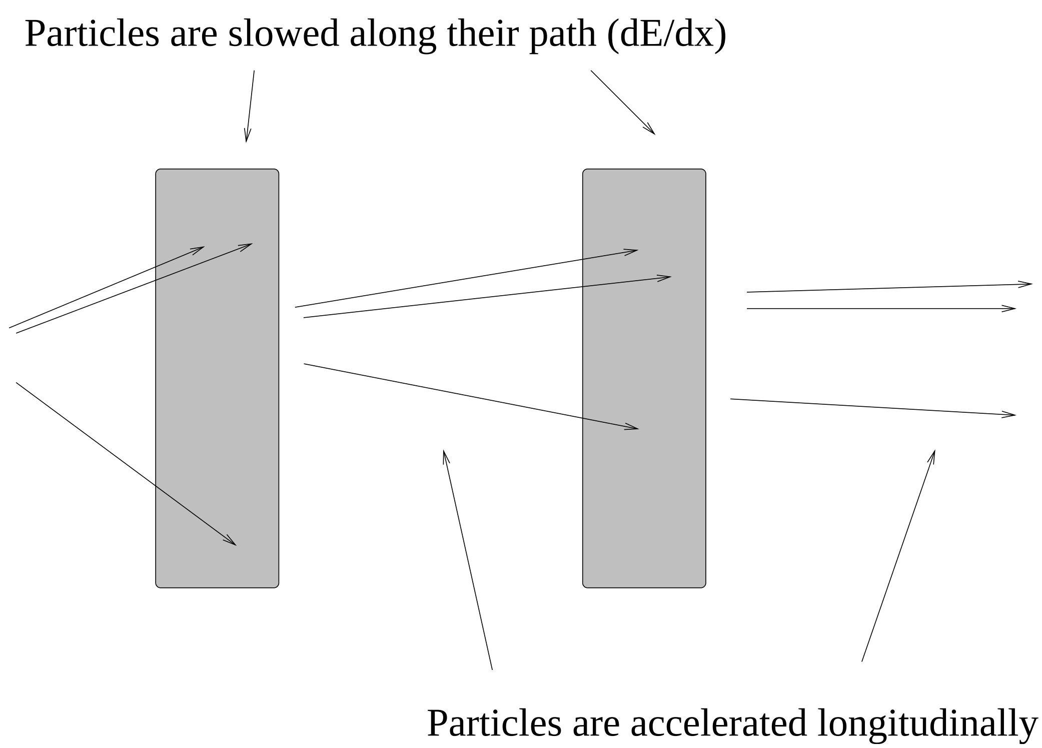
Mid Term (3-4 years): Add 20-T magnet to AGS beam tests;
Test 70-MHz rf cavity (+ 1.25-T magnet) downstream of target;
Characterize pion yield.



Ionization Cooling

(An Idea So Simple It Might Just Work)

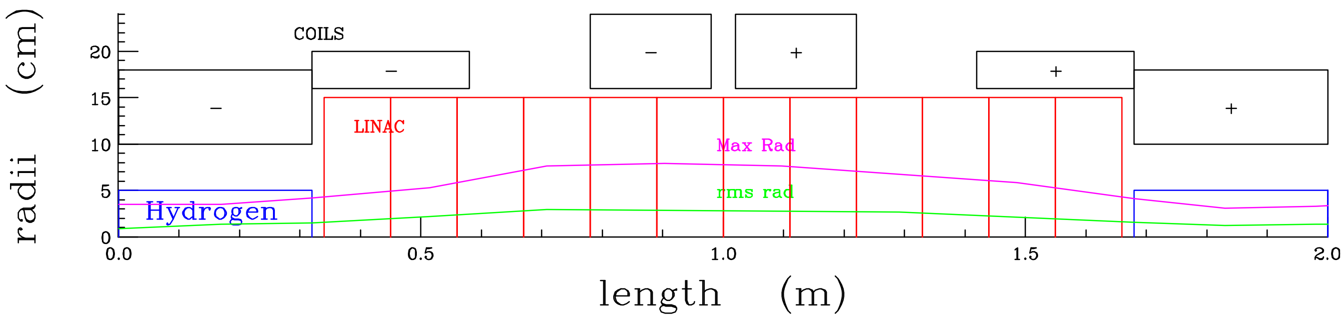
- Ionization: takes momentum away.
- RF acceleration: puts momentum back along z axis.
- $\Rightarrow$ Transverse "cooling".



- 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

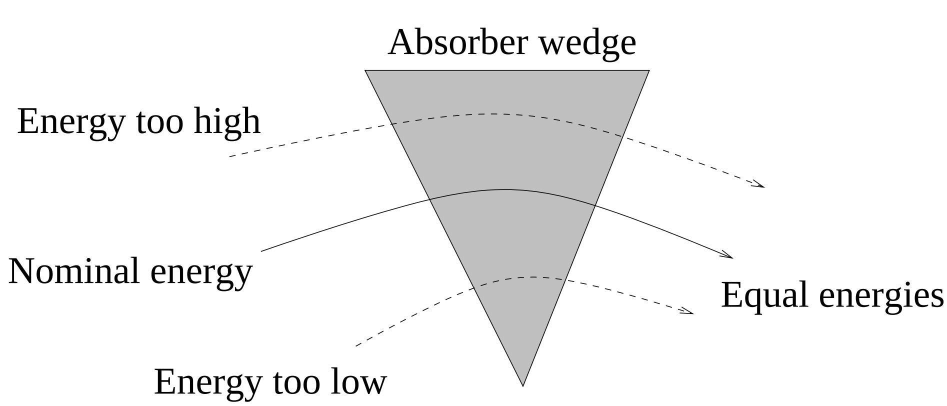
Use channel of LH_2 absorbers, rf cavities and alternating solenoids (to avoid buildup of angular momentum).



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:



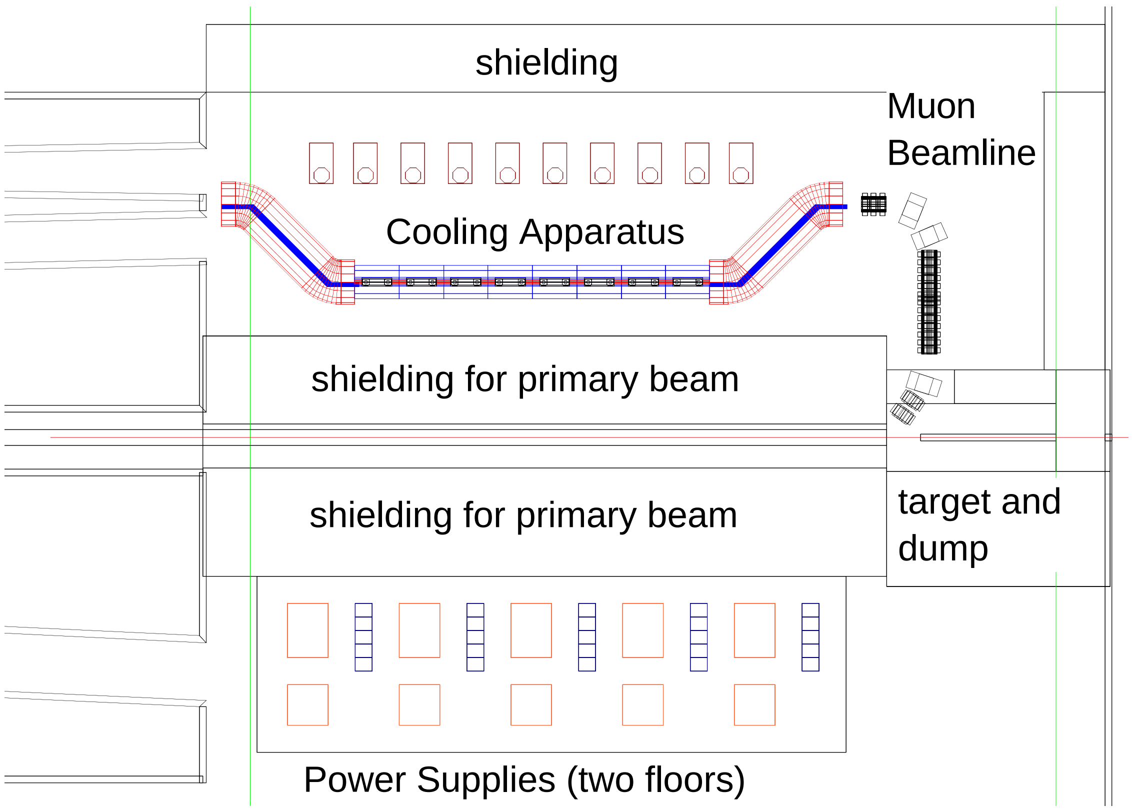
Cooling Demonstration Experiment

Test basic cooling components:

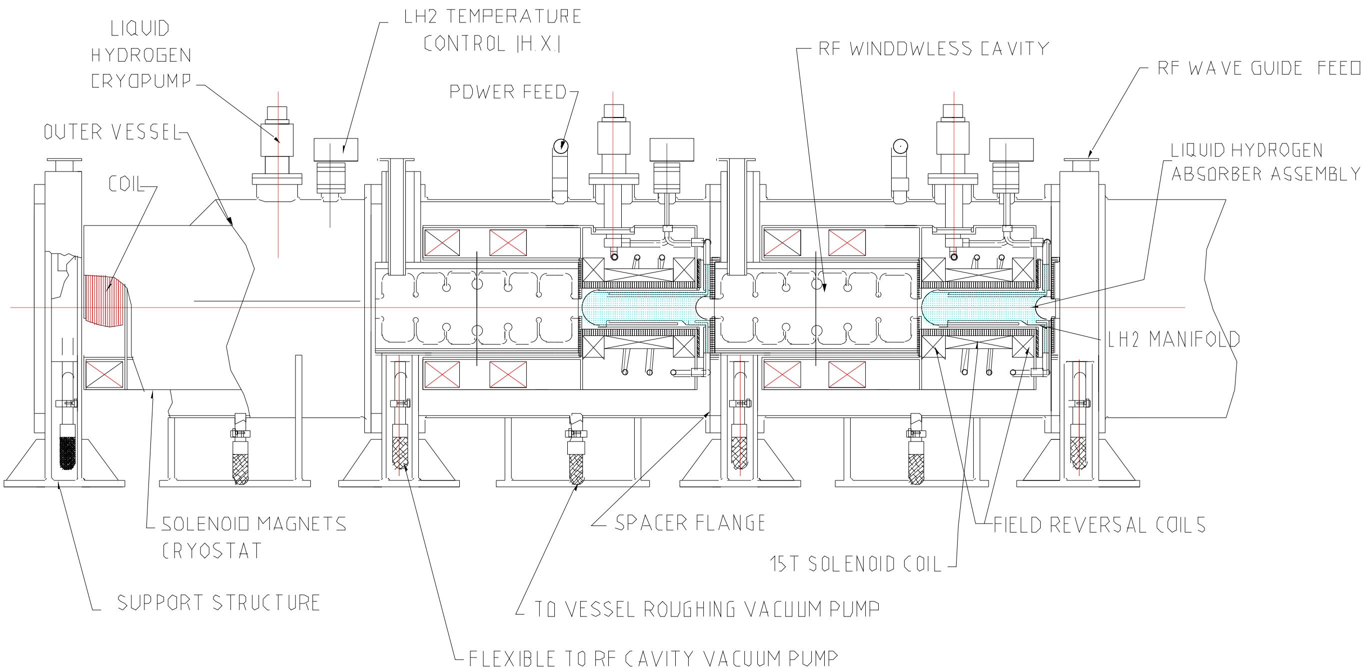
- Alternating solenoid lattice, RF cavities, LH_2 absorber.
- Lithium lens (for final cooling).
- Dispersion + wedge absorbers to exchange longitudinal and transverse phase space.

Track individual muons; simulate a bunch in software.

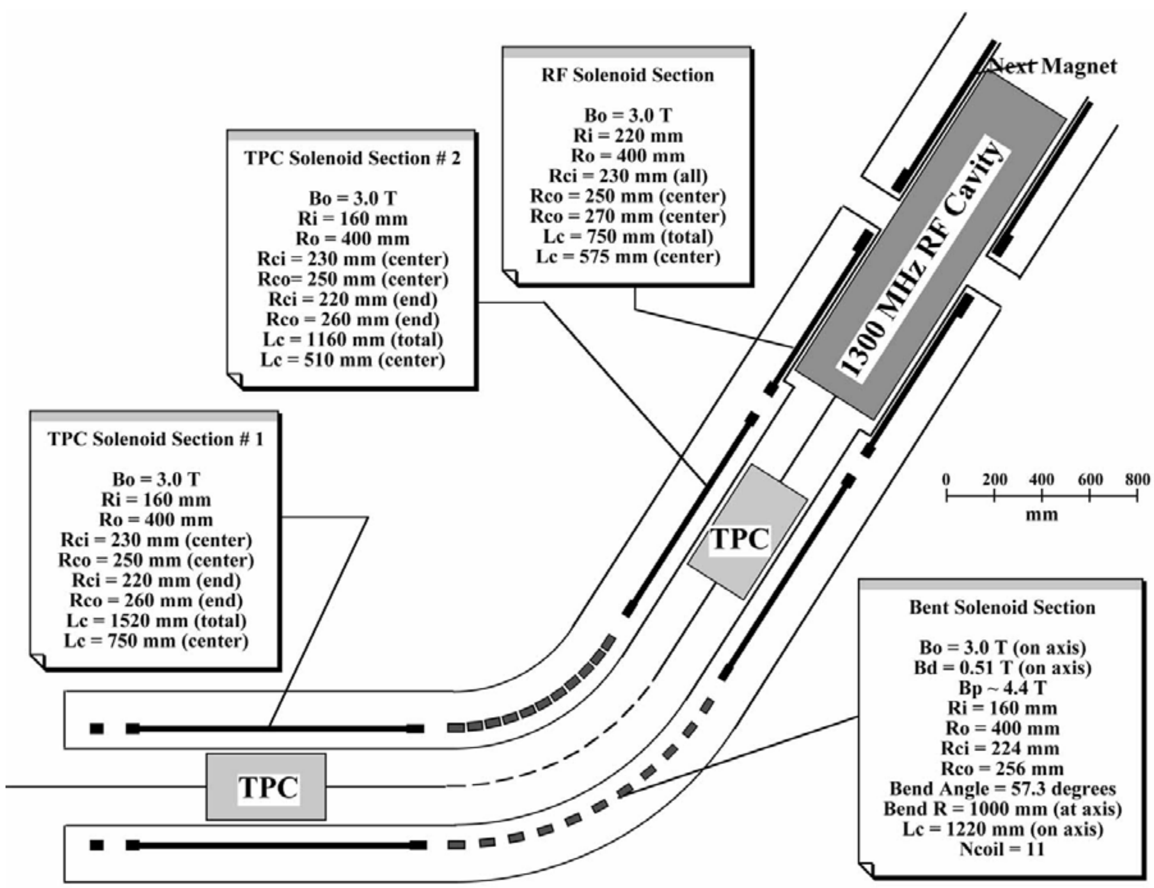
Possible site: Meson Lab at Fermilab:



3 cells of the cooling channel:



Emittance diagnostics via a bent solenoid spectrometer :



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.
- $\Rightarrow$ Join us in exploring the physics opportunities and solving the technical challenges of a muon collider!