MUON COLLIDERS: STATUS OF R&D AND FUTURE PLANS

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Abstract

The case for a future high-energy collider based on muon beams is reviewed briefly.

1 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 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, capable of extension to 10's of TeV of constituent CoM energy?

Many of us believe that a **Muon Collider** [1, 2, 3, 4, 5, 6] is the best answer to the above.

2 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 [7, 8].
- The cooled muons are accelerated and then stored in a ring [9, 10].
- $\mu^+\mu^-$ collisions are observed over the useful muon life of $\approx$ 1000 turns at any energy.
- Intense neutrino beams and spallation neutron beams are available as byproducts.

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

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

Table 1: 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	2.5e13	2.5e13	5e13
Bunches/fill	4	4	2
Rep. rate (Hz)	15	15	15
p power (MW)	4	4	4
μ/bunch	2e12	2e12	4e12
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 $(\pi \mathrm{m})^3$	1.7e−10	1.7e−10	1.7e−10
Rms ϵ_n (π mm-mrad	50	50	85- 290
β^*, 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 (cm^{-2}s^{-1})	7e34	1e33	1e31-1.2e32
Higgs/year			2-4e3

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

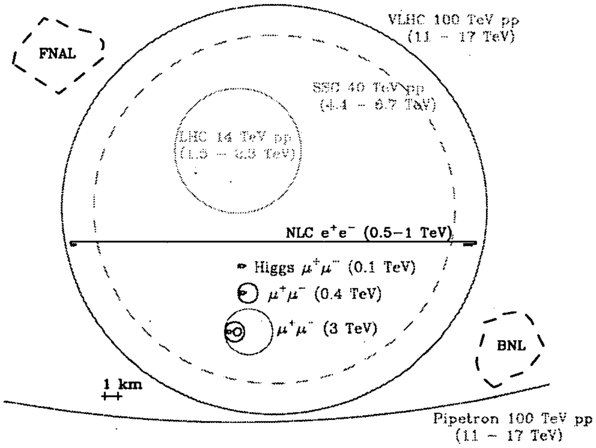

Figure 1: Comparison of footprints of various future colliders.

3 THE CASE FOR A MUON COLLIDER

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

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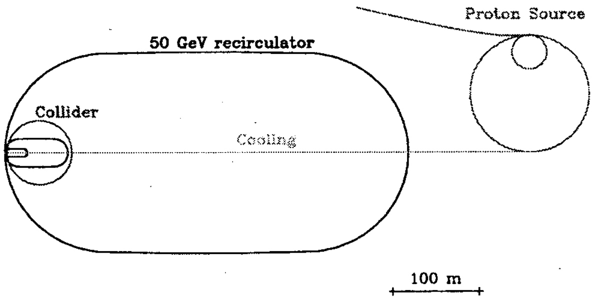


Figure 2: A First Muon Collider to study light-Higgs production.

- 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 [11].

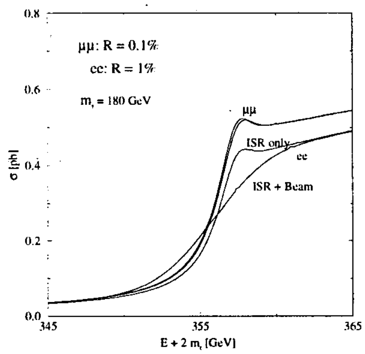


Figure 3: The effect of beam energy resolution at the $t\bar{t}$ threshold.

- Initial machine could produce light Higgs via s-channel [5]:
  - 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}, $\Rightarrow$ can measure Higgs width directly.
  - Add rings to 3 TeV later.
- Neutrino beams from μ decay about 10^4 hotter than present.
  - Possible initial scenario in a low-energy muon storage ring [12].
  - Study CP violation via CP conjugate initial states:

$$\begin{cases} \mu^+ \to e^+\bar{\nu}_\mu\nu_e \\ \mu^- \to e^-\nu_\mu\bar{\nu}_e \end{cases}.$$

4 TECHNICAL CHALLENGES

[*References in this section are to papers contributed to PAC'99.*]

- Proton Driver, 16-GeV, 15 Hz, 4MW, 1-ns bunch [19].
- Targetry and Capture [28, 32, 35, 49, 51, 53].
- Muon Cooling [14, 15, 16, 21, 24, 25, 27, 29, 33, 34, 36, 42, 48, 50, 52, 54, 55, 56].
- Acceleration [13, 31, 44, 57].

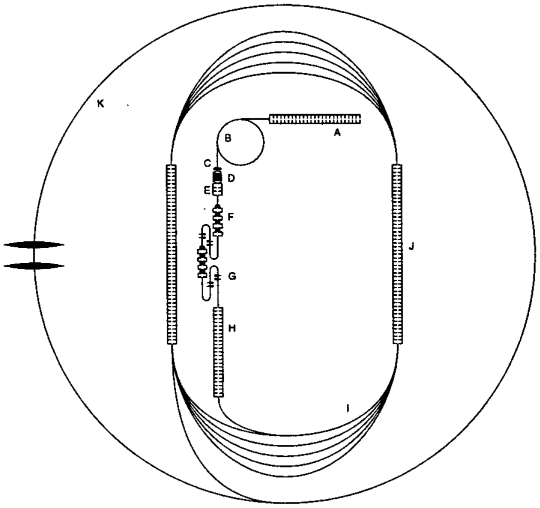


Figure 4: Muon collider components: A. Proton linac; B. Proton driver; C. Proton target; D. Capture solenoid; E. Phase rotation channel; F. Transverse cooling; G. Longitudinal cooling; H. Accelerating linac; I. Arcs of recirculator; J. Accelerating linac; L. Collider ring.

- Storage rings [17, 18, 37, 38, 39, 40, 41, 43, 47].

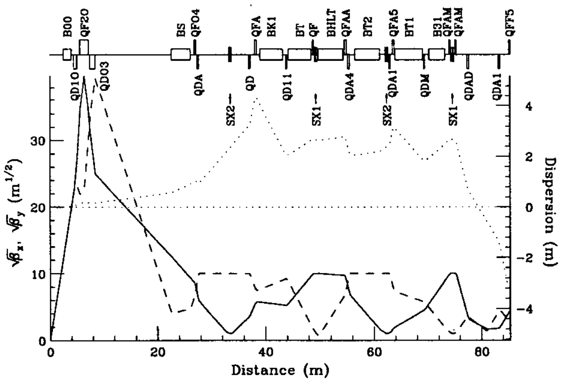


Figure 5: Collider ring lattice near the interaction point.

- Interaction region and detector design.
- Neutrino beams [22, 26, 30, 45, 46].

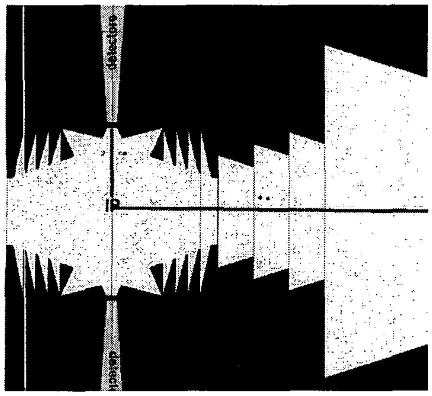


Figure 6: Tungsten masks around the interaction region.

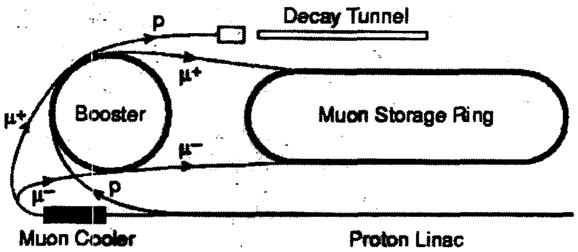


Figure 7: Sketch of an accelerator complex to produce neutrino beams via a muon storage ring.

5 MUON COLLIDER R&D PROGRAM

5.1 *Targetry and Capture at a Muon Collider Source*

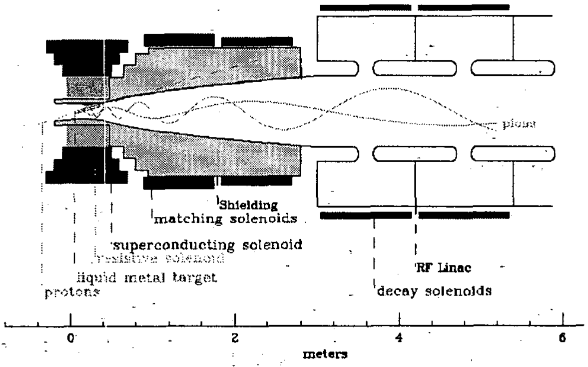


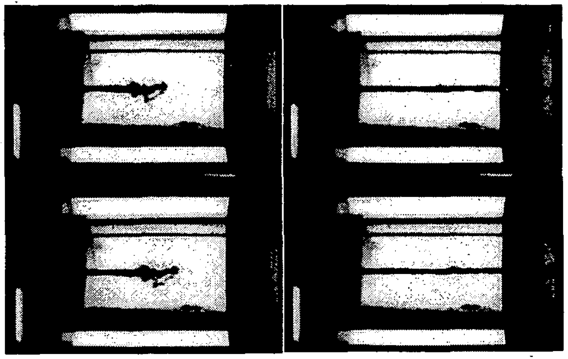
Figure 8: Baseline targetry scenario using a liquid metal jet inside a 20-T magnet.

To achieve useful physics luminosity, a muon collider must produce about 10^{14} μ/sec.

- $\Rightarrow >$ 10^{15} proton/sec onto a high-Z target – 4 MW beam power.
- Capture pions of $P_\perp \lesssim 200$ MeV/c in a 20-T solenoid magnet.
- Transfer the pions into a 1.25-T-solenoid decay channel.
- Compress π/μ bunch energy with rf cavities and deliver to muon cooling channel.

Targetry Issues:

- 1-ns beam pulse $\Rightarrow$ shock heating of target.
- Eddy currents arise as metal jet enters the capture magnet.



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

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Figure 9: Hg jet studied at CERN, but not in beam or magnetic field.

- Targetry area also contains beam dump.

Targetry 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 BNL AGS beam tests; Test 70-MHz rf cavity (+ 1.25-T magnet) downstream of target; Characterize pion yield.

5.2 *Ionization Cooling*

The Theory:

- Ionization: takes momentum away.
- RF acceleration: puts momentum back along z axis.

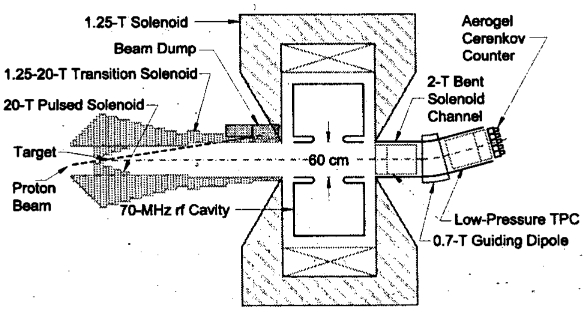

Figure 10: The proposed facility for targetry R&D at BNL [58, 59].

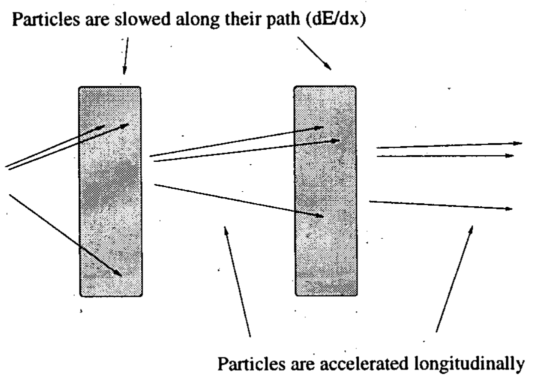

Figure 11: The concept of transverse ionization cooling.

- ⇒ Transverse "cooling"; O'Neill [7] (1956).
- This won't work for electrons or protons.
- So use muons: Balbekov [8], Budker [9], Skrinsky [10], late 1960's.

The Details are Delicate:

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

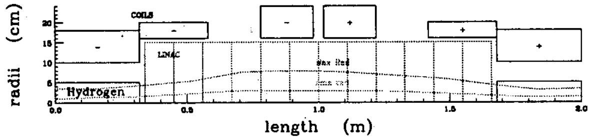

Figure 12: One cell of the cooling channel.

- But, 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:

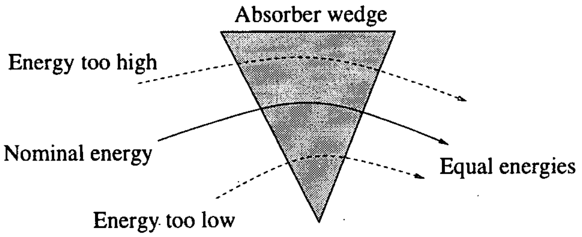

Figure 13: Longitudinal/transverse emittance exchange in a wedge absorber.

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.

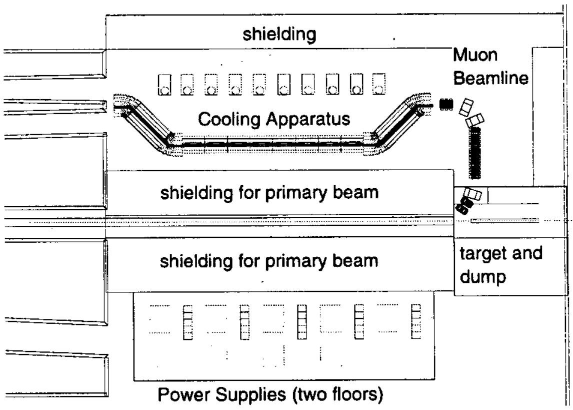

Figure 14: Possible site for the muon cooling experiment in the Fermilab Meson Hall [60, 61].

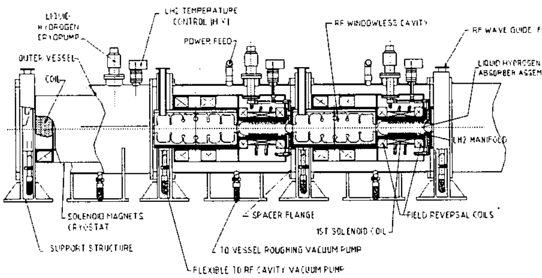

Figure 15: Side view of three cells of a cooling channel, incorporating LH_2 absorbers, 15-T alternating solenoid magnets, and high-gradient 800-MHz rf cavities.

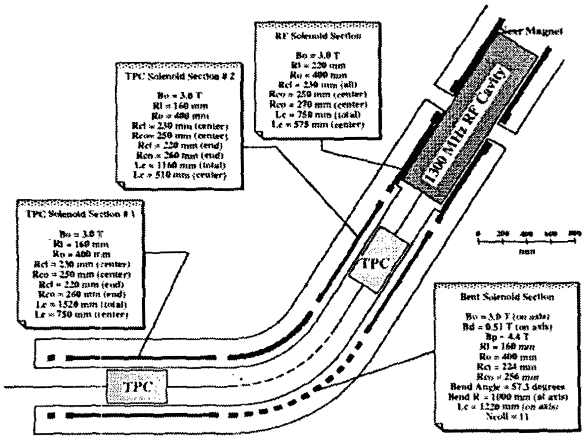

Figure 16: Emittance diagnostics via a bent solenoid spectrometer.

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