Muons for a Neutrino Factory
and a Muon Collider

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Muon Collider R&D Status Report:

Muon Collider Targetry page:
http://puhep1.princeton.edu/mumu/target/
Muon Requirements

- $\approx 10^{14} \mu^\pm/s$ for either a muon collider or a neutrino factory.
- The muons come from the decay of soft pions produced in $p$-nucleus collisions.
- Our strategy is to maximize the ratio of captured muons per proton. *i.e.*, to minimize the proton requirements.
- Goal: $0.1\mu/p$ delivered for physics use.
The Muon Source

- Pion production peaks at $P_{\parallel} \approx 350 \text{ MeV}/c; P_{\perp} \lesssim 200 \text{ MeV}/c$.

- $\Rightarrow$ Capture the soft pions in a solenoid magnet channel.

- Capture efficiency improved with a stronger (20 T) field on the target than in the main channel (1.25 T). [Adiabatic invariance reduces the pion $P_{\perp}$ when going from high to low $B$.]

- $\Rightarrow$ High-$Z$ target without nearby cooling structure that would absorb pions.

- $\Rightarrow$ Liquid mercury jet target.

- Soft pions have $v/c < 1$, $\Rightarrow$ Disperse while drifting
  $\Rightarrow$ Begin RF manipulation as soon as possible to form a bunch with reduced energy spread (Phase Rotation).
Overview of Targetry for a Muon Collider

- $1.2 \times 10^{14} \mu^+/\text{s}$ via $\pi$-decay from a 4-MW proton beam.
- Proton pulse $\approx 1$ ns rms for a muon collider.
- Mercury jet target.
- 20-T capture solenoid followed by a 1.25-T $\pi$-decay channel with phase-rotation via rf (to compress energy of the muon bunch).
Targetry Issues

- Is a liquid jet target viable?
  - 1-ns beam pulse $\Rightarrow$ 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)](image)

4,000 frames per second, Jet speed: 20 ms$^{-1}$, diameter: 3 mm, Reynold’s Number:$>100,000$

A. Poncet
• Is the first rf cavity viable?
  – High-gradient (5 MeV/m), low-frequency (≈ 70 MHz) rf cavity only 3 m downstream of target.
  – > $10^{14}$ particles traverse the cavity each proton pulse; many hit the cavity wall.
  – Cavities tested against breakdown from beam-induced showers only up to $\approx 10^{12}$ particles/pulse.

• Is the 20-T Solenoid viable?
  – Even with water-cooled tungsten inserts, this hybrid (copper/superconductor) magnet will experience a very high radiation dose.
  – LANL has experience with superconducting magnets in high radiation areas.

• Other Radiological Issues
  – A 4-MW beam leads to activation issues characteristic of neutron spallation sources.
  – Remote handling of activated liquid target material is under study at CERN ISOLDE, the ORNL NSNS, ...
**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.
An R&D Program for Targetry and Capture at a Muon Collider Source

A Proposal to the BNL AGS Division (P951)

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Beam Tests at BNL

The BNL AGS has proton beam parameters closest to those desirable for a muon collider source.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Muon Collider</th>
<th>BNL AGS</th>
<th>FNAL Booster</th>
<th>CERN PS</th>
<th>LANSCE PSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton Energy (GeV)</td>
<td>16-24</td>
<td>24</td>
<td>8.9</td>
<td>24</td>
<td>0.8</td>
</tr>
<tr>
<td>( p/\text{bunch} )</td>
<td>( 5 \times 10^{13} )</td>
<td>( 1.6 \times 10^{13} )</td>
<td>( 6 \times 10^{10} )</td>
<td>( 4 \times 10^{12} )</td>
<td>( 3 \times 10^{13} )</td>
</tr>
<tr>
<td>No. of bunches</td>
<td>2</td>
<td>6</td>
<td>84</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>( p/\text{cycle} )</td>
<td>( 1 \times 10^{14} )</td>
<td>( 1 \times 10^{14} )</td>
<td>( 5 \times 10^{12} )</td>
<td>( 3 \times 10^{13} )</td>
<td>( 3 \times 10^{13} )</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
<td>( \approx 1000 )</td>
<td>440</td>
<td>18.9</td>
<td>250</td>
<td>–</td>
</tr>
<tr>
<td>Bunch train length (( \mu \text{s} ))</td>
<td>( \approx 1 )</td>
<td>2.2</td>
<td>1.6</td>
<td>2.0</td>
<td>0.25</td>
</tr>
<tr>
<td>RMS Bunch length (ns)</td>
<td>( \approx 1 )</td>
<td>( \approx 10 )</td>
<td>( \approx 1 )</td>
<td>( \approx 10 )</td>
<td>( \approx 60 )</td>
</tr>
</tbody>
</table>
The 8 Steps in the R&D Program

1. Simple tests of liquid (Ga-Sn, Hg) and solid (Ni) targets with AGS Fast Extracted Beam (FEB).
2. Test of liquid jet entering a 20-T magnet (20-MW cw Bitter magnet at the National High Magnetic Field Laboratory).
3. Test of liquid jet with $10^{14}$ ppp via full turn FEB (without magnet).
4. Add 20-T pulsed magnet (4-MW peak) to liquid jet test with AGS FEB.
5. Add 70-MHz rf cavity downstream of target in FEB.
6. Surround rf cavity with 1.25-T magnet. At this step we have all essential features of the source.
7. Characterize pion yield from target + magnet system with slow extracted beam (SEB).
8. Ongoing simulation of the thermal hydraulics of the liquid-metal target system.
Issues, 1: Initial Tests with FEB

- Site presently under consideration: A3 line.

- What beamline upgrades are needed to bring a 100 mm-mrad beam to a spot with $\sigma_r = 1$ mm? (Kevin Brown)
- Beamline instrumentation upgrades: spot size, beam current, FEB radiation monitoring.

- Run first tests parasitic to $g-2$ expt. in Mar/Apr 2000.

- Data taking via pulse-on-demand once every few minutes; but desire 1-Hz running for beam tuning.

- Shielding needed for 1-Hz running with $10^{14}$ ppp = 100 TP (Ripp Bowman, Ralf Prigl).

- First test: liquid metal in a trough, a pipe and in free flow (Princeton).
• Instrumentation: high-speed camera, fiberoptic strain sensors (Duncan Earl, ORNL).
• Inspiration:

• Prototype jet using Ga-Sn, a room temperature liquid (Princeton).
- May 18, 1999: Ga-Sn jet breaks up too quickly, forms oxide scum:

- Hg jet under construction at CERN (Colin Johnson, Helge Ravn), and at Princeton.
Issues, 3: Full Turn Extraction

- G10 kicker can deliver beam to A-C lines as well as to U line.
- Present power supply sufficient to kick out only 1 bunch.
- Upgrade to kick out all 6 bunches requires $\approx 18$ months.
- Initiate design work in FY99 to complete upgrade in early FY01.
Issues, 4: Pulsed 20-T Magnet

- The copper magnet will be cooled by LN$_2$, and can be pulsed once every 10 minutes. Pulse duration $\approx 1$ s.
- 4 MW (peak) power to be bussed from the MPS power supply house to the A3 line (Andy Soukas).
- 100 liters of LN$_2$ boiled off each pulse; vent outside of cave.
- A DC magnet is required as a transition between the pulsed magnet and the DC superconducting magnet around the rf cavity. This will require $\approx 1$ MW average power.
Issues, 5: 70-MHz RF Cavity

- Cavity has 60-cm-diameter iris, 2-m outer diameter.
  (Werner Pirkl, CERN)

- 4-6 MW peak power to be supplied by four 8973 tubes recommissioned from the LBL Hilac.
  (Vince LoDestro, BNL; Don Howard, LBL)
• Transmit rf power to the cavity via four 6''-diameter coax lines. Couple to upstream face of cavity (to avoid need for power combiner).

• The tubes and electronics should arrive at BNL early FY00.

• Ideal test site would be just outside A3 cave, close to final location.

• The 8973 tubes may need magnetic shielding.

• We are also embarking on an R&D program with industry to develop a 50-MW peak power, 70-MHz power supply (EEV, Eimac, Litton, Thomson).
Issues, 6: 1.25-T Solenoid Around RF Cavity

• Present plan: use PEP-4 TPC superconducting solenoid (Mike Green, LBL).

• Use 100-W LHe refrigerator from E-850.

• Need DC transition magnet to protect the superconducting magnet from quenching during pulsing of the 20-T magnet (Bob Weggel).

• Need end plate steel and/or bucking coils to complete the isolation of the superconducting magnet.

• The magnet fringe fields will extend a considerable distance.
Issues, 7: Characterization of Pion Yield

- The final measure of system performance is the capture of soft pions that later decay to muons.

- Add bent solenoid spectrometer downstream of TPC magnet.

- Instrument with low-pressure TPC’s and aerogel Čerenkov counters.

- Collect data with slow beam, \(< 10^6 \) ppp.

- Compare with extrapolations from data of E-910.
Issues, 8: Simulation of Beam-Jet-Magnet

- ANSYS simulation (Changguo Lu, Princeton):

- HEIGHTS simulation (Ahmed Hassanein, ANL):
  
  Mercury Jet with 4 mm Beam and B-field Diffused in
Pressure and Temperature Profiles

Pressure inside Hg Jet with Field Diffused

Temperature Inside Hg Jet with Field Diffused
Effect of a Scaled-Down Target

HEIGHTS Analysis of Total Edge Pressure Inside Mercury Jet

HEIGHTS Analysis of Jet Center Temperature Inside Mercury Jet
Schedule

• FY99:
  Prepare A3 area; begin work on liquid jets, extraction upgrade, magnet systems, and rf systems.

• FY00:
  Initial beam tests in A3 line. Liquid jet test at NHMFL. (600 hours of AGS beamtime).

• FY01:
  Complete extraction upgrade; test of liquid jet + beam. (600 hours).

• FY02:
  Complete magnet and rf systems; test with 2 ns beam. (600 hours).

• FY03:
  Complete pion detectors; test with low intensity SEB. (600 hours).
AGS Operations Issues

- In FY00/01, HEP operation of AGS is only for the $g-2$ experiment, with fast extraction. P951 is very compatible with parasitic running in this condition.

- After FY01, no DOE approved HEP operation of the AGS.

- The AGS2000 program proposes running slow extracted proton beam 30-35 weeks/yr, for 16-20 hours/day during RHIC operation.

- P951 requires fast extracted beam, so cannot parasite off the AGS2000 program; we must interleave running with AGS2000, but seek $\lesssim 6$ weeks/yr.

- If there is no other HEP operation of the AGS after FY01, P951 would then bear the full incremental cost of proton beam running.