Muon Collider Targetry R&D

[http://www.hep.princeton.edu/mumu]

K.T. McDonald

Princeton U.

May 1, 1998

Muon Collider Targetry Workshop

Brookhaven National Laboratory
Overview of Targetry

- Get muons from pion decay: \( \pi^\pm \rightarrow \mu^\pm\nu \).

- Pions from proton-nucleus interactions in a target.

- Goal: \( 1.2 \times 10^{14} \mu^\pm/\text{s} \).

- \( \Rightarrow \) High-Z target,
  
  High-energy proton beam,

  High magnetic field around target to capture soft pions.

- \( \mu_{\text{collider}}/p_{\text{target}} \approx 0.08 \Rightarrow 1.5 \times 10^{15} p/\text{s} \) at 16 GeV.

- 15-Hz proton source.

- 4 MW power in \( p \) beam.

- Compare: 0.1 MW in 900-GeV extracted \( p \) beam at FNAL;
  
  0.25 MW in 30-GeV extracted beam at BNL AGS.

- Target should be short, narrow and tilted to minimize \( \pi \) loss.

- \( \Rightarrow \) No cooling jacket.

- High power of beam would crack stationary target (or pipe).

- \( \Rightarrow \) Pulsed heavy-metal liquid jet as target.
Baseline Scenario

- Liquid metal target: Ga/In, Hg, or solder (Bi/In/Pb/Sn alloy).
- 20-T capture solenoid followed by 5-T phase-rotation channel.
- 20 T = 6-T, 8-MW water-cooled Cu magnet
  + 14-T superconducting magnet.
- Cost of 14-T magnet ≈ 0.8 M$ \ (B[T] \ R[m])^{1.32} (L[m])^{0.66}
  = 0.8 M$ \ (14[T] \ 0.6[m])^{1.32}(0.75[m])^{0.66} \approx $11M.
Capture pions with $P_\perp < 220$ MeV/c.

Adiabatic invariant: $\Phi = \pi r^2 B$ as $B$ drops from 20 to 5 T.

$r = P_\perp / eB =$ radius of helix.

$\Rightarrow P_\perp,f = P_\perp,i \sqrt{B_f/B_i} = 0.5P_\perp,i$ (and $P_\parallel,f > P_\parallel,i$).

Yield vs. Beam Energy

Yield vs. Magnetic Field

Yield vs. Target Radius

Yield vs. Target Angle
Mercury Jet Studied at CERN

3-mm jet flowed smoothly at 20 cm/s.

But not tested in a magnetic field or in a beam.
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: $\sigma = \sigma_{Cu}/60$, $\rho = 10 \text{ g/cm}^3$, $\Rightarrow$
  $$v_{\text{min}} > 60 \text{ m/s} \left[ \frac{r}{1 \text{ cm}} \right] \left[ \frac{r}{D} \right] \left[ \frac{B_0}{20 \text{ T}} \right]^2.$$  
  Ex: $B_0 = 20 \text{ T}$, $r = 1 \text{ cm}$, $D = 20 \text{ cm}$, $\Rightarrow v_{\text{min}} = 3 \text{ m/s}$.
- Drag force is larger at larger radius $\Rightarrow$ planes deform into cones:
  $$\frac{\Delta z(r)}{r} \approx -3\alpha \left[ \frac{r}{1 \text{ cm}} \right] \left[ \frac{B_0}{20 \text{ T}} \right]^2 \left[ \frac{10 \text{ m/s}}{v} \right].$$  
  Ex: $\alpha = L/D = 2$, $r = 1 \text{ cm}$, $v = 10 \text{ m/s} \Rightarrow \Delta z = 6 \text{ cm}$.
- Radial pressure: compression as jet enters magnet, expansion as it leaves:
  $$P \approx 50 \text{ atm.} \left[ \frac{r}{1 \text{ cm}} \right] \left[ \frac{r}{D} \right] \left[ \frac{B_0}{20 \text{ T}} \right]^2 \left[ \frac{v}{10 \text{ m/s}} \right].$$  
  Ex: $P = 2.5 \text{ atm}$ for previous parameters.
- Will the jet break up into droplets?
- Need both FEA analysis and lab tests.
⇒ Capture magnets and phase rotation front end are, in effect, the beam dump.

⇒ Serious materials issues!
What More Should We Learn from Simulations?

- Target parameters should be optimized with regard to acceptance at end of phase rotation channel,
  ⇒ Combine MARS with ICOOL and/or DPGEANT.

- Shock damage to target.

- Magnetohydrodynamics of liquid metal jets.

- Thermal analysis and radiation damage analysis of materials around target.
What Should We Learn from Experiment?

• Pion production spectrum at low momentum.
  ⇒ Finish analysis of BNL E-910!

• Behavior of liquid metal jets entering a strong magnetic field.

• Behavior of a liquid jet when hit by a pulse of $10^{14}$ protons.

• Behavior of an rf cavity downstream of the primary target.
Experiments without Beam

• Exploding wire inside liquid jet.

Need:

– Liquid jet – could be vertical flow thru an aperture.
– Insulated wire down center of jet; return current in jet.
– 30-J capacitor bank; \( \approx 1 \mu s \) discharge.
– Brave graduate student.

• Liquid jet in magnet.

Need:

– Pulsed liquid jet, perhaps Ga/In first.
– High-field solenoid:
  * 20-T facility at FSU.
  * Build LN\(_2\)-cooled copper magnet; 15 min. cycle; MPS supply.
  * ... (Report by Bob Weggel)
– Diagnostic: camera with frame rate \( \approx 1000/s \).
Experiments with Beam

• Liquid jet in beam.
  Need:
  – Pulsed liquid jet.
  – Double-wall containment system
  – High-field solenoid in Phase II.
  – Diagnostics:
    * Camera with frame rate \(\approx 10^6/s\).
    * Strain gauges on inner containment vessel.

• RF cavity downstream of target.
  Need:
  – Solid target OK.
  – Solenoid around target in Phase II.
  – \(\approx 200\)-MHz rf cavity; high gradient \(\Rightarrow\) custom built.
  – RF power source: klystron, modulator...
  – 5 T magnet surrounding cavity.
Location: BNL F.E.B. U-Line

Area previously used by Hg spallation target test.
Beam Requirements

• 24-GeV proton beam.

• Single turn extraction.

• All 8 bunches.

• 2-ns pulse width desirable for rf cavity test.

• Variable spot size: $\sigma_x \approx \sigma_y = 1-5$ mm.
Facility Requirements

- ≈ 5 m along beam.
- 4 MW (10 desirable) power for pulsed magnet.
- 300 gpm cooling water, if water-cooled magnets.
- LN2, LHe dewars inside tunnel.
- Access ports for RF power, HV and LV electrical cables....
- Shed for RF power station outside tunnel.
- Personnel trailer.
Proposal to BNL in Summer 1998

Tasks:

• Complete previous experiment (E-910).

• Choose target parameters via simulation of target + phase rotation.

• Simulate beam shock in target.

• Design pulsed liquid jet.

• Choose option of test capture solenoid; design system.

• Design 200-MHz rf cavity, power source, and 5-T magnet.

• Design diagnostic systems.

• Clarify radiation safety issues.

• Refine beam and facilities requirements.

Next Targetry Workshop

BNL: Monday, June 1, 1998