Muon Collider Targetry R&D

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

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Muon Collider Targetry Workshop

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Overview of Targetry

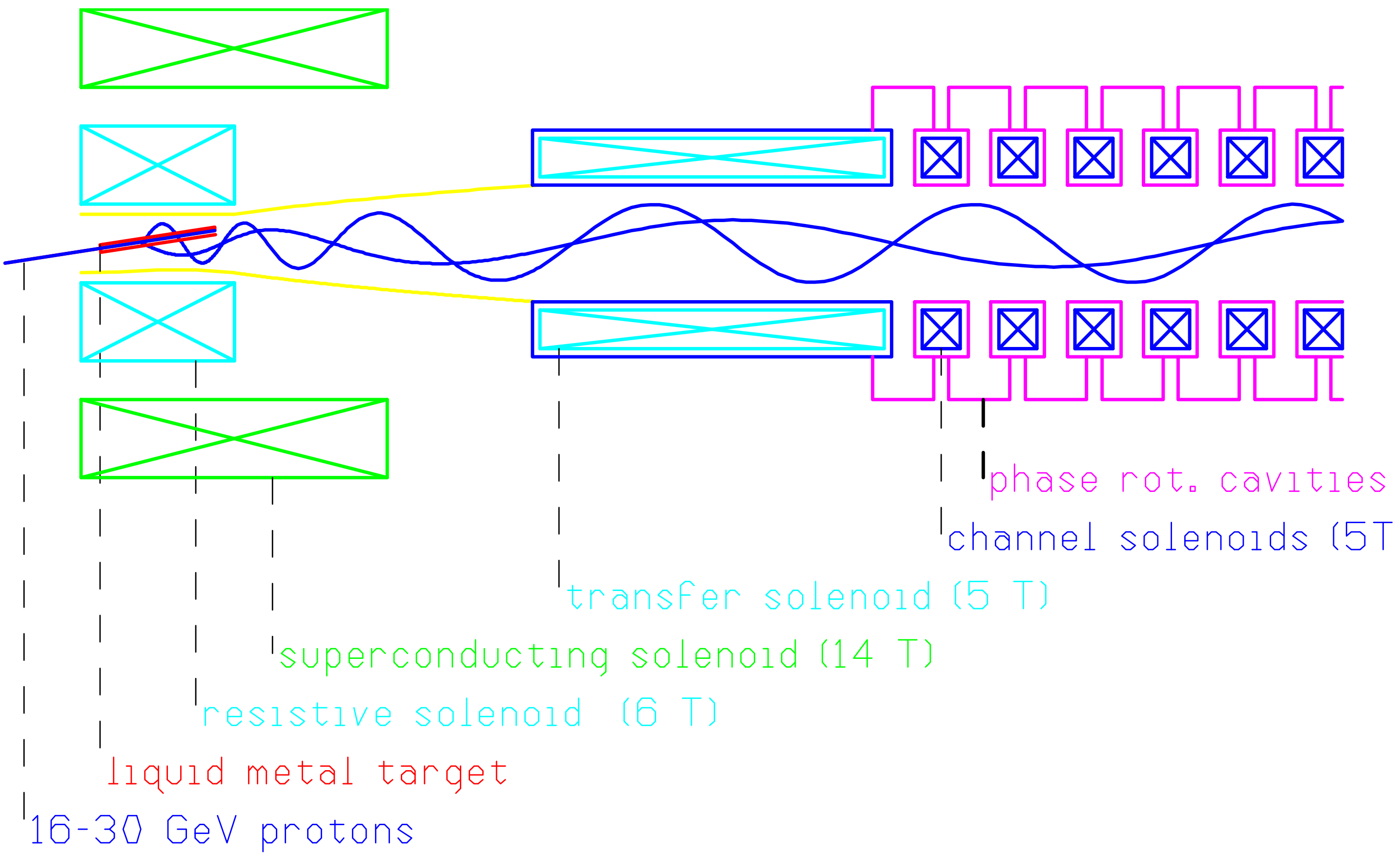
- Get muons from pion decay: $\pi^\pm \to \mu^\pm \nu$.
- Pions from proton-nucleus interactions in a **target**.
- Goal: 1.2×10^{14} $\mu^\pm$/s.
- $\Rightarrow$ High-Z target,

  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/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 π 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



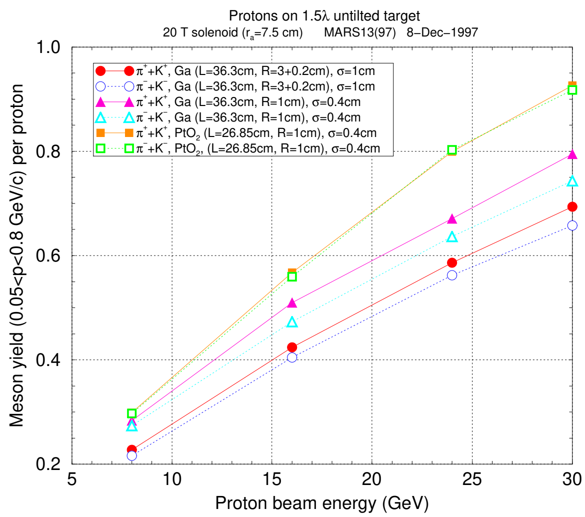
- Liquid metal target: Ga/In, Hg, or solder (Bi/In/Pb/Sn alloy).
- 20-T capture solenoid followed by 5-T phase-rotation channel.
- 20 T = 6-T, 8-MW water-cooled Cu magnet

  + 14-T superconducting magnet.
- Cost of 14-T magnet ≈ 0.8 M\$ $(B[\mathrm{T}]\ R[\mathrm{m}])^{1.32}(L[\mathrm{m}])^{0.66}$

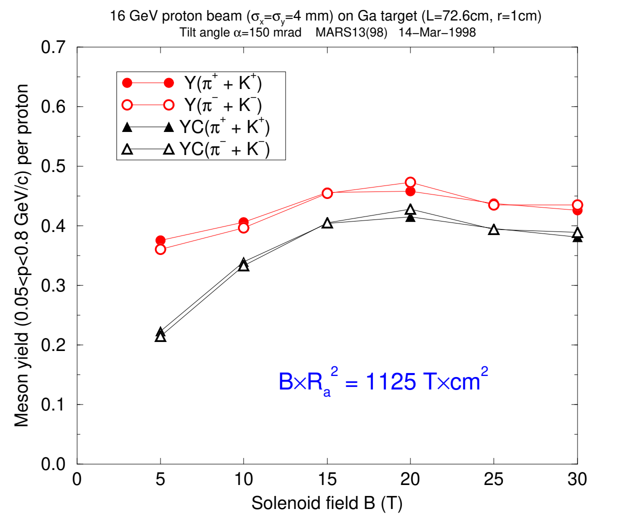
  $= 0.8$ M\$ $(14[\mathrm{T}]\ 0.6[\mathrm{m}])^{1.32}(0.75[\mathrm{m}])^{0.66} \approx$ \$11M.

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

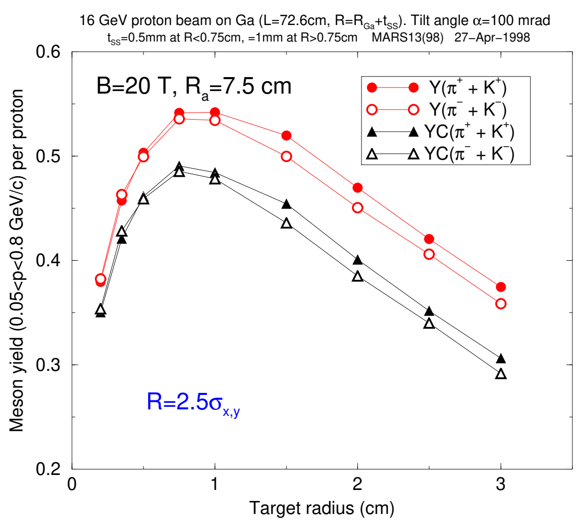
Yield *vs.* Beam Energy



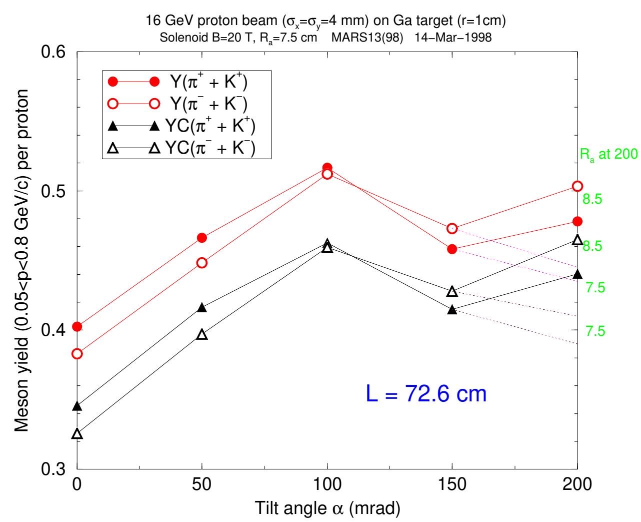
Yield *vs.* Magnetic Field



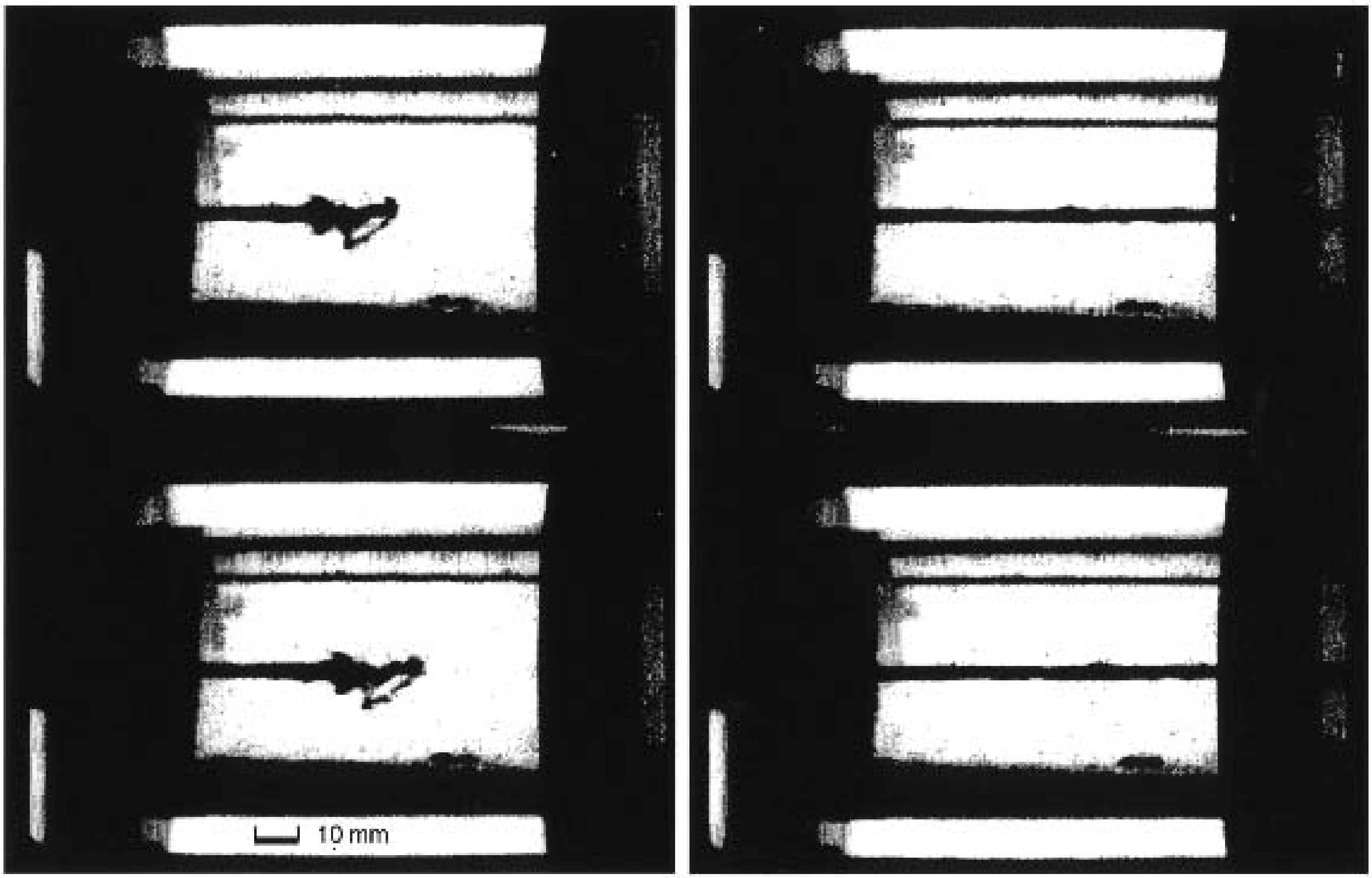
Yield *vs.* Target Radius



Yield *vs.* Target Angle



Mercury Jet Studied at CERN



High-speed photographs of mercury jet target for CERN-PS-AA. (laboratory test)
4,000 frames per second, Jet speed: 20 ms^{-1}, diameter: 3 mm, Reynold's Number: >100,000
A. Poncet

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: $\sigma = \sigma_{\rm Cu}/60$, $\rho = 10$ g/cm^3, $\Rightarrow$

$$v_{\rm min} > 60 \text{ m/s} \left[\frac{r}{1 \text{ cm}}\right] \left[\frac{r}{D}\right] \left[\frac{B_0}{20 \text{ T}}\right]^2 .$$

Ex: $B_0 = 20$ 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:

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

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

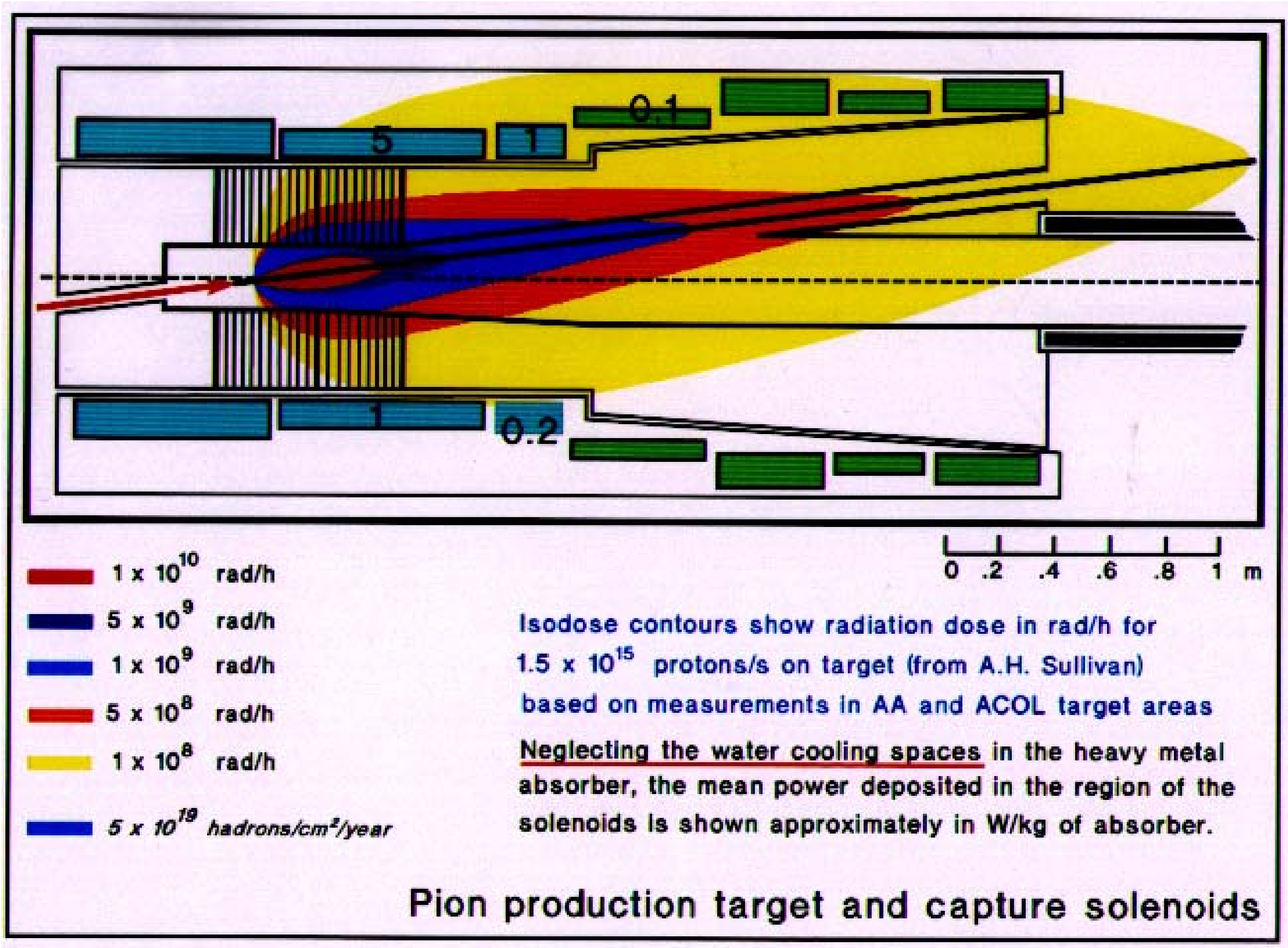
- Radial pressure: compression as jet enters magnet, expansion as it leaves:

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

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

- Will the jet break up into droplets?
- Need both FEA analysis and **lab tests**.

High Radiation Dose Around Target



⇒ 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,
  $\Rightarrow$ 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.
  $\Rightarrow$ 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 ≈ 1000/s.

Experiments with Beam

- Liquid jet in beam.

  Need:

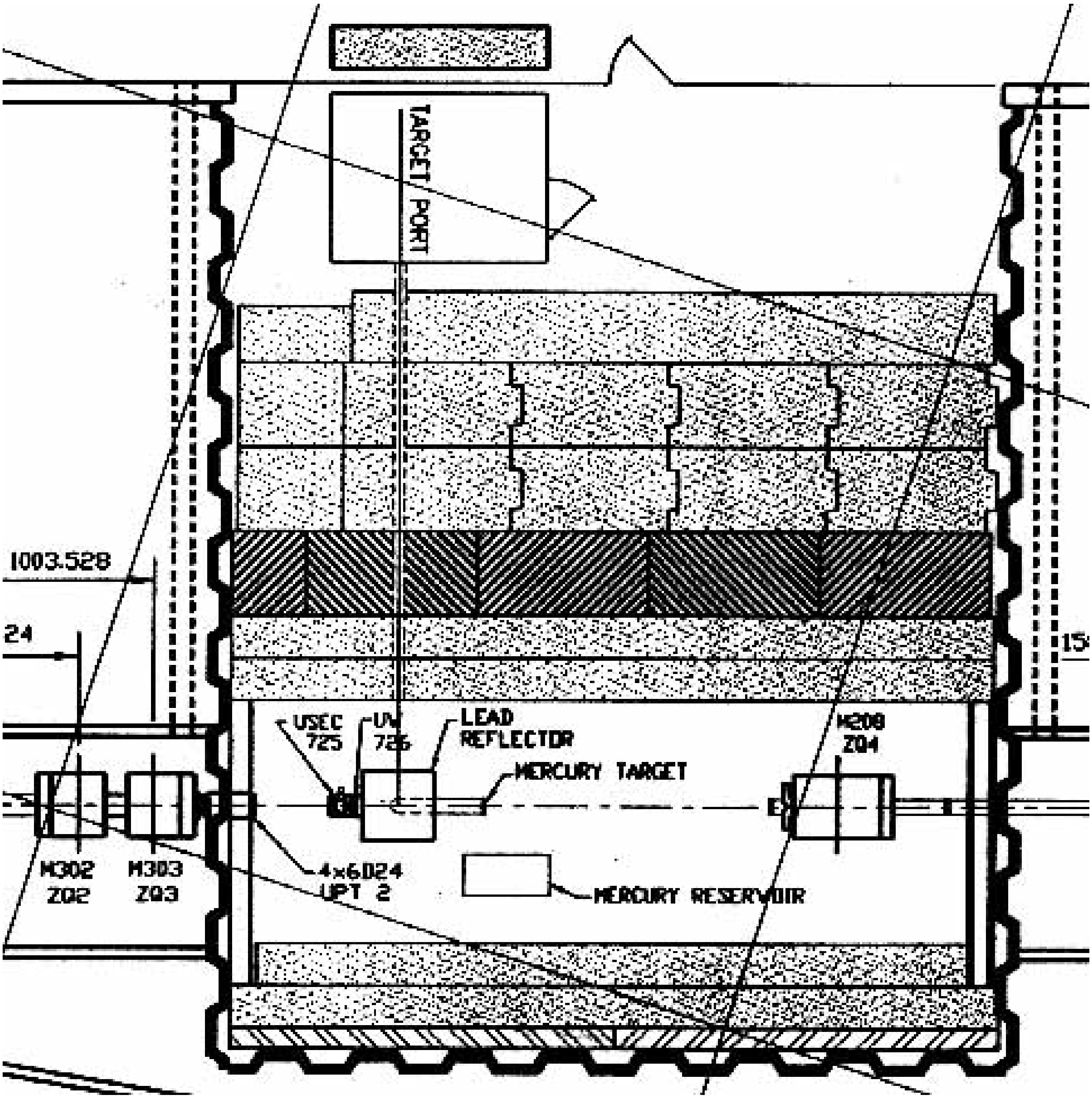
  - Pulsed liquid jet.
  - Double-wall containment system
  - High-field solenoid in Phase II.
  - Diagnostics:
    - Camera with frame rate $\approx 10^6$/s.
    - Strain gauges on inner containment vessel.

- 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.
  - Diagnostics: secondary-flux monitors.

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