J-PARC 50-GeV Program LOI-30
Studies of a Target System for a 4-MW, 50-GeV Proton Beam

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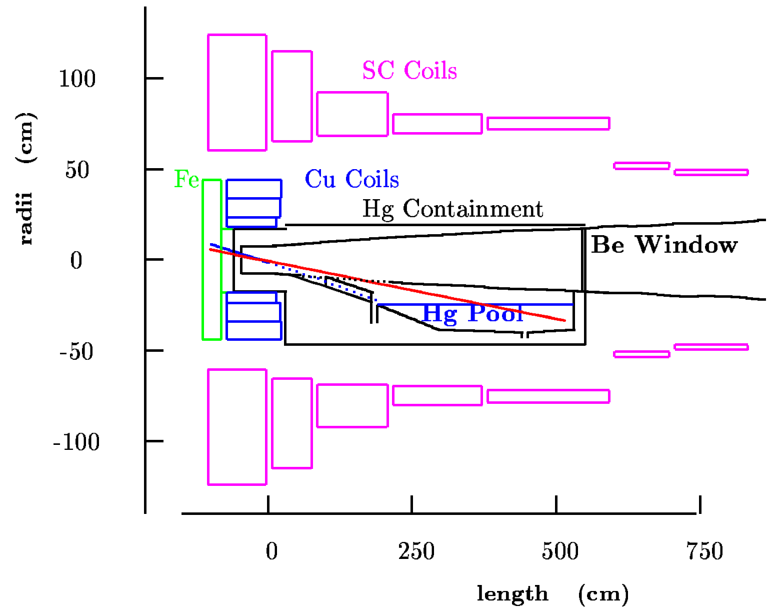

K.T. McDonald
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KEK, June 27, 2003
http://puhep1.princeton.edu/mumu/target/

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Executive Summary

We propose to perform a proof-of-principle demonstration of a target system based on a free mercury jet, including magnetic focusing/capture of secondary pions/muons, suitable for use in a 4-MW, 50-GeV proton beam as part of a neutrino "superbeam" and/or neutrino factory facility.

Such a target system would also be provide higher intensity muon beams for the PRISM project.

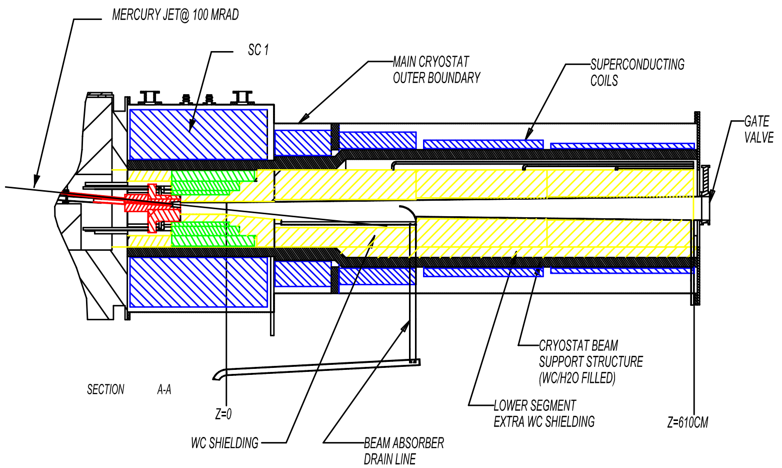
The proposed studies emphasize the survival of a prototype target system against issues of single proton pulses: dispersal of the jet target by mechanical "shock" and/or vaporization due energy deposition by the proton beam, and possible damping of these effects by the strong magnetic field of the capture solenoid.

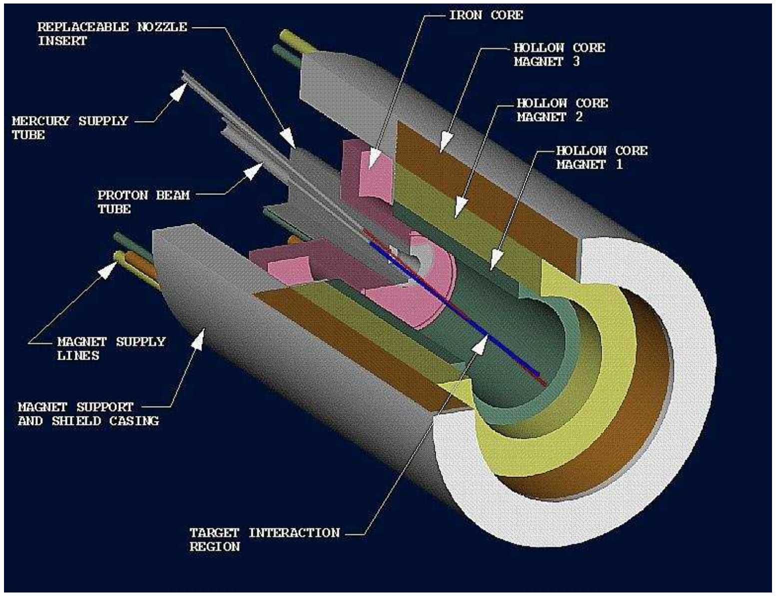
A first phase of such studies has been carried out at BNL and CERN, in which the interaction of a mercury jet with a proton beam, and with a 20-T solenoid magnet, have been investigated separately, with encouraging results.

Long-term issues of radiation damage and materials fatigue are to be addressed in separate studies.

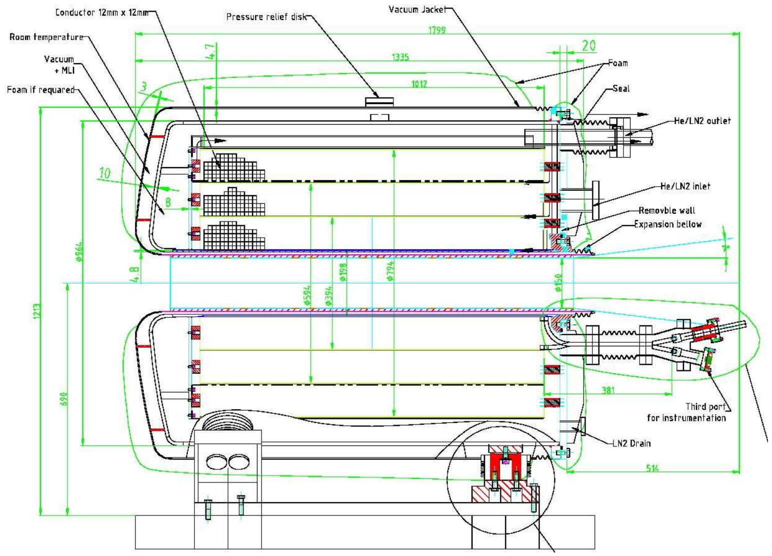
- The studies proposed here are to be made using small numbers (≈ 1,000 total) of intense proton pulses from the 50-GeV ring at J-PARC. (Preliminary studies could also be performed with pulses from the 3-GeV booster ring.)
- A "pulse-on-demand" mode of operation is desired, in which a proton pulse is used at most every few minutes. A higher repetition rate would be useful during beam setup.
- The studies should be carried out in an area suitable for use with primary proton beam, which implies substantial shielding. The small number of beam pulses will limit the activation of materials to low levels.
- The target system + surrounding (pulsed) 15-T solenoid magnet could occupy as little as 2 m along the beamline. However, a target "cave" of at least 4×4 m^2 floorspace is more desirable.
- The beam should be focusable to a spot of rms radius 1-2 mm at the target location.
- It is desirable to be able to extract any number from 1 to 9 of the bunches in the J-PARC 50-GeV ring during a single turn; a programmable fast-kicker is required for this.
- The mercury jet is to be about 1-cm diameter, flowing at 10-20 m/sec, entirely within a stainless-steel containment vessel (with beam entrance and exit windows of a higher-strength alloy). Diagnostics of the beam/jet interaction are primarily optical.
- The pulsed magnet is advantageously operated at about 70K to lower the resistance of its copper coils. The coils are cooled by flowing He gas, which is cooled by LN_2 in an external heat exchanger. A LN_2 storage dewar of capacity at least 20,000 liters is required.
- The magnet requires a special power supply, capable of 4-5 MW peak power. This could be a "conventional" power supply (that would require 5 MW (peak) wall power), or it could be a power supply based on an array of batteries (that would require only ≈ 50 kW wall power for a "battery charger").

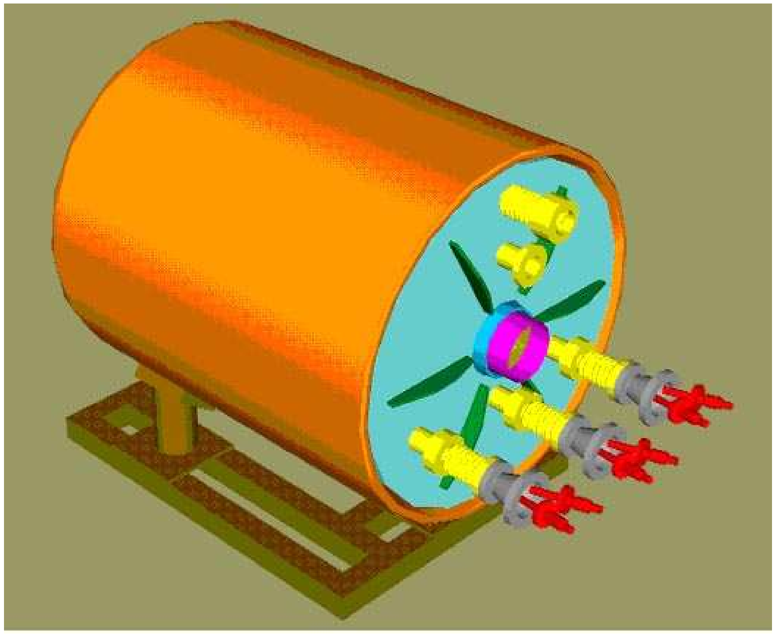
Sketches of a 4-MW Target Station



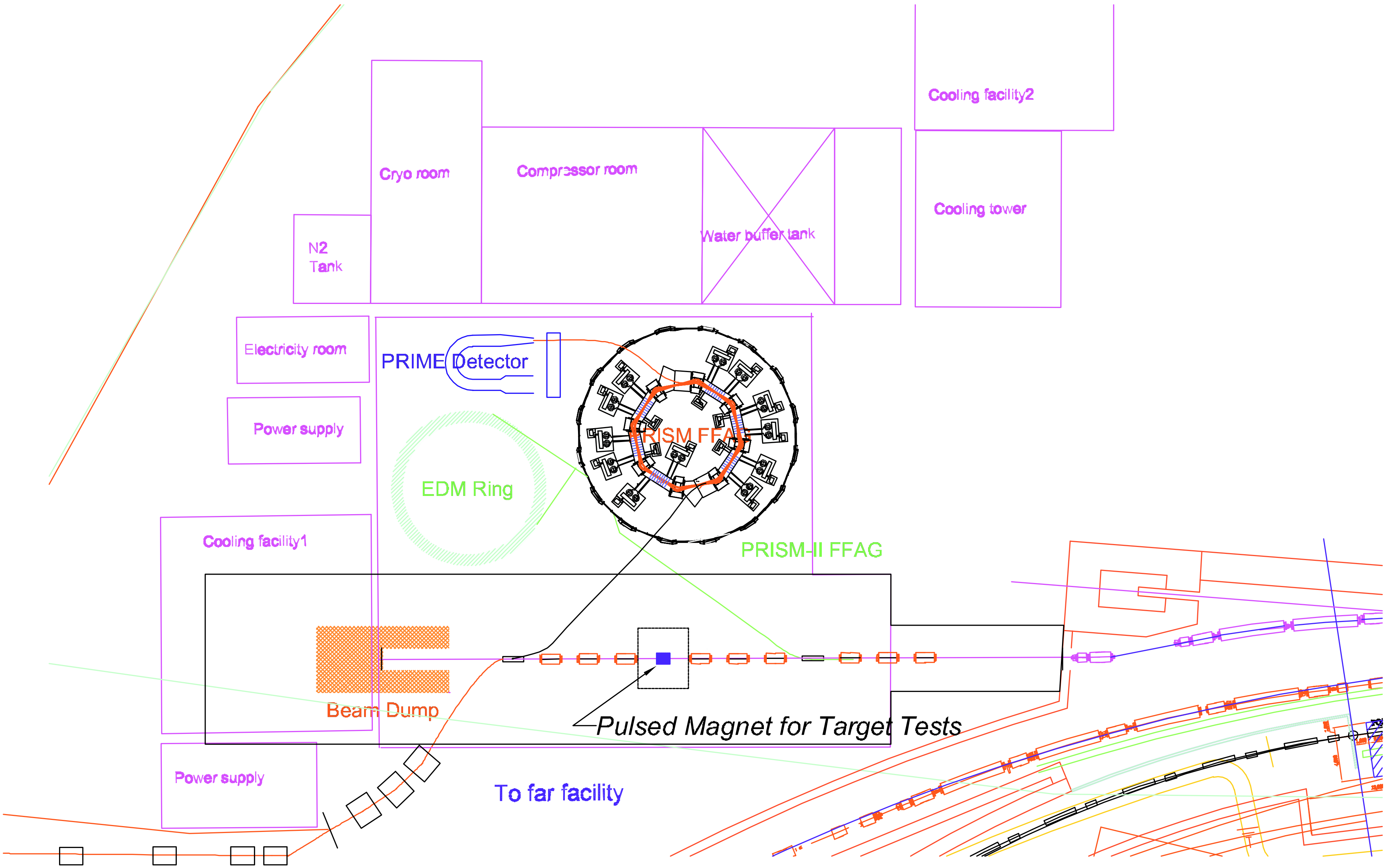


Sketches of a Pulsed Magnet Test Facility





Possible Siting of the Target Test Facility at the Pulsed Proton Beam Facility (LOI-26)



Why Targetry?

- **Targetry** = the task of producing and capturing π's and μ's from proton interactions with a nuclear target.

- At a **lepton collider** the key parameter is **luminosity**:

$$\mathcal{L} = \frac{N_1 N_2 f}{A}\,\mathrm{s}^{-1}\mathrm{cm}^{-2},$$

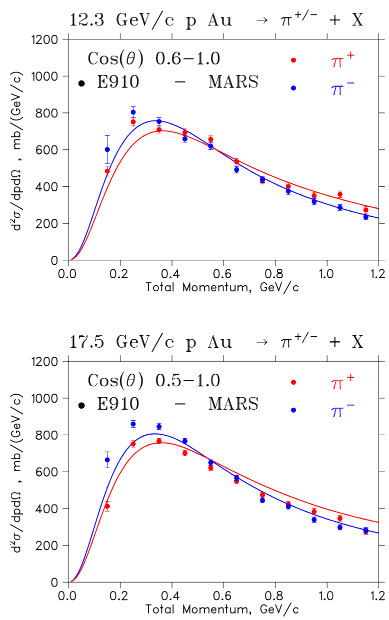
  $\Rightarrow$ Gain as square of source strength (targetry),
  but small beam area (cooling) is also critical.

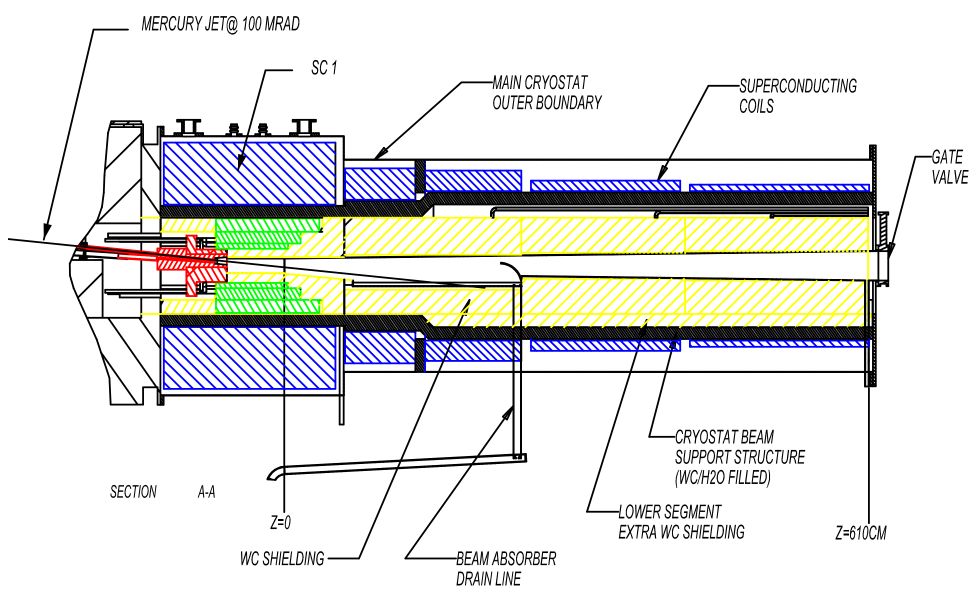
- At a **neutrino factory** the key parameter is **neutrino flux**, $\Rightarrow$ Source strength (targetry) is of pre-eminent concern.
  [Beam cooling important mainly to be sure the beam fits in the pipe.]

- The exciting results from atmospheric and reactor neutrino programs (Super-K, SNO, KamLAND) reinforce the opportunity for neutrino physics with intense accelerator neutrino beams, where **targetry is the major challenge**.

Targetry Challenges for Intense Muon and Neutrino Beams

- Use of a multimegawatt proton beam for maximal production of soft pions → muons.
- Capture pions in a 15-20-T solenoid, followed by a 1.25-T decay channel (with beam and target tilted by 100 mrad w.r.t. magnetic axis).

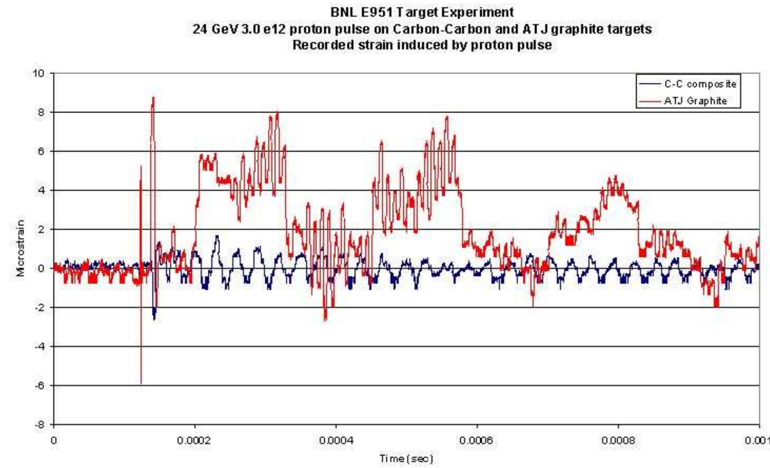




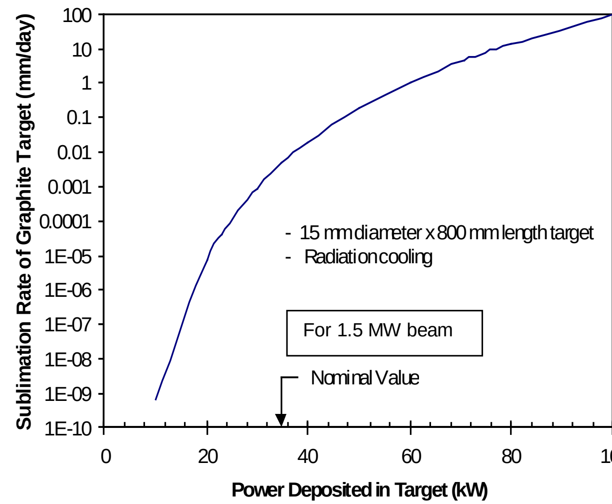
- A carbon target is feasible for 1.5-MW proton beam power.
- For $E_p \gtrsim 16$ GeV, factor of 2 advantage with high-Z target.
- Static high-Z target would melt, ⇒ Moving target.
- A free mercury jet target is feasible for beam power of 4 MW (and more).

A Carbon Target is Feasible at 1-MW Beam Power

A carbon-carbon composite with near-zero thermal expansion is largely immune to beam-induced pressure waves.



A carbon target in vacuum sublimates away in 1 day at 4 MW.



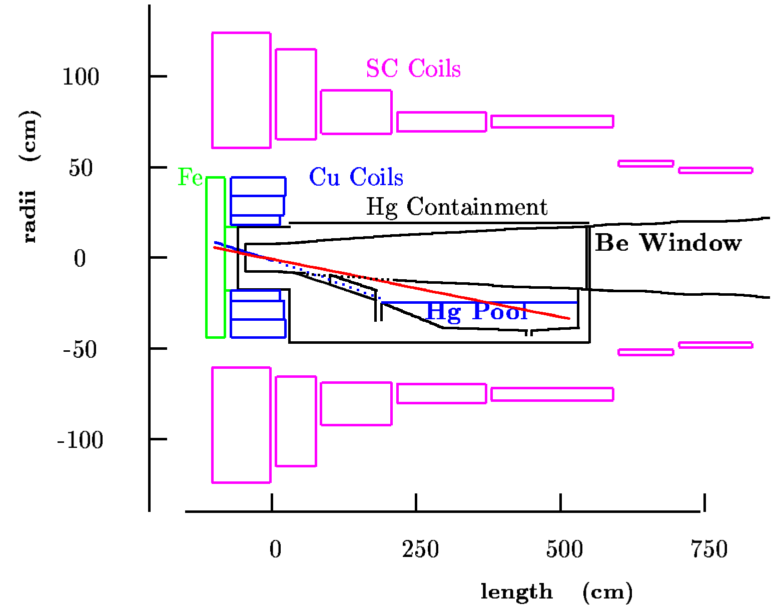
Sublimation of carbon is negligible in a helium atmosphere.

Tests underway at ORNL to confirm this.

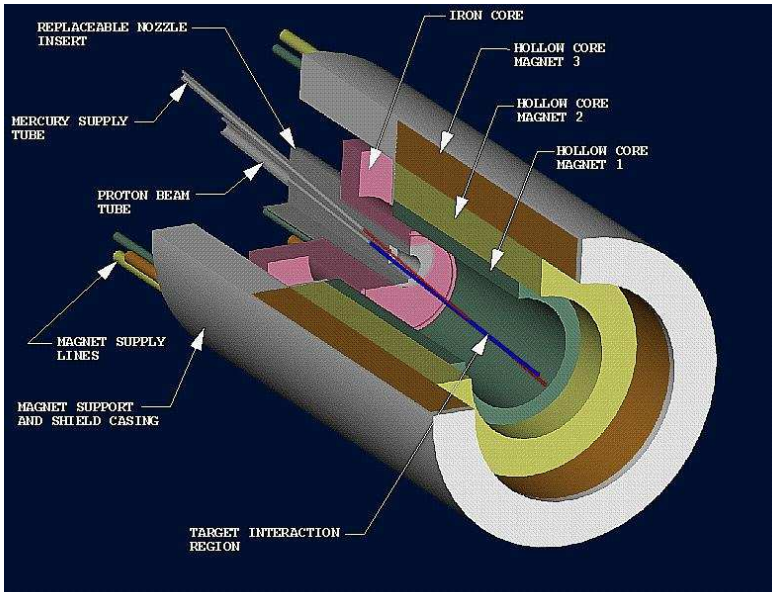
Radiation damage is limiting factor: $\approx$ 12 weeks at 1 MW.

A Liquid Metal Jet May Be the Best Target for Beam Power above 1.5 MW

Mercury jet target inside a magnetic bottle: 20-T around target, dropping to 1.25 T in the pion decay channel.

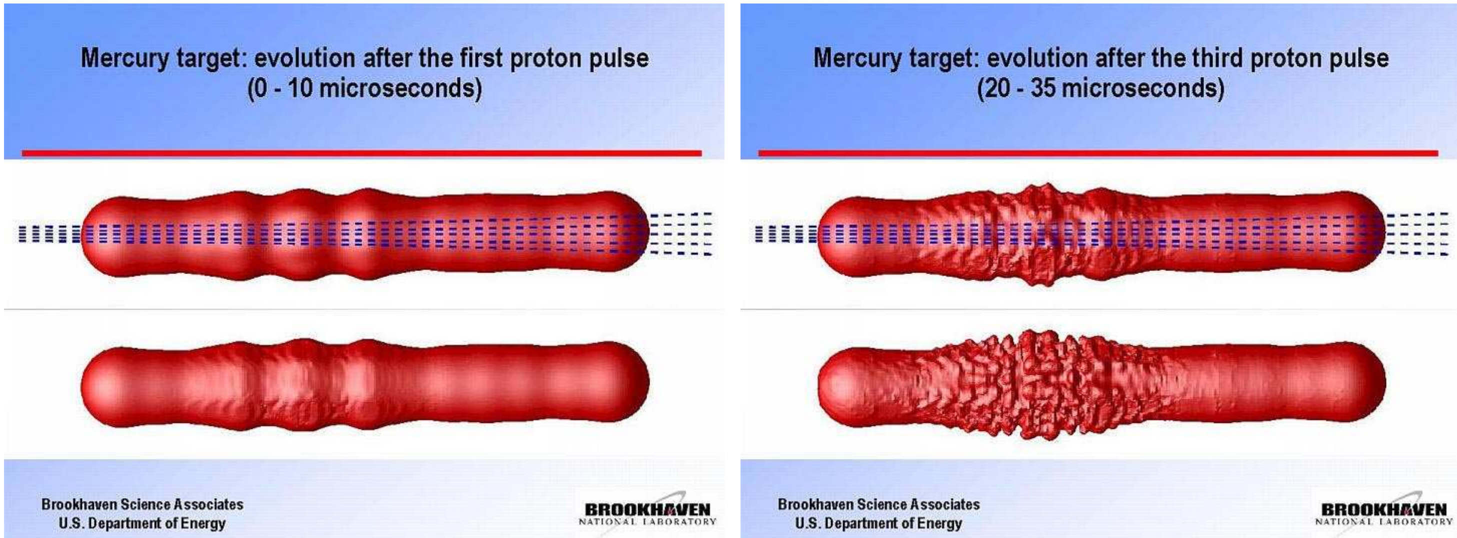


Mercury jet tilted by 100 mrad, proton beam by 67 mrad, to increase yield of soft pions.

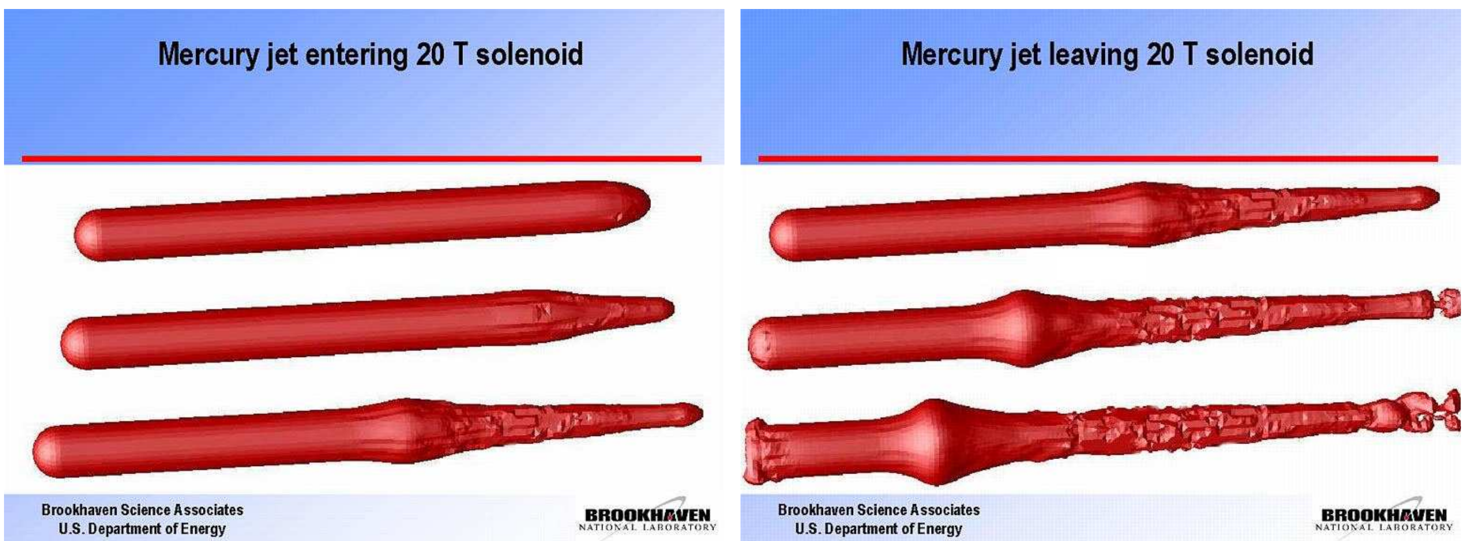


Viability of Targetry and Capture For a Single Pulse

- Beam energy deposition may disperse the jet.

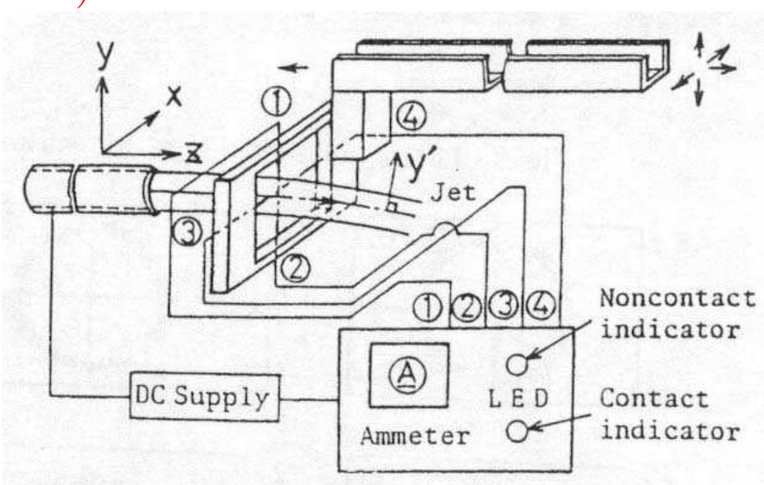


- Eddy currents may distort the jet as it traverses the magnet.



The Shape of a Liquid Metal Jet under a Non-uniform Magnetic Field

S. Oshima *et al.*, JSME Int. J. **30**, 437 (1987).



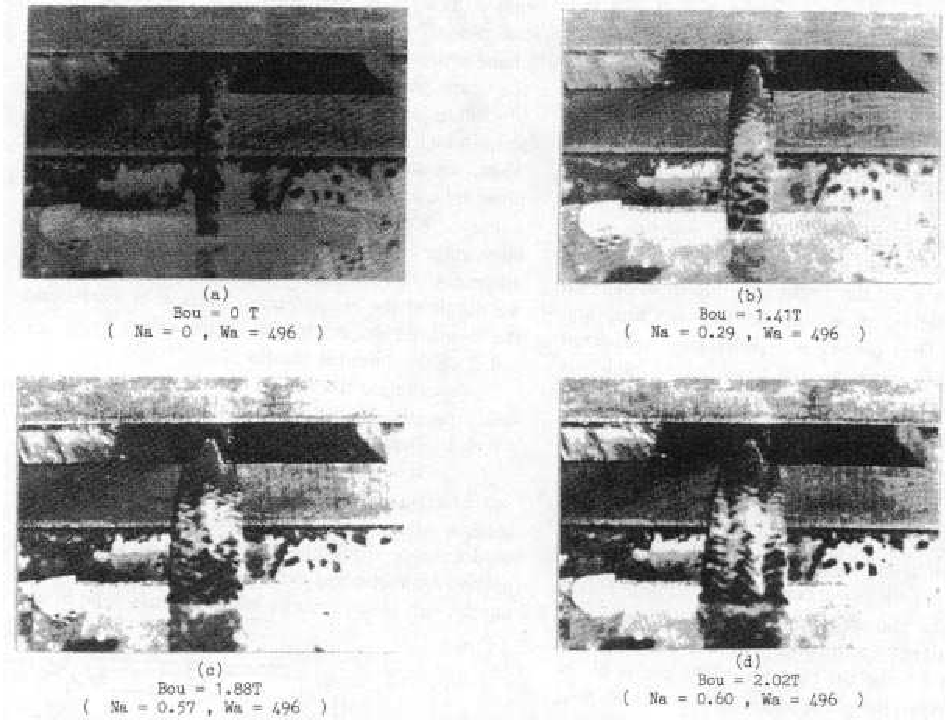


Fig. 9 Photographs of the jet for various applied mag- netic field strengths

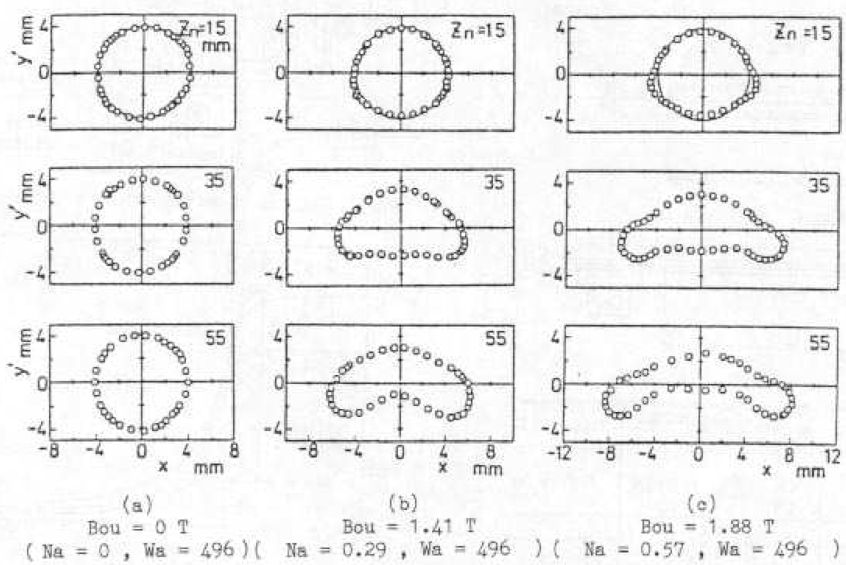
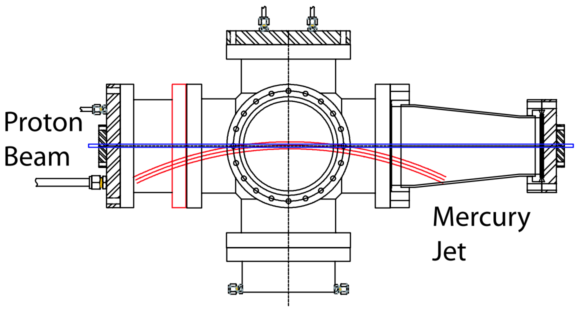
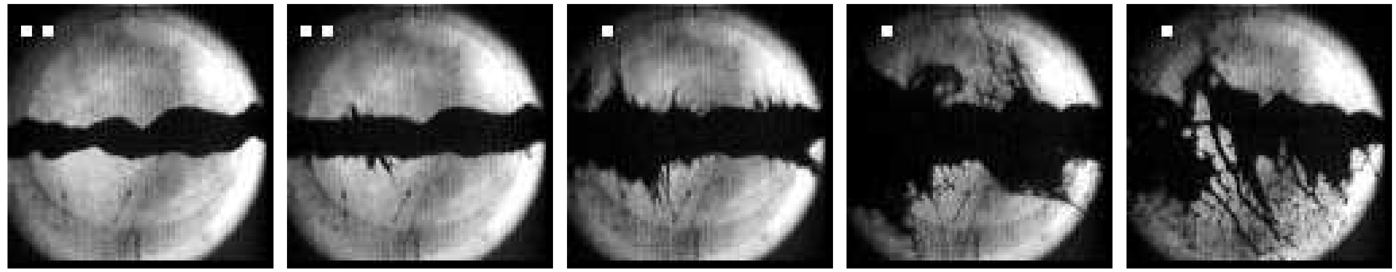


Fig. 10 Cross-sectional shape of the jet obtained by spot a electrode probe

Studies of Proton Beam + Mercury Jet (BNL)





1-cm-diameter Hg jet in 2e12 protons at $t = 0$, 0.75, 2, 7, 18 ms.

$$\text{Model:} \qquad v_{\rm dispersal} = \frac{\Delta r}{\Delta t} = \frac{r \alpha \Delta T}{r / v_{\rm sound}} = \frac{\alpha U}{C} v_{\rm sound} \approx 50 \text{ m/s}$$

for $U \approx 100$ J/g.

Data: $v_{\rm dispersal} \approx 10$ m/s for $U \approx 25$ J/g.

$v_{\rm dispersal}$ appears to scale with proton intensity.

The dispersal is not destructive.

Filaments appear only ≈ 40 μs after beam,

$\Rightarrow$ after several bounces of waves, or $v_{\rm sound}$ very low.

Tests of a Mercury Jet in a 20-T Magnetic Field
(CERN/Grenoble, A. Fabich, Ph.D. Thesis)

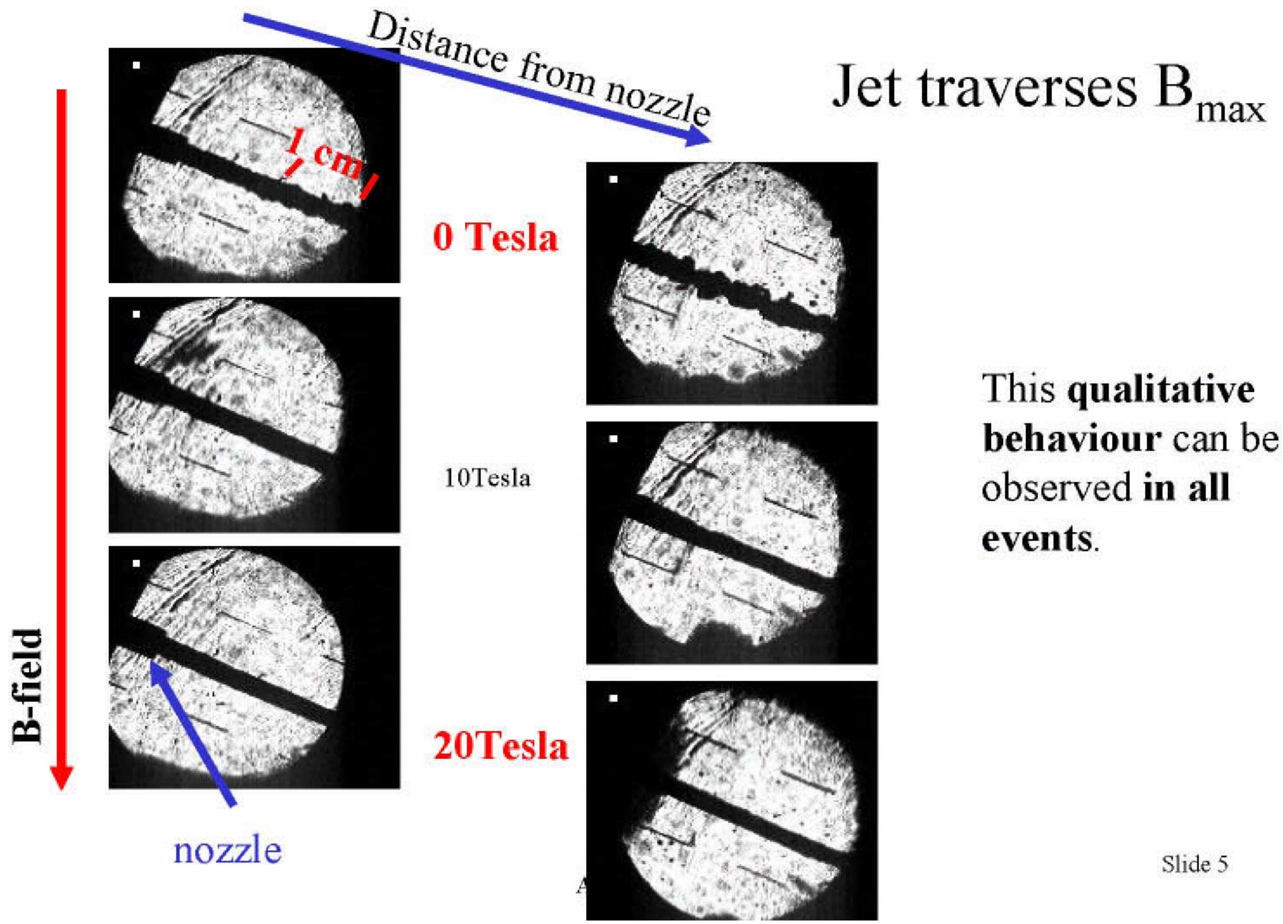
Eddy currents may distort the jet as it traverses the magnet.

Analytic model suggests little effect if jet nozzle inside field.

4 mm diam. jet, $v \approx 12$ m/s, $B = 0, 10, 20$ T.

$\Rightarrow$ Damping of surface tension waves (Rayleigh instability).

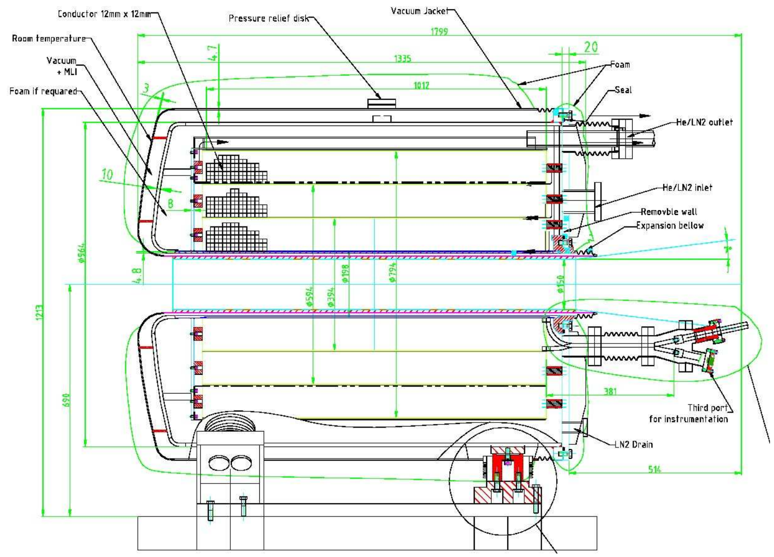
Will the beam-induced dispersal be damped also?

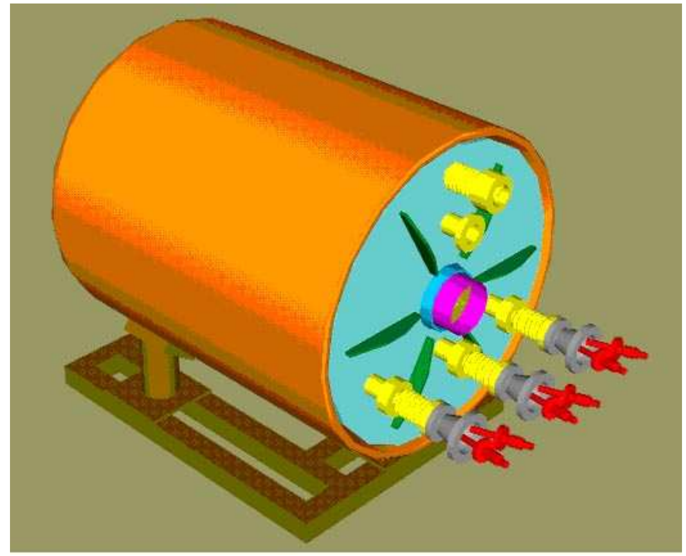


Issues for Further Targetry R&D

- Continue numerical simulations of MHD + beam-induced effects.
- Continue tests of mercury jet entering magnet.
- For solid targets, study radiation damage – and issues of heat removal from solid metal targets (bands, chains, *etc.*).
- Confirm manageable mercury-jet dispersal in beams up to 10^{14} protons/pulse – for which single-pulse vaporization may also occur. Test Pb-Bi alloy jet.
- Study issues when combine intense proton beam with mercury jet inside a high-field magnet.
  1. MHD effects in a **prototype target configuration**.
  2. Magnetic damping of mercury-jet dispersal.
  3. Beam-induced damage to jet nozzle – in the magnetic field.
- ⇒ We propose to construct a 15-T pulsed magnet, that can be staged as a 5-T and 10-T magnet.

A 15-T LN_2-Cooled Pulsed Solenoid





- Simple solenoid geometry with rectangular coil cross section and smooth bore (of 20 cm diameter)
- Cryogenic system reduces coil resistance to give high field at relatively low current.
  - Circulating coolant is gaseous He to minimize activation, and to avoid need to purge coolant before pulsing magnet.
  - Cooling via N_2 boiloff.
- Most cost effective to build the 4.5-MW supply out of "car" batteries! (We need at most 1,000 pulses of the magnet.)

Summary of J-PARC LOI-30

- The excellent physics opportunities for intense muon and neutrino beams lead us to consider multimegawatt target stations, where solid targets are not viable.
- A moving liquid metal target, inside a high-field solenoid magnet, is a leading candidate for a high-power target.
- Initial tests of a mercury jet + proton beam, and of a mercury jet + 20-T magnet, are very encouraging.
- The next step is a full-scale proof-of-principle test of mercury jet + 15-T magnet + intense proton beam.
- The J-PARC 50-GeV proton synchrotron is well suited for the proof-of-principle test — and for future implementation of a 4-MW target station.
- Therefore, we request that J-PARC include a high-power target test station in its 50-GeV fast-extracted-beam facilities.