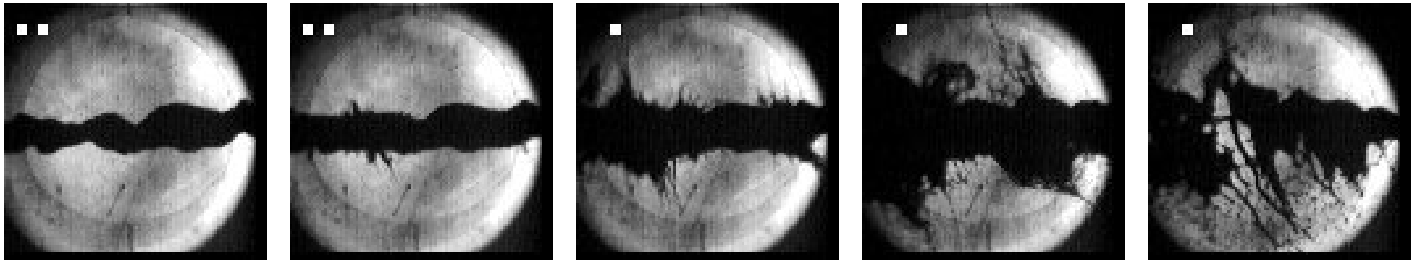
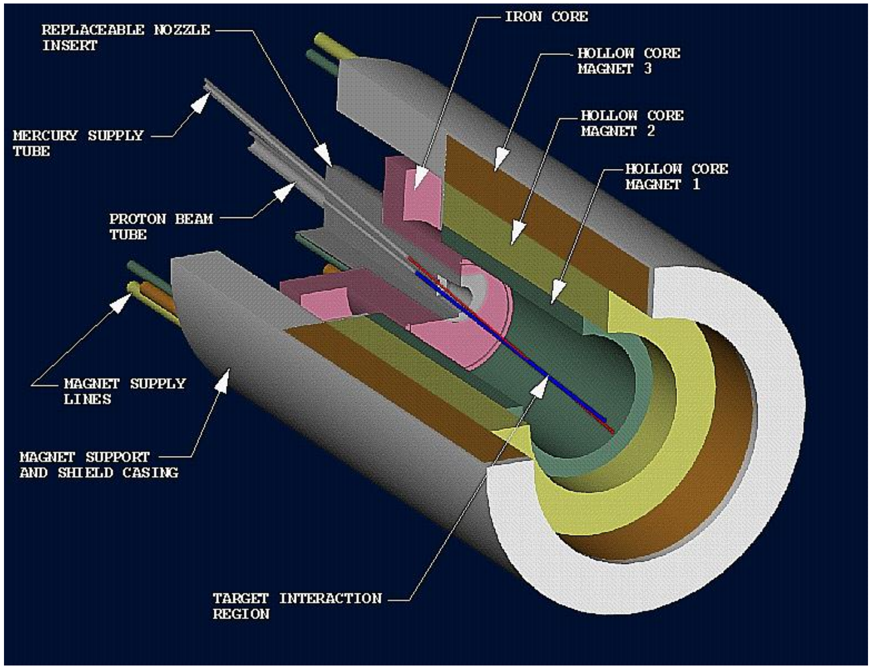
Overview of the Targetry R&D Program





K.T. McDonald
Princeton U.
NFMCC Meeting
Fermilab, March 18, 2008

Targetry Web Page: `http://puhep1.princeton.edu/mumu/target/`

Targetry Challenges of a Neutrino Factory and Muon Collider

- **Desire $\approx 10^{14}$ μ/s from $\approx 10^{15}$ p/s (≈ 4 MW proton beam).**
- **Highest rate μ^+ beam to date: PSI μE4 with $\approx 10^9$ μ/s from $\approx 10^{16}$ p/s at 600 MeV.**
- **$\Rightarrow$ Some R&D needed!**

Palmer (1994) proposed a solenoidal capture system.

Low-energy π's collect from side of long, thin cylindrical target.

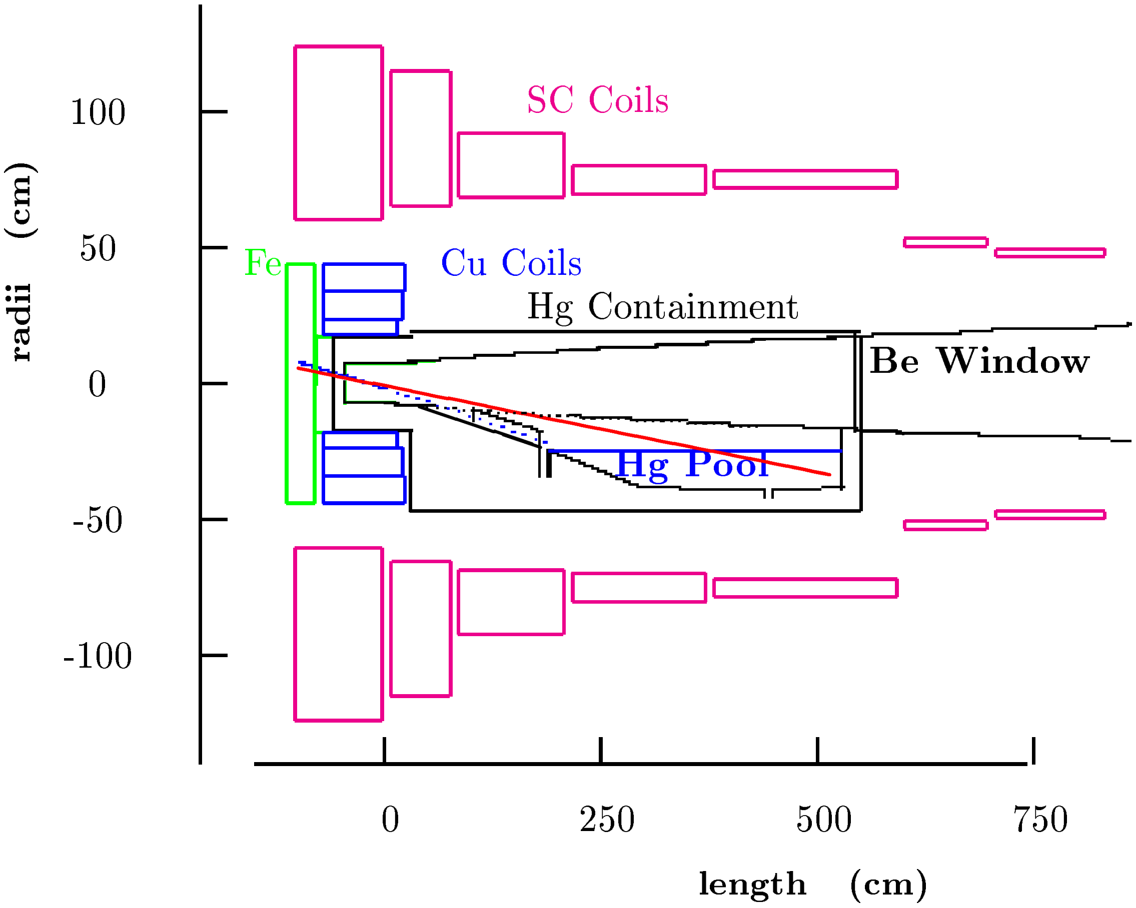
Collects both signs of π's and μ's, $\Rightarrow$ Shorter data runs (with magnetic detector).

Solenoid coils can be some distance from proton beam.

$\Rightarrow \gtrsim 4$ year life against radiation damage at 4 MW.

$\Rightarrow$ Proton beam readily tilted with respect to magnetic axis.

$\Rightarrow$ Beam dump (mercury pool) out of the way of secondary π's and μ's.



Target Survival

- Plausible that a new "conventional" graphite target could survive pulsed-beam-induced stresses at 2 MW.
  - Graphite target should be in helium atmosphere to avoid rapid destruction by sublimation, ⇒ Cool target by helium gas flow.
  - Radiation damage will require target replacement ≈ monthly(?).
  - Graphite target less and less plausible beyond 2 MW.
  - Secondary particle collection favors shorter target, ⇒ High-Z materials.
- High-Z targets for > 2 MW should be replaced every pulse!
  - ⇒ Flowing liquid target: mercury, lead-bismuth, ...
  - Pulsed beam + liquid in pipe ⇒ Destruction of pipe by cavitation bubbles, ⇒ Use free liquid jet.
  - Free liquid metal jets are stabilized by a strong longitudinal magnetic field.
  - Strong solenoid field around target favorable for collection of low-energy secondaries, as needed for ν Factory and Muon Collider.
  - ⇒ High-power liquid jet target R&D over last 10 years, sponsored by the Neutrino Factory and Muon Collider Collaboration.

Ongoing Targetry R&D

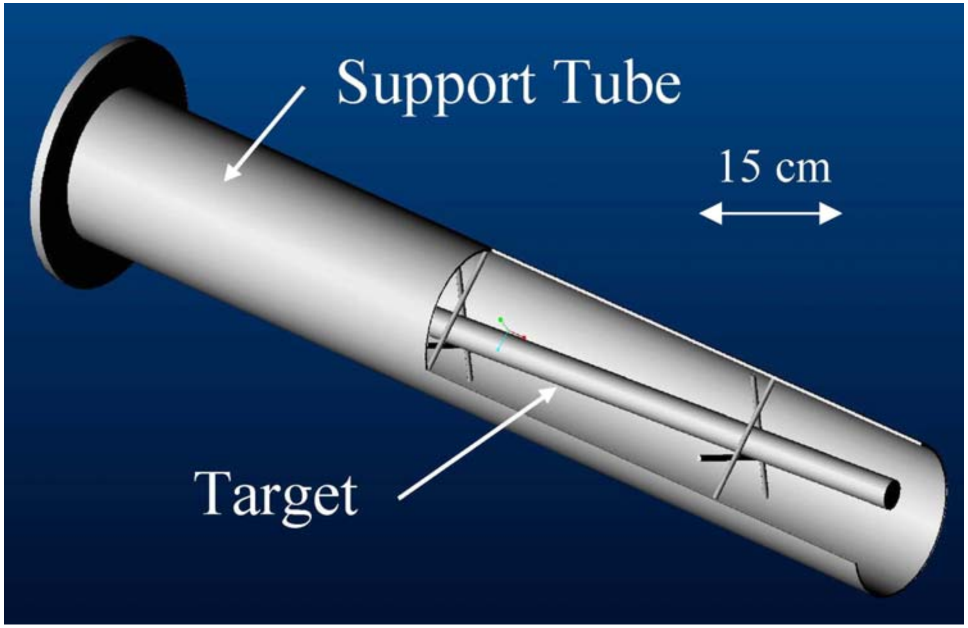
- Solid Targets (briefly reviewed in the rest of this talk).
- Free Mercury Jet Target (this session).

Thermal Issues for Solid Targets, I

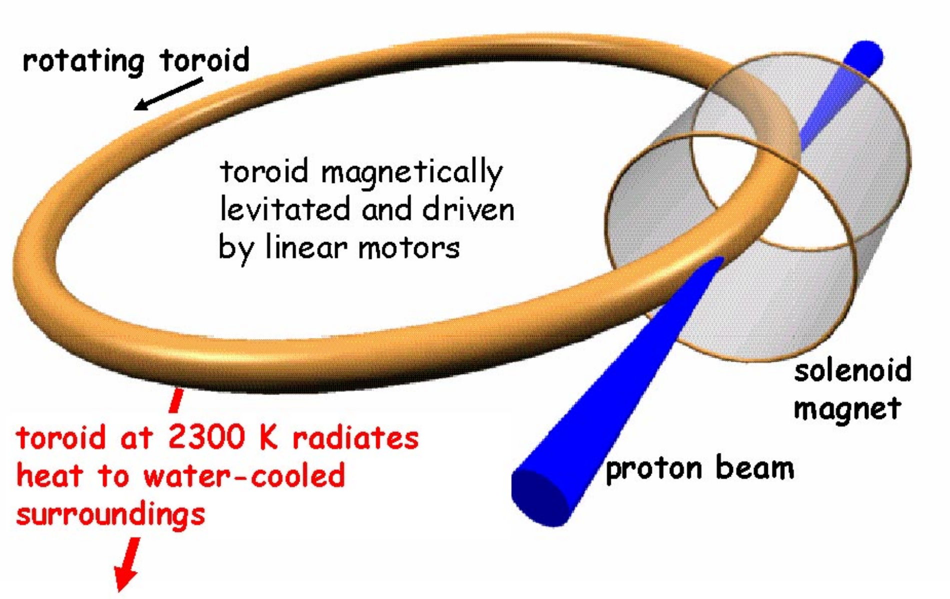
The quest for efficient capture of secondary pions precludes traditional schemes to cool a solid target by a liquid. (Absorption by plumbing; cavitation of liquid.)

A solid, radiation-cooled stationary target in a 4-MW beam will equilibrate at about 2500 C. ⇒ Carbon is only candidate for this type of target.

Carbon target must be in He atmosphere to suppress sublimation.
(Neutrino Factory Study 1)



A moving band target (Ta, W, ...) could be considered (if capture system is toroidal).



Thermal Issues for Solid Targets, II

When beam pulse length t is less than target radius r divided by speed of sound $v_{\rm sound}$, beam-induced pressure waves (thermal shock) are a major issue.

Simple model: if U = beam energy deposition in, say, Joules/g, then the instantaneous temperature rise ΔT is given by

$$\Delta T = \frac{U}{C}, \qquad \text{where } C = \text{heat capacity in Joules/g/K.}$$

The temperature rise leads to a strain $\Delta r/r$ given by

$$\frac{\Delta r}{r} = \boldsymbol{\alpha}\Delta T = \frac{\boldsymbol{\alpha} U}{C}, \qquad \text{where } \boldsymbol{\alpha} = \text{thermal expansion coefficient.}$$

The strain leads to a stress P (= force/area) given by

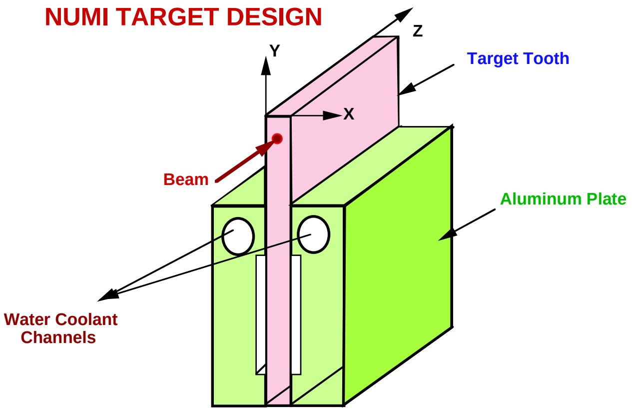
$$P = E\frac{\Delta r}{r} = \frac{E\boldsymbol{\alpha} U}{C}, \qquad \text{where } E = \text{modulus of elasticity.}$$

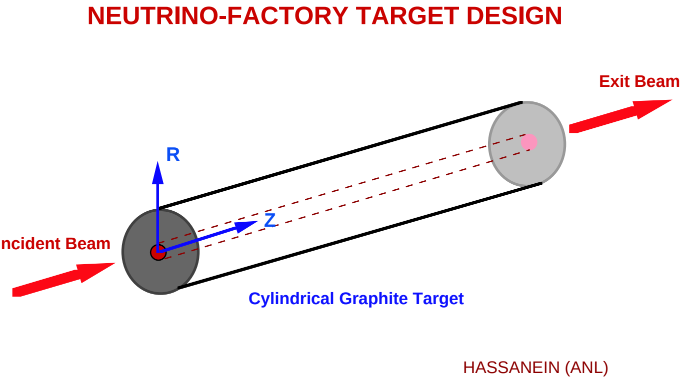
In many metals, the tensile strength obeys $P \approx 0.002E$, $\boldsymbol{\alpha} \approx 10^{-5}$, and $C \approx 0.3$ J/g/K, in which case

$$U_{\rm max} \approx \frac{PC}{E\boldsymbol{\alpha}} \approx \frac{0.002 \cdot 0.3}{10^{-5}} \approx \textbf{60 J/g}.$$

⇒ Best candidates for solid targets have high strength (Vascomax, Inconel, TiAl6V4) and/or low thermal expansion (Superinvar, Toyota “gum metal”, carbon-carbon composite).

A Carbon Target is Feasible at 1-2 MW Beam Power





Low energy deposition per gram and low thermal expansion coefficient reduce thermal “shock” in carbon.

Operating temperature > 2000C if use only radiation cooling.

A carbon target in vacuum would sublimate away in 1 day at 4 MW, but sublimation of carbon is negligible in a helium atmosphere.

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

$\Rightarrow$ Carbon target is baseline design for most neutrino superbeams.

Useful pion capture increased by compact, high-Z target,
$\Rightarrow$ Continued R&D on solid targets.

How Much Beam Power Can a Solid Target Stand?

How many protons are required to deposit 60 J/g in a material?

What is the maximum beam power this material can withstand without cracking, for a 10-GeV beam at 10 Hz with area 0.1 cm^2.

Ans: If we ignore "showers" in the material, we still have dE/dx ionization loss, of about 1.5 MeV/g/cm^2.

Now, 1.5 MeV $= 2.46 \times 10^{-13}$ J, so 60 J/ g requires a proton beam intensity of $60/(2.4 \times 10^{-13}) = 2.4 \times 10^{14}$/cm^2.

So, $P_{\rm max} \approx 10$ Hz $\cdot 10^{10}$ eV $\cdot 1.6 \times 10^{-19}$ J/eV $\cdot 2.4 \times 10^{14}$/cm$^2 \cdot 0.1$ cm$^2 \approx 4 \times 10^5$ J/s = 0.4 MW.

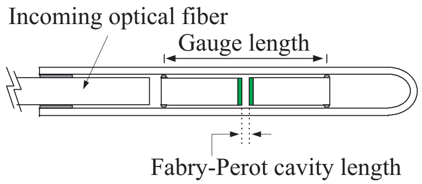
If solid targets crack under singles pulses of 60 J/g, then safe up to only 0.4 MW beam power!

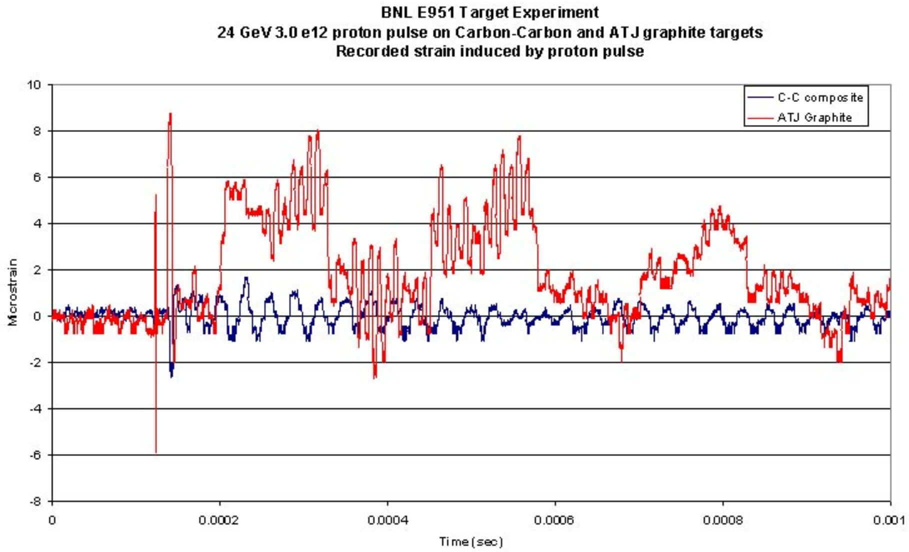
Empirical evidence is that some materials survive 500-1000 J/g,
$\Rightarrow$ May survive 4 MW if rep rate $\gtrsim$ 10 Hz.

Ni target in FNAL $p$bar source:
"damaged but not failed" for peak energy deposition of 1500 J/g.

Lower Thermal Shock If Lower Thermal Expansion Coefficient

ATJ graphite and a 3-D weave of carbon-carbon fibers instrumented with fiberoptic strain sensors, and exposed to pulses of 4×10^{12} protons @ 24 Gev.

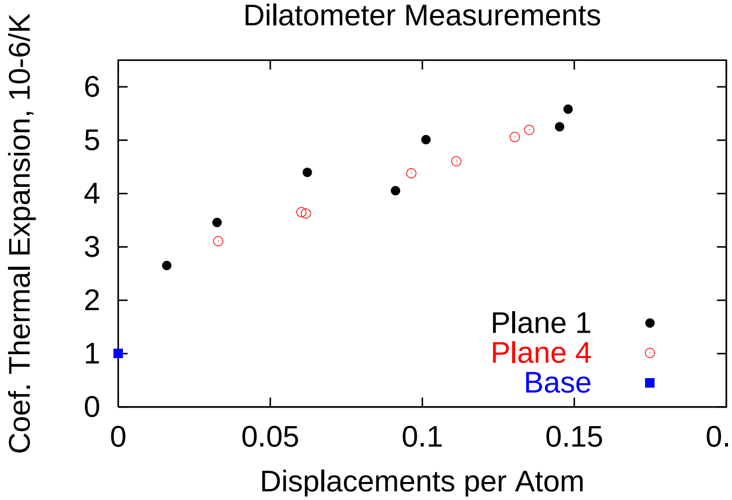




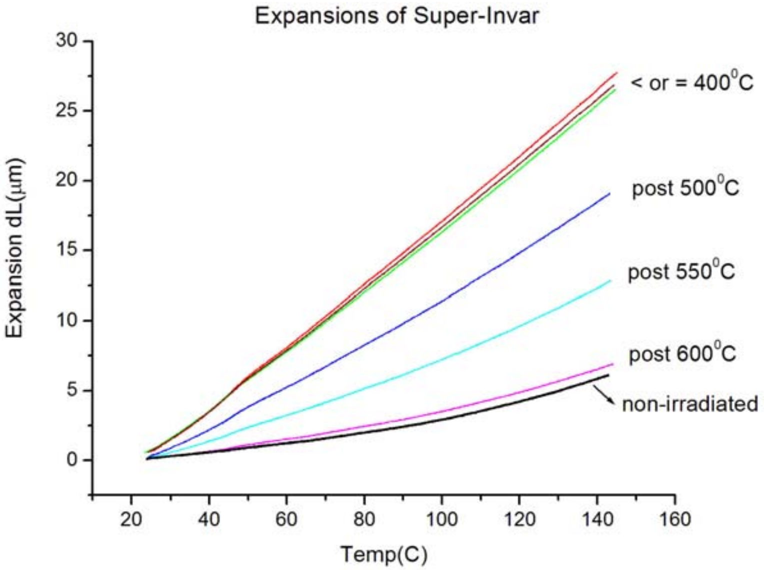
Carbon-carbon composite showed much lower strains than in the ordinary graphite – but readily damaged by radiation!

Thermal expansion coefficient of engineered materials is affected by radiation.

Super-Invar: CTE *vs.* dose:



Super-Invar: recovery of the CTE by thermal annealing:



Recent/Ongoing Solid Target Projects

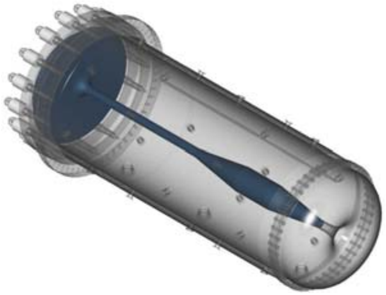
MiniBooNE Horn Target

Up to 5×10^{12} 8-GeV protons.

Survived 10^8 pulses.

Gas-cooled Be target.

30 kW beam power.



CNGS Target System

Up to 7×10^{13} 400-GeV protons every 6 s.

Beam $\sigma = 0.5$ mm.

5 interchangeable graphite targets.

Designed for 0.75 MW.

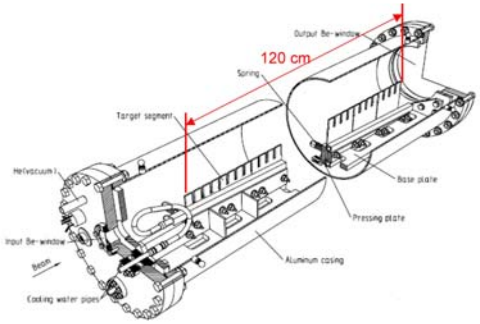
NUMI Target Upgrade

Up to 1.5×10^{14} 120-GeV protons every 1.4 s.

Beam $\sigma = 1.5$ mm.

Designed for 1-2 MW.

Graphite + water cooling.



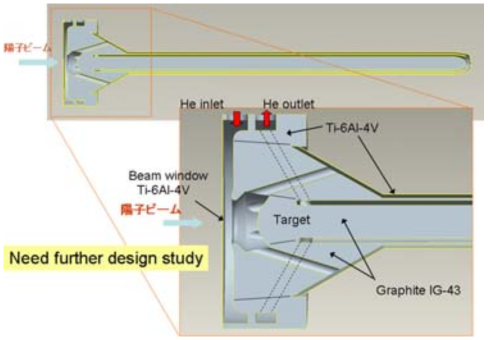
JPARC ν Horn Target

Up to 4×10^{14} 50-GeV protons every 4 s.

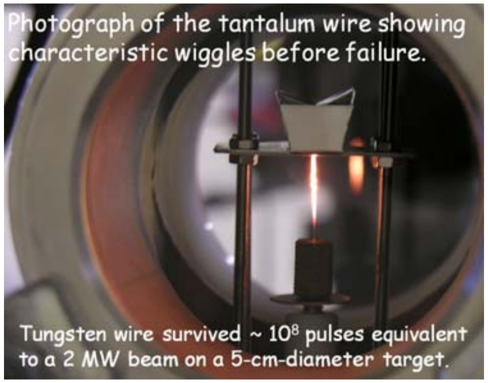
Beam $\sigma = 4$ mm.

Designed for 0.75 MW.

Graphite + He gas cooling.

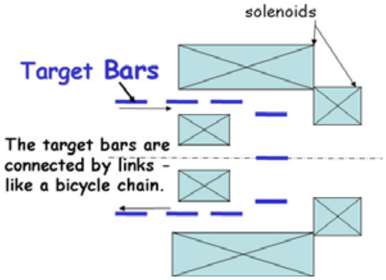


Pulsed-Current Studies of Ta & W Wires at RAL (R. Bennett *et al.*)



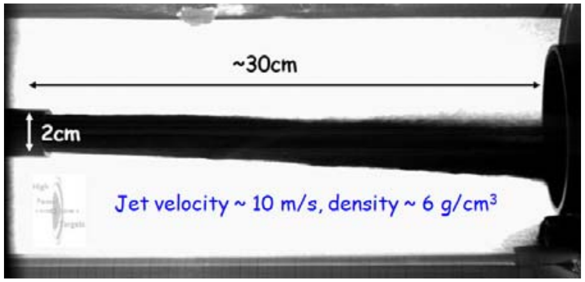
Photograph of the tantalum wire showing characteristic wiggles before failure.

Tungsten wire survived ~ 10^8 pulses equivalent to a 2 MW beam on a 5-cm-diameter target.



The target bars are connected by links like a bicycle chain.

New: Flowing Tungsten Powder Targets



Jet velocity ~ 10 m/s, density ~ 6 g/cm^3

(C. Densham *et al.*, RAL)

Liquid Jet Targets

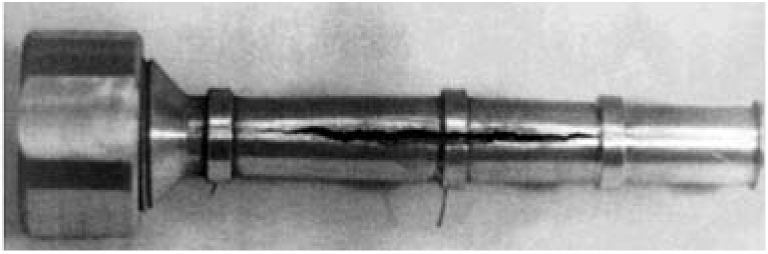
A. Calder, Paris (1937):

Now at Fundació Joan Miró, Barcelona

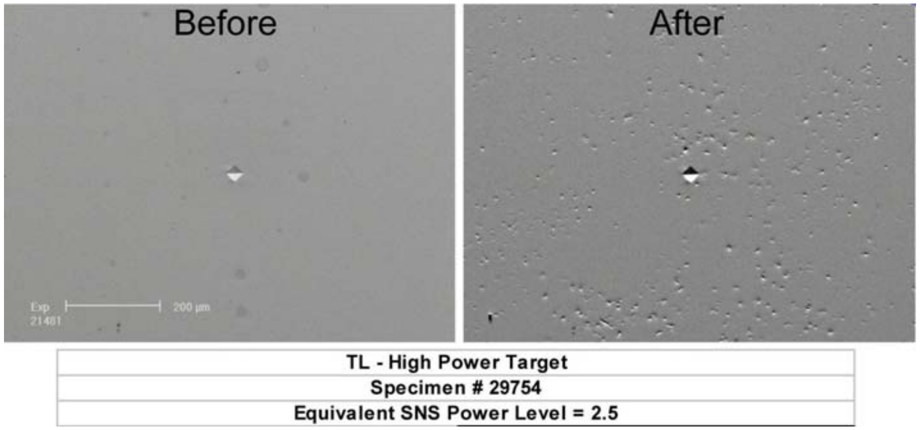
Beam-Induced Cavitation in Liquids Can Break Pipes

ISOLDE:

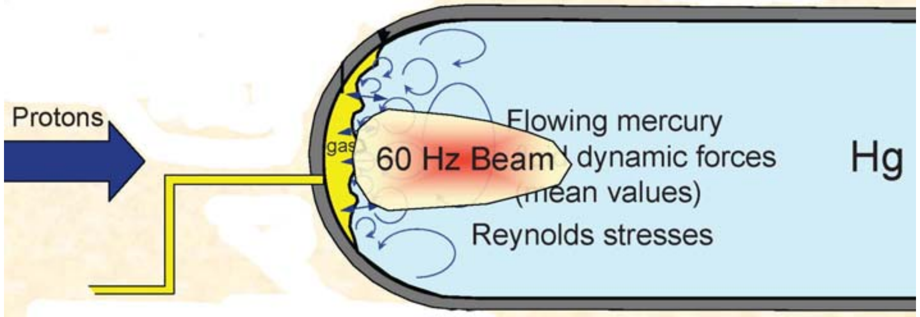
Hg in a pipe (BINP):



Cavitation pitting of SS wall surrounding Hg target after 100 pulses (SNS):



Mitigate(?) by gas buffer ⇒ free Hg surface:



Water jacket of NuMI target developed a leak after ≈ 1 month. Perhaps due to beam-induced cavitation.

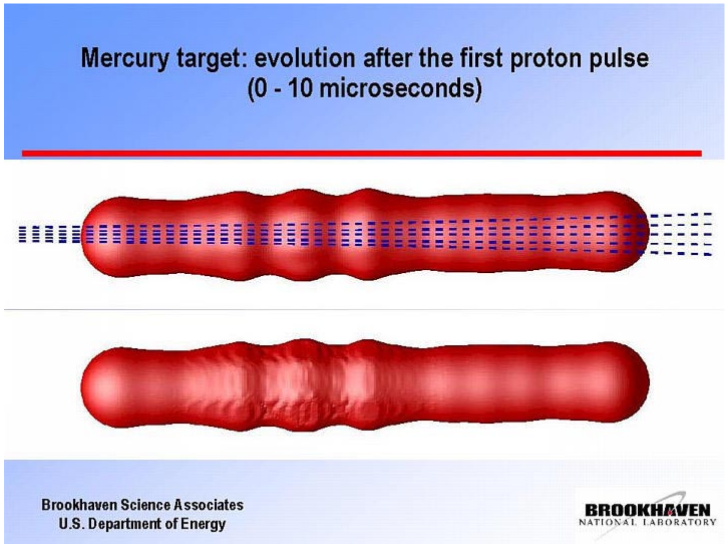
Ceramic drainpipe/voltage standoff of water cooling system of CNGS horn failed after 2 days operation at high beam power. (Not directly a beam-induced failure.)

⇒ Use free liquid jet if possible.

Beam-Induced Effects on a Free Liquid Jet

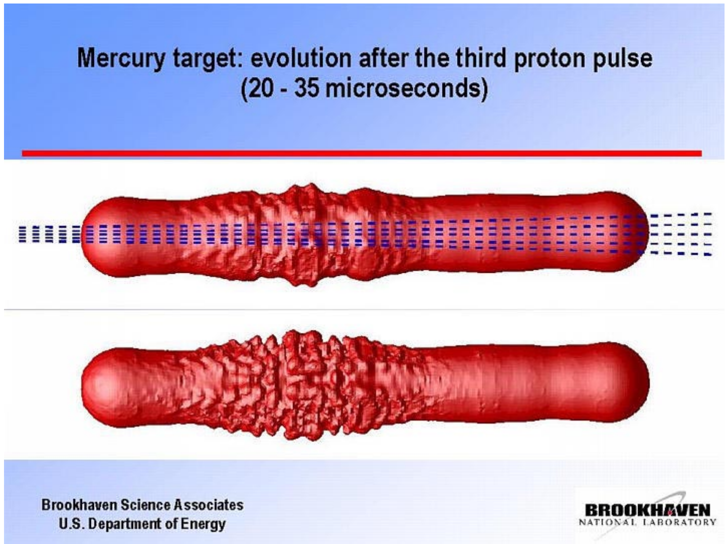
Beam energy deposition may disperse the jet.

FRONTIER simulation predicts breakup via filamentation on mm scale:



Mercury target: evolution after the first proton pulse
(0 - 10 microseconds)

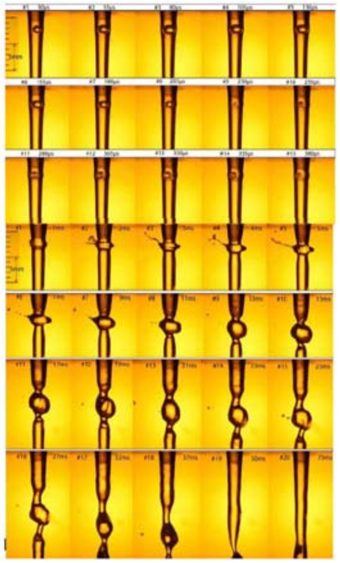
Brookhaven Science Associates
U.S. Department of Energy



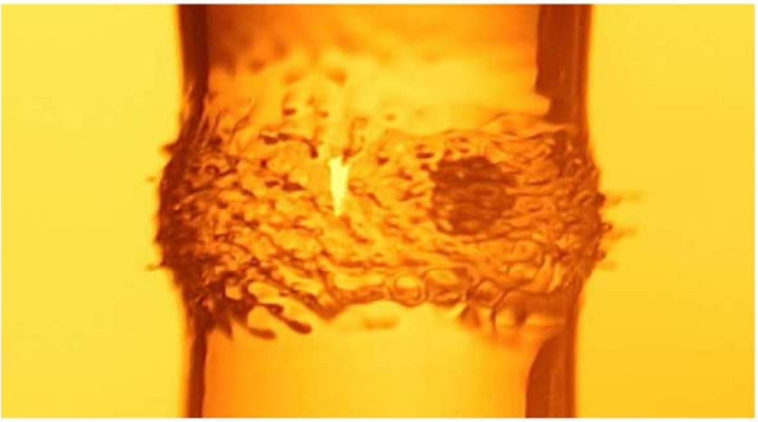
Mercury target: evolution after the third proton pulse
(20 - 35 microseconds)

Brookhaven Science Associates
U.S. Department of Energy

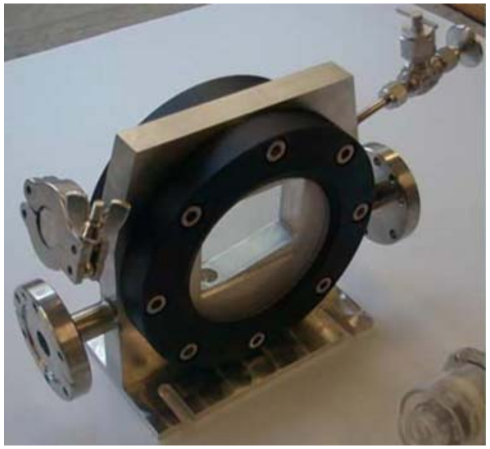
Laser-induced breakup of a water jet:
(J. Lettry, CERN)

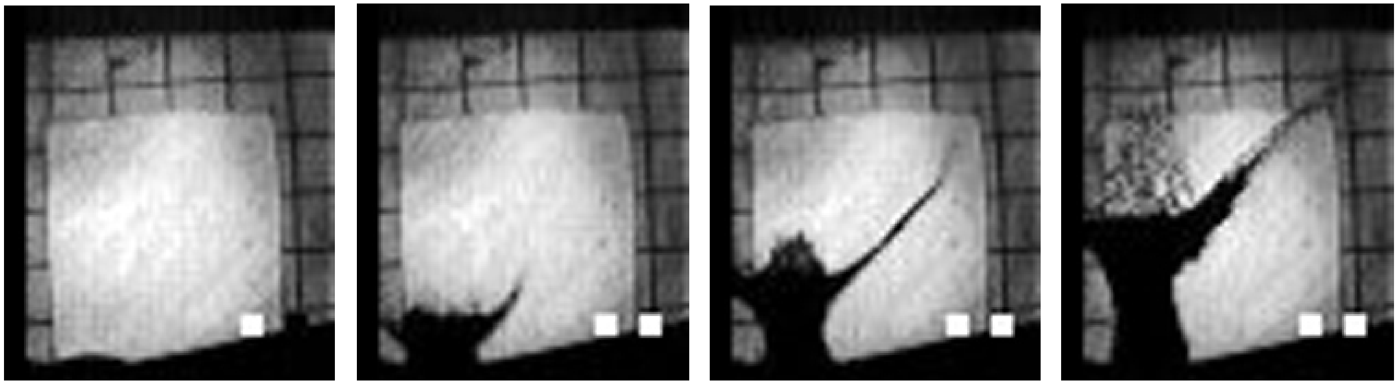


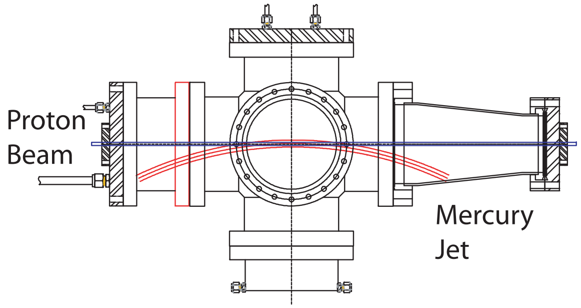
Water jet ripples generated by a
8 mJ Laser cavitation bubble

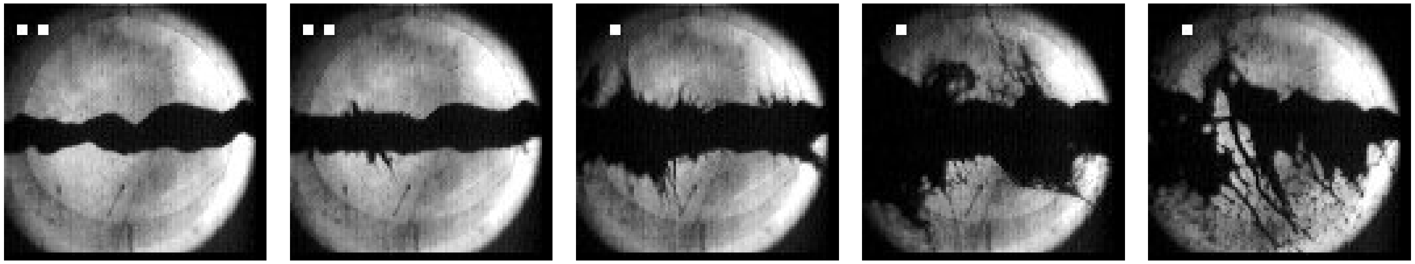


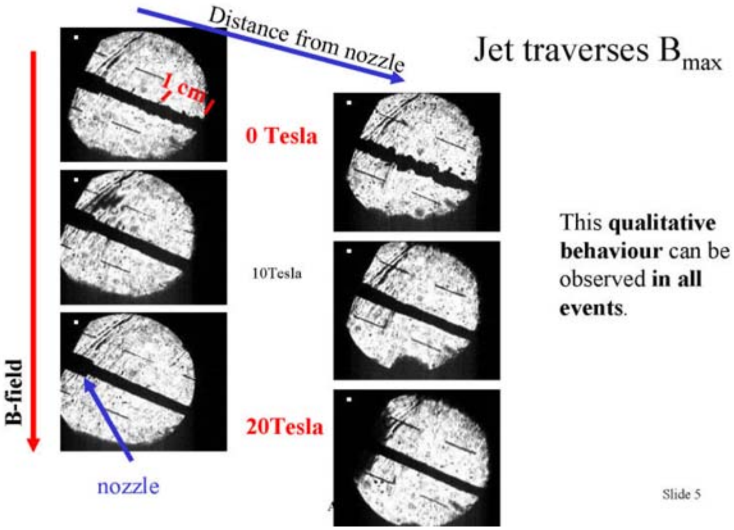
Mercury Target Tests (BNL-CERN, 2001-2002)











Jet traverses B_{max}

This **qualitative behaviour** can be observed **in all events**.

Slide 5

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.

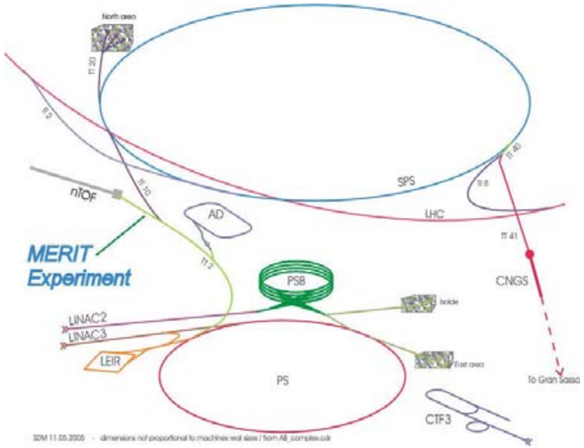
Filaments appear only $\approx 40\ \mu$**s after beam,**

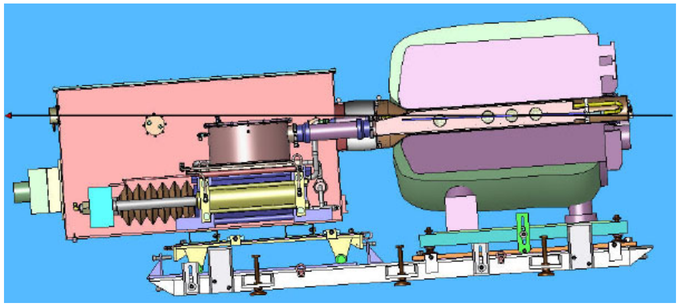
$\Rightarrow$ **After several bounces of waves, OR** $v_{\rm sound}$ **very low.**

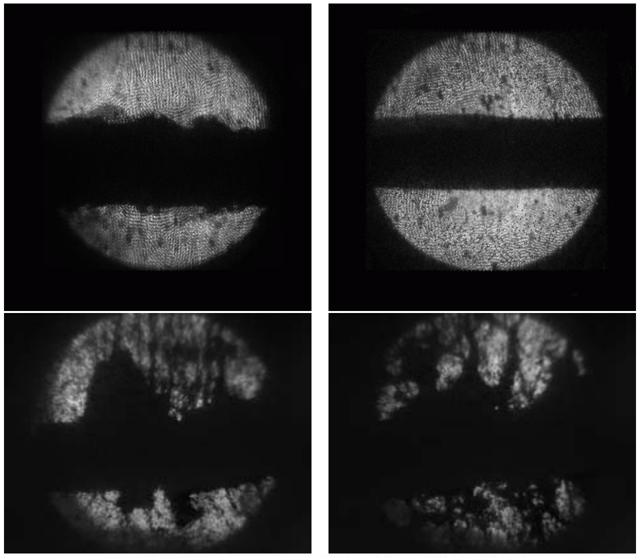
Rayleigh surface instability damped by high magnetic field.

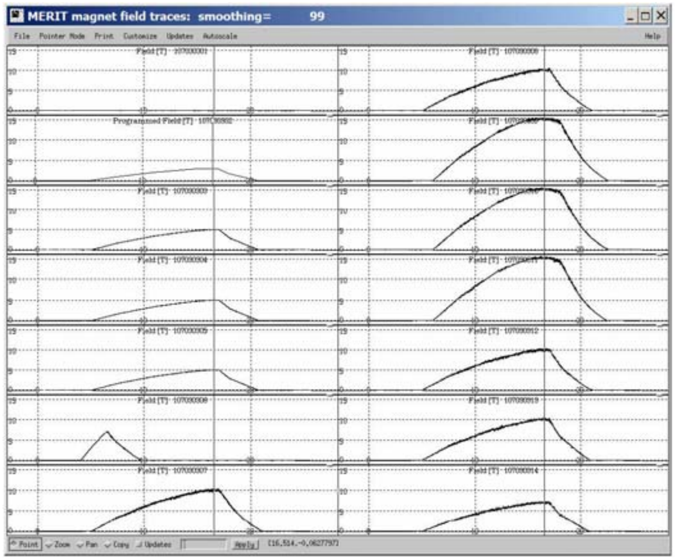
CERN nToF11 Experiment (MERIT)

- **The MERIT experiment is a proof-of-principle demonstration of a free mercury jet target for a 4-megawatt proton beam, contained in a 15-T solenoid for maximal collection of soft secondary pions.**
- **MERIT = MERcury Intense Target.**
- **Key parameters:**
  - **24-GeV Proton beam pulses, up to 16) bunches/pulse, up to 2.5×10^{12} p/bunch.**
  - **σ_r of proton bunch = 1.2 mm, proton beam axis at 67 mrad to magnet axis.**
  - **Mercury jet of 1 cm diameter, $v = 20$ m/s, jet axis at 33 mrad to magnet axis.**
  - **$\Rightarrow$ Each proton intercepts the Hg jet over 30 cm = 2 interaction lengths.**
- **Every beam pulse is a separate experiment.**
  - **~ 360 Beam pulses in total.**
  - **Vary bunch intensity, bunch spacing, number of bunches.**
  - **Vary magnetic field strength.**
  - **Vary beam-jet alignment, beam spot size.**


North area
TT20
E2
nTOF
MERIT Experiment
AD
TT10
SPS
LHC
TI8
TT40
TT41
CNGS
TI2
PSB
isolde
LINAC2
LINAC3
LEIR
PS
East area
To Gran Sasso
CTF3
SDM 11.05.2005 - dimensions not proportional to machines real sizes / from AB_complex.cdr






MERIT magnet field traces: smoothing= 99
File
Pointer Mode
Print
Customize
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Updates
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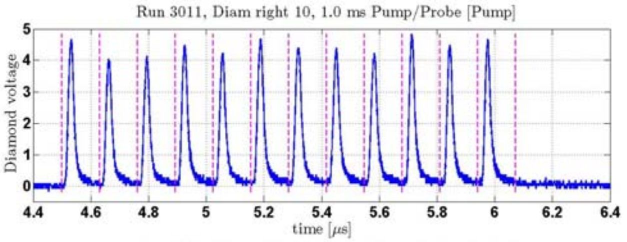
Run 3011, Diam right 10, 1.0 ms Pump/Probe [Pump]
Diamond voltage
0
1
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3
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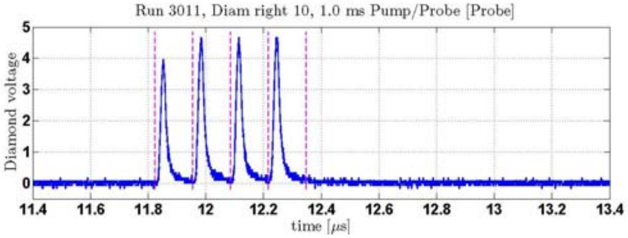
6.2
6.4
time [μs]


Run 3011, Diam right 10, 1.0 ms Pump/Probe [Probe]
Diamond voltage
0
1
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5
11.4
11.6
11.8
12
12.2
12.4
12.6
12.8
13
13.2
13.4
time [μs]

CERN nToF11 Experiment (MERIT), II

- Data taken Oct. 22 – Nov. 12, 2007 with mercury jet velocities of 15 & 20 m/s, magnetic fields up to 15 T, and proton pulses of up to 3×10^{13} in 2.5 μs.
- As expected, beam-induced jet breakup is relatively benign, and somewhat suppressed at high magnetic field.
- "Pump-Probe" studies with bunches separated by up to 700 μs indicated that the jet would hold together during, say, a 1-ms-long 8-GeV linac pulse.
- ⇒ Good success as proof-of-principle of liquid metal jet target in strong magnetic fields for use with intense pulsed proton beams.

MERIT Experiment Talks

- **Magnetohydrodynamic Simulations (R. Samulyak).**
- **MERIT Experiment Status (H. Kirk).**
- **Optical Diagnostics Results (H.-J. Park).**
- **MERIT Particle Production Simulations (S. Striganov).**

- **Next Phase of Targetry R&D (K. McDonald, Wed. Mar. 19).**