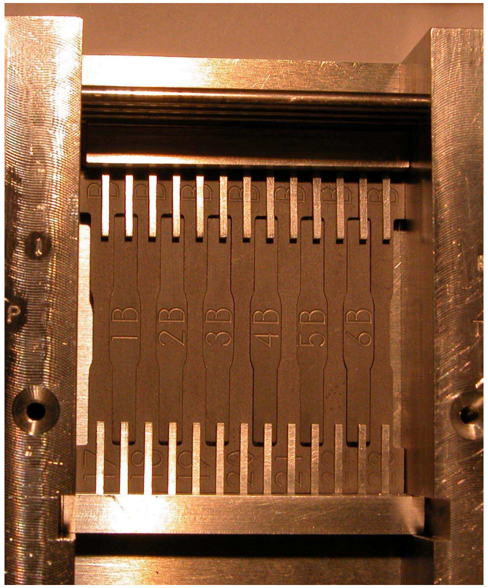
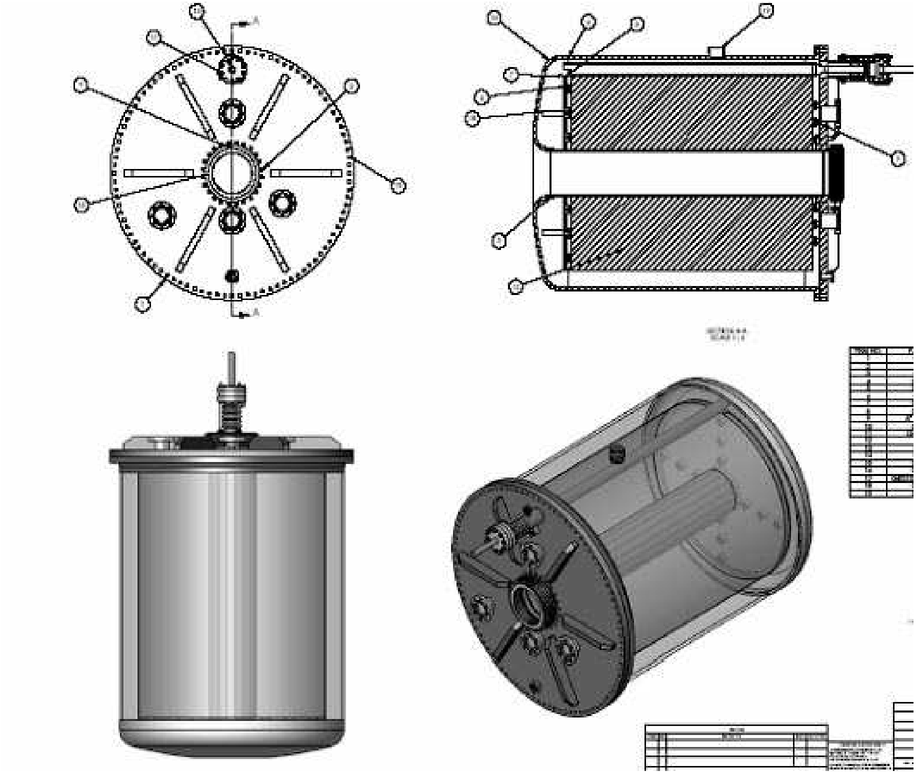
The High-Power Targetry R&D Program





K.T. McDonald
Princeton U.
MUTAC Review
Brookhaven National Laboratory
April 28, 2004

`http://puhep1.princeton.edu/mumu/target/`

High Performance Muon and Neutrino Beams Require a High Performance Source

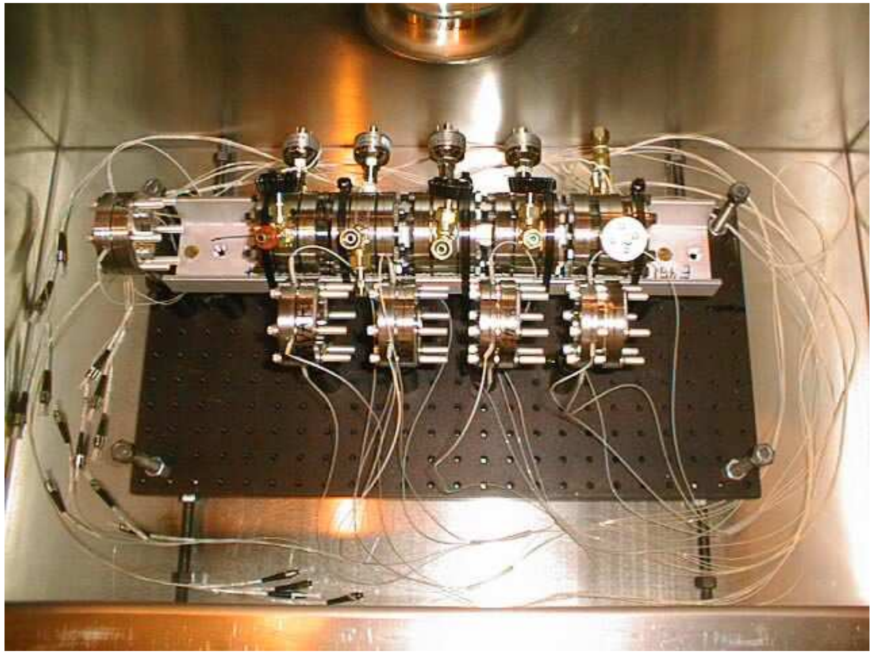
- Existing target technologies can perhaps be extrapolated for use in 2 MW proton beams.
- High-power targetry is important for muon colliders, neutrino factories, "conventional" secondary beams, accelerator production of tritium, accelerator transmutation of waste, fusion materials test facilities, ...
- Common targetry challenges explored in the Ronkonkoma Workshop (Sept. 2003).
- For modest extrapolations of solid targets, key issues are materials properties after irradiation.
  ⇒ Continuation of solid target studies at the BNL BLIP.
- For use in $\gtrsim 2$ MW beams, need new options such as liquid metal jet targets.
- BNL/CERN tests of mercury + beam and mercury + 20-T magnet are encouraging.
- Beam tests are supplemented by magnetohydrodynamic numerical simulations (Roman Samulyak).
- The R&D program should be brought a significant conclusion by a proof-of-principle test of mercury + magnet + beam (CERN 2006, Harold Kirk).

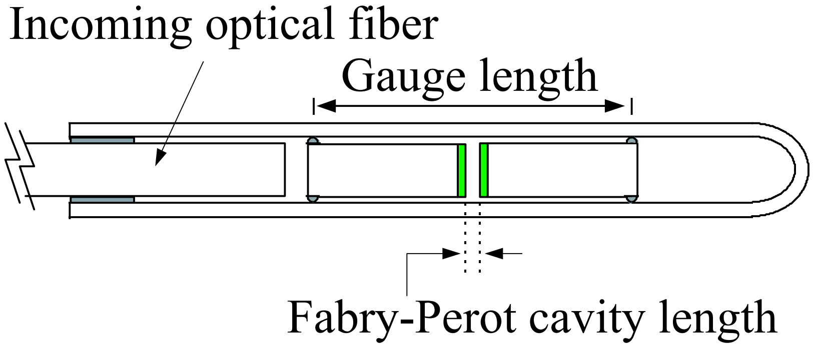
R&D During 2001-2003

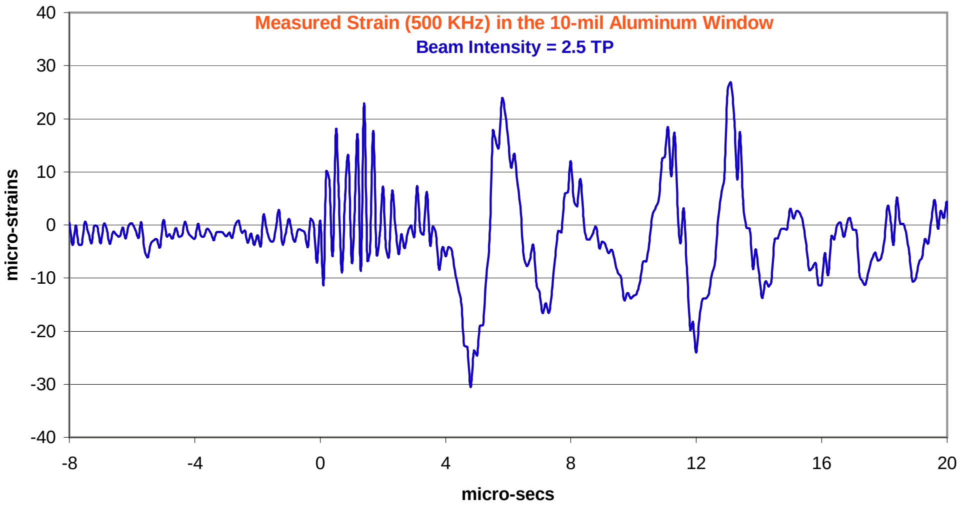
- **Solid Target Studies**
  - **Qualification of windows in intense proton beams.**
  - **Demonstration that a carbon-carbon composite with low coefficient of thermal expansion shows much less beam-induced strain than does graphite.**
  - **Demonstration that the low coefficient of thermal expansion of SuperInvar becomes large with only ≈ 0.01 dpa radiation dose.**
- **Liquid Target Studies**
  - **Demonstration that dispersion by a proton beam of mercury in a "thimble" is benign.**
  - **Demonstration that dispersion by a proton beam of mercury in a free jet, in zero magnetic field, is also benign.**
  - **Demonstration that a mercury jet is stabilized by a 20-T magnetic field.**

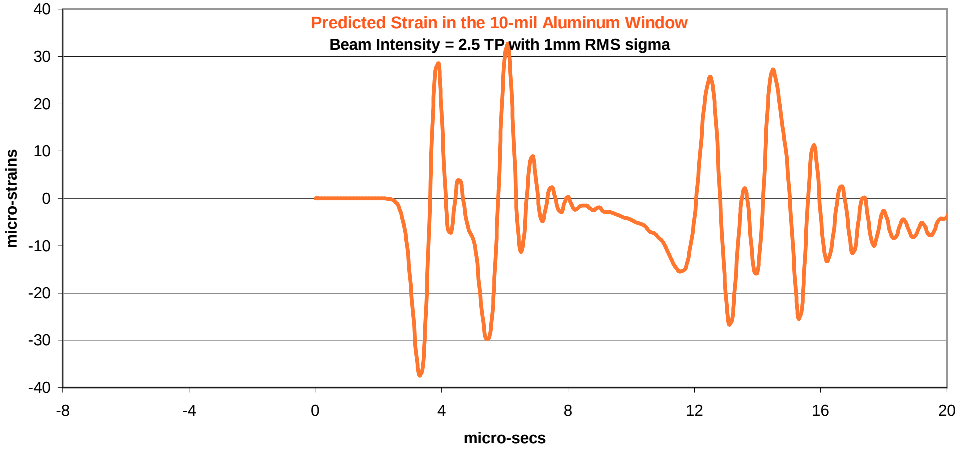
Window Tests (5e12 $p$pp, 24 GeV, 100 ns)

Aluminum, Ti90Al6V4, Inconel 708, Havar, instrumented with fiberoptic strain sensors.



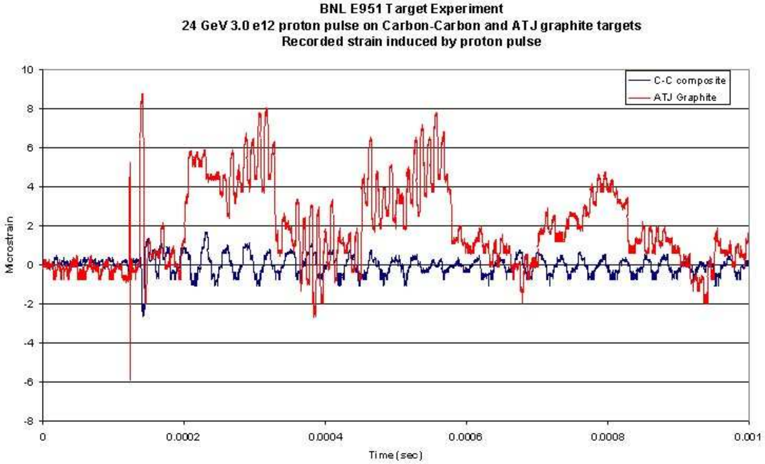




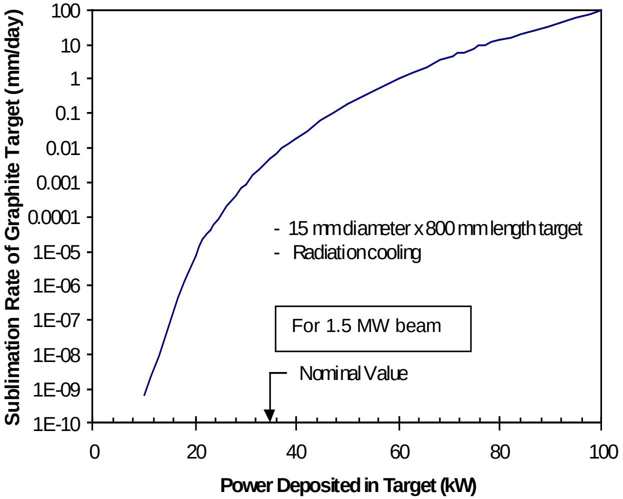


A Carbon Target is Feasible at 1-MW Beam Power

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.



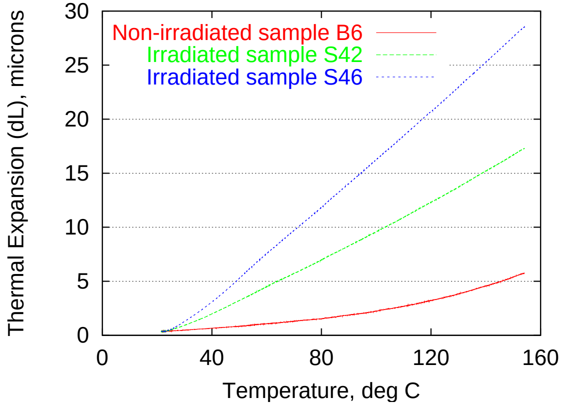
Sublimation of carbon believed to be negligible in a helium atmosphere.

Tests underway at ORNL to confirm this.

Radiation damage is limiting factor: ≈ 12 weeks at 1 MW.

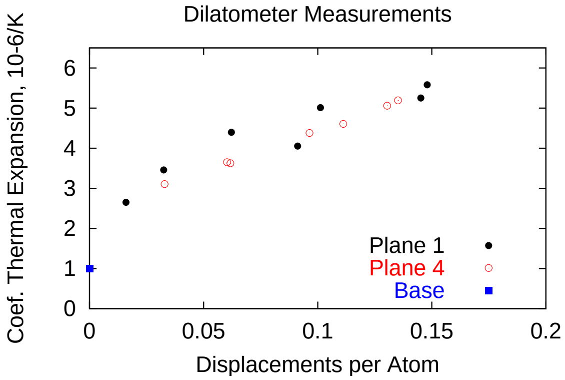
Effects of Radiation on SuperInvar

SuperInvar has a very low coefficient of thermal expansion (CTE),
⇒ Resistant to “thermal shock” of a proton beam.



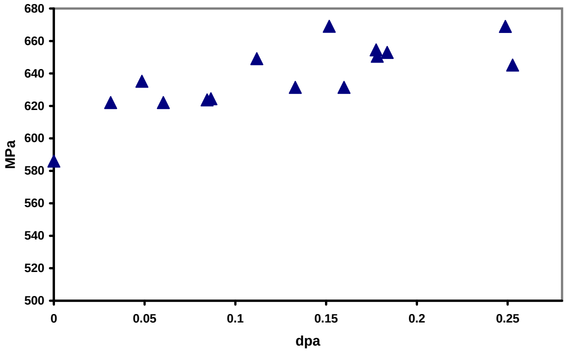
However, irradiation at the BNL BLIP facility show that the CTE increases rapidly with radiation dose.

CTE *vs.* dose ⇒



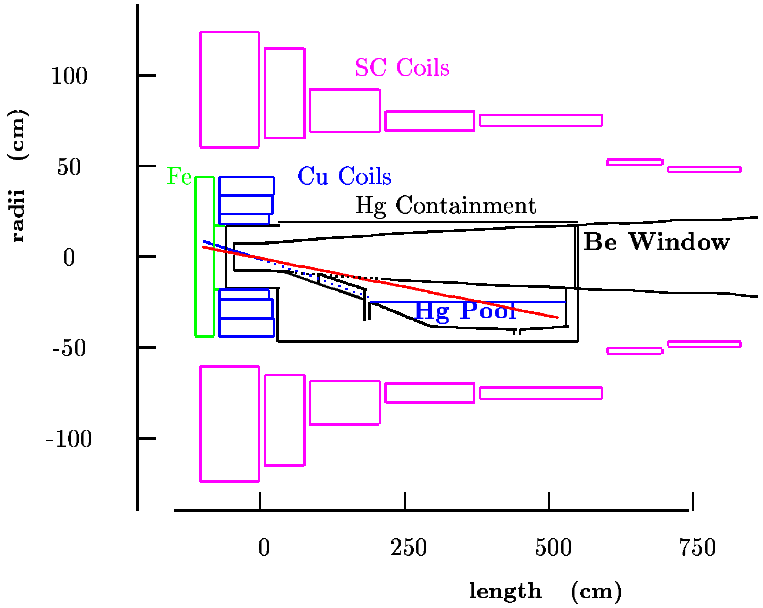
SuperInvar is made stronger by moderate radiation doses (like many materials).

Yield strength *vs.* dose ⇒

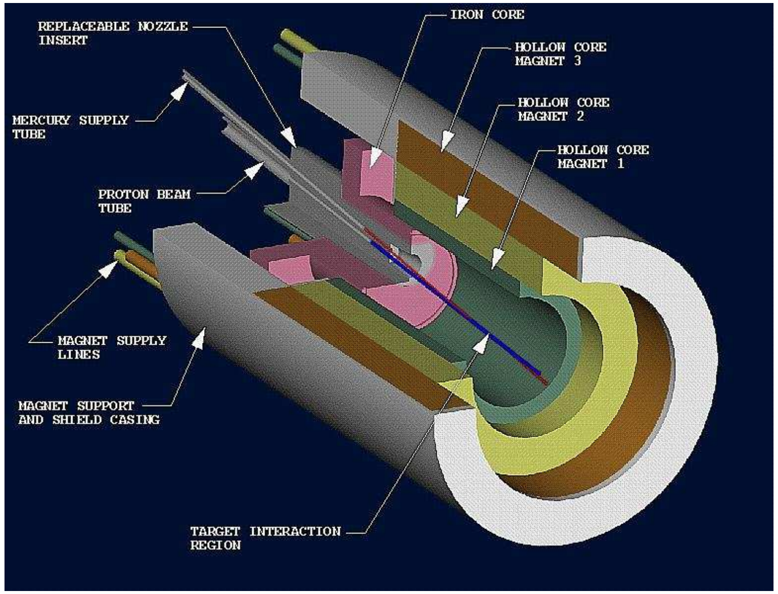


A Liquid Metal Jet May Be the Best Target for Beam Power above 1.5 MW

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



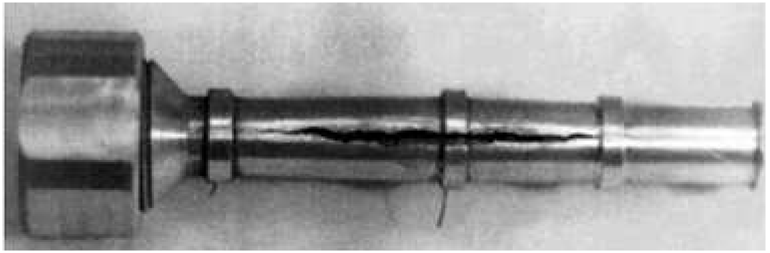
Mercury jet tilted by 100 mrad,
proton beam tilted by 67 mrad,
to increase yield of soft pions.



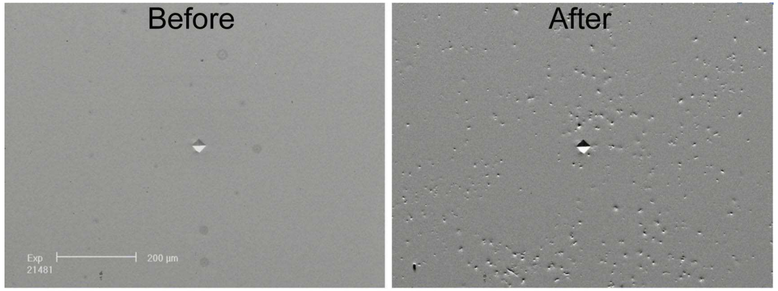
Beam-Induced Cavitation in Liquids Can Break Pipes

ISOLDE:

BINP:

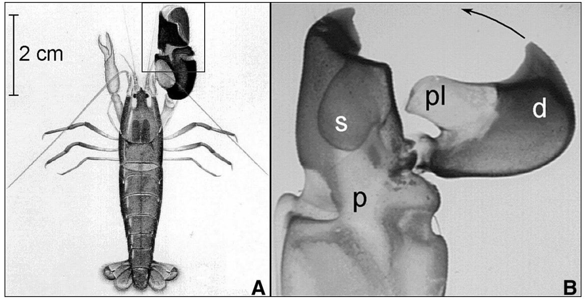


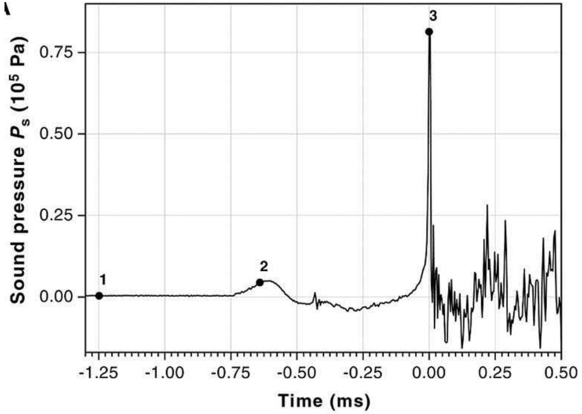
SNS:

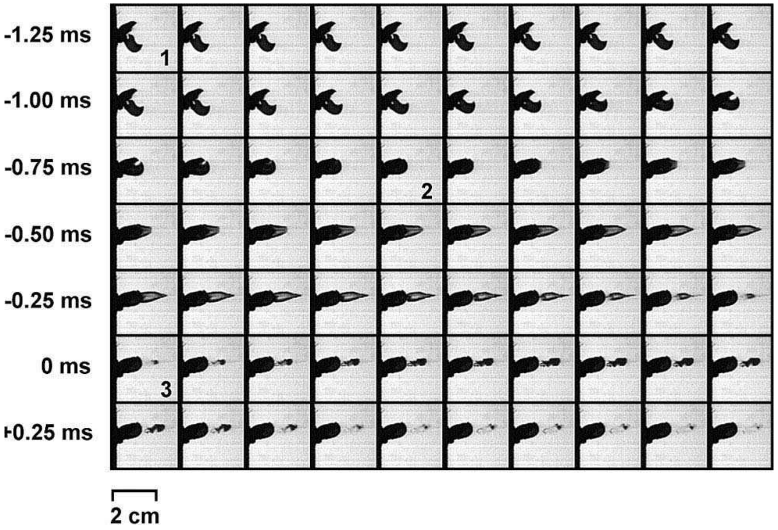


TL - High Power Target
Specimen # 29754
Equivalent SNS Power Level = 2.5

Snapping shrimp stun prey via cavitation bubbles.

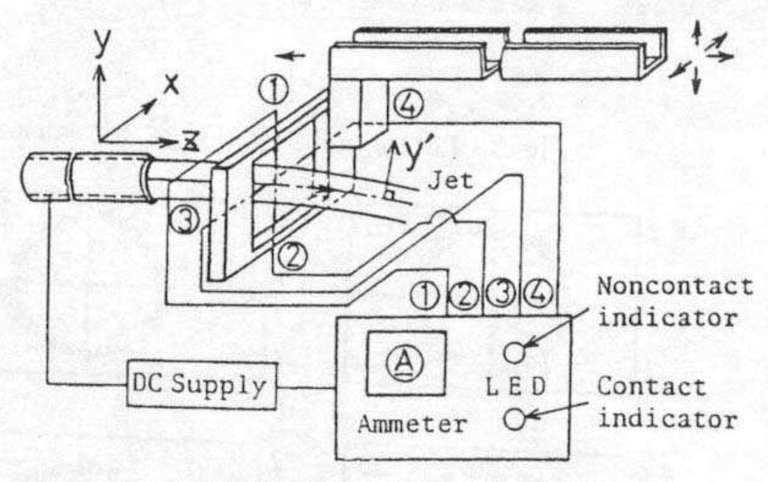


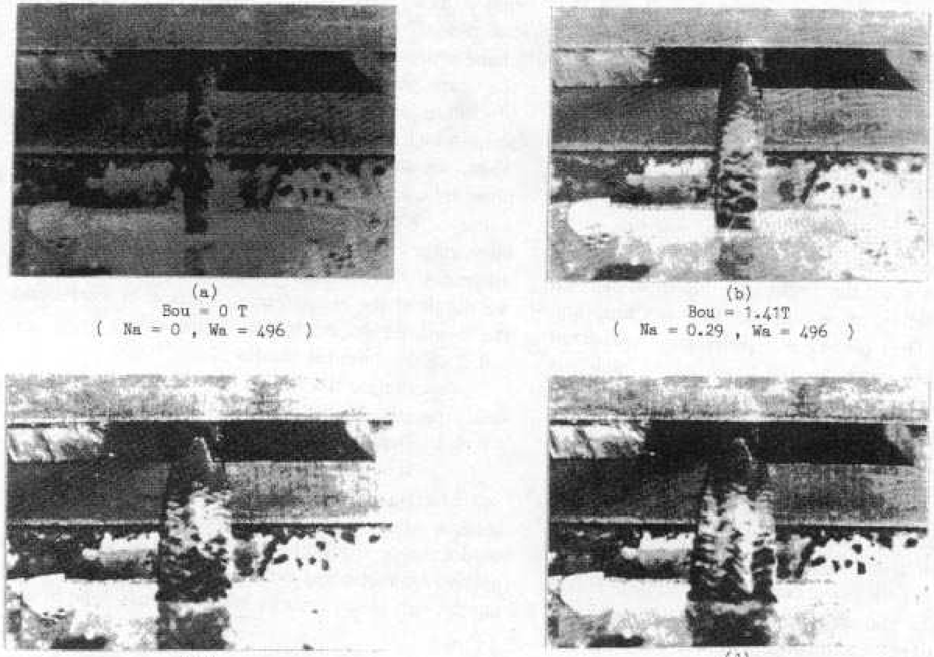




The Shape of a Liquid Metal Jet under a Non-uniform Magnetic Field

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



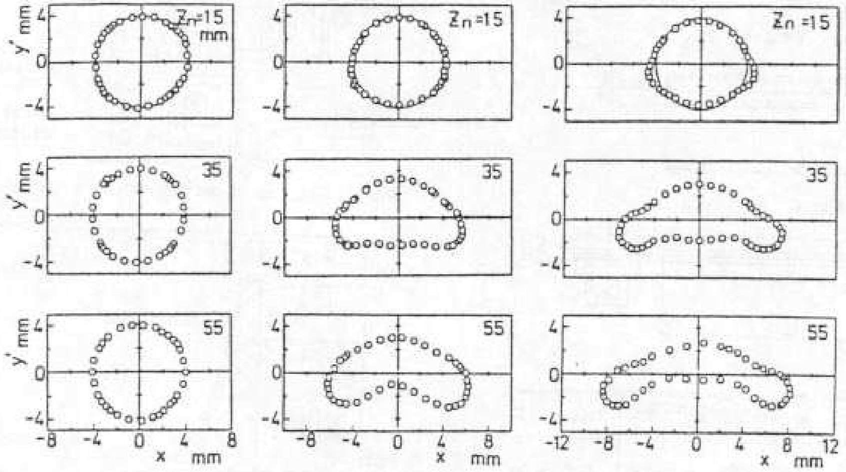

(a) Bou = 0 T (Na = 0 , Wa = 496)

(b) Bou = 1.41T (Na = 0.29 , Wa = 496)

(c) Bou = 1.88T (Na = 0.57 , Wa = 496)

(d) Bou = 2.02T (Na = 0.60 , Wa = 496)

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



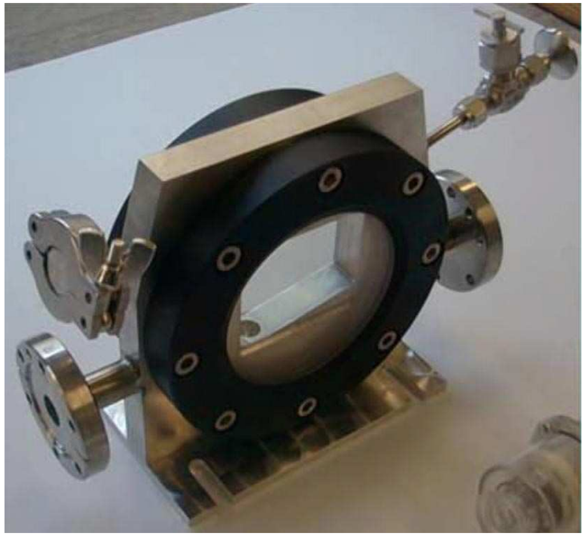
(a) Bou = 0 T (Na = 0 , Wa = 496)

(b) Bou = 1.41 T (Na = 0.29 , Wa = 496)

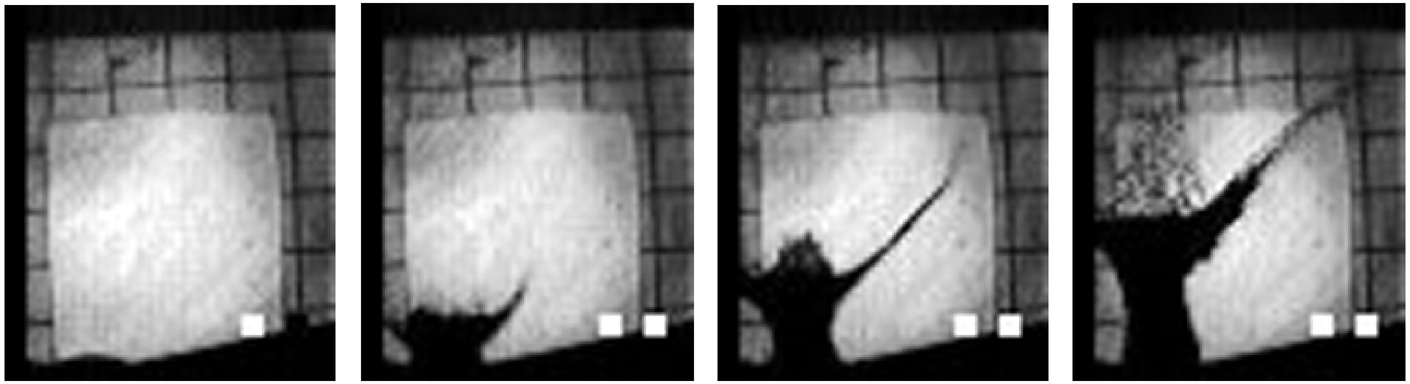
(c) Bou = 1.88 T (Na = 0.57 , Wa = 496)

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

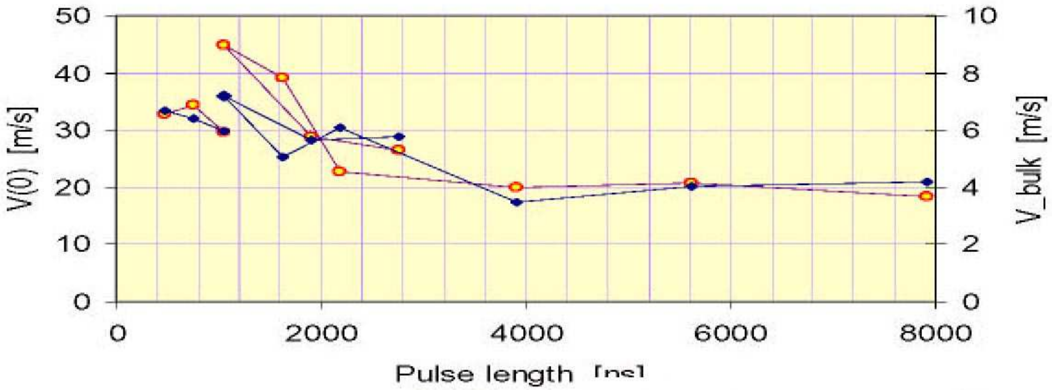
Passive Mercury Target Tests (BNL and CERN)



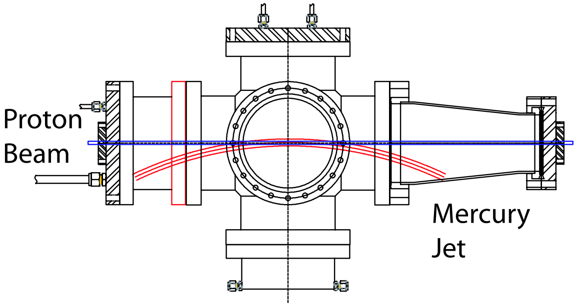
Exposures of 25 μs at $t = 0$, 0.5, 1.6, 3.4 msec, $\Rightarrow v_{\rm splash} \approx 20 - 40$ m/s:

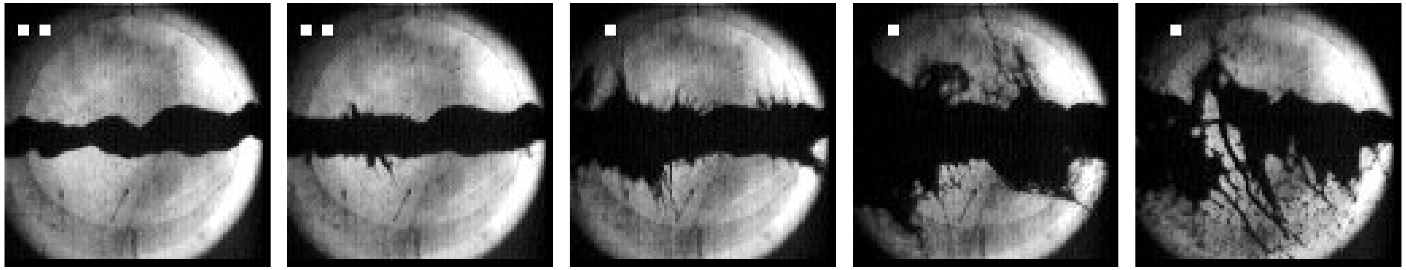


Two pulses of ≈ 250 ns give larger dispersal velocity only if separated by less than 3 μs.



Studies of Proton Beam + Mercury Jet (BNL)





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

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

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)

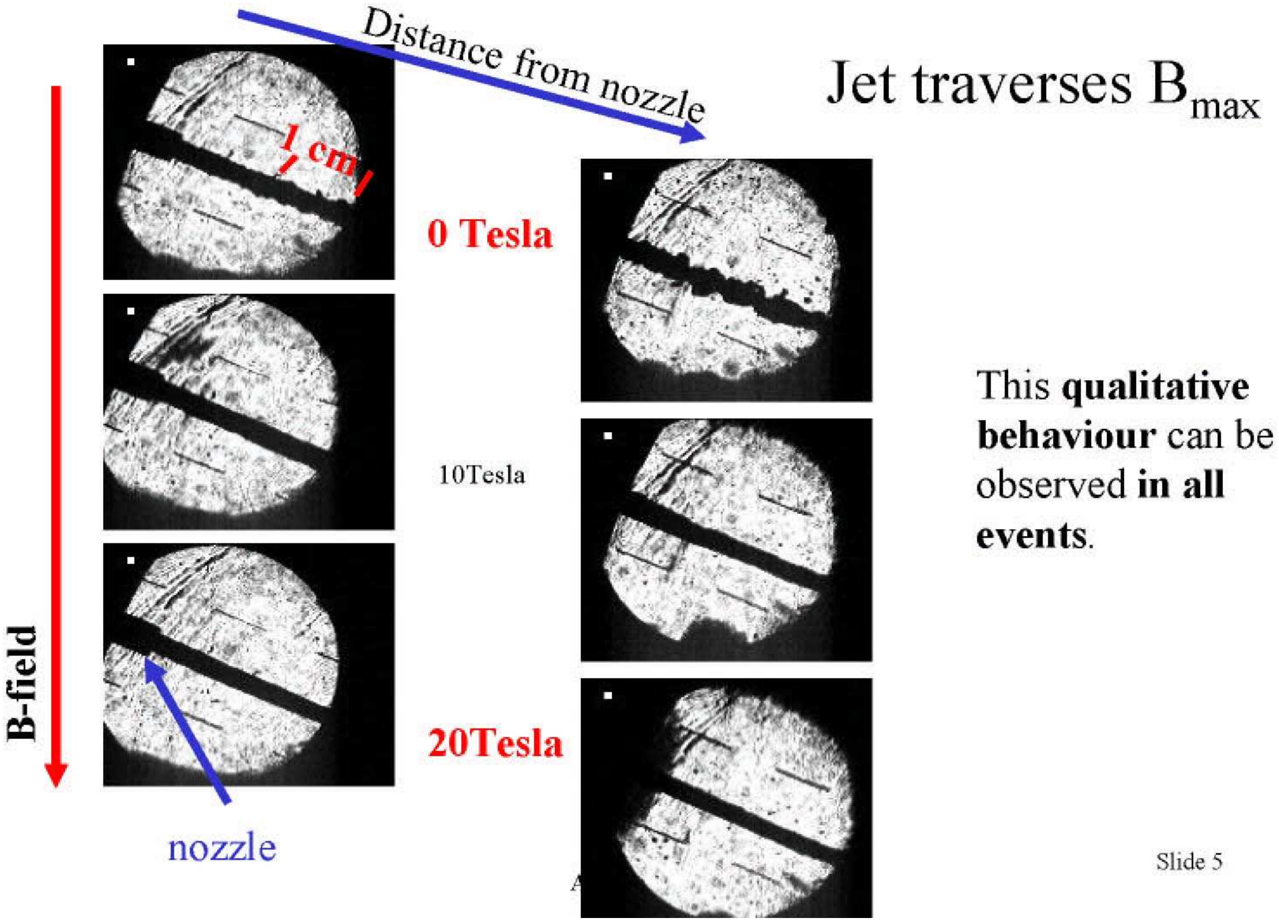
Eddy currents may distort the jet as it traverses the magnet.

Analytic model suggests little effect if jet nozzle inside field.

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

⇒ Damping of surface-tension waves (Rayleigh instability).

Will the beam-induced dispersal be damped also?



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

A 2-5 m/s Continuous Flow Mercury Jet

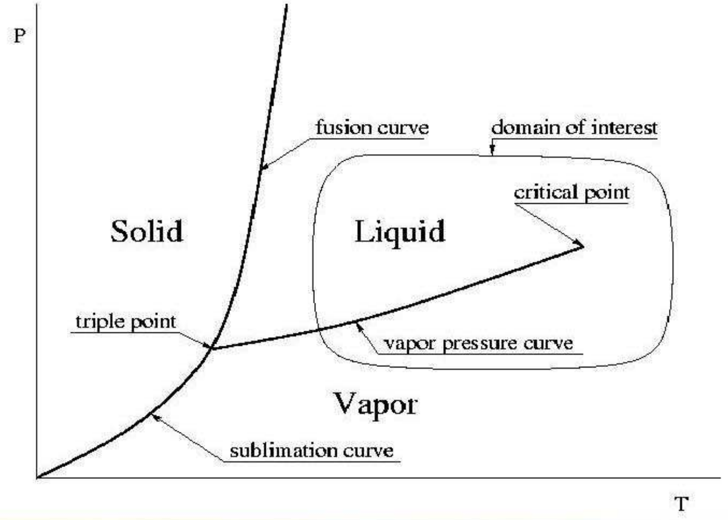
A 2.5-m/s, continuous-flow version of the free mercury jet target was constructed for use in the BNL A3 line.

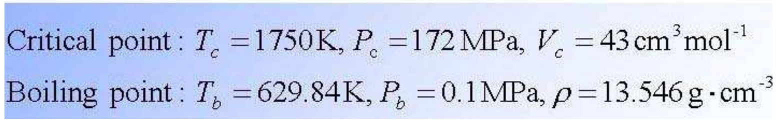
Completed Oct 2003. Now in storage.

Most components fabricated for a 2nd version using Wood's metal. (However, the Wood's metal wets the quartz windows.)

Computational Magnetohydrodynamics (R. Samulyak, Y. Pyrkarpatsky)

Use equation of state that supports negative pressures, but gives way to cavitation.

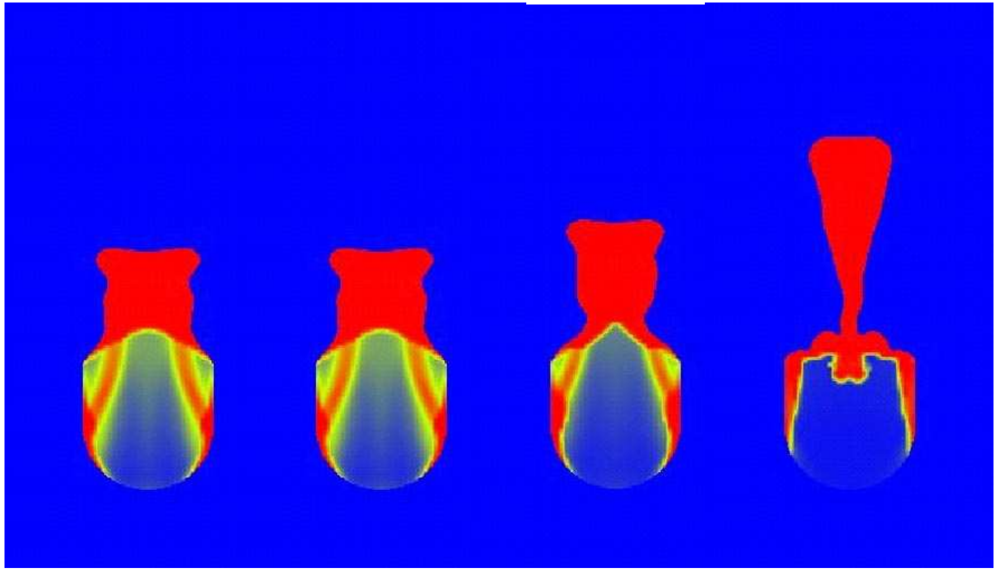




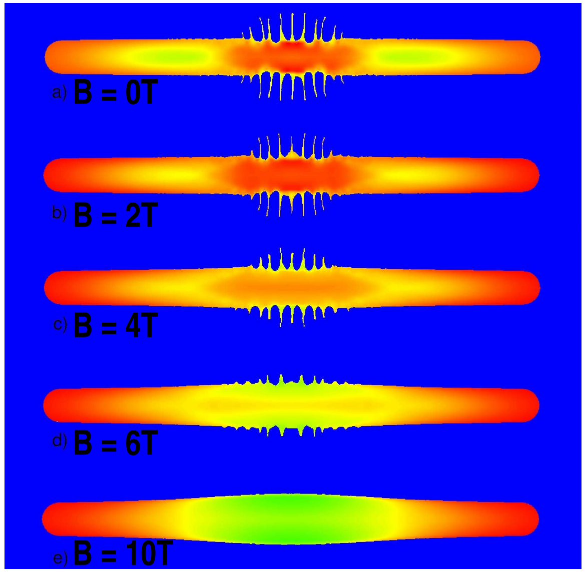
Critical point : $T_c = 1750\,\mathrm{K}$, $P_c = 172\,\mathrm{MPa}$, $V_c = 43\,\mathrm{cm}^3\mathrm{mol}^{-1}$

Boiling point : $T_b = 629.84\,\mathrm{K}$, $P_b = 0.1\,\mathrm{MPa}$, $\rho = 13.546\,\mathrm{g}\cdot\mathrm{cm}^{-3}$

Thimble splash at 0.24, 0.48, 0.61, 1.01 μs



Magnetic damping of beam-induced filamentation:



What Have We Learned?

- **Solid targets are viable in pulsed proton beams of up to 1-2 MW.**
- **Engineered materials with low coefficients of thermal expansion are desirable, but require further qualification for use at high radiation dose.**
- **A mercury jet appears to behave well in a proton beam at zero magnetic field, and in a high magnetic field without proton beam.**
- **Acceptance by the accelerator physics community of the concept of a mercury jet target in a high magnetic field requires further R&D efforts – such as a proof-of-principle demonstration.**

Muon Collaboration

The 2003 Targetry Workshop

High-power Targetry
for
Future Accelerators

Ronkonkoma, NY
September 8-12, 2003

BROOKHAVEN
NATIONAL LABORATORY

Harold G. Kirk
Brookhaven National Laboratory

Muon Collaboration

Workshop Participation

Over 40 attendees from:

- Argonne
- Brookhaven
- CERN
- Fermilab
- FZ-Julich
- KEK
- Los Alamos
- Michigan State
- Oak Ridge
- Princeton
- PSI-Zurich
- Rutherford Lab
- SLAC

Facilities Represented

- AGS
- ESS
- EURISOL
- IFMIF
- ISIS
- JPARC
- LANCE
- Neutrino Factory
- NUMI
- NLC
- RIA
- SINQ
- SNS

Workshop Organization

Facilities Overview

Summary by John Haines, ORNL

Solid Targets

Summary by Roger Bennett, RAL

Liquid Targets

Summary by Helge Ravn, CERN

Theory/Simulations

Summary by Nikolai Mokhov, FNAL

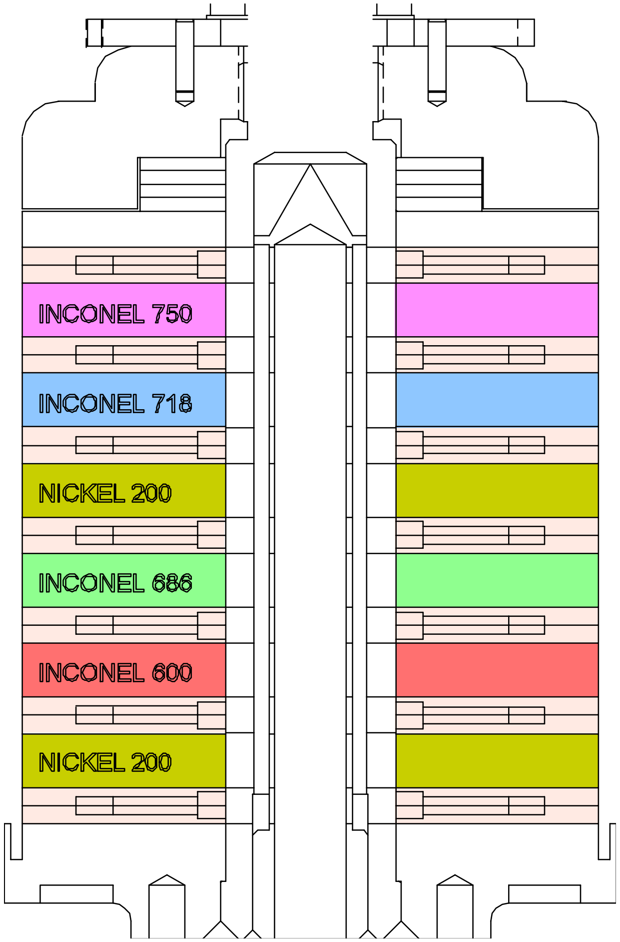
http://www.cap.bnl.gov/mumu/conf/target-030908/agenda.xhtml

Google: high power targetry

Target Parameters from John Haines Summary

Facility	Status	Target Material	Beam Pulse		Energy (GeV)	Time Ave Power in Beam (MW)	Peak Time Ave Power Density (MW/m^3)	Peak Energy Density (MJ/m^3/pulse)
			Duration (ms)	Rep Rate (Hz)				
BNL Neutrino Superbeam	Under Study	C-C Composite	2.6	2.5	28	1	4,060	1,630
ESS - short pulse	Under Study	Hg	1.2	50	1.334	5	2,500	50
ESS - long pulse	Under Study	Hg	2,000	16.7	1.334	5	2,500	150
EURISOL	Under Study	Hg	3	50	2.2	4	100,000	2,000
IFMIF	Under Study	Li	CW		0.04 (D_2)	10	100,000	NA
JPARC - Hadron beam line	Under Construc	Ni	7.E+05	0.3	50	0.75	7,600	5,300
JPARC - Neutrino beam line	Under Study	C	5	0.3	50	0.75	83	300
LANSCE - APT irradiation tests	Dismantled	W	1,000	20	0.8	0.8	800	40
LANSCE - Lujan	Existing	W	0.25	20	0.8	0.1	350	18
LANSCE - Mats Test Station	Under Study	Pb-Bi	1,000	120	0.8	0.8	2,400	20
LEDA as fusion mats test facility	Under Study	Li	CW		0.04 (D_2)	2	100,000	NA
MiniBoone	Existing	Be	150	5	8	0.032	120	24
NLC - conventional	Under Study	W Re	0.26	120	6.2	0.086	334,800	2,790
NLC - undulator	Under Study	Ti alloy	0.26	120	0.011	0.126	1,110,000	9,200
NuMI	Existing	C	8.6	0.53	120	0.4	318	600
Pbar	Existing	Inconel 600 + ...	1.6	0.5	120	0.052	7,650	15,300
RIA	Under Study	Li, Be, Hg, W, ...	CW		1-96 (p to U)	0.4	< 4,000,000	NA
SINQ/Solid Target	Existing	Pb, SS-clad	CW		0.575	0.72	720	NA
SINQ/MEGAPIE	Under Construc	Pb-Bi	CW		0.575	1	1,000	NA
SNS	Under Construc	Hg	0.7	60	1	2	800	13
US Neutrino Factory	Under Study	Hg	0.003	15	24	1	3,800	1,080

The Pbar Target System



W
Target

W-Re
Target

Harold G. Kirk

Muon Collaboration

The assembled Mini-boone Target

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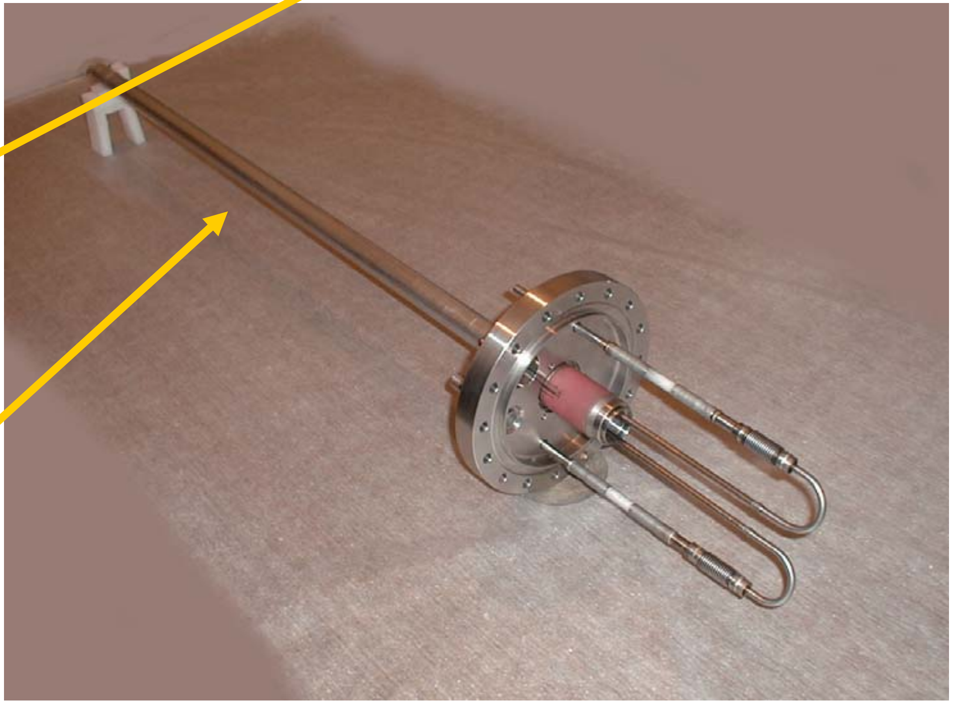
NuMI Low Energy Target for Minos



Graphite Fin Core

2 int. len.

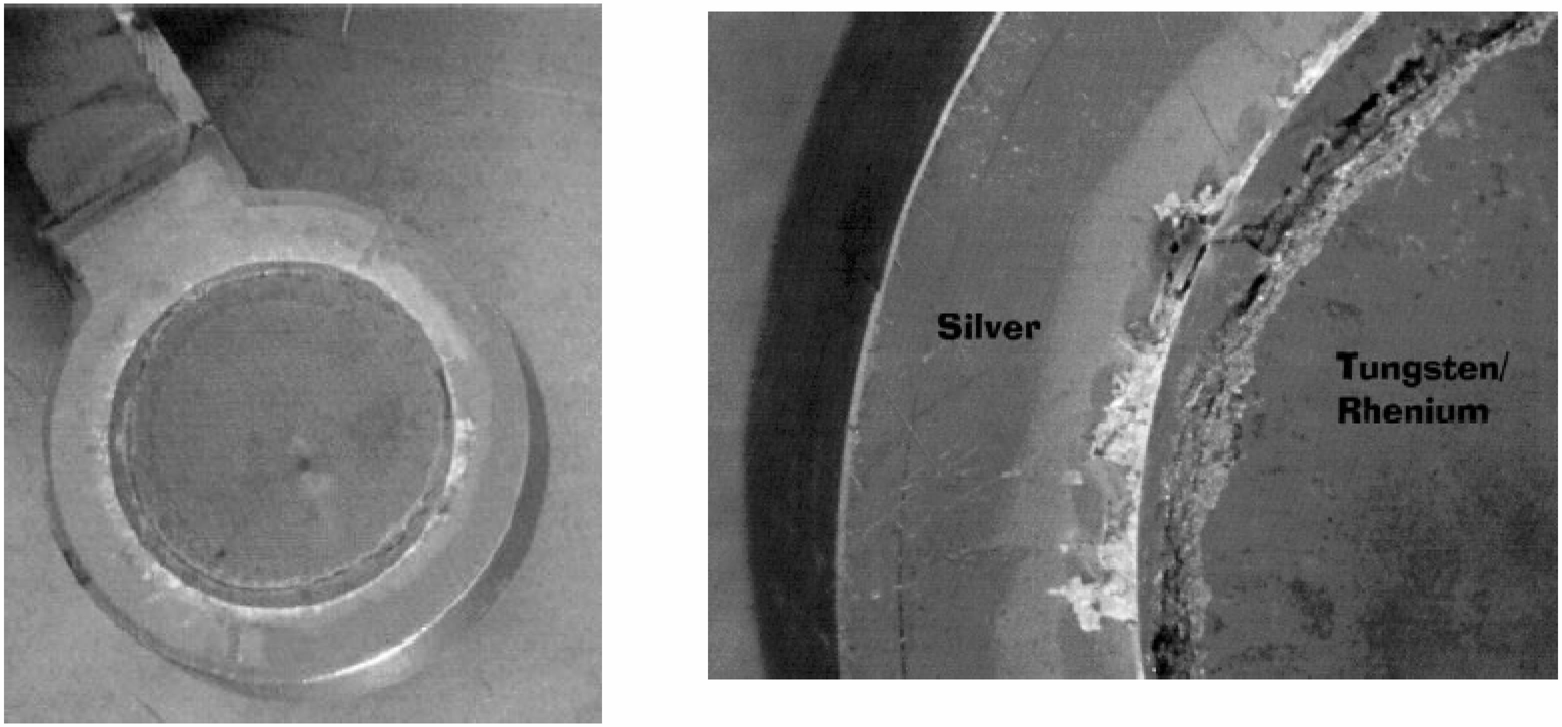
Water cooling tube

also provides mechanical

support

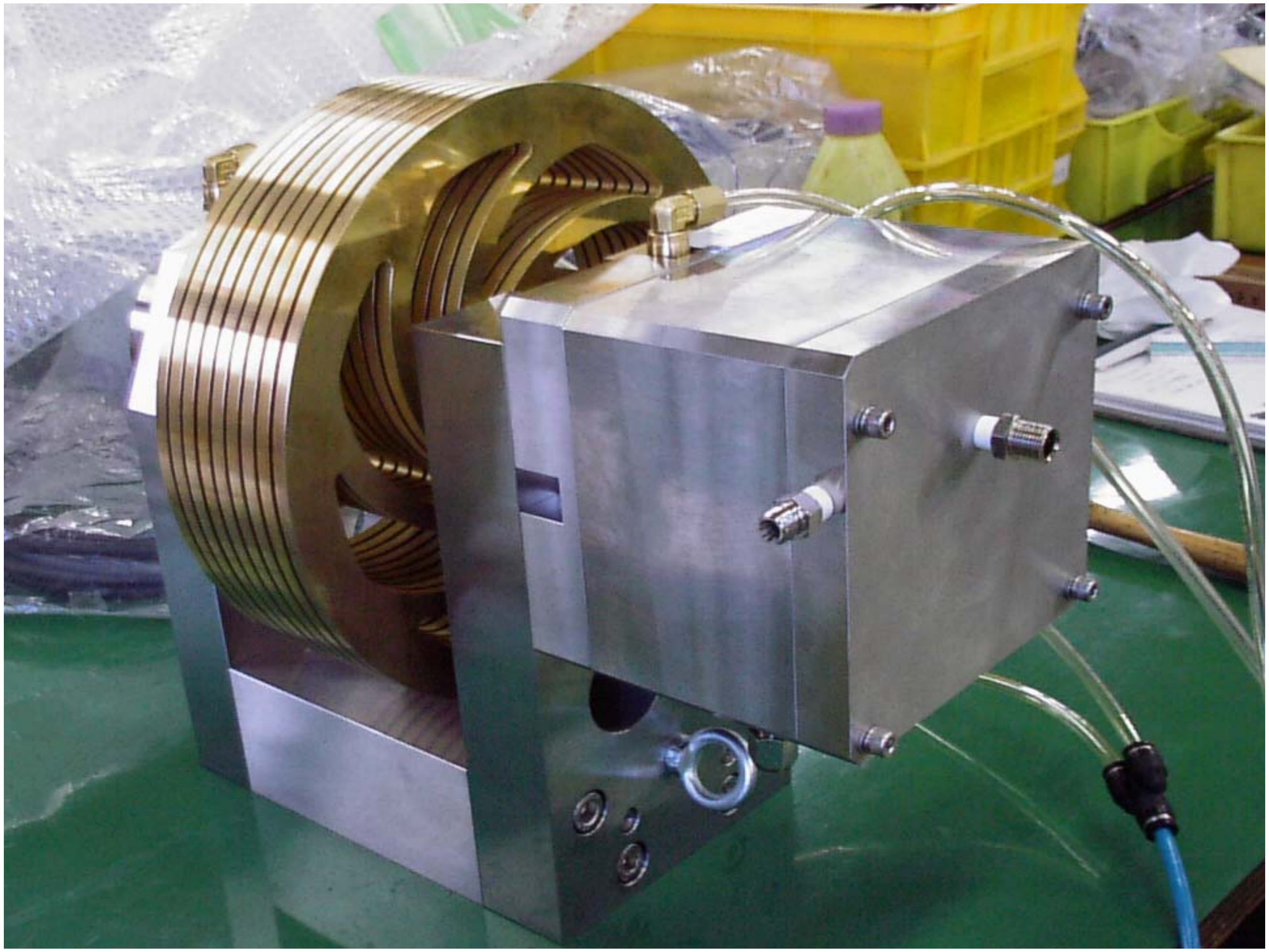
Aluminum vacuum tube

SLC Target Damage



SLC target damage studies were done at LANL. Results show evidence of cracks, spalling of target material and aging effects.

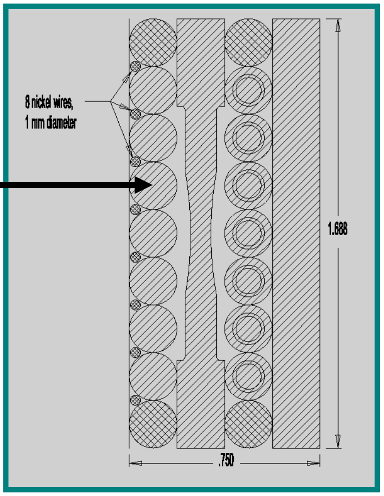
The T1 Kaon Target Prototype



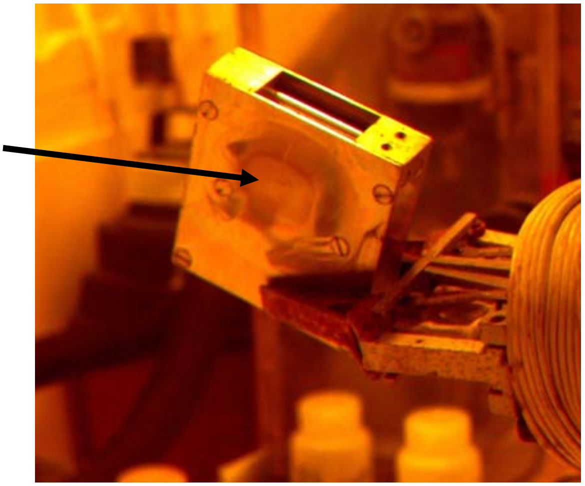
Muon Collaboration

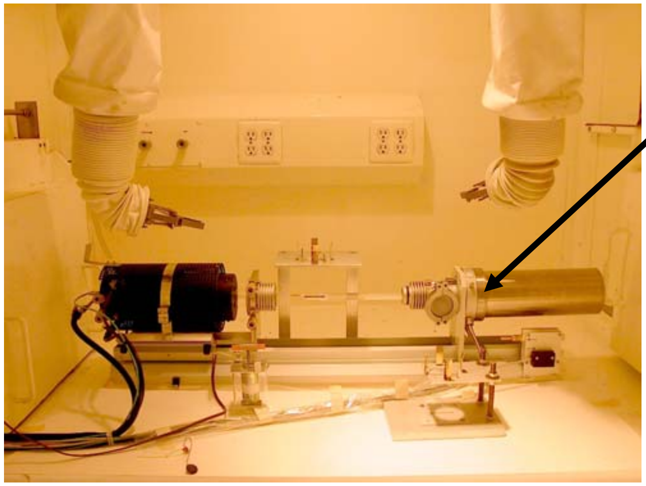
Super-invar Irradiation at BNL

The cylindrical samples of super-invar.



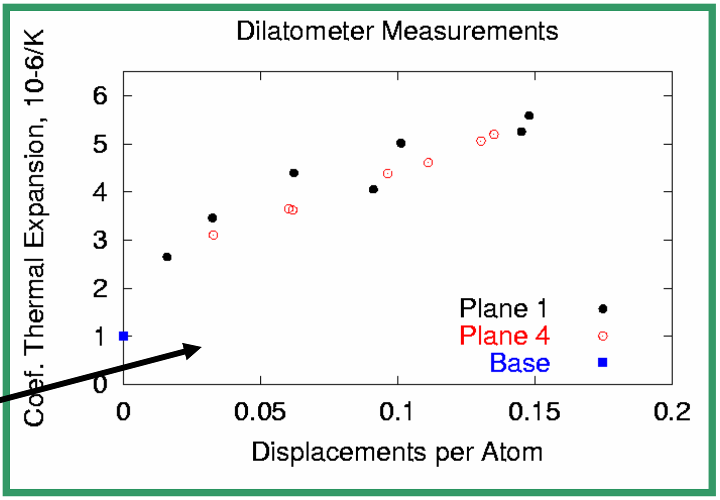
The target basket after irradiation





Dilatometer in Hot cell

Results of coefficient of thermal expansion measurements



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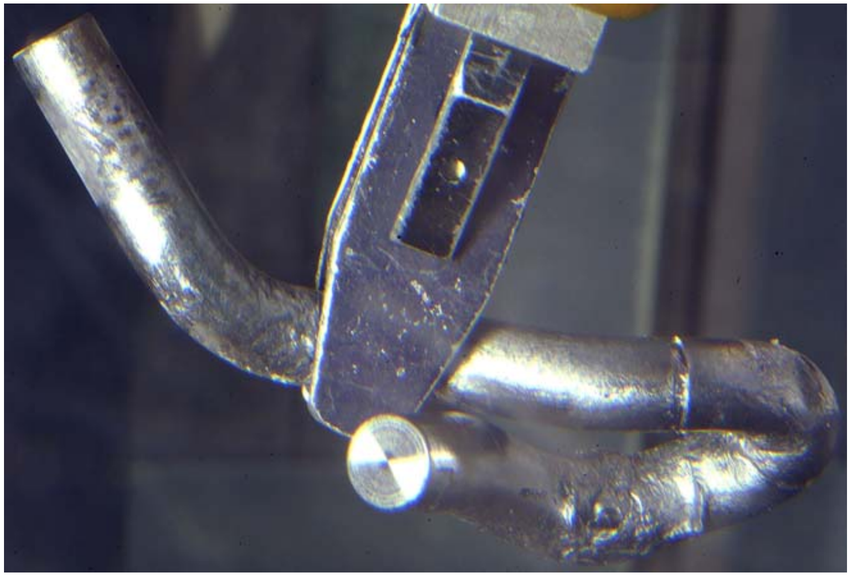
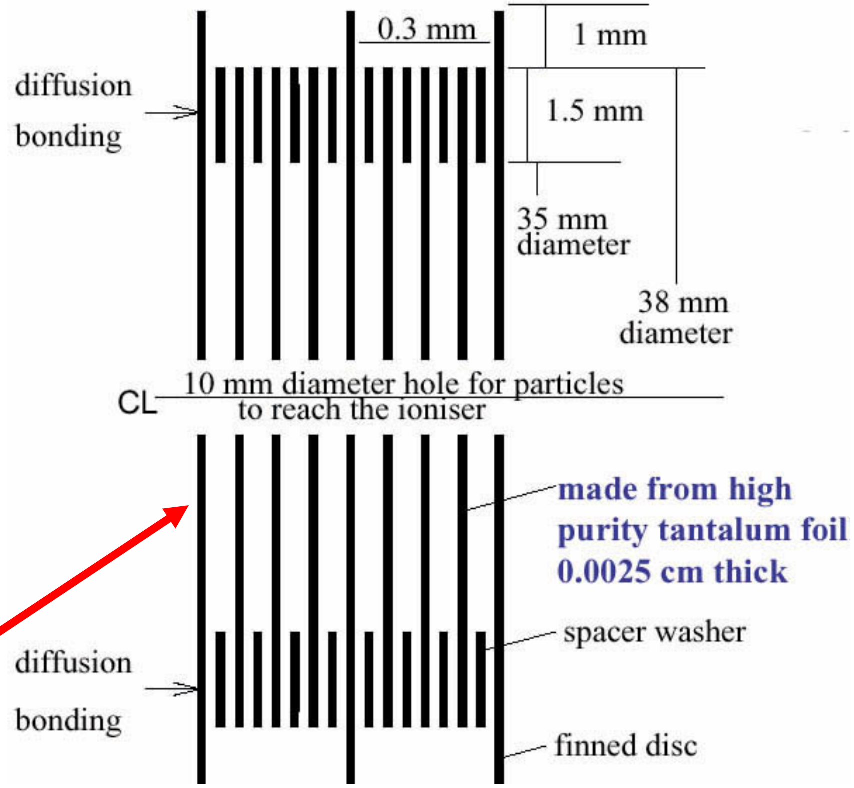
CERN Experience with Tantalum



Tantalum rod after one week of ISOLDE running

The radiantly cooled RIST tantalum target



Los Alamos Solid Target R&D

Neutron source production

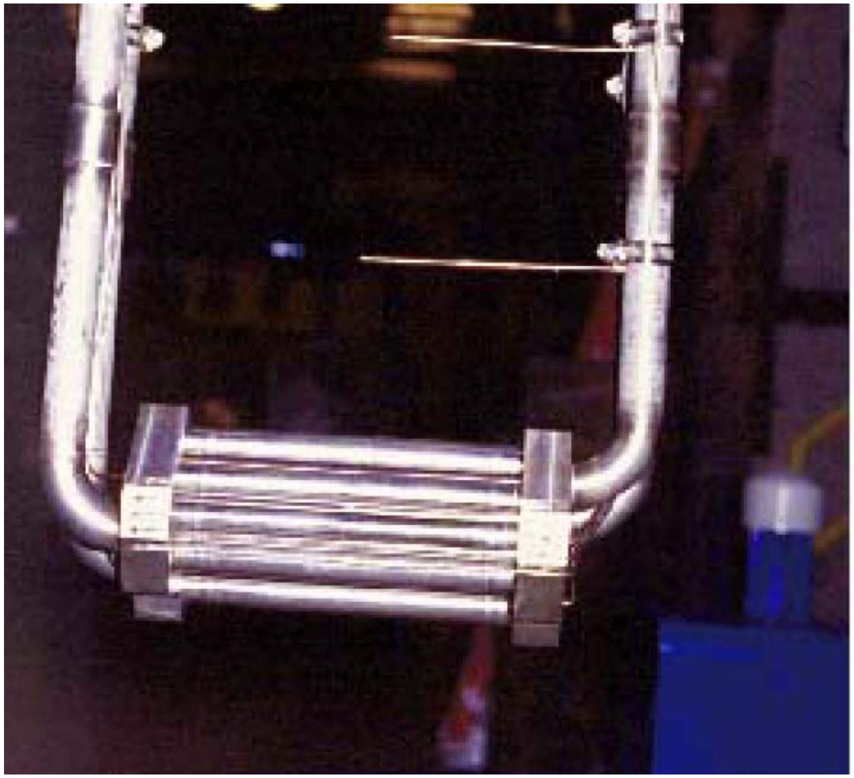
Lance p beam 0.8 GeV 0.8 MW

Stainless Steel Claded Tungsten

Water Cooled 100 W/g

Results: 2 Months successful running

Post-irradiation studies confirm that the target integrity is uncompromised.



Liquid Metal Targets—PbBi Eutectic

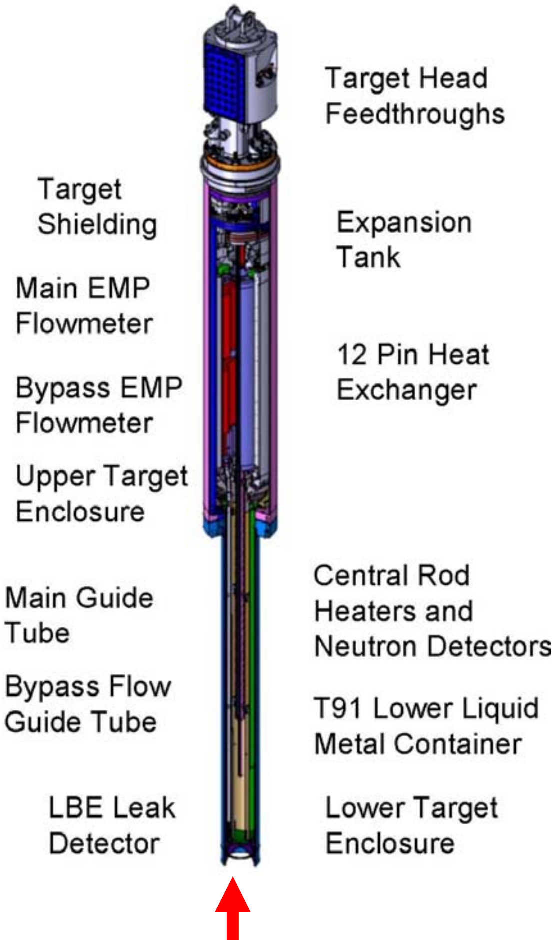
MEGAPIE Project at PSI

0.59 GeV proton beam

1 MW beam power

Goals:

- Demonstrate feasablility
- One year service life
- Irradiation in 2005



Proton Beam

Harold G. Kirk

Liquid Metal Targets--Hg

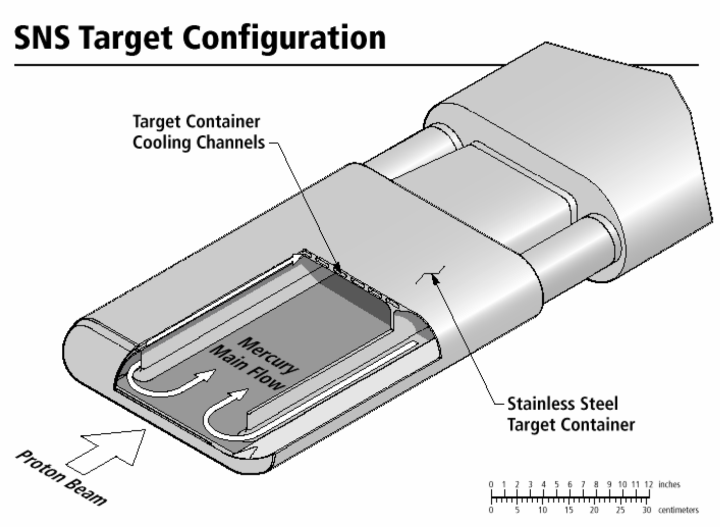
Neutron Sources – SNS and ESS

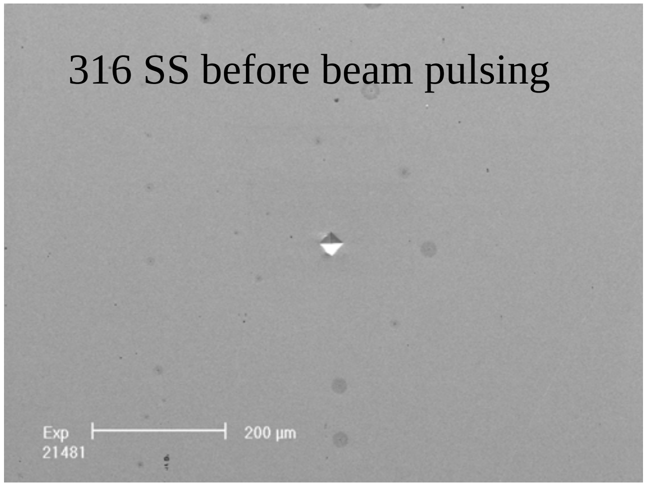
Proton beam 1 GeV and 1 MW

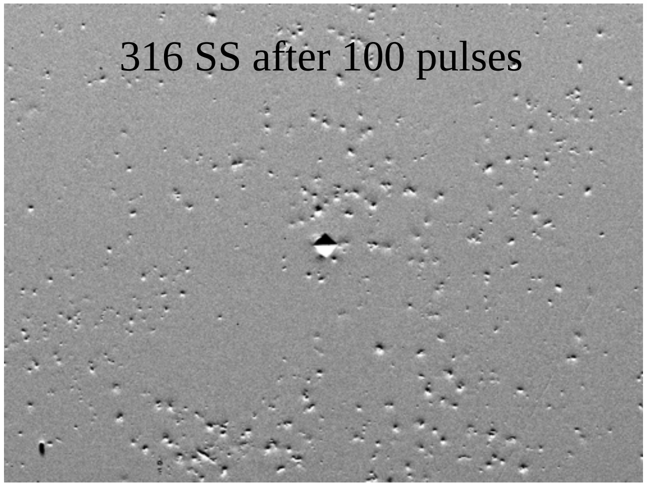
60 Hz operation with large beam spot

Peak energy deposition ~ 1 J/g

Pitting of stainless steel containment vessel significant issue. Pitting results from collapsing cavitation induced bubbles.




316 SS before beam pulsing

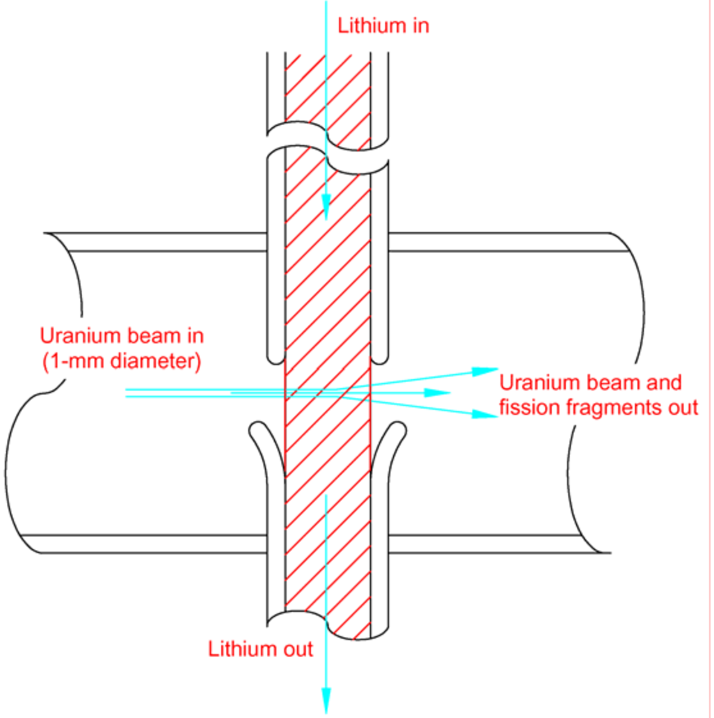

316 SS after 100 pulses

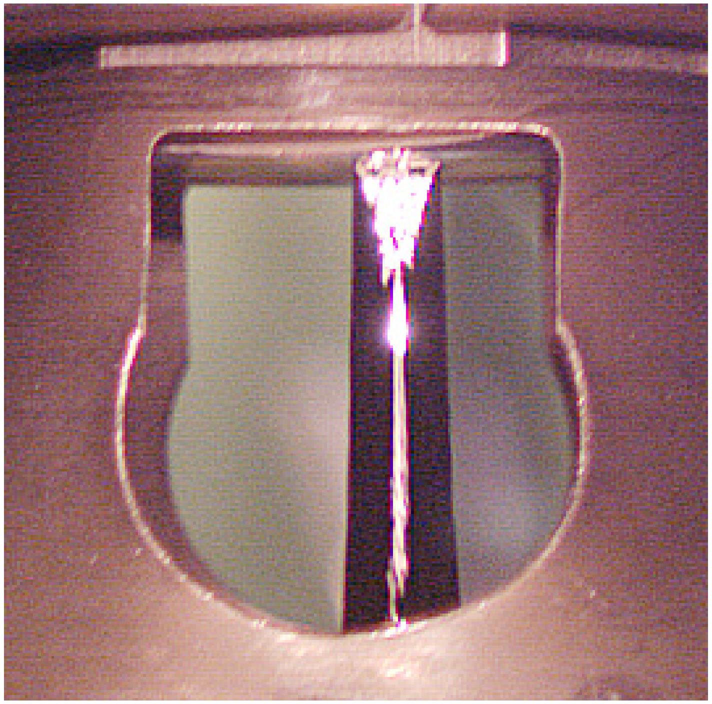
RIA Windowless Liquid Li Target

Rare Isotope Accelerator

Production of rare isotopes by ISOL method and target fragmentation method.

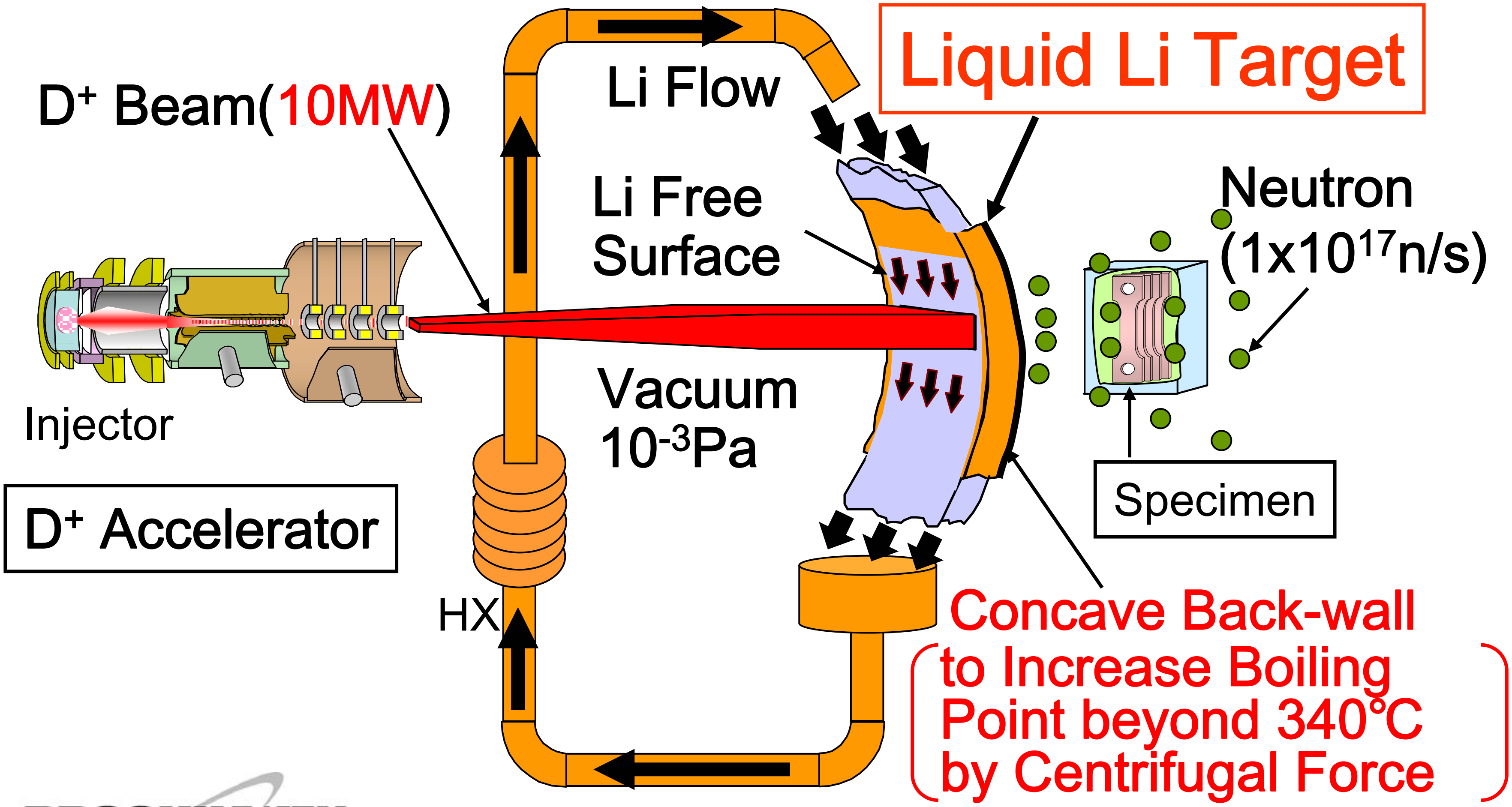
A windowless liquid Li sheet is proposed as a target for producing heavy ion projectiles. This method also show promise as a thin film stripper.





The IFMIF Liquid Li Target

Fast Neutron Source -- Operations in 2017



Concave Back-wall (to Increase Boiling Point beyond 340°C by Centrifugal Force)

Harold G. Kirk

fact
Muon Collaboration

Simulation and Theory Summary

1. **Particle Yields, Energy Deposition and Radiation (N. Mokhov, L. Waters)**
   - Needs and Specs
   - Codes
   - Uncertainties
   - Benchmarking
   - Future Work

2. **Structural Analyses of Solid Targets and Li-lenses (N. Simos, P. Hurh, B. Riemer)**

3. **Magnetohydrodynamics in Liquid Targets (R. Samulyak, Y. Prykarpatskyy)**

4. **Misc (L. Waters)**
   - Materials Handbook
   - Hydraulics

Conclusions

- New physics opportunities are demanding more intense proton drivers.
- 1 MW machines are almost here! 4 MW machines are planned.
- Targets for 1 MW machines exist but are unproven.
- But no convincing solution exists yet for the 4 MW class machines.
- Worldwide R&D efforts underway to develop targets for these new machines.
- A key workshop concern was the lack of worldwide support facilities where promising new ideas can be tested.

Issues for Further Targetry R&D

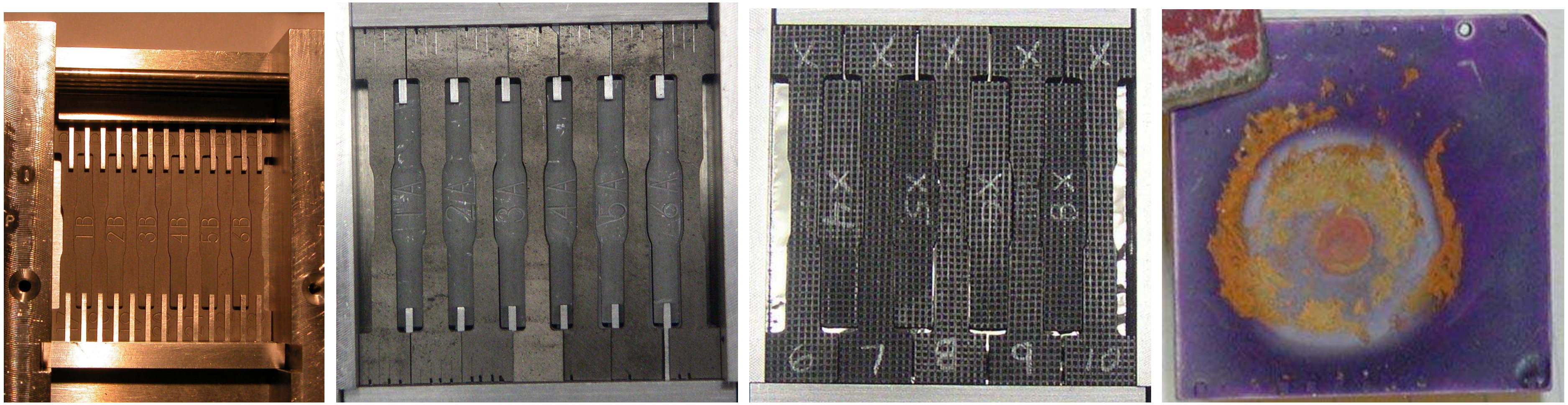
- **Continue numerical simulations of MHD + beam-induced effects.**
- **For solid targets, study radiation damage – and issues of heat removal from solid metal targets (carbon/carbon, Toyota Ti alloy, bands, chains,** *etc.*).
- **Proof-of-Principle test of an intense proton beam with a mercury jet inside 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.**

New Round of Solid Target Irradiation Studies

Are “high performance” alloys still high-performance after irradiation?

Materials irradiated at the BNL BLIP, March 2004:

1. Vascomax 350 (high strength steel for bandsaw target).
2. Ti90-Al6-V4 (titanium alloy for linear collider positron target).
3. Toyota “gum” metal (low-thermal expansion titanium alloy).
4. AlBeMet (aluminum/beryllium alloy).
5. IG-43 Graphite (baseline for J-PARC neutrino production target).
6. Carbon-carbon composite (3-d weave with low-thermal expansion).



Opportunities for European Targetry R&D Projects

Now: Studies of self annealing of tantalum targets at 2000C (RAL).

Future: a proposal to the European Union Sixth Framework Programme (FP6) for a "Design Study for Neutrino Factory Target R&D" will be submitted in early 2005. Lead: R. Edgecock (RAL).

Topics:

1. The Mercury Jet Target.
2. The Granular Target.
3. The Contained Metal Jet Target.
4. Target Station Design Studies.
5. Simulations of Beam/Target Interactions.

The Muon Collaboration Targetry Group will have an adjunct status on this proposal.

Proof-of-Principle of Liquid Jet + Magnet + Proton Beam

- Foreseen since inception of the targetry R&D program in 1997.
- Active planning since 2002, after success of separate beam + jet, and magnet + jet studies.
- Diminished option to perform the test at BNL.
- Long-term option to perform the test at JPARC (LOI submitted Jan 2003).
- Good opportunity at CERN in 2006 (LOI submitted Nov 2003).
- Contract awarded in late 2003 for fabrication of the 15-T pulsed solenoid coil + cryostat.
- Proposal submitted to CERN in Apr 2004 by a collaboration from BNL, CERN, KEK, ORNL, Princeton and RAL.

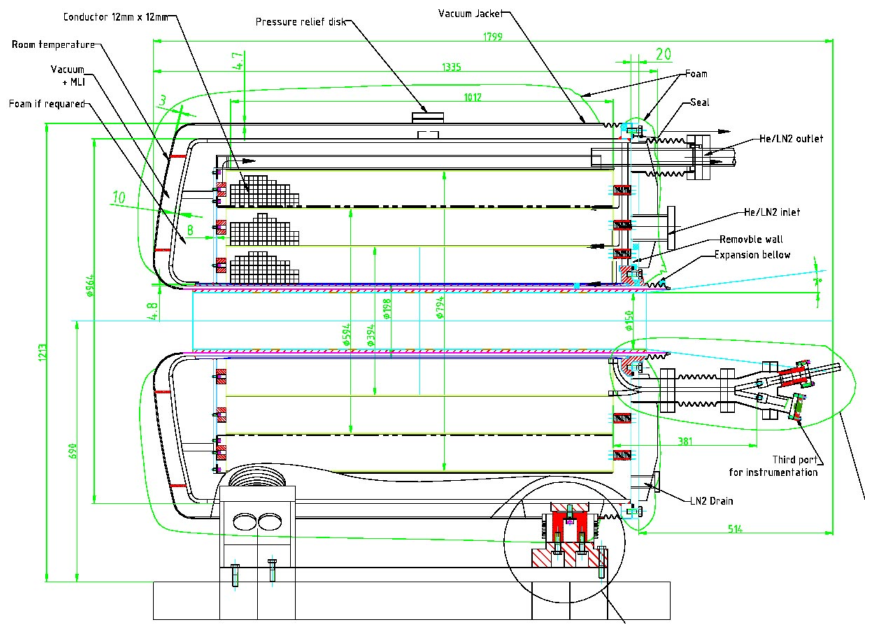
CERN-INTC-2004-016
INTC-P-186
26 April 2004

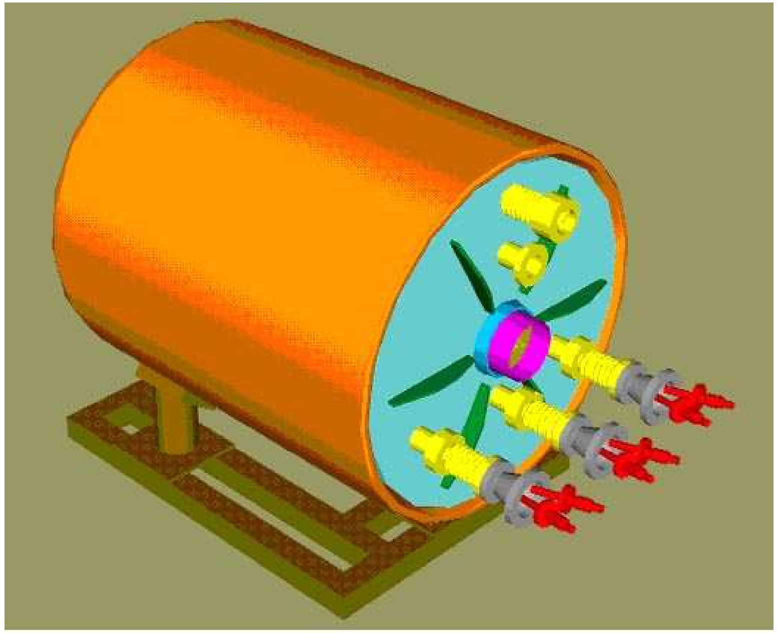
A Proposal to
the ISOLDE and Neutron Time-of-Flight Experiments
Committee

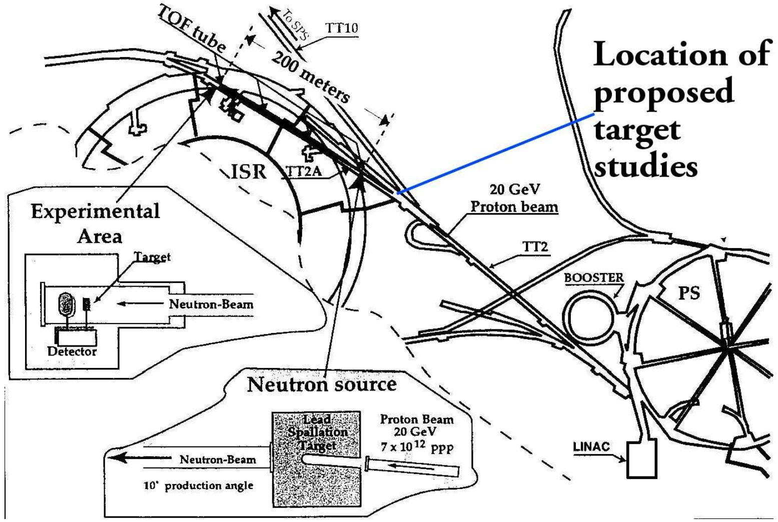
Studies of a Target System for a 4-MW, 24-GeV Proton Beam

J. Roger J. Bennett[1], Luca Bruno[2], Chris J. Densham[1], Paul V. Drumm[1],
T. Robert Edgecock[1], Adrian Fabich[2], Tony A. Gabriel[3], John R. Haines[3],
Helmut Haseroth[2], Yoshinari Hayato[4], Steven J. Kahn[5], Jacques Lettry[2], Changguo Lu[6],
Hans Ludewig[5], Harold G. Kirk[5], Kirk T. McDonald[6], Robert B. Palmer[5],
Yarema Prykarpatskyy[5], Nicholas Simos[5], Roman V. Samulyak[5], Peter H. Thieberger[5],
Koji Yoshimura[4]

Spokespersons: H.G. Kirk, K.T. McDonald
Local Contact: H. Haseroth



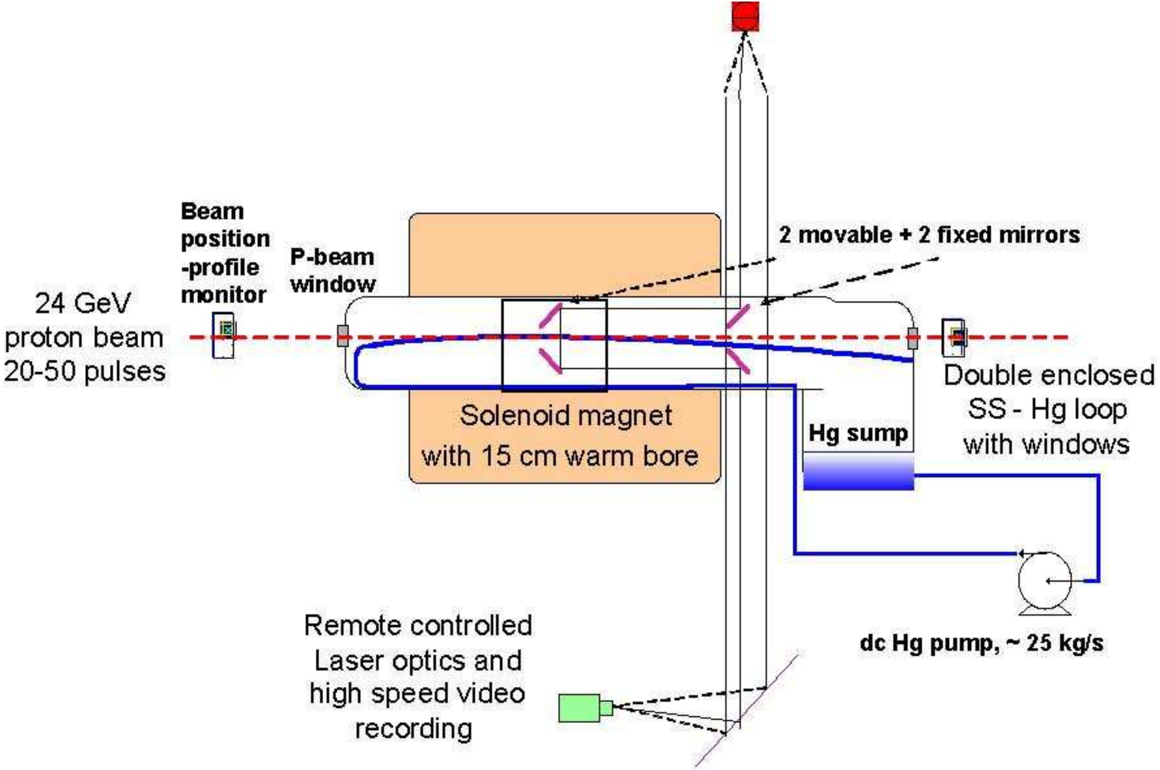




Location of proposed target studies

Optical Diagnostics

Based on designs successfully used in BNL and CERN tests.



Beam position -profile monitor

P-beam window

2 movable + 2 fixed mirrors

24 GeV proton beam 20-50 pulses

Double enclosed SS - Hg loop with windows

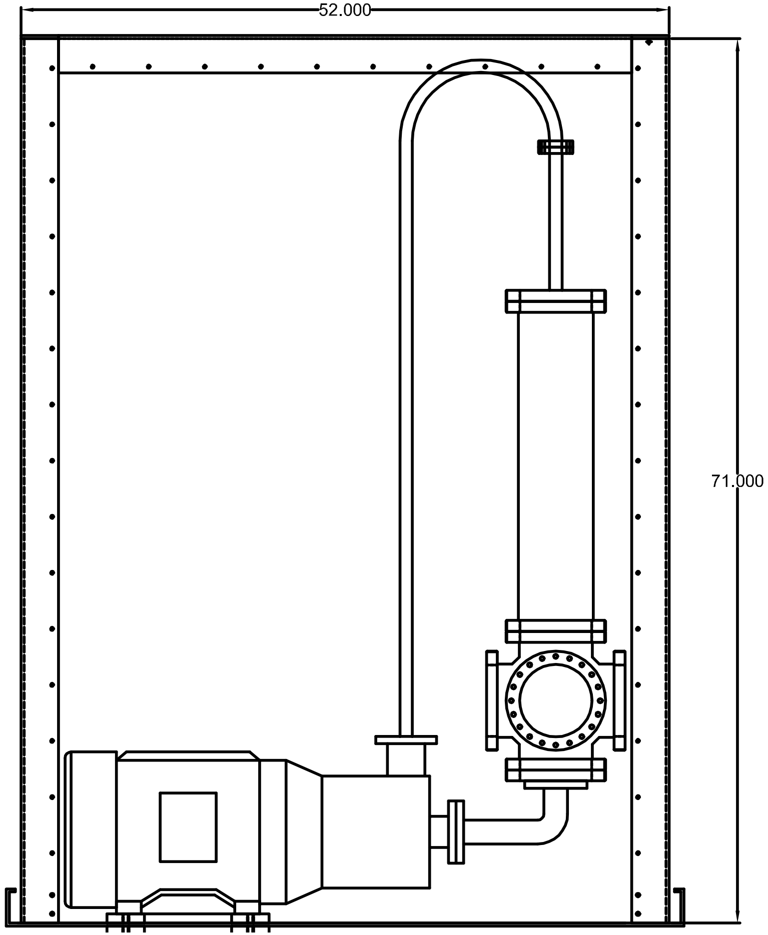
Solenoid magnet with 15 cm warm bore

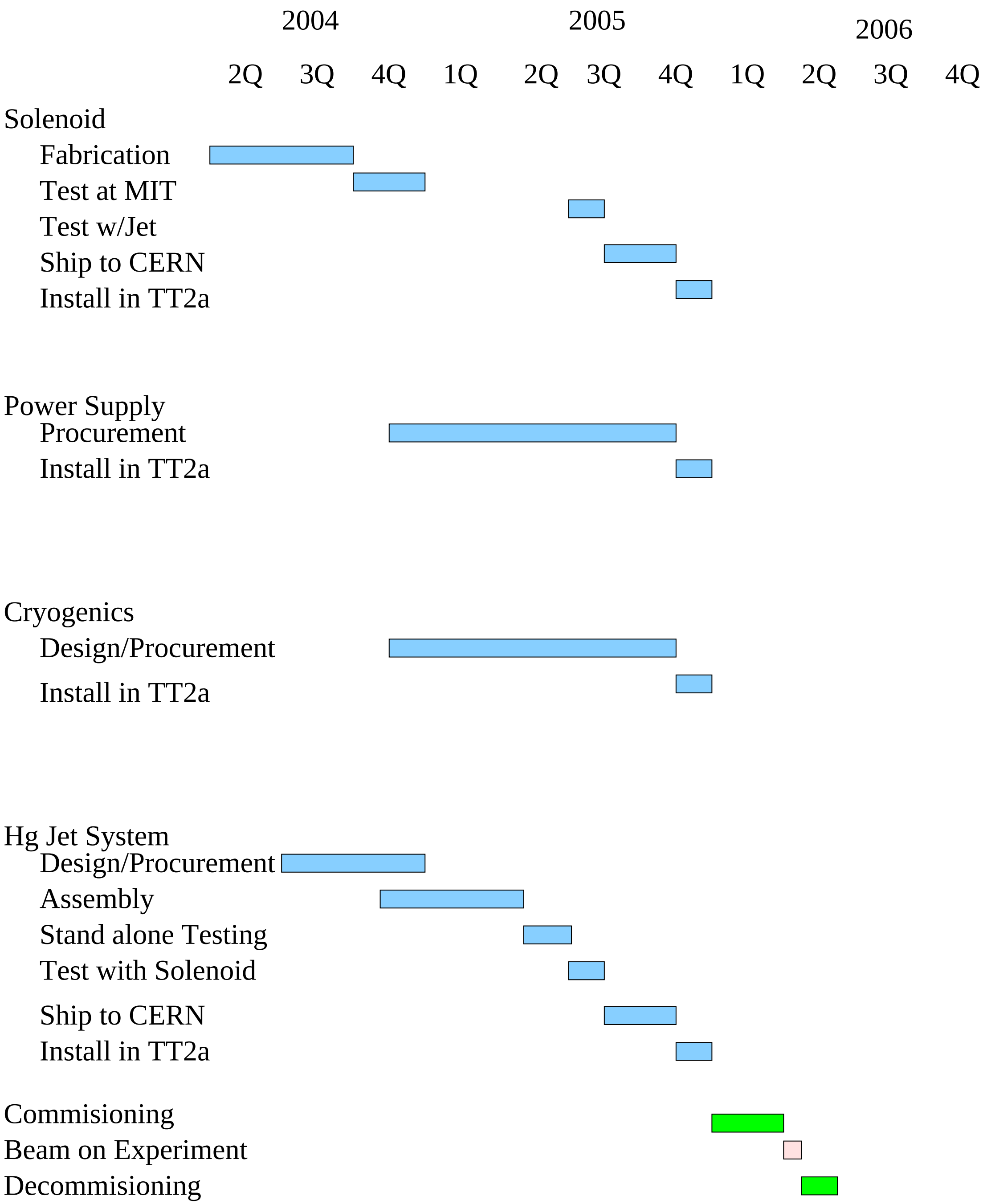
Hg sump

dc Hg pump, ~ 25 kg/s

Remote controlled Laser optics and high speed video recording

20 m/s continuous-flow mercury jet under development:





		Cost US k$	Effort Man*Mo
Solenoid			
	Testing	90	2
	Shipping	15	1
	Installation	20	1
	Decommisioning	25	1
Power Supply			
	Engineering Support	50	3
	Procurement	300	2
	Installation	80	1
	Decommisioning	20	1
	Contingency	70	
Cryogenics			
	Engineering Support	45	4
	Procurements	50	1
	Controls	40	2
	Installation	110	6
	Decommisioning	10	1
	Contingency	40	
Hg Jet			
	Engineering Support	30	12
	Components	30	6
	Optical System	35	12
	Windows	15	2
	Decomminsioning	20	1
	Contingency	20	
Beam Systems			
	Profile/Position	40	3
	Dump	25	3
	Scintillators	10	2
Support Services			
	Data Acquistion	40	3
	Proj. Management	150	24
Total		1380	94

Summary

- Improved performance of High Power Targets is a cost-effective path to improved performance of future muon and neutrino beams
  – but significant R&D is required to realize these improvements.
- Relevant R&D on high-performance solid targets is being carried out by members of the Muon Collaboration, + international partners, at little direct cost to the Collaboration.
- The largest impact of our efforts on the accelerator community would be the acceptance of the concept of a free liquid jet target in a high-field solenoid for use in $\gtrsim 2$ MW proton beams.
- Step-by-step R&D on liquid jet targets has been very successful, but is not sufficient.
- We are poised to perform the needed proof-of-principle test of a liquid jet + magnet + beam, with an outstanding near-term opportunity for this at CERN.