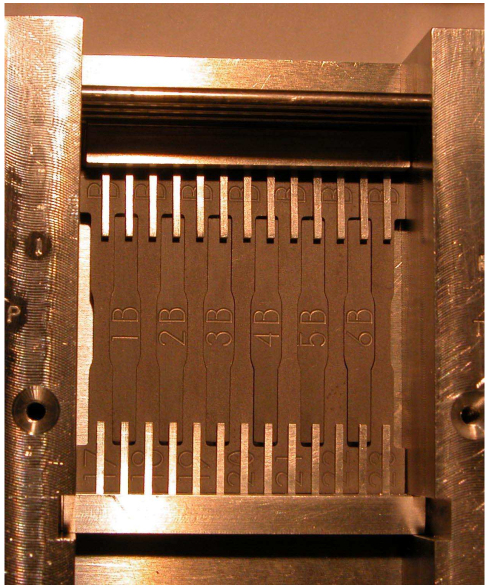
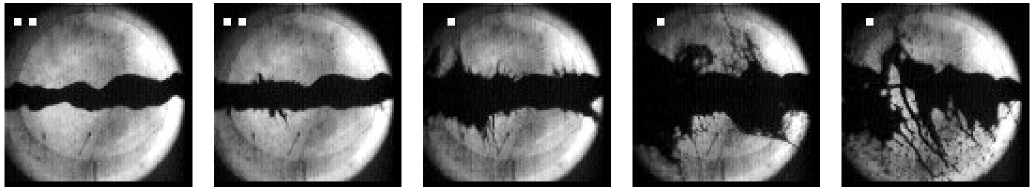
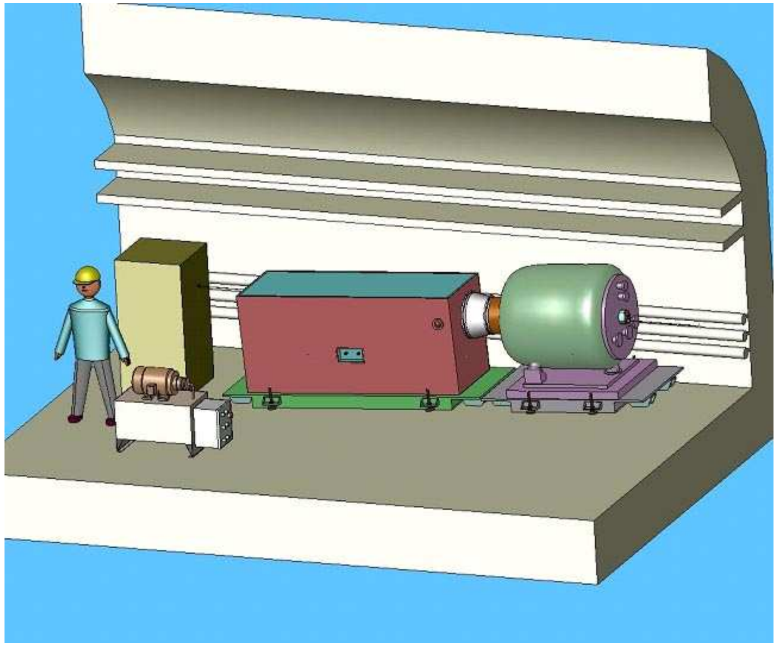
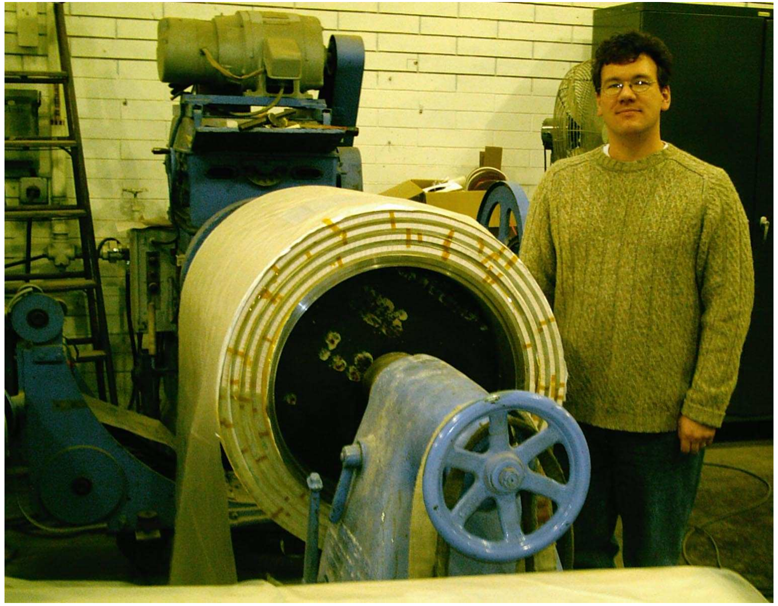
The High-Power Targetry R&D Program









K.T. McDonald

Princeton U.

MUTAC

Lawrence Berkeley Laboratory

April 25, 2005

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

High-Performance Muon and Neutrino Beams Require a High-Performance Source

- **The concept of a muon collider (Budker & Skrinsky – 1970's, Neuffer – 1980's) is enthusiastically revived during the 1992 Port Jefferson workshop.**

  Bob Noble proposes π/μ collection via a Li lens.

- **Bob Palmer proposes solenoid capture of π's & μ's from a multimegawatt proton beam during the 1994 Sausalito workshop (BNL-61581, 1995).**

  Possibly inspired by Djilkibaev and Lobashev, Sov. J. Nucl. Phys. **49**, *384 (1989), which also led to MECO.*

- **Colin Johnson proposes use of a mercury jet target for muon production during the (Jan.) 1997 Oxford, MS workshop, based on studies for an ACOL target in 1988.**

- **The Muon Collaboration is formed during the 1997 Orcas Island workshop, and inaugurates a program of high-power targetry R&D based on solenoid capture of π's & μ's from a free mercury jet target.**

Major Milestones in the Targetry R&D Program

- **Sept. 1998: Targetry R&D proposal submitted to BNL.**
- **Oct. 1999: BNL E951 approved.**
- **Summer 2000: Conceptual studies of a carbon target + 20-T hybrid solenoid for the 1.5-MW proton beam of Neutrino Factory Feasibility Study 1.**
- **Mar.-Apr. 2001: Tests of solid targets, a mercury "thimble" and a free mercury jet target with 24-GeV protons in the BNL A3 beamline.**
- **Spring 2001: Conceptual studies of mercury jet + 20-T solenoid for the 4-MW proton beam of Neutrino Factory Feasibility Study 2.**
- **July 2001: Beta beams for ν_e and $\bar{\nu}_e$ from ISOL targets (Zucchelli).**
- **Aug. 2001: Mercury "thimble" tests in the 2-GeV ISOLDE proton beam at CERN.**
- **May, 2002: 1st irradiation of solid targets at the BNL BLIP facility.**
- **June 2002: Studies of a mercury jet in a 20-T magnetic field, Grenoble. (A. Fabich Ph.D. thesis, Nov. 2002).**

Major Milestones, cont'd.

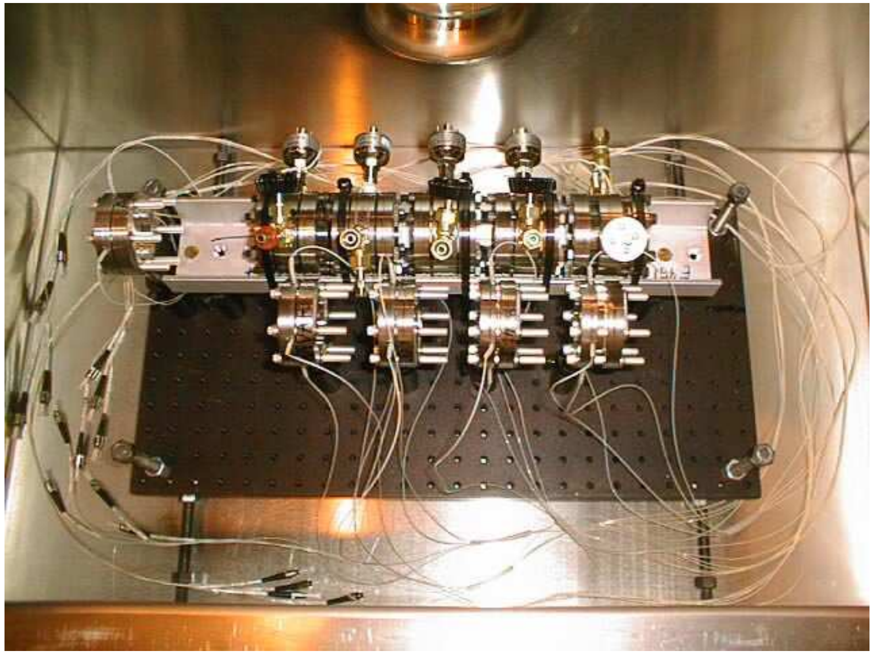
- **Jan. 2003: Letter of Intent to J-PARC for targetry R&D in a 50-GeV proton beam.**
- **Sept. 2003: High-Power Targetry workshop, Ronkonkoma, NY.**
- **Oct. 2003: Contract let to CVIP/Everson-Tesla for fabrication of a 15-T pulsed solenoid magnet.**
- **Mar. 2004: 2nd irradiation of solid targets at the BNL BLIP facility.**
- **Apr. 2004: Proposal for studies of a mercury jet + 15-T solenoid + 24-GeV proton beam at CERN.**
- **Apr. 2005: The CERN targetry experiment is approved as nTOF11.**

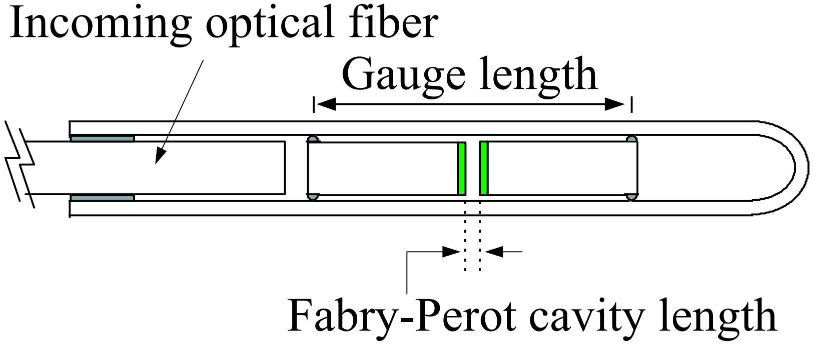
The rest of this talk consists of illustrations of the above highlights of the targetry R&D program. Solid targets first, then liquid targets.

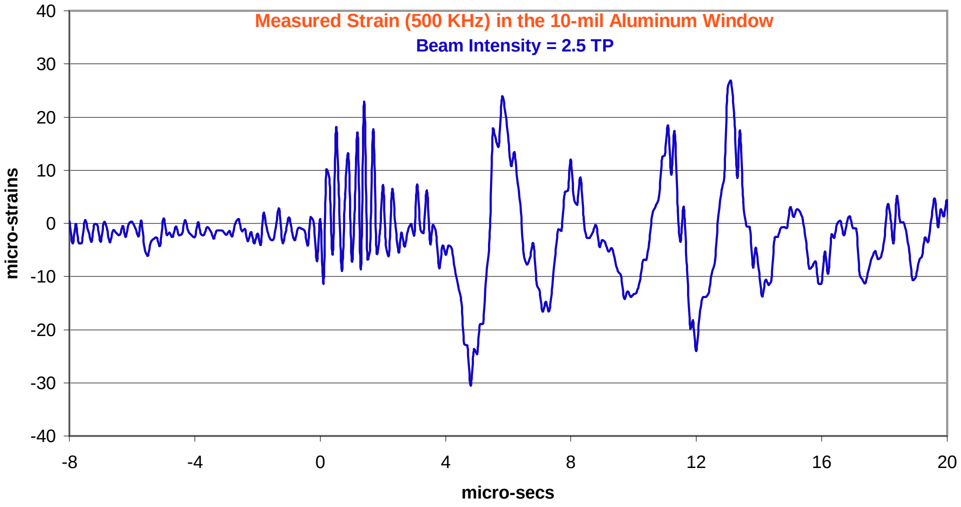
Window Tests (5e12 $p$pp, 24 GeV, 100 ns)

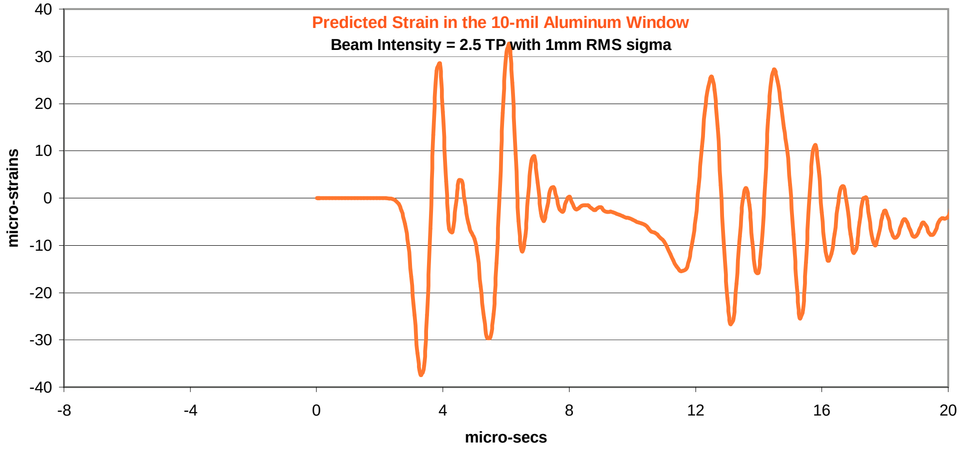
Aluminum, Ti90Al6V4, Inconel 708, Havar,

instrumented with fiberoptic strain sensors.



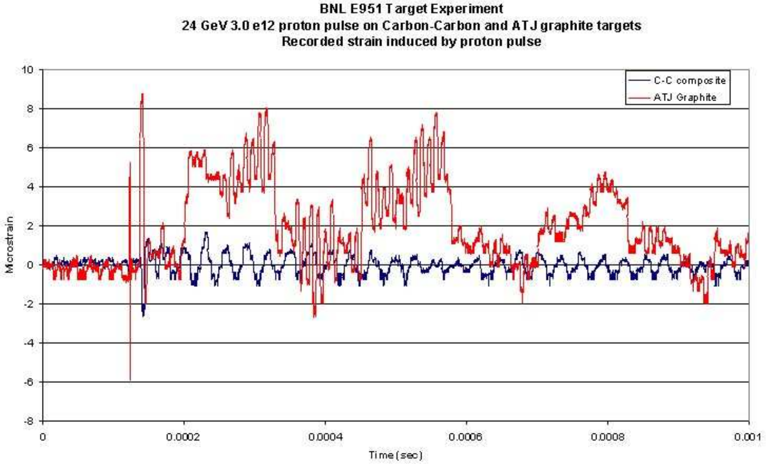




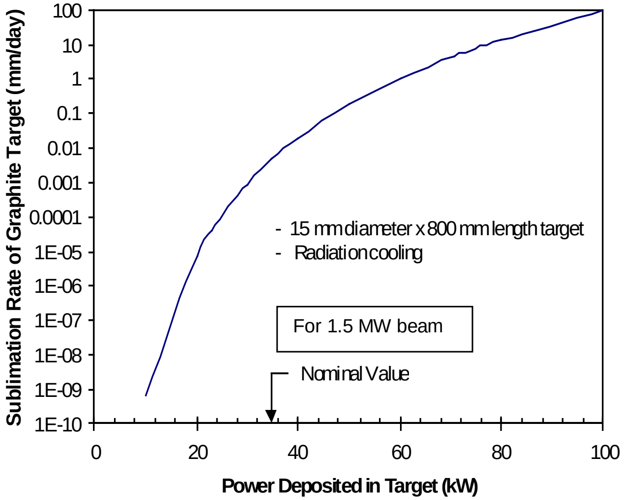


A Carbon Target is Feasible at 1-MW Beam Power

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.



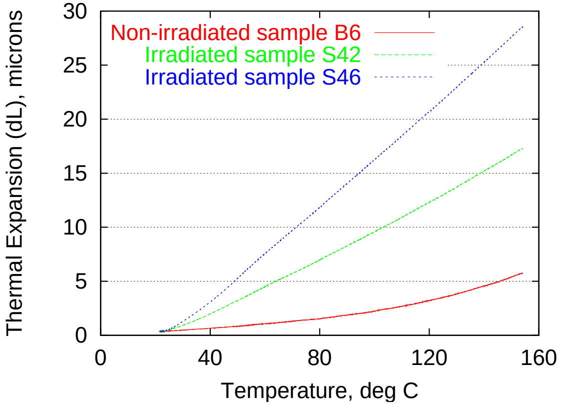
Sublimation of carbon believed to be negligible in a helium atmosphere.

Tests underway at ORNL to confirm this.

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

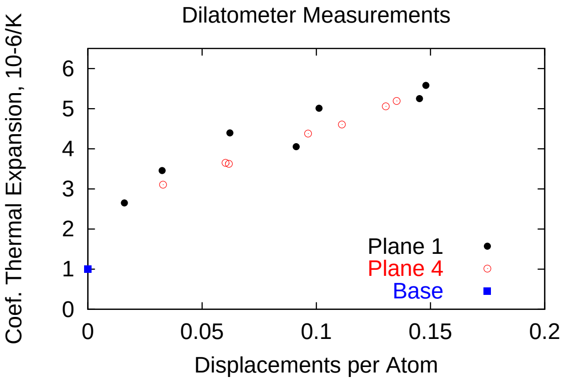
Effects of Radiation on SuperInvar

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



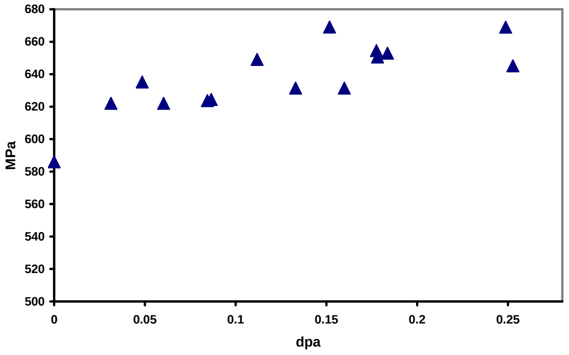
However, irradiation at the BNL BLIP facility show that the CTE increases rapidly with radiation dose.

CTE *vs.* dose ⇒



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

Yield strength *vs.* dose ⇒

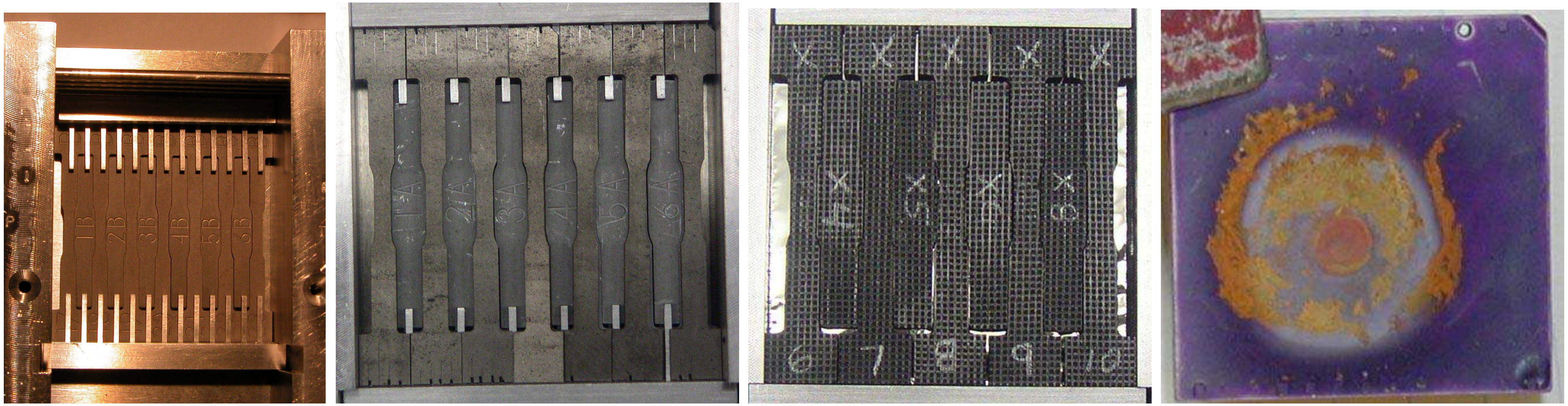


New Round of Solid Target Irradiation Studies

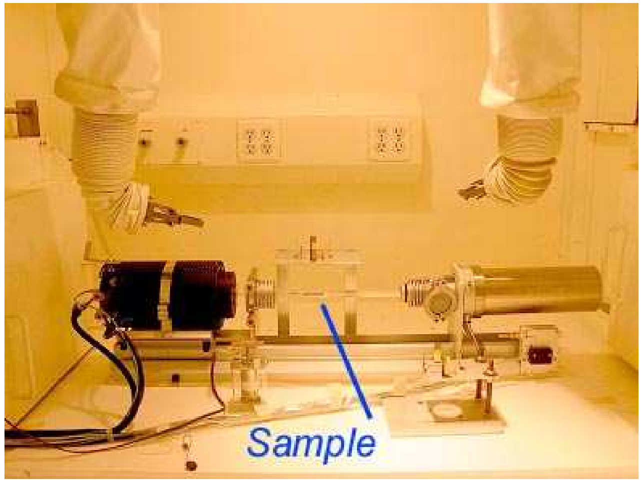
Are “high performance” alloys still high-performance after irradiation?

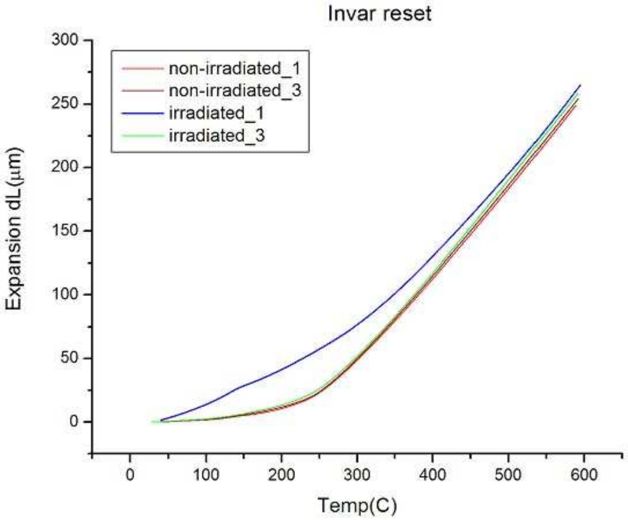
Materials irradiated at the BNL BLIP, March 2004:

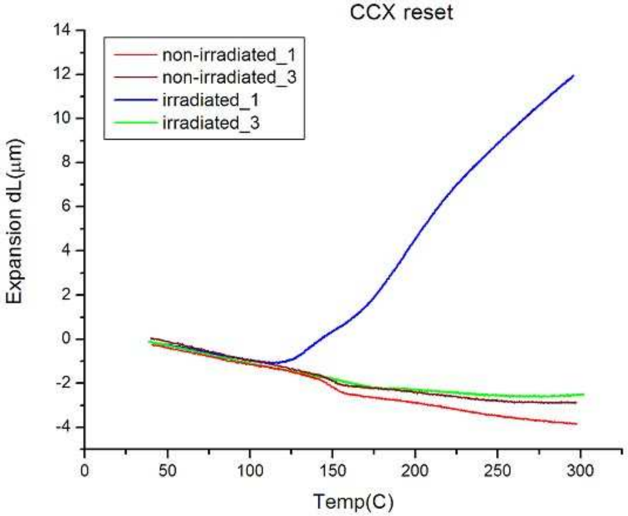
1. Vascomax 350 (high strength steel for bandsaw target).
2. Ti90-Al6-V4 (titanium alloy for linear collider positron target).
3. Toyota “gum” metal (low-thermal expansion titanium alloy).
4. AlBeMet (aluminum/beryllium alloy).
5. IG-43 Graphite (baseline for J-PARC neutrino production target).
6. Carbon-carbon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



Annealing of the CTE by High-Temperature Cycles







The Linseis dilatometer can now be cycled to 600 C (in the hot cell).

Thermal cycling of superinvar above 500 C anneals the radiation damage of the CTE.

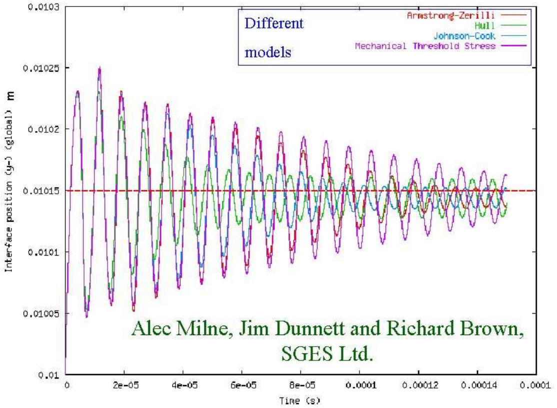
The 3-d weave of carbon-carbon composite also showed deterioration of its CTE due to radiation, but the CTE was restore by thermal cycling to 300 C.

Small effects of radiation damage, and also of thermal annealing, seen in the Toyota titanium superalloy ("gum metal").

Solid Target R&D at RAL

PPARC Award – 550k (J.R.J. Bennett *et al.*)

- Measure mechanical strength characteristics of tantalum under shock conditions at 2000C.
- Model the shock for different geometries, using codes from the explosives community.
- In-beam tests with proton at ISIS and/or ISOLDE.

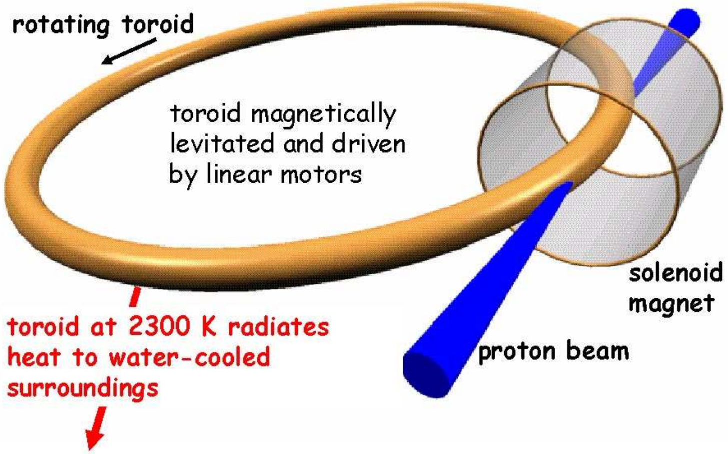


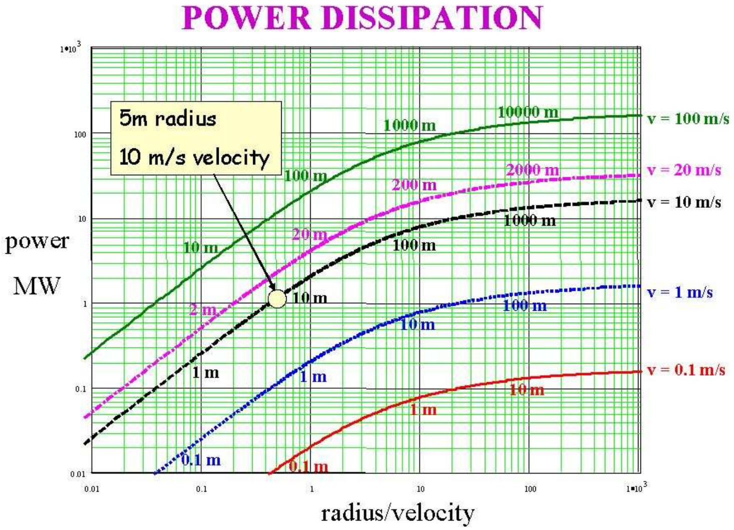
The radius of the bar versus time for a single pulse. Temperature jump from 300 to 2300 K.

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 2005.

Lead: R. Edgecock (RAL).

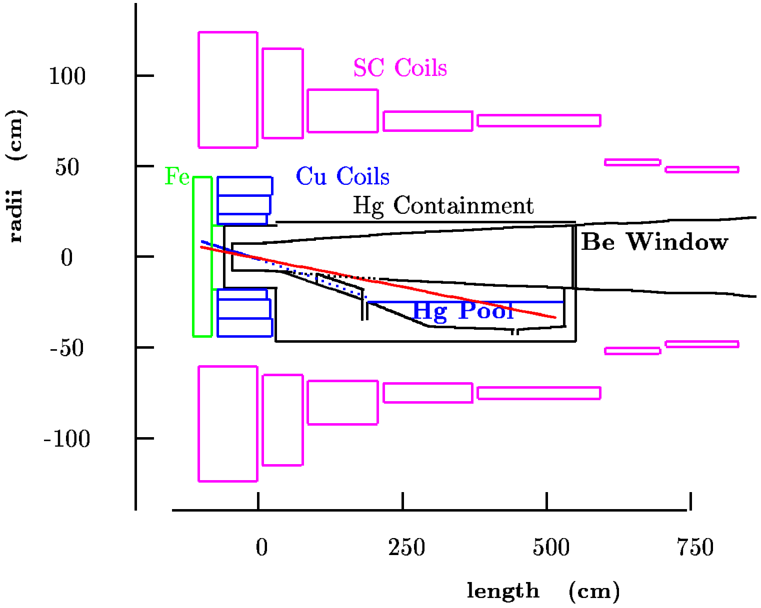
Rotating band option:



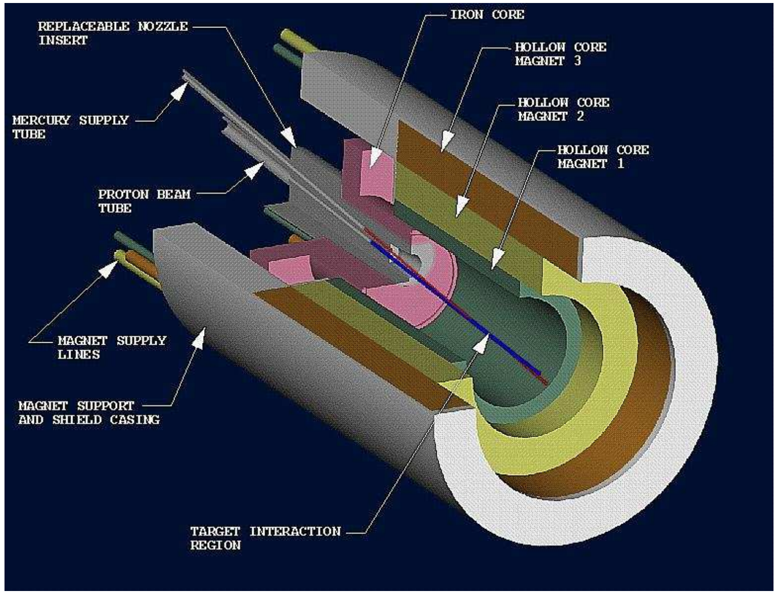


A Liquid Metal Jet May Be the Best Target

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.

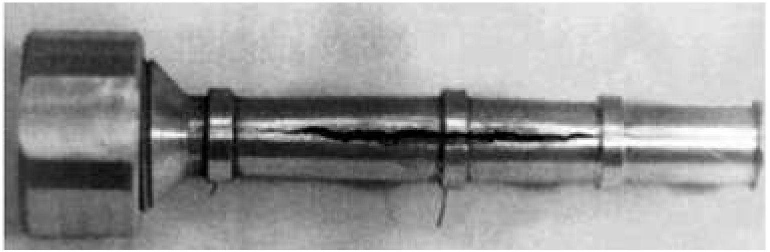


Mercury jet tilted by 100 mrad,
proton beam tilted by 67 mrad,
to increase yield of soft pions.

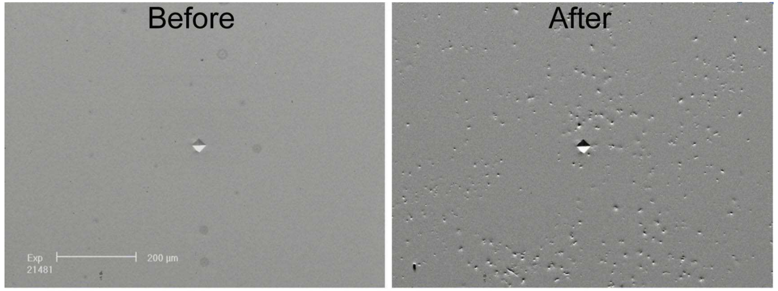
Beam-Induced Cavitation in Liquids Can Break Pipes

ISOLDE:

BINP:

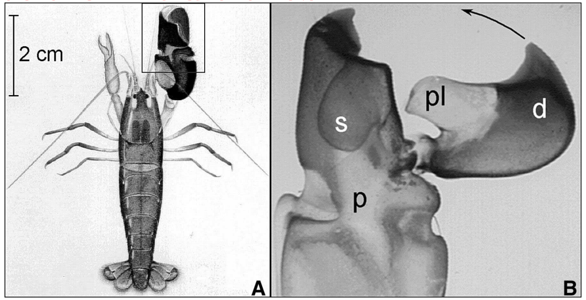


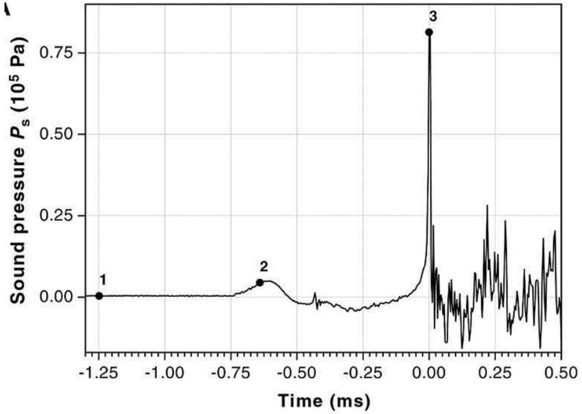
SNS:

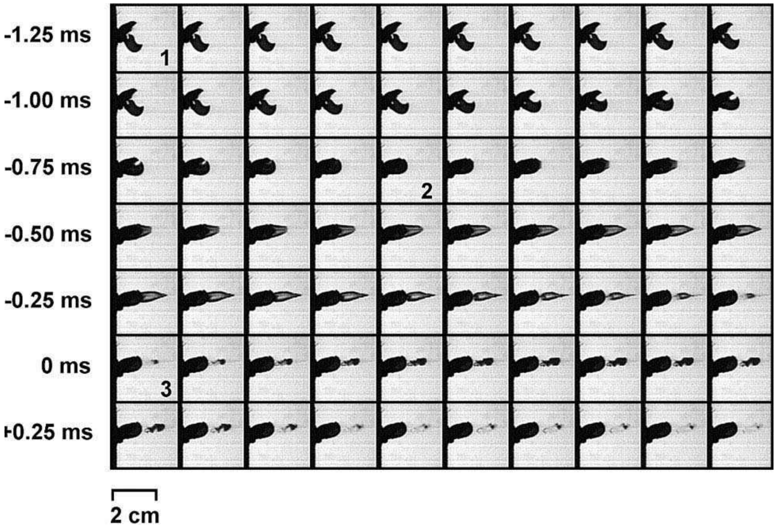


TL - High Power Target
Specimen # 29754
Equivalent SNS Power Level = 2.5

Snapping shrimp stun prey via cavitation bubbles.

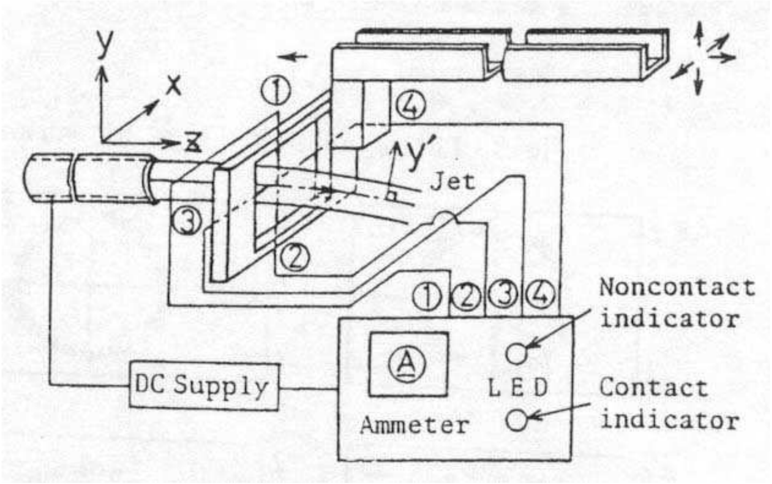


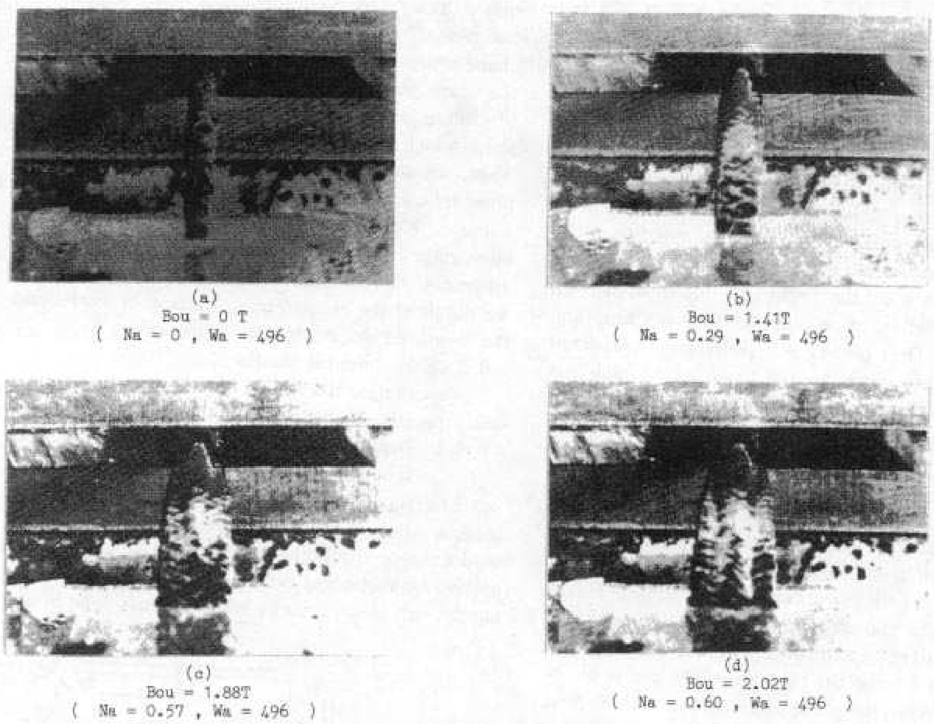




The Shape of a Liquid Metal Jet under a Non-uniform Magnetic Field

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



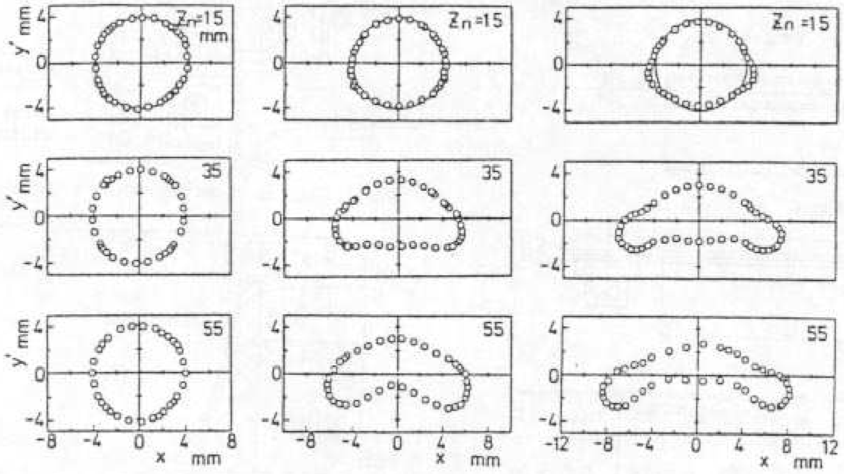

(a)
Bou = 0 T
(Na = 0 , Wa = 496)

(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



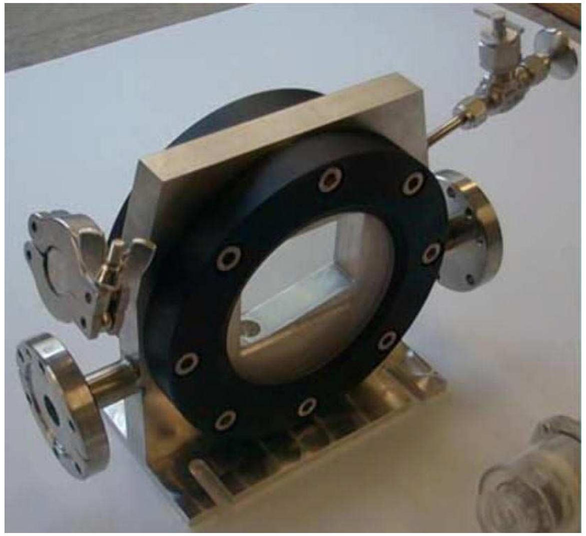
(a)
Bou = 0 T
(Na = 0 , Wa = 496)

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

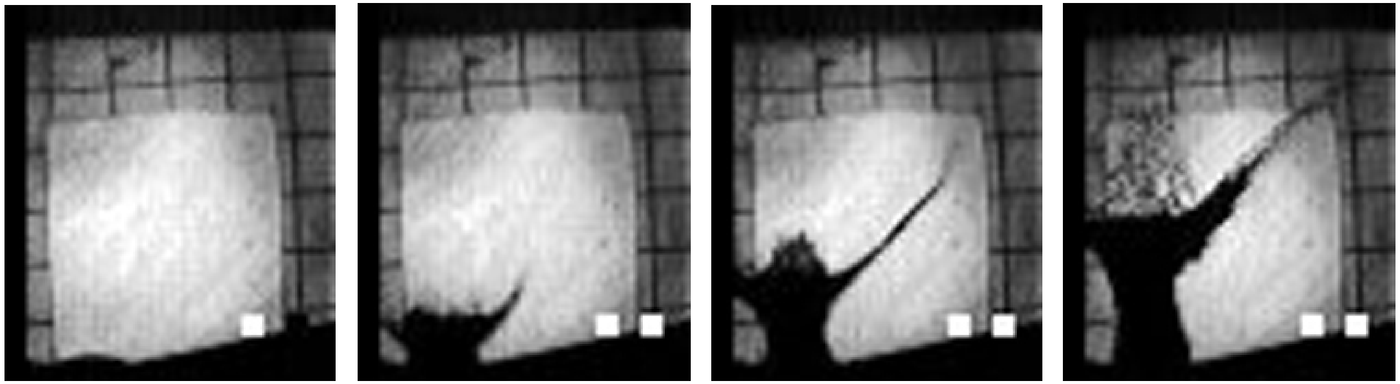
(c)
Bou = 1.88 T
(Na = 0.57 , Wa = 496)

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

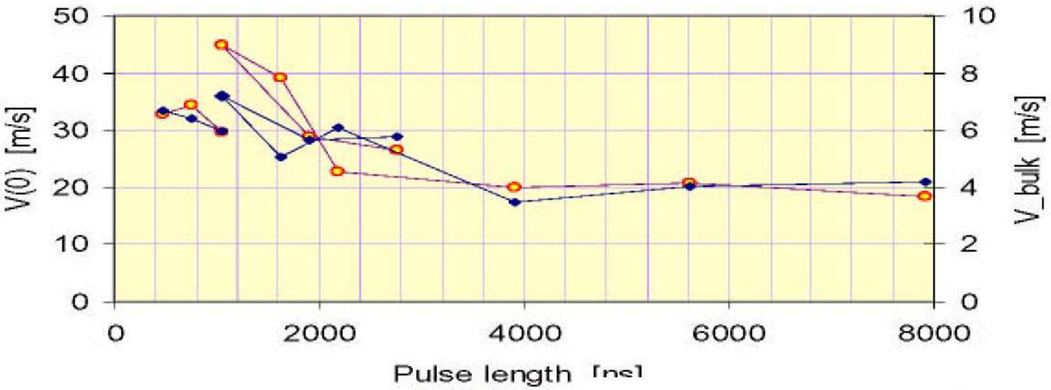
Passive Mercury Target Tests (BNL and CERN)



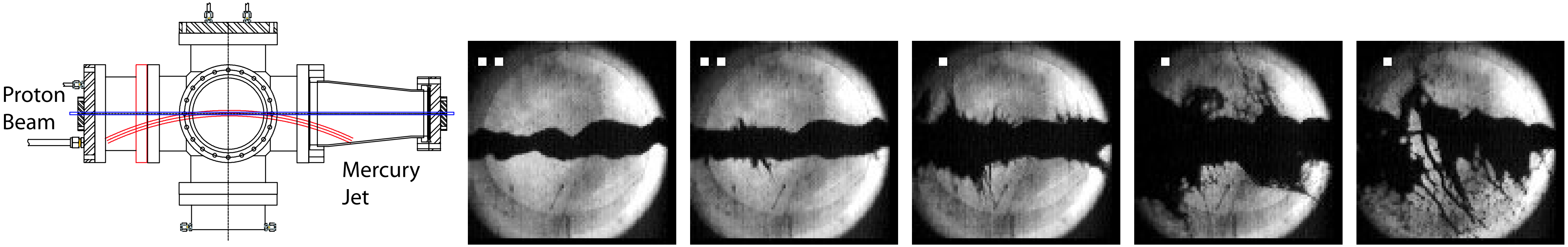
Exposures of 25 μs at
$t = 0$**, 0.5, 1.6, 3.4 msec,**
$\Rightarrow v_{\text{splash}} \approx 20 - 40$ **m/s:**



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

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)

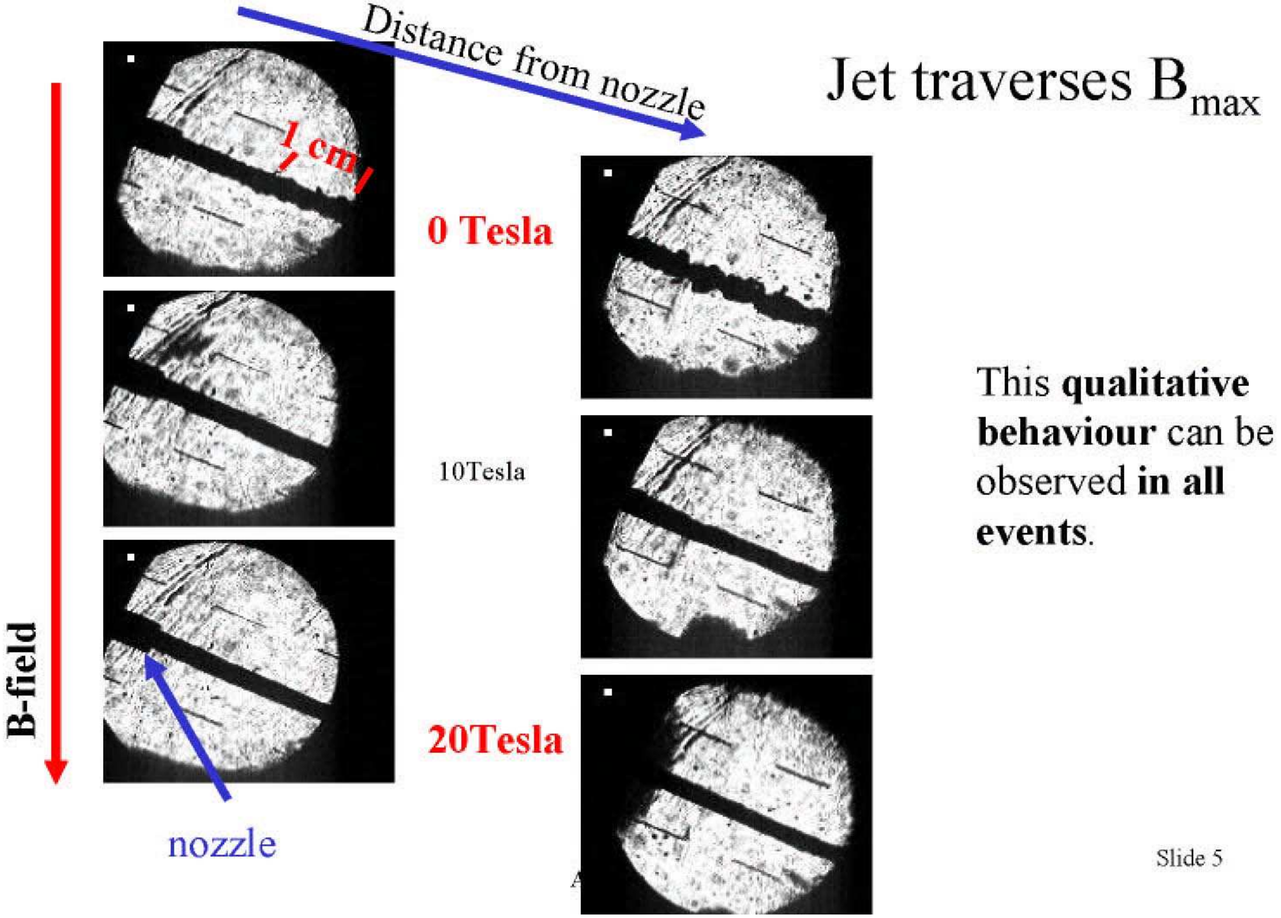
Eddy currents may distort the jet as it traverses the magnet.

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).

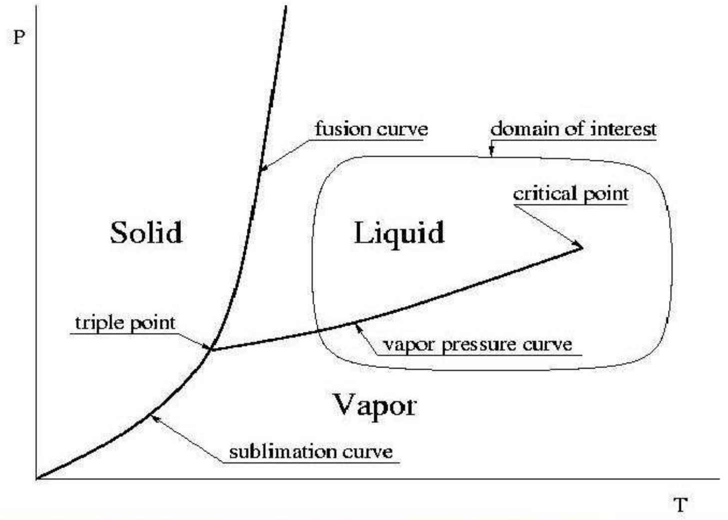
Will the beam-induced dispersal be damped also?

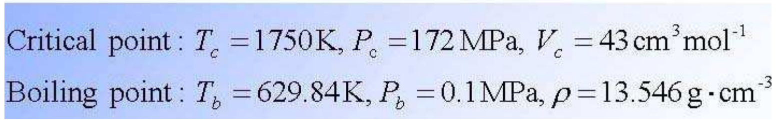


This **qualitative behaviour** can be observed **in all events**.

Computational Magnetohydrodynamics

(R. Samulyak, Y. Pyrkarpatsky)



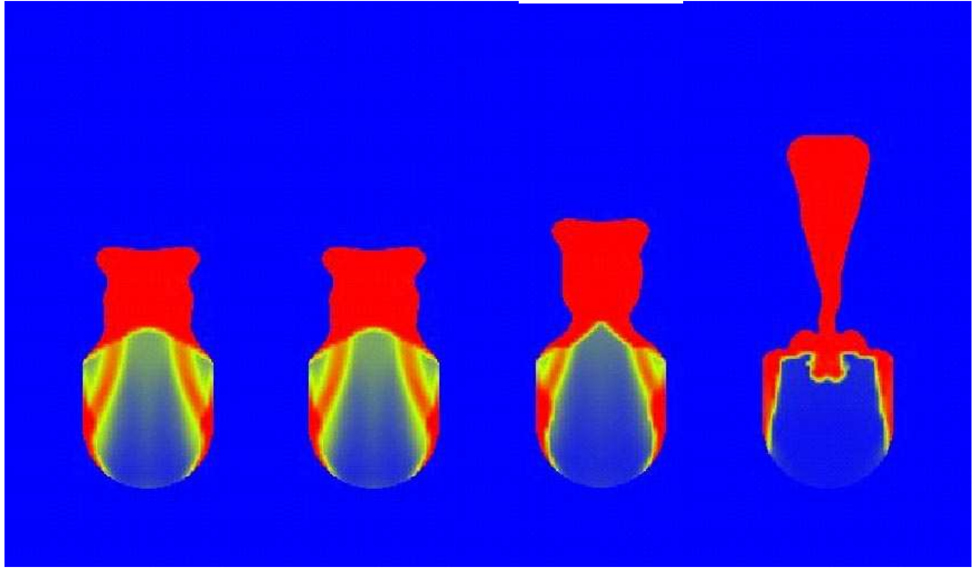


Critical point: $T_c = 1750\,\mathrm{K}$, $P_c = 172\,\mathrm{MPa}$, $V_c = 43\,\mathrm{cm^3\,mol^{-1}}$

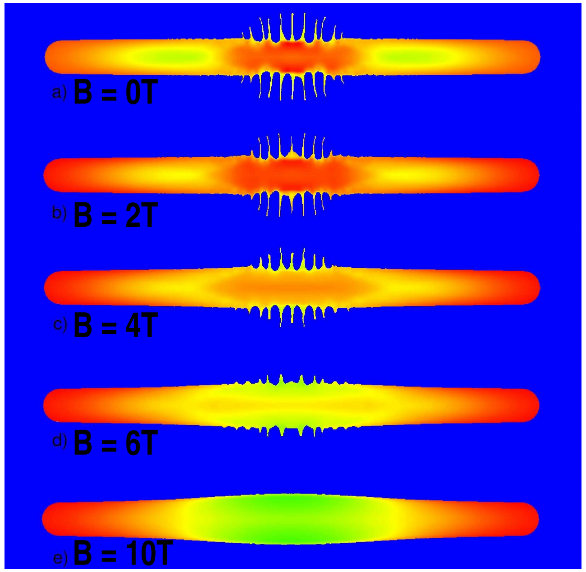
Boiling point: $T_b = 629.84\,\mathrm{K}$, $P_b = 0.1\,\mathrm{MPa}$, $\rho = 13.546\,\mathrm{g \cdot cm^{-3}}$

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

Thimble splash at 0.24, 0.48, 0.61, 1.01 μs

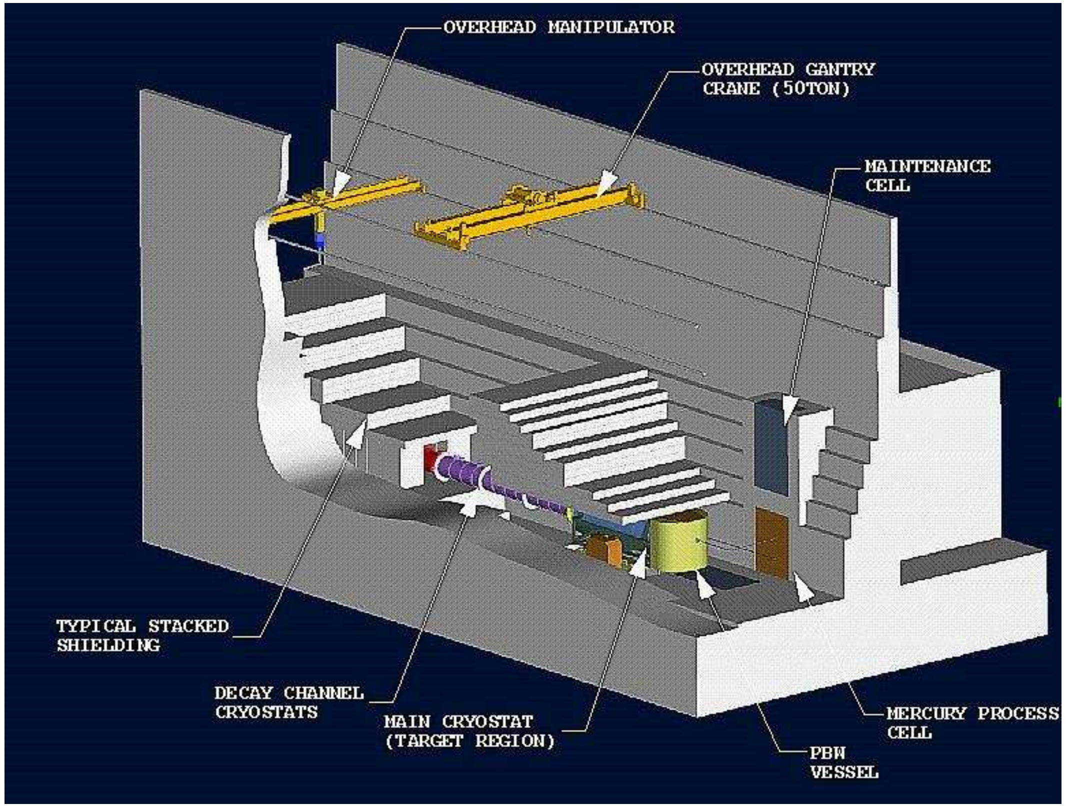


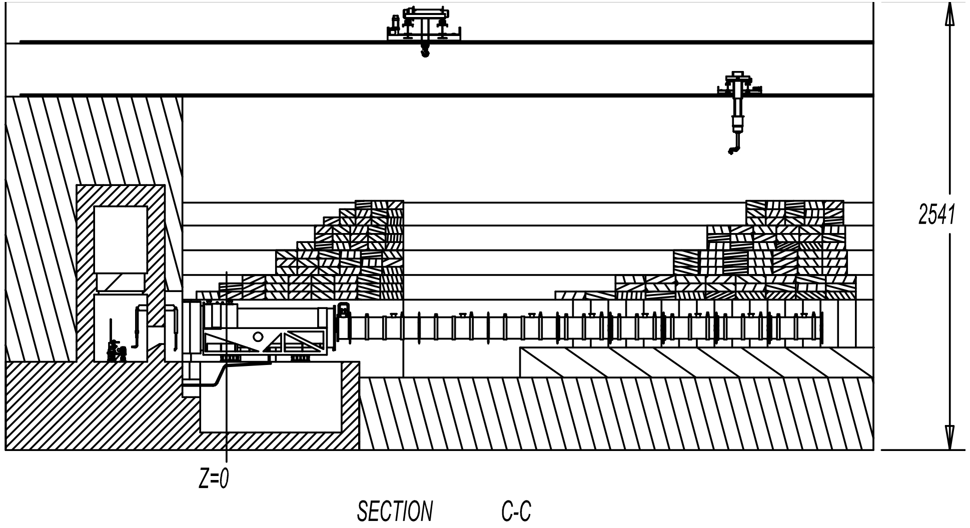
Magnetic damping of beam-induced filamentation:

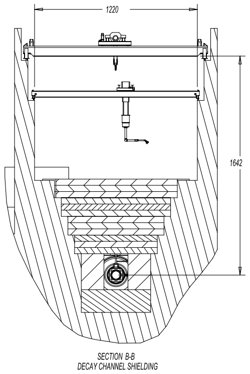


Target System Support Facility

Extensive shielding and remote handling capability.
[Spampinato *et al.*, *Neutrino Factory Feasibility Study 2* (2001)]





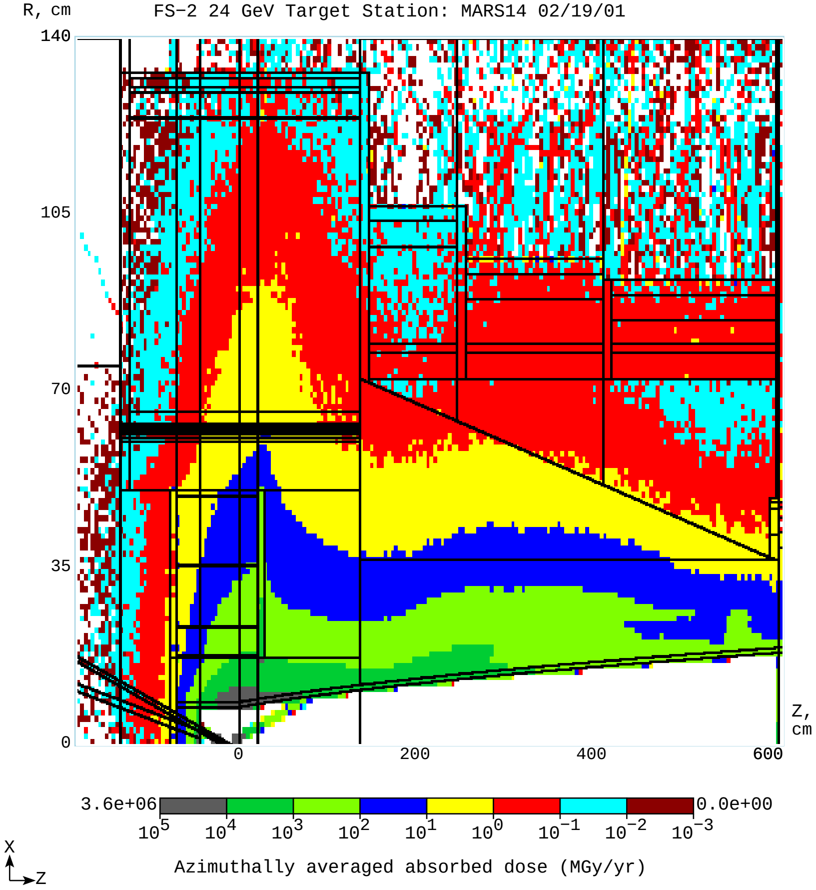


Lifetime of Components in the High Radiation Environment

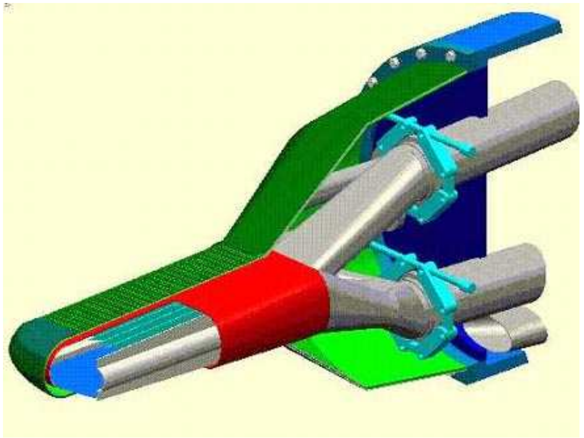
Component	Radius (cm)	Dose/yr (Grays/2×10^7 s)	Max allowed Dose (Grays)	1 MW Life (years)	4 MW life (years)
Inner shielding	**7.5**	5×10^{10}	10^{12}	**20**	**5**
Hg containment	**18**	10^9	10^{11}	**100**	**25**
Hollow conductor coil	**18**	10^9	10^{11}	**100**	**25**
Superconducting coil	**65**	5×10^6	10^8	**20**	**5**

Some components must be replaceable.

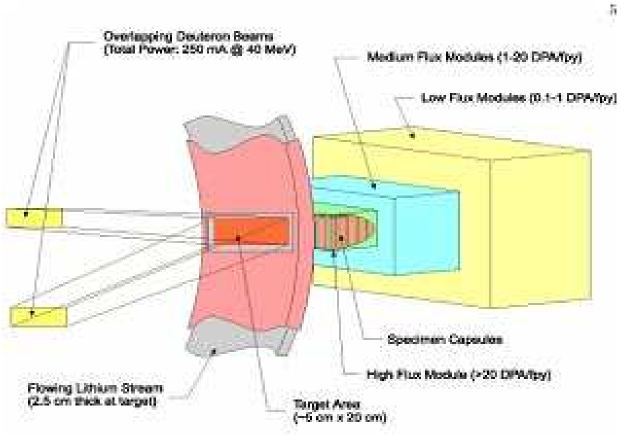
[MARS calculations:]



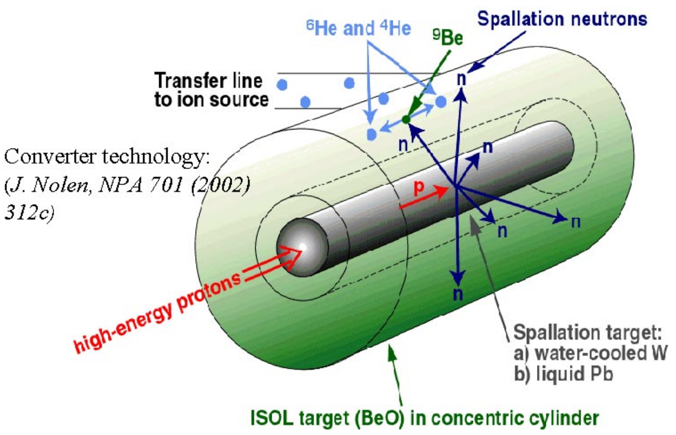
High-Power Targets Essential for Many Future Facilties



ESS

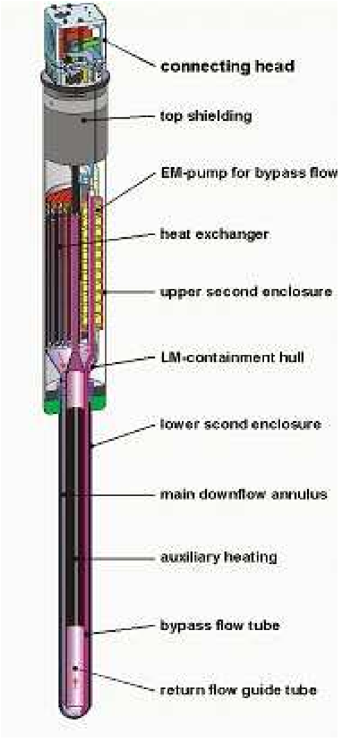


IFMIF

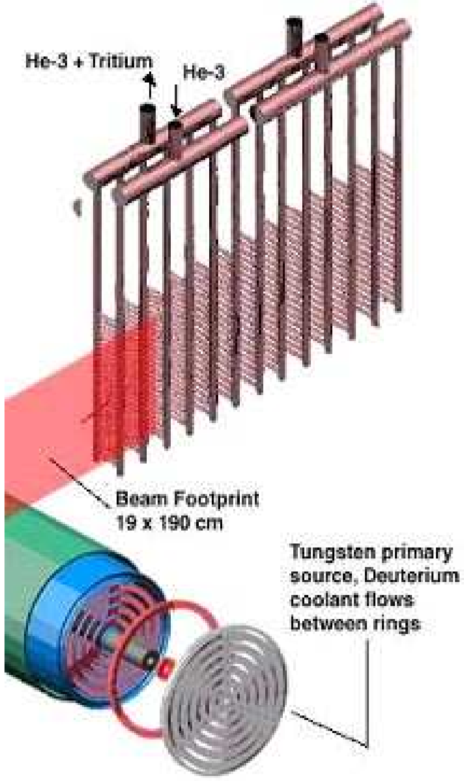


Converter technology:
(J. Nolen, NPA 701 (2002) 312c)

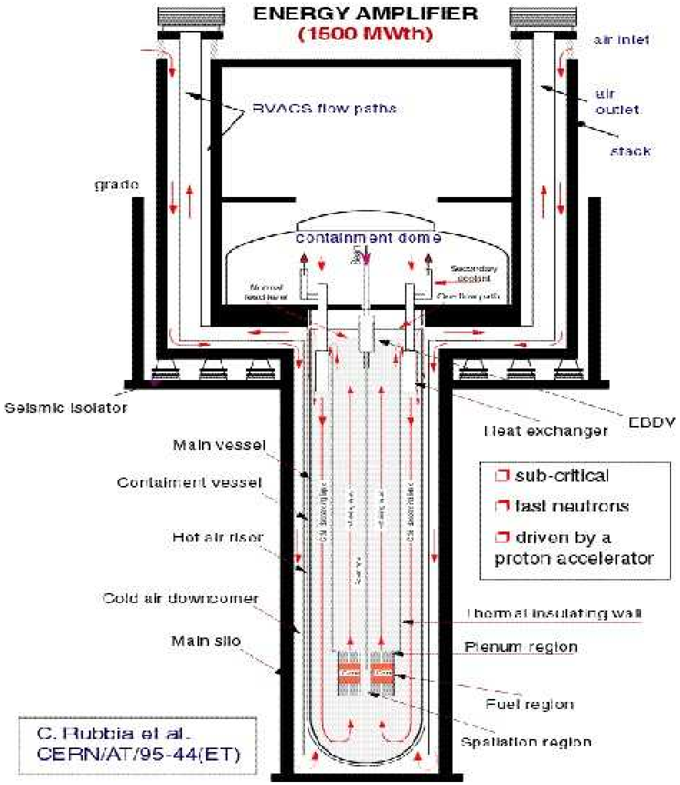
ISOL/β Beams



PSI



APT



ATW

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.**
- **The concept of a mercury jet target in a high magnetic field is still not taken seriously by the targetry community.**

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.

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 J-PARC (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

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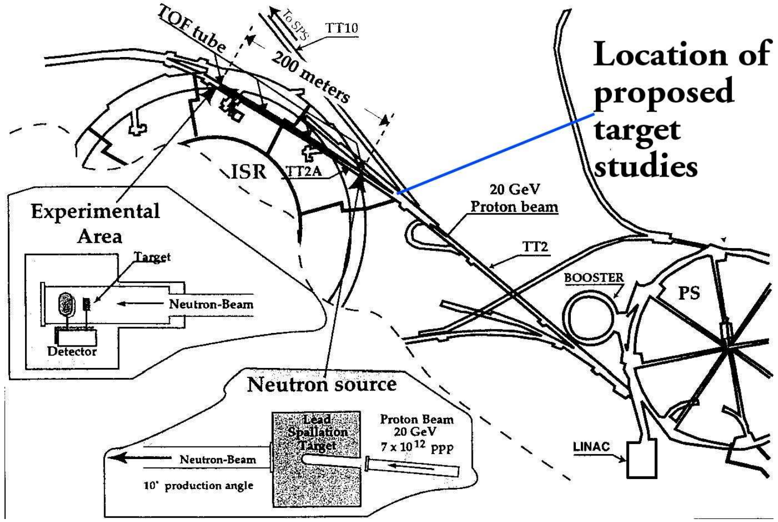
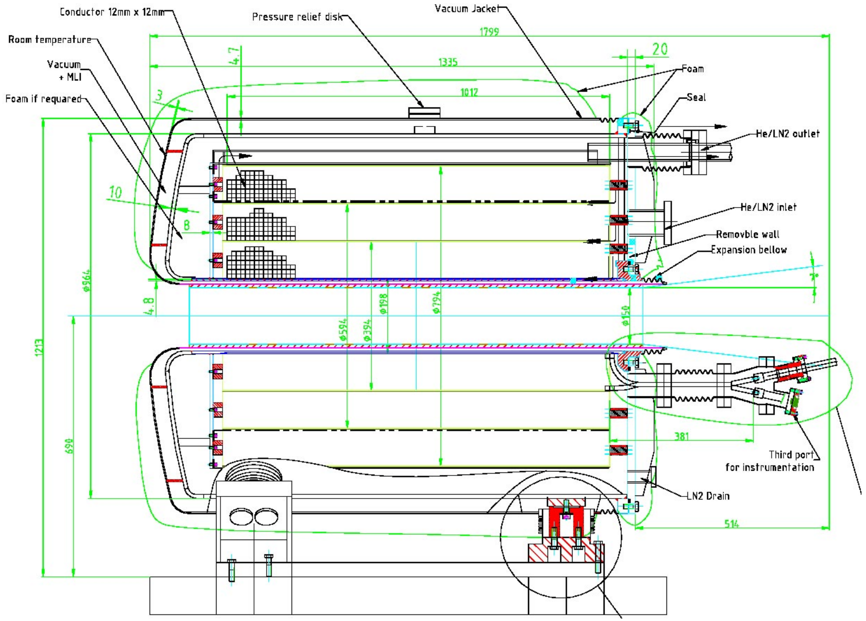
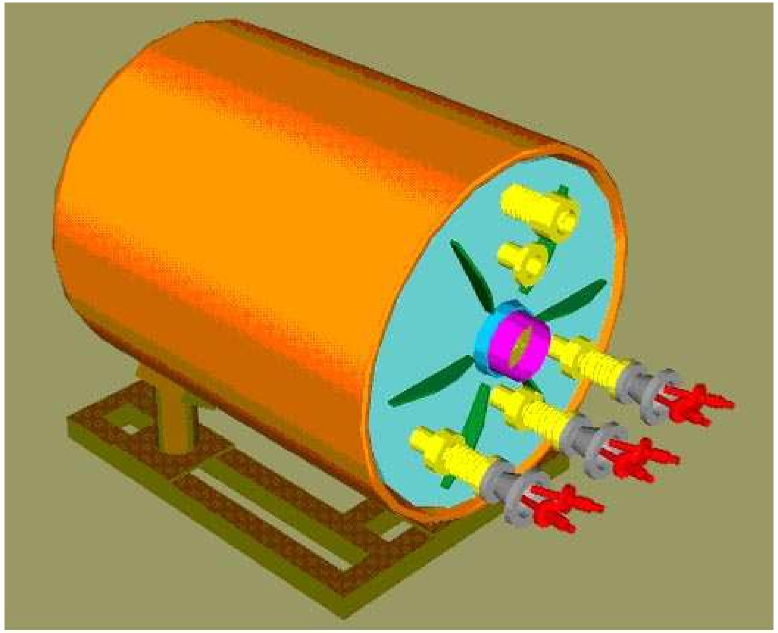
Koji Yoshimura[4]

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



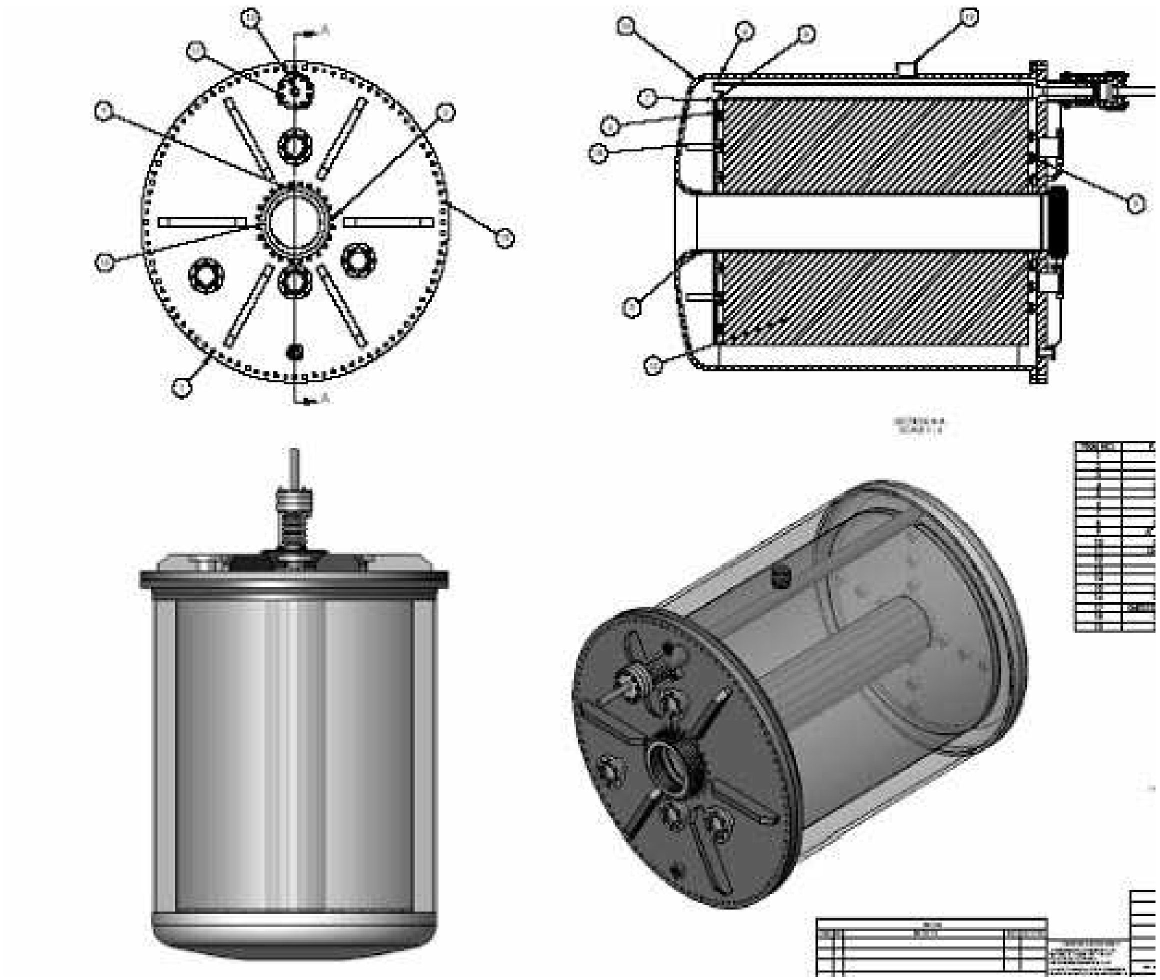
Location of proposed target studies

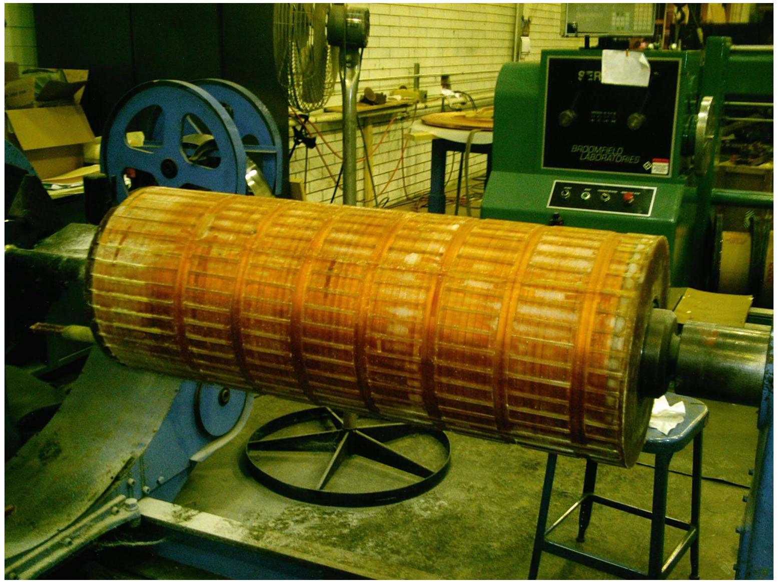


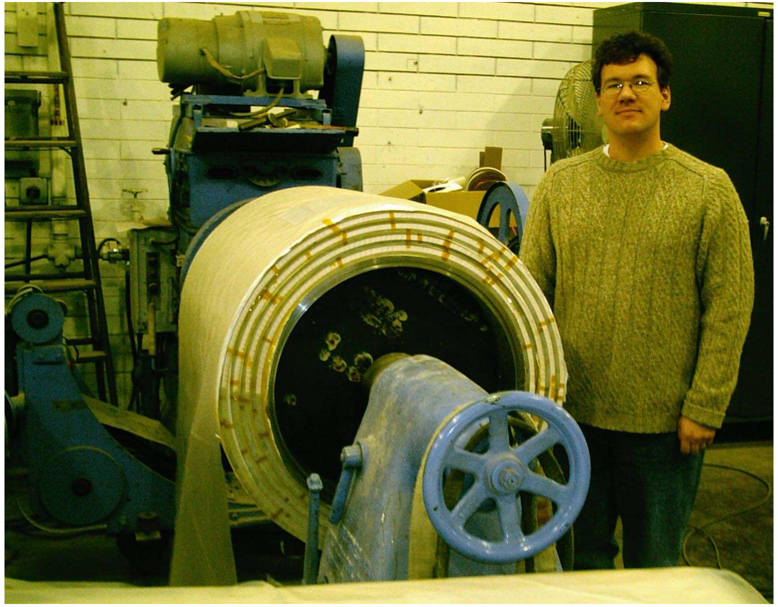


Approved on 5 April 2005 as nTOF11; to run in 2007.

Coil/Cryostat Fabrication at CVIP & Everson-Tesla

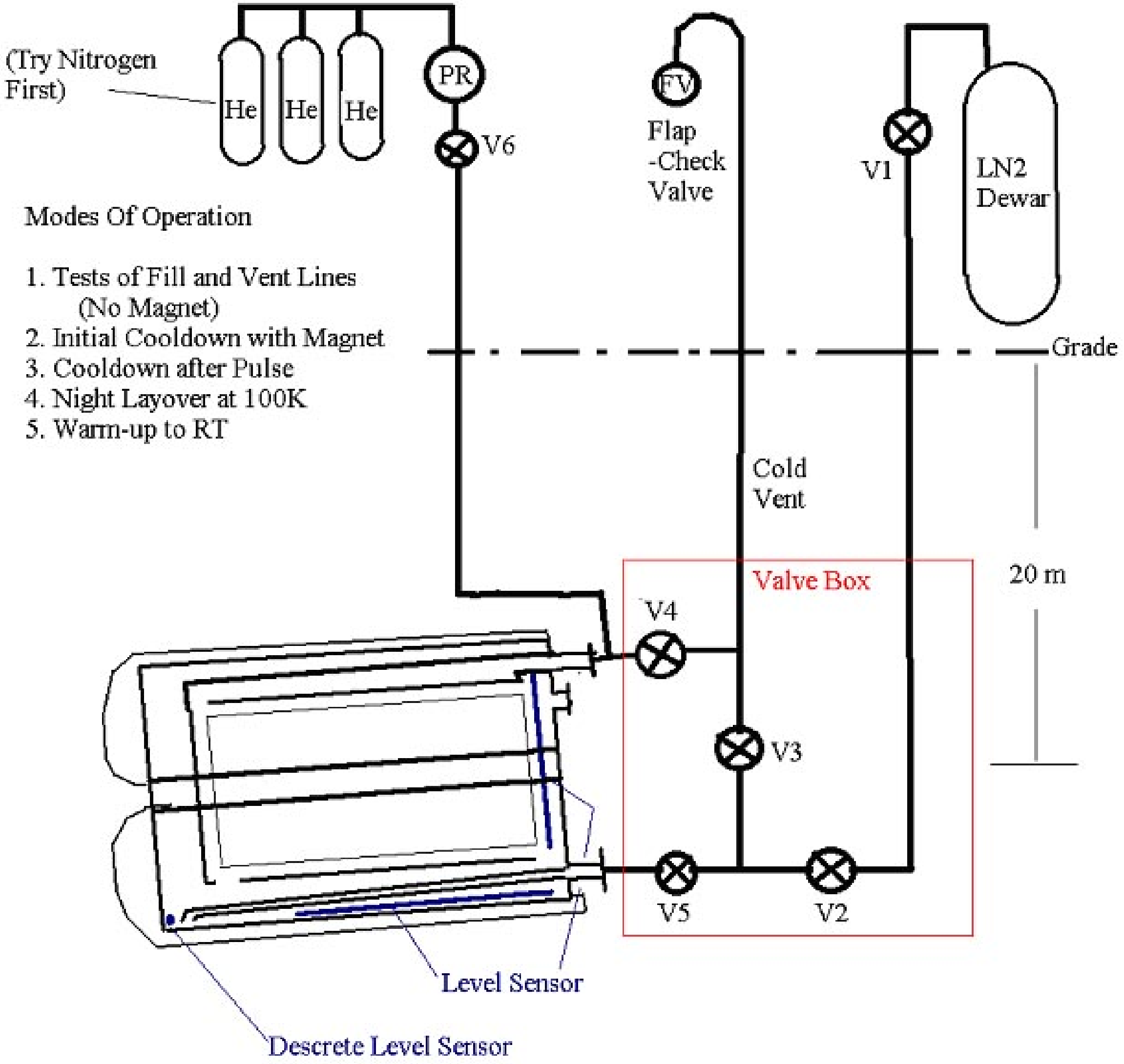






The LN_2 Cryogenic System

- RAL responsibility (Y. Ivanyushenkov), in consultation with CERN (F. Haug).
- Operate magnet at 80K.
- Vent cold LN_2/gas directly to outside.
- Purge magnet of LN_2 before each beam pulse to minimize air activation.



Modes Of Operation

1. Tests of Fill and Vent Lines (No Magnet)
2. Initial Cooldown with Magnet
3. Cooldown after Pulse
4. Night Layover at 100K
5. Warm-up to RT

5-MW Power Supply Options

Purchase new supply based on Alice/LHCb design.

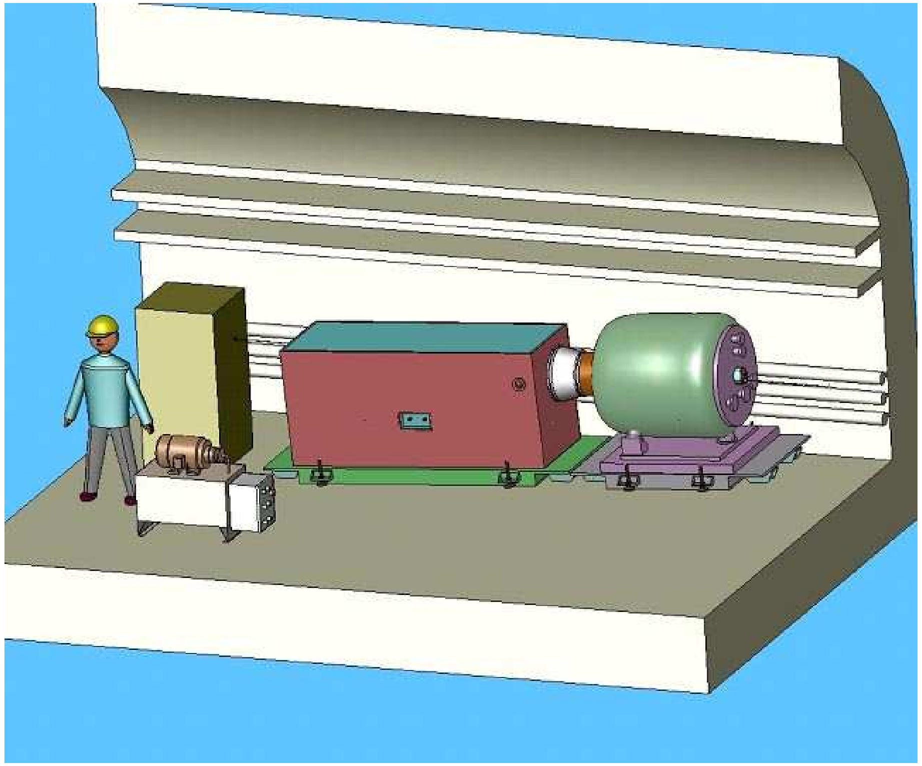
Up to 6.5 MW: 900 V @ 7200 A.

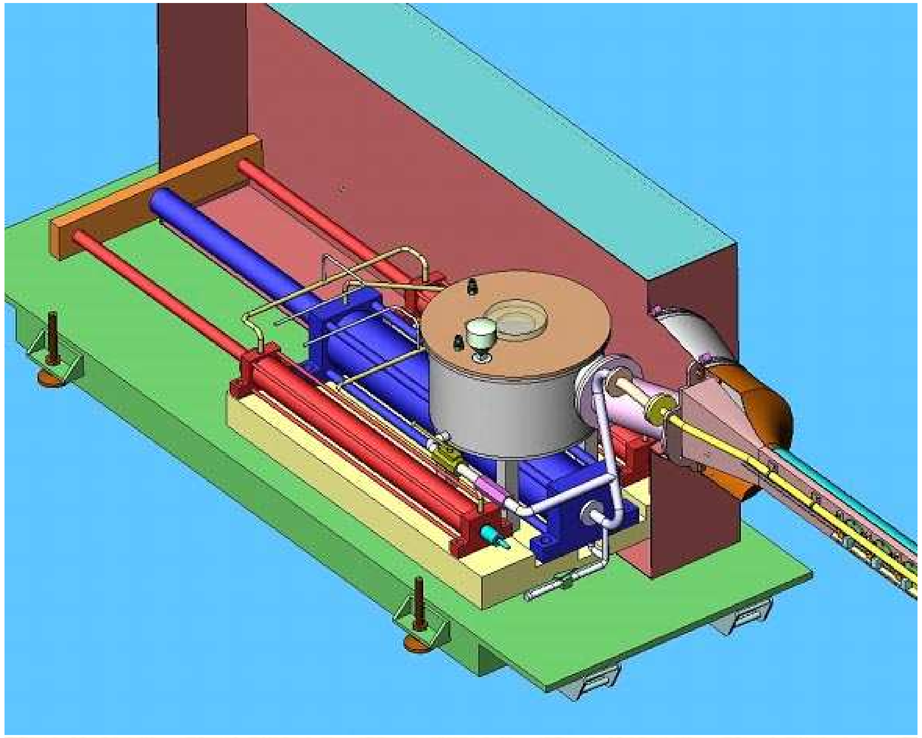
Rebuild an 8-MW supply "discovered" in the CERN West Hall, Nov. '04.

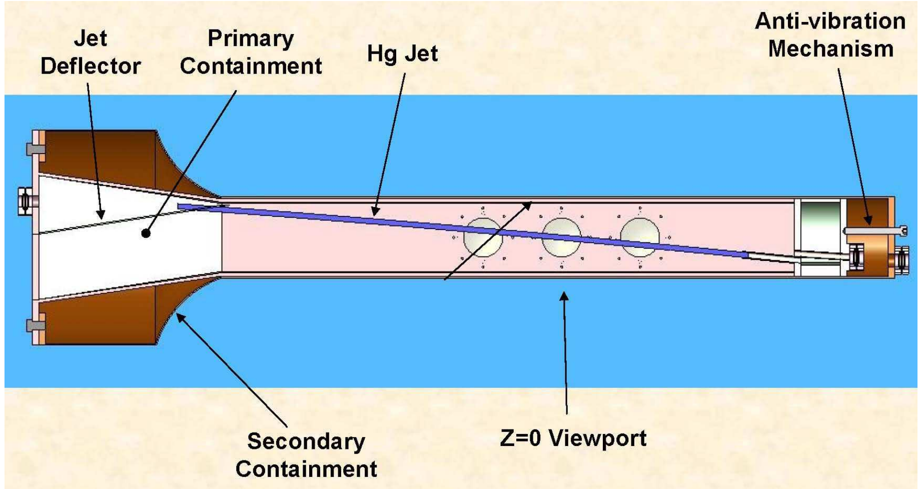
Mercury Jet System

(Van Graves/Phil Spampinato, ORNL)

"Syringe" pump system delivers 1.6 l/s of mercury in a 20-m/s jet for 10-20 s.







Optical Diagnostics

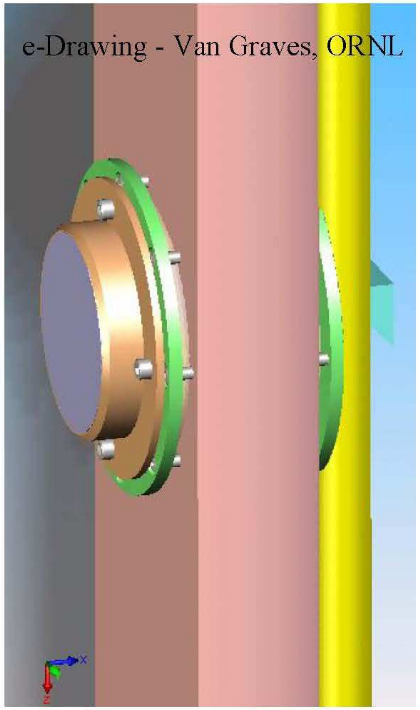
(Thomas Tsang, BNL)

Variant of E-951 optics.

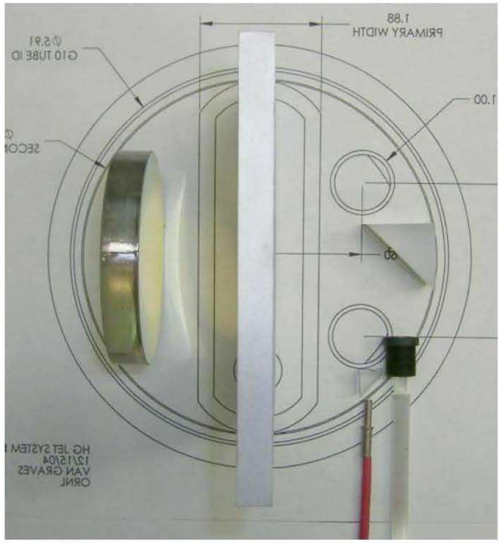
Fiber bundle delivers laser light to 45° mirror.

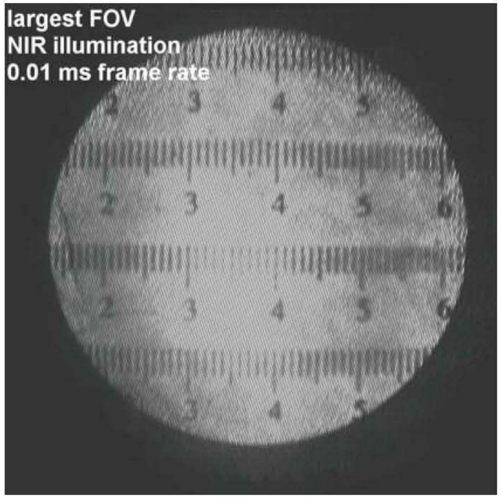
Light is retroreflected by spherical mirror.

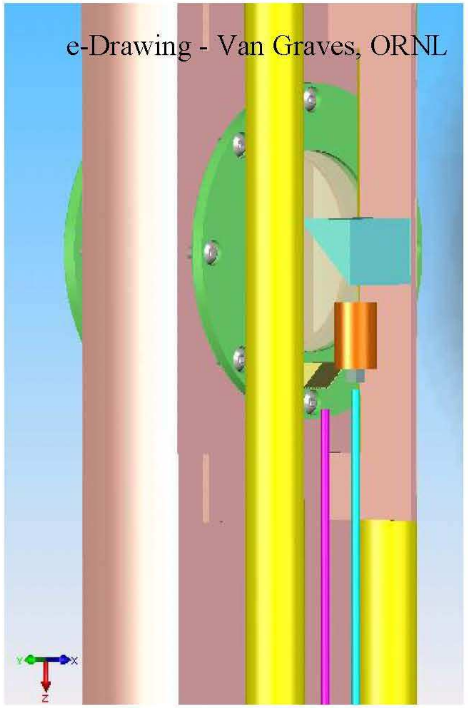
Fiber bundle carries shadow image to remote camera.



One set of optics per viewport







Conceptual design completed

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.