2nd Oxford-Princeton Workshop on High-PowerTargets

Held at Princeton U.

Nov 6-7, 2008

O-P Workshop Web Page:

http://www.hep.princeton.edu/~mcdonald/mumu/target/index.html#2nd_OP_workshop

K.T. McDonald

Princeton U.

Euroν-IDS-NF Target Meeting

CERN, Dec 15-17, 2008

2nd Oxford-Princeton Workshop Agenda

Thursday AM

1. McDonald: Introduction
2. Graves: Hg Containment Concepts†
3. Ding: Hg Jet Optimization
4. Park. MERIT Results
5. Kadi: Eurisol Liquid Target Studies†(Dracos)

Thursday PM

6. Rennich: SNS 3-MW Rotating Target
7. Fitton: T2K Target†(Densham)
8. Rooney: T2K Beam Window †(Densham)
9. Davenne:. Pelletized Target for ISIS
10. Hylen: DUSEL Target Options†(Simos)
11. Bennett: Solid Target Studies†
12. Bennett: Absorption in Solid Targets†
13. Skoro: Visar Studies for Solid Targets †(Bennett)
14. Loveridge: Helmholz Coils for Wheel Target †(Bennett)
15. Caretta: Tungsten Powder Jet Target†
16. Brooks: Model for Production by Low-Density Targets †(Bennett)
17. Brooks: Pion Production Update†(Kirk)

Friday AM

18. Bricault: e- Targets
19. Samulyak: Hg Jet Simulations
20. Davenne: Hg Jet/Pool Simulations†
21. Skoro: Simulations of Thermal Shock in Solids
22. Simos: Material Irradiation Studies
23. Efthymiopoulos: CERN Target Test Facilities†
24. Hurh: Fermilab AP-0 Target Test Facility

Friday PM

25. Long: Discussion (IDS)

† Related presentation at this meeting

Targets for 2-4 MW Proton Beams

- 10-50 GeV beam energy appropriate for Superbeams, Neutrino Factories and Muon Colliders.
  □ $0.8\text{-}2.5 \times 10^{15}$ *pps*; $0.8\text{-}2.5 \times 10^{22}$ protons per year of 10^{7} s.

- Rep rate 15-50 Hz at Neutrino Factory/Muon Collider, as low as ≈ 2 Hz for Superbeam.
  ⇒ Protons per pulse from 1.6×10^{13} to 1.25×10^{15}.
  ⇒ Energy per pulse from 80 kJ to 2 MJ.

- Small beam size preferred:
  ≈ 0.1 cm^2 for Neutrino Factory/Muon Collider, ≈ 0.2 cm^2 for Superbeam.

- Pulse width ≈ 1 μs OK for Superbeam, but ≈ 1 ns desired for Neutrino Factory/Muon Collider.

⇒ Severe materials issues for target AND beam dump.

  - Radiation Damage.
  - Melting.
  - Cracking (due to single-pulse "thermal shock").

- MW energy dissipation requires liquid coolant somewhere in system!
  ⇒ No such thing as "solid target only option" at this power level.

Radiation Damage

The lifetime dose against radiation damage (embrittlement, cracking, ...) by protons for most solids is about $10^{22}/cm^2$.

⇒ Target lifetime of about 5-14 days at a 4-MW Neutrino Factory
(and 9-28 days at a 2-MW Superbeam).

⇒ Mitigate by frequent target changes, moving target, liquid target, ...
[Mitigated in some materials by annealing/operation at elevated temperature.]

Remember the Beam Dump

Target of 2 interaction lengths ⇒ 1/7 of beam is passed on to the beam dump.
⇒ Energy deposited in dump by primary protons is same as in target.

Long distance from target to dump at a Superbeam,
⇒ Beam is much less focused at the dump than at the target,
⇒ Radiation damage to the dump not a critical issue (Superbeam).

Short distance from target to dump at a Neutrino Factory/Muon Collider,
⇒ Beam still tightly focused at the dump,
⇒ Frequent changes of the beam dump, or a moving dump, or a liquid dump.

A liquid beam dump is the most plausible option for a Neutrino Factory, independent of the choice of target. (This is so even for a 1-MW Neutrino Factory.)

The proton beam should be tilted with respect to the axis of the capture system at a Neutrino Factory, so that the beam dump does not absorb the captured π's and μ's.

Target Options

- Static Solid Targets
  - Graphite (or carbon composite) cooled by water/gas/radiation [CNGS, NuMI, T2K]
  - Tungsten or Tantalum (discs/rods/beads) cooled by water/gas [PSI, LANL]

- Moving Solid Targets
  - Rotating wheels/cylinders cooled (or heated!) off to side [SLD, FNAL $\overline{p}$, Bennett]
  - Continuous or discrete belts/chains [King]
  - Flowing powder [Densham]

- Flowing liquid in a vessel with beam windows [SNS, ESS]

- Free liquid jet [Neutrino Factory Study 2]

Static Solid Targets

Pros:

- Tried and true – for low power beams.
- Will likely survive "thermal shock" of long beam pulses at 2 MW (Superbeam).

Cons:

- Radiation damage will lead to reduced particle production/mechanical failure on the scale of a few weeks at 2 MW.
- If liquid cooled, leakage of radioactive coolant anywhere in the system is potentially more troublesome than breakup of a radioactive solid.

⇒ Must consider a "moving target" later if not sooner.

R&D: Test targets to failure in high-power beams to determine actual operational limits.

Moving Solid Targets

Pros:

- Can avoid radiation damage limit of static solid targets.
- Will likely survive "thermal shock" of long beam pulses at 2 MW (Superbeam).

Cons:

- Target geometry not very compatible with neutrino "horns" except when target is upstream of horn (high energy ν's: CNGS, NuMI).
- If liquid cooled, leakage of radioactive coolant anywhere in the system is potentially more troublesome than breakup of a radioactive solid.

R&D:

- Engineering to clarify compatibility with a target station for Superbeams.
- Lab studies of erosion of nozzle by powders.

Personal view: this option is incompatible with Neutrino Factories.

Flowing Liquids in Vessels

Pros:

- The liquid flows through well-defined pipes.
- Radiation damage to the liquid is not an issue.

Cons:

- The vessel must include static solid beam windows, whose lifetime will be very short in the small proton spot sizes needed at Superbeams and Neutrino Factories.
- Cavitation in the liquid next to the beam windows is extremely destructive.
- Leakage of radioactive liquid anywhere in the system is potentially more troublesome than breakup of a radioactive solid.

R&D: This option is not very plausible for Superbeams and Neutrino Factories, and no R&D is advocated.

Free Liquid Jet Targets

Pros:

- No static solid window in the intense proton beam.
- Radiation damage to the liquid is not an issue.

Cons:

- Never used before as a production target.
- Leakage of radioactive liquid anywhere in the system is potentially more troublesome than breakup of a radioactive solid.

R&D: Proof of principle of a free liquid jet target has been established by the CERN MERIT Experiment. R&D would be useful to improve the jet quality, and to advance our understanding of systems design issues.

Personal view: This option deserves its status as the baseline for Neutrino Factories and Muon Colliders. For Superbeams that will be limited to less than 2 MW, static solid targets continue to be appealing.

Target and Capture Topologies: Solenoid

Desire ≈ 10^{14} μ/s from ≈ 10^{15} p/s (≈ 4 MW proton beam).

Highest rate μ^+ beam to date: PSI μE4 with ≈ 10^{9} μ/s from ≈ 10^{16} p/s at 600 MeV.

⇒ Some R&D needed!

R. Palmer (BNL)
Neutrino Factory Study 2

Palmer (1994) proposed a solenoidal capture system.

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

Collects both signs of π's and μ's,

⇒ Shorter data runs (with magnetic detector).

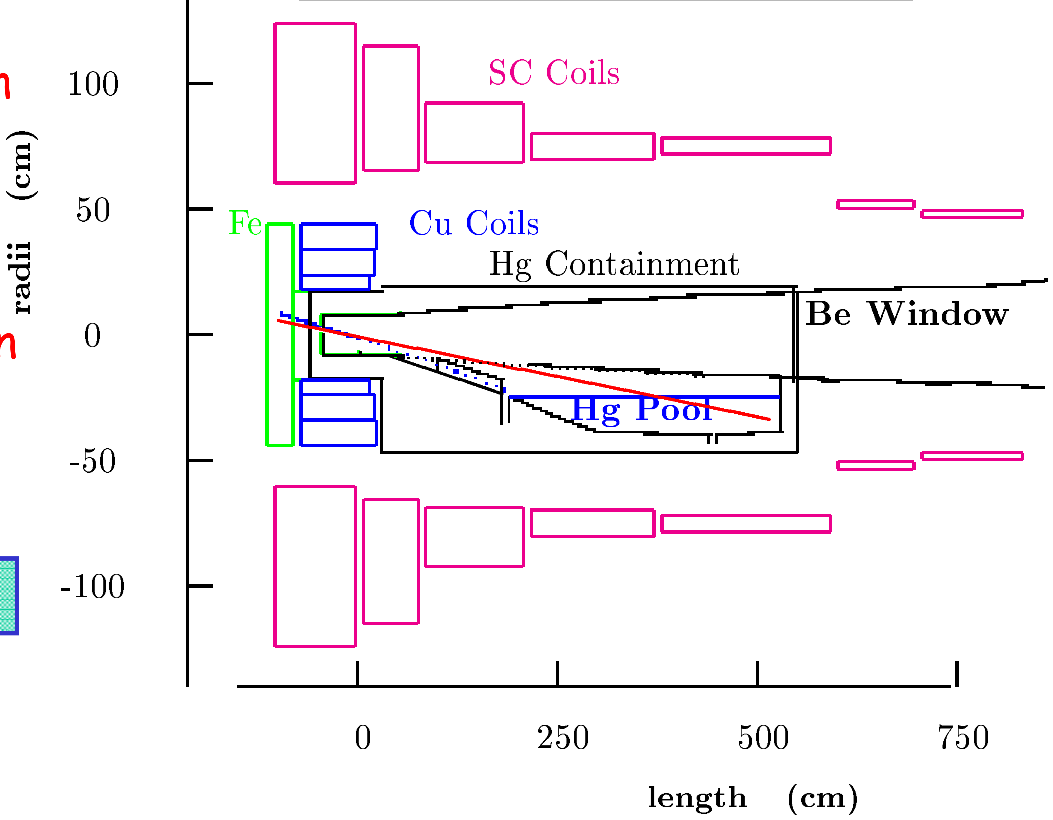
Solenoid coils can be some distance from proton beam.

⇒ ≥ 4-year life against radiation damage at 4 MW.

Liquid mercury jet target replaced every pulse.

Proton beam readily tilted with respect to magnetic axis.

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



Solenoid Capture System for a Superbeam

- Pions produced on axis inside the (uniform) solenoid have zero canonical angular momentum, $L_z = r(P_\varphi + eA_\varphi / c) = 0, \;\Rightarrow\; P_\varphi = 0$ on exiting the solenoid.
- If the pion has made exactly 1/2 turn on its helix when it reaches the end of the solenoid, then its initial P_r has been rotated into a pure P_φ, $\Rightarrow P_r = 0$ on exiting the solenoid.

$\Rightarrow$ Point-to-parallel focusing for

$$P_\pi = eBd\,/\,(2n \underset{\bar{\nu}}{+} 1)\;\pi c.$$

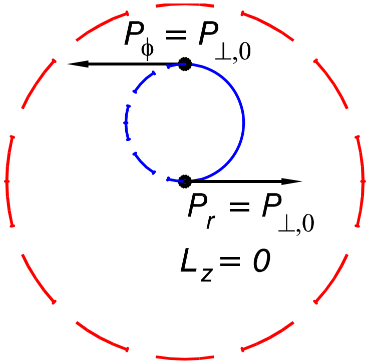
$\Rightarrow$Narrowband (less background) neutrino beams of energies

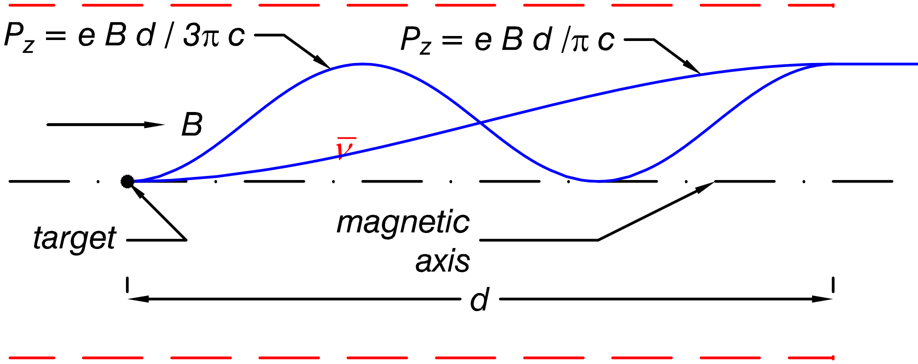
$$E_\nu \approx \frac{P_\pi}{2} = \frac{eBd}{(2n+1)2\pi c}.$$

$\Rightarrow$ Can study several neutrino oscillation peaks at once,

$$\frac{1.27 M_{23}^2[\mathrm{eV}^2]\;L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]} \underset{\bar{\nu}}{=} \frac{(2n+1)\pi}{2}.$$

(Marciano, hep-ph/0108181)





(KTM, physics/0312022)

Study both ν and $\bar{\nu}$ at the same time.

$\Rightarrow$ Detector must tell ν from $\bar{\nu}$.

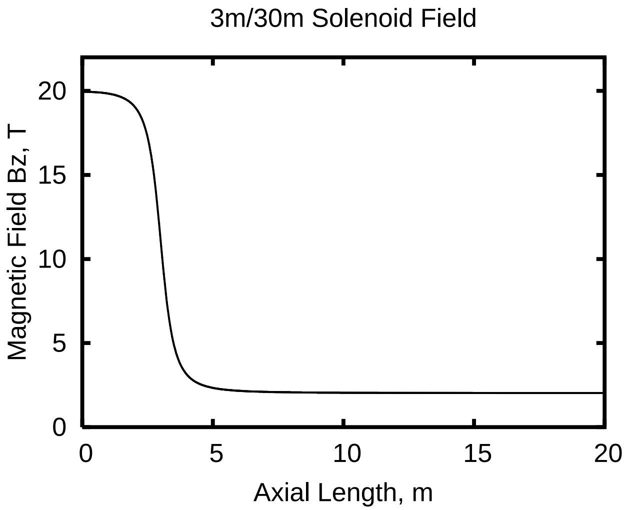
$\Rightarrow$ Liquid argon TPC that can identify slow protons:

$$\nu\, n \rightarrow p\, e^- X \quad \text{vs.} \quad \bar{\nu}\, p \rightarrow n\, e^+ X$$

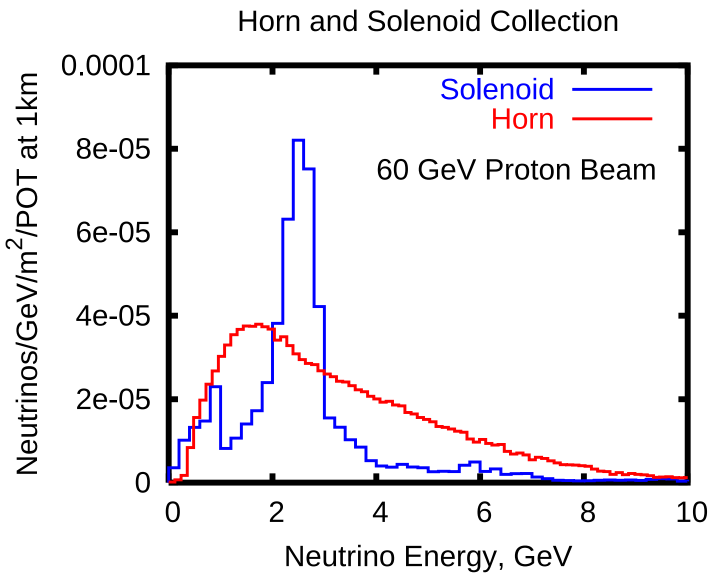
Simulation of Solenoid Horn

(H. Kirk and R. Palmer, NuFACT06)

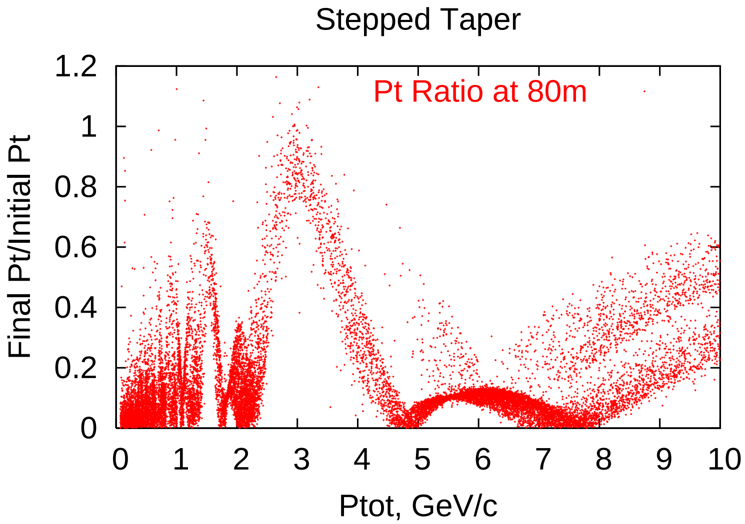
B vs. z for 3 + 30 m solenoid:



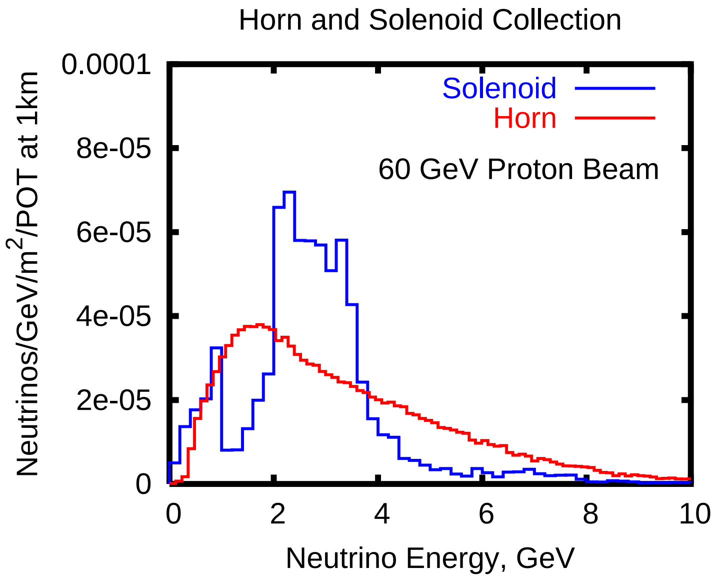
3-m solenoid gives
2 narrow peaks
in ν spectrum:



$\Delta P_{\perp}$ minimized at selected P_{tot}:

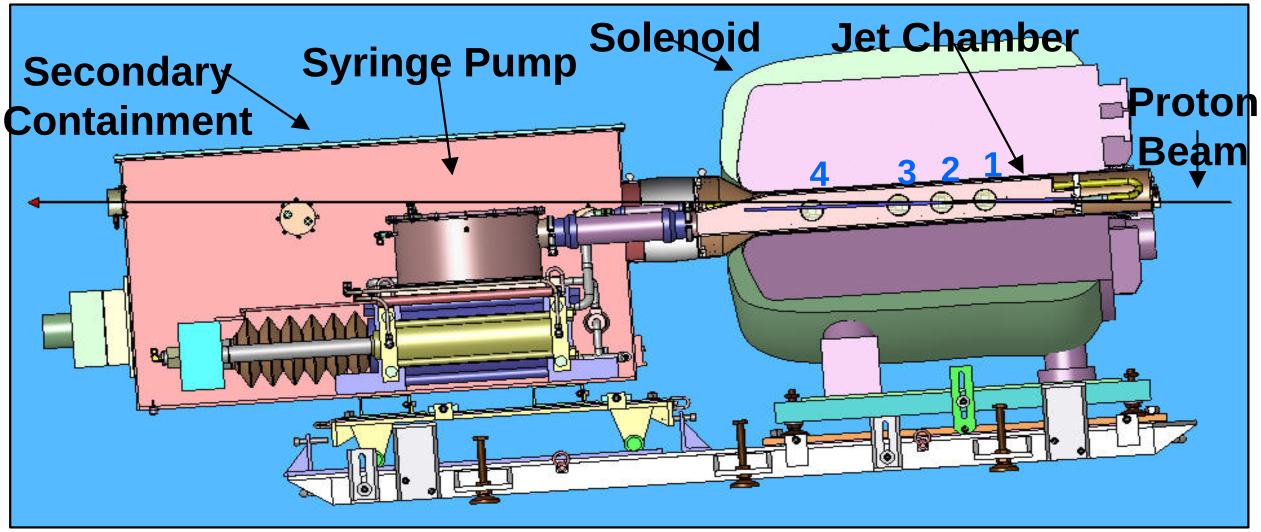


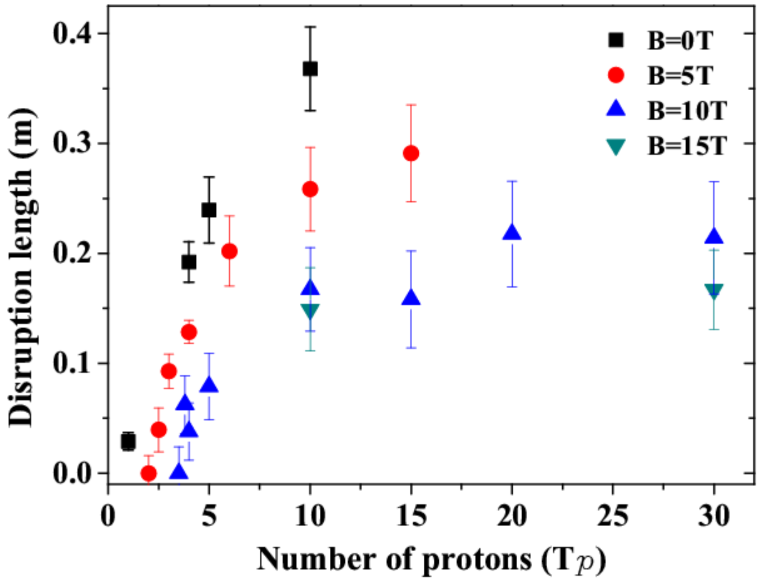
3+30-m solenoid
broadens the
higher energy
peak:

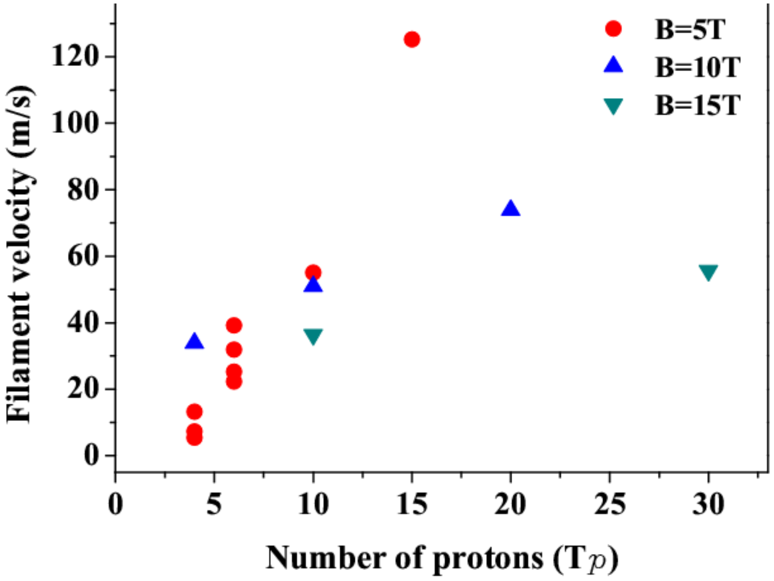


Results very encouraging, but comparison with toroid horn needs confirmation.

CERN MERIT Experiment (Park, BNL)





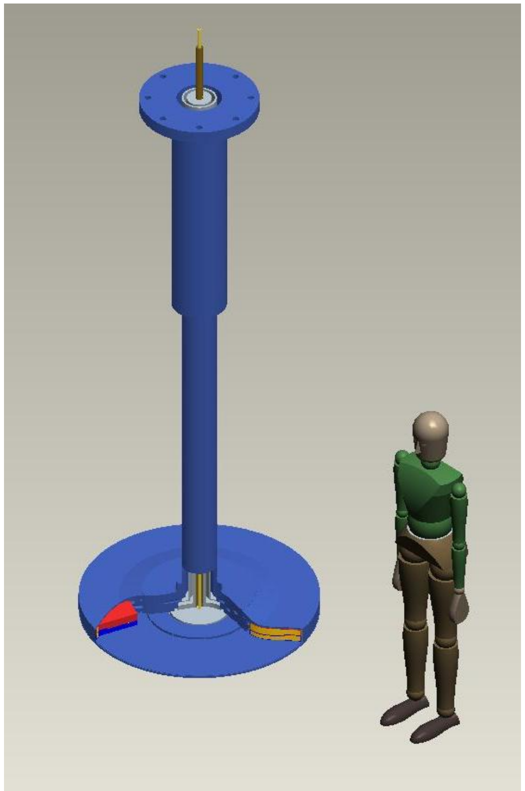


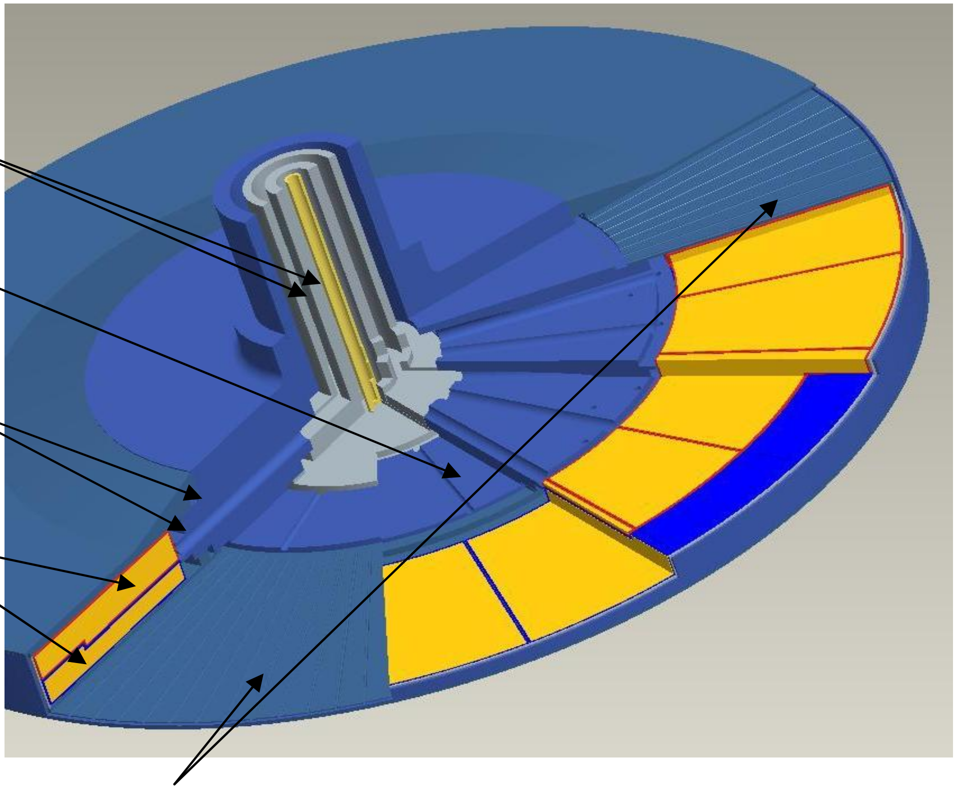
Proof-of-principle demonstration of a mercury jet target in a strong magnetic field, with proton bunches of intensity equivalent to a 4 MW beam.

Jet disruption suppressed (but not eliminated by high magnetic field.

Particle production remains nominal for several hundred μs after first proton bunch of a train.

SNS 3-MW Target Option (Rennich, ORNL)





Concentric Shaft Channels

Gun Drilled Hub

Circumferential Manifolds

Tantalum Clad Tungsten Blocks

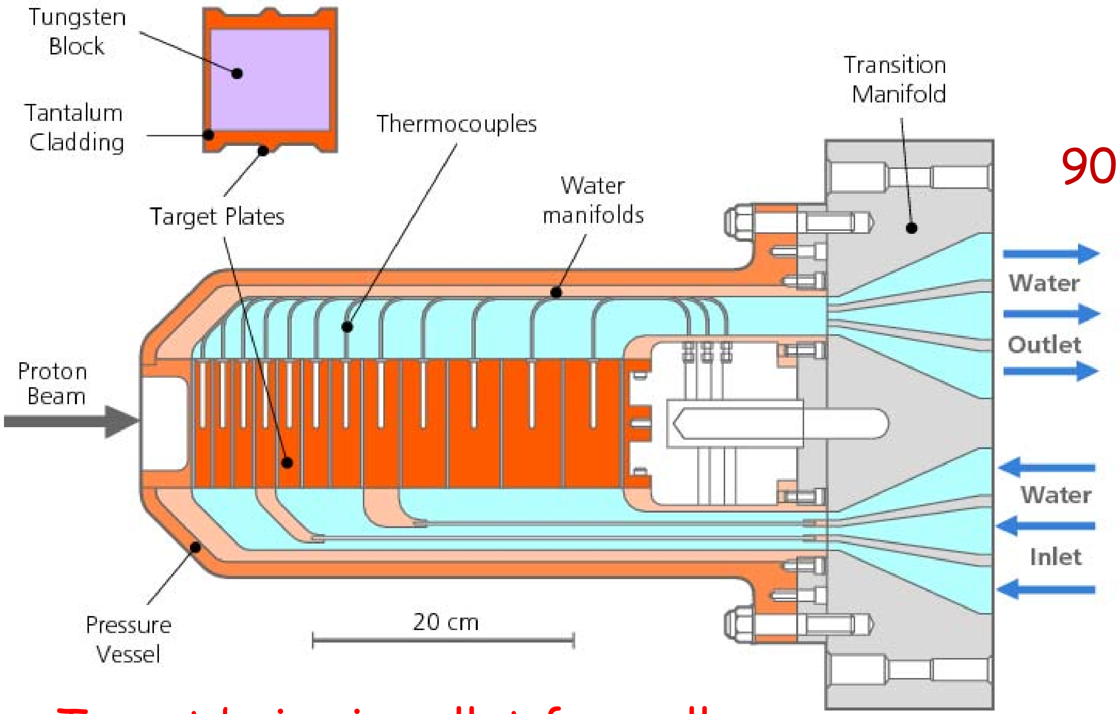
Shroud Cooling Channels

30 rpm with 20-Hz pulse frequency and 1-ms pulse length, 7-cm diameter.

Water cooled by 10-gpm total flow.

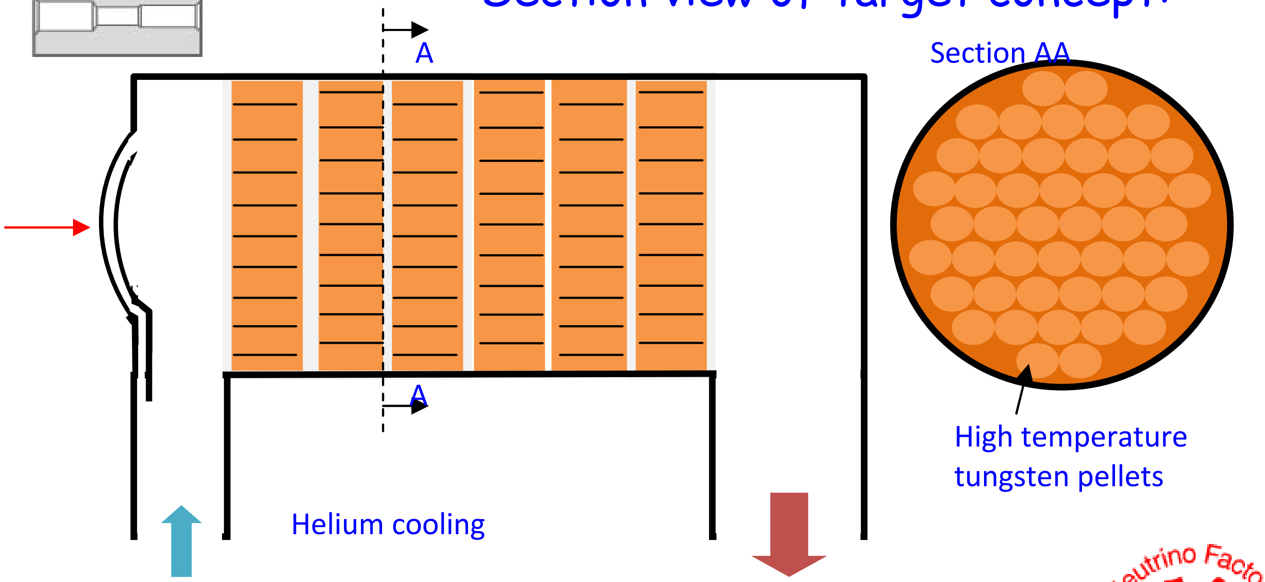
Design life: 3 years.

Pelletized Target Option for ISIS (Davenne, RAL)



800MeV, 160kW, 50Hz
90kW heat removed in water

Section view of target concept:



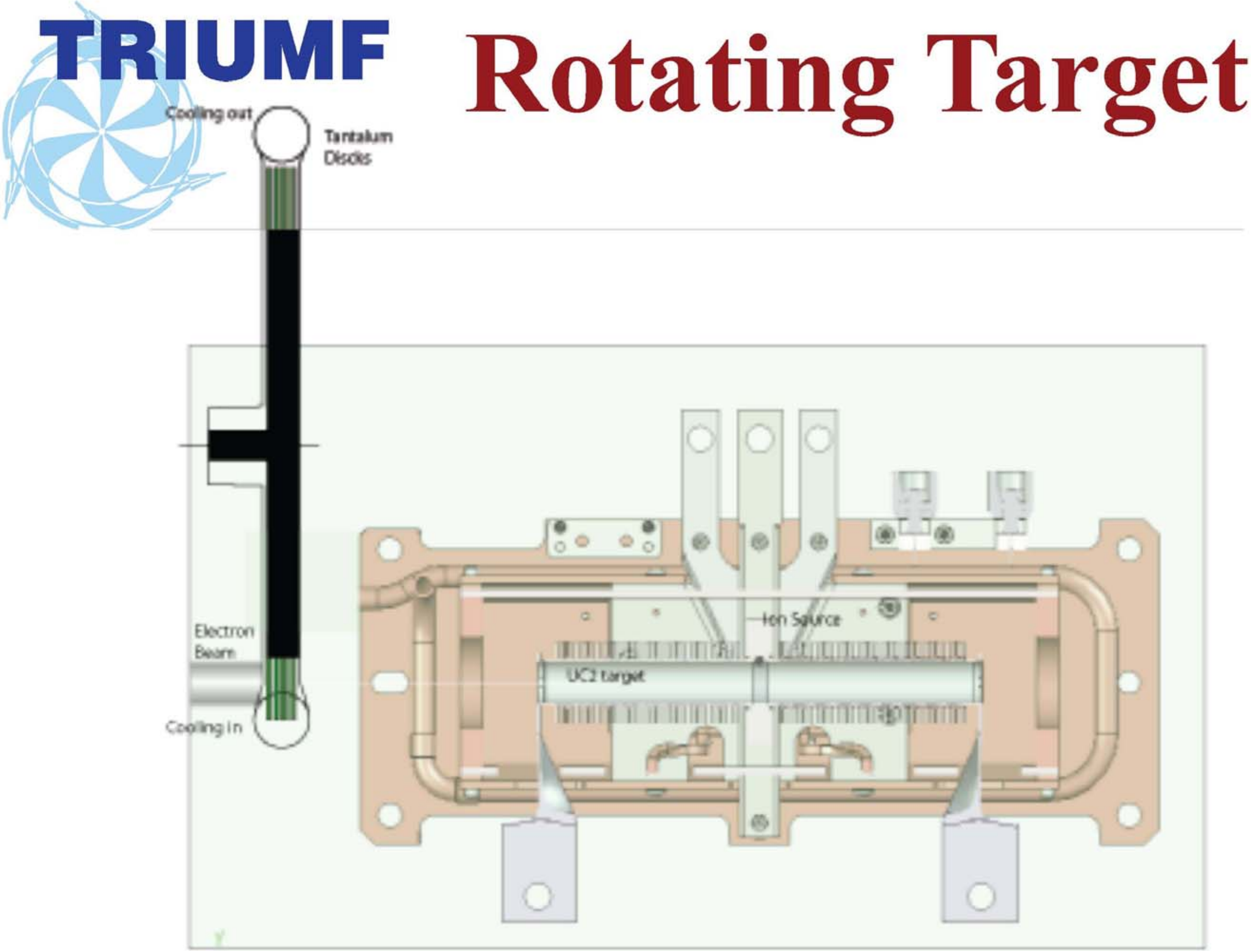
Target being in pellet form allows high temp operation without high stresses

No cooling water to moderate neutron flux

Scope for more than 160kW?

Ref: Sievers (2003)

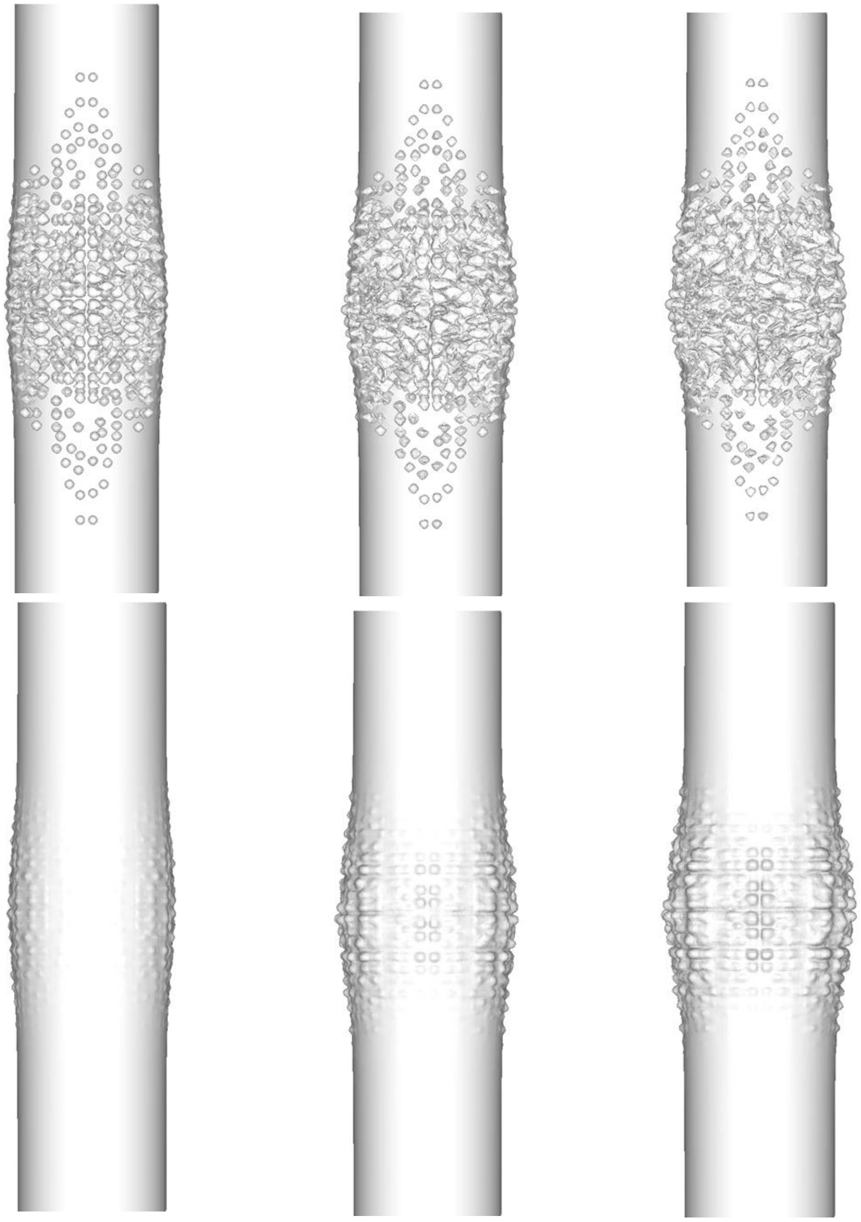
U Target for 0.5-MW e Beam (Bricault, TRIUMF)



Hg Cavitation Simulations (Samulyak, BNL)

"Transparent mercury":

Exterior view:

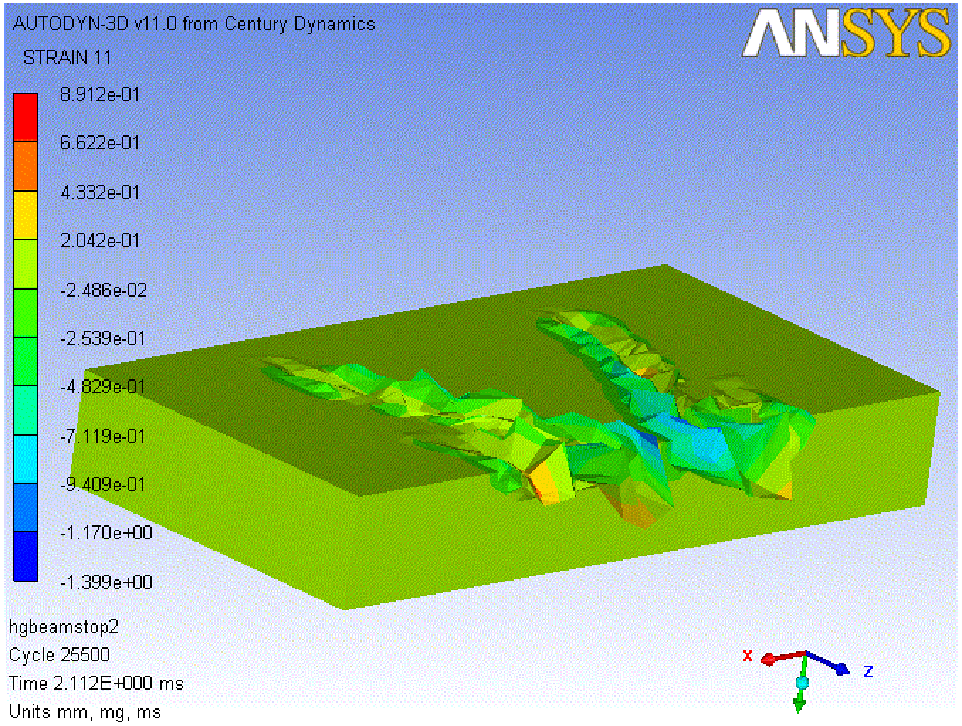


15 μs 30 μs 45 μs

Damage by Mercury Droplets (Davenne, RAL)

A 3-mm-diameter mercury droplet impacting a stainless steel plate at 75 m/s is predicted to cause significant damage.

Ti-6Al-4V is predicted to be more resistant to damage due to higher ultimate strength and shear strength.



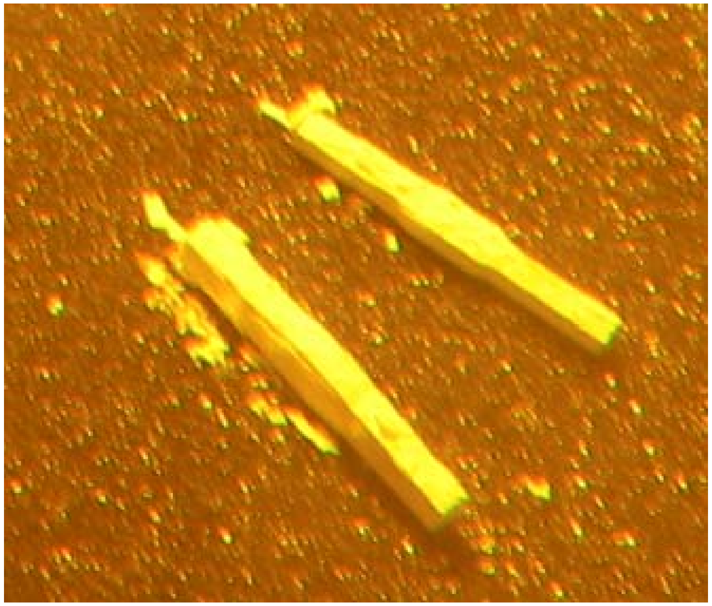
Model: A drop of radius r and density ρ vith velocity v causes pressure
$P = F / A \sim (\Delta p / \Delta t) / \pi r^2 \sim [2 m v / (r/v)] / \pi r^2 \sim 8 \pi r^3 \rho v^2 / 3 \pi r^3$,
$\Rightarrow P \sim 8 \rho v^2 / 3$ independent of the radius!

Example: $\rho_{\text{mercury}} = 13.6e3$, $v = 100$ m/s $\Rightarrow P \sim 325$ MPa ~ tensile strength of steel.

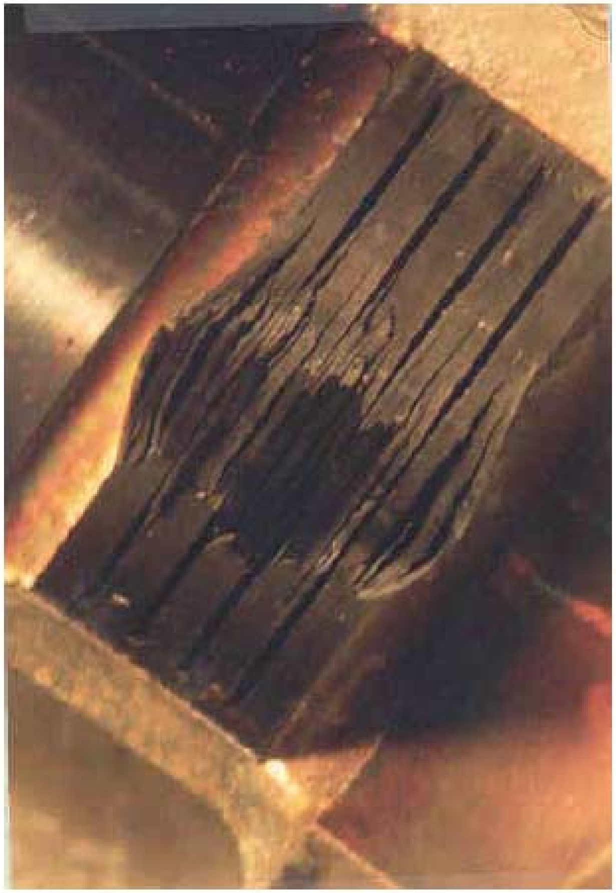
The velocity of an atom of mercury vapor at room temperature is 200 m/s.

Material Irradiation Studies (Simos, BNL)

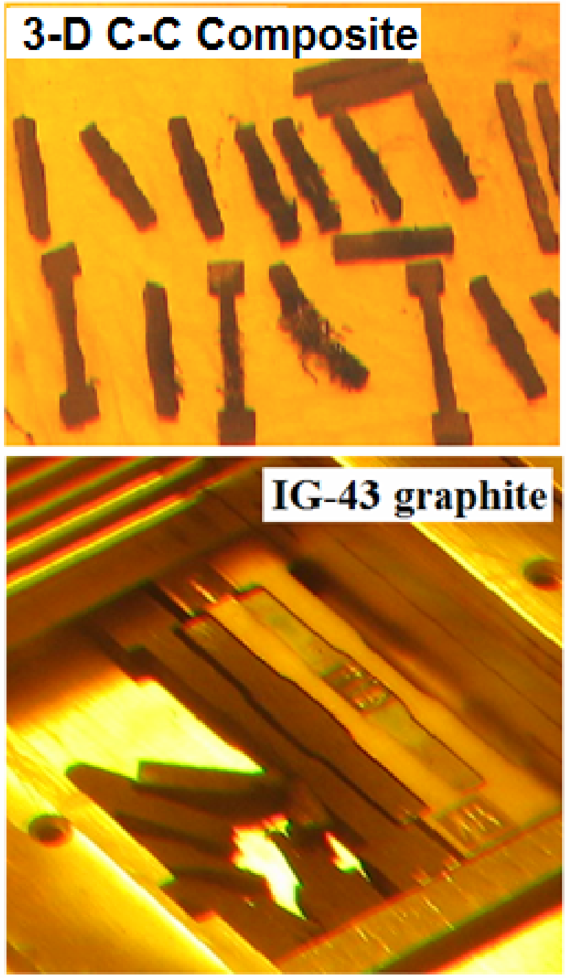
BNL BLP Studies:
Tantalum (0.25 dpa):



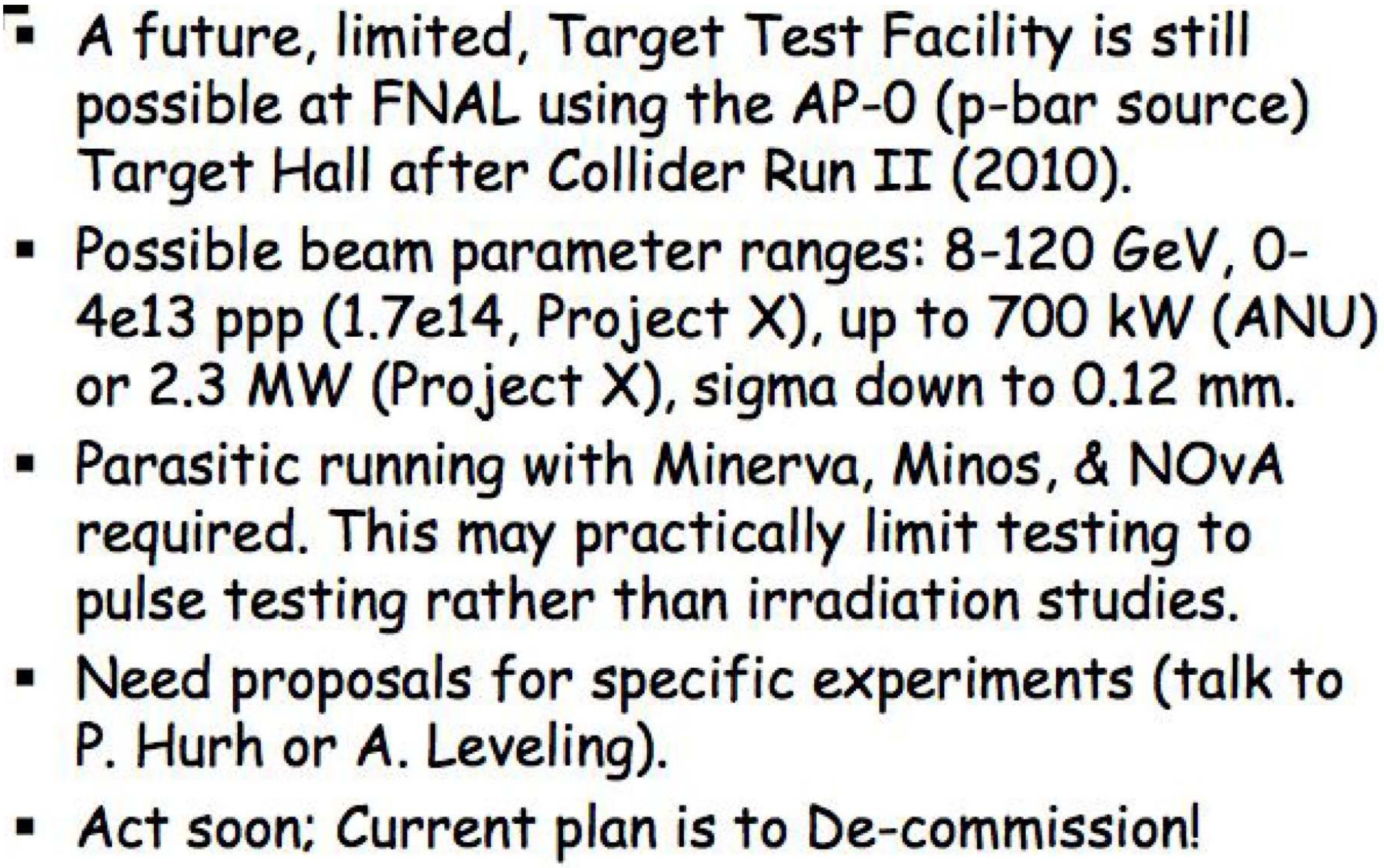
Water-cooled/Edge-cooled
TRIUMF target (10^{22} *p*/cm2):



BNL BLP Studies:
Carbon (0.25 dpa):



AP-0 Target Test Facility (Hurh, FNAL)



- A future, limited, Target Test Facility is still possible at FNAL using the AP-0 (p-bar source) Target Hall after Collider Run II (2010).
- Possible beam parameter ranges: 8-120 GeV, 0-4e13 ppp (1.7e14, Project X), up to 700 kW (ANU) or 2.3 MW (Project X), sigma down to 0.12 mm.
- Parasitic running with Minerva, Minos, & NOvA required. This may practically limit testing to pulse testing rather than irradiation studies.
- Need proposals for specific experiments (talk to P. Hurh or A. Leveling).
- Act soon; Current plan is to De-commission!

Next Oxford-Princeton Target Workshop

April 2009 in Oxford