Experimental Assessment of Radiation Damage in Targets Considered in Neutrino Superbeam and Neutrino Factory Initiatives

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Targets – How far can they go?

1 MW ?	4 MW ?
Answer is **YES** for several materials Irradiation damage is of primary concern Material irradiation studies pushing ever closer to anticipated atomic displacements while considering new alloys are needed	**Answer dependant on 2 key parameters:** 1 – rep rate 2 - beam size compliant with the physics sought A1: for rep-rate > 50 Hz + spot > 2mm RMS ➔ 4 MW possible (see note below) A2: for rep-rate < 50 Hz + spot < 2mm RMS ➔ Not feasible (ONLY moving targets) **NOTE:** While thermo-mechanical shock may be manageable, removing heat from target at 4 MW might prove to be the challenge. CAN only be validated with experiments

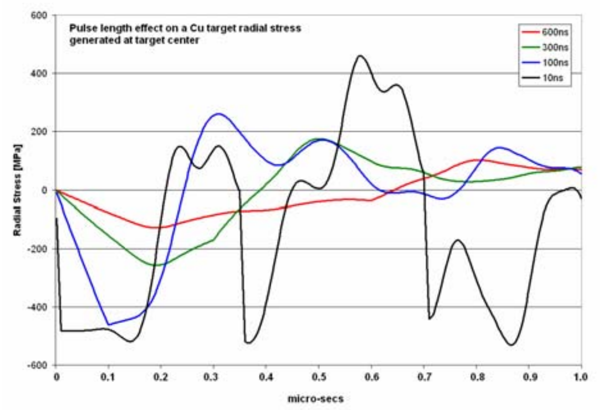
4 MW proton driver?

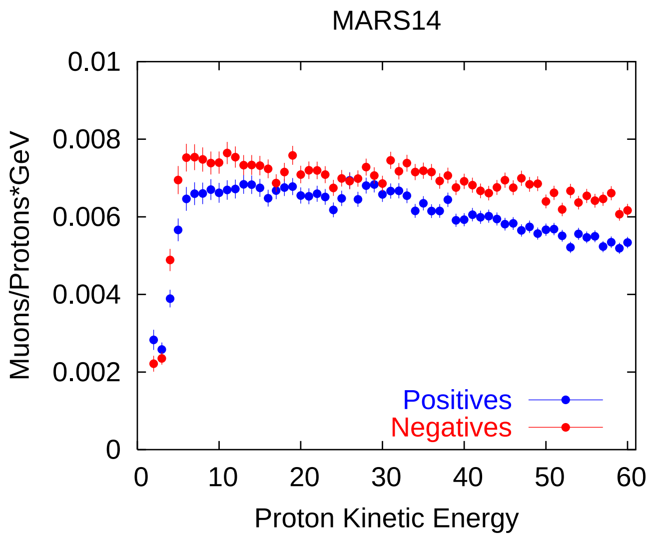
Protons per pulse required for 4 MW

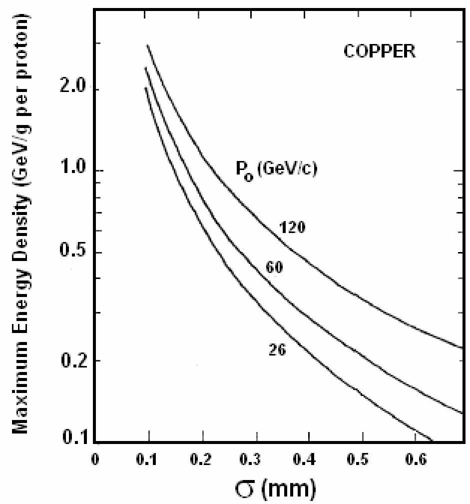
$$\overline{P}_{arc}(w) = E[eV] \times N \times e \times f_{rep}[Hz]$$

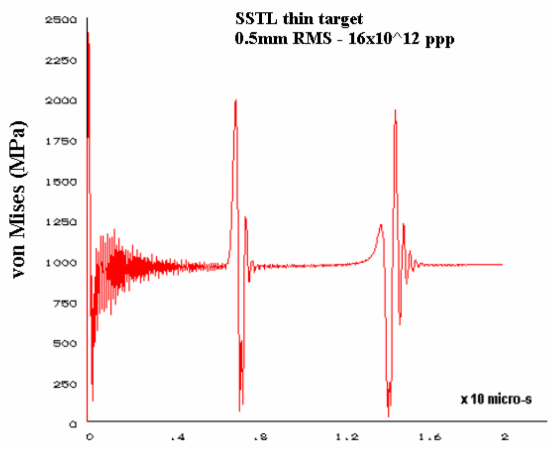
	10 Hz	25 Hz	50 Hz
10 GeV	250×10^{12}	100×10^{12}	50×10^{12}
20 GeV	125×10^{12}	50×10^{12}	25×10^{12}

Some schemes desired bunch lengths < 3 ns !!!

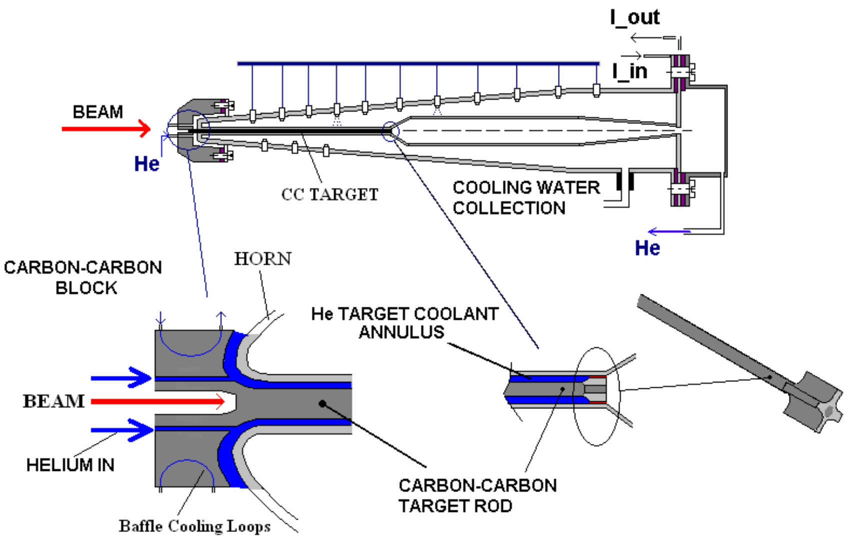


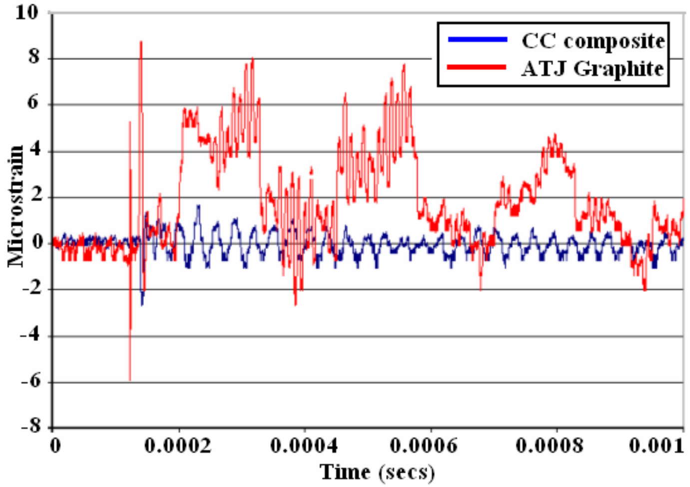


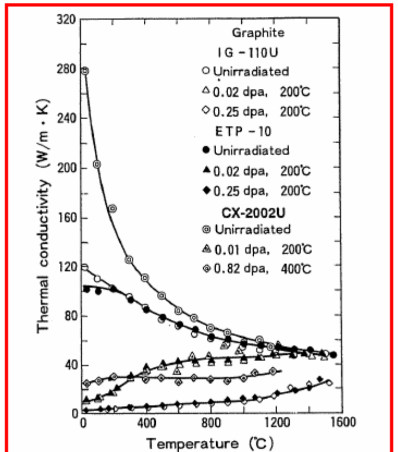




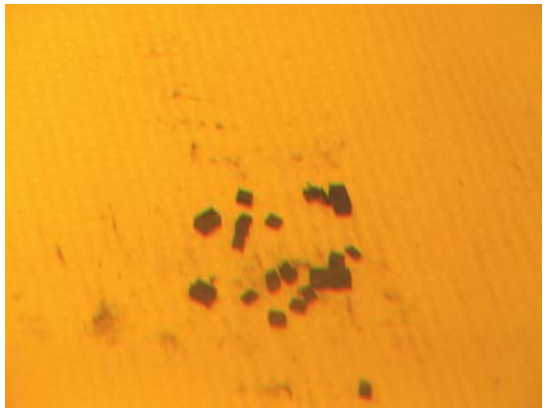
Target Concept – Neutrino Superbeam



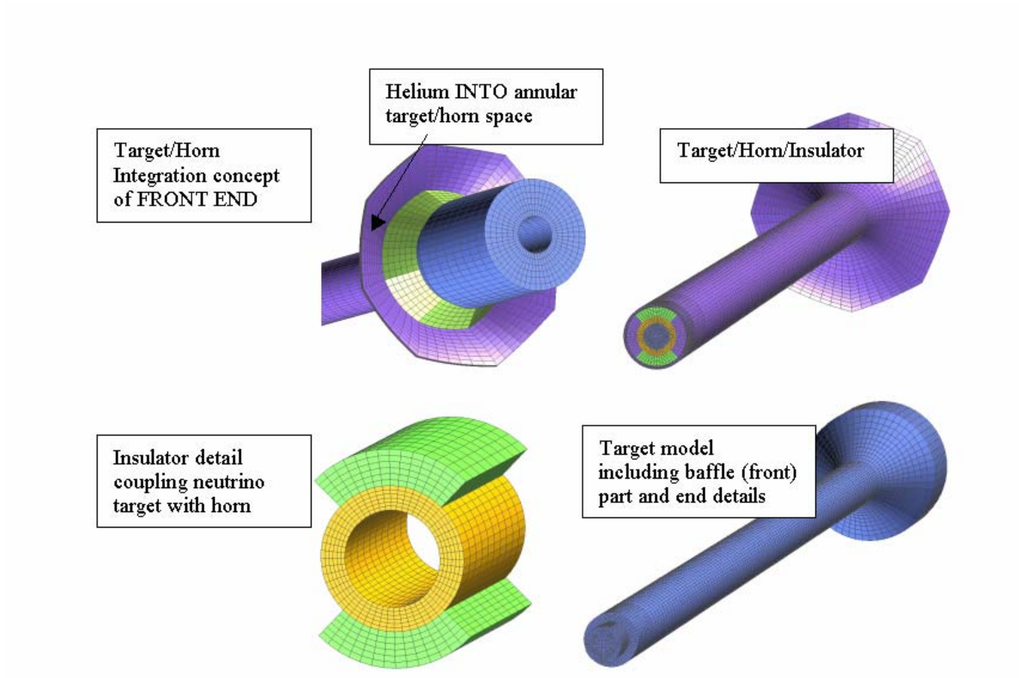


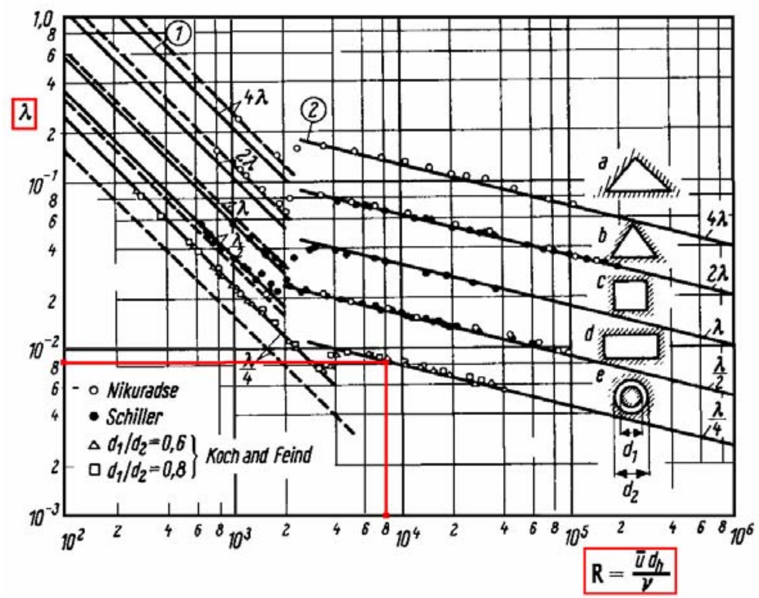


Thermal conductivity of neutron-irradiated graphites.



Challenges ➔ R&D





Liquid metal targets?

No rad damage, no shock concerns ➔ free of problems?

- **phase transitions during beam interaction**
- **vaporization**
- **effects on infrastructure**
- **delivery & quality of interaction zone**

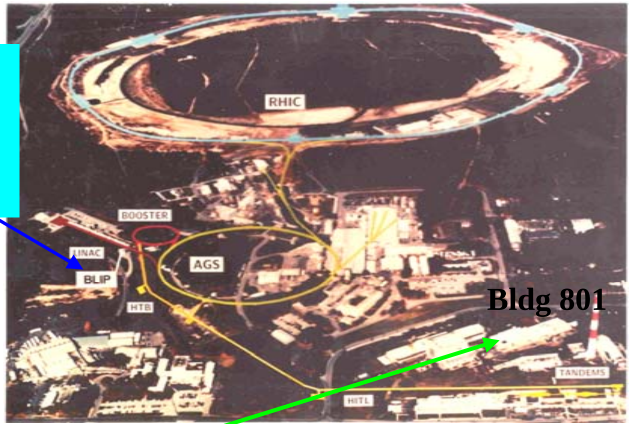
However, even with liquid targets we are not home free from solid targets !!!

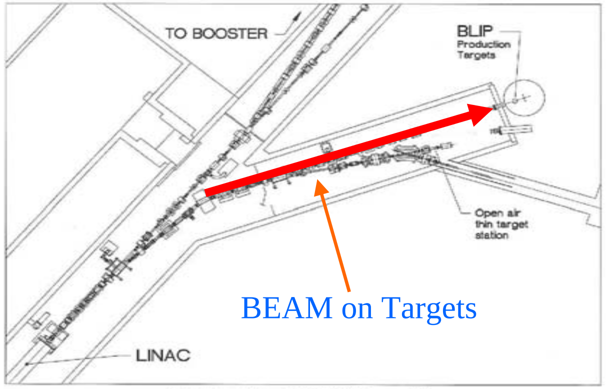
We have to deliver the same beam trough widows

If not a liquid jet but a contained liquid ➔ cavitation-induced erosion (pitting)

Experimental Process
Utilizing BNL Accelerator Complex

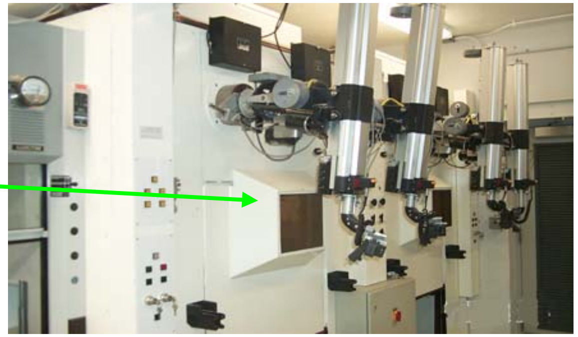
Irradiation at BNL Isotope Facility place 200 or 117 MeV protons



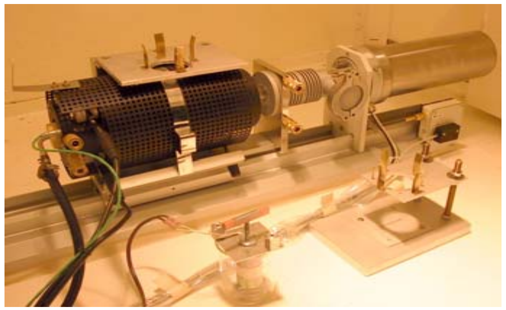


Schematic of BLIP Beam Line

Post irradiation analysis at BNL Hot Labs

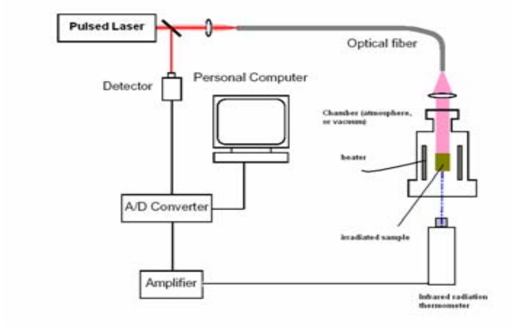


Thermal Expansion/Heat Capacity Measuring System



Remotely operated mechanical testing system

Laser Flash System (under construction) for thermal diffusivity measurements



Phases of Irradiation Studies

PHASE I:

Super Invar and Inconel-718

PHASE II:

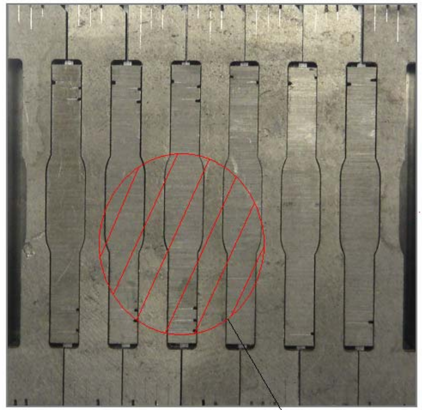
- 3D Carbon-Carbon Composite
- Toyota “Gum Metal”
- Graphite (IG-43)
- AlBeMet
- Beryllium
- Ti Alloy (6Al-4V)
- Vascomax
- Nickel-Plated Alum.

PHASE II-a:

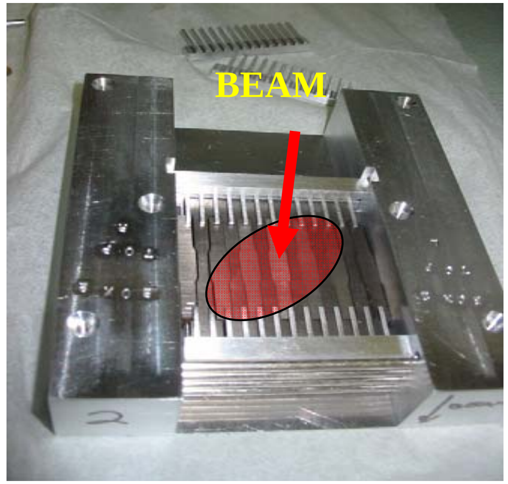
- 2D Carbon-Carbon

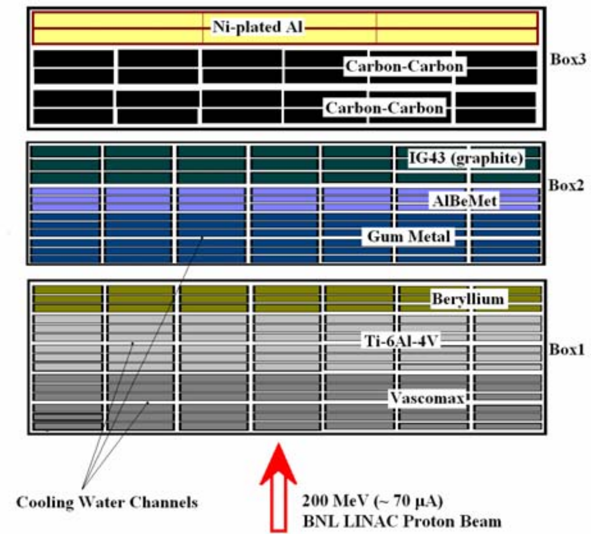
PHASE III:

- 3D & 2D Carbon-Carbon
- 90% cold-worked “Gum Metal”
- Graphite (IG-43 & IG-430)
- AlBeMet
- Ti Alloy (6Al-4V)
- Copper & Glidcop
- W and Ta
- Vascomax
- Nickel-Plated Aluminum
- Super-Invar ➔ following annealing
- Graphite/titanium bonded target

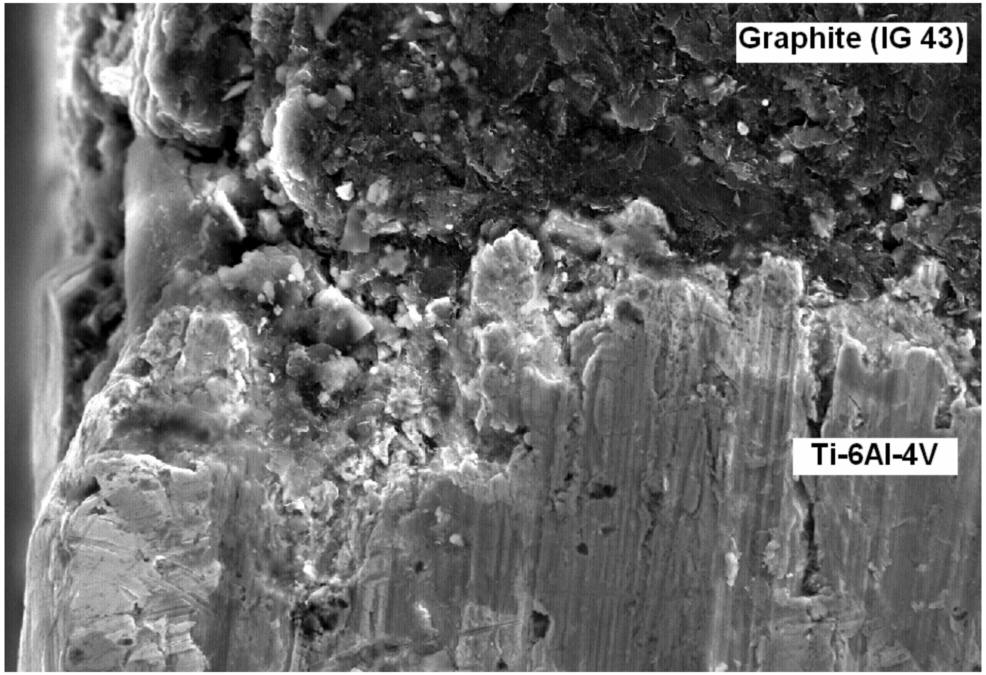


Proton Beam Footprint (1σ)





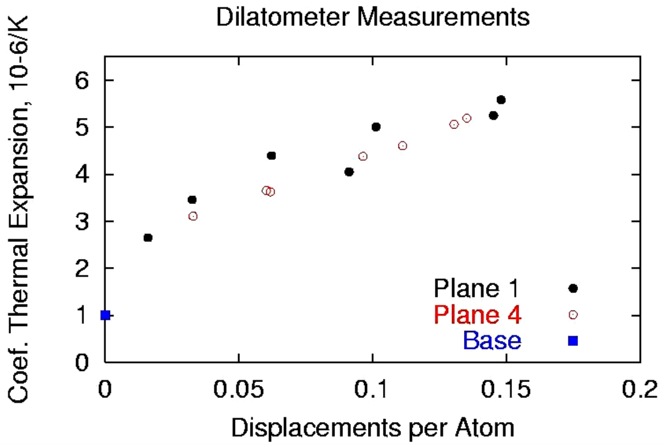
Specially bonded graphite/titanium specimens exposed to proton irradiation – Post-irrad analysis pending



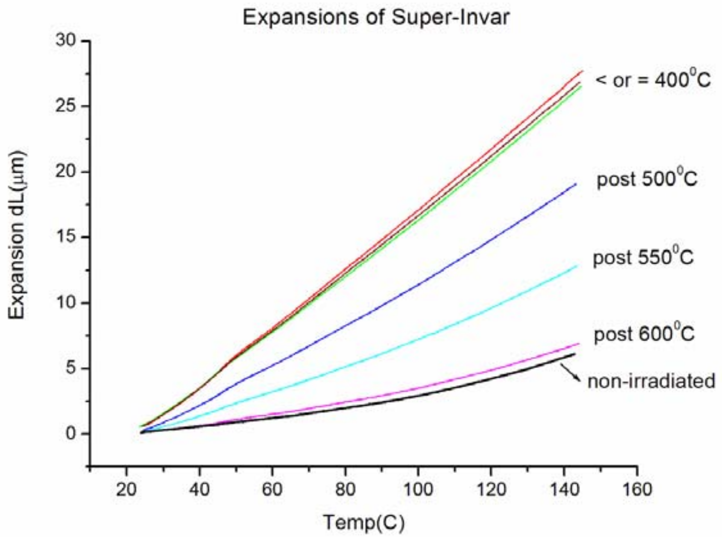
What was observed during post-irradiation analysis was intriguing

Super INVAR (low CTE)

Modest level of irradiation takes away the low thermal expansion exhibited by the un-irradiated super Invar

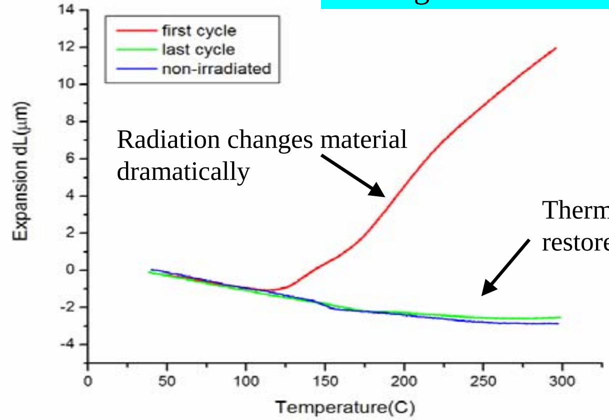


Thermal cycling with temp. threshold identified experimentally as $T_{threshold} > 600$ C restores material !!

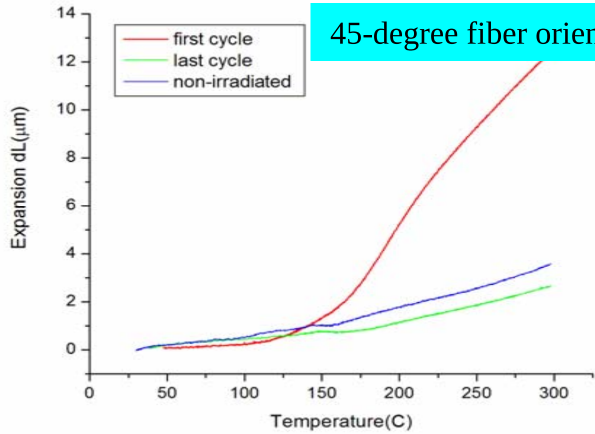


3-D Carbon Composite also exhibits low CTE (even negative for Temp < 800 C !!)

90-degree fiber orientation



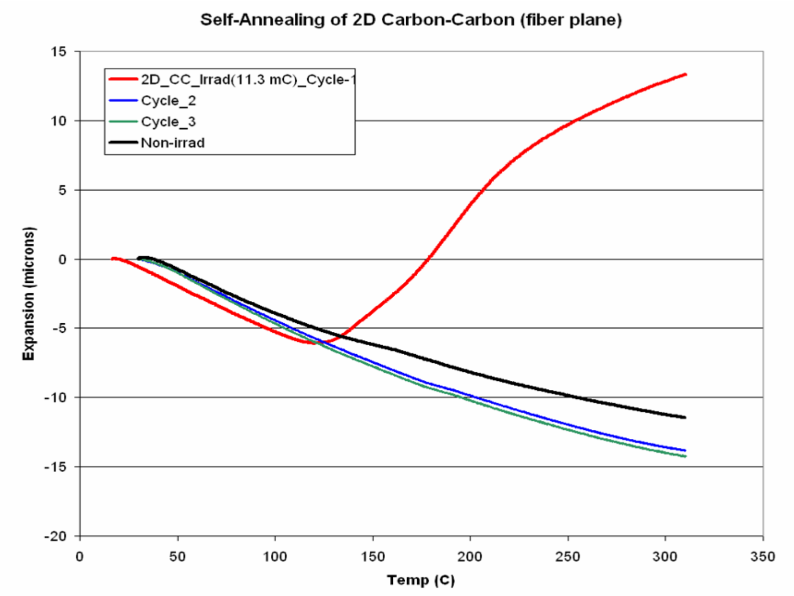
45-degree fiber orientation

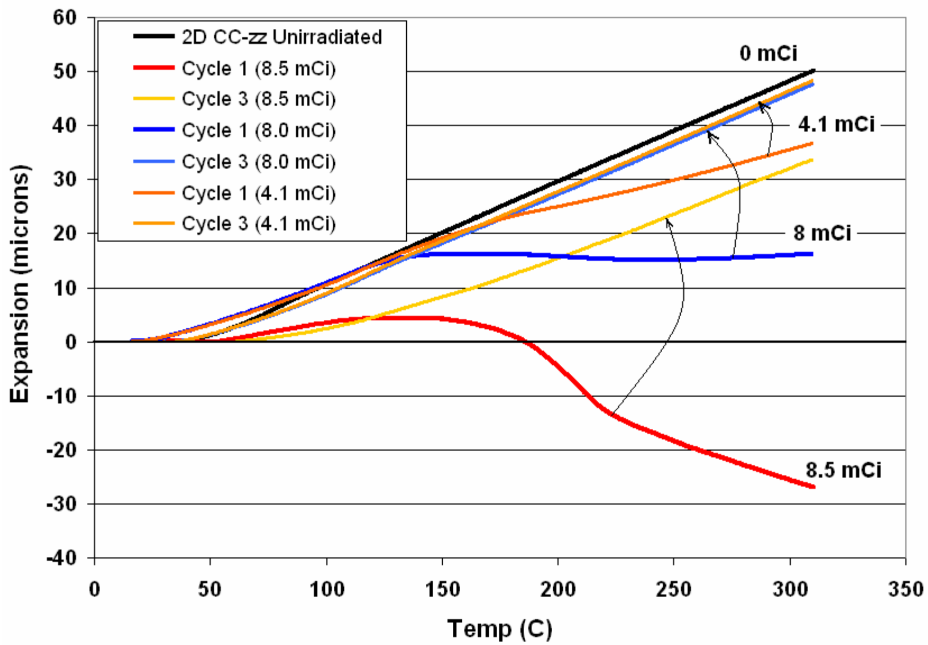


Annealing behavior also exhibited by 2D Carbon

Fiber (strong) direction

Weak direction (orientation normal to fibers)



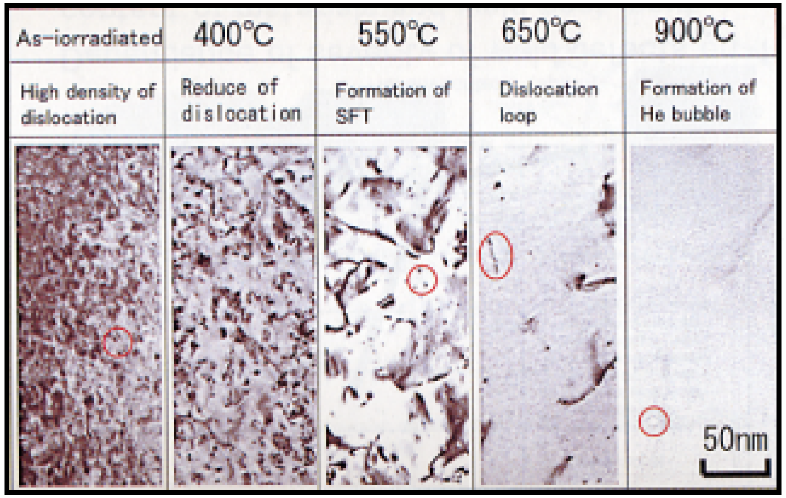


- **Non-irradiated shown in BLACK**
- **Effects of irradiation (captured in 1st post-irradiation thermal cycle) shown in RED**
- **Rest are additional thermal cycles that restore material through annealing**
- **Also shown are specimen activations in mCi**
- **Worth noting is the similar annealing behavior of specimens with same activation**

Questions to be answered regarding annealing

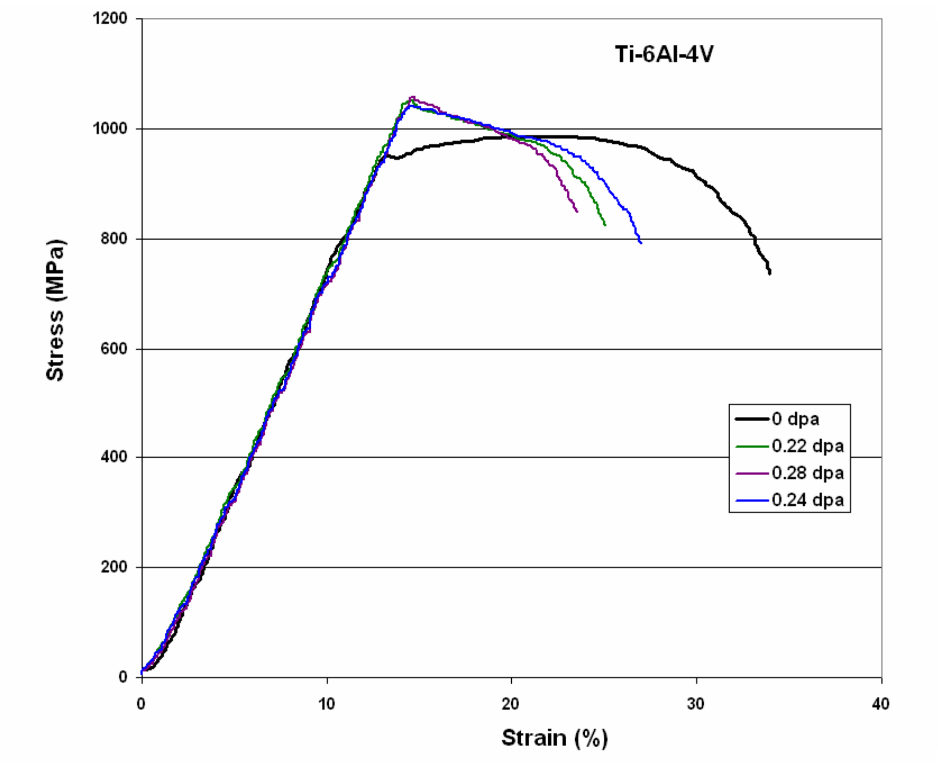
- How is irradiation damage influenced by high temperatures during irradiation and if yes where is the threshold
  - Identifying the temperature threshold will allow for life extension of the material in the irradiation environment
- Do materials exhibit similar damage following annealing and re-irradiation ?
  - Studies from neutron exposure indicate that the number of voids, while decrease in size, increase in number during re-irradiation
  - To address that, irradiated and then annealed super-Invar has been exposed to irradiation

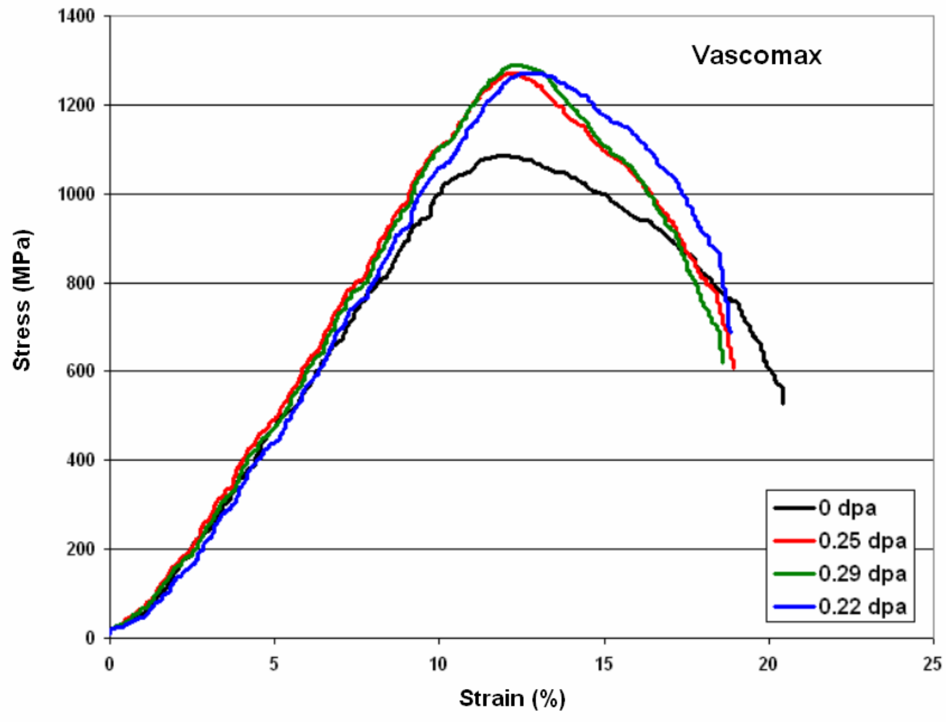
Recovery of damaged microstructure in 404 Steel through annealing (neutron fluence of 1.4 E+24 n/m^2)



from Y. Ishiyama et al, J. Nucl. Mtrls 239 90-94 (1996)

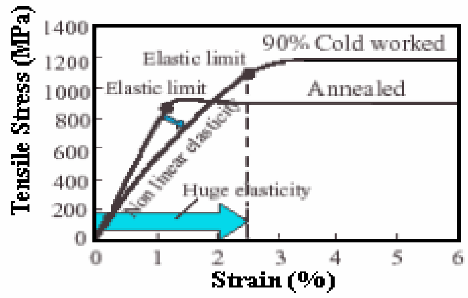
Radiation effect on ductility & strength – How important is ductility?

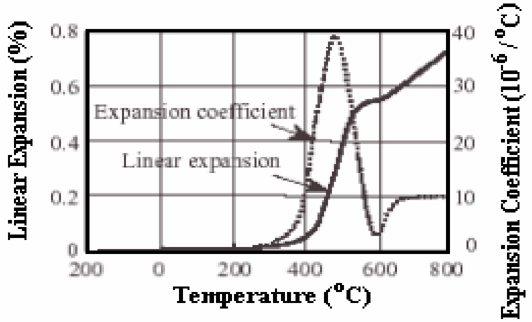


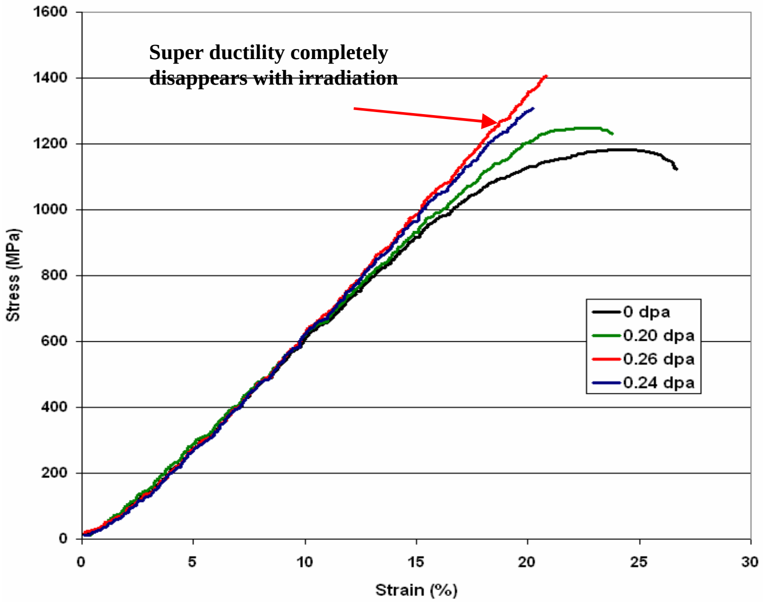


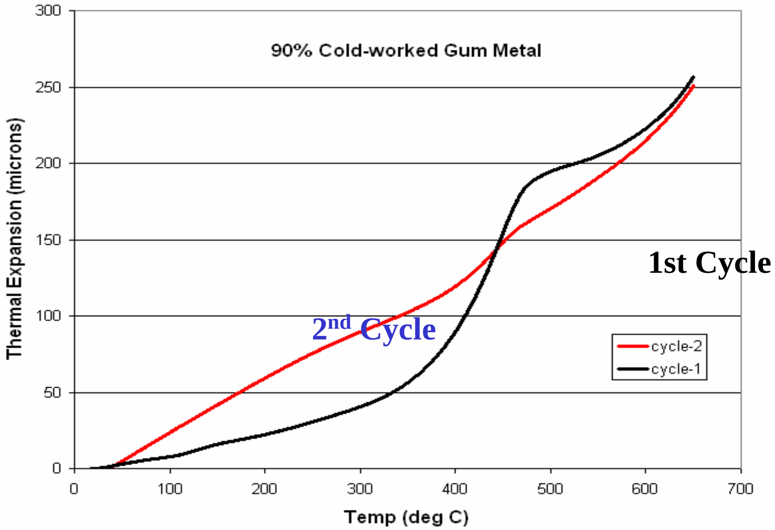
The high expectations of gum metal

Enhancement of properties are attributed to the “dislocation-free” plastic deformation mechanism

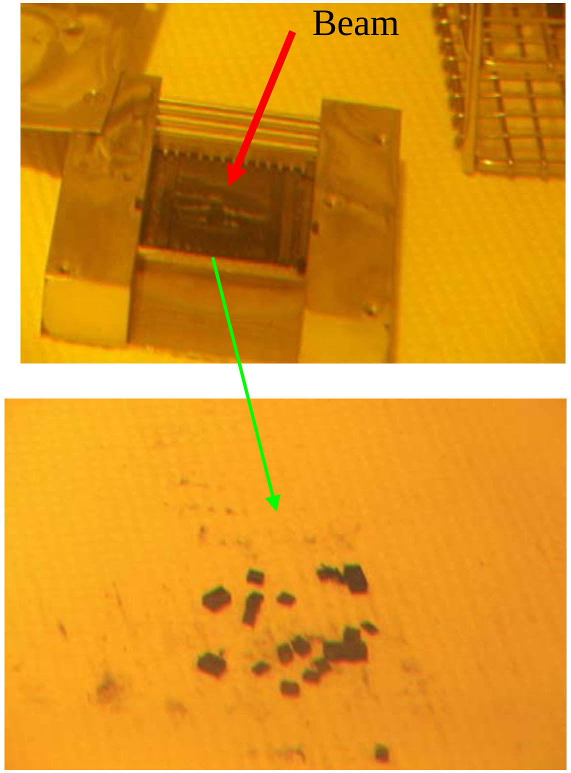




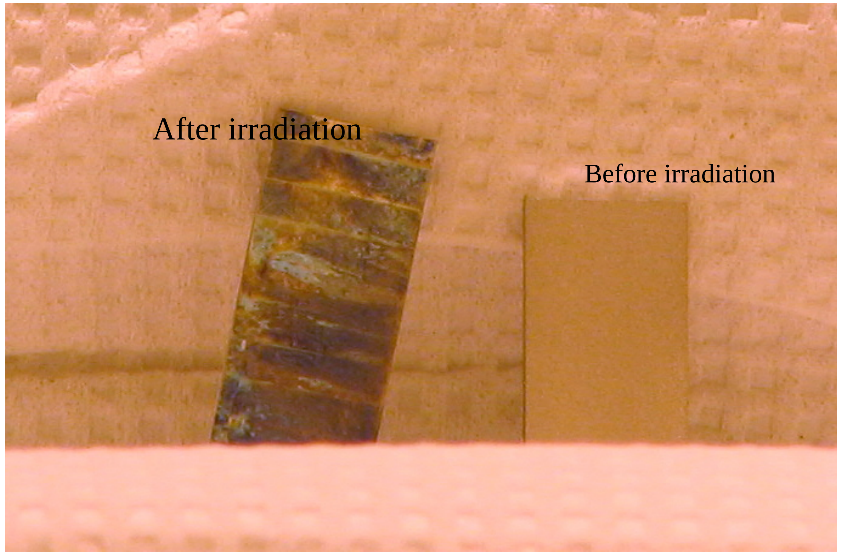




. . . irradiation damage on 2D composite and nickel-plated aluminum



Serious degradation of magnetic horn material
(nickel-plated aluminum) used in the NuMI experiment at FNAL!
Retested during Phase III with double the exposure and waiting examination

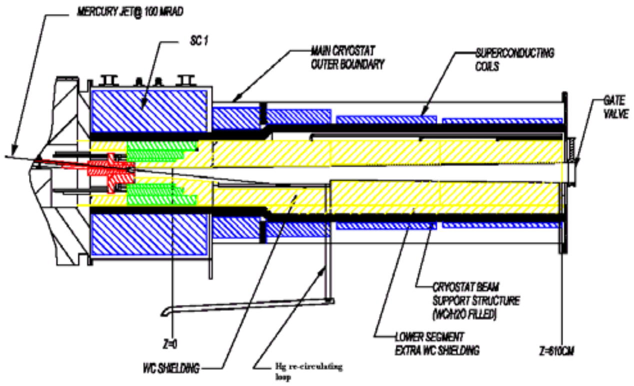


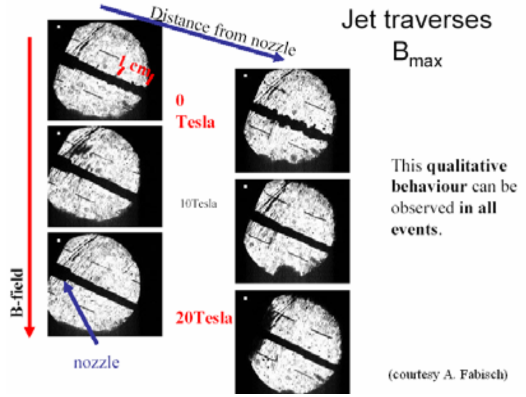
Structural damage of **2-D CC** composite at the center of the beam

Fluence where damage occurred ~7x10^21 protons/cm2

BROOKHAVEN NATIONAL LABORATORY

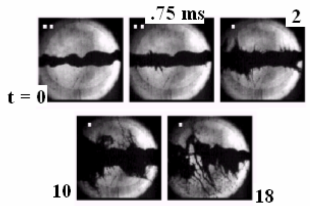
LIQUID JET TARGETS



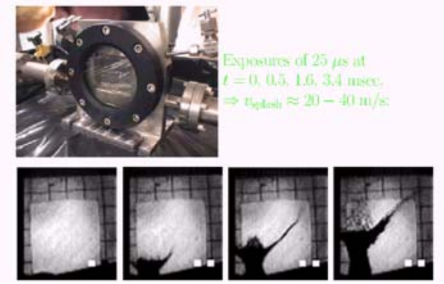


E951 Experiment

(focus on Hg jet delivery and interaction with 24 GeV protons, hg/nozzle interaction)

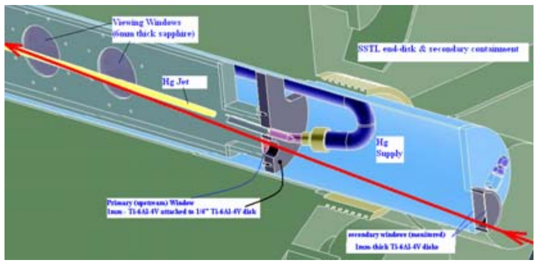


Mercury jet interaction with 24 GeV 3.8 TP beam of the E951 experiment

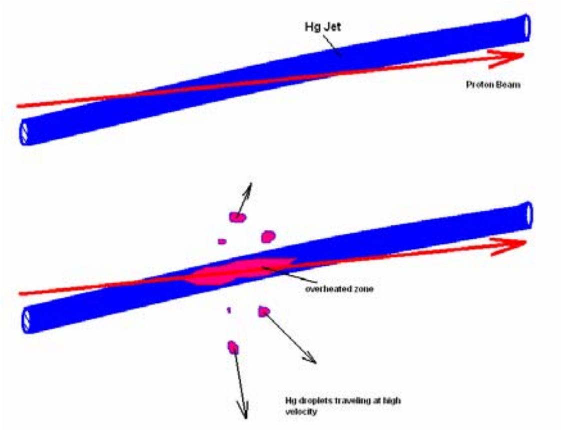


MERIT Experiment

proton beam/high velocity Hg jet interaction in a 15 Tesla magnetic field



Hg Jet Destruction & Viewing Window Safety Analysis



$$\boxed{K.E. = \tfrac{1}{2}\,\rho\, dV\, \boldsymbol{U}_r^2 = \Delta P\, \delta(dV)}$$

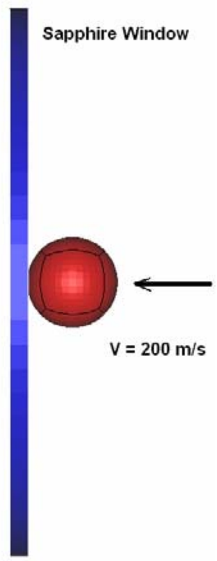
$$\Delta P \approx \alpha_V\, \Delta T / k$$

$$\alpha_V = (\partial V / \partial T)_P$$

$$\delta(dV) = \alpha_V\, dV\, \Delta T$$

$$\boldsymbol{U}_r^2 / \boldsymbol{c}^2 = 2\, \alpha_V^2\, \Delta T^2$$

$$\boxed{\boldsymbol{U}_r = \sqrt{2}\, [\alpha_V\, \Delta T]\, \boldsymbol{c}}$$



Beam-induced Hg jet destruction

SUMMARY

- **Solid targets, regardless of the physics they will support, are inherently coupled with material R&D (shock and irradiation damage)**

- **Information to-date available from low power accelerators and mostly reactor (neutron irradiation) experience. Extrapolation is risky!**

- **Advancements in material technology (alloys, smart materials, composites) provide hope BUT must be accompanied by R&D for irradiation damage**

- **Liquid targets (Hg jets) may present a valid option initiative BUT the necessary experiments of the integrated system must be performed**