Status of High Power Target R&D for Neutrino Factory and Neutrino Superbeam

N. Simos
Brookhaven National Lab

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4 MW Proton Drivers - Realistic ?

- An order of magnitude higher of operating drivers
- Are sub-systems capable in providing/dealing with such power?
- While the target may represent a tiny portion of the overall infrastructure, its role in the functionality of the system is paramount
- Since no one-size-fits all works, the target choice must satisfy accelerator parameters that are set by physics
- Unfortunately, it is a two-way negotiation !!!!

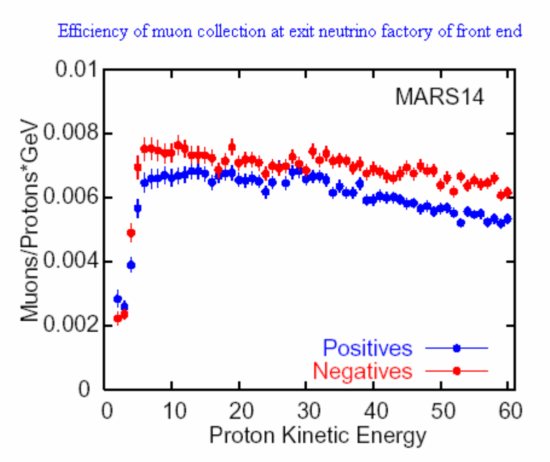
Parameter Space

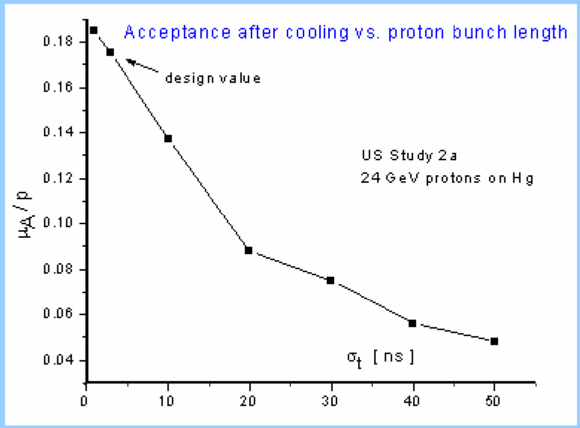
A happy medium between physics goals and engineering reality

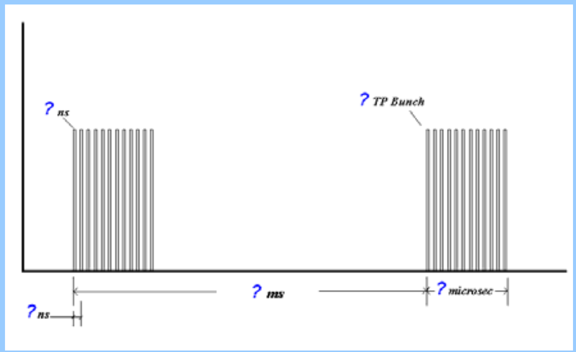
Protons per pulse required for 4 MW

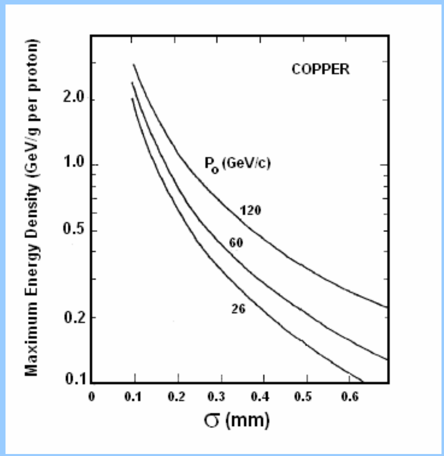
$$\bar{P}_{arc}(w) = E[eV] \times N \times e \times f_{rep}[Hz]$$

	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}









Neutrino factory

8.0 GeV < Energy < 20.0 GeV

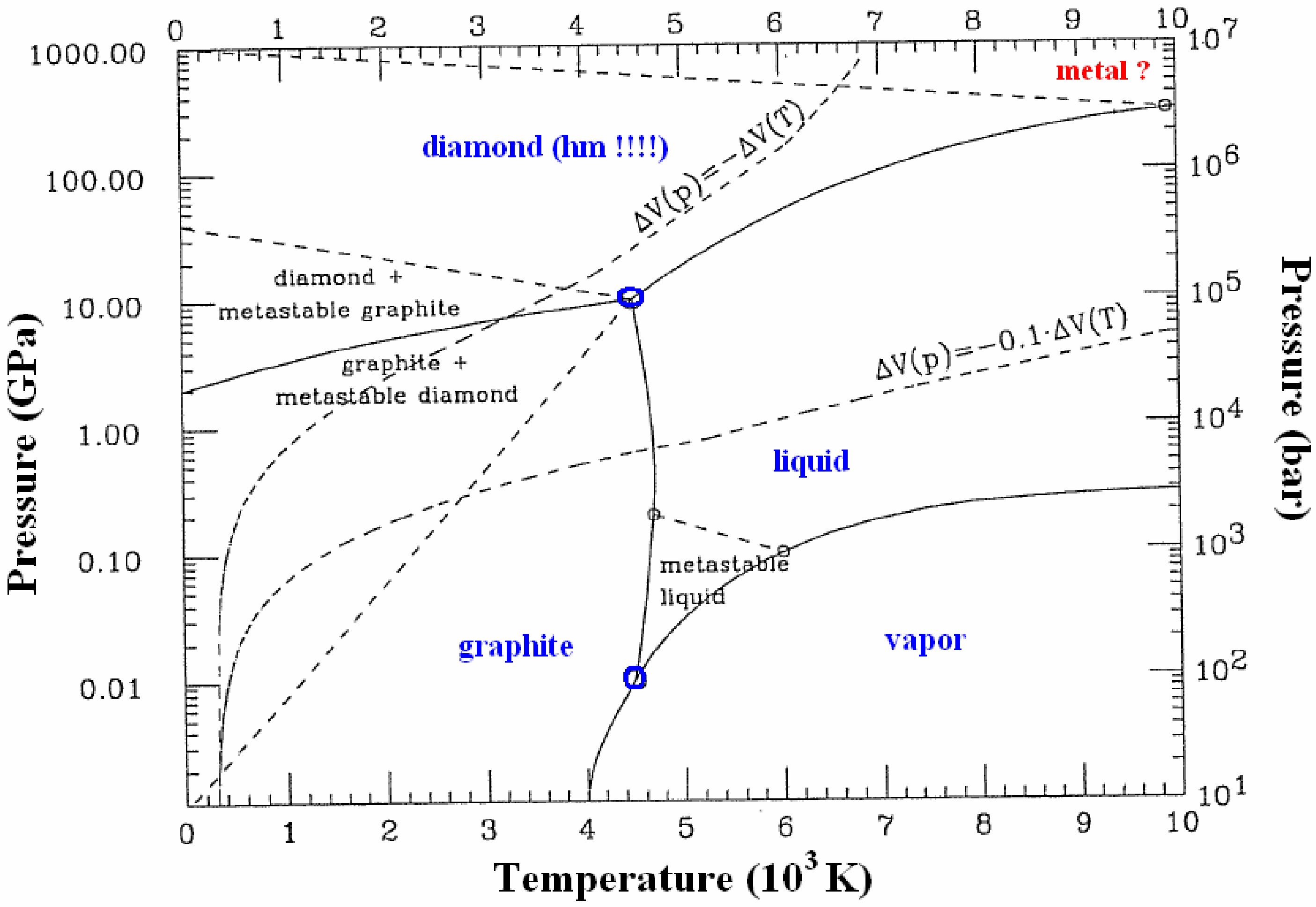
Rep Rate ~ 50(25) Hz

Intensity 50*10**(12) ppp, at 10(20) GeV

Bunch Length < 3 ns, for longitudinal acceptance

Proton Driver MAY NOT be dedicated to Neutrino Factory and must have the potential of serving other experiments ➔ compromise

The functionality of any scheme is most definitely controlled by our target choice



Whether we generate and sell isotopes or diamonds we are into a new branch of targetry named MRT

Money

Recovering

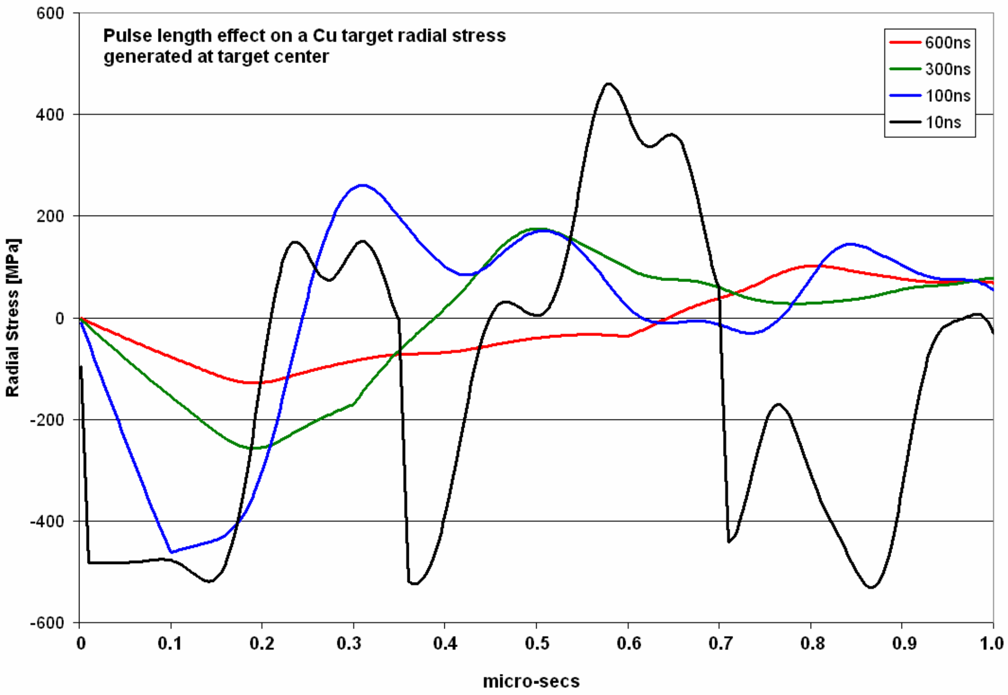
Target

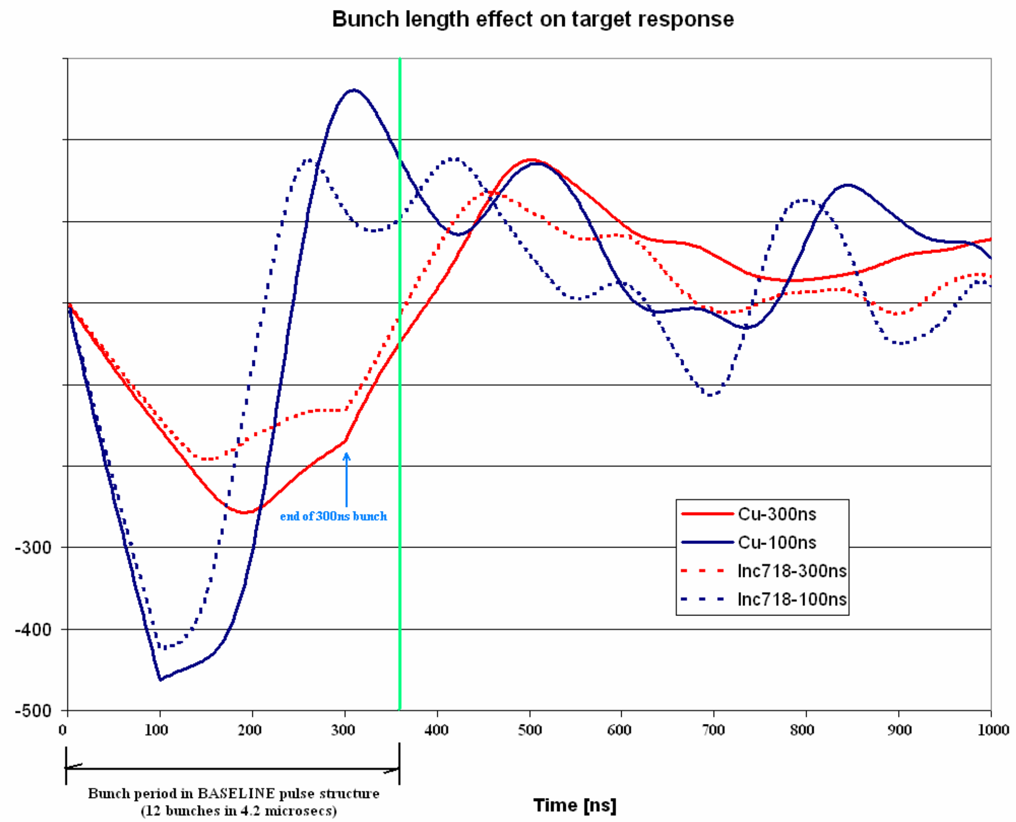
How Can We Get There?

- Liquid or Solid?
- Stationary or Moving?
- Something in between (i.e. packed particle beds) ?

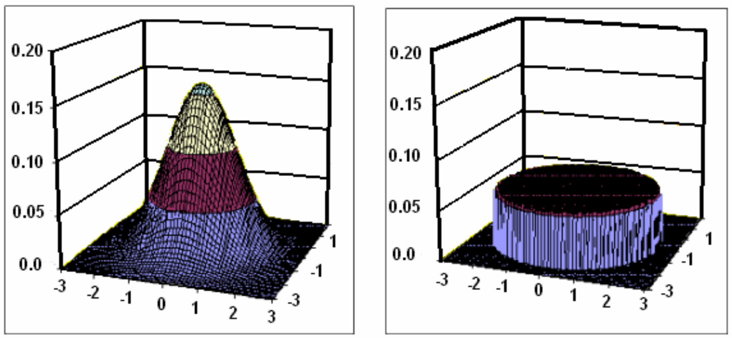
<u>Common denominator</u>: always going through window or a "solid" target !!!!

Pulse Structure



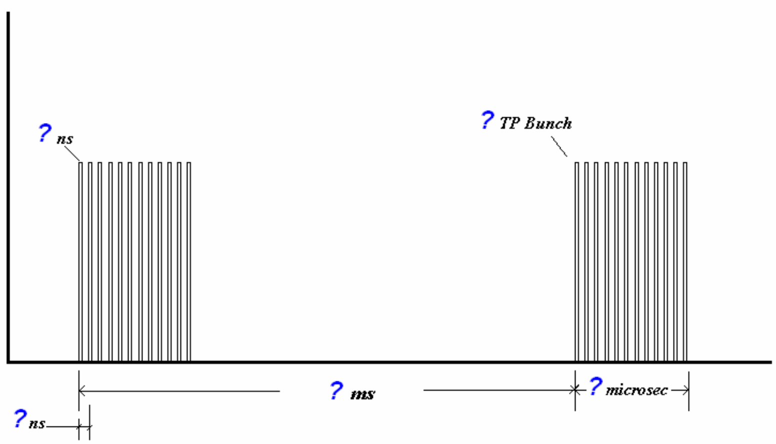


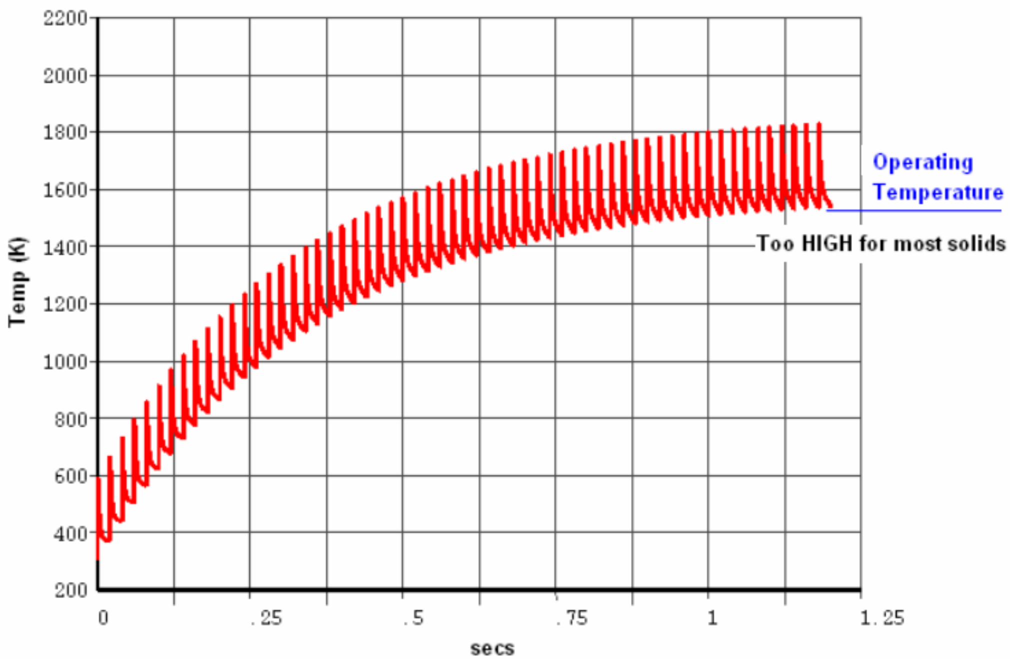
Why is Pulse Structure Important?



Gaussian and equivalent uniform beam distribution for same number of particles

Target	25 GeV	16 GeV	8 GeV
	Energy Deposition (Joules/gram)		
Copper	376.6	351.4	234





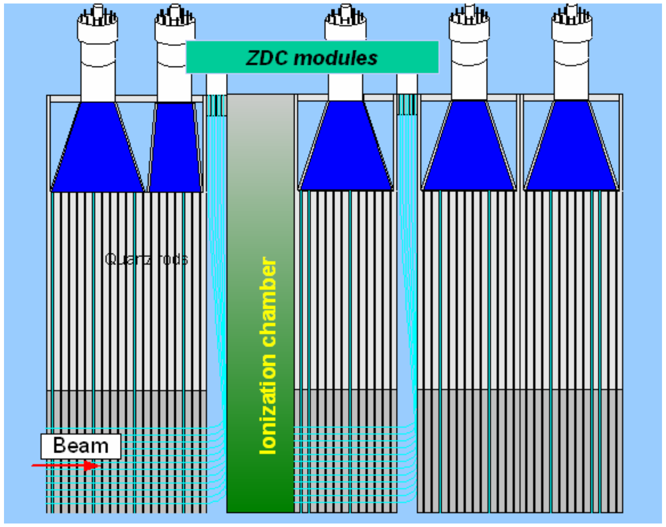
What R&D is a MUST in addressing the desired or optimized parameter space?

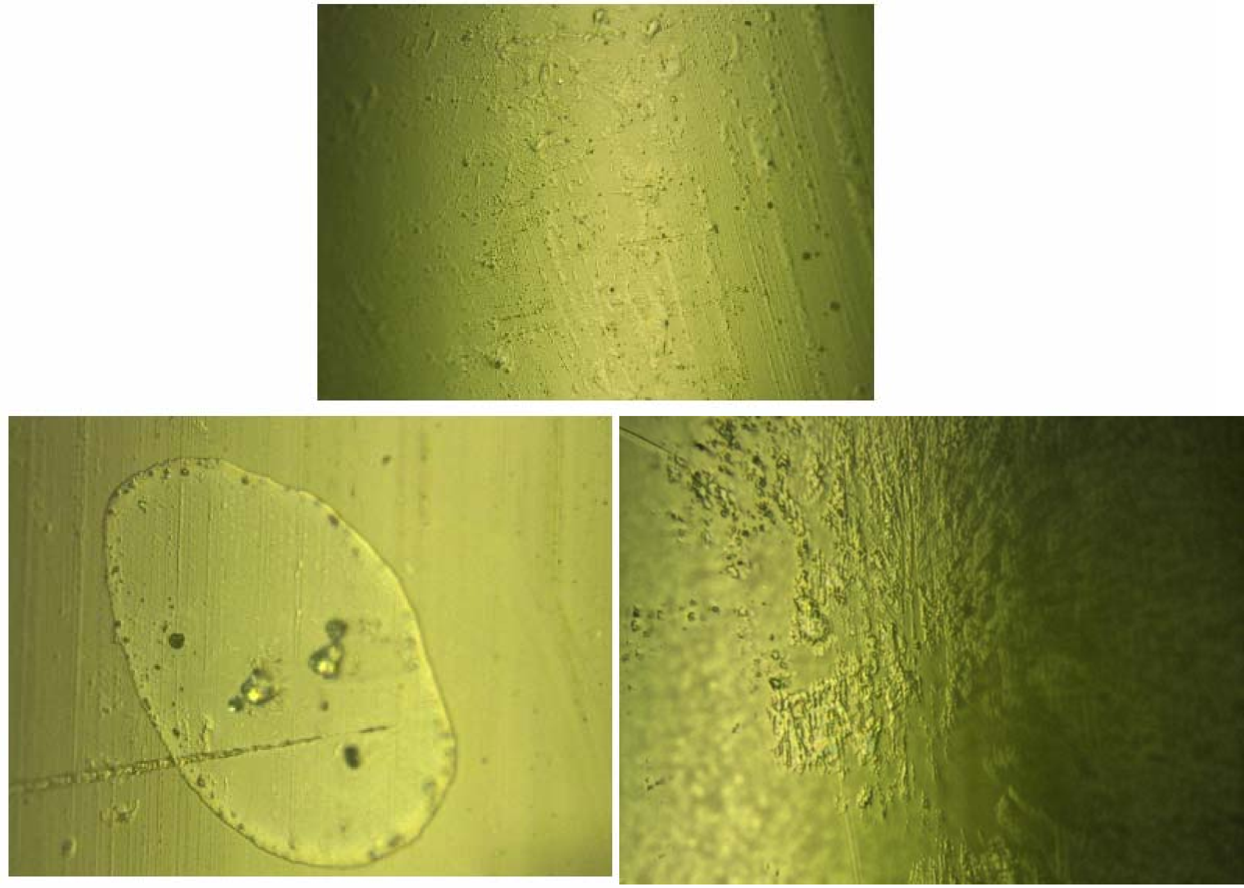
Solid Target Considerations

- Low, mid- or high Z? (we have been looking into all of them)
- Stationary or moving?
- Primary concerns:
  - Absorption of beam-induced shock
  - premature failure due to fatigue (RAL thermal shock studies and their central role)
  - radiation damage from long exposure

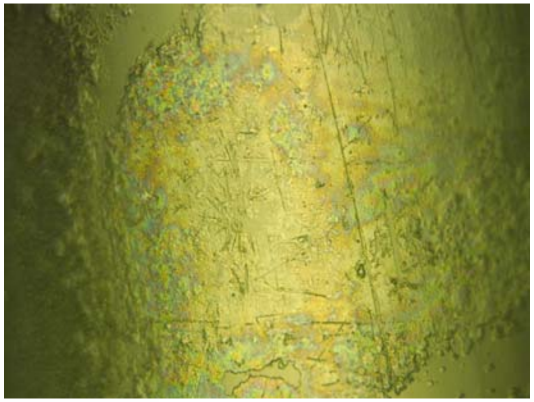
Putting a real face to radiation damage !!

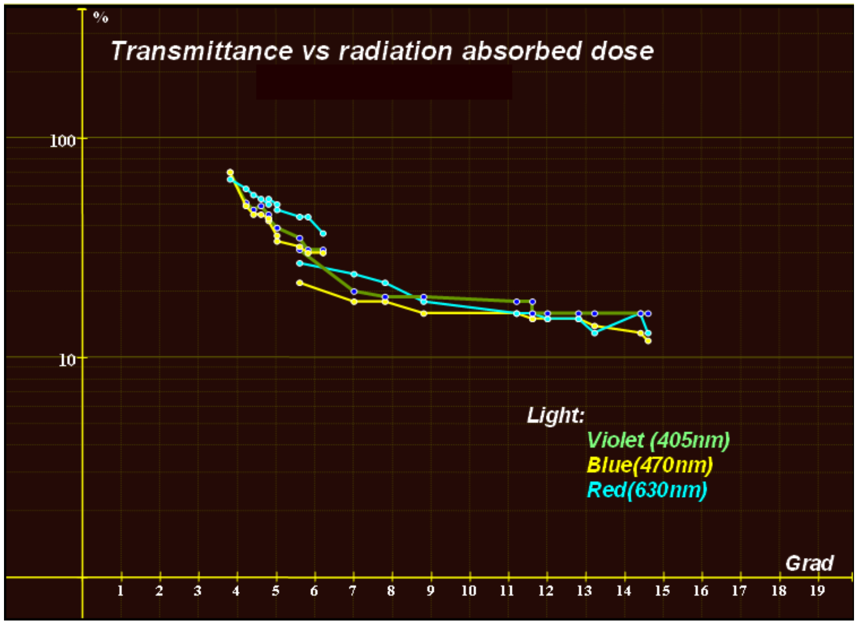
Proton and neutron exposure of fused silica (LHC 0-degree Calorimeter)





Fused silica damage visualization





Solid Target Option

- Anticipated cocktail far exceeds what current facilities can provide
  - while past experience (material behavior from reactor operation; experimental studies) can provide guidance, extrapolation to conditions associated with multi-MW class accelerators is risky
  - inch ever closer to the desired conditions by dealing with issues individually
- Embark on a comprehensive R&D in hope to:
  - deal with the implications of high power
  - identify promising candidates ==> target schemes
  - identify limits

Solid Targets – How far we think they can go?

1 MW ?	4 MW ?
Answer is YES for several materials Irradiation damage is of primary concern Material irradiation R&D pushing ever closer to anticipated atomic displacements while considering new alloys is 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

Overview of R&D Realized to-date on Solid Targets

- Target Shock Studies (BNL-E951)
- Radiation damage Studies (BNL)
- Target Lifetime Studies (RAL)

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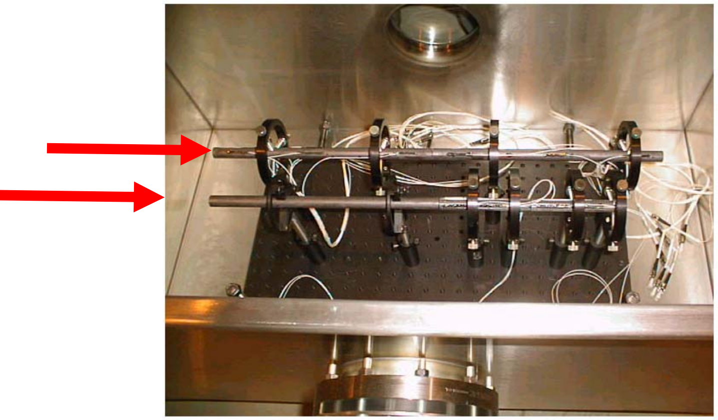
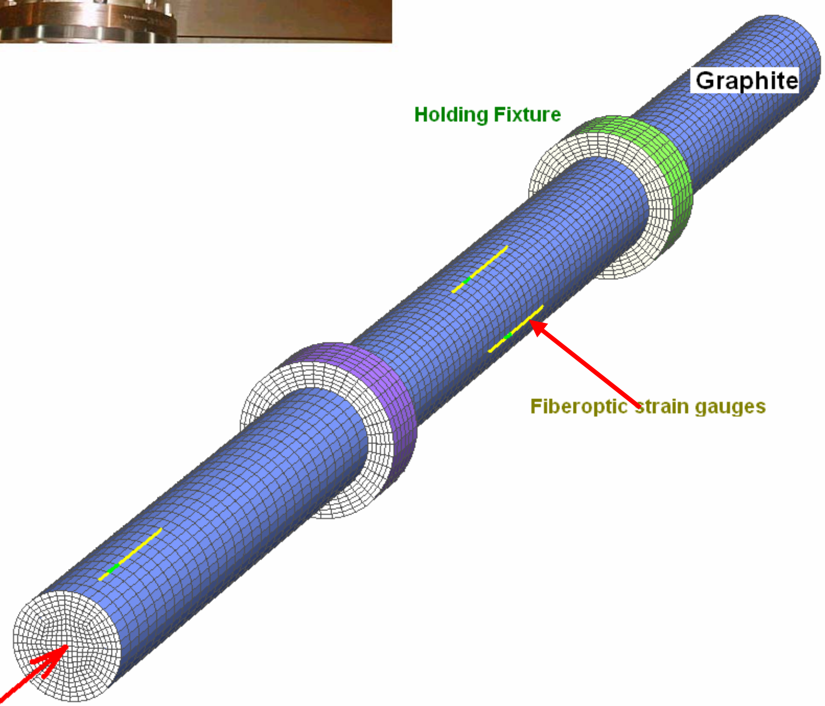
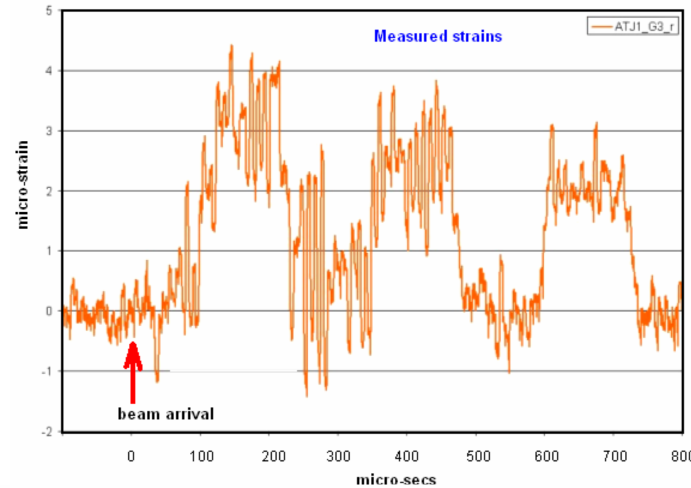
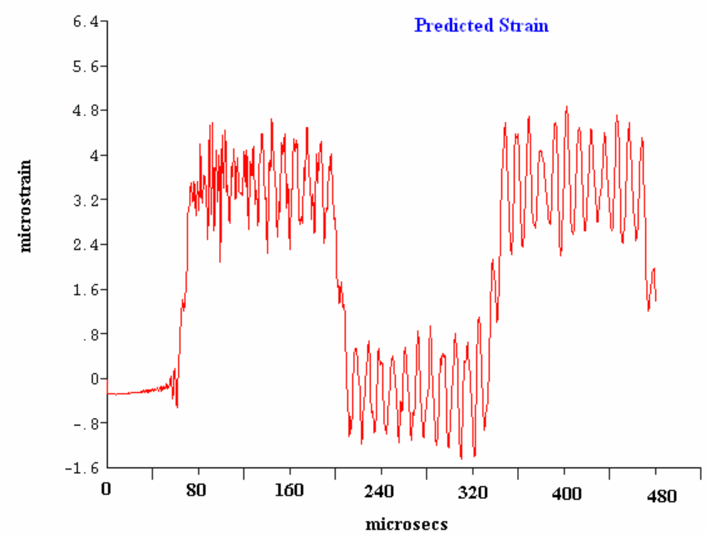
Target Shock Studies

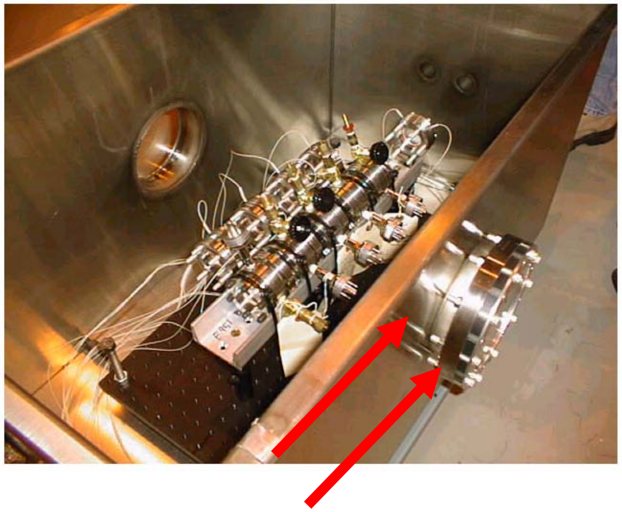


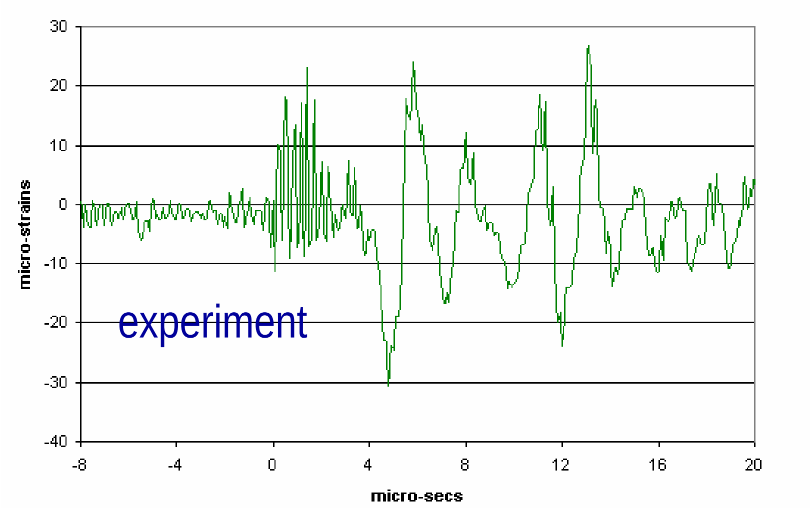


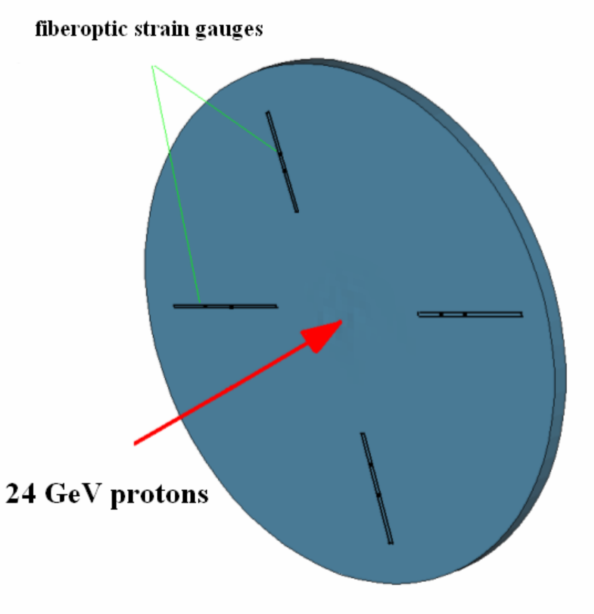


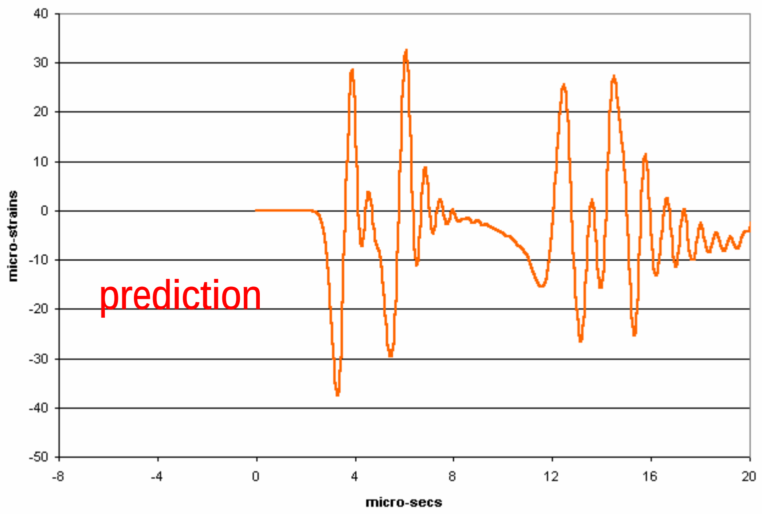


Beam-induced shock on thin targets









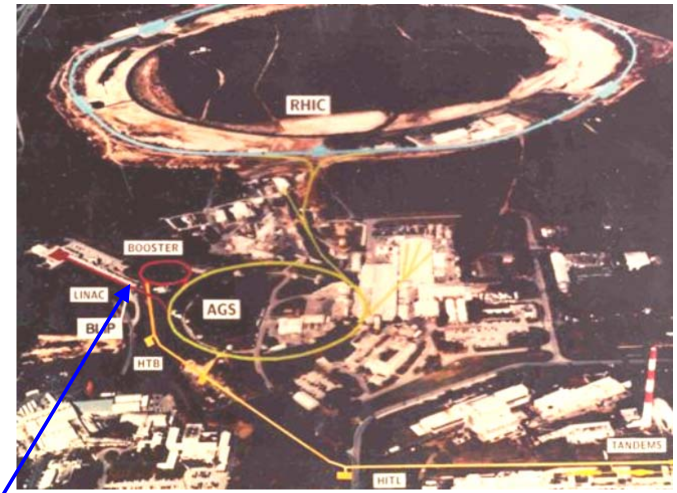
Solid Target Shock Studies – Assessment Overview

- Delineated between Graphite and Carbon composites
- Some super-alloys (titanium, inconel) exhibit favorable
- Materials "appear" more shock resilient than conventional estimates
- Simulation-based predictions based proved that computational tools can help push the envelope to higher power
- BUT, computational tools need scrutiny at even more severe conditions

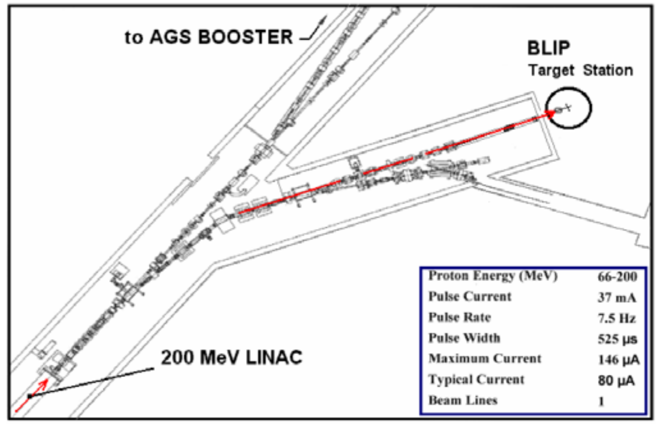
Tracking code prediction on energy deposition (GEANT, MARS) were confirmed

Shock, however, is one part of the story !!!

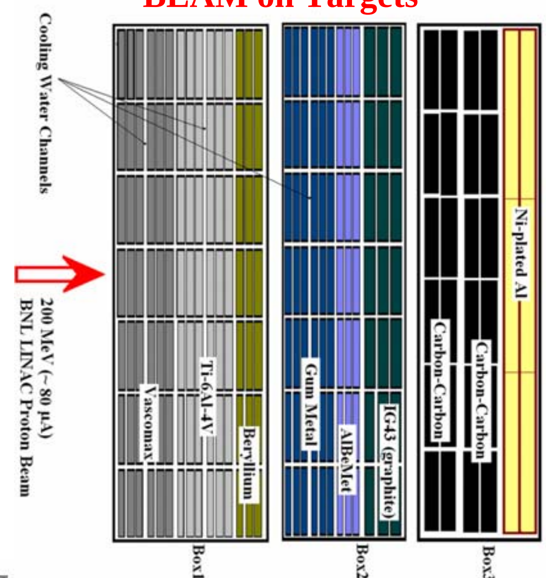
Target Radiation Damage R&D

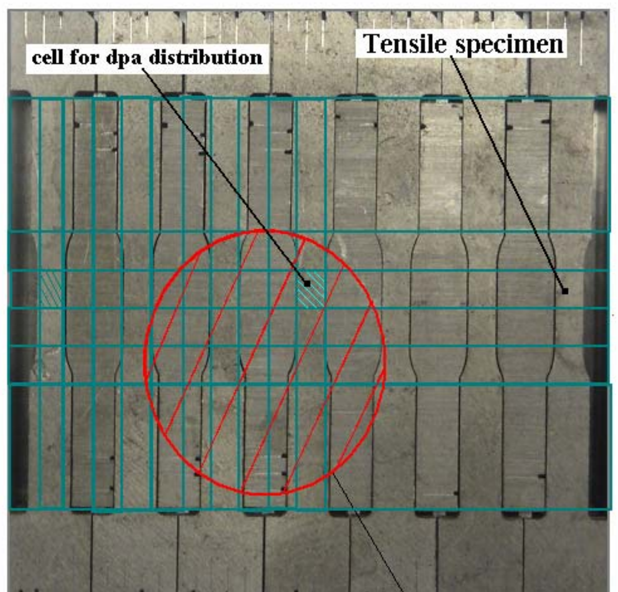


Irradiation at BLIP
(200 MeV or 117 MeV
protons at the end of Linac)



BEAM on Targets



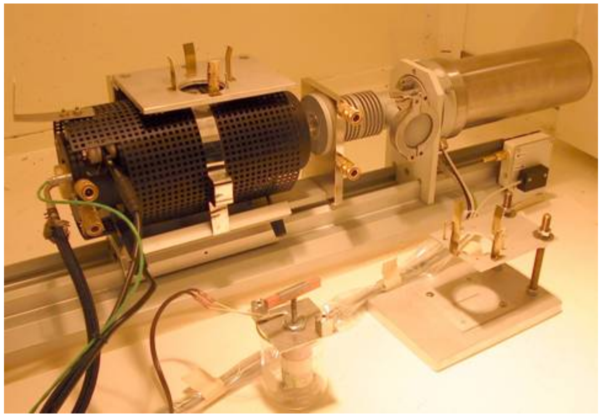


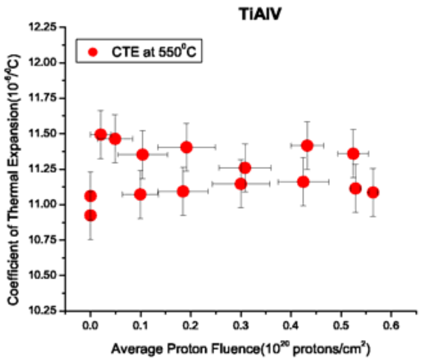
Beam footprint on targets (1σ)

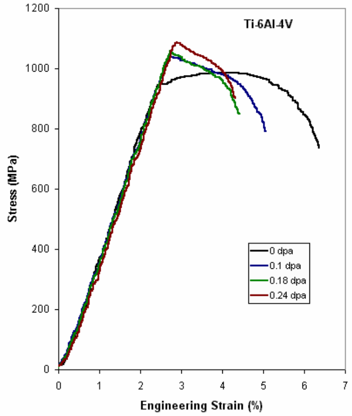
→ dpa

Irradiation Damage Analysis

Thermal Expansion/Heat Capacity Measuring System







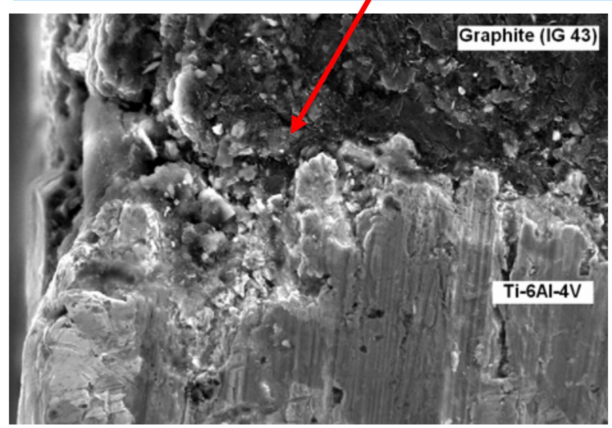
Remotely operated mechanical testing system

Target Irradiation Damage R&D in a Nutshell

- PHASE I: Super-Invar & Inconel-718
- PHASE II:
  - 3D-weaved Carbon-Carbon
  - Toyota "Gum Metal"
  - Graphite (IG-43)
  - AlBeMet
  - Beryllium
  - Ti Alloy (6Al-4V)
  - Vascomax
  - Nickel-Plated Aluminum
- PHASE II-a: 2D-weaved CC composite

PHASE III:

- 3-D and 2-D weaved Carbon-Carbon Composites
- Toyota "Gum Metal" (90% cold-worked)
- Graphite (IG-43 and isotropic IG-430)
- Ti Alloy (6Al-4V)
- Copper (annealed)
- Glidcop_15AL – Cu alloyed with .15% Al
- Bonded graphite to Titanium and Copper
- Tungsten and Tantalum
- Re-irradiation of super-Invar
- AlBemet and Vascomax
- Nickel-Plated Aluminum of the NuMI horn
- Fused Silica (LHC) and special ceramics



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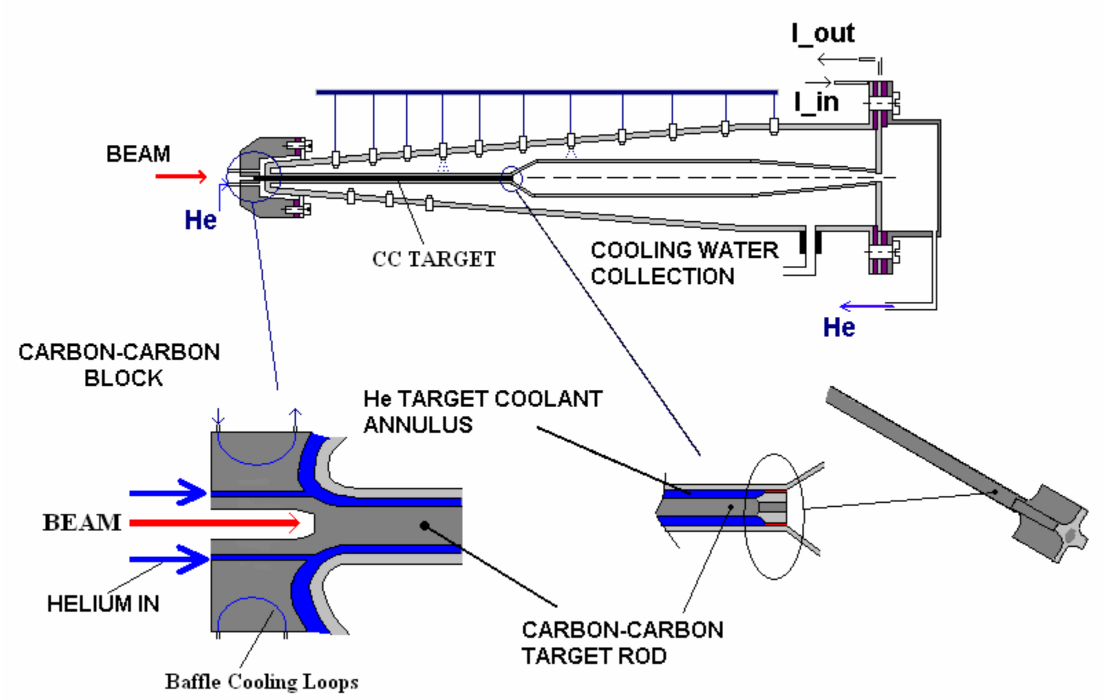
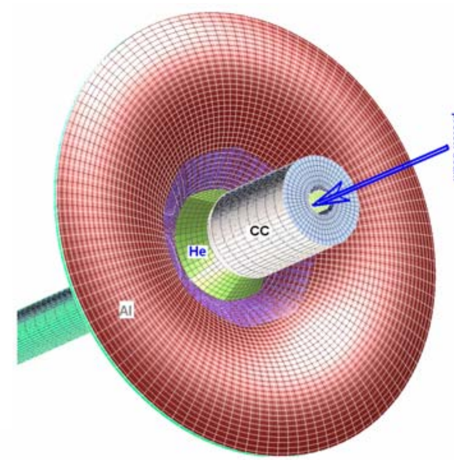
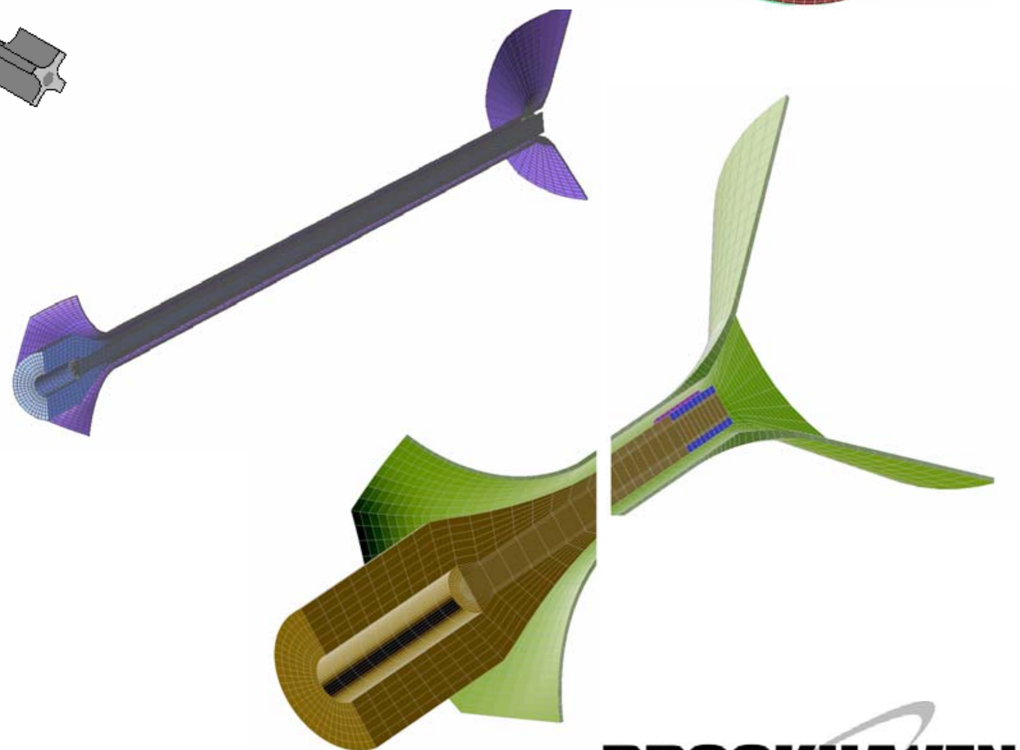
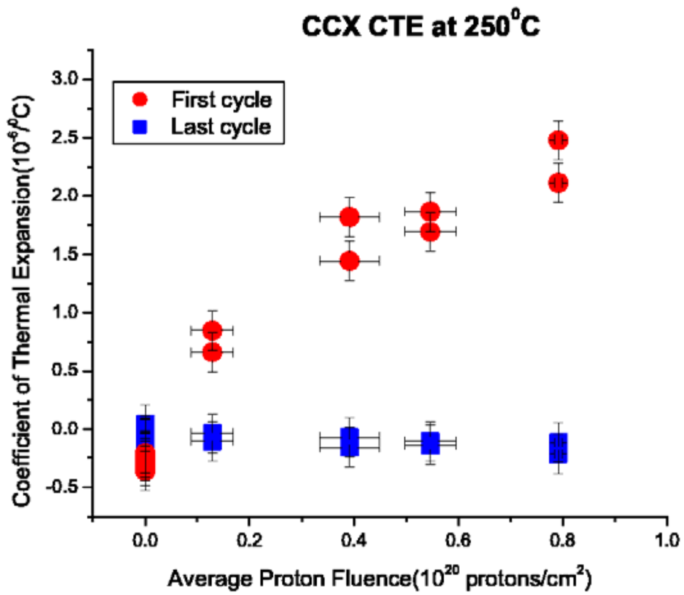
Superbeam Target Concept

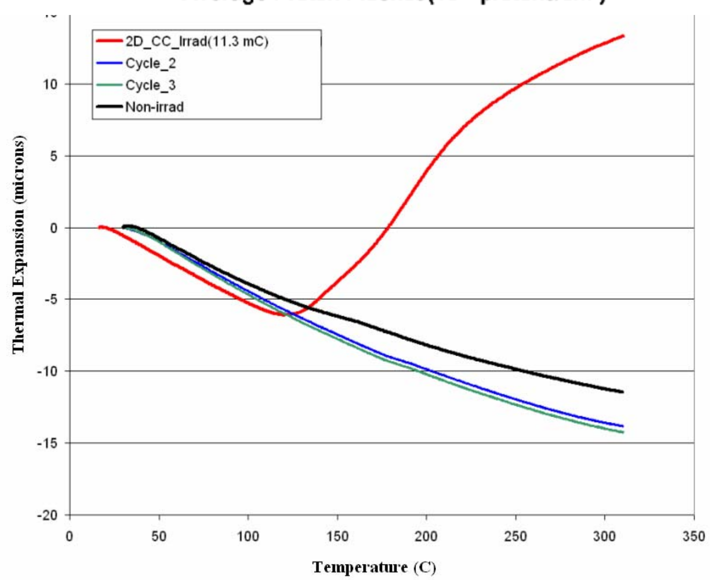


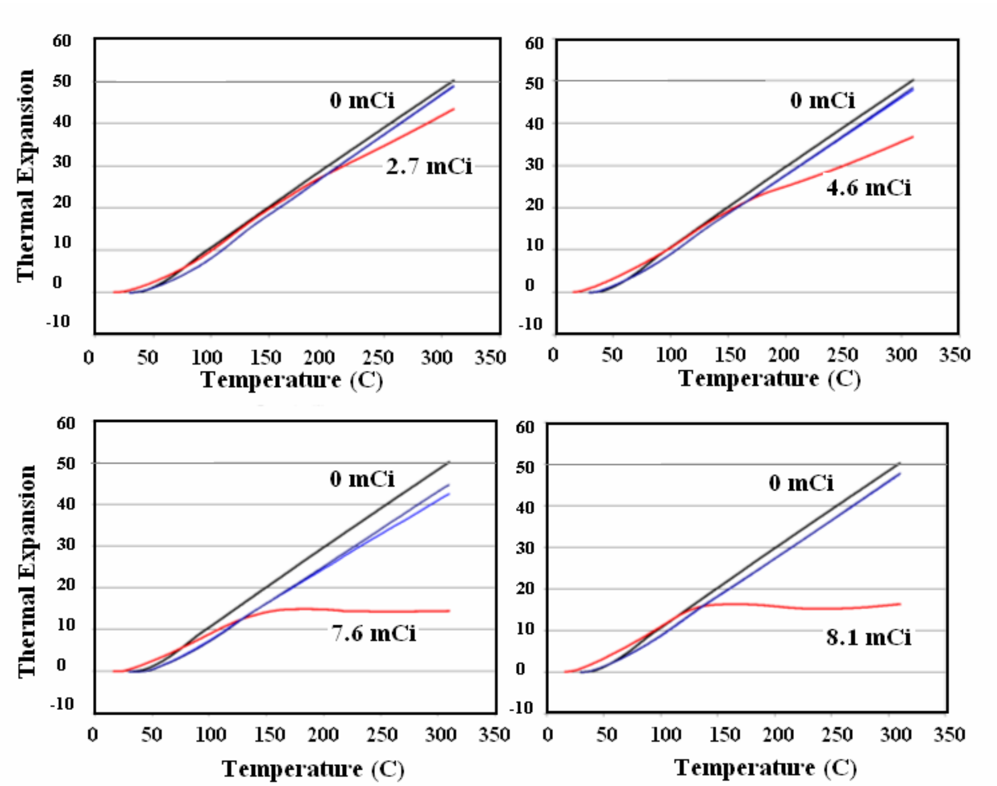




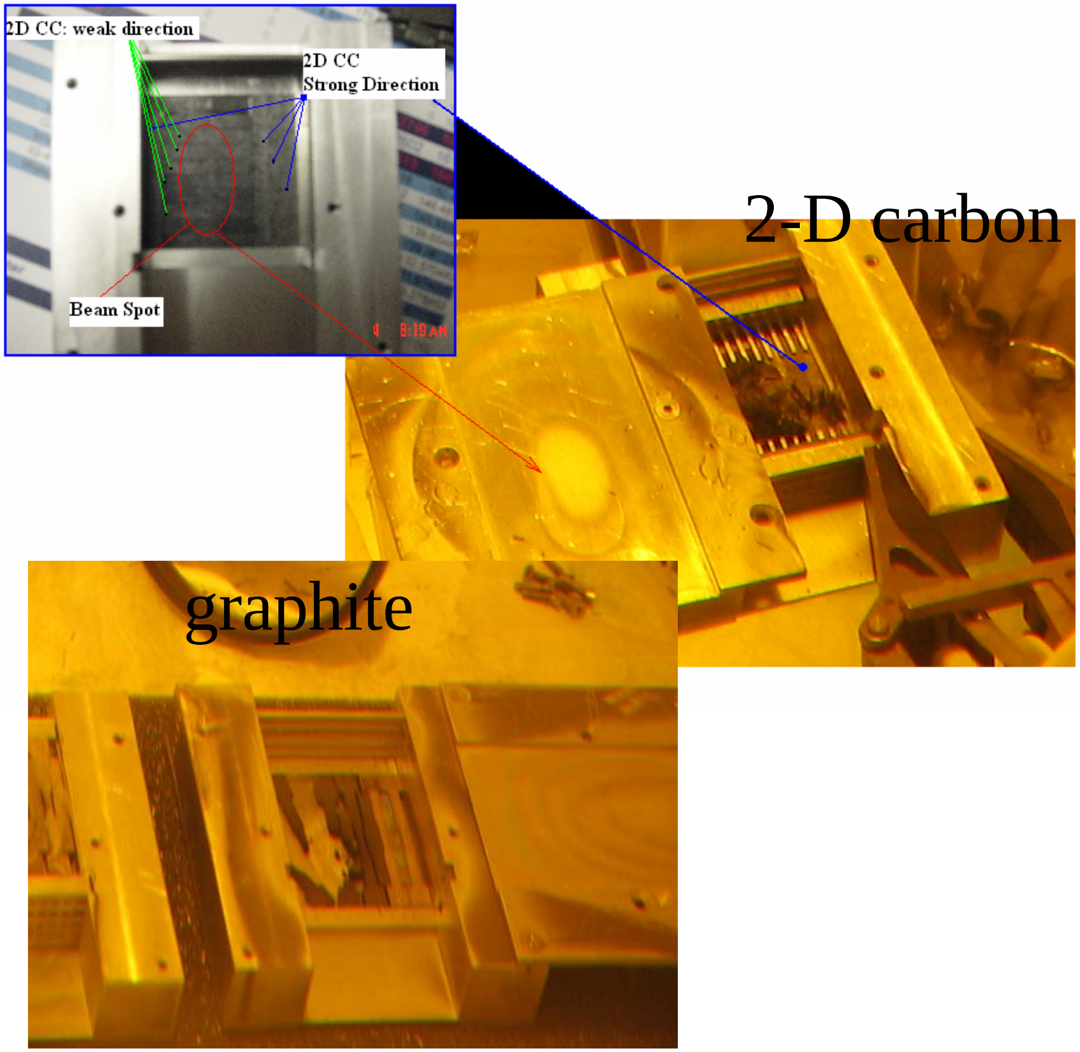
Radiation Damage in Carbon-Carbon Composites
The GOOD News

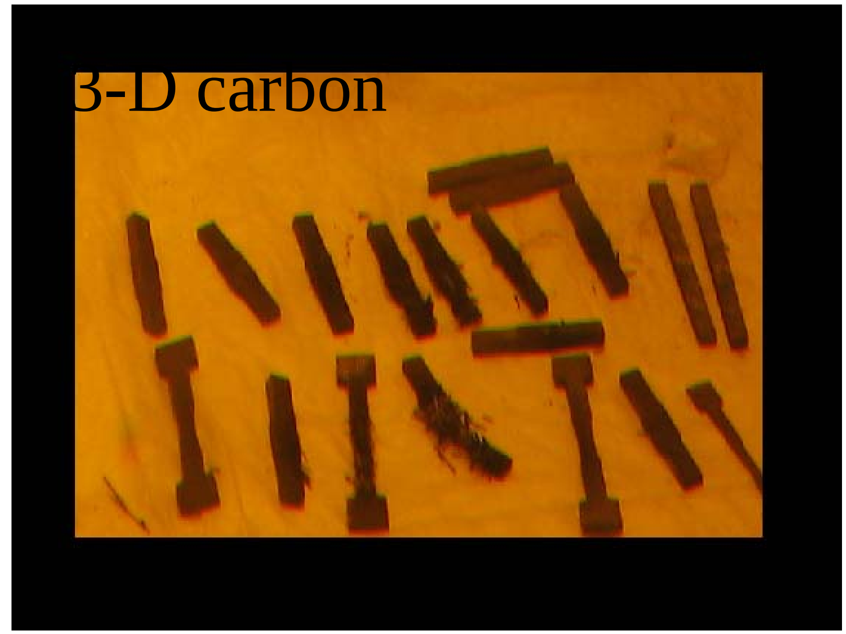






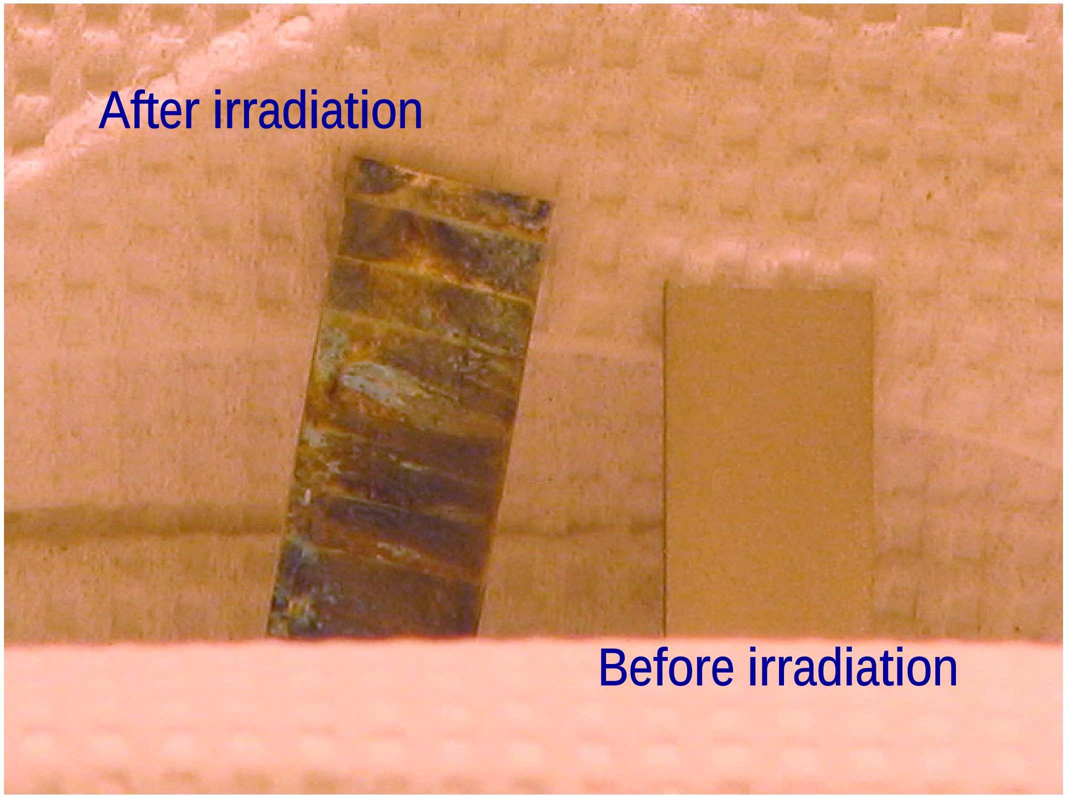
Radiation Damage in Carbon-Carbon Composites and Graphite
The BAD News





[fluence ~10^21 p/cm2]

Irradiation effect on magnetic horn
(Ni-plated aluminum)

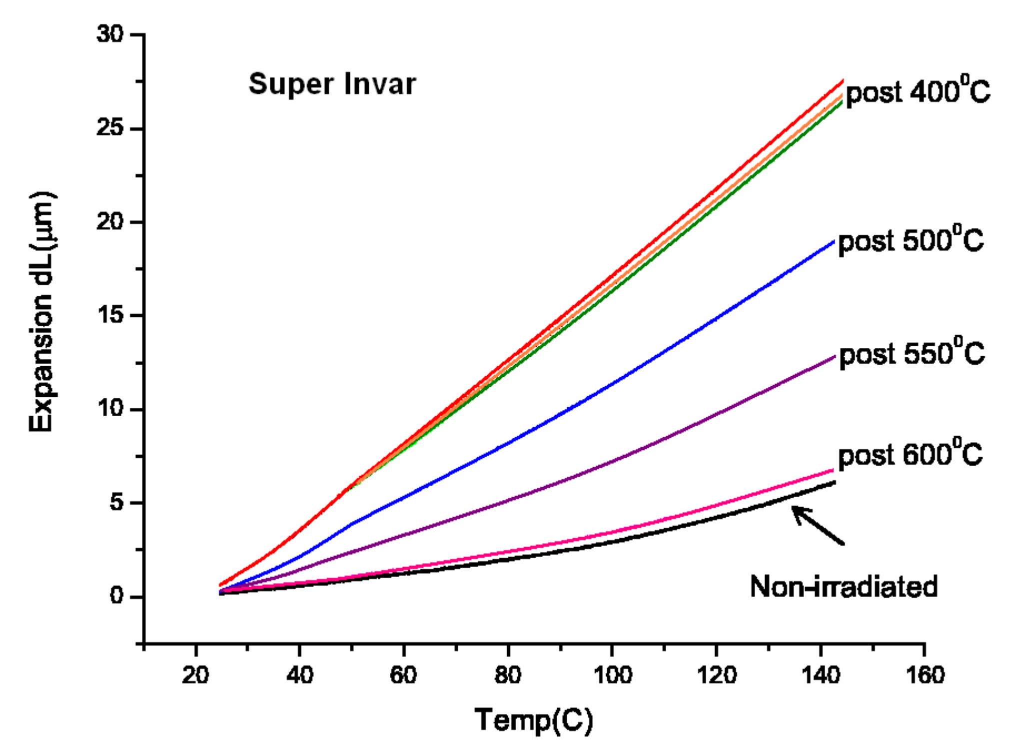


A low-Z material such as AlBemet (need low-Z but with good strength to not impede the flight of pions produced in the target) that has exhibited (thus far) excellent resistance to corrosion while maintaining strength and ductility under irradiation could be the magnetic horn material

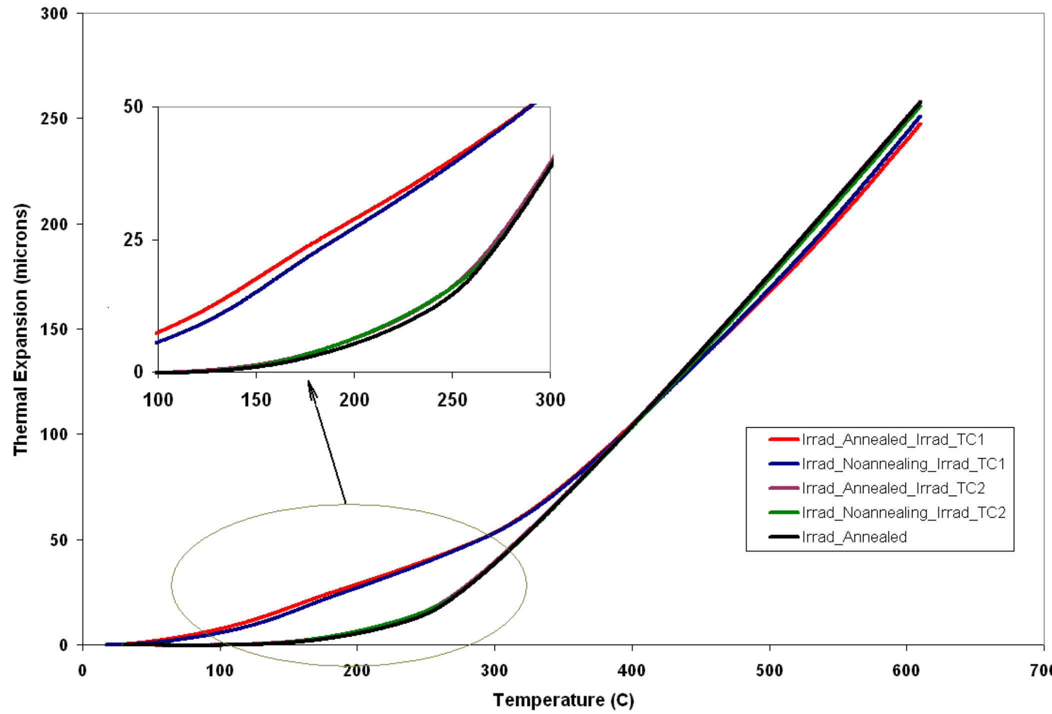
Radiation Damage - mid-Z Target Options

"annealing" of super-Invar

Following 1st irradiation



Following annealing and 2nd irradiation



ONGOING 3rd irradiation phase: neutron exposure

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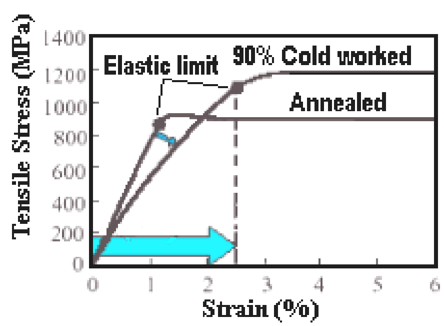
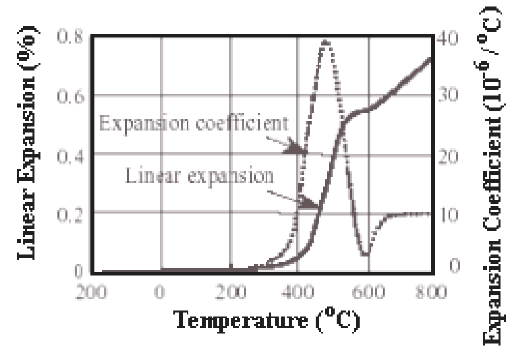
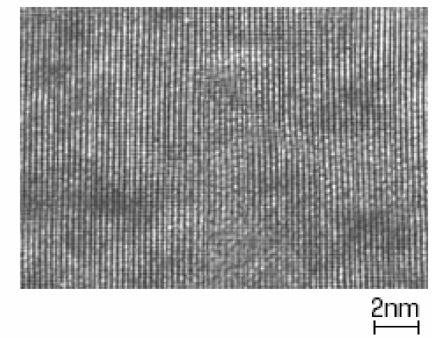
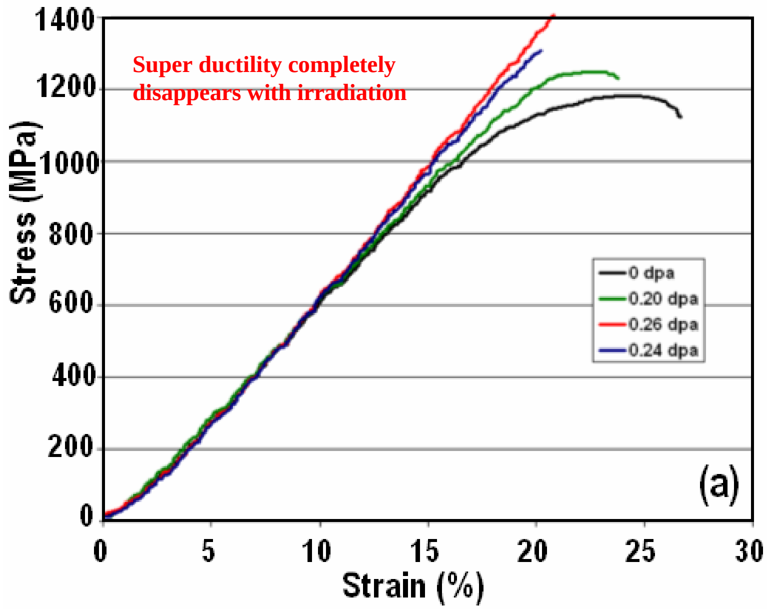
Radiation Damage of Super Alloy “Gum” metal

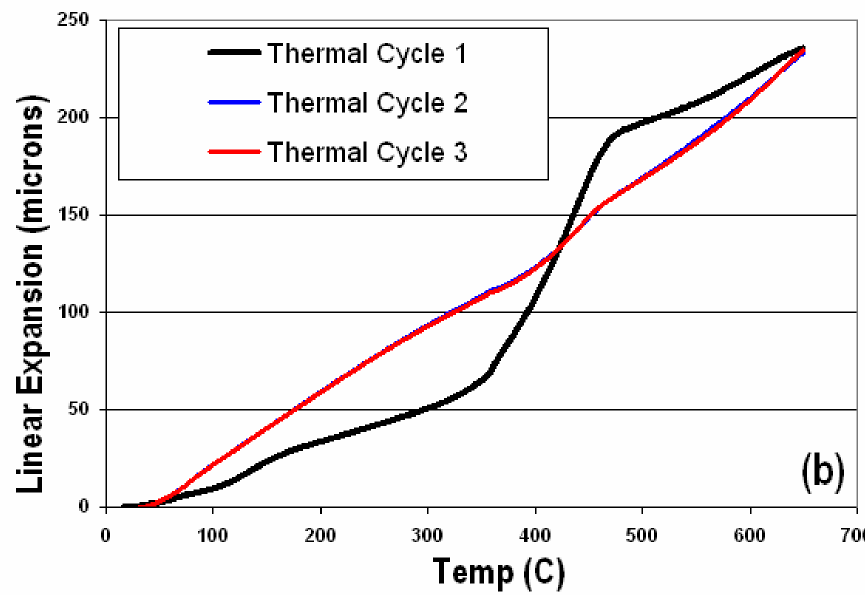
Enhancement of properties are attributed to the “dislocation-free” plastic deformation mechanism











As observed in other studies (AlMg-alloy)

0.2 dpa was enough to remove cold-work microstructure

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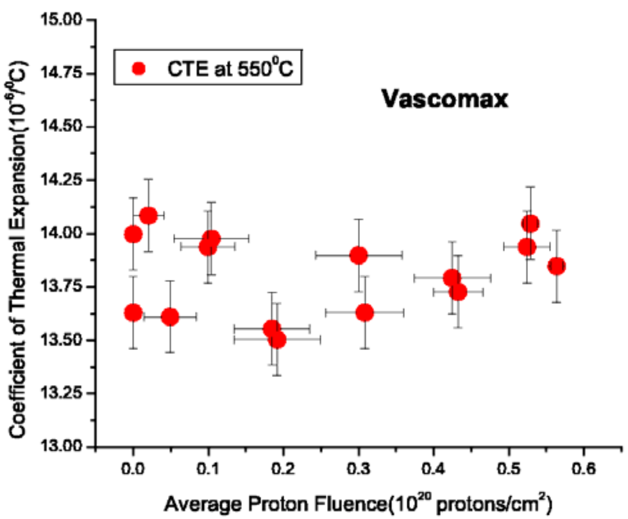
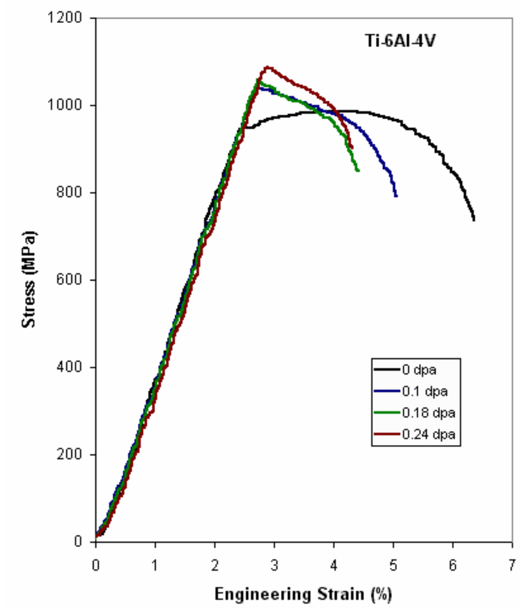
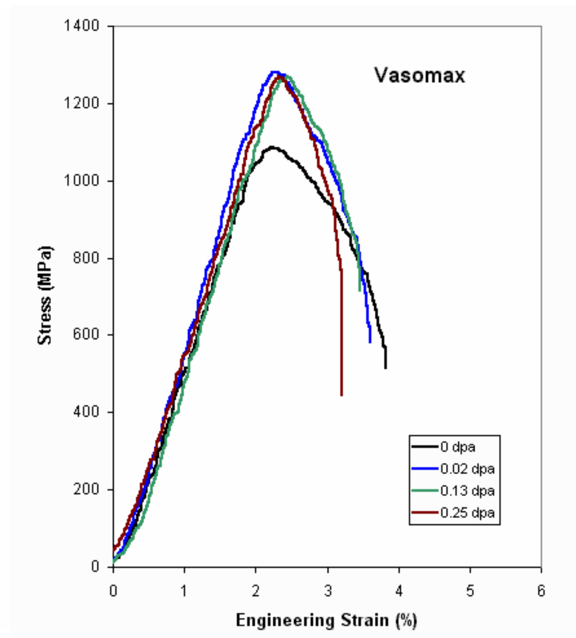
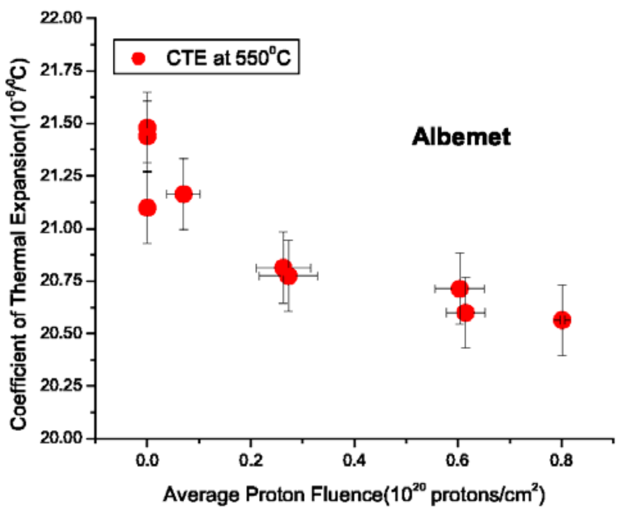
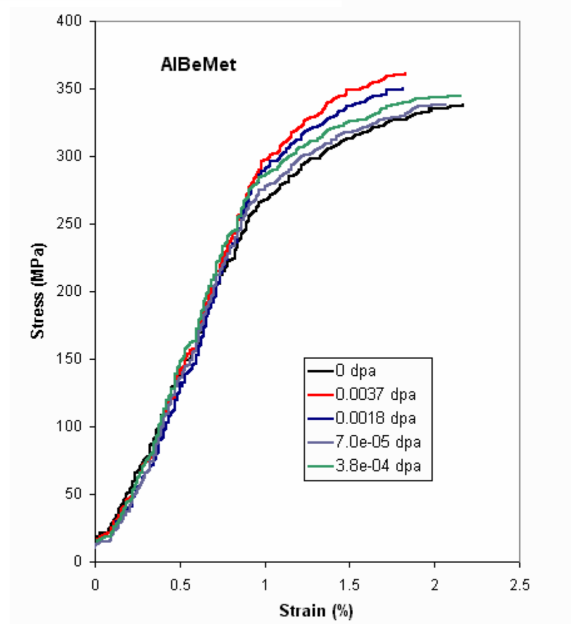
Radiation Damage Studies – Super-alloys with encouraging results





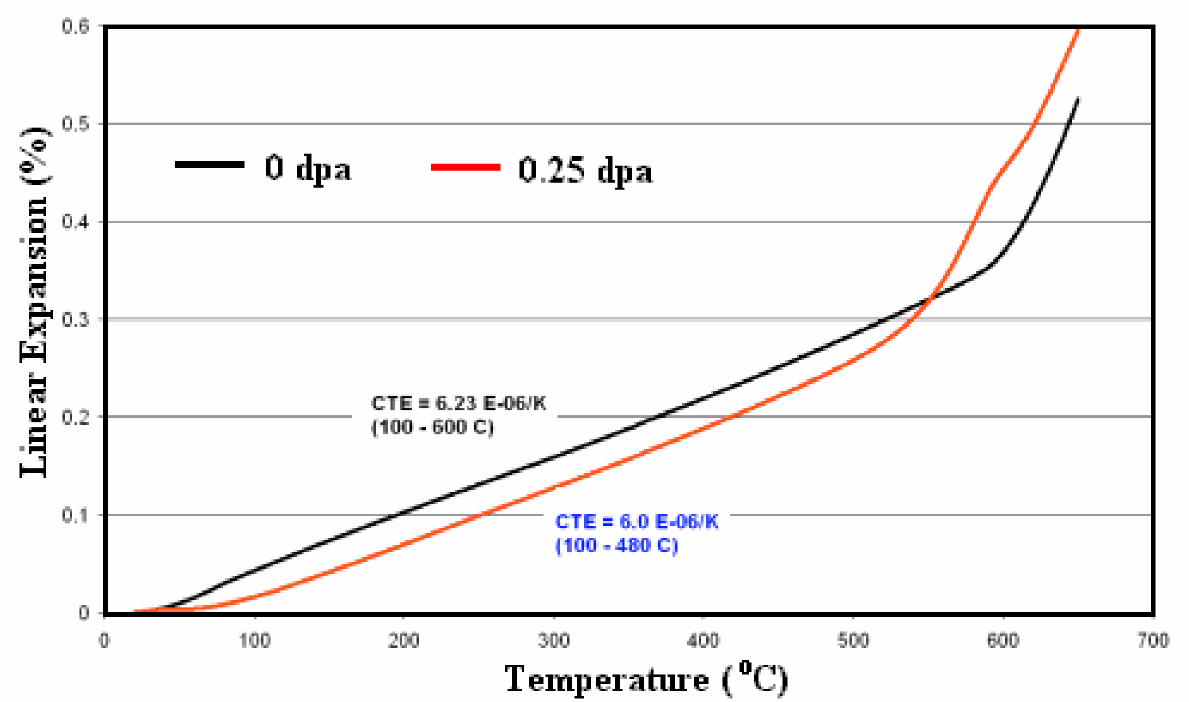


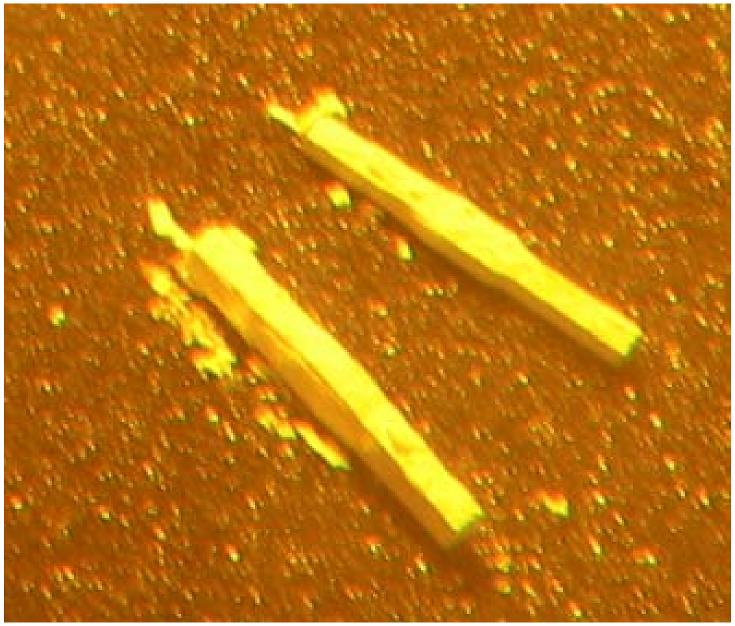




Radiation Damage Studies – High-Z Materials

Tantalum





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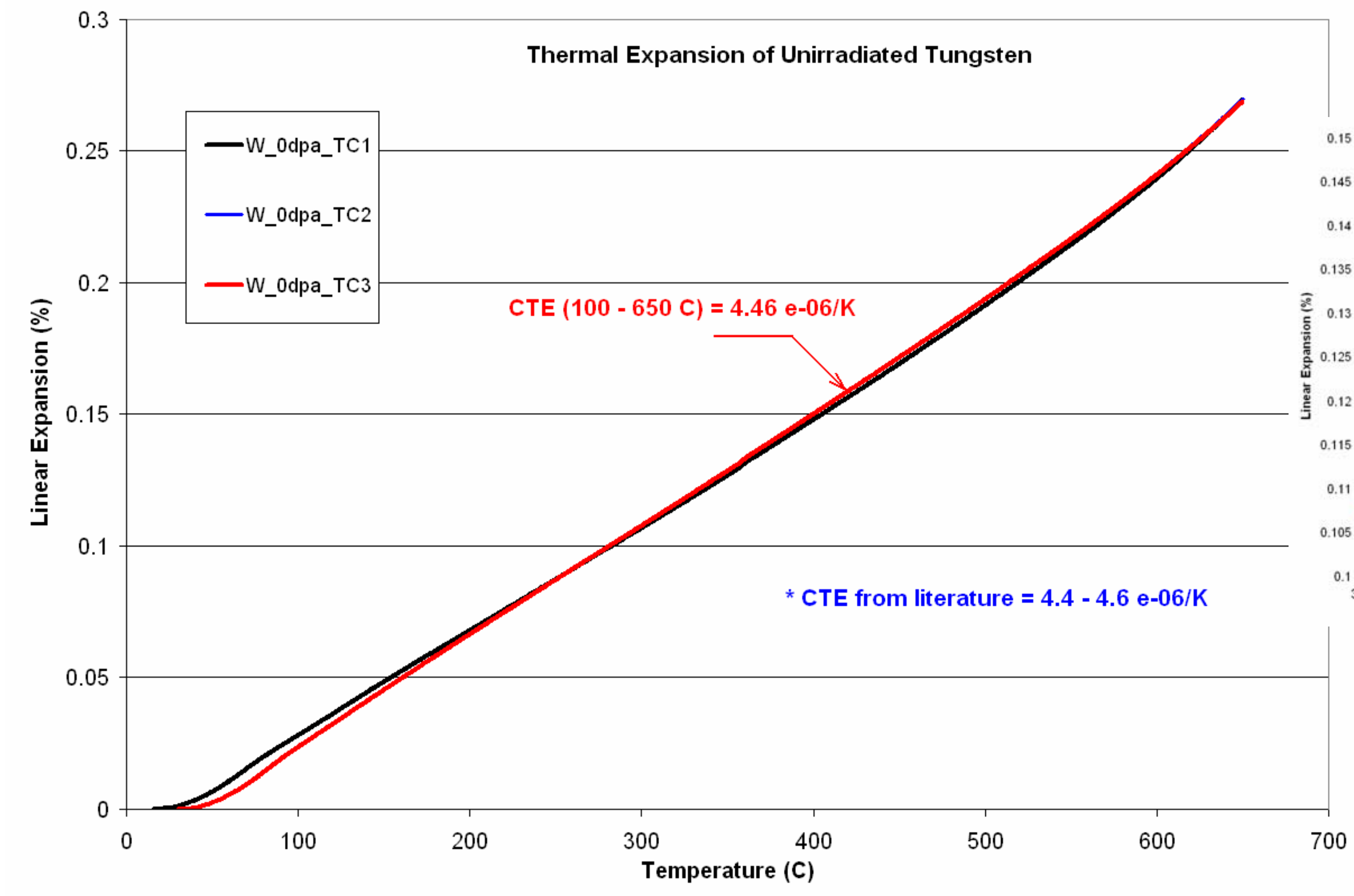
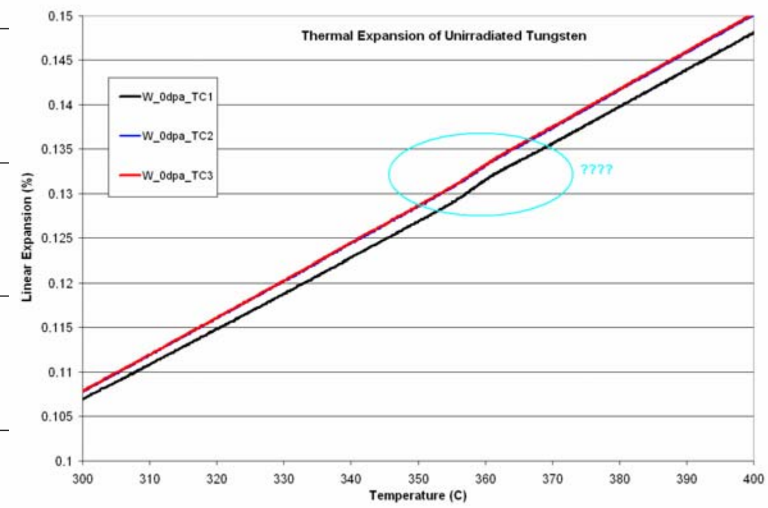
Tungsten

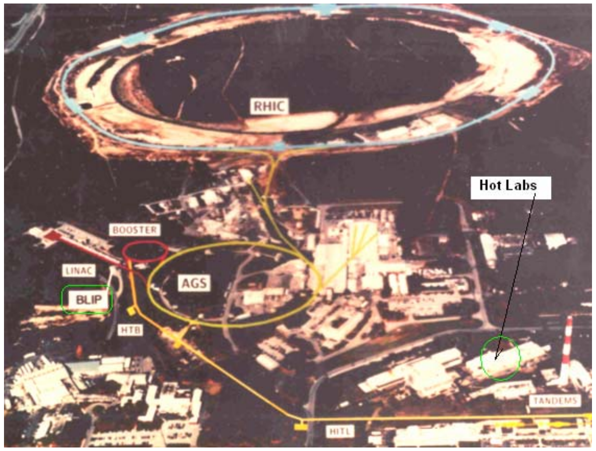


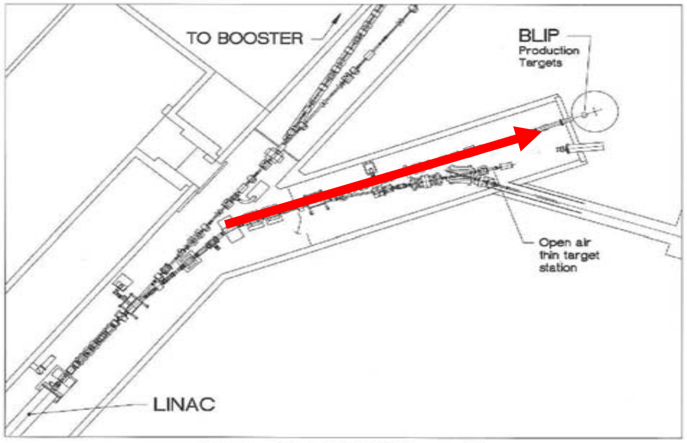
Thermal Expansion of Unirradiated Tungsten
W_0dpa_TC1
W_0dpa_TC2
W_0dpa_TC3
CTE (100 - 650 C) = 4.46 e-06/K
* CTE from literature = 4.4 - 4.6 e-06/K
Linear Expansion (%)
Temperature (C)
0.3
0.25
0.2
0.15
0.1
0.05
0
0
100
200
300
400
500
600
700



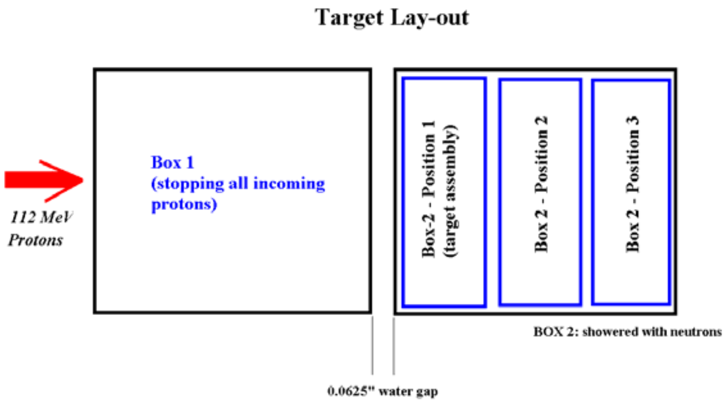
Thermal Expansion of Unirradiated Tungsten
W_0dpa_TC1
W_0dpa_TC2
W_0dpa_TC3
????
Linear Expansion (%)
Temperature (C)

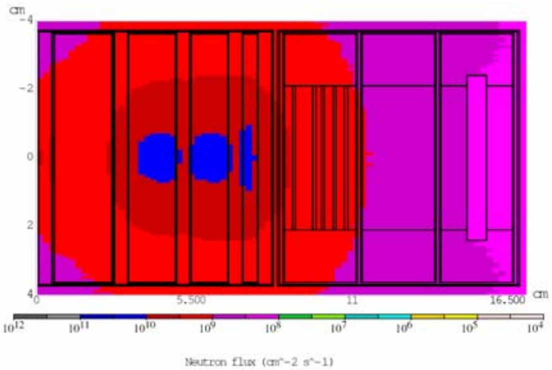
Neutron Irradiation Studies using the BNL Accelerator Complex and its potential benefits





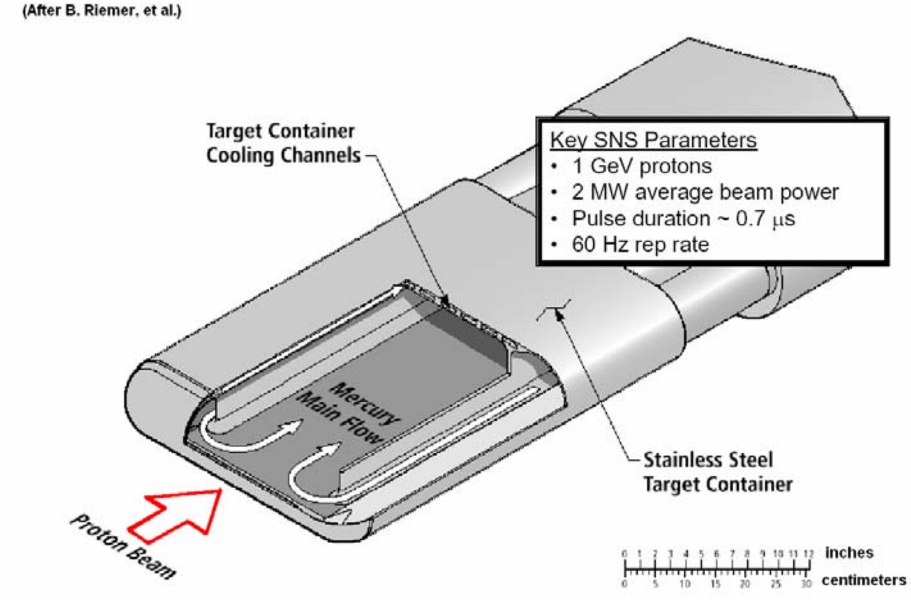
Schematic of BLIP Beam Line



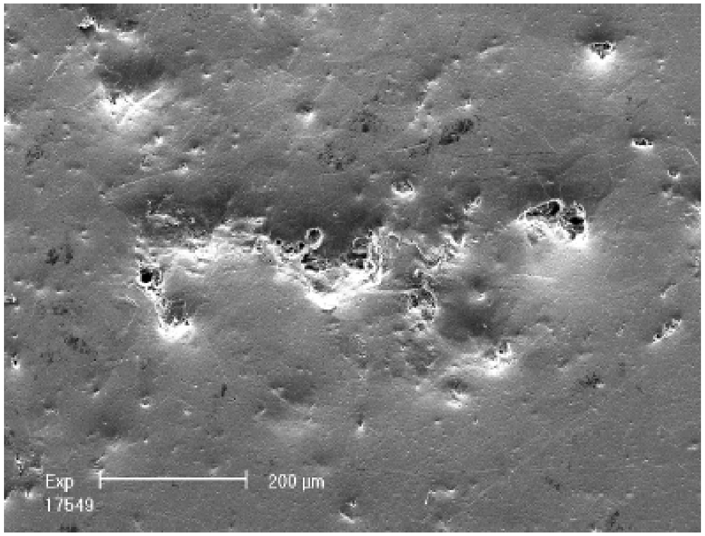


Whether Hg Jet or Solid, it is the functionality/survivability of the overall target infrastructure that is important

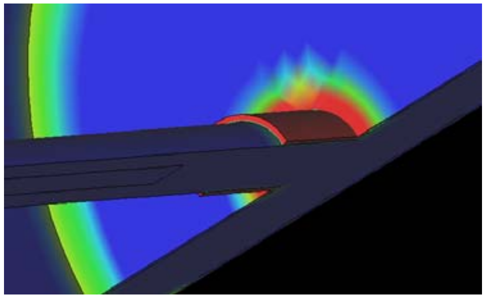
(After B. Riemer, et al.)



Molten Lead – Tantalum Vessel Target



Relevance to Hg Jet: Jet nozzle survivability



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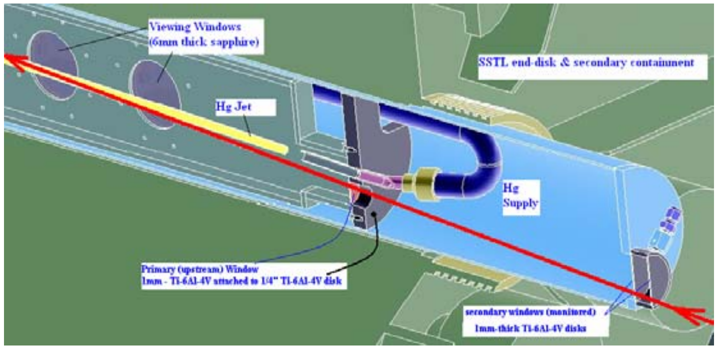
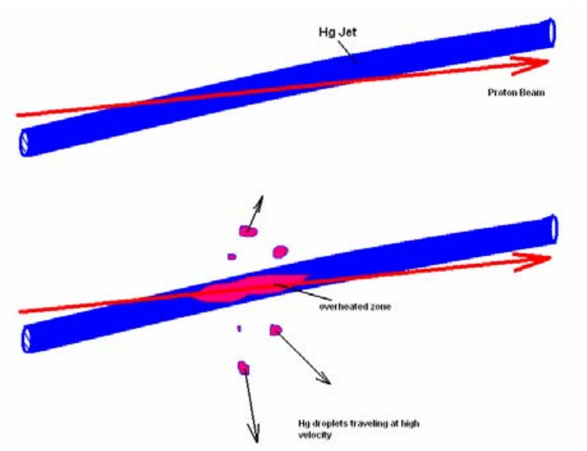
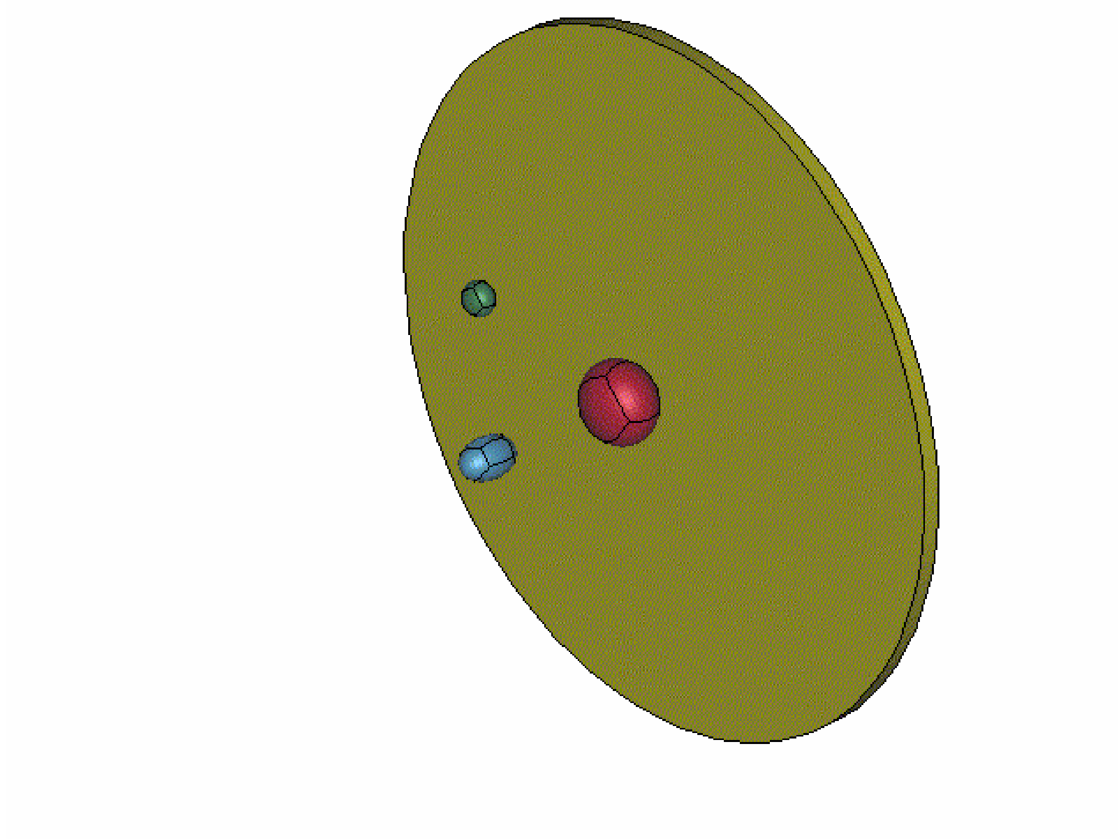
We need to venture outside the safety envelope to identify the limits

Simulations around MERIT for example can allow the study of beam structure/jet velocity/jet destruction etc.

Hg Explosion Simulations







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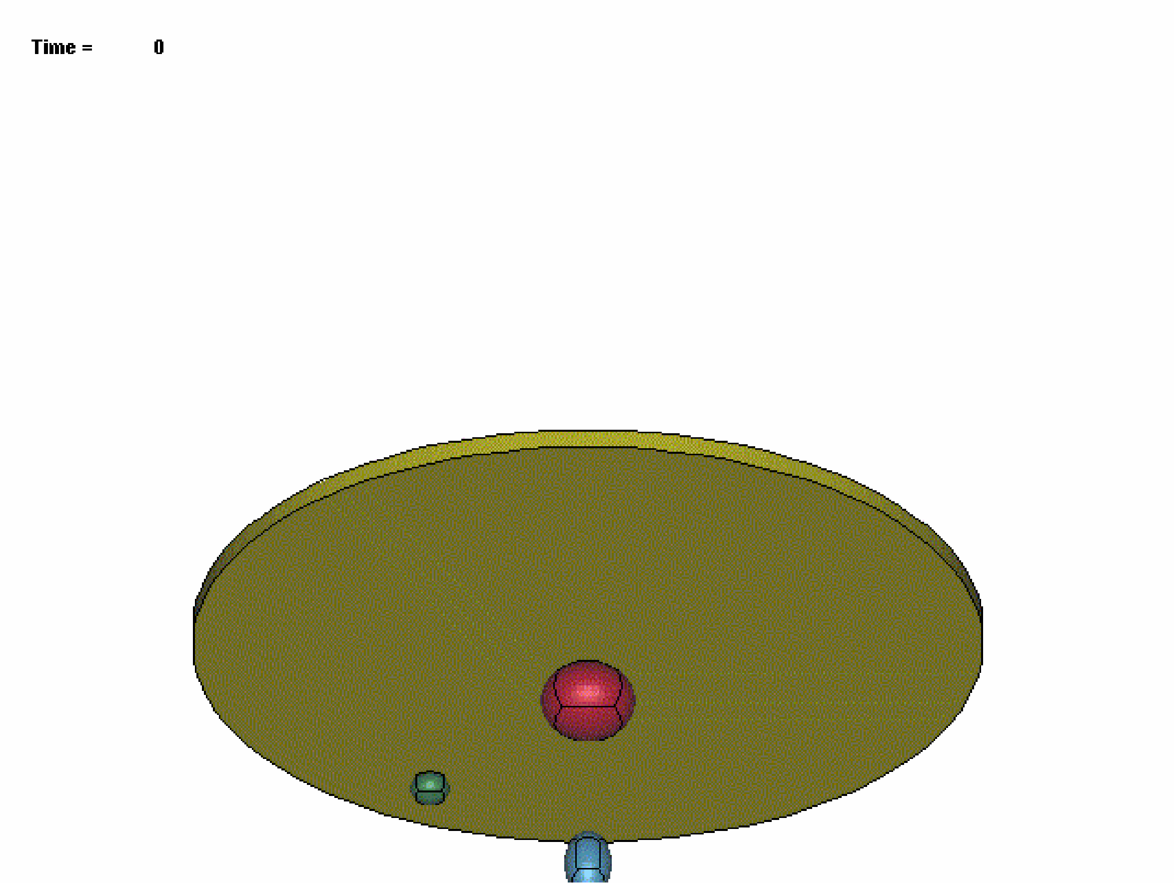
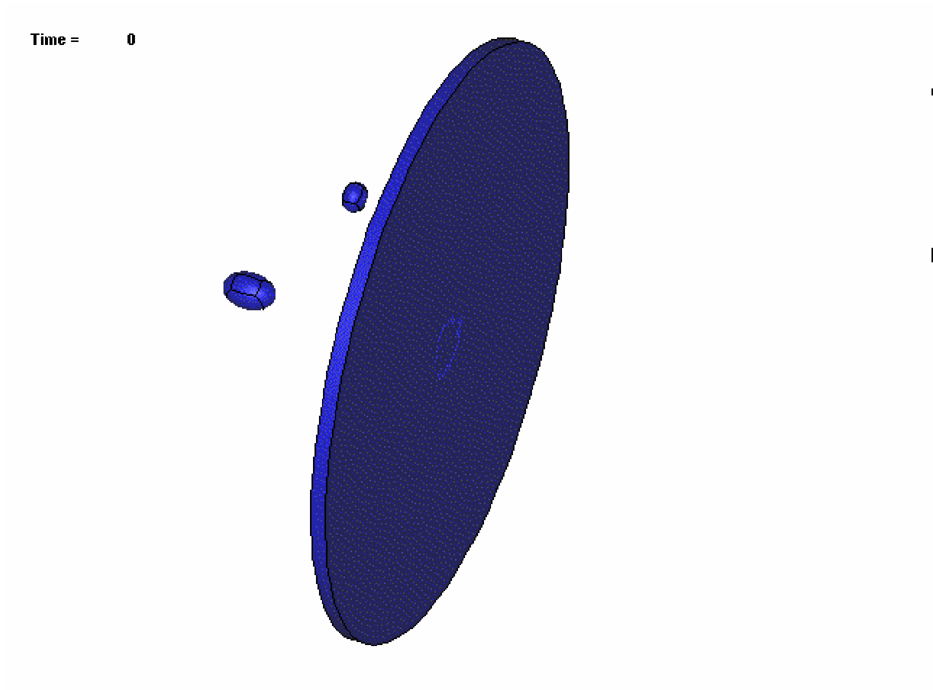
Hg explosions and Target Infrastructure





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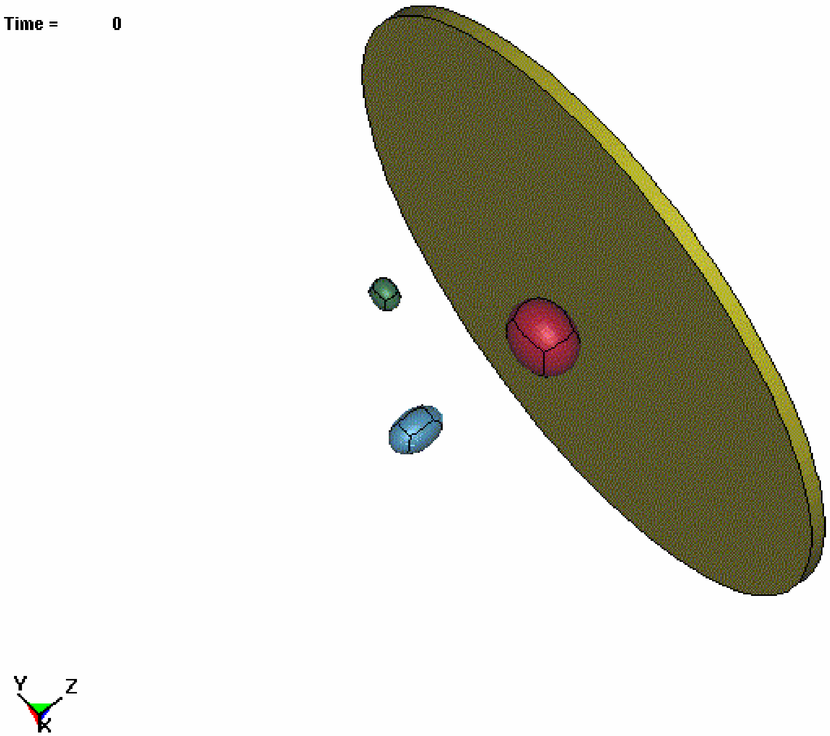
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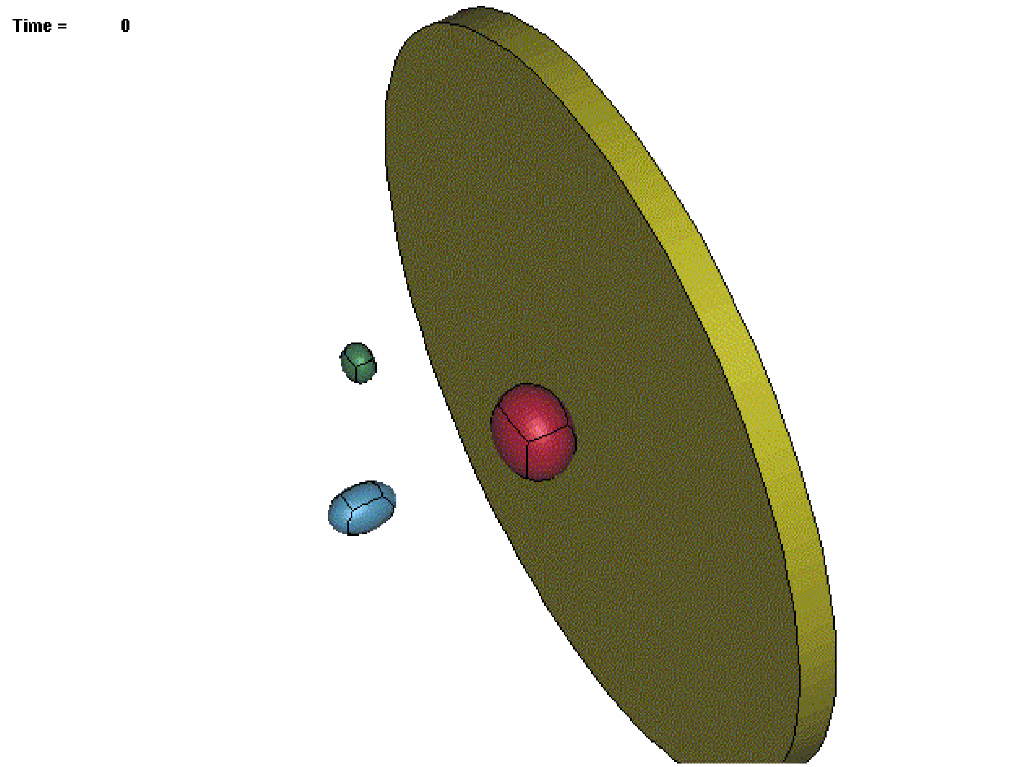
Y
Z
X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SUMMARY

- Keep inching closer to the baseline conditions of a multi-MW class accelerator by solving pieces of the puzzle individually and with proof-of-principle experiments
  - We do not have or can have all the conditions in a single setting because these accelerators have not materialized as of yet
- Focus on irradiation damage and thermal shock/fatigue of key components that could be the limiting factors in the lifetime of the overall experiments
- Appreciate the value of multi-physics based simulations for the engineering side of things (where actual limitations lie) and use them to push the envelope