Solid Targets for Neutrino Factory

REPORT to the Collaboration On

what have we been doing since we last reported!
(amazing how fast a year goes by !!!!)

N. Simos

Brookhaven National Laboratory

NuMu Collaboration - March 2006

Solid Targets & Power Limits

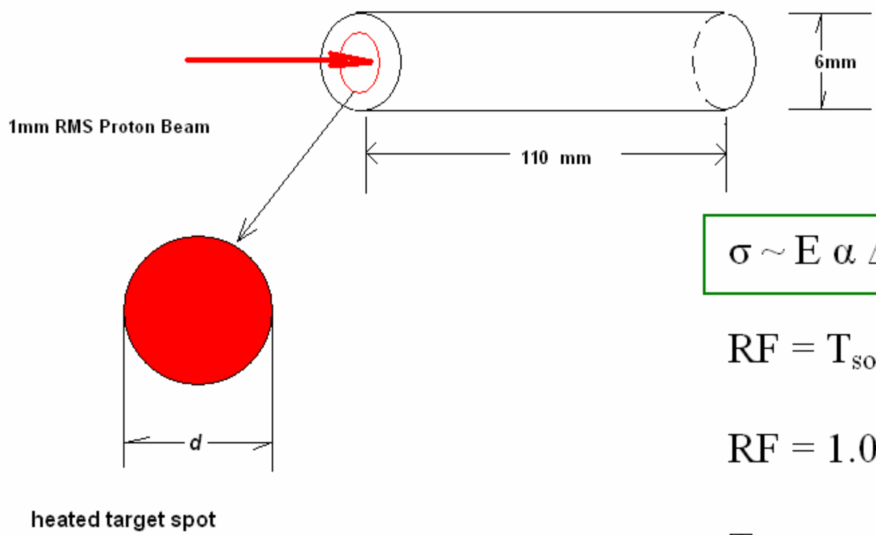
What do we need materials to possess to get us to multi-MW Power Levels?

- low elasticity modulus (limit ➔ Stress = $E\alpha\Delta T/1\text{-}2\nu$)
- low thermal expansion
- high heat capacity
- good diffusivity to move heat away from hot spots
- high strength
- resilience to shock/fracture strength
- resilience to irradiation damage

That's All !

The Fundamental Problem

24 GeV Protons on Copper Target



$$\sigma \sim E\,\alpha\,\Delta T / (1 - 2\nu) \cdot RF$$

$RF = T_{sound}/T_{pulse}$ (if $T_{sound} < T_{pulse}$)

$RF = 1.0$ (if $T_{sound} > T_{pulse}$)

$T_{sound} = d/V_s$

V_s = sound velocity in material

Parameters Affecting Shock Level in Solid Target

- Heat capacity (controlling temperature spike)
- Speed of sound in the material
- pulse length
- coeff. of thermal expansion
- Young's modulus

NOTE: If pulse is too short NO reduction in peak stress can be realized since heated zone does not have time to relax during deposition

How do these parameters control limits?

Change in hydrostatic pressure ΔP is related to the energy density change ΔE_m through the Gruneisen equation of state

$$\Delta P = \Gamma \rho \Delta E_m$$

Γ is the Gruneisen parameter related to material thermo-elastic properties such as:

Young's Modulus E
Poisson's ratio ν
density ρ
thermal expansion α
constant volume specific heat c_v.

$$\Gamma = [E/(1-2\nu)]\, \alpha/(\rho\, c_v)$$

What are we after on the way to 4 MW?

- Look for new alloys, composites, “smart” materials (low to high Z)
- Irradiation damage of these non-traditional materials
- Establish 4 MW-target feasibility by pushing the limits through state-of-art simulations (simulations based on physical models benchmarked on increasingly available experimental data)

Is there hope?

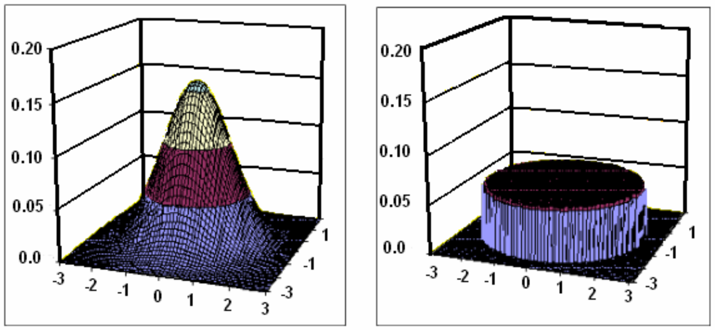
Several “smart” materials or new composites may be able to meet some of the desired requirements:

- **new graphite grades**
- **customized carbon-carbon composites**
- **Super-alloys (gum metal, albemet, super-invar, etc.)**

While calculations based on non-irradiated material properties may show that it is possible to achieve 2 or even 4 MW, irradiation effects may completely change the outlook of a material candidate

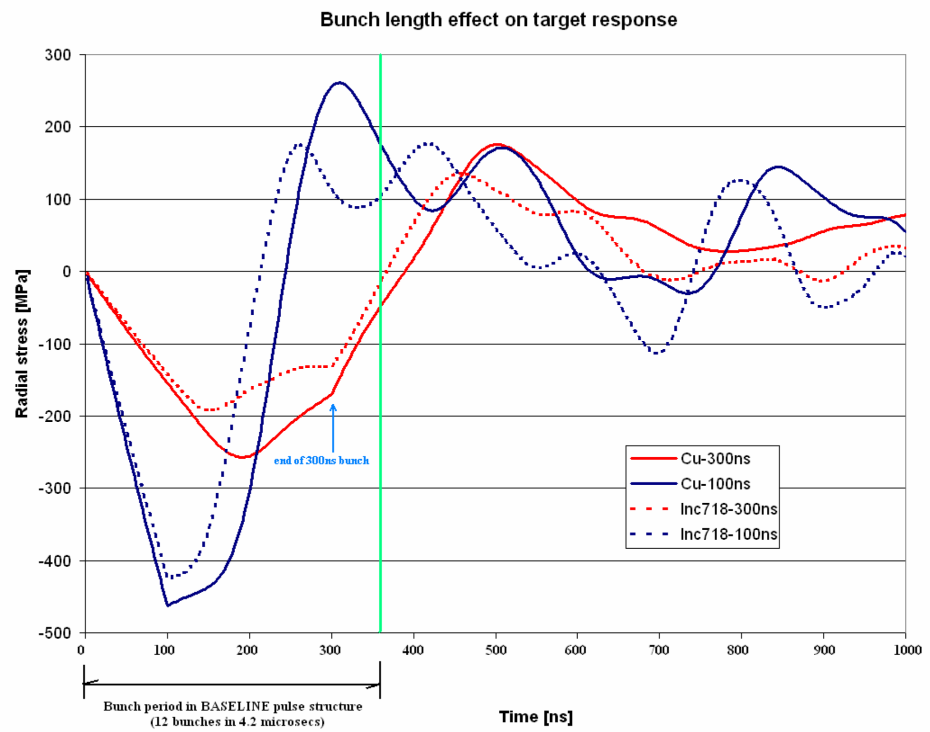
ONLY way is to test the material to conditions similar to those expected during its life time as target

Are there things we can do?



Gaussian and equivalent uniform beam distribution for same number of particles

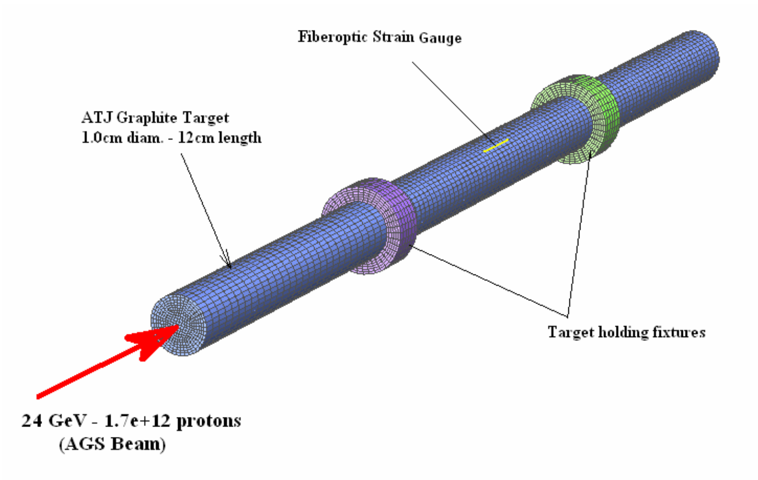
Target	25 GeV	16 GeV	8 GeV
	Energy Deposition (Joules/gram)		
Copper	376.6	351.4	234

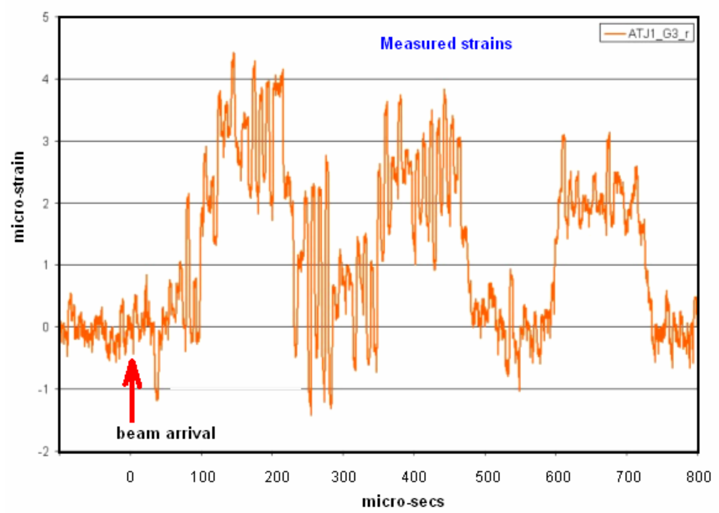


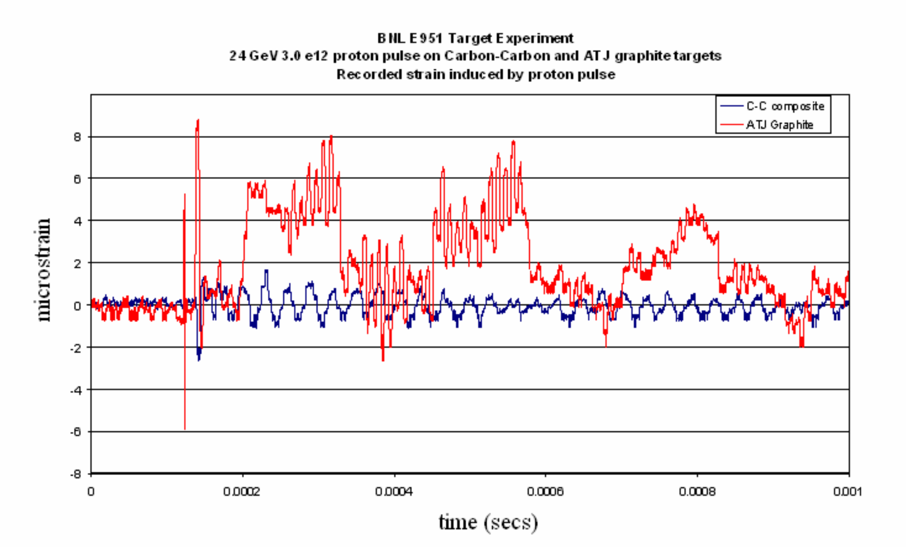
Relevant Activity Status

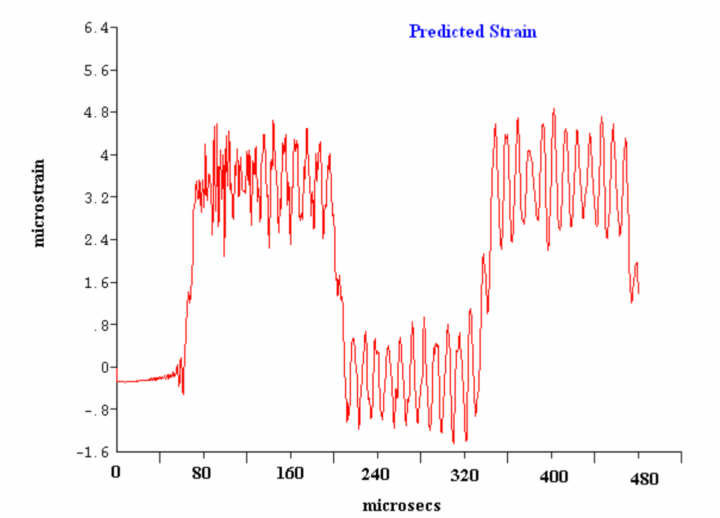
- Beam on targets (E951)
- Material irradiation
- New activities
  - irradiation studies/beam on targets
  - Laser-based shock studies
- Simulations and benchmarking
  - LS-DYNA (highly non-linear simulations which reflect on the 4-MW conditions)

CC Shock Response (BNL E951)









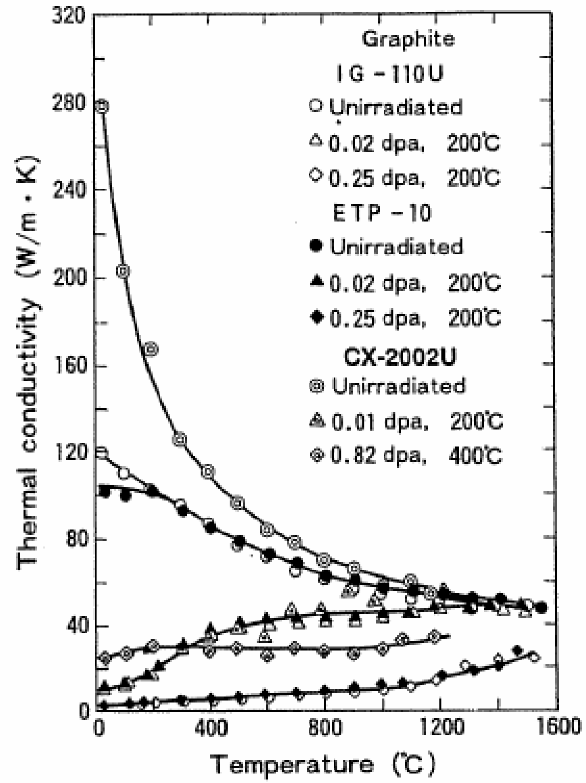
WHY Carbon-Carbon and not graphite?

IRRADIATION EFFECTS ON GRAPHITE

Irradiation has a profound effect on thermal conductivity/diffusivity

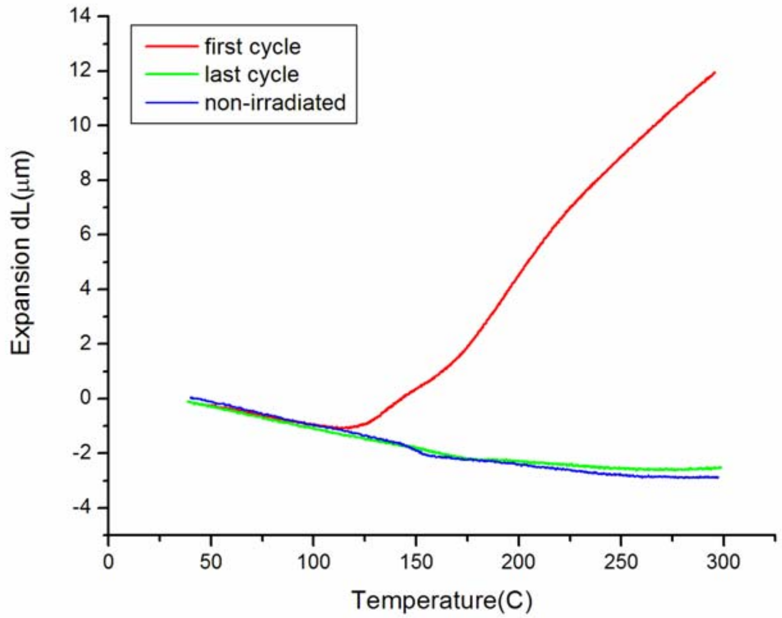
CC composite at least allows for fiber customization and thus significant improvement of conductivity.

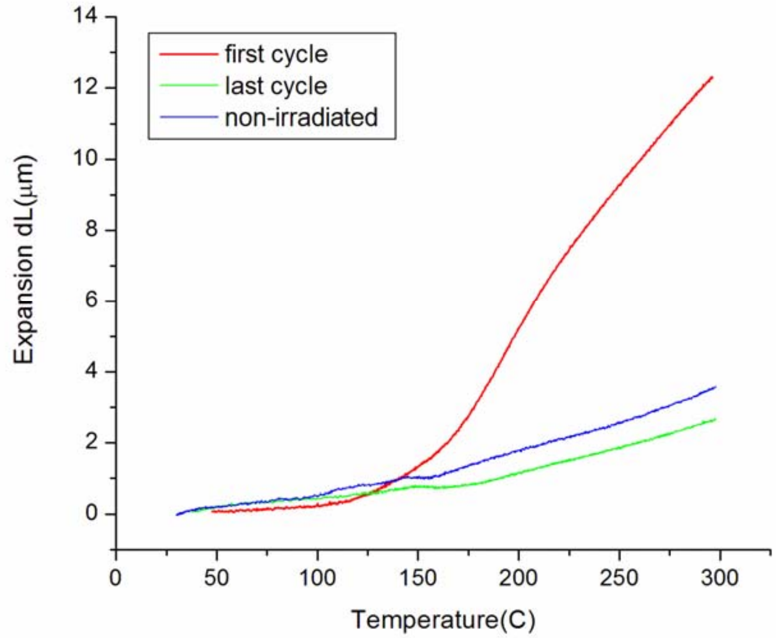
NOTE that assessment of irradiation effects on conductivity of CC composite yet to be completed



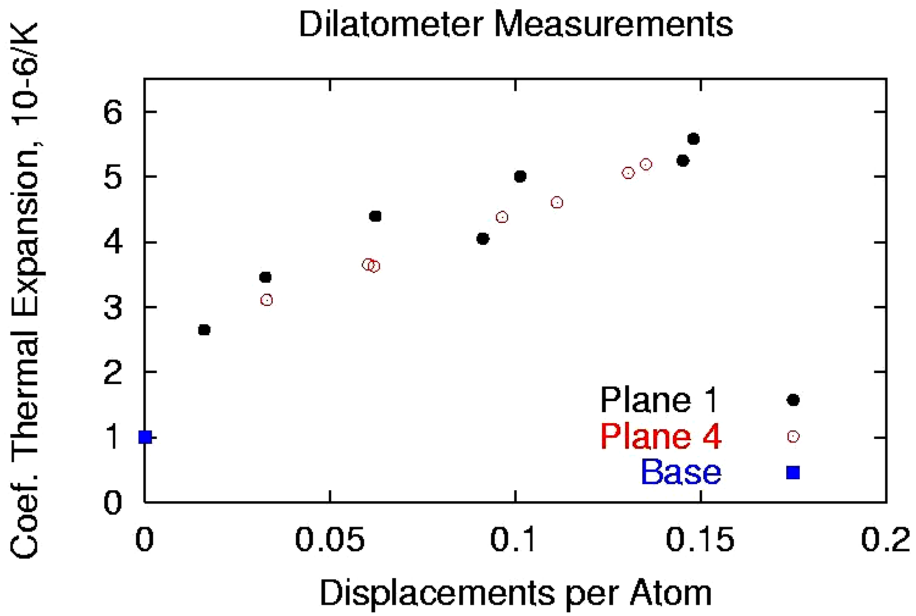
Thermal conductivity of neutron-irradiated graphites.

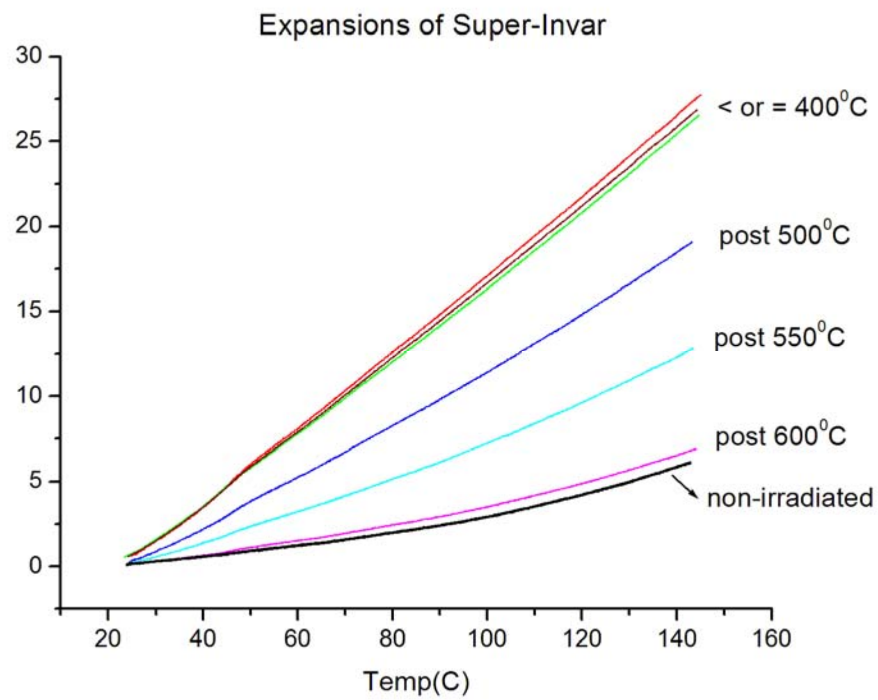
CC composite “annealing” behavior

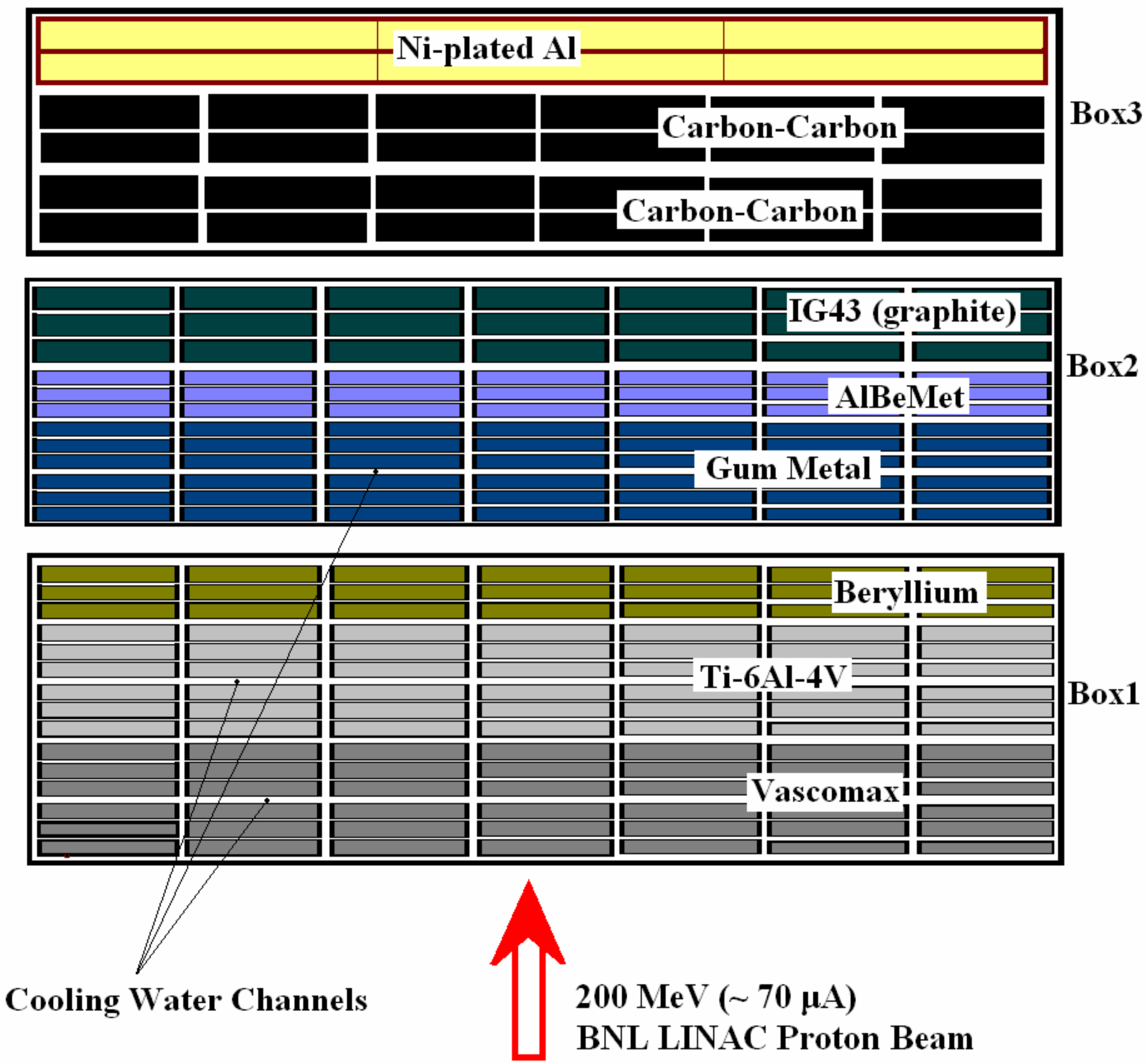




Super Invar: Serious candidate?

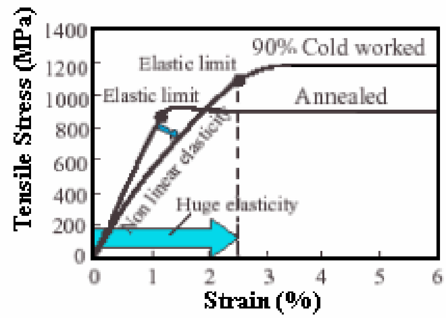


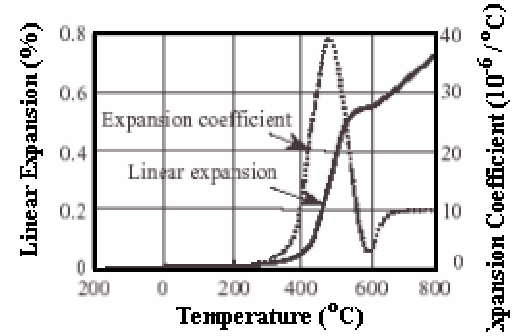


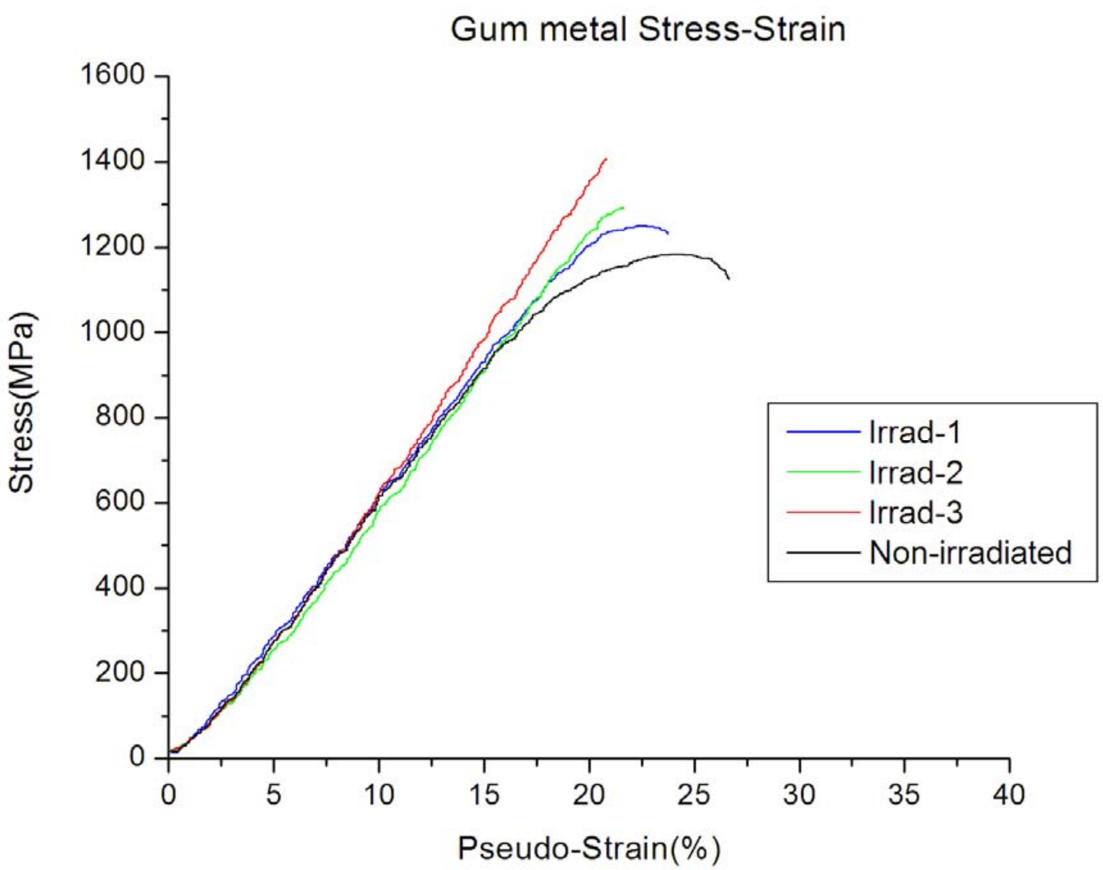

Ni-plated Al
Carbon-Carbon
Carbon-Carbon
Box3
IG43 (graphite)
AlBeMet
Gum Metal
Box2
Beryllium
Ti-6Al-4V
Vascomax
Box1
Cooling Water Channels
200 MeV (~ 70 µA)
BNL LINAC Proton Beam

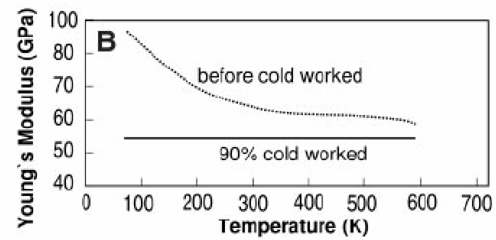
GUM Metal

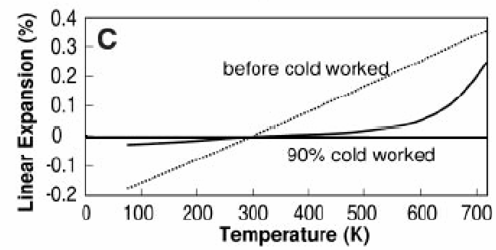
90% cold-worked may be of interest (if it holds these properties after irradiation)

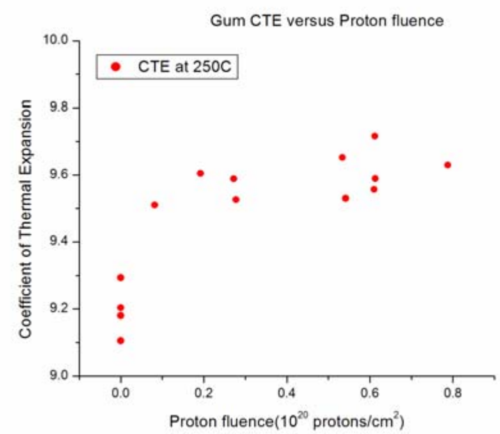




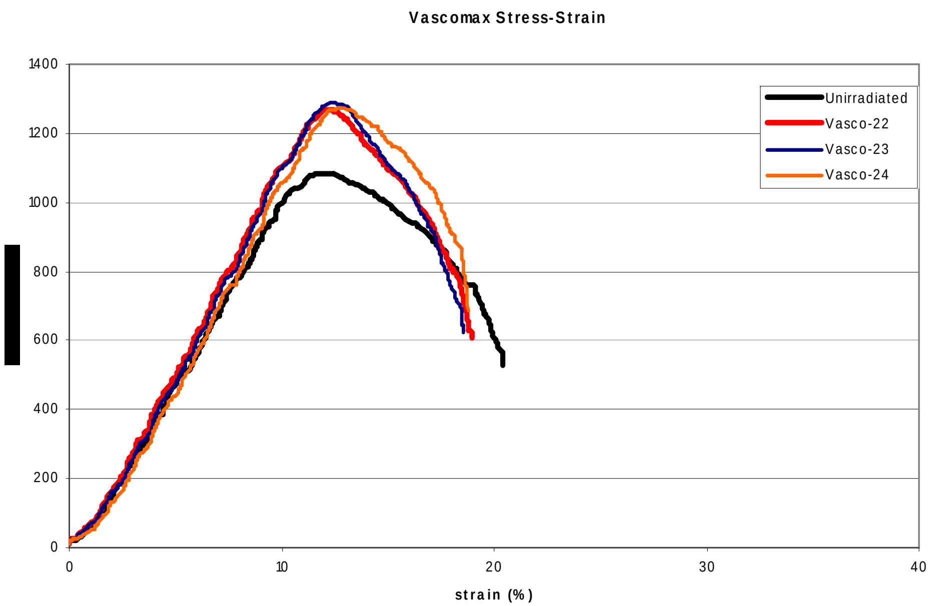


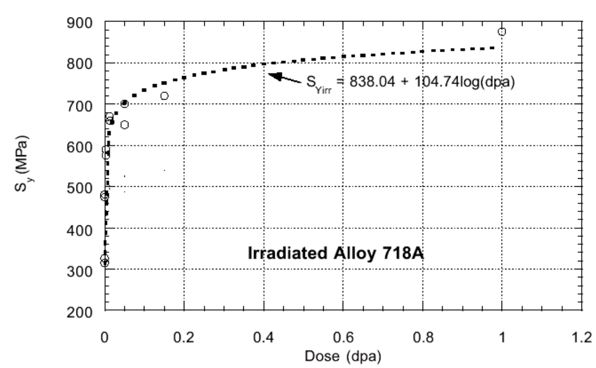






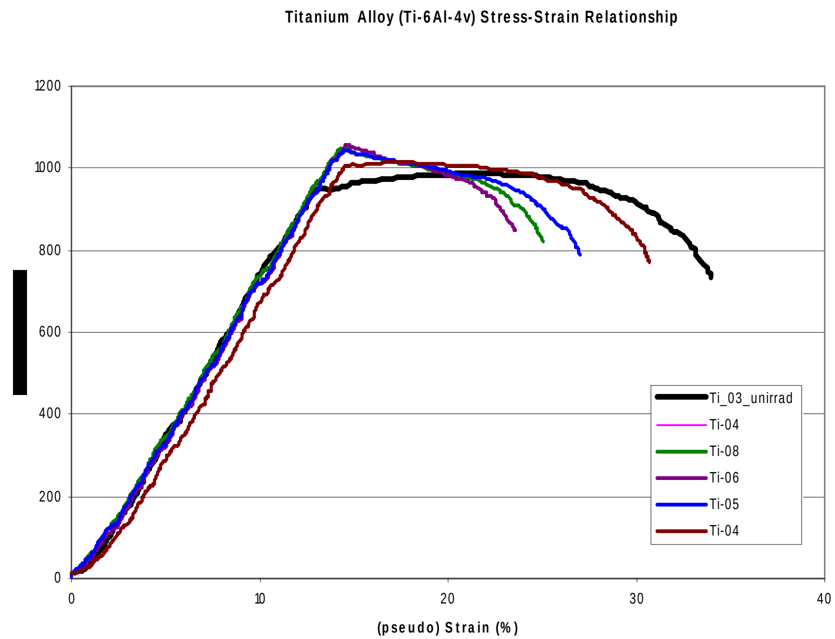
Vascomax

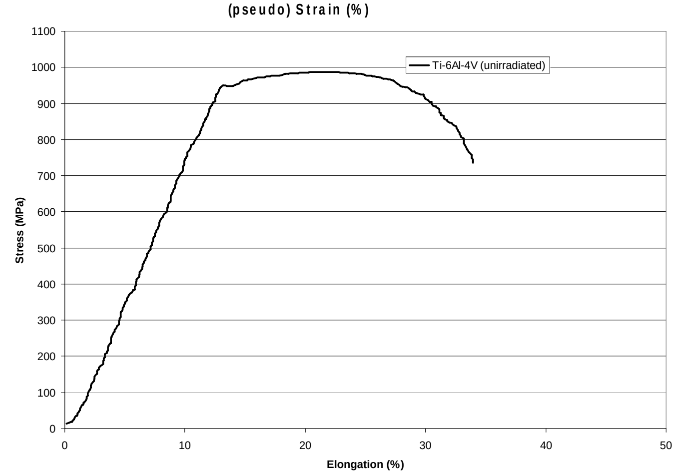




Effect of irradiation in HFIR on the room-temperature yield strength of Alloy 718A

Ti alloy (6Al-4V)





Solid Targets – How far can they go?

1 MW ?	4 MW ?
Answer is **YES** for several materials Irradiation damage is of concern Material irradiation studies are still 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

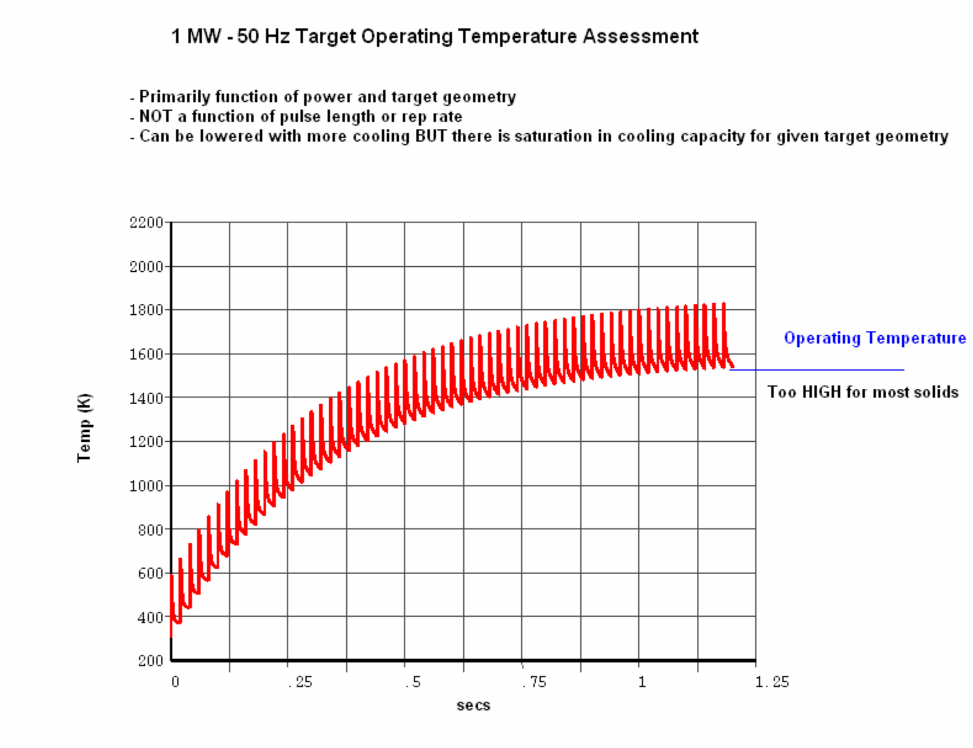
Why so?

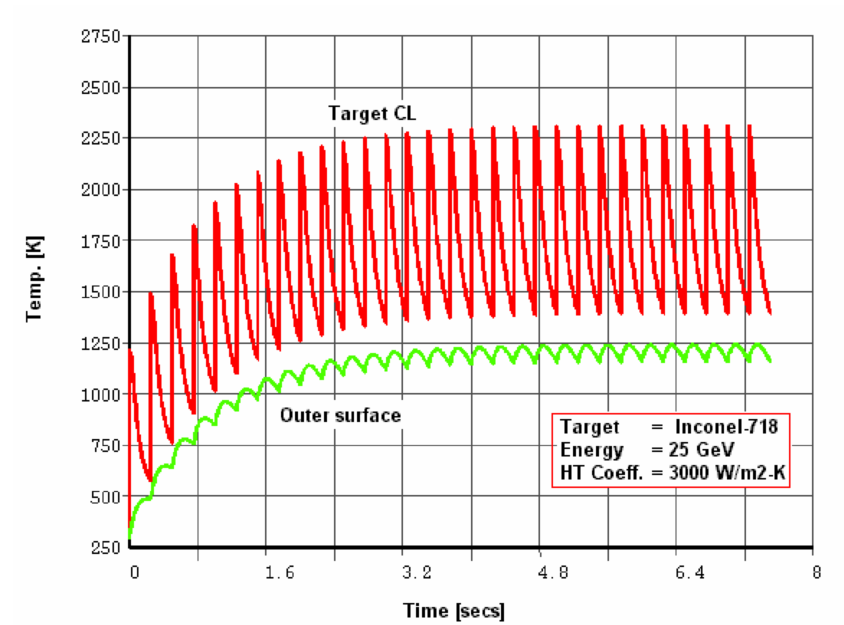
It is not ONLY the thermo-mechanical shock due to pulse intensities that prevents targets from operating at high power BUT also the ability to remove heat from target

Even at 1 MW it is tough to keep a high-Z target operating within reasonable temperatures

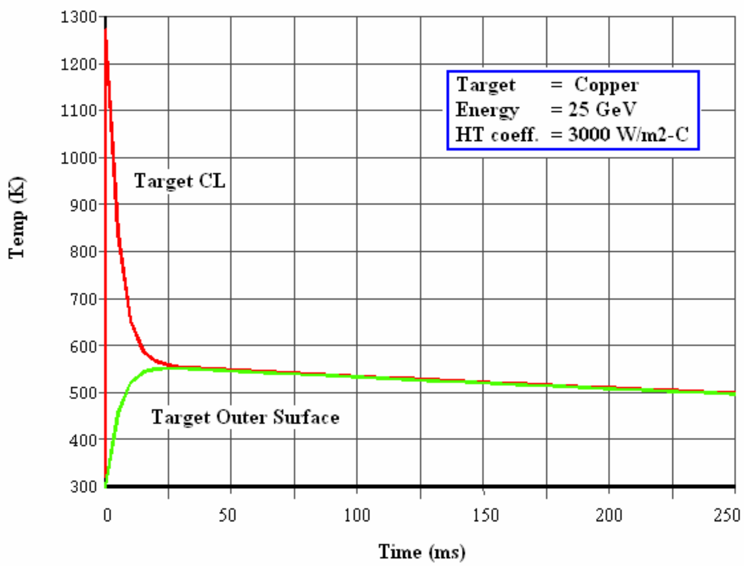
2 MW is most likely the limit for low-Z stationary target (Carbon composite, graphite) operating at low rep rate and 2mm beam spot

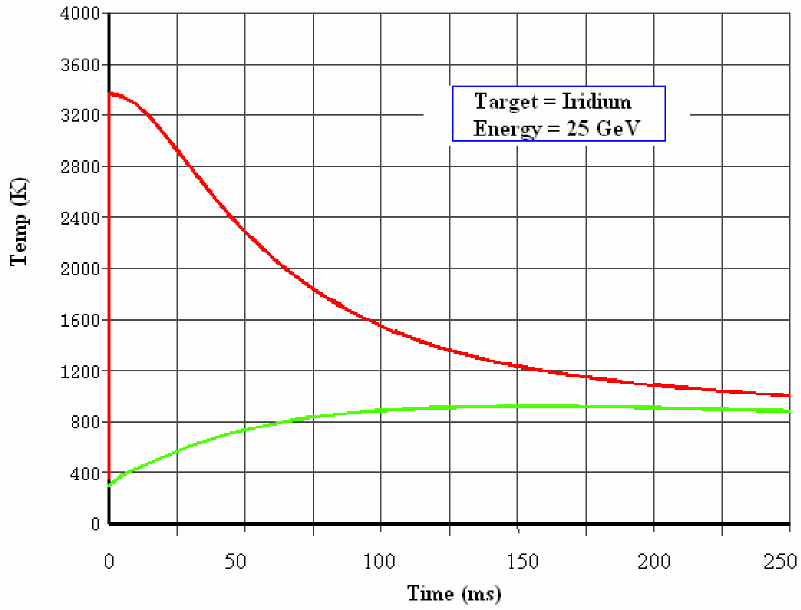
Operating Solid Targets at 1 MW – 24 GeV





Solid Target Rep-Rate Challenge





“Moving” Solid Targets

A number of scenarios have been studied

1 MW ?	4 MW ?
YES	LIKELY

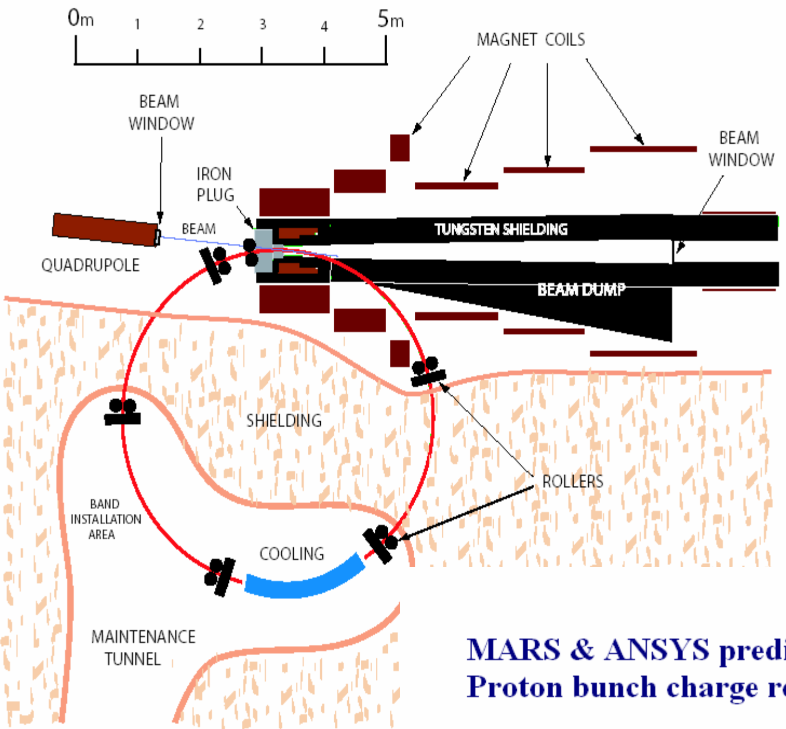
Issues

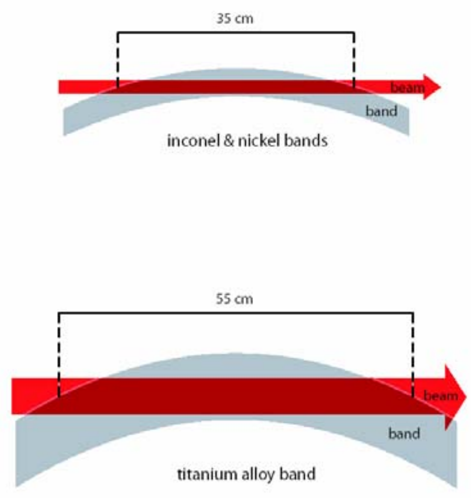
Beam size

Irradiation damage

Operational challenges

Rotating Band Concept





MARS & ANSYS predictions for pion yields, energy depositions and induced stress.
Proton bunch charge resulting in 3.2 x 10^{13} captured protons.

band material	inconel 718		Ti-alloy		nickel	
proton energy [GeV]	6	24	6	24	6	24
captured π^+ yield/proton	0.102	0.303	0.080	0.249	0.102	0.302
captured π^- yield/proton	0.105	0.273	0.083	0.224	0.105	0.292
$ppp^{3.2}$ [10^{13}]	15.5	5.56	19.6	6.78	15.5	5.39
$E^{3.2}_{pulse}$ [kJ]	149	214	188	260	149	207
$U^{3.2}_{max}$ [J/g]	32.0	31.7	25.6	21.3	32.5	37.4
$\Delta T^{3.2}_{max}$ [°C]	74	73	49	40	71	81
stress, $VM^{3.2}_{max}$ [MPa]	330	360	72	68	330	340
% of fatigue strength	53-69%	58-75%	10-14%	10-13%	N.A.	N.A.

A "Liquefied" Particle Bed Concept

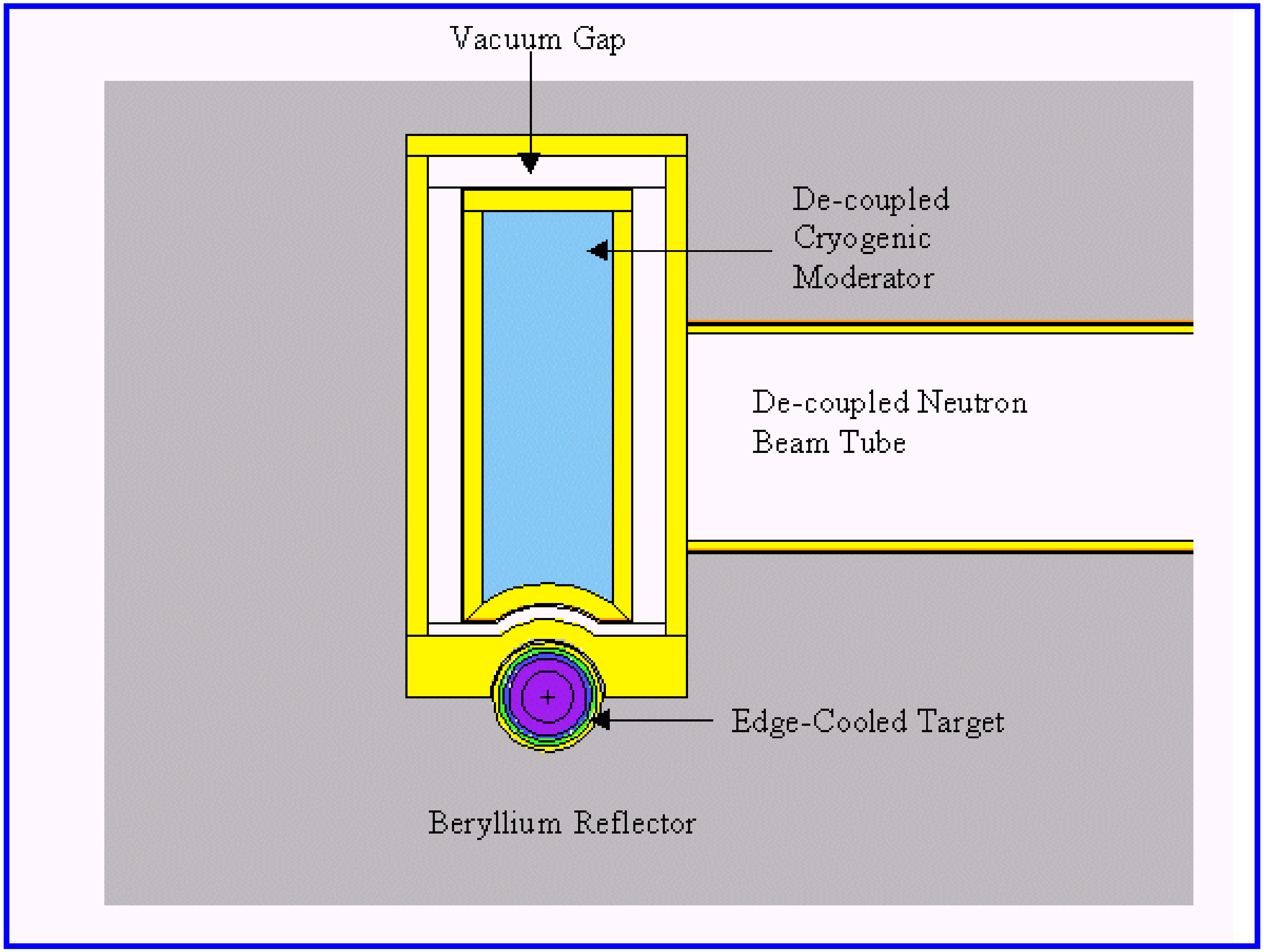
WHAT IS IT ?

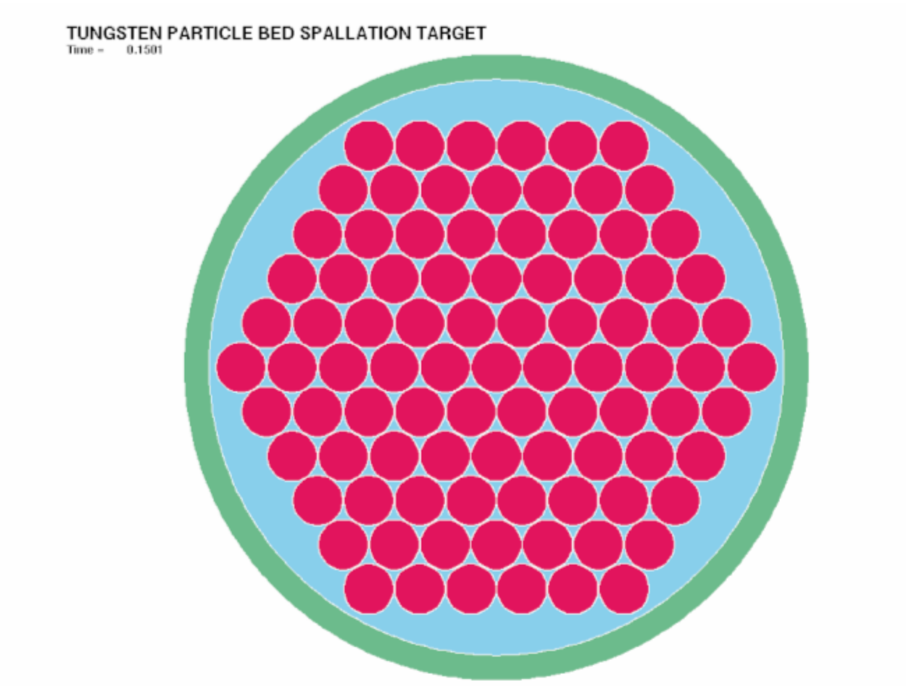
- **A loosely packed particle bed wetted by a liquid metal (i.e. Hg)**
- **particle/liquid interaction ➔ "attenuate" the shock induced + provide yield**
- **Randomly packed particle beds have been considered in the past (BNL, CERN)**

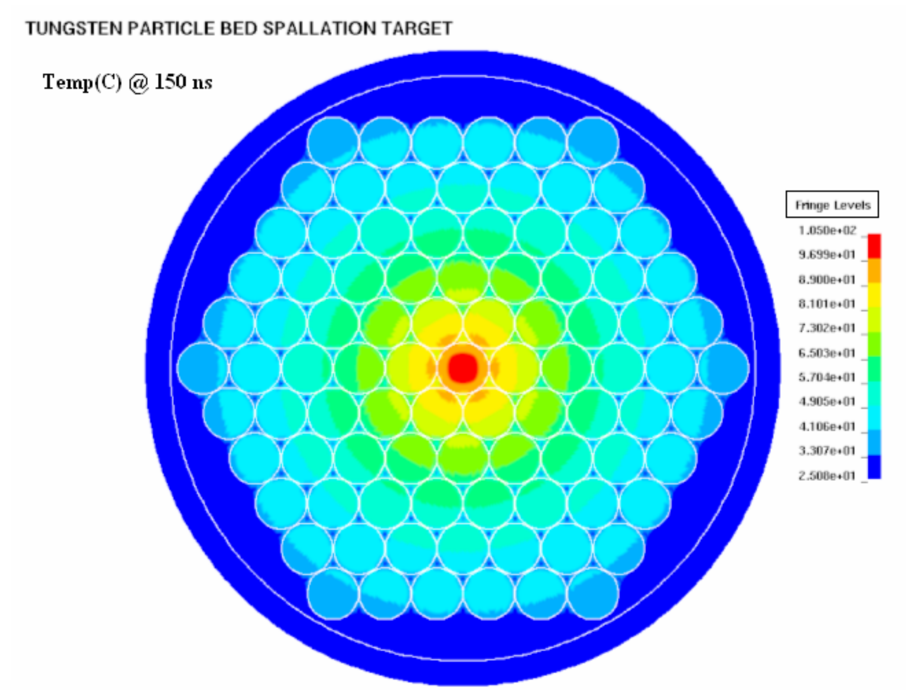
  - **pebble bed reactor**
  - **neutron sources**
  - **SNS collimators/absorbers**
  - **Studies of poro-elasticity in granular media**

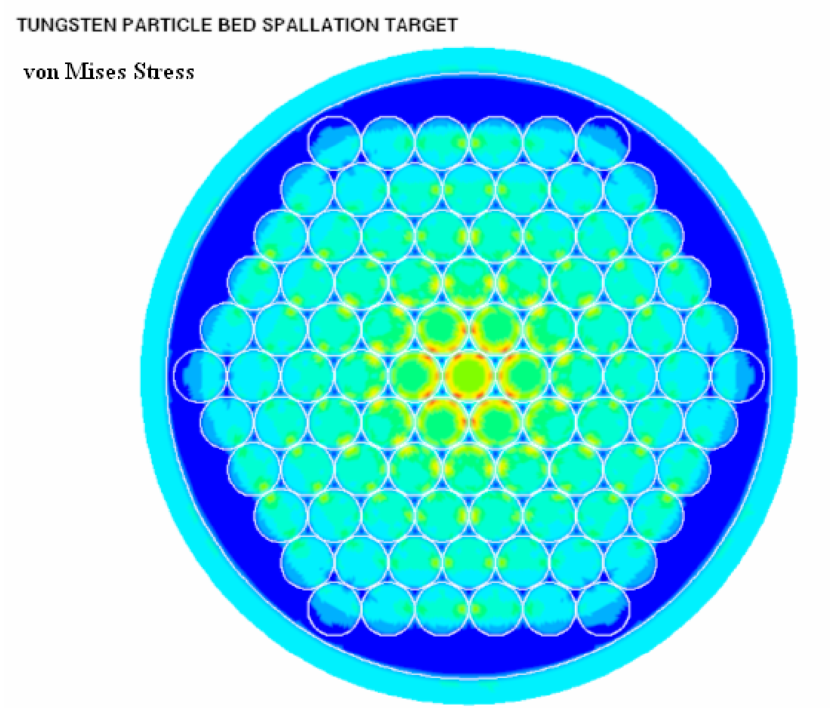
Concept for an Edge Cooled Target for Use at the BNL-AGS

H.Ludewig, N. Simos, J. Hastings, P. Montanez, and M. Todosow.



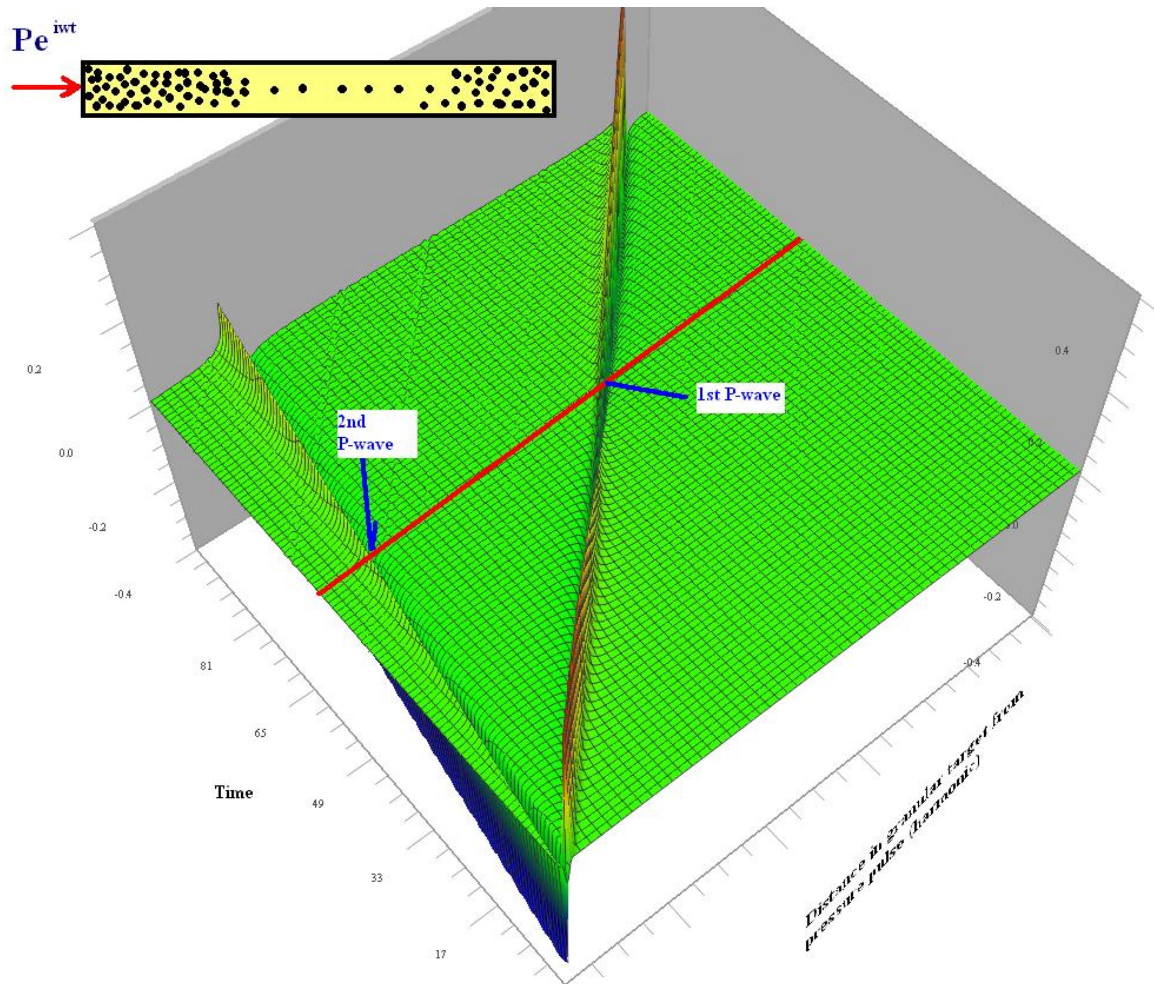

TUNGSTEN PARTICLE BED SPALLATION TARGET
Time = 0.1501


TUNGSTEN PARTICLE BED SPALLATION TARGET
Temp(C) @ 150 ns
Fringe Levels
1.050e+02
9.699e+01
8.900e+01
8.101e+01
7.302e+01
6.503e+01
5.704e+01
4.905e+01
4.106e+01
3.307e+01
2.508e+01


TUNGSTEN PARTICLE BED SPALLATION TARGET
von Mises Stress

Experimental + Theoretical work has been done in this area

Figure shows analytical results of a pulse propagating in the medium with two (2) velocities ➔ leading to sharing of energy



WHAT'S NEXT?

Phase III Target Irradiation

Target Heat Removal Experiments

Series of Post-Irradiation Tests/Analyses

Off beam Shock Tests

Last (but not least) Beam-Target Simulations

PHASE III Target Irradiation

Materials exhibiting interesting properties

(Carbon-Carbon, super Invar, AlBeMet, Tantalum, Gum Metal)

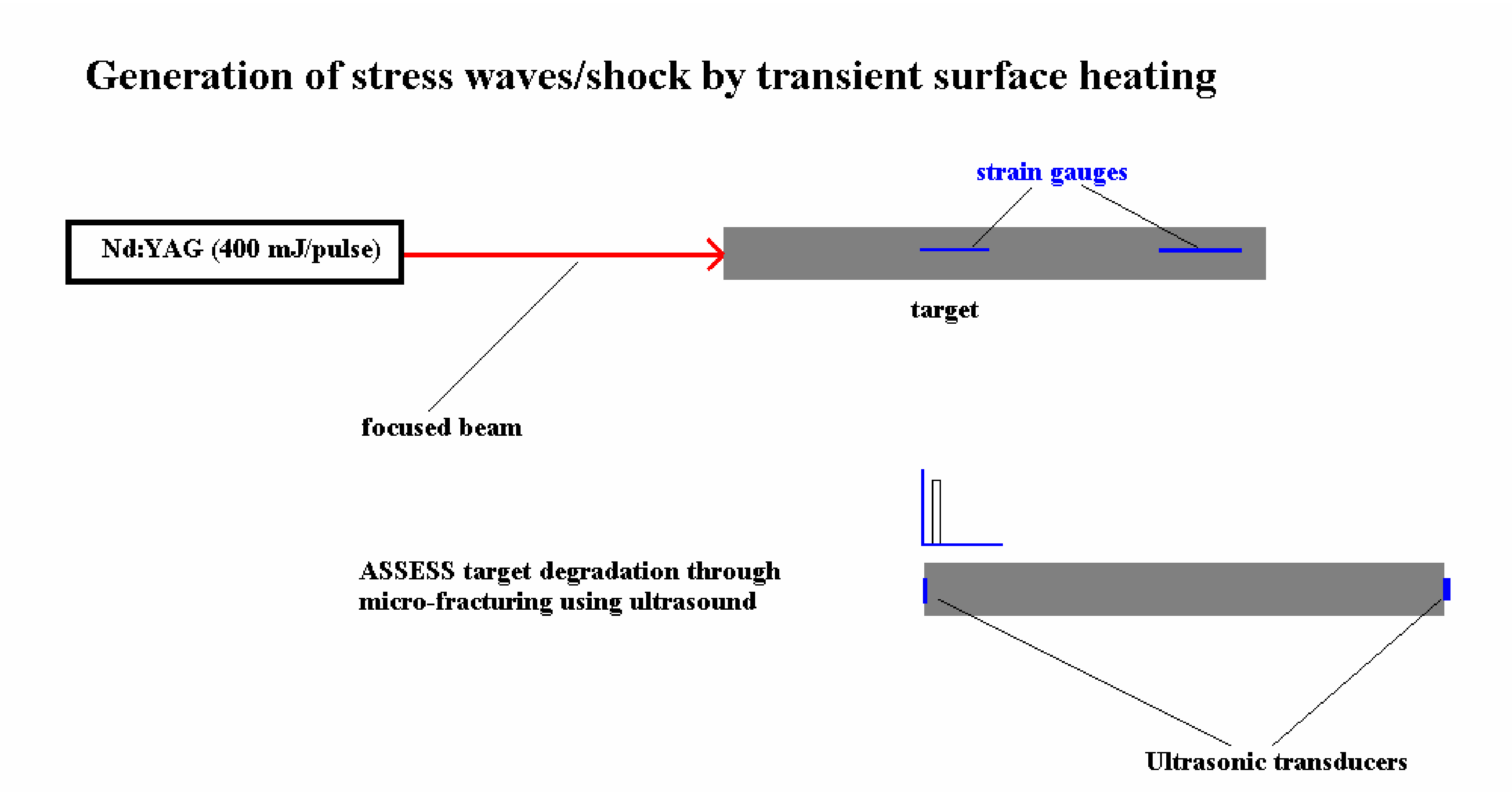
are going back in

GOAL: assess the relation between damage and self-healing through annealing

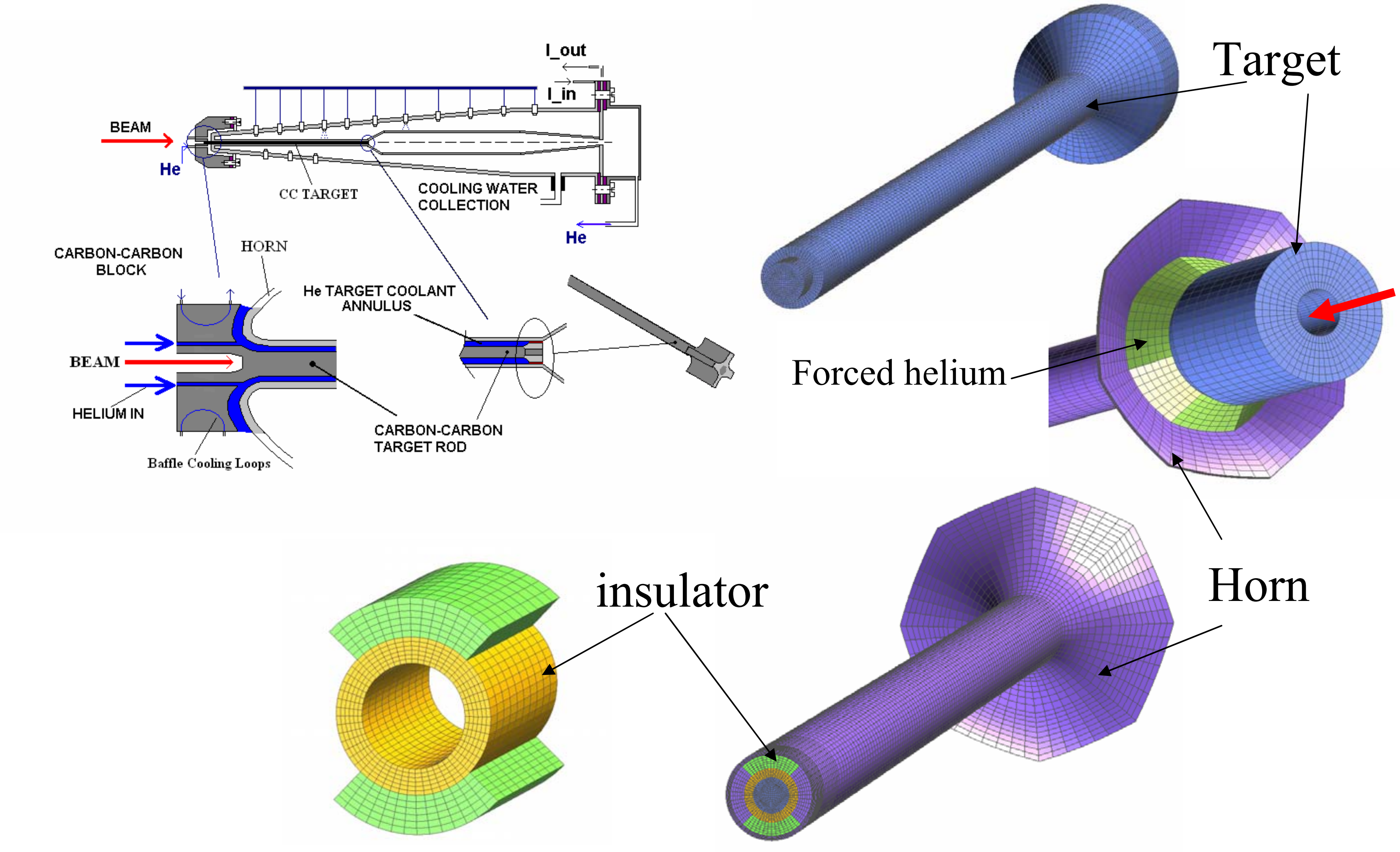
Push for damage up to 1 dpa.

Off-beam Target Shock Studies

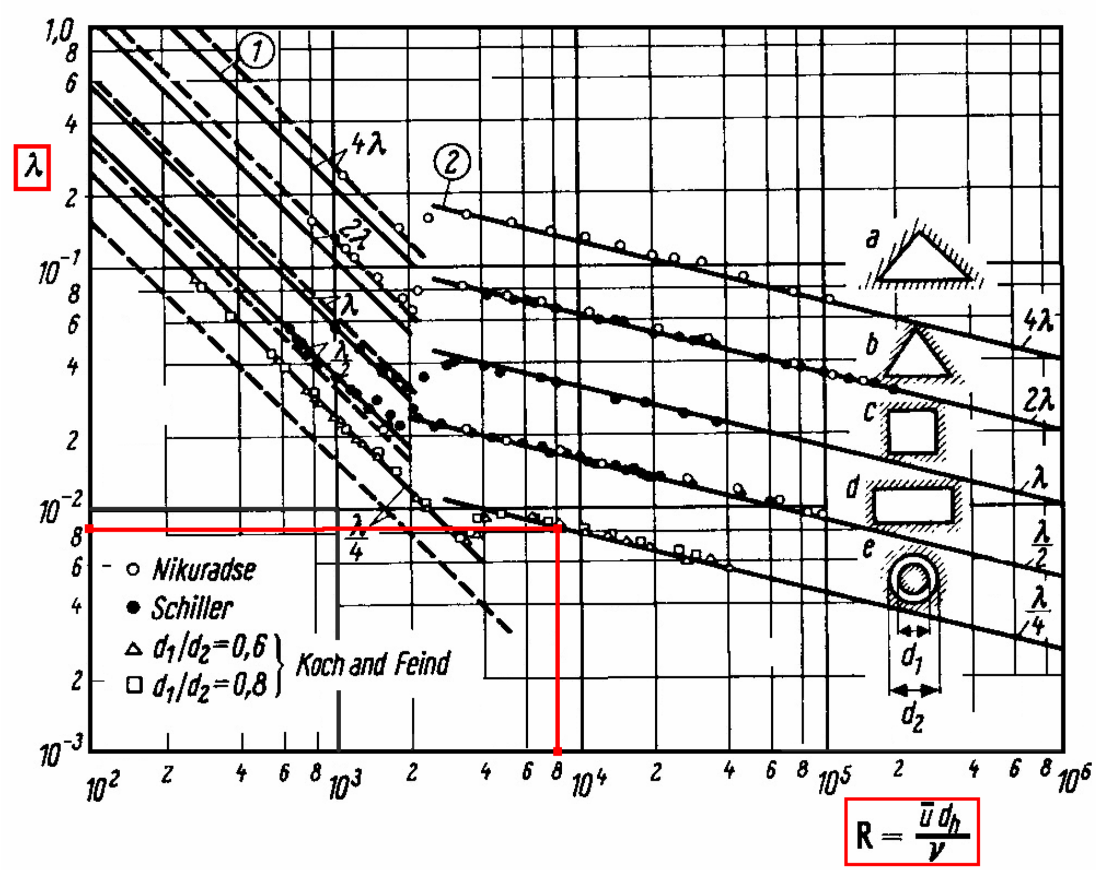
Use of High-Power Laser (BNL) – to be completed by Summer '06



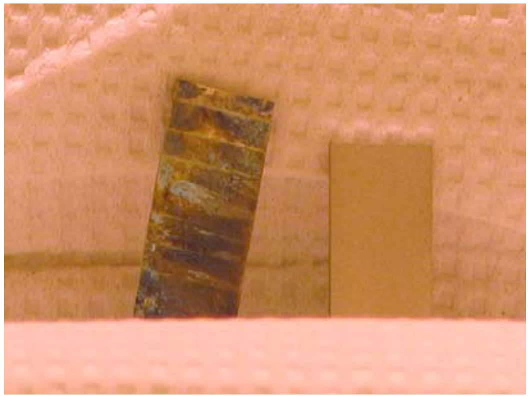
Solid Target Concepts – Neutrino Beam

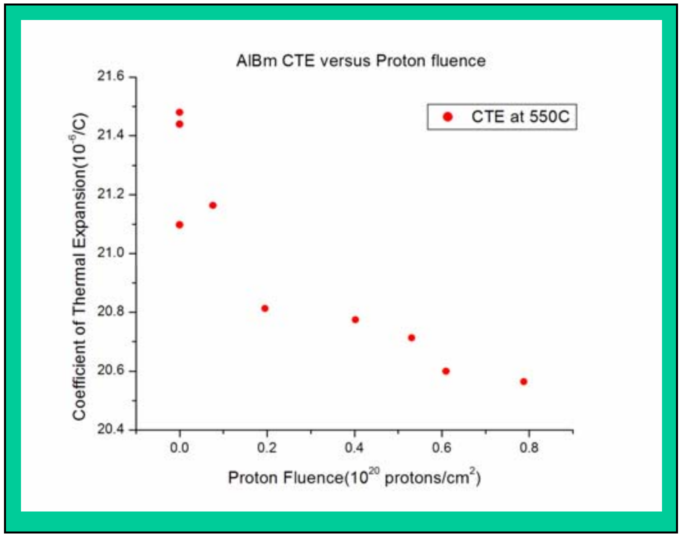


Target Heat Transfer Experiments



$$\frac{p_1 - p_2}{L} = \frac{1}{2}\frac{\lambda}{d_h}\rho u^{-2}$$





SUMMARY

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

- **Information to-date is available from low power accelerators and mostly from reactor (neutron irradiation) experience. Extrapolation is not allowed!**

- **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 be the answer to neutrino factory initiative BUT the necessary experiments of the integrated system must be performed. Too many unknowns to be left unexplored**

SUMMARY (cont.)

- **Solid target shock experiments with pulse intensities anticipated in the multi-MW proton driver are necessary**
- **Simulations of target/beam interaction (solids and liquid jets) that are benchmarked on the various experiments are a MUST. Predicting the mechanics of shock and of magneto-hydrodynamics (while benchmarking simulations to experiments) will allow us to push the envelope to the conditions of the multi-MW drivers**