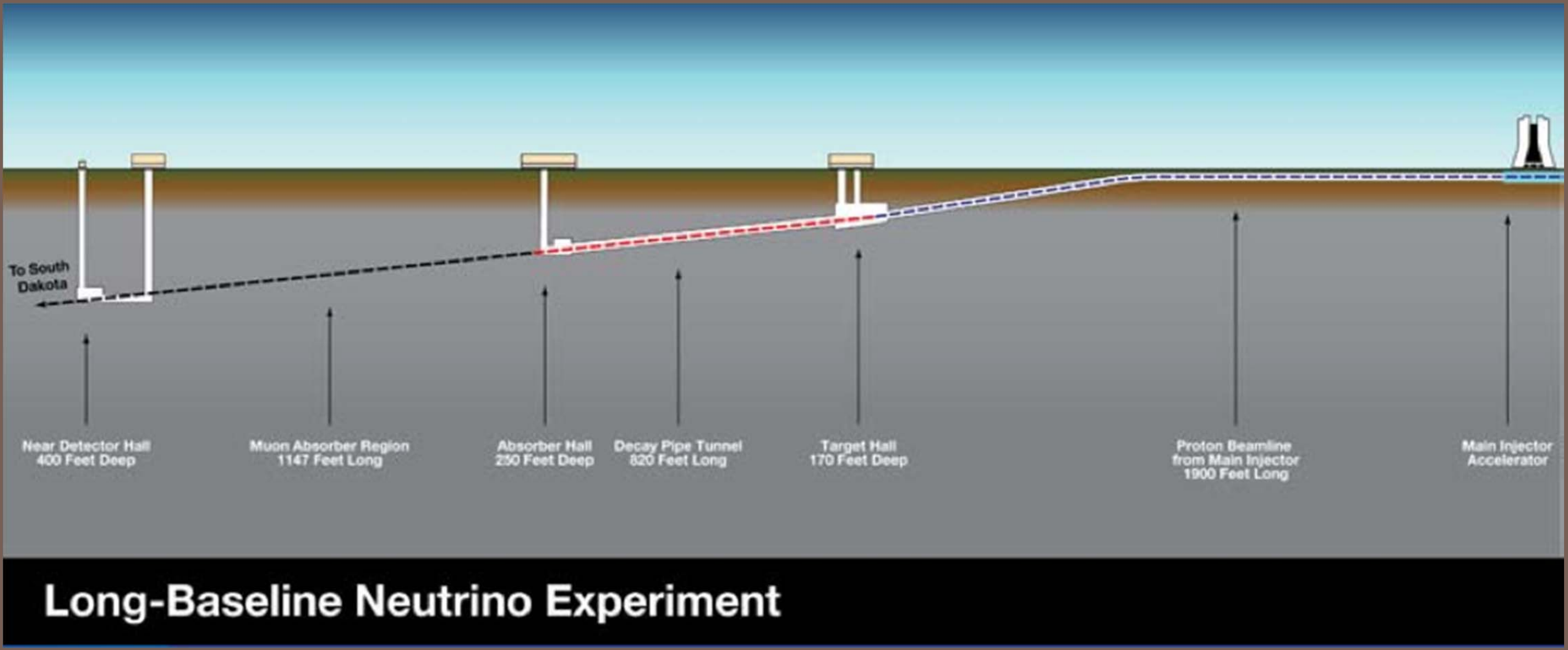


HIGH-POWER TARGETS R&D FOR LBNE: STATUS AND FUTURE PLANS

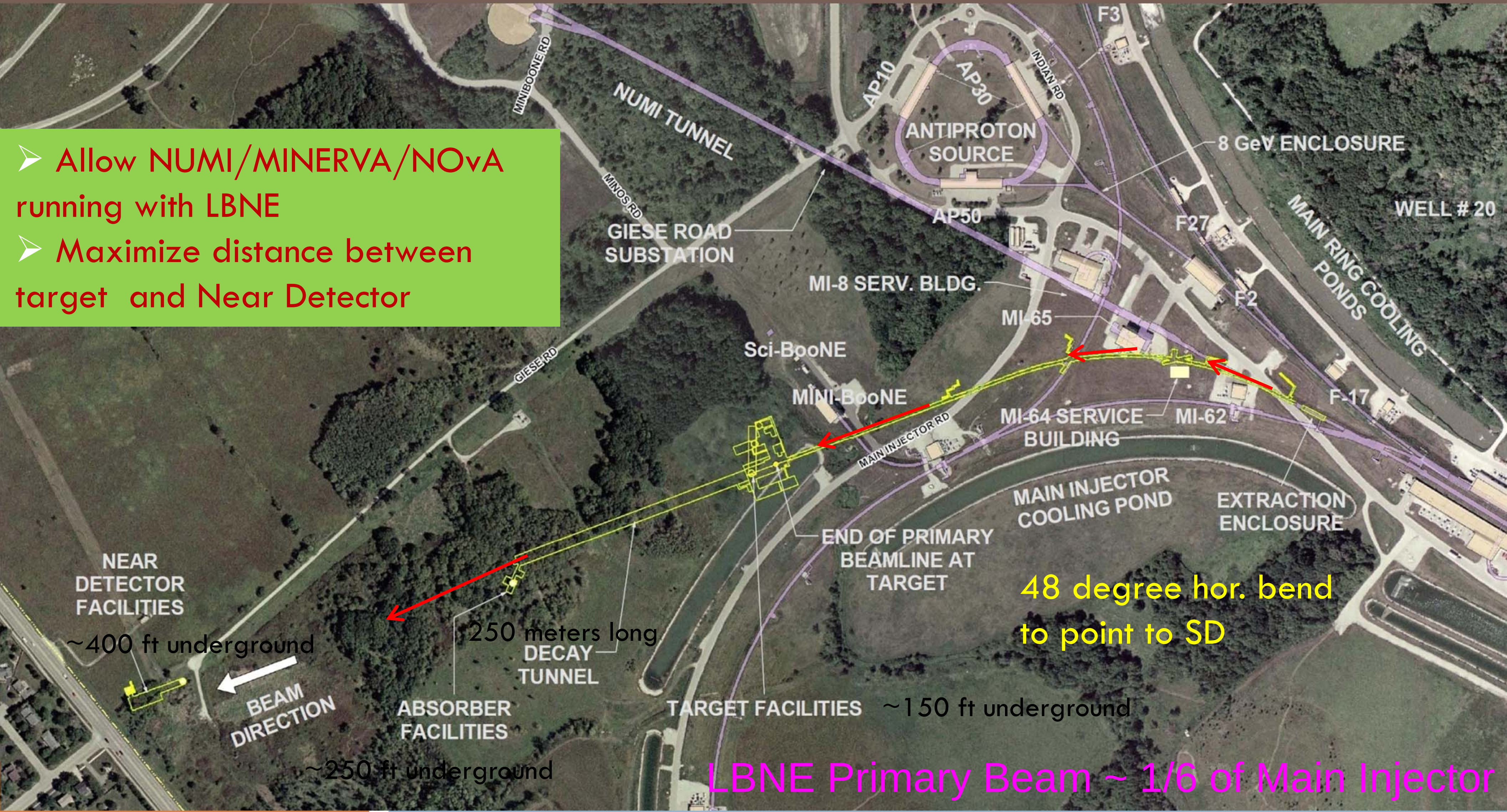
P. Hurh FNAL 5/2/11

Neutrino beam to DUSEL, South Dakota

THE NEUTRINO BEAM FACILITY AT FERMILAB

Start with a 700 kW beam. Upgradeable to > 2.0 MW.

- Allow NUMI/MINERVA/NOvA running with LBNE
- Maximize distance between target and Near Detector



48 degree hor. bend to point to SD

~400 ft underground

250 meters long

~150 ft underground

~250 ft underground

LBNE Primary Beam ~ 1/6 of Main Injector

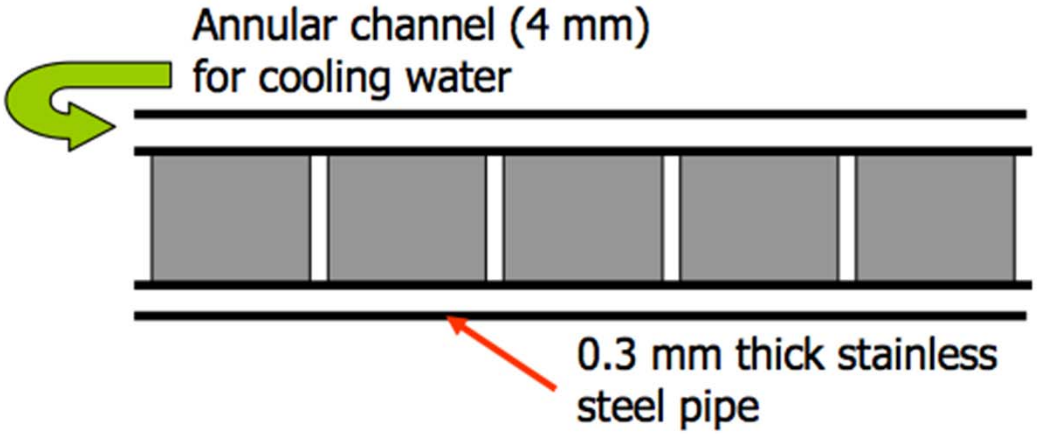
Primary beam energy (protons from the Main Injector) from 60 to 120 GeV

Overview

- LBNE 2.3 MW Default design
- LBNE Target R&D
  - Graphite irradiation tests
  - Beryllium target analysis
  - Beryllium survival in high intensity beam

LBNE “default” target design

- Based on 2005 IHEP study
- Graphite cylindrical segments pre-loaded in stainless steel sheath with annular water cooling



NUMI Target for 2 MW upgrades (IHEP, Protvino)

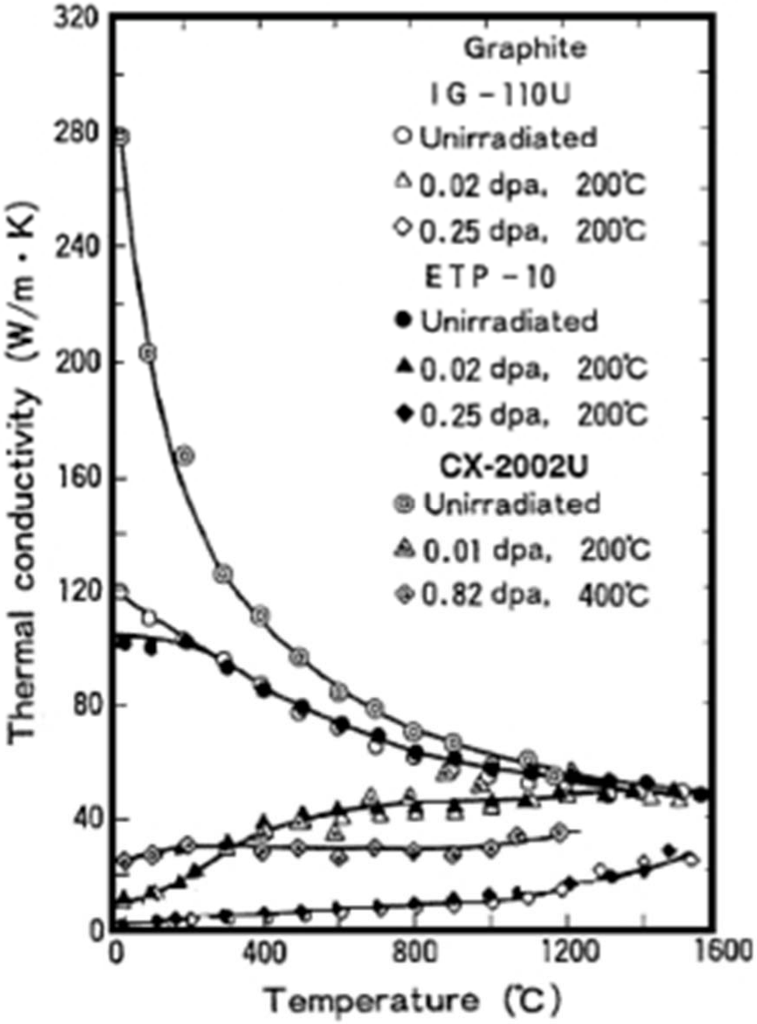
LBNE “default” target design issues

- Hydraulic thermal shock in water (“water hammer”)
- Off-center beam (accident conditions)
- Beam windows
- Graphite radiation damage

LBNE Graphite R&D

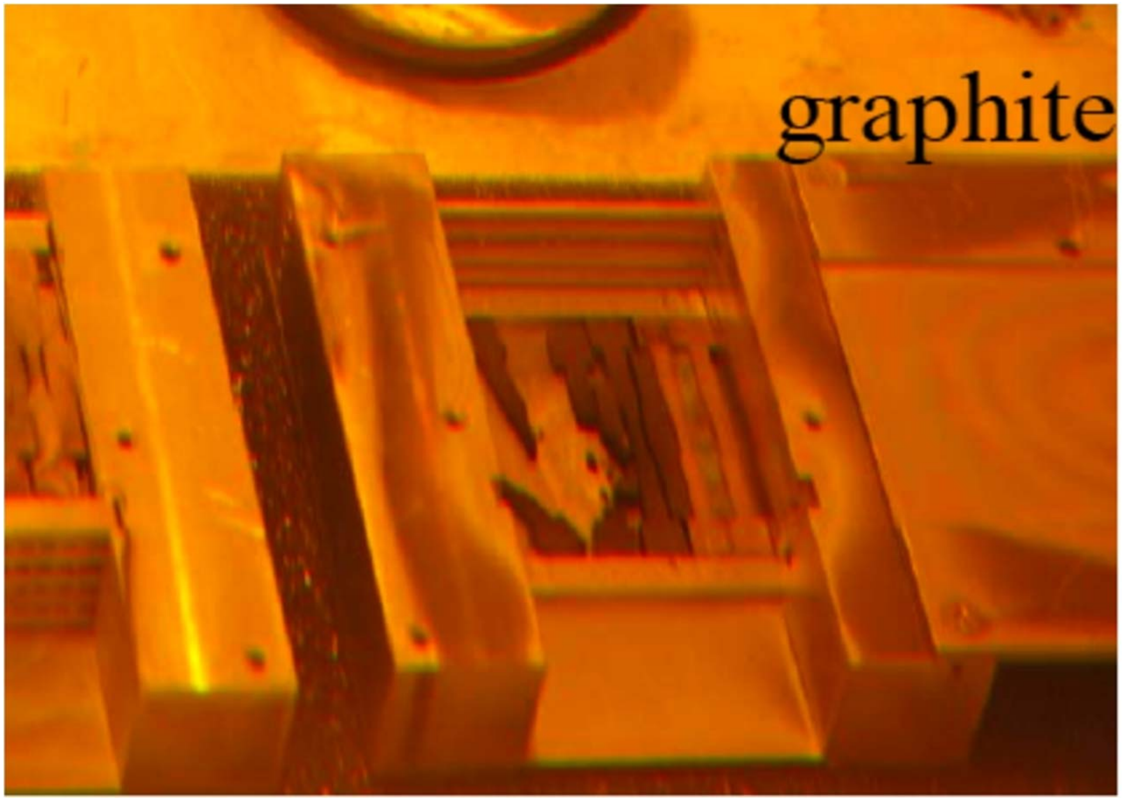
- Why Graphite?
  - Excellent for thermal shock effects (lower CTE, very low E, high strength at high temperatures)
  - Not toxic (no mixed waste created)
  - Readily available (inexpensively) in many grades and forms
- Why not Graphite?
  - Rapid oxidation at high temperatures
  - Radiation damage

Graphite R&D: Radiation Damage

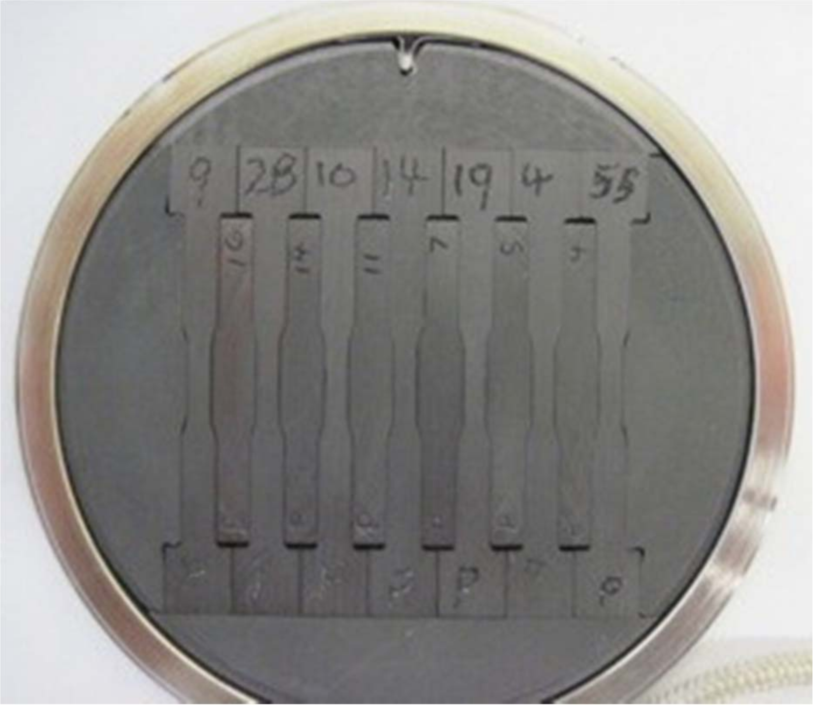


N. Maruyama and M. Harayama, "Neutron irradiation effect on … graphite materials," Journal of Nuclear Materials, 195, 44-50 (1992)

- ☐ Rapid degradation of properties at relatively low levels of DPA
- ☐ Evidence of complete structural failure at 1e21 p/cm^2 (BLIP test)



Graphite R&D: Irradiation Testing at BLIP



Tensile samples have gauge width of 3 mm and thickness of 1 mm

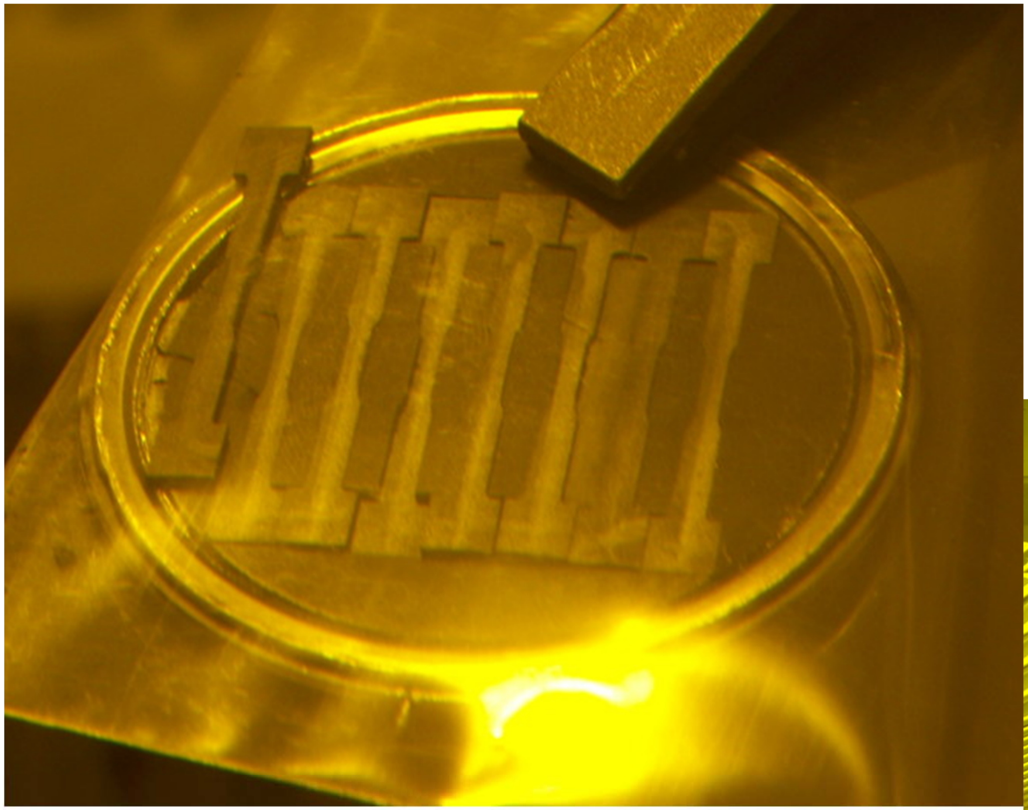
- Working with N. Simos and H. Kirk at BNL to test samples irradiated by 181 MeV proton beam at BLIP
- Testing for:
  - Tensile properties (YS, UTS, …)
  - Coef. of thermal expansion
  - Conductivity
- Most samples encapsulated in argon filled, stainless steel capsules to isolate from water cooling bath
- About 150 samples in total

Graphite R&D: Irradiation Testing at BLIP

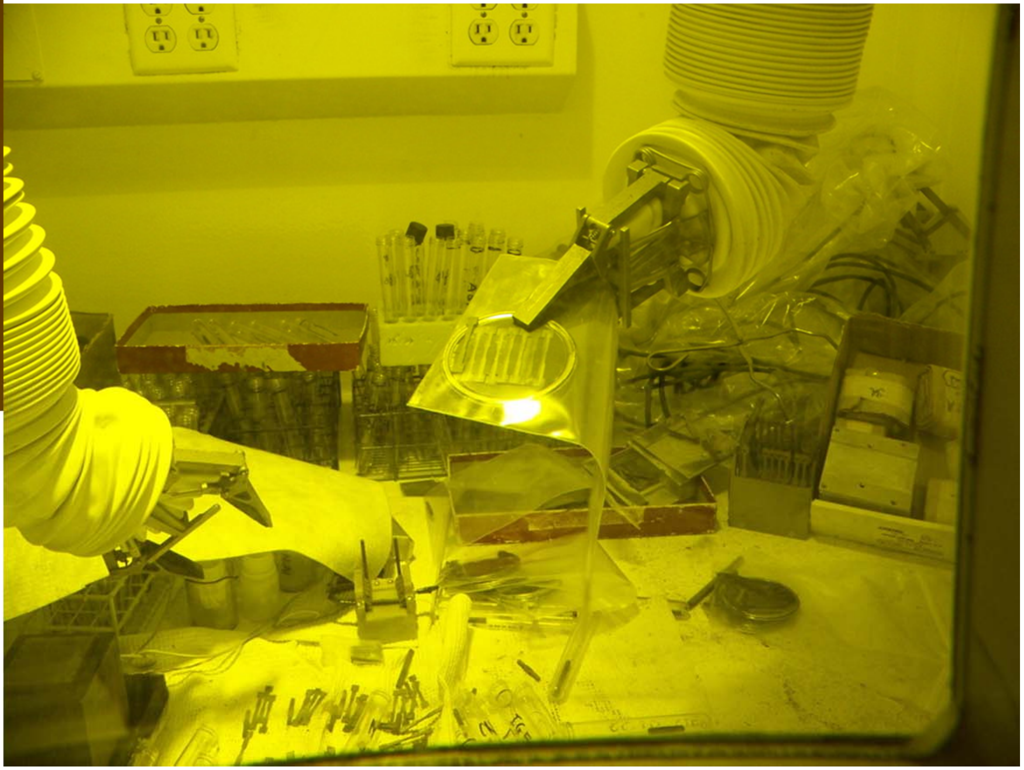
Material	# Tensile	# CTE	K	Motivation
C-C Comp (3D)	10	8	?	First BLIP test showed massive failure
POCO ZXF-5Q	21	6	.46	NuMI/NOvA target material
Toyo-Tanso IG 430	42	6	.51	“Nuclear Grade” used for T2K
Carbone-Lorraine 2020	21	6	.60	CNGS target material
SGL R7650	21	6	.66	NuMI/NOvA Baffle material
Saint-Gobain AX05 hBN	0	6	.80	Highest K wild card (low flex strength)

- K Factor is a thermal shock resistance parameter used by Luca Bruno to evaluate candidate materials for targets/windows
    - K=(UTS*Cp)/(E*CTE)

Graphite R&D: Irradiation Testing at BLIP

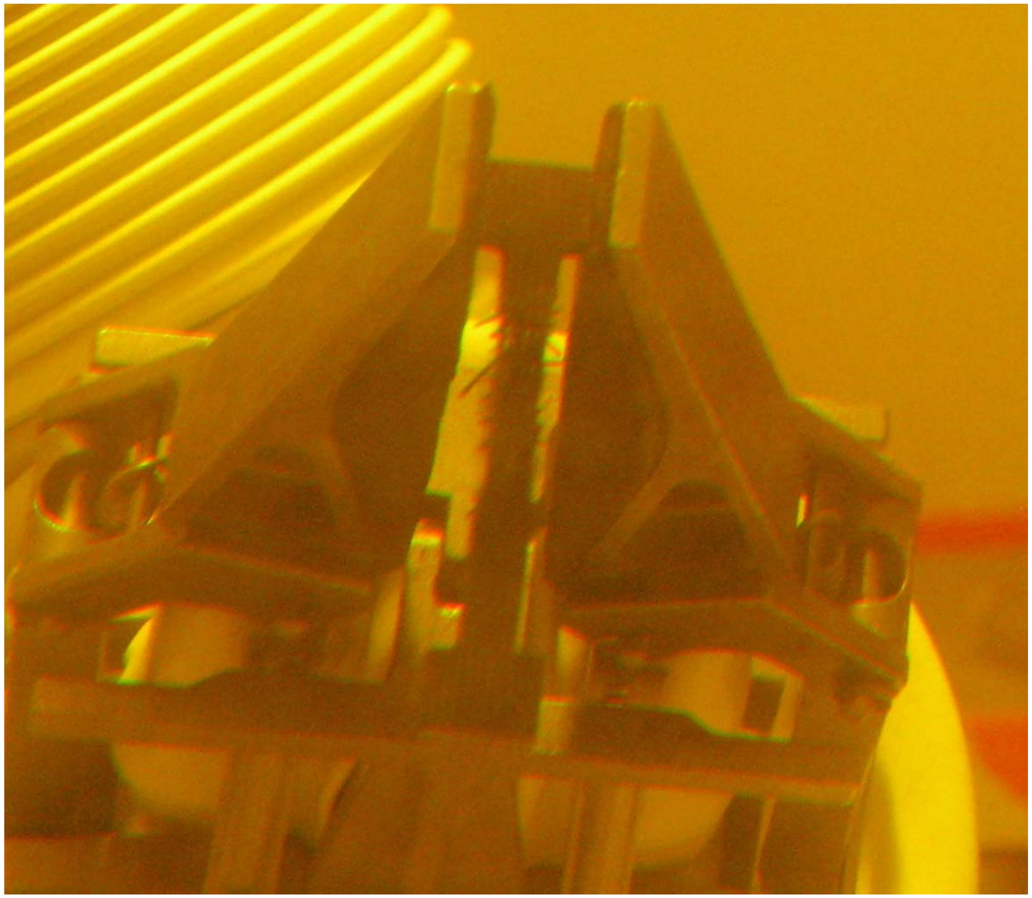


- Irradiation run complete
- Currently in testing phase
- Preliminary results on CTE changes now available
- Tensile tests starting (2 weeks ago)

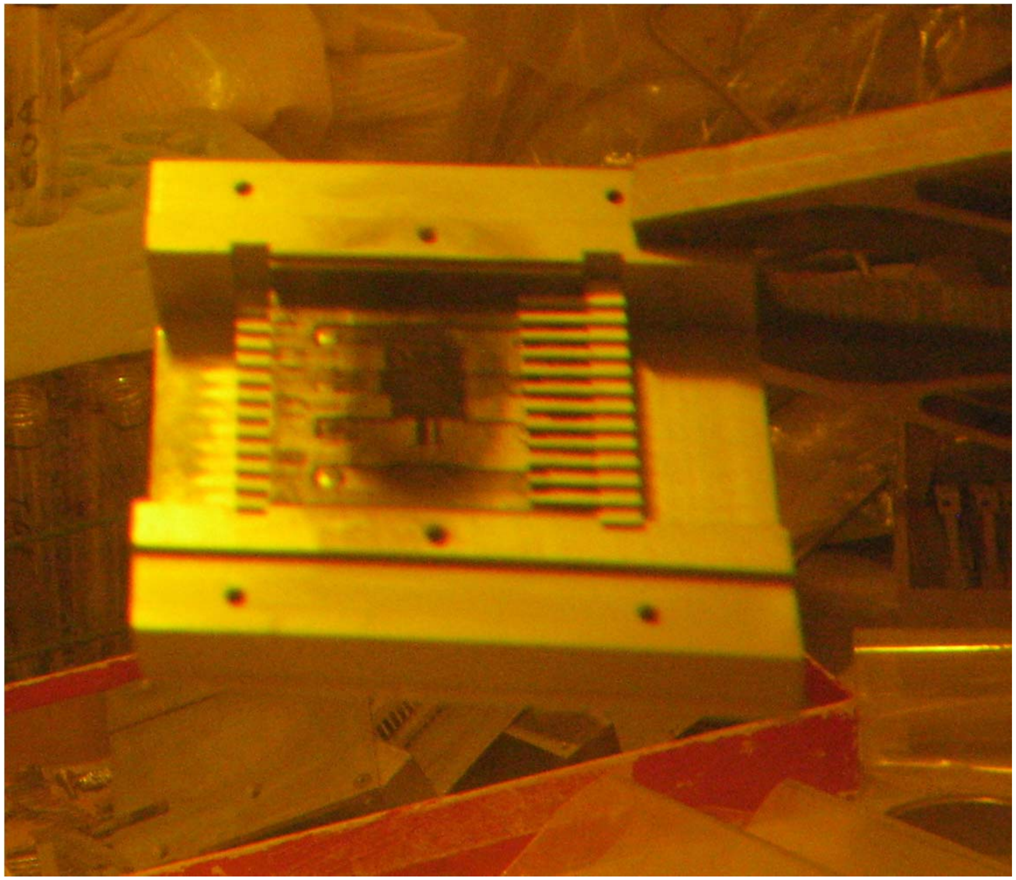


- 181 MeV proton beam
- Peak integrated flux about 5.9e20 proton/cm^2
- Corresponds to 0.14 DPA

Graphite R&D: Irradiation Testing at BLIP

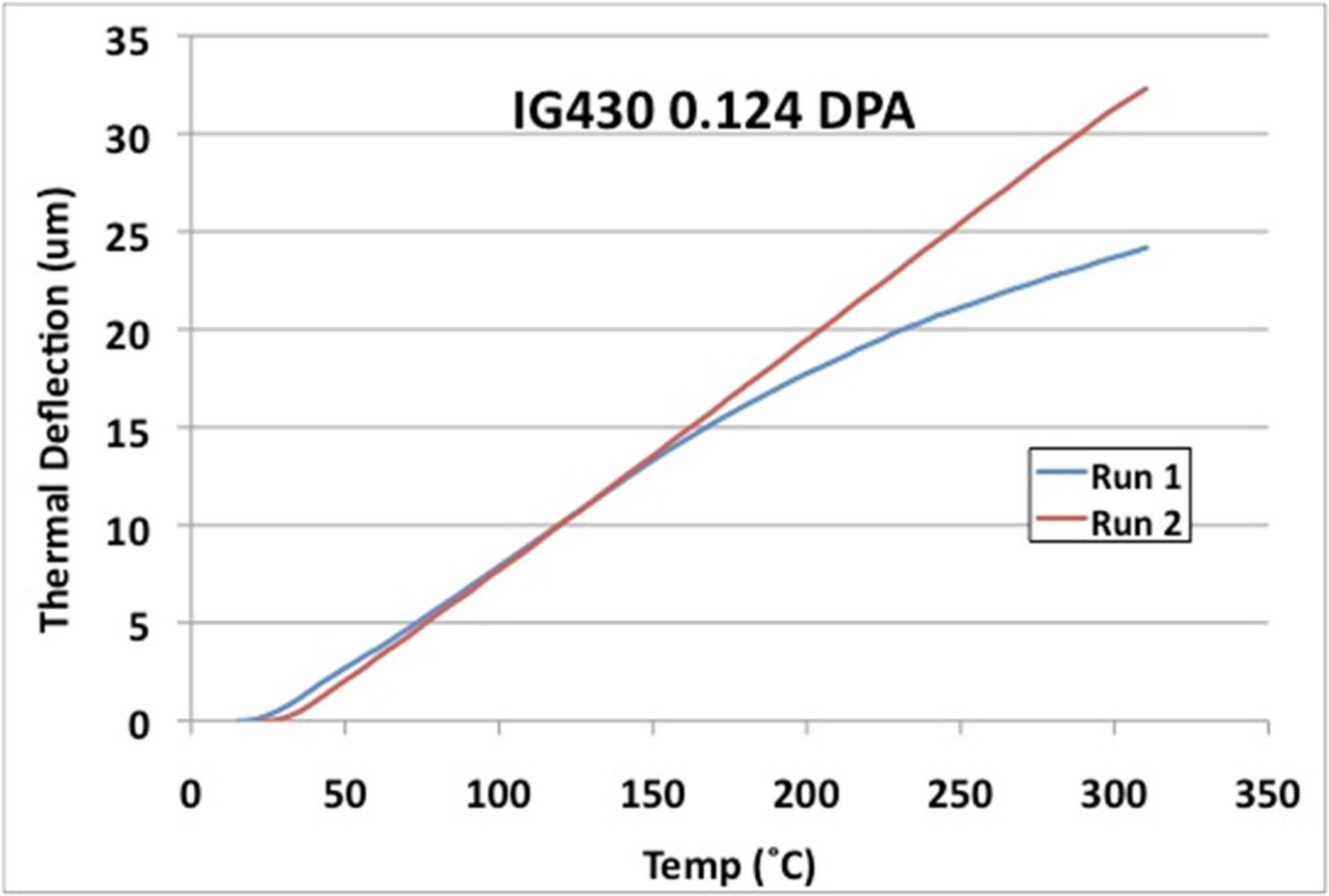


- Water immersed c-c samples showed structural damage (as before).

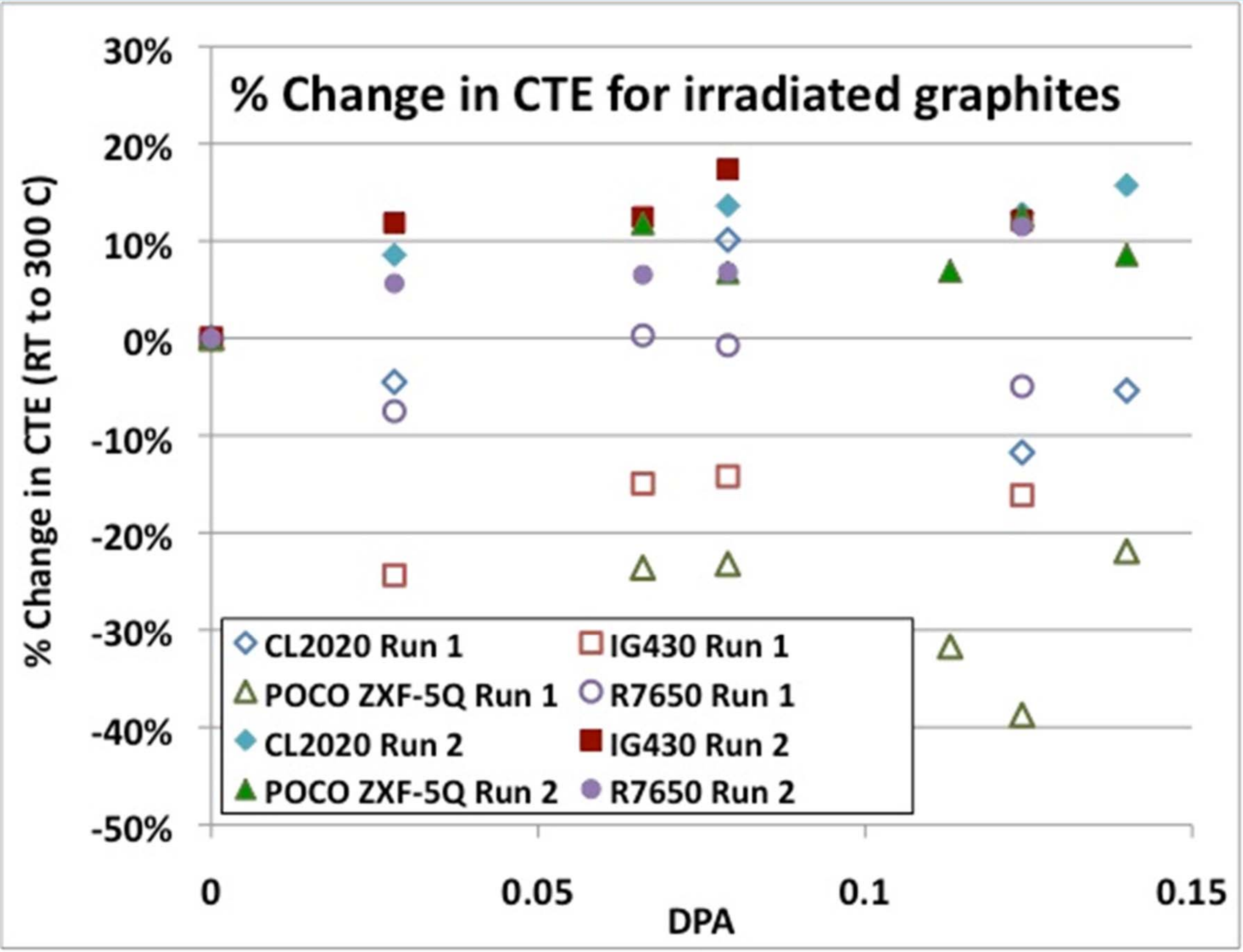


- Argon encapsulated c-c and graphite samples showed little damage (not pictured here)

Graphite R&D:
Irradiation Testing at BLIP



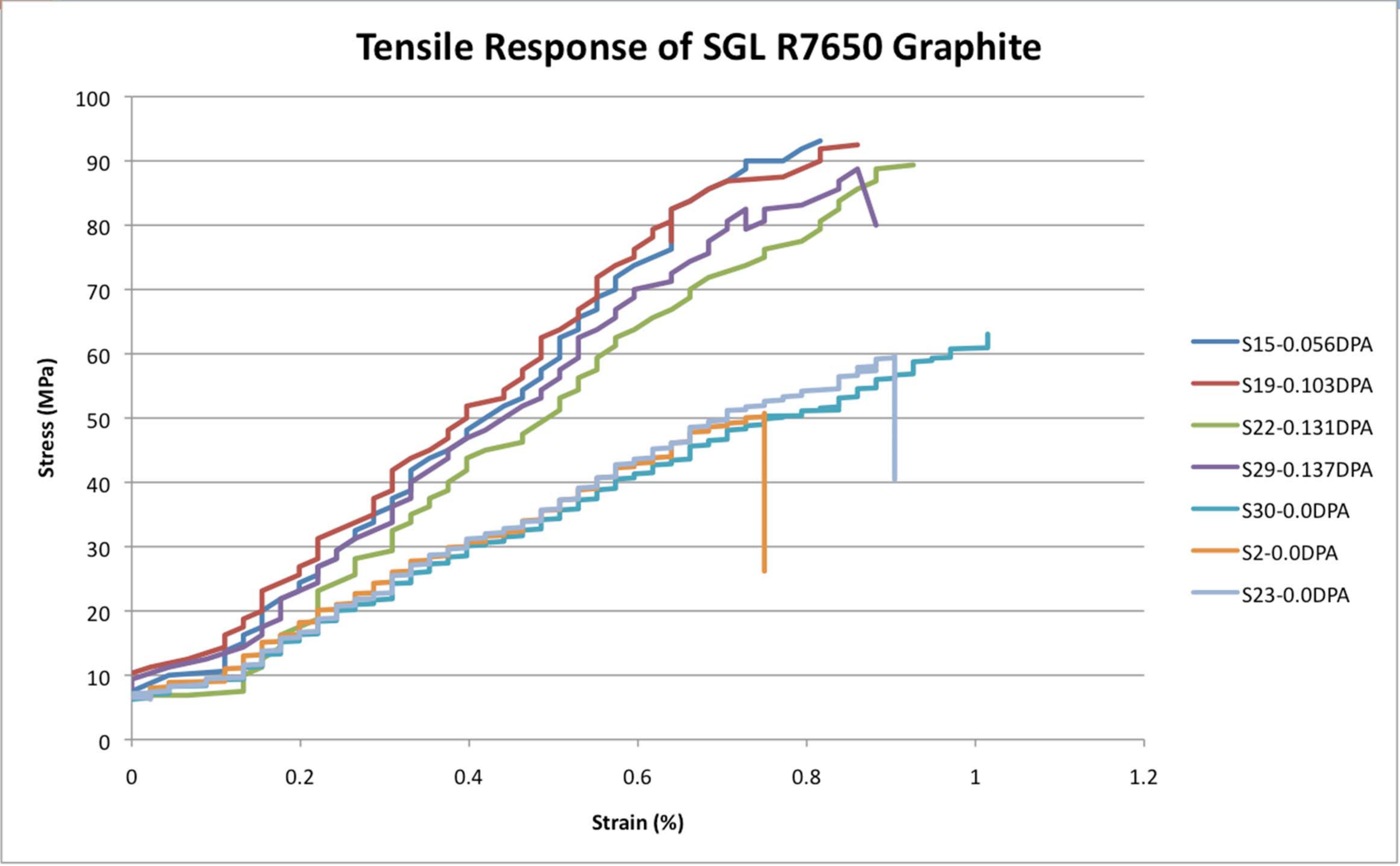
Graphite R&D:
Irradiation Testing at BLIP



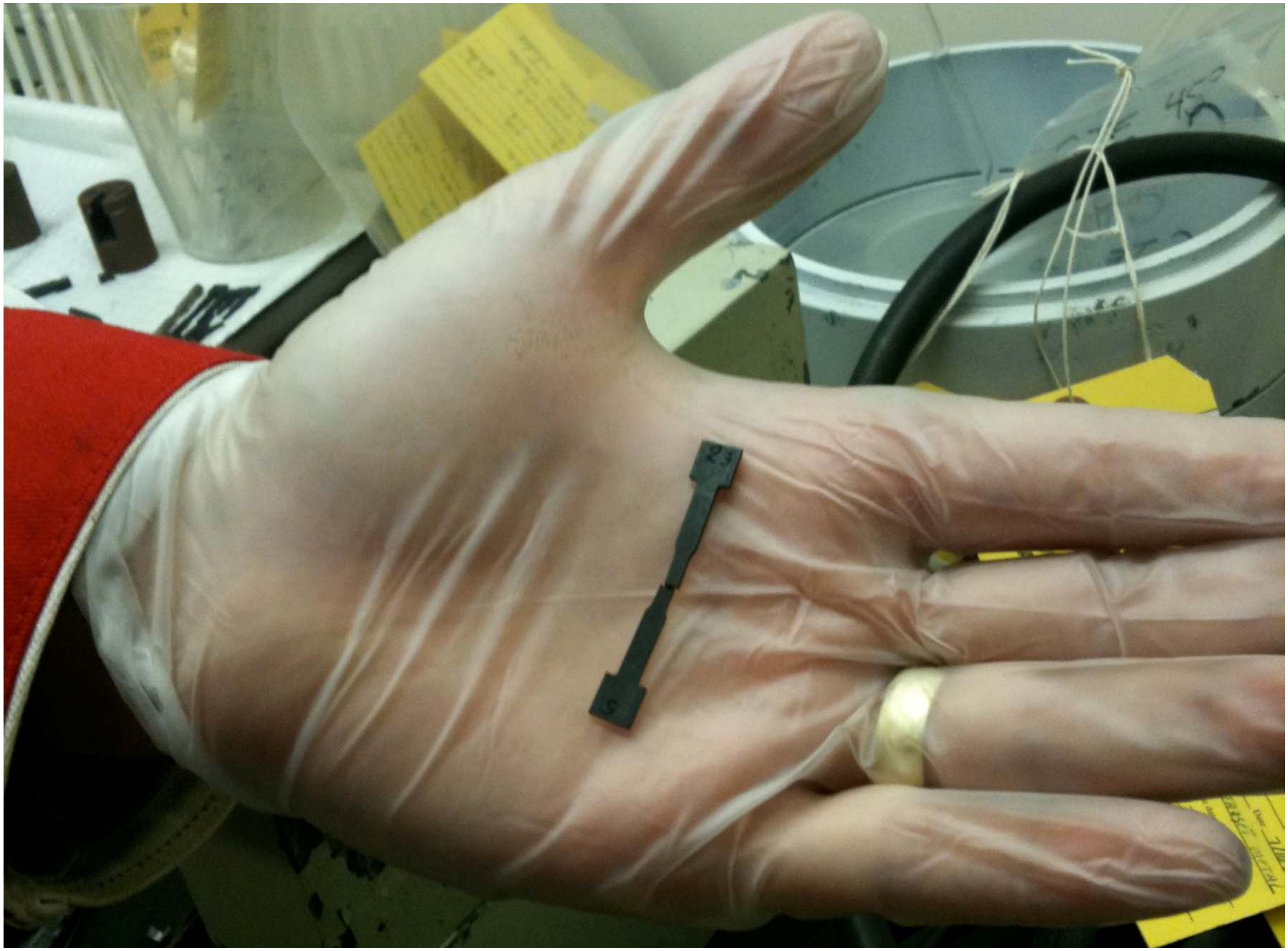
Graphite R&D:
Irradiation Testing at BLIP

- CTE of almost all graphite samples reduced after irradiation (0.07-0.14 DPA) on first thermal cycle to 300 °C depending on graphite type
- After first cycle CTE is increased to about 10% more than un-irradiated samples, regardless of graphite type
- Neutron irradiation studies on graphite consistent with 10% rise in CTE (closure of Mrozowski cracks) and inconsistent with "annealing" at 300 °C (significant annealing only above 1000 °C)
- Behavior might be explained by gas production or other mechanism associated with high energy proton irradiation (or lower irradiation temperatures)?

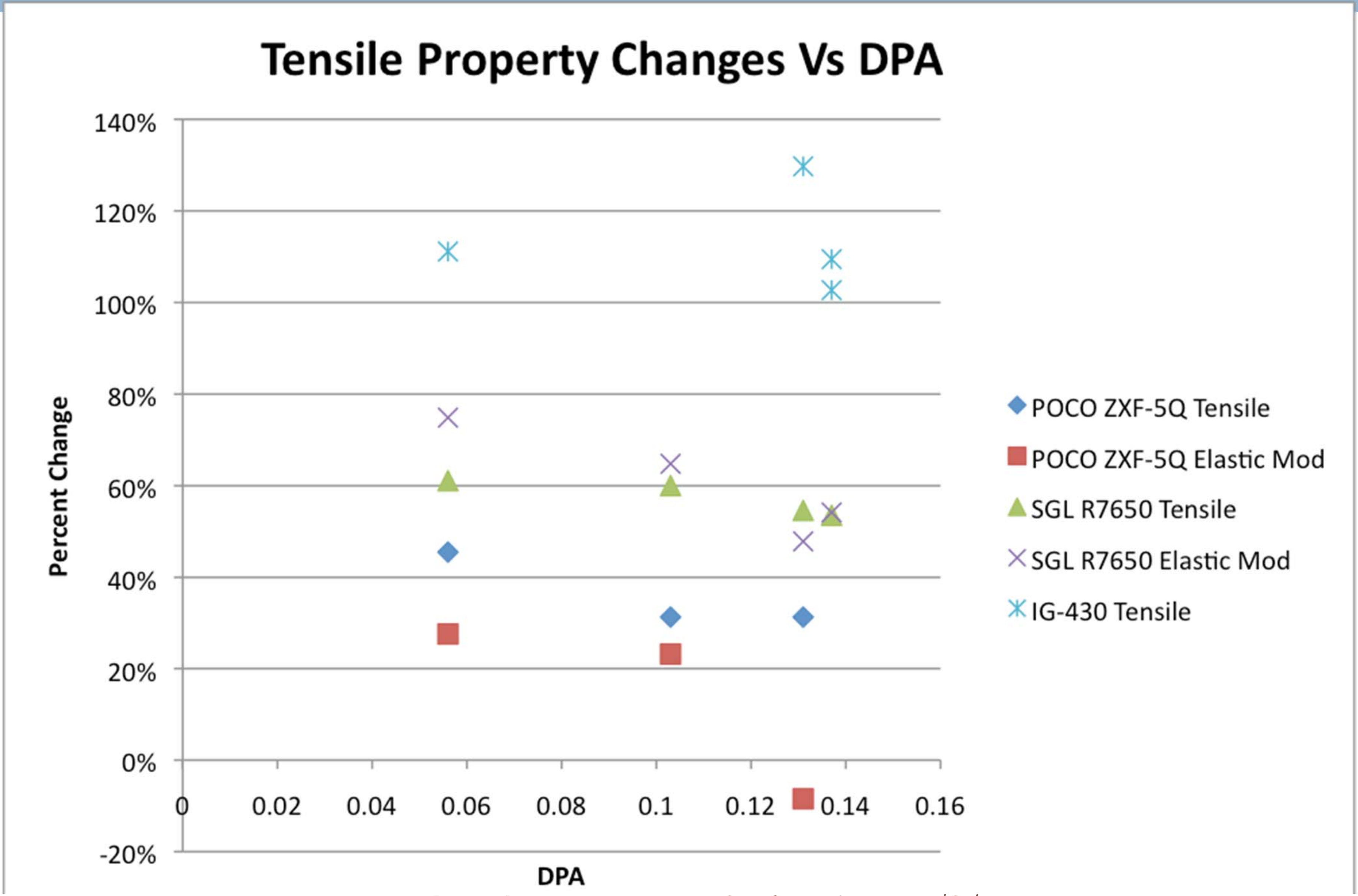
Graphite R&D: Irradiation Testing at BLIP
Preliminary Tensile Test Results



Graphite R&D: Irradiation Testing at BLIP Preliminary Tensile Test Results



Graphite R&D: Irradiation Testing at BLIP Preliminary Tensile Test Results



Beryllium R&D:
Conceptual Design Studies at STFC-RAL

<u>High Power Target Group:</u>

CJ Densham
O Caretta
TR Davenne
MD Fitton
P Loveridge
M Rooney

- Graphite radiation damage issues prompted LBNE to look at Beryllium as an alternative target material for 2+ MW proton beam power
- Accord with (STFC) RAL's Target Engineering Group
  - Beryllium target simulations at 2+ MW
  - Integrated Be target and horn conceptual design
  - Cooling technology R&D (gas, water, water spray)
  - Proton beam window conceptual design
  - Air cooled Be target for 700 kW

Focus On: →

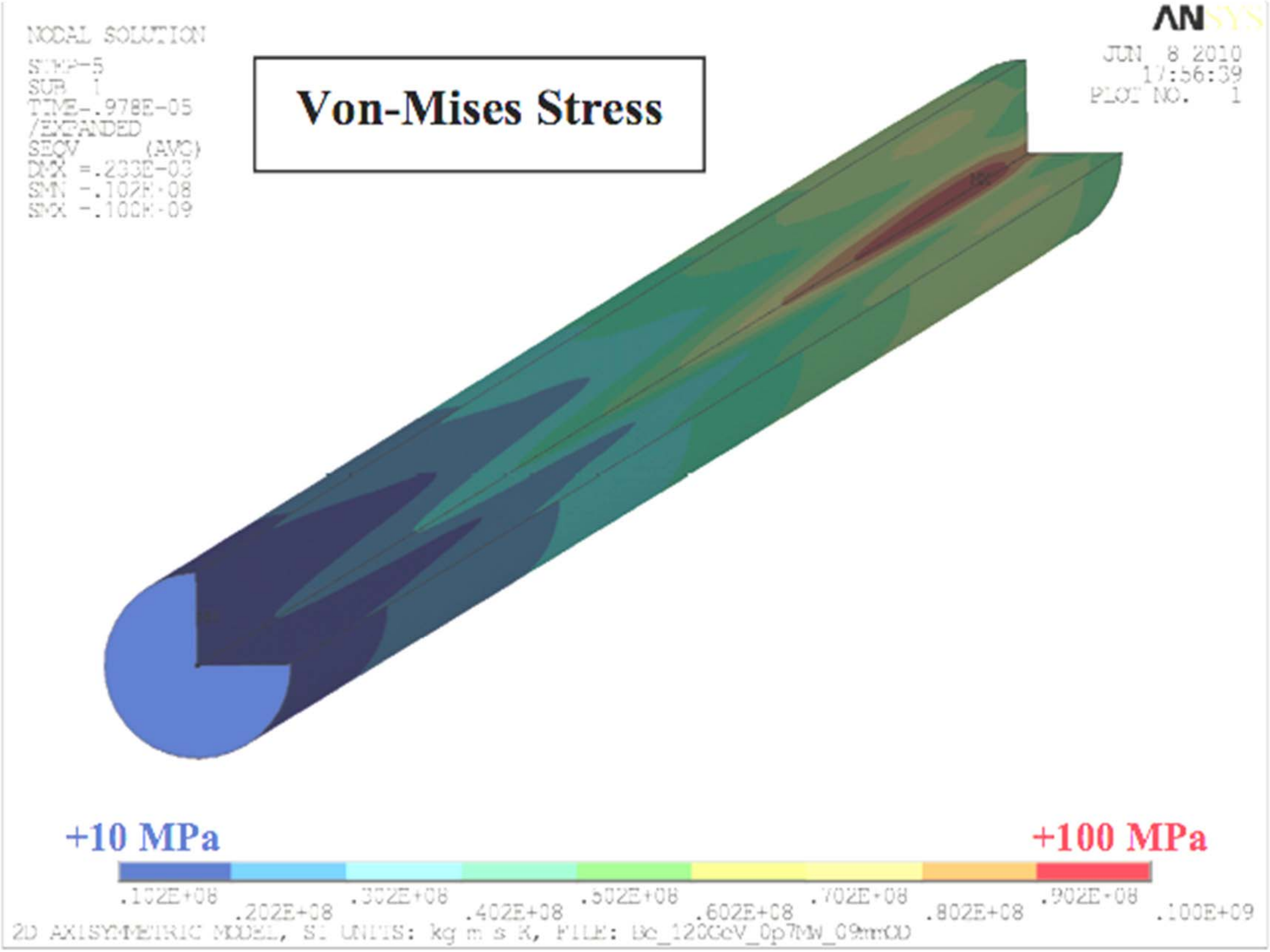
Beryllium R&D:
Be Target Simulations

- Analysis encompasses:
    - Physics (FLUKA) – Energy Deposition & Figure of Merit
    - Thermal/Structural (ANSYS)
    - Dynamic/Stress-wave (Autodyn & ANSYS)
    - Off-center beam cases
- Beam Parameters:

Pulse Length = 9.78 micro-sec

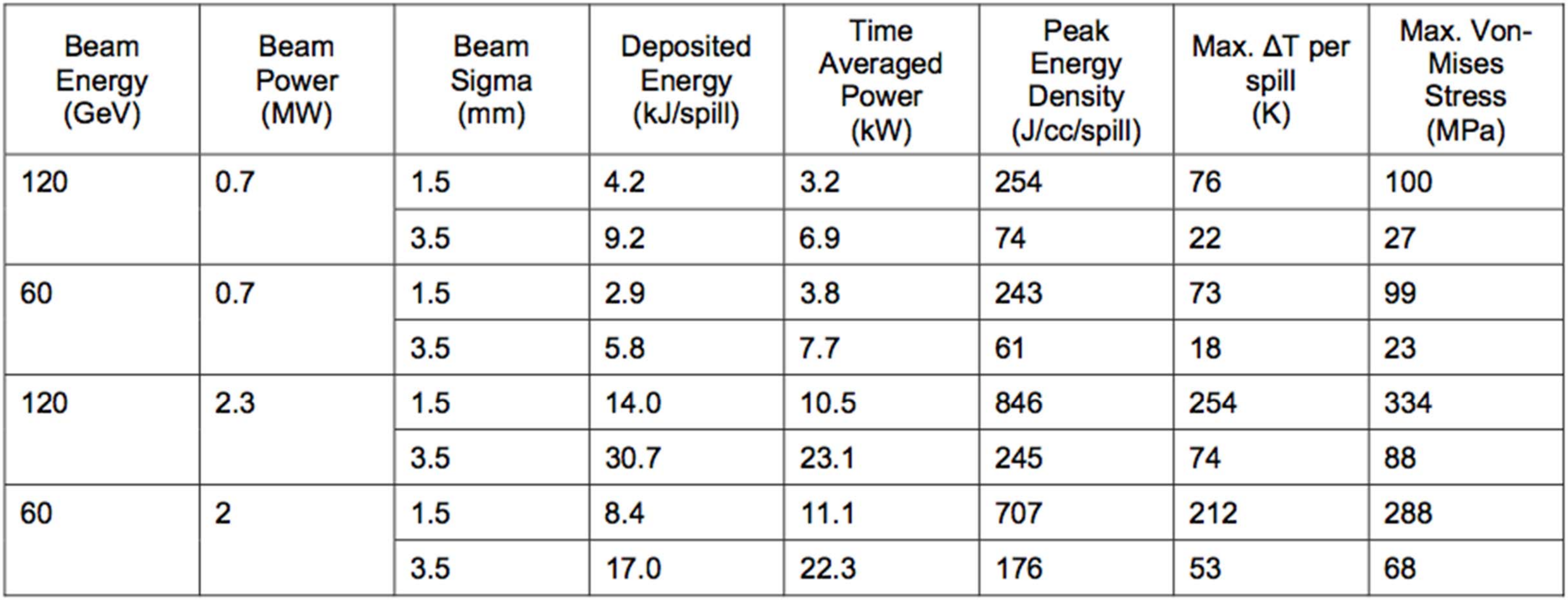
Proton Beam Energy (GeV)	Protons per Pulse	Repetition Period (sec)	Proton Beam Power (MW)	Beam sigma, radius (mm)
120	4.9e13	1.33	0.7	1.5-3.5
60	5.6e13	0.76	0.7	1.5-3.5
120	1.6e14	1.33	2.3	1.5-3.5
60	1.6e14	.76	2	1.5-3.5

Beryllium R&D:
Be Target Simulations: Structural



- Representative plot of equivalent stress
- End of Pulse
- 120 GeV, 0.7 MW beam
- 9mm radius Be
- Sy~270 MPa at 150 C

Beryllium R&D:
Be Target Simulations: Structural (non-dynamic)

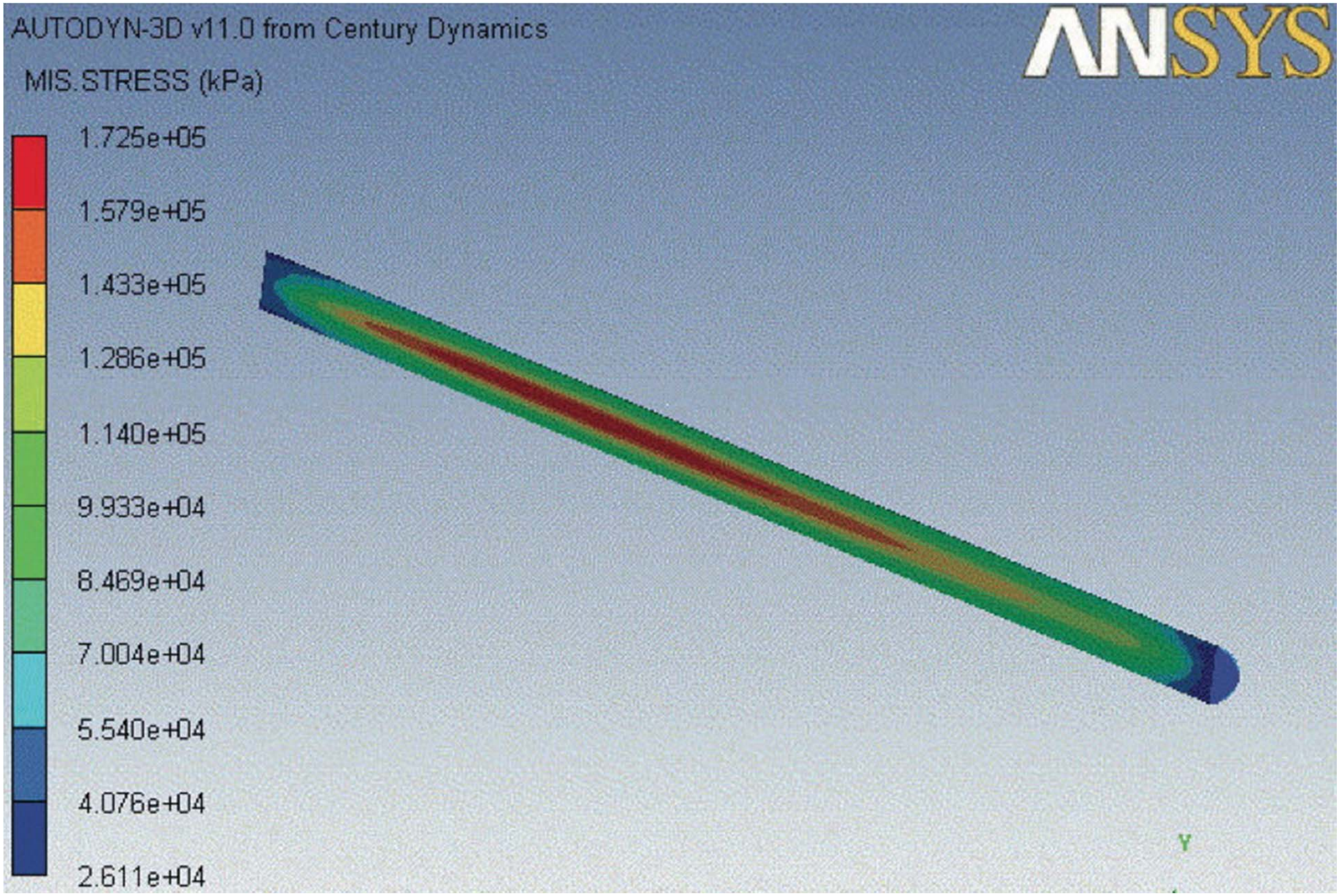


Beam Energy (GeV)	Beam Power (MW)	Beam Sigma (mm)	Deposited Energy (kJ/spill)	Time Averaged Power (kW)	Peak Energy Density (J/cc/spill)	Max. ΔT per spill (K)	Max. Von-Mises Stress (MPa)
120	0.7	1.5	4.2	3.2	254	76	100
		3.5	9.2	6.9	74	22	27
60	0.7	1.5	2.9	3.8	243	73	99
		3.5	5.8	7.7	61	18	23
120	2.3	1.5	14.0	10.5	846	254	334
		3.5	30.7	23.1	245	74	88
60	2	1.5	8.4	11.1	707	212	288
		3.5	17.0	22.3	176	53	68

Stresses probably too high for 2 MW cases with 1.5 mm beam sigma radius, but well within reason for 3.5 mm beam sigma radius

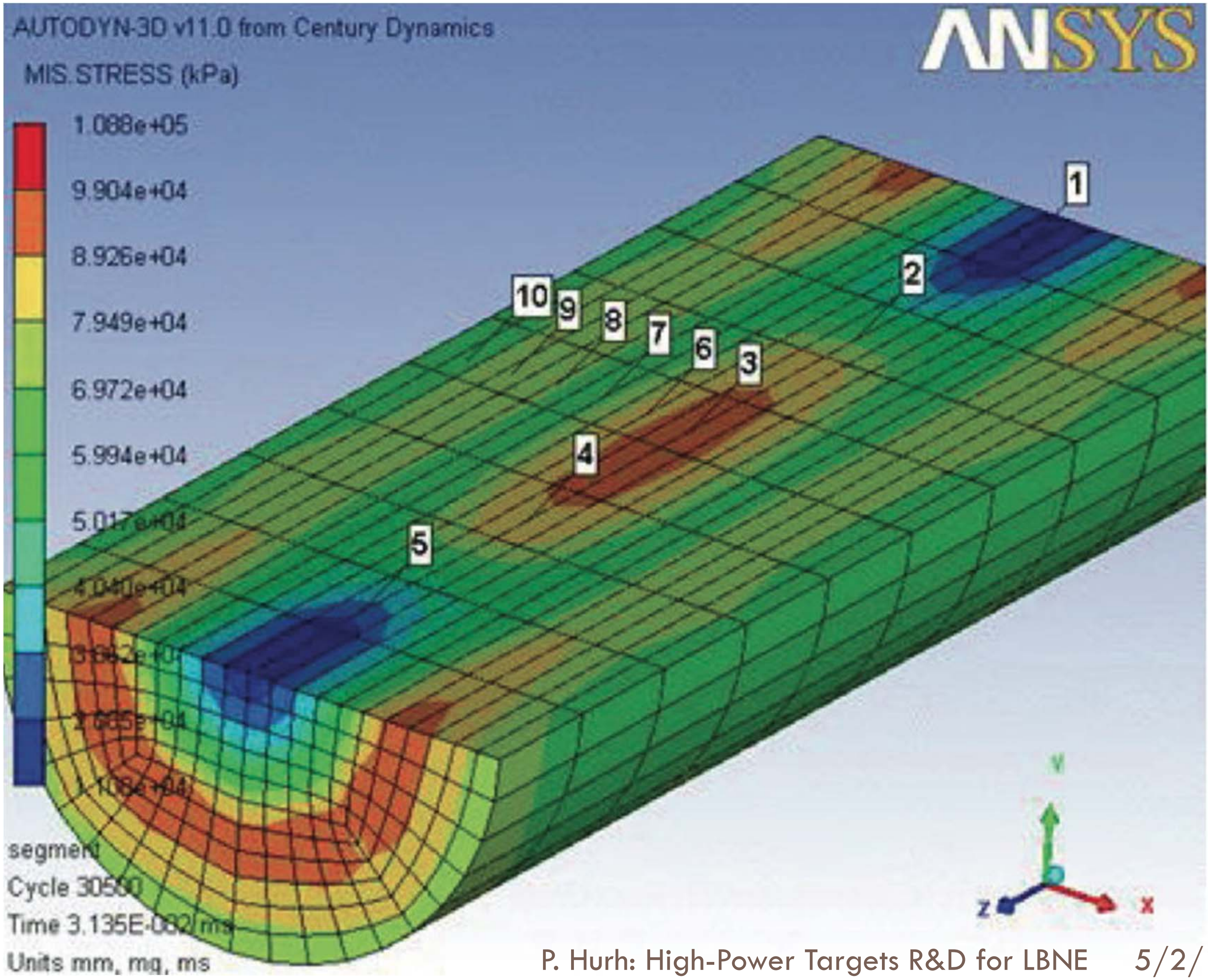
Room for optimization (in length as well)!

Beryllium R&D: Be Target Simulations: Dynamic



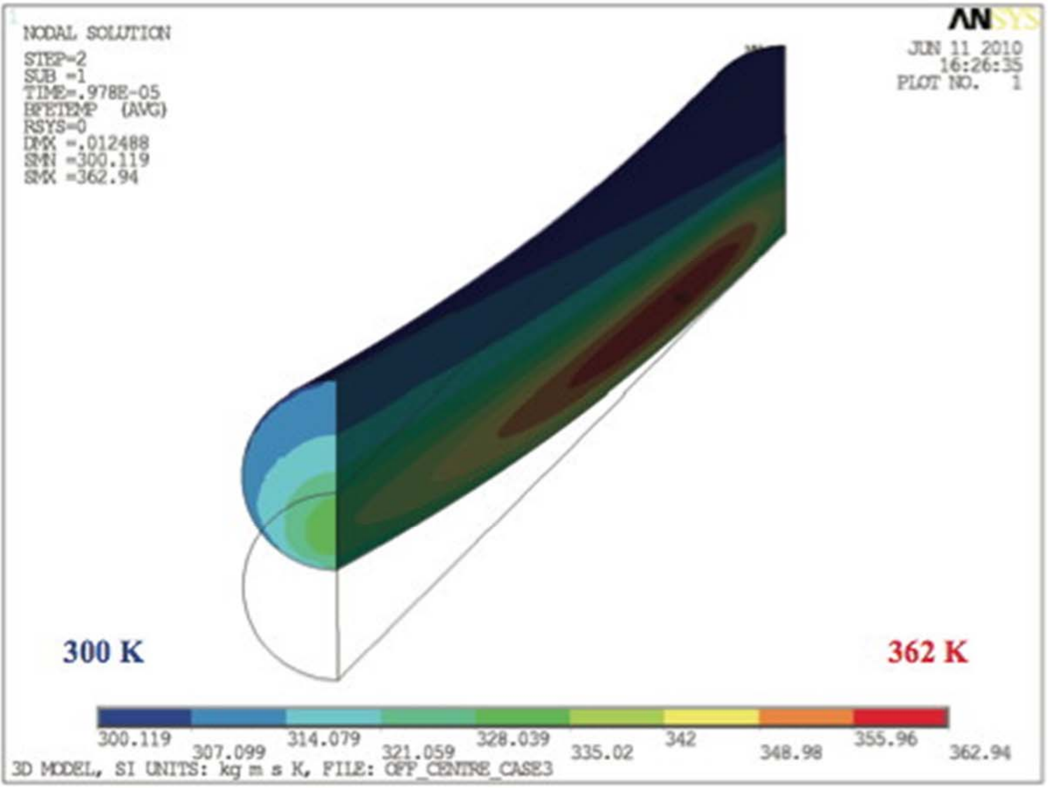
- 2.3 MW
- 120 GeV
- 3.5 mm sigma spot
- Compare to 88 Mpa for static case (double)
- Mainly longitudinal stress-waves

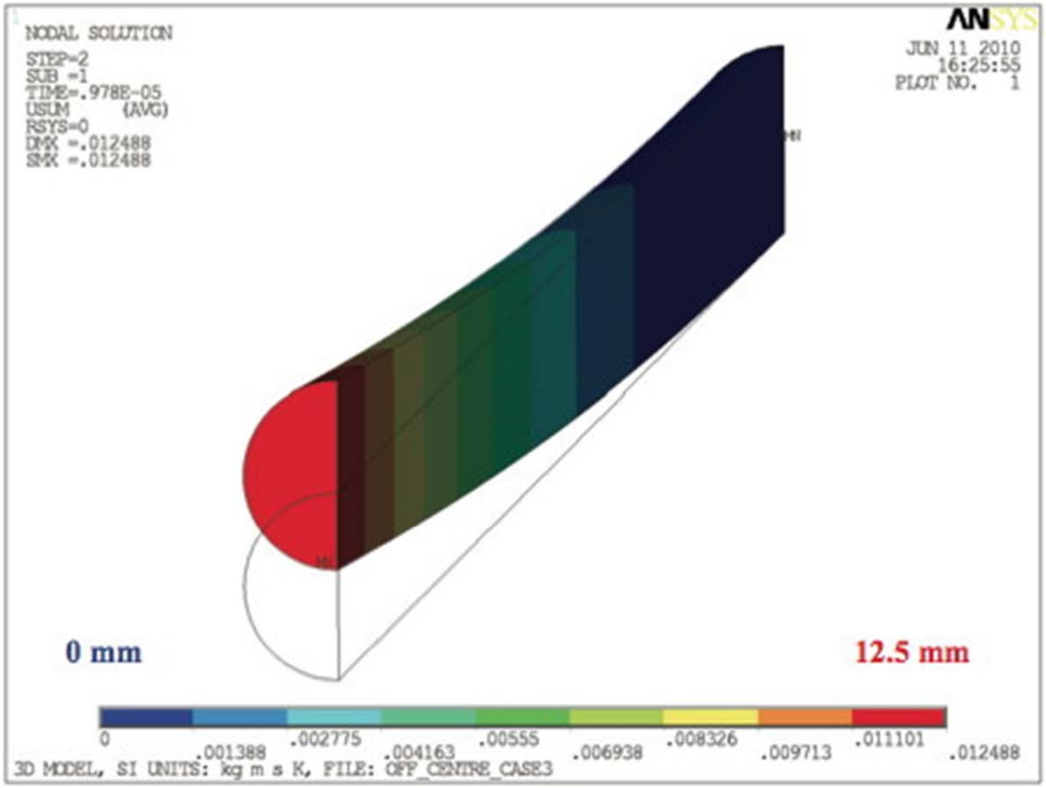
Beryllium R&D:
Be Target Simulations: Dynamic



- ☐ 2.3 MW
- ☐ 120 GeV
- ☐ 3.5 mm sigma spot
- ☐ 50 mm Segments
- ☐ Peak eqv stress reduced to 109 MPa from 173 MPa

Beryllium R&D:
Be Target Simulations: Off Center Beam

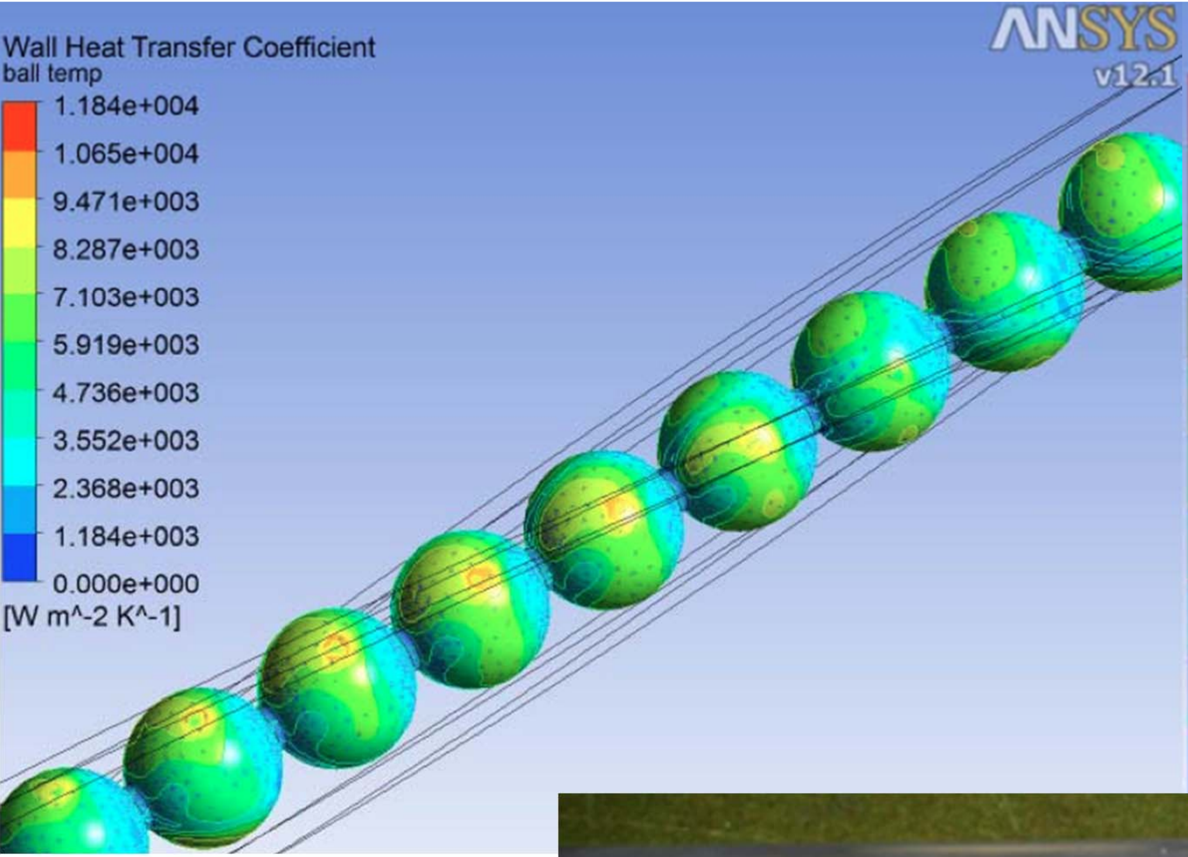


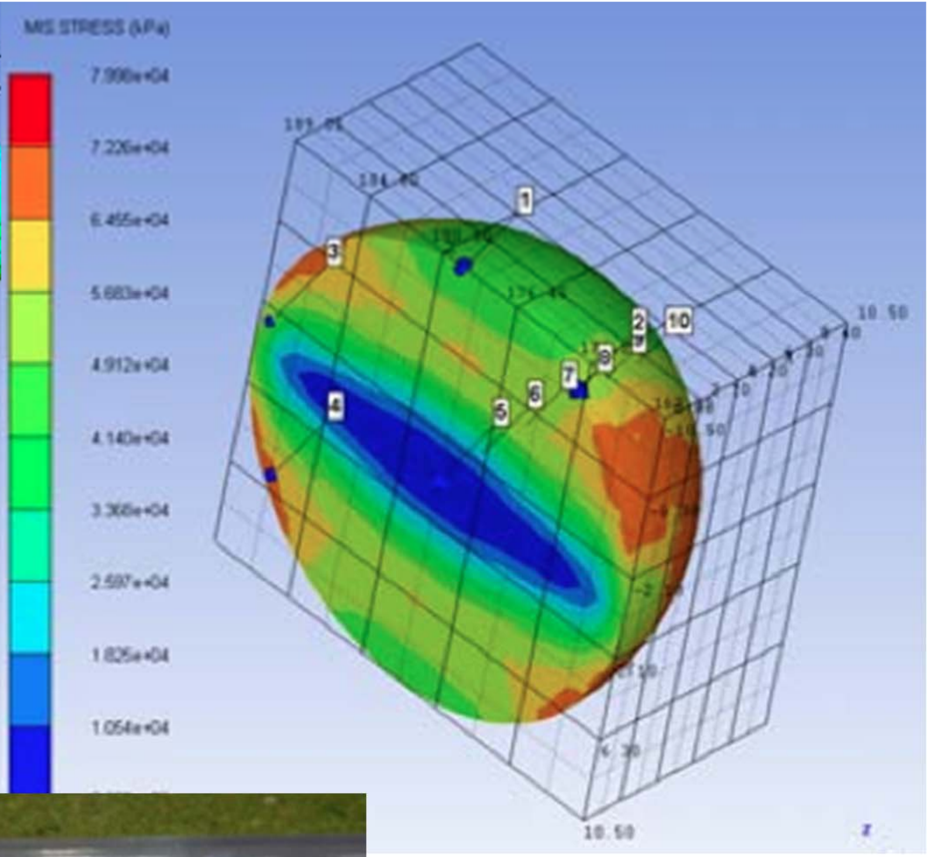


- 2.3 MW
- 120 GeV
- 3.5 mm sigma spot
- 2 sigma offset

- Clearance to Horn Inner Conductor is ~5mm
- Bending stress and resonance is a problem
- Target will need radial supports

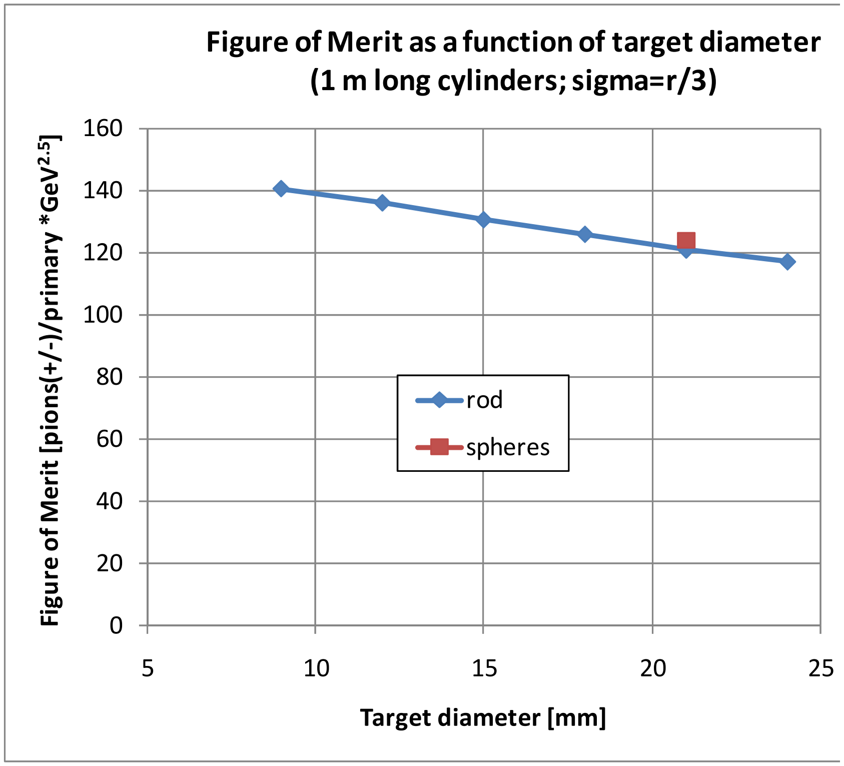
Beryllium R&D:
Be Target Simulations: Spherical

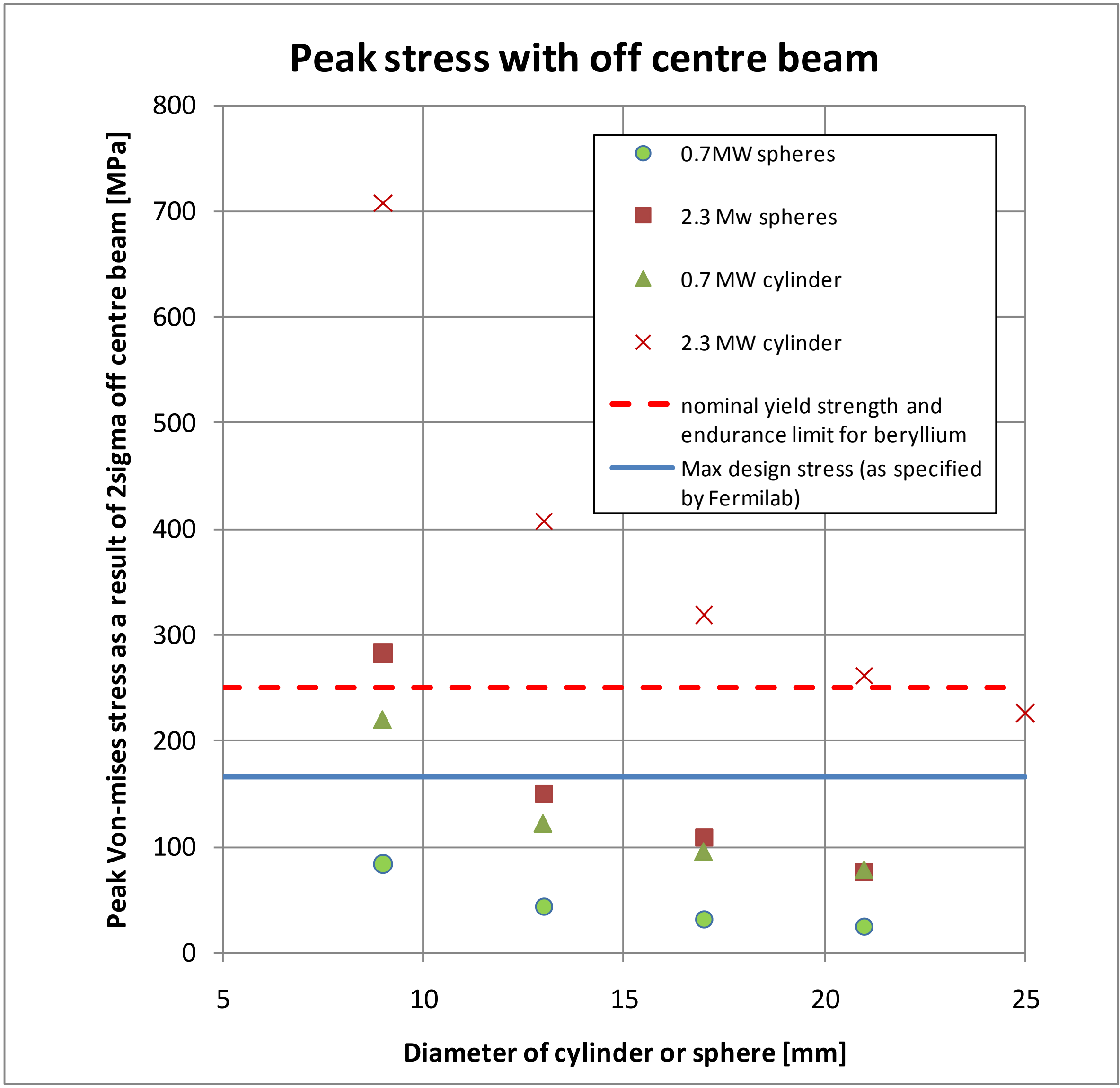




Beryllium R&D:
Be Target Simulations: Spherical

- Spherical shape advantages
  - Eliminates stress concentrations
  - Reduces dynamic stress
  - Allows pions to escape
  - Allows cooling in target central area

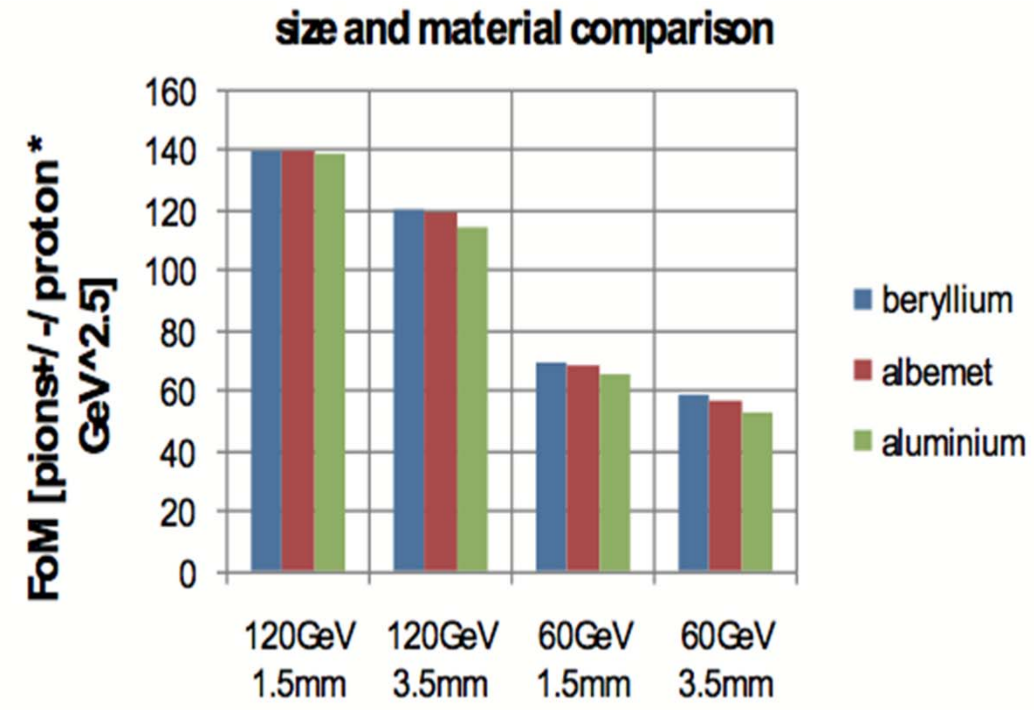


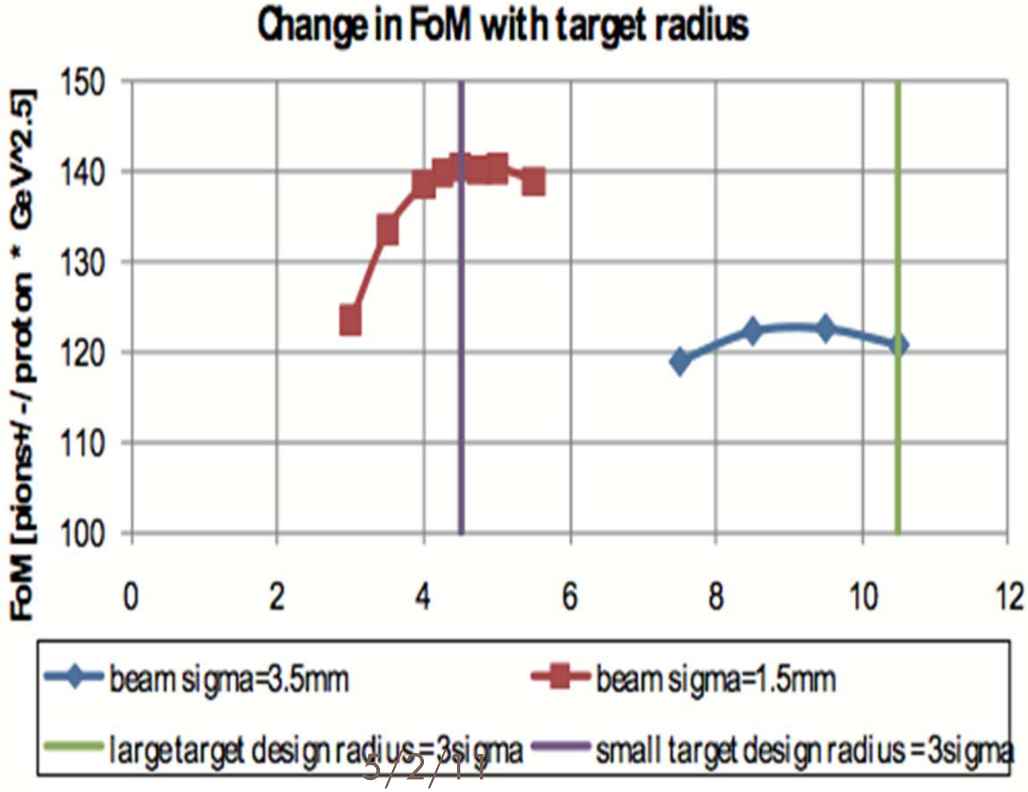


Beryllium R&D:
Be Target Simulations: FoM

- Figure of Merit
  - Provide simple, faster way to gauge effects of target/beam parameter changes on yield of neutrinos of interest
  - Proposed by R. Zwaska

$$FoM = \sum_{n=1}^{21} (Ecen_n)^{2.5} \int_{E\min_n}^{E\max_n} \int_0^{\Delta p} \frac{\partial^2 N}{\partial E \partial p} \partial p \, \partial E$$

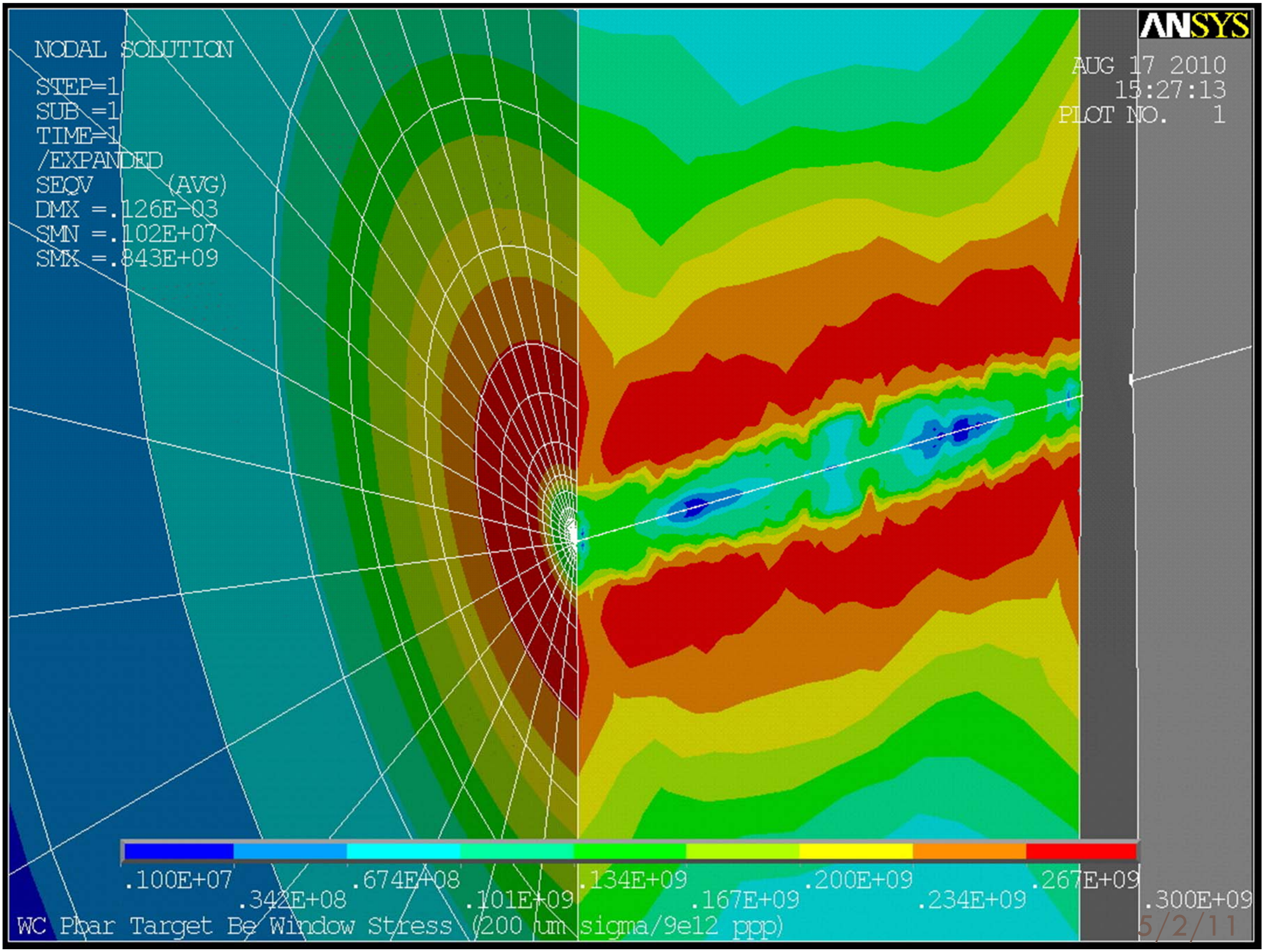




Beryllium R&D: Failure Criteria – Simulation versus Reality

- Predicted Peak Energy Deposition for LBNE 2.3 MW with 1.5 mm beam sigma radius was 846 J/cc and thought to cause stresses too high for Be to survive
- But P-bar Target (FNAL) has a Beryllium cover that regularly sees 1000 J/cc and shows no evidence of damage
- ANSYS analysis for similar conditions suggests peak equivalent stresses of 300 Mpa (elastic-plastic, temp-dependent mat'l properties, but not dynamic)
- Dynamic stresses could be 30-50% higher

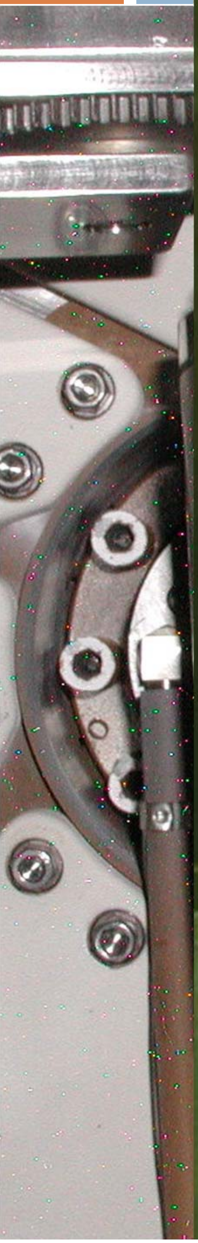
Beryllium R&D:
Failure Criteria – Simulation versus Reality



- 120 GeV
- 0.2 mm sigma
- Elastic/plastic
- Temp Dependent Mat’l Properties
- Peak Seqv is 300 MPa
- Peak Temp is ~800 C
- Be Melting Temp is 1278 C
- Be UTS at 600 C is ~150 MPa

Beryllium R&D:

Fo tion versus Reality



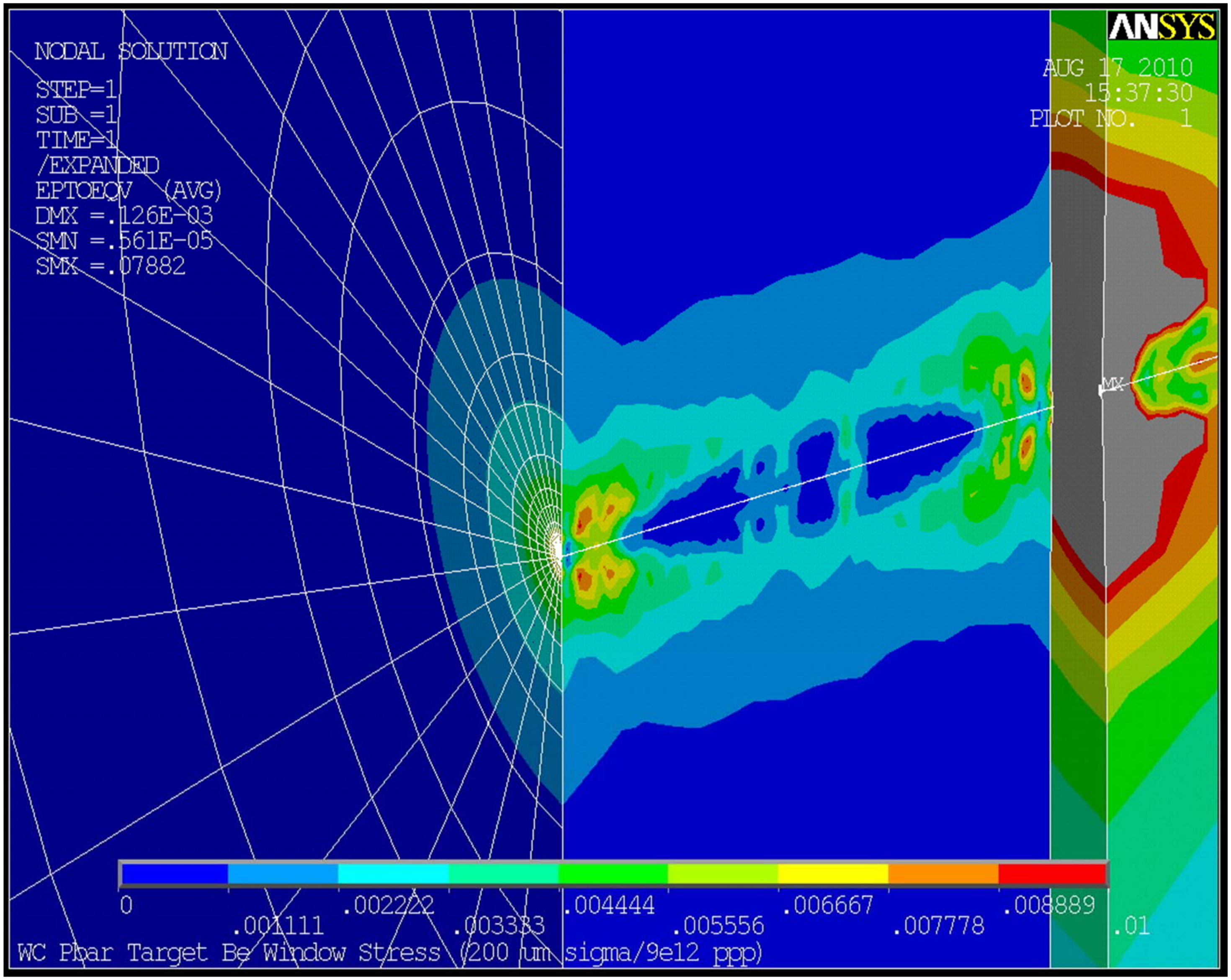
Pbar Target 7 without Be cover.
Inconel Target Material is
Consumable!

- Rotated 17 degrees every pulse
- Moved 1 mm vertically every 2e17 protons
- Typical beam sigma was 0.195 mm (last 1-2 months of running at 0.15 mm)
- Typical ppp was 8E12
- This target saw about 5e6 pulses at the time photo was taken

Beryllium R&D:
Failure Criteria – Simulation versus Reality

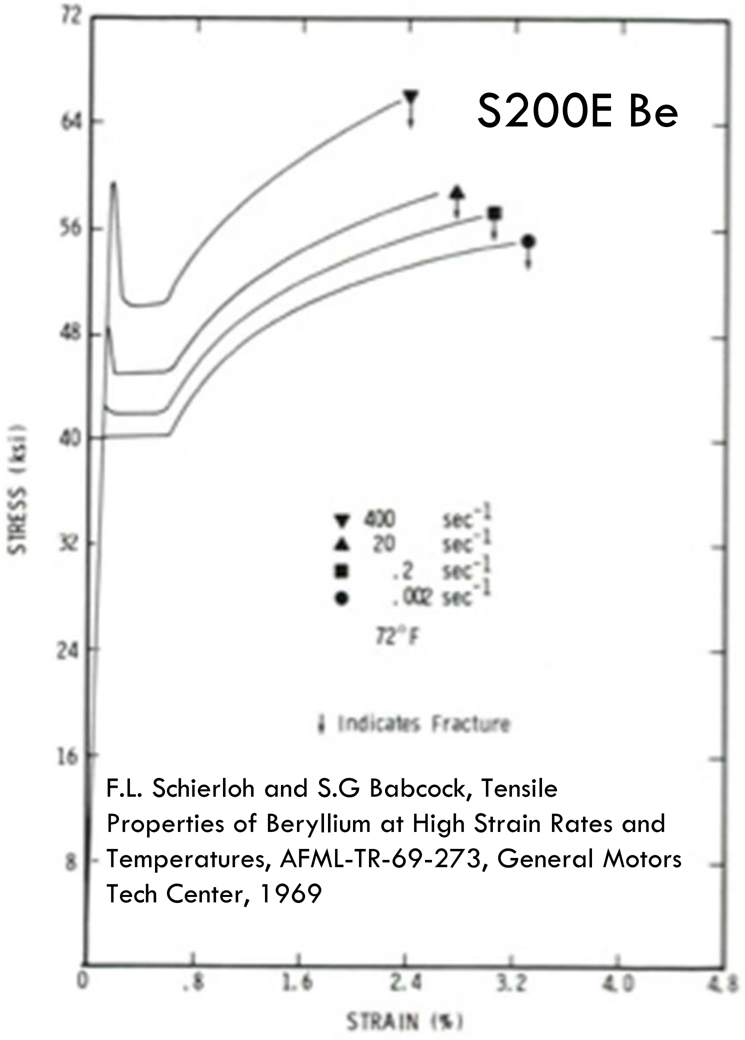
- Possible explanations
  - Small areas of deformation not visible
    - Analysis indicates about 0.05 mm of plastic deformation on surface in an outward “bump” with diameter of about 1 mm
  - Beam profile is not gaussian
    - At such small sigma, peak energy deposition would be reduced greatly if profile were flat in center of beam
  - Fast energy deposition rate creates high strain rates
    - Yield strength of metals increases for high strain rates

Beryllium R&D:
Failure Criteria – Simulation versus Reality

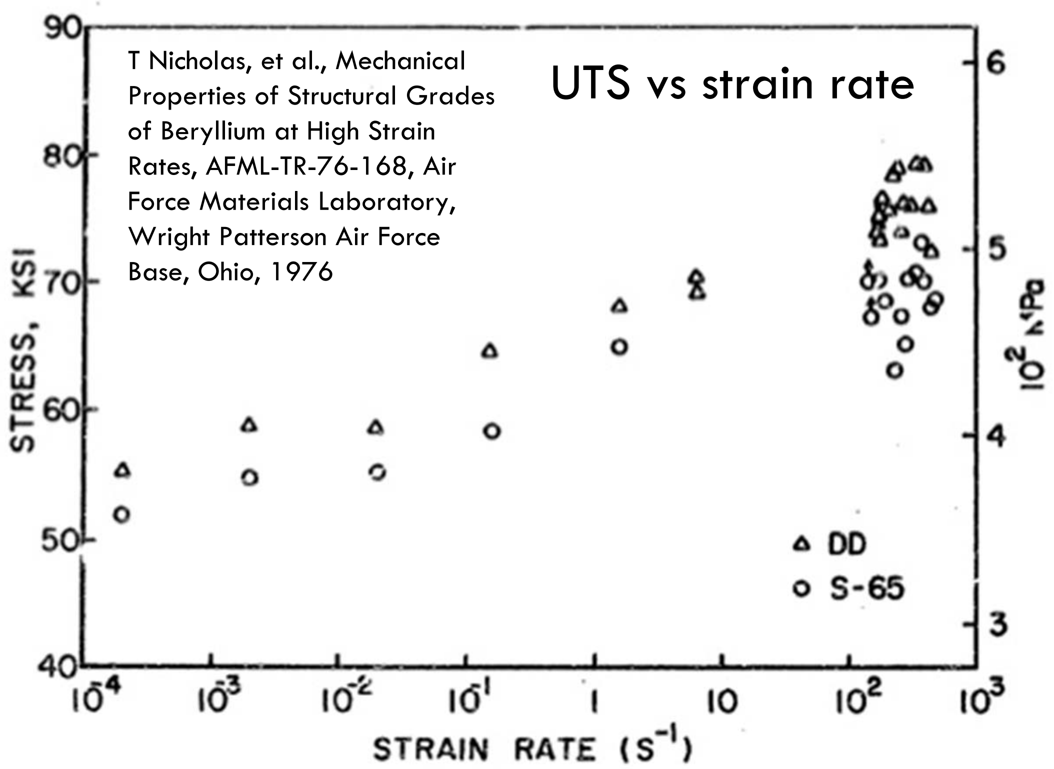


- Max strain predicted is 0.01 strain
- Pulse length is 1.6 micro-sec
- Strain rate is over 6,000 s^{-1}
- For LBNE 2.3 MW, 3.5 mm sigma, strain rate=100 s^{-1}
- For LBNE 2.3 MW, 1.5 mm sigma, strain rate=340 s^{-1}

Beryllium R&D:
Failure Criteria – Simulation versus Reality



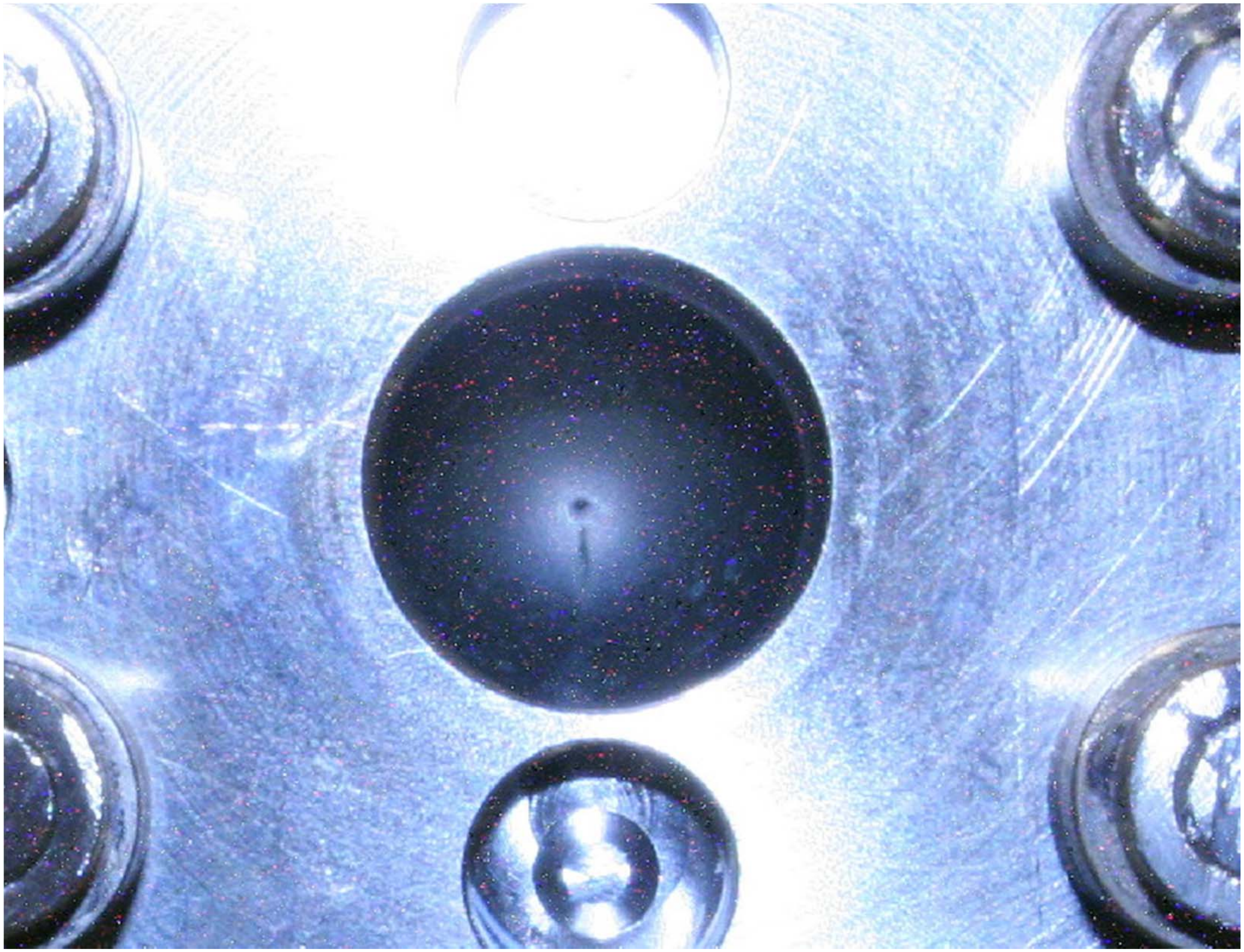
F.L. Schierloh and S.G Babcock, Tensile Properties of Beryllium at High Strain Rates and Temperatures, AFML-TR-69-273, General Motors Tech Center, 1969



T Nicholas, et al., Mechanical Properties of Structural Grades of Beryllium at High Strain Rates, AFML-TR-76-168, Air Force Materials Laboratory, Wright Patterson Air Force Base, Ohio, 1976

- Yield and Ultimate Stresses increase by 25-40% at strain rates greater than 100 s^{-1}
- Significant increased hardening as well

Beryllium R&D: Failure Criteria – Simulation versus Reality



- Damage seen on Be Lithium Lens Windows
- Just DS of Target
- Higher Temperature
- Higher Stress (10,000 psi of Li pressure on other side)
- Damage observed after 8 months of running at reduced spot size of 0.15 mm sigma and not at larger spot size (0.19 mm sigma)

Beryllium R&D:
Failure Criteria – Simulation versus Reality

- More work needs to be done in this area to set limits of Be in high power proton beams
  - Effects of irradiation and temperature
  - Refined simulation of actual conditions
  - In beam validation/benchmarking test
- For now, set conservative limits and push the envelope later…

Summary

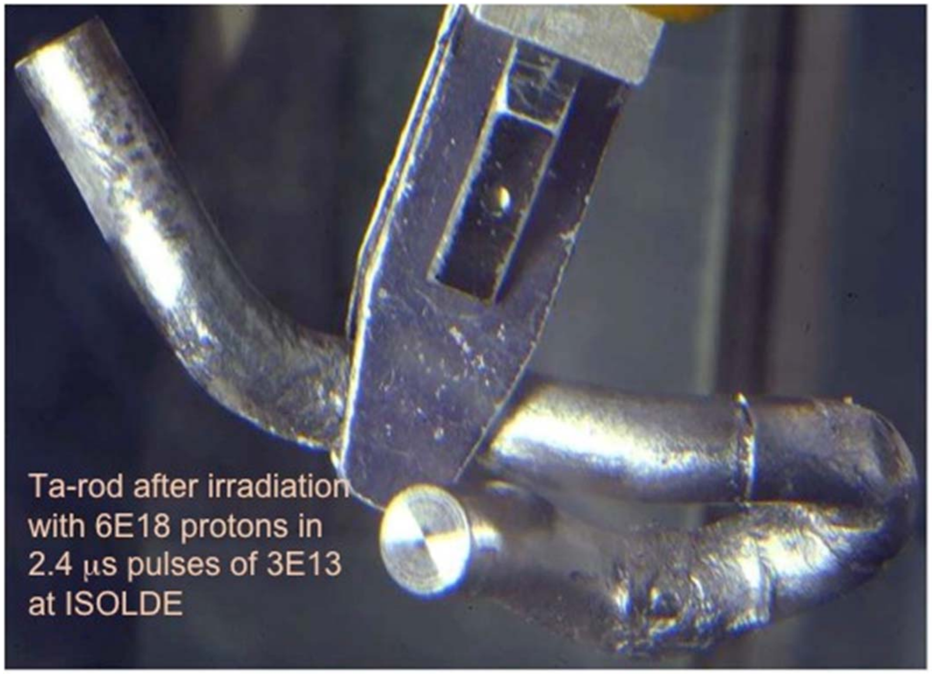
- Although challenging, critical design issues have been identified for high power, solid targets
- Graphite radiation damage testing at BNL
- First stage Be target design study by RAL shows promise of Be target for LBNE at 2.3 MW
- Future work includes:
  - Continuation of graphite sample testing
  - Further Be design studies
  - Be target testing at P-bar source OR new High RadMat Facility (CERN)?

Thanks to all

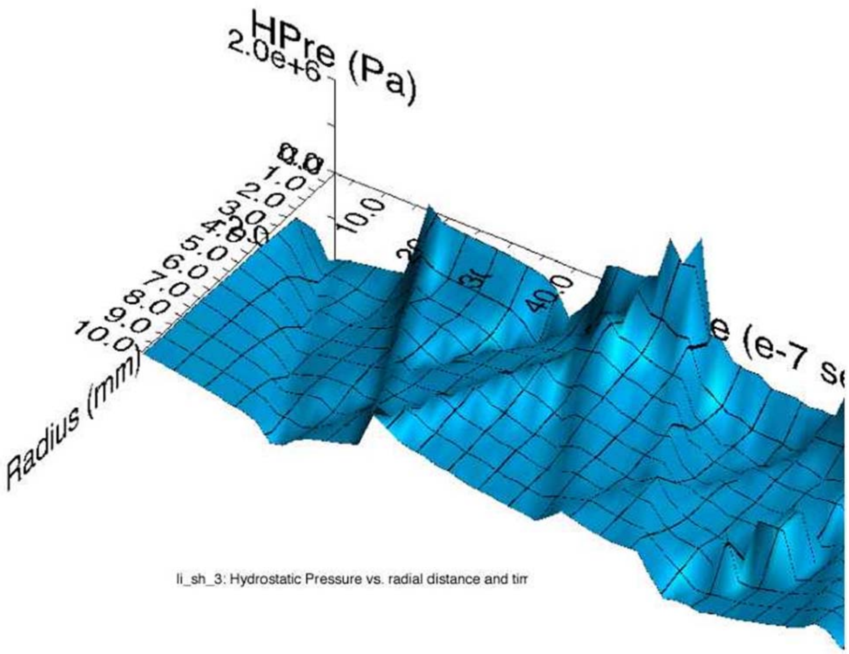
- N. Simos, J. Misek, H. Kirk, J. O'Conor, C. Densham, T. Davenne, P. Loveridge, M. Fitton, M. Rooney, O. Caretta, J. Hylen, R. Campos, N. Mokhov, T. Grumstrup, R. Zwaska, V. Sidorov, A. Leveling and many others…

Additional slides, if time…

Thermal Shock



Ta-rod after irradiation with 6E18 protons in 2.4 µs pulses of 3E13 at ISOLDE (photo courtesy of J. Lettry)



Simulation of stress wave propagation in Li lens (pbar source, Fermilab)

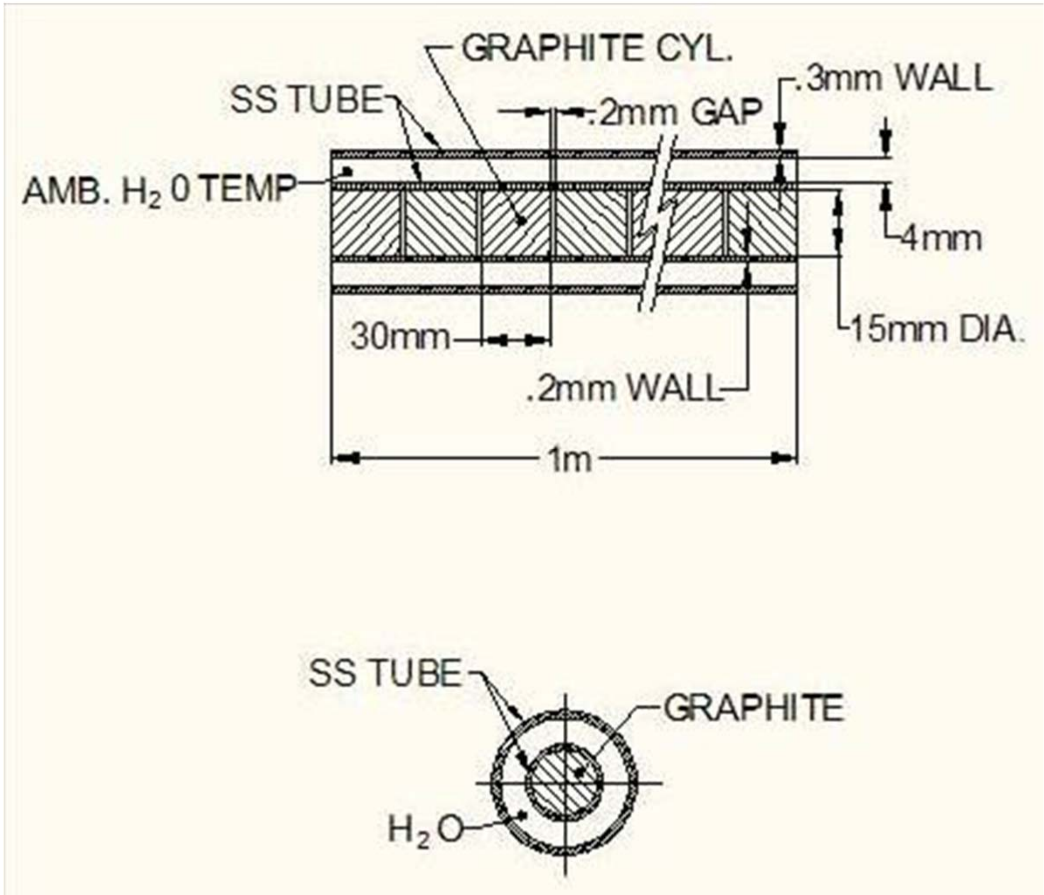
- Fast expansion of material surrounded by cooler material creates a sudden local area of compressive stress
- Stress waves (not shock waves) move through the target
- Plastic deformation or cracking can occur

Thermal Shock

- Methods to overcome thermal shock:
  - Material Selection
    - High specific heat
    - Low coefficient of thermal expansion
    - Low modulus of elasticity
    - High strength (tensile and fatigue) at elevated temperature
  - Segment target length
  - Avoid stress concentration prone target shapes
  - Pre-load in compression
  - Manipulate beam parameters (spot size, intensity)
- Must design for accident conditions
  - Maximum intensity and smallest spot size
  - Mis-steered beam on target

Heat Removal

- 25-30 kW total energy deposited (2.3 MW proton beam)
- Easy to remove with water



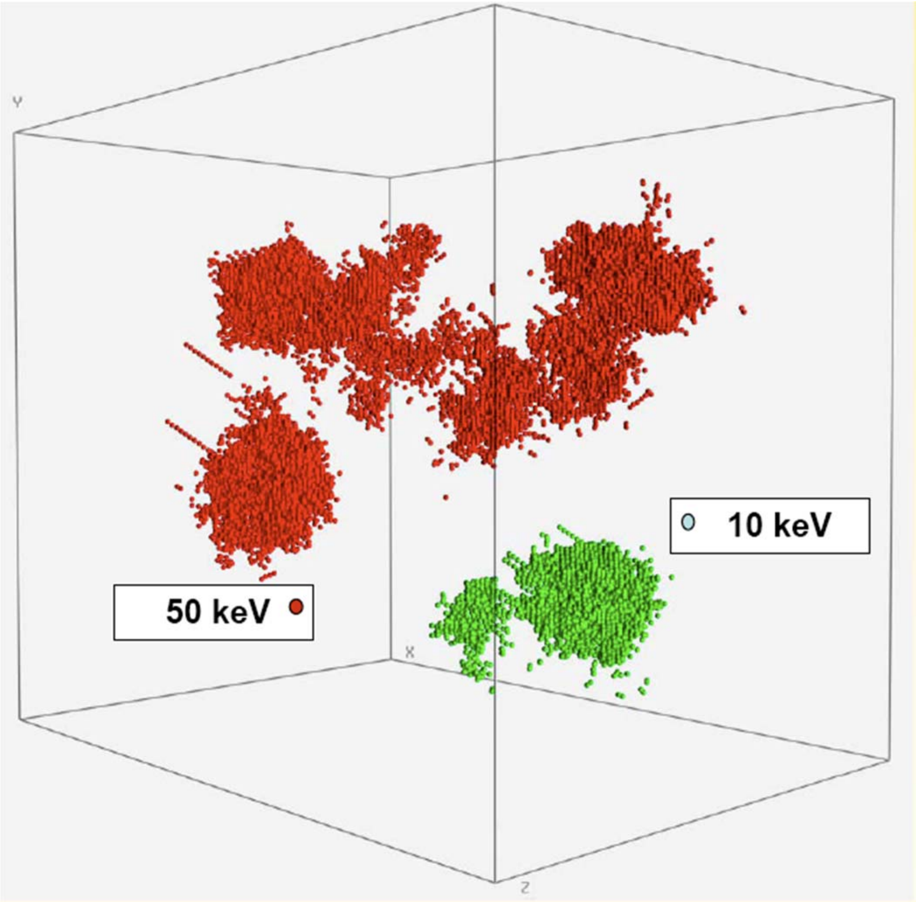
- Tritium production
- Hydrogen gas production
- Thermal shock in water (Water Hammer)
- 150 atm IHEP report (actual pressure rise will be much less due to flexibility of pipe)

Heat Removal

- Methods of avoiding “water hammer”
  - 2 Phase cooling (bubbles)
  - 2 Phase cooling (heat pipe)
  - Spray cooling (NuMI horn)
  - Gas cooling
    - T2K 750 kW graphite target, Helium cooling
    - Mini-BooNE beryllium target, Air cooling

Radiation Damage

- Displacements in metal crystal lattice
  - Embrittlement
  - Creep
  - Swelling
- Damage to organics/plastics
  - Cross-linking (stiffens, increase properties)
  - Scission (disintegrate, decrease properties)

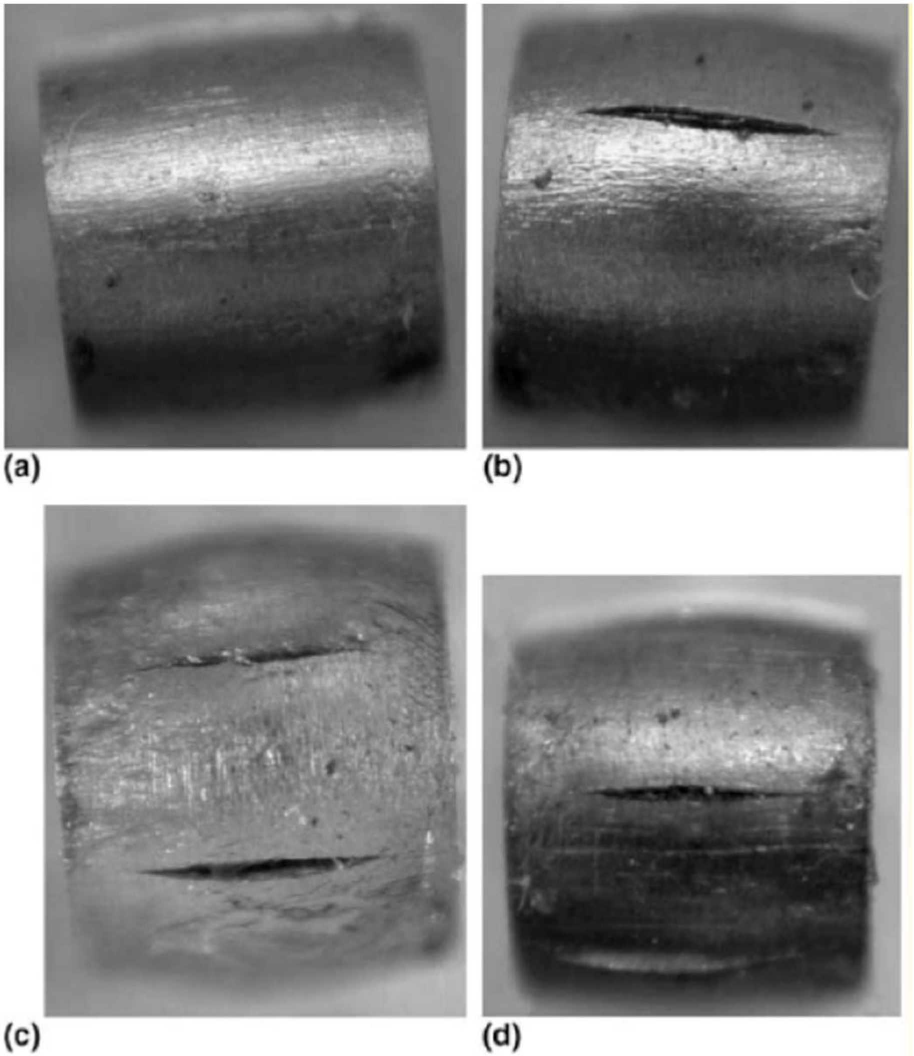


Molecular Damage Simulations of peak damage state in iron cascades at 100K.

R. E. Stoller, ORNL.

Radiation Damage

- Tungsten cylinders irradiated with 800 MeV protons and compressed to 20% strain at RT.
  - A) Before irradiation
  - B) After 3.2 dpa
  - C) After 14.9 dpa
  - D) After 23.3 dpa
- Data exists for neutron irradiation, less for proton irradiation
  - Gas production much higher for high energy particle irradiation



S. A. Malloy, et al., Journal of Nuclear Material, 2005. (LANSCE irradiations)

Oxidation

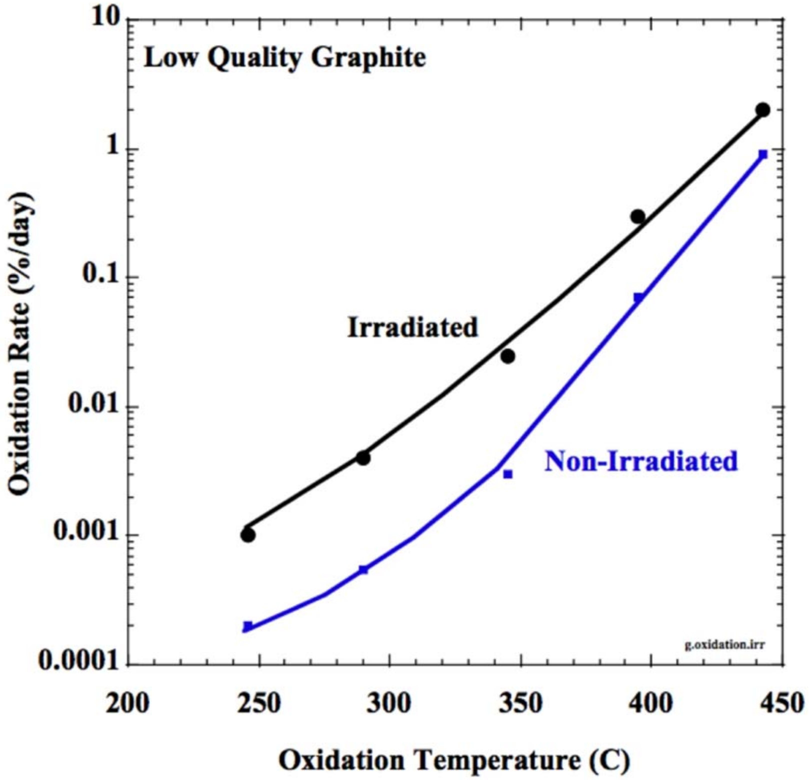


Figure 2 : Effect of irradiation on poor quality graphite. Kosiba and Dienes USAEC RID-7565 Ppart 1) 1959.

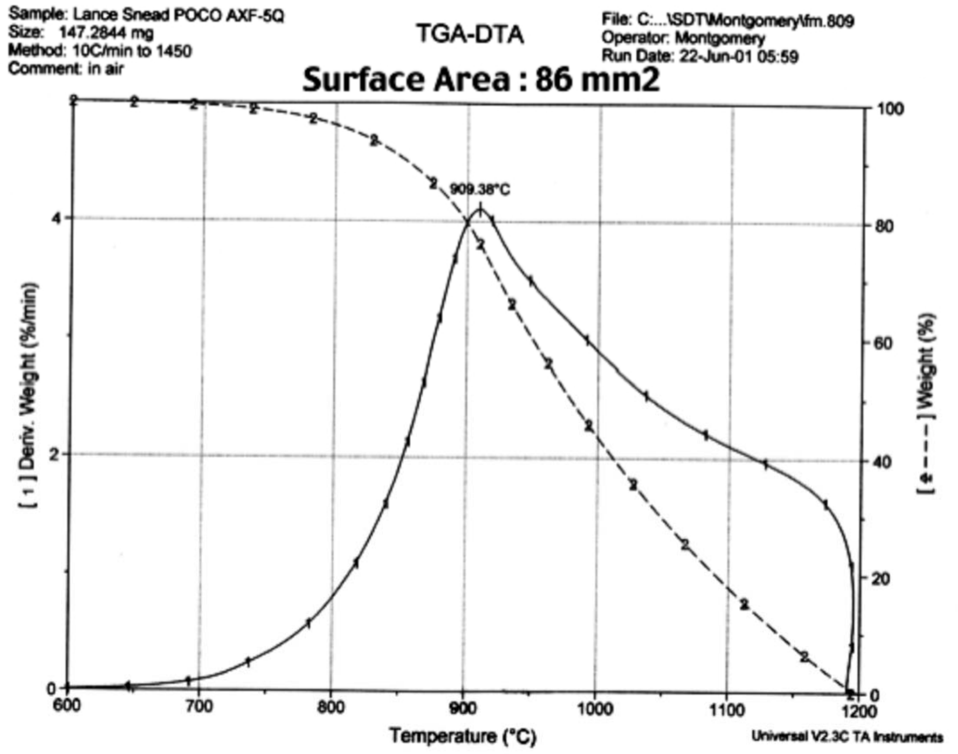


Figure 3a :Oxidation of Poco AXF-5Q in flowing air.

- Oxidation reaction is very fast for carbon at high temperatures
- Need sealed target jacket with beam windows and pump/purge system
- Beryllium avoids this?

Lance Snead and Tim Burchell
Oak Ridge National Laboratory

Radiation Accelerated Corrosion

- Al 6061 samples displayed significant localized corrosion after 3,600 Mrad exposure
- NuMI target chase air handling condensate with pH of 2
- NuMI decay pipe window concerns

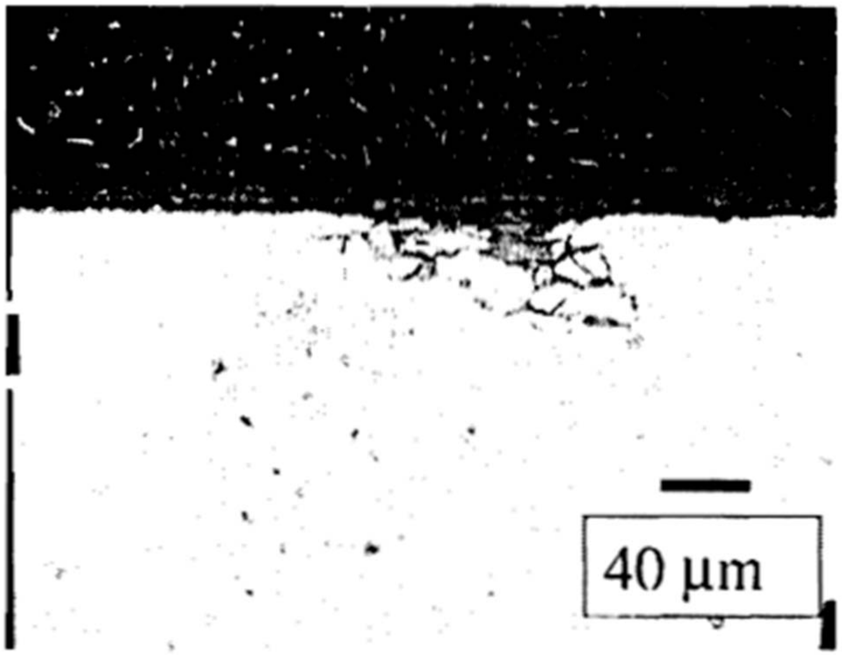
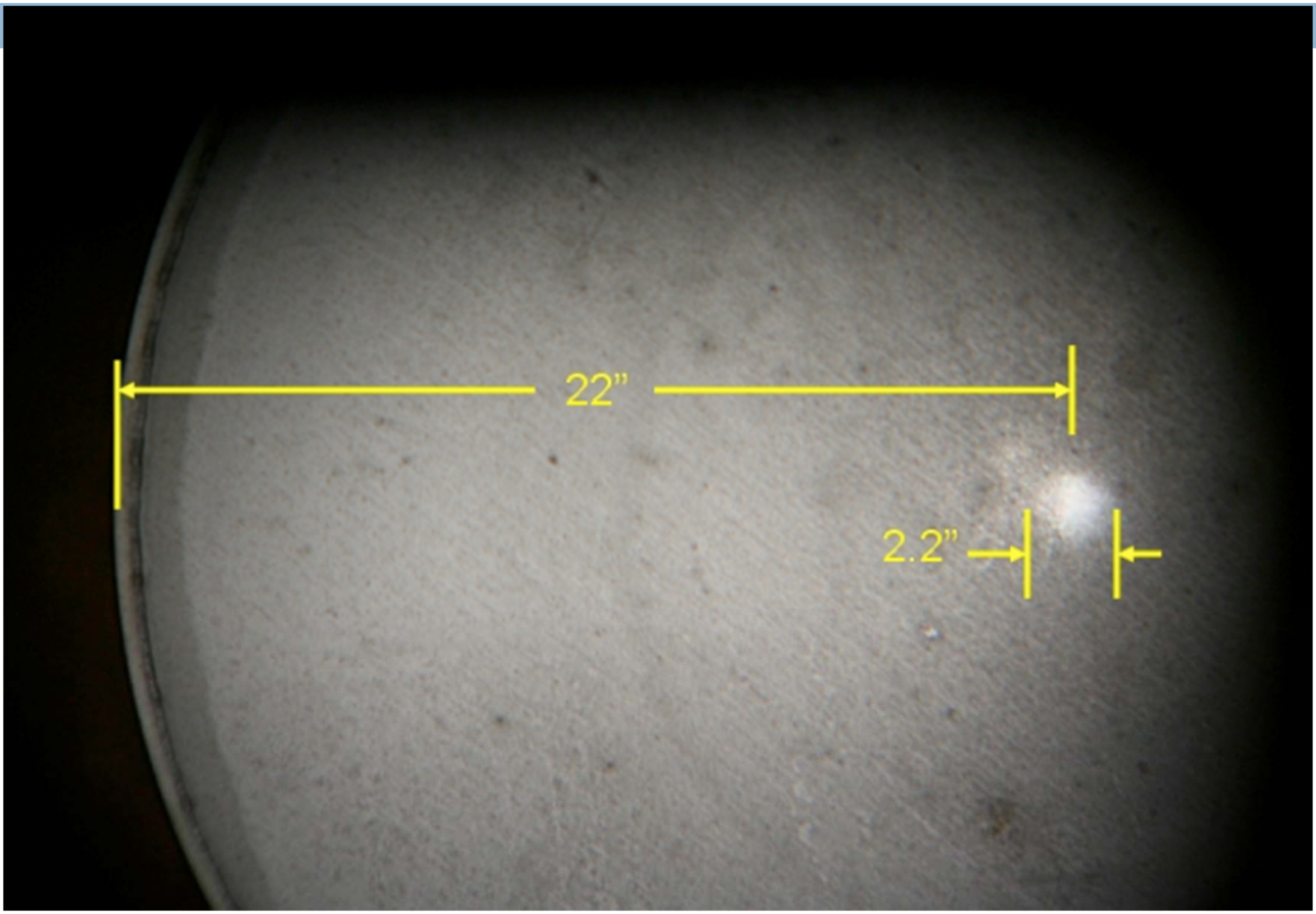


FIG. 8. Localized corrosion on 6061 Al sample exposed 12 weeks to saturated water vapor at 200°C and gamma irradiation.

R.L. Sindelar, et al., *Materials Characterization* 43:147-157 (1999).

Radiation Accelerated Corrosion

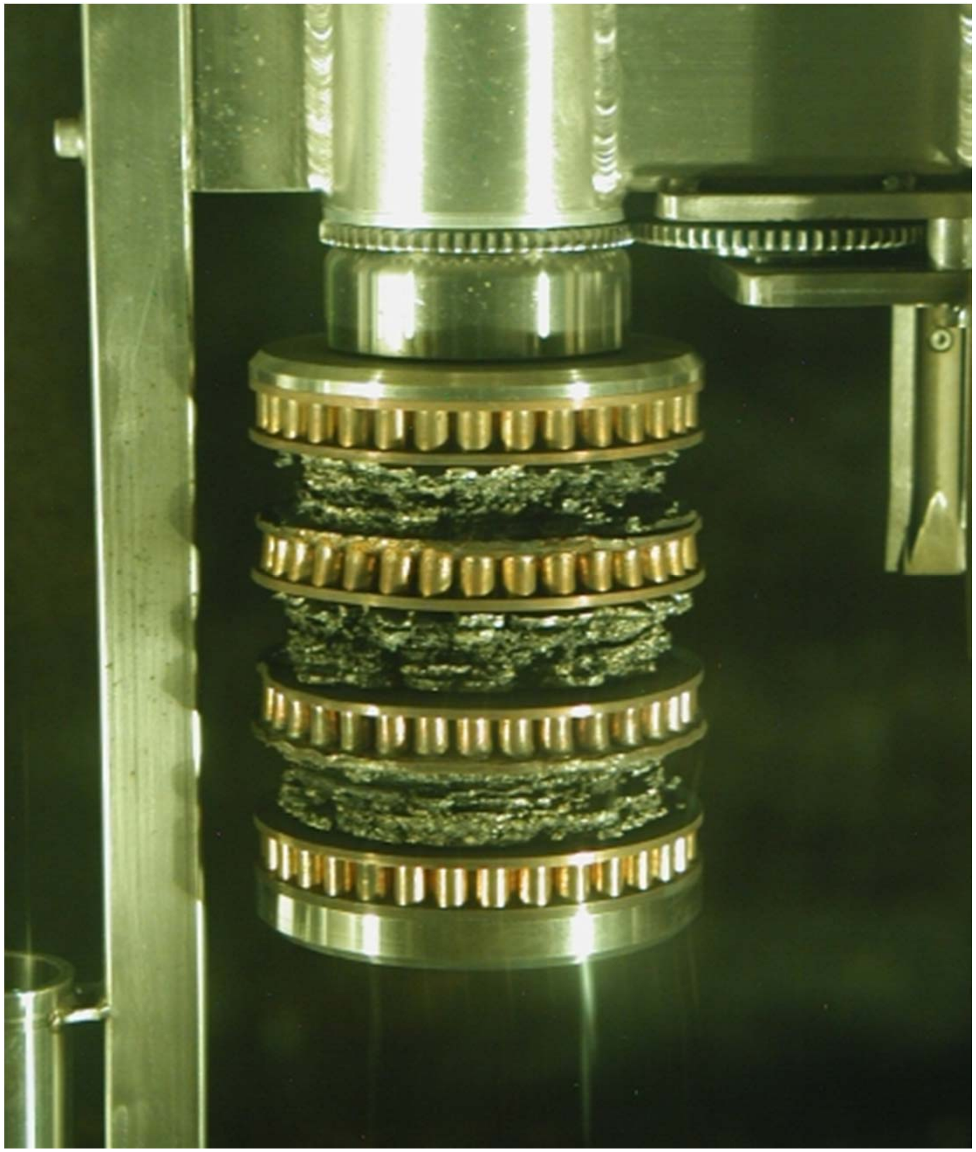


- Photograph of NuMI decay pipe US window showing corroded spot corresponding to beam spot

Radiation Accelerated Corrosion

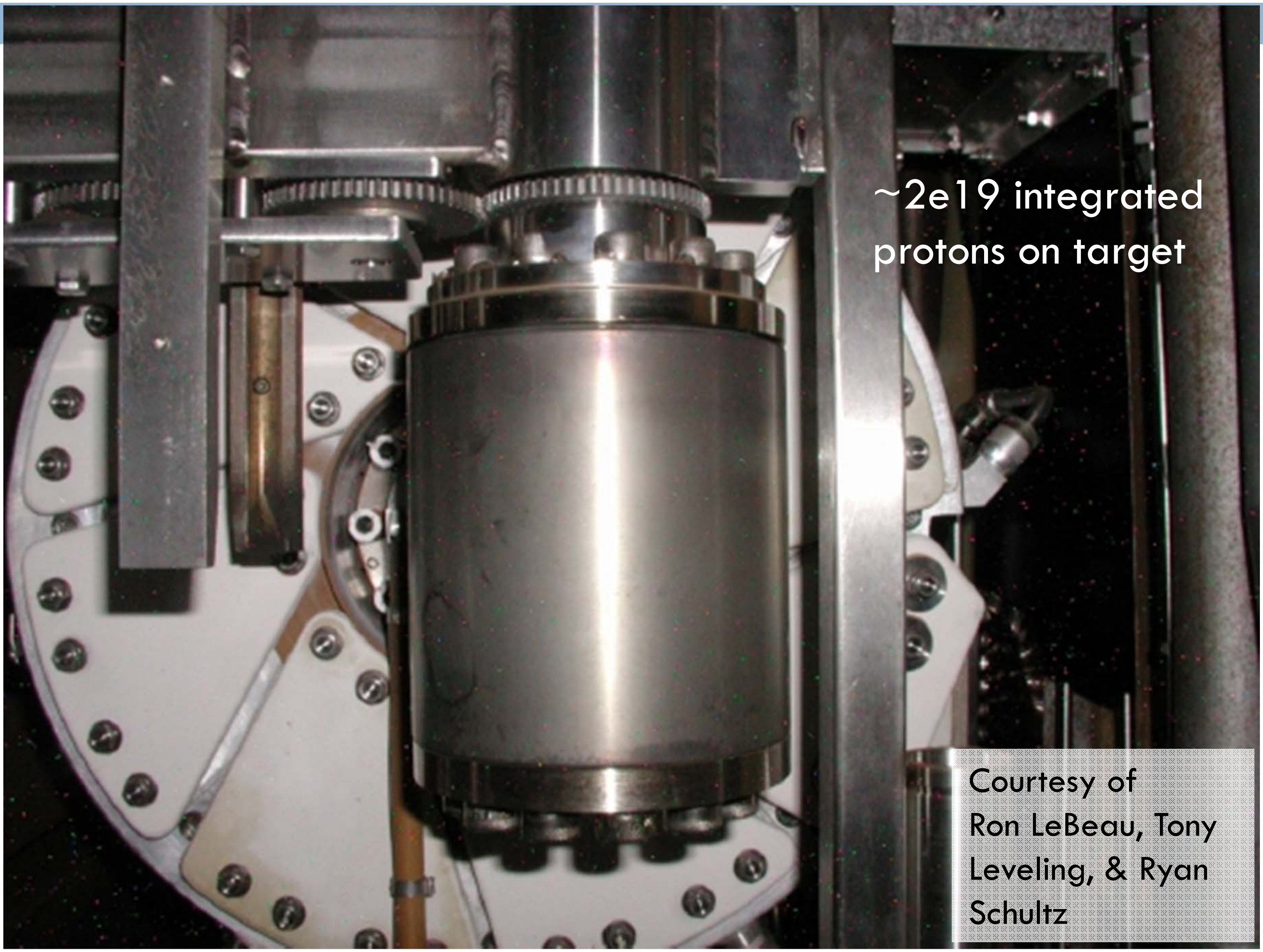
- MiniBooNE 25 m absorber HS steel failure
- (hydrogen embrittlement from accelerated corrosion).

Survivability is relative



- P-bar consumable target
  - Ran in consumable mode for 2 plus years
  - Change-out time 12 hours maximum
  - Over-heating, oxidation, thermal shock led to damage

New P-bar Target



~2e19 integrated protons on target

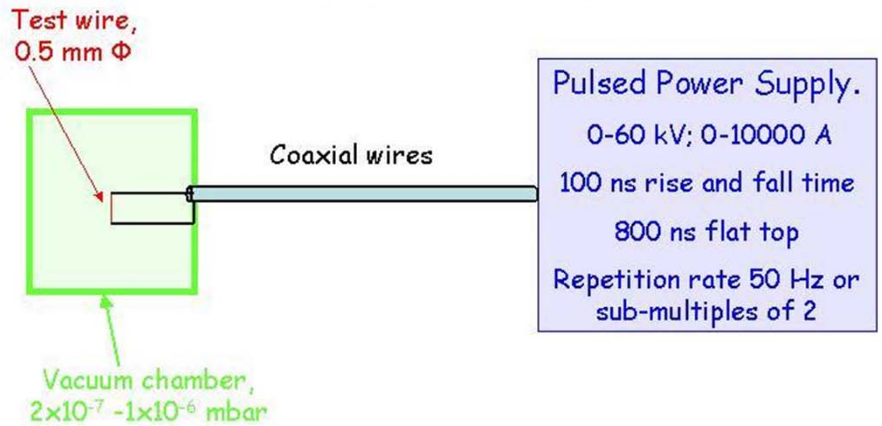
Courtesy of Ron LeBeau, Tony Leveling, & Ryan Schultz

Thermal Shock

- Work at RAL-Sheffield by R. Bennett and G. Skoro to study solid targets for NuFact
  - Pulsed Ta & W wire testing
  - Benchmark simulation techniques
  - Show promise of solid W at 4 MW
- Upcoming Publications:
  - G.P. Skoro et al. / Journal of Nuclear Materials 409 (2011) 40–46
  - Nuclear Inst. and Methods in Physics Research A, DOI:10.1016/j.nima.2011.03.036

Current pulse – wire tests at RAL

Schematic circuit diagram of the wire test equipment



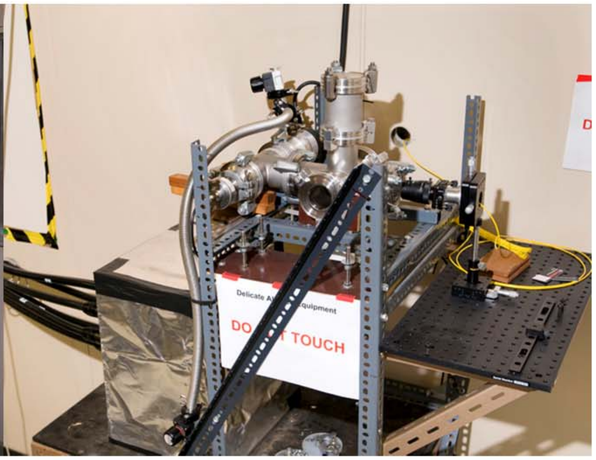
Pulsed Power Supply.

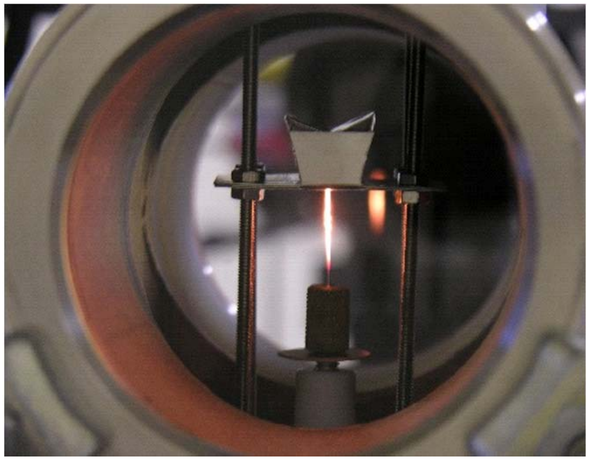
0-60 kV; 0-10000 A

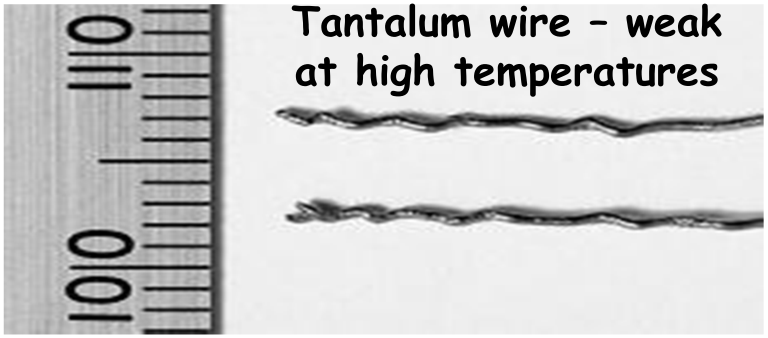
100 ns rise and fall time

800 ns flat top

Repetition rate 50 Hz or sub-multiples of 2







Tantalum wire – weak at high temperatures

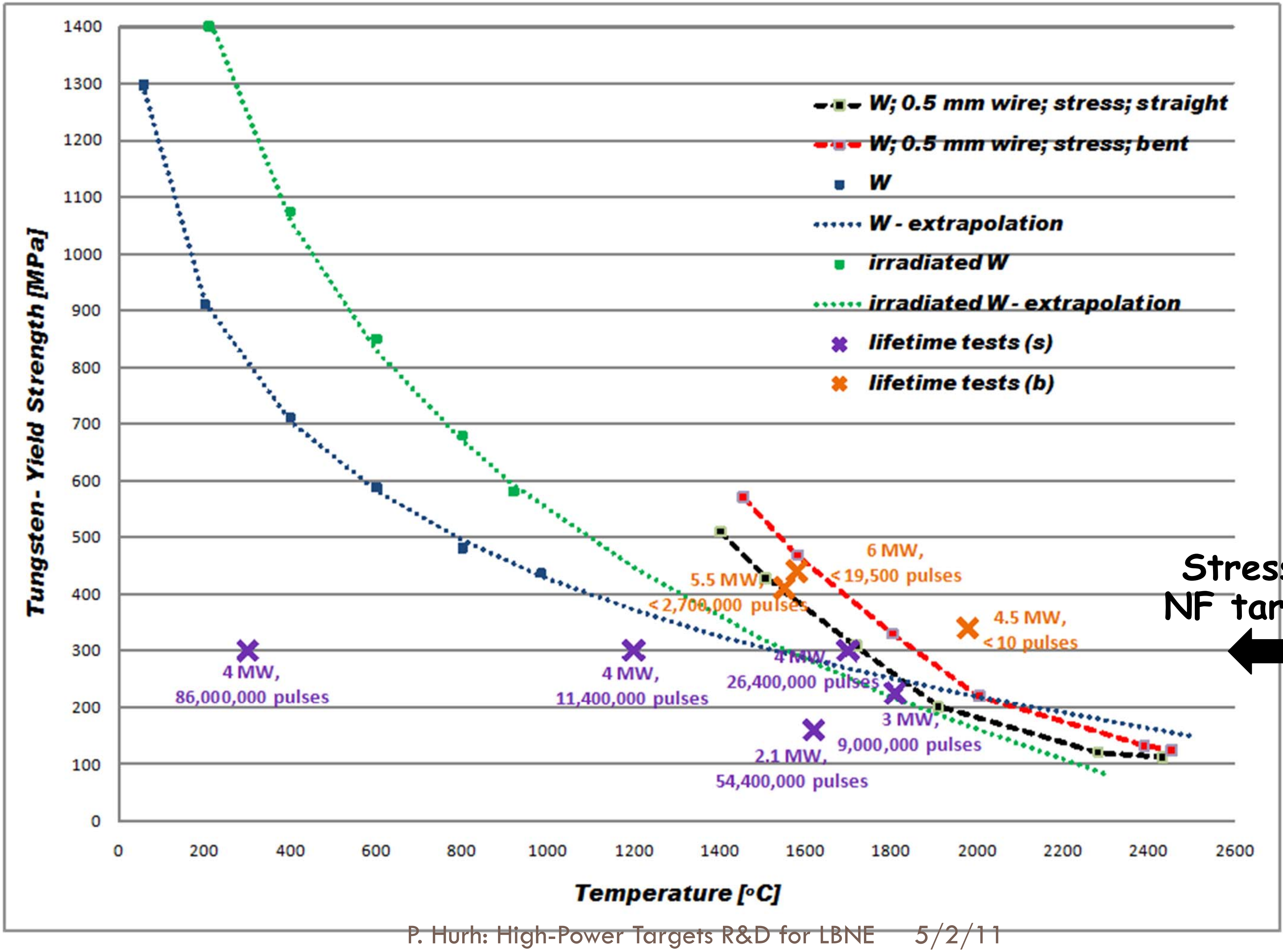
Tungsten – much better!!!

<u>The Finite Element Simulations have been used to calculate equivalent beam power in a real target and to extract the corresponding lifetime.</u>

Goran Skoro
The University Of Sheffield.

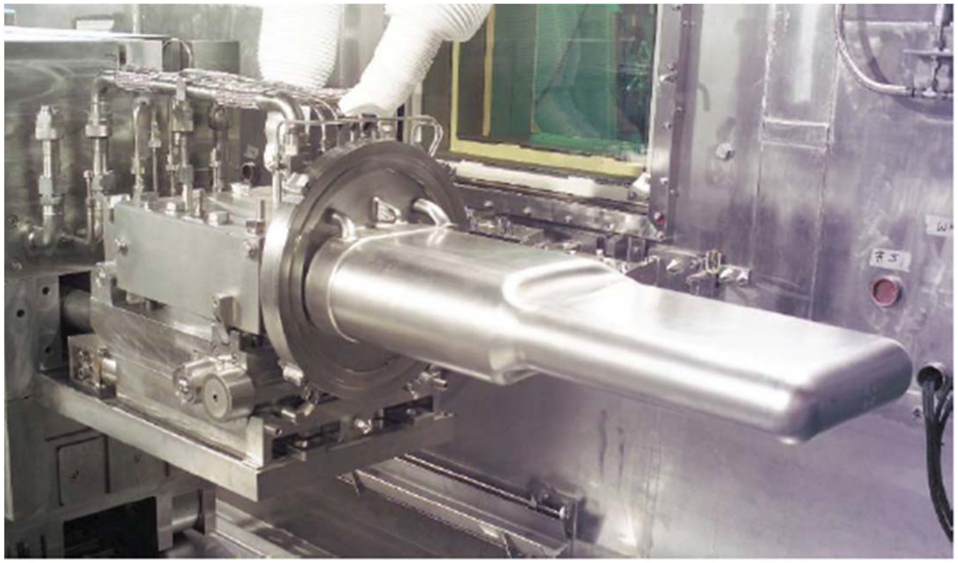
Yield strength of tungsten – our results

Combination of visual observation of the wire and LS-DYNA simulations



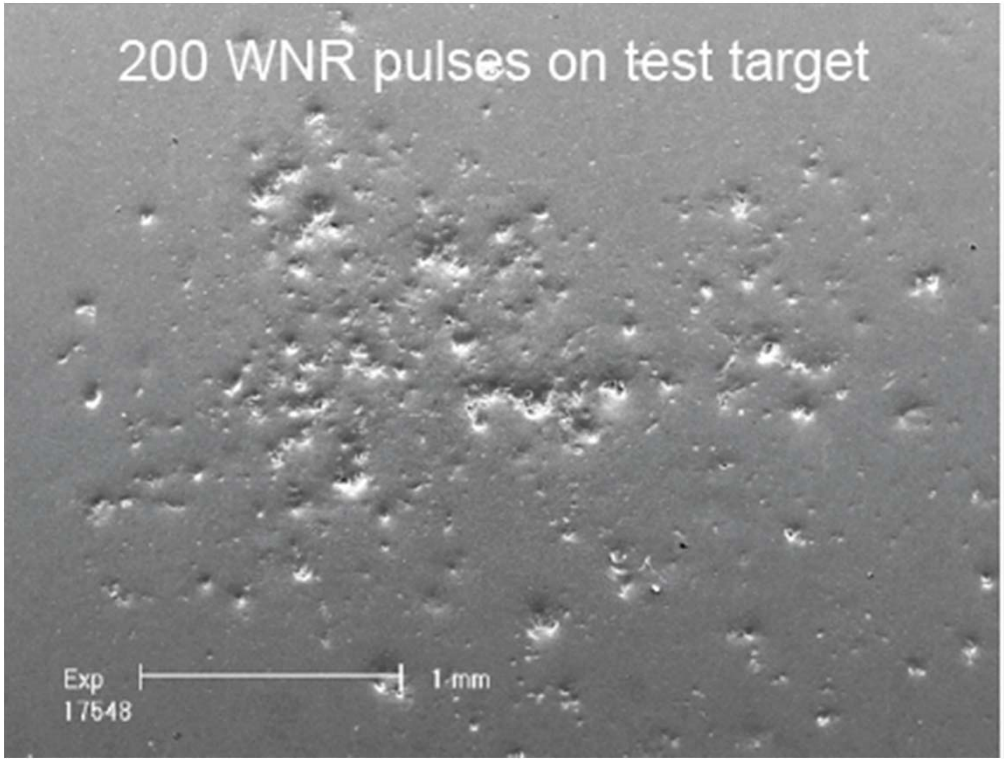
Stress in NF target

Thermal Shock

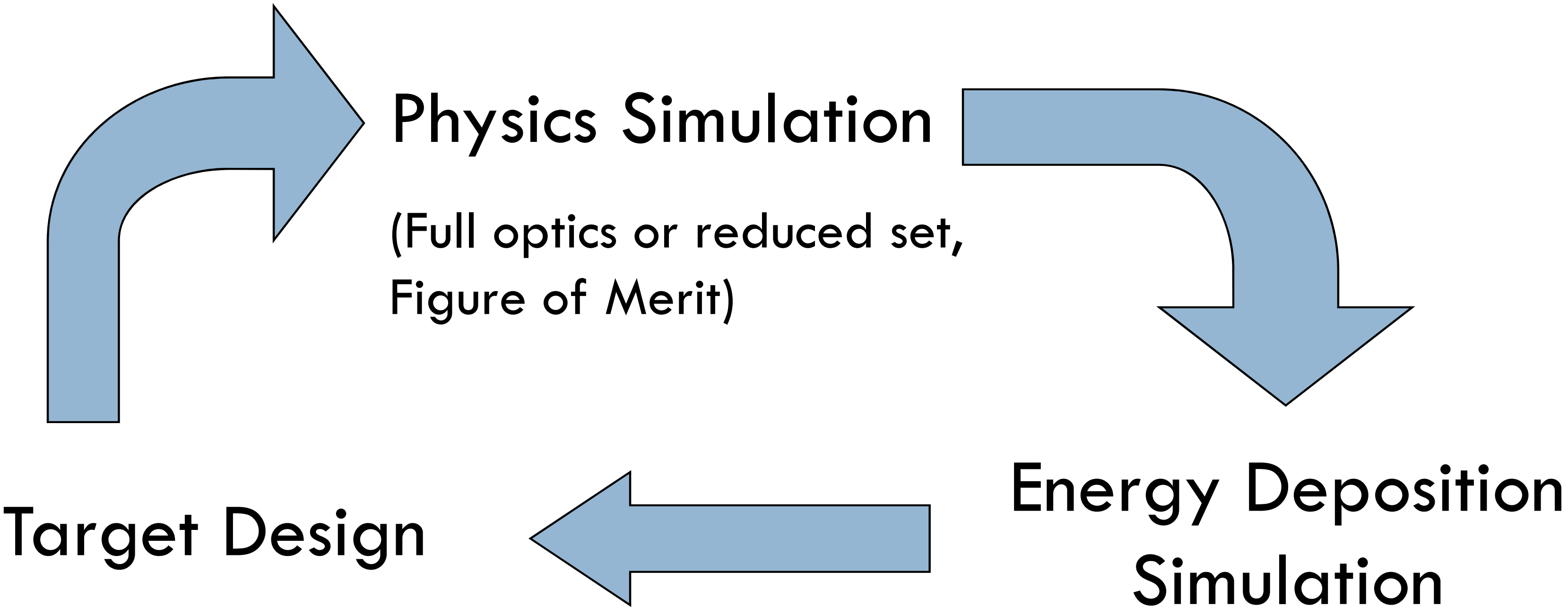


J. Haines, B. Riemer, ORNL

- SNS Hg Target
  Cavitation problems



Physics Optimization



Physics Simulation

(Full optics or reduced set,
Figure of Merit)

Energy Deposition
Simulation

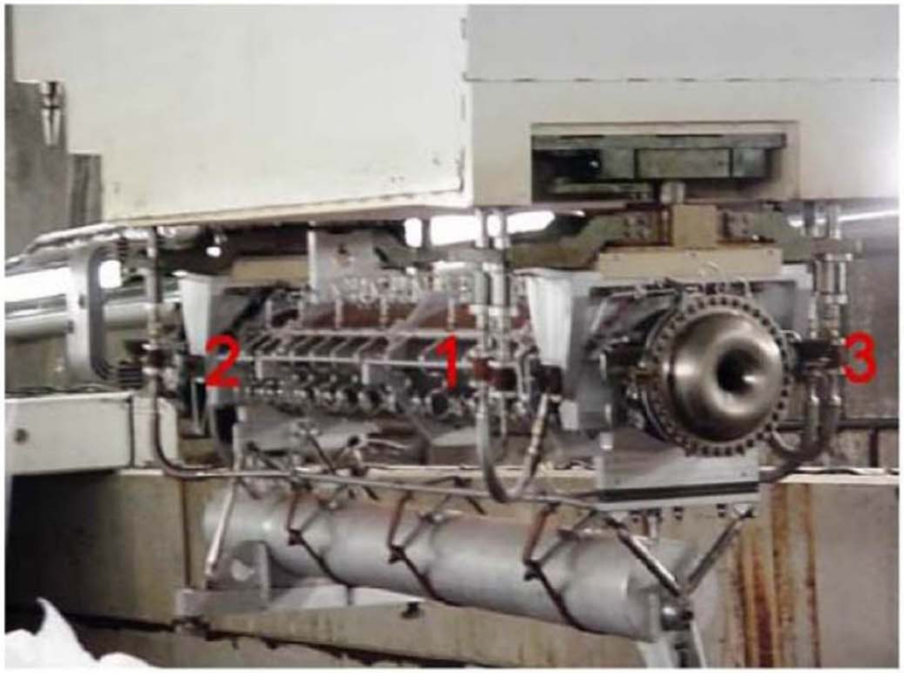
Target Design

Iterative process makes it difficult to isolate the design efforts

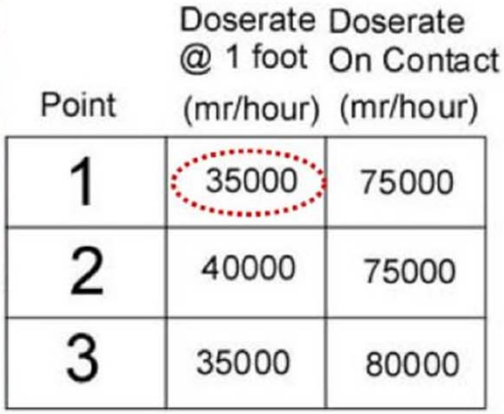
Figure of Merit helps to reduce simulation requirements

Leads to novel target ideas (multiple materials, spherical targets)

Residual Radiation



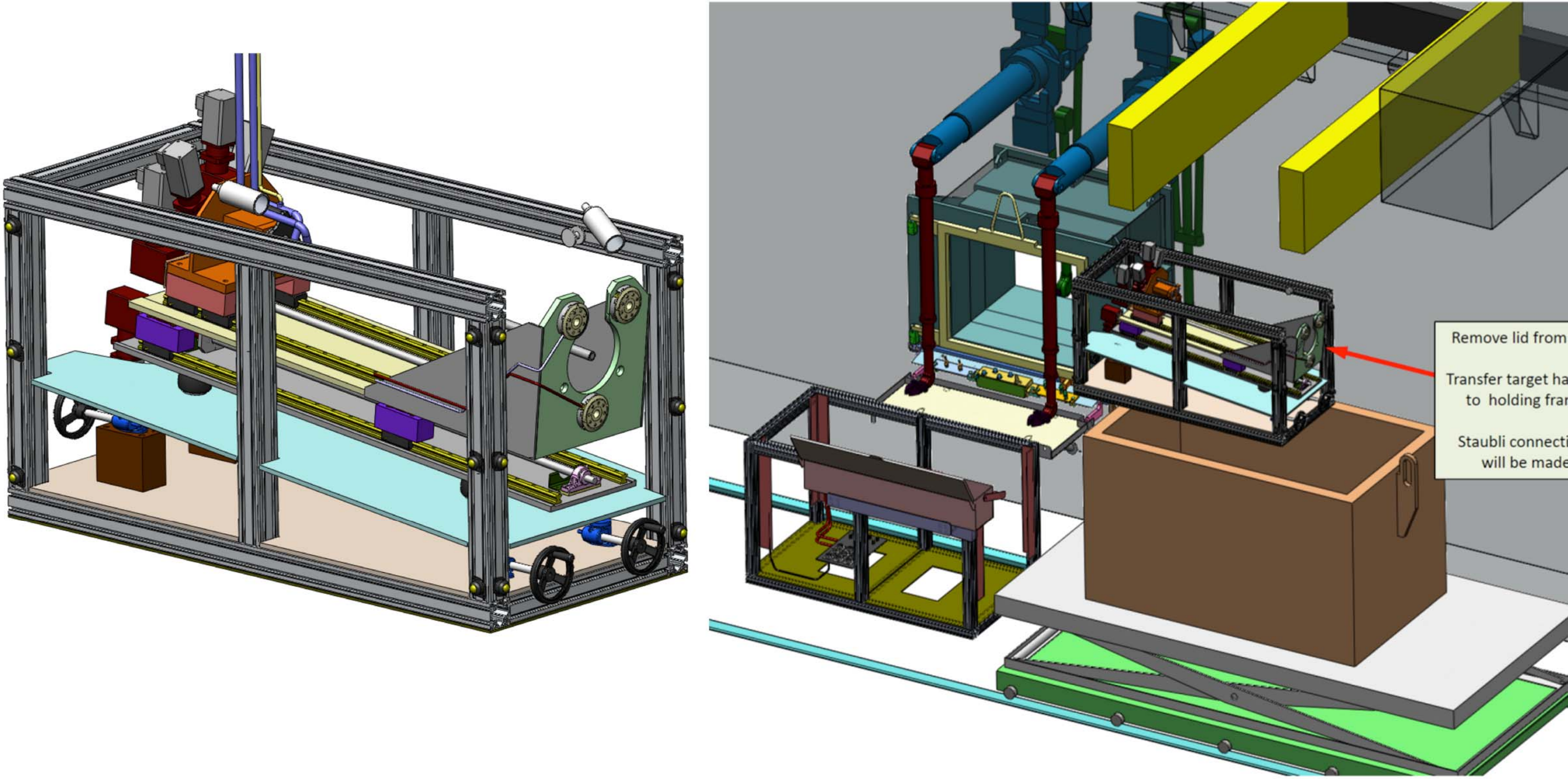
Measured dose rates for NuMI Horn 1 water line repair (250 kW proton beam)



Point	Doserate @ 1 foot (mr/hour)	Doserate On Contact (mr/hour)
1	35000	75000
2	40000	75000
3	35000	80000

- Dose rates for 2.3 MW beam components estimated at 300-800 Rad/hr
- Systems for component change-out and repair must be developed (IE Remote Handling)
- Operations activities must be integrated into the conceptual design of target components

Residual Radiation



Remove lid from

Transfer target ha
to holding fra

Staubli connecti
will be made

LBNE Remote Handling Equipment (courtesy of V. Graves and A. Carroll, ORNL)