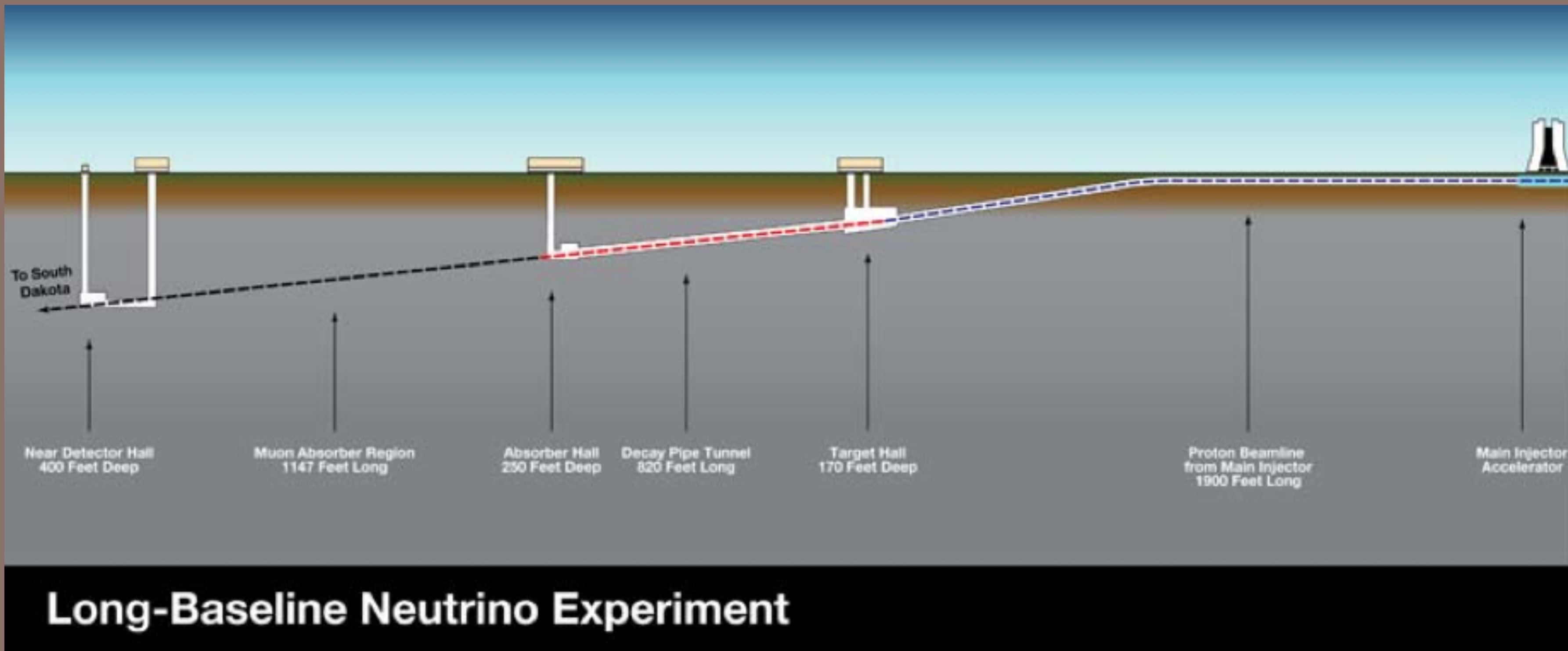


LBNE 2+ MW TARGET R&D OVERVIEW FOR HB 2010

P. Hurh FNAL

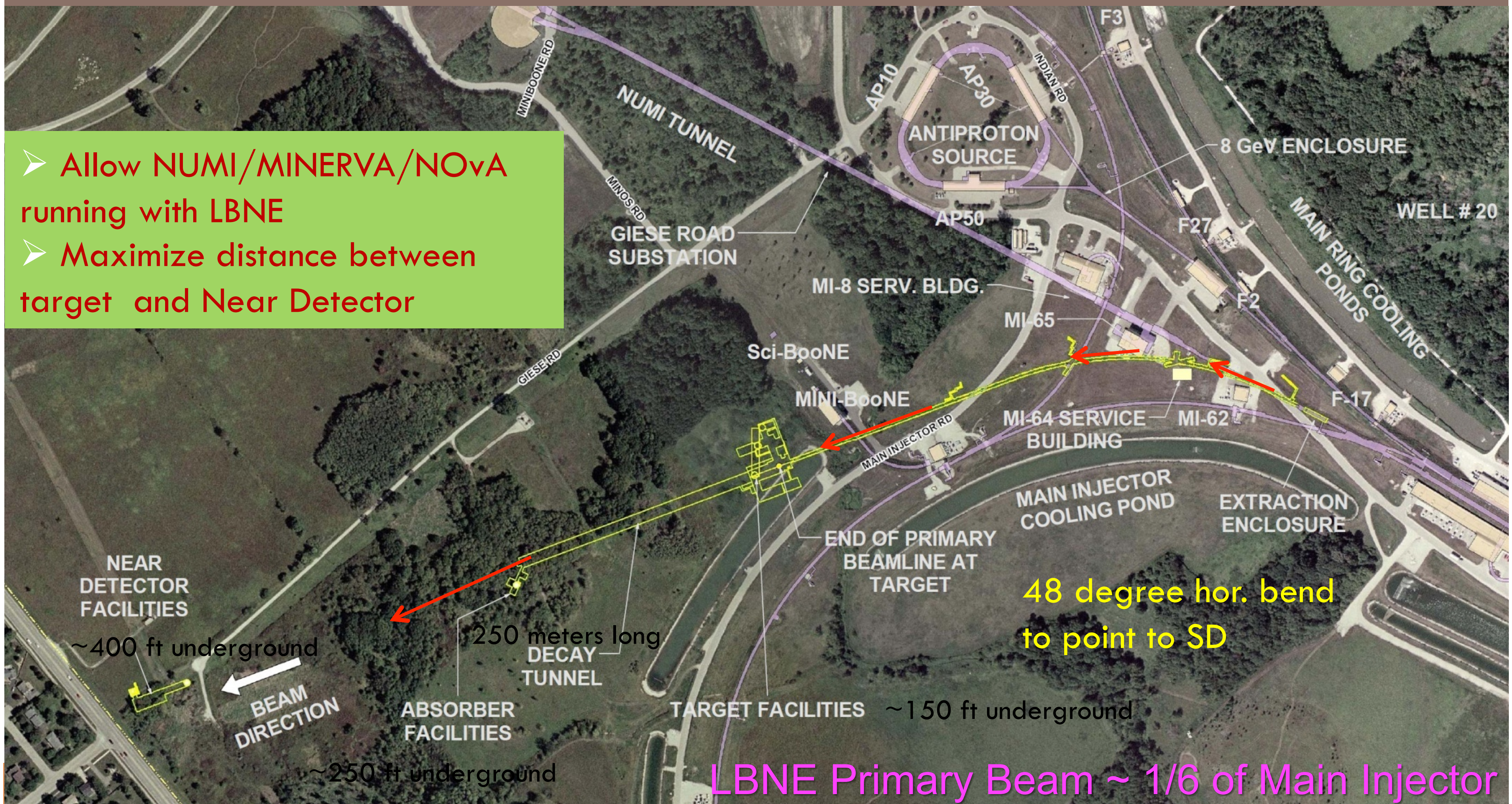
9/30/10

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



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

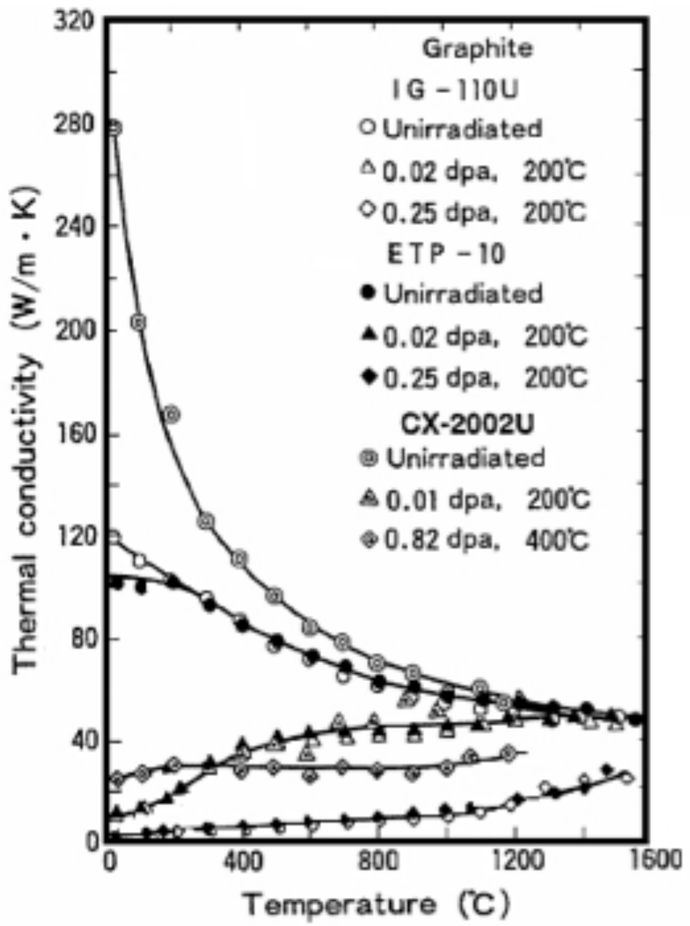
Focus of this Presentation

- **Graphite target material** (LBNE target IHEP conceptual design for 2 MW and baseline design for 700 kW)
  - Autopsy of NuMI Target NT-02 (FNAL)
  - Irradiation Damage Testing at BLIP (BNL, N. Simos)
- **Beryllium target material** (alternative LBNE target design for 2.3 MW)
  - Physics, Thermal, Structural Simulation Studies (RAL, C. Densham, et al.)
  - Correlation of predicted single pulse stress failure with empirical evidence (FNAL)

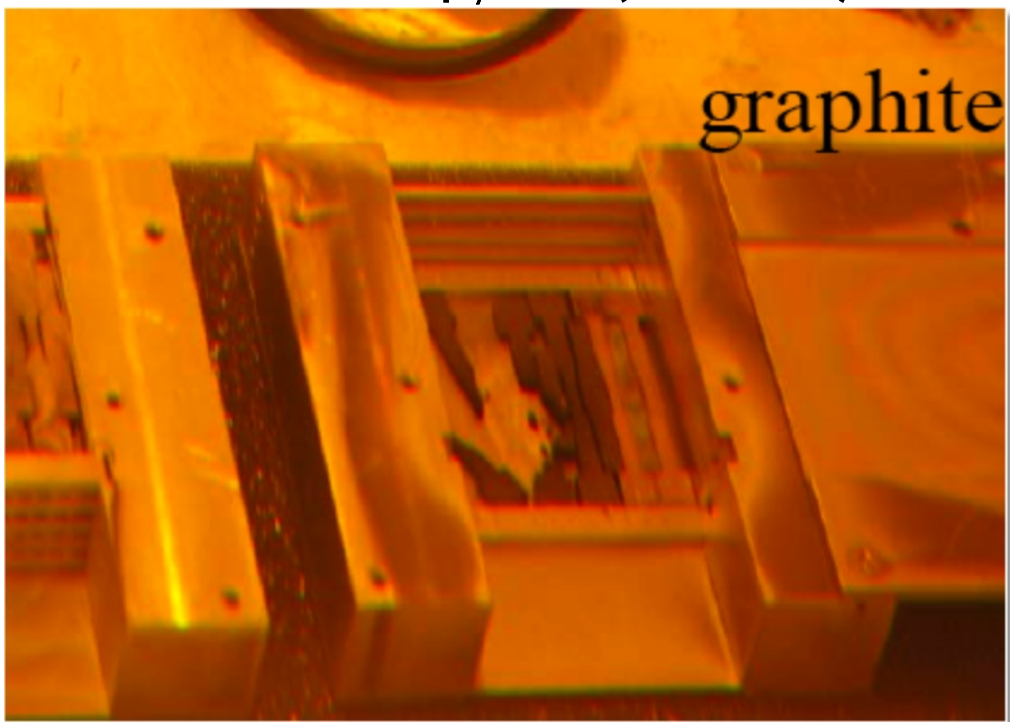
Graphite R&D

- Why Graphite?
  - Excellent for thermal shock effects (lower Cp, lower CTE, very low E, high strength at high temperatures)
  - Not toxic
  - Not dual-use technology (not export controlled)
  - Readily available (inexpensively) in many grades and forms
- Why not Graphite?
  - Rapid oxidation at high temperatures
  - Radiation damage

Graphite R&D: Radiation Damage



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

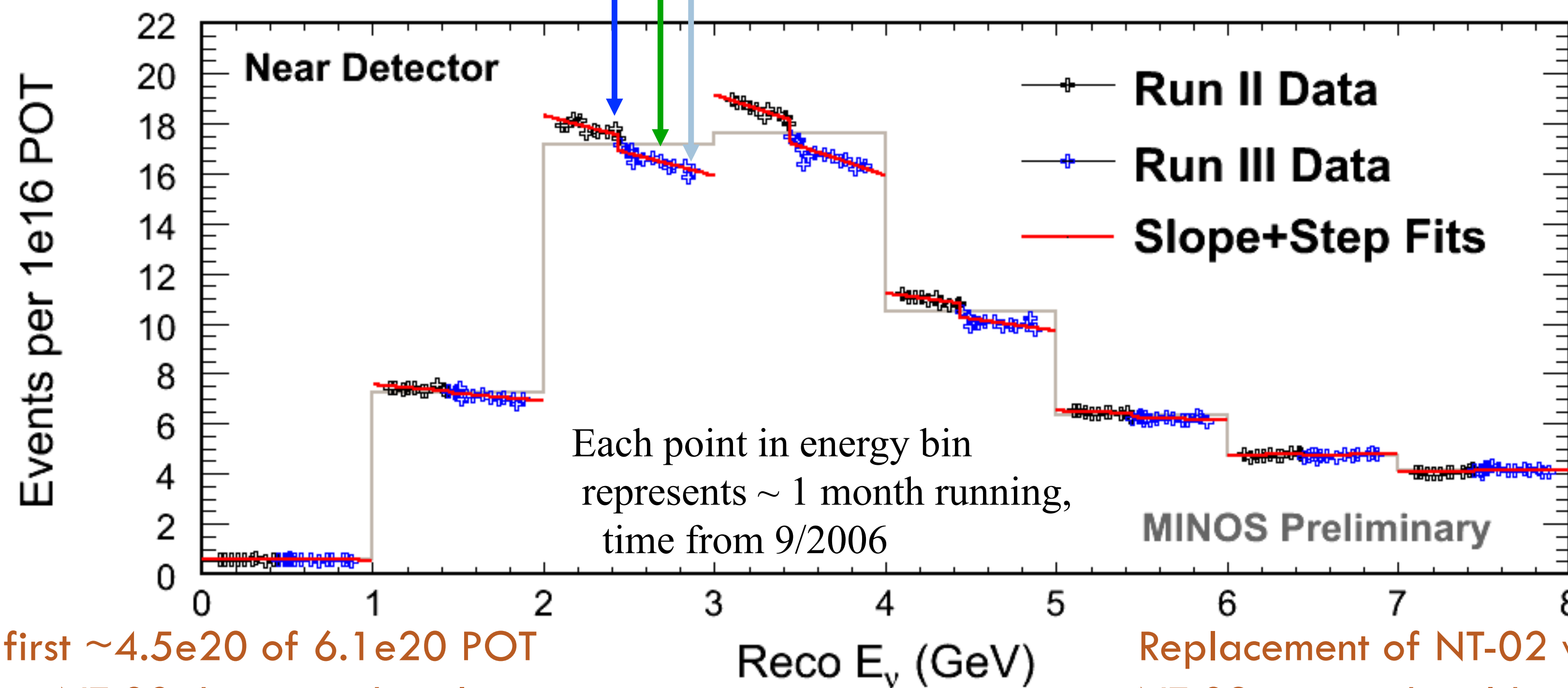


Graphite R&D: Autopsy of NuMI Target NT-02

Decrease as expected when decay pipe changed from vacuum to helium fill

No change when horn 1 was replaced

No change when horn 2 was replaced

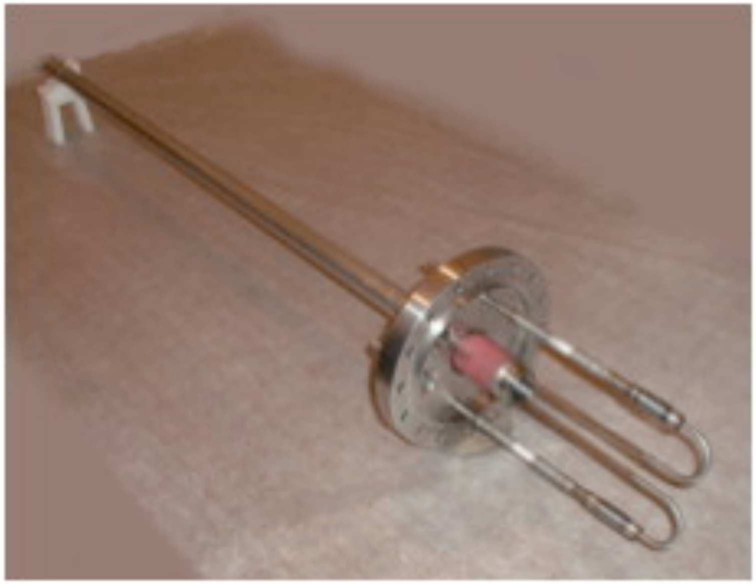


first ~4.5e20 of 6.1e20 POT on NT-02 shown on this plot

Replacement of NT-02 with NT-03 restored yield to expected levels

Graphite R&D: Autopsy of NuMI Target NT-02

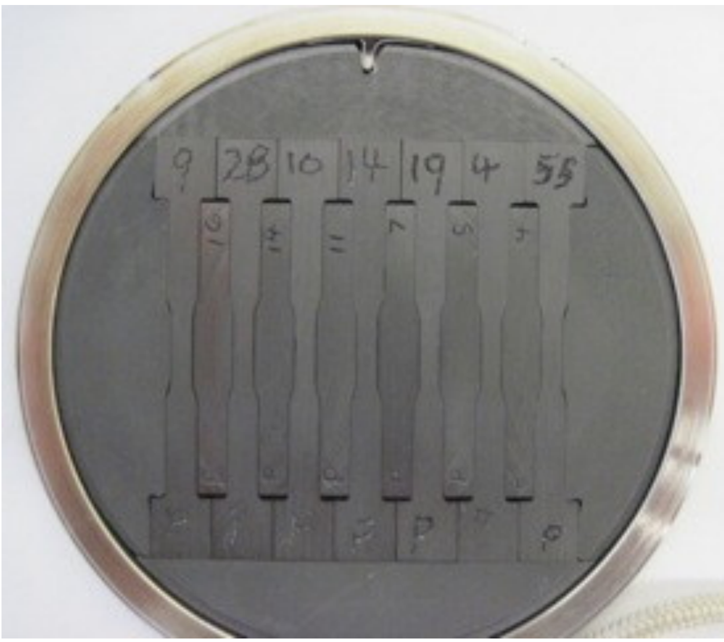
- Must remove sheath to see graphite fins within
- Work cell to accomplish this autopsy is not yet available at FNAL (being built)
- Autopsy planned, but not performed yet (pictures are prior to installation)



Graphite R&D: Autopsy of NuMI Target NT-02

- Work Cell at the new C-0 Remote Handling Facility is under construction
- Will have lead glass window, internal crane, manipulators, and shielding to work on items up to 1,000 R/hr
- Hope to complete in late Fall 2010

Graphite R&D: Irradiation Testing at BLIP



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

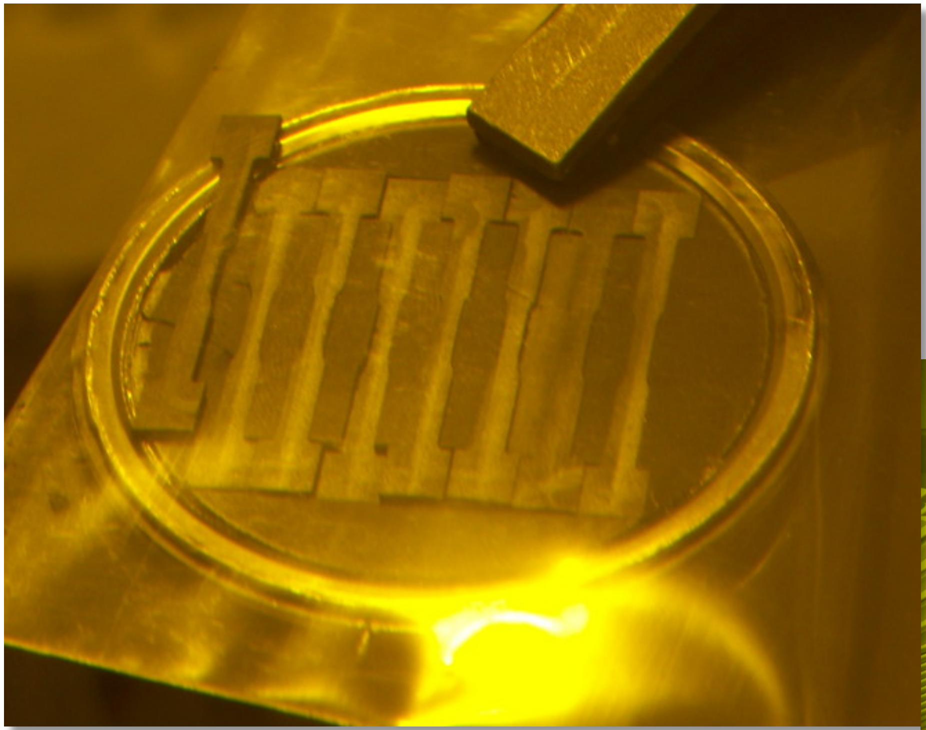
- Working with N. Simos and H. Kirk at BNL to test samples irradiated by 181 MeV proton beam at BLIP
- Testing for:
  - Tensile properties (YS, UTS, …)
  - Coef. of thermal expansion
  - Thermal (electrical) conductivity
- Most samples encapsulated in argon filled, stainless steel capsules to isolate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

Graphite R&D: Irradiation Testing at BLIP

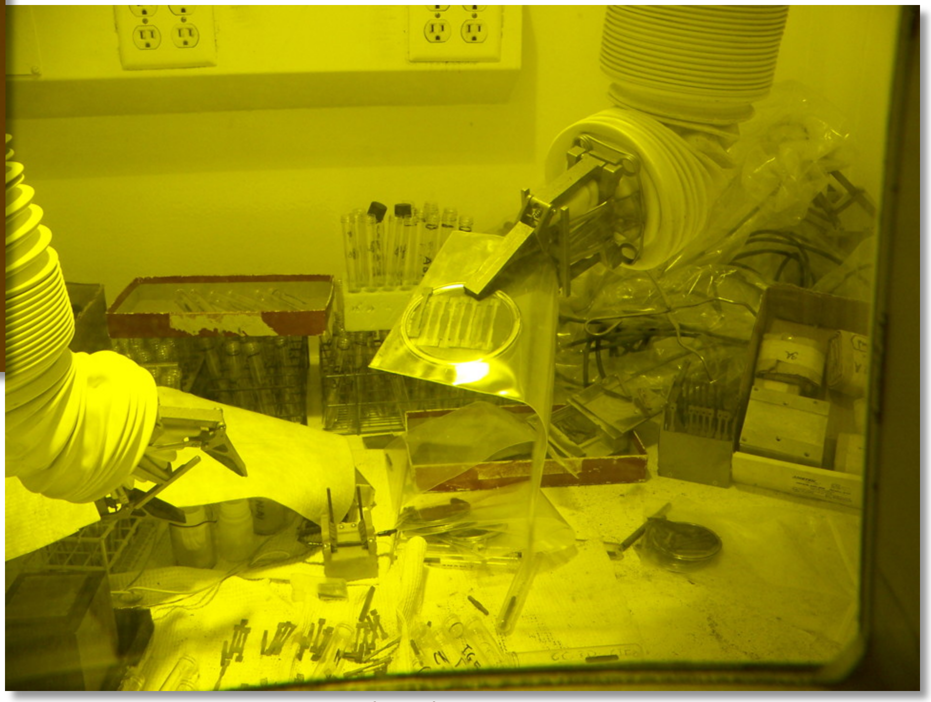
Material	# Tensile	# CTE	K	Motivation
C-C Comp (3D)	10	8	?	First BLIP test showed massive failure
POCO ZXF-5Q	21	6	.46	NuMI/NOvA target material
Toyo-Tanso IG 430	42	6	.51	"Nuclear Grade" planned for T2K
Carbone-Lorraine 2020	21	6	.60	CNGS target material
SGL R7650	21	6	.66	NuMI/NOvA Baffle material
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

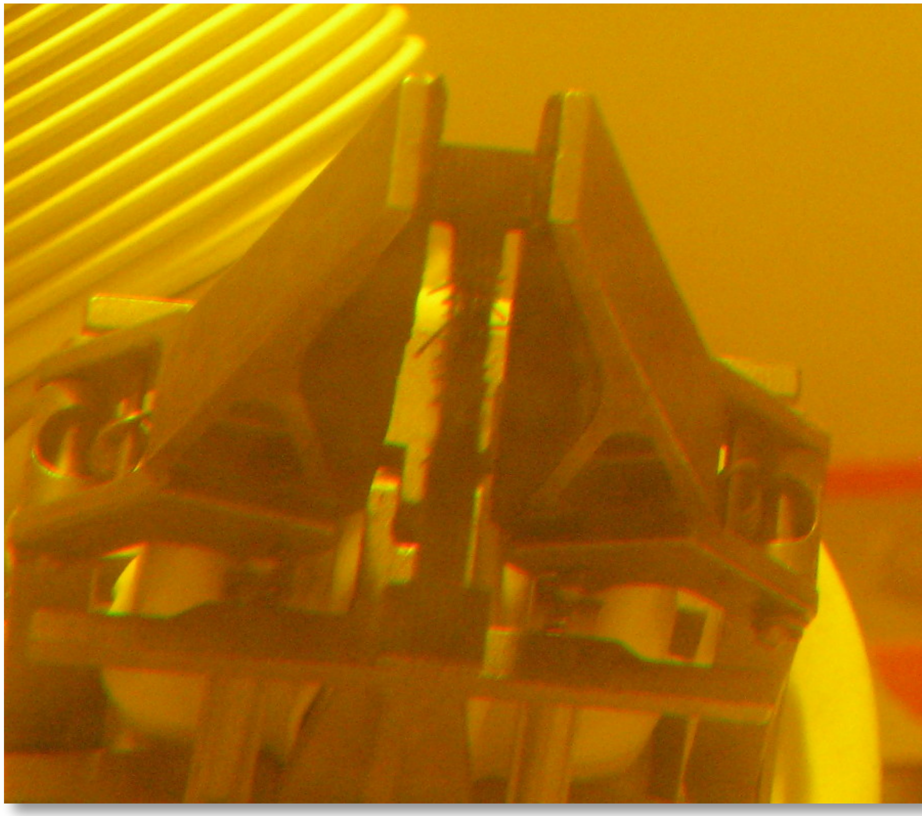


- Irradiation run complete
- Currently beginning testing phase
- Preliminary results in October, 2010

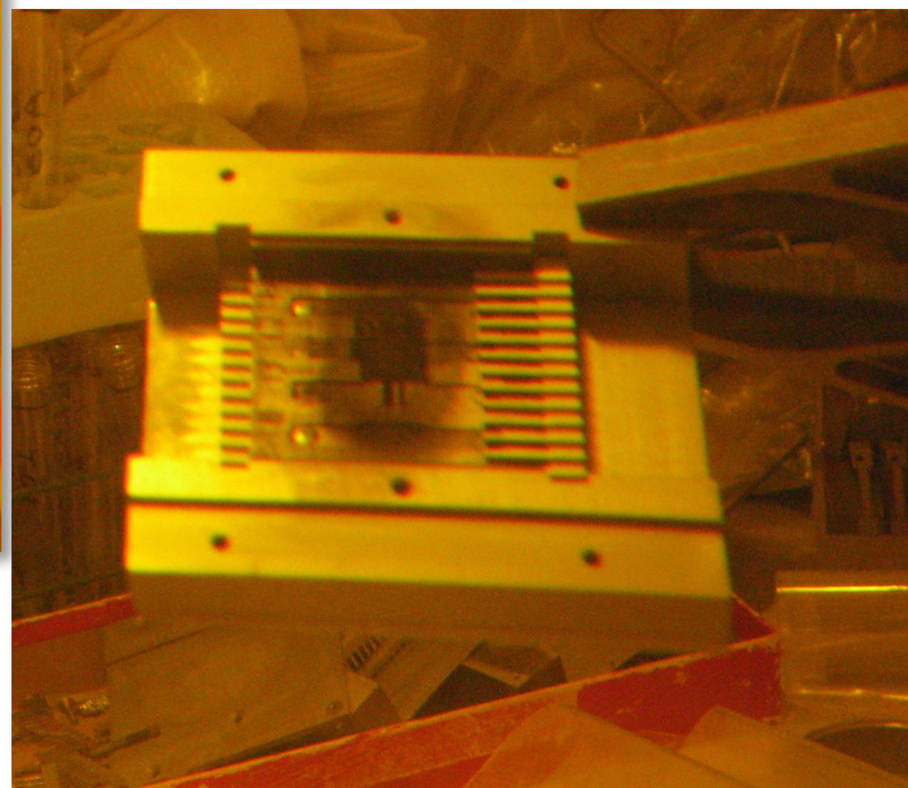


- 181 MeV proton beam
- Peak integrated flux about 5.9e20 proton/cm^2
- Average over 1 sigma area about 4.6e20 proton/cm^2

Graphite R&D: Irradiation Testing at BLIP



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



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

High Power Target Group:
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: (arrows to the first two items)

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:

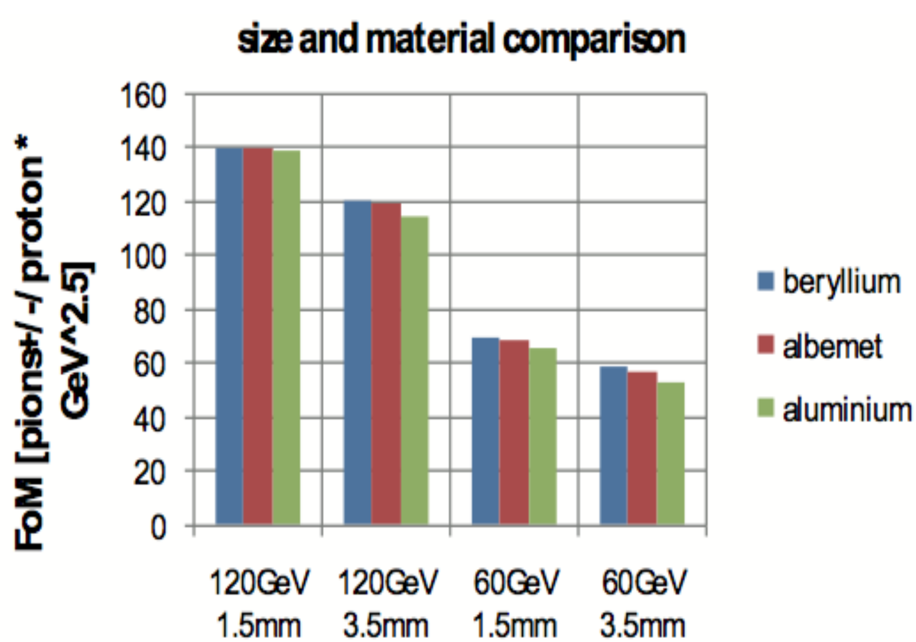
Pulse Length = 9.78 micro-sec

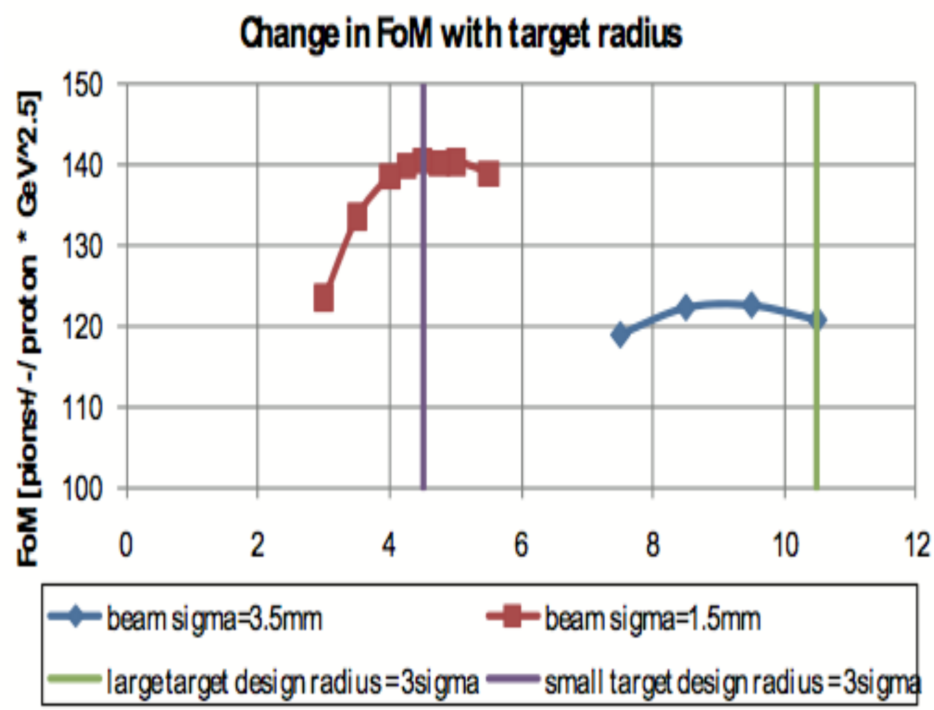
Proton Beam Energy (GeV)	Protons per Pulse	Repetition Period (sec)	Proton Beam Power (MW)	Beam sigma, radius (mm)
120	4.9e13	1.33	0.7	1.5-3.5
60	5.6e13	0.76	0.7	1.5-3.5
120	1.6e14	1.33	2.3	1.5-3.5
60	1.6e14	.76	2	1.5-3.5

Beryllium R&D: Be Target Simulations: FoM

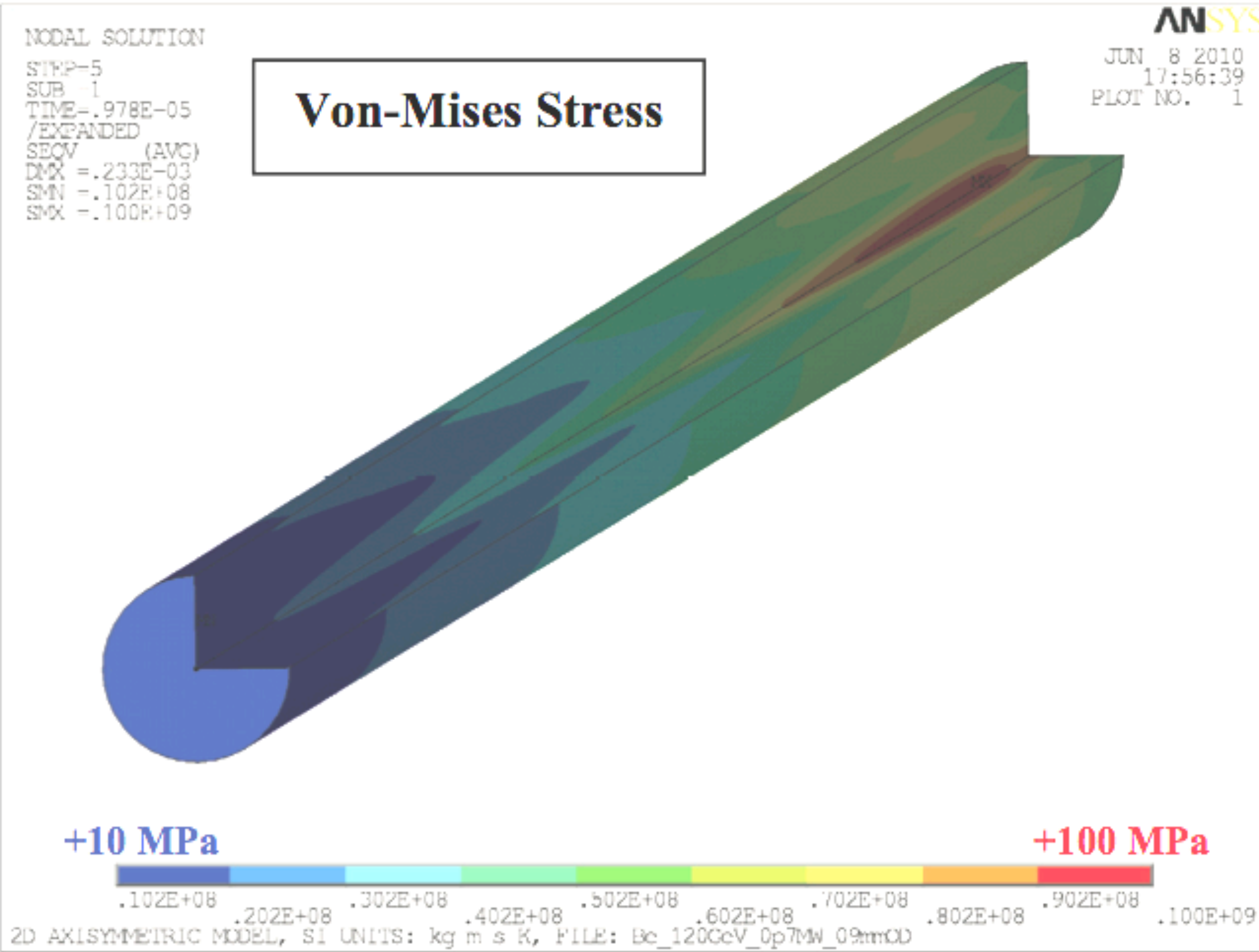
- Figure of Merit
  - Provide simple, faster way to gauge effects of target/beam parameter changes on yield of neutrinos of interest
  - Proposed by R. Zwaska

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





Beryllium R&D:
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

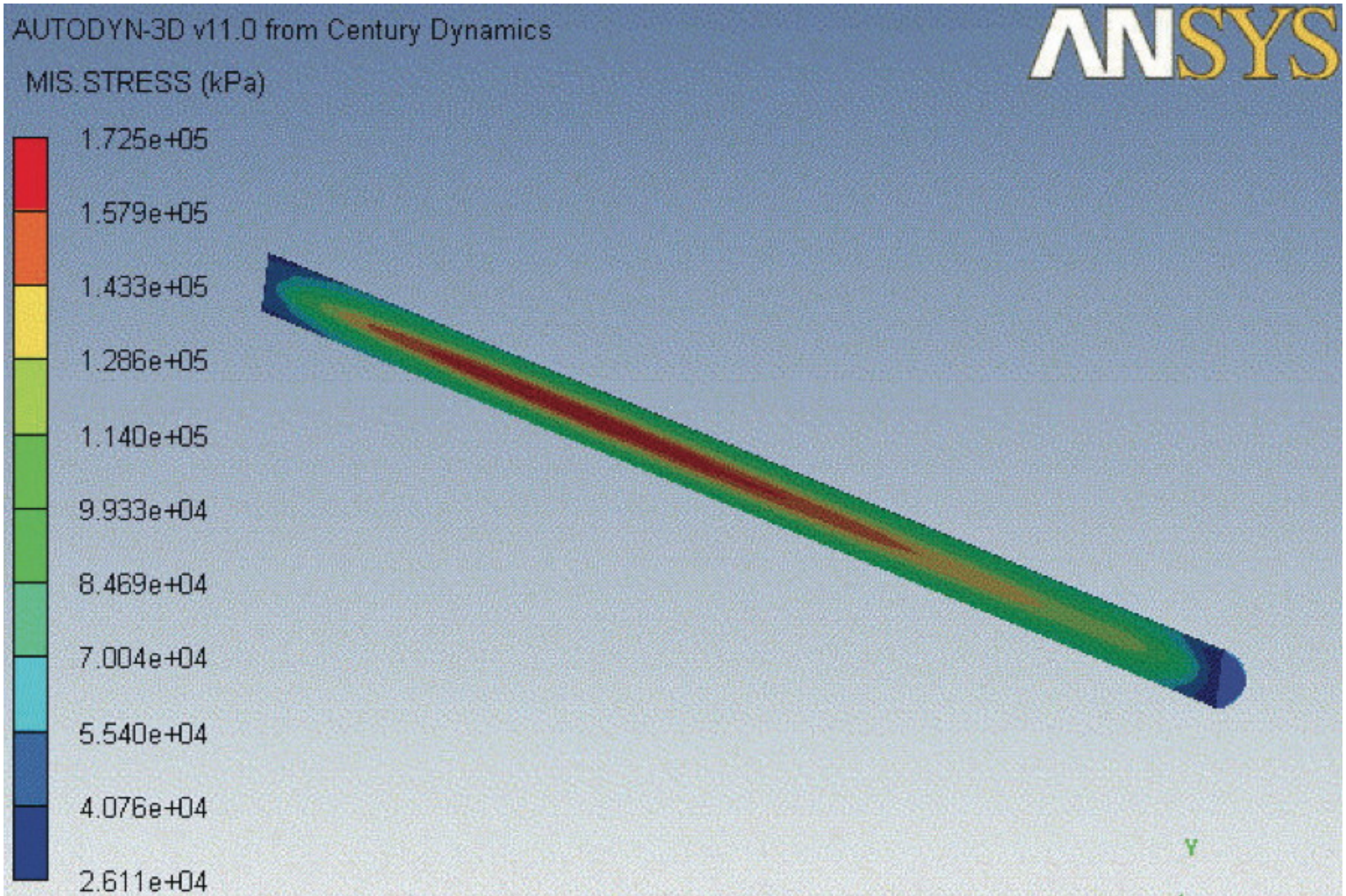
Beryllium R&D: Be Target Simulations: Structural (non-dynamic)

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

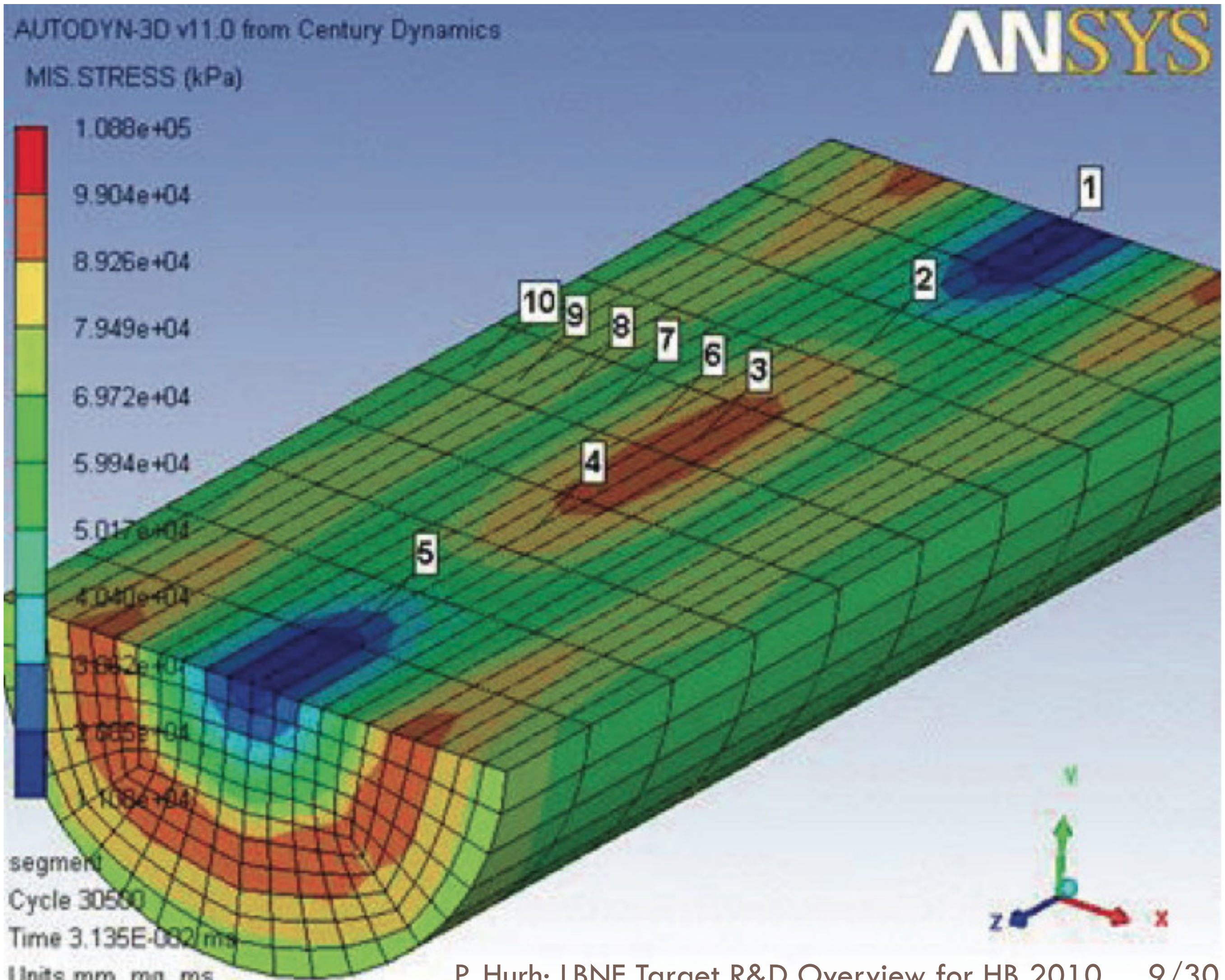
Room for optimization!

Beryllium R&D: Be Target Simulations: Dynamic



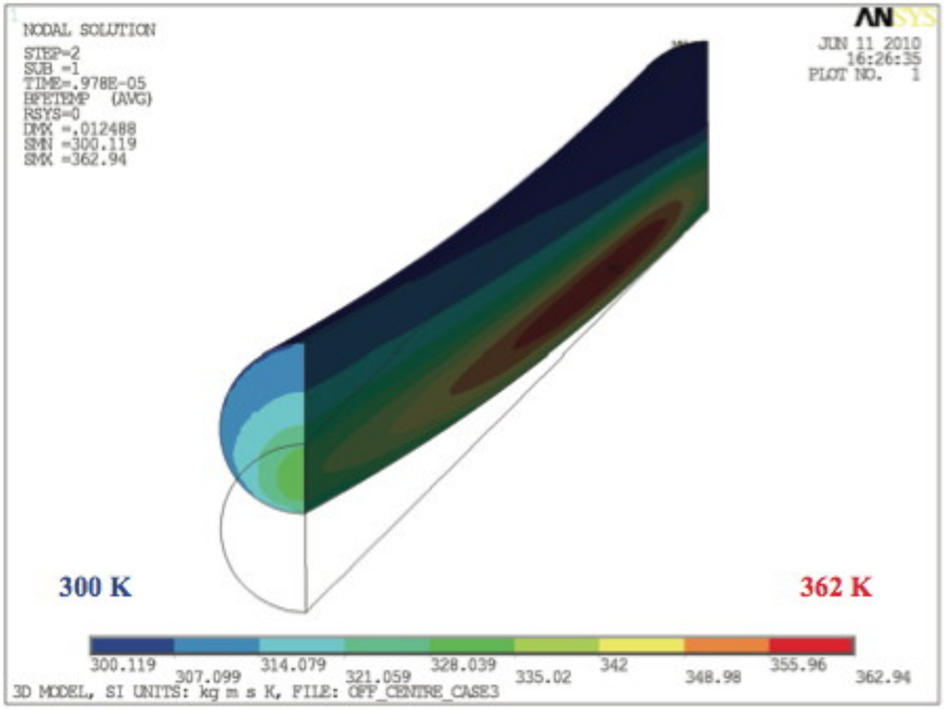
- 2.3 MW
- 120 GeV
- 3.5 mm sigma spot
- Compare to 88 Mpa for static case (double)
- Mainly longitudinal stress-waves

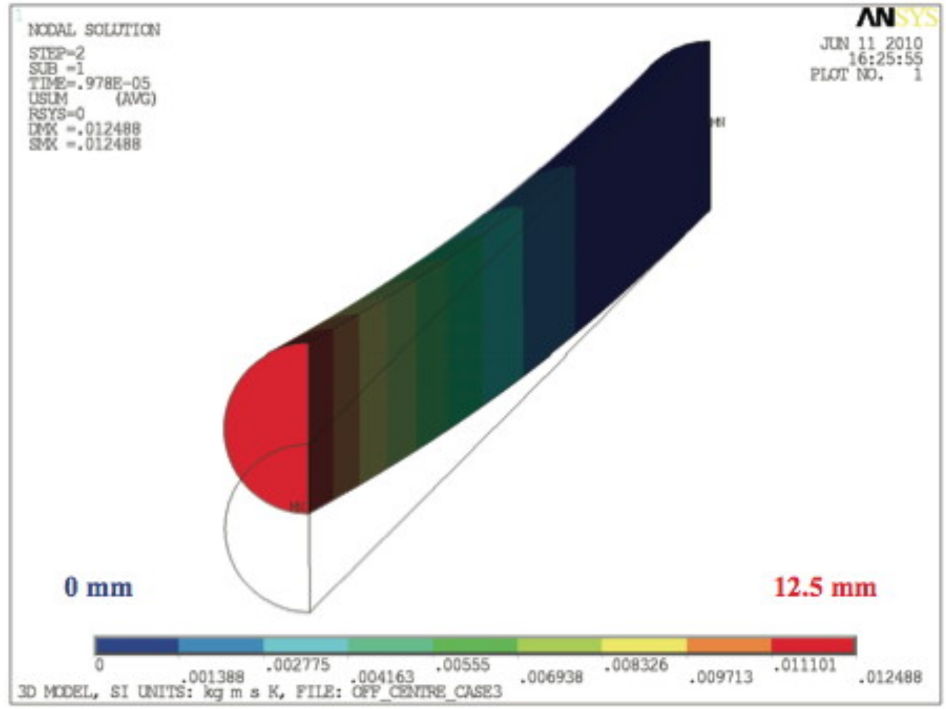
Beryllium R&D: Be Target Simulations: Dynamic



- 2.3 MW
- 120 GeV
- 3.5 mm sigma spot
- 50 mm Segments
- Peak eqv stress reduced to 109 MPa from 188 MPa

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

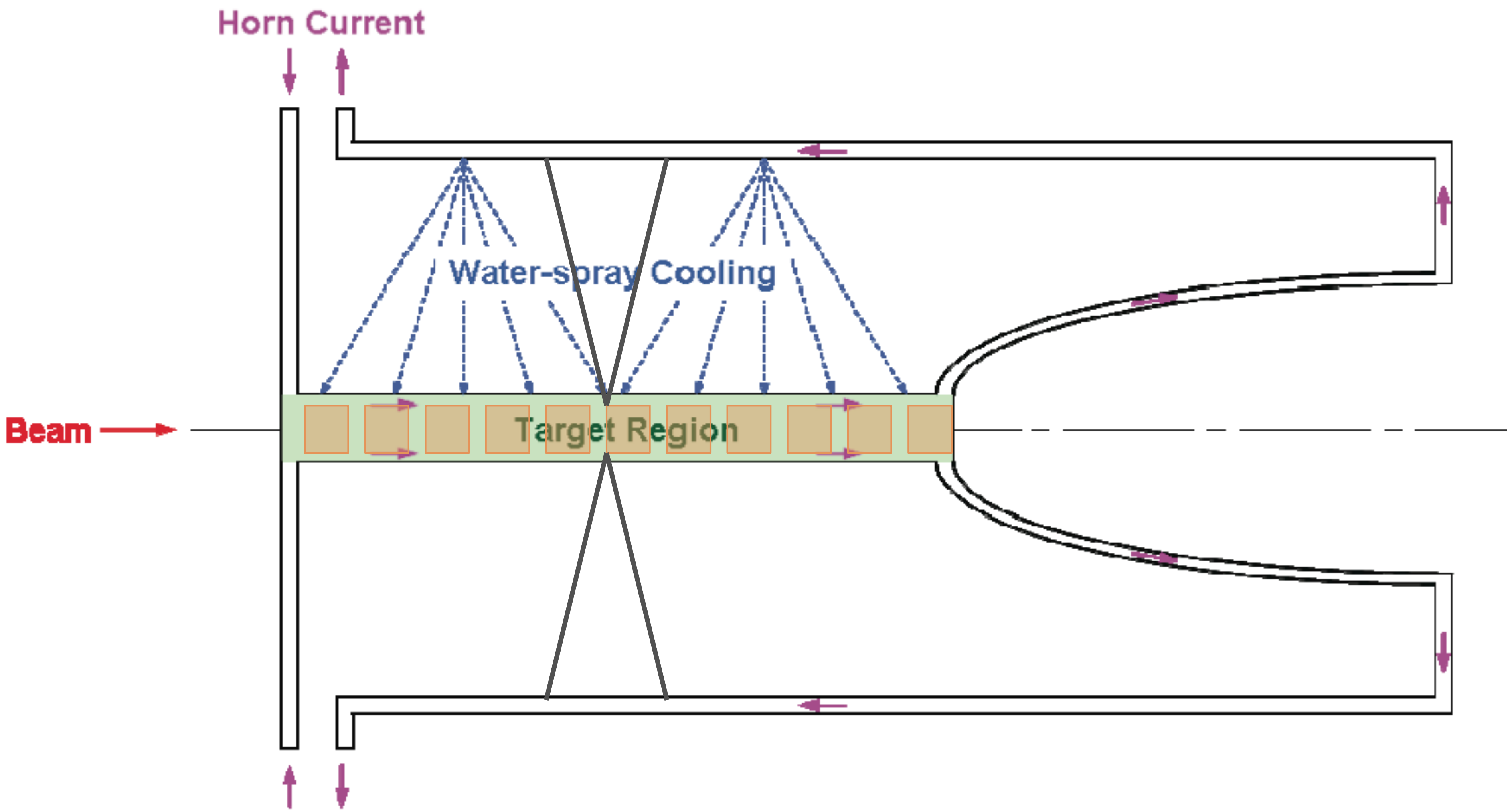




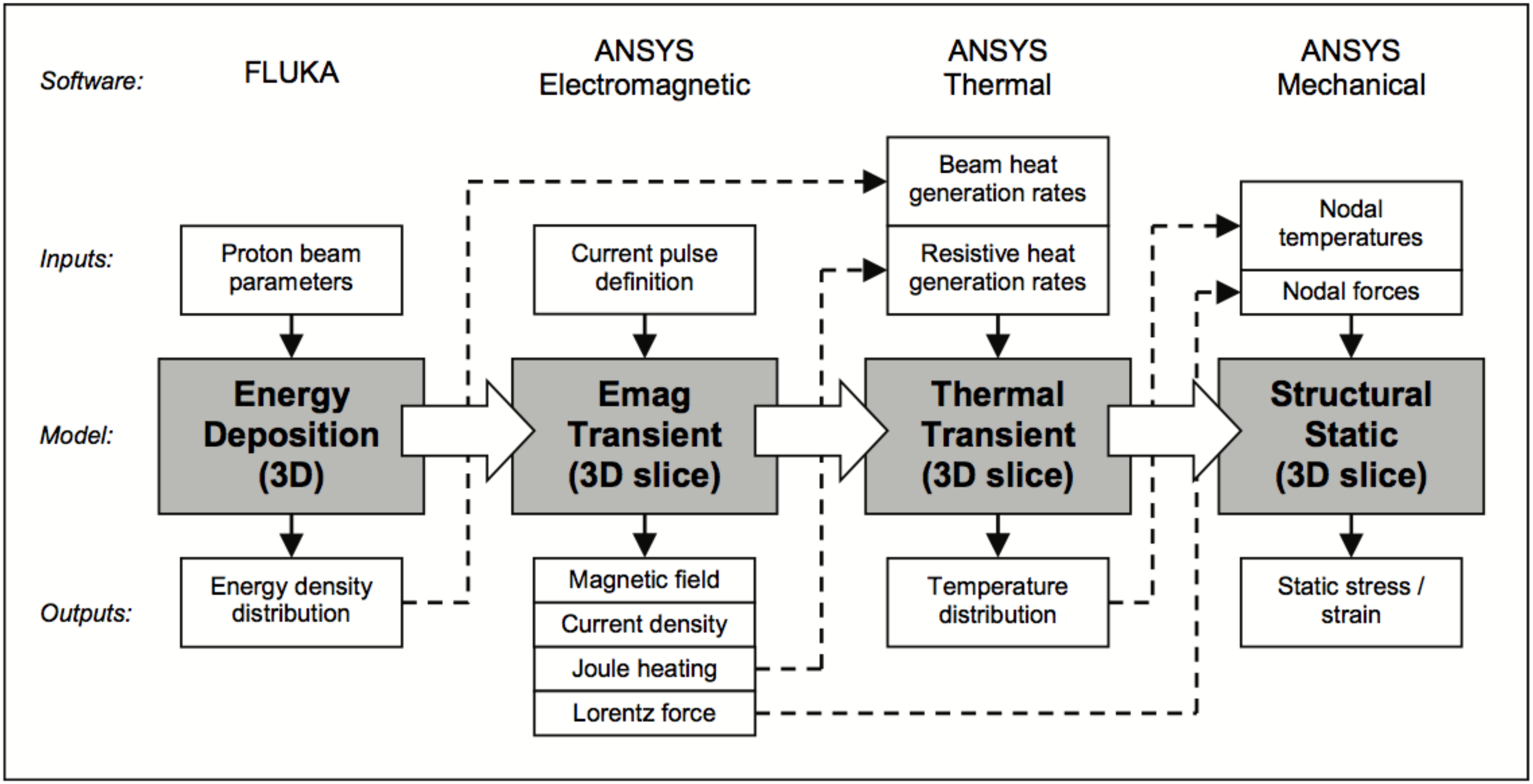
- 2.3 MW
- 120 GeV
- 3.5 mm sigma spot
- 2 sigma offset

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

Beryllium R&D: Integrated Target Conceptual Design



Beryllium R&D: Integrated Target Conceptual Design



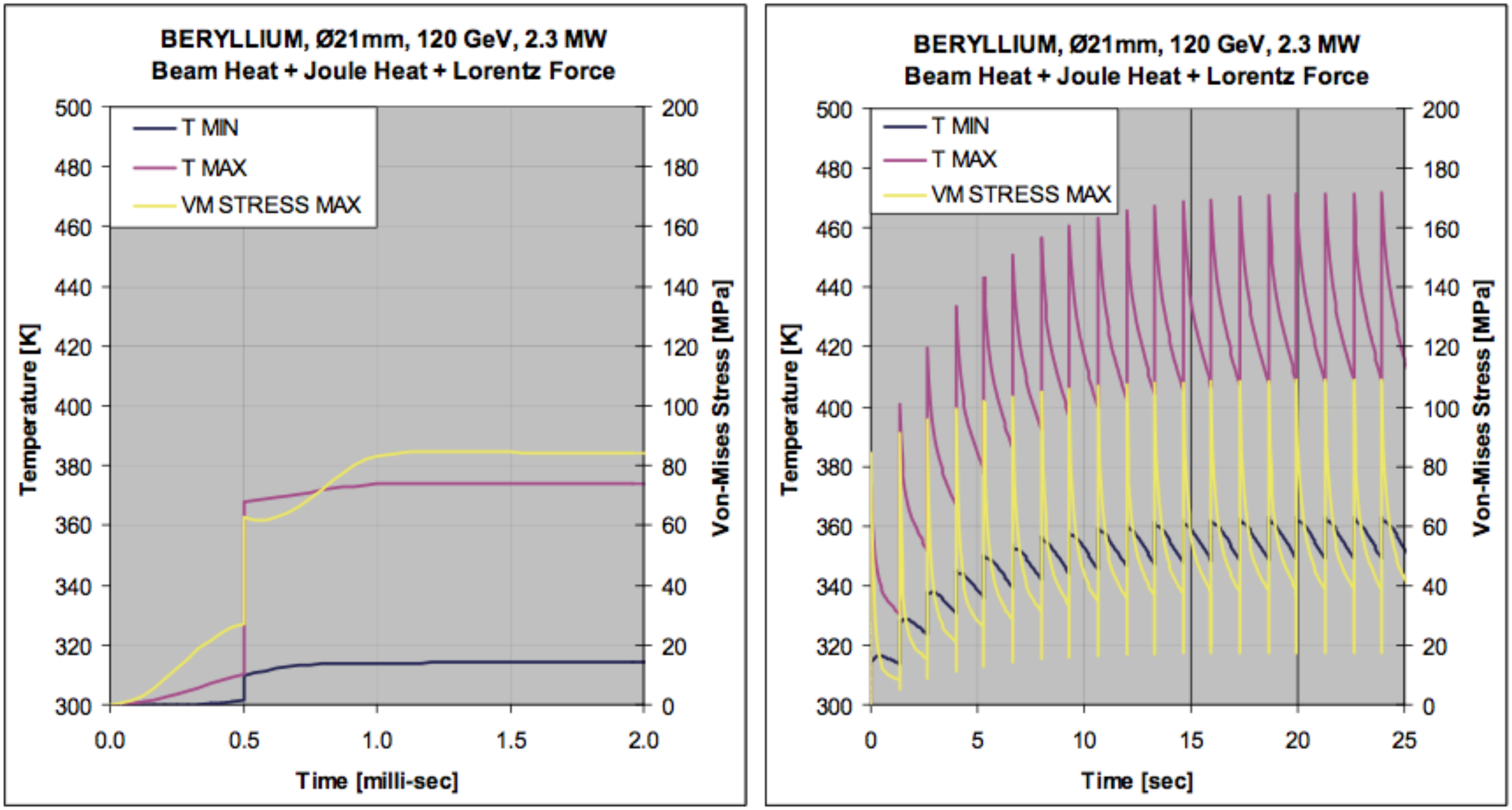


Figure 5.20, multi-pulse results, 2.3 MW beam

Table 5.4, multi-pulse results summary

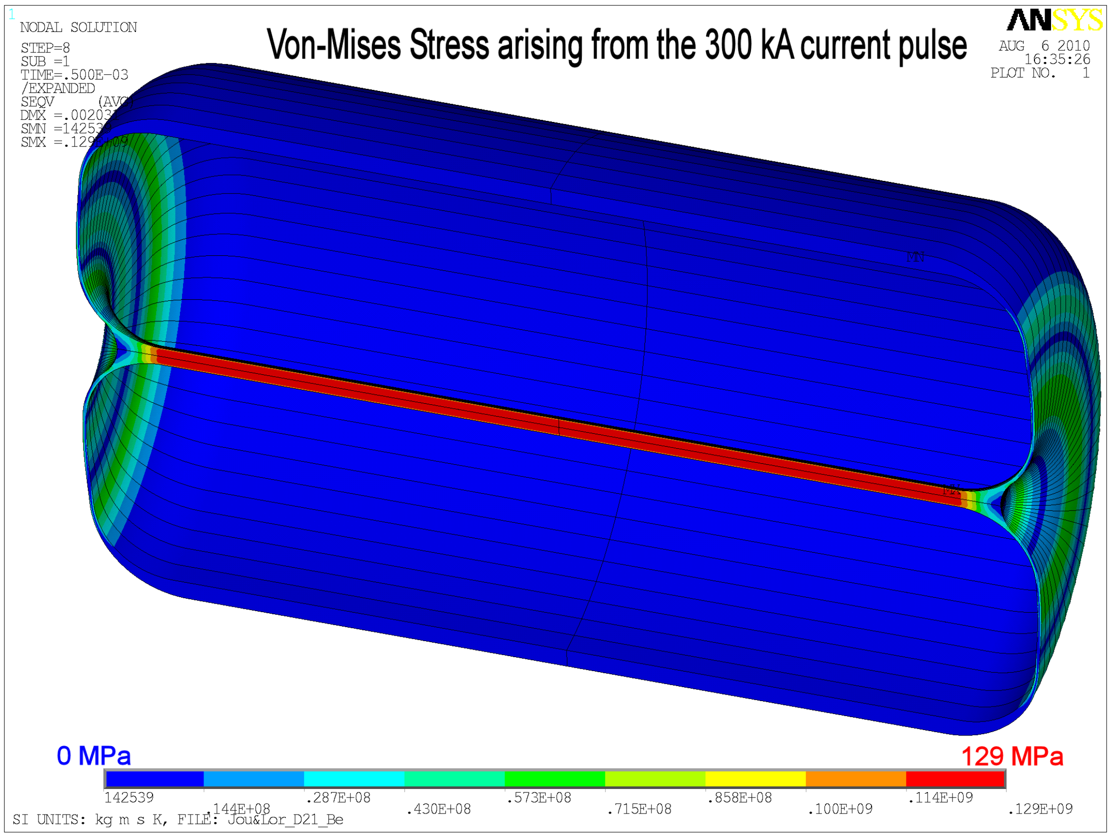
Beam Energy (GeV)	Beam Power (MW)	Beam Sigma (mm)	Target / Conductor Diameter (mm)	Peak Current (kA)	Current Pulse Length (milli-sec)	Deposited Beam Energy (kJ/Spill)	Deposited Resistive Energy (kJ/pulse)	Steady-state Power (kW)	Maximum Temp. 1st Cycle (K)	Maximum Temp. 20th Cycle (K)	Maximum VM-Stress 1st Cycle (MPa)	Maximum VM-Stress 20th Cycle (MPa)
120	0.7	3.5	21	300	1.0	9.2	7.6	12.6	326	369	28.3	29.8
120	2.3	3.5	21	300	1.0	30.7	7.6	28.8	377	472	84.0	109

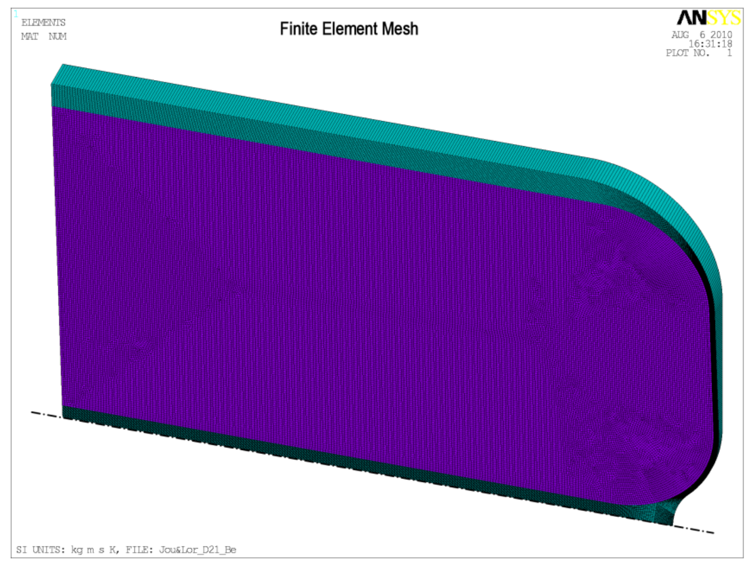
Beryllium R&D: RAL Simulation Study Summary

- Beryllium is a viable option for 2+ MW beam
- Probably need to increase beam spot size to a sigma radius of 3 to 3.5 mm
- Segmenting the target longitudinally is beneficial
- Off center beam pulses will require mechanical supports along length of target
- Integrated target/horn design looks promising
- RAL Target Group continues working on:
  - Optimizing beam/target radius for good compromise between physics and target survivability
  - Add end effects to integrated target simulations
  - Investigating cooling technology options
  - And more…

Progress on Combined target and horn concept

- Electromagnetic – Thermal – Structural modelling
  - Including the horn "end bells" allows the axial Lorentz forces transmitted by the inner conductor to be captured in the simulation





ANSYS model of the combined target / inner conductor concept.
Axial Lorentz forces induce a significant tensile stress component in the solid inner conductor.

Progress on Separate target

Drill down on dynamic stresses

Total stresses = "Quasi-steady" stresses + Dynamic stresses

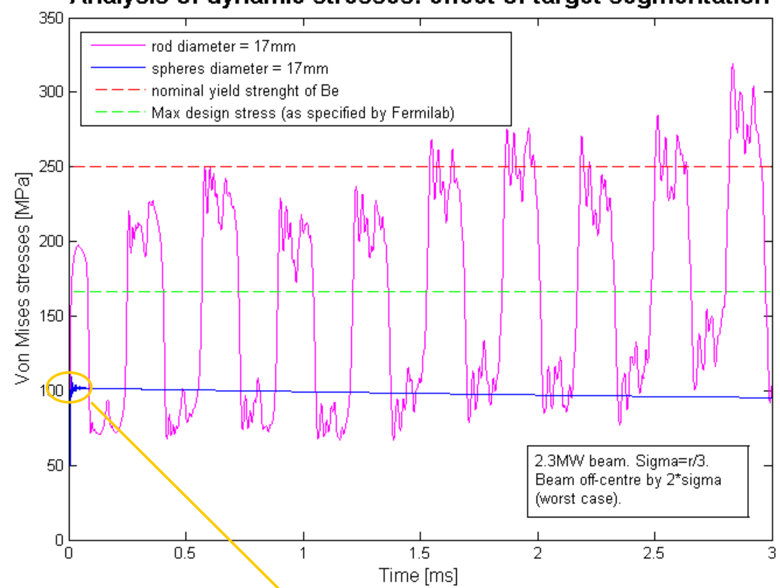
"Quasi-steady" stresses: i.e. thermal gradient.

Time scale: thermal diffusivity

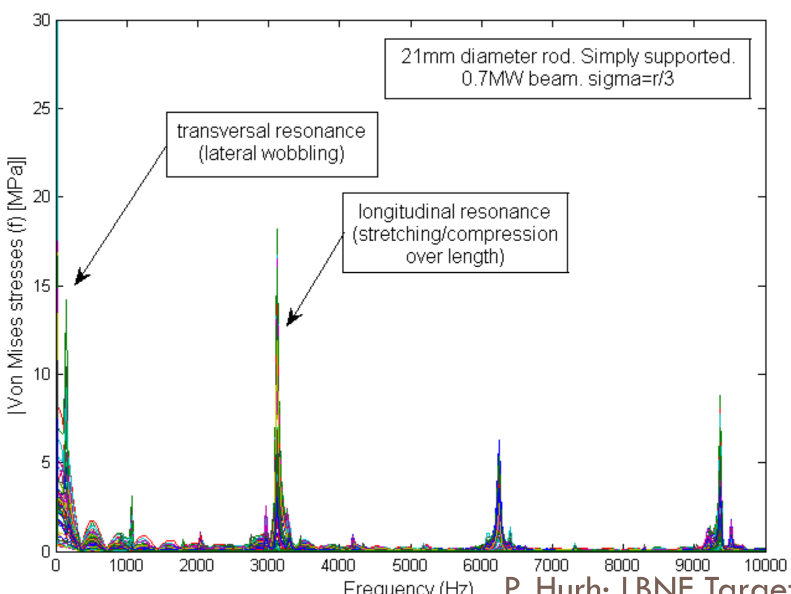
Dynamic stresses: i.e. reflection and resonance of stress waves within the geom.

Time scale: sound speed

Analysis of dynamic stresses: effect of target segmentation



Amplitude Spectrum analysis of Von Mises stress throughout the target rod

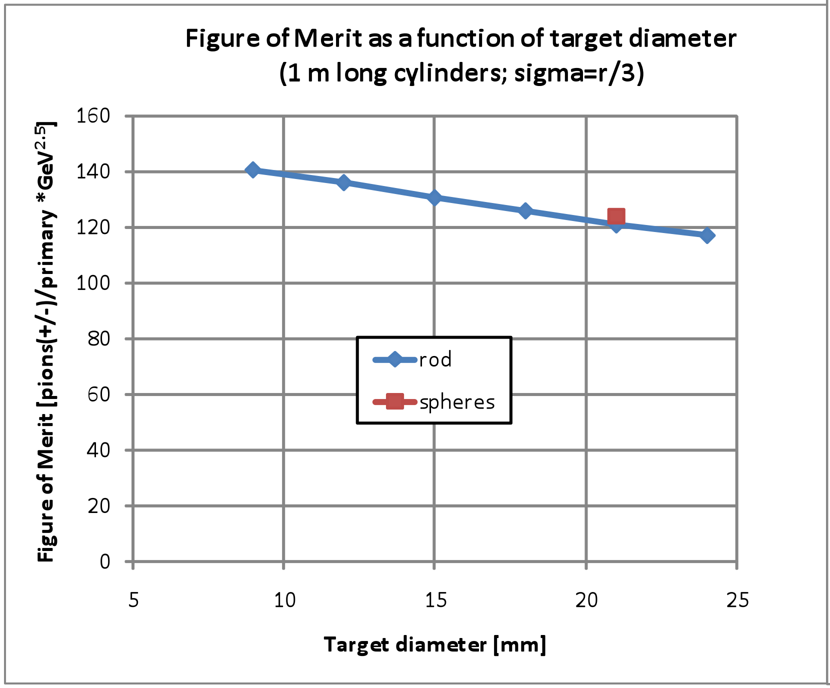


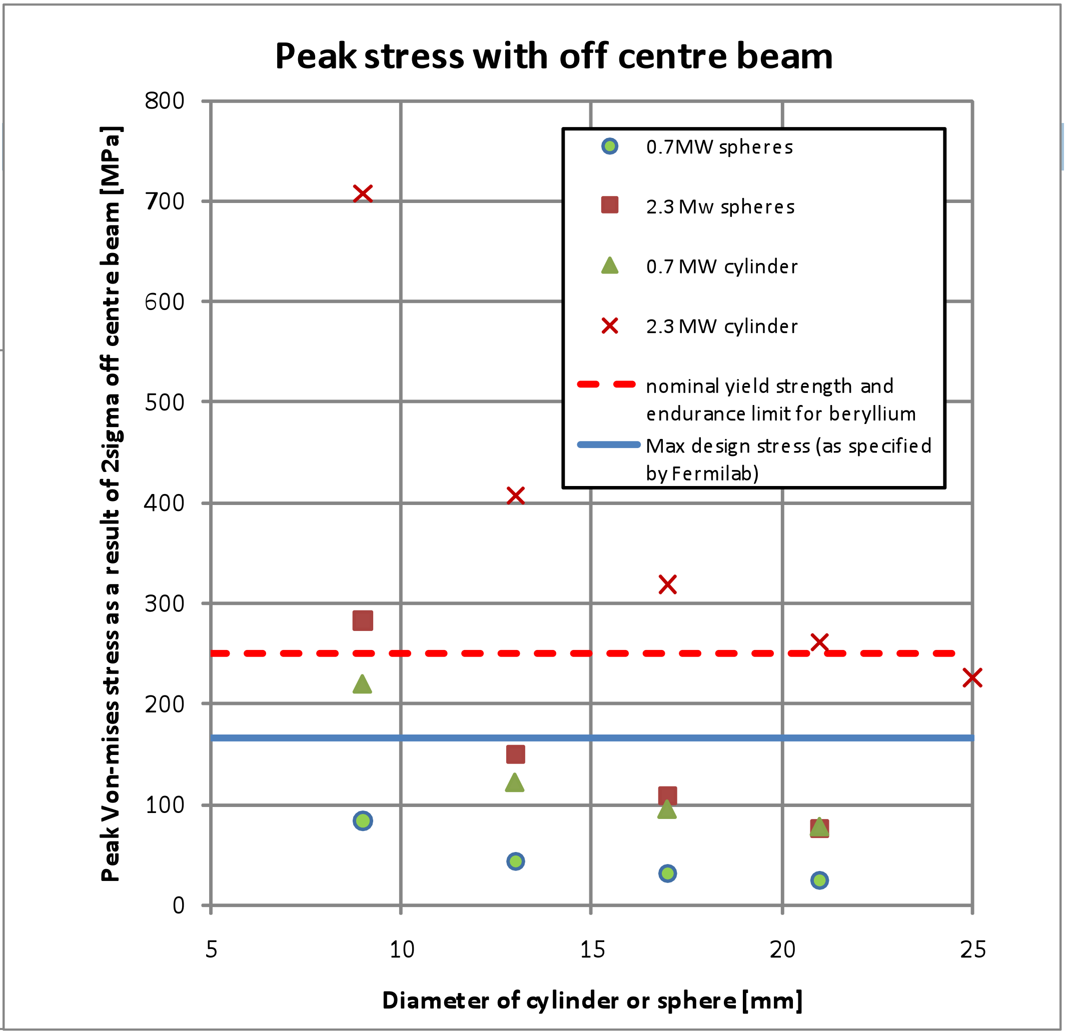
Segmentation of the target minimises the dynamic components quickly resolving to the "quasi-steady" stress field

Avoiding sharp edges in the target geometry reduces both stress concentrations and constructive wave interference

Progress on Separate target continued

- Design Selection Parameters
  - Peak stress with off centre beam & FoM
- Design choice
  - Diameter & Shape (Rod vs Segments)



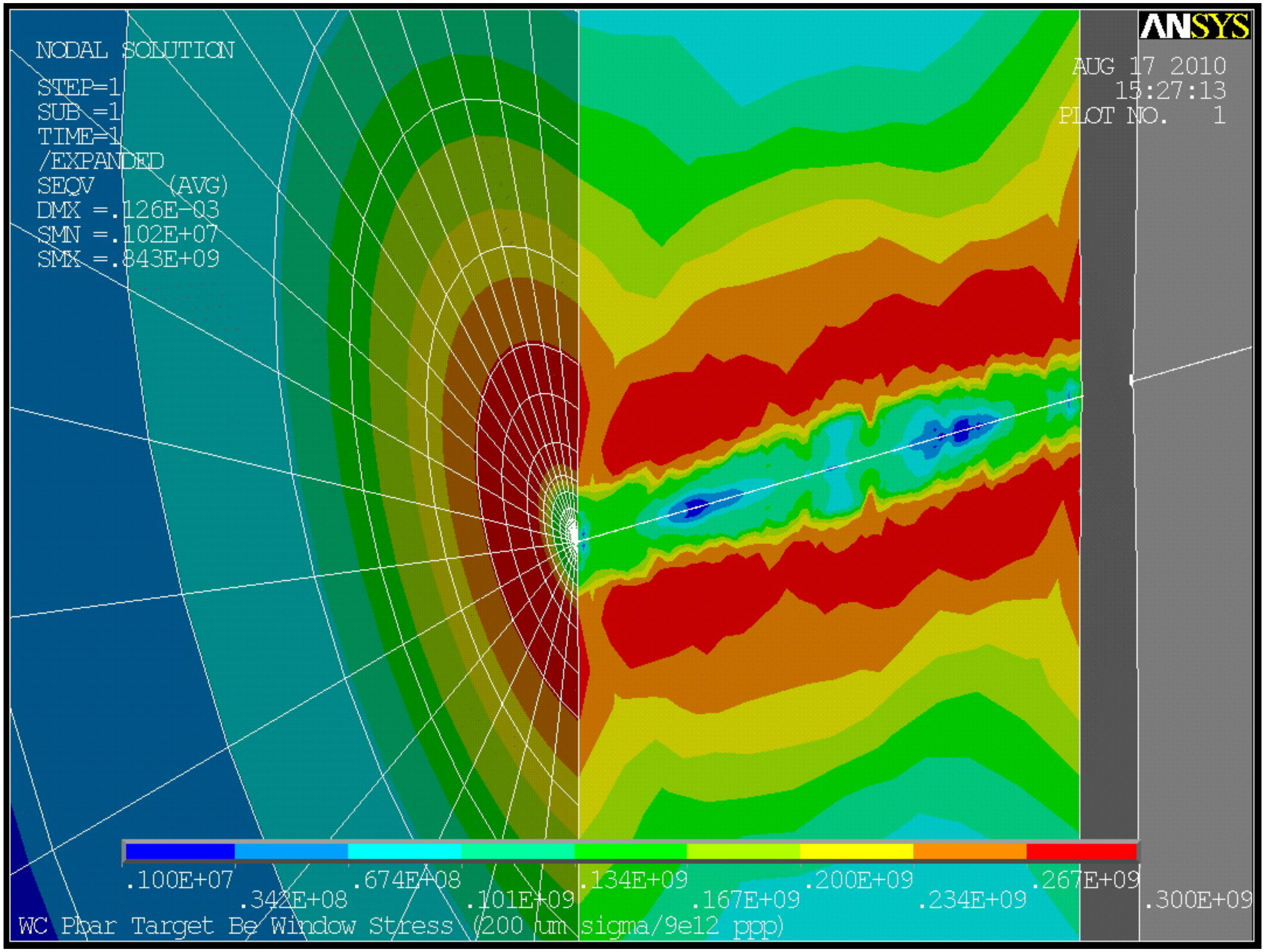


1. *Reducing target diameter gives better pion yield but more stress.*
2. *Beam induced dynamic stress in the form of longitudinal stress waves and from induced vibrations are significant in a beryllium rod ruling it out for 2.3MW operation.*
3. *Segmenting the target (a series of spheres for example) has been identified as a potential option for achieving the desired diameter with reasonable stress levels.*
4. *FoM is comparable between spheres and rod.*

Beryllium R&D: Failure Criteria – Simulation versus Reality

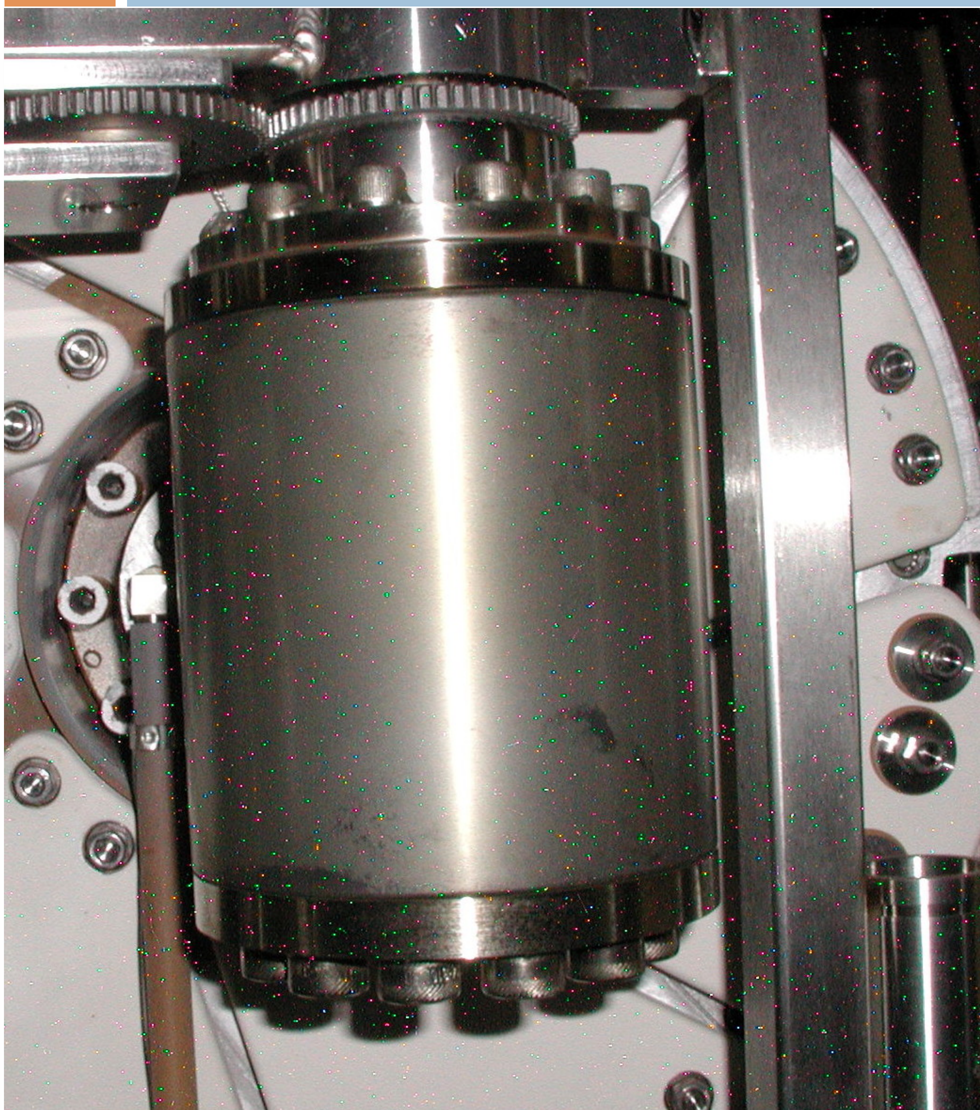
- Predicted Peak Energy Deposition for LBNE 2.3 MW with 1.5 mm beam sigma radius was 846 J/cc and thought to cause stresses too high for Be to survive
- But P-bar Target (FNAL) has a Beryllium cover that regularly sees 1000 J/cc and shows no evidence of damage
- ANSYS analysis for similar conditions 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:
Failure Criteria – Simulation versus Reality

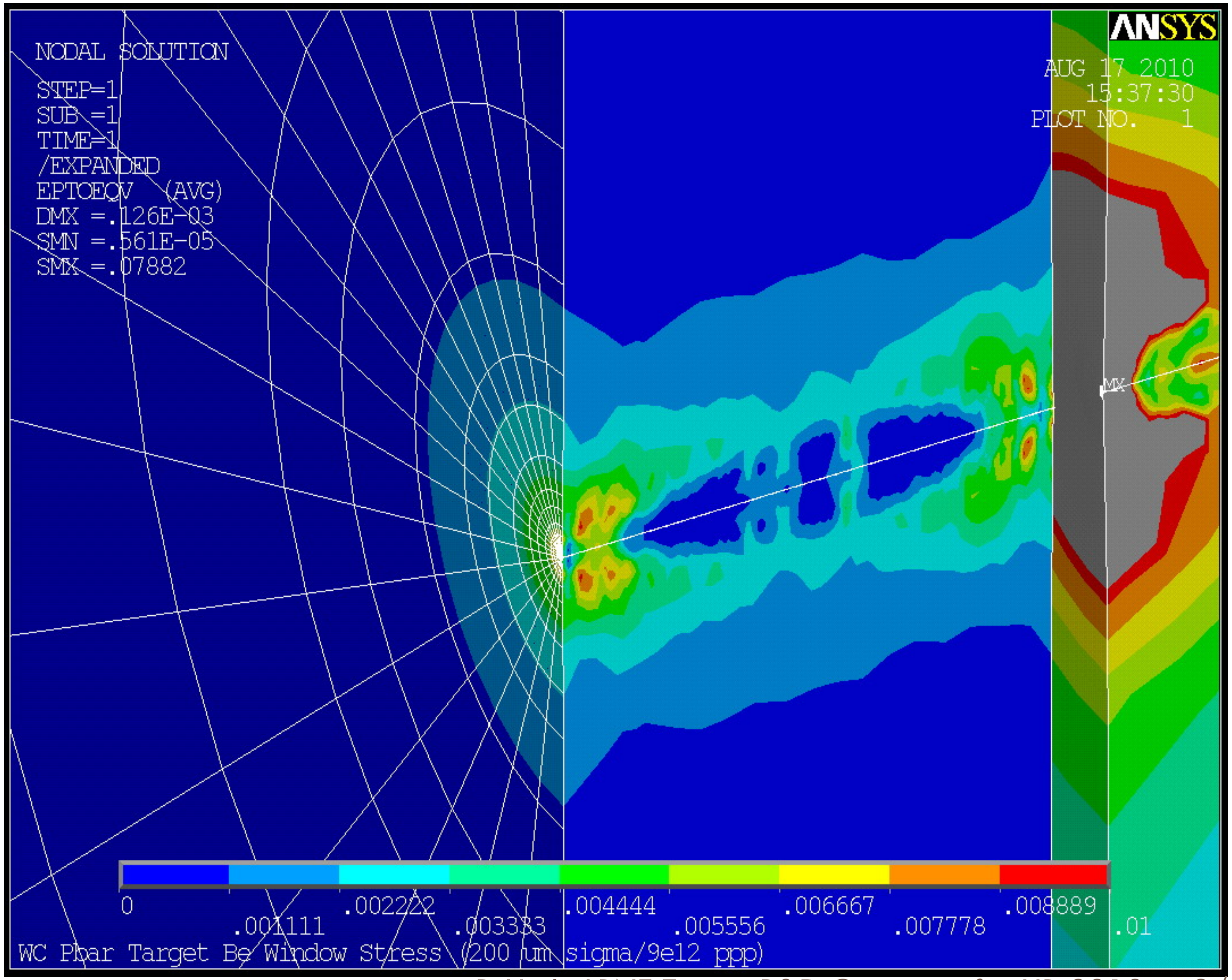


- Rotated 17 degrees every pulse
- Moved 1 mm vertically every 2e17 protons
- Typical beam sigma was 0.195 mm (last 1-2 months of running at 0.15 mm)
- Typical ppp was 8E12
- This target saw about 5e6 pulses at the time photo was taken

Beryllium R&D: Failure Criteria – Simulation versus Reality

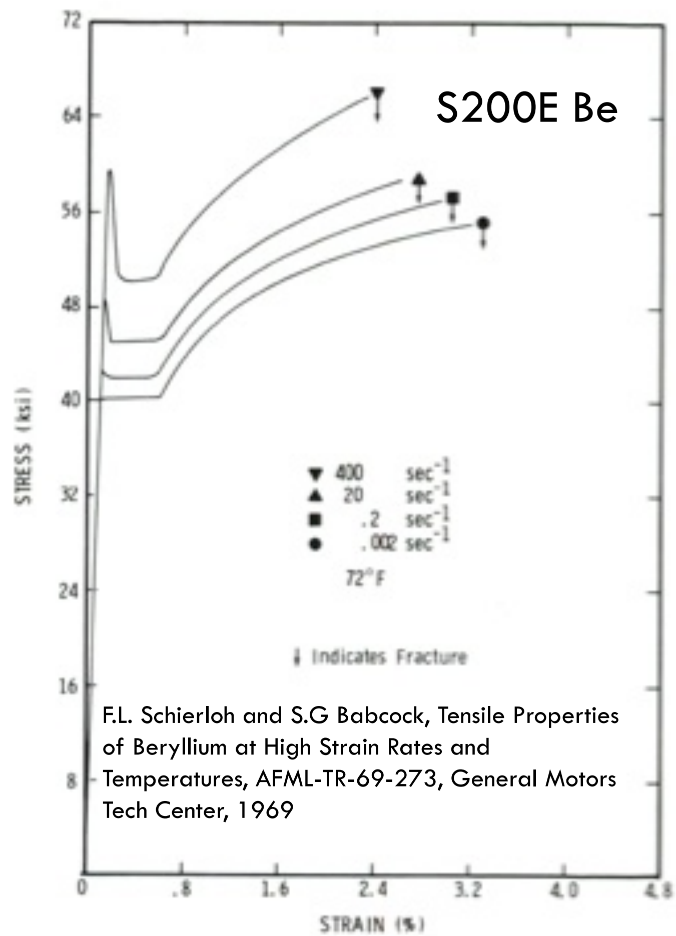
- Possible explanations
  - Small areas of deformation not visible
    - Analysis indicates about 0.05 mm of plastic deformation on surface in an outward "bump" with diameter of about 1 mm
  - Beam profile is not gaussian
    - At such small sigma, peak energy deposition would be reduced greatly if profile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

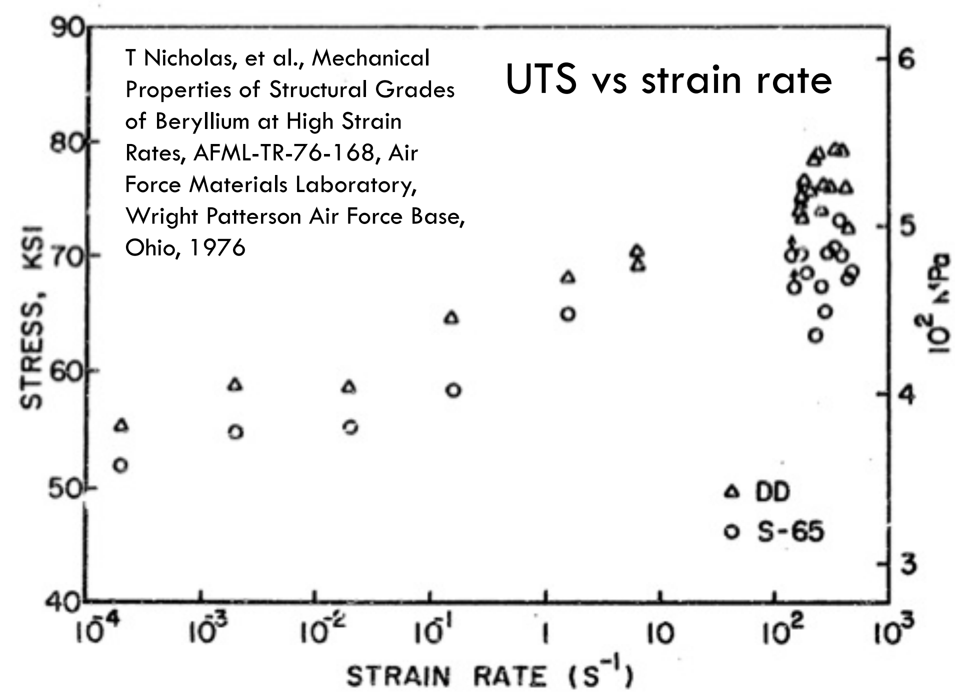
Beryllium R&D: Failure Criteria – Simulation versus Reality



- 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}

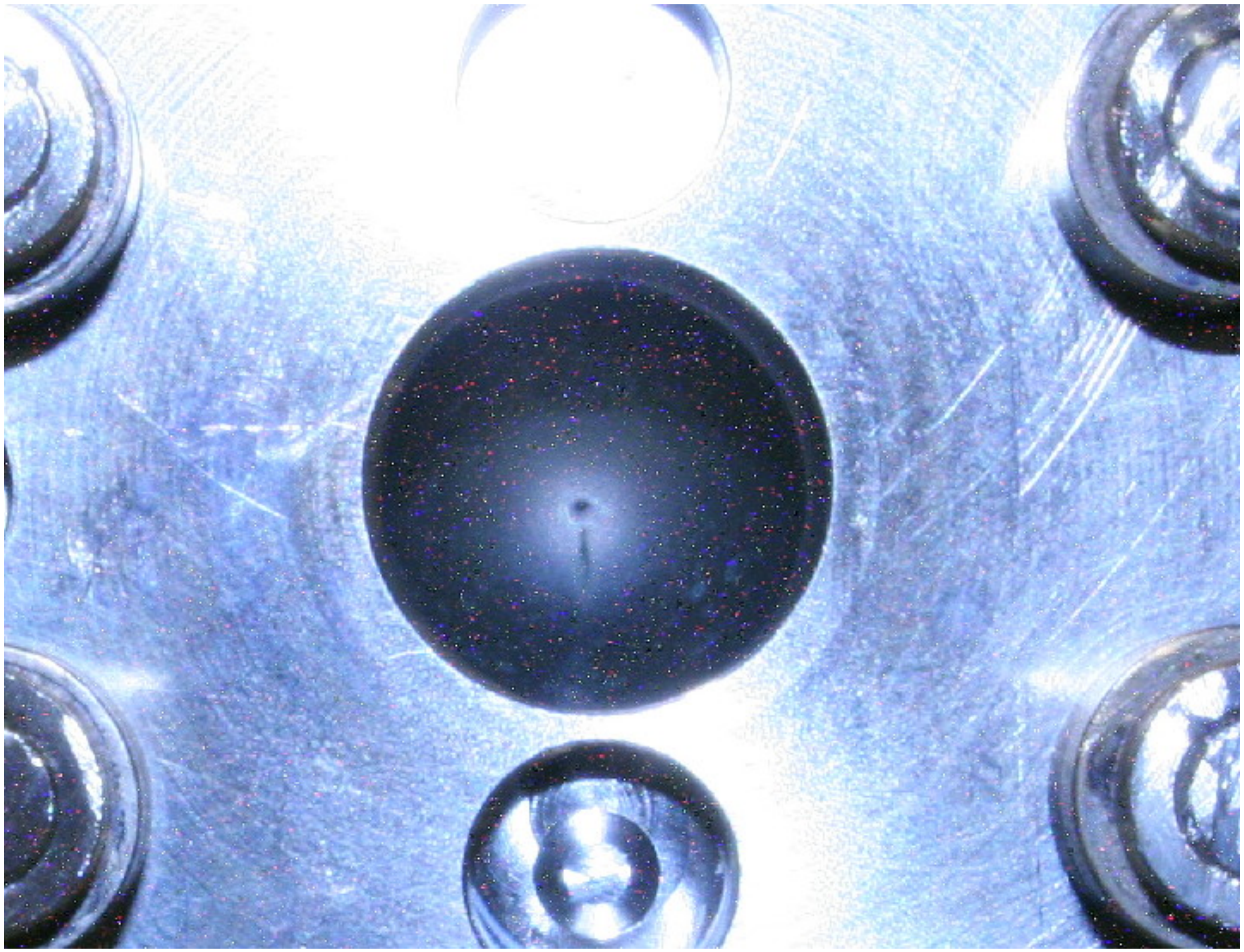
Beryllium R&D: Failure Criteria – Simulation versus Reality





- 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…

LBNE 2+ MW Target R&D Summary

- Graphite target material
  - Autopsy of NuMI Target NT-02 (FNAL)
  - Irradiation Damage Testing at BLIP (BNL, N. Simos)
- Beryllium target material
  - Physics, Thermal, Structural Simulation Studies (RAL, C. Densham, et al.)
  - Correlation of predicted single pulse stress failure with empirical evidence (FNAL)
- Work will progress in all areas, stay tuned…

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, B. Zwaska, V. Sidorov, A. Leveling and many others…