Superbeam target work at RAL

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EuroNu Meeting, Kracow
October 2010

LBNE vs EUROnu

LBNE:

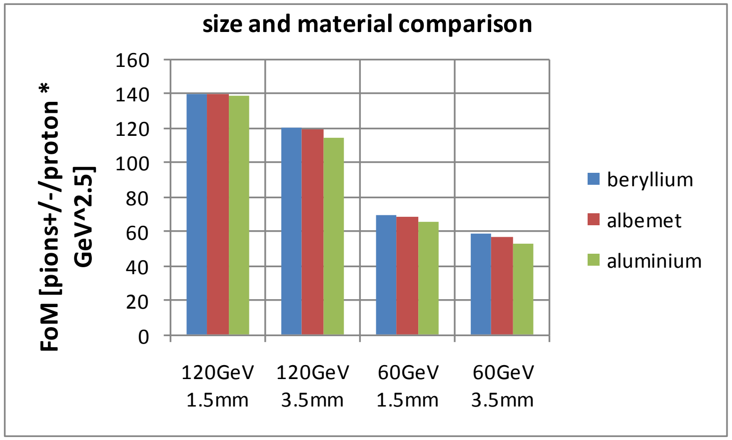
- 120Gev (or 60Gev)
- 0.7MW or 2.3MW (of which less than 10kW on target)
- rep rate ~1s
- beam sigma? r/3 seems roughly best for pion yield
- Target diameter 9 to 21 mm (~1m long)
- Materials: Be, Al, AlBeMet

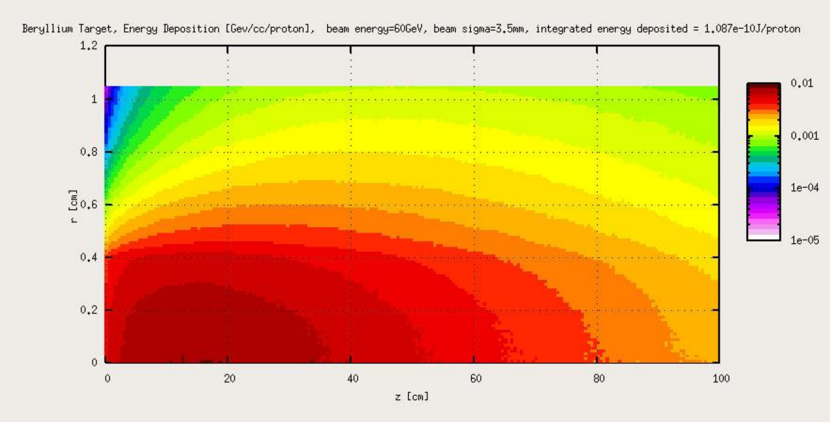
EUROnu SPL:

- 4.5GeV
- 1MW (of which 50kW on target)
- rep rate 12.5Hz
- beam sigma 4mm
- Target diameter 30mm (around 780mm long)
- Material: graphite

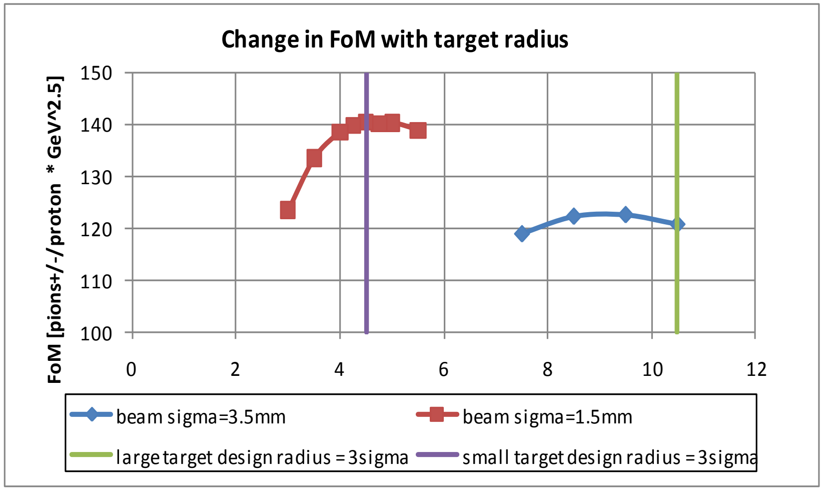
LBNE targets comparison: physics

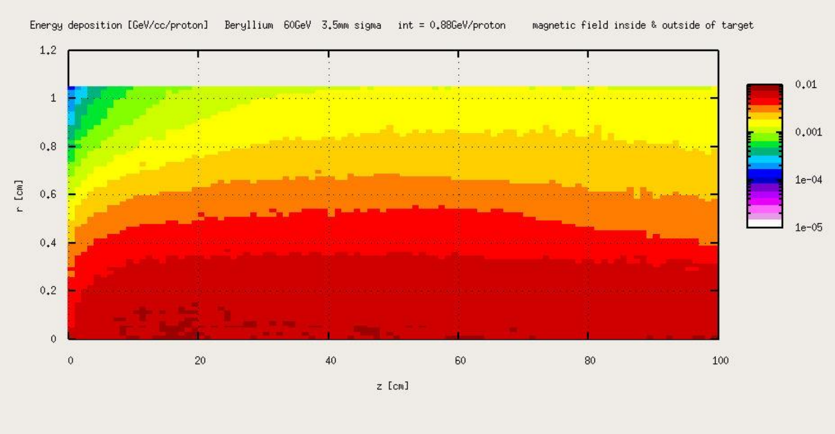
$$FoM = \sum_{n=1}^{21} (Ecen_n)^{2.5} \int_{Emin_n}^{Emax_n} \int_0^{\Delta p} \frac{\partial^2 N}{\partial E \partial p} \partial p \partial E$$





Energy deposition in beryllium target with 60GeV 3.5mm sigma beam, Integrated energy deposition=16.9kJ/spill





Energy deposition in Beryllium target with 60GeV 3.5mm beam sigma with magnetic field, Integrated energy deposition=22.6kJ/spill

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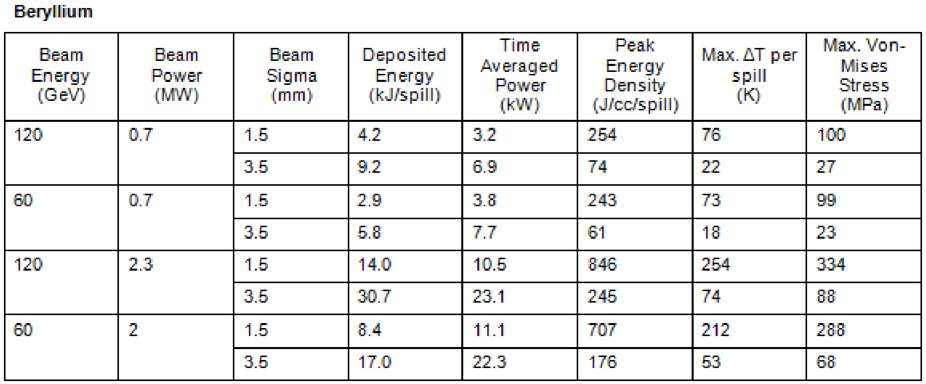
High Power Targets

LBNE targets comparison: engineering

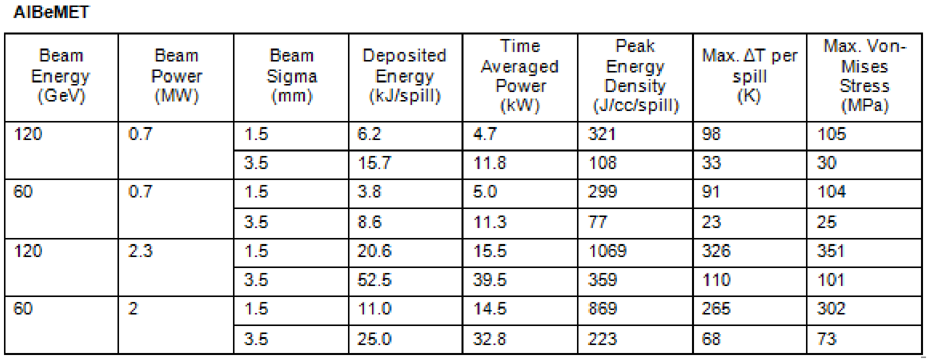
Table 3.5.1, beam heating parameter study results



Beryllium

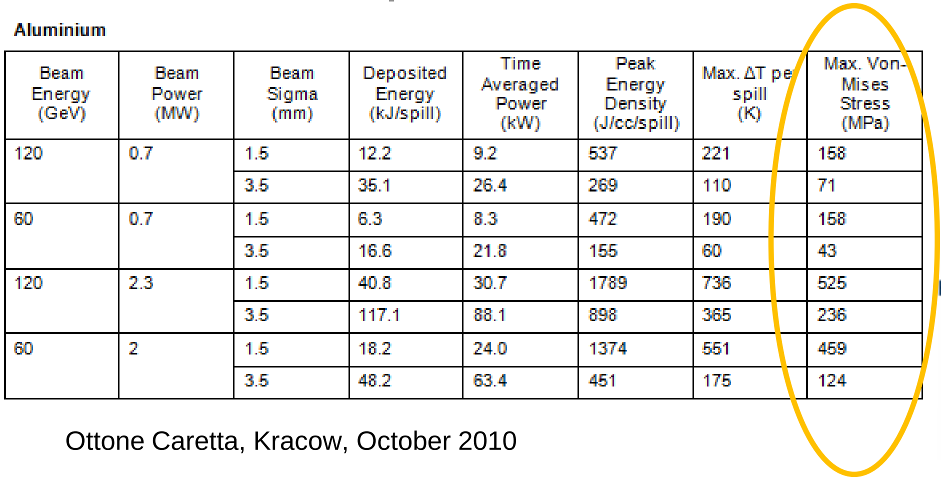
Beam Energy (GeV)	Beam Power (MW)	Beam Sigma (mm)	Deposited Energy (kJ/spill)	Time Averaged Power (kW)	Peak Energy Density (J/cc/spill)	Max. ΔT per spill (K)	Max. Von-Mises Stress (MPa)
120	0.7	1.5	4.2	3.2	254	76	100
		3.5	9.2	6.9	74	22	27
60	0.7	1.5	2.9	3.8	243	73	99
		3.5	5.8	7.7	61	18	23
120	2.3	1.5	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

e.g. Static stresses are much higher in Al



AlBeMET

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	6.2	4.7	321	98	105
		3.5	15.7	11.8	108	33	30
60	0.7	1.5	3.8	5.0	299	91	104
		3.5	8.6	11.3	77	23	25
120	2.3	1.5	20.6	15.5	1069	326	351
		3.5	52.5	39.5	359	110	101
60	2	1.5	11.0	14.5	869	265	302
		3.5	25.0	32.8	223	68	73

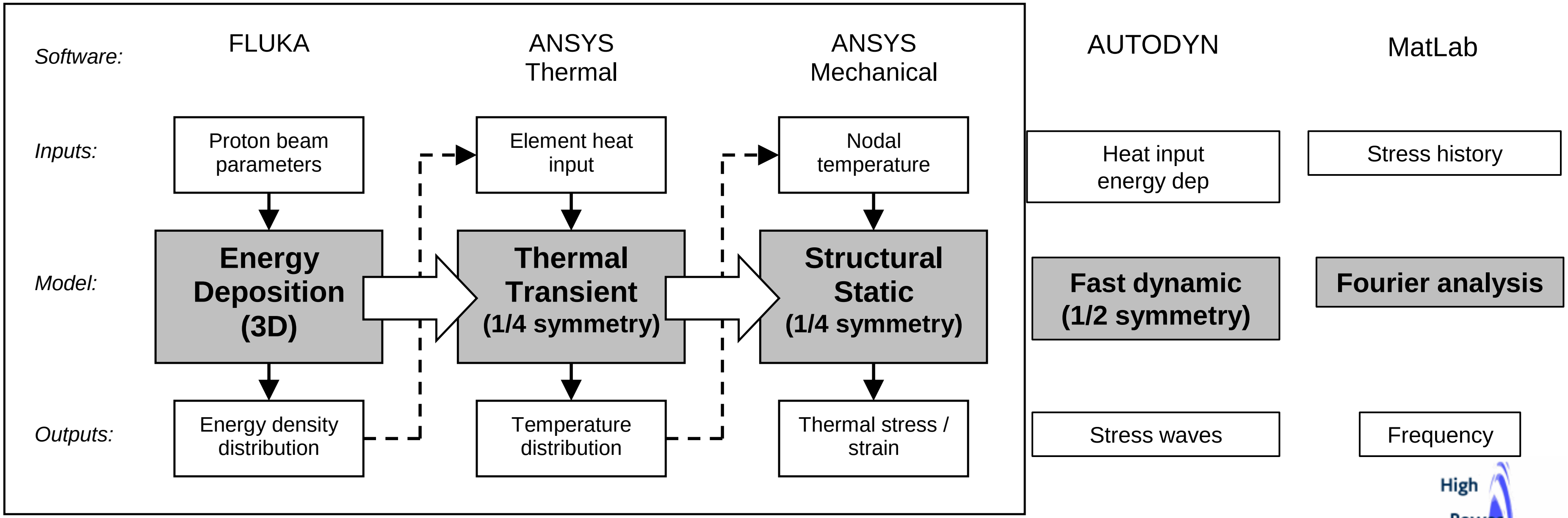


Aluminium

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 pe spill (K)	Max. Von-Mises Stress (MPa)
120	0.7	1.5	12.2	9.2	537	221	158
		3.5	35.1	26.4	269	110	71
60	0.7	1.5	6.3	8.3	472	190	158
		3.5	16.6	21.8	155	60	43
120	2.3	1.5	40.8	30.7	1789	736	525
		3.5	117.1	88.1	898	365	236
60	2	1.5	18.2	24.0	1374	551	459
		3.5	48.2	63.4	451	175	124

Engineering Analysis Procedure

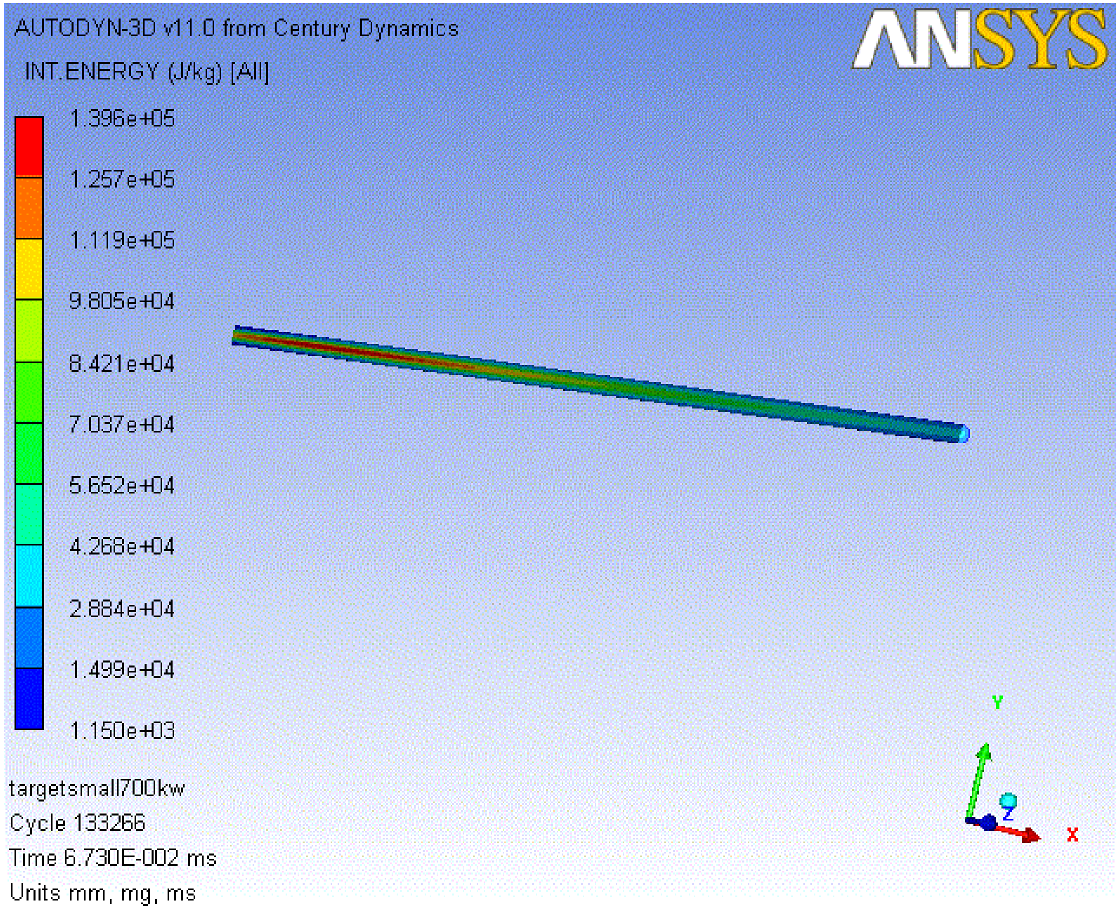
- Multi-stage process involving linked FLUKA, ANSYS and AUTODYN simulations
  - Can choose whether or not to include inertial effects. This enables one to isolate the consequences of various stress mechanisms:
    - "Quasi-static" thermal stress
      [thermal conduction timescales of the order ~seconds]
    - Inertial stress due to bulk oscillations ("violin modes")
      [1st mode period typically of the order ~milliseconds]
    - Elastic stress wave propagation
      [characteristic time period of the order ~microseconds]



Software:	FLUKA	ANSYS Thermal	ANSYS Mechanical	AUTODYN	MatLab
Inputs:	Proton beam parameters	Element heat input	Nodal temperature	Heat input energy dep	Stress history
Model:	**Energy Deposition (3D)**	**Thermal Transient (1/4 symmetry)**	**Structural Static (1/4 symmetry)**	**Fast dynamic (1/2 symmetry)**	**Fourier analysis**
Outputs:	Energy density distribution	Temperature distribution	Thermal stress / strain	Stress waves	Frequency

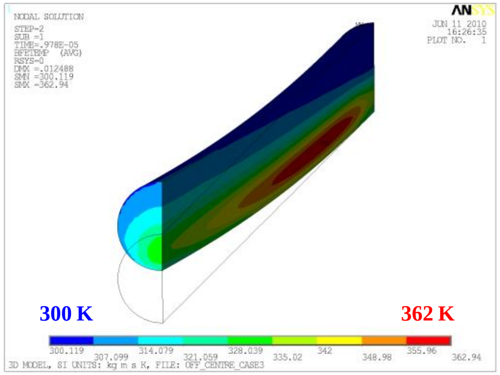
Process flow diagram: beam induced heating

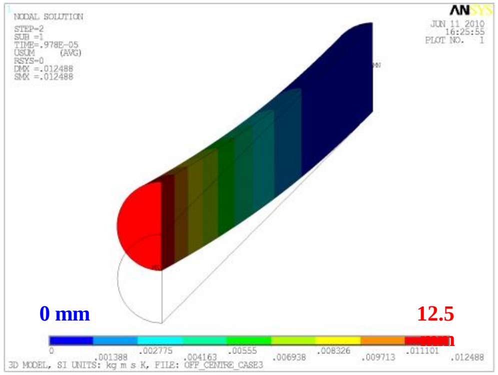
Drilling down on different effects: Static – dynamic – off-centre beam



Dynamic stresses can be as much as double the static ones and then grow by another 50% if off-centre beam effects are included

Worse case scenario: off-centre beam (not that uncommon?!) static stresses & resonance





Off-centre effects include:

- thermal gradient (with associated residual stresses and deformation)
- Inertial stress waves and stress resonance

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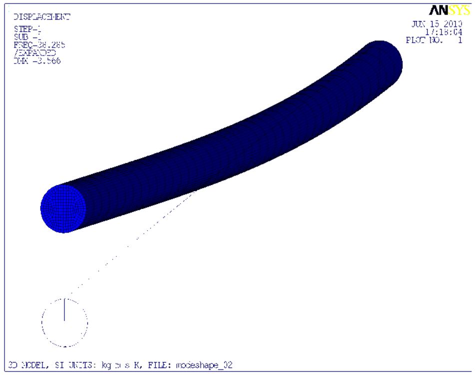
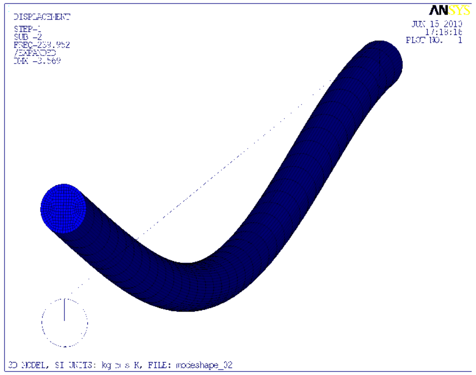
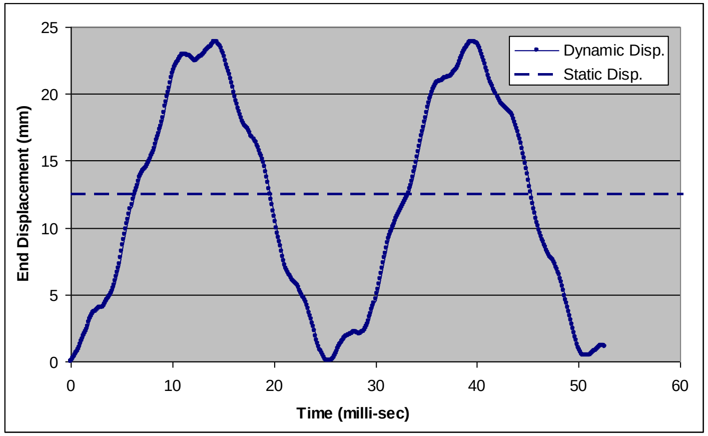






A look at dynamic stresses

Total stresses = “Quasi-steady” stresses + Dynamic stresses

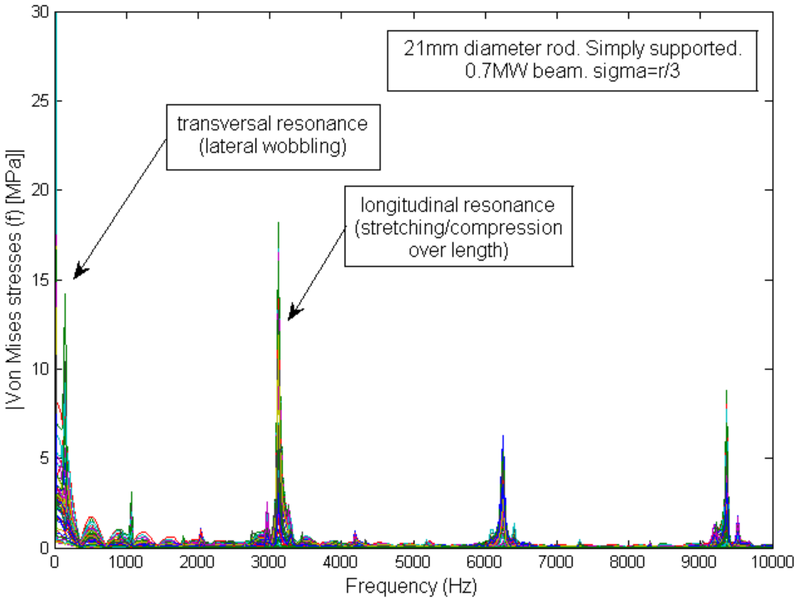
“Quasi-steady” stresses: i.e. thermal gradient.

Time scale: thermal diffusivity

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

Time scale: sound speed

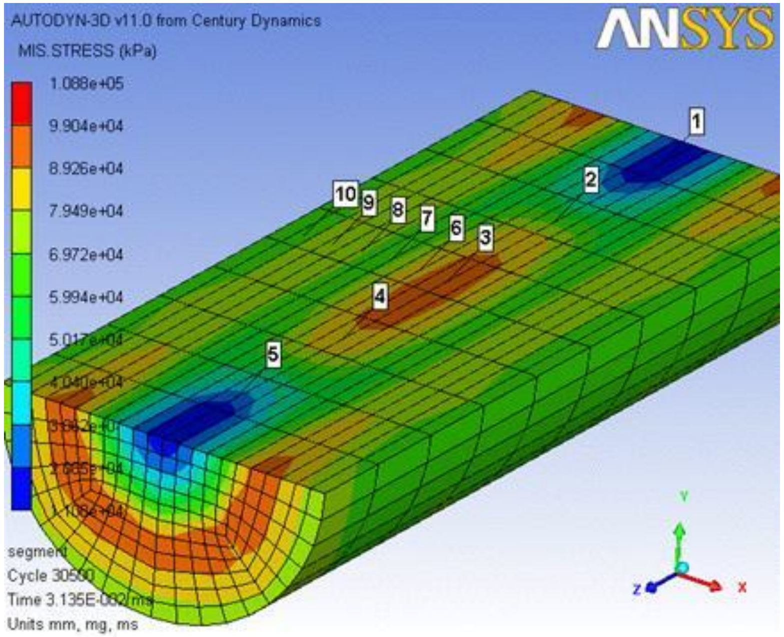
Amplitude Spectrum analysis of Von Mises stress throughout the target rod

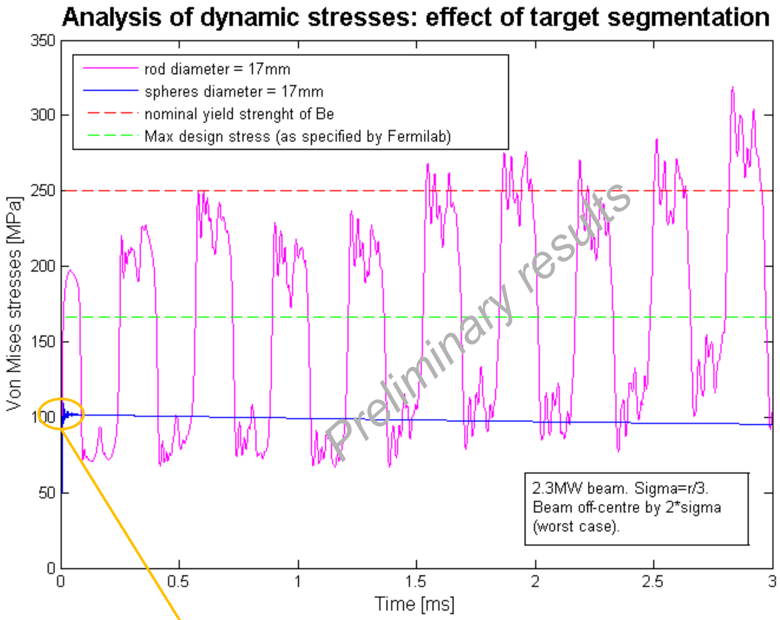

21mm diameter rod. Simply supported. 0.7MW beam. sigma=r/3

transversal resonance (lateral wobbling)

longitudinal resonance (stretching/compression over length)

Target segmentation reduces the stresses



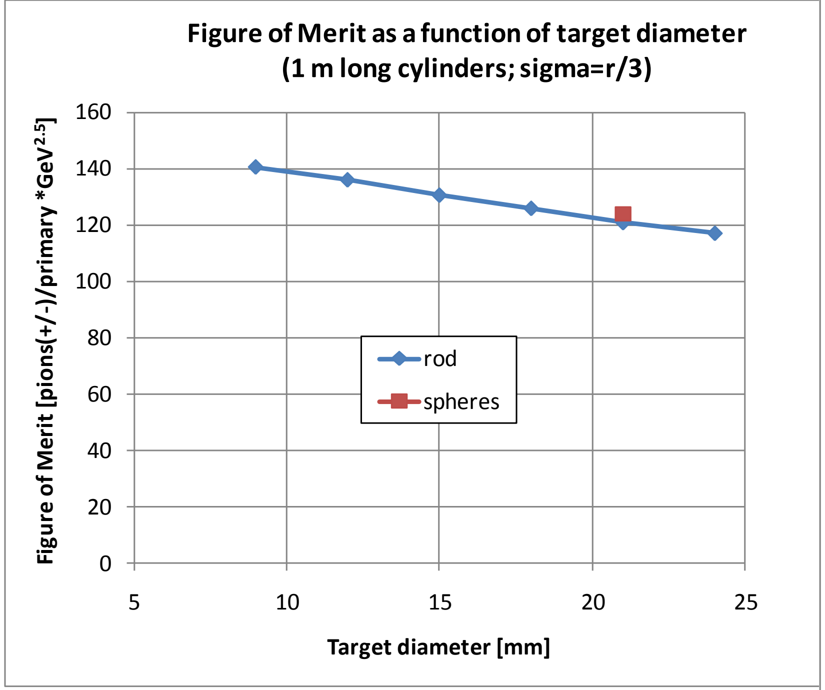


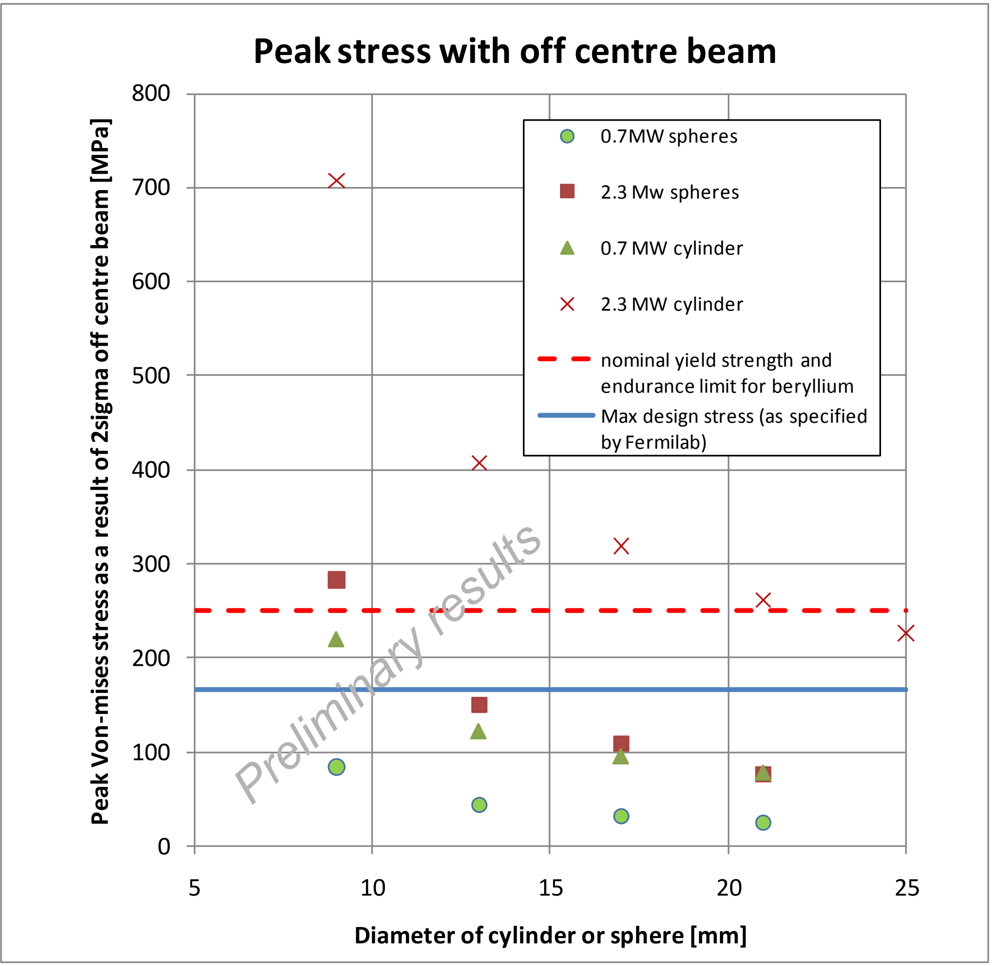
Segmentation of the target minimises the dynamic components quickly resolving to the "quasi-steady" stress field

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

Stresses as a function of rod/spheres diameter

- 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.*

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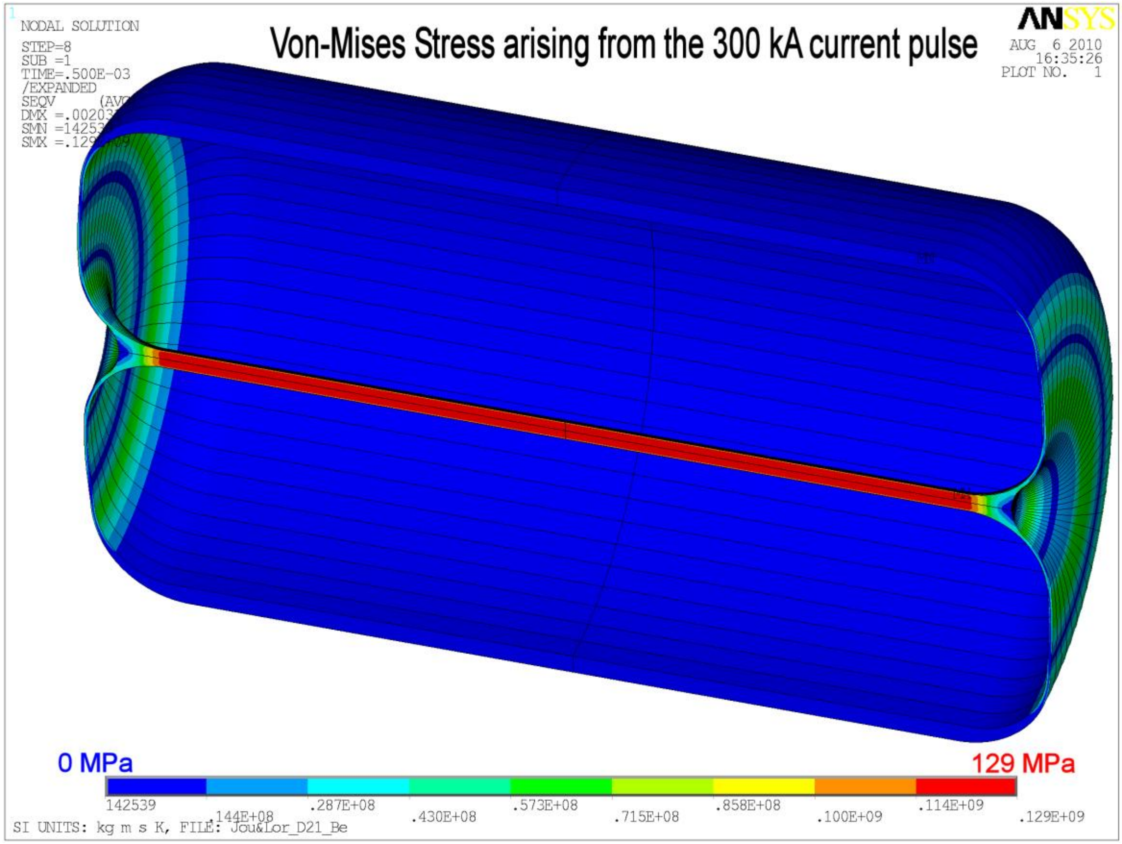
High Power Targets

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



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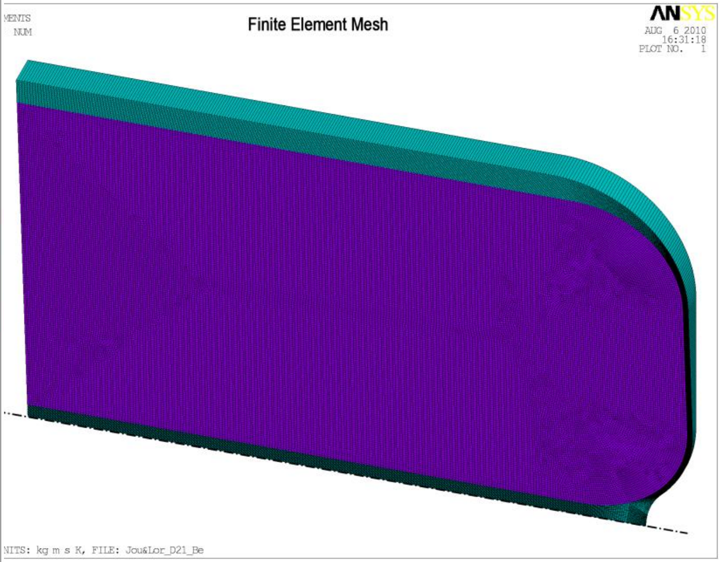
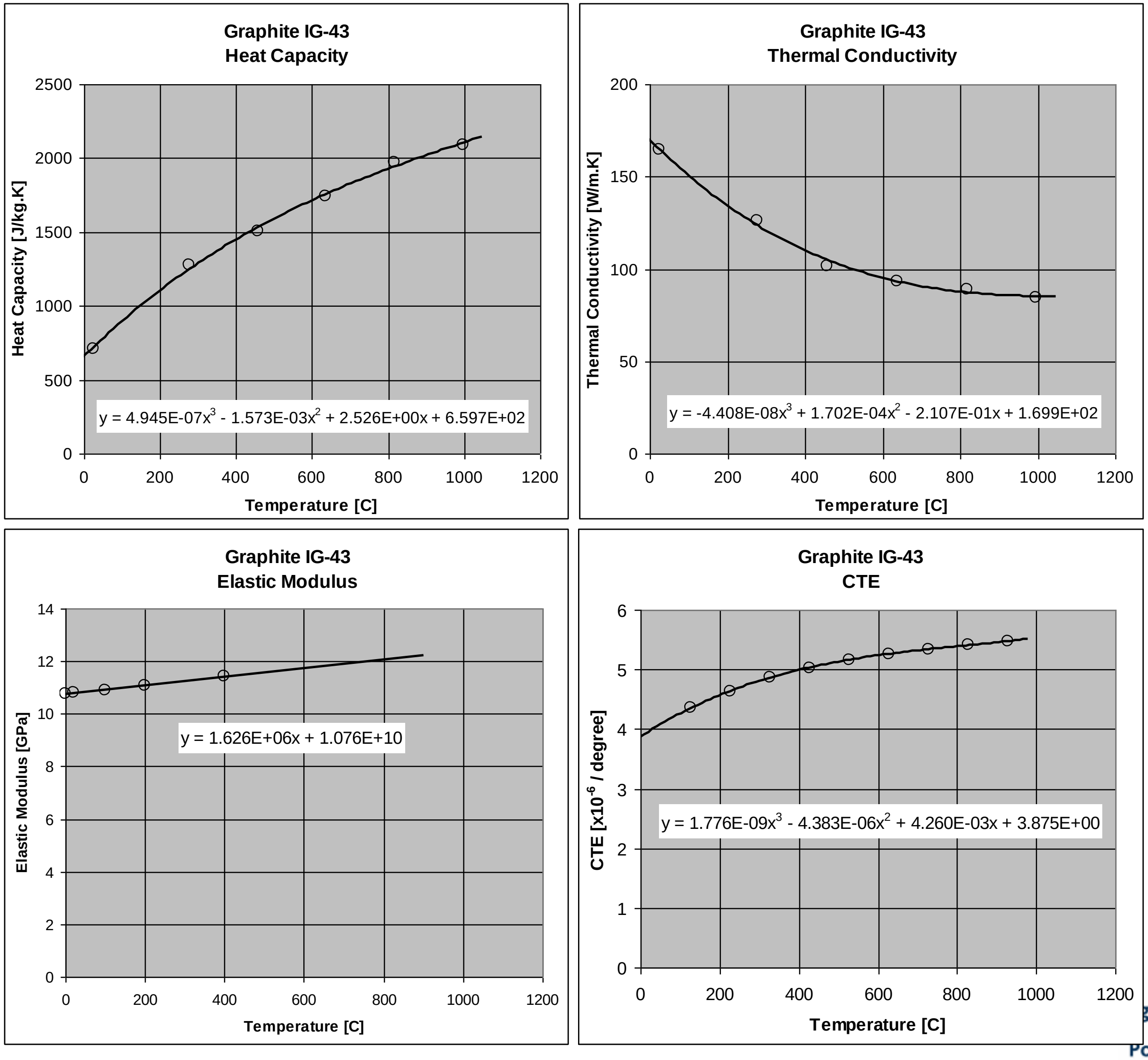


ANSYS model of the combined target / inner conductor concept.
Axial Lorentz forces induce a significant tensile stress component in the solid inner conductor.

Preliminary work on the EURONu-SPL baseline graphite rod

Temperature Dependent Properties of Graphite IG-43



Numerical Fit to Measured Data used in Non-Linear Material Property Definition

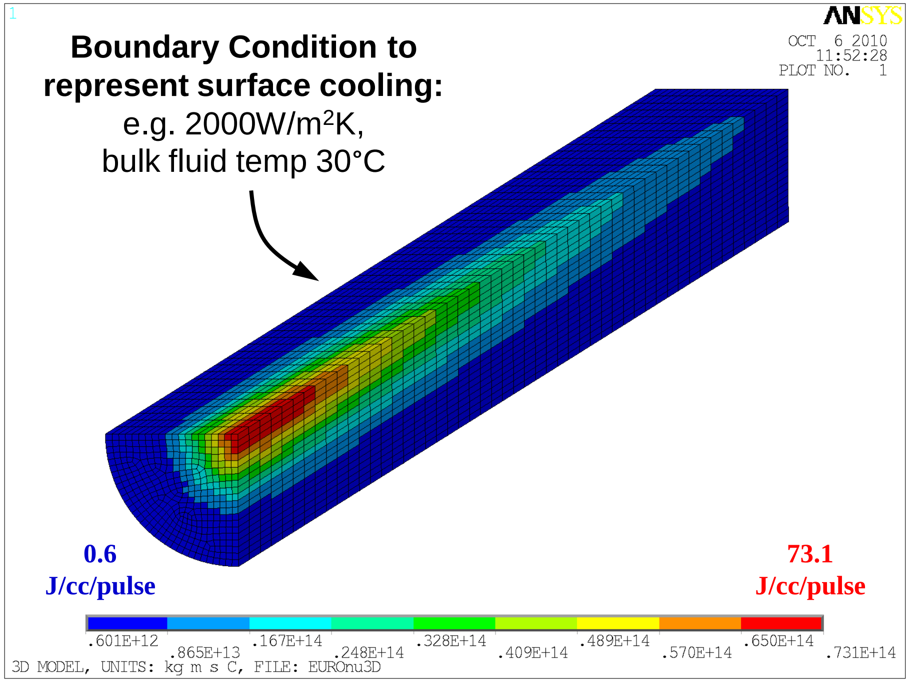
Beam Heating Model (ANSYS)

- 78 cm long, 3 cm diameter cylindrical graphite target
- ¼ symmetry 3D finite element model
- “Instantaneous” power density used as input heat load
- Convection heat transfer applied at outer surface

Integrated Energy Deposition:
4.1 kJ/pulse

Time averaged Power on Target:
4.1 kJ/pulse x 12.5 Hz = 51 kW

Peak Energy Density in Target:
73 J/cc/pulse



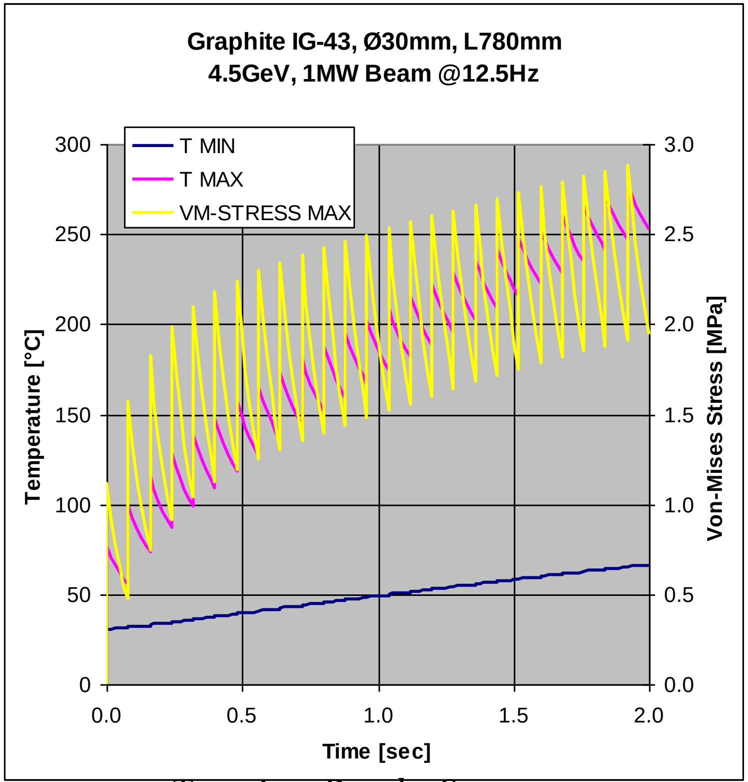
Boundary Condition to represent surface cooling:
e.g. 2000W/m^{2}K,
bulk fluid temp 30°C

0.6 J/cc/pulse

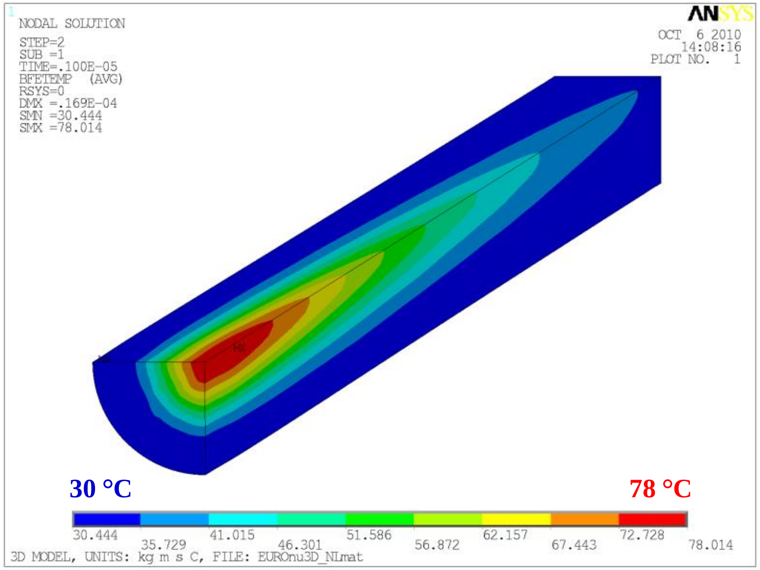
73.1 J/cc/pulse

Beam Heat Load Input to ANSYS Thermal Simulation

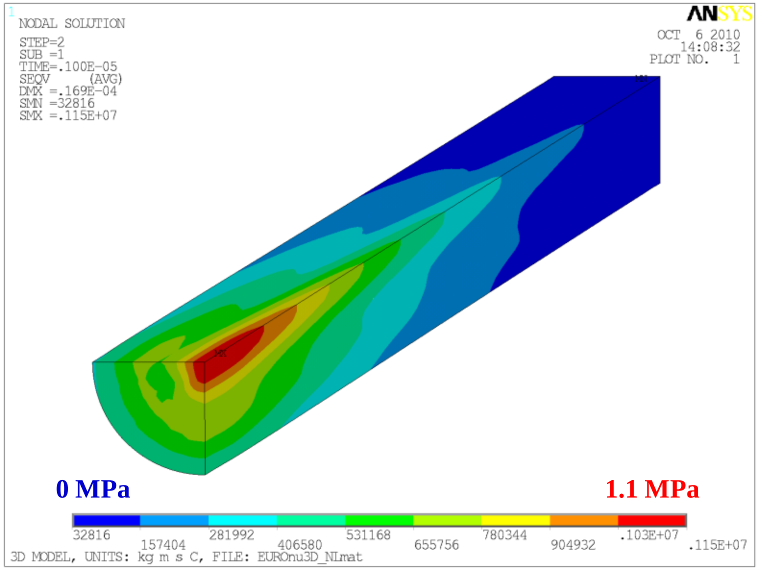
Transient Analysis Results (ANSYS)



Transient Results Summary



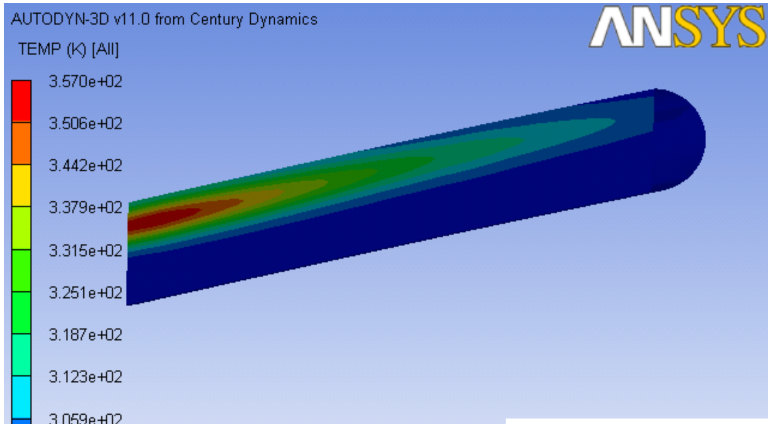
Temperature at End of 1st Pulse



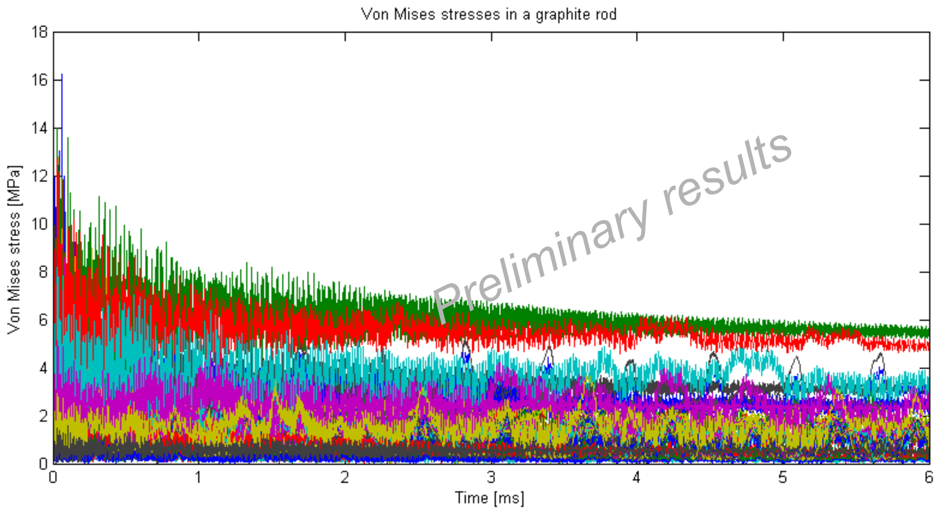
Von-Mises Stress at End of 1st Pulse

- But many more pulses required to reach steady-state conditions…

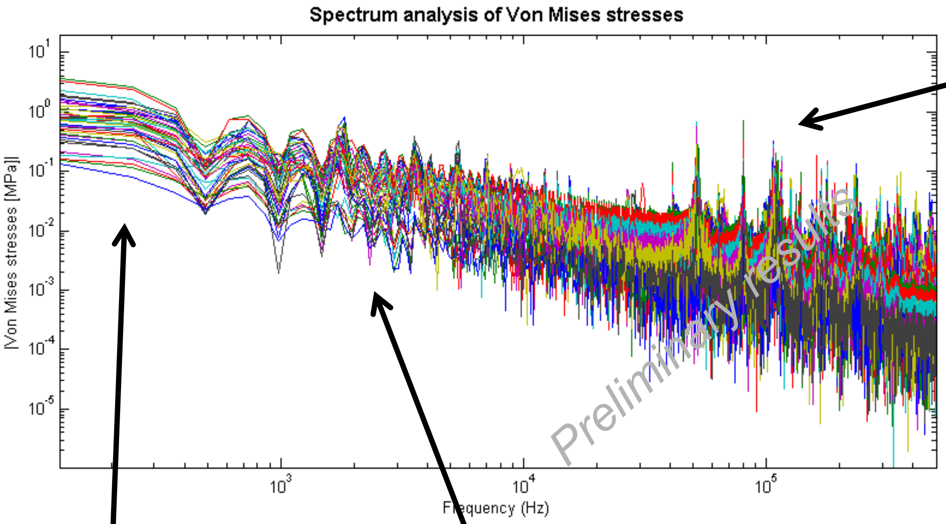
Preliminary analysis of dynamic stresses in a EUROnu SPL graphite rod



4.5 GeV beam. 4mm sigma. 1MW beam
30mm diameter rod. 11mm off-centre beam



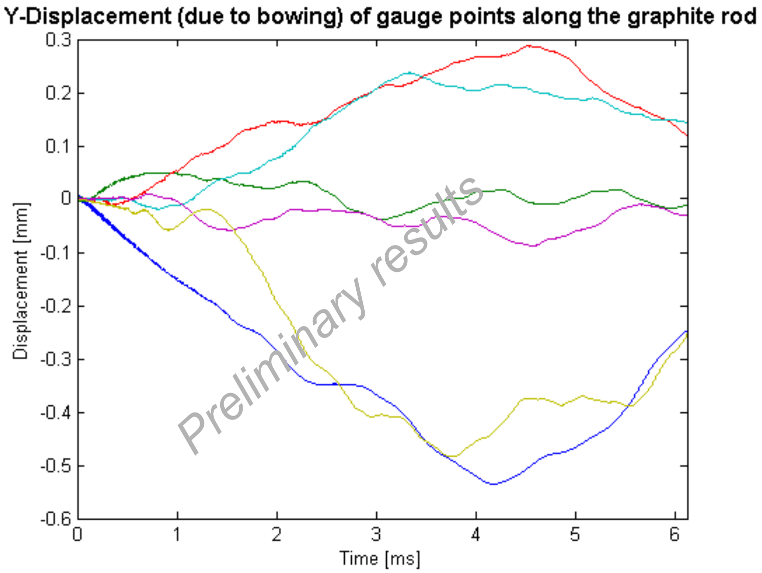
Preliminary analysis of dynamic stresses in a EUROnu SPL graphite rod


Spectrum analysis of Von Mises stresses

Radial resonance
Expansion/ contraction of radius

Longitudinal resonance
Stretching/compression over length

Transverse resonance
bowing


Y-Displacement (due to bowing) of gauge points along the graphite rod

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High Power Targets

Conclusions

- There is more to the target than just the physics e.g:
    - Structural integrity
    - Heat removal
    - Ancillaries such as support structure, cooling channels, etc (this also has an affects on the pion yield!)
    - Safety & chemical compatibility
    - Etc.
- Preliminary analysis indicates that the stresses in the EUROnu SPL baseline graphite rod for 1 bunch train look significant
- At high rep rate (12.5Hz) the effects of subsequent bunch trains may constructively interfere (quasi-static stresses, attenuation coefficient for stress waves?)
- Cooling will not be trivial: 50kW may not seem much but the surface area available for heat transfer is rather small!
- Segmentation of the target may help to reduce stresses (see LBNE example)
- Beryllium may be a better candidate material (e.g. Better yield strength)?