Science & Technology Facilities Council

Engineering simulations and methodology as applied to the LBNE target study

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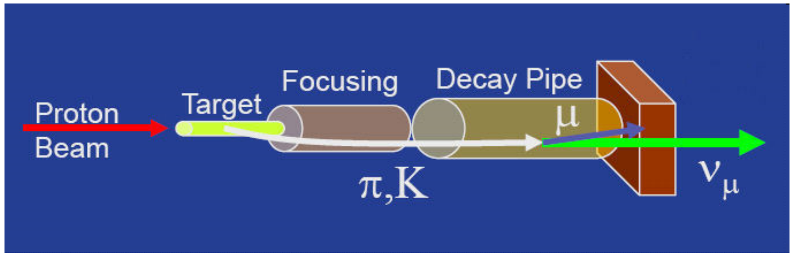
What is LBNE?

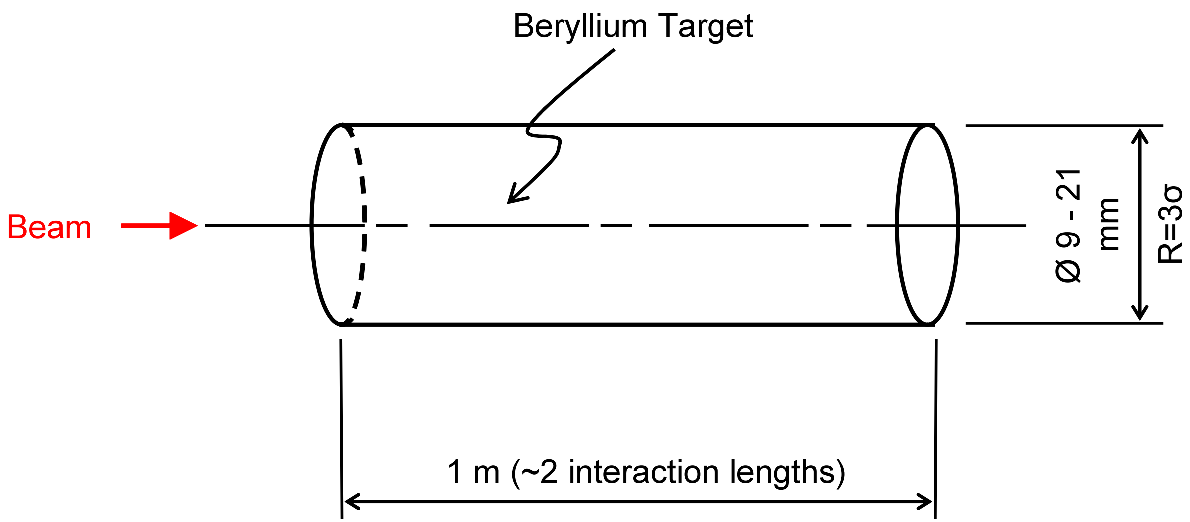
- The proposed Long Baseline Neutrino Experiment (LBNE) will use the main injector accelerator at Fermilab to produce 120 GeV protons that collide with a fixed target to generate a beam of Neutrinos.
- The Neutrino beam will then travel several hundred miles to reach a far detector possibly sited at DUSEL, South Dakota.
- Design of a target that is able to withstand the pulsed heating and radiation damage effects from the 2.3 MW beam is a particularly challenging task



LBNE will use a fixed target and horn system

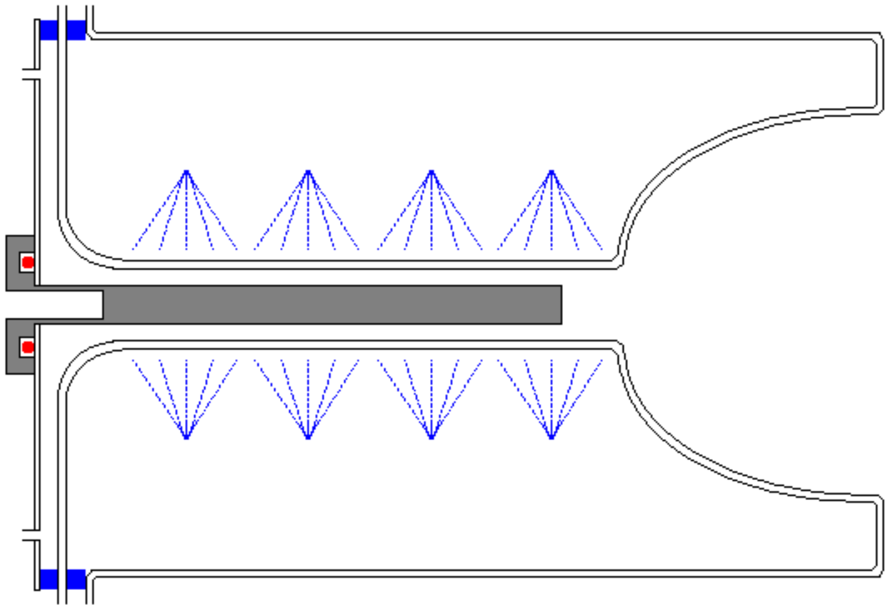
LBNE Beam and Target Parameters

Proton Beam Energy (GeV)	Repetition Period (sec)	Protons per Spill	Proton Beam Power (MW)	Beam sigma, radius (mm)
120	1.33	4.8 e13	0.7	1.5 – 3.5
120	1.33	1.6e14	2.3	1.5 - 3.5
Pulse length (micro-sec)	**Bunches per Pulse**	**Bunch length (nano-sec)**	**Bunch spacing (nano-sec)**	**Protons per Bunch**
9.78	519	2-5	18.8	3.1e11



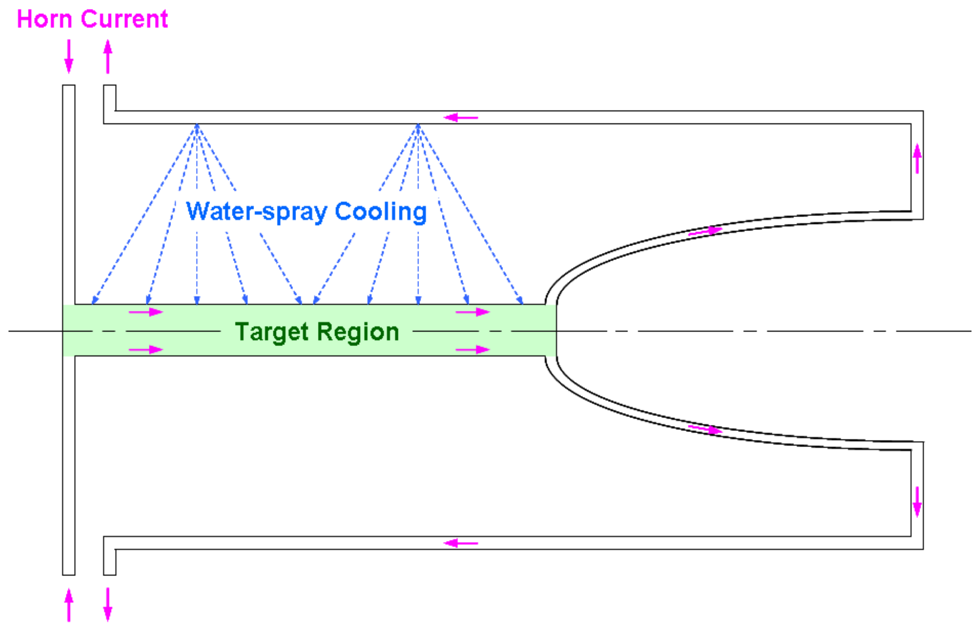
Concepts Studied

1. *'Separate'* target and Horn



- Conventional concept
- Target inserted inside horn inner conductor
- Separate target and horn cooling systems

2. *'Combined'* target and Horn



- Alternative concept
- Target doubles as current carrying inner conductor
- Must withstand beam interactions and pulsed current effects

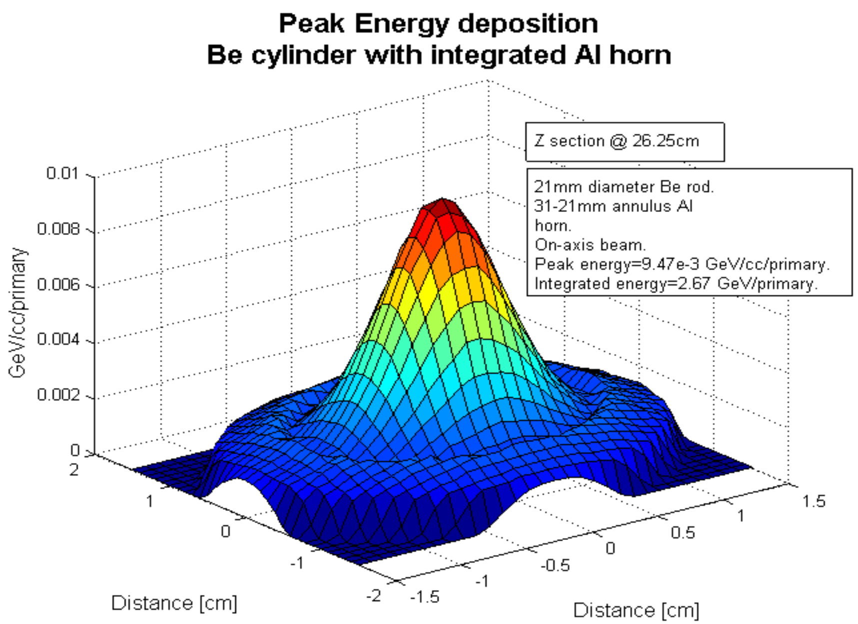
Simulation Challenges

- RAL High Power Targets (HPT) group used a suite of simulation tools to study the proposed LBNE target system

Physical Effect	Timescale	Simulation Software
Beam induced heating	micro-seconds	FLUKA
Acoustic stress-waves	micro-seconds	ANSYS, AUTODYN
Violin Modes	milli-seconds	ANSYS, AUTODYN
Pulsed current / skin depth	milli-seconds	ANSYS
Thermal Conduction	seconds	ANSYS, AUTODYN, CFX
'Static' Stress	seconds	ANSYS

MonteCarlo Simulations

- Used FLUKA to study the physics and engineering performance of the target:
  - Physics
    - Yield of useful particles investigated using a figure-of-merit (FoM)
  - Engineering
    - Deposited energy distribution taken as an input to further engineering simulations

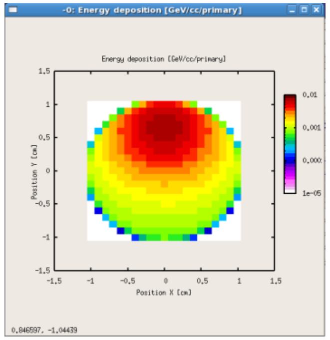


Energy deposition at a section through the target and horn inner conductor

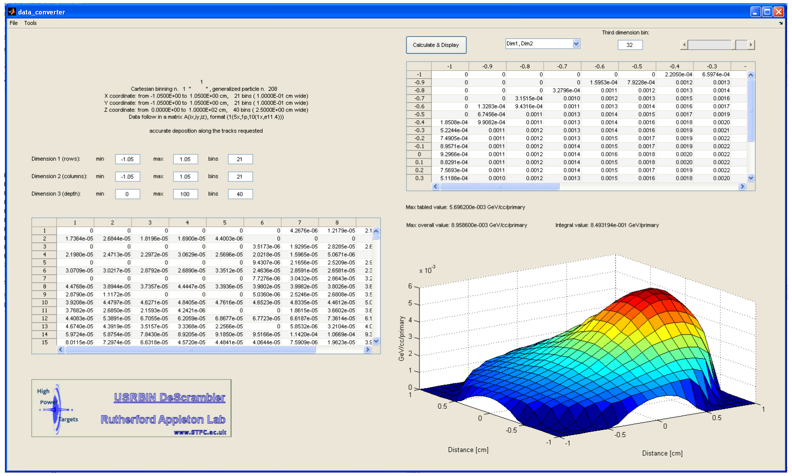
- 'Figure of Merit' (FoM) devised by R.Zwaska (FNAL)
- FoM is convolution of selected pion energy histogram by a weighting function:
  - $W(E)=E^{2.5}$ for
    - 1.5 GeV < E < 12 GeV
    - pT <0.4 GeV/c
- Weighting function compensates for low abundance of most useful (higher energy) pions

MatLab Interface Developed In-House

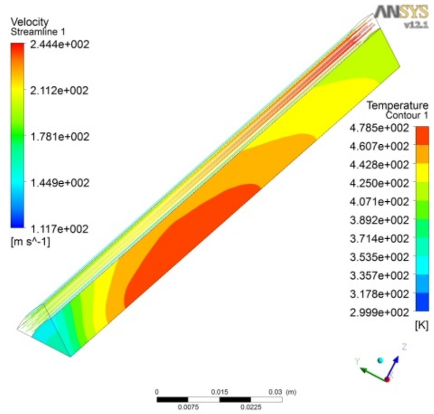
- FLUKA post-processing GUI developed in-house
  - Reads the FLUKA output file
  - Writes out the energy deposition data in a suitable format for CFX, ANSYS, AUTODYN
- Semi-automated process permits multiple case runs



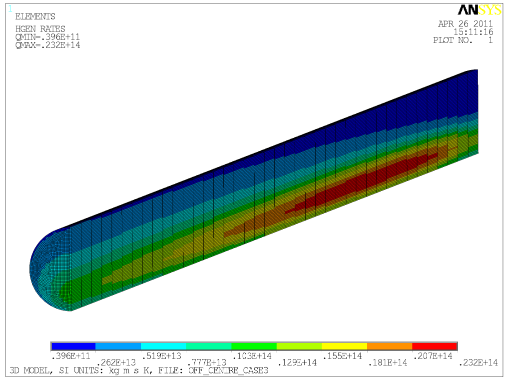
FLUKA:
energy deposition



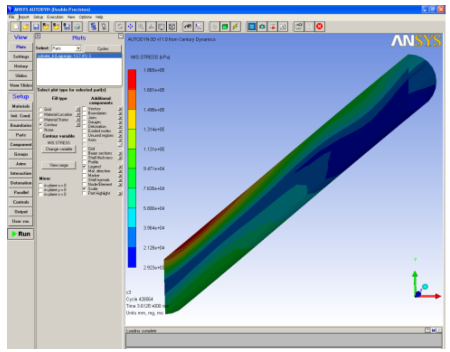
MatLAB:
semi-automated interface
[Ottone Caretta]



CFX: fluid dynamics code



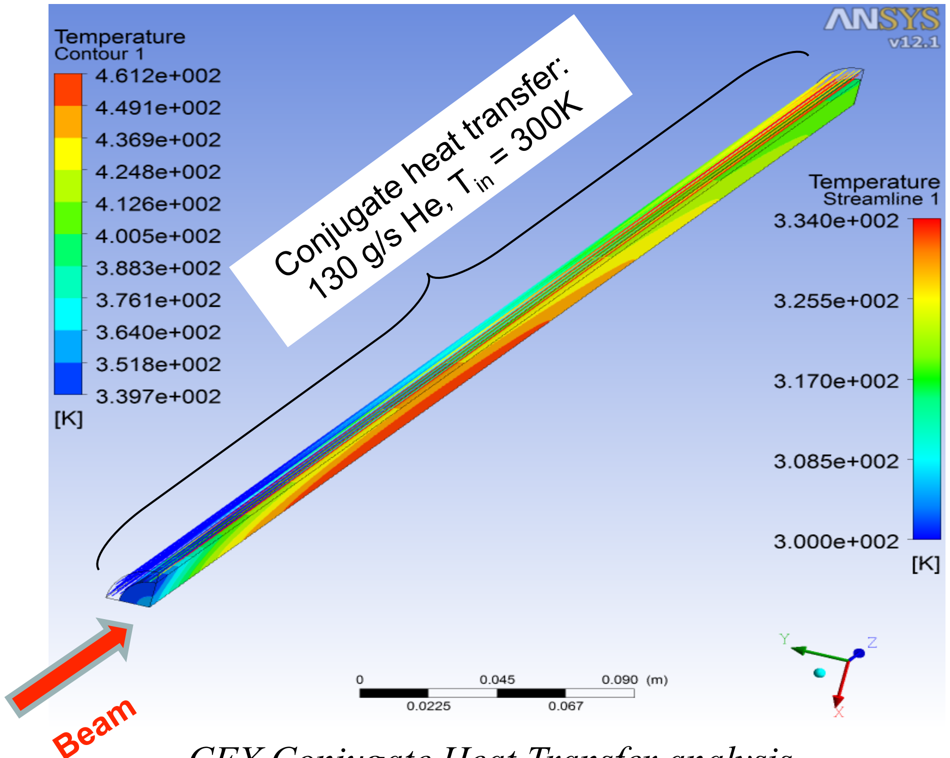
ANSYS: multi-physics simulation



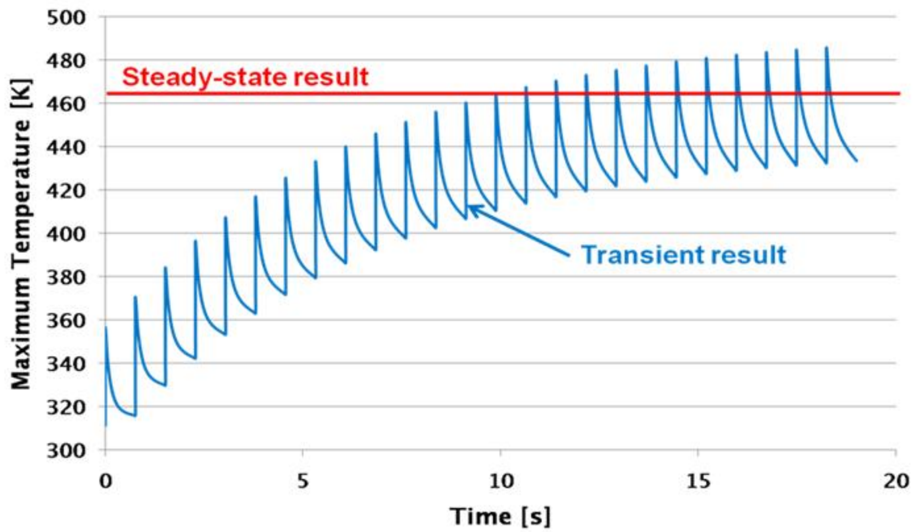
AUTODYN: dynamic simulation

Computational Fluid Dynamics (CFD)

- Used CFX to investigate various forced convection cooling options
  - Water, air, helium,
- Conjugate Heat Transfer Analysis
  - Solid and fluid domains solved simultaneously
  - Local heat-transfer coefficient evaluated at solid/fluid interface



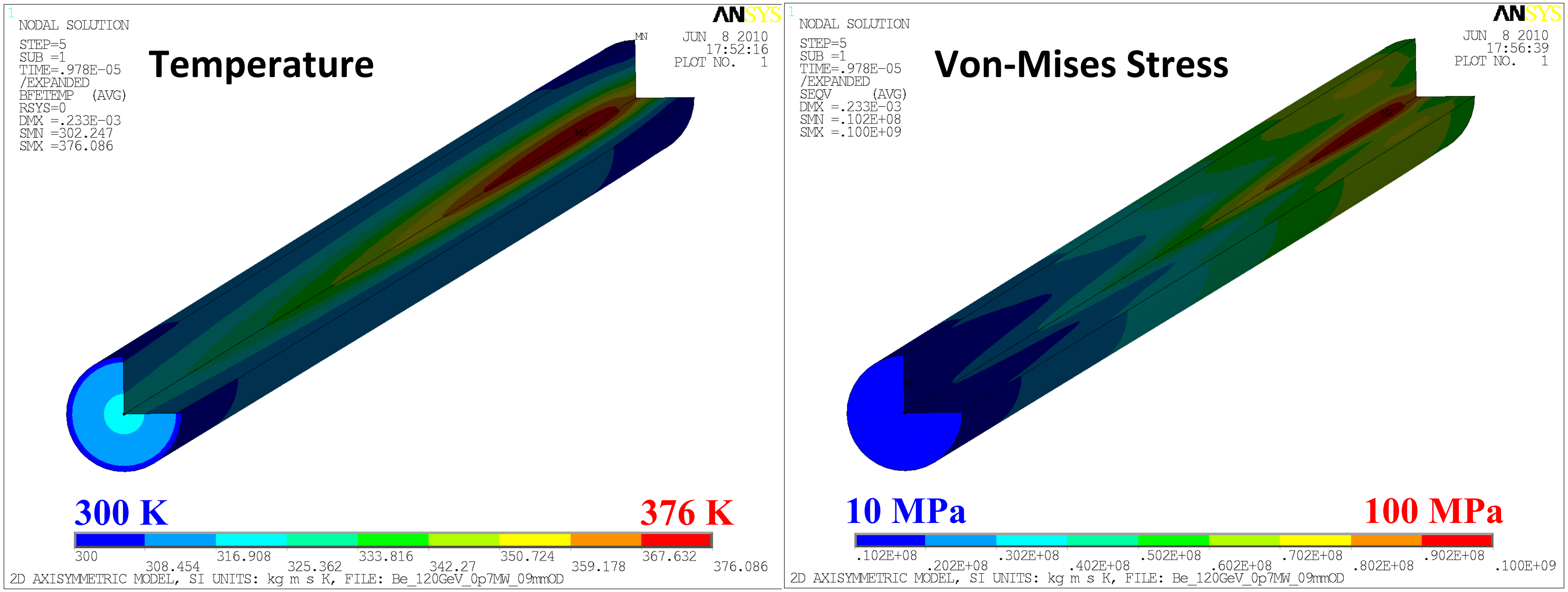
CFX Conjugate Heat Transfer analysis



The peak target temperature will oscillate around the steady-state value

“Static” Thermal Stress

- Depends primarily on temperature difference between target core and surface
- Can be reduced by enlarging the beam sigma and target radius
- Smallest (1.5 mm) beam sigma excluded for highest power (2.3 MW) operation



Temperature and Von-Mises stress contour plots at the end of the first beam spill (700 kW operation)

Stress-Waves

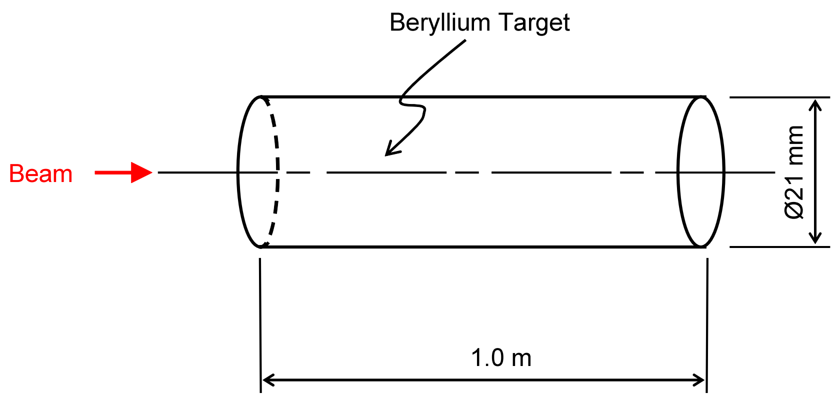
- Are superimposed on top of the "static" stress
- (Acoustic) stress waves may be generated if the energy deposition time is short compared to the characteristic expansion time of the target
  - These are elastic waves that travel at the speed of sound in the target material
- The Longitudinal and shear wave speeds in Beryllium are:

$$C_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} = 13.1\,\text{km/sec} \qquad C_S = \sqrt{\frac{G}{\rho}} = 8.9\,\text{km/sec}$$

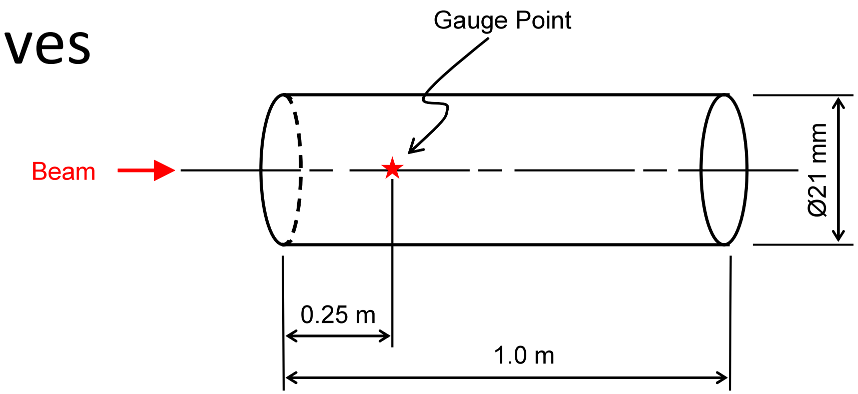
- The Longitudinal and radial stress-wave periods are then:

$$T_L = \frac{2L}{C_L} = 150\,\mu\text{sec} \qquad T_R = \frac{2R}{C_S} = 2.4\,\mu\text{sec}$$

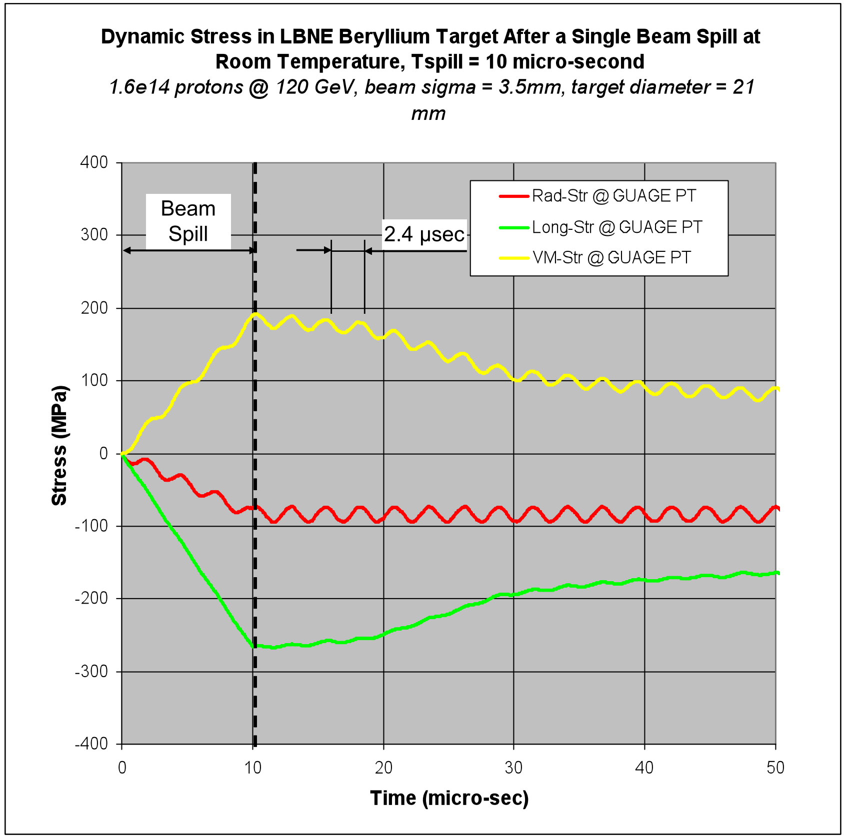
- Recall the beam spill duration in LBNE was 9.78 μsec

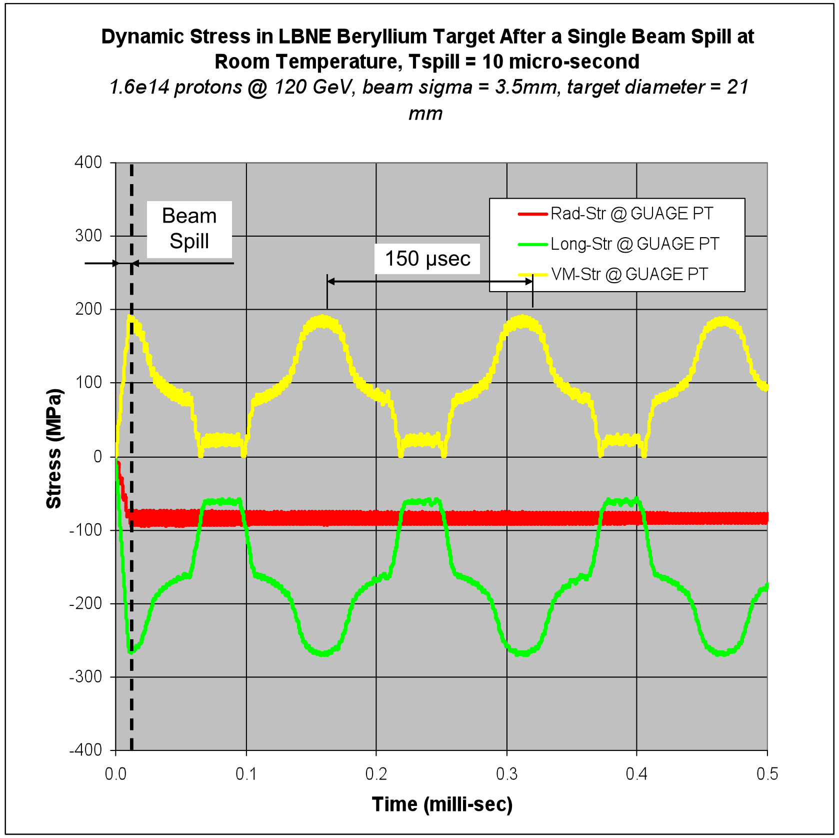


Stress-Waves

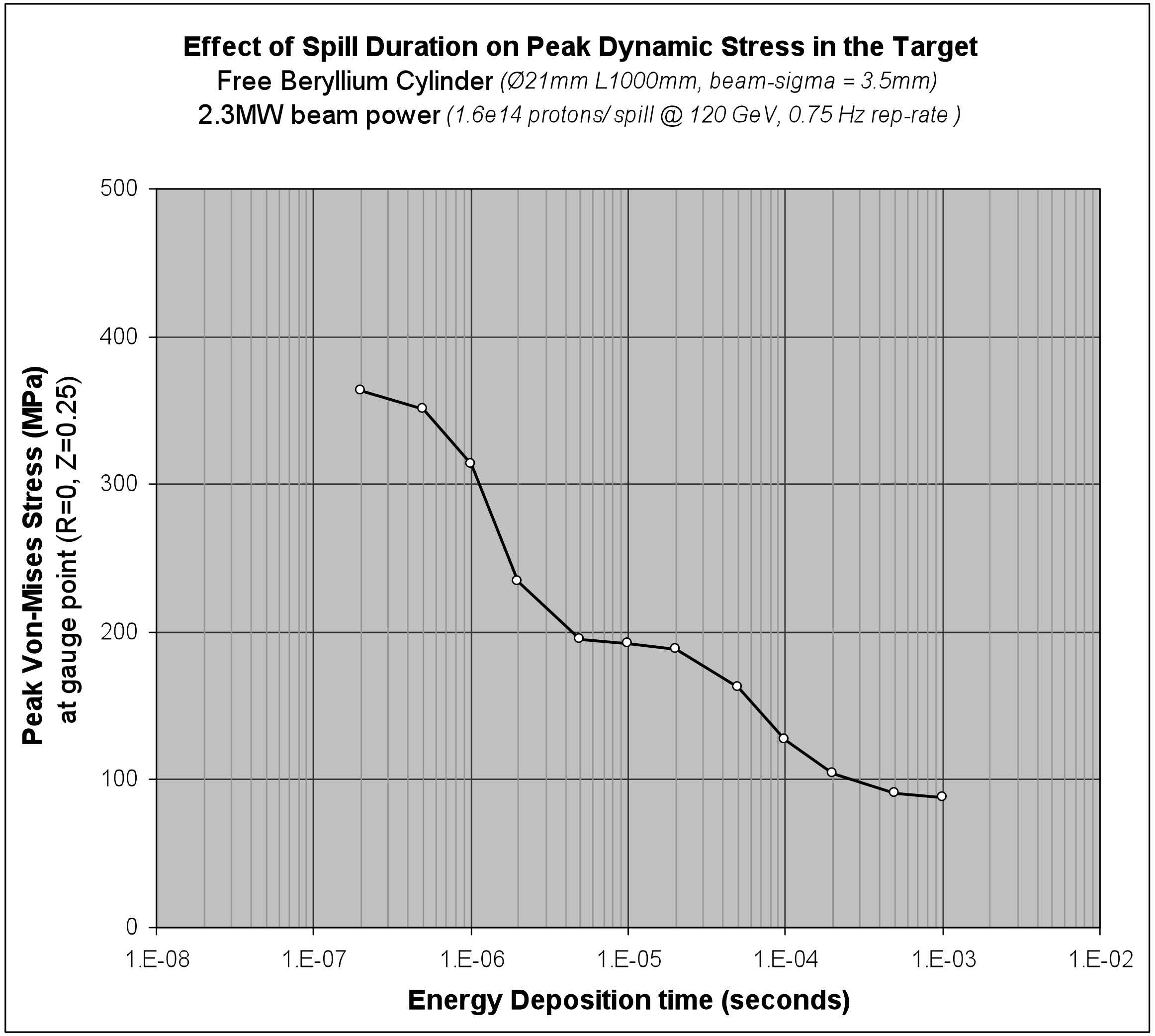


- The response of the target to a single beam spill is recorded at “gauge points” in the model





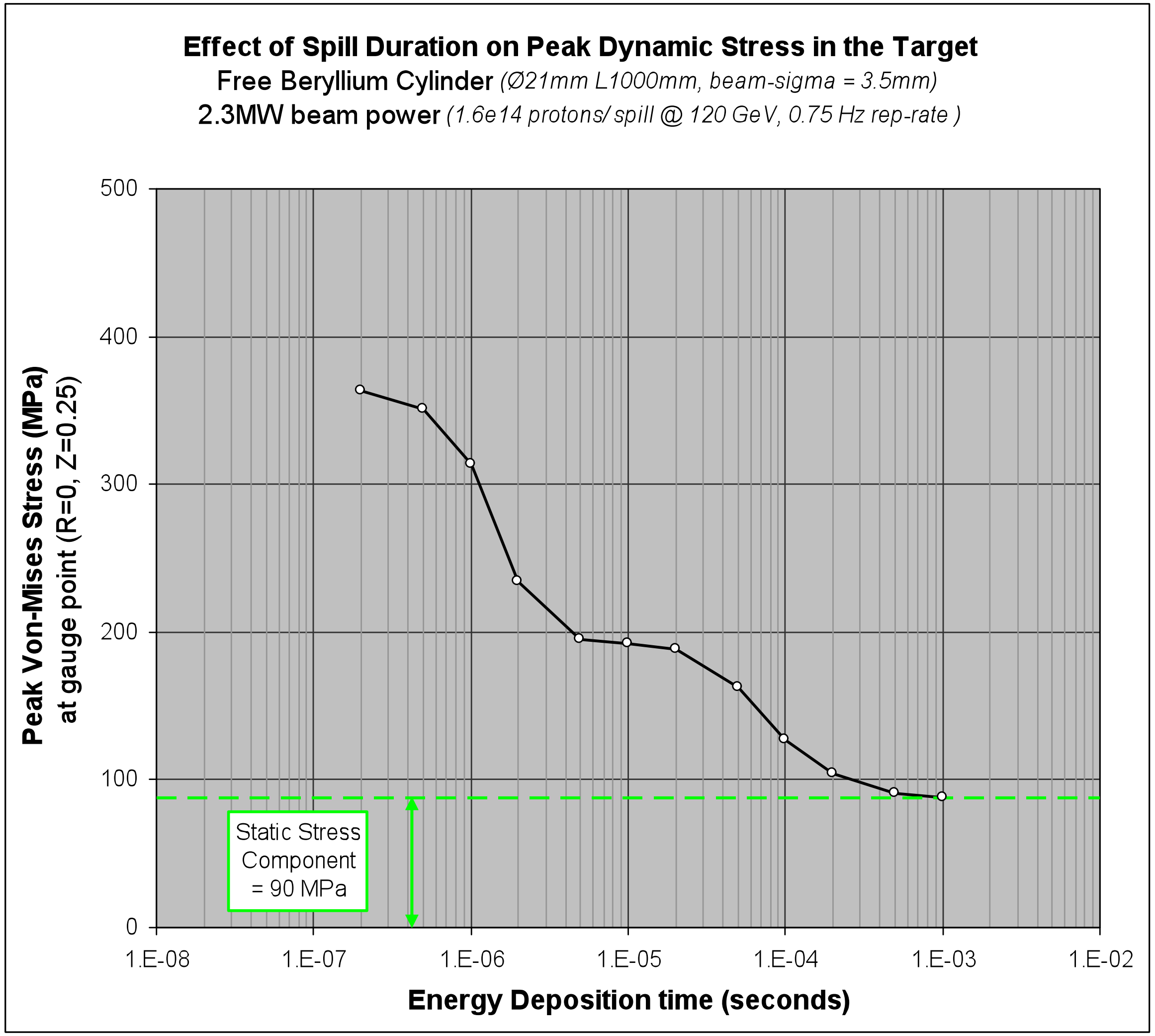
Stress-Waves



Effect of beam spill time on the peak dynamic stress in the target

Stress-Waves

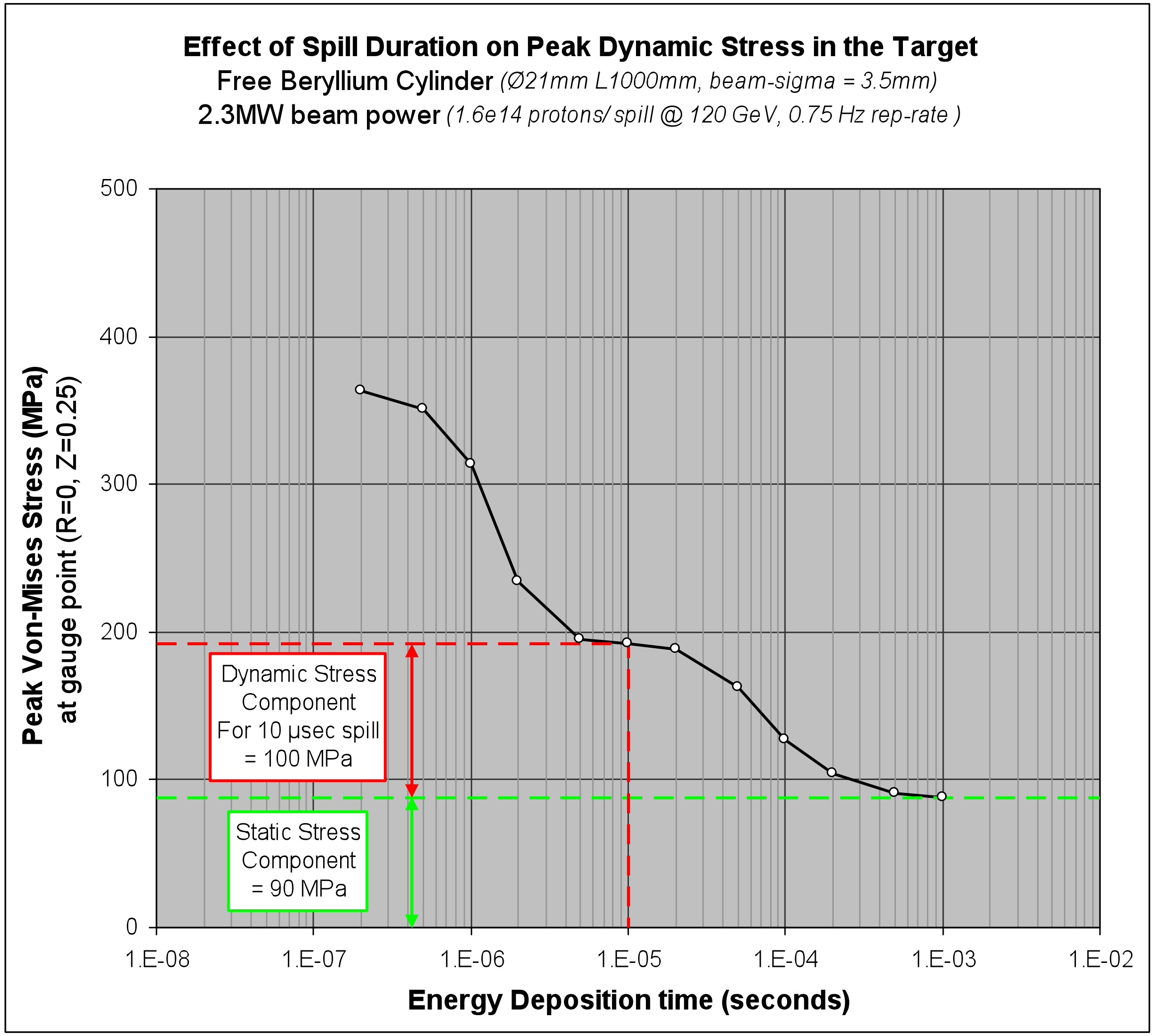
- “static” stress component is due to thermal gradients
  - Independent of spill time



Effect of beam spill time on the peak dynamic stress in the target

Stress-Waves

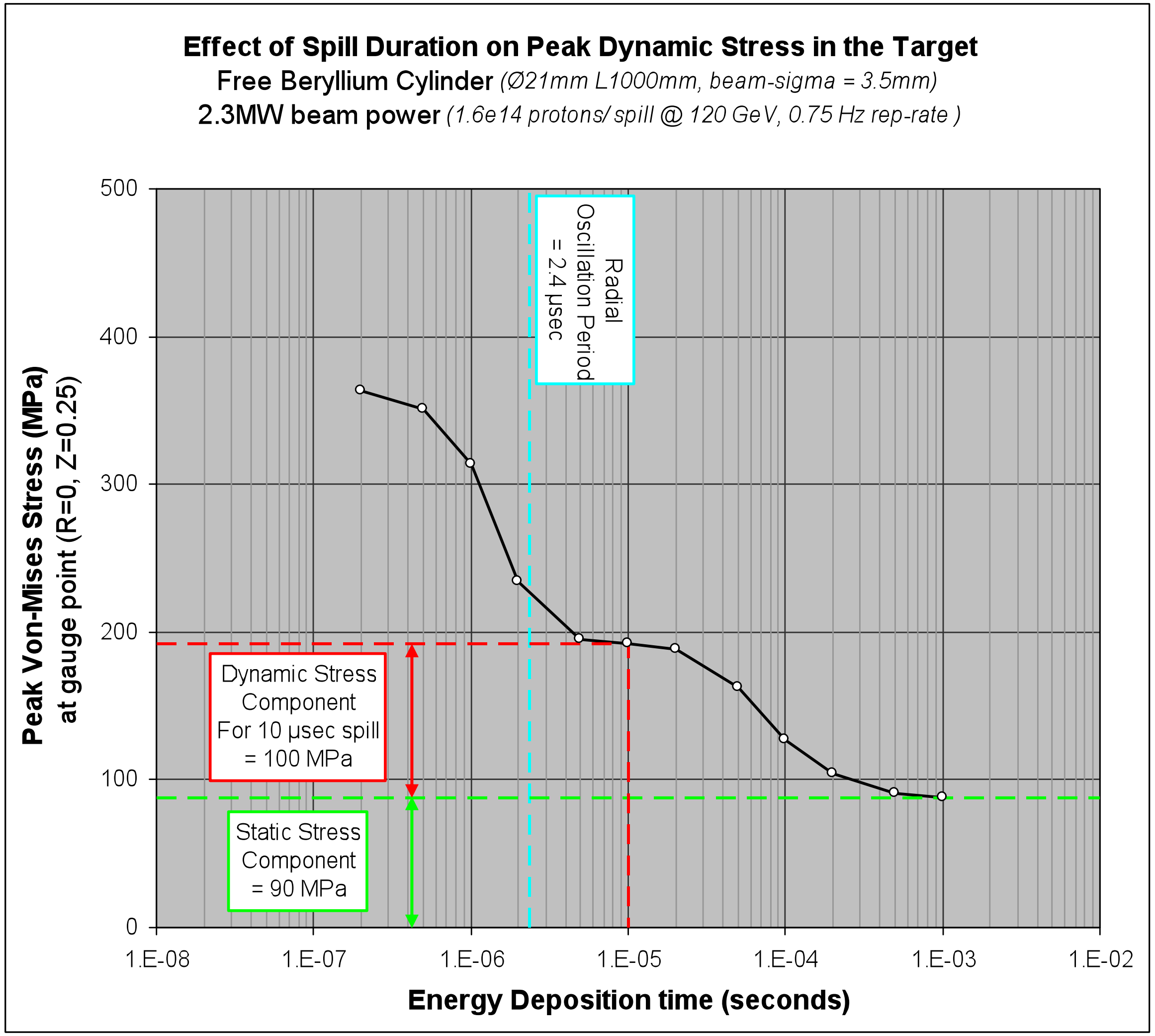
- "static" stress component is due to thermal gradients
  - Independent of spill time
- "dynamic" stress component is due to stress waves
  - Spill time dependent



Effect of beam spill time on the peak dynamic stress in the target

Stress-Waves

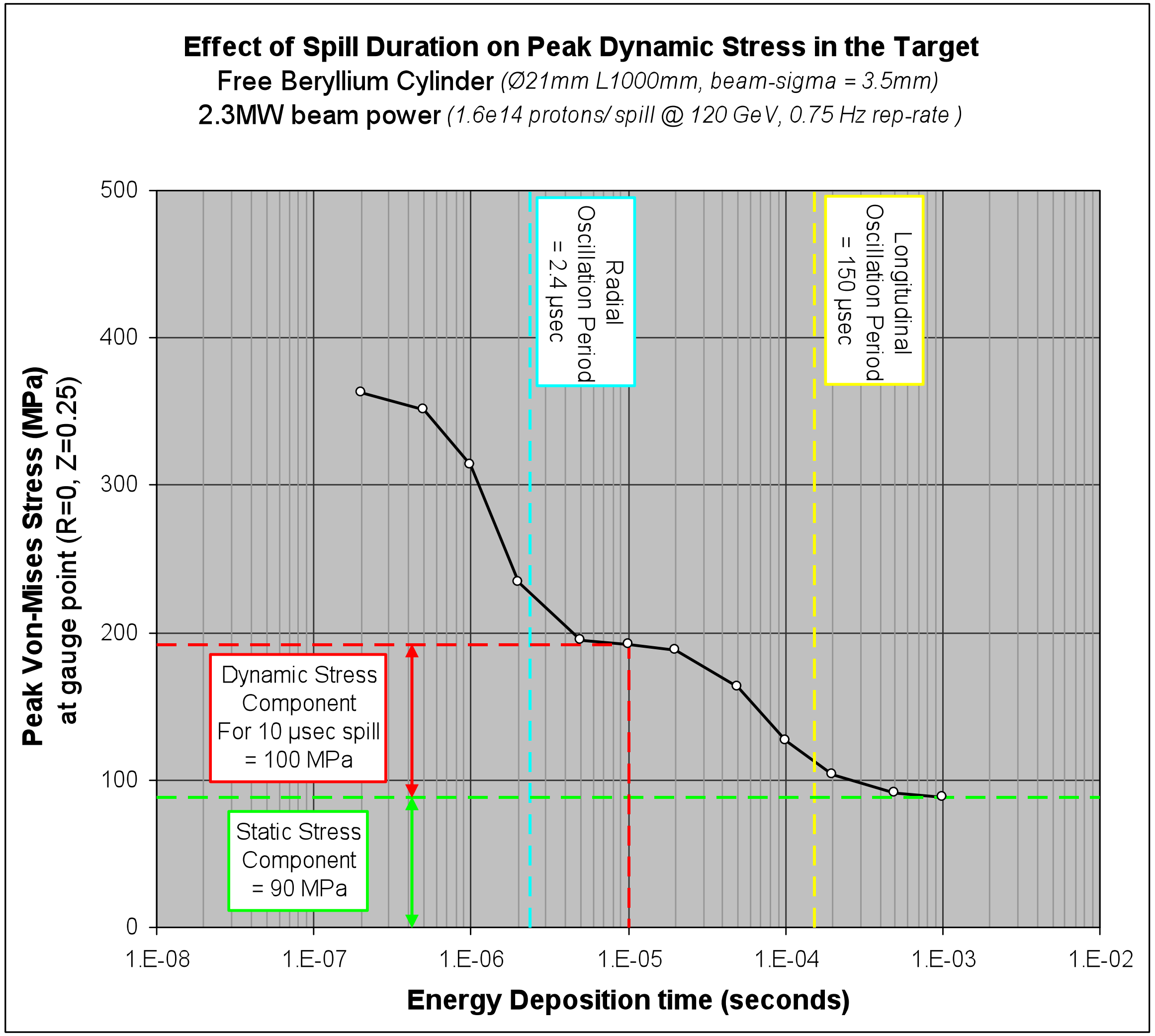
- "static" stress component is due to thermal gradients
  - Independent of spill time
- "dynamic" stress component is due to stress waves
  - Spill time dependent
- Tspill > Radial period
  - Radial stress waves are not significant



Effect of beam spill time on the peak dynamic stress in the target

Stress-Waves

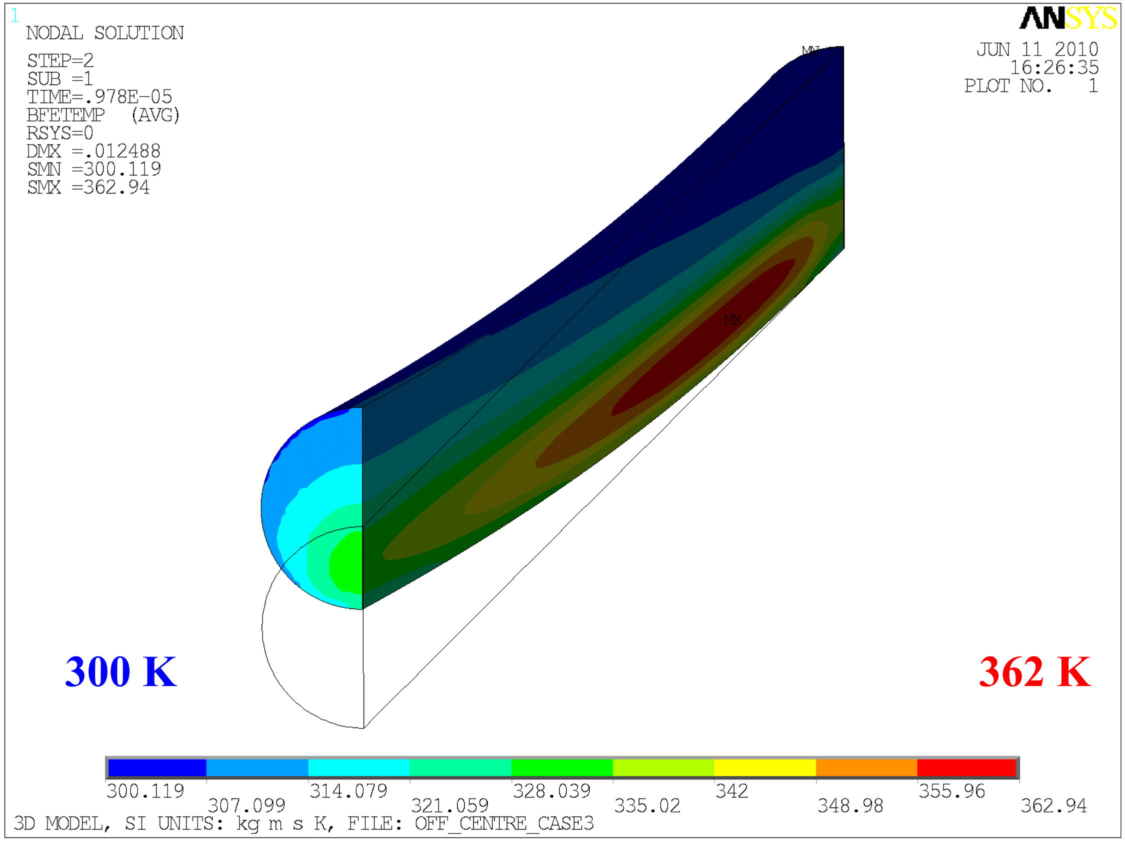
- “static” stress component is due to thermal gradients
  - Independent of spill time
- “dynamic” stress component is due to stress waves
  - Spill time dependent
- Tspill > Radial period
  - Radial stress waves are not significant
- Tspill < Longitudinal period
  - Longitudinal stress waves are important!



Effect of beam spill time on the peak dynamic stress in the target

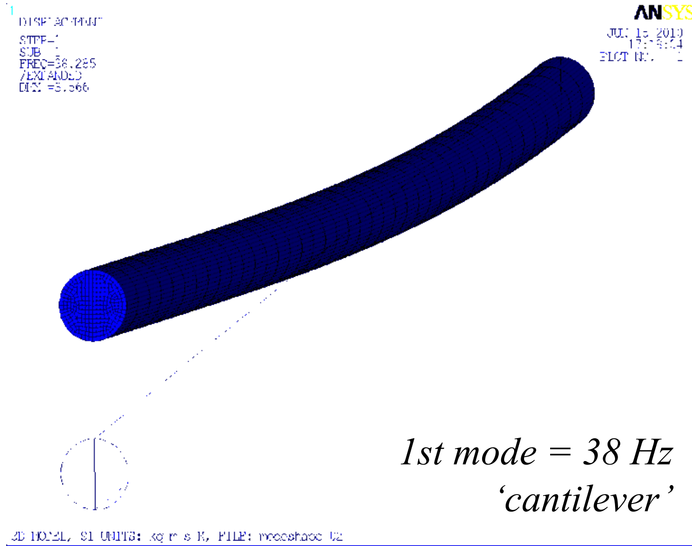
Violin Modes

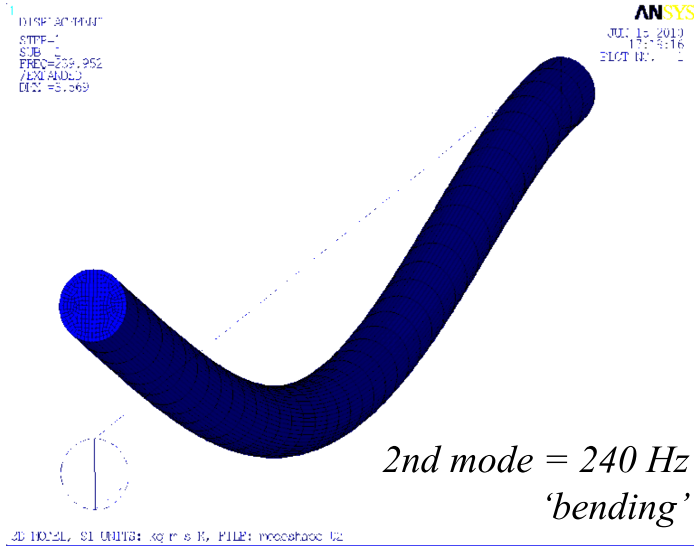
- Asymmetric heating due to an off-centre (mis-steered) beam initiates bulk lateral vibrations ('violin modes')
  - Modal and transient analyses used to identify the vibration modes and deflection magnitudes in the target structure



Temperature after a 2-sigma offset beam pulse

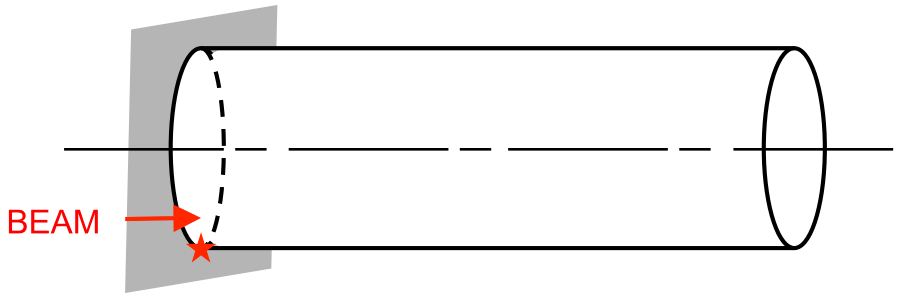
* lateral deflection shown at true scale

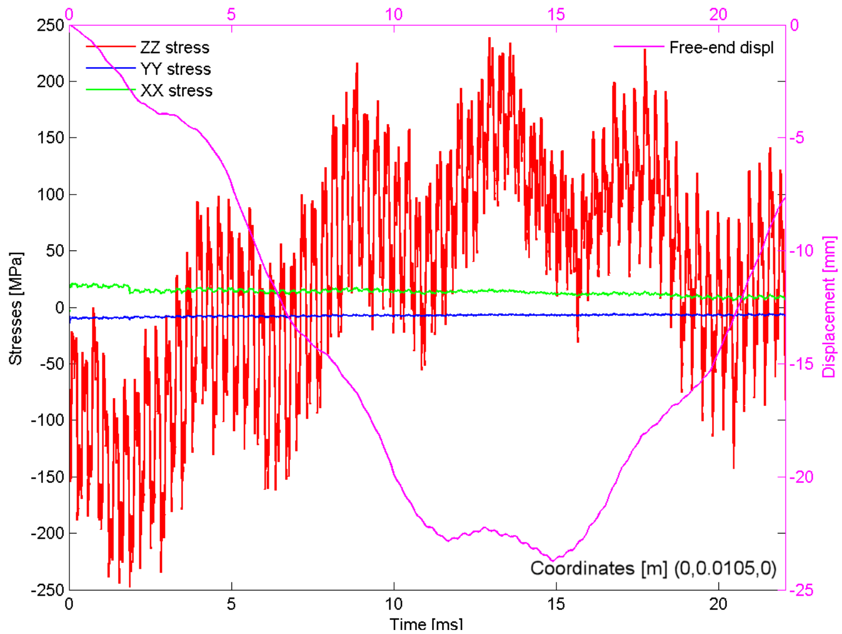




Off-centre beam effects: dynamic stress

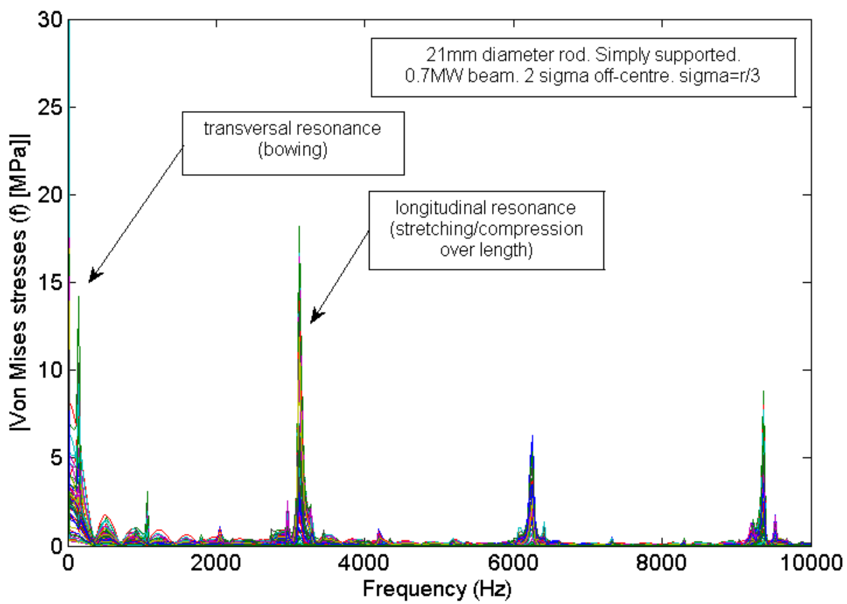
- Consider a gauge point located at the outer radius at the constrained end of the target:





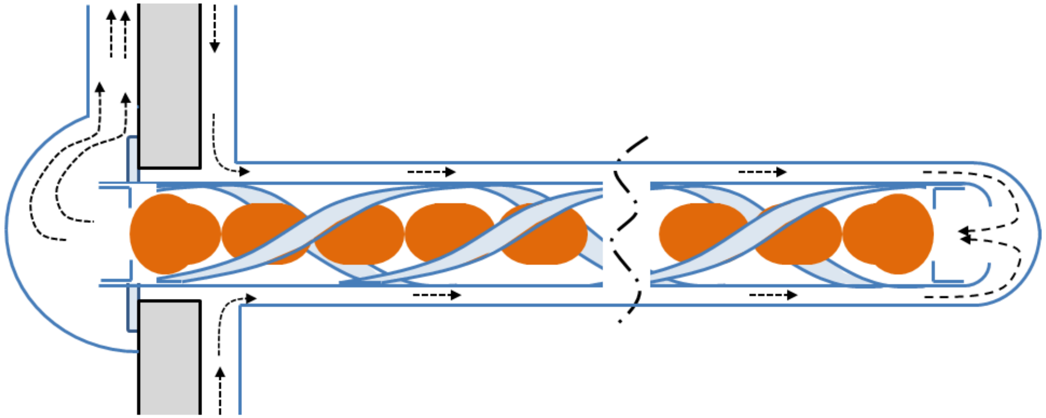
- Longitudinal stress oscillations dominate
- Can clearly identify a number of superimposed frequencies in the longitudinal stress:
  - Longitudinal acoustic waves
  - Bending violin mode
  - Cantilever violin mode

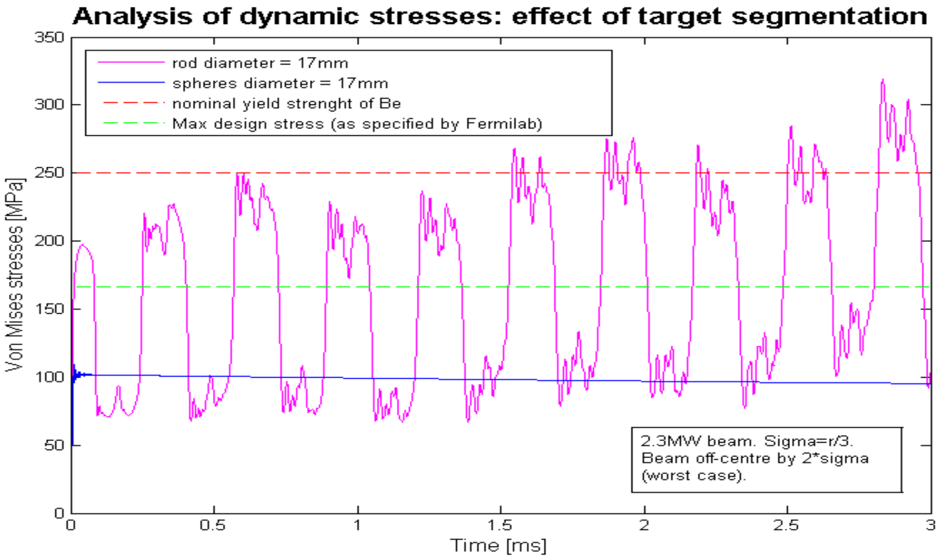
Amplitude Spectrum analysis of Von Mises stress throughout the target rod

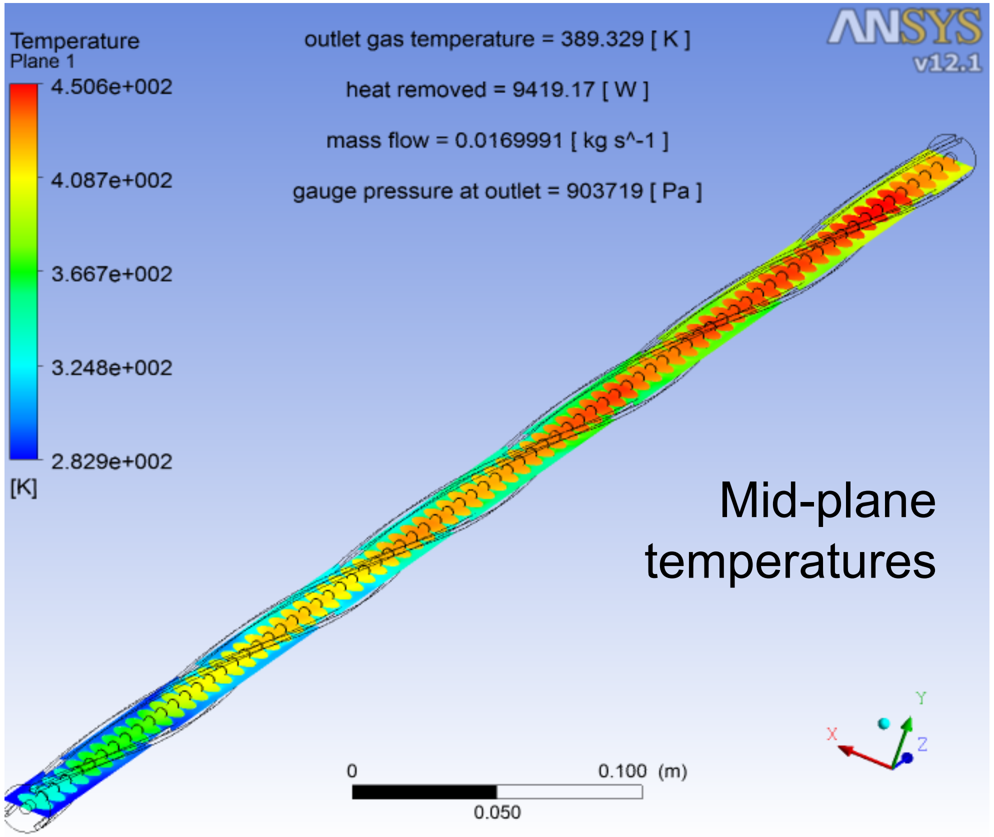


A Potential 2MW Target Concept: Beryllium Spheres

- Longitudinal segmentation
  - Spheres avoid inertial stress
- High Pressure helium cooling loop
  - Helical flow guides
  - 10 bar outlet pressure
  - Little energy deposited in coolant
  - Coolant applied close to region of peak energy deposition

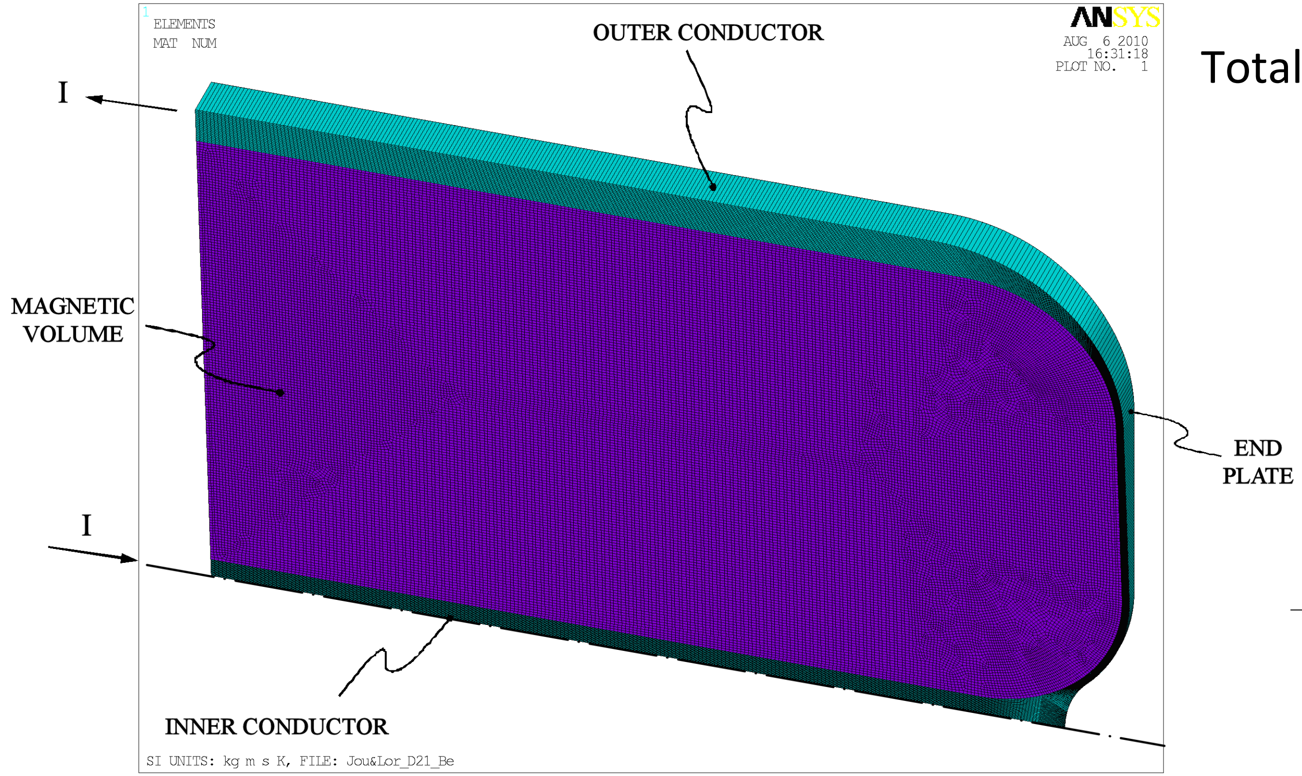






Combined Target and Horn Concept

- Multiphysics magneto-thermo-structural analysis using ANSYS



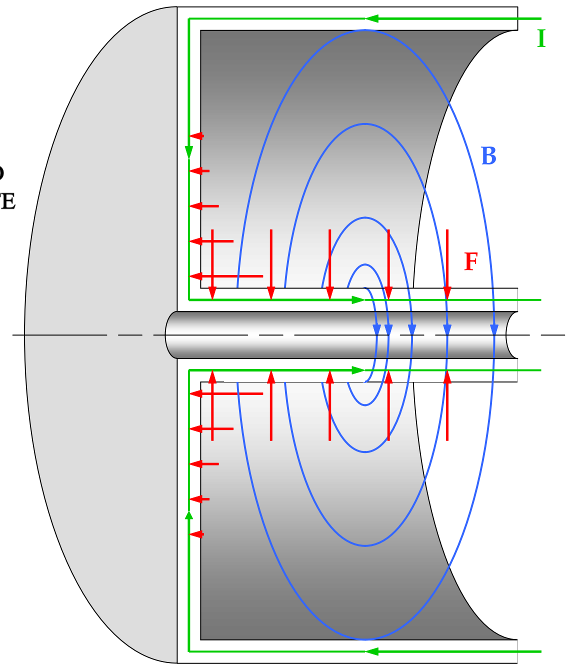
ANSYS finite element model of a magnetic horn

Magnetic "pressure" on conductor

$$P = \frac{\mu_0 I^2}{8\pi^2 R^2}$$

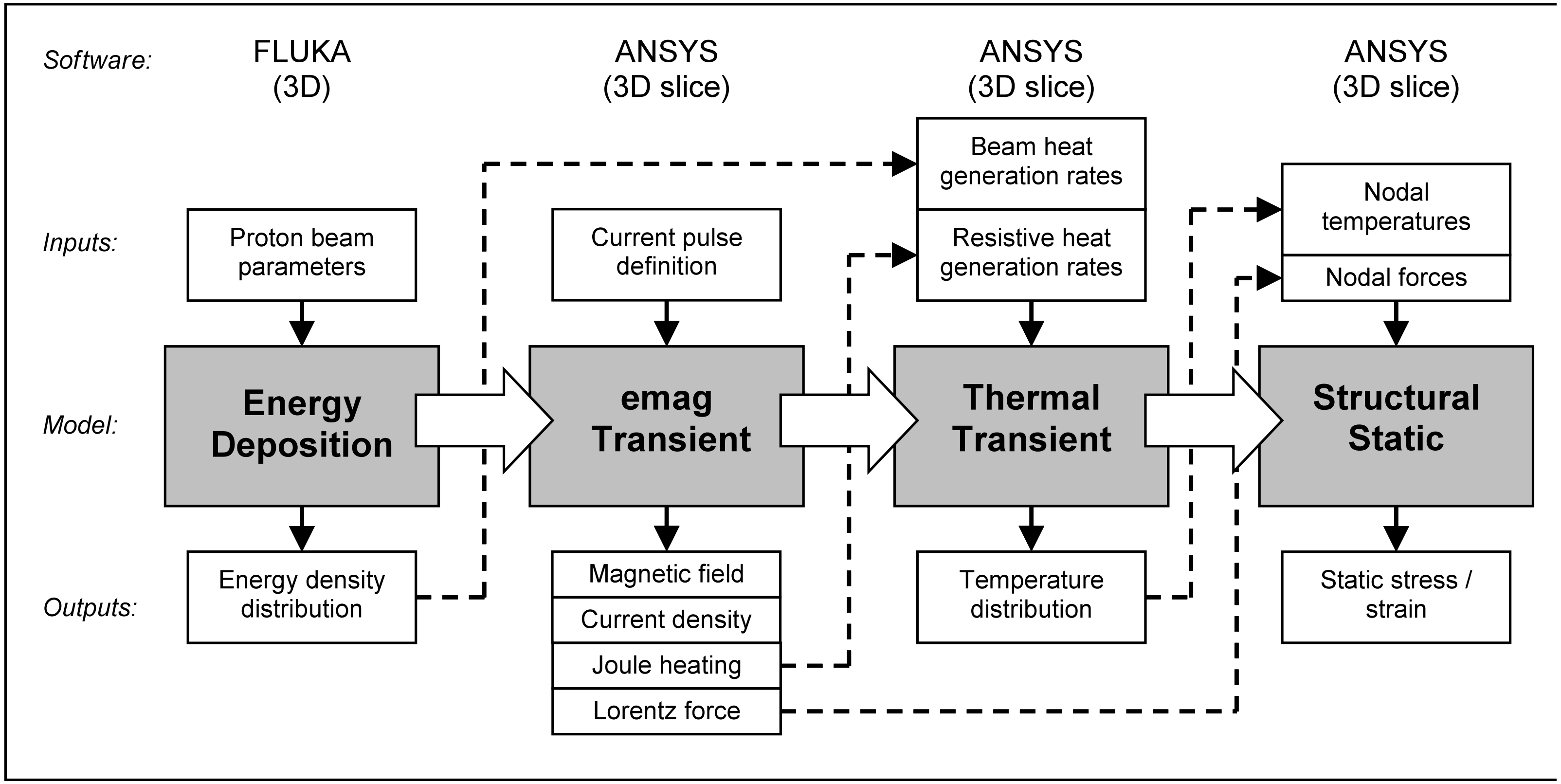
Total longitudinal force

$$F_{long} = \frac{\mu_0 I^2}{4\pi} \ln\left(\frac{R_2}{R_1}\right)$$

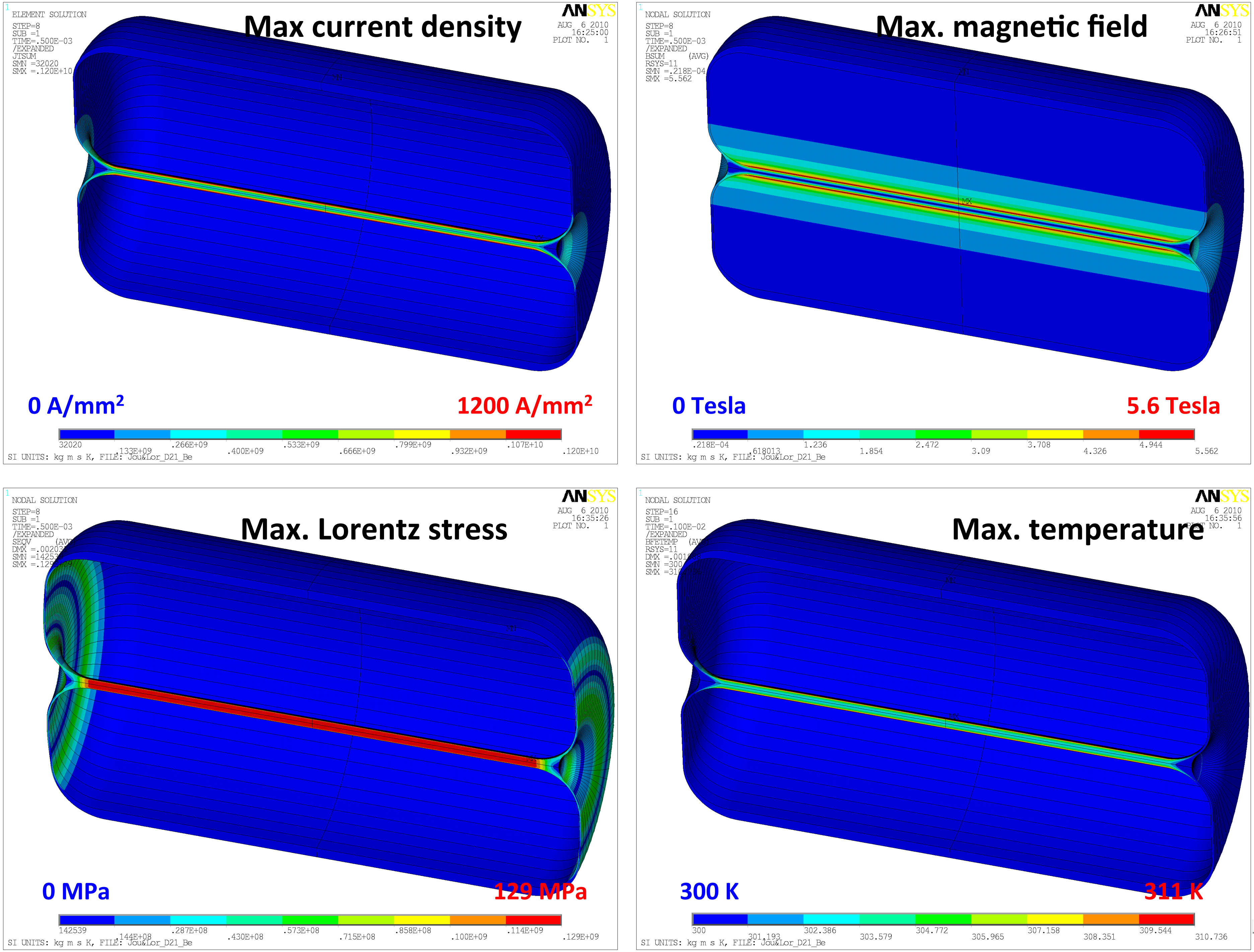


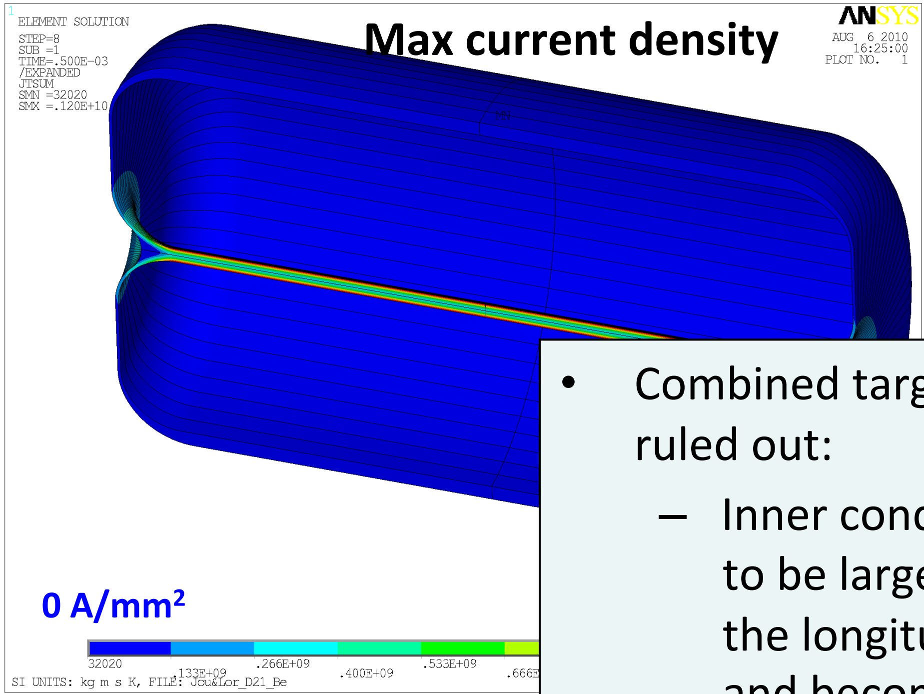
Multiphysics simulation

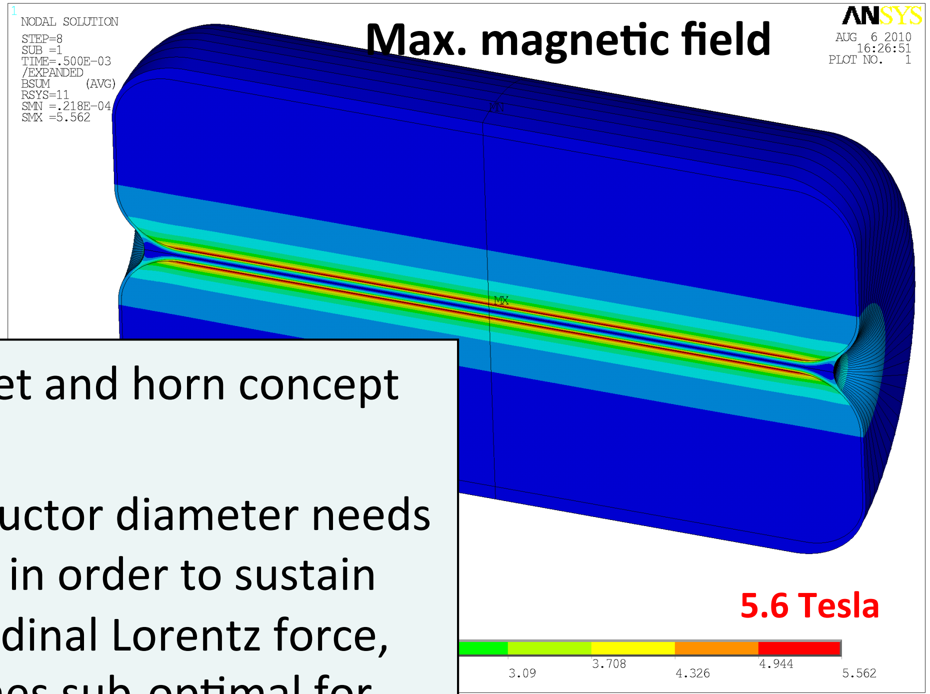
- ANSYS is well suited to multiphysics simulation
  - Can investigate the combination of effects from several different physics environments

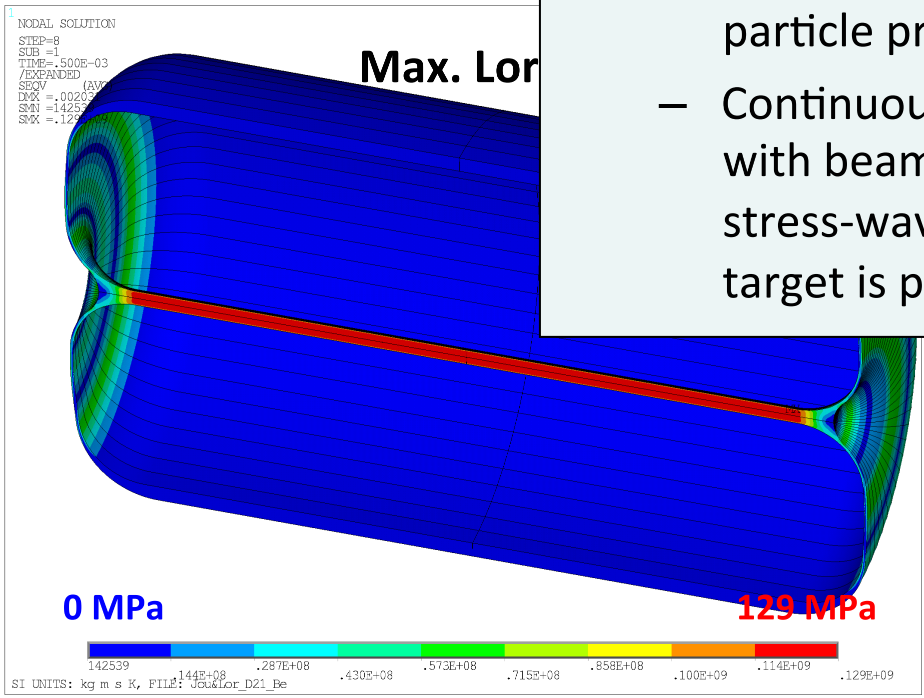


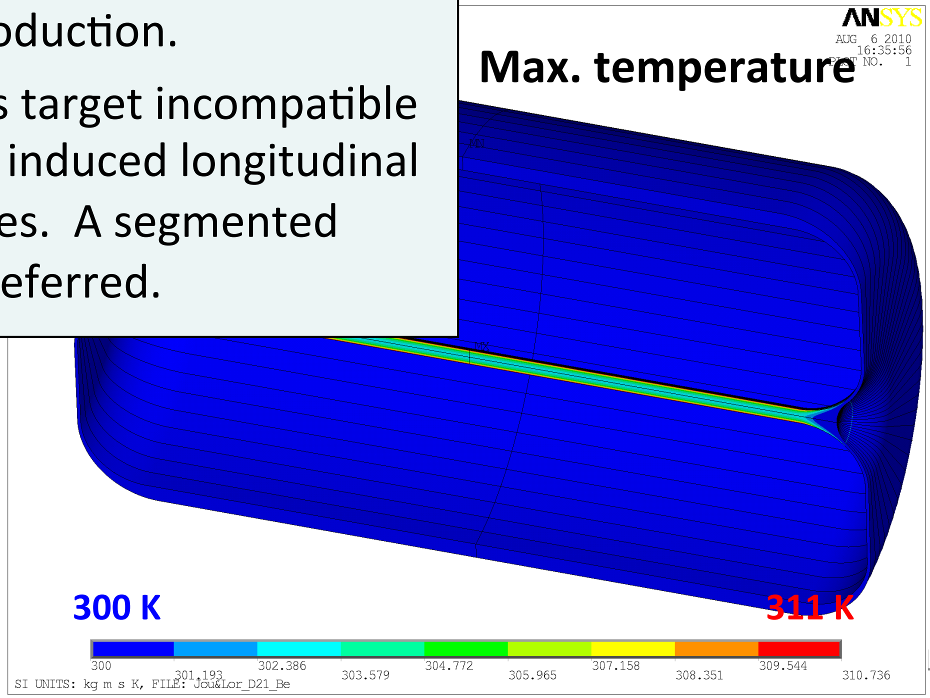
Procedure for magneto-thermo-structural analysis of a magnetic horn


Max current density
0 A/mm²
1200 A/mm²
32020
.133E+09
.266E+09
.400E+09
.533E+09
.666E+09
.799E+09
.932E+09
.107E+10
.120E+10
Max. magnetic field
0 Tesla
5.6 Tesla
.218E-04
.618013
1.236
1.854
2.472
3.09
3.708
4.326
4.944
5.562
Max. Lorentz stress
0 MPa
129 MPa
142539
.144E+08
.287E+08
.430E+08
.573E+08
.715E+08
.858E+08
.100E+09
.114E+09
.129E+09
Max. temperature
300 K
311 K
300
301.193
302.386
303.579
304.772
305.965
307.158
308.351
309.544
310.736
SI UNITS: kg m s K, FILE: Jou&Lor_D21_Be









- Combined target and horn concept ruled out:
  - Inner conductor diameter needs to be large in order to sustain the longitudinal Lorentz force, and becomes sub-optimal for particle production.
  - Continuous target incompatible with beam induced longitudinal stress-waves. A segmented target is preferred.

Summary

- RAL High Power Targets (HPT) group used a suite of simulation tools to study the proposed LBNE target system:
  - **FLUKA** *(MonteCarlo code)*
    - energy deposited in target components by the beam
    - optimisation of useful particle yield
  - **CFX** *(fluid dynamics code)*
    - Cooling options
    - conjugate heat transfer analysis
  - **ANSYS "classic"** *(Implicit FEA)*
    - Multiphysics magnetic, thermal, mechanical analyses
    - 'Long duration' dynamic simulations
  - **AUTODYN** *(Explicit FEA)*
    - 'Short duration' dynamic simulations