Thermo-Mechanical Analysis of ISIS TS2 Spallation Target

Dan Wilcox

High Power Targets Group, Rutherford Appleton Laboratory

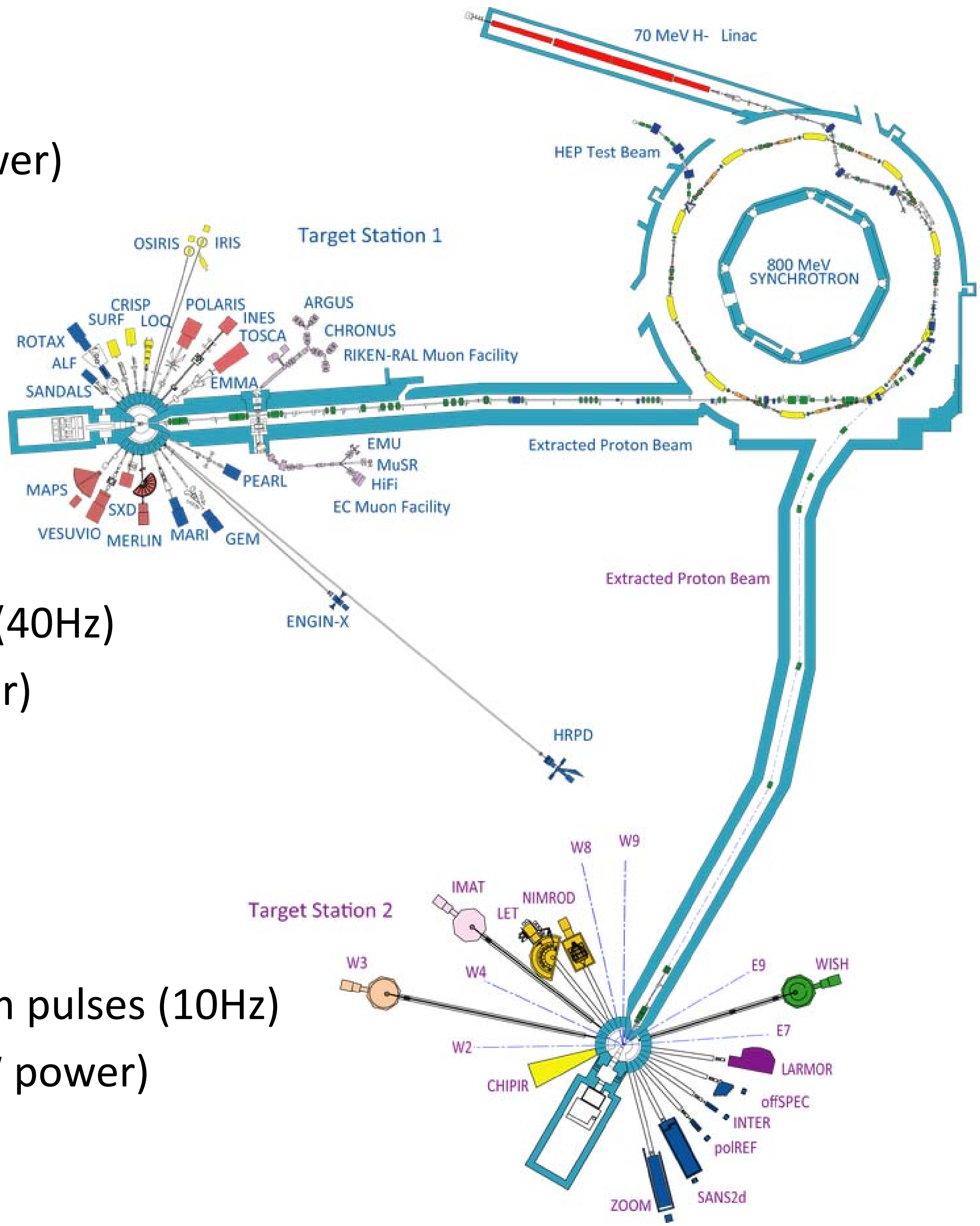
5th High Power Targetry Workshop, Fermilab

21/05/2014

ISIS Overview

Synchrotron

- 800MeV proton energy
- 200µA beam current (160kW power)
- Pulses at 50Hz



Target Station 1

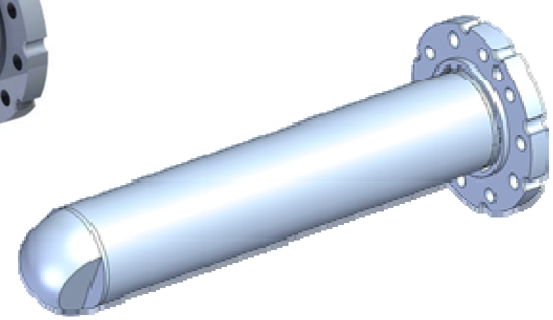
- Receives 4 of every 5 beam pulses (40Hz)
- 160µA beam current (128kW power)
- Target: tungsten plates

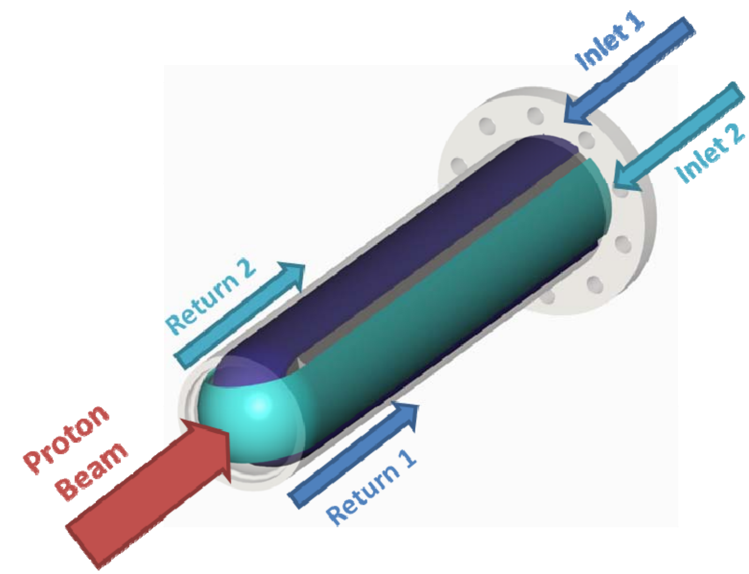
Target Station 2

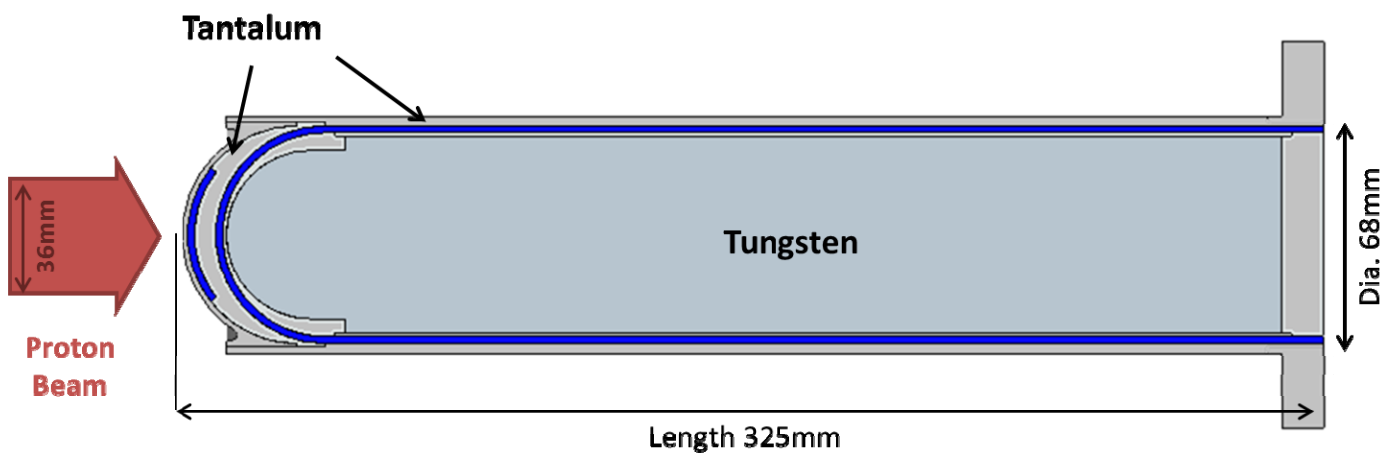
- Receives 1 of every 5 beam pulses (10Hz)
- 40µA beam current (32kW power)
- Target: solid tungsten rod

Background

- Aim: model the operating condition of the current ISIS TS2 target
  - Identify factors limiting target lifetime
  - Mk II target had to be replaced after radioactive material (thought to be tungsten) was detected in the cooling water
  - Inform design of future targets, e.g. TS1 upgrade







Overview of Beam-Induced Stresses

- Must also consider pre-stress from manufacturing methods

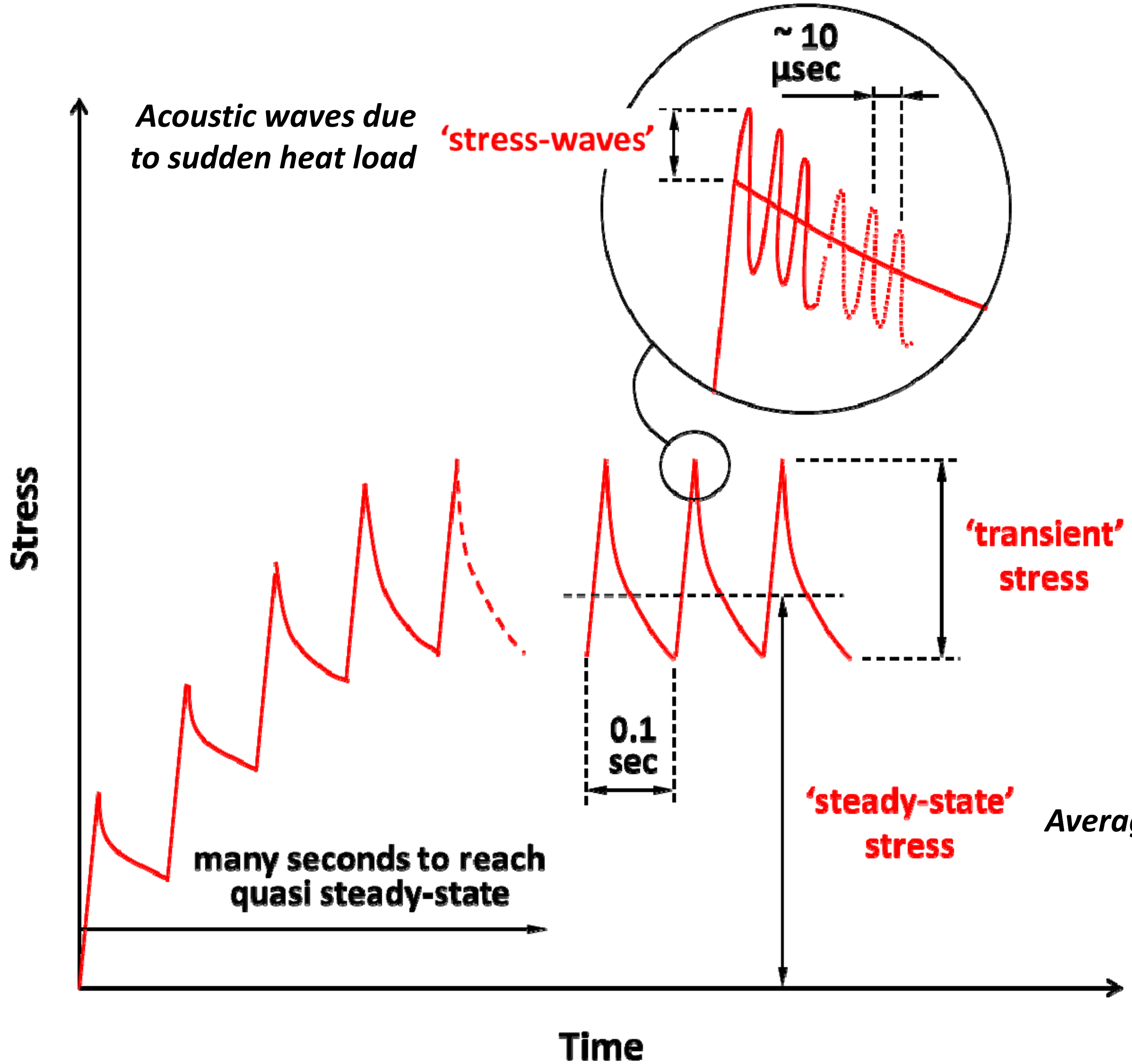
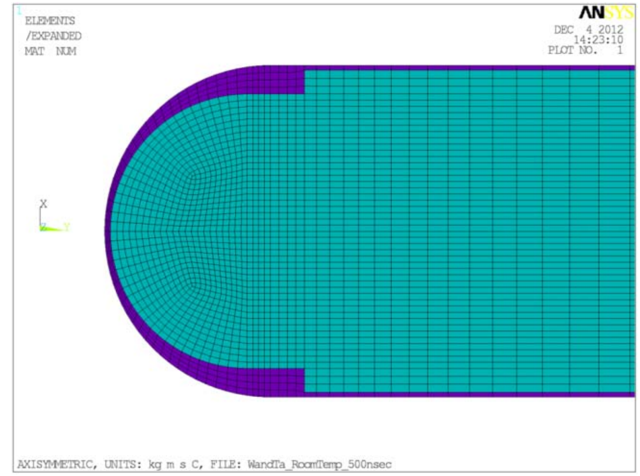
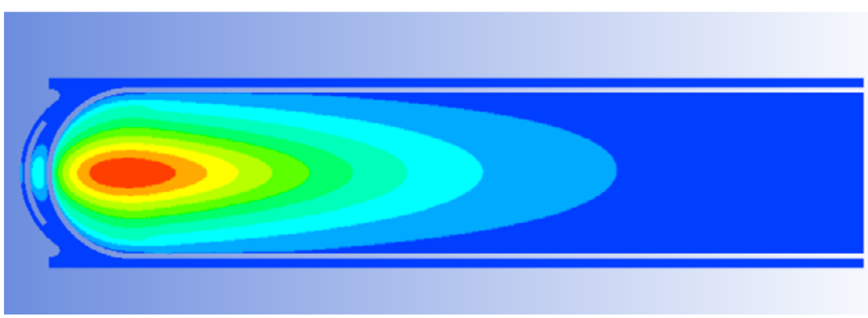


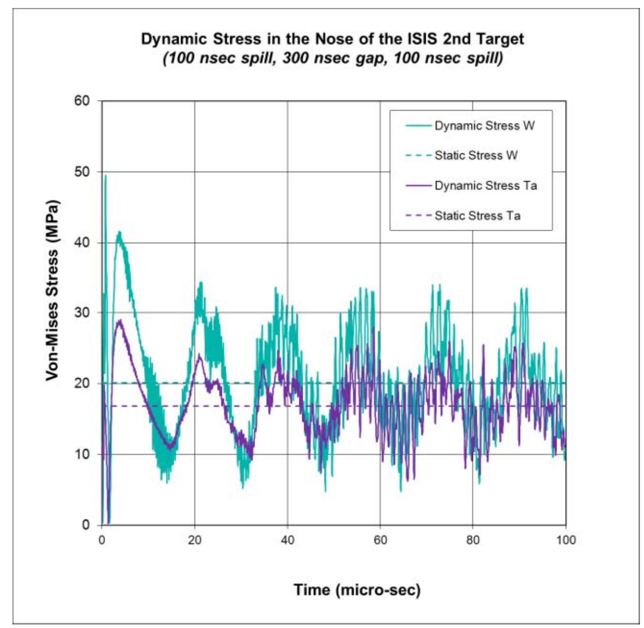
Image credit: Peter Loveridge, HPTG

Modelling Beam Stresses

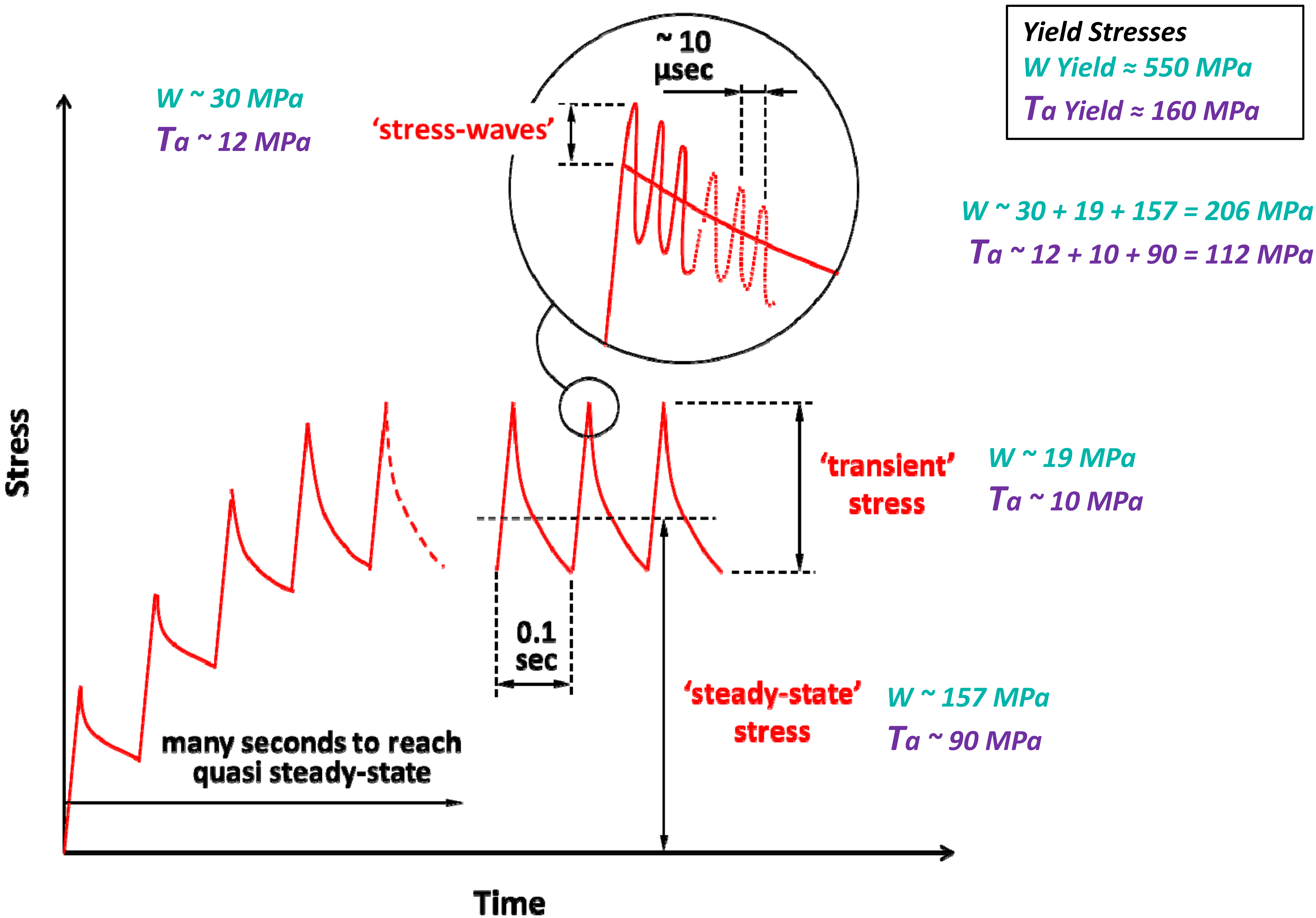
- Steady State and Transient
  - Full 3D geometry
  - Conjugate heat transfer for steady state
  - HTC assumed constant during transient model
  - Thermal results input to structural model
- Stress waves
  - 2D model in ANSYS Classic, many time steps required
  - Inertia effects included (dynamic stress response)







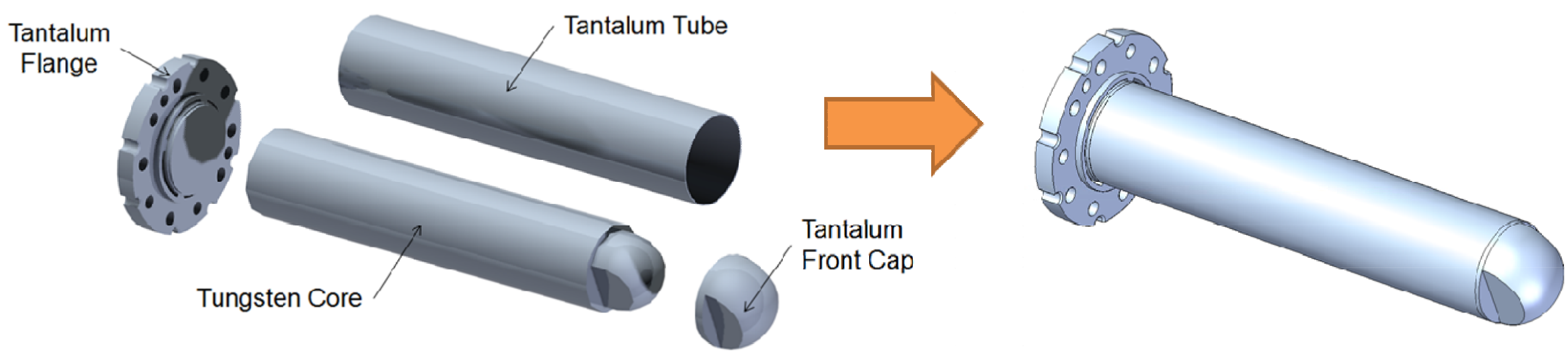
Summary of Stress Results at the Target Nose



Pre-Stress: the HIP Process

- Hot Isostatic Press (HIP) used to diffusion bond tantalum to tungsten
  - Tungsten core sealed inside tantalum 'can'
  - Assembly heated to ≈1200°C
  - Pressure of ≈140MPa applied to force parts together until they bond
  - Gradually returned to room temperature and pressure, then machined to final size

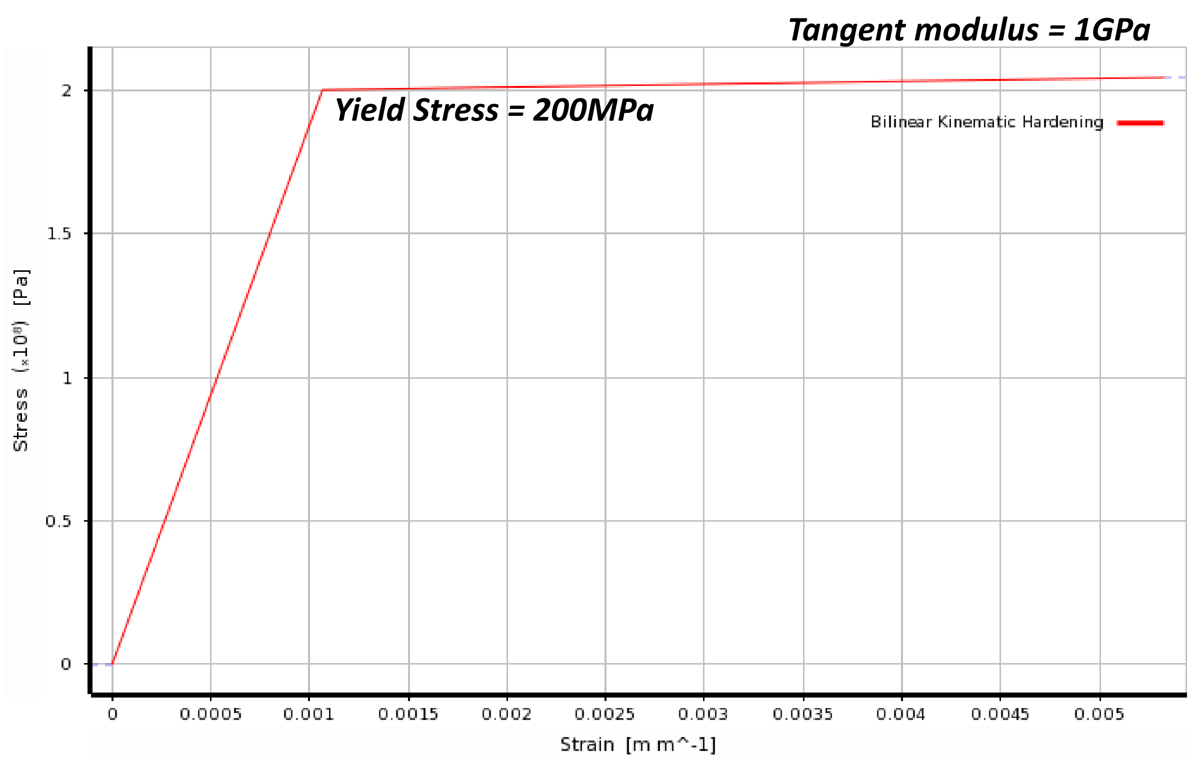
- Results in significant pre-stress
  - High pressure deforms tantalum can, but this occurs above annealing temperature
  - Cooling causes shrink-fit residual stress (tantalum contracts more than tungsten)
  - Stresses thought to 'lock in' at around 500°C
  - Heating in an impure environment will affect material properties – getter foils will reduce but not eliminate this



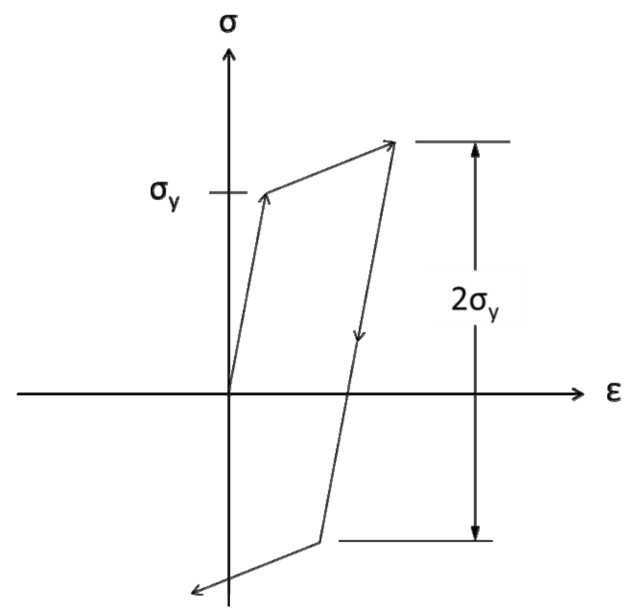
Components of HIP assembly

Including Plasticity

- Bilinear material model applied for tantalum
- 'Kinematic Hardening' behaviour selected
  - An increase in yield stress in one direction is compensated for by a decrease in yield strength in the opposite sense (Bauschinger effect)
  - The total linear stress range is equal to twice the yield stress



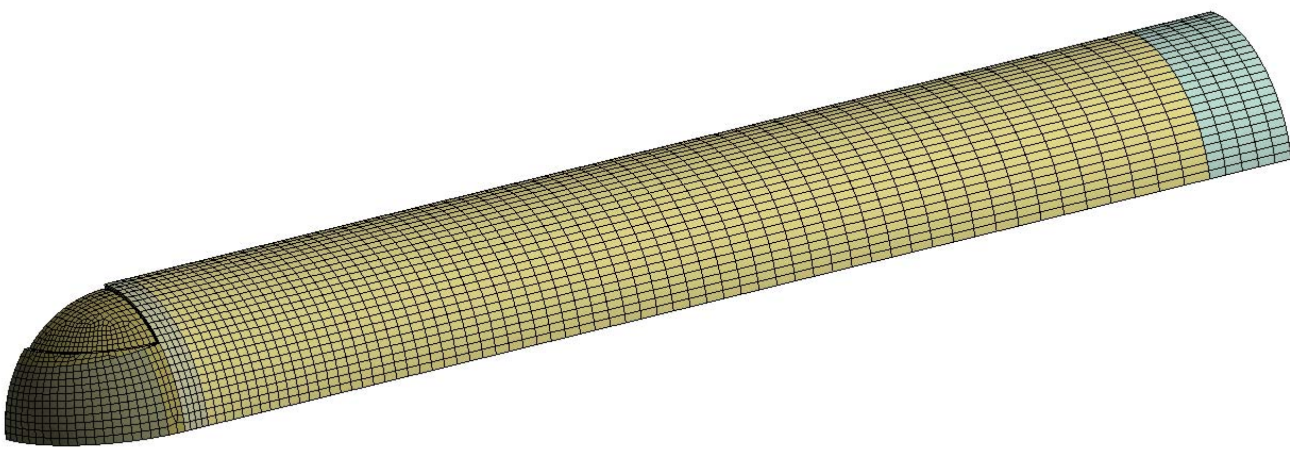
ANSYS material property "Bilinear Kinematic Hardening"

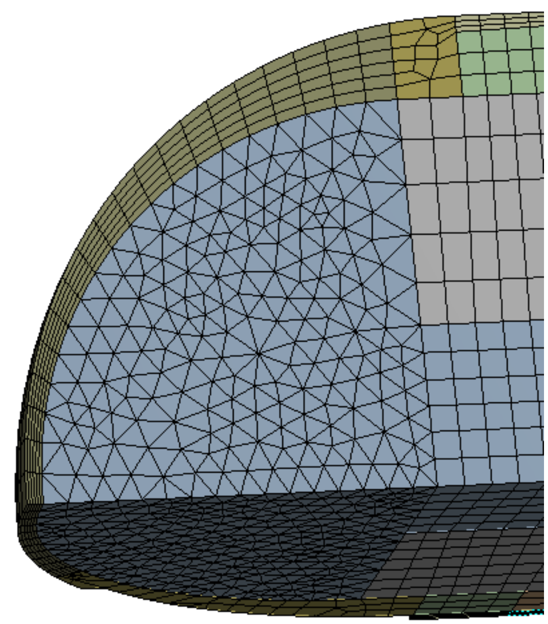


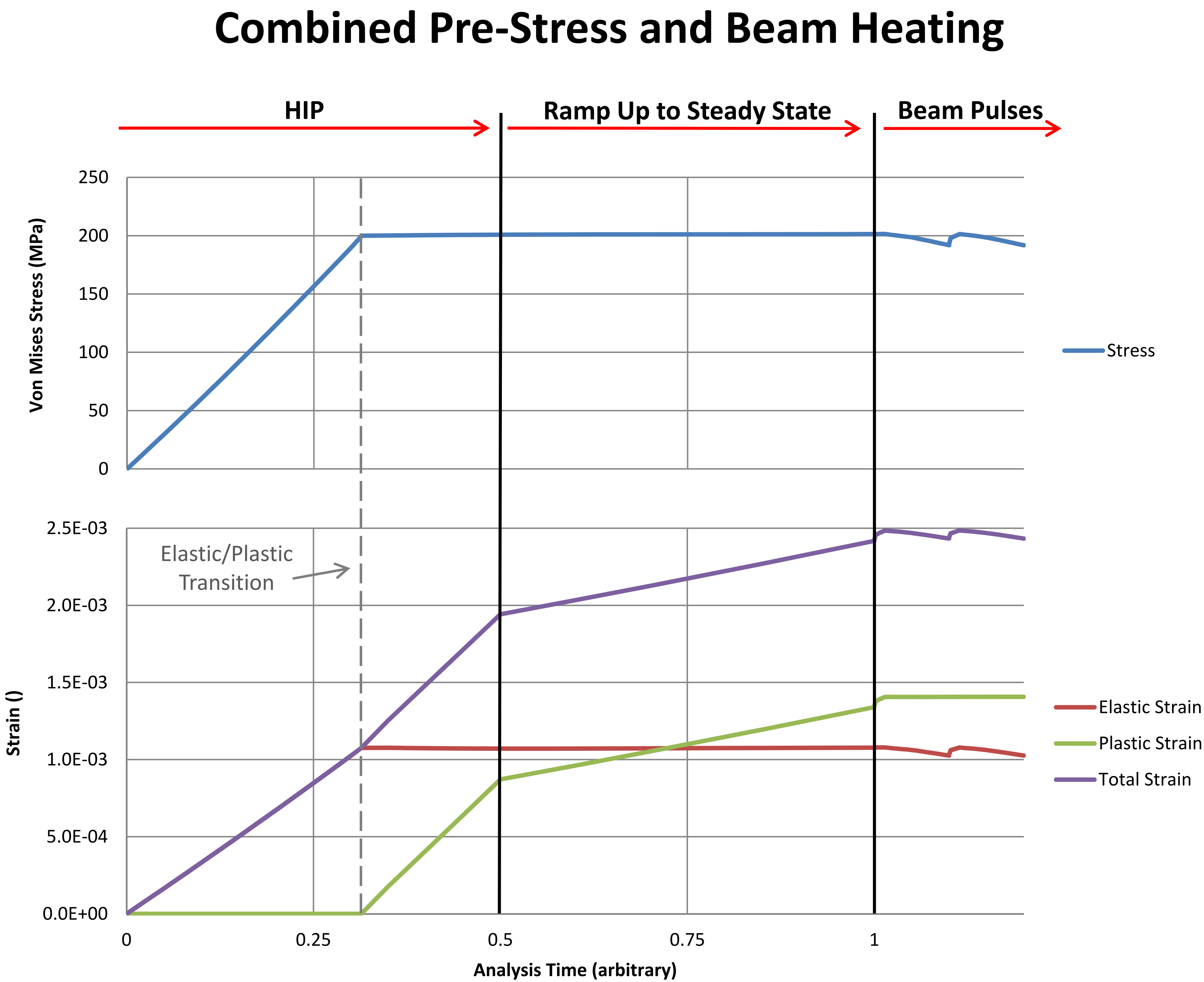
Kinematic Hardening Model

Combined Pre-Stress and Beam Heating

- 3D geometry in ANSYS Mechanical – target core only
- Stress wave effects were not included
- Assuming HIP does not affect heat transfer properties, thermal results do not change
- Static structural model with multiple load steps:
  1. The model starts in an unstressed state at 500°C
  2. A body temperature of 20°C is applied – resulting in HIP stress
  3. The model is heated to the steady state temperature
  4. Two beam pulses are applied

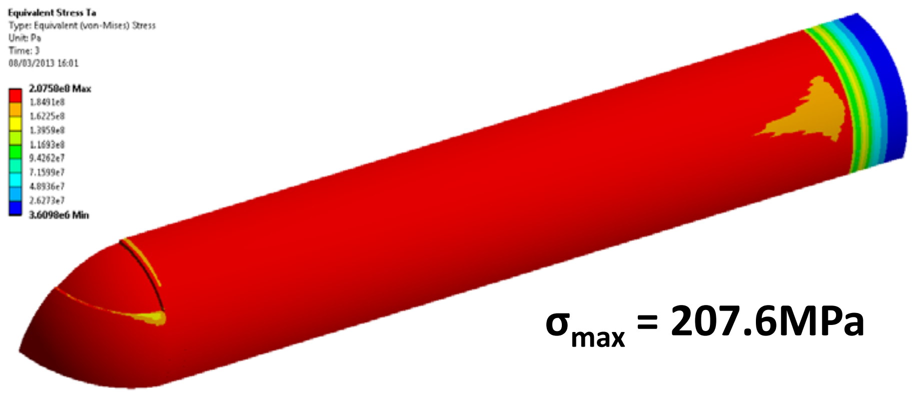




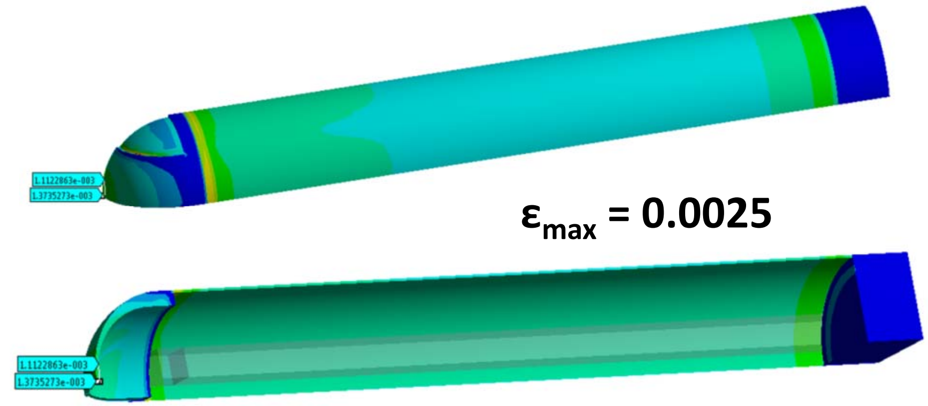


Stress and strain components at the target nose

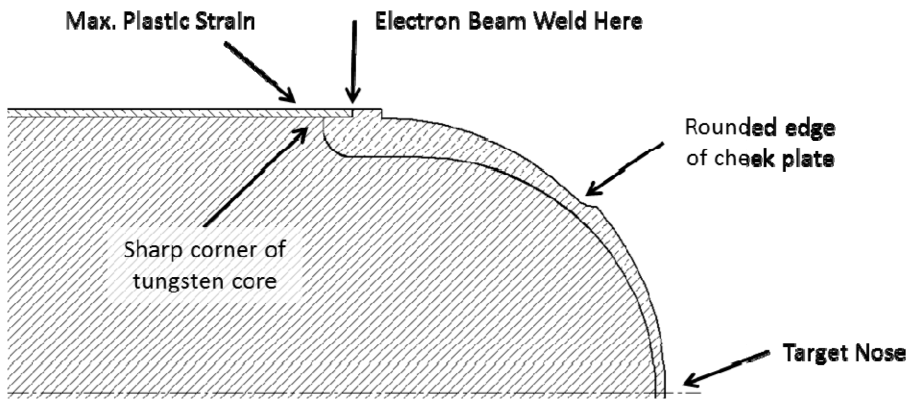
Steady State Results with Pre-Stress



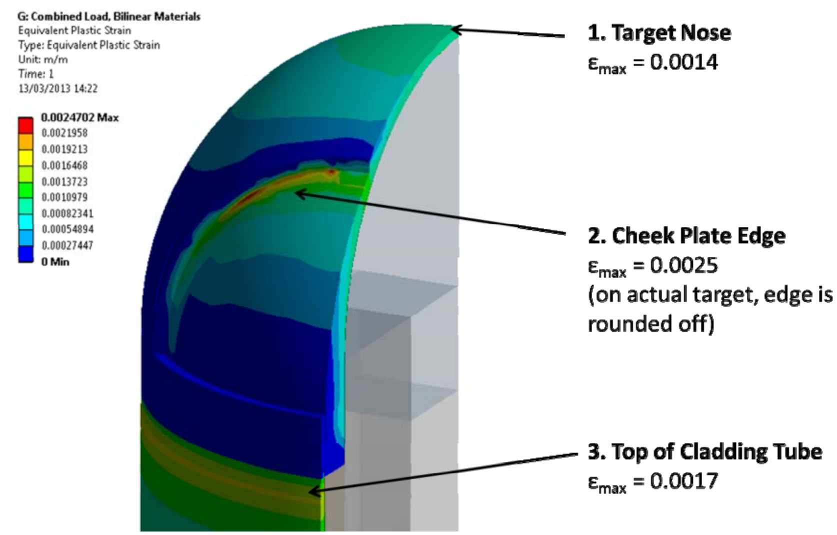
Von Mises Stress in Tantalum



Equivalent Plastic Strain in Tantalum



Geometry features around cladding front end

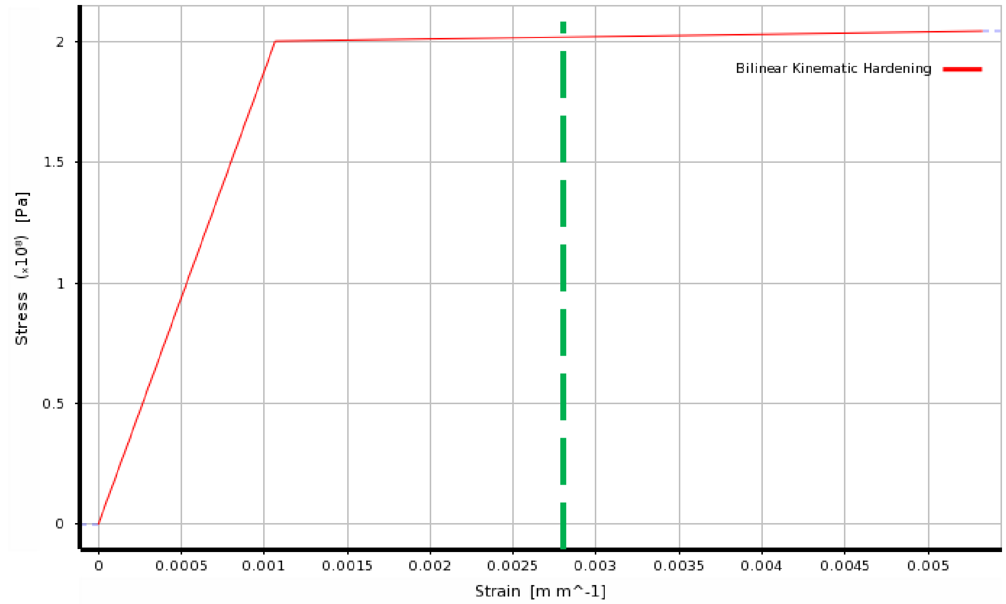


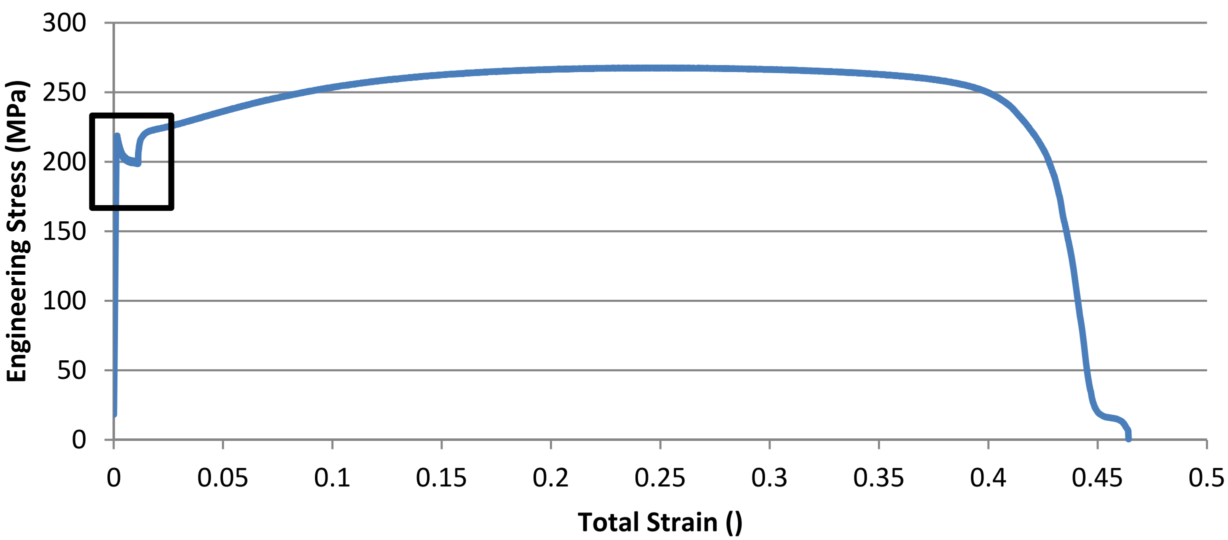
Areas of maximum steady state plastic strain

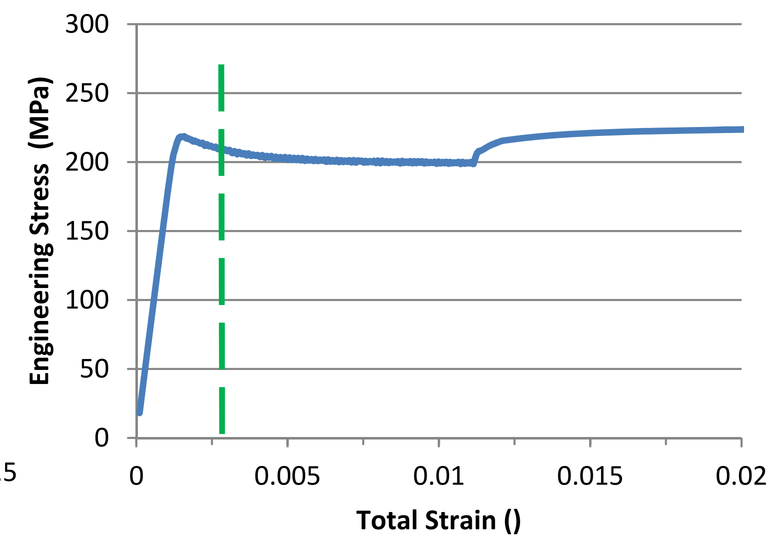
Steady State Plastic Strain

In cladding tube:
Elastic strain = 0.0011
Plastic strain = 0.0017
Total strain = 0.0028 (0.28%)

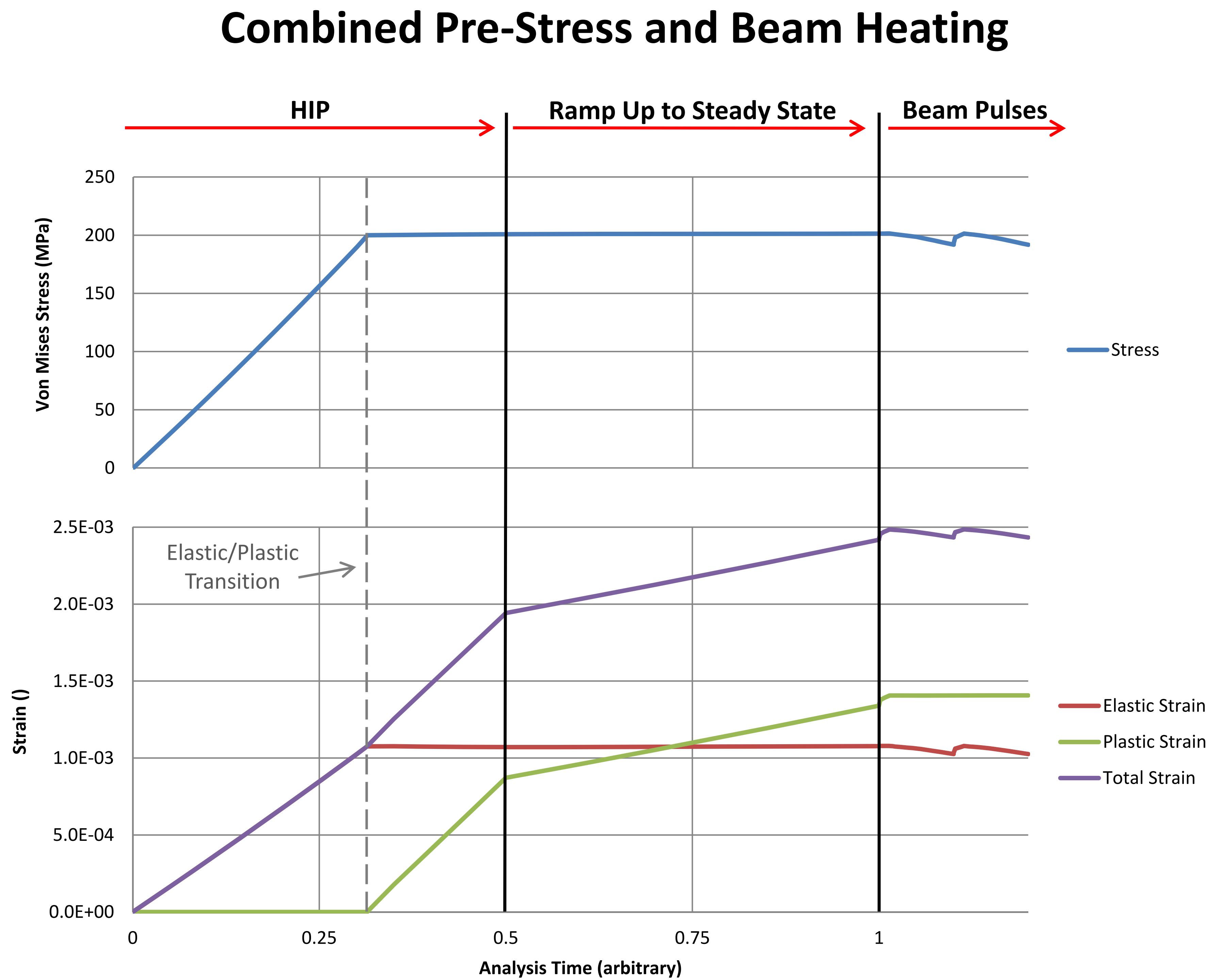
- *Not enough to cause structural failure*





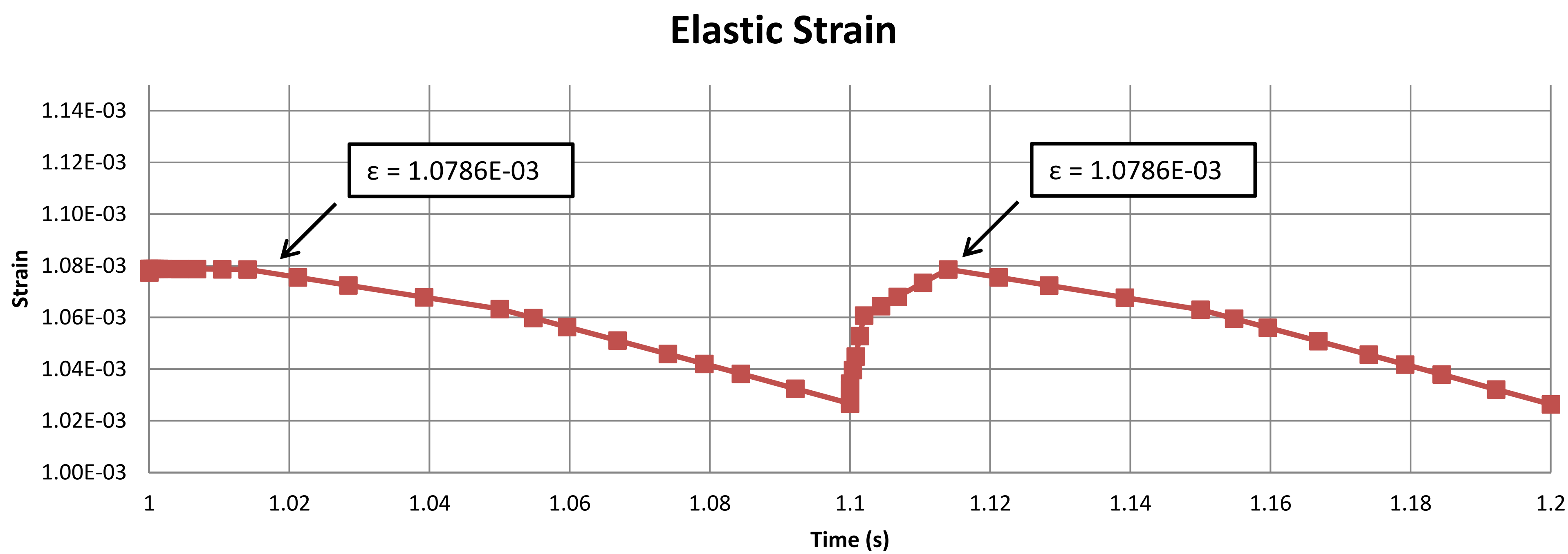


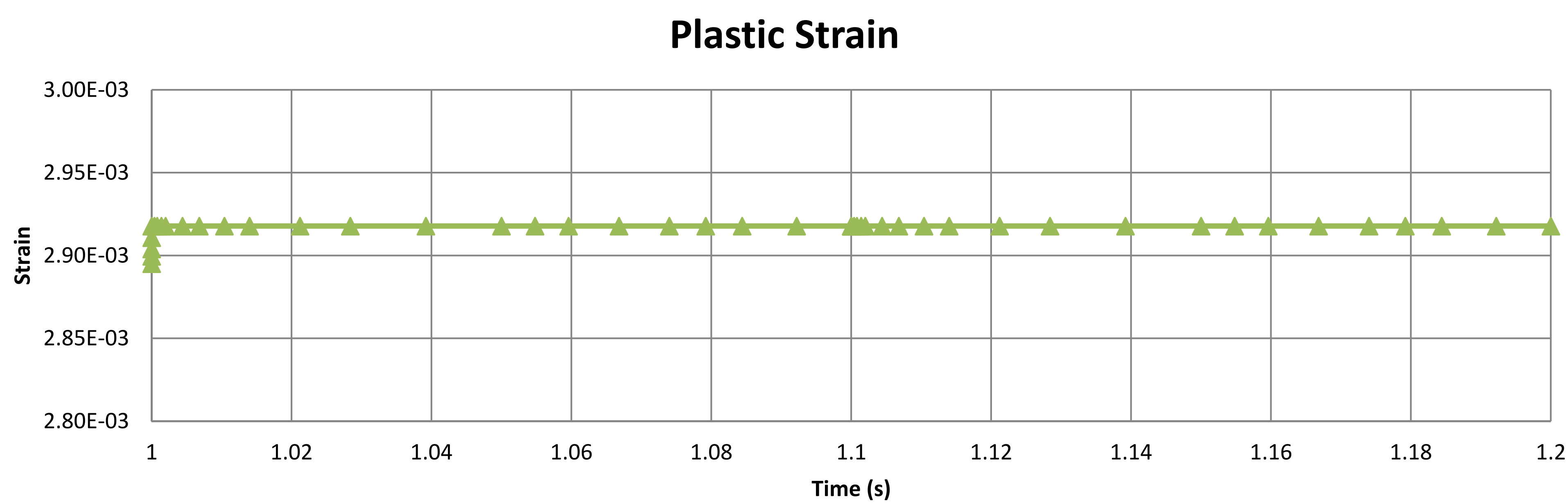
Tensile test data for post-HIP Tantalum, carried out by Eamonn Quinn of ISIS



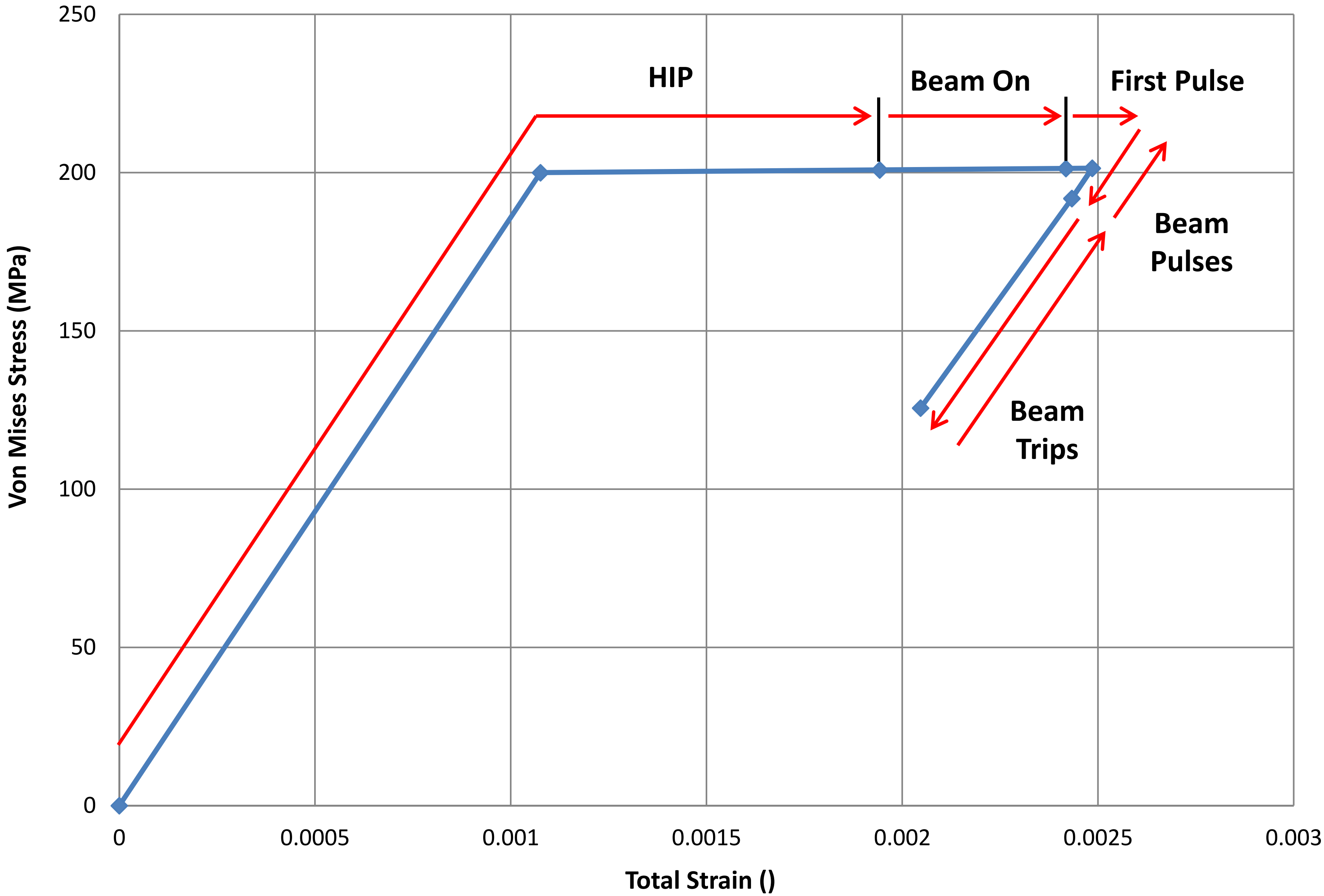
Stress and strain components at the target nose

Strain Components During Pulsed Operation



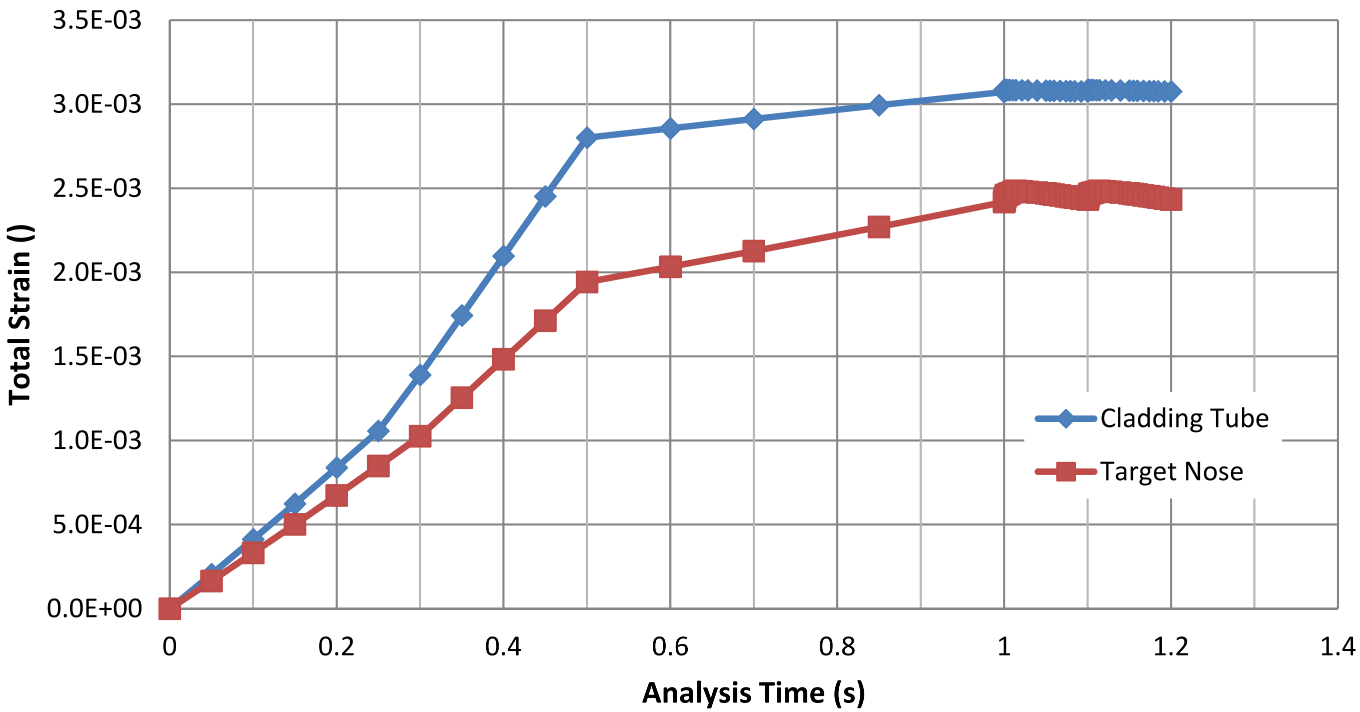


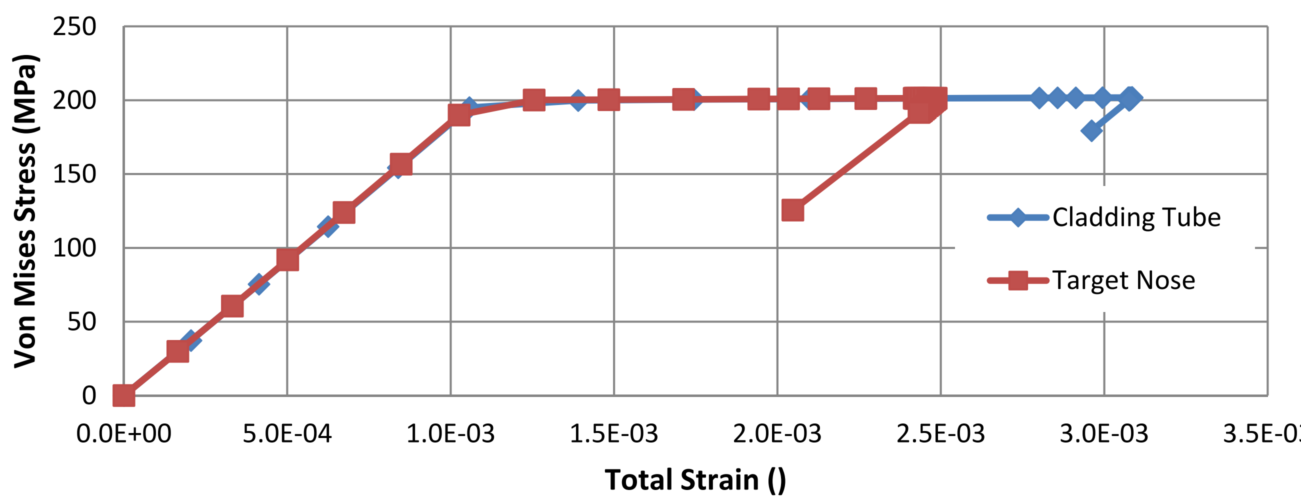
Transient Model with Pre-Stress and Bilinear Materials



Stress/strain plot at the target nose

Comparison of Cladding Tube and Target Nose



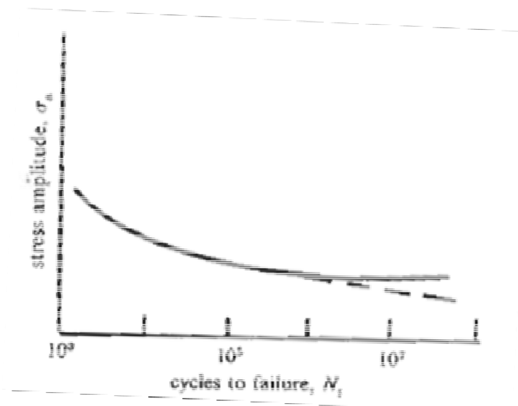


Fatigue Analysis

- ISIS beam data suggests there are 0.6 beam trips per hour, or one trip every 60000 pulses
  - Number per year estimated based on frequency and average facility uptime

Load Case	*Beam Pulse*	*Beam Trip*
Frequency [Hz]	10	0.00017
Number Per Year	134,000,000	2230

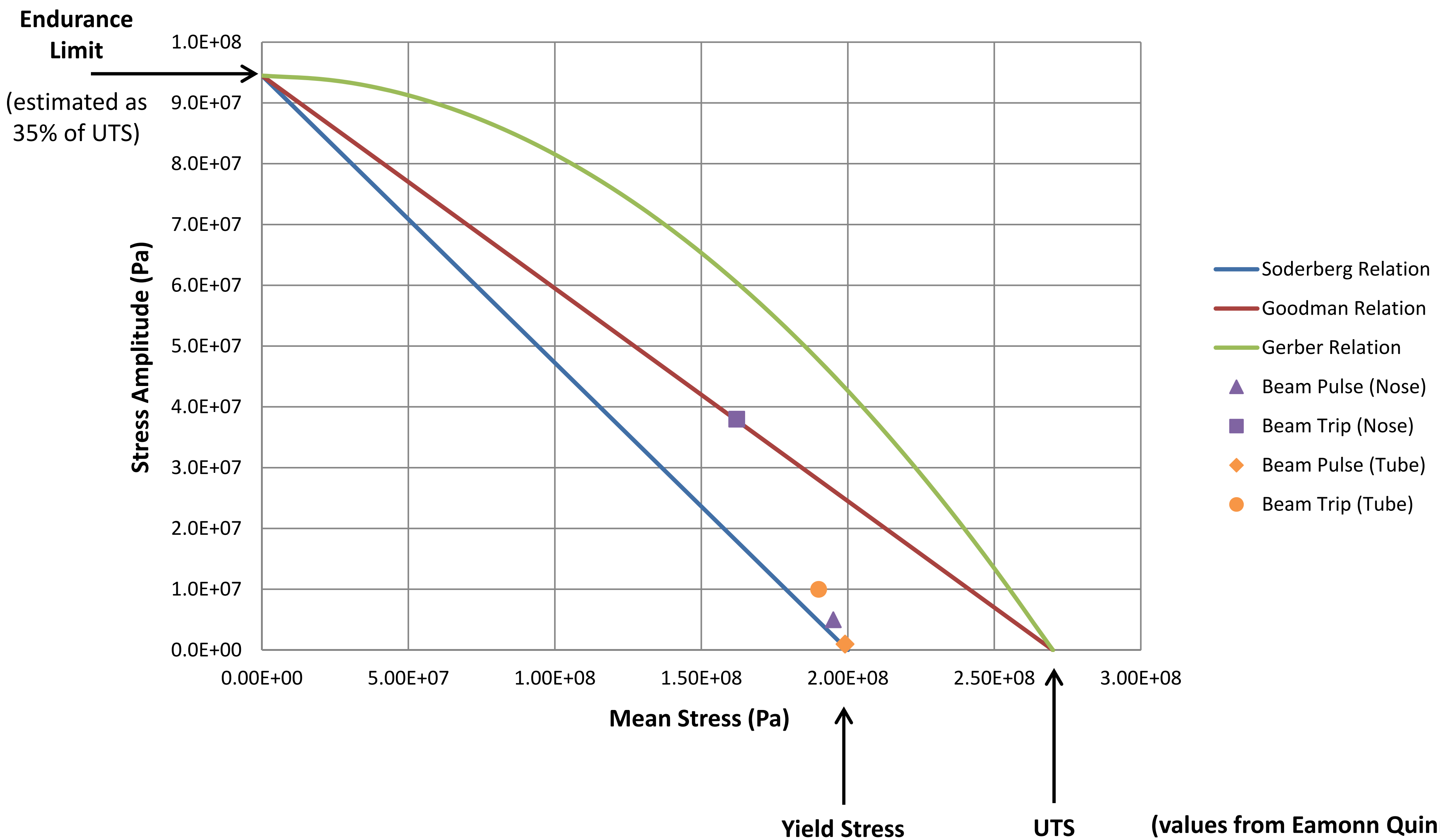
- Stress waves ignored - material response is different on microsecond timescales



- Based on a simple total-life approach
  - Assumes an initially uncracked surface
  - Stress-life (high-cycle) fatigue

- Stress amplitudes are low, but average stresses are very high
  - Use a constant life diagram to see if this will be a problem

Constant Life Diagram



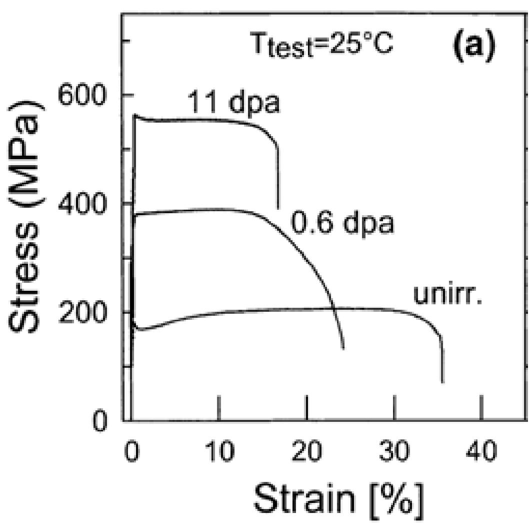
(values from Eamonn Quinn's tests on HIPed Ta samples)

Stress amplitude = Δσ/2
Mean stress = yield stress − Δσ/2

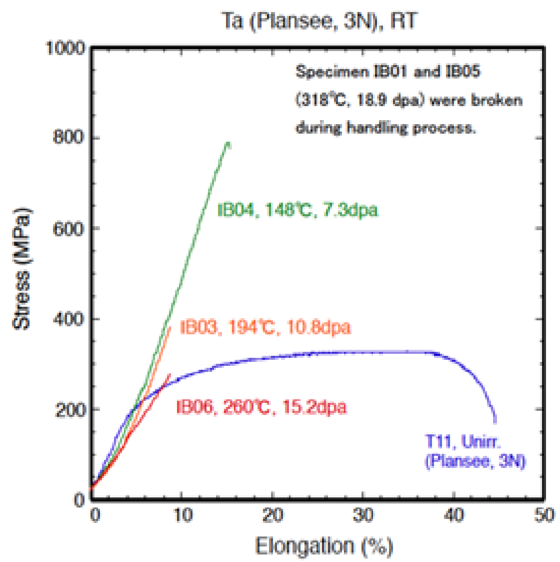
Fatigue Analysis - Limitations

- Difficult to draw conclusions due to lack of material property data
  - No data could be found for tantalum fatigue
  - Very limited irradiation data
  - What will happen to HIPed, yielded, irradiated tantalum under periodic loading?

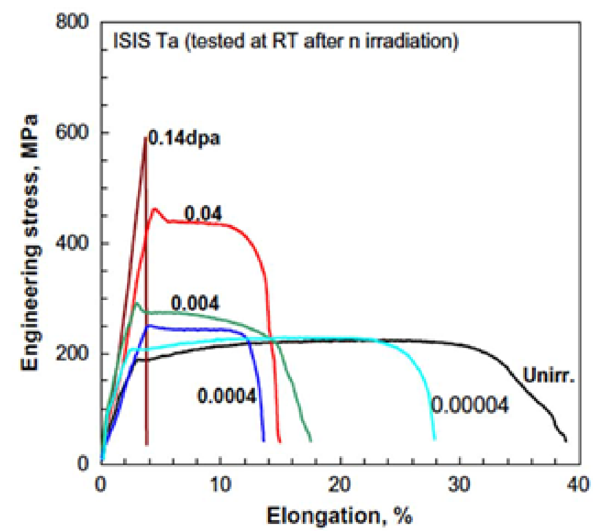
- The effect of stress waves is still unknown
- Are we including plastic effects in the right way?
- Stress concentration on cladding tube



ISIS target cut up at FZ-Juelich



Specimen from STIP-II at PSI



Neutron irradiated specimen from HFIR at ORNL

Conclusions on TS2 Target

- HIP pre-stress looks like the most significant stress component
  - This will be validated against experiments on the ISIS instrument Engin-X, data analysis is currently underway

- Current theory is that fatigue failure of tantalum cladding will be the limiting factor of target lifetime
  - Tensile pre-stress and radiation embrittlement will make the fatigue situation worse
  - Irradiation creep and stress relaxation may reduce the average stress?
  - TS1 has much lower periodic loading, and has proven very reliable
  - Stress concentration on cladding tube will be removed on future targets

- Beam accident case is another possible explanation
  - Current instrumentation will not immediately detect an over-focused beam
  - Thought to be more of a risk for TS1 than TS2

- Understanding is limited by availability of material property data
  - There are spent ISIS targets available for PIE

Relevance to TS1 Upgrade

- Aim: Design a target which combines the neutronic performance of TS2 and the reliability of TS1
  - Designed in collaboration with ISIS Neutronics and ISIS Target Engineering
- Reliability is the top priority
- Neutronic optimisation goals include thinner cladding and fewer plates
  - Difficult to set material limits without fully understanding the operating condition of current targets
  - Better understanding of current target issues will ultimately allow for more highly optimised targets in future