Lifetime Assessment – An Overview of Solid Target Modeling from Neutronics through Fatigue

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Target Simulations Workshop

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Background

Parameter	LANSCE MkIII [1]	ISIS TS1 [2]	ISIS TS2 MkI [3]	ISIS TS2 MkII [4]	STS
Power (kW)	80	160	36	32	700
Energy (GeV)/proton	0.8	0.8	0.8	0.8	1.3
Frequency, f (Hz)	20	40	10	10	15
Average current (μA)	100	200	45	40	538
Protons/pulse, N_p (10^{14})	0.312	0.312	0.281	0.250	2.241
Gaussian horizontal, σ_x (mm)	15.0	16.3	6.0	6.0	74.4
Super Gaussian, n_x	2.0	2.0	2.0	2.0	3.9
Gaussian vertical, σ_y (mm)	15.0	16.3	6.0	6.0	19.8
Super Gaussian, n_y	2.0	2.0	2.0	2.0	4.0
Peak protons/m^2/pulse, I_0 (10^{16})	2.2	1.9	12.4	11.0	3.3
Peak Current Density, J (μA/cm^2)	7.1	12.0	19.9	17.7	7.8
Peak heating (MW/m^3)	246	441	600	600	21
Peak energy per pulse (MJ/m^3/pulse)	12.3	11.025	70	70	29.7
Ta clad thickness (mm)	0.25	2	1	1	1
Ta peak temperature (°C)	161	100	480	~100	110
W peak temperature (°C)		177	475	250	136
W peak steady stress (MPa)		200		157	133
W peak total stress (MPa)				206	173
Lifetime (years)	>10	~4.5	1.25	~1.5	10
Uptime	0.27	0.45	0.45	0.51	0.57
Beam pulses	1.69E+09	2.55E+09	1.75E+08	2.37E+08	1.29E+08

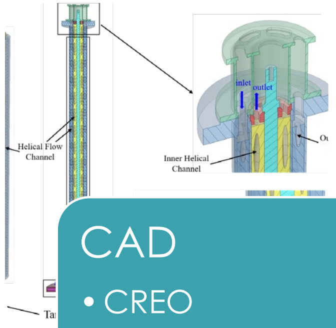
[1] Eron Kerstiens, Personal Communication, January 2021.
& Eric Olivas, "1L Target Mark III – Upper Target Production Run Conditions," LANL, 03/08/2018

[2] Dan Wilcox, IWSMT-13, 02 November 2016.
& T. Davenne, "Heat Flux and Stress Limits of the existing TS1 target with reference to future proposed upgrades," Oct. 2012.

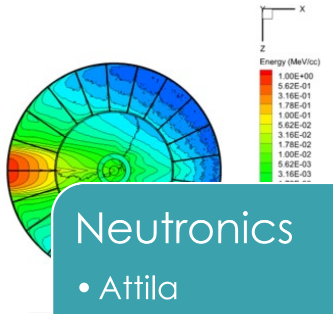
[3] Wilcox et al., J Nuc Matls, 2018.
& Mike Parkin, "ISIS Target Station 2: Target Mark 1 Front End Failure," High Power Targets Group, August 2019.

[4] Dan Wilcox, "Thermo-mechanical Analysis of ISIS TS2 Target," High Power Targets Group, August 2013.
& Dey and Jones, J Nuc Matls, 2018.

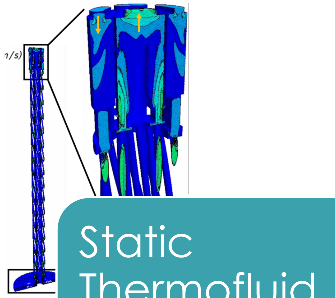
Analysis Process



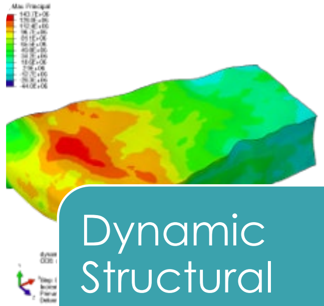
CAD
- CREO
- ANSYS SpaceClaim



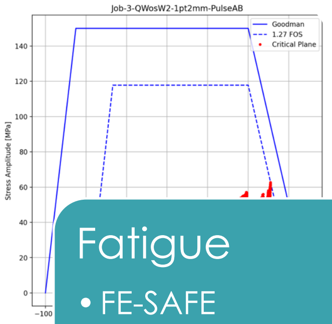
Neutronics
- Attila
- MCNP



Static Thermofluid
- STAR-CCM+

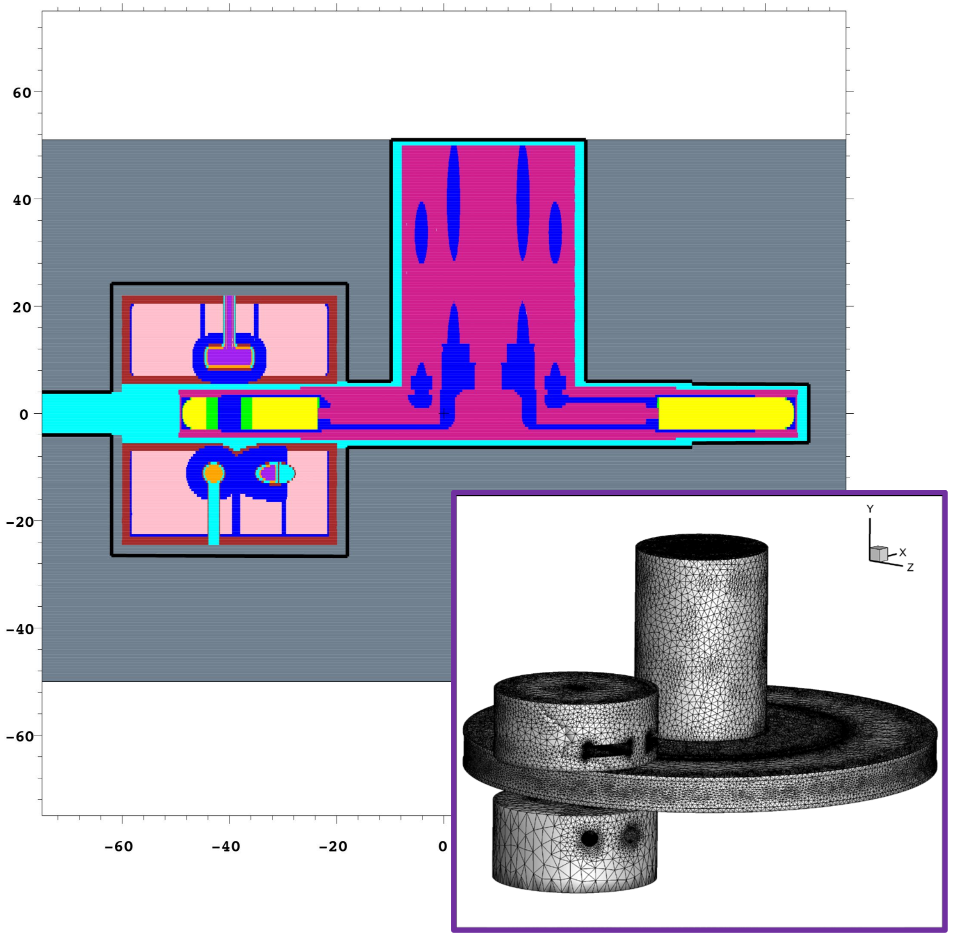


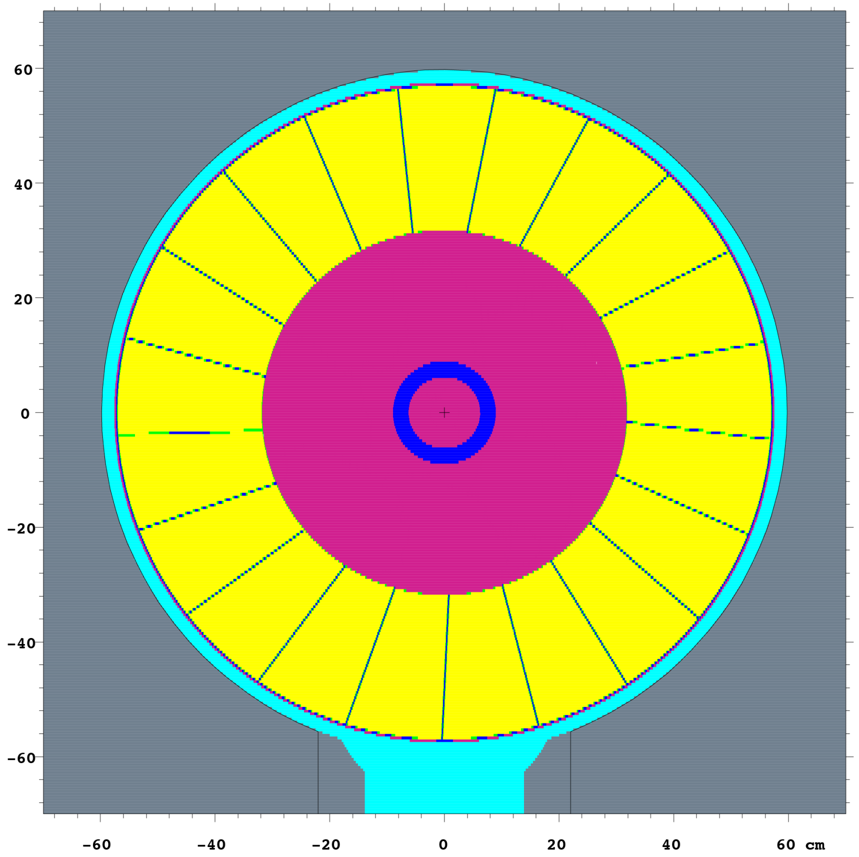
Dynamic Structural
- Abaqus | Explicit



Fatigue
- FE-SAFE

Neutronics





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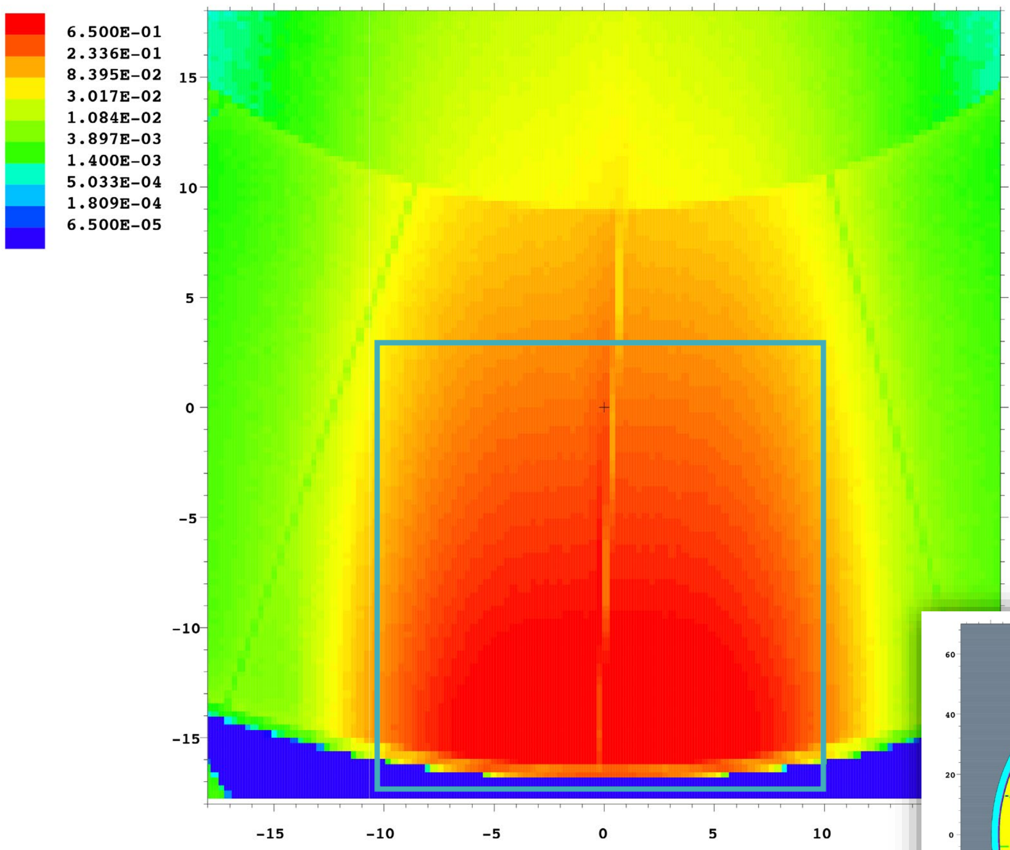
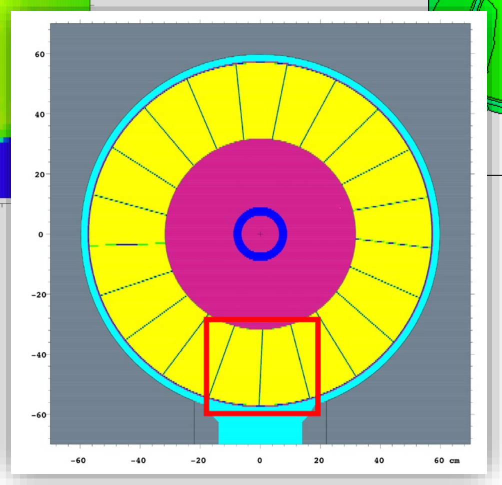
Images Courtesy of L. Zavorka

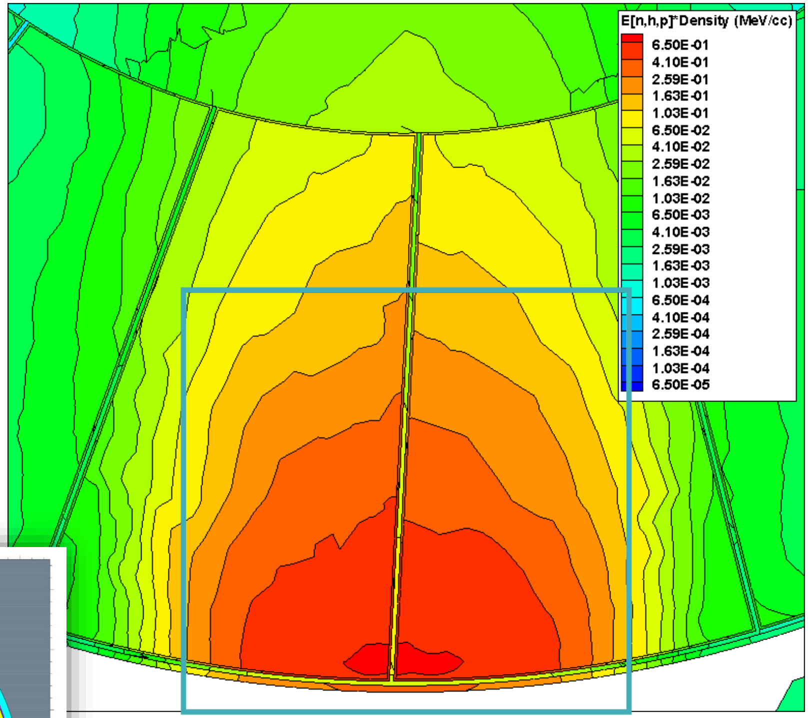
Neutronics

Constructive Solid Geom. / DAGMC





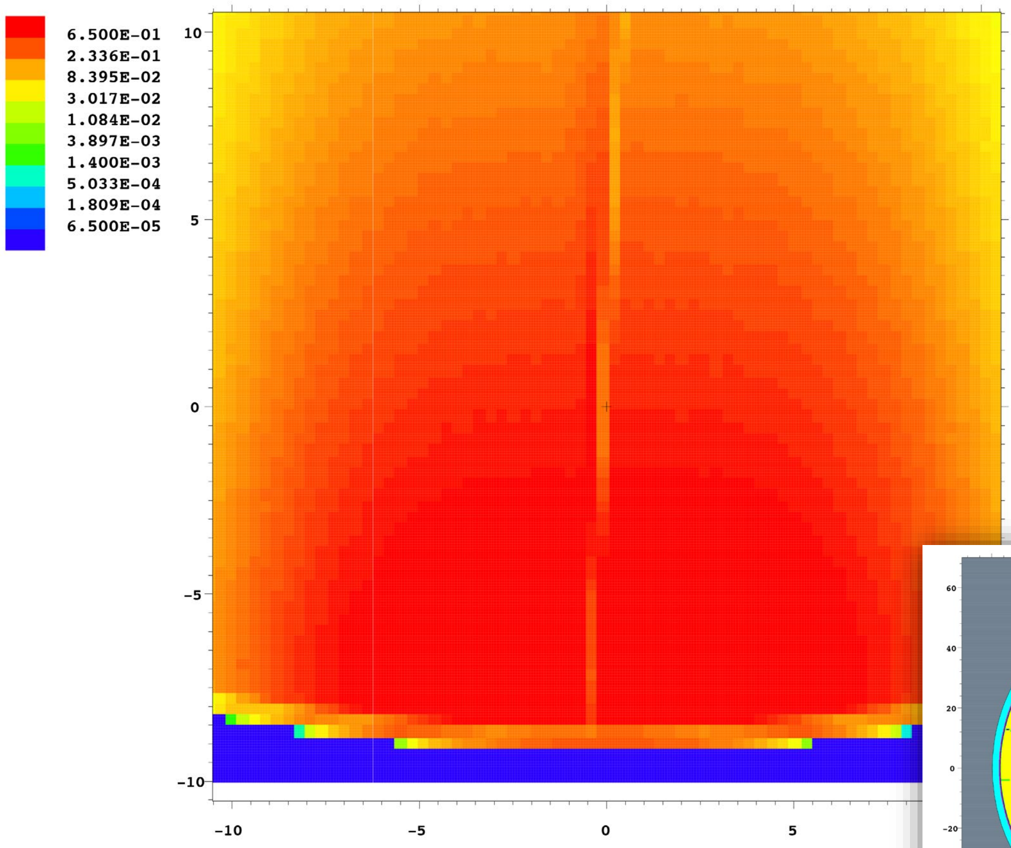
Attila Unstructured Mesh

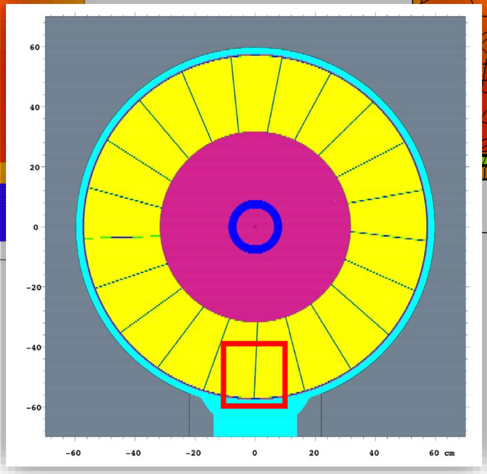


Images Courtesy of L. Zavorka

Neutronics

Constructive Solid Geom. / DAGMC





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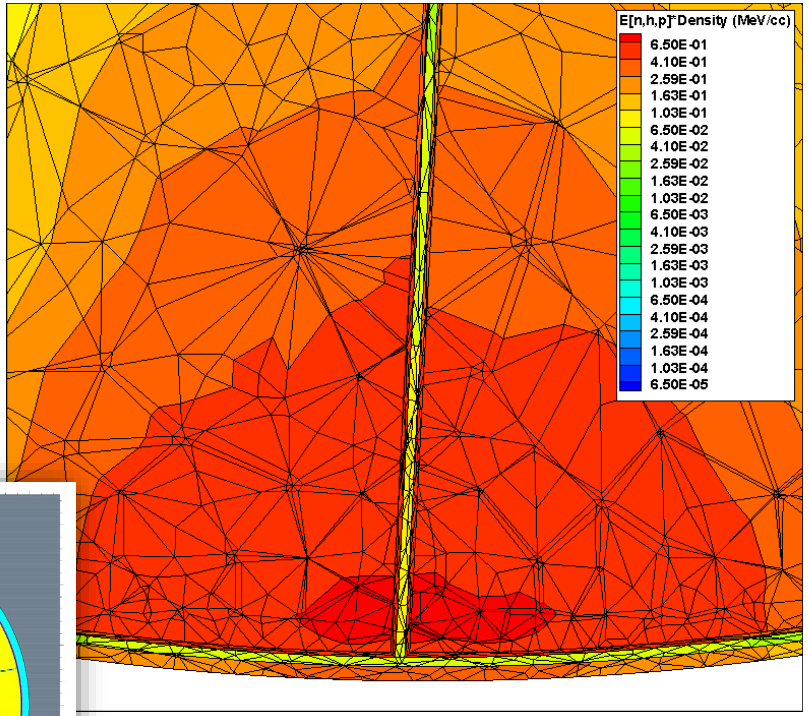
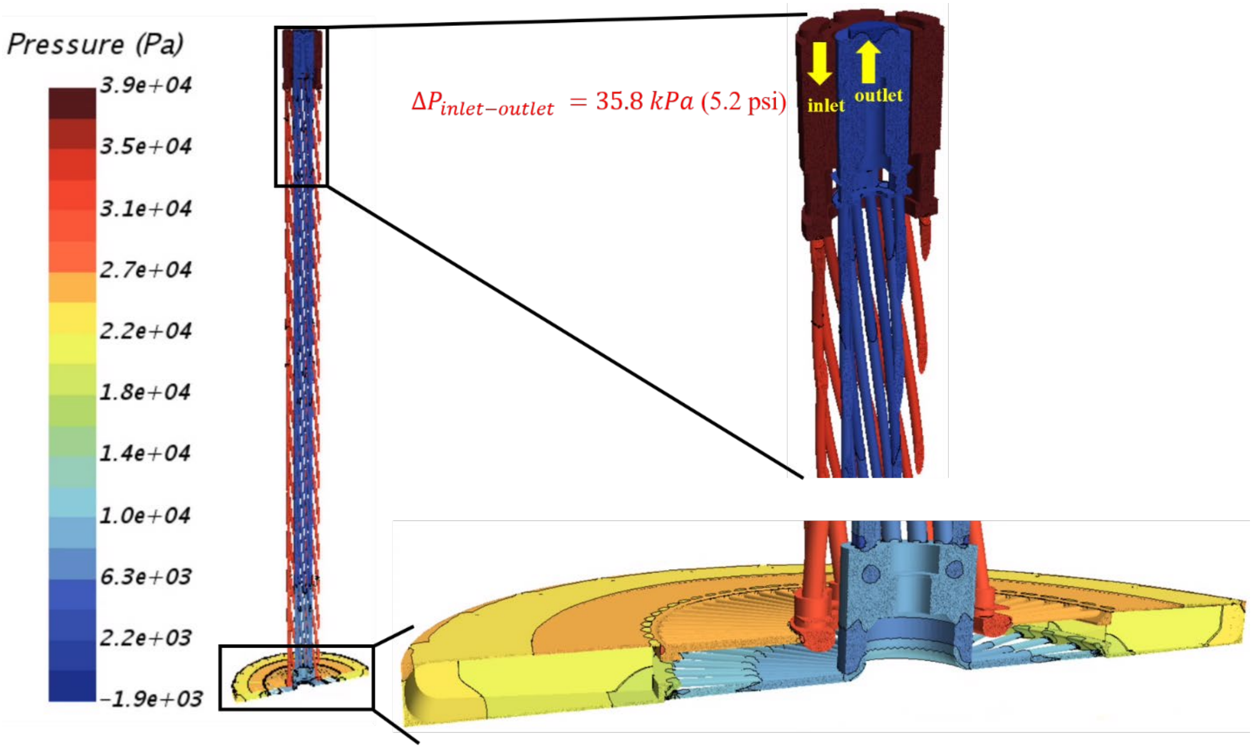
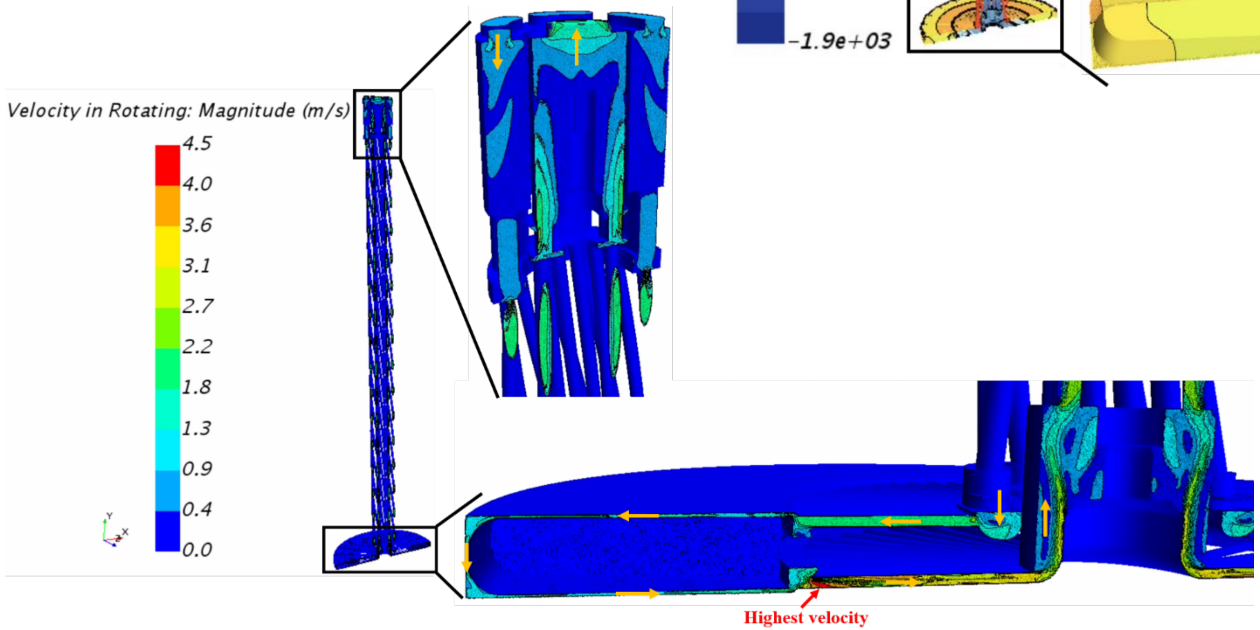


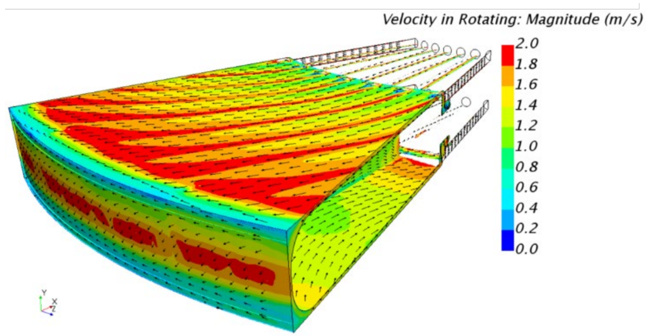
Images Courtesy of L. Zavorka

Static Thermofluid

- Full CFD model of target system
- Flow balance between segments
- Coriolis effects included



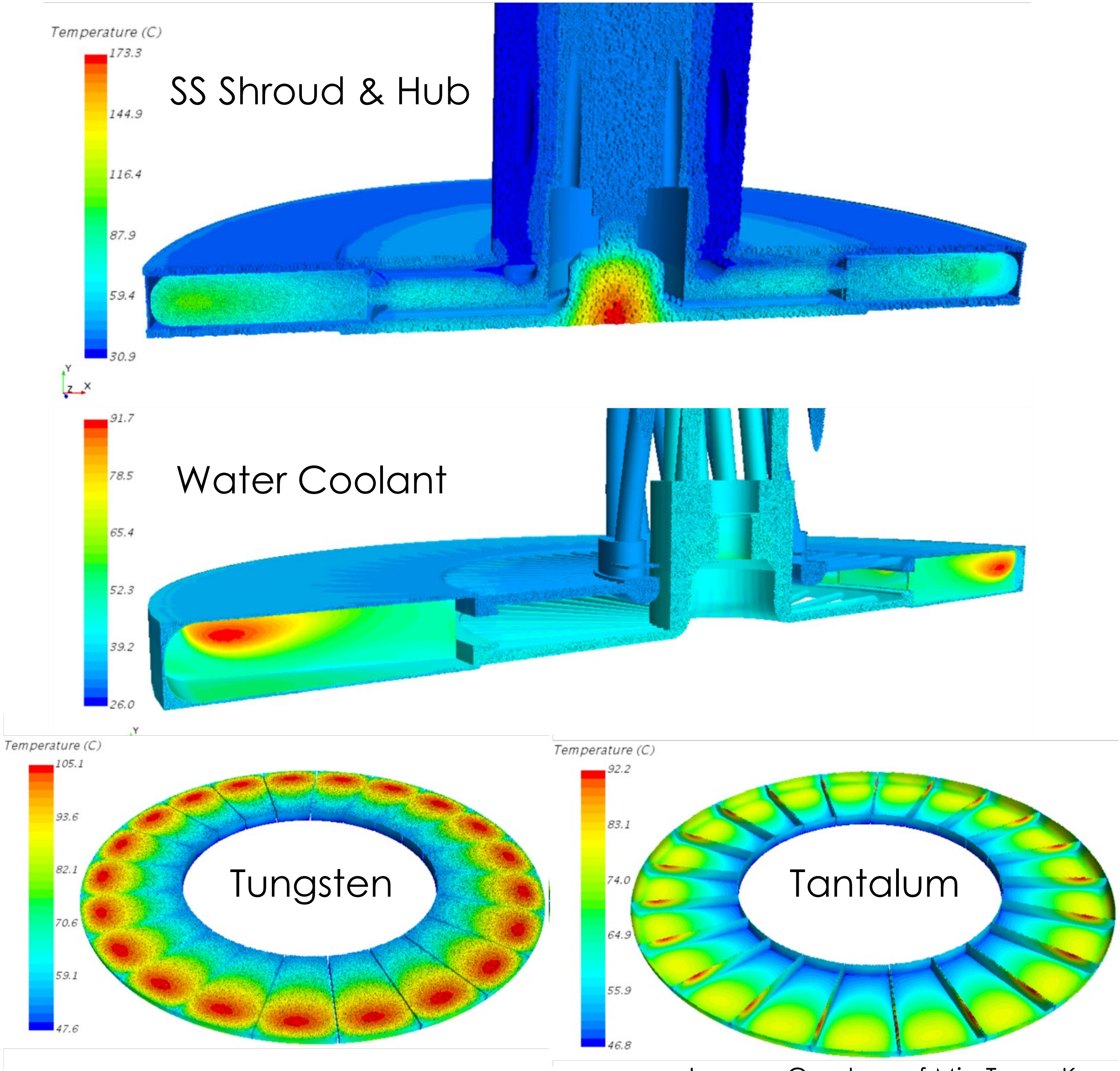




Images Courtesy of Min-Tsung Kao

Static Thermofluid

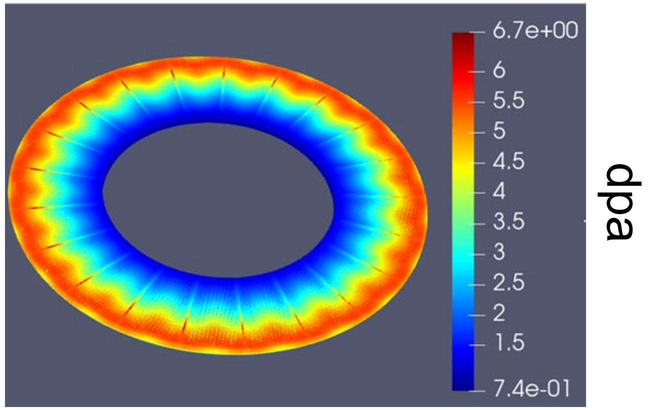
- Heat transfer analysis using interpolated energy deposition point cloud

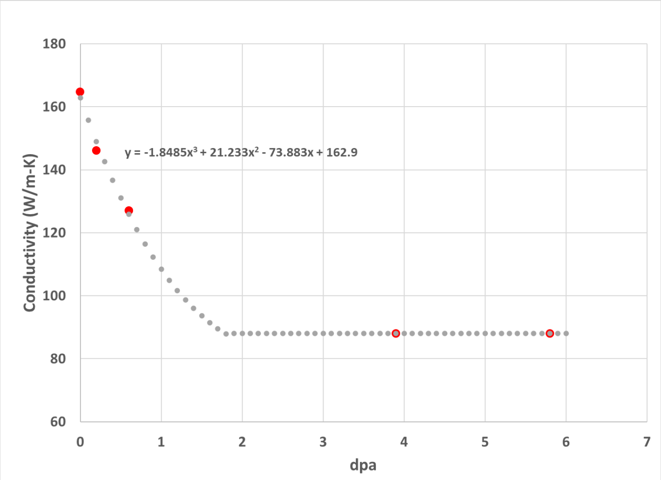


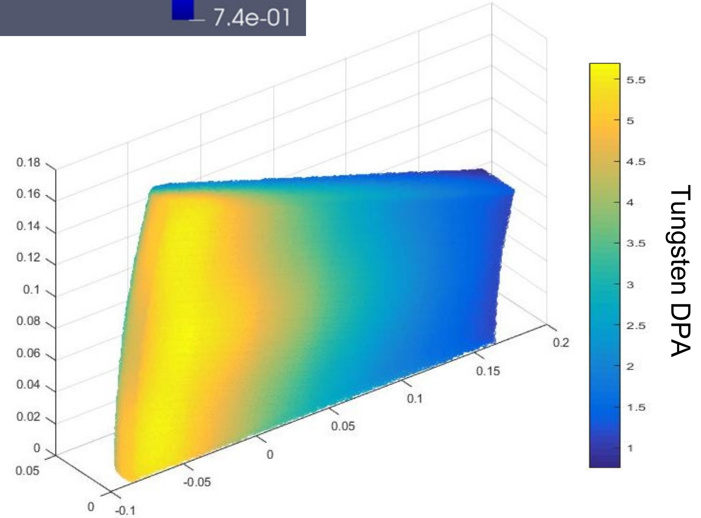
Images Courtesy of Min-Tsung Kao

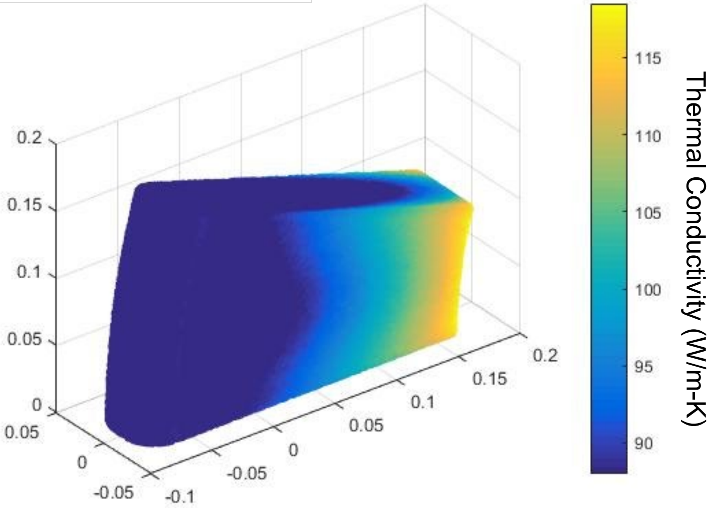
Static Thermofluid

- Neutronics DPA point-cloud mapped to W thermal conductivity
- Tungsten maximum temperature
  - Unirradiated Thermal Conductivity = 105 °C
  - Irradiated Thermal Conductivity Field = 136 °C



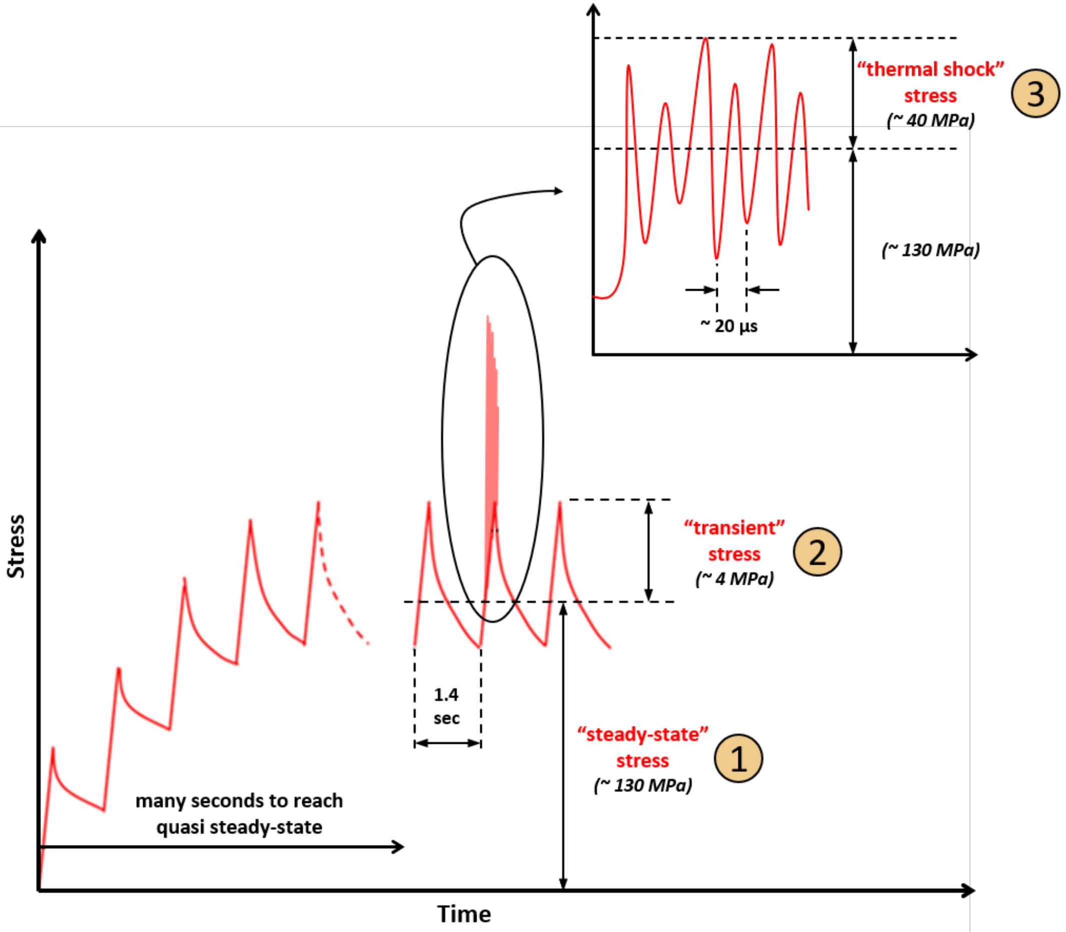






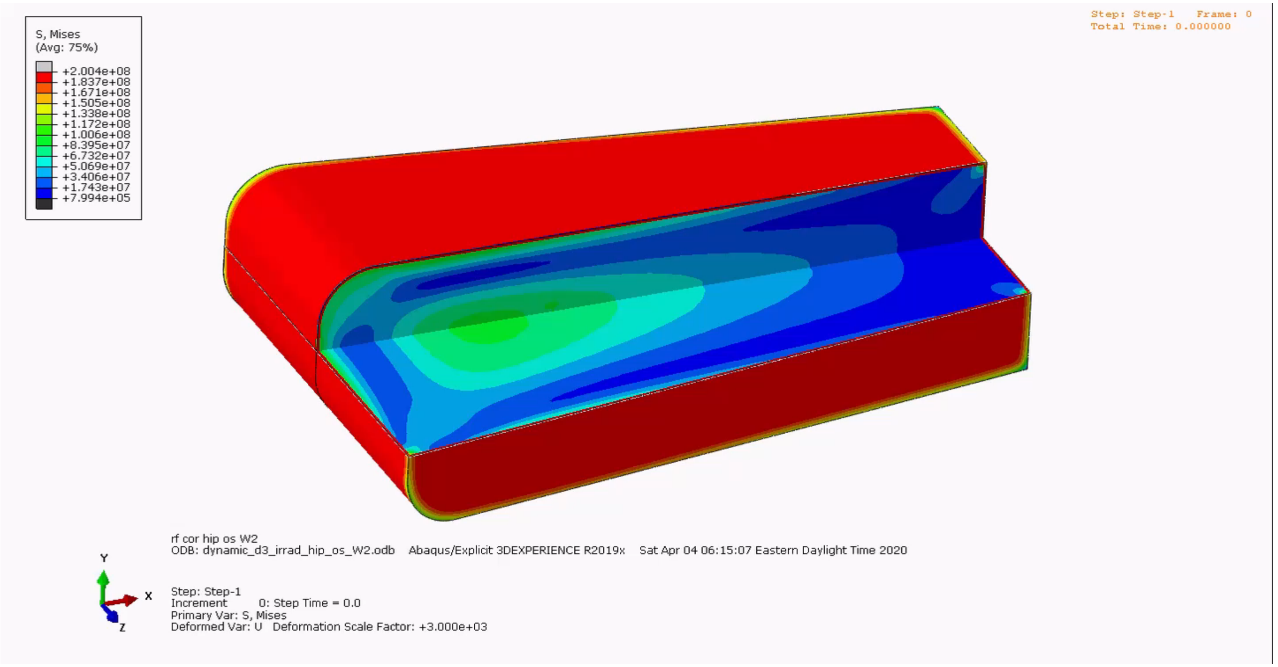
Dynamic Structural

- Dynamic stress regimes



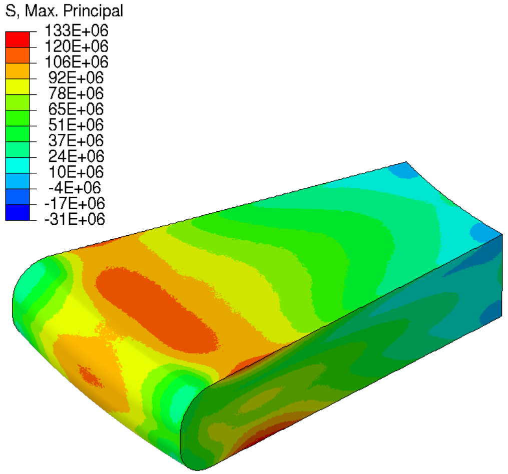
Modified from Peter Loveridge, ISIS Spallation Source

- Abaqus | Explicit
  - HIP & SS applied as quasi-static steps
  - Captures full Ta strain history
  - Beam pulses imposed as ΔT fields
  - Elastic waves ("thermal shock") reflect through block and cladding

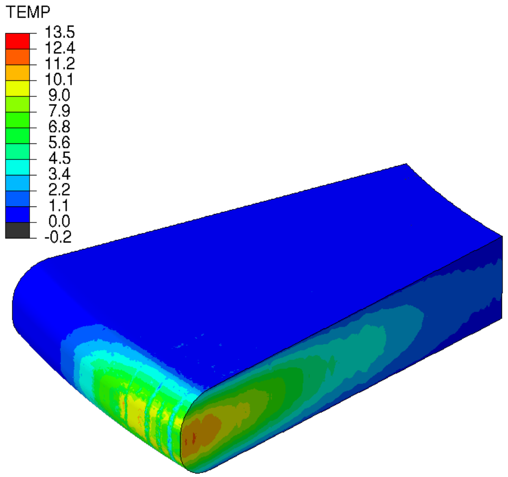


Dynamic Structural

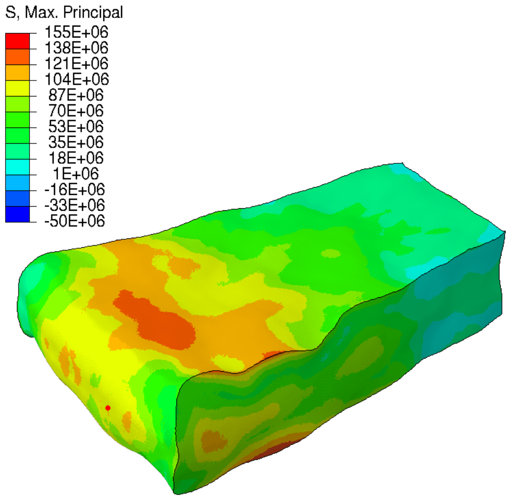
Quasi-static Stress

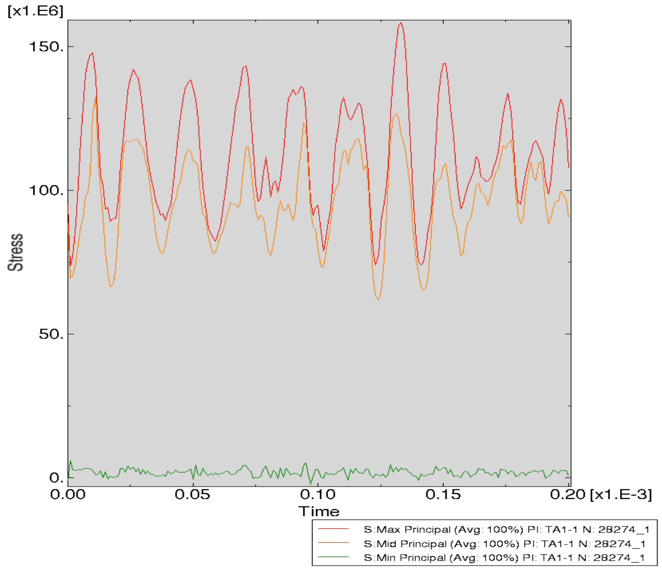


Thermal Pulse A

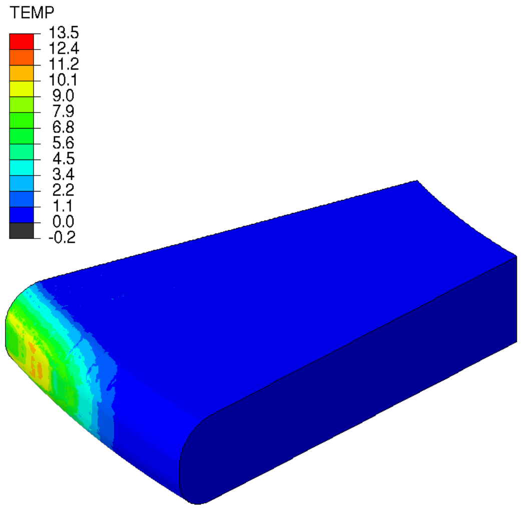


Dynamic Stress Response

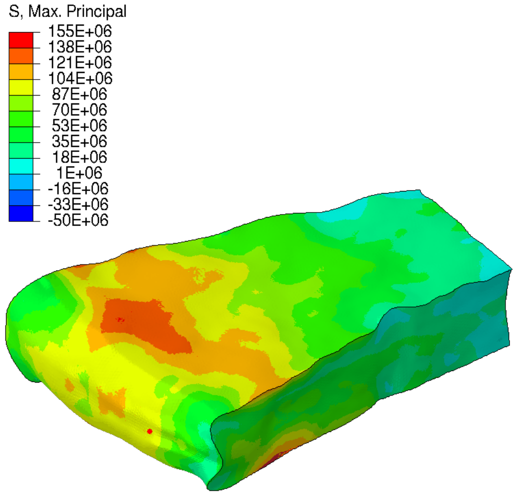


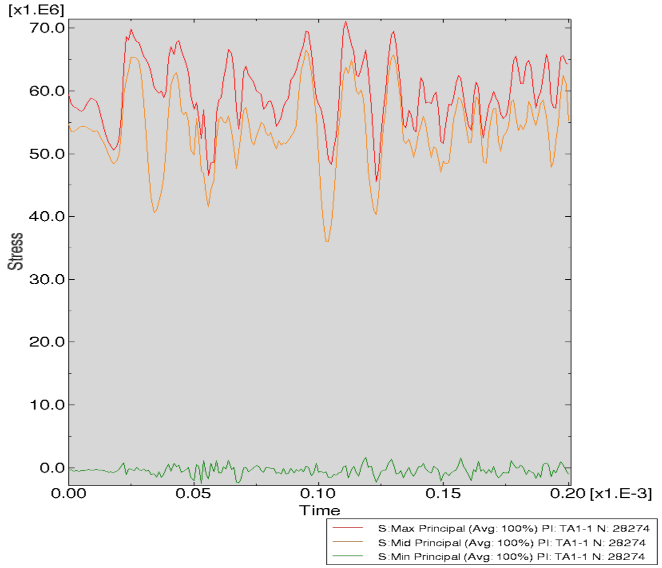


Thermal Pulse B



Dynamic Stress Response





Fatigue Lifing Concerns

Tungsten Block

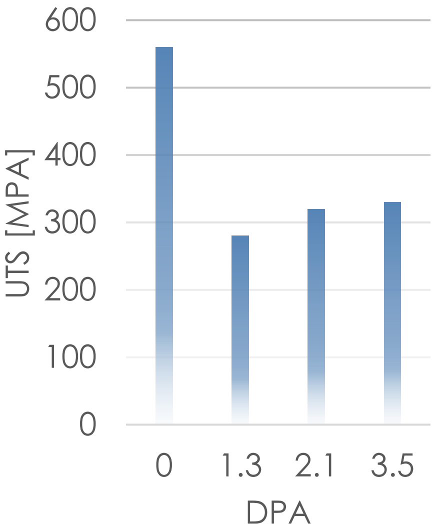
- Properties of Concern
  - Thermal conductivity as function of dpa
  - Irradiated elastic modulus
- Critical Life Stage = Later Operation
  - Irradiation reduces thermal conductivity
  - Ta stress relaxation above 1 dpa expected to remove any beneficial HIP residual stresses on W

Tantalum Cladding

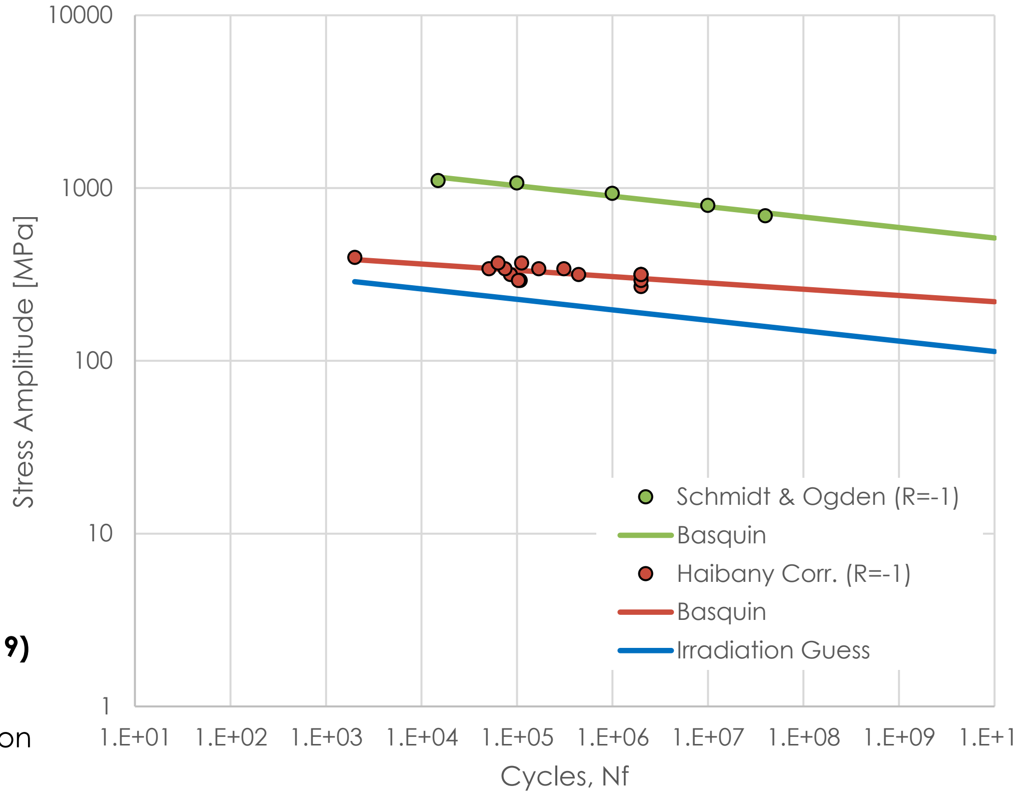
- Properties of Concern
  - Cold creep
  - Strain rate hardening
  - Temperature softening
  - Irradiation creep induced stress relaxation
- Critical Life Stage = Early Operation
  - Unirradiated properties
  - HIP pre-stress
  - Plastic yield

Fatigue – Tungsten

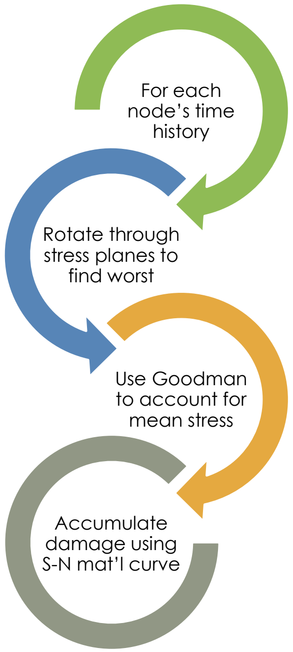
- FE-SAFE Analysis
  - S/N Curve
  - Goodman's Linear Relationship
  - Critical Plane
  - Brittle Failure Theory
- Best guess irradiated properties
  - Irradiated, HIPed, Tungsten
  - Assume $\sigma_{UTS} \approx 300$ MPa
  - Assume $\sigma_N \approx \frac{\sigma_{UTS}}{2} = 150$ MPa

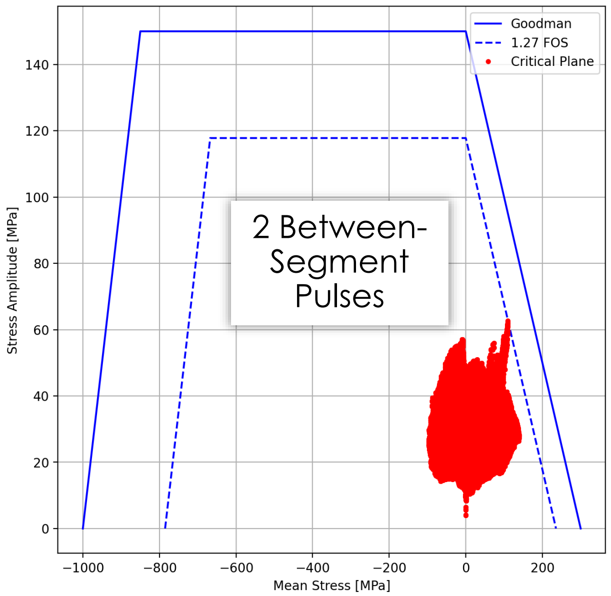


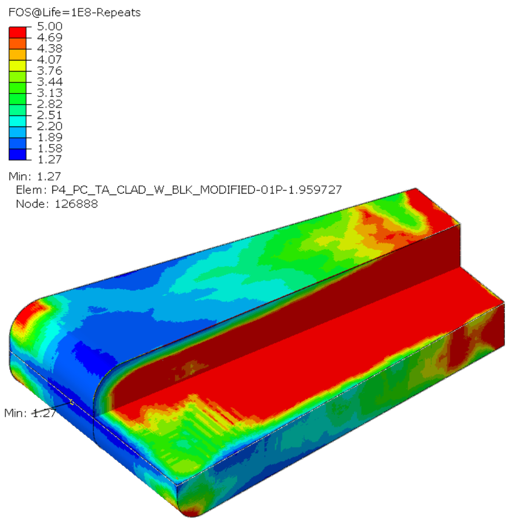
Habainy et al., *J Nuc Matl* (2019)
- Milled & Cross-Rolled W
- 3-point bend testing
- Room Temperature Irradiation

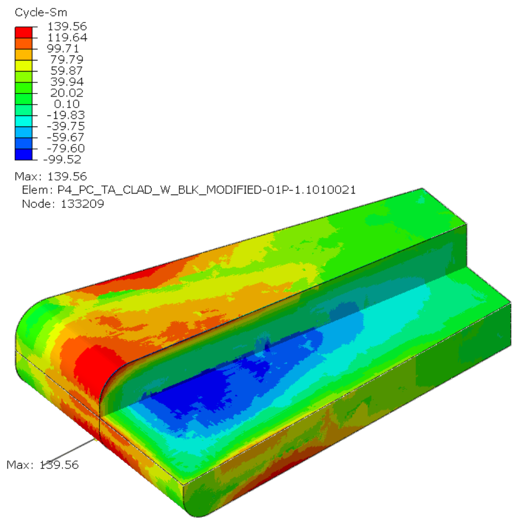


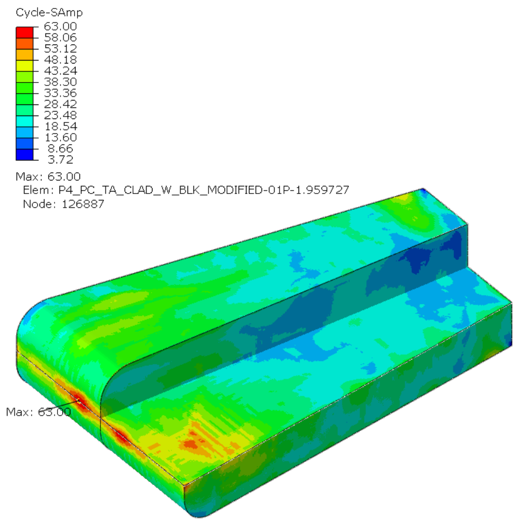
Fatigue – Tungsten – Beam Placement Effect

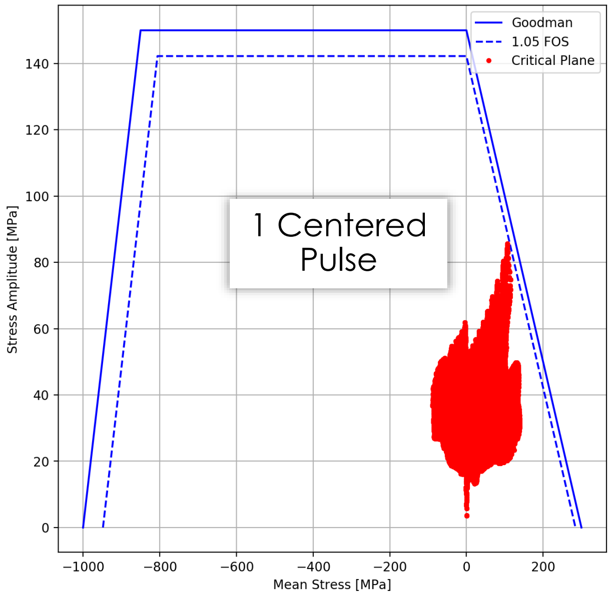


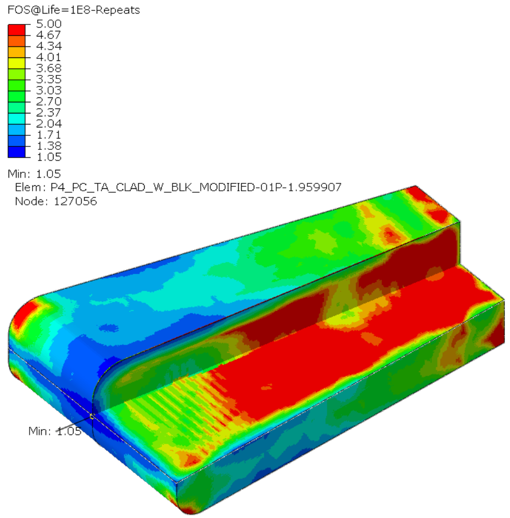


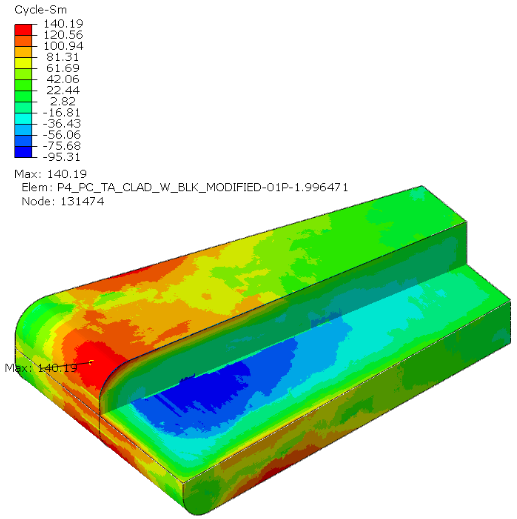


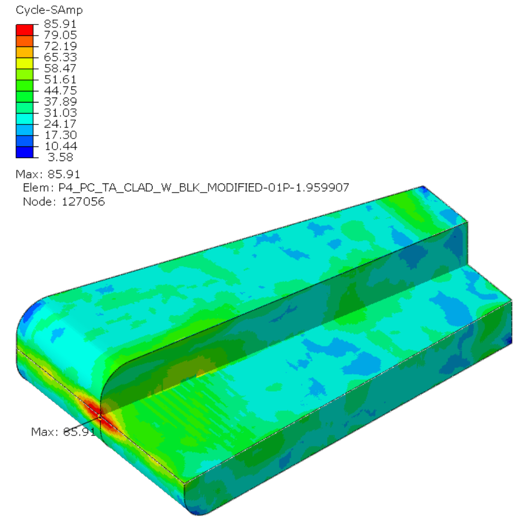






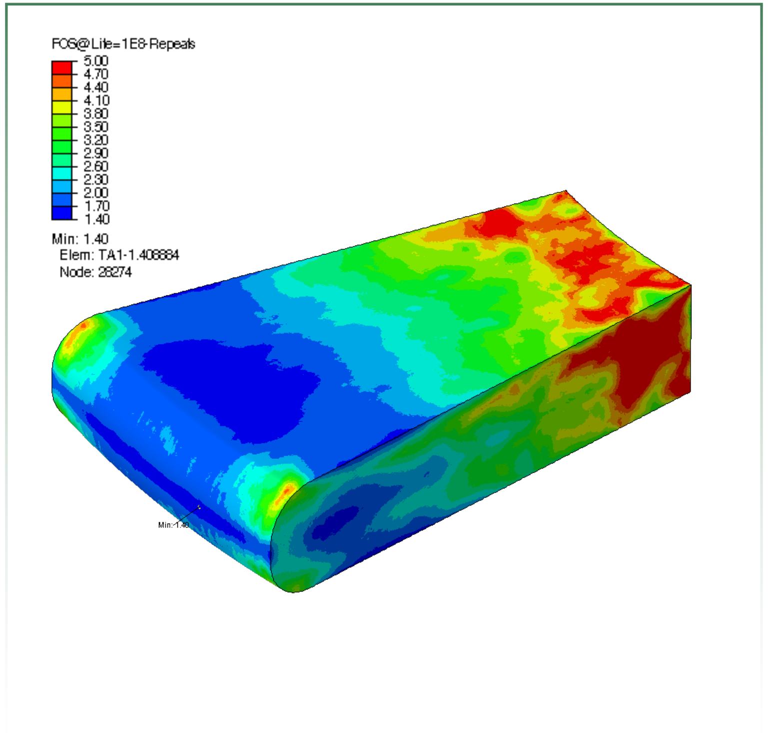




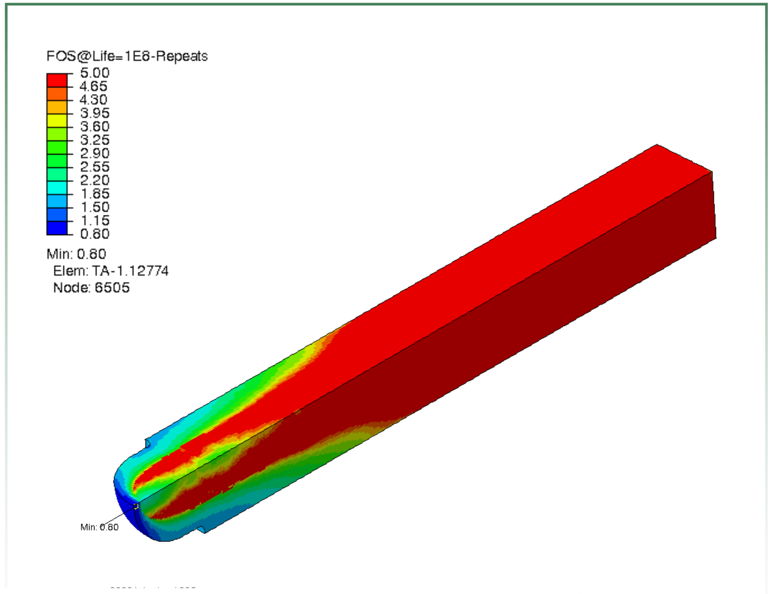


Fatigue – Tungsten

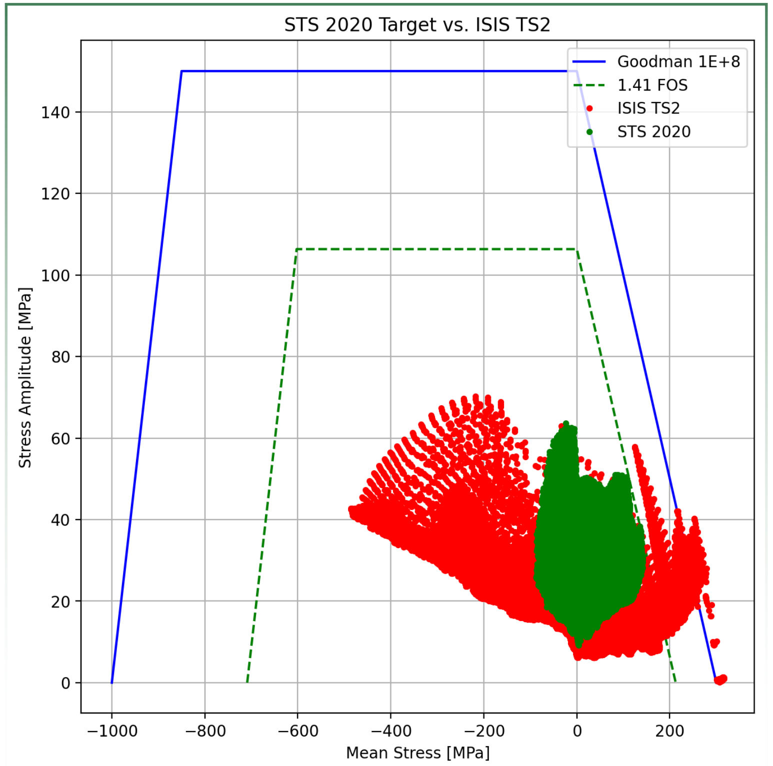
STS Wide Beam with Between-Segment Pulses



ISIS TS2 with Thermal Conductivity/DPA Variation

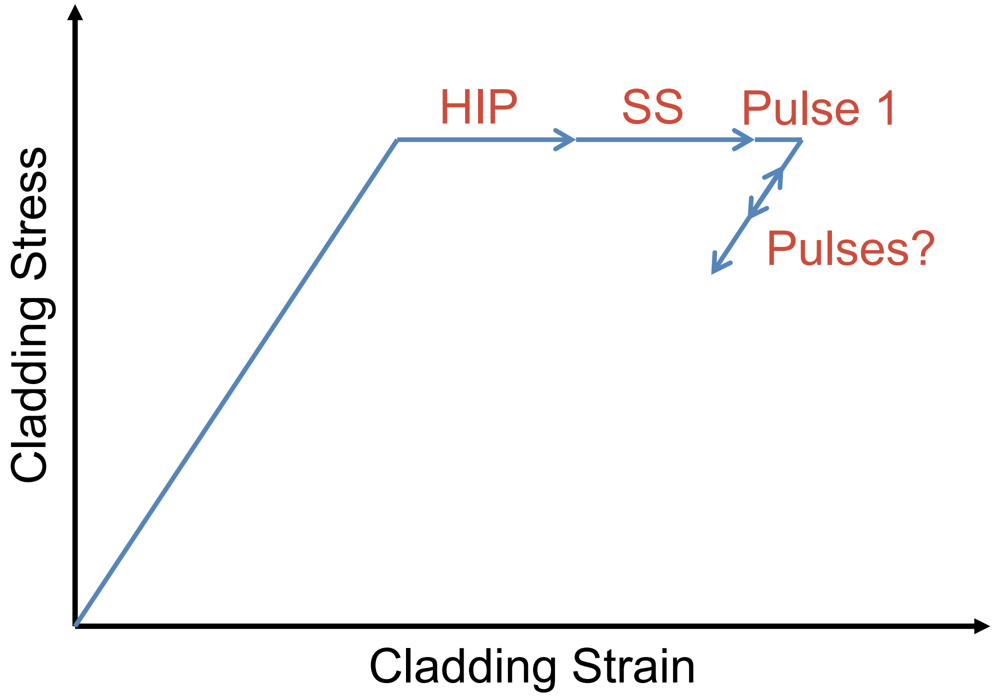


Comparisons using Fatigue Envelope for Irradiated Tungsten



Fatigue – Tantalum

- Strain controlled
- Begins service life in a state of plastic yield
- Elastic shakedown phenomenon
  - ISIS TS2 → elastic shakedown with 1st pulse
  - CERN BDF → justification for Ta-2.5W clad
  - ORNL STS → currently in analysis, R&D



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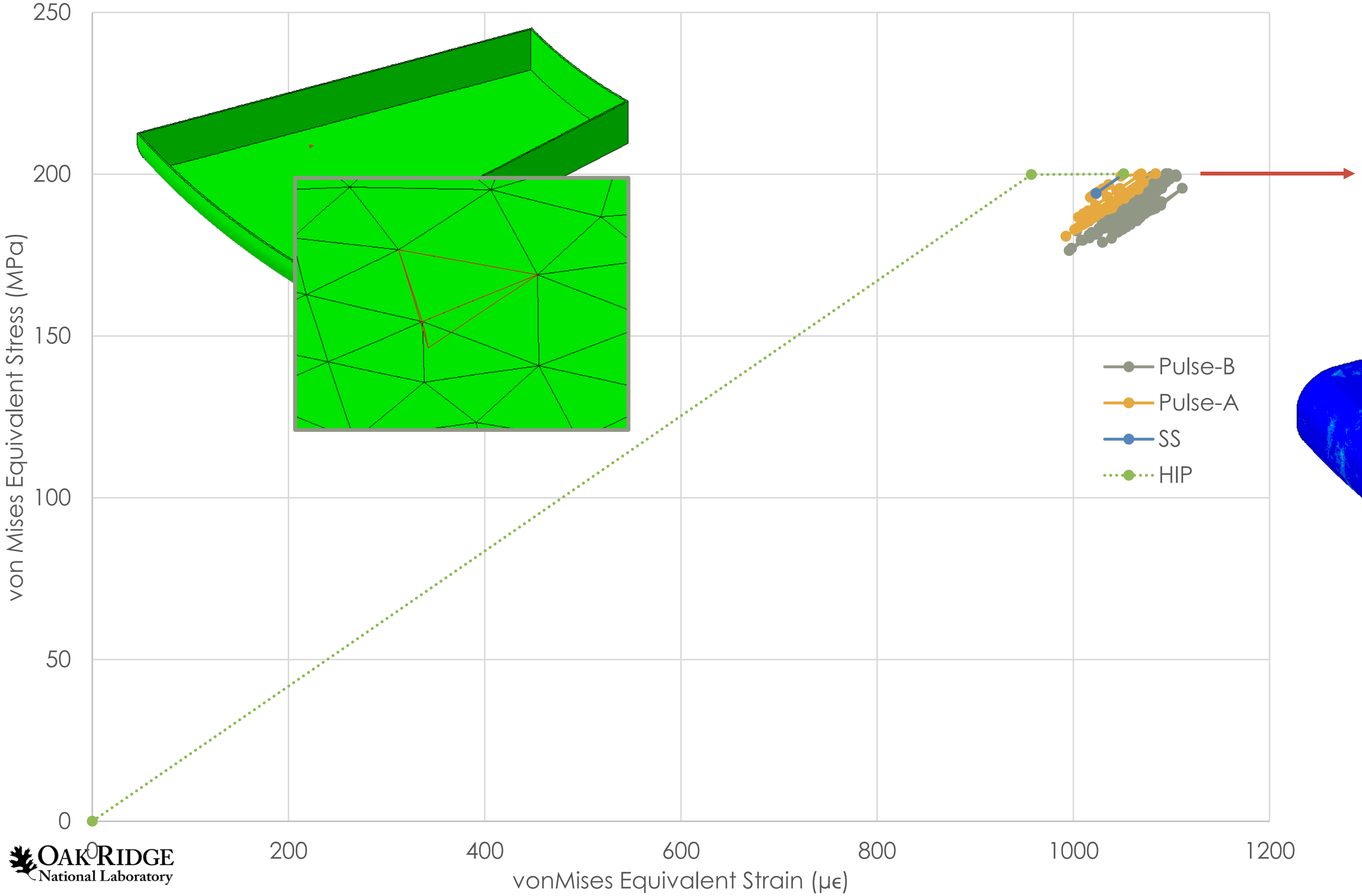
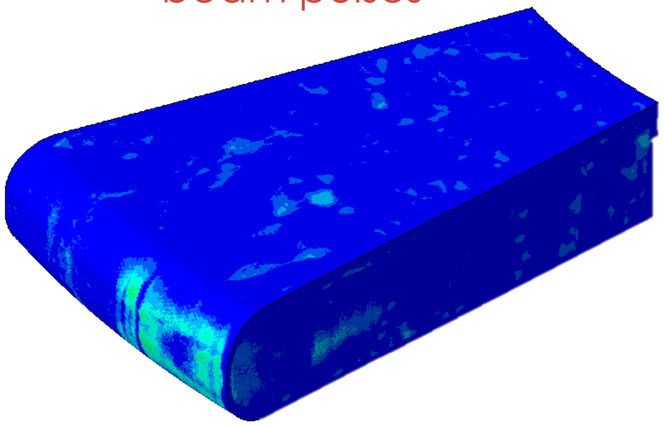
Fatigue – Tantalum

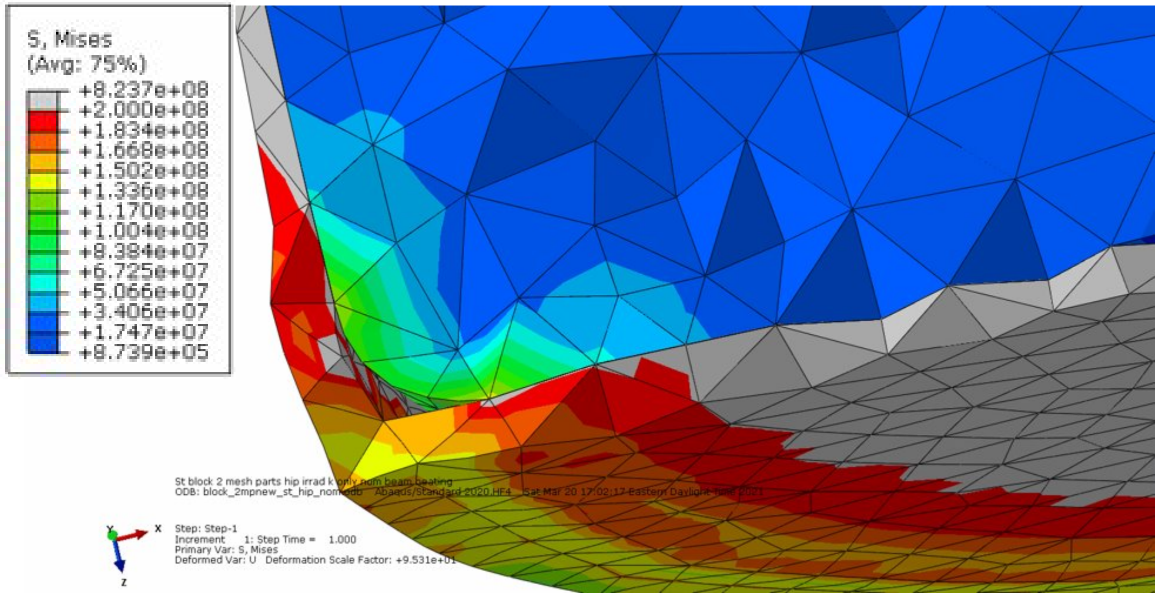


Plastic strain ratcheting seen after first set of beam pulses

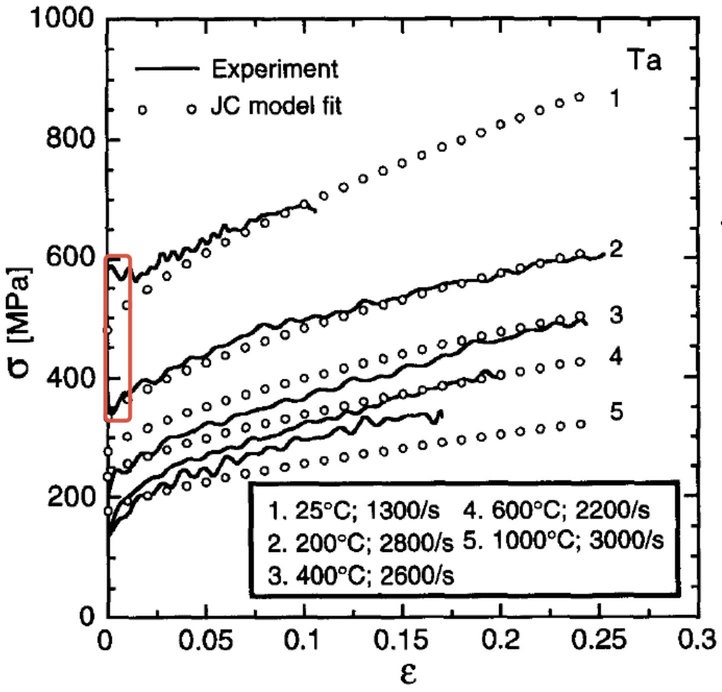


Future Work

- Resolving Ta-W interface in edges and corners
  - Front edge after HIP (450°C – 30°C)



- Meshing Ta and Ta-W interface
- LOCA; Ta corrosion in steam
- Advanced Ta constitutive models
  - Johnson-Cook to capture strain rate, temperature, yield effects



Chen & Gray, Metall Mater Trans A, 1996

Summary

- STS Analysis Team has developed high fidelity analysis capabilities:
  - Neutronics (improved resolution of energy deposition in thin materials)
  - Structural (resolving time strain history in dynamic response)
- Tungsten Block: Initial indications appear to be conservative compared to existing targets
- Tantalum Cladding: Pursuing questions about Ta behavior and plastic ratcheting
  - Johnson Cook constitutive model
  - Effects of CTE temperature dependence
  - FEA discretization
- Will incorporate R&D results and geometry iterations in target analyses