Sandia National Laboratories

HIGH FIDELITY MULTI-PHYSICS MODELING TOOLS FOR PMI EXPERIMENTS AT DIII-D

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Introduction

A new multi-physics modelling workflow has been applied to SNL-led material exposure experiments at the DIII-D National Fusion Facility. Diagnostic data is combined with magnetic field-line tracing and finite-element thermomechanical modelling tools to interpret the complex surface evolution of specially-shaped samples after ELMing H-mode plasma exposure.

Modeling Workflow

DIII-D Data
- Collect IRTV (60°) heat flux data along flat tiles, EFIT equilibria, FASTCAM data, other shot information
- Calculate along outer-midplane
- Characterize ELMs (avg profile, frequency)

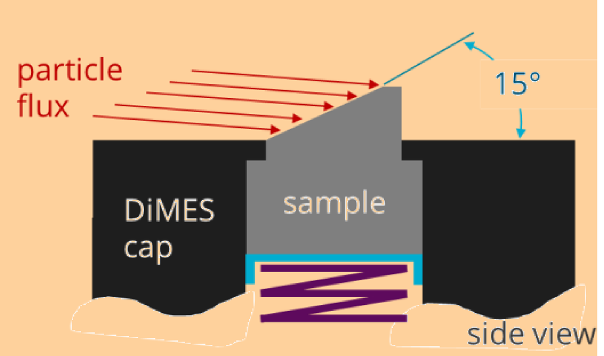
SMITER
- Use **SMITER field-line tracing** to calculate **inter-ELM distribution on 3D first-wall components**, including DiMES holder and angled samples
- Use CAD files for high-resolution 3D DIII-D wall meshes

SIERRA
- Use **SIERRA thermal modeling** to estimate internal temperature evolution for all samples
- Layer **inter-ELM** & **intra-ELM** onto 3D DiMES model

Example Experiment at DIII-D

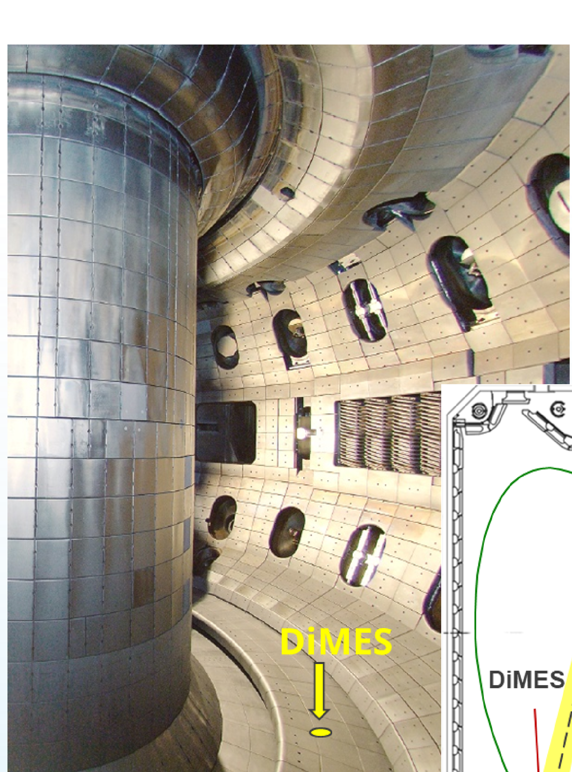
Exposure of angled tungsten (W) samples to reactor-relevant perpendicular heat flux $q_\perp$ [1,2]

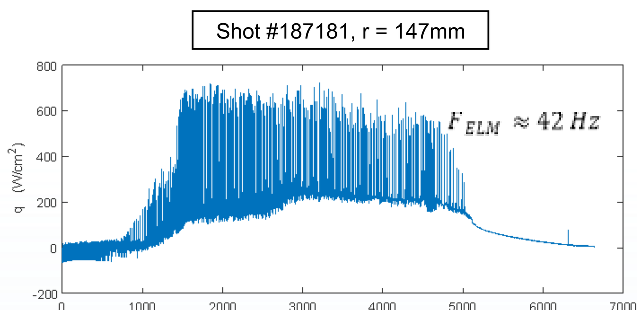
- 15° angled surface
- 9 H-mode discharges
- ~42 Hz ELMs
- $\lambda_{q,OMP}$ ~3-4mm

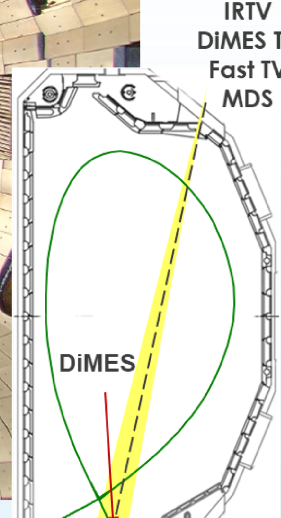


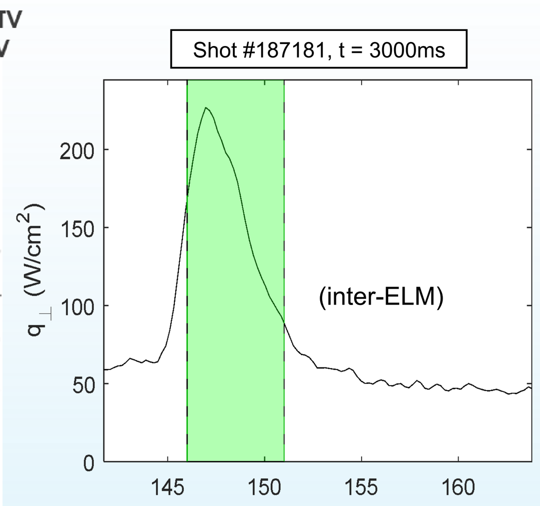
$q_{\perp,inter-ELM} \approx 25 \frac{MW}{m2}$ $q_{\perp,ELM} \approx 115 \frac{MW}{m2}$

Wide range of material response: near-surface cracking, dispersoid evaporation, recrystallization, macroscopic melting & JxB melt motion



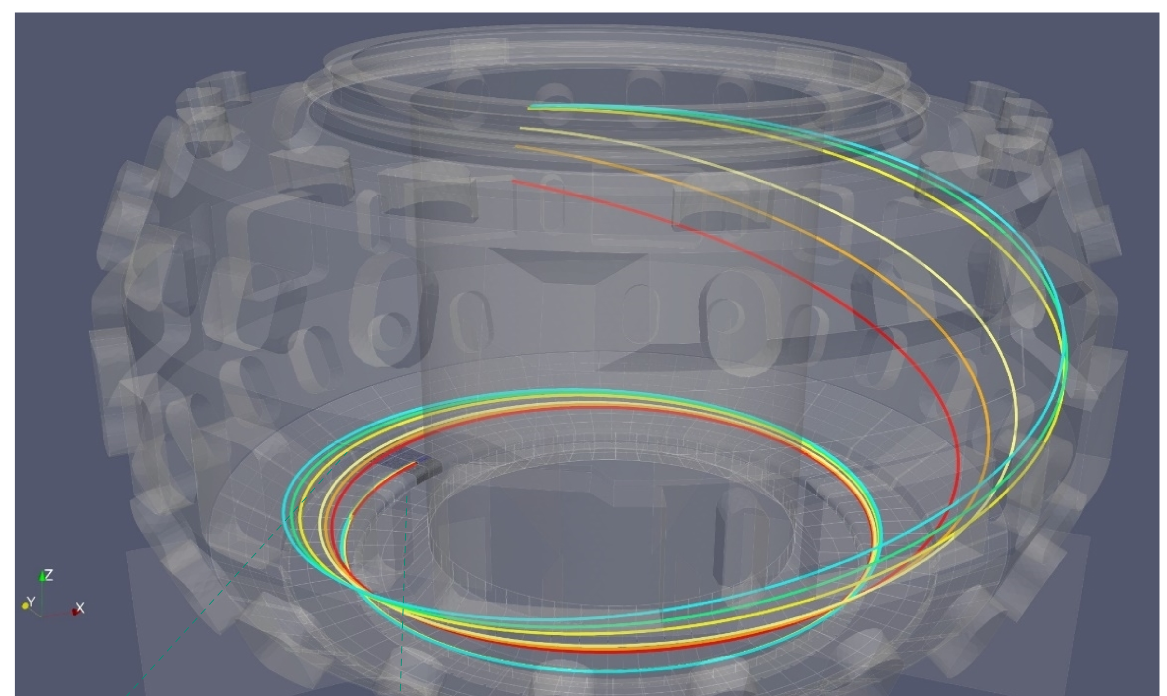




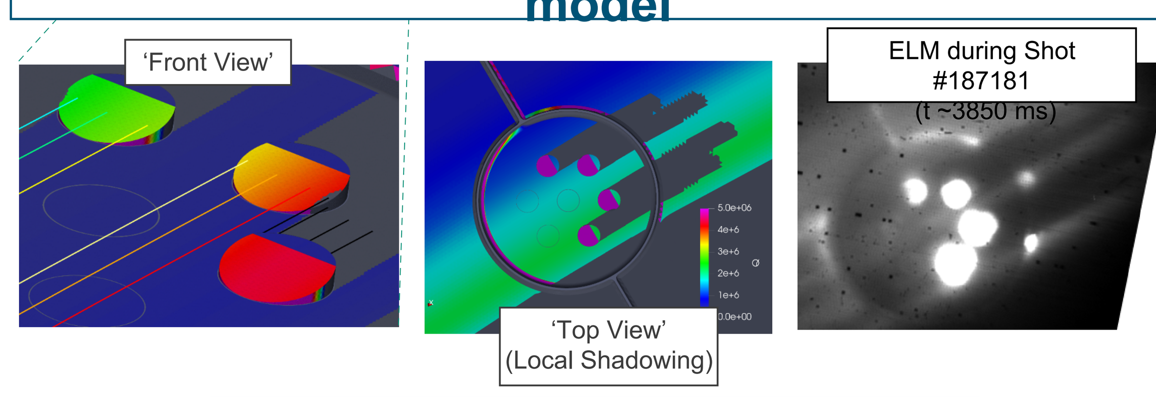


DiMES Location in green

SMITER Field-line Tracing

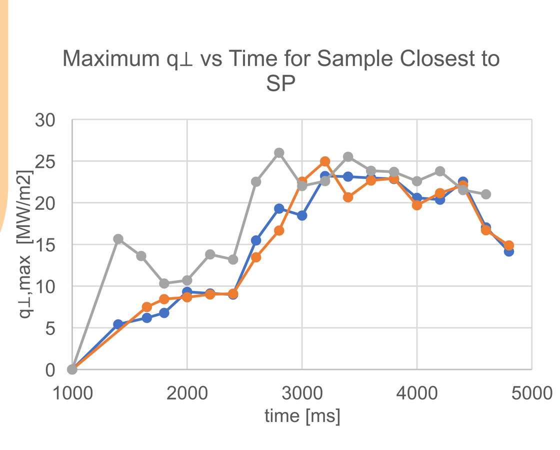


SMITER Field-line Tracing with 3D DIII-D wall model

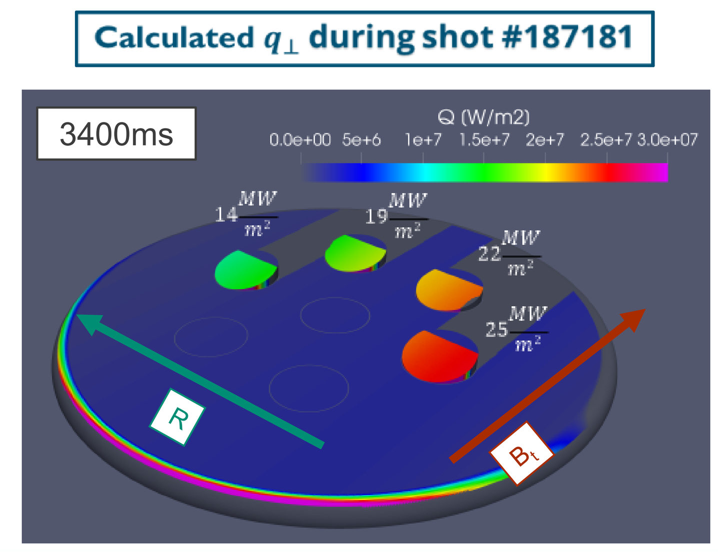


The SMITER code package is a GUI framework for performing magnetic field-line tracing and power deposition mapping for tokamak plasma-facing components (PFCs) [3]. SMITER provides a 3D map of $q_\perp$ impinging on surfaces, accounting for local shaping and flux shadowing. Parallelization allows for fast simulation times (~minutes). The code package has been developed for ITER, but is open for use by any ITER member and can be utilized for similar modelling of any tokamak environment. It is version-controlled and incorporated within ITER Integrated Modeling and Analysis Suite (IMAS). DIII-D results will be used in validation studies by the ITER Organization.

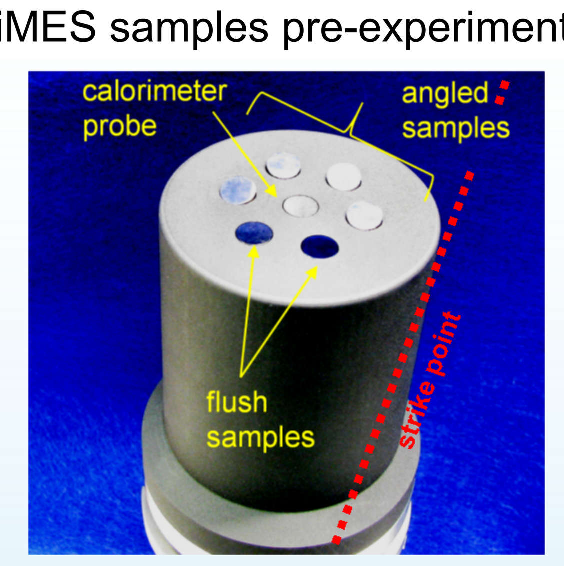
Features include:
- 3D CAD model imports of tokamak components
- High-resolution meshing (sub-mm)
- Visualization via ParaView
- Python scripting and batch processing
- Hierarchical data file storage
- Parallelized runs with MPI for code speed-up

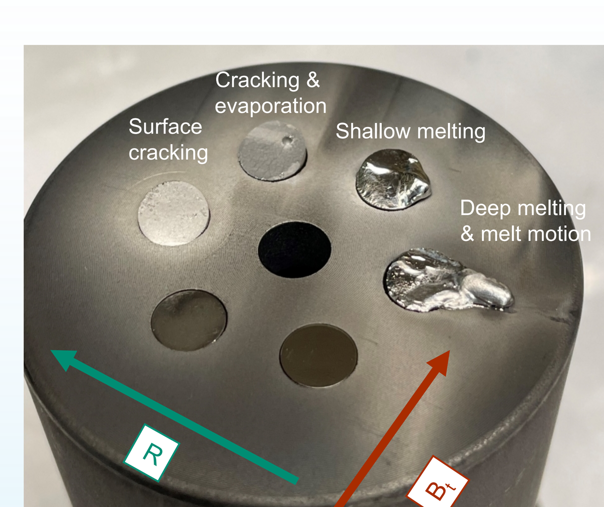


Calculated $q_\perp$ during shot #187181



DiMES samples pre-experiment



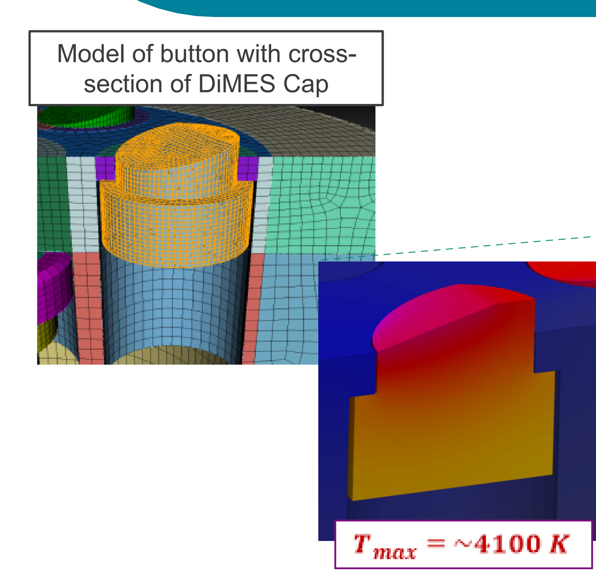


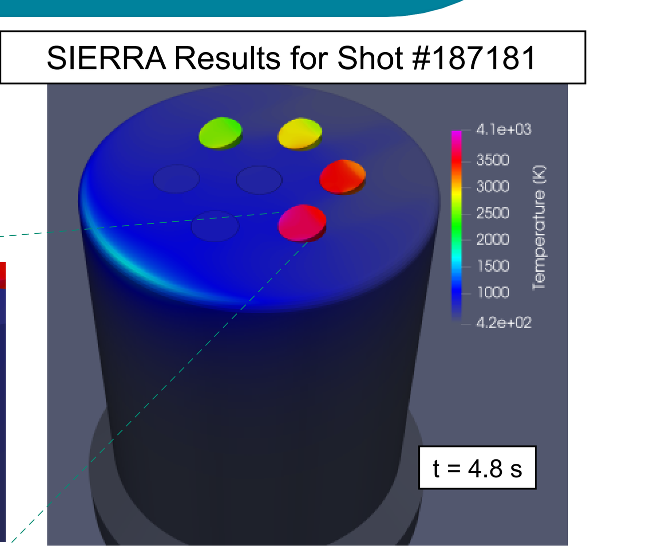
DiMES samples post-experiment

SIERRA Multiphysics Suite

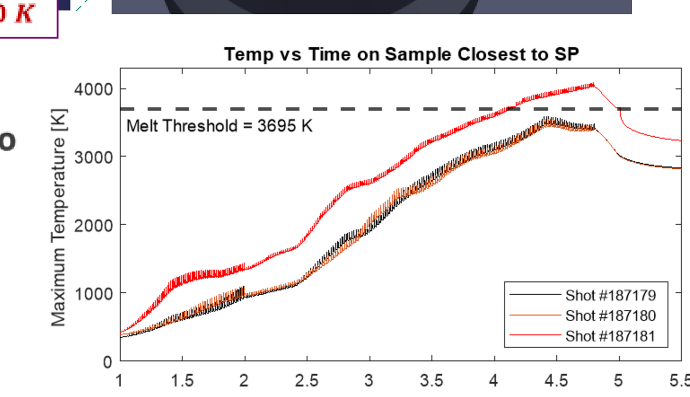
The SIERRA Multimechanics Module: Aria was developed at SNL under the ASC program to approximate linear and nonlinear continuum models of heat transfer. Aria uses the SIERRA Framework [4] to facilitate the development of coupled, multi-mechanics applications for massively-paralleled simulations. Current capabilities include thermal energy transport, species transport, electrostatics, and generalized scalar, vector, and tensor transport equations. For this application, the impinging $q_\perp$ profiles from SMITER serve as input for 3D, time-dependent thermal modelling of the DIII-D samples and their DiMES holder.

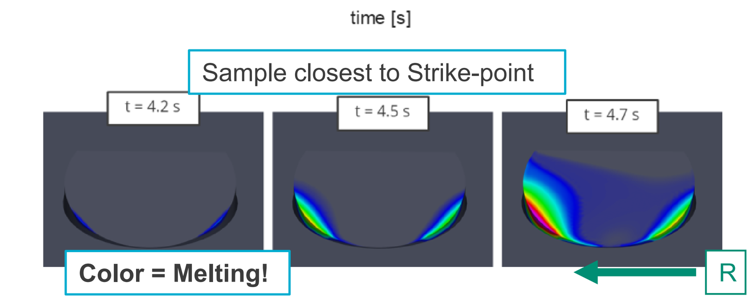
Model includes:
- Inter- and intra-ELM heat loads
- Temperature-dependent material properties
- Conductive & radiative heat losses
- Variable thermal contact efficiency
- Phase change
- Electric current flows
- B-field vectors





- **Inter- + intra-ELM heat loads at 110% is essential to reproduce melt**
  - *Melt depth* ≈ 0.4 *mm*
- **Melt patterns roughly match FastCam timing**
  - Intra-ELM melting at sample edge → $t \approx 4.2\ s$
  - Sustained inter-ELM melting along face/bulk → $t \approx 4.7\ s$
  - Intra-ELM edge melting for next-closest sample near end of shot





Future Applications and Development

The SMITER + SIERRA workflow has been invaluable for matching the timing and extent of observed melt formation in previous DIII-D experiments. Knowledge of the final surface and bulk temperatures also helped explain the post-experiment SEM observations of PMI-induced surface damage as well as the recrystallization profiles in sample cross-sections.

These modelling tools are actively being implemented for experiment planning at DIII-D, allowing for optimized experiment conditions ($q_\perp$,T, exposure time) for a range of experiments. This includes low-power L-mode retention experiments as well as more high-power H-mode exposures with ELMs. Further desired additions and improvements to modelling capabilities include:
- Local sheath physics effects
- Time-dependent mesh deformation & melt flow
- ~μm-scale erosion/redeposition effects
- Local stress/strain

[1] R. Kolasinski et al., oral presentation, *25th International Conference on Plasma-Surface Interactions*, 13-17 June 2022, FO29(A).
[2] J. Coburn et al., oral presentation, 64th Annual Meeting of the APS Division of Plasma Physics, 17-21 October 2022, NO05.
[3] L. Kos et al., *Fusion Engineering and Design*, 146 (2019) 1796-1800.
[4] SIERRA Multiphysics Module: Aria Thermal Theory manual – Version 5.0 (2021) doi:10.2172/1777076

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