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SUBJECT: SWEPT HEAT FLUX INACCURACIES IN PFC REQUIREMENTS

Findings

- PFC SRD heat flux specifications for 'swept' scenarios use the time-averaged heat flux, but the final surface temperature depends on both the time-averaged heat flux and the sweep frequency.
- ANSYS modeling of a Sigrafine 6510 IBDH castellation indicates that for 16 MW/m^2 applied as a square wave with 50% duty cycle for 5 seconds, surface temperatures > 1700 degC were obtained for frequencies < 20 Hz. This is in contrast to 8 MW/m^2 applied steady-state for 5 seconds leading to a surface temperature of 1600 degC.

Recommendations

- During re-evaluation of the requirements to accommodate uncertainties in the coil positions and the physics used in heat flux modeling, an enhancement factor of 1.10 for scenarios that use sweeping should be included in NSTX-U-RQMT-SRD-003.
  - IBDH: CASE 2
  - IBDV: CASE 1, 2
  - OBDR1/2: CASE 2, 3
  - OBDR3: CASE 2
  - OBDR4/5: CASE 1, 2, 3
  - CSAS: CASE 1, 2, 3
- As tools are developed to model controlled sweeping for NSTX-U (R18-1/1 in PFCR-MEMO-014), thermal modeling should be completed to examine the expected limits in surface temperature reduction as a function of sweep frequency and spatial extent.

Background

Strike point sweeping has been invoked for high heat flux scenarios to extend the ability of NSTX-U to operate with localized heat fluxes, up to several 10's of MW/m^2, that would not be able to be sustained for multiple seconds at a fixed location. These tend to be plasmas with weaker poloidal flux expansion including those with limited elongation and x-points farther from the horizontal surface. These will likely be encountered earlier in operations compared to the high poloidal flux expansion shots. An example of a 'scenario' is shown in Figure 1, assembled from individual stationary equilibria generated by hand as part of the IBDH PFC Requirements (PFCR-MEMO-010). The time access was defined arbitrarily. Future work to generate controlled sweeping examples, described by PFRC-MEMO-017, is expected to provide more realistic swept scenarios.

Swept scenarios are also used for defining Cases for IBDV, CSAS, OBDR1/R2 and OBD R3/4 in NSTX-U-RQMT-SRD-003. To generate the heat flux requirements for swept scenarios for these regions, heat flux was defined by integrating the heat flux over time at specific (R,Z) location for an integer number of sweeps and dividing by the Δt. This made the heat flux independent of assumptions of the sweep frequency. It was assumed that sweeping could be done sufficiently fast relative to heat diffusion that the time-averaged heat flux, applied for the specified duration would be sufficiently accurate. Discussion with Scott Silburn (CCFE) who designs and operates IR systems for machine protection and physics at JET indicated that this was unlikely to be accurate. This was recently published as well [S.A. Silburn, *et al*. Phys. Scr. vT170 pg14040 (2017)] showing modeling and experimental JET IR measurements where sweeping resulted in temperatures above those expected from simply time-averaging the instantaneous heat flux.

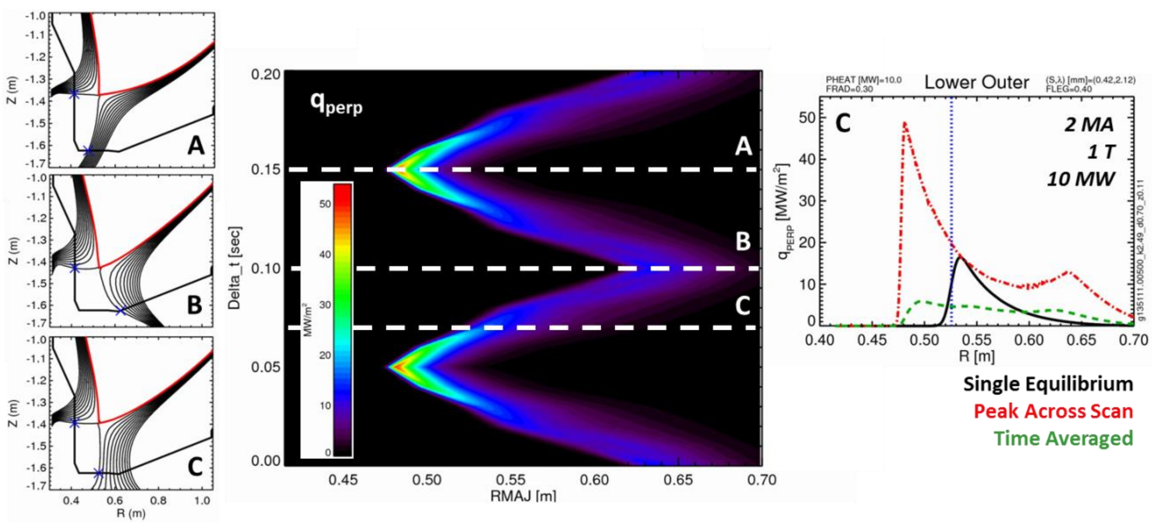

Figure 1: Example of a sweeping scenario (Case 2, Scan 4) assembled for the IBDH PFC Requirements.

Note that a result from the JET indicated the possibility of correlated ELM triggering with sweeping. ELMs have not been a part of the NSTX-U heat flux requirements or modeling. If ELMs are triggered at a specific point in the sweep localized heat flux enhancements could occur. In general examining expectations of NSTX-U ELM energy flux using recent scalings [T. Eich, *et al*. Nucl. Mater. Energy v12 pg 84 (2017)] is worth examining during late Recovery prior to commissioning.

These considerations indicated a need to re-evaluate benefits of sweeping, with the possibility of an increase to PFC Requirements or adjustment of expected scenarios. A simple scoping study using ANSYS was executed showing indeed that time-averaging heat flux for cyclic loads leads to marginally higher surface temperature for frequencies expected of NSTX-U divertor sweeping.

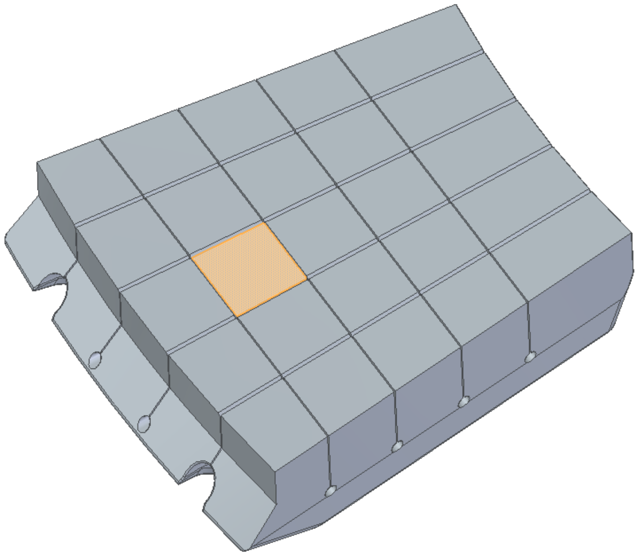

Figure 2: IBDH tile model, highlighting the castellation isolated for ANSYS simulations.

Simulation Methodology

To evaluate for a case relevant to the in-progress PFC design, a single castellation was cut out of an IBDH model, obtained from the CAD design group on 1/18/2018. This is not the final design but is a close representation of what is expected for the NSTX-U high heat flux regions. The specific castellation is highlighted in Figure 2 and for this castellation, the chamfer was removed which as of January 2018 was still present in the IBDH model.

ANSYS 18.2 was used to simulate the castellation's temperature evolution during time evolving heat flux. Figure 3 shows the castellation and the boundary conditions. The top surface was allowed to radiate with emissivity of 0.7 to an ambient region of 22 degC. The bottom surface was fixed to be 22 degC, which for short duration simulations does not impact the result as the heat pulse takes 10's of seconds to move through the thickness of the PFC. The temperature dependent material properties from the XML database generated by A. Khodak were used and Sigrafine 6510 was assumed.

XML files were generated which specified the time-evolving heat flux on the top surface. Square waves with 50% and frequencies from 1-20 Hz were simulated,

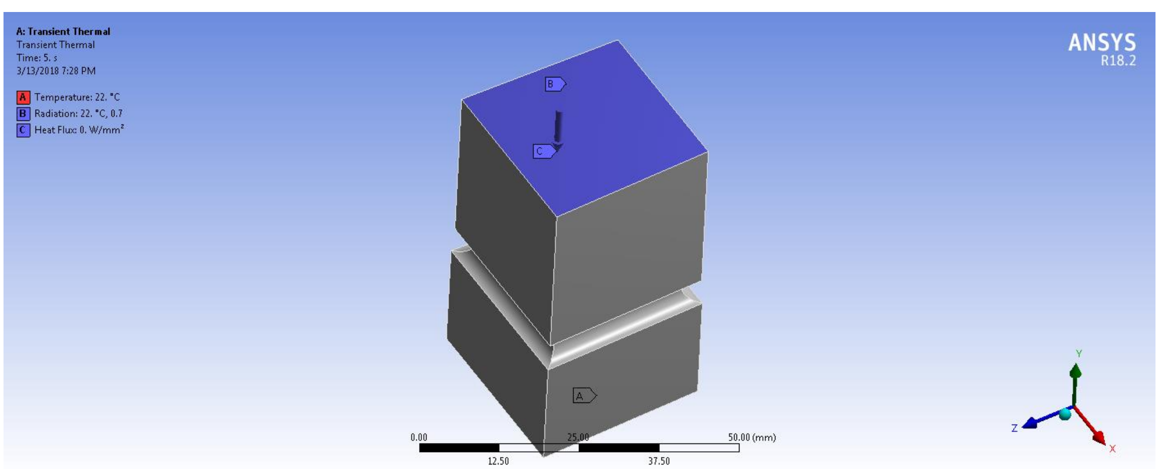

Figure 3: Geometry of the single IBDH castellation, showing the ANSYS Transient Thermal boundary conditions.

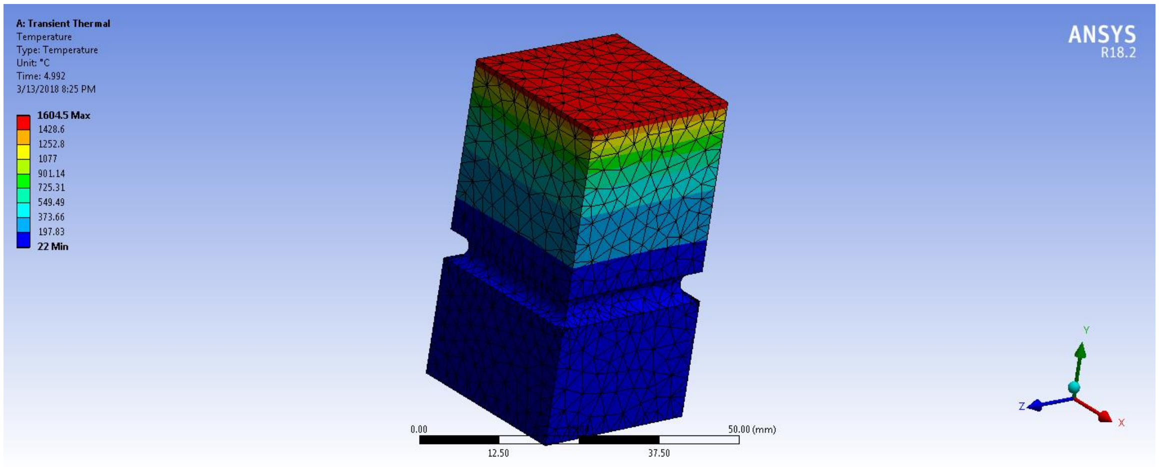

Figure 5: Resulting temperature distribution after 5 seconds of 8 MW/m² applied to the top surface for Sigrafine 6510

each with 16 MW/m^2 heat flux. The step-up/down time of the square wave was set to 0.1 ms. Simulations for 8 MW/m^2 and 16 MW/m^2, steady-state were also completed for comparison. The simulation was run for a duration of 5 seconds and the time history of the top surface temperature saved. Auto Time Stepping was turned on and all simulations had an Initial and Minimum Time Step of 0.1 ms. There was sensitivity of the final maximum surface temperature to the Maximum Time Step, assumed to be due to aliasing of the square wave heat flux. Convergence tests were done at each frequency and Maximum Time Steps of 2 ms to 0.5 ms were used, and most final temperatures showed convergence to within ~10 degC. The Workbench files are available on the Drag'N'Drop here.

The simulation for the steady 8 MW/m^2 is shown in Figure 4, highlighting the mesh and the limited penetration of the thermal wave. This reaches just over the present surface temperature limit, 1600 degC, specific in NSTX-U-RQMT-SRD-

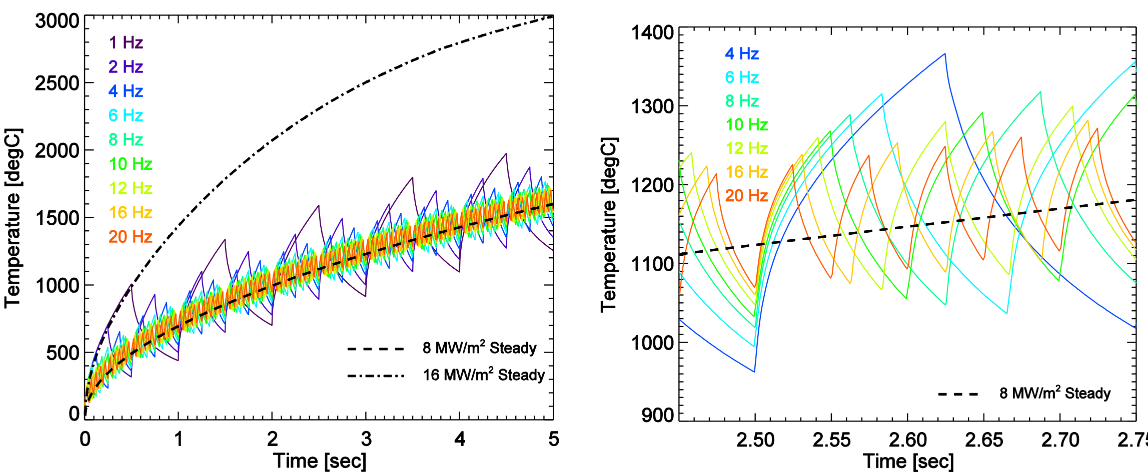

Figure 4: Time evolving surface temperature for the castellation over five seconds (left) and zoomed in for comparison for higher frequencies.

003. For 16 MW/m^2 steady for 5 seconds the surface temperature reaches 3000 degC, showing the slightly less than linear dependence of the ΔT, expected to be due to radiation. In reality, sublimation is expected to further depress the linear rise in surface temperature with

Simulation Results

Figure 5 shows the time-evolving surface temperature for the steady-state and modulated heat fluxes. The trend is clear that increasing the heat flux causes the surface temperature to for the 16 MW/m^2 cases to oscillate about solution for the 8 MW/m^2 steady-state. Figure 6 shows the reduction in the final peak surface temperature as a function of square wave frequency. There is clear evidence of diminishing returns to increasing the frequency above ~10 Hz, and the final temperature remains ~100 degC above the assumption made in the derivation of the PFC Requirements. Lower oscillation frequencies would result in even strong enhancement above the temperature limit. For moderate sweeping frequencies, an enhancement factor of ~10% to the heat flux would be warranted when setting the heat flux requirements in NSTX-U-RQMT-SRD-003. Future evaluation of swept scenarios using time-evolving equilibria are planned within working group activities and will allow NSTX-U operational space to be evaluated using final as-built PFC designs.

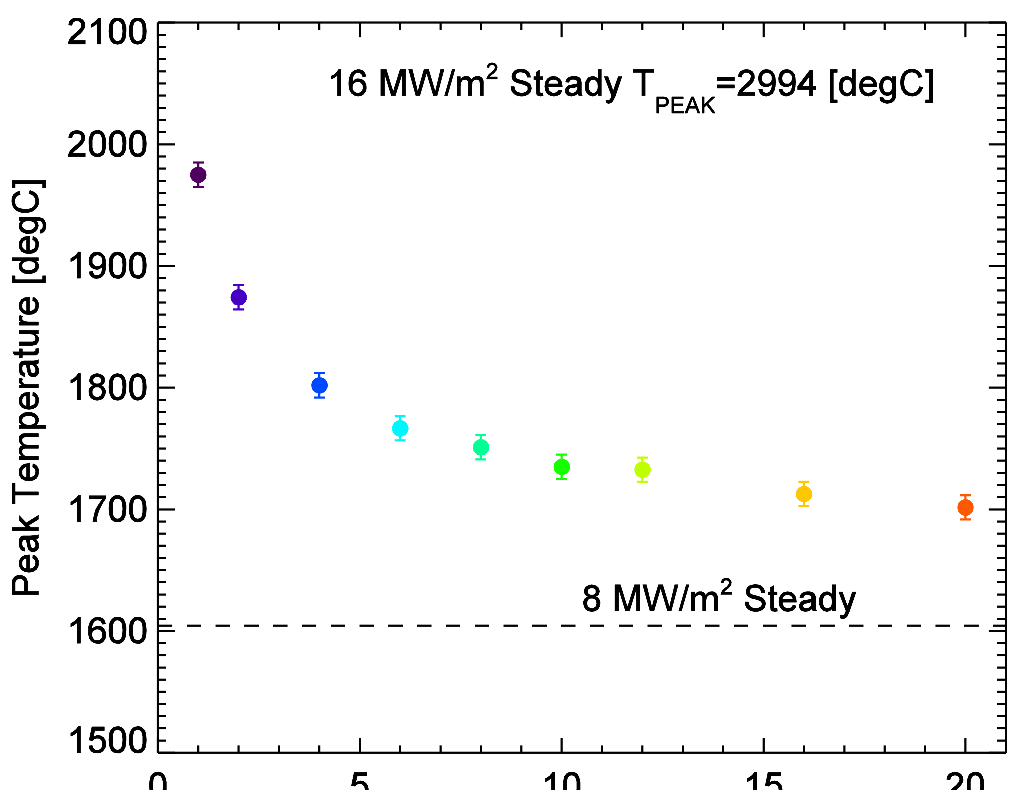

Figure 6: Trend in the reduction of peak surface temperature as a function of frequency.

Record of Changes

Rev.	Date	Description of Changes
0	3/16/18	Initial release for review