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SUBJECT: IMPACT OF COIL ALIGNMENT TOLERANCES ON PFC HEAT FLUX REQUIREMENTS

Recommendations

- A. The heat flux requirements in Tables 4.2-1, 4.3-1, 4.4-1, 4.4-2, 4.4-3 and 4.5-1 in NSTX-U-RQMT-SRD-003 should be based solely on assumptions of axisymmetric heat flux from the plasma.
- B. The impact of 3D fields on PFC heat flux limits should be evaluated using results from initial plasma operations. A plan should be developed to that includes its evaluation, along with uncertain assumptions used in the PFC design to avoid delays in reaching high power operation post-Recovery.
- C. To assist in this process, PFC designs that are shown to be temperature limited should also provide as part of the design verification process (ENG-033) the heat flux and surface temperature for which they become stress limited.

Findings

1. Defining heat flux requirements based on coil alignment pre-assumes a design and decouples from PFC requirements from physics needs.
2. Present methods to define requirements for PFCs to support non-axisymmetric heat flux do not accurately specify the expected conditions.
3. If tiles are temperature limited, lowering the axisymmetric heat flux requirement is overly conservative if done to correct for non-axisymmetric PFC heat flux.
4. The impact of heat flux enhancements from coil misalignments be accounted for when evaluating PFCs during initial, low power plasma operation.

Supporting Comments

The purpose of the System Requirements Document, per ENG-050, is to “contain the engineering requirements that must be met for the system to function in accordance with the GRD [General Requirements Document]”, the latter of which has performance criteria for PFCs (6.1.1.1.1) that the tiles absorb the exhausted power and ‘minimize the influx of impurities into the plasma’.

The present version of NSTX-U-DOC-101 outlines the physics basis for Magnet Alignment Requirements, captured in NSTX-U-RQMT-RD-011, and proposes reduced heat fluxes to be included in a revision of NSTX-U-RQMT-SRD-003:

- The CASE#1 IBDH heat flux be reduced from 7.0 MW/m² to 6.5 MW/m²
- The CASE#1 OBDR1/R2 heat flux be reduced from 6.0 MW/m² to 5.4 MW/m²

These changes are based on accommodating the estimated enhancement to the heat flux only adding non-axisymmetric PFC features, e.g. fishscaling, and not the impact of non-axisymmetric plasma. NSTX-U-DOC-101 illustrates that for specified coil tolerances, the axisymmetric heat flux would have to be further reduced, for example to 5.5-5.8 MW/m² for IBDH depending on the chosen alignment.

This MEMO outlines a rationale to support that decision, effectively decoupling the PFC requirements that drive the tile design from the coil alignment. While this appears to be a step backward in system integration, the four findings delivered here demonstrate that modifications to the PFC requirements are not the ideal way to capture the impact of possible coil misalignments on the PFCs. Ultimately it will play a role in setting operational limits of NSTX-U as coil misalignments indeed can locally increase heat flux, as discussed in NSTX-U-DOC-101. But, it is important to remember that NSTX-U can generate heat fluxes and impact angles beyond those documented in the requirements, and presently there is no system in place to ensure NSTX-U operation is operated within limits set by the PFC System Requirements Document, which call on the NSTX-U structural design criteria. Thus, there is a functional need for a future activity to validate assumptions made in the PFC design process during early plasma operations which can include the effect of the as-built TF and PF coils.

F-1: Defining heat flux requirements based on coil alignment pre-assumes a design and decouples from PFC requirements from physics needs.

NSTX-U-DOC-101 outlines how PFC requirements that account for 3D field from TF/PF coil misalignments could be derived. From an estimated ultimate heat flux handling of 8 MW/m² applied uniformly to the surface, there is a lower axisymmetric heat flux limit in the presence of fishscaled tiles (6.5 MW/m² for IBDH) which has to be reduced even further if there are non-axisymmetric field effects (5.5 MW/m² for IBDH). The starting 8 MW/m² is derived from a semi-infinite heat flux simulation, assuming a particular set of graphite thermal properties reaching a specified critical temperature, in this case 1600 degC. It assumes that tiles are designed to be temperature limited instead of stress-limited. If the temperature limit or material were to change, or the tile design had to be altered from the present PDR concept, PFC requirements derived from coil tolerances would also change. Such a process has design defining requirements instead of requirements driving design and could iterate to a system that no longer can support the required physics mission.

F-2: Present methods to define requirements for PFCs to support non-axisymmetric heat flux do not accurately specify the expected conditions.

While vacuum field approximations have been used in NSTX-U-DOC-101 to estimate reasonable coil alignment tolerances for NSTX-U-RQMT-RD-011, there is a known deficiency in that they are limited to vacuum approximations. Results from M3D-C¹ modeling in PFCR-MEMO-006 indicated that plasma response was important for setting the IBDH heat flux enhancement, and code predictions were sensitive to input assumptions. Additionally, the coil alignment specification is a tolerance range and does not indicate where the installed coil positions would be. Lastly, the evolution of the coil positions, due to thermal settling following bake as well as creep, is not known. Together these results indicate we need to be aware that heat flux is expected to have a 3D component and its approximate magnitude in various scenarios. For example, NSTX-U-DOC-101 indicates that scenarios with low angles of incidence, ~1 deg, are affected the most, $\Delta q_{\text{PERP}} \sim 1.0 \text{ MW/m}^2$, which helps to evaluate impact during early operations.

F-3: If tiles are temperature limited, lowering the axisymmetric heat flux requirement is overly conservative if done to correct for non-axisymmetric PFC heat flux.

While not a specific requirement, the design intent of the high heat flux tiles is to make temperature limited, rather than stress limited tiles. The PDR designs have achieved this. That temperature limit reflects a difficult to derive requirement that the carbon influx from sublimation be limited to a rate that is tolerable with a given plasma. Since the latter is difficult to derive, the result is to assume some surface (1600 degC) and edge (2000 degC) temperature limits for PFCs. A literature survey summarized in PFCR-MEMO-003 showed these values to have wide uncertainties of ~300 degC. Coil alignments will result in increased temperatures, but in limited toroidal regions. This will peak the carbon influx rate in places, but integrated over the entire divertor surface it is less than would be implied by forcing the entire surface to be less than the divertor limit. In addition, designing tiles assuming axisymmetric heat flux still reflects the GRD requirement that PFCs ‘minimize the influx of impurities into the plasma’, unless the toroidal phase of the error field is knowable (and remains fixed) at installation and could be corrected. This is not presently expected.

F-4: 4.The impact of heat flux enhancements from coil misalignments be accounted for when evaluating PFCs during initial, low power plasma operation.

The work done in NSTX-U-DOC-101 has already driven updates to the PFC Diagnostics and Fueling Requirements (NSTX-U-TQMT-RD-004) to install redundant and toroidally dispersed thermocouples to assist in evaluating non-axisymmetric energy deposition. Future IR thermography system requirements

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would also expect to accommodate this in their design. There is an acknowledgement that PFC heat flux requirements are not as firm as others due to plasma physics uncertainty and the expectation that they cannot accommodate 100% of TSG requests. Thus, there is need, which is presently not captured in the Recovery project planning, to commission NSTX-U to confirm uncertainties assumed in the design (e.g. heat flux and halo currents, effective temperature limits) prior to pursuing operations that approach the facility limits. The need to characterize 3D heat flux patterns to understand effects of PF and TF coil misalignments should be added. This further reinforces the need to explicitly include time and resources for this activity. While likely not part of Recovery, work to prepare for this will be done in parallel to allow for execution in early NSTX-U operations.

To aid in judging how NSTX-U can be operated to stay within the design envelope of the PFCs with acceptable risk and measurement uncertainty it is important to differentiate between PFCs reaching temperature limit and stress allowable, typically $\frac{1}{2}$ ultimate per Section 2.5.2.4 of the NSTX Structure Design Criteria, NSTX-CRIT-0001-02. Maintaining NSTX-U PFCs is within the material stress allowable is arguably more important than keeping the surface below the temperature limit. Thus, for designs which are shown to be temperature limited, it is important to know at what load conditions they become stress limited.

References

defined within the document

Record of Changes

| Rev. | Date | Description of Changes |
|------|---------|--|
| 0 | 2/21/18 | Initial draft release to PFCR-WG for comment |
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