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

The document below captures viewpoints and discussions held within the PFCR Working Group related to impacts of coil misalignments on heat flux requirements. There was not a uniform consensus reached on where the impact should be accounted for within the Recovery Project, but there was agreement that the ability of NSTX-U PFCs to sustain plasmas that meet high level machine goals (e.g. 2 MA, 1 T, 10 MW, 5 sec) needs to be better documented in the context of heat flux enhancements due to coil misalignments that were not known when the original version of the PFC System Requirements Document flowed down from the Topical Science Group MEMOs (PFCR-MEMO-008, -009, -010).

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 on assumptions of axisymmetric heat flux from the plasma, unambiguously defining load conditions. At a minimum, the heat flux requirement should accommodate enhancement factors due to geometry, but there is not a Working Group consensus on if the requirement should account for an enhancement factor due to coil misalignments.

B. To ensure there remains a metric for evaluating how 3D fields (and other integration uncertainties) impact the likelihood that high level machine goals can still be met using the requested PFCs, the PFCR-WG/Recovery should develop a probabalistic approach that combines engineering and physics uncertainties.

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 PFCs become stress limited.

Findings

1. The methods used in NSTX-U-DOC-101 to define heat flux requirements based on coil alignment pre-assumes a design and decouples 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. There is substantive physics uncertainty in evaluating the impact of 3D heat flux on making sure NSTX-U can achieve whole machine performance.

4. The impact of heat flux enhancements from coil misalignments should be accounted for along with physics uncertainty when evaluating if PFCs can support high level machine goals

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/m^2 to 6.5 MW/m^2
- The CASE#1 OBDR1/R2 heat flux be reduced from 6.0 MW/m^2 to 5.4 MW/m^2

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 be further reduced, for example to 5.5-5.8 MW/m^2 for IBDH depending on the chosen alignment.

There is partial support within the Working Group for the NSTX-U-DOC-101 recommendations, but concern that it decouples the PFC requirements that drive the tile design from the coil alignment. While this appears to be a step backward in system integration, suggesting there is no flow down from the machine level requirements to the system level requirements, the four findings delivered here suggest that modifications to the PFC requirements are not the ideal way to capture the impact of possible coil misalignments on the PFCs. Ultimately, the later will play a role in setting operational limits of NSTX-U as coil mis-alignments 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 ensure NSTX-U operation is operated within limits set by 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 should include the effect of the as-built TF and PF coils. Currently, these remain as coupled physics and engineering uncertainties that impact the prediction of a given plasma operational scenario being successful.

F-1: The methods used in NSTX-U-DOC-101 to define 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. There is the nominal heat flux out of the plasma which challenges the tile in the same way as a theoretical uniform surface flux would. For example, if the IBDH was qualified to handle 8 MW/m^2 applied as a uniform surface load, the "equivalent effective" heat flux would drop to 6.5 MW/m^2 with consideration of specific choice of fishscaling, tile gaps, and plasma impingement direction. This effective heat flux would drop further from axisymmetric effects, the magnitude of which depending on the as-built/installed coils. The methods outlined in NSTX-U-DOC-101 suggest this could be as low as 5.5 MW/m^2 The starting 8 MW/m^2 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 PFC heat flux requirement 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-C^1 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 is not known. Together these results indicate that at the design stage 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, Δq_{PERP} ~1.0 MW/m^2, which has driven a toroidally dispersed placement of thermocouples in high heat flux PFCs (NSTX-U-RQMT-RD-004). Final metrology and early operations are required to determine the final as-built conditions. These will set NSTX-U operations limits, not design requirements.

F-3: There is substantive physics uncertainty in evaluating the impact of 3D heat flux on making sure NSTX-U can achieve integrated machine performance.

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 are thought to have achieved this. That temperature limit reflects a 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 having the entire surface at the 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. In addition to the uncertainty in the temperature limit, there are uncertainties in the allowable radiation fraction which is what would be increased at higher surface temperatures due to carbon influx.

F-4: The impact of heat flux enhancements from coil misalignments should be accounted for along with physics uncertainty when evaluating if PFCs can support high level machine goals.

The implications of non-axisymmetric heat flux need to be retained with the Recovery Project and assurances made to the sponsor and fusion community that PFCs designs can support the NSTX-U mission. NSTX-U-DOC-101 has already driven updates to the PFC Diagnostics and Fueling Requirements for thermocouples to assist in evaluating non-axisymmetric energy deposition. Future IR thermography system requirements would also expect to accommodate this in their design. We should also acknowledge that PFC heat flux requirements are not as firm as others due to plasma physics uncertainty (e.g. λ_q, S, f_{RAD}, T_{LIMIT}) and the expectation that PFCs cannot accommodate 100% of TSG requests. Thus, there is need, which is presently not captured to continue to evaluate the likelihood that research goals can be met given physics uncertainty and present and future system integration tolerances. It will be important to continue to ensure that the high level (e.g. 2 MA, 5 seconds, 10 MW, 1 T) scenario continues to be supportable. A probabilistic approach, extending on NSTX-U-DOC-101 seems feasible for power exhaust questions for the PFCs and may help identify and be useful in resolving potential design questions.

To aid in judging how NSTX-U can be operated to stay within the design envelope of the PFCs with acceptable risk and physics uncertainty it is important to differentiate between PFCs reaching temperature limit and stress allowable, typically ½ 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
1	2/23/18	Revisions to R-A, R-B, F-3 and F-4 which emphasize the need for a risk-based approach to combine physics and engineering uncertainty for evaluating the ability to claim machine performance is possible within tolerances.
2	3/15/18	Revisions to F-1, R-A and the addition of the intro text before the recommendations to highlight the lack of WG consensus. Minor wording fixes.