

National Spherical Torus eXperiment Upgrade

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SUBJECT: RESPONSE TO EOC INTERIM REPORT [R12] AND [R34]

The interim report for the Extent of Condition has two recommendations related to the deployment of monitoring and protection systems for the plasma facing components, [R12] and [R34], the text of which is given below.

R12 Deploy IR cameras (and similar devices) viewing in-vessel components to provide real-time monitoring and protection against excessive tile temperatures.

R34 Provisions must be incorporated in DCPS or a similar system for real time control actions to be based upon the signals from new tile monitoring diagnostics.

These activities fall within the charges given to the PFC Performance and Monitoring Requirements Working Group (PFCR-WG) which are to develop an “instrumentation plan for intra- and inter-shot PFC monitoring” (3a) and give “guidance on how to best integrate monitoring with operations” (3c). This memo outlines the reasoning to reach the following conclusion in response:

The requirement to develop and deploy a DCPS-like, intra-shot, real-time protection system for PFCs would be unprecedented for a NSTX-U class facility and should not be pursued. An intra-shot, PCS-based control system using real-time PFC temperature data should be considered only if tile designs in high heat flux areas remain stress-limited. In contrast if PFCs are shown to be surface temperature limited, leading to sublimation or ‘carbon bloom’, then marginally exceeding the design requirements would not risk mechanical failure and significant operational down-time. For surface temperature limited tiles, a detailed instrumentation plan for inter-shot monitoring as well as operations and commissioning procedures would be sufficient.

To start, we define the difference between protection, control and monitoring systems for the purposes of this discussion. A protection system is assumed to have a measurement and reaction layer that is independent from shot-to-shot human interfaces and the Plasma Control System (PCS), the latter of which performs actions in real-time such as ramping the plasma current, maintaining plasma shape and controlling the input power. An example of a protection system on NSTX-U is the Digital Coil Protection System (DCPS), which is discussed in more detail in its System Design Description, NSTX-U-SDD-RTC+P-R0. The DCPS has a detailed, version controlled set of algorithms developed to prevent damage to the coils and can take a single action – raise a Level 1 fault that results in disabling the power systems. A PCS-based control approach would likely consist of real-time measurement of tile temperatures, through tools like IR thermography. These would be interface with PCS and

algorithms developed to avoid exceeding temperature limits or define remedial action if temperatures cross given limits. The Chief Operating Engineer (COE), Physics Operators (PO) or diagnosticians investigating tile temperatures between shots, for example via thermocouples or IR thermography, is considered here to be monitoring since it is unreliable (i.e. a human factor) and post-hoc, although it may be referred to as protection in other documentation within the Recovery Project. The cost and schedule implications, as well as the impact on experimental flexibility and reliability, of having a DCPS-like protection system for PFCs are not known at this time, but they are expected to be larger than an intra-shot, PCS-based control system or an inter-shot, personnel-based monitoring system.

Systems to avoid overheating plasma facing components (PFCs) were recently (non-exhaustively) surveyed to gain insight into possible actions in response to [R12] and [R34]. The JET, ASDEX Upgrade and WEST tokamaks all have high-Z plasma facing components that can permanently deform (i.e. melt) from transient overheating. To protect this investment, these devices have real-time, camera-based NIR/IR monitoring. To reduce the complexity of real-time image analysis, camera data typically have regions of interest (ROI) pre-defined where a real-time analysis communicates potential overheating and in some cases remedial action back to their version of PCS. None of these facilities has a protection system for the PFCs, as defined above, and it is always up to PCS to define a response such as reducing heating power or shutting down the discharge. In addition WEST benefits from calorimetry interlocks on water-cooled components due to its expected operation as a long-pulse facility. We are also currently unaware of any short pulse tokamak with inertially cooled, carbon-based PFCs that requires an intra-shot control system and no facility that requires an intra-shot protection system. Historically, major US devices (NSTX, Alcator C-Mod and DIII-D) have never been run with a control system, and inter-shot monitoring has not been standardized or strictly enforced. For example, melting of high-Z PFCs on Alcator C-Mod had occurred despite inter-shot calorimetry being available as it was used to guide but not direct shot-to-shot actions.

We conclude that requiring a real-time protection system for PFCs forces NSTX-U to operate unlike any other facility of its class, in the U.S. or internationally, and is unjustified.

A control system that uses real-time temperature estimates, linked to the PCS, has been used on NSTX-U class devices but is generally driven by the failure mode of the PFCs. For high-Z PFCs, if the tile melts then either an entry into the device to replace a tile must be done, or operations of the machine must be adjusted to avoid this area until an entry can be scheduled. On C-Mod operation of certain magnetic geometries were curtailed after a mid-campaign failure of the tungsten lamella in FY09. Additionally, JET intentionally installed a mis-aligned tile for melt experiments, but well away from normal strike point operations. This

motivates why JET, AUG and WEST operate with an intra-shot monitoring system: to prevent melt damage from impacting operations.

For carbon, sublimation occurs rather than melting and the long-term surface distortion is expected to be negligible. Here, 'surface temperature limited' tile designs are those where sublimation results in plasma contamination by carbon, leading to a disruption or a PCS-controlled shutdown prior to mechanical failure of the tiles. This so-called 'carbon bloom' acts as a soft failure limit, although repeatedly encountering it should not be encouraged as this reduces the scientific efficiency of the facility. The exact temperature (and tile surface extent) at which sublimation impacts operations is under discussion. MAST-U has chosen to design tiles to 1300 °C the JET MK-II divertor used 1600 °C, and both projects shaped tiles to avoid leading edges. Higher temperatures of 1800-2200 °C have been observed in the literature for other devices. In contrast, we refer to designs as 'stress-limited' when a tensile/compressive limit in the material is reached prior to the sublimation process overwhelming the discharge. This could result in macroscopic pieces of the tile being removed or relocated, risking further damage and impacting subsequent operations. This results in either a short-term outage to remove debris, similar to the FY16 stoppage of NSTX-U to remove the BES shutter from the IBDH surface, or a longer outage with personnel access to replace tiles.

It is presently thought that the IBDH tiles with a front-surface, T-bar based mounting scheme is a type of stress-limited design, as discussed in NSTXU-CALC-11-03-01. New designs are being investigated as part of the Recovery Project that would both meet updated heat flux handling requirements (NSTX-RQMT-RD-002-XX) and be surface temperature limited. The safety margin between operating conditions that would violate a stress limit versus reaching an active (via intra-shot control) or passive (via carbon bloom) surface temperature limit is important to consider as part of any new design. Too little of a gap between the two means that uncertainty in the pre-shot estimate of experimental heat flux, unexpected shot-to-shot variation or tile-to-tile variations could risk macroscopic damage to the tiles. If this were the case, then an intra-shot control system using PCS would be required for a range of high power NSTX-U operations. If the gap is sufficiently large, then inter-shot monitoring coupled with operational procedures is all that should be needed to significantly reduce the risk of PFC failure. Estimates of expected temperature rise can be computed before the shot to ensure that when added to the pre-shot temperature, the surface temperature limit is not reached. The margin to the stress-limit acts as a buffer for uncertainty and the 'carbon bloom' acts as a passive safety system. Procedures for increasing the power shot-to-shot within configurations would allow the pre-shot estimates to be confirmed. This scheme would benefit from off-line testing of tile behavior as heat fluxes approach those that would lead to stress-limits. An instrumentation plan would need to be developed to ensure inter-shot PFC monitoring would have sufficient coverage of the full NSTX-U installation.

We conclude that if an improved tile design can be implemented that is surface temperature limited and has a meaningful safety margin before reaching a stress limit, only an inter-shot PFC monitoring system is required. If not, then a PCS-based intra-shot control system that uses real-time PFC temperature measurements should be strongly considered.

The development, implementation and *adherence to* inter-shot monitoring of the PFC temperatures is not a trivial task. But, much of this work can be done in parallel to PFC design, fabrication and installation. Further MEMOs on this topic are expected from the PFCR-WG as this relates directly to its charges. This would likely include discussion of:

- NSTX-U or off-line testing to confirm thermal modeling of tiles
- pre-shot check of scenarios above some heating/duration/plasma current thresholds to ensure they are within the tile design limits
- post-shot check of achieved conditions against pre-shot expectations, confirming results or exploring differences
- ‘playbook’ of next-shot changes to avoid repeatedly hitting a ‘carbon-bloom’ limit, minimizing impact on experimental goals (i.e. strike point sweeps, gas injection, etc)

Regardless of inclusion of real-time temperature measurements, the PCS system will likely need to be upgraded to ensure that sufficient equilibrium information is constrained to be within the tile requirements, such as ensuring the angle of incidence and strike point positions.

Record of Changes

Rev.	Date	Description of Changes
0	4/17/2017	Initial draft release to PFCR-WG
1	5/2/2017	Grammar/typo fixes and changed language to from “intra-shot monitoring” to “intra-shot control” to distinguish PCS-based approaches versus COE/PO based monitoring. Inclusion of comments regarding real-time equilibrium