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Modification of the NSTX-U Outboard and Inboard Divertor Tiles for the Protection of the PF-1C Coils

K. Tresemer, S. Gerhardt, A. Brooks, A. Jariwala, R. Raman, P. Titus
Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA
Corresponding Author: ktreseme@pppl.gov

Abstract*—The National Spherical Torus Experiment (NSTX) is a low aspect ratio, spherical torus (ST) located at the Princeton Plasma Physics Laboratory (PPPL). Its Centerstack Assembly (CSA) consists of the inner legs of the Toroidal Field windings, the Ohmic Heating solenoid, the inner Poloidal Field (PF) coils, thermal insulation, diagnostics, and an Inconel casing which forms the inner wall of the vacuum vessel boundary. The outside surface of this casing is protected from the heat loads by a layer of Plasma Facing Components (PFCs), in this case, a combination of ATJ and POCO TM graphite. The CSA is electrically isolated from the outer, large major radius part of the vacuum chamber by ceramic insulators. The gaps at the top and bottom of the machine between the CSA and the outer vessel are known as the "Coaxial Helicity Injection (CHI) Gaps". The PF-1C divertor coils are located in this region shadowed by the CHI gap, however, late in the design of the NSTX Upgrade PFCs, MHD equilibria were discovered which could direct field lines through these CHI gaps and onto the PF-1C stainless steel casings. This could result in thermal flux from the main plasma body to flow along the field lines directly onto the coil. Though the probability of such an event is low, the heat flux on the 0.125" thick stainless steel casing could damage the coil beneath, or in worst case, rupture the casing itself, resulting in an accidental vent of the vacuum vessel. By extending downward the overhanging edge of the row 1 PFCs on the Outboard Divertor (OBD) and the Inboard Divertor (IBD) and by increasing their outermost radii, effectively narrowing the CHI gap, this should provide significant protection to the PF-1C casing.

***Keywords*—NSTX-U; Plasma-Facing Components; PF-1C; Poloidal Field Coils; CHI Gap; Coaxial Helicity Injection**

I. INTRODUCTION & BACKGROUND

A. The CHI Gap

Coaxial helicity injection (CHI) is a technique used to produce the initial plasma and to provide enough toroidal plasma current to study other methods of non-inductive current generation and sustainment. This is done by running a voltage (1-2 kV) between the electrically-isolated inner and outer divertor flanges and puffing in a small amount of deuterium gas. A discharge consequently forms between the two flanges and, when subjected to a toroidal field, propagates vertically though the gap and vessel as the plasma current peaks [1]. The gap between the inner and outer vessel, required by CHI, is called the "CHI gap". Given that the discharge depends sensitively on the distance between the inner and outer flanges, the narrowest dimension within this gap was required to be no smaller than 0.75".

B. Emergence of a Problem

Early in 2012, an opportunity arose to design shielding for the horizontal surface of the Outboard Divertor (OBD) vacuum flange. Due to some thermal discoloration and small evidence of sputtering, it was determined that this stainless steel surface experienced some significant heating. During the preliminary analysis of the field lines in this area, it became clear that during certain coil scenarios, there existed MHD equilibria which caused a steepening of the field lines at the CHI Gap and moved the Outboard Strike Point (OSP) not only on top of the OBD flange, but also onto the stainless steel casing of the PF-1C Coil. (Fig.1).Though the probability of these equilibria occurring during normal NSTX operations is low, the risks associated with such an event are significant. The Polodial Field Coil 1-C is a new addition to the NSTX coils, part of the NSTX upgrade project [2]. Its location at the base and top of the Centerstack Assembly (CSA) allows for enhanced control of the magnetic fields and consequently, the plasma, which will increase the experimental capabilities of the machine. The PF-1C casing is constructed from 0.125" thick stainless steel and serves two purposes: it acts as a mold for the vacuum pressure impregnation phase of the coil manufacturing and then, once a panel is welded into place, the casing becomes the boundary between the coil and the vacuum of the vessel. In order to act as a vacuum boundary, the mold is vacuum welded at the top corner. Unfortunately, this weld is one of the areas on the casing that seems to see a large convergence of field line scenarios (Fig.2).

Fig. 1. OSP resting on the PF-1C casing. Notice the steep angle of incidence in the field lines.

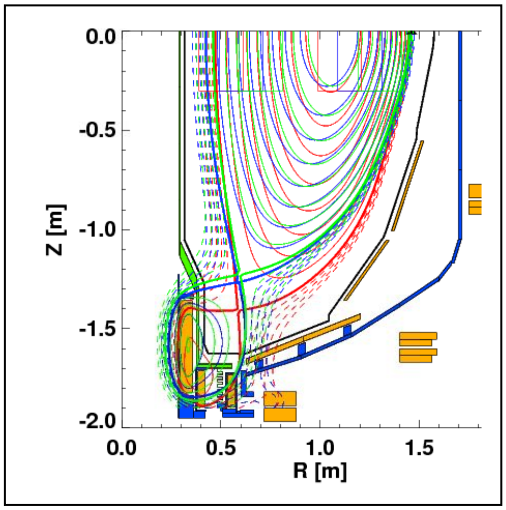

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Fig. 2. Position of PF-1C coil and vacuum weld in reference to CHI gap.

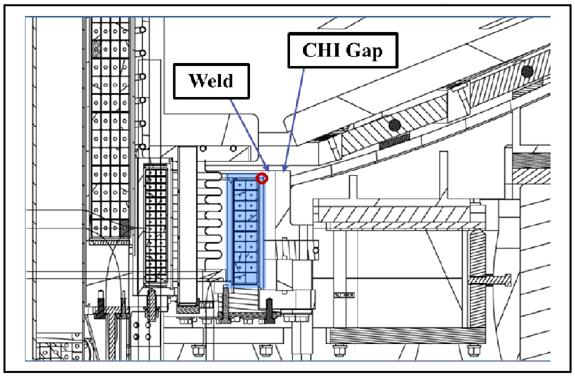
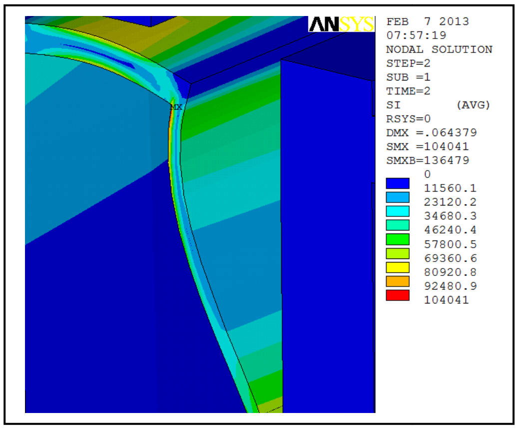


Fig. 3. Concentrated stresses in the PF-1C vacuum weld due to plasma heat deposition. (Assumes 200C peak casing temperature)



If the casing experiences high heat flux, there are at least two possible failure modes. In the first scenario, vacuum weld might undergo softening and melting from direct OSP exposure, leading to a leak in the weld material. In the second scenario, the side of the casing may see heating and, through expansion of the metal, would exert significant mechanical forces on the weld (Fig. 3), causing failure of the weld material over time from fatigue. Both of these failure modes come with a high cost of repair. The PF-1C coil is not accessible without removing the CSA, and even then, is still difficult to reach. A large enough leak on the casing would effectively halt experimentation, force a pre-mature venting of the vacuum vessel, and require months of work to correct the leak. For these reasons, this problem underwent many weeks of review and design effort to find a solution

II. HEAT FLUX AMELIORATION & ADDITIONAL DIAGNOSTICS

A. Shields

A solution was needed that would protect all the surfaces in the CHI gap without narrowing the gap beyond its design limit, yet be affordable and minimize negative impact to the NSTX upgrade schedule. The solution to shield the OBD flange from field line impingement was simple: a TZM plate could be easily built from on-hand stock and bolted into place. However, protecting the sensitive PF-1C casing and coil was not so simple and would need additional design. Initial design modifications to protect the PF-1C included mounting a thin TZM molybdenum shield to the PF-1C casing. TZM, with its high thermal conductance and elevated melting point, is an excellent thermal shielding material. A TZM shield would allow any "hot spots" generated by the OSP to be wicked away from the strike point and perhaps limit localized melting and lower stress concentrations. Unfortunately, there were several problems with this proposal. It proved to be quite difficult to attach a thin metal shield to the PF-1C casing. Space constraints were extremely tight in the areas above and below the PF-1C coil and casing and the design was limited by the requirement to maintain the 0.75" width of the CHI gap so as not to interfere with its operational parameters. Additional problems arose when a design was produced and modeled. It was discovered that a TZM shield would be complicated to fabricate, time-consuming to install, prohibitively costly, and would suffer the same problems (weld melting, low-cycle fatigue) as the stainless steel casing it would protect, necessitating a maintenance and repair program. Therefore, this line of protection for the PF-1C coil was abandoned.

Fig. 4. OBD and IBD tile configuration prior to design changes.

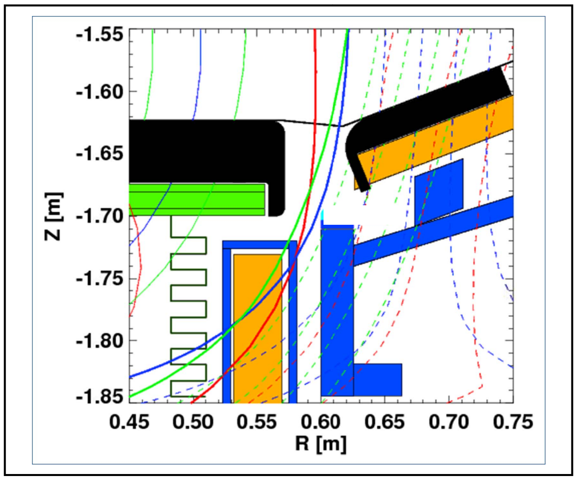
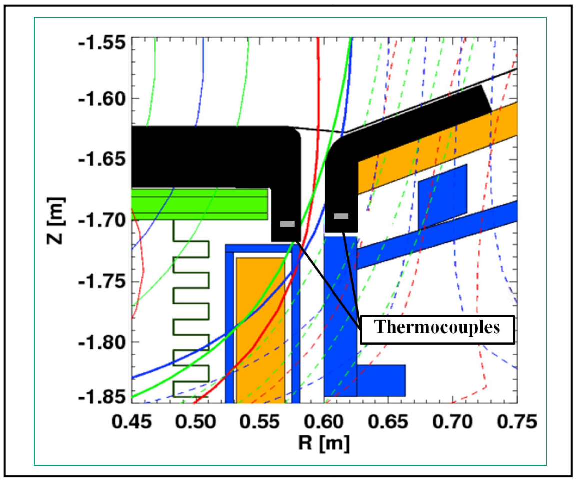


Fig. 5. OBD and IBD tile configuration after design changes. (Lower divertor)



B. Tiles

A more-promising solution was found by modifying the ATJ graphite Plasma-facing Components (PFCs) which line both tops of the inboard and outboard sections of the divertor. These tiles already featured a “bull nose”-style edge, which wrapped around their respective flanges to guard against plasma interaction with the metal beneath (Fig. 4). By increasing the profile of these “bull noses”, it was possible to shield the PF-1C from a large percentage of field lines. The edge of the Inboard Divertor (IBD) tiles was extended out to R22.875” and the lower divertor tiles’ thickness increased an additional 0.675” to meet up with the top of the PF-1C casing. The upper divertor tiles could not be thickened in this way, as the CS undergoes significant thermal growth during bakeout and operations and space between the upper IBD flange and the PF-1C coil needed to be preserved. The OBD tile edges were also extended into the CHI Gap, to R23.625” and thickened down to meet the OBD flange below (Fig. 5).

There were significant benefits from adopting a PF-1C protection scheme based on tile modifications. These tiles, once part of a larger fabrication package, were pulled from production without negative impact to the NSTX upgrade schedule due to the fact that the row 1 IBD and OBD tiles are one of the final components installed in NSTX, just prior to final vessel pump down and bakeout. This resulted in enormous cost-savings in terms of material procurement and designer time, as well as practically no interruption to the upgrade schedule.

Fig. 6. Thermal distribution on OBD and IBD tiles after a given time and the locations of future thermocouples.

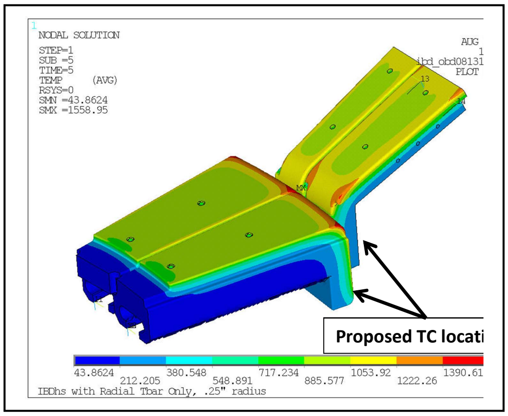
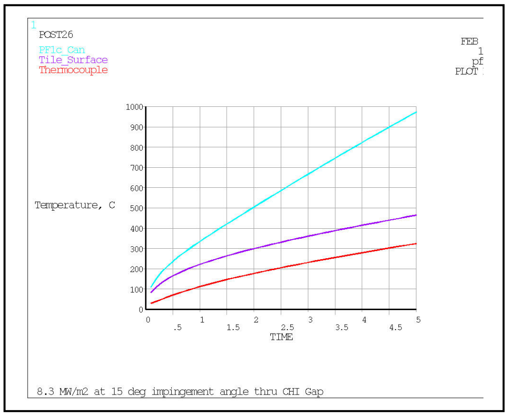


Fig. 7. Thermal ratcheting of the casing, PFC, and thermocouple, for 8.3MW/m^2 assumed heat flux.



C. Magnetics

The modifications to the IBD and OBD PFC tiles should successfully ameliorate the heat flux on the PF-1C casing for most cases. However, there exist scenarios that still expose the casing to high heat fluxes. Modification of the coil operation protocols will be needed to ensure that PF-1C is never threatened. This, along with the mechanical changes outlined in this paper, should provide adequate protection to the PF-1C coil.

D. CHI Gap Diagnostic Support

Though it is known that the OSP will pass over the CHI gap, the actual magnitude of heat deposition from the strike point is not perfectly understood. That is why, for the upgrade of NSTX, the number of thermocouples imbedded in the IBD row 1 tiles has been increased. This also justified the addition of thermocouples to both the OBD and IBD, CHI-facing surfaces. This thermal feedback will be useful in gathering empirical data about the heat flux on these surfaces during normal operations (Fig. 6 & Fig. 7).

III. SUMMARY

This paper has covered the process through which a potentially critical design issue concerning the unprotected interaction of the OSP on the PF-1C stainless steel casing was identified, assessed for risk, and resolved through mechanical design and magnetic protocol guidance. Through simple alterations to the OBD and IBD tile geometries, most of the threatening field line scenarios were eliminated. With additional planning and guidance to operations, any additional problems with errant strike points can be remedied with magnetic control. Adequate diagnostic monitoring of this zone has been implemented or planned for the immediate future and there has been very little negative impact to the schedule or budget of the NSTX upgrade effort.

ACKNOWLEDGMENT

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Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2245
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov