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Preliminary Neutronics Analysis of ITER Tip Diagnostic Corner Cube Retroreflectors

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PRELIMINARY NEUTRONICS ANALYSIS OF ITER TIP DIAGNOSTIC CORNER CUBE RETROREFLECTORS

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ITER is an international project under construction in France that will demonstrate nuclear fusion at a power plant-relevant scale. The Toroidal Interferometer and Polarimeter (TIP) Diagnostic will be used to measure the plasma electron line density along 5 laser-beam chords. This line-averaged density measurement will be input to the ITER feedback-control system. The TIP is considered the primary diagnostic for these measurements, which are needed for basic ITER machine control. Therefore, system reliability & accuracy is a critical element in TIP's design.

There are two major challenges to the reliability of the TIP system. First is the survivability and performance of in-vessel optics and second is maintaining optical alignment over long optical paths and large vessel movements. Both of these issues greatly depend on minimizing the overall distortion due to neutron & gamma heating of the Corner Cube Retroreflectors (CCRs). These are small optical mirrors embedded in five locations in the vacuum vessel wall, corresponding to certain plasma tangency radii. During the development of the design and location of these CCRs, several iterations of neutronics analyses were performed to determine and minimize the total distortion due to nuclear heating of the CCRs.

I. THE TIP DIAGNOSTIC

The primary goal of ITER's Toroidal Interferometer/Polarimeter (TIP) is to measure chord-averaged electron density along 5 distinct channels in the plasma. Each channel corresponds with a certain tangency radius and uses a corner-cube retro-reflector (CCR) embedded in the vacuum vessel wall to return the signal. (Fig. 1.) This information will be used for active machine control and thus reliability and signal consistency are critical to the successful design of this system.[1]

Interferometers can provide very precise estimates of plasma density, provided the environment is stable and there are negligible signal perturbations. The basic principle relies on the sampling of two unique optical paths where one is affected by the plasma. The resulting different path lengths can be interpreted as a sequence of light and dark bands, or fringes, by the photo detector.[2] However, in a challenging environment such as the one ITER is expected to experience, issues such as vibrations which affect signal integrity, vacuum vessel geometry fluctuations which interfere with the signal path length, causing "fringe skips", and temperature gradients in the CCRs which cause signal misalignment during operations.

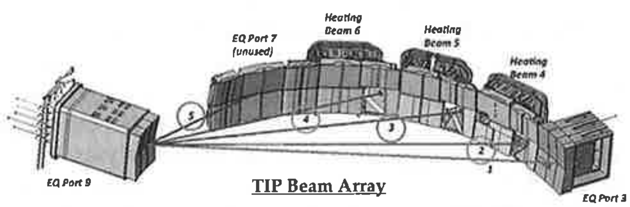

Fig. 1. TIP Beam Array with Channels (Ref. 1)

To remedy the vibration issue, the laser interferometry system uses two lasers of different colors per signal and compares between the two beams (a two-color system, 10.6 and 5.3 μm). The fluctuation in the geometry of the vacuum vessel size is compensated by using the polarimetry system as a coarse estimate, which reduces fringe skip error. However, signal loss due to temperature gradients in the CCRs from nuclear and radiant heating cannot be fully corrected during operation, and the CCRs must be analyzed to ensure they function in the ITER environment.

I.A. The Corner Cube Retroreflector

I.A.1. CCR Design

The Corner Cube Retroreflectors are made of three 120-degree segments, semi-kinematically bolted together, and mounted to the vacuum vessel via a central bolt and Belleville washer system. (Fig. 2.) The design allows the CCRs to be cooled via conduction to the surfaces to which they are attached.

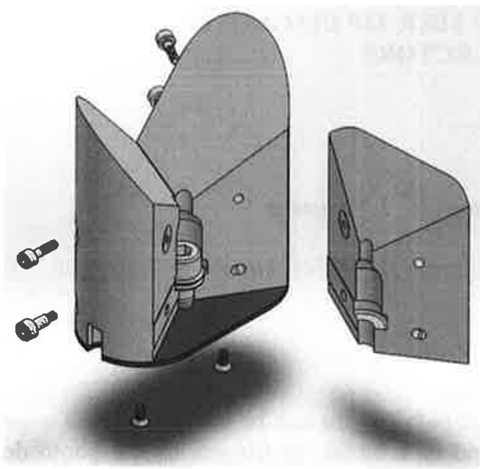

Fig. 2. Model of the CCR, showing internal mounting details. (Ref. 3)

I.A.2. CCR Materials

Material selection for the CCRs is an important consideration. Materials must be vacuum compatible, approved by the ITER organization for in-vessel use, and must have a low α/k ratio to minimize the thermal deformation in the parts. Of the few materials which meet these requirements, Copper and Beryllium seem the most suitable. Cu is a better thermal conductor by far, but has a higher gamma cross section than Be. Early analyses showed that, in several locations, up to half of the nuclear heating in the CCRs is a result of gamma radiation, Be is the best material for CCRs which lack sufficient gamma shielding, though Cu will be used when feasible. (Fig. 3)

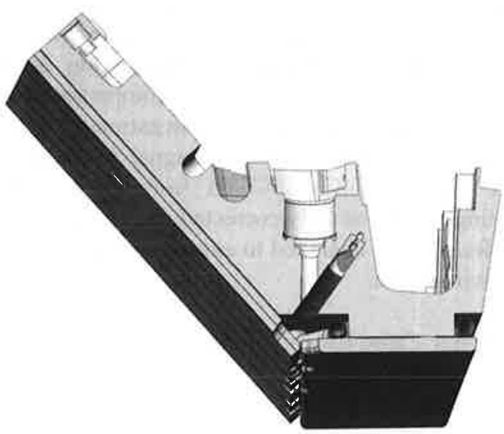

Fig. 3. Channel 2 location in vacuum vessel wall.

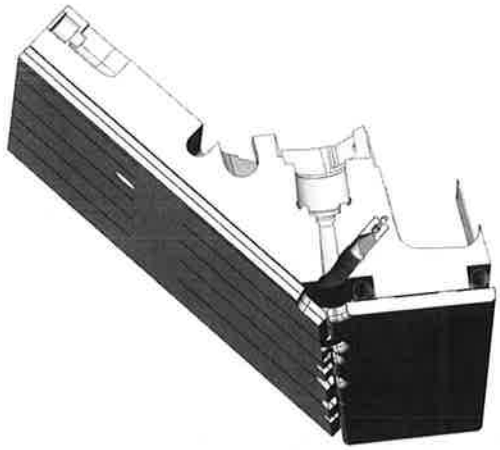

Fig. 4. Channel 3 location in vacuum vessel wall.

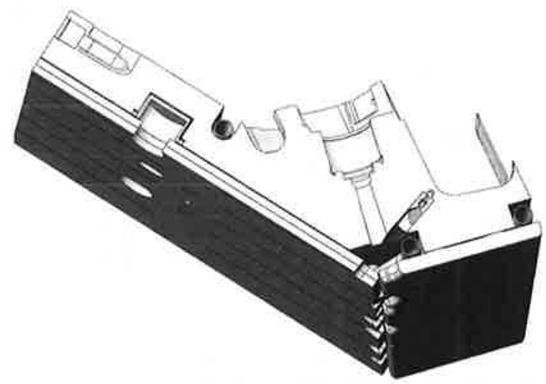

Fig. 5. Channel 4 location in vacuum vessel wall.

I.A.3. Critical CCR Design Requirements

Due to the fact that the TIP diagnostic will be used for active machine control, it is crucial to preserve signal integrity. A major contributor to this issue springs from the thermal distortion in the CCR due to radiant and nuclear heating. If sufficient mechanical distortion is achieved, the interferometry signal could be lost completely. The design of the CCR sees a "mushroom" effect if thermally loaded, when the lobes of the optic bloom apart. The distortion limit has been defined by the ITER organization as $\lambda/20$, peak-to-valley, where λ is the wavelength of the incident diagnostic beam.[3]

There are presently two types of thermal loading on the CCRs: radiant and nuclear. Radiant heating is attributed mainly to Bremsstrahlung radiation and some charge-exchange neutral atoms. The CCR depth from the plasma and the texturing of the walls of the CCR passage varies the total radiant heat load depending on the CCR, but a worst-case loading of. 0.5 W/cm^2 has been assumed for this analysis.

Nuclear heating in the CCRs, both for neutrons and gammas, is significantly impacted by how deeply the CCR is embedded into the vacuum vessel wall and how much shielding is between the optic and the plasma. This depth varies widely across all five TIP channels with Channel 2 being the median depth. It was for this reason that this paper uses Channel 2 as an example of the probable nuclear heating loads on the CCR.

II. ANALYSIS & RESULTS

A nuclear heating analysis was performed using Attila[5] with volume source information from the most current ITER models. This analysis confirmed that, for Channel 2, approximately half the nuclear heating is due to gamma radiation. (Fig. 6)

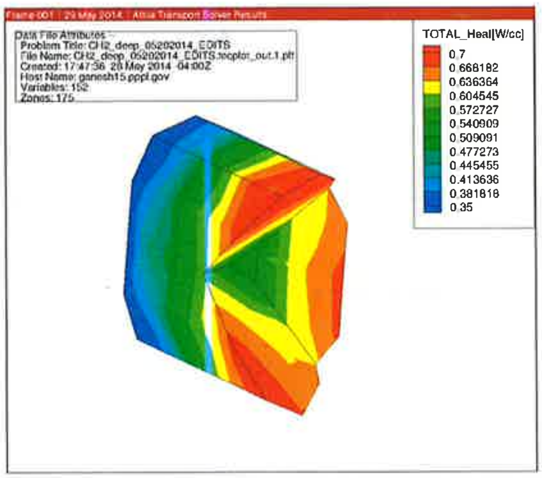

Fig. 6. Total nuclear heating results (gamma & neutrons) from Attila (Ref. 3)

These nuclear heating loads were transferred to a mesh in ANSYS, combined with the radiant heating loads (0.5 W/cm^2), and then applied to a thermo-mechanical model (Fig. 7) to estimate the total thermal deformation across the Channel 2 CCR. (Fig. 8)

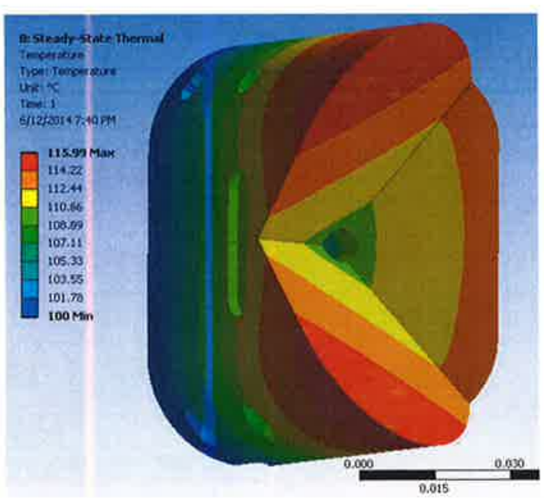

Fig. 7. Heating in CCR due to nuclear heating. A 100°C temperature was applied to the rear of the model. (Ref. 3)

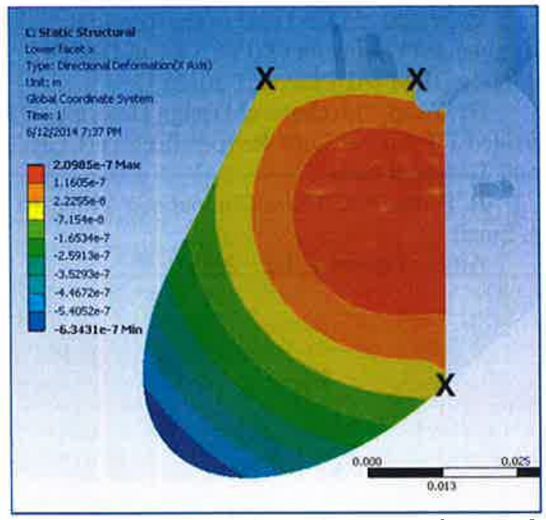

Fig. 8. Peak-to-valley deformation across face (Ref. 3)

The TIP diagnostic has a requirement that the peak-to-valley deformation not exceed $\lambda/20$.[3] Thus, for the smaller of the two beams (5.3 μm), we have a working limit of .26 μm for the thermal deformation. Figure 6 shows that Channel 2 CCR meets this requirement, but just barely.

III. CONCLUSIONS

The combined results from the neutronic and thermo-mechanic analyses supported the conclusion that the Channel 2 CCR will meet the requirements for minimum thermal deformation for the TIP Diagnostic. However, there are two additional channels (Channels 3 & 4) which are located at smaller radial positions and have even less shielding. These initial results for Channel 2 suggest that the CCRs associated with these other channels might be at risk of higher than allowable thermal deformation, and therefore might lose signal during operation. It would be prudent to apply further analysis to this issue, perhaps looking into what controls can be applied to the TIP system to absorb some of the thermal misalignment.

ACKNOWLEDGMENTS

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