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# Structural Thermal Optical Performance (STOP) analysis method for optical components of megawatt electron cyclotron heating systems

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**Abstract**
Large scale tokamak fusion reactors such as ITER require precise deposition of high-power mm-wave beams to control certain instabilities in their plasma, such as a Neo-Classical Tearing Mode (NTM). The ITER fusion reactor has therefore strict beam deposition requirements imposed on its optical system that steers and focuses up to 6.7 MW in mm-wave beams. This work investigates the effect of thermally induced deformations on these beam deposition requirements. To link the effect of the thermal deformation to the optical system requirements, a Ray Heated (RH) Structural Thermal Optical Performance (STOP) model has been developed. The modelling approach is applied to a Simplified Multi-Mirror (SMM) model of the ITER reference design. The results of the study demonstrate the necessity of the RH-STOP model approach and shows that the Gaussian beam waist of the SMM simulations differs significantly from the required shape of the ITER optical system.

Nuclear fusion, Mirror, Structural analysis, Thermal analysis, Optical performance, STOP, High power.

## 1. Introduction

Nuclear fusion reactors can provide a stable renewable energy source by harnessing the energy emitted when two hydrogen isotopes fuse together. To facilitate this reaction, an extremely hot plasma is required. In this plasma, instabilities can develop because of slight perturbations of the plasma current. The suppression of these instabilities is essential for the effective operation of a large-scale fusion reactor. In the ITER fusion reactor, one particular form of these instabilities, the Neo-Classical Tearing Mode (NTM) takes the form of small magnetic islands rotating around the tokamak plasma [1]. To supress these islands high power electron cyclotron (EC) radiation needs to be deposited at (sub-)centimetre precision inside these magnetic islands [2]. The current optical system tasked with this requirement, the upper launcher (UL), must therefore focus and steer up to 6.7 MW in mm-wave beam using four mirrors [3], see Fig. 1. Given these extreme thermal loads and the importance of instability suppression, a detailed analysis of the optical system performance under thermal disturbance is required. This work therefore presents a detailed methodology to assess the influence of thermally induced deformations on the optical performance through the developed Ray Heated Structural Thermal Optical Performance (RH-STOP) model. This model structure is an extension of the original STOP model approach [4]. The method is demonstrated on a 3-dimensional simplified multi-mirror (SMM) model of the detailed ITER UL design [5, 6].

## 2. Modelling approach

Due to the extreme power of the mm-wave beams requires that the thermal analysis of the ITER-UL cannot assume the thermal expansion of the mirror surface to be independent of mm-wave power deposition, schematically illustrated in Fig. 2. Hence, a modelling approach that incorporates the effect of mirror heating due to changing beam losses is required to capture the realistic optical performance. The steady state RH-STOP model approach operates as a loop of five sequential steps: (i) Solve for the thermal equilibrium of the system given the different thermal loads. (ii) Translate the temperature distribution into thermal expansion. (iii) Apply this thermal expansion as an input to the structural model, along with the additional mechanical loads, and deform the mirror geometry accordingly. (iv) Perform a ray tracing analysis on the deformed geometry. (v) Use the new ray positions to assess both the new ray output profile of the optical system and the new ray positions on the mirror surfaces and hence location of their new thermal load input. This loop is repeated until the difference in ray positions no longer changes significantly. It is this looped

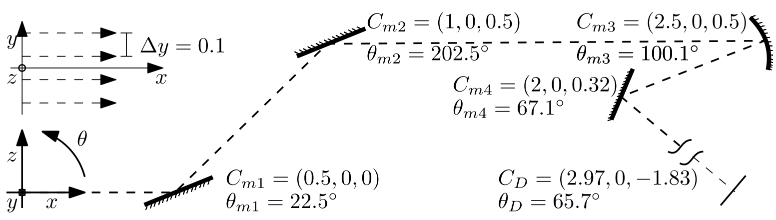


**Figure 1.** Schematic representation of SMM mirror and detector plane placement. Coordinates of mirrors (x,y,z) in meters mirror angles in degrees. Optical path of four parallel beams indicated by the dashed lines.

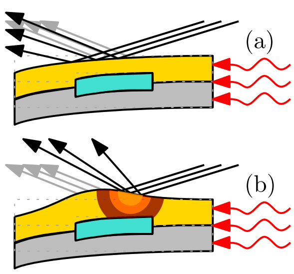


**Figure 2.** Schematic representation of thermal disturbances on ray paths (black arrows) because of mirror surface (gold) and support (Gray) deformation. (a) thermal disturbance from external heat sources, like conduction and cooling channel convection, (b) thermal disturbance from the localized ray heating effect

interconnection that sets the RH-STOP approach apart from the original STOP modelling approach, which did not require this interconnection structure [4]. The complete RH-STOP analysis routine is implemented in the COMSOL Multiphysics software [7].

## 3. Simplified Multi-Mirror model

To investigate the optical performance of the ITER-UL under the RH-STOP framework the SMM model is developed. The SMM mirrors are based on the original UL design but omit the, for analysis, less critical design features such as fillets and mounting geometry. However, the asymmetric design and loads prevent further simplification to a two-dimensional analysis. The relative mirror placement is depicted in Fig. 1 while the exact but deformed geometry is shown in Fig. 3. The mirrors themselves are made of a copper alloy (CuCrZr) with a stainless-steel support. The material properties [8] of the materials are both assessed at the equilibrium temperature of 87 C° and as fully temperature dependent variables. The latter analysis is performed to assess the effect of the significant temperature differences across the mirror surfaces. The thermal boundary conditions of the model are defined as: a Newton cooling law for the internal cooling channels, a constant temperature of 87 C° [6] for the connection to the rest of the system and a radiative boundary condition for the other surfaces. The reference temperature of the mirrors is assumed to be 20 C°.

## 3. Results & Conclusions

To investigate the necessity of the RH-STOP modelling approach and its predictions for the SMM model, four distinct simulations are performed. Fig. 4 shows the result of the tests in the form of a spot diagram at the focal plane of the unperturbed base line simulation. As can be concluded from Fig. 4, the addition of only the STOP analysis, without ray heating, has the effect of dealigning the four optical beams. When the ray heating effect is introduced a significant beam broadening is observed because of the local heating and hence local deformation of some of the mirror surfaces. This effect is amplified when the material properties are made temperature dependent, resulting in a beam spot size of approximately 15 mm by 30 mm in the case of the RH-STOP with temperature dependent material properties. The prime cause of this change is attributed to the individual mirror deformations shown in Fig. 3.

The RH-STOP model therefore demonstrates, not only, the necessity to include the ray heating effect in the analysis of the optical performance indicators of the ITER-UL mirrors, but also the significance of temperature dependent material properties. In addition, it can be concluded that if the current ITER-UL reference design behaves similar to the SMM model its instability suppression capability cannot be assumed invariant to thermal disturbances.


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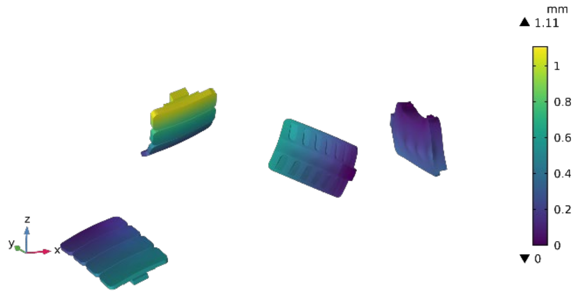


**Figure 3.** Deformation of the SMM model for the RH-STOP simulation with temperature dependent material properties. Note deformation are amplified by a factor 500× for visualization.

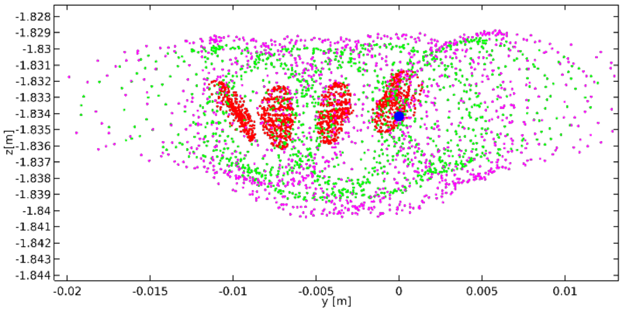


**Figure 4.** Spot diagram of the ray positions at the focus plane for the different SMM simulations: No deformation (Blue), STOP model without ray heating (red), RH-STOP with constant material properties (green), RH-STOP with temperature dependent material properties (pink).

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