CONFERENCE PRE-PRINT

STRAY RF EVALUATION AND DESIGN IMPROVEMENT OF THE ITER EQUATORIAL EC H&CD LAUNCHER

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1. ABSTRACT

The ITER Equatorial Launcher (EL) is designed to inject 170 GHz millimeter-wave power of up to 20 MW into the plasma to perform electron cyclotron (EC) heating and current drive (H&CD), while simultaneously having neutron shielding capability. Such shielding restricts internal clearances and can induce internal RF reflections, giving rise to stray RF power that may deposit unintended heat loads on internal components. In this paper, a stray RF evaluation methodology is presented based on geometric optics (GO), implemented in a sequence of a simulation toolkit. The toolkit handles millions of rays reflecting off a finely meshed internal structure (~2×10^6 triangle meshes) and computes local surface heat flux

profiles via Fresnel absorption models. To reduce computational costs, a grid subdivision approach is adopted to find intersections between the triangle meshes and grid cells in the manner of a bisectional search. Applying the method to the EL design, localized hot spot exceeding 200 kW/m^2 is identified on fixed mirror modules, and an non-negligible heat load (≥1 kW/m^2) is identified around mirror actuators. By modifying internal apertures and installing RF shields near actuator regions, these peaks are suppressed to acceptable levels. The final design significantly mitigates stray RF risk and provides robust thermal safety.

2. INTRODUCTION

Electron cyclotron (EC) heating and current drive (H&CD) system is an essential tokamak subsystem for plasma control, stability, and performance in tokamak devices. In the latest baseline of ITER project, the EC system aims to deliver 60 MW at 170 GHz with controlled directivity and polarization [1]. The equatorial launcher (EL) is designed with an adjustable steering mirror to deliver 20 MW EC beam power for core H&CD in the range of R<0.6, where R is a plasma minor radius normalized by toroidal flux [2]. Furthermore, the EL enables pure ECH for impurity exhaust by dividing the injection power into three rows (Top, Middle, and Bottom rows) with similar optics and incorporating a counter ECCD (Fig. 1). Unlike other tokamaks, ITER's extremely intense neutron flux (500 MW steady-state D-T reaction) demands heavy volumetric shielding, which reduces available space and optical flexibility. As a result, internal reflections can lead to risks of overheating and damage to actuators.

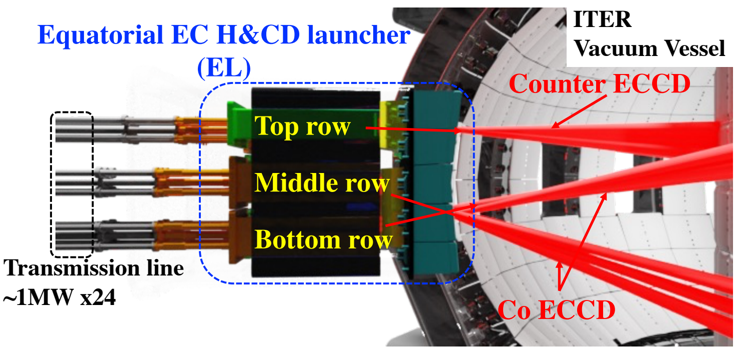

FIG. 1. EL design concept. RF power transmission up to 20 MW is divided into 3 rows (Top, Middle, and Bottom)

Although the optical design of the EL has been optimized in earlier work [3] to reach a transmission efficiency of ~99.0 % under operational and radiation constraints, the rest 1 % (~200 kW) of input power remains in internal reflections and stray trajectories. Experiments with a mock-up launcher suggest that only 20–40 % of this stray power emerges from the output aperture; the remainder (~60 %, ~120 kW) must be absorbed internally [4]. Since there is a possibility of stray power concentration, an evaluation method should be developed to investigate stray RF heat load profiles for EL design. The surface heat flux profile in the unit of W/m^2 would also be beneficial in the EL's thermal and structural analyses.

In this paper, we describe our approach based on geometric optics (GO) ray tracing to compute local heat flux distributions from stray RF inside the EL. We show results for the baseline design, propose mitigation strategies (aperture enlargement, RF shields), and evaluate their effectiveness.

3. BACKGROUND AND REVIEW

Stray RF radiation is a known concern in EC systems and, in general, stray RF has been studied outside of an EC launcher, mainly for other in-vessel devices and diagnostic lines [5]. However, since the ITER EL is the first device on earth whose power transmission efficiency was substantially limited by neutron shielding, stray RF evaluation is also necessary inside the EL. Some major simulation techniques (full-wave, physical optics, and geometric optics) have been explored. To decide the best approach in this study, the EL condition was considered for each technique as follows:

- **Full-wave electromagnetic solvers** (e.g. finite difference time domain, finite element) can model diffraction, interference, and other natural wave behaviors, but are computationally impossible for large and intricate structures whose dimensions are much larger than the wavelength (e.g. ~2 m EL dimensions vs 1.8 mm wavelength).

- **Physical optics (PO)** is an approximation that treats wave behaviors on smooth surfaces via integral equations. PO handles small-angle diffraction and interference in a single beam but still intractable with multiple-split beams or highly complex and multi-reflection paths.

- **Geometric Optics (GO)** is a high-frequency approximation that traces rays (like light) through reflections and refractions, ignoring coherence and diffraction. GO is often valid when feature scales (gap, slit, or surface dimensions) are much larger than wavelength.

Given the high-frequency and large intricate scale of the EL, GO would be acceptable, provided that coherence and diffraction do not dominate stray paths.

4. OPTICS AND RF TRANSMISSION

The EL optical layout (optimized in 2020) adopt a "dog-leg" structure with two mirrors to prevent direct neutron flux while preserving beam path into the plasma, using internal mirrors and apertures to steer and guide beams (Fig. 2). Besides the dog-leg structure, volumetric neutron shielding is essential for an acceptable radiation level in maintenance region for workers (EL rear side) but constrains available clearances, mirror sizes, and mirror spacing. Additionally, the mirror peak heat load and the EC H&CD controllability are also the constraints for EL design. The optical optimization, subject to these constraints, achieved a transmission efficiency up to 99.0 %, implying ~1 % of input power remains in internal reflections (i.e. stray). Additional dedicated full-wave tolerance study reports that achievable transmissivities with 95% probability is evaluated for each waveguide as shown in Table. 1

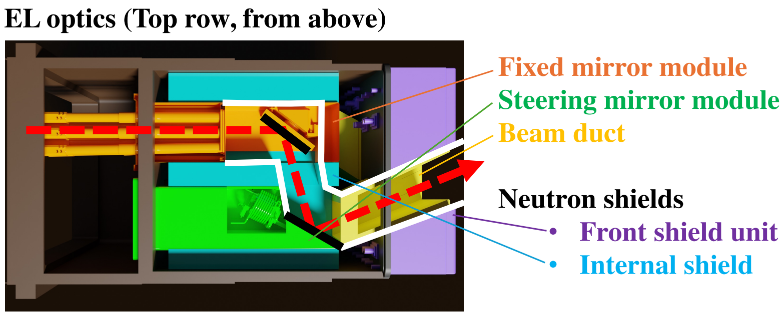

FIG. 2. Internal optics of the EL. The second mirror is steerable so that the output beam angle can be controlled.

TABLE1. EL RF TRANSMISSIVITIES

	Top row	Mid row	Bottom row
Waveguide #1	0.9729	0.9341	0.9848
Waveguide #2	0.9848	0.9955	0.9913
Waveguide #3	0.9698	0.9855	0.9865
Waveguide #4	0.9962	0.9976	0.9983
Waveguide #5	0.9970	0.9978	0.9985
Waveguide #6	0.9569	0.9378	0.9816
Waveguide #7	0.9839	0.9954	0.9923
Waveguide #8	0.9750	0.9747	0.9870

5. EVALUATION METHODOLOGY

We developed a custom GO-based ray-tracing toolkit with the following pipeline to find stray RF heat load profile:

1. **Ray bunch generation:** Generate a statistical ensemble of rays approximating the waveguide LP01 mode angular spread and beam waist distributions (Fig. 3).
2. **Trace ray reflections:** Trace each ray through reflections inside the EL structure made of ~2×10^6 triangle meshes. At reflections, random vector components are introduced to reproduce RF power transmission efficiency obtained in full-wave analysis. (Note: full-wave analysis is available only for single beam tracing along main path.)
3. **Fresnel reflection / absorption modeling:** For each reflection, compute the Fresnel reflection coefficient R (a function of incidence angle and wall conductivity) and derive the absorption fraction $1-|R|^2$. The RF power mitigation is traced (Fig. 4).
4. **Local absorption accumulation:** Map a point cloud of absorbed RF power onto spatial grid cells to build a heat-load map [W per cell].
5. **Heat flux computation:** Divide the absorbed power by the local surface area of that cell (m^2) to obtain heat flux [W/m^2] (Fig. 5).
6. **Variance reduction:** Several diffusive smoothing steps are applied in post-processing to reduce non-physical thermal gradient at poor-statistic regions.

Since the mirrors and other internal plates have thickness of not less than 20mm, 10mm resolution is sufficient to distinguish surface heat load on fronts and rears. However, mapping area profile (m^2) in step 5 is challenging for such fine grids because naive search between all surface meshes (~2×10^6) and all grid cells (~2×10^7) is combinatorially large. Additionally, step 2 would also be costly if each ray reflection point is searched for all meshes.

To avoid such naive search in the step 5, we employ an adaptive bisectional search algorithm using multi-resolution grids:

- Begin finding mesh intersection against coarse grid cells (e.g. 640 mm resolution), flagging each triangle mesh to intersecting grid cells.

- Recursively subdivide blocks (e.g. 640→320→160→80→40→20→10 mm) only where a triangle is flagged (intersecting). Finally, when mapping at 10 mm resolution, only triangles flagged in the relevant 20 mm grid cell need to be considered.

This flag can also reduce computational cost in tracing ray reflections (step 2) because, once grid cells that a ray passes are identified, the reflection point can be found only from the flagged meshes for those grids.

Finally, using ~3×10^7 rays and the above algorithm, the full stray RF evaluation over the EL was accomplished in ~1 week on ~20 CPU cores.

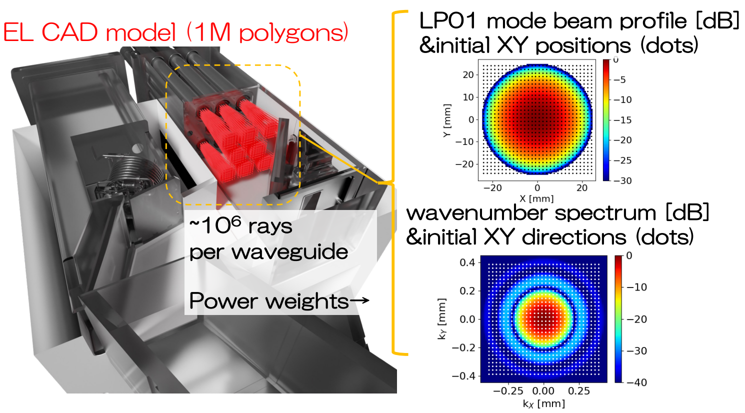

FIG. 3. Generated ray bunch and power weights according to an LP01 intensity and the wave spectrum

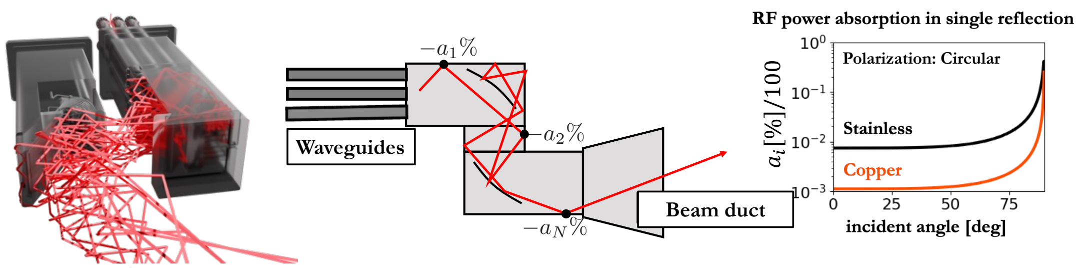

FIG. 4. Fresnel reflection/absorption modeling. For each scattering rays (≥ 3 reflections), sequential power mitigation (absorption) is calculated and traced until a ray comes out or 1000 reflections. The absorption ratio is dependent only on an incident angle, assuming circular polarization.

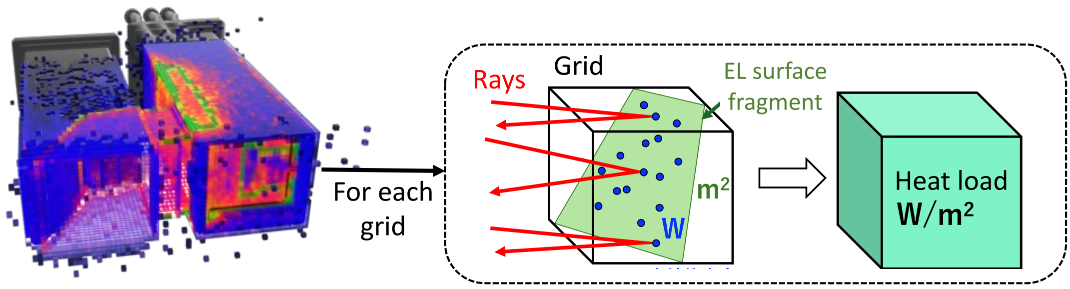

FIG. 5. Heat flux computation. Heat flux profile [W/m²] is generated after evaluating intersectional area [m²] and RF power absorption [W] for each grid cell.

6. RESULTS

6.1 Hot spots on baseline optical design

Applying the tool to the baseline EL design reveals a dominant hot spot exceeding 200 kW/m² on the fixed mirror module in the Middle row (Fig. 6b). After analyzing the ray paths, it is found that a bunch of stray rays are reflected at the edge of the internal aperture (Fig. 6a). Therefore, to mitigate that hot spot, we modified the internal aperture geometry (enlargement or chamfer) and reran the simulation. In the revised design, the peak flux is reduced significantly, and the hot spot disappears (Fig. 6c).

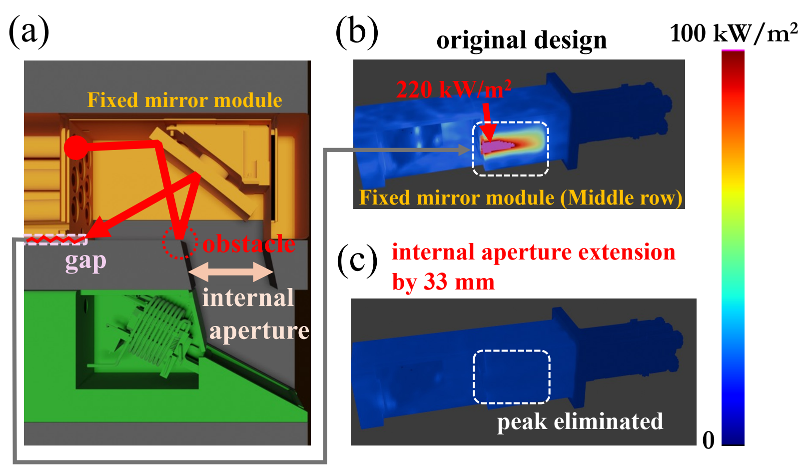

Fig. 6 Calculated heat load profiles and EL design improvement. Removing an obstacle in (a) eliminates a peak in (b) as shown in (c).

6.2 Penetration to Actuators

Unexpectedly, some stray rays penetrate the steering mirror actuator region (white rectangle in Fig. 7 left), impacting on small components (springs, bellows) that lack direct cooling. These components, typically made of alloy 718 and operating at high temperature (~300 °C), can radiate only ~1 kW/m². After ray path analysis, it is found that the main stray power flow comes from behind the steering mirror. Therefore, in order to reduce the heat flux level, an RF shield is designed behind the mirror. The simulation with the RF shield shows the heat flux dropped to acceptable levels (Fig. 7 right).

After these improvements, the stray RF risk is substantially mitigated, and the final EL design achieves adequate thermal level.

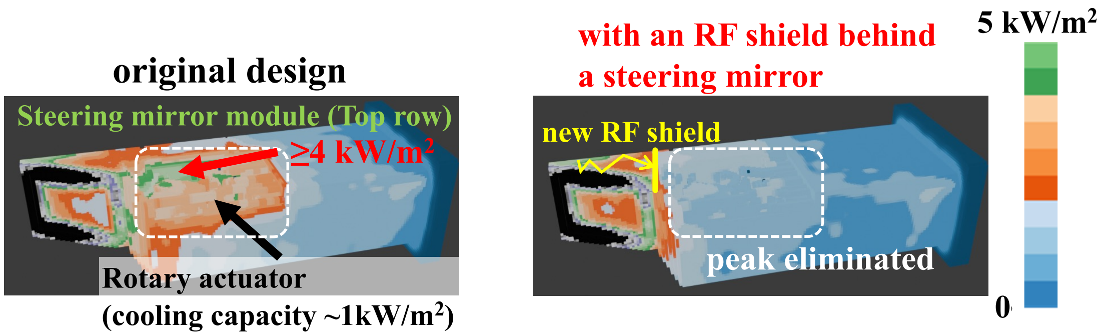

Fig. 7 Calculated heat load profiles and EL design improvement. Non-negligible heat flux (>1 kW/m²) in the left figure is eliminated by a new RF shield as shown in the right figure.

7. CONCLUSION AND FUTURE WORKS

We have developed and applied a geometric–optics–based stray RF evaluation methodology for the ITER equatorial EC H&CD launcher. Using an adaptive bisectional search algorithm and efficient ray-tracing engine, we identified critical hot spots, proposed geometric and shielding improvements, and verified their effectiveness with sufficient resolution. The refined design shows significantly reduced stray RF risks, supporting thermal design safety. In order to assess the contribution of diffraction, our approach would be compared with a mock-up experiment. The EL thermal/structural analyses would also be carried out by using the obtained heat flux profiles as an input.

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