Ray tracing calculations for the First Plasma configuration of ITER Electron Cyclotron Heating system

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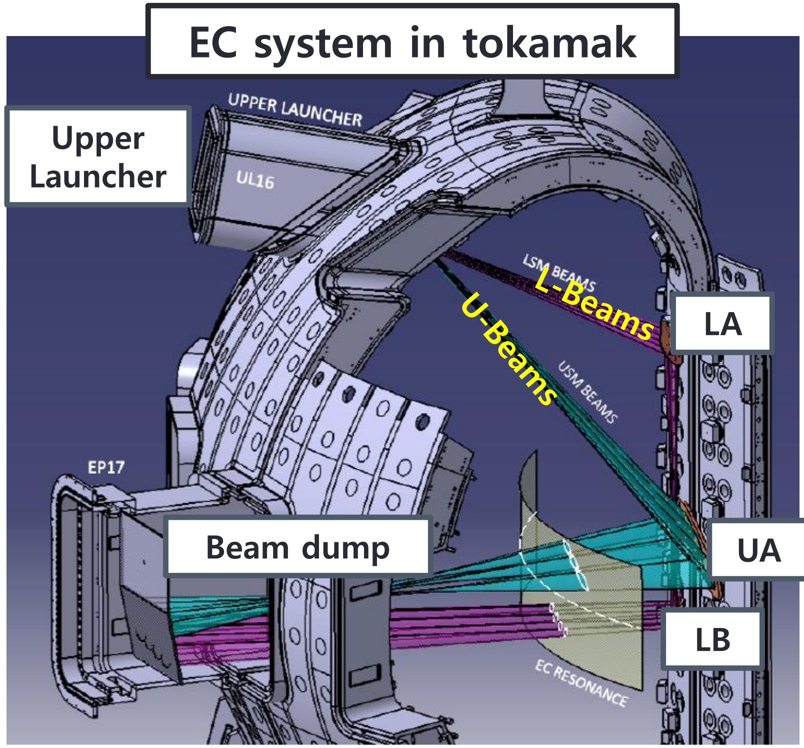
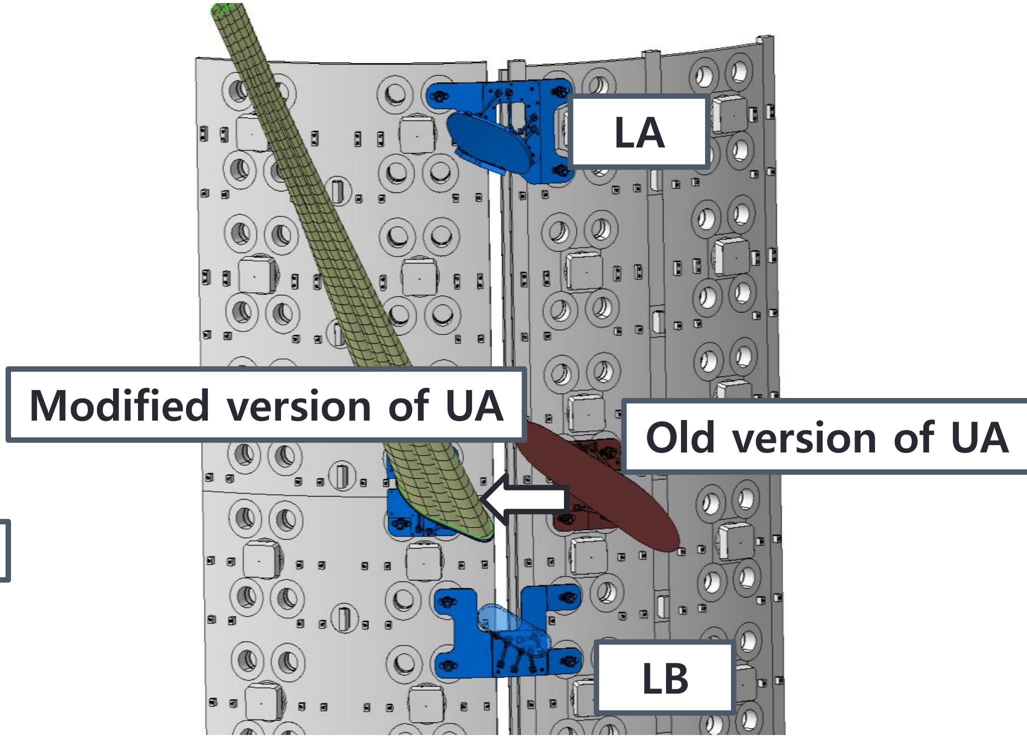
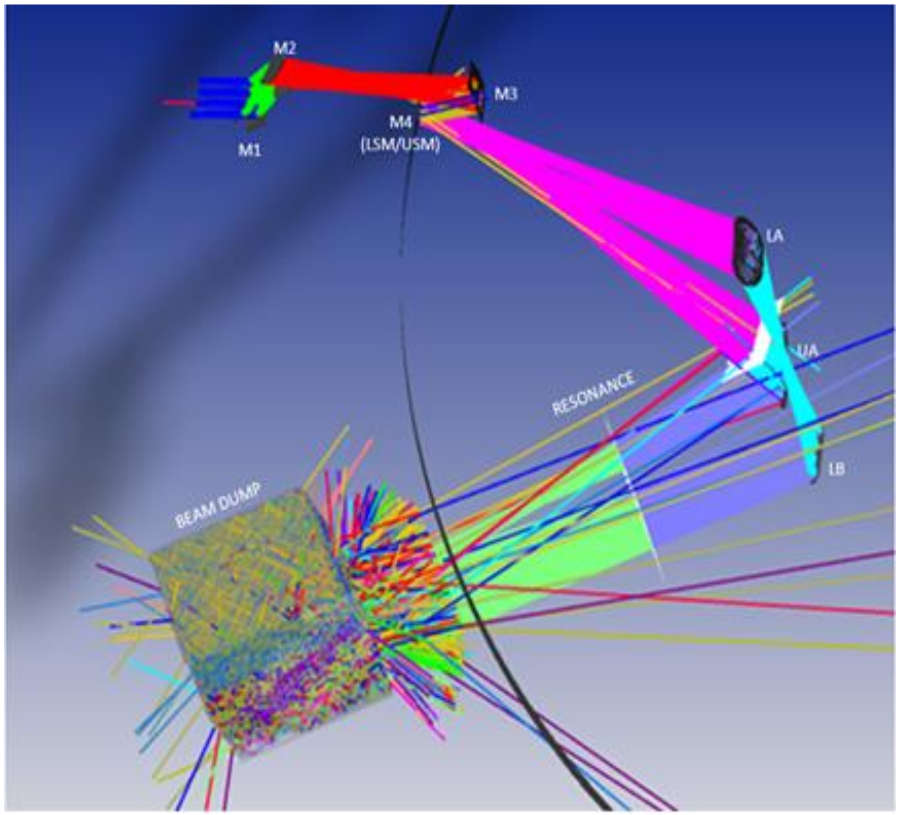
Introduction

- Electron Cyclotron (EC) beam will be used for plasma breakdown assist.
- The optical design of the 'U' beams were modified following issue raised of the FPPC FDR. The configuration presented at the FDR required the use of a diffraction grating that resulted in roughly 20% of the power in a spurious mode.
- A thin cover plate has been added on to the surface of USM, which has a different reflective surface that shifts the beams to the left. This reduces the projected beam size on the UA mirror, which allowed the use of an ellipsoidal curved mirror to redirect and focus the beams toward the resonance plan avoiding the spurious power.
- According to modify trajectory of 'U' beams, coating thickness profile on the side plates of Beam dump are also modified.





Ray tracing simulation using ZEMAX



- **Existing model was designed by CNR. [1] Meanwhile, modified UA mirror is designed by ITER Organization. For validation of modified design, we select ZEMAX ray tracing simulation.**

[1] A. Moro, *"Design of Electron Cyclotron Resonance Heating protec tion components for first plasma operations in ITER" (2020)*

Advantage of ZEMAX simulation

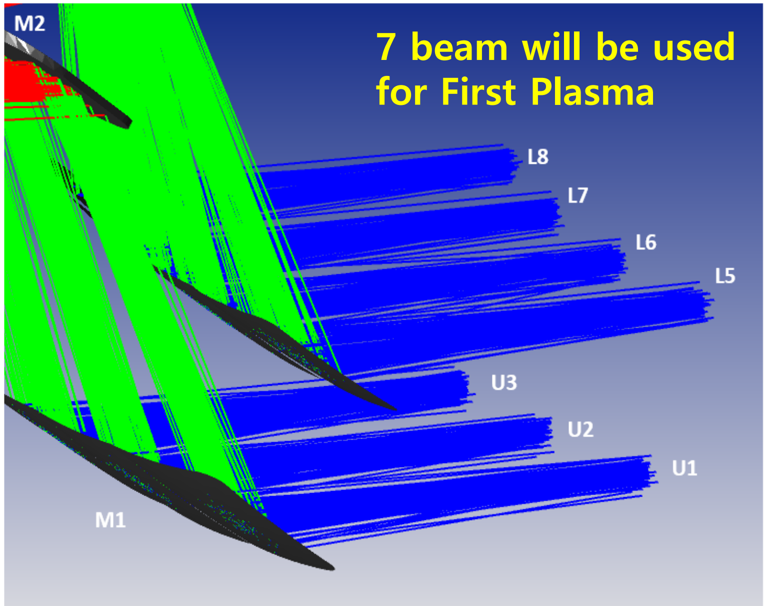
1. **Commercial Ray tracing simulation tool (Good accessibility and support)**

2. **Useful tool for Engineering design (Import of CAD and CATIA model)**

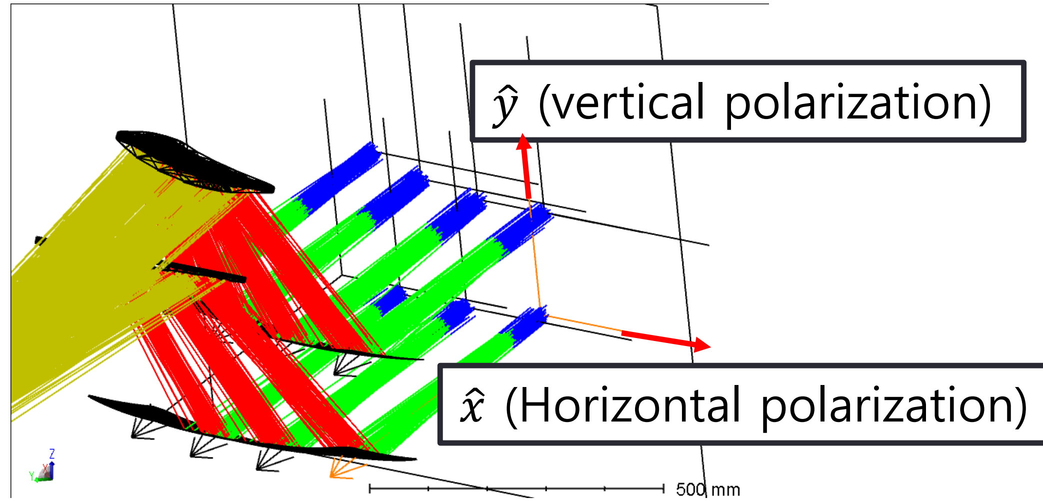
Disadvantage of ZEMAX simulation

1. **Physics limitation of ray tracing calculation (No diffraction and no interference)**

Definition of Source (1/2) : Upper Launcher



- Beam coordinates are defined to ease polarization settings

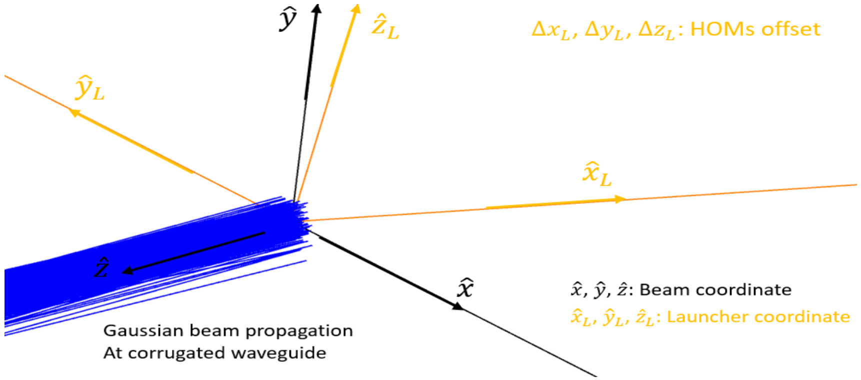


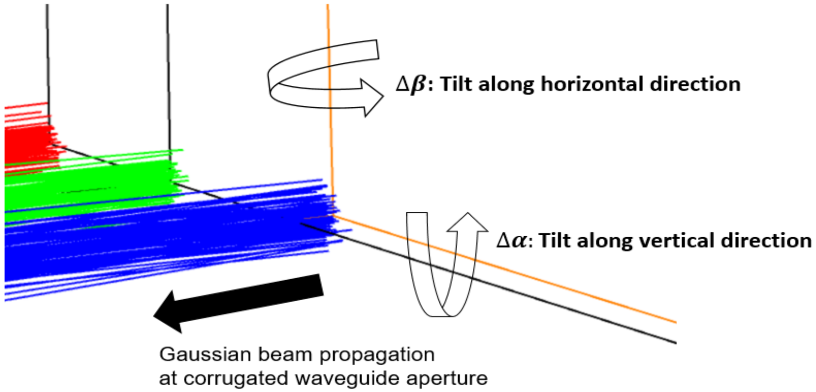
Initial setting parameters in source	
Beam type	Gaussian beam
Initial power	0.875 MW
Beam waist	16.0875 mm
Number of rays	1e6
Polarization	Vertical polarization 100%

- **Gaussian beam is applied as a source in ZEMAX to generate HE11 mode from In Vessel Transmission Lines (IVTL)**
- **Setting for initial polarization is useful to trace polarization of EC beam in tokamak for future study. (Current drive, X2 mode injection)**

Definition of Source (2/2) : Tilt and offset caused by Higher order modes (HOMs)

HOMs can be considered in ZEMAX by setting tilt and offset of Gaussian beam at the source





Cases of pure tilts caused by 7.5% of LP11 mode are mainly considered for HOMs cases in Source (Tab.1 and Tab.2)

Case1 HOMs 7.5%	$\Delta\alpha$	$\Delta\beta$
U1	0°	0.495°
U2	-0.495°	0°
U3	-0.495°	0°
L5	0°	0.495°
L6	-0.495°	0°
L7	-0.495°	0°
L8	0.35°	0.35°

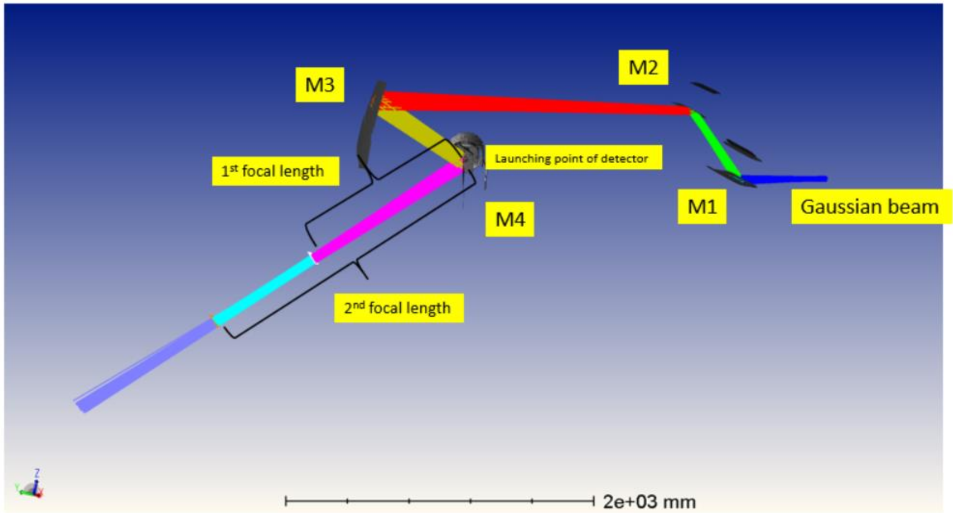
Tab. 1. Tilt from HOMs case1

Case2 HOMs 7.5%	$\Delta\alpha$	$\Delta\beta$
U1	0.35°	0.35°
U2	0°	-0.495°
U3	-0.35°	-0.35°
L5	0.35°	0.35°
L6	0°	-0.495°
L7	-0.35°	-0.35°
L8	-0.35°	-0.35°

Tab. 2. Tilt from HOMs case2

Validation of ZEMAX simulation in Upper Launcher

Ray tracing on Upper Launcher (UL)



1. ZEMAX simulation reproduced the theoretical beam optics propagation in the Upper Launcher (UL).

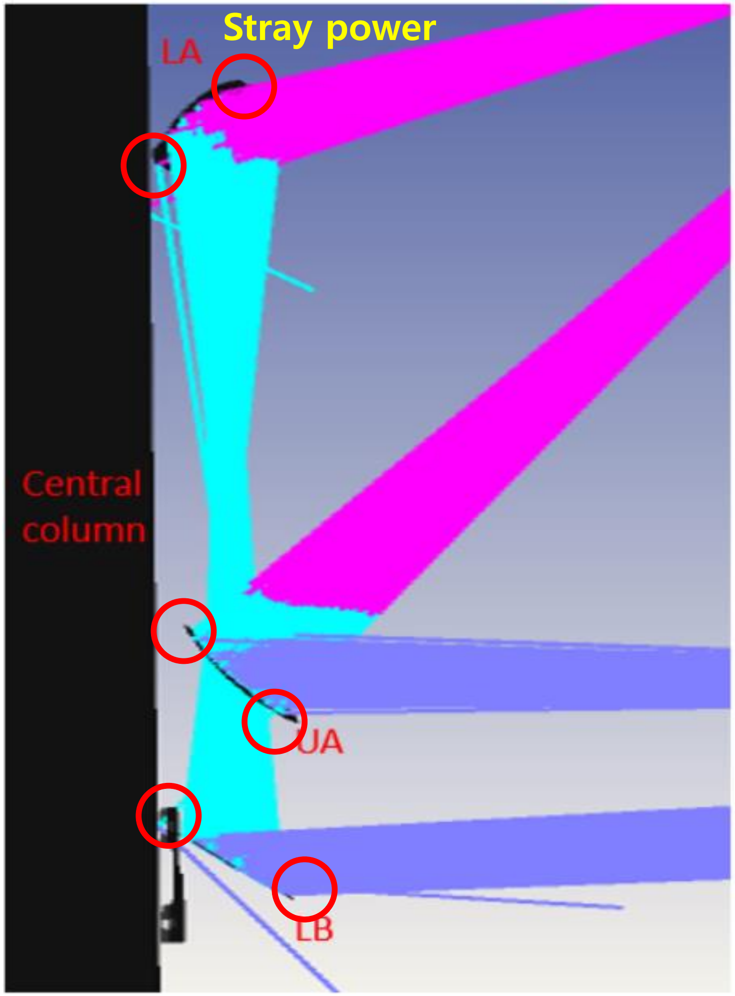
2. Beam is well focusing on 1st and 2nd focal length compared with original design parameter. (Tab. 3)

3. Simulation of quasi-optical system for UL is validated in ZEMAX.

Beam	Beam waist at 1st focal length in ZEMAX®	Beam waist at 2nd focal length in ZEMAX®	Beam waist at 1st focal length in design description	Beam waist at 2nd focal length in design description
U1	19.5	30.5	19.03	28.96
U2	20	30.25	19.32	29.34
U3	19.75	30	19.34	29.39
L5	20.5	20.5	19.55	21.07
L6	20.5	20.5	19.75	20.92
L7	20.25	20.25	19.62	20.39
L8	19	19.25	19.07	19.6

Tab. 3. Beam waist at two focal length after LSM and USM [unit: mm], ±0.25 mm tolerance

Ray tracing on FPPCs mirrors: Spillover characterization (1/2)

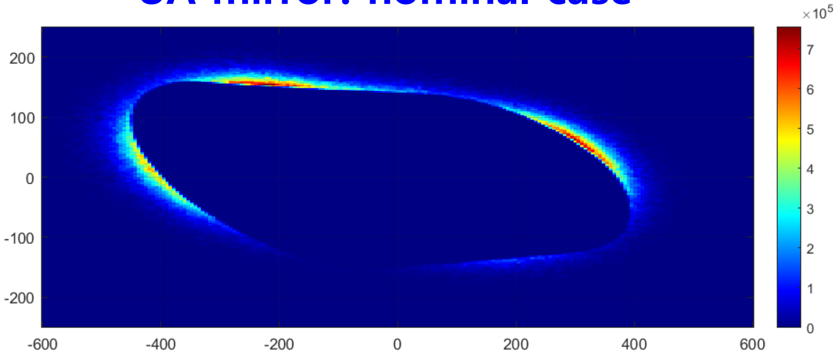


1. FPPCs mirrors are only designed for First Plasma operation. It is included in First Plasma Protection Components (FPPCs)
2. EC beam used to simulate the EC beam spillover on edge of FPPCs mirrors.
3. Setting of a detector behind of mirrors can capture the ray bundle which spillover on the mirrors.
4. Higher number of rays (~1e7) are needed to estimate peak power density of spillover. (High resolution is required for side lobe in ray tracing calculation)

Ray tracing on FPPCs mirrors: Spillover characterization (2/2)

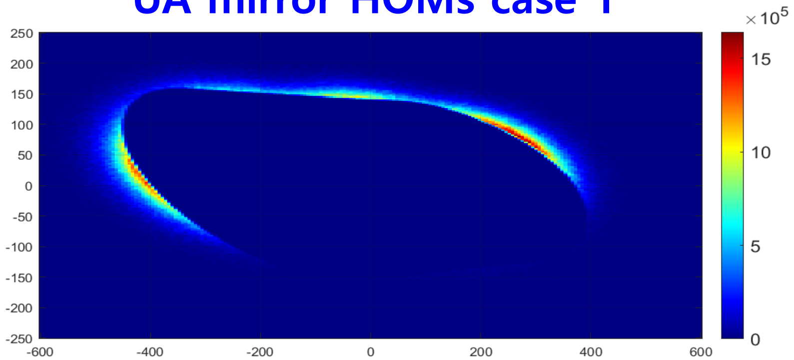
- Modified UA mirror
- Detector is positioned behind of mirrors
- Misalignment of beam caused by HOMs increase spillover on mirrors
- Spillover on LA and LB will be updated in future work.

UA mirror: nominal case



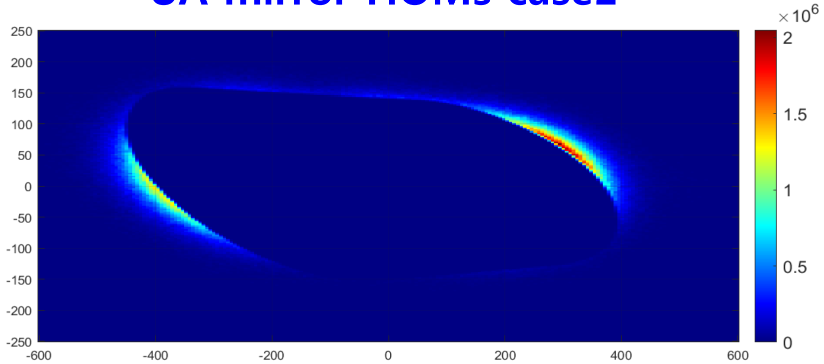
Peak power density
: **0.756 MW/m²**
Total absorbed power: **8.93 kW**

UA mirror HOMs case 1



Peak power density
: **1.636 MW/m²**
Total absorbed power: **18.2 kW**

UA mirror HOMs case2

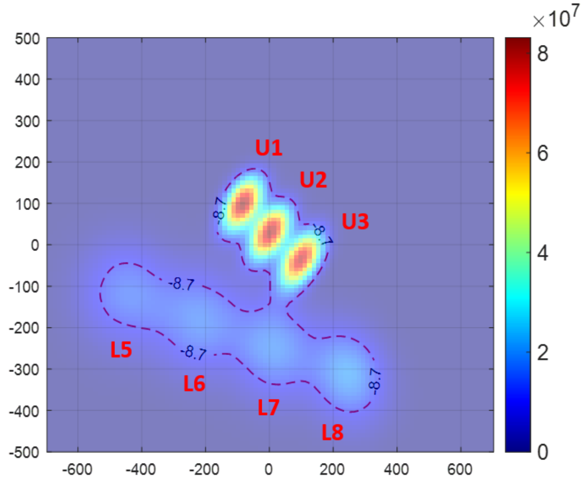


Peak power density
: **2.0493 MW/m²**
Total absorbed power: **16.783 kW**

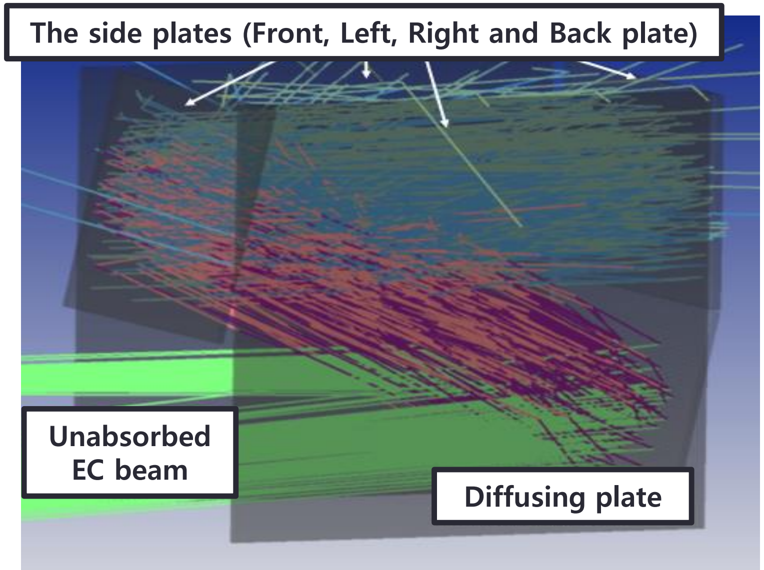
Ray tracing in Beam dump

1. Beam dump is required for protection of Vacuum Vessel from EC stray radiation.
2. It will be temporary installed in Equatorial Launcher #17 (EL17) for First Plasma Operation.
3. Beam dump was originally designed by CNR for beam trapping and dissipation. [2]
4. The side plates can absorb EC beam by ceramic coating using Al_2O_3-TiO_2.
5. Coating is uniformly covered with optimized thickness. Optimization is finalized by ITER Organization.
6. ZEMAX shows that multi-bounce simulation is possible to analyze effective beam dissip ation in beam dump.

Incident EC beam at diffusing plate



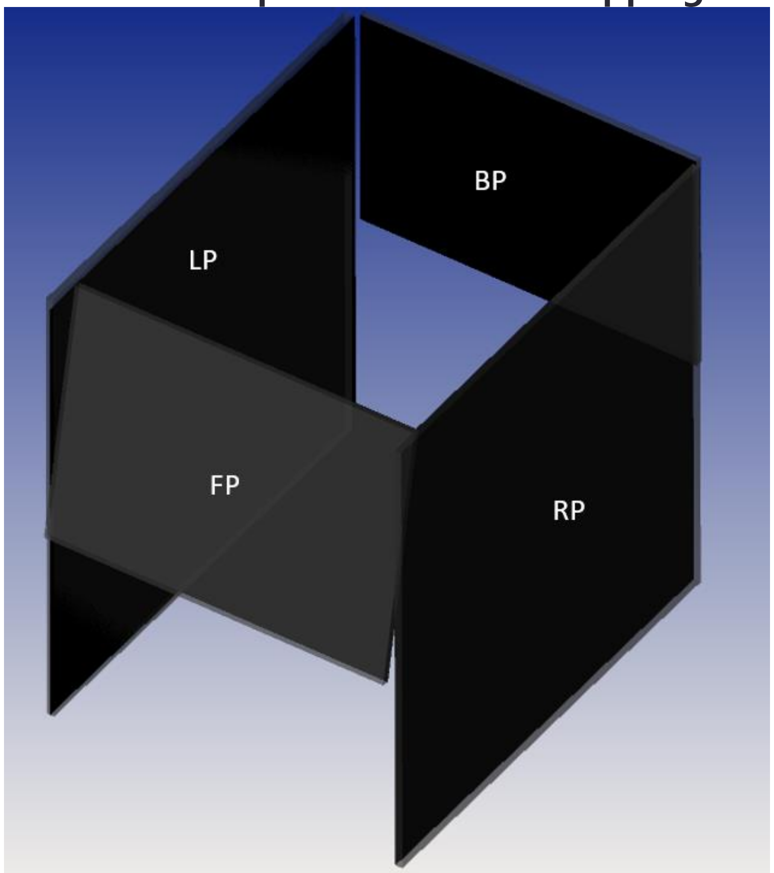
Multi-bounce simulation using ZEMAX



[2] F. Fanale et al, *"Design validation of in-vessel mirrors and beam dump for first plasma operation in ITER" (2021)*

Absorption of coating plate on beam dump

The side plates for beam trapping



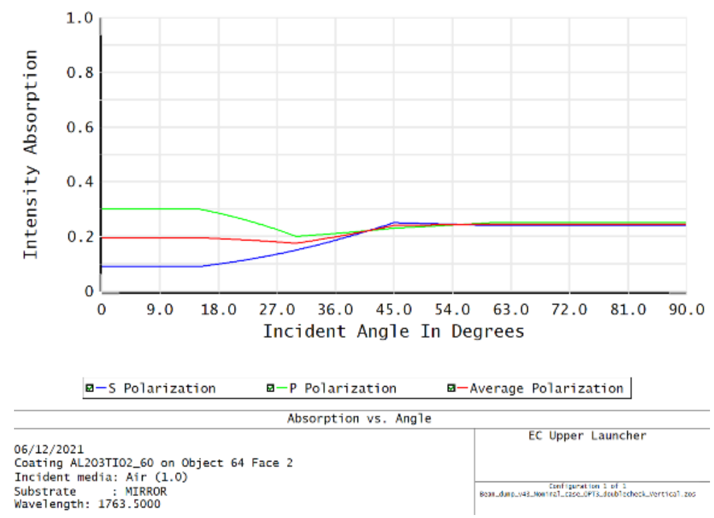
RP : Right plate
LP : Left plate
FP : Front plate
BP : Back plate

Optimized coating profile

Part	Material	Thickness (um)
RP	Al_2O_3-TiO_2	60
LP	Al_2O_3-TiO_2	60
FP	Al_2O_3-TiO_2	60
BP	Al_2O_3-TiO_2	60

Tab. 4. Optimized coating material and thickness

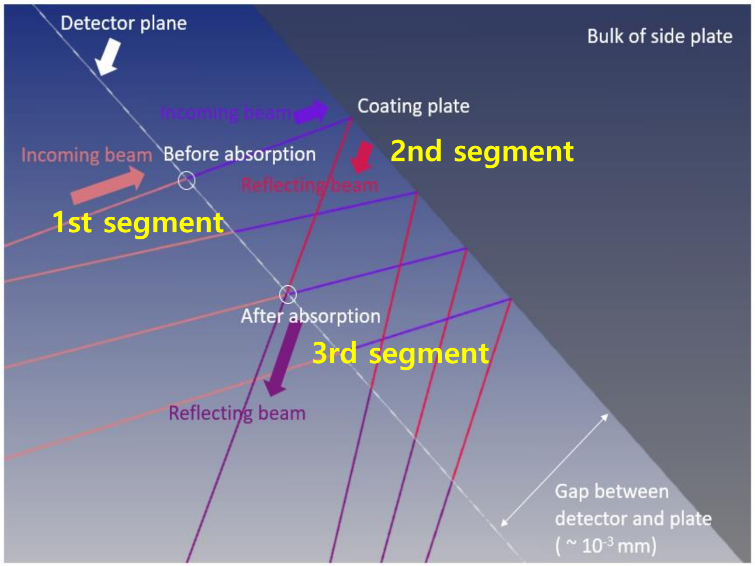
170 GHz Absorption data of Al_2O_3-TiO_2 according to incident angle [3]



[3] Report, *A.Hentrich, Achim Zeitler, C.Lechte, B.Plaum*, "Dump sample measurements IGVP Stuttgart v1" (2021)

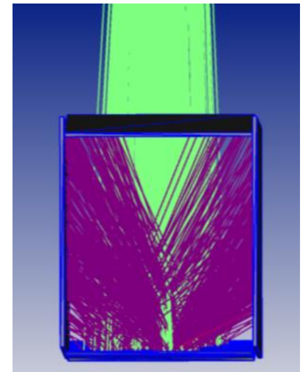
Detector and ray segments to validate ray tracing in beam dump

Absorption calculation using duplicated detectors

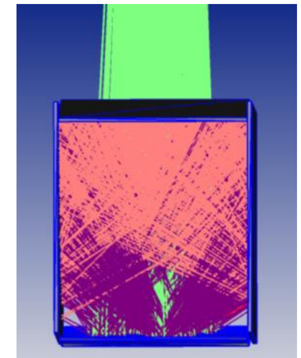


- A detector in ZEMAX have a role to capture a ray and define a segment of ray tracing calculation.
- Therefore, we can use it to define number of bounce (1 bounce: 3 segments of the ray tracing) in beam dump.
- Furthermore, Two of detectors at same position can capture incoming beam toward coating plate and outgoing beam reflecting from coating plate after absorption.
<u>- We can estimate absorption of the ray on coating plate by calculating difference between two detectors.</u>

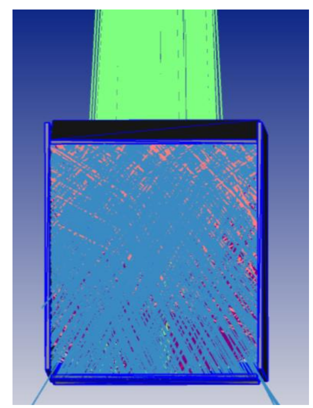
1st bounce



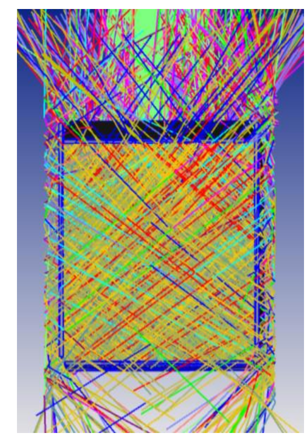
2st bounce



3rd bounce



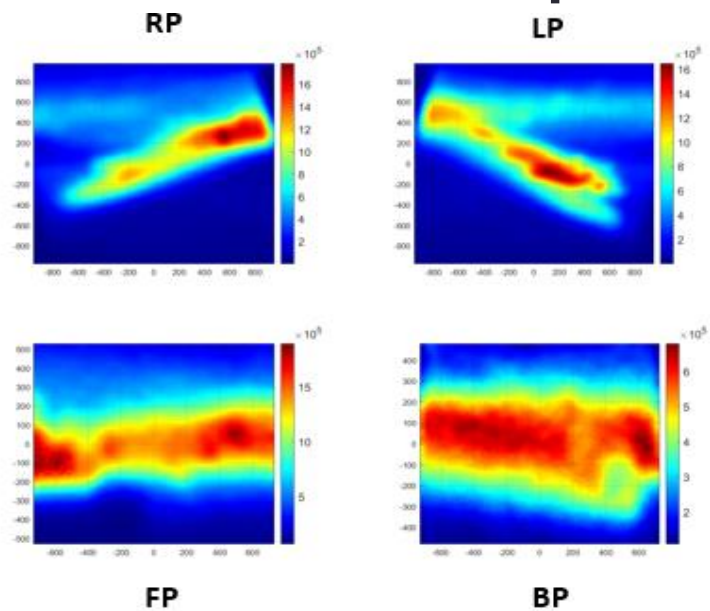
10th bounce



Coating optimization on Beam dump

Part	Material	Thickness	Peak P_{abs} (MW/m2)
RP	AL2O3-TiO2	60	1.79
LP	AL2O3-TiO2	60	1.65
FP	AL2O3-TiO2	60	1.9
BP	AL2O3-TiO2	60	0.68

Part	MW	Loss	Total Loss
Initial Power	5.829		
Entrance	0.68565	11.76 %	15.18 %
The gap between TP and FP	0.1989	3.41 %	
Total absorption on side plates			73.37 %
Other gap loss			11.45 %
Total loss			26.63 %



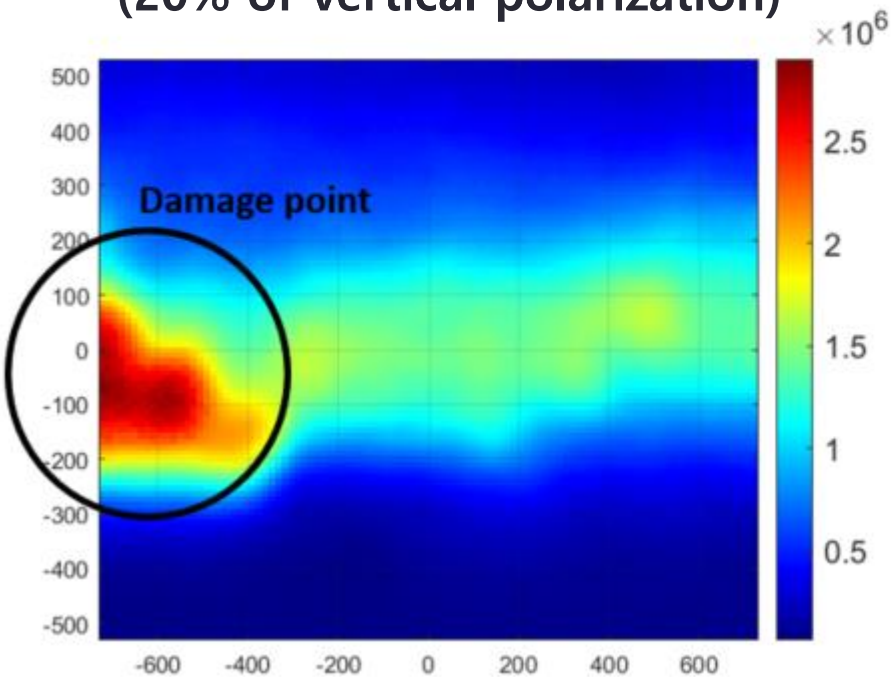
- **Coating thickness profile are optimized by ZEMAX simulation (Total absorption: 73.37 %)**
- **For safety check, 5 cases of polarization also are checked to estimate risk.**

Part	Vertical polarization			Horizontal polarization			20% vertical Polarization			50% vertical Polarization			80% vertical Polarization		
	AL_2O_3-TiO_2 Thickness (um)														
LP	60			60			60			60			60		
RP	60			60			60			60			60		
FP	60	40	80	60	40	80	60	40	80	60	40	80	60	40	80
BP	60			60			60			60			60		
Peak power density on FP	1.9	2.0	1.9	2.89	2.97	2.83	2.9	2.88	2.87	2.53	2.61	2.58	2.1	2.0	2.0

Tab. 5. Cases of coating optimization (Red: nearby damage level)

Operation recommendation for safety in beam dump

Worst case: EC beam on FP (20% of vertical polarization)



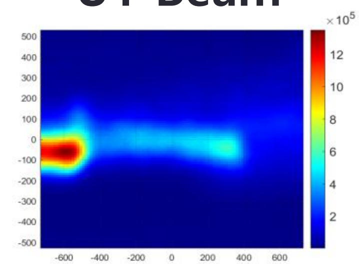
Peak power density
: 2.9 MW/m²

To reduce risk which is damaging ceramic coating, we recommend to reduce or switch off initial power of U1, L7, L8 beams

Single beam analysis

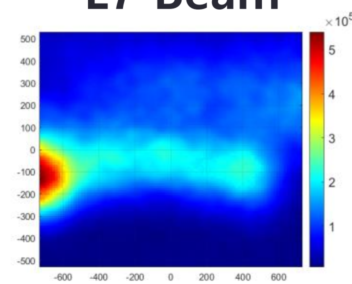
Representative beam having higher power density on damage point

U1 Beam



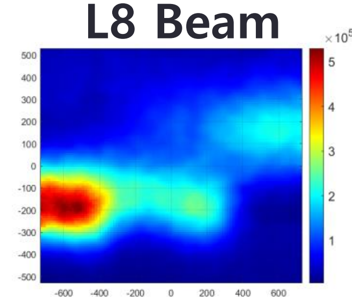
Peak power density
: **1.35 MW/m²**

L7 Beam



Peak power density
: **0.54 MW/m²**

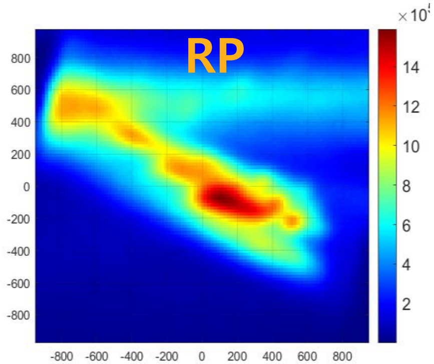
L8 Beam



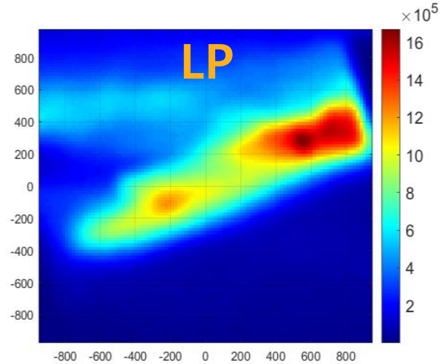
Peak power density
: **0.53 MW/m²**

EC beam misalignment by HOMs on Beam dump

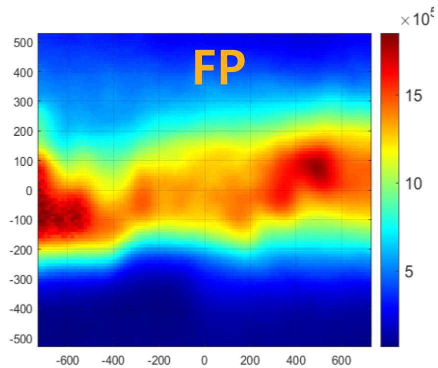
HOMs case 1



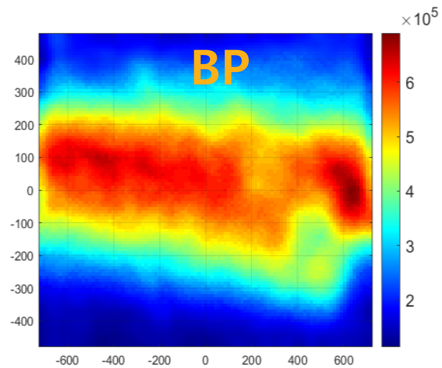
Peak power density
: **1.59 MW/m²**
Total absorbed power
: **1.3344 MW**



Peak power density
: **1.67 MW/m²**
Total absorbed power
: **1.3137 MW**

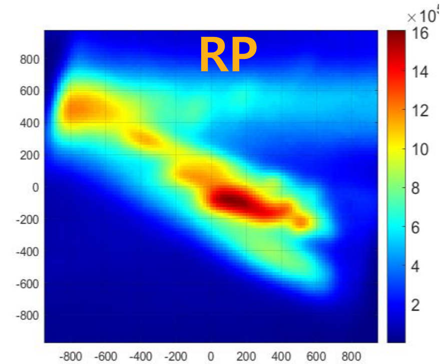


Peak power density
: **1.85 MW/m²**
Total absorbed power
: **1.0762 MW**

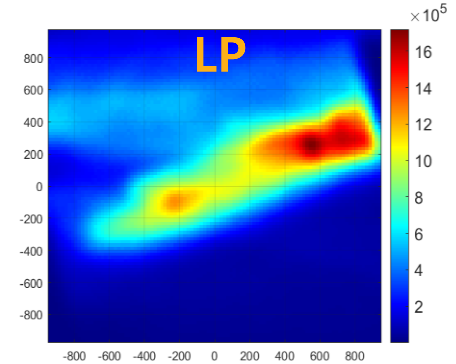


Peak power density
: **0.69 MW/m²**
Total absorbed power
: **0.50625 MW**

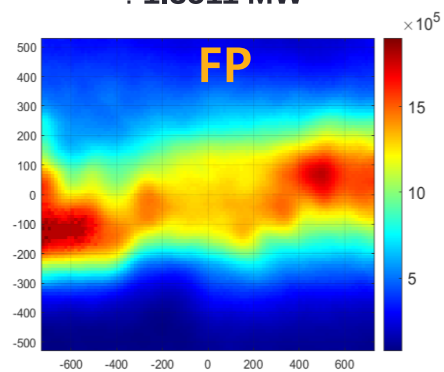
HOMs case 2



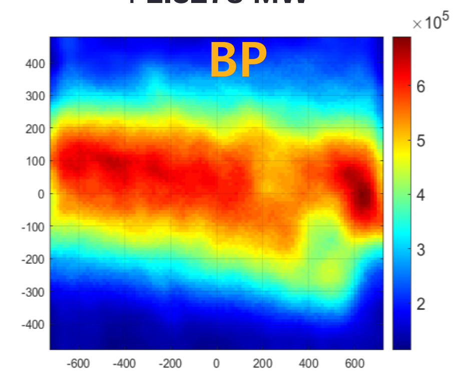
Peak power density
: **1.61 MW/m²**
Total absorbed power
: **1.3511 MW**



Peak power density
: **1.72 MW/m²**
Total absorbed power
: **1.3278 MW**



Peak power density
: **1.9 MW/m²**
Total absorbed power
: **1.086 MW**

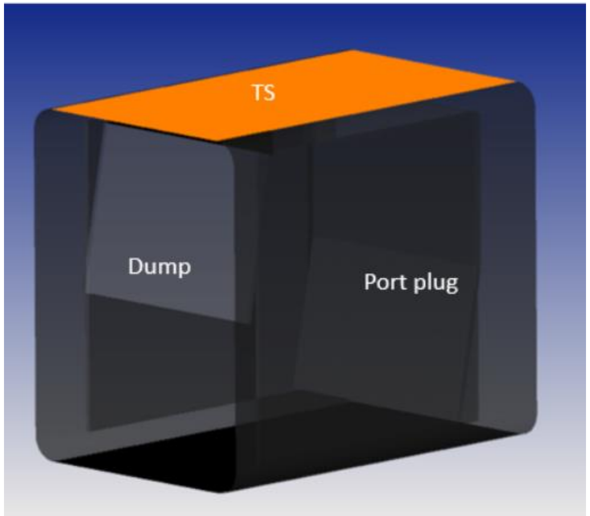


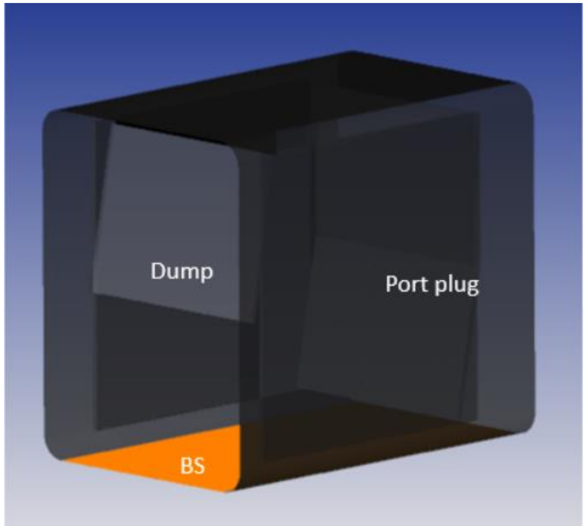
Peak power density
: **0.68 MW/m²**
Total absorbed power
: **0.50667 MW**

- Misalignment of EC beam caused by HOMs have rare influence on Beam dump

Stray power of EC beam escaping Beam dump (1/3)

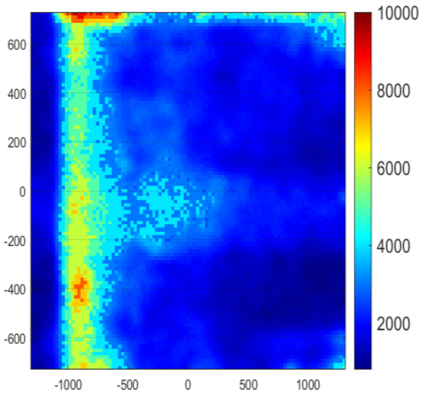
1. Stray power on bottom and top surfaces of port plug





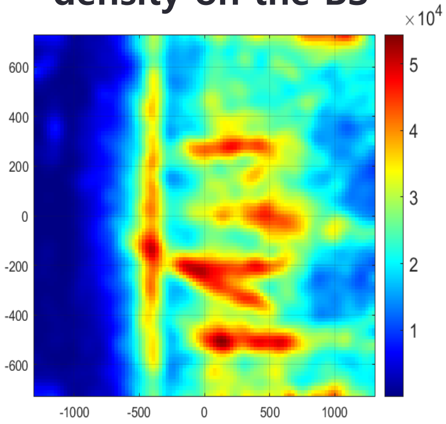
- Trapped EC beam in beam dump can be leaked out of beam dump.
- Escaping the rays are going to TS and BS.
- 3% of absorption rate is applied on TS and BS. (Material: Stainless steel)

Absorbed power density on the TS



Peak power density : **10 kW/m²**
Total absorbed power: **9.5194 kW**

Absorbed power density on the BS



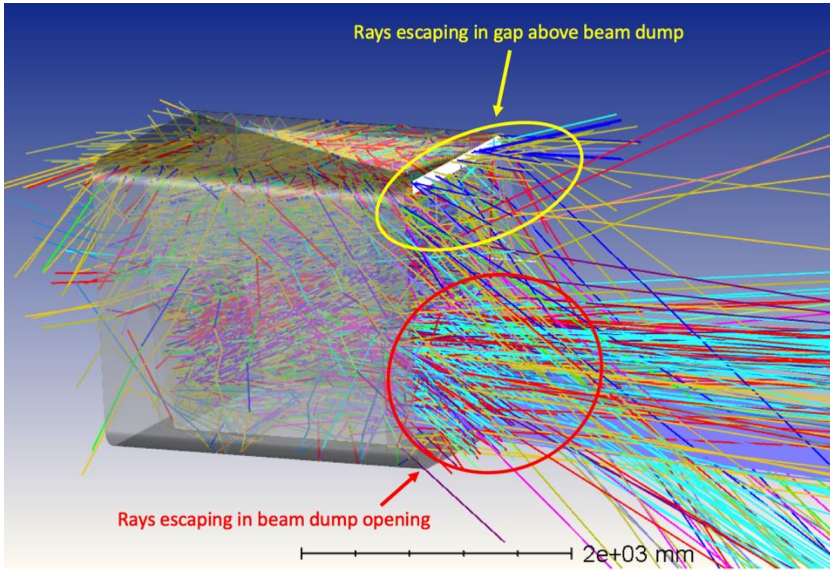
Peak power density : **54.4 kW/m²**
Total absorbed power: **76.546 kW**

No risk

TS: Top Surface (TS) of port plug
BS: Bottom Surface (BS) of port plug

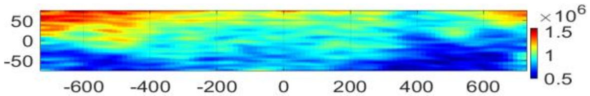
Stray power of EC beam escaping Beam dump (2/3)

2. Stray power on the gaps above beam dump and beam dump opening



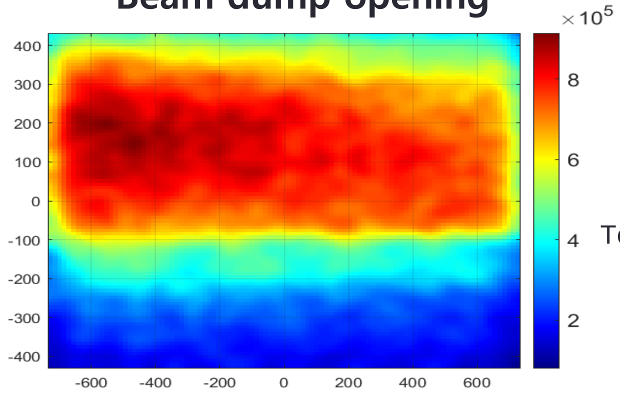
1. The gap above beam dump and opening also is checked.
2. 15% of EC power coming out from the gap above beam dump and the opening.
3. Unabsorbed beam propagate to central column

The gap above beam dump



Peak power density
: **1.57 kW/m²**
Total absorbed power: **0.1989 MW**

Beam dump opening



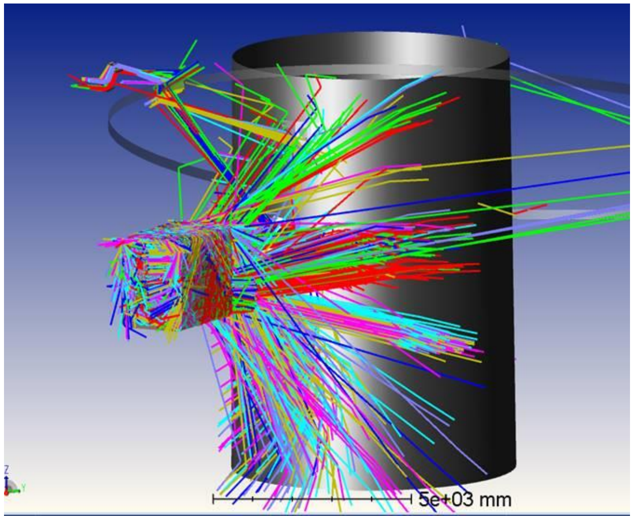
Peak power density
: **0.914 kW/m²**
Total absorbed power: **0.6856 MW**

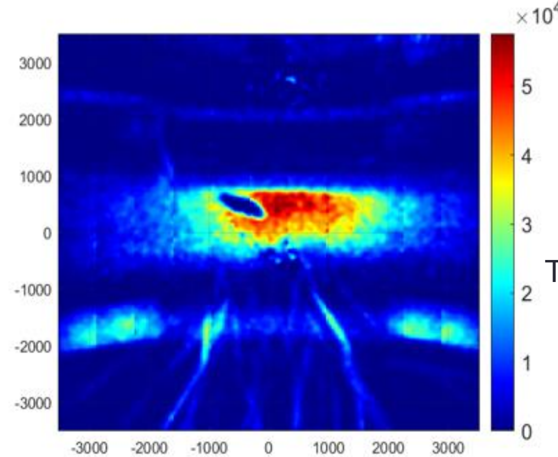
No risk

Stray power of EC beam escaping Beam dump (3/3)

3. Stray power on the central column and PBS18 cable in port plug

Central column

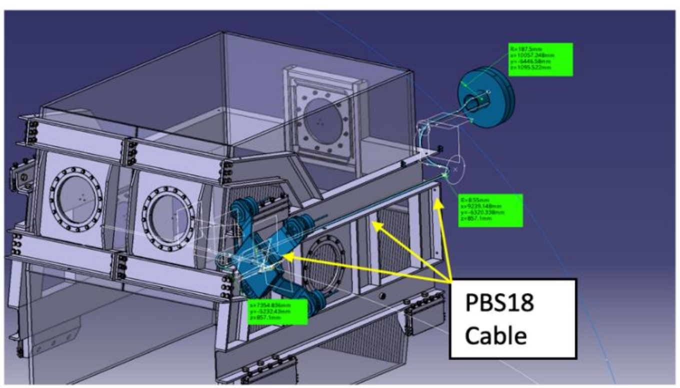


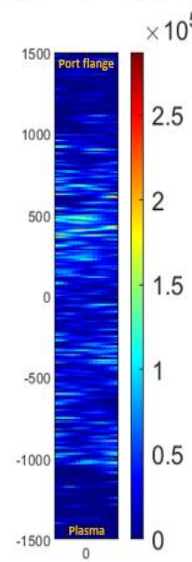


Peak power density
: **57.6 kW/m²**
Total absorbed power: **0.265 MW**

No risk

PBS18 cable in port plug





Peak power density
: **0.287 MW/m²**
Total absorbed power: **2.3 kW**

- Sum of the stray power from beam dump is still in margin.

Conclusion

1. ZEMAX simulation are consistent with Gaussian optics propagation.

2. There is no beam distortion from perturbing effects and independent cross check of mirror curvature.

3. Spillover on FPPCs mirrors is estimated by ZEMAX. Misalignment caused by Higher Order Modes (HOMs) increase spillover. It can dam age FPPC components and other systems.

4. Coating thickness profile has been optimized. Depending on initial polarization, recommendation operation is proposed for protection of beam dump.

5. ZEMAX is appropriate tool to design EC components and simulate EC beam tracing. It is relatively easy to use as the model comes from CATIA.