Refinement of the EC stray radiation estimates for ITER

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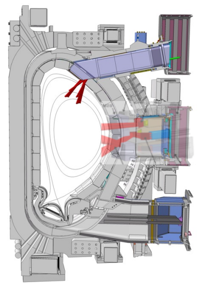
The ITER ECRH&CD system is composed by 24 gyrotrons at 170 GHz that will deliver 20 MW at the plasma. Up to 6.7 MW will be used to provide the gas breakdown. A certain level of EC non-absorbed power (stray radiation) will be present. The optical design of the EC equatorial launcher has been entirely redesigned to optimize the power deposition and minimize interaction with the launcher structures.

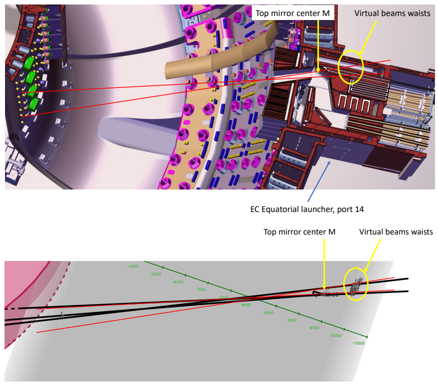
- The updated parameters for the 24 launched beams have been used to estimate the interaction of the beams to be used for the breakdown phase with the tokamak structures.
- The preliminary stray radiation model described every opening of the tokamak as a "black" hole, that is a perfect power sink. Refining this crude description using for the openings a "grey" hole model provided a better agreement with benchmarks from other alternative models (Moseev at all., "Stray radiation energy fluxes in ITER based on a multiresonator model ", Fusion Eng. Des., Volume 172, 2021,112754).

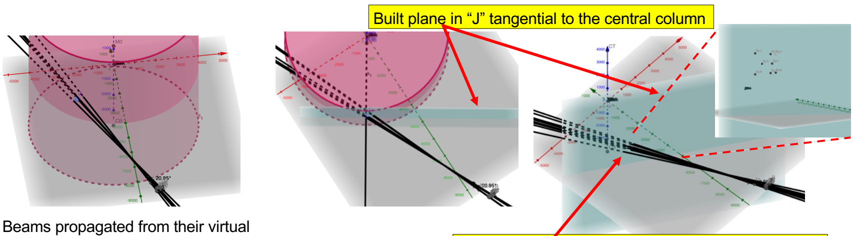
Shine through wall loading at breakdown – 8 beams from Equatorial Launcher top mirror

Assumptions:

- Pure gaussian propagation from virtual waists locations
- Central column represented as cylindrical surface at R=4.0 m
- Low field side wall (LFSW) represented as cylindrical surface at R=8.5 m
- Mirror-like reflections at tangential plane at beam axis incident points
- Merged beams described as gaussian (conservative assumption)

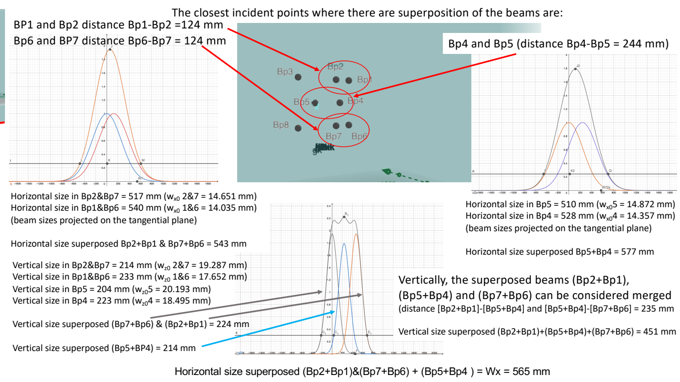






Beams propagated from their virtual waist location along their k vectors, estimated path length from waists area to the central column (7.3 m), identified point "J" at 6.6 m from "M"

Angle between beams axis and plane normal is about 57.19°



Combined beams (Bp2+Bp1)+(Bp5+Bp4)+(Bp7+Bp6) area (containing 99.97% of the power) = 4π Wx * Wz = 3.20 m^2

[worst case single beam (Bp5) = 4π Wx * Wz = 4π 0.510 * 0.204 = 1.31 m^2]

P_{in} = 0.8375 * 6 = 5.025 MW

[Power single beam ⇒ $P_{in(Bp5)}$ = 837.5 kW]

Incident Power density results

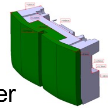
All combined beams:

on axis	⇒ $P_{axis} = P_{in} * 2/(\pi * Wx * Wz)$ = 12.55 MW/m^2
average	⇒ $P_{aw} = P_{in} / (4\pi\, Wx * Wz)$ = 1.57 MW/m^2

Single beam (Bp5) case:

Power density on the axis	⇒ $P_{axis\,(Bp5)} = P_{in(Bp5)} * 2/(\pi * Wx * Wz)$ = 9.46 MW/m^2
Average Power density	⇒ $P_{aw(Bp5)} = P_{in(Bp5)} / (4\pi\, Wx * Wz)$ = 639 kW/m^2

- The model here described is a simplification of reality with the purpose of providing a conservative assessment of the expected level of EC incident power on the central column and on the Low Field Side Wall
- The real surface of the Blanket panels at the central column is different from an ideal cylinder and even more different from a plane: the reflected beams from such shaped surface will diverge more than considered here, lowering the power density at LFSW
- The merged beams are described as they would have gaussian shape, as consequence both the peak power and the average power density are overestimated
- What described here is the **INCIDENT** Power density, the power absorbed by the Be is about 1% of such incident power
- For a more realistic assessment of the wall loading is needed a beam tracing and accurate model of the reflecting wall shape



Diffuse stray radiation

Calculation of the ambient stray radiation considering a simplified description of the tokamak cavity: formulas from integrating sphere throughput with multiple openings

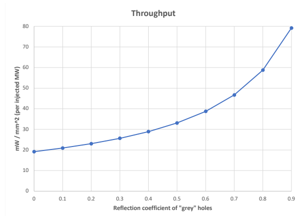
(see Goebel "Generalized Integrating-Sphere Theory", App. Opt. Vol.6, n.1, Jan 1967; Lovell "Theory and Application of Integrating Sphere Technology", Laser focus/Electro-optics, May 1984)

The equation on the left assumes that the openings act as "black" holes, that is all the incident radiation on the opening is absorbed and nothing is re-emitted (or reflected).
Most of the large opening considered (equatorial and upper ports openings, divertor gap, NBI ports) have a complex structure and considering them as "black" hole is not completely justified. It is possible to include a term in equation and treat the holes as "grey", that is attributing them a reflection coefficient ρ_G (equation on the right).

"Black" holes model - "Grey" holes model

$$\tau_{BH} = \frac{A_i}{A_S}\frac{\rho}{1-\rho\left(1-\frac{\sum A_j}{A_S}\right)} \rightarrow \tau_{GH} = \frac{A_i}{A_S}\frac{\rho}{1-\rho\left(1-\frac{\sum A_j}{A_S}\right)-\rho_G\frac{\sum A_j}{A_S}}$$

- A_i = Output opening surface
- A_s = Total surface area = Vacuum exposed to first wall= 858.3 m^2
- Σa_j = Total opening surfaces = 43.5 m^2
- ρ = Wall reflectivity = 0.99 average
- ρ_G = "grey" holes reflectivity



Output flux (throughput) from a small opening as function of "grey" hole's reflection coefficient

A conservative preliminary assumption is to consider an average reflection coefficient ρ_G = 0.6 for the openings and therefore a throughput of about 40 mW/mm^2 per injected MW.
In the tables are reported few examples of expected output flux from some openings and behind the blankets during the breakdown phase (6.7 MW injected in the empty chamber).

	Opening surface m^2	Output flux (kW) black holes 20 mW/mm^2	Output flux (kW) grey holes 40 mW/mm^2
NBI large port	1.19	160	319
Reflectometer (LFS, EqP11) ϕ31.75 mm	0.00079	0.10	0.21
Reflectometer (LFS, EqP11) ϕ50.8 mm	0.0020	0.27	0.54
Reflectometer (LFS, EqP11) ϕ63.5 mm	0.0032	0.43	0.86
Reflectometer (LFS, EqP11) ϕ88.9 mm	0.0062	0.83	1.66

	mW/mm^2 per injected MW Black holes	mW/mm^2 per injected MW Grey holes
HFS – mod 1÷5 – vertical and horizontal gaps	4.5	9.0
HFS – modules 6÷7 – vertical gaps	8.6	17.2
HFS – modules 6÷7 –horizontal gaps	6.1	12.2
LFS – vertical and horizontal gaps	16.7	33.4