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EUROfusion

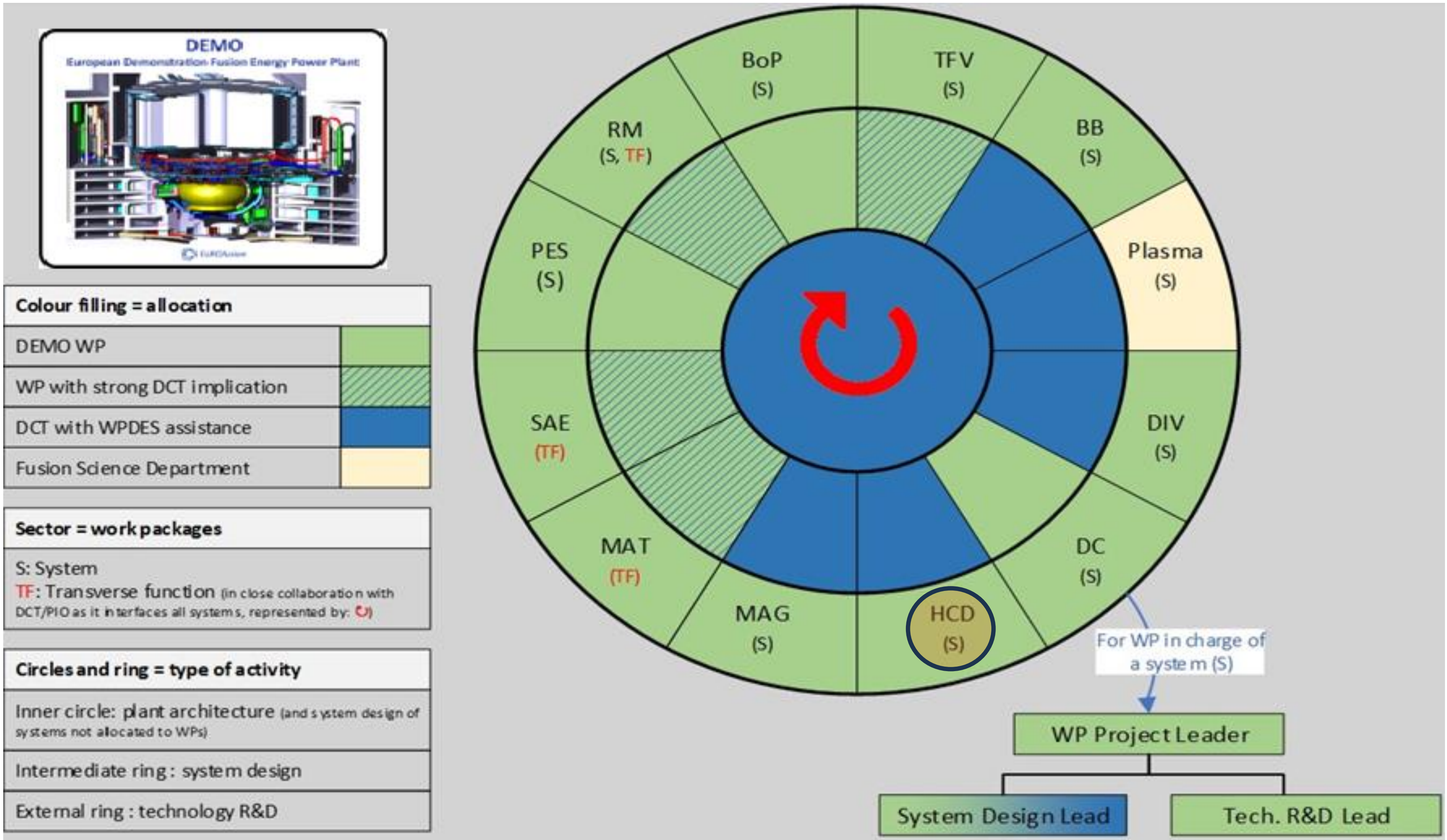
# Beam-tracing analysis of EC-assisted breakdown and high-frequency core heating in various DEMO scenarios

C. Tsironis[1], B. Baiocchi[2], A. Bruschi[2], L. Figini[2], J. P. Hogge[3], M. Siccinio[4], I. Tigelis[5], C. Wu[6]

[1]*National Technical University of Athens, Athens, Greece*
[2]*Institute for Plasma Science and Technology – National Research Council, Milan, Italy*
[3]*Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland*
[4]*Max-Planck-Institute for Plasma Physics, Garching bei Muenchen, Germany*
[5]*National and Kapodistrian University of Athens, Athens, Greece*
[6]*Karlsruhe Institute of Technology, Karlsruhe, Germany*

# EUROfusion DEMO design

## Fusion Technology Department (FSD) works on DEMO R&D



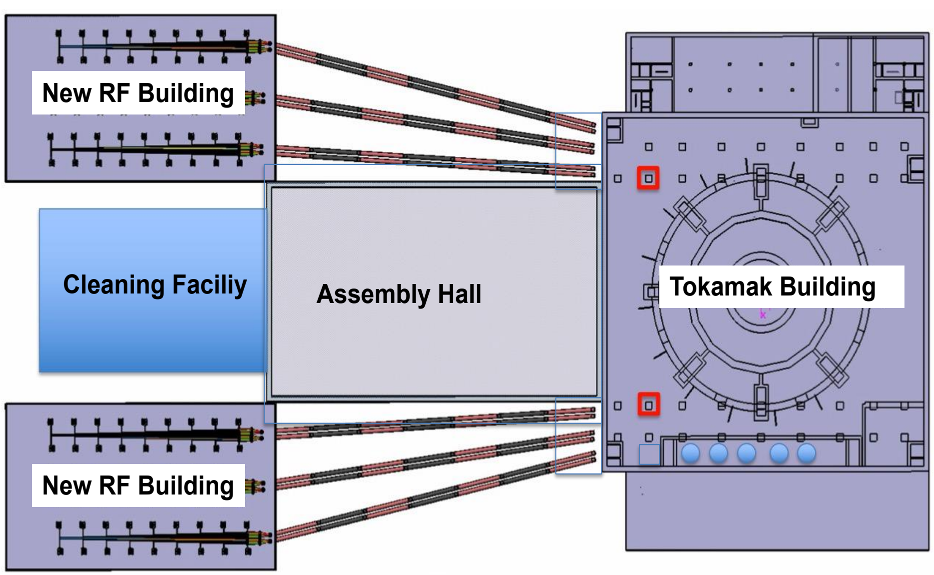
# Heating and Current Drive work package

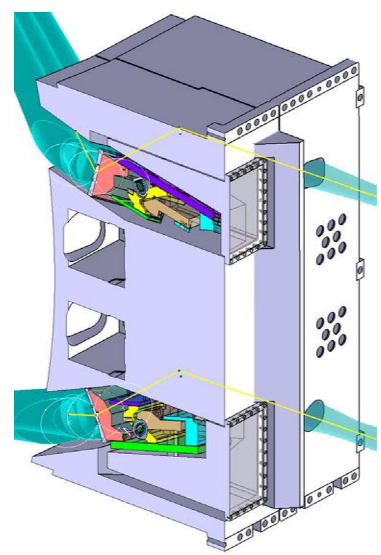
## WP HCD for EC system conceptual design (phys + tech)

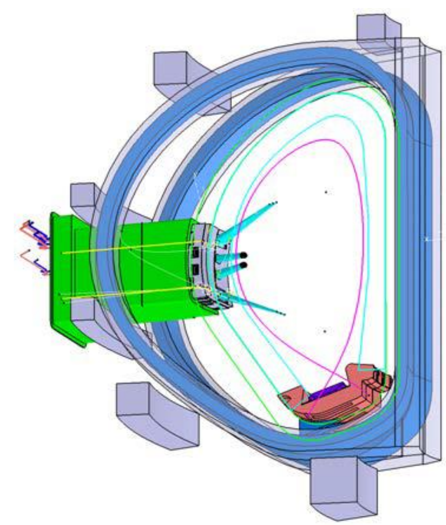
**Launcher**
- Optical design
- Structural & mechanical design
- Integrated control system
- Switches & broadband windows

**Transmission**
- Port-cell
- Multi-beam
- Individual lines
- Connection with gyrotrons

**Gyrotron**
- Basic concepts
- Control system
- Interfaces with system components
- Auxiliaries





# Organization of launcher design studies

**S.01.03-T003: Port Plug (Launcher) optical component design**

**S.01.03-T004: Port Plug (Launcher) structural design**

**S.01.08-T002: Numerical analysis of broadband window concepts**
- D001: Brewster windows & polarization aspects
- D002: Alternative joinings
- D003: Simulation of EM resonances in broadband windows

**S.01.01-T003: WPHCD Launcher optical design**
- D001: Stray radiation evaluations
- D002: Study of compatibility with higher frequency
- D003: Beam-tracing evaluations

**S.01.02-T003: Thermal analysis on launcher components & cooling design**
- D001: Cooling of M1 mirrors
- D002: Cooling design of M2 fixed mirror for BH

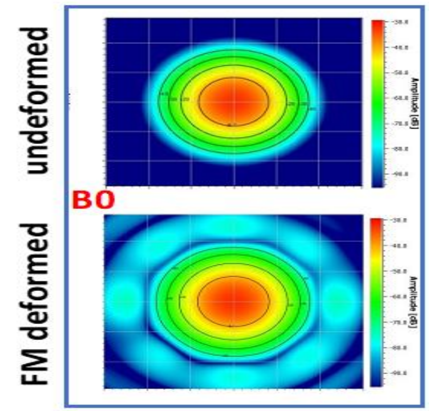
**S.01.04-T002: Port-cell transmission line integration**
- D001: TL Layout update
- D002: Waveguide components preliminary design
- D003: Integration of the components in the CAD design

**S.01.05-T004: Multi-Beam transmission line design**
- D001: TL Layout update
- D002: W7-X MBTL design, including mirrors and supporting structures
- D003: First design of MBTL mirror with cooling circuit

**S.01.06-T004: Individual transmission line design**
- D001: Study of losses for multi- frequency polarisers

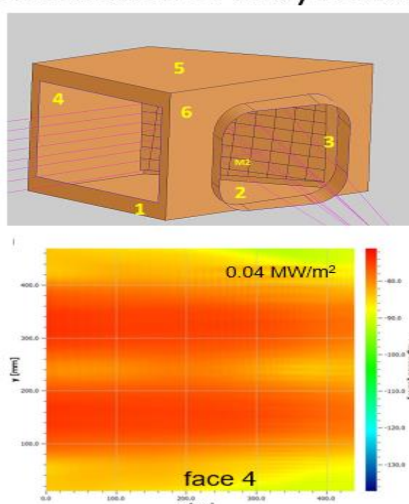
**S.01.07-T002: Impact of RAMI on the ECH system and its functions**
- D001: Functional analysis
- D002: FMEA of the ECH system
- D003: Component reliability & control system techniques to improve W7-X system

**Post-mirror beam pattern**




WP HCD tasks & deliverables

Distribution of stray radiation



# Overview of beam-tracing analysis subtask

**Beam tracing analysis in DEMO plasma scenarios of**
***core ECRH* • *EC-assisted breakdown***

**INPUT**

Magnetic field equilibrium,
plasma density & temperature profiles
based on latest *EU DEMO Reference Design*

equilibrium data (EQDSK)
https://idm.euro-fusion.org/default.aspx?uid=2PCR4X

profile data (MATLAB)
https://idm.euro-fusion.org/default.aspx?uid=2MMUDB

**INPUT**

Launcher design (launch coordinates/directions),
beam parameters (frequency, width/curvature radius)
based on latest *ECRH Beam Configuration Data DEMO**

*Beam input data (EXCEL) based on *EC Optical System Design*

design model (CAD)
http://idm.euro-fusion.org/?uid=2MHNBC

**CODE**

***TORBEAM***

pWKB beam tracing code

code manual (PDF)
https://www.sciencedirect.com/science/article/pii/S001046551730423X

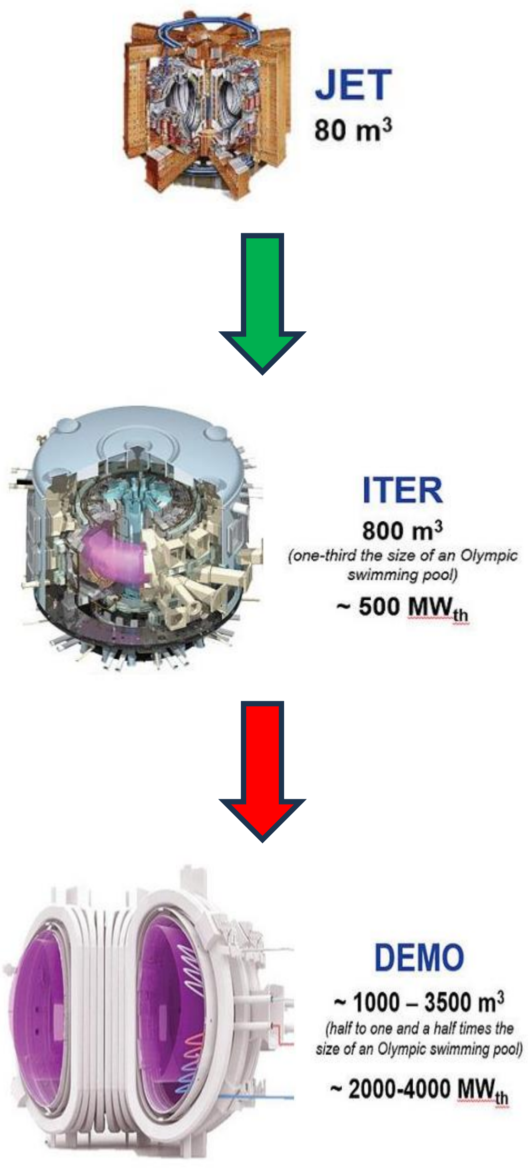
**OUTPUT**

Beam trajectory
Power absorption
Driven current

task report (DOCX)
https://idm.euro-fusion.org/?uid=2QC8DZ

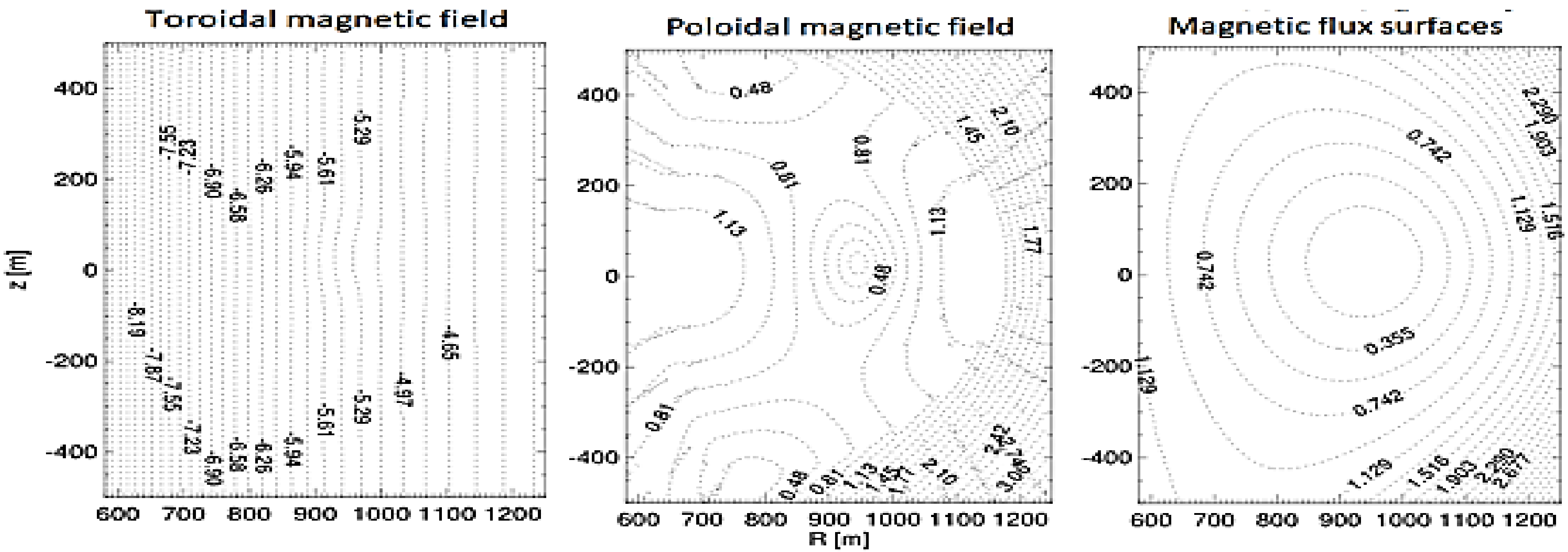
# DEMO reference design parameters

| | |
|---|---|
| Major radius [m] | 8.938 |
| Minor radius [m] | 2.883 |
| Aspect ratio | 3.1 |
| Plasma volume [$m^3$] | 2448 |
| Plasma surface area [$m^2$] | 1374 |
| Elongation at 95% of plasma minor radius | 1.65 |
| Triangularity at 95% of plasma minor radius | 0.333 |
| Safety factor at 95% of plasma minor radius | 3.936 |
| Vacuum toroidal magnetic field on axis [T] | 5.744 |
| Plasma electric current [MA] | 18.27 |
| Fusion power [MW] | 1871 |
| Average electron density [$10^{19}$ $m^{-3}$] | 8.058 |
| Ratio of peak vs average electron density | 1.52 |
| Average electron temperature [KeV] | 11.31 |
| Ratio of peak vs average electron temperature | 3.542 |
| Effective charge of ions | 1.18 |
| Bootstrap vs inductive current fraction | 0.362/0.477 |
| Bootstrap vs auxiliary current fraction | 0.362/0.162 |

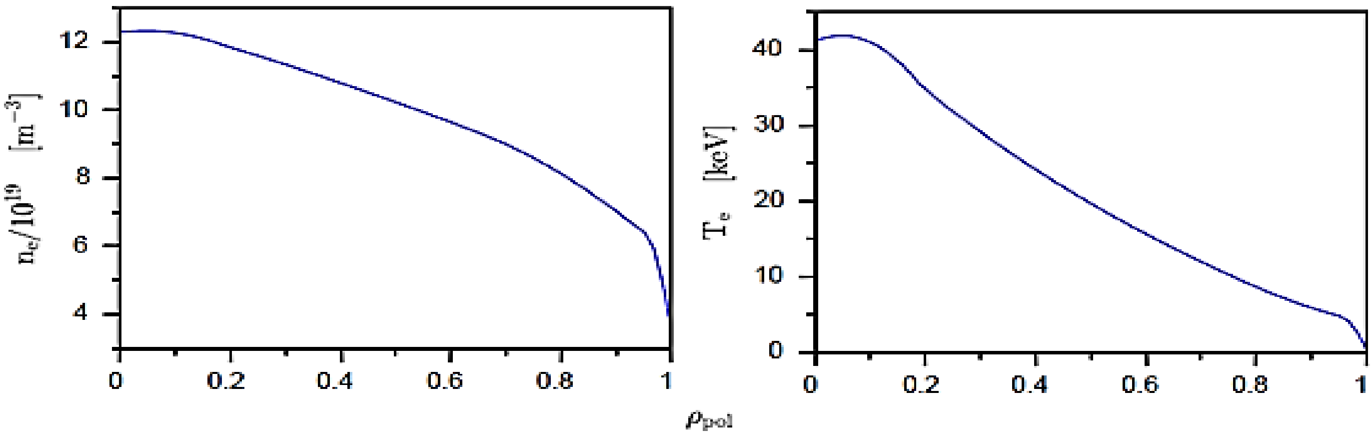


# DEMO plasma configuration

**Magnetic equilibrium**

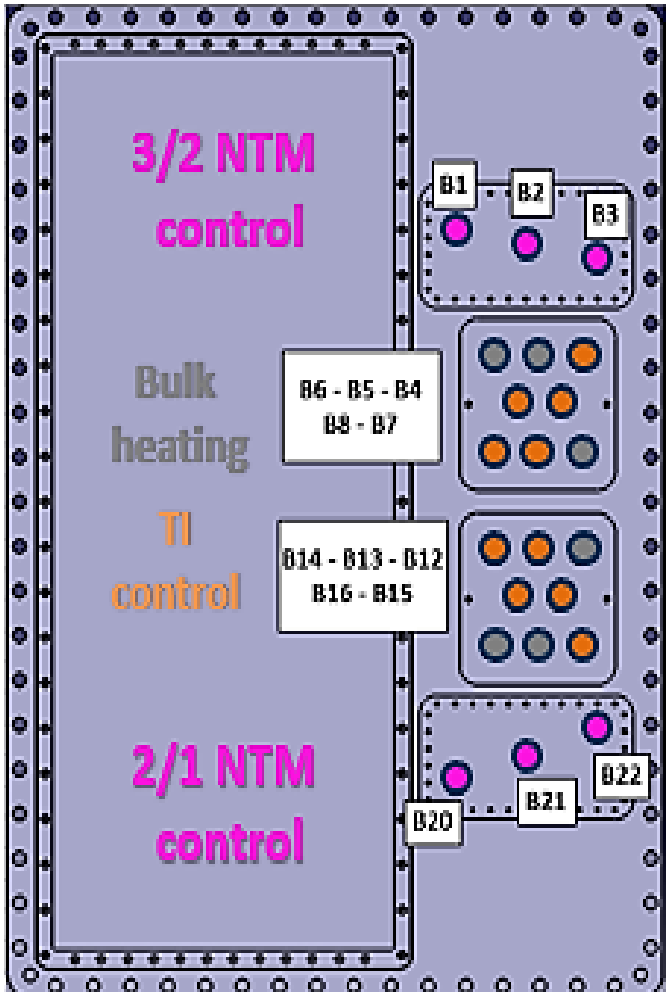



**Density & temperature profiles**



# ECRH beam configuration

## Equatorial Port Plug




## Beam launching conditions

| Launching conditions | Launch point coordinates | | | Launching angles | | Initial beam parameters | |
|---|---|---|---|---|---|---|---|
| | X (mm) | Y (mm) | Z (mm) | α (deg) | β (deg) | w (mm) | Rc (mm) |
| BEAM 1 (NOMINAL α) | 13573.362 | -1187.598 | 955.833 | -15.16 | 24.67 | *f* = 170 GHz 123.92 | *f* = 170 GHz -4466.01 |
| BEAM 1 (α + 3.5°) | 13573.362 | -1187.596 | 955.833 | -11.62 | 24.59 | | |
| BEAM 1 (α - 3.5°) | 13573.362 | -1187.595 | 955.833 | -18.70 | 24.59 | | |
| BEAM 2 (NOMINAL α) | 13400.000 | -1295.000 | 1000.000 | -15.20 | 25.00 | | |
| BEAM 2 (α + 3.5°) | 13400.000 | -1295.000 | 1000.000 | -11.70 | 24.91 | *f* = 204 GHz 103.88 | *f* = 204 GHz -4415.05 |
| BEAM 2 (α - 3.5°) | 13400.000 | -1295.000 | 1000.000 | -18.70 | 24.91 | | |
| BEAM 3 (NOMINAL α) | 13222.651 | -1395.138 | 1045.271 | -15.24 | 25.33 | | |
| BEAM 3 (α + 3.5°) | 13222.651 | -1365.136 | 1045.271 | -11.78 | 25.24 | | |
| BEAM 3 (α - 3.5°) | 13222.651 | -1365.135 | 1045.271 | -18.70 | 25.24 | | |
| BEAM 4 | 13507.130 | -1120.234 | 464.452 | 7.23 | 18.16 | *f* = 136 GHz 64.02 | *f* = 136 GHz 141203.00 |
| BEAM 5 | 13397.596 | -1190.596 | 465.143 | 7.52 | 20.45 | | |
| BEAM 6 | 13289.359 | -1256.336 | 465.909 | 7.82 | 22.71 | *f* = 170 GHz 67.32 | *f* = 170 GHz 18242.73 |
| BEAM 7 | 13453.069 | -1160.741 | 380.000 | 4.91 | 19.52 | | |
| BEAM 8 | 13344.239 | -1228.802 | 380.000 | 5.13 | 21.81 | | |
| BEAM 9 | 13507.036 | -1129.939 | 295.673 | 2.36 | 18.49 | *f* = 204 GHz 57.22 | *f* = 204 GHz 25263.39 |
| BEAM 10 | 13397.595 | -1199.793 | 294.980 | 2.51 | 20.80 | | |
| BEAM 11 | 13289.450 | -1266.091 | 294.213 | 2.67 | 23.07 | | |
| BEAM 12 | 13507.036 | -1129.939 | -295.673 | -2.36 | 18.49 | *f* = 136 GHz 64.02 | *f* = 136 GHz 141203.00 |
| BEAM 13 | 13397.595 | -1199.793 | -294.980 | -2.51 | 20.80 | | |
| BEAM 14 | 13289.450 | -1266.091 | -294.213 | -2.67 | 23.07 | *f* = 170 GHz 67.32 | *f* = 170 GHz 18242.73 |
| BEAM 15 | 13453.069 | -1160.741 | -380.000 | -4.91 | 19.52 | | |
| BEAM 16 | 13344.239 | -1228.802 | -380.000 | -5.13 | 21.81 | | |
| BEAM 17 | 13507.130 | -1120.234 | -464.452 | -7.23 | 18.16 | *f* = 204 GHz 57.22 | *f* = 204 GHz 25263.39 |
| BEAM 18 | 13397.596 | -1190.596 | -465.143 | -7.52 | 20.45 | | |
| BEAM 19 | 13289.359 | -1256.336 | -465.909 | -7.82 | 22.71 | | |
| BEAM 20 (NOMINAL α) | 13565.187 | -1167.865 | -934.645 | 23.13 | 15.81 | *f* = 170 GHz 123.92 | *f* = 170 GHz -4466.01 |
| BEAM 20 (α + 3.5°) | 13565.188 | -1167.869 | -934.645 | 19.58 | 15.72 | | |
| BEAM 20 (α - 3.5°) | 13565.187 | -1167.855 | -934.645 | 26.67 | 15.71 | | |
| BEAM 21 (NOMINAL α) | 13400.000 | -1295.000 | -1000.000 | 23.15 | 16.00 | | |
| BEAM 21 (α + 3.5°) | 13400.000 | -1295.000 | -1000.000 | 19.67 | 15.90 | *f* = 204 GHz 103.88 | *f* = 204 GHz -4415.05 |
| BEAM 21 (α - 3.5°) | 13400.000 | -1295.000 | -1000.000 | 26.63 | 15.90 | | |
| BEAM 22 (NOMINAL α) | 13229.134 | -1415.660 | -1067.495 | 23.17 | 16.19 | | |
| BEAM 22 (α + 3.5°) | 13229.134 | -1415.663 | -1067.495 | 19.76 | 16.09 | | |
| BEAM 22 (α - 3.5°) | 13229.135 | -1415.651 | -1067.494 | 26.59 | 16.11 | | |

# Core ECRH (high magnetic field scenario)

***SRD REFERENCE VALUES***
Up to 30 MW EC @ f < 240 GHz
ECRH/ECCD @ $\rho_t < 0.3$

***Considerations of DEMO baseline with higher magnetic field***

Central toroidal field: $6\ T < B_0 < 9\ T$

**Equilibrium & plasma input?**

Rescale $\mathbf{B_0}$ (assuming an increase to $\mathbf{q_{95}}$ so that $\mathbf{B_p}$, $\mathbf{n_e}$ & $\mathbf{T_e}$ are retained)

**RESULTS for f = 238 GHz**

**Complete (single-pass) absorption**

**Deposition obeys SRD limit ($0.02 < \rho_t < 0.27$)**

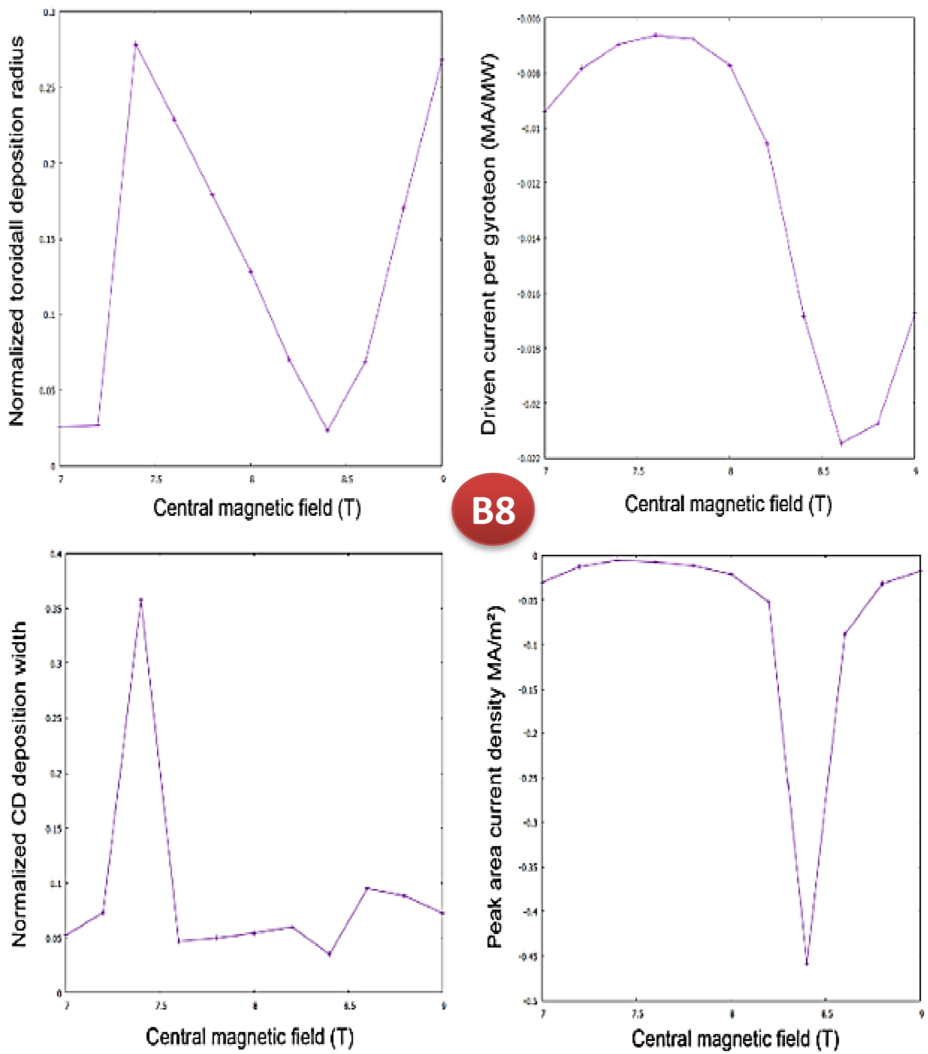
**$|I_{CD}|/P_{abs}$ [A/W] ranges from 0.003 to 0.054**

**Parasitic (O2) absorption decreases vs $B_0$**

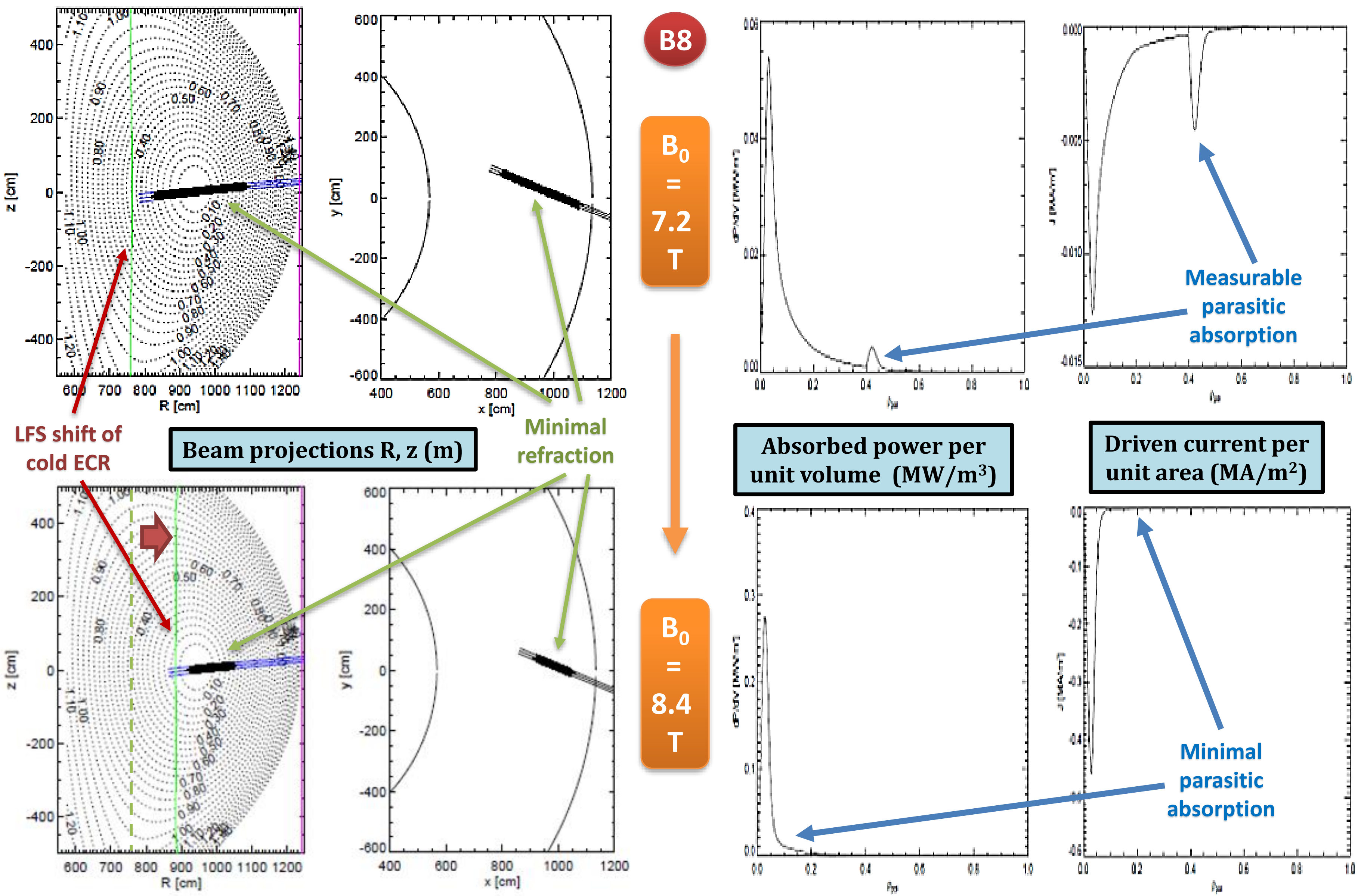
**Deposition seems to become narrower vs $B_0$ ($0.01 < \Delta\rho_p < 0.05$ when $7.5 < B_0$ [T] $< 8.5$)**

**|Peak CD| [MA/m$^2$] ranges from 0.01 to 0.5**

## HCD parameters vs central magnetic field



# Beam tracing results for high magnetic field



# Core ECRH (low magnetic field scenario)

***SRD REFERENCE VALUES***

Same as in the high magnetic field scenario

***Considerations of DEMO baseline with lower magnetic field***

<u>Central toroidal field:</u> 2 T < $B_0$ < 5 T

**<u>Relevant to the analysis of low aspect ratio (AR) scenario</u>**

Baseline with lower central field (to be analysed from late 2023 on)

## <u>RESULTS for f = 136 GHz</u>

**Complete (single-pass) absorption**

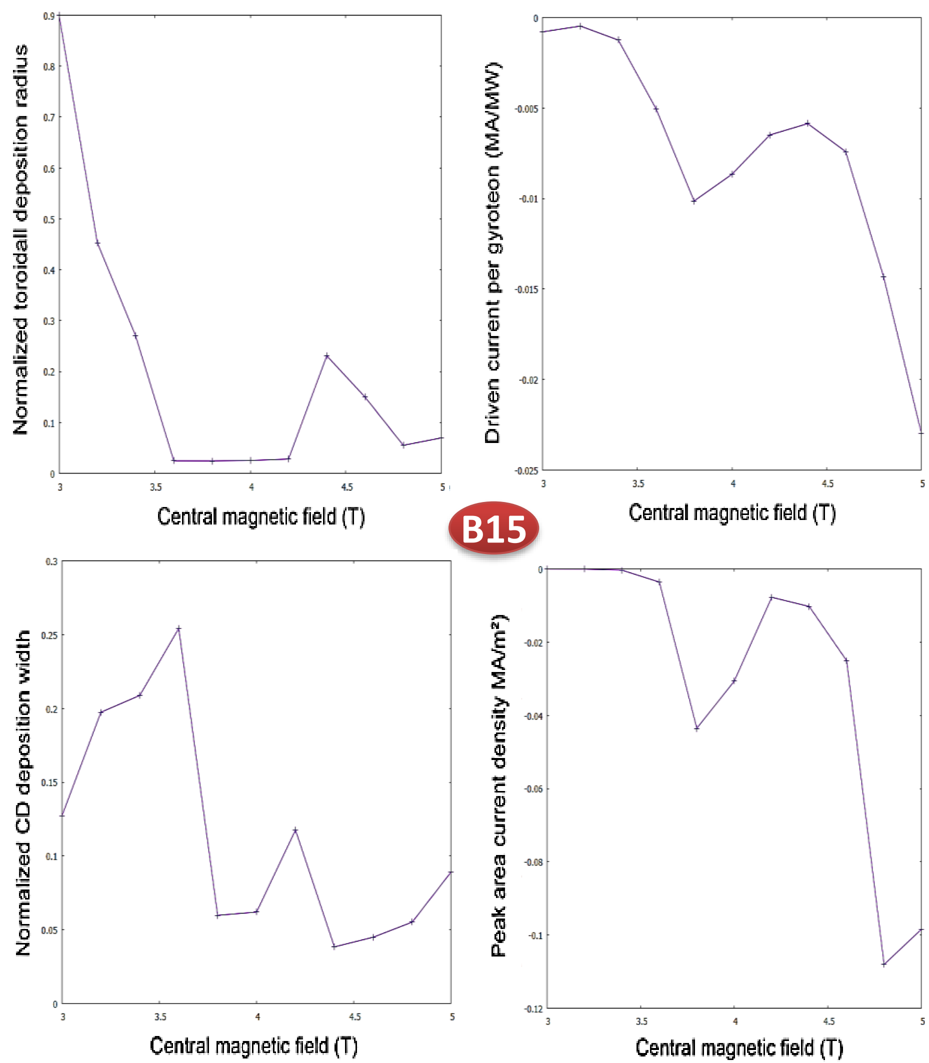
**Deposition obeys SRD limit only for $B_0$ [T] > 3.5 ($\rho_t$ > 0.3 for $B_0$ [T] < 3.5 T)**

**$|I_{CD}|/P_{abs}$ [A/W] is smaller than 0.025**

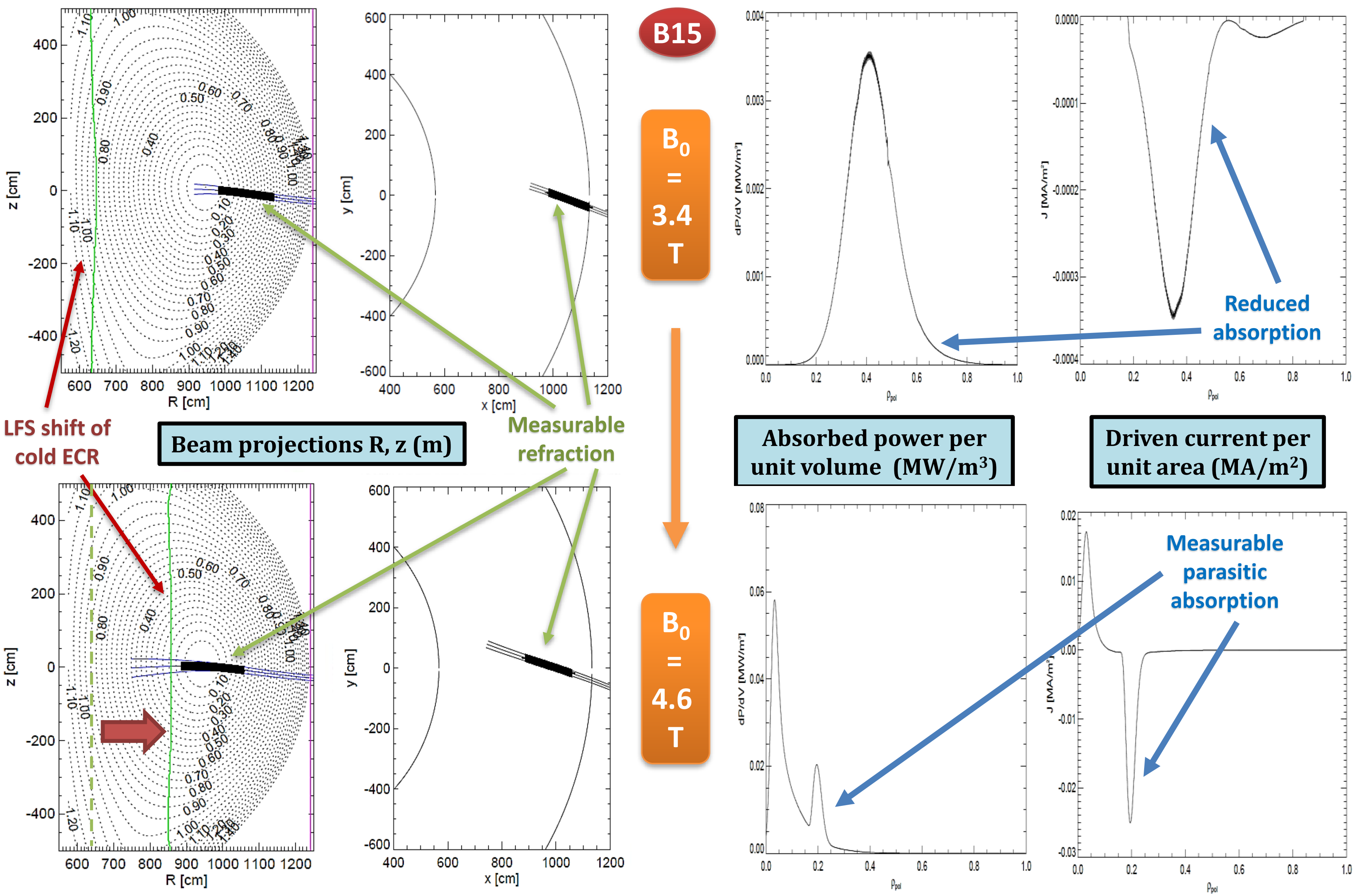
**Deposition seems to narrow down vs $B_0$ (0.05 < $\Delta\rho_p$ < 0.1 when $B_0$ [T] > 3.7)**

**|Peak CD| [MA/m²] is smaller than 0.11**

**HCD parameters vs central magnetic field**



# Beam tracing results for low magnetic field



# EC-assisted breakdown

***SRD REFERENCE VALUES***
Up to 10 MW EC @ f < 240 GHz
ECRH @ 1.5 ± 0.5 m from inner wall

**Plasma & device parameters**

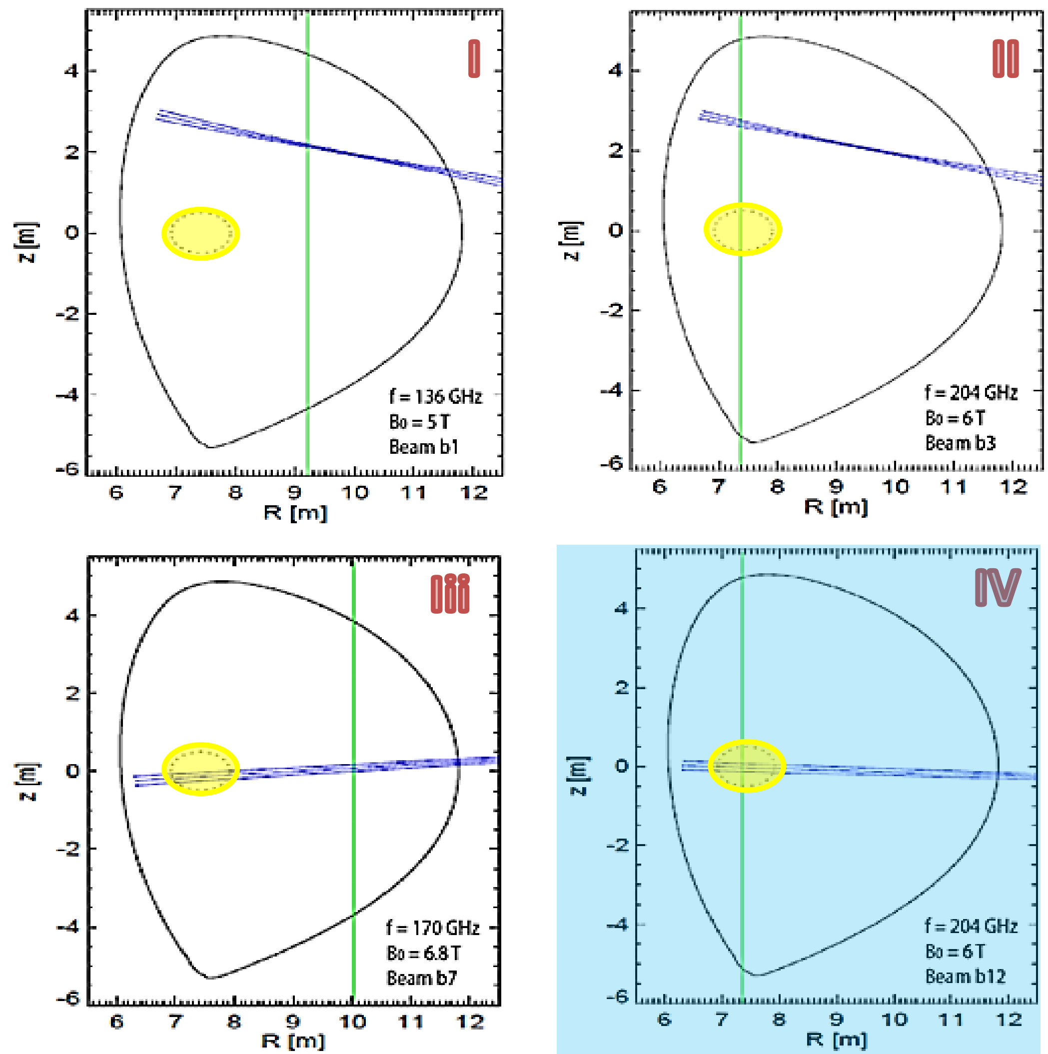
***Low $n_e$***
($< 10^{18}$ $m^{-3}$)
***Very low $T_e$***
(≈ 100 eV)

***$B = B_t$***
(3 – 7 T)

**EC-based breakdown (BKD) condition**

Beam trajectory & EC cold resonance line should both cross the region specified by SRD

**Four different scenarios in the BKD setup**



# Qualified magnetic field scenarios

## BEAM TRACING RESULTS

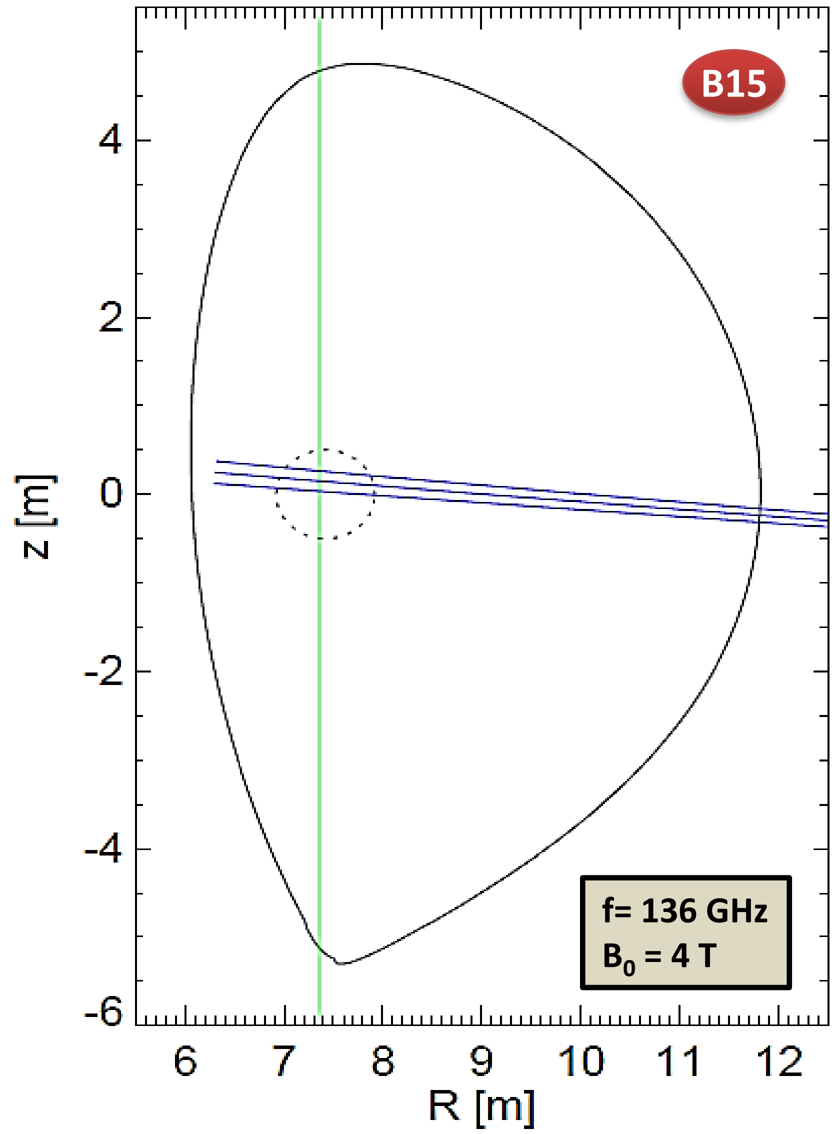
All Mid Module beams target the SRD region!

*f-$B_0$ scenarios qualified for SRD*

| Frequency (GHz) | Central magnetic field (Tesla) | | | |
|---|---|---|---|---|
| 136 | 3.8 | 4.0 | 4.2 | |
| 170 | 5.0 | 5.2 | | |
| 204 | 5.8 | 6.0 | 6.2 | 6.4 |
| 238 | 6.6 | 6.8 | 7.0 | |

Linear absorption becomes effective (> 10%) after density threshold ($n_e > 10^{19}\ m^{-3}$)

Reflection(s) of the EC beam to the inner/outer wall are not taken into account



# Conclusion – Discussion of results

## *Core ECRH*

- ❑ Launch conditions at the Mid Modules of the EC port plug, depending on f-$B_0$ combination, provide satisfactory operation within current SRD requirements
- ❑ Parasitic absorption is measurable for lower $B_0$, because cold ECR is located in HFS and beam path becomes longer in regions far from 1st harmonic absorption
- ❑ Frequency option 238 GHz more effective for $B_0$ ranging from 7.5 T to 8.5 T
- ❑ Frequency option 136 GHz more effective for $B_0$ larger than 3.5 T
  - ▻ First step in the analysis of DEMO low-AR scenario (ongoing work 2023 – 24)

## *EC-assisted breakdown*

- ❑ All beam conditions from the Mid Modules cross the BKD region
- ❑ Optimal/required gyrotron frequency depends on the central magnetic field:
  - ▻ 136 GHz for $3.7\ T < B_0 < 4.3\ T$ (*relevant to low-AR scenario*)
  - ▻ 170 GHz for $4.9\ T < B_0 < 5.3\ T$ } (*as seen in HCD 2021 & 2022 reports*)
  - ▻ 204 GHz for $5.7\ T < B_0 < 6.5\ T$ } (*as seen in HCD 2021 & 2022 reports*)
  - ▻ 238 GHz for $6.5\ T < B_0 < 7.1\ T$ (*relevant to high magnetic field scenario*)

☛ Current design may fulfil the SRD goals for BH & BKD

# References – Acknowledgements


| | | | |
|---|---|---|---|
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