Feasibility of an ECRH system for JET: wave propagation, absorption and current drive

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Outline

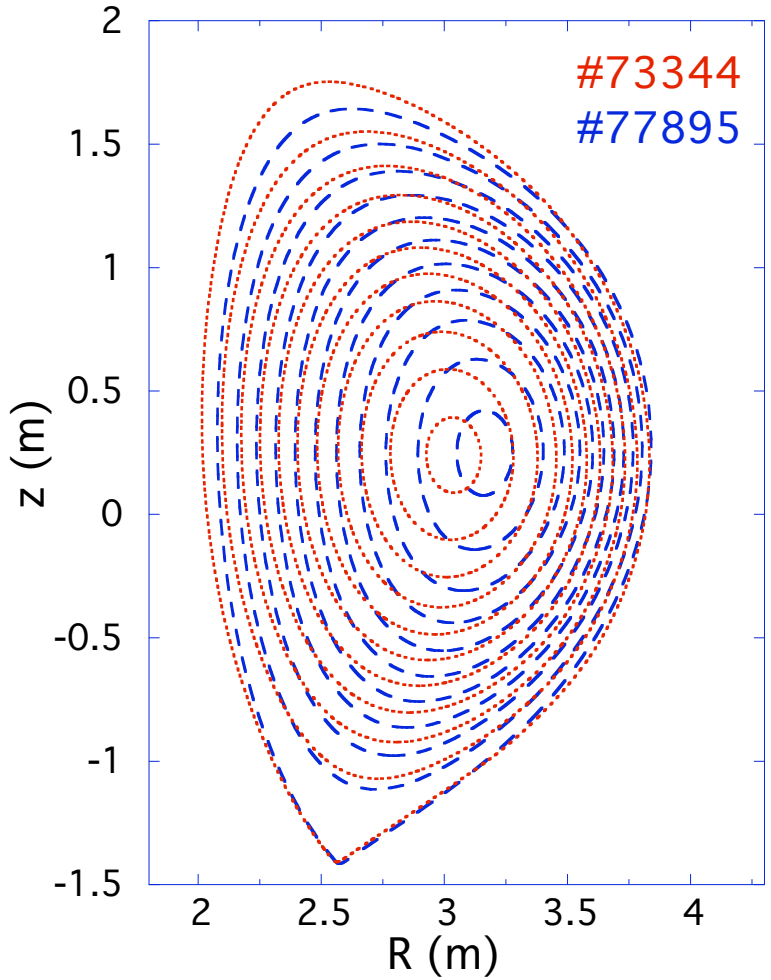
- **JET reference scenarios for ECRH&CD**
- **ECRH setup**
- **Frequency choice**
  - **113 &150 GHz** *(see details in poster session II)*
  - **170 GHz**
- **ECRH&CD performance at 170 GHz**

Basis for an EC system design

Recipe

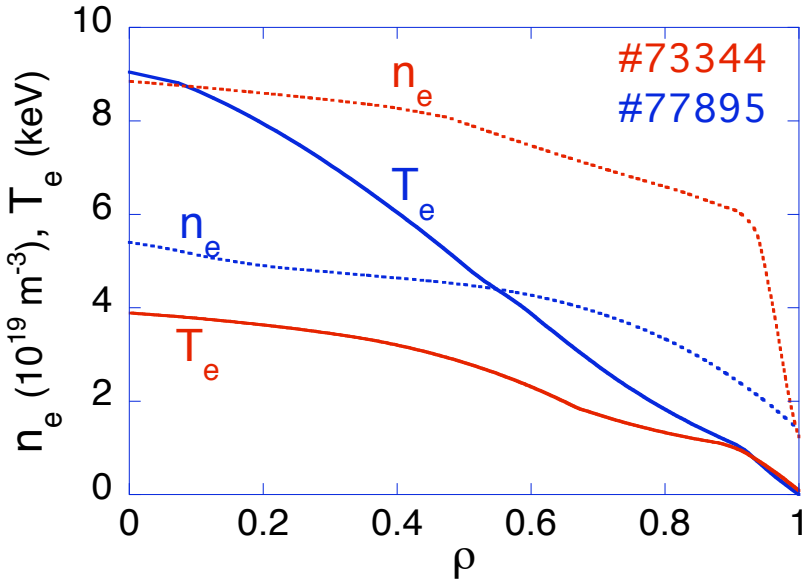
- **Good absorption** → up-shifted CD: $\tau_{OM1,XM2} \sim n_e T_e$
- **Large ECCD efficiency**: $I_{CD} \sim T_e / n_e \, F(T_e, N_{//}, \ldots)$
- **Large I_{CD} / J_{CD}** for large/small toroidal angles
- **HFS EC interaction** to minimize trapping effects
- use **poloidal angle** to change ρ
- check **refraction** effects (cut-offs)
- check **harmonic** overlap: $\Delta\omega/\omega \sim 1/n$

Reference Scenarios



#73344, standard H-mode scenario:
high n_e& low T_e, small ratio T_e/ n_e

#77895, advanced scenario:
low n_e& high T_e, large ratio T_e/ n_e



Equilibrium rescaled keeping q_{95}, plasma β and n_e/n_{GW} constant:
plasma current, density and temperature rescaled with B

ECRH&CD set-up

Two mirror locations:

R = 4.3 m z = 34.5 cm UM
R = 4.3 m z =-34.5 cm LM

Divergent beam *(not optimized):*

waist=3 cm at the mirror

α and β poloidal&toroidal angles

$N_R = -\cos\alpha \cos\beta$

$N_\phi = \sin\beta$

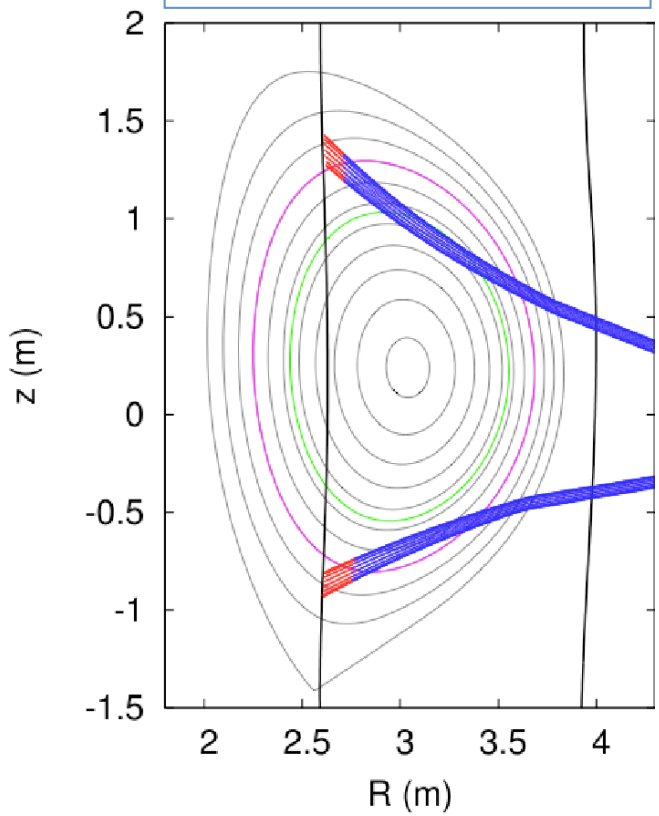
$N_z = -\cos\beta \sin\alpha$

Calculations performed for a wide scan of injection angles:

$0^o \leq \beta \leq 26^o$, step $\Delta\beta = 2^o$

$-50^o \leq \alpha \leq 40^o$, step $\Delta\alpha = 2^o$

B=2.65 T - 170 GHz



GRAY code:
beam tracing code,
relativistic absorption
CD via adjoint method

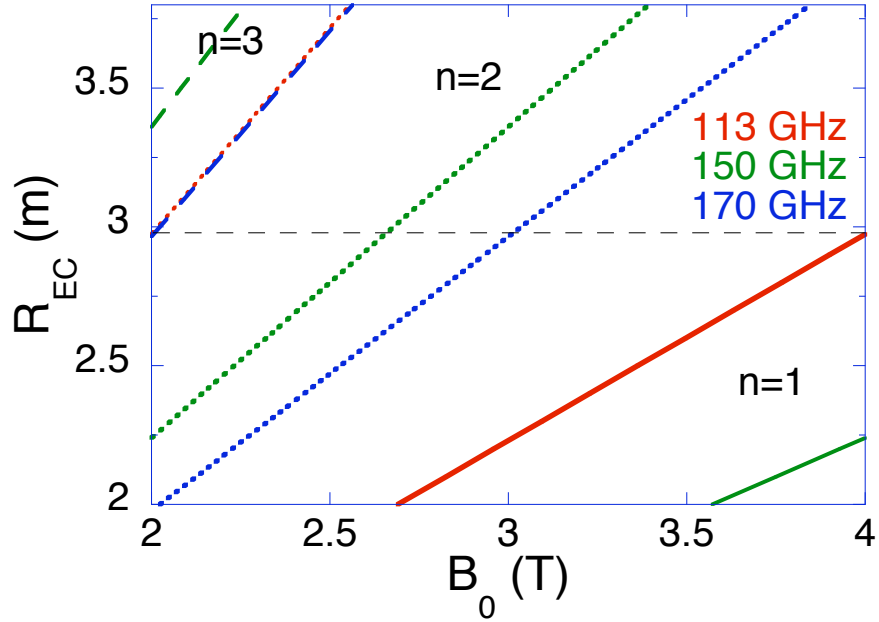
EC frequency & magnetic field

Choice of the optimal EC frequency based on:

- E4J physics goals => ρ_{EC}
- B range of operation: **2.5 T ≤ B ≤ 3.4 T**

- **113 GHz:**
  - *same frequency of the previous EC Project for JET*
  - OM1 - HFS interaction at high B>3 T
- **150 GHz:**
  - *option double freq. gyr. 113/150 GHz*
  - XM2 - HFS for B < 2.8 T
- **170 GHz:**
  - *ITER EC frequency*
  - XM2 - HFS for B < 3 T, LFS B>3 T

EC resonance radius vs B_0
$R_{EC} = R_0 B_0 / (28 f_{EC})$

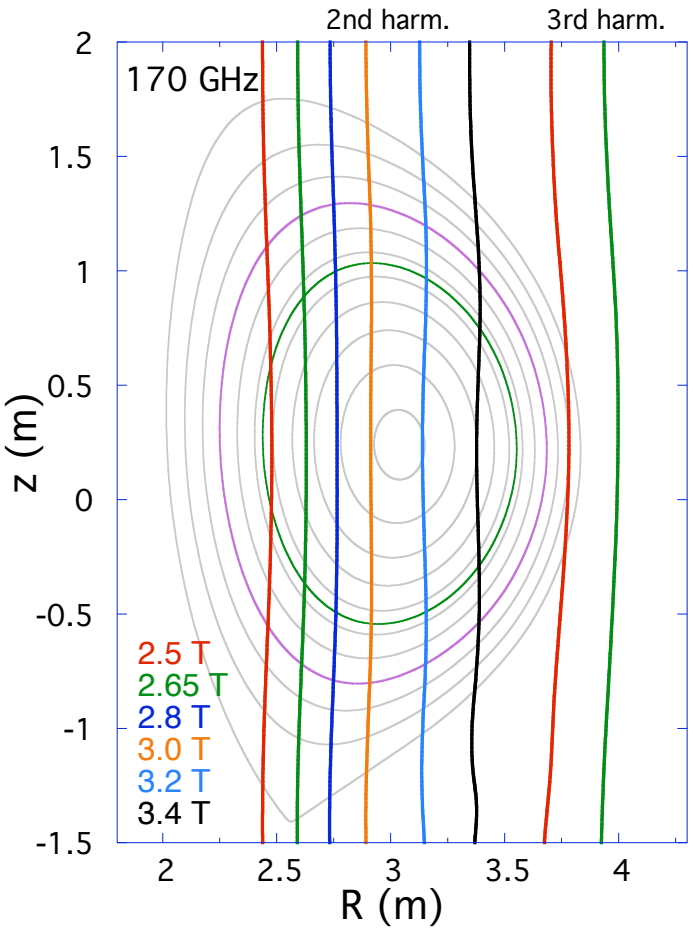


Cut-off density:

- 113 GHz OM1 n_{co}= 1.6 10^{20} m^{-3}
- 150 GHz XM2 n_{co}= 1.4 $10^{20}\cos^2\phi$ m^{-3}
- 170 GHz XM2 n_{co}= 1.8 $10^{20}\cos^2\phi$ m^{-3}

f =170 GHz

EXTRAORDINARY mode
2nd harmonic (+3rd)



- **2.8 T ≤ B ≤ 3.2 T:**

EC resonance in a wide region close to centre

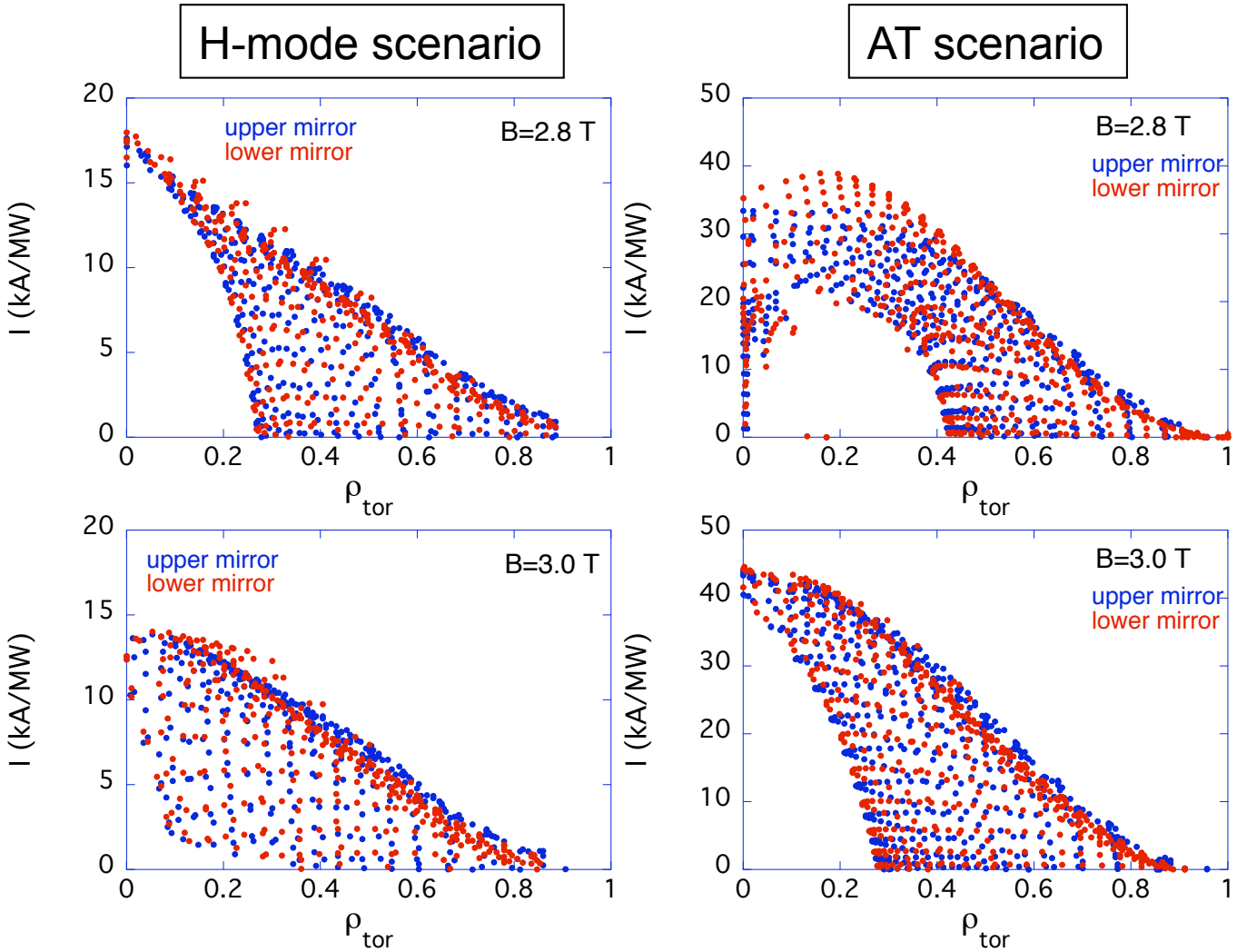
- **B ≤ 2.7 T:**

LFS 3rd harmonic absorption

- **B > 3.2T:**

LFS EC resonance

170 GHZ – H-mode&AT scenarios

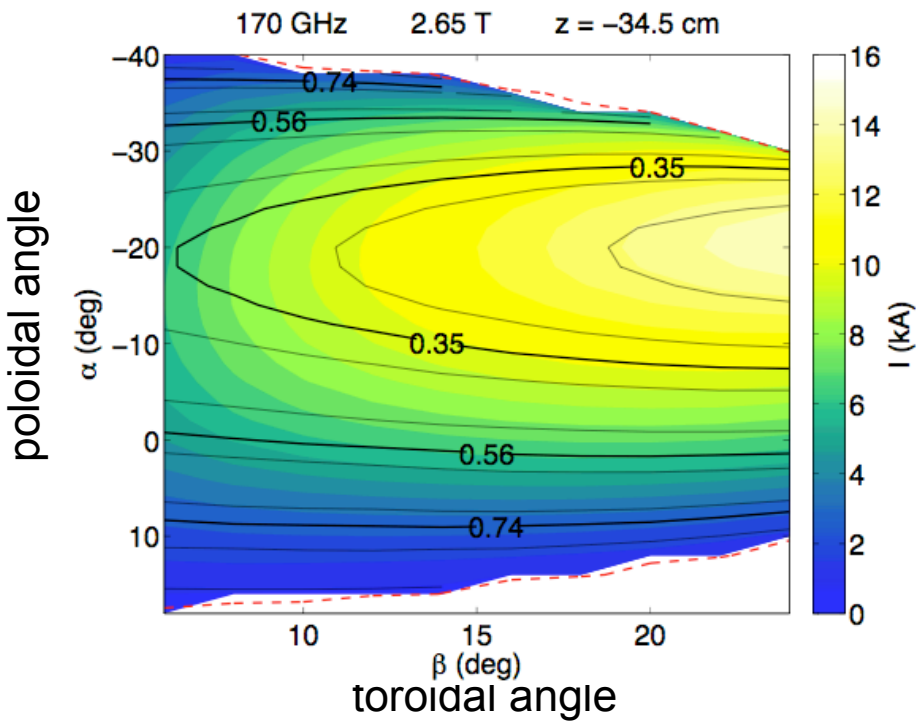


170 GHz: XM2 (XM3)

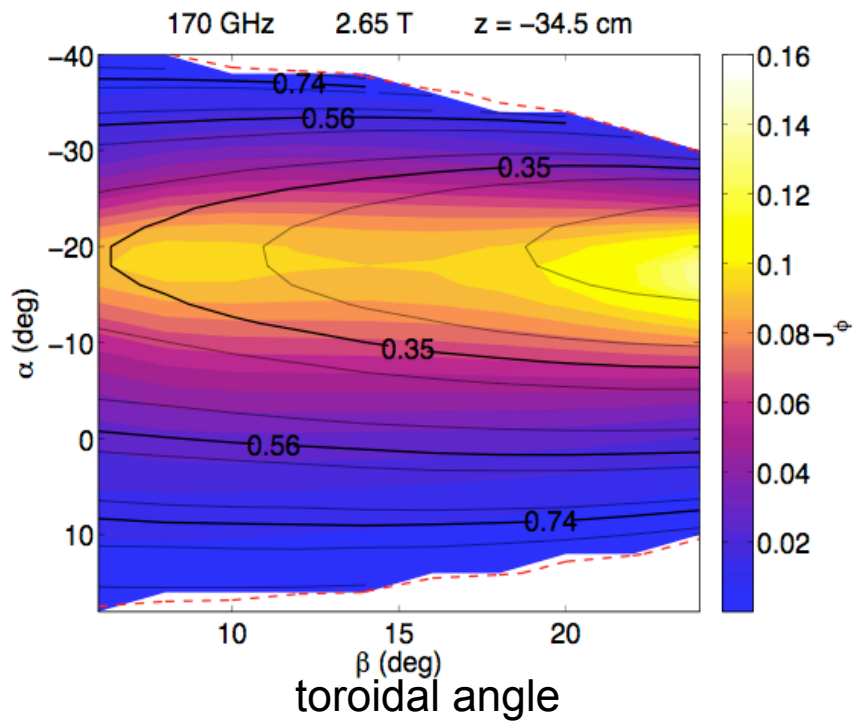
- **2.7 T≤ B ≤ 3.2 T:** up to plasma centre
- **B ≤ 2.7 T:** parasitic XM3
- **B=2.5 T**, large XM3 absorption in AT scen.
- **B>3.2 T**: EC resonance in the LFS
- ***ECCD up to 3 times larger in AT w.r.t. H-mode scenario***

optimal launching set-up

EC driven current



EC driven current density



Most favorable launching conditions *(at any frequency):*
Upper mirror: *upward* Lower mirror: *downward*

max J achieved at lower toroidal angle β than max I_{cd}

Effective steering range:
toroidal angle -25º/+25º, poloidal steering range 30º

170 GHZ - 3rd harm. absorption

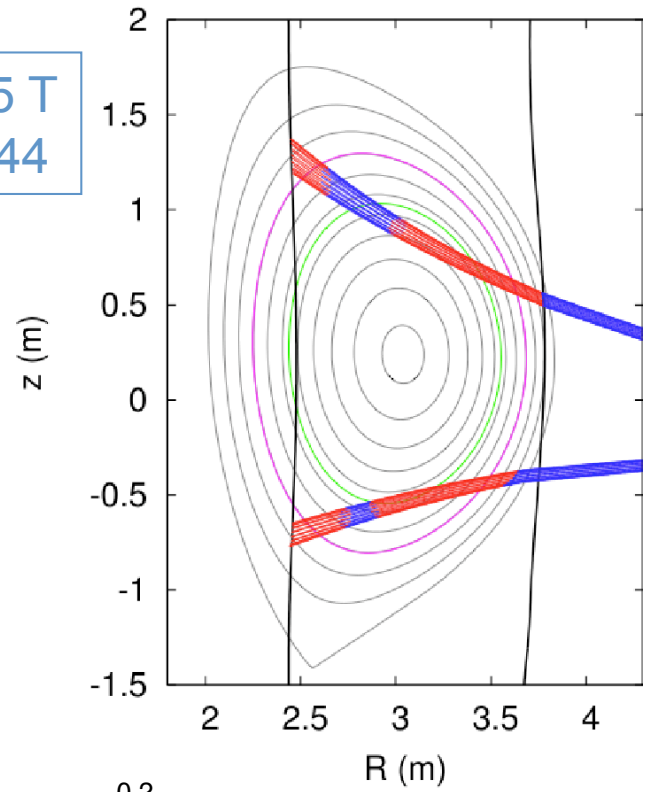
Main drawback at 170 GHz:
Third harmonic interaction can take place at low B and/or at high T_e.

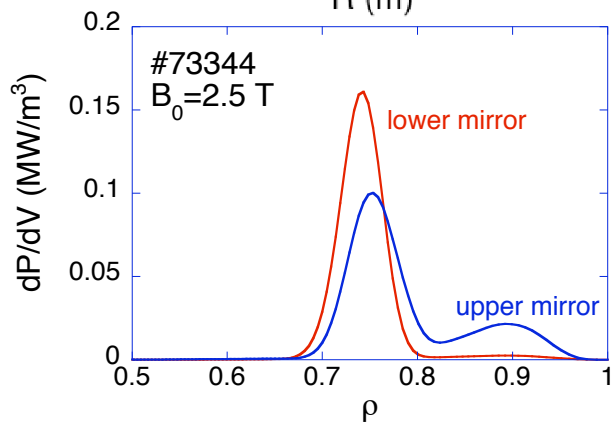
- B=2.5 T: large fraction of power may be absorbed as 3rd harmonic, reducing the power available at the 2nd harmonic.

- B= 2.65 T: 3rd harmonic absorption is less than 5%, but it may become relevant at large T_e .

-P_3/P_0 is larger in case of the upper mirror, since the beam crosses inner plasma regions (at larger T_e).

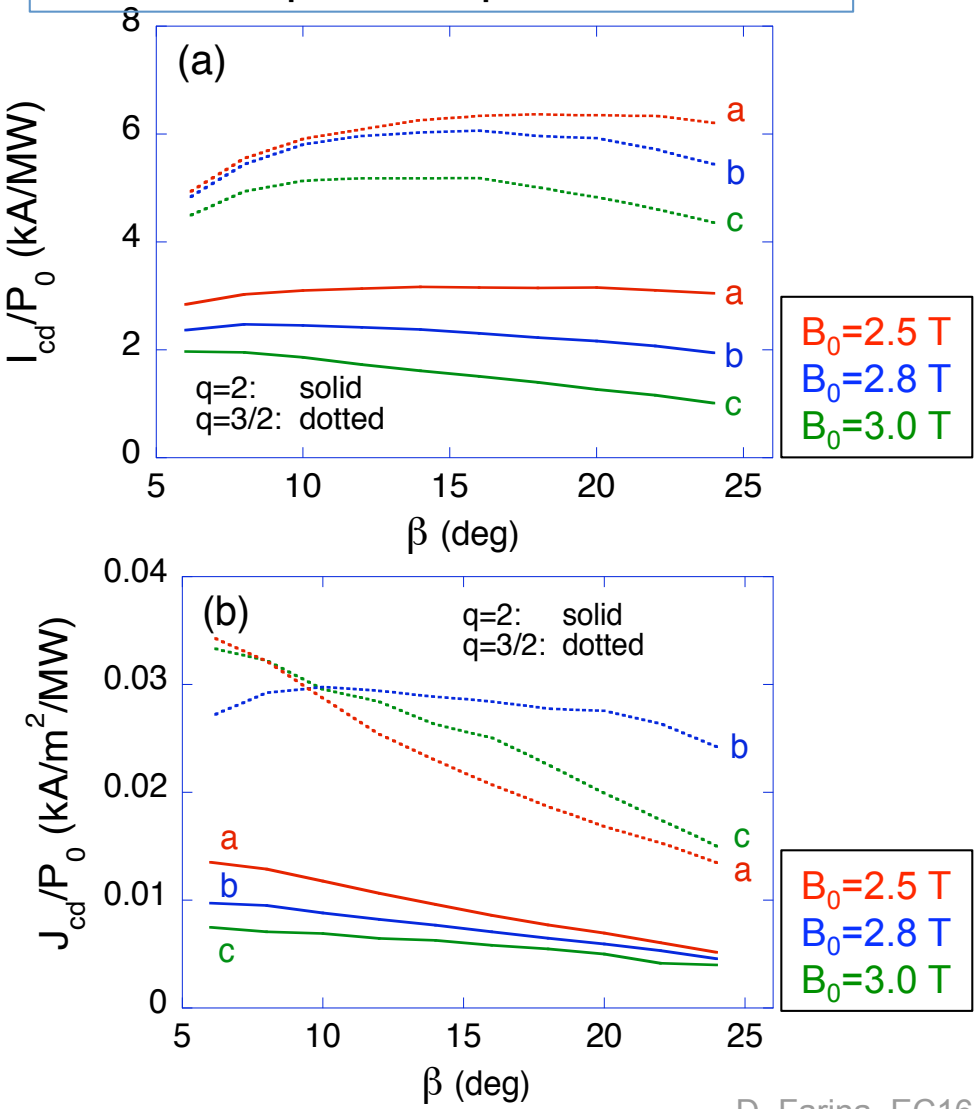
B=2.5 T
#73344





ECCD for NTMs stabilization

I_{cd} & J_{cd} vs toroidal injection angle β on the q=2 and q=3/2 surface



I_{cd} and J much larger at q=3/2 wrt to q=2

I_{cd} increases with β

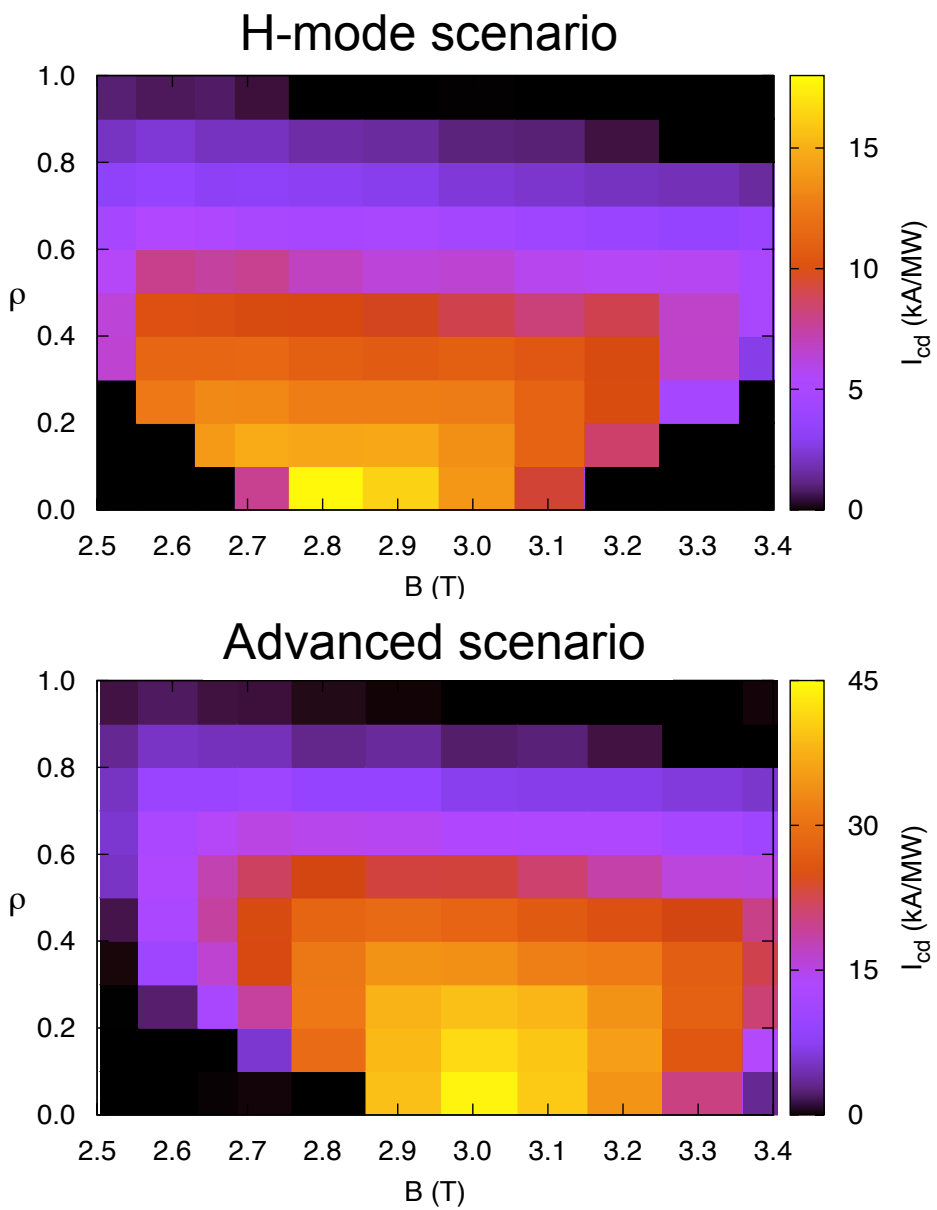
peak J maximum at moderate β

- **$P_{EC,stab}$ < 6 MW** sufficient to control the **(3,2)** mode

- **$P_{EC,stab}$ > 10 MW** needed to stabilize the **(2,1)** mode for current profile width ≥ 0.1m and B > 2.9 T

see details in S. Nowak's poster

ECCD summary at 170 GHz



- B_0 varied in steps ΔB=0.1T
- α, β scan for each B_0 value
- Data filtering: P_a>95%, $\delta\rho$<0.1
- Data grouping: step $\Delta\rho$=0.1

- $ECCD_{AT} \approx 2.5 \times ECCD_{H\text{-}mode}$ (more favorable T_e/n_e ratio)
- Max ECCD efficiency at: B_0=2.8 T (H-m) and 3.0 T (AT)
- region ρ<0.2 accessible up to: B_0=3.2 T (H-m) and 3.4T (AT)
- ECCD affected by
  - trapping effects at high B_0 (hfs)
  - 3rd harm. absorption at low B_0 and high T

Frequency choice

Main criteria:
- good accessibility
- large absorption
  $P_a > 95\%$, $P_3 < 20\%$
- large ECCD

113+150 GHz :
- Broad magnetic field range
- Poor performance at B_0~3T
- Low ITER relevance

170 GHz :
- Best performances at B_0~2.8-3T
- 3rd harm. absorpt. at B_0<2.6T
- Low efficiency at $B_0 \geq 3.4$T
- Fully ITER relevant

113 GHz

ρ \ B	2.5 T	2.65 T	2.8 T	3.0 T	3.2 T	3.4 T
ρ<0.3						
0.3<ρ<0.5						
0.5<ρ<0.8						

150 GHz

ρ \ B	2.5 T	2.65 T	2.8 T	3.0 T	3.2 T	3.4 T
ρ<0.3						
0.3<ρ<0.5						
0.5<ρ<0.8						

170 GHz

ρ \ B	2.5 T	2.65 T	2.8 T	3.0 T	3.2 T	3.4 T
ρ<0.3						
0.3<ρ<0.5						
0.5<ρ<0.8						

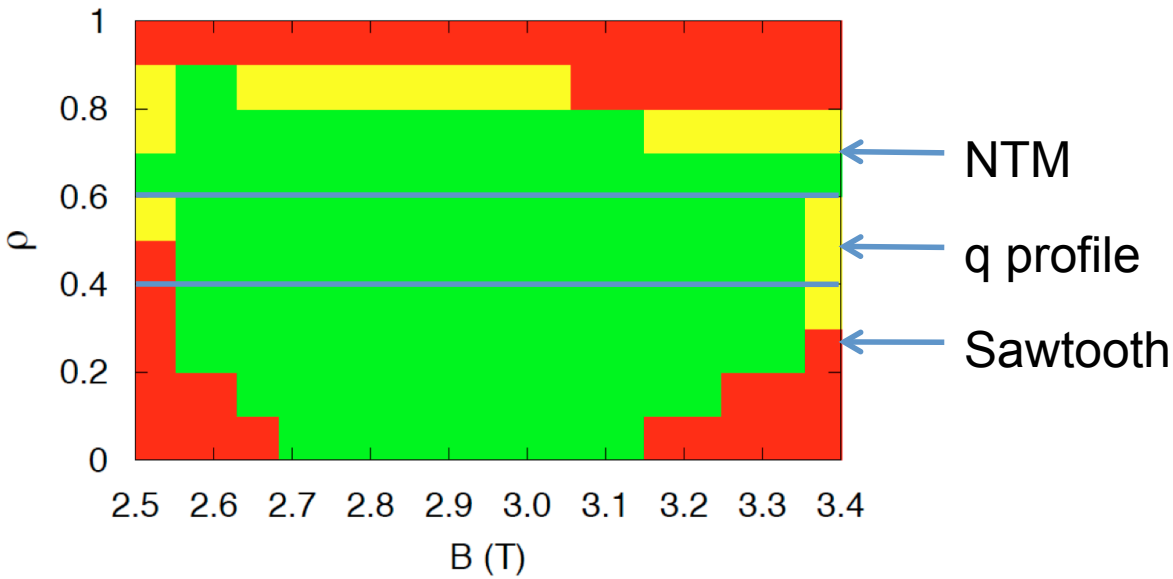
Conclusions

- **Frequency 170 GHz** *(same as in ITER)* has been chosen since it allows very good performance in the interval 2.7-3.1 T
  - extensive analysis of ECCD efficiency performed varying the launching angles in a wide magnetic field range
  - input to launcher design

ECCD performances at 170 GHz

H-mode scenario - Summary

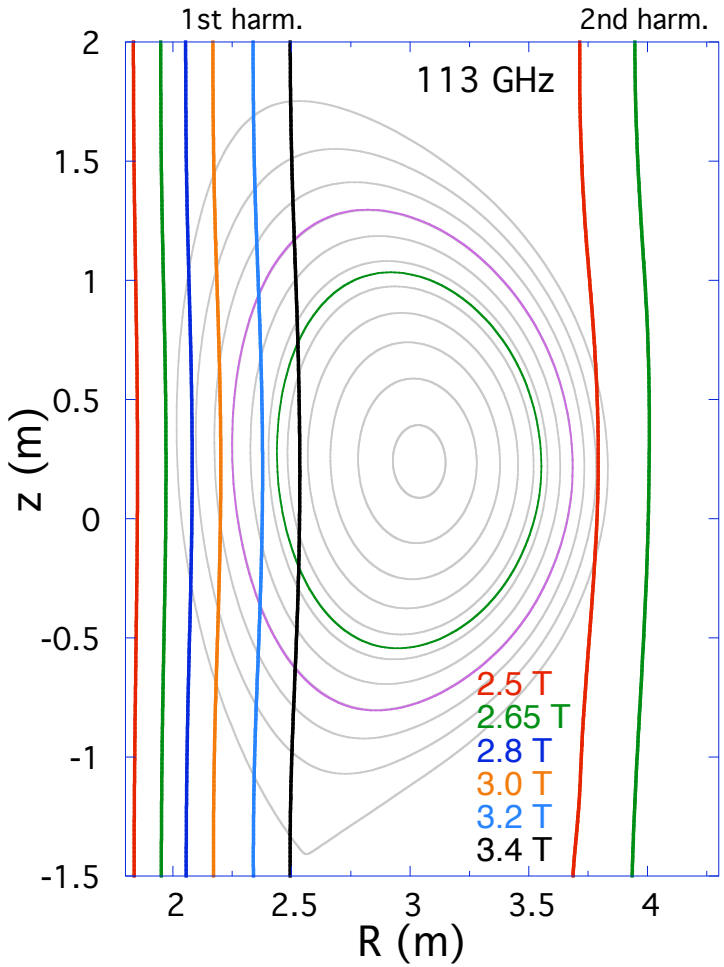
Physics Application	Plasma Region	Icd Efficiency (kA/MW) color coding		
		Green	Yellow	Red
NTM stabilization	$\rho > 0.6$	$I_{cd} > 2$	$1 < I_{cd} < 2$	$I_{cd} < 1$
q profile control	$0.4 < \rho < 0.6$	$I_{cd} > 6.5$	$4.5 < I_{cd} < 6.5$	$I_{cd} < 4.5$
Sawtooth stabilization	$\rho < 0.4$	$I_{cd} > 2$	$1 < I_{cd} < 2$	$I_{cd} < 1$



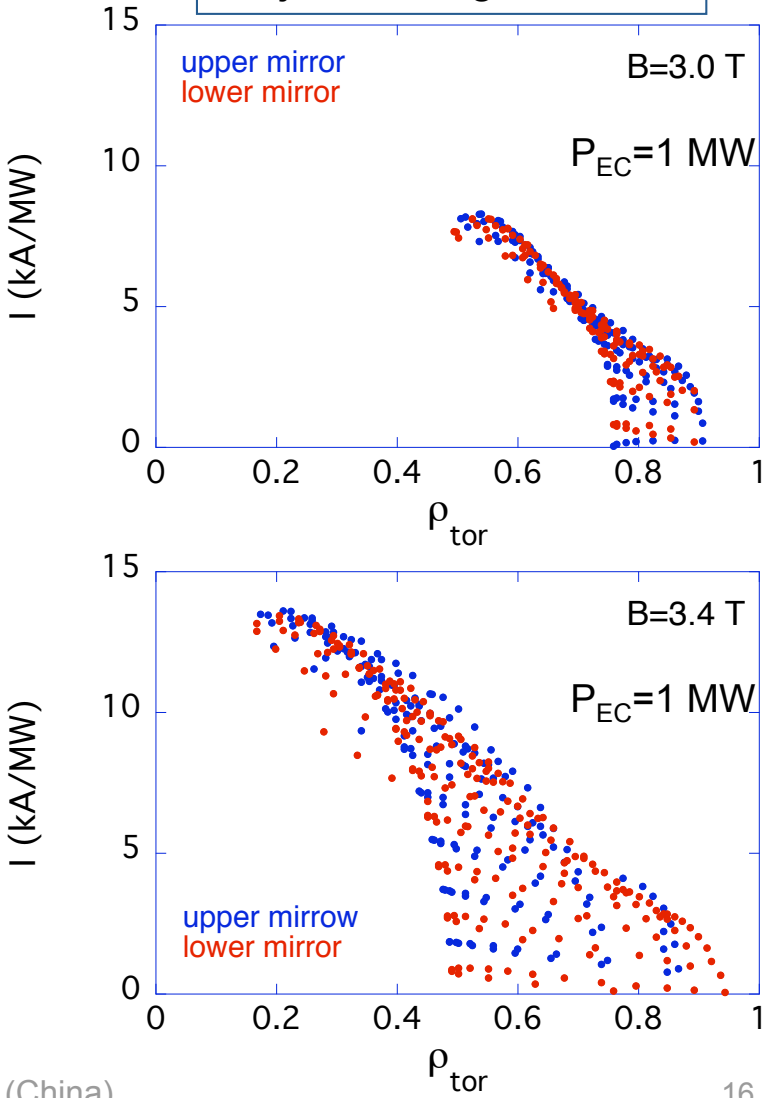
113 GHz

113 GHz: OM1

- *B*≤3.0 T: EC resonance in the outer region
- *B*>3.0 T: EC resonance for $\rho < 0.8$ (HFS)



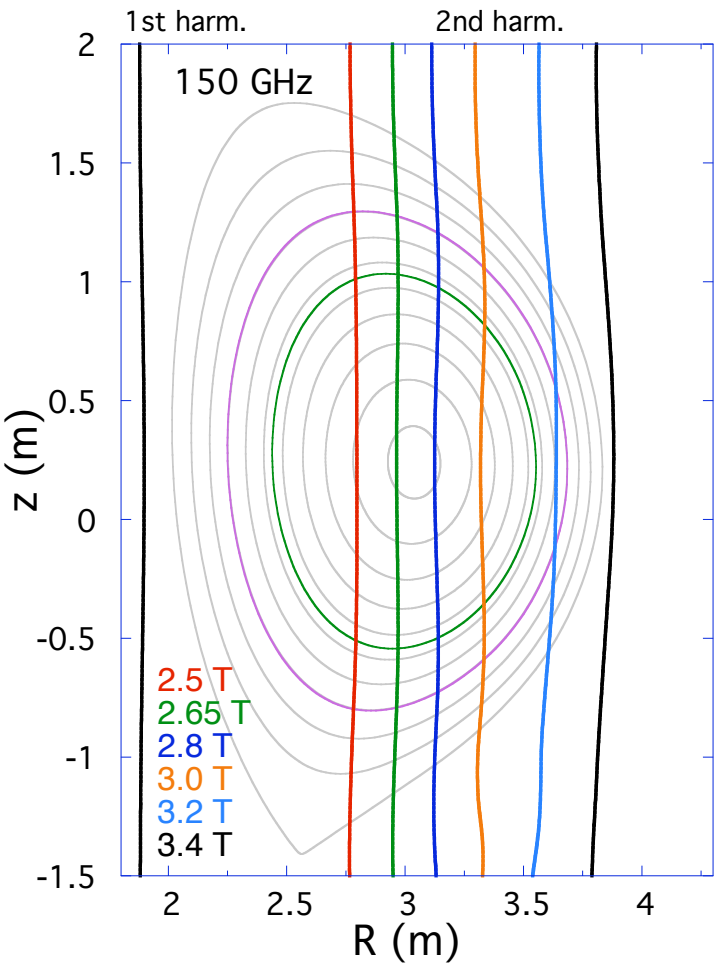
Driven current versus ρ
injection angles scan



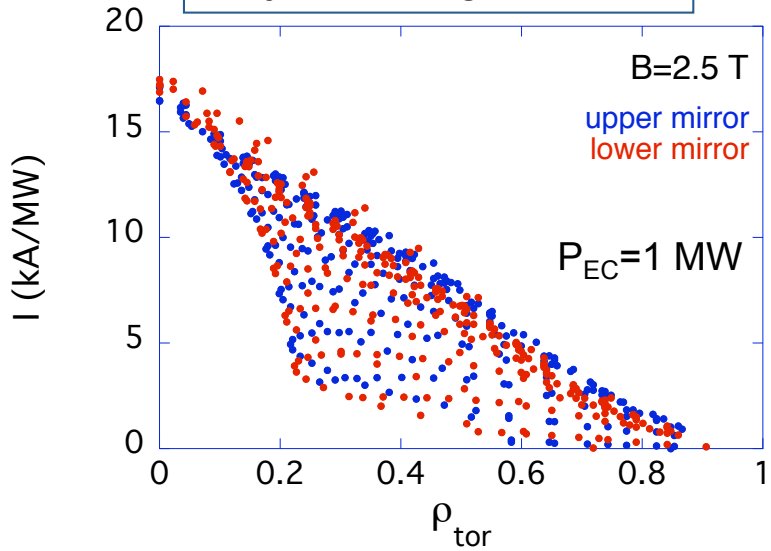
150 GHz

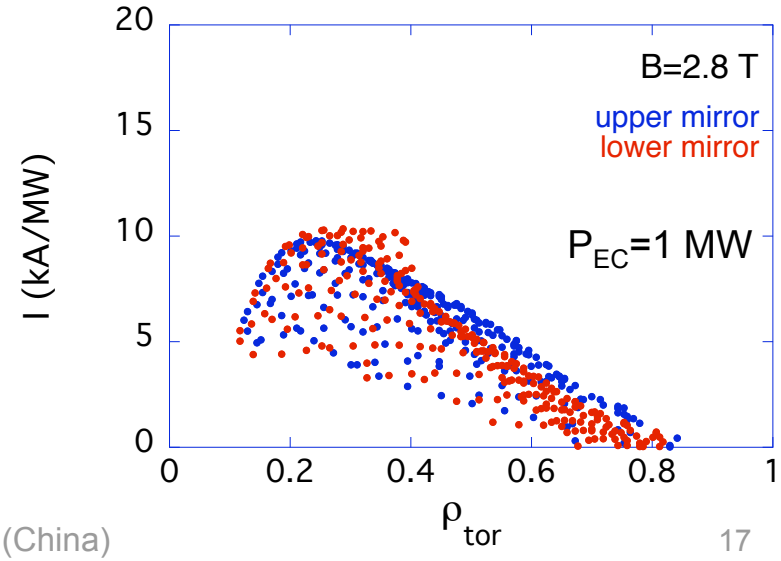
150 GHz: XM2

- *B*≤3.0 T: EC resonance in a wide region
- *B*>3.0 T: EC resonance in the outer region



Driven current versus ρ injection angles scan

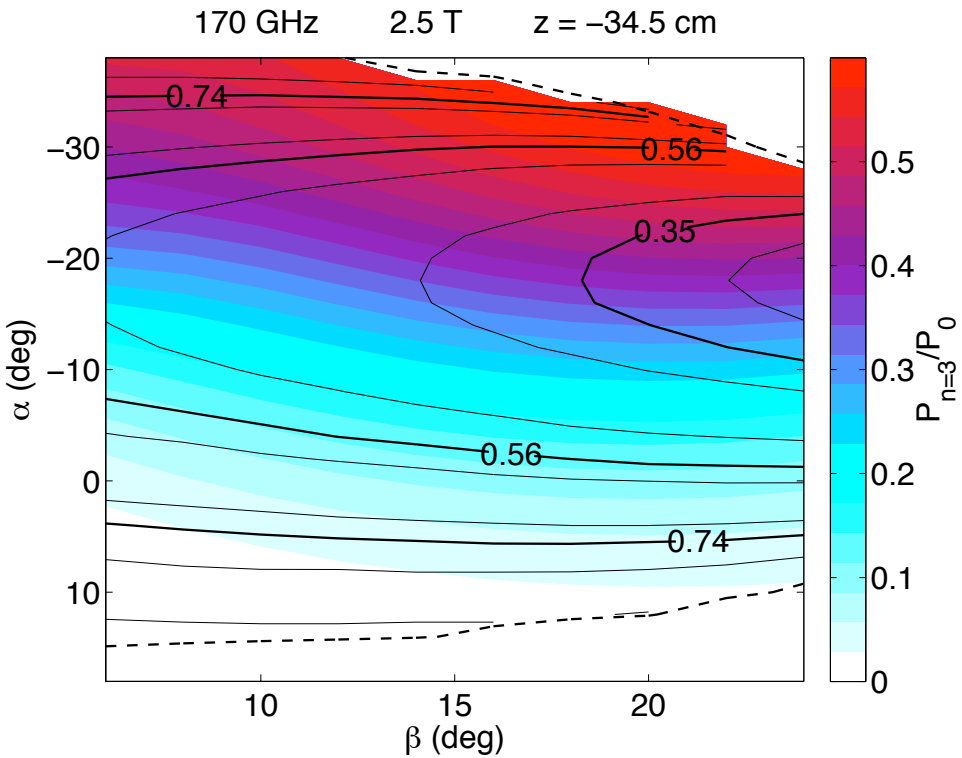




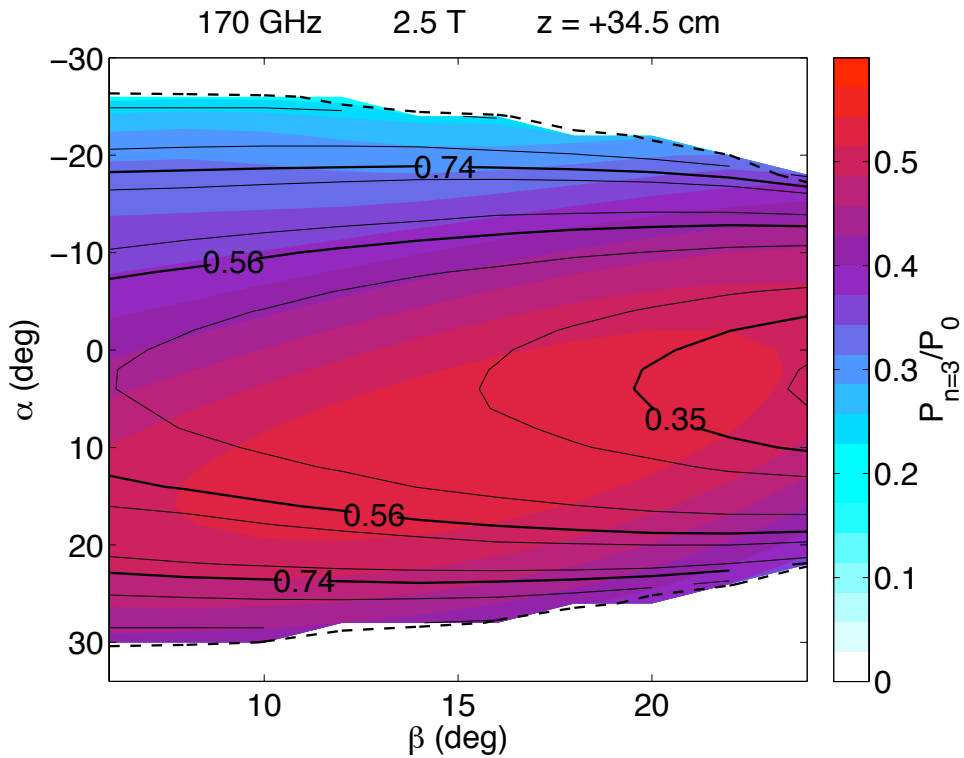
170 GHZ - 3rd harm. absorption

B=2.5 T

Lower mirror



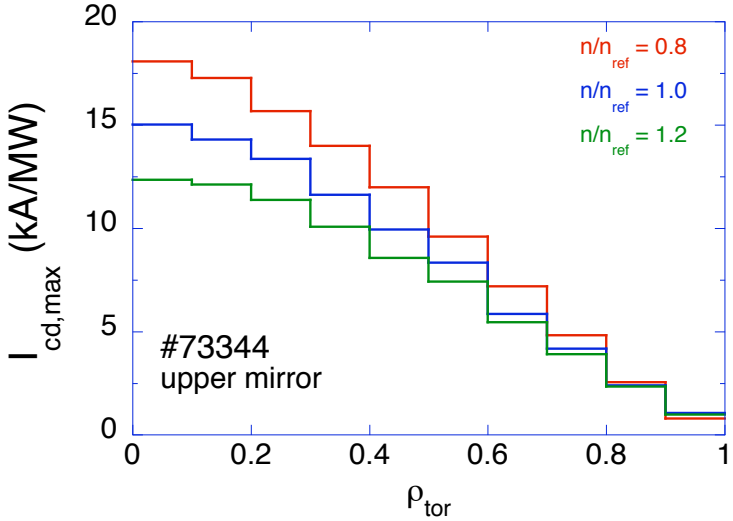
Upper mirror



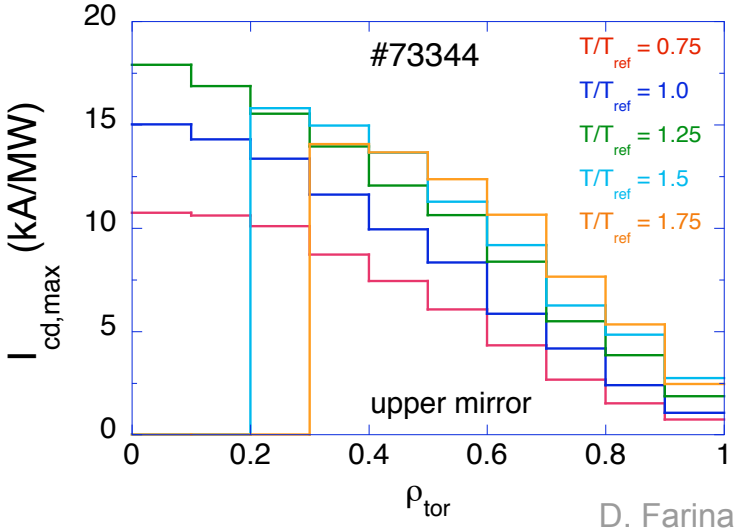
P_3/P_0 is larger in case of the upper mirror, since the beam crosses inner plasma regions at larger temperature.

ECCD Sensitivity to n_e, T_e

Scenario #73344 at B_0 = 2.65 T, independent variations of n_e and T_e



- $\Delta n_e/n_e = \pm 20\%$: $I_{cd} \sim 1/n_e$ as expected
- Note: I_{cd} maximized for different α, β when n_e is varied



- $\Delta T_e/T_e = \pm 25\%$: $I_{cd} \sim T_e$
- $\Delta T_e/T_e > 50\%$: I_{cd} "saturates" in inner regions
  Here no I_{cd} at $\rho<0.3$ due to parasitic absorption on 3rd harm.