Capabilities of the ITER Electron Cyclotron Equatorial Launcher for Heating and Current Drive

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Outline

• **ITER Equatorial Launcher (EL) goals**

• **EC capabilities within present EL design**
  – ECCD in scenarios at burn @ full field
  – ECCD in plasma current ramp-up phase @ full field
  – ECRH @ nominal and reduced B field

• **Proposal of a new EL design with poloidal steering mirrors**

  *work done under ITER Contracts*

  *see Farina et al NF 2012*
ITER Equatorial Launcher (EL)
170 GHz @ 20 MW

Present design *(still to be finalized)*
- 3 sets of 8 beams, equatorial port
  - 3 mirrors same R @ different z, TOP, MID, BOTTOM
- Toroidal steering

Physics Objectives
- Access in range of $0 \leq \rho_T < 0.45$)
- Drive Current (co-ECCD)
- Current Profile tailoring (co&cnt-ECCD)
- Central Heating
- Assist L-H transition
- SS operation
- *Breakdown & Burnthrough*
Beam tracing analysis

• Beam tracing code GRAY (Farina, FS&T 2007):
  – astigmatic Gaussian beam propagation
  – relativistic power absorption (Farina, FS&T 2008)
  – ECCD moment conservation model (Maruschenko FS&T 2009)

• J and $p_d$ profile characterization
  – almost Gaussian profile:
    • $\rho_{\text{tor}}$, $\Delta \rho_{\text{tor}}$: peak radius, profile width at 1/e
  – generic profiles:
    • $<\rho>$, $\sigma_{\rho}=(<\delta \rho^2>)^{1/2}$: “average” radius and width

\[
<\rho> = \frac{\int \rho p(\rho)dV}{\int p(\rho)dV} = \frac{\int \rho dP}{\int dP}
\]

\[
<\delta \rho^2> = \frac{\int (\rho - <\rho>)^2 p(\rho)dV}{\int p(\rho)dV}
\]

• Launching set up
  – 3 mirror locations (beam / single ray analysis)
    R=926.5 cm z=2, 62, 122 cm
  – poloidal $\alpha$ and toroidal $\beta$ launching angles
    $\tan \alpha = N_z/N_R$, $\sin \beta = N_\phi$

20° ≤ |$\beta$| ≤ 45°
$\alpha = 0°$, ± 5°
Two main ITER scenarios at full field (ITER IDM):

a) “15 MA Elmy H-mode Scenario”
   Low $T_e$ & high $n_e$ -> low ECCD efficiency

b) “9 MA non inductive Scenario”
   High $T_e$ & low $n_e$ -> high ECCD efficiency
ECCD results at full field

**SCEN 15 MA:**
- ~15% larger $I_{cd}$ wrt old scen. 2 estimates
  (momentum conservation model)

**SCEN 9 MA:**
- quite large $I_{cd}$, up to 60 kA/MW
- up to +50% more than for previous scen. 4 (larger $T_e$)

dotted lines: non monotonic J profile
(2nd harm contribution)

Achievable radial range: $0 < \rho < 0.5$
The present EL design foresees co-injection from TOP and LOW rows and counter injection from MID row.

Various H&CD combinations are feasible delivering power either to a single row or to more than one row in different directions.

**LIMITATION**

*upper radial limit around $\rho \approx 0.45$*

**OPEN ISSUE**

*How to further optimize EC interaction region?*
EC potential at various time slices

4 time slices of a 15 MA Scenario
(courtesy T Casper, ITER):

a) after diverting (L-mode)
b) during current ramp-up (L-mode)
c) at the end of current ramp-up (H-mode)
d) at an early burn stage (H-mode)

<table>
<thead>
<tr>
<th>case</th>
<th>time slice</th>
<th>$I_{pl}$ (MA)</th>
<th>$n_{e0}$ ($10^{20}$ m$^{-3}$)</th>
<th>$T_{e0}$ (keV)</th>
<th>Fusion power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>11.7 s</td>
<td>3.7</td>
<td>0.075</td>
<td>4.6</td>
<td>0.002</td>
</tr>
<tr>
<td>(b)</td>
<td>58 s</td>
<td>11.5</td>
<td>0.30</td>
<td>8.0</td>
<td>1.6</td>
</tr>
<tr>
<td>(c)</td>
<td>80 s</td>
<td>15</td>
<td>0.40</td>
<td>14.4</td>
<td>4.4</td>
</tr>
<tr>
<td>(d)</td>
<td>130 s</td>
<td>15</td>
<td>0.85</td>
<td>29.0</td>
<td>471.7</td>
</tr>
</tbody>
</table>

D Farina, EC-17
10.5.2012
ECCD in the ramp-up phase

- **t=130 s**
  - wide radial deposition range
  - lower ECCD efficiency due to 2\textsuperscript{nd} harm. parasitic absorption

- **t=80 s**
  - OM absorption, large ECCD efficiency

- **t=58 s**
  - both XM & OM absorption but at different location
  - higher $I_{cd}$ for XM injection

- **t=11 s**
  - XM absorption only, close to plasma center
  - quite high $I_{cd}$ because of low $n_e$
XM absorption at low density

XM1 interaction usually prevented in case of low field side injection due to presence of right cutoff

\[ \frac{\omega_p^2}{\omega^2} = (1-N_r^2)(1-\frac{\Omega}{\omega}) \]

(blue dotted line)

At low \( n_e \) and high \( T_e \), XM absorption may occur along the trajectory far ahead of the EC cold resonance (red line) in the upshifted resonance region at

\[ \Omega(x)/\omega = [1-N_r^2(x)]^{1/2} \]

(red dashed line)

Right cutoff shifts outwards for increasing \( n_e \) (a->d)

XM1 interaction cannot occur anymore after a given time depending on the injection angle.
EC heating capabilities at $B \leq 5.3\ T$

Radial power localization versus magnetic field for $20^\circ \leq |\beta| \leq 42^\circ$ and XM&OM injection, $P_{\text{abs}} > 95%$

**GOAL:**
- **Central Heating:**
  - Power absorbed inside $\rho \leq 0.5$
- **L to H-mode:**
  - Heat inside separatrix $\rho \leq 0.85$

OM efficient
- at large $T_e$, $n_e$ ($t=80s$, 130s)
- high $B$ (OM1)

XM efficient
- at low $n_e$ ($t \leq 58s$) as XM1
- at low $B$ (XM2-3)

**at $B \approx 4\ T$: 1$\text{st}$ harm. at hfs boundary & 2$\text{nd}$ harm. at lfs boundary**
Heating potential at lower B

Maximum EC power deposited inside radius $\rho$

$$P_{\text{ins}}(\rho) = \int_0^\rho \rho \, dV$$

High EC absorption in a quite wide $B_0$ range

ECRH efficient not only close to nominal and half values $5.3 \, T$ & $2.65 \, T$

2 critical $B_0$ intervals:
- $3.6 \, T < B_0 < 4 \, T$: 1$^{\text{st}}$ and 2$^{\text{nd}}$ harmonic are close to inner/outer plasma boundary
- $B_0 < 2.5 \, T$: EC interaction occurs at 2$^{\text{nd}}$ and 3$^{\text{rd}}$ harmonic (less efficient, especially at low $n_e$ & $T_e$).

Maximum over OM&XM, and $20^\circ \leq |\beta| \leq 42^\circ$
How to extend EC deposition region?

Driven EC current
Full poloidal and toroidal angle scan

15 MA – MID ROW

9 MA – MID ROW

Driven EC current
Full poloidal and toroidal angle scan

toroidal steering

poloidal

$\alpha$ (deg)

$|\beta|$ (deg)

$|I_{cd}|$ (kA/MW)
Which is the best path in $\alpha$ & $\beta$?

- at present pure toroidal steering
- should we move to poloidal steering?
- or to a combination of the two?
- PROS and CONS in all options

\[ \rho_T < 0.42 \]
\[ \rho_T < 0.45 \]
\[ \rho_T < 0.42 \]
How to maximize ECCD?

EL @ toroidal steering
\( I_{cd} \) up to \( \rho \approx 0.45 \)

UL @ poloidal steering
\( I_{cd} \) at \( \rho > 0.5 \)

EL poloidal steering allows to:
- maximize \( I_{cd} \) at mid radius
- drive current beyond mid radius

Constraint on the choice of the toroidal angle:
- \( \beta < \sim 23^\circ \) to allow for EC assisted breakdown and startup from EL

CAVEAT
Present analysis based on 2 scenarios at burn, results sensitive to \( n&T \) values
Toroidal versus poloidal steering

15 MA Scenario:
- poloidal steering allows to extend radial deposition region
- $I_{cd}$ values almost the same as for toroidal steering

9 MA Scenario:
- much lower $I_{cd}$ at $0.2<\rho<0.4$ *(2\text{nd} harm. absorption at low beta)*
- much wider radial interaction region in case of poloidal steering
Conclusions

- Two reference ITER scenarios investigated with new CD momentum conservation model (+15% ECCD)

- ECH&CD during plasma ramp-up conditions at nominal magnetic, high to full absorption in spite of reduced $n_e$ and $T_e$

- EC system applicable for central heating (inside mid radius) for the majority of the toroidal magnetic field range from half to full field

- Proposal for a poloidal steering EL setup to increase ECCD beyond mid radius, further investigation still required, final assessment in the near future