Recent Progress in the ITER EC H&CD System

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With the help of many, many other colleagues:
Outline

- General Overview of the EC system
- Progress in 2009
  - RF-building
  - Gyrotrons
  - Transmission Line
  - Launchers
  - Auxiliaries
- Scenario I Schedule
- Next Years (foreseen) Challenges
# ITER H&CD Systems

All four heating systems envisioned for ITER in preparation for DEMO

<table>
<thead>
<tr>
<th></th>
<th>NB</th>
<th>IC</th>
<th>EC</th>
<th>LH</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>33MW</td>
<td>20MW</td>
<td>20MW</td>
<td>0MW</td>
<td></td>
</tr>
<tr>
<td>+17MW</td>
<td>+20MW</td>
<td>+20MW</td>
<td>+40MW</td>
<td></td>
</tr>
<tr>
<td>Plasma Rotation for stabilizing RWM</td>
<td>Bulk ion heating</td>
<td>Localized H&amp;CD for MHD control</td>
<td>off-axis Bulk current drive</td>
<td></td>
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</tbody>
</table>

**Note:**

- Plasma Rotation for stabilizing RWM
- Bulk ion heating
- Localized H&CD for MHD control
- off-axis Bulk current drive
ECH is ITER's only Heating and Current drive source that is both \textit{localized} and \textit{steerable}.

\textbf{ECH is a surgical tool} that can \textit{“pen point”} a spot in the plasma cross section to \textit{heat} and/or \textit{drive current}

- Localized: power deposited in a small region $\sim 0.04m$ ($a=2.0m$)
- Electron heating: 20MW
- Driven current: 0.1 to 0.8 MA
The PCR optimizes the toroidal and poloidal steering angles of the EC launchers to provide increased access from on-axis to near the plasma boundary.

2008 baseline:

- **EL**
  - Access $0.0 \leq \rho_T < 0.5$ (Central heating and current drive applications)
- **UL**
  - Access $0.5 \leq \rho_T < 0.85$ ($q=3/2$ and 2 NTM locations)

EL can't access due to beam shine thru
EL limited access (geometrical limitation)
No access for $\rho_{NTM} > 0.85$
No pure heating (EL and UL in co-CD)
The **EL** modifications are:

- Introduce ±5° poloidal tilt in top and bottom steering mirror
- Limit toroidal steering angle to ≤40° (avoid beam shine thru)
- Flip middle steering row for counter ECCD.

The **UL** modifications are:

- Access $\rho_T \leq 0.3$ with upper steering mirror
- Access $\rho_T \geq 0.95$ with two lower steering mirrors.
- Access $\rho_T > 0.88$ with two lower steering mirrors.
\[ B_{\text{TOR}} \text{ EC system Operating Window} \]

EC System achieves full functionality around two operating windows \( (X2 \text{ and } O1) \)

![Graph showing the operating windows X2 and O1 with \( B_T \) vs. \( I_p \).]

Concern for Power scaling of L to H-mode

\[ P_{L-H} \propto B_T \]

\( \leq 2023 \) improve scaling laws for DT in 2026

\( B_T \) window for EC inside of \( \rho_T < 0.5? \rho_T < 0.9? \)
D. Farina (CNR) investigated EL accessibility between O1 and X2 ranges decreasing $B_{\text{tor}}$
Increased Operational range in $B_{\text{tor}}$

- L to H-mode: Heat inside separatrix $\rho_T \leq 0.95$
- Central Heating: Power absorbed inside $\rho_T \leq 0.5$
- Range of $B_T$ increases
  - $2^{nd}$ harmonic: $2.3 \leq B_T \leq 3.7T$
  - $3^{rd}$ harmonic: (same)

Increased operating regions useful during ITER commissioning from 2018 to 2016 (D-T)

Aid in answering:
How much power is needed for L to H-mode transition prior to DT operation (2026)
5 Parties provide in-kind procurement of the 4 subsystems

EU
- Gyrotrons: 8MW
- 12 H&CD PS
- 4UL

IN
- Gyrotrons: 2MW
- 1 H&CD PS

JA
- Gyrotrons: 8MW
- 1 EL

RF
- Gyrotrons: 8MW

US
- 24 T- Lines

2008-9 Procurement Changes/proposals:
IN-DA Procures two 1MW 170GHz gyrotrons and associated PS system
IN-EU proposal to share PS procurement (8 from EU, 5 from IN)
### PCR-160 Startup Gyrotrons

3 127GHz + 24 170GHz gyrotrons

#### Phase

<table>
<thead>
<tr>
<th>Phase</th>
<th>LFS with 127GHz</th>
<th>Central/HFS with 170GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance in null region</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Limited in $B_T$ range</td>
<td>Limited in $B_T$ range</td>
</tr>
<tr>
<td>Available Power</td>
<td>$\sim 2\text{ MW}$</td>
<td>$\leq 20\text{ MW}$</td>
</tr>
<tr>
<td>Pulse length</td>
<td>10 sec (PR)</td>
<td>$&lt; 3'600\text{ sec}$</td>
</tr>
<tr>
<td>TL &amp; launcher interface</td>
<td>Dual frequency window (increased cost, loading, risk)</td>
<td>No change</td>
</tr>
<tr>
<td>System availability</td>
<td>1 PS to 3 gyrotrons</td>
<td>12 PS to 24 gyrotrons</td>
</tr>
</tbody>
</table>

170GHz can achieve the required functionality for breakdown and burn through

Study concluded: Simplify EC system remove 127GHz, reduce investment costs
IN-DA would procure:
- two 170GHz 1MW H&CD RF Sources
- one power supply set: MHVPS, BPS, APS (if necessary) and auxiliaries

IO encouraged:
- Minimize interface complexity, spare parts, procurement monitoring, etc.
- Request IN-DA to procure same RF source set as EU, JA or RF
- Request IN-DA to procure same power supply set as EU

Range of options:
- IN-DA procurement is same as another DAs
- IN-DA procurement is “Functional”

IN-DA stance:
- IN-DA procures 2MW RF source possibly from EU, JA or RF (TBD at PA)
- IN-DA use similar components for IC PS as EC PS
Sept. '2008

Tokamak Building

Assembly Hall

RF Building

Sept. '2009

Efforts to reduce cost: reduce RF building for 40MW (no upgrade)

IC: 20MW
Upgrade 20MW
EC: 20MW
Building split in half between IC and EC

**1st Level**
- IC: Transformers
- EC: MHVPS 12+1 PS

**2nd Level**
- IC: Modules
- EC: BPS + APS 24+2 PS

**3rd Level**
- IC: Sources, TL
- EC: Gyro, TL, InC zone
PCR-120 Revised the PS specifications

The proposed modifications are:

- **Technical specifications**: Compatibility with the 3 gyrotron types.
- **Anode Power Supplies**: reduce from 24 to 8 (EU & RF are diode gyrotrons)
- **Modularity**: 1 PS to two 1MW gyrotron or one 2MW gyrotron, + PSM design.
- **Space allocated**: The EC PS fit inside available space
- **Modulation**: \( \geq 1 \text{kHz} \) from 100% to 0% RF power (via MHVPS) and \( \geq 5 \text{kHz} \) from 100% to 50% (via BPS).
- **Input voltage**: 22kV rather than 66kV.

**Cost Impact**
- Compatibility with 3 gyrotron types: + 2.1M€ (taken from Gyrotron DAs)
- Modularity (PSM based): +1.7M€
- Power Modulation: +3.6M€
Transmission line (Conceptual Design Completed)

Switches to EL or UL

Gallery (12 & 13)

Inside Port Cell 12, 13, 15, 16

From RF building
**TL to Launchers**

### Switching network

- **24 gyrotrons**
  - 24 switches
  - 8 TEs
  - 8 LSM
  - 8 USM

- **48 gyrotrons**
  - 16 switches
  - 16 TEs
  - 16 LSM

#### Maximum Power at any given Location

- **20MW**: Provides nearly complete access across the plasma cross section
- **40MW**: 40MW inside mid radius without new launchers
PCR-117: Internal Interfaces (decision tomorrow)

Simplification of internal interfaces and maintenance access

- in-situ and hands on maintenance of window
- in-situ diamond window leak detection
- ≤1 day access to valve and window
EC Launchers

To be Covered by JAEA Team

Issues under resolution:

- Cooling efficiency of BSM flange
- EM deflections of port plug
- Complete quasi-optical model
- Test of 2nd prototype steering mirror
Scenario I

Aim to spread out resource profile (economic crisis, additional costs, etc.)

- 2018: first plasma (no BSM, 4–6MW EC for plasma initiation)
- 2021: Installation of BSM, 20MW EC, 10MW IC, 16MW NBI
- 2023: Complete construction phase (73MW)
- ~2026: D-T phase

EC manufacturing and assembly relaxed (start 2015 to 2019)

- 2018: Simple EL with 8 beams, all TL and >8MW
- 2019: Full system installed, 1 year commissioning
- 2020: Full system ready, 1 year float
- 2021: Full system operating
- 2023: Upgrade could be consider for power available in 2026
Objectives and Collaborations

Initial 2010 Objectives

- Sign TL Procurement Arrangement, draft gyrotron and PS PAs
- Start final design activities for launchers
- Preliminary DR for EL, start Conceptual DR for gyrotrons
- Complete building layout, supported by an ITER Task Agreement (ITA)
- Re-write DDD
- Complete all Interface Control Documents
- Preliminary design of cooling manifold, plant host and other auxiliaries

>2010 Possible Collaborations and support

- DAs: PS design, gyrotron reliability, TL PA, EL and UL design work
- **Gyrotron**: integration meeting
- **TL**: Support in HE_{11} mode monitor and tapers
- **TL**: Collaborate in beam combiner high power tests
- Collaborate with FZK on launcher outgassing estimates
- Collaborate with CRPP on modeling plant host
- **All**: request support for design review meetings
- **All**: open to any ideas for collaboration