ITER EC H&CD System

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With the help of many, many other colleagues:
Outline

- EC System Procurement
- General Overview
- Envisioned Functional Capabilities
- Today’s Hot Ideas
- Steps Toward First Plasma
### Presentations associated with the ITER EC System

#### Physics

| Poster II | Sakamoto, K. | Development of high power long pulse ITER gyrotrons |

#### Launchers

| Tuesday PM | Strauss, D. | Deflections and Vibrations of the ITER ECRH Upper Launcher |
| Poster II  | Scherer, T. | Recent upgrades of the ITER ECRH CVD torus diamond window design and investigation of dielectric diamond properties |

#### Transmission Lines

| Tuesday PM | Gandini, F. | An Overview of the ITER EC Transmission Line |
| Poster II  | Rasmussen, D. | R&D progress on the ITER EC transmission line |
| Poster II  | Olstad, R. | Progress on Design and Testing of Corrugated Waveguide Components Suitable for ITER ECH&CD Transmission Lines |

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| Monday am | Albajar, F. | The European 2 MW gyrotron for ITER |
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| Poster II  | Jin, J. | Improved Design of a Quasi-Optical Mode Converter for the Coaxial-Cavity ITER Gyrotron |
# 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></td>
<td><img src="image1" alt="NB System" /></td>
<td><img src="image2" alt="IC System" /></td>
<td><img src="image3" alt="EC System" /></td>
<td><img src="image4" alt="LH System" /></td>
</tr>
<tr>
<td>Power</td>
<td>33MW +17MW</td>
<td>20MW +20MW</td>
<td>20MW +20MW</td>
<td>0MW +40MW</td>
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<tr>
<td>Purpose</td>
<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>
</tr>
</tbody>
</table>

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EC System Requirements

Based on present version of System Requirements Document (SRD52):

- Provide auxiliary heating (20MW) to assist in accessing H mode and achieve Q=10.
- Provide steady state on-axis and off-axis current drive in the range of 0<\(\rho T<0.4\).
- Control MHD instabilities by localized current drive.
- Assist initial breakdown and heat during current ramp-up.
- Provide ~7MW of counter-ECCD in the range of 0<\(\rho T<0.4\).
- Provide ON-OFF power modulated from CW to 1kHz and 100 to 50% power modulation from 1 to 5kHz.

170GHz gyrotrons (24MW)
in-line switches
4 Main EC Sub-systems

- PS to Gyrotron: HV connection at cathode
- Gyrotron to TL: Flange at MOU output
- TL to Launcher: Flange prior to diamond window
### EC System Assembled from In-kind Procurements

#### Integration, interface management, some installation

<table>
<thead>
<tr>
<th>IO</th>
<th>EU</th>
<th>IN</th>
<th>JA</th>
<th>RF</th>
<th>US</th>
<th>CH</th>
<th>KO</th>
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<tr>
<td>Integration, interface management, some installation</td>
<td>Gyrotrons²</td>
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<td>Gyrotrons²</td>
<td>Gyrotrons²</td>
<td>24 T- Lines</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8MW</td>
<td>2MW</td>
<td>8MW</td>
<td>2MW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 PS¹,²</td>
<td>1 PS¹,²</td>
<td>1 EL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4UL</td>
<td></td>
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</table>

#### 5 Parties provide in-kind procurement of the 4 subsystems

### Notes:

1. IO-DA has changed PS partitioning: 8 from EU and 5 from IN
2. DAs are responsible for installation
### Division of Responsibilities

<table>
<thead>
<tr>
<th>PA Type:</th>
<th>Functional</th>
<th>Build to Print</th>
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<tbody>
<tr>
<td></td>
<td>PS and Gyrotrons</td>
<td>TL</td>
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<tr>
<td>Conceptual Design</td>
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<td>IO</td>
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<td>Preliminary Design</td>
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<td>DA</td>
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<tr>
<td>Final Design</td>
<td>DA</td>
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<td>DA</td>
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<td>DA</td>
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<tr>
<td>Installation</td>
<td>DA</td>
<td>IO</td>
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<tr>
<td>On-site Tests</td>
<td>DA</td>
<td>IO</td>
</tr>
<tr>
<td>Commissioning &amp; Operation</td>
<td>IO</td>
<td>IO</td>
</tr>
</tbody>
</table>

1) Work shared between IO and DA via task agreement or on voluntary basis
Envisioned Functional Capabilities

- EC System Procurement
- General Overview
- Envisioned Functional Capabilities
- Today’s Hot Ideas
- Steps Toward First Plasma

1. General Layout
2. RF Building
3. Transmission Line
4. Launchers
EC System Layout in RF Building

Tokamak Building

Assembly Hall

RF Building

5 Launchers (20MW)

≤24 Transmission lines

≤26 sources (24MW)

≤ 13 Power Supplies (50MW)

Upgrade 20MW

Upgrade 20MW
RF Building 2009

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
Space Constraints in RF Building

Building has been reduced in size (almost 50%) to reduce cost over runs

Limited space for:
- Cooling feeder pipes
- Cable trays
- Air ducts

Possible solutions:
- Move some equipment into Assembly hall
- Increase height of each level
- Avoid including RF building into assembly hall

Strong Pressure to avoid changes and proceed with Procurement Arrangement

Even stronger pressure not to increase building size
**RF Sources**

**Gyrotrons are rated for:**
- Yesterday 800sec, today 3’000sec
- ≥0.96MW after MOU with ≥95% HE_{11} mode purity
- LHe free cryomagnets
- >50% efficiency (P_{out}/P_{in})

<table>
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<tr>
<th>JA</th>
<th>RF</th>
<th>EU</th>
<th>IN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1MW</td>
<td>1MW (0.8)</td>
<td>1.4MW (2.2)</td>
<td>TBD</td>
</tr>
<tr>
<td>800s</td>
<td>200s (800s)</td>
<td>15ms (≤10ms)</td>
<td></td>
</tr>
</tbody>
</table>

**Challenges:**
- Mass production
- High Reliability (no arcs)
- Higher Power (≥1.2MW)
- Long life (≥5 years)
- High mode purity (≥98%)
- Higher Electrical efficiency
- Partial Power modulation 5kHz

**Discussion for Thursday AM**
**Principle Functions:**

1. Transmit the RF power from 24 gyrotrons to 5 the launchers
2. Transmission efficiency $\geq 90\%$ using evacuated 63.5mm corrugated HE$_{11}$ waveguide.
3. Compatible with 2.0MW transmission of 3000 sec long pulses and 25% duty cycle
4. Provide the secondary confinement barrier
5. Independent switching of 24 microwave beams between EL and UL in $\leq 2.0\text{sec.}$
6. Capable of deviating the power to a short pulse load
Transmission Line Layout in Assembly Hall
Both Launchers have been modified for improved Accessibility

**Upper launcher**
- 4 ports, 8 entries each
- Control of MHD activity (NTM, sawteeth)
- steering range: $0.3 < \rho_T \leq 0.95$

![Upper Launcher Diagram](image)

**Equatorial launcher:**
- 1 Port, 24 entries
- Central heating and current drive
- EL steering range: $0.0 < \rho_T \leq 0.4$

![Equatorial Launcher Diagram](image)

**NTM stabilization**
- objective: $\frac{j_{CD}}{j_{BS}} > 1.2$
- (achieved $1.8 < \frac{j_{CD}}{j_{BS}} < 3.6$)
Equatorial Launcher

three sets of eight beams
Toroidal steering

Focusing mirror
first wall
Steering mirror
Shielding
Closure Plate
Ex-vessel waveguide

EC Launchers
**Equatorial Launcher**

- Three sets of eight beams
- Toroidal steering

**Upper Launcher**

- Two sets of four beams
- Poloidal steering

**Key Components**

- Focusing mirror
- First wall
- Steering mirror
- Ex-vessel waveguide
- Shielding
- Closure Plate
- Mirror 1
- Mirror 2
- Mirror 3
- Taper
EC Launchers

Equatorial Launcher

- JAEA
- Three sets of eight beams
- Toroidal steering

Upper Launcher

- Mirror 1
- Mirror 2
- Mirror 3
- Taper
- Ex-vessel waveguide
- Shielding
- Closure Plate
- Ex-vessel waveguide

Challenges:
- High Power long pulse operation
- Remote handling compatibility (robust design)
- Steering mechanism (vacuum, nuclear, thermal)
- Electro-Magnetic forces
- Higher Thermal loading on mirrors
Envisioned Functional Capabilities

1. Accessibility in $\rho_T$
2. Decoupling Heating and CD
3. Accessibility in $B_T$
4. Start-up and Burn through
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)

No access for $\rho_{NTM} > 0.85$

EL can't access due to beam shine thru

EL limited access (geometrical limitation)

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.
Switching network

- **24 gyrotrons**: Provides nearly complete access across the plasma cross section
- **40 (1.2MW) gyrotrons**: 40MW inside mid radius without new launchers

**Maximum Power at any given Location**

- 20MW
- 40MW

**Deposited Power [MW]**

- **20MW**: Provides nearly complete access across the plasma cross section
- **40MW**: 40MW inside mid radius without new launchers
**B\textsubscript{TOR} EC system Operating Window**

EC System achieves full functionality around two operating windows (X2 and O1)

- 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 $B_{\text{tor}}$. 

Peak in deposition for fixed angle Toroidal scan for given $B_{\text{tor}}$. 

1st Harmonic O and X mode 
2nd Harmonic O and X mode 

$\rho_{\text{tor}}$ vs $B_{\text{tor}}/B_{\text{nom}}$ 

$B_{\text{nom}}$ 

$\text{EOB2}$ 

$\text{XM}$ 

$\text{OM}$ 

$B (\text{T})$
Increased Operational range in $B_{\text{tor}}$

**L to H-mode:** Heat inside separatrix $\rho_T \leq 0.90$

**Central Heating:** Power absorbed inside $\rho_T \leq 0.5$

**Range of $B_T$ increases**
- 2$^{\text{nd}}$ harmonic: $2.3 \leq B_T \leq 3.7T$
- 3$^{\text{rd}}$ 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)

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### PCR-160 Startup Gyrotrons

**3 127GHz + 24 170GHz gyrotrons**

#### Table: Comparison of 127GHz and 170GHz Gyrotrons

<table>
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<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>Available Power</td>
<td>(~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 is to procure two 170GHz gyrotrons, (up to 26 gyrotrons in total)**
Today’s views of possible changes to EC System

- EC System Procurement
- General Overview
- Envisioned Functional Capabilities
- Today’s Hot Ideas
- Steps Toward First Plasma

1. Dual Frequency Gyrotrons
2. Diplexers
3. Increase $I_{CD} \rho_T = 0.5$
**EC System Optimization**

**Cost is the driver of Functionality and Reliability**

- Improve efficiency
- Optimize launcher access
- Tech.+Physics Collaboration
- Follow EC Physics Community
- Support Gyrotron development
- Design from proven Tech.
- Follow growing Tech.
- Learn from existing EC plants

**Cost**

**Value Engineering**

**Proven Technology**

**Functionality**

**Reliability**

**Cost**
Today’s Hot Topics

Dual Frequency Gyrotrons:
- Increases functionality at $B_T \approx 4T$
- Technology advancing

We wait until reliable operation is demonstrated:
- Cost increase on windows and MOU(?)
- Higher stray radiation at EL
- Not compatible with UL design
- ITER has to run at nominal field
- Decrease in gyrotron operating reliability

Increase $I_{CD}$ at mid radius

Diplexers:
Dual Frequency Gyrotrons:
- Increases functionality at $B_T \sim 4T$
- Technology advancing

We wait until reliable operation is demonstrated
- Cost increase on windows and MOU(?)
- Higher stray radiation at EL
- Not compatible with UL design
- ITER has to run at nominal field
- Decrease in gyrotron operating reliability

Diplexers:
- Provides fast switching
- Avoids increase cost to PS
- Minimizes high loading on collector

We wait until reliable operation is demonstrated
- Concern about overall transmission efficiency ($1W \leq 10\€$)
- Demonstration of power handling for two 1MW beams from two gyrotrons and CW
- Size of component relative to waveguide spacing

Increase $I_{CD}$ at mid radius
Today’s Hot Topics

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We wait until reliable operation is demonstrated
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- Demonstration of power handling for two 1MW beams from two gyrotrons and CW
- Size of component relative to waveguide spacing

Increase $I_{CD}$ at mid radius
- Only UL accesses mid radius
- Increase toroidal angle increases ICD
- Limitation on toroidal angle due to Blanket Module
- Limitation on time and resources to redesign UL

New Task Agreement to be launched to analyze potential

Scenario 4

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Steps Toward First Plasma

1. Present Schedule

EC System Procurement
General Overview
Envisioned Functional Capabilities
Today’s Hot Ideas

Steps Toward First Plasma
Schedule: Scenario I

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

- 2019: first plasma (no BM, 4–6MW EC for plasma initiation)
- 2021: Installation of BM, 20MW EC, 10MW IC, 16MW NBI
- 2023: Complete construction phase (73MW)
- ~2026: D-T phase

EC manufacturing and assembly relaxed

- 2014: Access to RF Building
- 2015: Start installation of PS, Gyrotrons, TL
- 2018: Simple EL with 8 beams, all TL and >8MW of gyrotrons
- 2019: All ex-vessel installed, 1 year commissioning
- 2020: Launchers installed
- 2020: Full EC system ready, 1 year float
- 2021: Full EC system operating
- 2023: Know if more power is needed; +20MW could be ready in 2026
Schedule: Present status

Future position of the tokamak

Future position of the EC system
Thank you for your Contribution!!!
Presentations associated with the ITER EC System

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