Overview of ITER Heating and Current Drive Systems

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H&CD Roles and Requirements

- Initiate the discharge and provide the bulk of plasma current ramp up and ramp down
- Provide reliable long pulse H&CD - ions and electrons to reach and maintain H mode
- Modification of the bulk and tail distributions to maintain steady state current, pressure, rotation and shear profiles, internal transport barriers and to enhance reactivity
- Suppression and avoidance of instabilities
- Have all PFCs be resistant to high heat and neutron fluxes with acceptable levels of impurity production
ITER Auxiliary Heating and Current Drive Systems

Neutral Beam Injection 33 MW
✓ Electron Heating
✓ Profile Current Drive

Electron Cyclotron 20 MW
✓ Electron Heating
✓ Profile Current Drive and Control of NTMs

Ion Cyclotron 20 MW
✓ Ion and Electron Heating
✓ Central Current Drive

Lower Hybrid (upgrade) 20 MW
✓ Fast Electron Heating
✓ Edge Current Drive
NBI, ECH and ICH Provide 73 MW for H-Mode Q=10 Operation

<table>
<thead>
<tr>
<th>Operating Parameters</th>
<th>Inductive</th>
<th>Hybrid</th>
<th>Non-inductive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroidal Field $B_T$ (T)</td>
<td>5.3</td>
<td>5.3</td>
<td>5.15</td>
</tr>
<tr>
<td>Plasma Current $I_p$ (MA)</td>
<td>15.0</td>
<td>13.8</td>
<td>9.0</td>
</tr>
<tr>
<td>Auxiliary Power $P_{add}$ (MW)</td>
<td>50</td>
<td>73</td>
<td>59</td>
</tr>
<tr>
<td>Fusion Power $P_{fus}$ (MW)</td>
<td>500</td>
<td>400</td>
<td>356</td>
</tr>
<tr>
<td>Energy Multiplication $Q$</td>
<td>10</td>
<td>5.4</td>
<td>6</td>
</tr>
<tr>
<td>Thermal Energy $W_{th}$ (MJ)</td>
<td>353</td>
<td>310</td>
<td>287</td>
</tr>
</tbody>
</table>

40 MW Upgrade (LH or NBI, ICH, ECH) planned for Steady State Q=5 Operation

Hydrogen, Helium and Deuterium operation planned prior to DT phase
Launchers and Transmission Systems
ITER Port Plugs and Port Cells

Port Space Reserved for Upgrades
Burning Plasma Requires Maximum Auxiliary Power Before and After Burn
Mix of H&CD Systems (NB, EC, IC) Needed for ITER Q=10

Fusion gain $Q$ for 40 MW of either pure ICH heating (blue lines), pure NNBI with 1 MeV ions (green lines) and pure ECH (red lines) as function of thermal plasma pressure on top of the pedestal. Solid lines correspond to simulations with flat density profiles and dashed lines to peaked densities. The dashed-dotted vertical line is the expected edge pressure stability limit. 6 cm is taken for the barrier width.

Mix of H&CD Systems Needed for ITER Q=5 Steady State

Role of NB, Fast Wave (IC) and EC H&CD in Steady State – Provide steep pressure gradients and global current

- Fully non-inductive; (102%)
- Central fast Wave Current Drive (IC)
- Large bootstrap current; (63%)
  - Peaks at internal transport barrier
  - Peaks at temperature pedestal

Weak reverse shear q profile

M. Murakami et al, “Integrated modelling of steady-state scenarios and heating and current drive mixes for ITER”
- Nucl. Fusion 51 (2011) 103006 (9pp)
Neutral Beam Injection H&CD, 33 MW and Diagnostic Neutral Beam

2 Neutral Beam Injectors
16.5 MW each
40 A, 1 MV beams
Pulse length up to 3600 s

IN - IPR Diagnostic Neutral Beam Source

JA - JAEA HV Ceramic Bushing

EU - MITICA Megavolt Test Stand at Padua Neutral Beam Test Facility
Electron Cyclotron H&CD - 170 GHz, 20 MW

Sources

• High Voltage Supplies
• 24 Gyrotrons (JA, RF, EU, IN)

Transmission line (US)

• Overmoded waveguide from 24 gyrotrons to 56 outputs
• Power loads for commission and test

Launchers

• Upper Launchers (EU)
• Equatorial Launcher (JA)
• Steerable mirrors

JA- JAEA
1.0 MW (800 s)
0.8 MW (3600 s),
>55% efficiency
RF gyrotron has similar performance

US- Transmission line goals
2 MW/line
90% eff.

EU- F4E
2.0 MW short pulse

JA- JAEA Equatorial Launcher

EU- IPP/CRPP Mirror and Drive Mechanism
General EC Access Capabilities

UL: applications requiring narrow/peaked $j_{CD}$ profile
EL: applications requiring increased driven current ($I_{CD}$)
Ion Cyclotron H&CD 40 – 55 MHz, 20 MW

Sources
- High Voltage Supplies (EU)
- 8 transmitters; 35-60 MHz (IN)

Transmission line (US)
- 16 coaxial lines to 2 antennas
- Matching components – broadband prematch, tuning, power balancing and load resilience
- Power loads for commissioning and conditioning

Antenna (EU)
- 2 antennas
- 24 current strap phased arrays
Modeling Shows Good ICRF Absorption in ITER

AORSA ITER Simulation of RF Heating
Lower Hybrid H&CD 3.7, 4.6 or 5 GHz

Sources
- Klystron sources in use on Tore Supra, FTU, Alcator C-Mod, KSTAR and EAST

Transmission line
- Rectangular waveguide
- Power splitters

Antenna
- Passive Active Multijunction (PAM) waveguide grill
- >1000 waveguides and windows
- Tore Supra ¼ section prototype
ITER-relevant power density for 78s

- 2.75MW (25MW/m²) coupled with PAM for 78 seconds
- Low RC (< 2%) at large plasma-launcher gap (> 10cm)
- Efficient cooling: Waveguides and side protections below 270°C

A Ekedahl et al., Nucl. Fusion (2010)
Technical Challenges Ahead

- **NBI**
  - Improvement of neutralization efficiency
  - Long pulse, 1 MV operation at 40 A beam current on EU test stand
  - Minimize shine through to blankets and losses through beam duct

- **ECH**
  - Long pulse operation of 2 MW EU gyrotrons.
  - 2 MW, long pulse operation of US transmission line components
  - Validation of steering mirror and PFC designs for full microwave, plasma and nuclear heating conditions
  - Improve mode and polarization control; gyrotron->transmission->launcher->plasma

- **ICH**
  - Optimization of detailed antenna design to maximize coupling
  - Development of robust tuning algorithms
  - Validation of Faraday shield and PFC designs for full rf, plasma and nuclear heating conditions
  - Improved modeling of scrape of layer density profile including local gas puffing

- **LH**
  - Development of high power 5 GHz sources
  - Gas puff modification of scrape of layer density profile
  - Minimization of transmission line losses
**H&CD Research Opportunities**

**ECH** Increase ECCD efficiency with larger poloidal injection angle for midplane launch and larger toroidal angle for upper launch

**ICH**
- Improve coupling with control of spectra, local density and density gradient
- Reduce parasitic coupling and minimize E// and impact of resultant RF sheaths

**NB/EC/IC** Optimize power mix during discharge
Heavy Lifting Underway to Bring ITER on Line
Arches National Park
Moab, UT