Technology of Heating and Current Drive in ITER

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Heating and Current Drive System

**EC**
170 GHz, 20 MW (+ 20 MW)
Horizontal port: 20 MW / port
  Heating and Current drive
  Toroidally steerable mirror
Upper port: 7 MW/port x 3
  Localized current drive to stabilize NTM
  Poloidally steerable mirror

**ICRF**
40 – 56 MHz, 20 MW (+20 MW)

**LH**
5GHz, 0 MW (+40 MW)

**NB**
1 MeV
  33 MW / 2 ports (+17 MW)
  $R_{tan} = 5.3$ m,
  Zaxis = (-42) – (+15) cm (Plasma axis = -32 cm)
Front and Back of RF Assembly Common Support Structure, Including Port Flange and Closure Plate (1.8 x 2.2 m)
### Table 2.5.4.1-1  Ion Cyclotron resonances

<table>
<thead>
<tr>
<th>Resonance</th>
<th>(MHz)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\Omega_\text{T}$=$\Omega_\text{3He}$</td>
<td>53</td>
<td>Second harmonic + minority heating.</td>
</tr>
<tr>
<td>$\Omega_\text{D}$</td>
<td>40</td>
<td>Minority heating. Strong competition of Be and $\alpha$-particles</td>
</tr>
<tr>
<td>FWCD</td>
<td>56</td>
<td>On axis current drive</td>
</tr>
<tr>
<td>$\Omega_\text{3He}$</td>
<td>45</td>
<td>Minority ion current drive at sawtooth inversion radius (outboard)</td>
</tr>
</tbody>
</table>

### Table 2.5.4.2-1  Summary of Array Parameters (at $R' = 4 \Omega/m$ and $f = 55$ MHz)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strap length (m)</td>
<td>0.3</td>
<td>MTL Voltage (kV)</td>
<td>12.25</td>
</tr>
<tr>
<td>Characteristic impedance ($\Omega$)</td>
<td>~35.0</td>
<td>Max voltage in tuner (kV)</td>
<td>32.1 &amp; 40.0</td>
</tr>
<tr>
<td>Input power (MW)</td>
<td>2.5</td>
<td>Max E-field in strap (V/mm)</td>
<td>1.3</td>
</tr>
<tr>
<td>Input voltage (kV)</td>
<td>5.5</td>
<td>Power transfer efficiency (%)</td>
<td>~95</td>
</tr>
<tr>
<td>Max. strap voltage (kV)</td>
<td>27</td>
<td>Max. strap current (kA)</td>
<td>1.30</td>
</tr>
</tbody>
</table>
Figure 2.5.4-2  View of the IC Array Seen From the Plasma
ICRF

All metal Vacuum Transmission Line Support
- Avoid dielectric material
- Cool through the inductive shunt

Prototype of Vacuum Transmission Line with All Metal Supports
Figure 2.5.5-1  LH Launcher

Table 2.5.5.2-1  Mechanical Dimensions of Multi-junction Stack

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of active wave-guides</td>
<td>24</td>
</tr>
<tr>
<td>Number of passive wave-guides</td>
<td>25</td>
</tr>
<tr>
<td>Cross section of active wave-guide (mm²)</td>
<td>9.25 x 171</td>
</tr>
<tr>
<td>Mechanical length (mm)</td>
<td>900</td>
</tr>
<tr>
<td>Fundamental transmission mode</td>
<td>TE₃₀</td>
</tr>
<tr>
<td>Mechanical length (mm)</td>
<td>925 to 1050</td>
</tr>
<tr>
<td>Phasing among active wave-guides</td>
<td>3 π / 2</td>
</tr>
<tr>
<td>Typical n// value</td>
<td>1.9-2.1</td>
</tr>
<tr>
<td>Max electric field in nominal power (22%) plasma reflection (kV/cm)</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Upper launcher: poloidal steering = -60 ~ -70°
Toroidal angle = 24°
Equatorial launcher: toroidal steering = 20 - 45°
Equatorial port: standardized port plug for IC/EC/LH
Fig. 12 - EC Launcher in the modified upper port plug

12 waveguides inserted in the enlarged port plug (remote steering option)

VIEW A

VIEW B

side wall of the Blanket Shield Module (in radial planes)

side wall of the port plug (trapezoidal shape)

Note on plug based on drawing:
15.0177 modification (increase in width 30 mm on each side)
ECRH/ECCD for ITER:
ITER-task: Remote steering antenna for ECRH/ECCD

Far-field measurements, distance ca. 1700 mm
Scan angles 0°, 5°, 10°

F = 142.42 GHz; (141.52 GHz with Mitrebends)
Length = 6720 mm; (6700 mm mit Miterbends)

• Collaboration with IAP Nizhny Novgorod
  and CRPP Lausanne
ITER Gyrotron Development

Major issues: 1) Cavity heat load, 2) Window heat load, 3) Collector heat load, 4) Low efficiency

Achievement (1999):
- 170GHz, 0.5MW x 8sec, 32%
- 110GHz, 1 MW x 2sec, 36%

• Reduction of diffraction loss by optimization of mode convertor design (~10% -> 5%)

Recent Research
- Reduction of Parasitic Oscillation by RF absorber in the beam tunnel. (SiC)

Suppression of undesired mode
170GHz, 1MW, 57% 1s
(0.9 MW/9 s/43% March 2001)

Limit;
Undesired mode
- Parasitic Osc.
- Diffraction
- Heating tube
- Reduce efficiency

Test from April 2001
Strengthen
- Cooling capability (SiC brazed to M.)
- Insulator against heat load (Al2O3, Si3N4)

ITER Target
170GHz, 1MW, >50%
>10s (CW in principle)
170 GHz long pulse gyrotron

Achieved in 1999: 170 GHz, 0.5 MW- 8s, Now commercially available with maintenance free SC magnet system

Six same type gyrotrons (168 GHz) in LHD from 2000

(Achieved in April 2001: 140 GHz, 0.8 MW-45 s, 0.45 MW-180 s)
165GHz Coaxial Cavity Gyrotron (left) and Frequency Tuning (right)

- Frequency Step Tuning -

Achieved: 1.2 MW, 0.015, 50 % efficiency, frequency tuning, 2.2 MW/1ms
Target: 1.5 MW, 0.15 s at 165 GHz

Operating Parameters: \( I_b \geq 50 \, \text{A}; U_c, B_{cav} \) and \( R_b \) adjusted individually. \( U_c, B_{cav} \) and \( R_b \) optimized for maximum rf-output power at \( \text{TE}_{31,17}, \text{TE}_{32,17}, \text{TE}_{30,16}, \text{TE}_{28,15}, \text{TE}_{27,14} \).
Current Drive Efficiency of Neutral Beam

N-NB: 360keV

\[ \eta_{CD-NB} = 1.55 \times 10^{19} \text{ A/m}^2/\text{W} \]

![Graph showing current drive efficiency with various experimental points and theoretical lines.](image-url)
NB System Layout. Plan View
Figure 2.5.1-3  Neutral Beam Injector, Isometric View
Ion Source Development

Neutralizer

60% is achieved with gas which gives 16.7 MW/beam. Plasma neutralizer may increase to 20 MW/beam.

The target current density is obtained and long life of Cs effect is demonstrated.

20 mA/cm² 1000 s (H⁻, H⁻/D⁻)
8 mA/cm² One week

Source Filling Pressure (Pa)

Negative Ion Current Density J⁻ (mA/cm²)

Lower pressure Lower stripping loss
Higher efficiency

KAMABOKO JAERI-Cadarache
H⁻ D⁻

ITER NBI

20 mA/cm² 1000 s (H⁻, H⁻/D⁻)
8 mA/cm² One week
The target current density is obtained and long life of Cs effect is demonstrated.

Neutralizer

60% is achieved with gas which gives 16.7 MW/beam. Plasma neutralizer may increase to 20 MW/beam.
JT-60U Ion Source

1.2m x 0.64 m, 5.2 MW/350 kV/15 A(D^0)/2s

(ITER 1.17 m x 0.9 m, 16 MW/1MeV/16 A(D^0)/3600 s)

The large current of negative ion beam is demonstrated.
High voltage bushing

I: One ring is fabricated and will be tested (5 rings in ITER)
II: 90% size, 900 kV/1000 s is achieved

A 1 MV Ceramic SINGAP Bushing - Prototype for ITER NBI. Left: original epoxy bushing with present 9 stage, Right: section of prototype insulator/screen assembly.

Test facility for the mockup bushing, located between two SF₆ tanks

High energy beam

0.9 MeV/180 m AH⁻, 1 MeV/25 m AH⁻, 0.4 MeV / 14 AD⁻
3-5 m rad is achieved at ~0.7 MeV
Non-Inductive Current Drive

\[
\eta_{CD} \quad (\text{m}^{-2} \text{A/W})
\]

- LHCD
- FWCD
- ECCD
- NBCD

- ACT-1
- OCTPOLE
- JIPPT-II
- JIPPT-IIU
- ASDEX
- Alcator-C
- JFT-2M
- PLT
- WT-2
- Versator-II
- DIIID
- T-10
- JT-60U
- DITE
- TFTR
- JET, JT-60U

\[
I_{CD} \quad (\text{A})
\]
Conclusion

R&D is confirming applicability of each system to ITER.

(R&D of Heating and Current Drive System will be continued.)
Current Drive Efficiency of Lower Hybrid wave

 JT-60 Scaling

\[ \eta_{CD} \left(10^{19} \, \text{m}^{-2} \, \text{A/W}\right) \]

\[ \frac{12 \langle T_e (\text{keV}) \rangle}{(5 + Z_{\text{eff}})} \]

- JT-60U
- JT-60
- JET
- ASDEX
Equatorial EC Launcher
Figure 2.5.1-1  Tokamak and H&CD Neutral Beam Geometry