IC Power Source System for ITER – Indian In-kind Contribution

A. Mukherjee,
On behalf of ITER-India

6th ITER International School.
Ahmedabad, India, 02-06 Dec 2012
IC H&CD System for ITER
- Functional Requirements & Layout
- Main Features & sub-systems

IC Power Source System
- Scope & Deliverables
- Functional specifications & Design consideration
- Technical Challenges involved
- R&D Activity
- Test facility
IC H & CD System for ITER
ITER require 20MW of ICRF power to a variety of ITER plasmas (with emphasis on D-T operation), in quasi-CW operation (pulses up to 3600 s with 25% duty cycle)

- It covers a broad range of magnetic field operation
- Major requirements are for heating plasmas & driving plasma current
- It will perform IC wall conditioning at low power between main plasma shots
- System will be resilient to rapid antenna loading variations (L→H transitions, ELMs)
### ITER IC H&CD Scenarios

<table>
<thead>
<tr>
<th>Resonance</th>
<th>MHz</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\Omega_T = \Omega_{^3\text{He}}$</td>
<td>53</td>
<td>Second harmonic tritium + minority heating of $^3\text{He}$ to optimize ion heating (Nominal $B_T = 5.3T$)</td>
</tr>
<tr>
<td>FWCD</td>
<td>55</td>
<td>On axis current drive (Nominal $B_T = 5.3T$)</td>
</tr>
<tr>
<td>$\Omega_{^3\text{He}}$</td>
<td>45</td>
<td>Minority ion current drive at sawtooth inversion radius (outboard) (Nominal $B_T = 5.3T$)</td>
</tr>
<tr>
<td>$\Omega_{^3\text{He}}$</td>
<td>40 - 55</td>
<td>Minority heating of $^3\text{He}$ in H, D, $^4\text{He}$ or DT ($B_T = 3.7$ to $5.3T$)</td>
</tr>
<tr>
<td>$\Omega_H$</td>
<td>40 - 55</td>
<td>Minority heating of H in D, He or DT at reduced magnetic field (2.5 to 3.8T)</td>
</tr>
</tbody>
</table>

‘Progress in the ITER Physics Basis’, Nucl. Fusion 47 6, June 2007

Freq. for RF Source: 35-65 MHz
Radio Frequency ranges from 30 kHz to 300 GHz

ICRF falls in VHF band
RF power to antenna via Tx-line & Matching

\[
\frac{1 + \sqrt{\frac{P_R}{P_F}}}{1 - \sqrt{\frac{P_R}{P_F}}}
\]

VSWR (Voltage Standing Wave Ratio):

\[\rho \text{ (reflection coefficient)} = \frac{V_r}{V_f} \text{ or } \frac{I_r}{I_f}\]

VSWR = \frac{(1 + \rho)}{(1 - \rho)}
**A: Terminated in Zo**

\[ \rho = \frac{Z_o - Z_o}{Z_o + Z_o} = 0 \]

**B: Short Circuit**

\[ \rho = \frac{0 - Z_o}{0 + Z_o} = -1 \]

**C: Open Circuit**

\[ \rho = \frac{\infty - Z_o}{\infty + Z_o} = 1 \]
Line diagram of IC system
**System procurement: under 4 packages**

- **Antennas**: EU DA, “Build to print”
- **Transmission lines and matching systems**: US DA, Functional Specifications.
- **RF sources**: IN DA, Functional Specifications
- **HV Power Supplies**: IN DA, Functional Specifications, + IO (part of HVPS).
Antenna Port Plug:

- Broadband (40-55MHz) antenna arrays will be installed in 2 equatorial ports (#13 & #15) having 20 MW capability
- Having two antennas
  - strongly reduces risks associated with
    - Very large uncertainties on the edge density profiles, hence on antenna coupling to the plasma
    - RF voltage stand-off (reduced risk of arcing)
    - RF current (i.e. dissipation) limit in CW
  - Allows dual frequency operation
  - Possibility of future up-gradation to 40 MW
Main Features of ITER IC H&CD System

Tx-line & Matching network:

- Provide efficient power transfer
- Coaxial transmission lines and matching/tuning system to minimize power transfer losses
- Pressurized lines transmit up to 6 MWs per line
- ~ 1.5 km of line – 8 sources to 16 antenna feeds

- Matching network:
  - Pre-matching system (reduces VSWR below 4),
  - Decouplers (reduces mutual coupling between antenna straps & improves matching)
  - Main Matching Unit (2 stubs: reduce VSWR < 1.5) + Hybrid splitter units (split RF power & provide ELM resilience by diverting reflected power towards DL)
RF power sources

- 9 nos. of RF power sources: 4 sources/antenna + 1 spare
- Each power source will have capability of handling
  - 2.5 MW @ VSWR 2.0 / 35-65 MHz/CW
  - 3.0 MW @ VSWR 1.5 / 40-55 MHz/CW
- Each source is made of 2 // amplifier chains (tube based) with a λ/4 combiner
- Dynamic control of Va to handle VSWR condition

High Voltage Power Supplies

Regulated 27kV/190A common supply for 2 amp. stages (2 no. of HVPS/source):
- Large number of low-voltage (<1 kV) modules stacked in series,
- Can be switched on/off individually for fine regulation of output voltage
Control System:

- Each IC H&CD subsystem includes a local controller.
- Plant Control System (PCS) manages the overall operation, safety and protection:
  - Coordination, synchronization
  - RF power feedback control
  - Conventional control functions, dispatching of all interlocks and safety control functions internal and external to the system
IC Power Source System
Scope includes
- Design, manufacturing, assembly & testing, packaging & shipment, site commissioning & site acceptance of 1 prototype + 8 RF Sources

Scope & Deliverables
This package is under Functional Specification

<table>
<thead>
<tr>
<th>Major sub-system</th>
<th>Qty.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low power RF section</td>
<td>9 sets</td>
</tr>
<tr>
<td>Pre-driver stage amp.</td>
<td>9 sets</td>
</tr>
<tr>
<td>Driver stage amplifier</td>
<td>9 sets</td>
</tr>
<tr>
<td>Final stage amplifier</td>
<td>9 sets</td>
</tr>
<tr>
<td>Auxiliary power supplies</td>
<td>9 sets</td>
</tr>
<tr>
<td>Combiner + DL (250kW)</td>
<td>9 sets</td>
</tr>
<tr>
<td>RF Electronics</td>
<td>9 sets</td>
</tr>
<tr>
<td>Local Control Unit (LCU)</td>
<td>9 sets</td>
</tr>
<tr>
<td>Interconnecting Tx-line</td>
<td>As needed</td>
</tr>
<tr>
<td>Internal cooling distribution</td>
<td>As needed</td>
</tr>
<tr>
<td>Test rig without 3 MW DL</td>
<td>1 set</td>
</tr>
<tr>
<td>Sr. No.</td>
<td>Parameters</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>Nominal O/P power / Duty Cycle</td>
</tr>
<tr>
<td>2</td>
<td>VSWR with any phase (0 – 360(^0))</td>
</tr>
<tr>
<td>3</td>
<td>Transient VSWR ((\Delta t \sim 1) s) max, 10% duty cycle</td>
</tr>
<tr>
<td>4</td>
<td>Accuracy of the output power</td>
</tr>
<tr>
<td>5</td>
<td>Frequency range covered</td>
</tr>
<tr>
<td>6</td>
<td>Frequency deviation over any central frequency (1 dB point)</td>
</tr>
<tr>
<td>7</td>
<td>Power modulation range</td>
</tr>
<tr>
<td>8</td>
<td>Electrical efficiency</td>
</tr>
<tr>
<td>9</td>
<td>Max. frequency modulation frequency</td>
</tr>
<tr>
<td>10</td>
<td>Maximum AM frequency</td>
</tr>
<tr>
<td>11</td>
<td>Maximum phase modulating frequency</td>
</tr>
<tr>
<td>12</td>
<td>Emergency Power shut down</td>
</tr>
<tr>
<td>13</td>
<td>Level of harmonics (dBc)</td>
</tr>
</tbody>
</table>
Design consideration

- Constant CW output power (2.5 MW) even with VSWR 2 – final stage tube shall withstand such stringent load condition
- Thermal capability of components/subsystems for CW operation (3600s)
- Large power modulation range: 2 kW – 2.5 MW
- 1 dB breakpoint at ± 1 MHz over any central frequency
- Real time control of Amp, Phase & Frequency
• No single high power tube exists as per ITER requirement
• 1 RF Source: Two independent chain of amplifiers + combiner

Amplitude & Phase detection module

All power stages: mechanically adjustable I/P and O/P cavities
Possibility of Phasing

PHASING DETAILS FOR ONE ANTENNA CONNECTED TO FOUR RF SOURCES

- **RF Switches**
- **1x4 Splitter**
- **Master Synthesizer (Triple Output)**

Synchronization Pulse (typically 1 MHz)

- **PS1 - 0**
  - Output of RFPS1 with phase 0 deg.
- **PS1 - 30**
  - Output of RFPS2 with phase 30 deg.
- **PS1 - 60**
  - Output of RFPS3 with phase 60 deg.
- **PS1 - 90**
  - Output of RFPS4 with phase 90 deg.
Active device for high power amplifier in MHz frequency range

Tetrodes (4 active electrodes) are often used as active device

\[ V_r = V_{dc} - V_{a_{peak}} \]

\[ \eta = \left( \frac{p}{V_{dc} \times I_{a_{av}}} \right) = \frac{V_{a_{peak}} \times I_{a_{peak}}}{2 \times V_{dc} \times I_{a_{av}}} \]
The Diacrod is a double ended Tetrode – TH628 Diacrod from TED is like 2 halves TH525 put together

Theoretical curve shows that Diacrod TH628 can deliver in ITER freq. range:
- 2 MW CW on VSWR = 1.5
- 1.5 MW CW on VSWR = 2
• Diacrode will have 2 output cavities whereas Tetrode will have 1

• Diacrode
  • Allow to adjust the position of the voltage antinode in the resonant circuit formed by the tube and its cavity
  • Possibility of reduction of RF losses, increase in RF peak power, pulse duration & frequency

**Maximum RF voltage & Minimum RF current in the middle of the active part.**

![Diagram of Tetrode vs. Diacrode showing maximum RF voltage and minimum RF current in the middle of the active part.](image)
Status of Tetrode / Diacrode development

<table>
<thead>
<tr>
<th>ITER Spec</th>
<th>CPI, USA</th>
<th>Thales, EU</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 MW at 2 VSWR</td>
<td>~1.9 MW /300 s tested on matched load</td>
<td>1 MW /24 hrs. on matched load</td>
</tr>
<tr>
<td>2000 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 % - 60 %</td>
<td>&gt; 60 %</td>
<td>&gt; 60%</td>
</tr>
<tr>
<td>35 – 65 MHz</td>
<td>30 – 60 MHz</td>
<td>200 MHz</td>
</tr>
</tbody>
</table>

Demonstration of 2.5 MW CW RF power / source @ VSWR 2 (35 – 65 MHz) at any phase angle with other stringent requirements is very challenging

Tetrode Developed by CPI

Diacrode Developed by Thales
Technical Challenges involved

• Combined high power & high VSWR are challenging, even for single chain of amplifiers
• CW aspect of the operation further constrains the design as efficient cooling is required for all components
• Broad frequency range associated with accurate instantaneous bandwidth (± 1 MHz at 1 dB point) requires specific designs for the tube input and output cavities
• Operational problems like, settling time of anode voltage, excess anode dissipation etc., during mismatch situation
• Unwanted oscillation & mode generation during operation
• Real time control of Amp, Phase & Frequency

To address major issues
Tube qualification phase using single chain (R&D) experimentation 1.5 MW / 3600s / 35 - 65 MHz at VSWR 2.0 with any phase of reflection coefficient launched
Final stage is being developed with industrial partner using both kind of technologies (i.e. Tetrode & Diacrode).

- Tubes and cavities will be integrated in a full amplifier chain developed by ITER-India.
- Tests under ITER specifications will validate each design.

Amplification: mW to MW  ~ 90 dB gain
## Gain & Power Level

<table>
<thead>
<tr>
<th>Modules</th>
<th>Max. Gain</th>
<th>Expected Gain</th>
<th>Input Power Level</th>
<th>Max. Output Power Level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LPA (wide band solid state)</strong></td>
<td>50dB</td>
<td>50-45dB</td>
<td>3-10mW</td>
<td>300W /chain</td>
</tr>
<tr>
<td><strong>HPA-1 (TH595/4CW25000B)</strong></td>
<td>20dB</td>
<td>17-18dB</td>
<td>240-190W</td>
<td>15kW /Chain</td>
</tr>
<tr>
<td><strong>HPA-2 (TH781/4CW150000E)</strong></td>
<td>14dB</td>
<td>12-13.5dB</td>
<td>8.0-5.6KW</td>
<td>125kW /Chain</td>
</tr>
<tr>
<td><strong>HPA-3 (TH628/4CM2500KG)</strong></td>
<td>14dB</td>
<td>11-13.5dB</td>
<td>120-67KW</td>
<td>1.5MW /Chain</td>
</tr>
</tbody>
</table>
## Typical tube specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Pre-driver Stage (HPA-1)</th>
<th>Driver Stage (HPA-2)</th>
<th>Final Stage (HPA-3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Tetrode</td>
<td>Tetrode</td>
<td>Tetrode/Diacrode</td>
</tr>
<tr>
<td>Max. CW Frequency</td>
<td>110MHz</td>
<td>110MHz</td>
<td>130MHz/200MHz</td>
</tr>
<tr>
<td>Filament Voltage</td>
<td>6.3±0.3V</td>
<td>15.5±0.75V</td>
<td>15.5±0.75V/30V</td>
</tr>
<tr>
<td>Filament Current</td>
<td>160A</td>
<td>215A</td>
<td>640A/960A</td>
</tr>
<tr>
<td>Plate Voltage</td>
<td>10.0kVdc</td>
<td>22.0kVdc</td>
<td>27.0kVdc/30kVdc</td>
</tr>
<tr>
<td>Plate Current</td>
<td>6.0Adc</td>
<td>20Adc</td>
<td>190Adc/220A</td>
</tr>
<tr>
<td>Plate dissipation</td>
<td>25kW</td>
<td>150kW</td>
<td><strong>2.5MW/1.8MW</strong></td>
</tr>
<tr>
<td>Screen Voltage</td>
<td>2.0kV</td>
<td>2.5 kV</td>
<td>2.5kV/2.0kV</td>
</tr>
<tr>
<td>Screen Dissipation</td>
<td>450W</td>
<td>1750W</td>
<td>20.0kW/14.0kW</td>
</tr>
<tr>
<td>Con. grid voltage</td>
<td>-650V</td>
<td>-1500V</td>
<td>-2000V/-1000V</td>
</tr>
<tr>
<td>Con. grid dissipation</td>
<td>200W</td>
<td>500W</td>
<td>8.0kW/4.5kW</td>
</tr>
</tbody>
</table>
Influence of VSWR

<table>
<thead>
<tr>
<th>Parameters</th>
<th>RT (Tube Load)</th>
<th>Power in kW</th>
<th>VSWR</th>
<th>Fixed Vr</th>
<th>Theta</th>
<th>Va(dc)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>87.5</td>
<td>1500</td>
<td>2</td>
<td>3000</td>
<td>0.5</td>
<td>25912.88</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reflection angle (fi) (Degree)</th>
<th>R (Ohm)</th>
<th>X (Ohm)</th>
<th>Iavg (A)</th>
<th>Va (rms Peak Volt)</th>
<th>Va(dc) (Estimated Volt)</th>
<th>Va(dc) (Fixed Volt)</th>
<th>Pd (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>175.00</td>
<td>0.00</td>
<td>83.40</td>
<td>22912.88</td>
<td>25912.88</td>
<td>25912.88</td>
<td>660.93</td>
</tr>
<tr>
<td>45</td>
<td>121.58</td>
<td>64.48</td>
<td>100.05</td>
<td>21617.97</td>
<td>24617.97</td>
<td>25912.88</td>
<td>1092.52</td>
</tr>
<tr>
<td>90</td>
<td>70.00</td>
<td>52.50</td>
<td>131.86</td>
<td>18114.22</td>
<td>21114.22</td>
<td>25912.88</td>
<td>1916.73</td>
</tr>
<tr>
<td>135</td>
<td>49.15</td>
<td>26.06</td>
<td>157.36</td>
<td>13744.58</td>
<td>16744.58</td>
<td>25912.88</td>
<td>2577.62</td>
</tr>
<tr>
<td>180</td>
<td>43.75</td>
<td>0.00</td>
<td>166.79</td>
<td>11456.44</td>
<td>14456.44</td>
<td>25912.88</td>
<td>2821.86</td>
</tr>
<tr>
<td>225</td>
<td>49.15</td>
<td>-26.06</td>
<td>157.36</td>
<td>13744.58</td>
<td>16744.58</td>
<td>25912.88</td>
<td>2577.62</td>
</tr>
<tr>
<td>270</td>
<td>70.00</td>
<td>-52.50</td>
<td>131.86</td>
<td>18114.22</td>
<td>21114.22</td>
<td>25912.88</td>
<td>1916.73</td>
</tr>
<tr>
<td>315</td>
<td>121.58</td>
<td>-64.48</td>
<td>100.05</td>
<td>21617.97</td>
<td>24617.97</td>
<td>25912.88</td>
<td>1092.52</td>
</tr>
<tr>
<td>360</td>
<td>175.00</td>
<td>0.00</td>
<td>83.40</td>
<td>22912.88</td>
<td>25912.88</td>
<td>25912.88</td>
<td>660.93</td>
</tr>
</tbody>
</table>

Plate dissipation variation with VSWR influence keeping plate voltage constant

Tube load & Plate current variation with VSWR influence

Reflection Coefficient Angle (Degree)

Power Dissipation (kW)

Tube Load & Plate Current

Variation in Tube load (Ohm)
Management of excess plate dissipation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>RT (Tube Load)</th>
<th>Power in kW</th>
<th>VSWR</th>
<th>Fixed Vr</th>
<th>Theta</th>
<th>Vdc</th>
</tr>
</thead>
<tbody>
<tr>
<td>reflection angle (fi)</td>
<td>RT (Variation)</td>
<td>XT (Variation)</td>
<td>Iavg</td>
<td>Va</td>
<td>Va(dc)</td>
<td>Va(dc)</td>
</tr>
<tr>
<td>(Degree) R (Ohm) X (Ohm) (A)</td>
<td>(A) (rms Peak) (Volts)</td>
<td>(Estimated) (Volts)</td>
<td>(Variable) (Volt) (Variable) (kW)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>175.00</td>
<td>0.00</td>
<td>83.40</td>
<td>22912.88</td>
<td>25912.88</td>
<td>25912.88</td>
</tr>
<tr>
<td>45</td>
<td>121.58</td>
<td>64.48</td>
<td>100.05</td>
<td>21617.97</td>
<td>24617.97</td>
<td>24617.97</td>
</tr>
<tr>
<td>90</td>
<td>70.00</td>
<td>52.50</td>
<td>131.86</td>
<td>18114.22</td>
<td>21114.22</td>
<td>21114.22</td>
</tr>
<tr>
<td>135</td>
<td>49.15</td>
<td>26.06</td>
<td>157.36</td>
<td>13744.58</td>
<td>16744.58</td>
<td>15500.00</td>
</tr>
<tr>
<td>180</td>
<td>43.75</td>
<td>0.00</td>
<td>166.79</td>
<td>11456.44</td>
<td>14456.44</td>
<td>15500.00</td>
</tr>
<tr>
<td>225</td>
<td>49.15</td>
<td>-26.06</td>
<td>157.36</td>
<td>13744.58</td>
<td>16744.58</td>
<td>15500.00</td>
</tr>
<tr>
<td>270</td>
<td>70.00</td>
<td>-52.50</td>
<td>131.86</td>
<td>18114.22</td>
<td>21114.22</td>
<td>21114.22</td>
</tr>
<tr>
<td>315</td>
<td>121.58</td>
<td>-64.48</td>
<td>100.05</td>
<td>21617.97</td>
<td>24617.97</td>
<td>24617.97</td>
</tr>
<tr>
<td>360</td>
<td>175.00</td>
<td>0.00</td>
<td>83.40</td>
<td>22912.88</td>
<td>25912.88</td>
<td>25912.88</td>
</tr>
</tbody>
</table>

**Plate dissipation with VSWR influence keeping plate voltage variable**

**Plate voltage Variation during VSWR to control excess plate dissipation**

---

Dynamic control of Va

---

Average power dissipation (kW)
Cases with different tube load

<table>
<thead>
<tr>
<th>Parameters</th>
<th>RT (Tube Load)</th>
<th>Power in kW</th>
<th>VSWR</th>
<th>Fixed Vr</th>
<th>Theta</th>
<th>Vdc</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td></td>
<td>1500</td>
<td>2</td>
<td>3000</td>
<td>0.5</td>
<td>26237.90</td>
</tr>
<tr>
<td>reflection angle</td>
<td>RT (Variation)</td>
<td>XT (Variation)</td>
<td>Iavg</td>
<td>Va</td>
<td>Va(dc)</td>
<td>Va(dc)</td>
</tr>
<tr>
<td>(fi) (Degree)</td>
<td>R (Ohm)</td>
<td>X (Ohm)</td>
<td>(A)</td>
<td>(rms Peak) (Volt)</td>
<td>(Estimated) (Volt)</td>
<td>(Fixed) (Volt)</td>
</tr>
<tr>
<td>0</td>
<td>180.00</td>
<td>0.00</td>
<td>82.23</td>
<td>23237.90</td>
<td>26237.90</td>
<td>26237.90</td>
</tr>
<tr>
<td>45</td>
<td>125.06</td>
<td>66.32</td>
<td>98.65</td>
<td>21924.62</td>
<td>24924.62</td>
<td>26237.90</td>
</tr>
<tr>
<td>90</td>
<td>72.00</td>
<td>54.00</td>
<td>130.01</td>
<td>18371.17</td>
<td>21371.17</td>
<td>26237.90</td>
</tr>
<tr>
<td>135</td>
<td>50.55</td>
<td>26.81</td>
<td>155.16</td>
<td>13939.54</td>
<td>16939.54</td>
<td>26237.90</td>
</tr>
<tr>
<td>180</td>
<td>45.00</td>
<td>0.00</td>
<td>164.46</td>
<td>11618.95</td>
<td>14618.95</td>
<td>26237.90</td>
</tr>
<tr>
<td>225</td>
<td>50.55</td>
<td>-26.81</td>
<td>155.16</td>
<td>13939.54</td>
<td>16939.54</td>
<td>26237.90</td>
</tr>
<tr>
<td>270</td>
<td>72.00</td>
<td>-54.00</td>
<td>130.01</td>
<td>18371.17</td>
<td>21371.17</td>
<td>26237.90</td>
</tr>
<tr>
<td>315</td>
<td>125.06</td>
<td>-66.32</td>
<td>98.65</td>
<td>21924.62</td>
<td>24924.62</td>
<td>26237.90</td>
</tr>
<tr>
<td>360</td>
<td>180.00</td>
<td>0.00</td>
<td>82.23</td>
<td>23237.90</td>
<td>26237.90</td>
<td>26237.90</td>
</tr>
</tbody>
</table>

Plate dissipation with VSWR influence keeping plate voltage constant

Tube load & Plate current variation with VSWR influence

- Variation in Tube load (Ohm)
- Variation In Plate current (A)
### Management of dissipation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>RT (Tube Load) 90</th>
<th>Power in kW 1500</th>
<th>VSWR 2</th>
<th>Fixed Vr 3000</th>
<th>Theta 0.5</th>
<th>Vdc 26237.90</th>
</tr>
</thead>
<tbody>
<tr>
<td>reflection angle</td>
<td>RT (Variation)</td>
<td>XT (Variation)</td>
<td>Iavg</td>
<td>Va</td>
<td>Va(dc)</td>
<td>Va(dc)</td>
</tr>
<tr>
<td>(fi) (Degree)</td>
<td>R (Ohm)</td>
<td>X (Ohm)</td>
<td>(A)</td>
<td>(rms Peak) (Volt)</td>
<td>(Estimated) (Vol)</td>
<td>(Variable) (Vol)</td>
</tr>
<tr>
<td>0</td>
<td>180.00</td>
<td>0.00</td>
<td>82.23</td>
<td>23237.90</td>
<td>26237.90</td>
<td>26237.90</td>
</tr>
<tr>
<td>45</td>
<td>125.06</td>
<td>66.32</td>
<td>98.65</td>
<td>21924.62</td>
<td>24924.62</td>
<td>24924.62</td>
</tr>
<tr>
<td>90</td>
<td>72.00</td>
<td>54.00</td>
<td>130.01</td>
<td>18371.17</td>
<td>21371.17</td>
<td>21371.17</td>
</tr>
<tr>
<td>135</td>
<td>50.55</td>
<td>26.81</td>
<td>155.16</td>
<td>13939.54</td>
<td>16939.54</td>
<td>16939.54</td>
</tr>
<tr>
<td>180</td>
<td>45.00</td>
<td>0.00</td>
<td>164.46</td>
<td>11618.95</td>
<td>14618.95</td>
<td>15500.00</td>
</tr>
<tr>
<td>225</td>
<td>50.55</td>
<td>-26.81</td>
<td>155.16</td>
<td>13939.54</td>
<td>16939.54</td>
<td>16939.54</td>
</tr>
<tr>
<td>270</td>
<td>72.00</td>
<td>-54.00</td>
<td>130.01</td>
<td>18371.17</td>
<td>21371.17</td>
<td>21371.17</td>
</tr>
<tr>
<td>315</td>
<td>125.06</td>
<td>-66.32</td>
<td>98.65</td>
<td>21924.62</td>
<td>24924.62</td>
<td>24924.62</td>
</tr>
<tr>
<td>360</td>
<td>180.00</td>
<td>0.00</td>
<td>82.23</td>
<td>23237.90</td>
<td>26237.90</td>
<td>26237.90</td>
</tr>
</tbody>
</table>

**Plate dissipation with VSWR influence keeping plate voltage variable**

**Plate voltage Variation during VSWR to control excess plate dissipation**

---

**Diagram:**
- **Pd with variable plate voltage (kW)**
- **Pd with fixed Plate voltage (kW)**
Cavity design for Input & Output

Input cavity

RF input

Coupling capacitor

Z1

Z2

Second tuning

First tuning

C_G1

C_FK

Output cavity

Tetrode

C_A

Primary tuning

Secondary tuning

C_A-G2

Primary to Secondary coupling

Load coupling

Z1

Z2

Z3

Z4

Load

No. of motors for each chain = 18
Tuning ≤ 180 sec.
Power Supply requirements

**HPA-1**

- **Anode PS**
  - Voltage: 6.5 kV DC
  - Current: 5 Amp
  - Regulation: 1 % Line & Load
  - Ripple: 1 % P-P @ 5 kV
  - Store energy < 10 Joule

- **Screen Grid PS**
  - Voltage: 1.5 kV DC
  - Current: 1 Amp
  - Bleeder: 0.5 Amp
  - Regulation: 1 % Line & Load
  - Ripple: 1 % P-P
  - Store energy < 10 Joule

- **Control Grid PS**
  - Voltage: -800 V DC
  - Current: 500 mAmp
  - Regulation: 1 % Line & Load
  - Ripple: 1 % P-P
  - Store energy < 10 Joule

- **Filament PS**
  - Voltage: 8.8 DC/AC
  - Current: 200 Amp
  - Ramp up / Ramp down: > 5 Min

**HPA-2**

- **Anode PS**
  - Voltage: 15 kV DC
  - Current: 20 Amp
  - Regulation: 1 % Line & Load
  - Ripple: 1 % P-P @ 18 kV
  - Store energy < 10 Joule

- **Screen Grid PS**
  - Voltage: 2 kV DC
  - Current: 2 Amp
  - Bleeder: 0.5 Amp
  - Regulation: 1 % Line & Load
  - Ripple: 1 % P-P
  - Store energy < 10 Joule

- **Control Grid PS**
  - Voltage: -1000 V DC
  - Current: 1.5 Amp
  - Bleeder: 3.75A @ -500V
  - Regulation: 1 % Line & Load
  - Ripple: 1 % P-P
  - Store energy < 10 Joule

- **Filament PS**
  - Voltage: 10 V DC
  - Current: 400 Amp
  - Ramp up / Ramp down: 8 Min

**HPA-3**

- **Anode PS**
  - Voltage: 15.5 - 27 kV DC
  - Current: 190 Amp
  - Regulation: 1 % Line & Load
  - Ripple: 1 % P-P @ 27 kV
  - Store energy < 10 Joule

- **Screen Grid PS**
  - Voltage: 2 kV DC
  - Current: 8 Amp
  - Bleeder: 1 Amp
  - Regulation: 1 % Line & Load
  - Ripple: 1 % P-P
  - Store energy < 10 Joule

- **Control Grid PS**
  - Voltage: -1000 V DC
  - Current: 6 Amp
  - Bleeder: 10 A @ -500 V
  - Regulation: 1 % Line & Load
  - Ripple: 1 % P-P
  - Store energy < 10 Joule

- **Filament PS**
  - Voltage: 20 VDC
  - Current: 1200 Amp
  - Ramp up / Ramp down: 8 Min
Ref signal for amp, phase & frequency

Interlocking Signal to the Source

PLC based Sequential operational system with safety Interlock
Real time control loop, Fast acquisition & On line monitoring
Fast interlock with pre & post triggering acquisition (<1μsec)
Display module for online & offline analysis
Cavity Tuning for different frequency operation

CODAC

Plant Controller

Local Controller (LC1)

LC2

LC for Tx line & Antenna

LC8
State Diagram for Sequence control

S0 → Off state
S1 → Stand By (Auxiliary On)
S2 → Heater & VG1 ON

S3 → Anode Voltage On
S4 → VG2 ON
S5 → RF ON

S1 Interlock
S2 Interlock
S3 Interlock
S4 Interlock
S5 Interlock
S5-S2 Interlock
S5-S3 Interlock

Command
Command
Command
Command
Command
3MW/3600s/35-65 MHz test setup

Load impedance $Z_T = R + jX$ covers the entire circle
High Power Test Facility

- Equipped with 3 MW test load, HVPS, Aux. PS, Cooling manifold, Tx-line system, Protection & Controls, mechanical tools, RF measuring equipment, radiation meter etc.
- Effective Floor space with additional mezzanine ~16mx16m
- Clear Height > 7.5 m
IC Power Source at ITER-RF building

RF Source enclosure

LCU + LP section

Pre-driver & Driver Stage Amp.

Final Stage Amp.

12”/3MW DC

Pressurized Gas Barrier

DL with Pressurized Gas Barrier

U Bend outside enclosure

Combiner

Note: End of U bend is IN-US Interface
• **RF Source for ITER will cover all scenarios required from operational point of view**
• **Very special design is involved to satisfy major requirements**
• **To identify critical components involved, specially in high power stage, R&D activity has been initiated considering different type of vacuum tubes (Tetrode & Diacrode)**
• **Outcome of R&D phase will lead to establish the technology, capable of delivering the ITER ICRF source specifications with reliability**