Conceptual design of ITER ECE Receiver systems and their performance parameters

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ITER operation magnetic field ~ 5.3 Tesla for scenario 2

The cyclotron frequency range:
- First harmonic frequency range ~ 120 – 220 GHz
- Second harmonic frequency range ~ 240 – 440 GHz

O-mode first harmonic and X-mode second harmonic optically thick for ITER plasma parameters.
Emission width for ITER scenario 2 (example)
First harmonic O-mode frequency ~ 120 – 230 GHz (IN-DA)
Radiometer with 52 channels with seven down conversion

Second harmonic X-mode frequency range ~ 240 – 350 GHz (US-DA)
Radiometer with 36 channels many down conversion system

Ultra wide band measurement in both (O & X) modes ~ 70 GHz to 1 THz

Two Michelson interferometer for frequency range 70 GHz to 1 THz (IN-DA)
Lay out of ECE system (CDR baseline)

Smooth-wall circ. WG
Corrugated waveguides

In-port mirrors
Sealing system
Splitter boxes
Diagnostic Bld

Calibration sources with shutters
Double-window assembly
Alignment system
Secondary window

Eq. Port Plug #09 (central DSM)
Interspace
Port Cell
Gallery

Michelson
Radiometers
Conceptual design of O-mode radiometer and its parameters

Conceptual design of Michelson interferometer and its parameters
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>122 GHz – 230 GHz</td>
<td></td>
</tr>
<tr>
<td>Channel separation for 122 – 139 GHz</td>
<td>1 GHz of 18 channels</td>
<td>F-Band waveguide (edge); 1 mixer</td>
</tr>
<tr>
<td>Channel separation for 141 – 169 GHz</td>
<td>2 GHz of 15 channels</td>
<td>D-Band waveguide (edge); 2 mixer</td>
</tr>
<tr>
<td>Channel separation for 172 – 218 GHz</td>
<td>3 GHz of 16 channels</td>
<td>G-Band waveguide (edge); 3 mixers</td>
</tr>
<tr>
<td>Channel separation for 222 – 230 GHz</td>
<td>4 GHz of 3 channels</td>
<td>1 mixer</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>Continuous</td>
<td></td>
</tr>
<tr>
<td>Video BW</td>
<td>DC – 1 MHz (as per requirement)</td>
<td>Further integration to be performed digitally</td>
</tr>
<tr>
<td>Dimensions (L x W x H)</td>
<td>3 x 3 x 2 m (tentative)</td>
<td>Only for receiver system</td>
</tr>
</tbody>
</table>
Schematic block diagram of Radial line

- Polarizer Splitter unit
- WG connection Unit
- O-mode Radiometer splitter unit
  - F-band Radiometer
  - D-band Radiometer
  - G-band Radiometer
  - Millimeter Radiometer

To Michelson

TL WG
Schematic diagram of the splitter unit

Input WG

EM1

G1

EM2

G2

EM3

G3

F-Band Radiometer 122 – 139 GHz

D-Band Radiometer 141 – 169 GHz

G-Band Radiometer 172 – 218 GHz

Millimeter wave Radiometer 222 – 230 GHz
F-band Radiometer block diagram

1 RF INPUT 122 – 139 GHZ oscillator of 121 GHZ
2 121 GHz high pass filter
3 Balanced Mixer of IF 1 – 18 GHz
4 Variable attenuator
5 Isolator
6 Local (Gunn) oscillator of 121 GHZ
7 IF Amplifiers
8 Power divider of 18 channels
9 Band pass filter
10 Diode detector
### O-mode radiometer parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Radiometer with frequency range 122 – 230 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-Band</td>
</tr>
<tr>
<td>Frequency Band</td>
<td>122 – 139</td>
</tr>
<tr>
<td>Frequency range (GHz)</td>
<td>18</td>
</tr>
<tr>
<td>Number of channels</td>
<td>1</td>
</tr>
<tr>
<td>Channels separation (GHz)</td>
<td>1</td>
</tr>
<tr>
<td>Transmission line loss (dB)</td>
<td>-13</td>
</tr>
<tr>
<td>Total loss up to detector</td>
<td>-44</td>
</tr>
<tr>
<td>Two stage IF amplifiers</td>
<td>80</td>
</tr>
<tr>
<td>Total gain</td>
<td>36</td>
</tr>
<tr>
<td>The sensitivity of the radiometer for detector sensitivity of 1000 V/W</td>
<td>4 x 10^6</td>
</tr>
<tr>
<td>Noise temperature (eV)</td>
<td>8</td>
</tr>
<tr>
<td>Noise power (W)</td>
<td>5.9 x 10^{-10} for ( B_{if} = 0.5 \text{ GHz} )</td>
</tr>
</tbody>
</table>
- Polarized interferometer of a Martin-Puplett type design
- Parallel metal wires grid used as beam splitter
Three important features for the design driver of the Michelson interferometer

1) Rapid scanning mechanism that decides time resolution of full spectrum measurement

2) Atmosphere shielding to avoid water vapor absorption of the millimeter wave radiation

3) High throughput of the interferometer for moderate integration time required for calibration

These features need to be optimized in the design of the ITER ECE Michelson interferometer
Michelson interferometer specifications

Spectral range (GHz) : 70 – 1000

Frequency resolution : 7.5 - 10 GHz

Linear path scan (mm) : 30 - 40

Path difference sampling (µm) : 50 - 100

Scanning repetition rate : 10 – 20 ms

Instruments throughput > 0.4 x 10^{-4} m^2Sr.

Number of Michelson interferometers : 2 (one for O-mode and other for X-mode)

Duty cycle : continuous
Existing available technology of optical components (like reflecting mirrors, wire grid polarizers etc.) work for 70 – 1THz

Hot electron detector optimized for frequency response and Noise Equivalent Power (NEP)
Typical Detector Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Bandwidth</td>
<td>60 to 1200 GHz</td>
</tr>
<tr>
<td>System Optical Responsivity</td>
<td>&gt; 2,000 V/Watt</td>
</tr>
<tr>
<td>System Optical N.E.P.</td>
<td>&lt; 1.25 x10^-12 Watts Hz^{1/2}</td>
</tr>
<tr>
<td>Maximum power handling capacity</td>
<td>10 μW</td>
</tr>
<tr>
<td>Upper level of dynamic range (3 dB)</td>
<td>1 μW</td>
</tr>
<tr>
<td>Total dynamic range</td>
<td>&gt; 29 dB</td>
</tr>
<tr>
<td>Frequency Response (-3 dB)</td>
<td>0 to 750 kHz</td>
</tr>
<tr>
<td>Active Area</td>
<td>25 mm^2</td>
</tr>
<tr>
<td>Typical Operating Resistance</td>
<td>5-10K ohms</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>4.2K</td>
</tr>
</tbody>
</table>
A circular smooth walled waveguide of 72 mm diameter is proposed for TL.

Two transmission lines (i.e. one for radial and other for oblique measurements of O-mode) for I/P to the Michelson.

coupling optics between the transmission line waveguide and the input of the Michelson.

Relation between dimensions of the waveguide (i.e. radius a or longer side a) to the beam waist radius (w) at the input of the waveguide.
For smooth-walled circular WG, ratio $w/a = 0.76$ gives optimum coupling of 87%.

For smooth-walled rectangular WG, $w/a = 0.3$ gives 85%.

For Corr. Circular WG, $w/a = 0.64$ gives 98%.

Two Gaussian beam telescope constructed by using four ellipsoidal mirrors.

Three mirrors have same focal length (~ 33 cm) with diameter of ~11 cm and last mirror has a focal length 12 cm.
Estimation of transmission attenuation

-10
-15
-20
-25
-30
-35
-40
100 200 300 400 500 600 700 800 900 1000

Frequency (GHz)

Attenuation (dB)

- For smooth walled circular WG
- For circular corrugated WG
- For smooth walled rectangular WG
- For smooth walled circular WG with TE + TM mode
Layout of Michelson interferometer
Gaussian beam size from WG output
 › For electron temperature profile measurement
  
  Total error \( \sim 5\% \), \( \text{R.M.S.} \sim 2.5\% \)

 › For power loss and spectral information, \( \text{R.S.M.} \) error \( \sim 2.5 \% \)

 › Measurement from two views should be compared. Therefore, the \( \text{R.M.S.} \) error for each line of sight would need to be \( < 1.8 \% \)

 › For time resolution \( \sim 10 \text{ ms} \) and the frequency resolution of the interferometer \( \sim 10 \text{ GHz} \), statistical noise during plasma measurement is negligible
Allowable error depends on calibration

Three factors have significant contribution

1) Source temperature measurement error
   < 0.13 %

2) Accuracy in Emissivity
   ±1.2 % or better

3) Statistical error during calibration
   should be 1.35 % in r.m.s. to achieve total error of 1.8 % r.m.s

reduce the random noise in the calibration and improve the calibration accuracy by long time integration of the measurement
The integration time for 2% accuracy (1 % r.m.s)

For this, the signal to noise ratio equals to 100

The integration time $T_i$

$$T_i = 40000 \left( \frac{NEP}{P_s} \right)^2$$

$P_s$ is the calibration source power falling on the detector

$$P_s = K \theta_s f^2 \Delta f E_t T_{tl}$$
NEP is of the detector $= 1 \times 10^{-12} \text{ W/Hz}^{-1/2}$

K = $2.44 \times 10^{-41}$

For ITER ECE Michelson interferometer parameters:
Frequency resolution ($\Delta f$) = 10 GHz
Source temperature of 973 oK
etendue of $1.28 \times 10^{-5}$ m$^2$Sr
Required integration time for the calibration

- For smooth walled Circular WG
- For smooth walled rectangular WG
- For circular corrugated WG
Thank you
Back up slides
Corrugated WG measurement

Measured and calculated Attenuation of 63.5 mm CWG TL of 15 meter length with 7 miter bends

Frequency (GHz)

Attenuation (dB)

-20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0

100 200 300 400 500 600 700 800 900

- Derived from measurements
- Measured

H₂O
Smooth-wall rectangular WG

Used for FTU ECE transmission line and measured radiation up to 1000 GHz. Measured attenuation = 2 (theoretical calculated attenuation)

- No Bragg scattering
- Poor coupling from the QO-splitter box to the waveguide
- Large side lobes for TE10 mode in the E-plane

Larger (than for corrWG) Ohmic losses below 350 GHz

Intremix of TE10 mode with other WG modes affecting the spatial localization of the ECE (depends also on how the splitting of modes is done)

Come to know more after rect. WG TL att. measurement (R &D)
- **Smooth-wall circular WG**
  - Fundamental TE mode whose attenuation varies $1/D$
  - **Ohmic Attenuation is not very different than rect. WG**
  - **No Bragg reflection effect**
  - **Adequate coupling between WG to quasi-optical component, no taper required**
  - **Polarization preservation could be problematic, especially for highly overmoded WG**

- **Dielectric Lined Circular Waveguide**
  - **Support HE11 mode, no Bragg reflection**
  - **Not work for full range of frequency 70 – 1000 GHz**
Taking the discussion above into account, the smooth-wall circular waveguide is a preferred solution for both lines-of-sight to enable simultaneous measurements of both X- and O-mode with acceptable level of losses.

R&D for the rectangular waveguide (72 x 34 mm) and corrugated circular waveguide (ID 63.5 mm) options will be performed during the Preliminary Design Phase for correct TL choice.
Many components in radiation path from the calibration source to the receiver system (Michelson)

Three vacuum window, polarizer splitter unit, 43 meter long WG TL with six miter bends, power splitter, optics for WG to Michelson interferometer coupling and Michelson interferometer

Consider attenuation of each component

The vacuum window attenuation taken from measured data
Polarizer splitter unit, WG coupling optics and Michelson attenuation are estimated by the Gaussian beam theory.

Estimation of Long (~ 43 meter) WG and miter bend attenuation.

For corrugated WG of 63.5 mm and miter bend, attenuation is taken from DIII-D TL measurement.

For smooth-wall rectangular (72 x 34 mm²), circular WG of diameter 72 mm & miter bend, attenuation is calculated theoretically and doubled it.

The attenuation would be conform by experiential measurement.
Thank you