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WHAT STARTS HERE CHANGES THE WORLD

Recent Progress on the Electron Cyclotron Emission Diagnostics Development for ITER

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with

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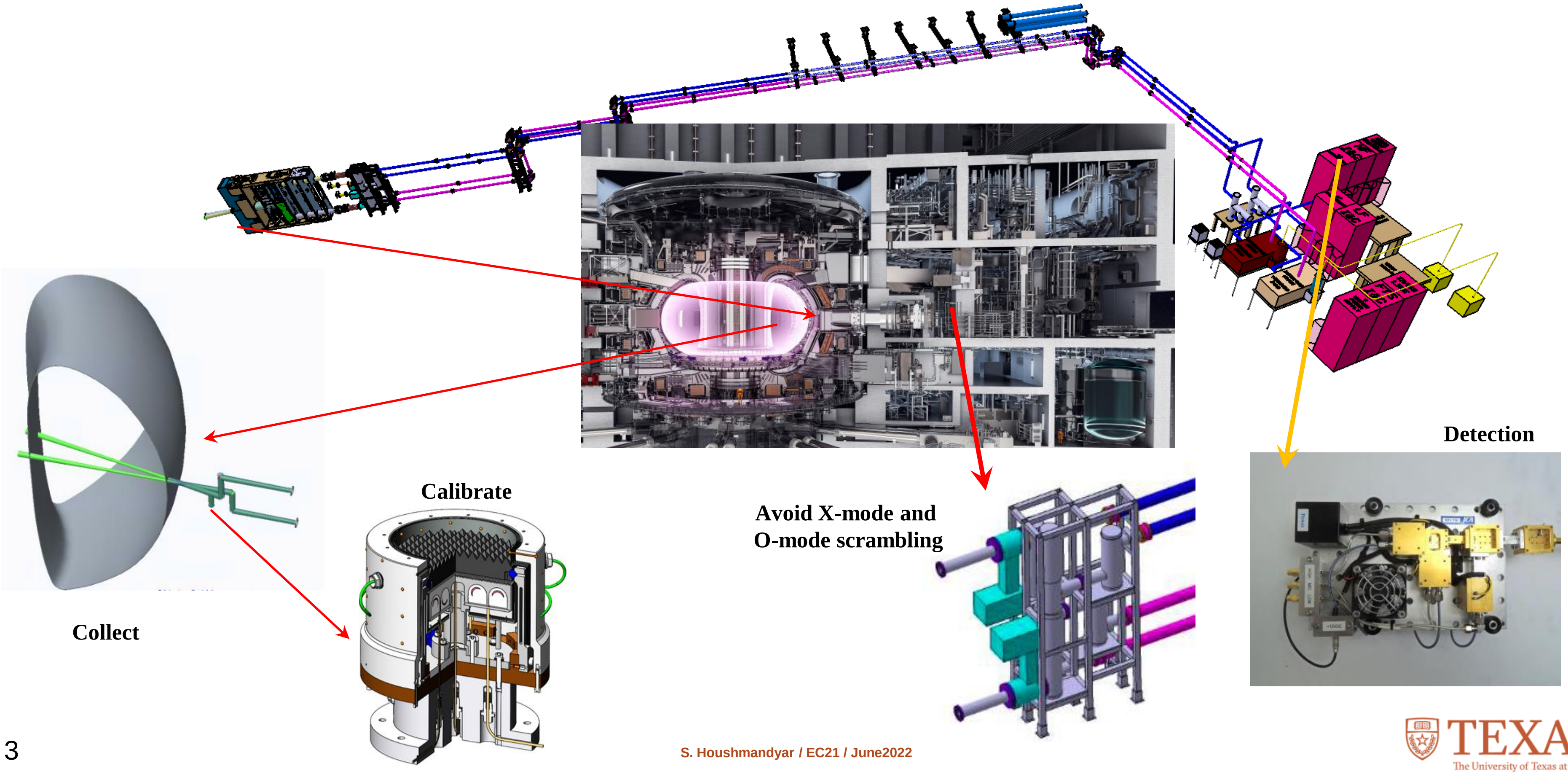
ECE Diagnostics are in Final Design Phase, Transitioning to Development

- **Electron Cyclotron Emission (ECE) diagnostics objectives:**
  - **Measuring high spatial and temporal resolution electron temperature (T_e) and electron temperature fluctuations (δT_e).**
  - **Provide temperature profiles to Plant Control System (PCS) for control purposes.**
  - **Detect Neoclassical Tearing Modes (to PCS), MHD activities and Alfven Eigen modes.**
  - **Assess non-thermal electron distributions (via the oblique view).**
- **The diagnostics design is a collaboration between Domestic Agencies of United States and India, as well as ITER Organization.**
  - **The efforts in the US-DA are shared with:**
    - **The University of Texas at Austin (UT): Front-end optics including hot calibration sources, high frequency radiometer (220 – 340 GHz), performance evaluation.**
    - **Princeton Plasma Physics Laboratory (PPPL): port integration, shutter actuators, mirror fabrication and fixtures.**
  - **IN-DA responsible for transmission lines, low frequency radiometer (122 – 230 GHz), Fourier Transform Spectrometers (70 – 1000 GHz), polarization splitter units (PSUs), switch yard, and ECH stary radiation protection system.**
  - **All parties involved in Instrumentation and Control: software and documentation.**

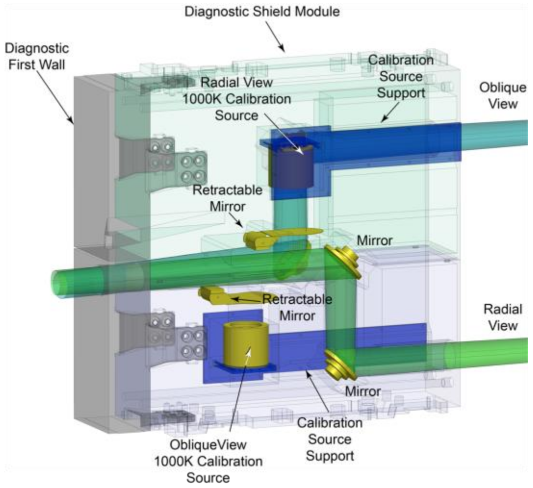
ITER ECE: The Big Picture

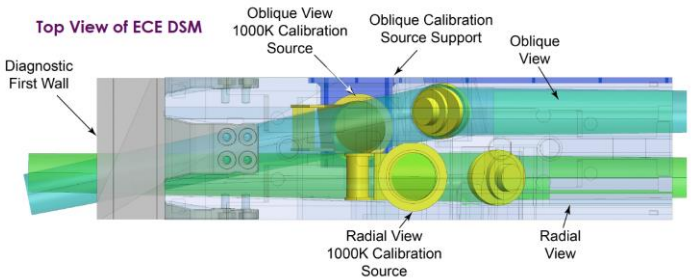


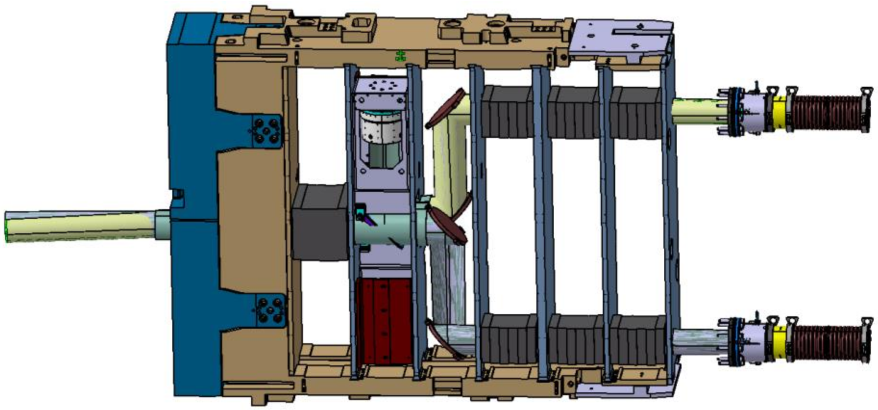
Outline

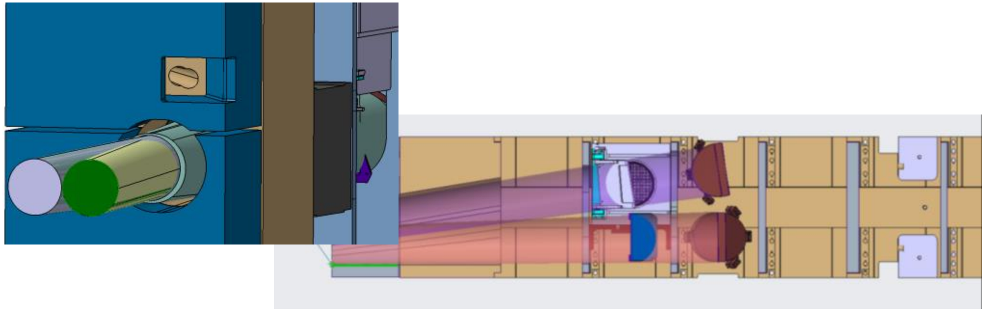
- Front-end design for the ITER ECE diagnostics.
  - Quasi-optical analysis.
  - In-situ hot calibration source.
- Polarization splitting of X and O modes.
- Transmission Line.
- Radiometer channel design.

Significant changes since 2017 Design of ITER ECE



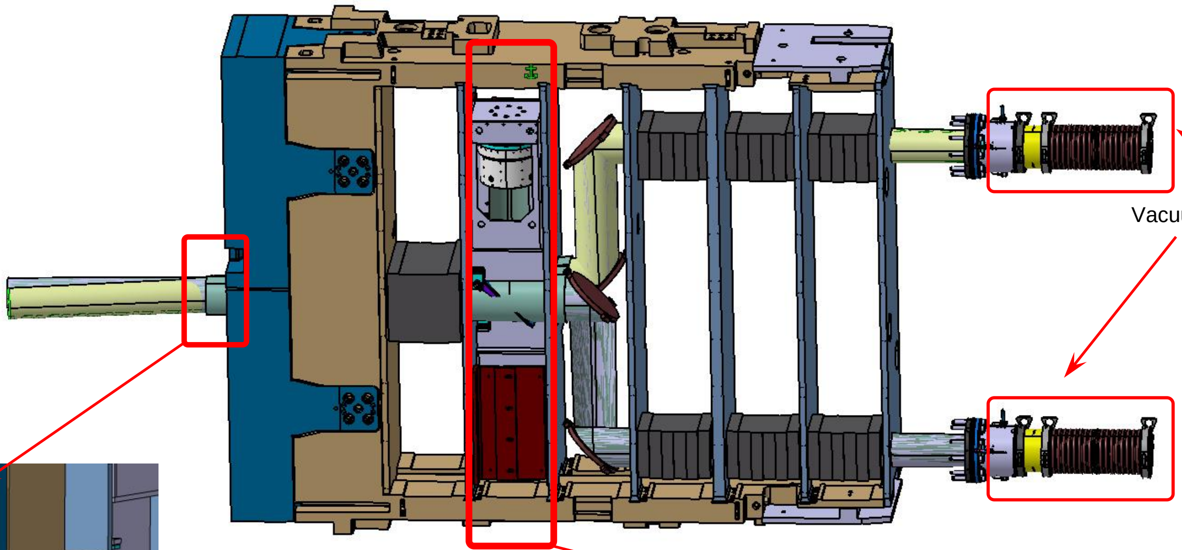






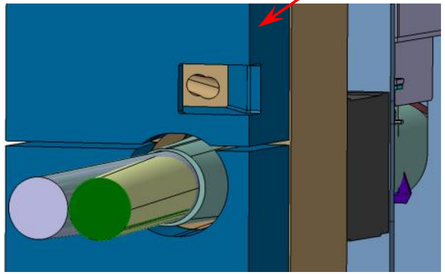
Pre 2017 design | **Current design**

New front-end design partially driven by the neutron shielding

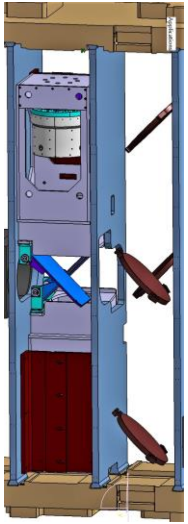


Vacuum termination assembly

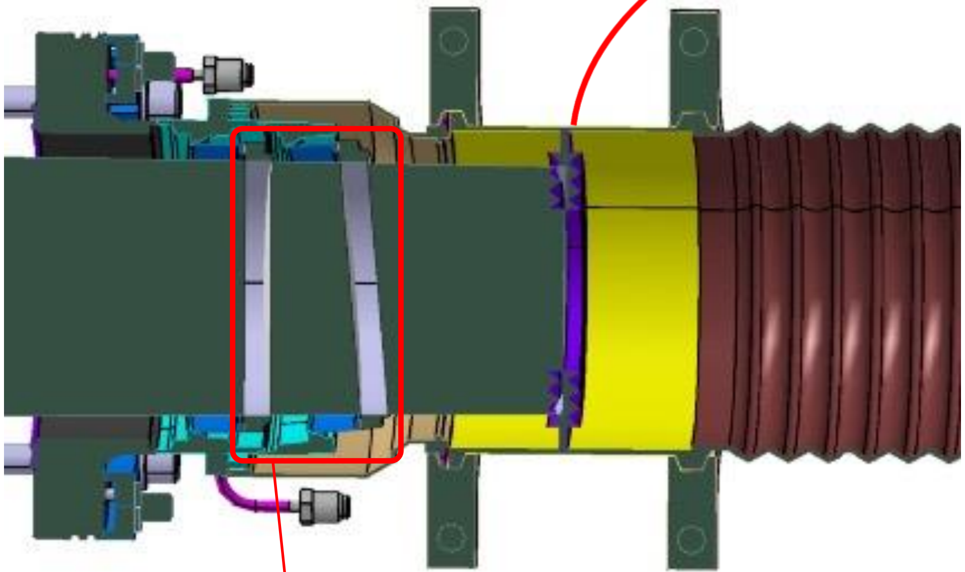
Modular hot source assembly includes, hot sources, shutter mirrors and actuators



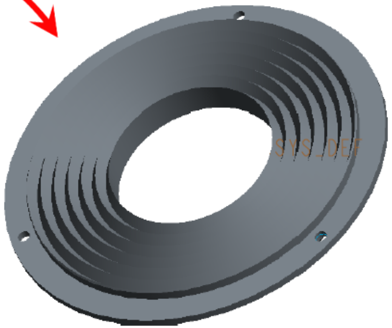
DFW cut outs to accommodate both views



Vacuum termination assembly and aperture (point D)



Window assembly avoids
interference patterns



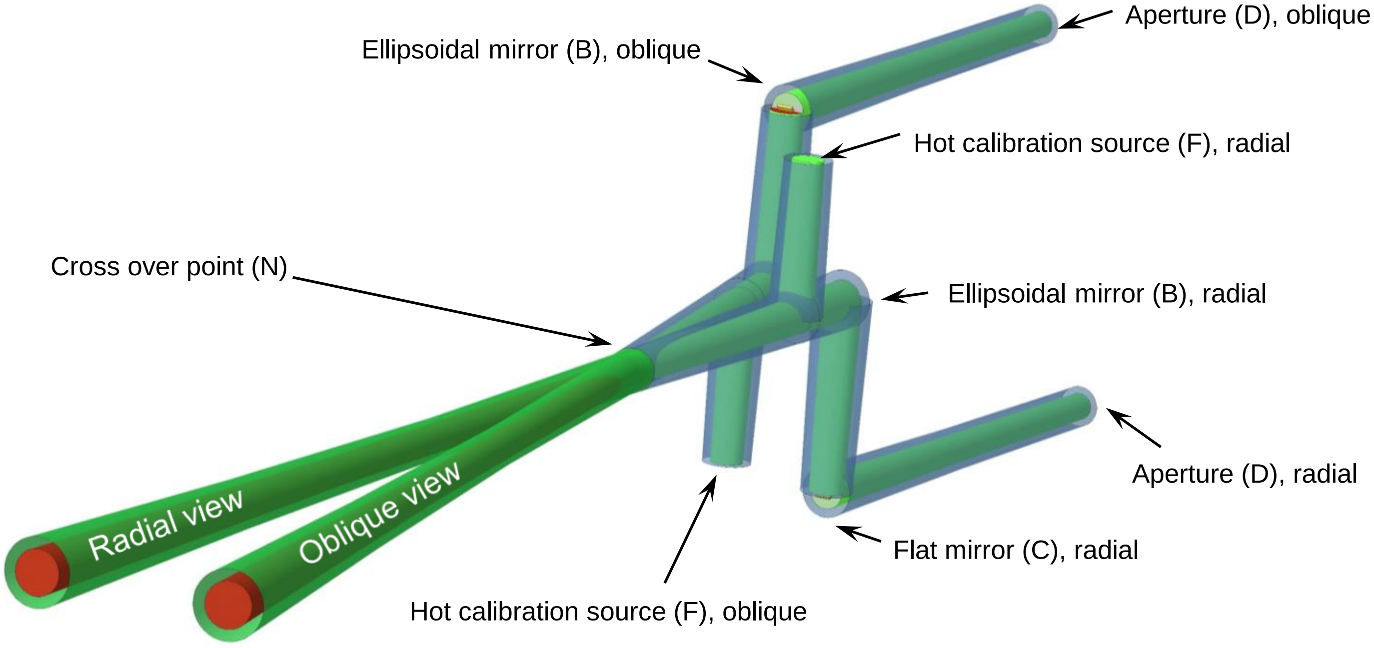
Silicon Carbide (SiC) aperture defines the view in the plasma, acting as field stop. 41.75 mm ID

Quasi optical design for ITER ECE controls the plasma view

"The large distance from the diagnostic flange to the plasma center (> 3 m) and the large plasma diameter (> 6 m) call for antennas for radiation collection with minimum divergence angles. ... Gauss beam collection optics probably offer the best means of achieving suitable antenna pattern control. "

-- Hans J. Hartfuss
Instrumentation of ECE for ITER
Diagnostics for Experimental Thermonuclear Fusion Reactors (1995)

Gaussian beam calculation for in-vessel optics



- Radial and Oblique Views, 115 GHz
- Modeled using Thomas Keating Gaussian Beam Library

Gaussian beam calculation for in-vessel optics

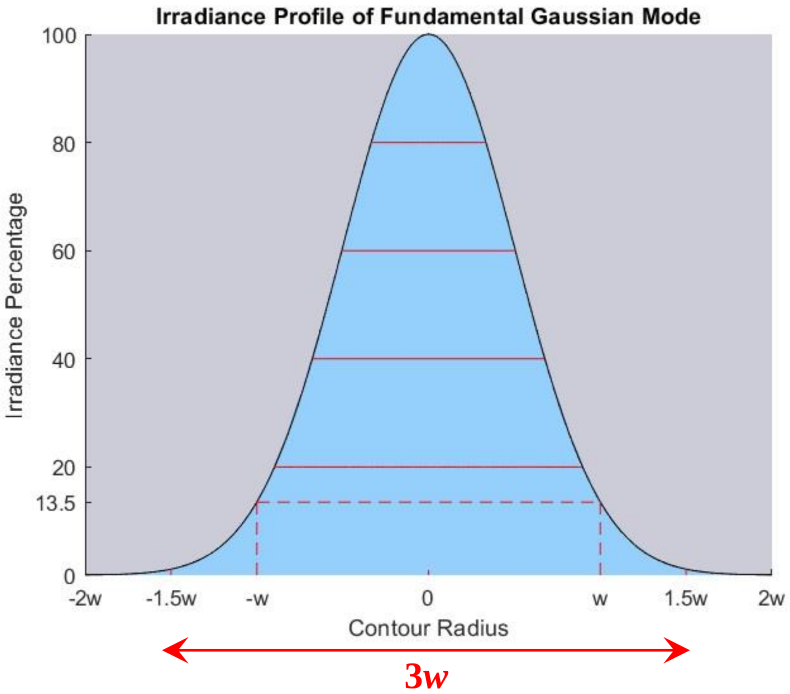
$$w(z) = w_0\sqrt{1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2} \quad \text{, and}$$

$$R(z) = z\left[1+\left(\frac{\pi w_0^2}{\lambda z}\right)^2\right]$$

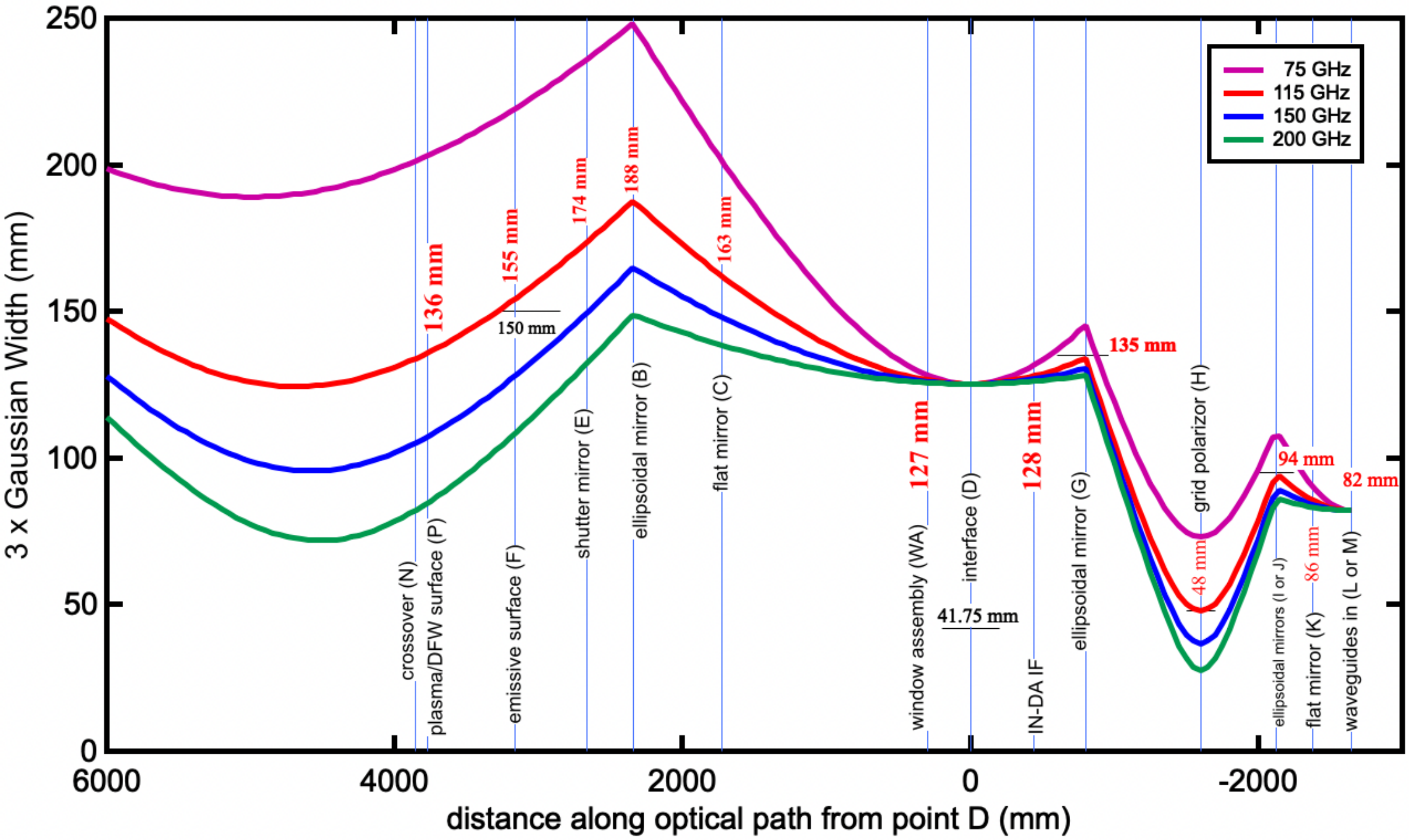
where $R(z)$ is the curvature of the wave front, w_0 is the aperture's radius at the aperture (D), z is the length along the beam and λ is beam's wavelength, and w_0 = 41.75 mm.

$$\frac{P}{P_0} = 1 - e^{-\frac{2a^2}{w^2}}$$

$2w$ is equivalent to 86.5% power throughput
$3w$ is equivalent to 98.88% power throughput



Viewing volume size for in-vessel optics



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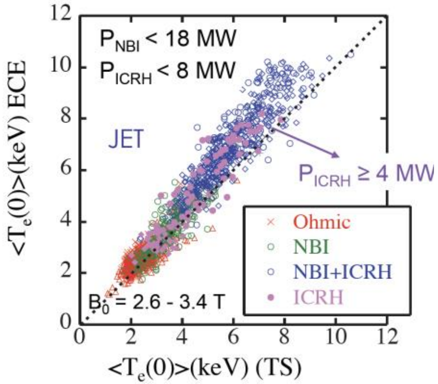
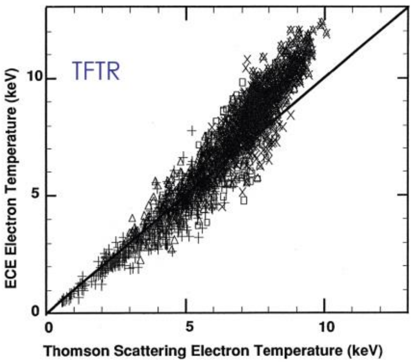
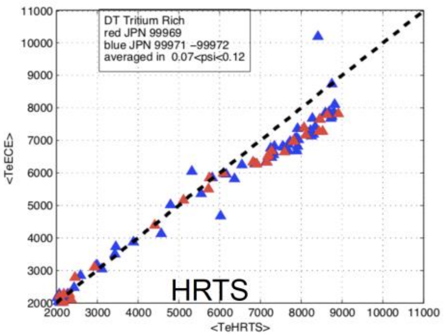
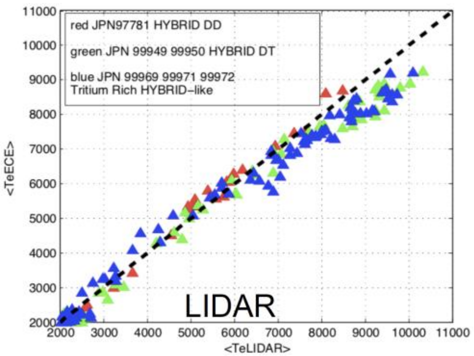
Oblique view will further our understanding of ECE vs Thomson Scattering T_e measurements discrepancies

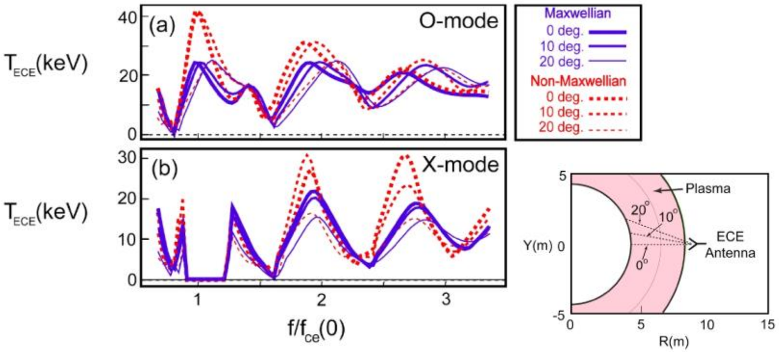


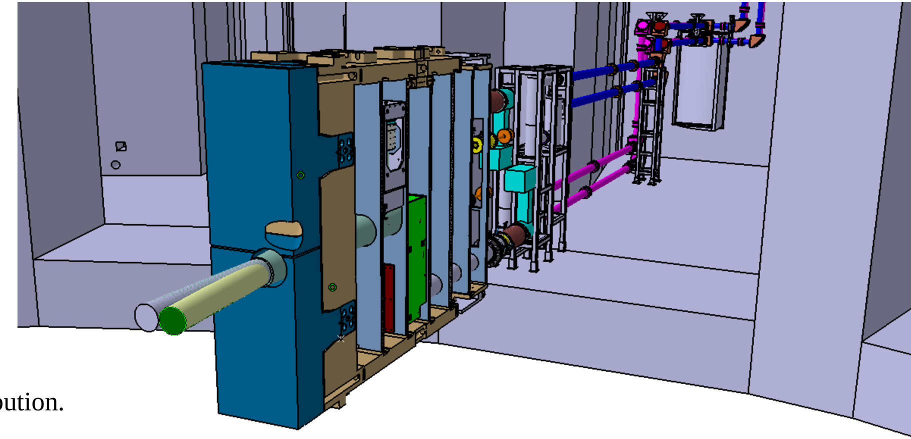






F. Orsitto *et al*, High Temperature Plasma Diagnostic Conference (2022)

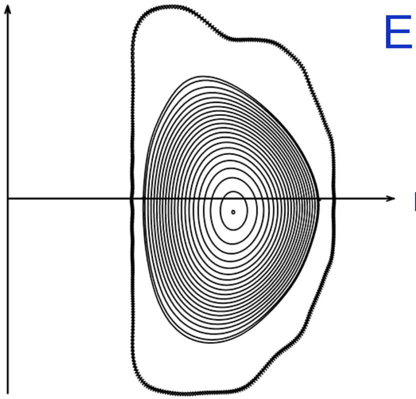




The oblique view can possibly detect non-thermal distribution.

Hot calibration sources ensure absolute T_e measurements

ECE Measurements



Plasma

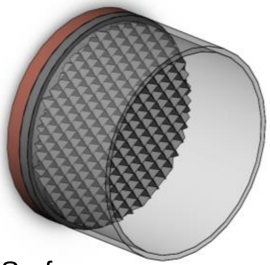
$$I(\nu, R) = \gamma T_e$$

Optics
Polarization splitter
Waveguide
View switcher

ECE Instrument
FTS
Radiometer

Hot Calibration Source

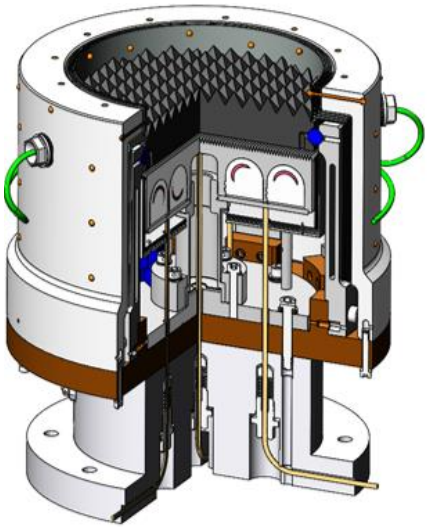
Heated Base



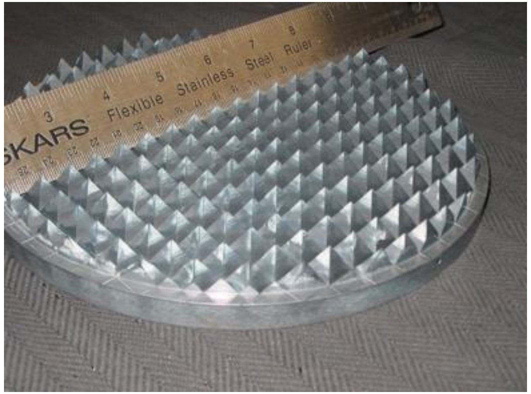
Emitting Surface w/ high emissivity

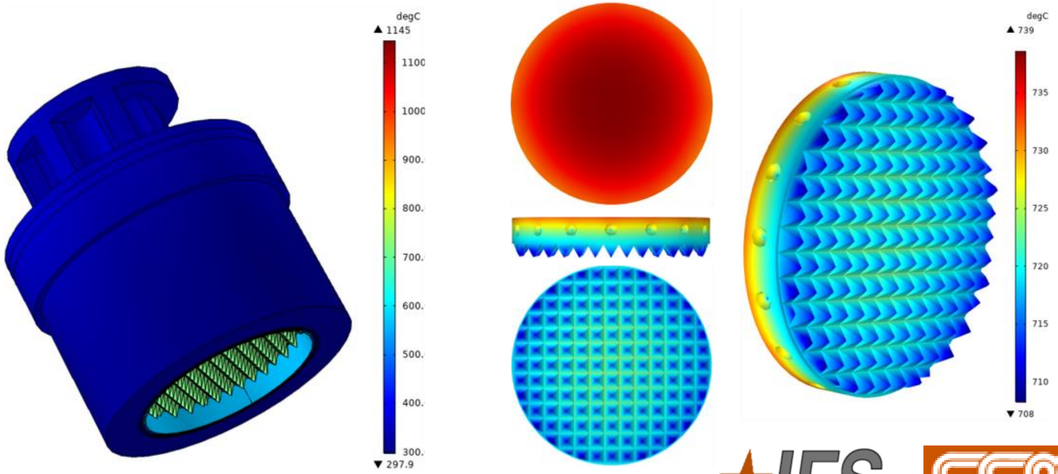
$$I(\nu, T) = \varepsilon \frac{2h\nu^3}{c^3} \frac{1}{exp\left(\frac{h\nu}{kT}\right) - 1}$$

Hot calibration sources ensure absolute T_e measurements



Engineered Hot Source





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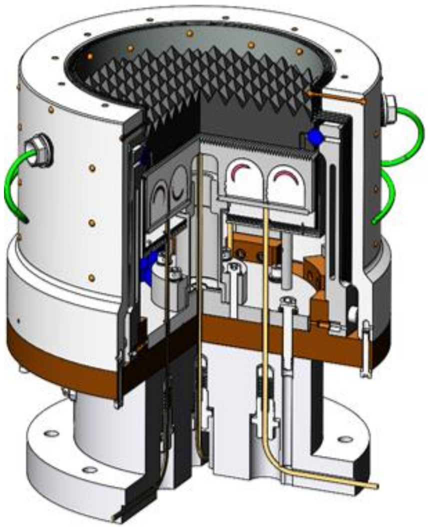
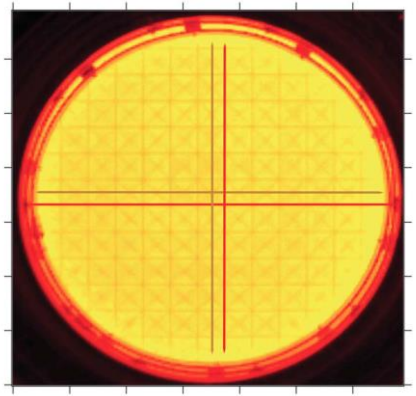
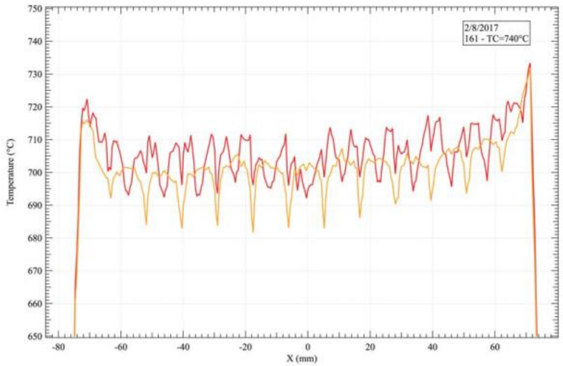
Prototype hot calibration source achieved a uniform (>700 °C) Blackbody emission



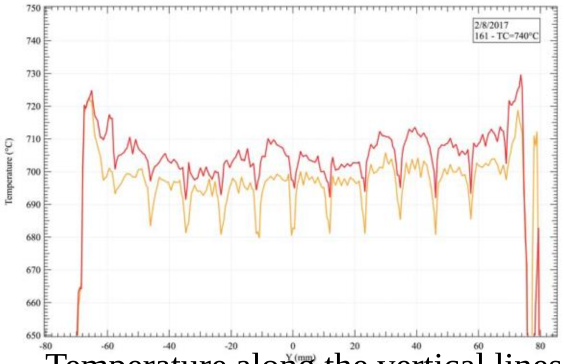


False color IR image
740 °C

Temperature Uniformity



Temperature along the horizontal lines



Temperature along the vertical lines

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Hot source testing

- Status
  - Conducted over 2000 hours of high temperature testing
    - Selected one of three alternatives

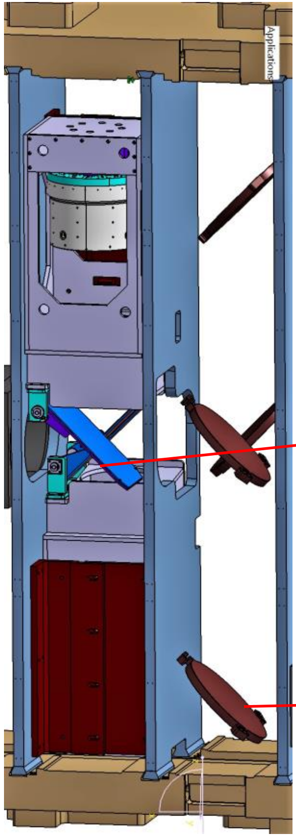
  - Encapsulated molybdenum heater successfully:
    - Heated SiC emitter to > 700 °C
    - Achieved emitter surface temperature uniformity < 10 °C
    - Operated in high vacuum: ~ 10^{-8} Torr
    - Demonstrated stable short term (24 hours) operation
    - Used feedback control so longer times are likely no problem

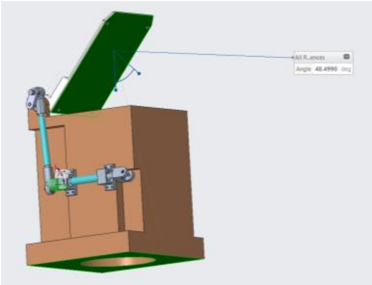
  - Outgassing test met ITER requirements

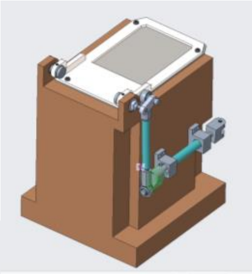
- Design revised following peer review
  - Primary change: removal of alumina potting due to swelling induced by neutron irradiation

- Next challenges to complete the new design
  - Longevity test for new design
  - Vibration test using ITER loads
  - Steam testing (VV ICE)

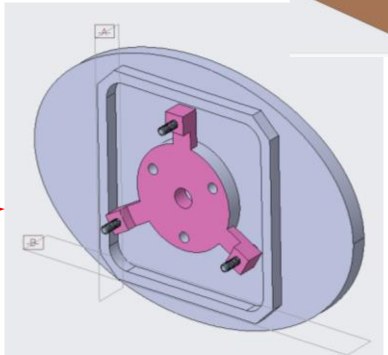
Shutter mirrors in front of hot sources allow remote switching between viewing the plasma and the hot sources





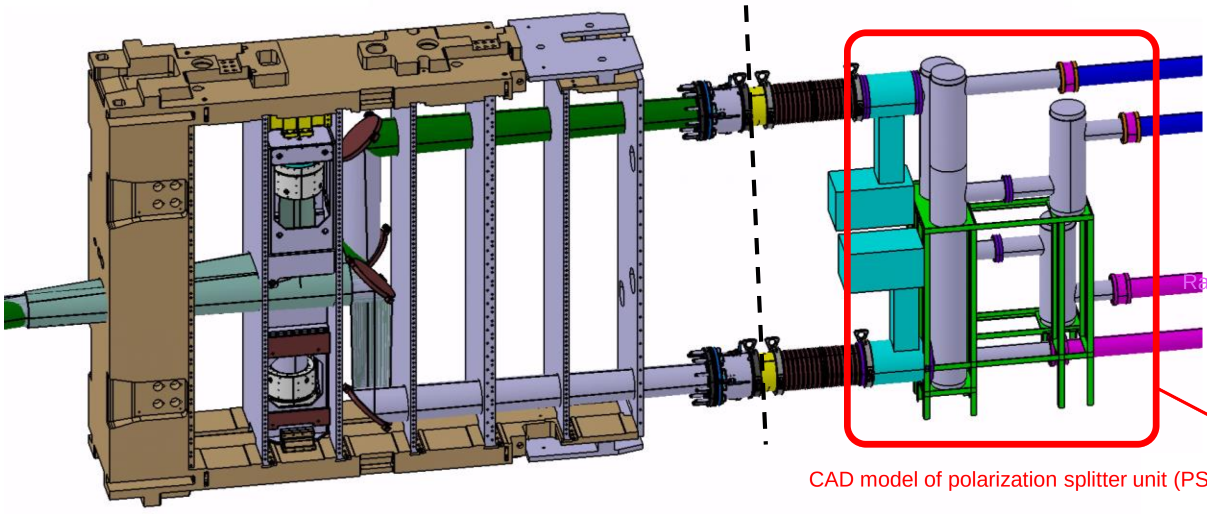


Shutter assembly



Ellipsoidal mirror

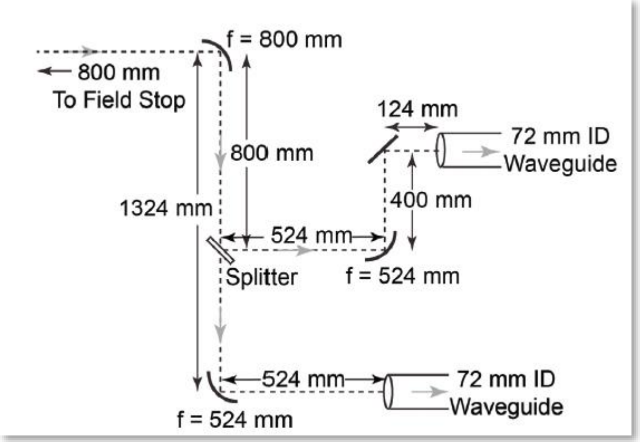
Polarization splitter unit separates modes prior to waveguides, avoids scrambling modes in waveguides



Oblique view emission

Radial view emission

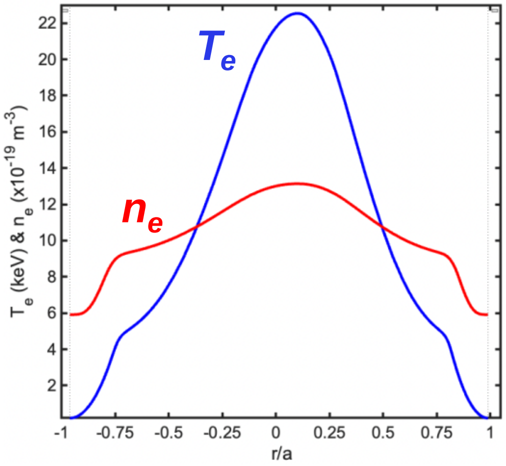
CAD model of polarization splitter unit (PSU)



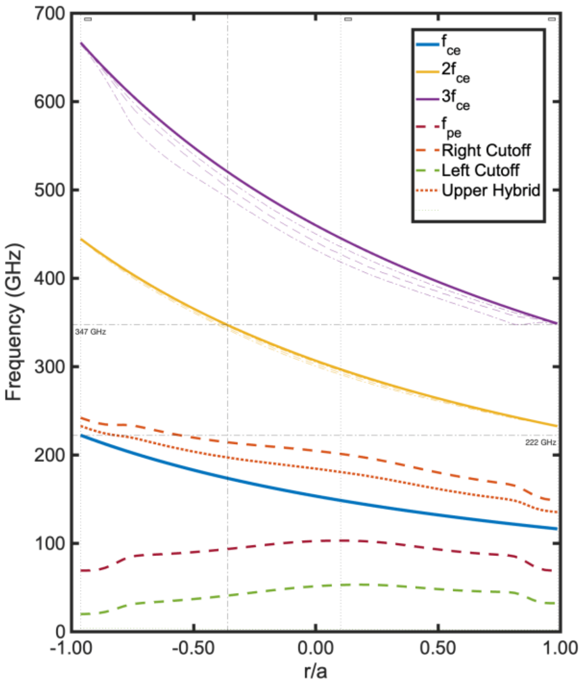
- Support structure design for the Polarization Splitter Unit was updated.
- Preliminary studies were carried out to assess the need of Displacement Compensation System.

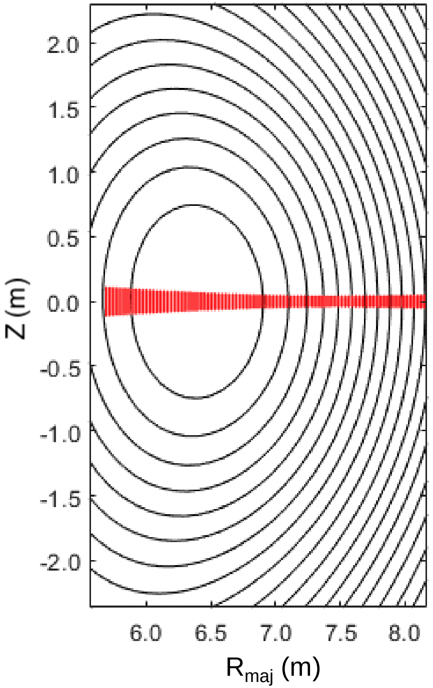
Radiometer channel design

- 2^{nd} harmonic is optically thick
- P = $k\, T_e\, \Delta f$ leads to temperature measurement
- Complications due to relativistic broadening for ITER plasmas



* ITER scenarios used to guide the design





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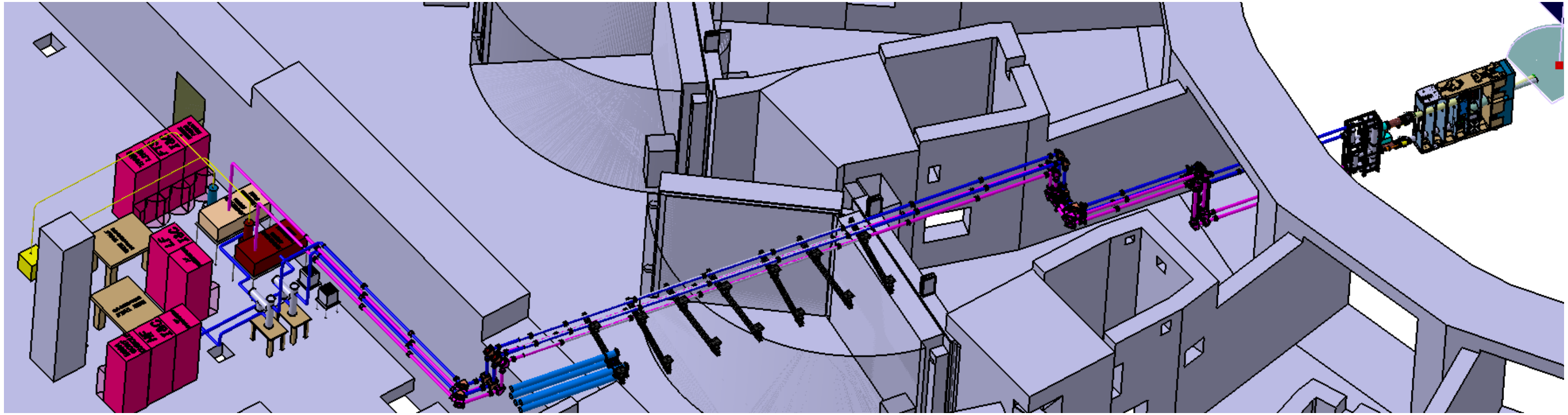
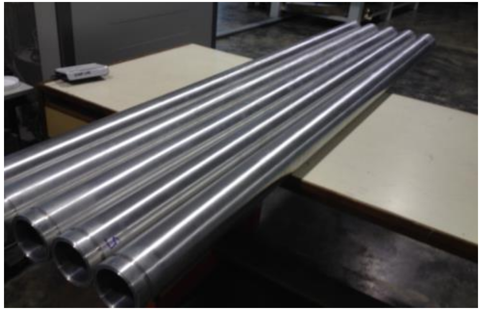
Transmission Line



- 43 meters long
- Desire loss less than:
  - 15 dB for 70 - 400 GHz
  - 22 dB for 400 – 1000 GHz
- Waveguide and not QO



Parameter	Specifications
Waveguide Material	Aluminium, 6061 T6 Alloy
Inner Diameter of Waveguide (mm)	72 ±0.05
Outer Diameter of tube (mm)	88±0.5
WG Inner surface finish	7.5 micron Ra
Ellipticity, WG tube inner surface [mm]	<0.1 mm

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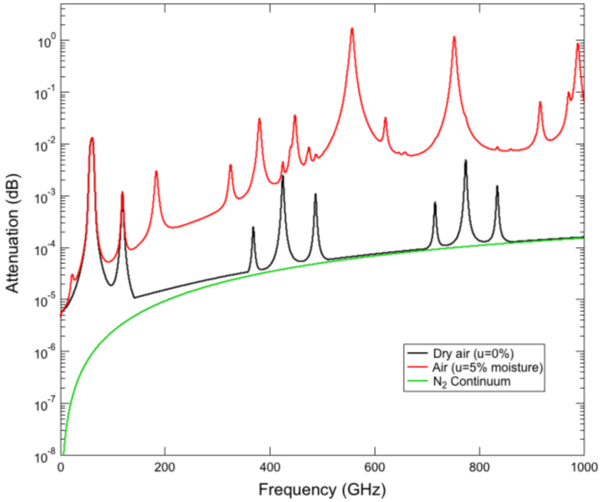
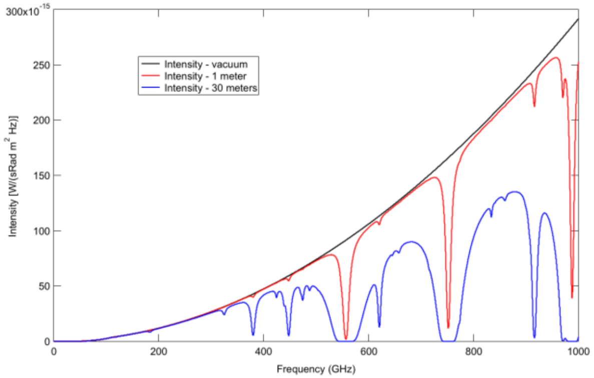
The transmission line is purged to minimize the microwave attenuation

Conduct Microwaves to Instruments

- ❑Minimize microwave attenuation
- ❑Consistent with lab safety
  - Contain radiation hazard if there is a tritium leak
  - Avoid asphyxiation hazard due to purge gas



Attenuation due to Purge

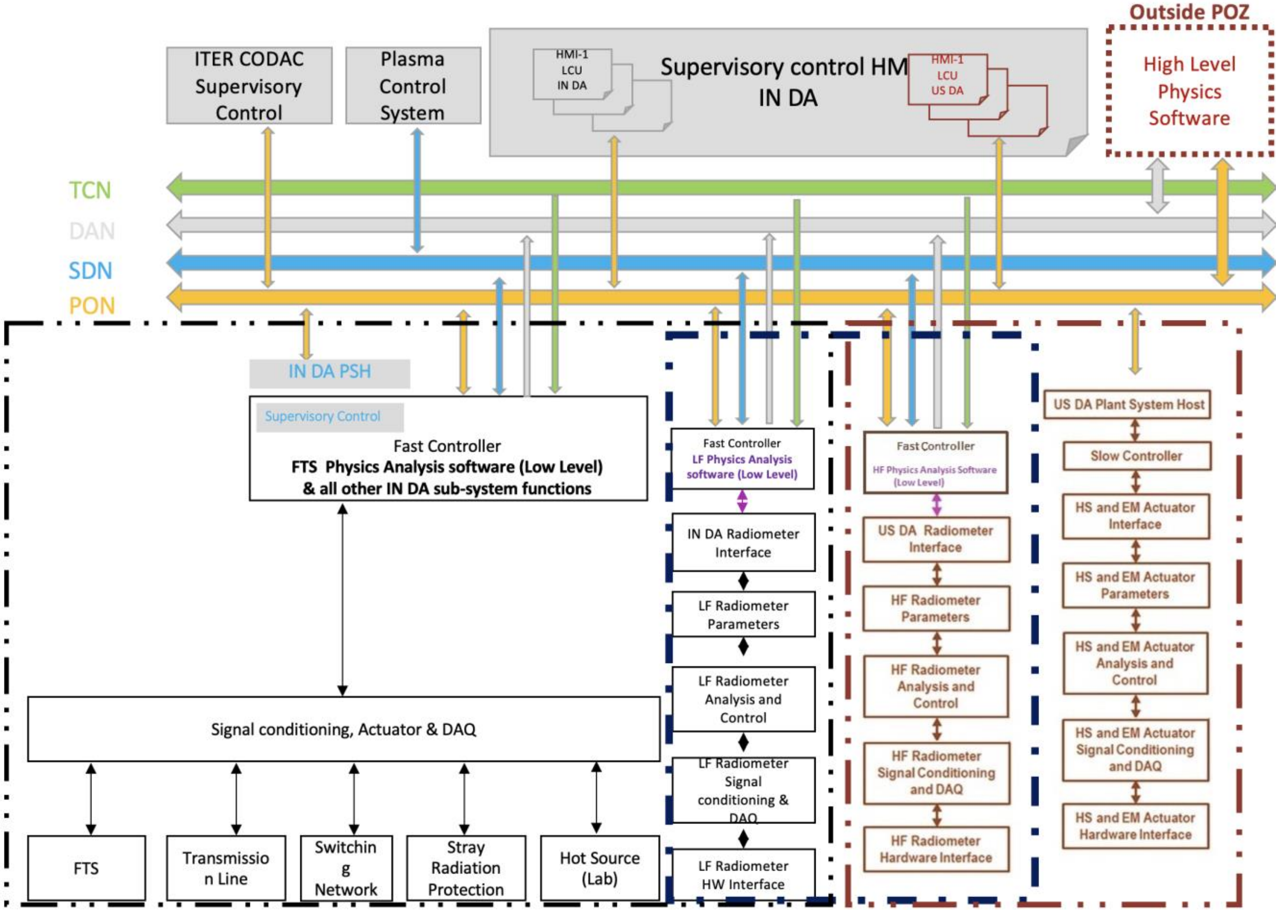


Typical Power Transmission

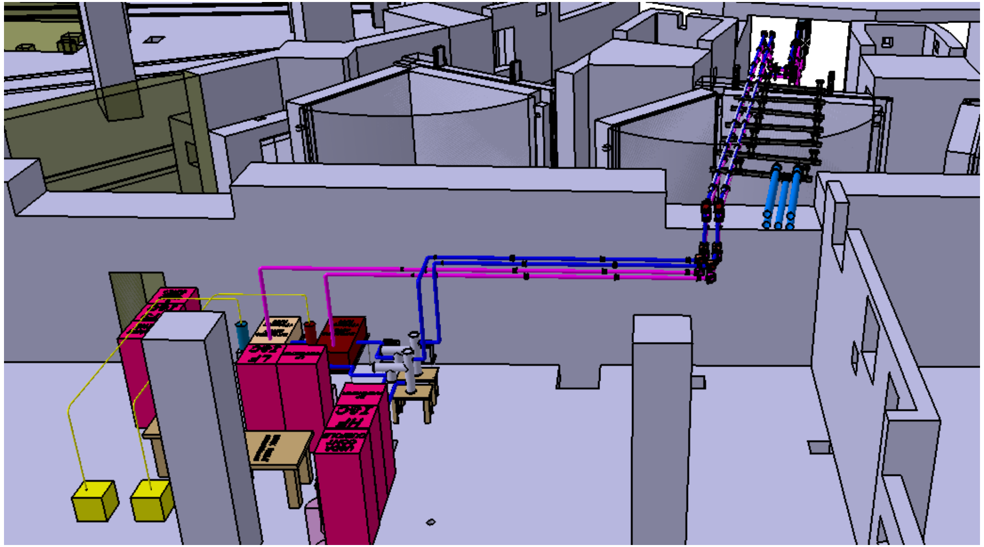
I&C Hardware Architecture

IN-DA
Created I&C hardware architecture.
Responsible for local control cubicle.

US-DA
Designs radiometer cubicles
Hot source control cubicles.



Diagnostics Hall Layout

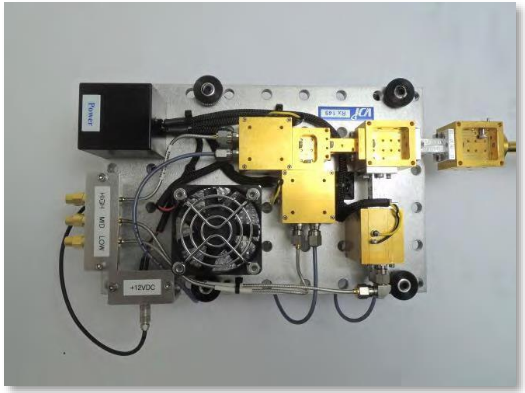


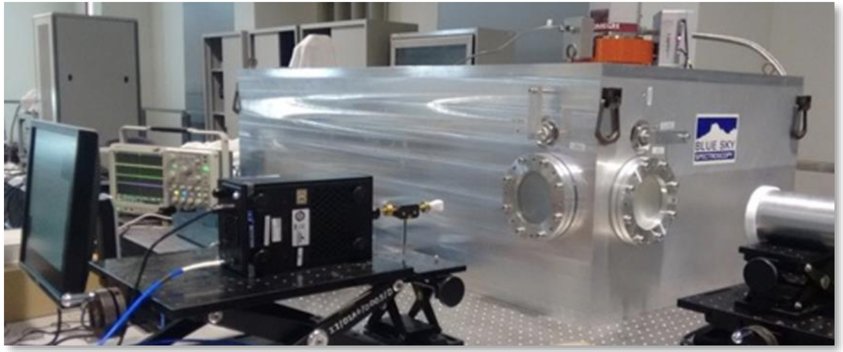
- Detect the EC emission.
- Select view and polarization for the experiment, then feed to instrument.
- Digitize the emission.
- Send profile and NTM information to PCS.
- Send complete data to data archive.
- IN-DA design of stray radiation (from ECH) sensor for ITER ECE Diagnostic was completed (next talk).

Instruments	Quantity
Low Freq Radiometer	1
High Freq Radiometer	1
FTS	2
Power Splitter	2
Hot Source	2
Working Table	2
Cryo-Compressor FTS	2
Cubicles	10

Diagnostics Hall Layout: Instruments

- The detection instruments are modest evolutions from exisiting instruments
- Two Radiometers.
  - High Frequency, 220 – 340 GHz
    Fielded on C-Mod and built prototype with improved reliability which is under test at DIII-D
  - Low Frequency 122 – 230 GHz
    Conventional frequency range
- Two FTS
  - Wide bandwidth 70-1000GHz





Summary

Components have been the focus

- Front end optics.
  - Design is complete.
  - It's a flexible design: Easily modified during port integration
- Radiometers
  - Similar to radiometer UT fielded for C-Mod, a 5.4 T tokamak
  - Prototype constructed to improve reliability: Under test
- Polarization Splitter Unit and transmission line: Prototyped
- Hot source (In-situ operation required a novel design)
  - Risk reduced by exhaustive testing (in progress) & painstaking design (continuing)

Now must put it all together and make it work

- Port integration: In progress
- Control Cubicles: Design underway, informed by prototyping
- Actuators for in-vessel components: Starting soon
- Fixturing for in-vessel optics: In progress