# Experimental Studies of Transmission Line Losses and Calibration Source Performance for ITER ECE Diagnostics

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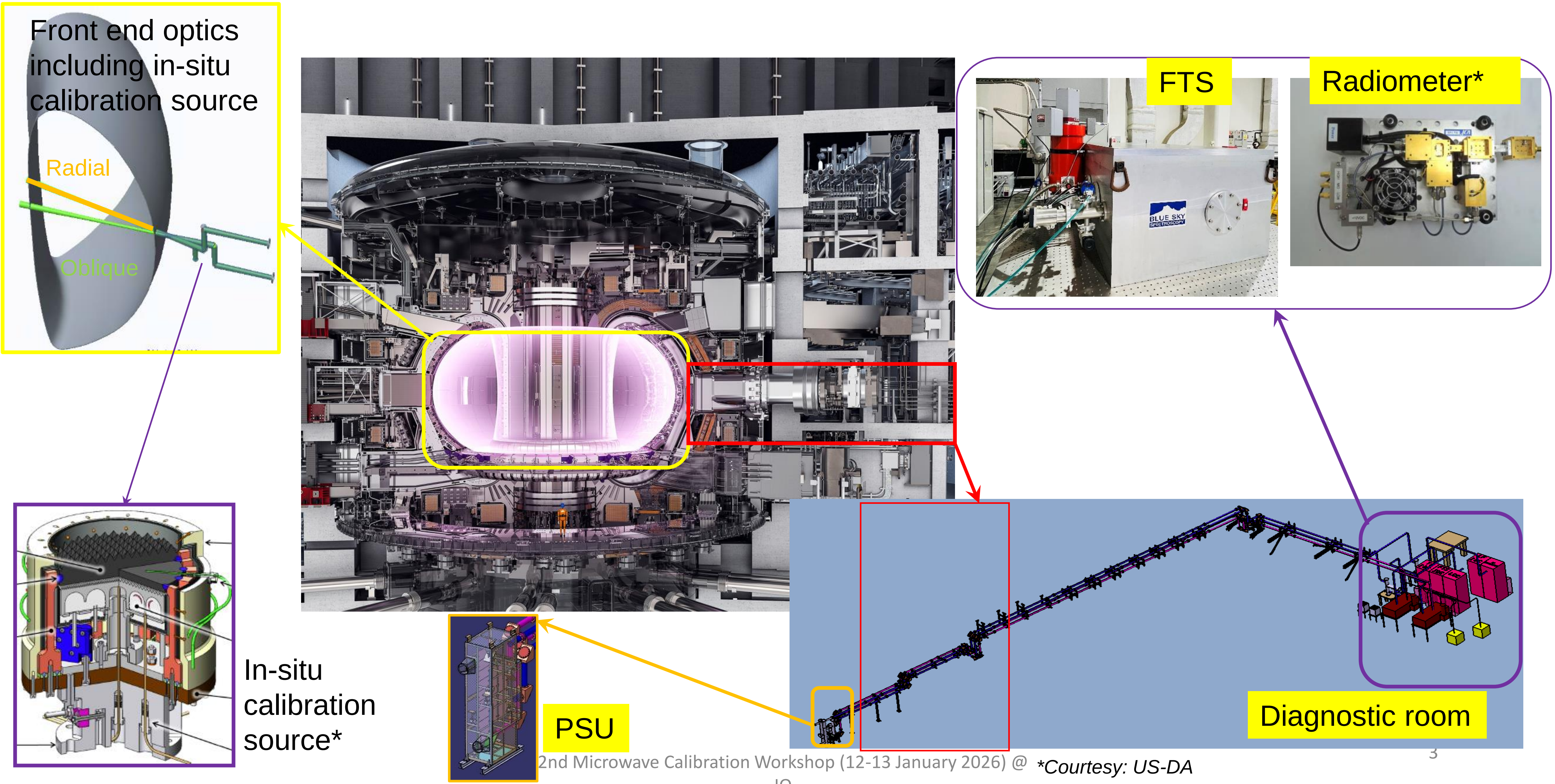
# Outlines

- ITER ECE Diagnostic: Measurement objectives and requirements
- Fast Scanning Fourier Transform Spectrometer (FTS) Diagnostic System
- Calibration Sources
- Transmission Line
- Measurements and Results
- Summary

# ITER ECE at a Glance




*Courtesy: US-DA

# ITER ECE Diagnostic: Overview and Measurement requirements

**Purpose**

- •Measures core electron temperature profiles
- •Detects high-frequency instabilities (e.g. NTMs)

**Location**

- •Installed at Equatorial Port EP9
- •EP9 port integrator: US ITER

**Frequency Coverage**

•Total range: 70–1000 GHz

- Low-frequency radiometer: 122–230 GHz
- High-frequency radiometer: 220–340 GHz
- Fourier Transform Spectrometers (×2): 70–1000 GHz

**Calibration**

- •In-situ hot calibration sources

**Two Lines of Sight**

- •Radial: 0° and Oblique: 9.25°

**Radiometer**

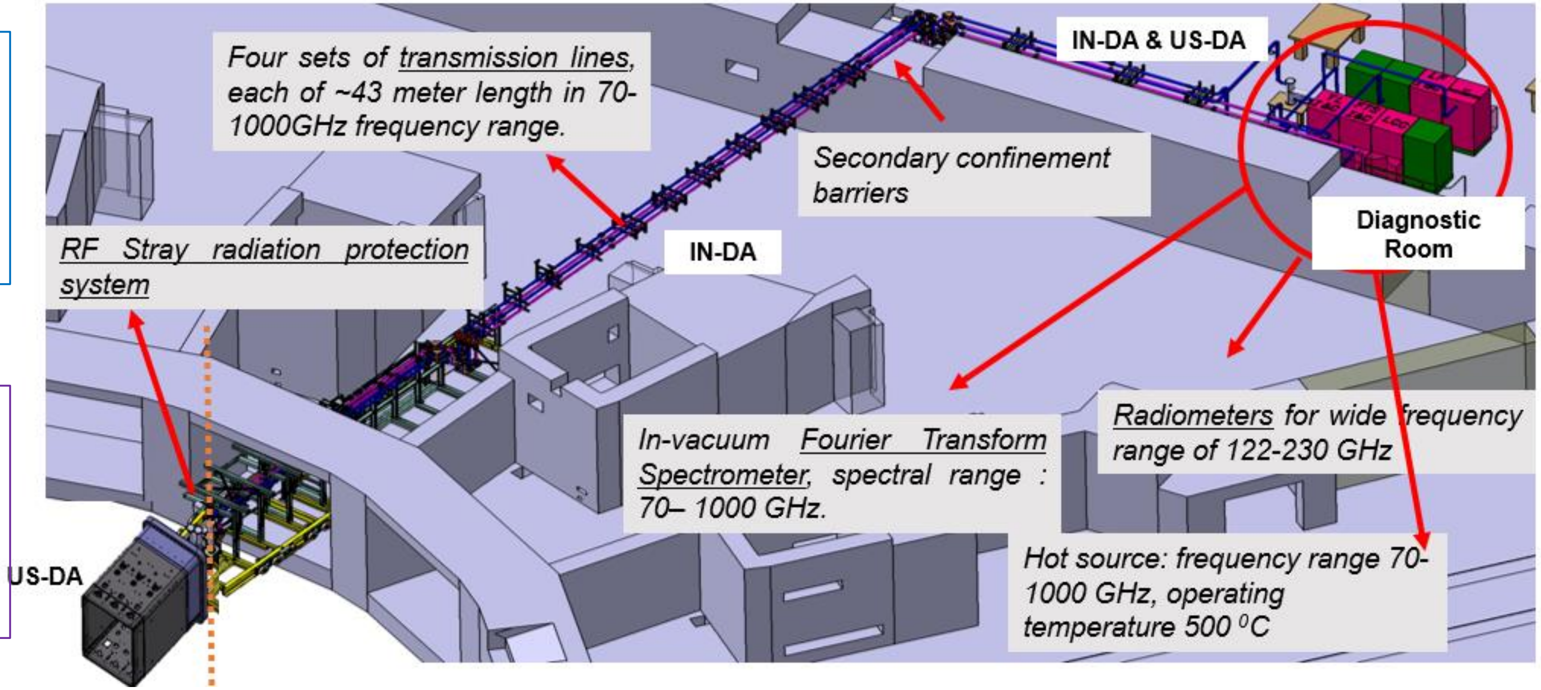
- $T_e$ Profile: **0.5–15 keV** at **20–50 mm**, **15–40 keV** at **50–130 mm** spatial resolution, **10 ms** temporal resolution (**1 μs**: fast physics studies)
- NTM Monitoring: Real-time (0.1–10 ms), ≥ 20 mm spatial resolution
- ECH Targeting: Precision deposition for suppression

**Fourier Transform Spectrometer (FTS)**

•Broadband ECE: Measure power loss up to 1 THz and beyond

•Non-Thermal Plasma: Identify deviations from Maxwellian

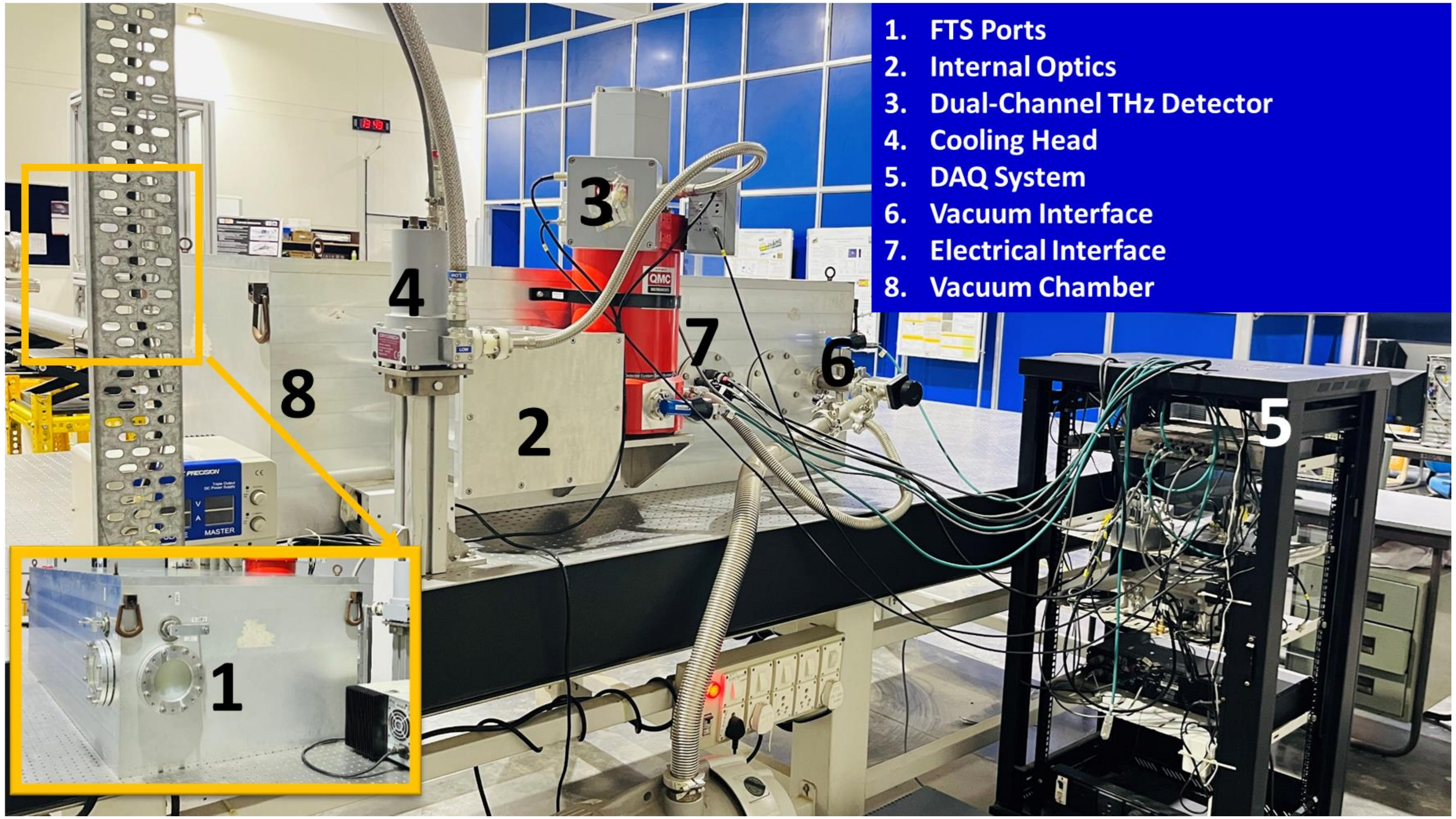
•Runaway Electrons: Detect via high-frequency ECE




**Collection optics → Transmission line → Spectrometer → Detectors → DAQ**

# ITER Prototype FTS

•Type: Dual-channel polarizing Fourier Transform Spectrometer (FTS)
•Spectral Range: 70 – 1800 GHz
•Frequency Resolution: ~10 GHz, Linear Scan Length: 15 mm
•Scanning rate: 20 ms, Temporal Resolution: 10 ms

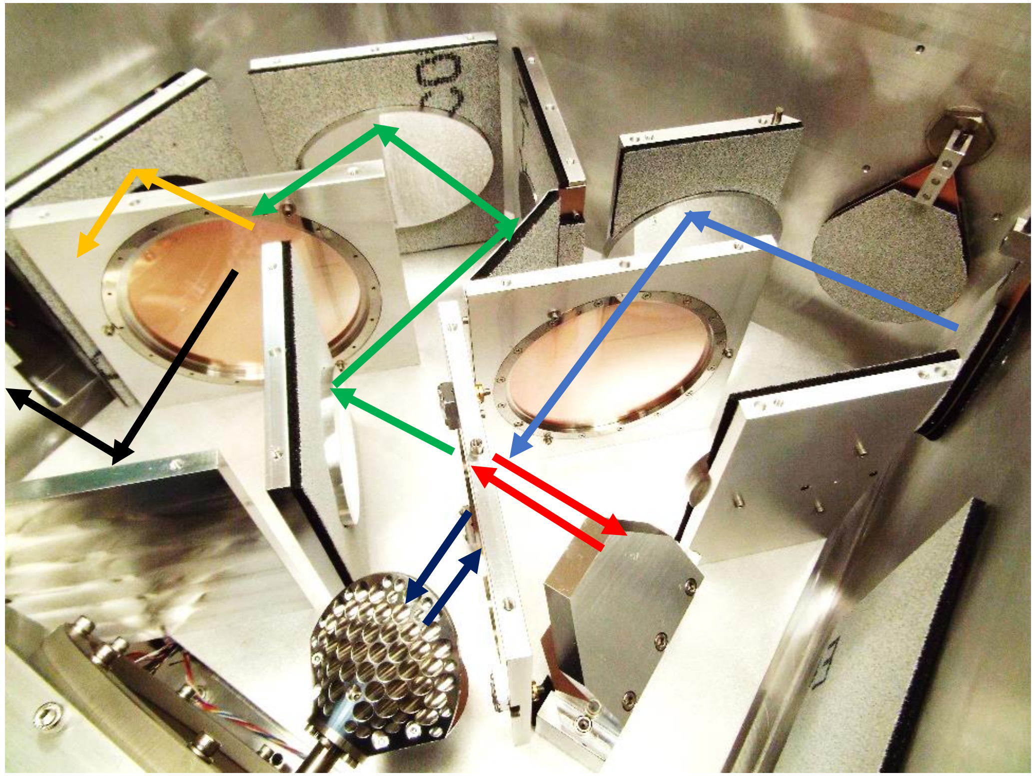



**Novel Features of FTS:**
•Vacuum-compatible scanning system eliminates water vapor absorption lines
•Gaussian beam telescope optics enhance transmission efficiency

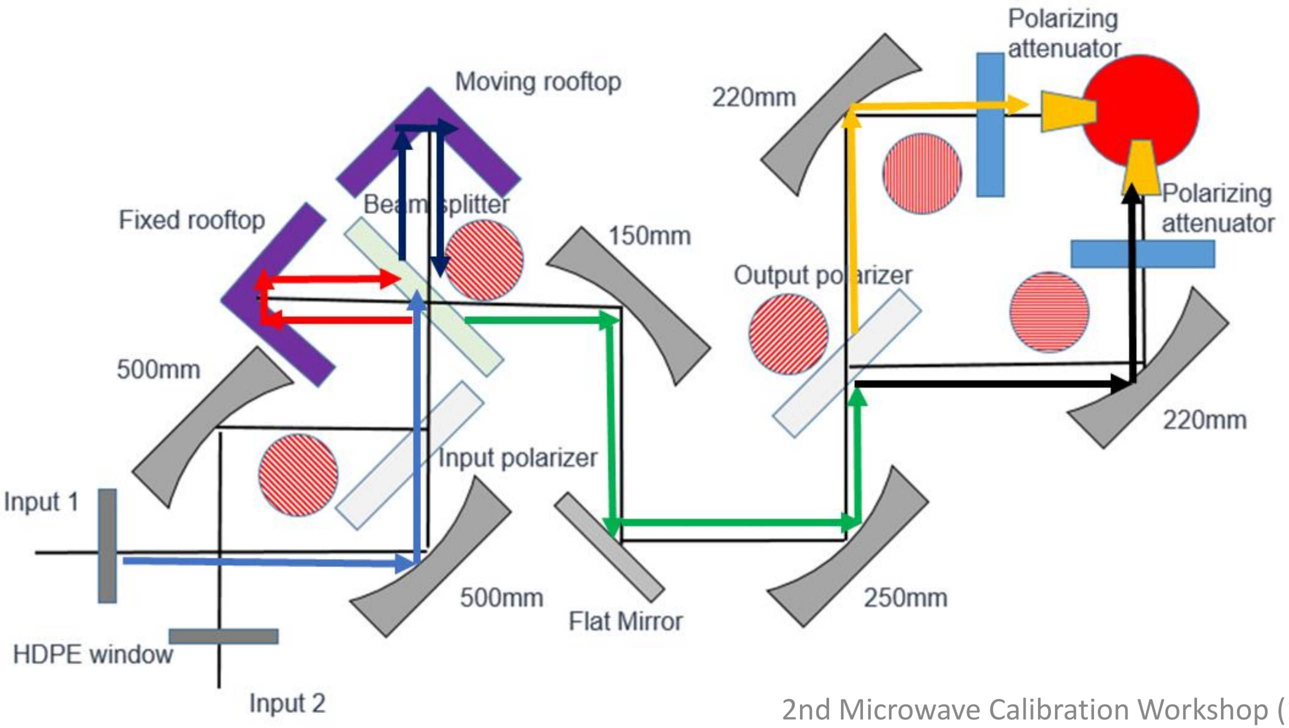
# FTS optical layout

**Performance of MP FTS:**

- Operates in a vacuum (~$10^{-3}$ Torr).
- Optical throughput: >4 × $10^{-5}$ $m^2$·sr.
- Total transmittance: ≥70%.
- System Stability**:** Maintained within ~1%



**Gaussian beam telescopes arrangement**




- Lightweight, dynamically balanced diamond-turned moving mirror.
- Compact laser-based interferometer for precision metrology. Provides 1.55 µm precision in interferogram sampling.
- Gaussian beam telescopes are used to increase the transmission efficiency of the FTS system.

# THz Broadband Detector and Pre-amplifier

**Detector: QFI/XBI – Cooled Hot Electron Bolometer**
•Spectral Range: 60 GHz – 1500 GHz
•Operating Temperature: 4.2 K
•Optical NEP: < 1.5 pW·Hz$^{-1/2}$
•Frequency Response: 500 kHz (3 dB)

**Pre-Amplifier: ULN95**
•Input Impedance: > 10 GΩ
•Bandwidth: 0.5 Hz – 1 MHz
•Voltage Gain: ×100 / ×1000 (40 or 60 dB switchable)
•Bias Supply: 0–10 V (multi-turn control)
•Output Noise:
- ~3 nV·Hz$^{-1/2}$ @ 10 Hz
- ~1 nV·Hz$^{-1/2}$ > 1 kHz

***A dual-channel detector is chosen to increase the signal-to-noise ratio (SNR)***

**Dual-channel detector configuration tailored for ITER prototype FTS**

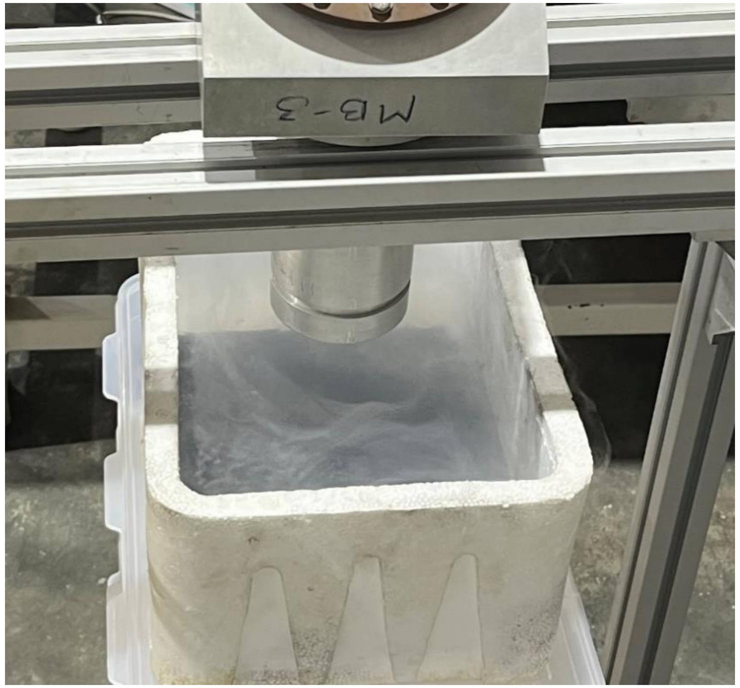
# Calibration Sources

TK RAM Blackbody Source for FTS Calibration

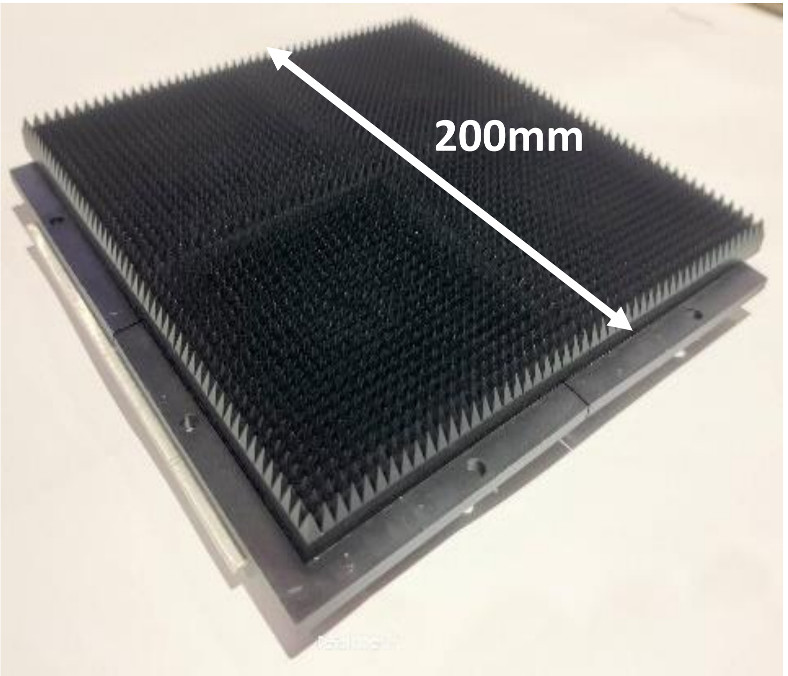
- High-emissivity (50–1000 GHz) broadband emitter
- Operates at ~300 K (air) and ~77 K (in $LN_2$)
- Large-area (200 × 200 mm) tile-based design
- Used for FTS calibration and sensitivity evaluation

Cold Source: Integration of TK RAM tiles with a thin aluminium plate

**LN2 Source**




**Ambient Source**



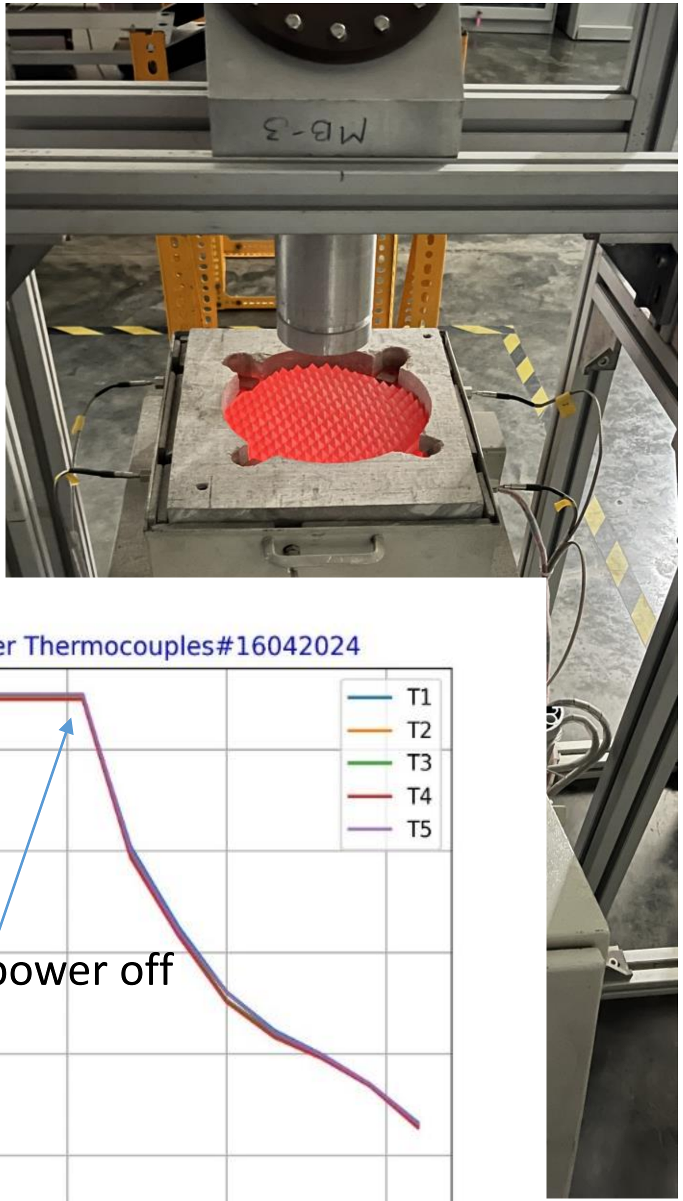

**QMC Instruments Ltd**

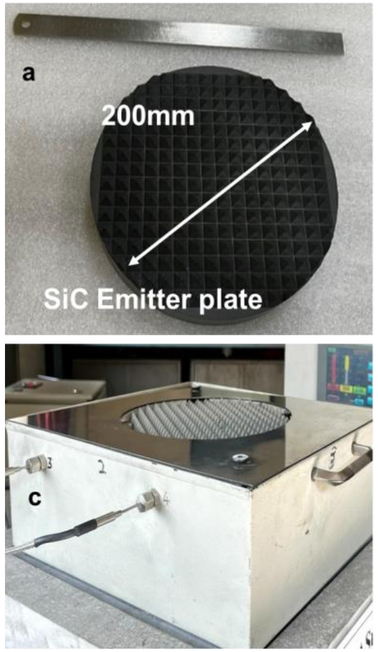
# Hot Source

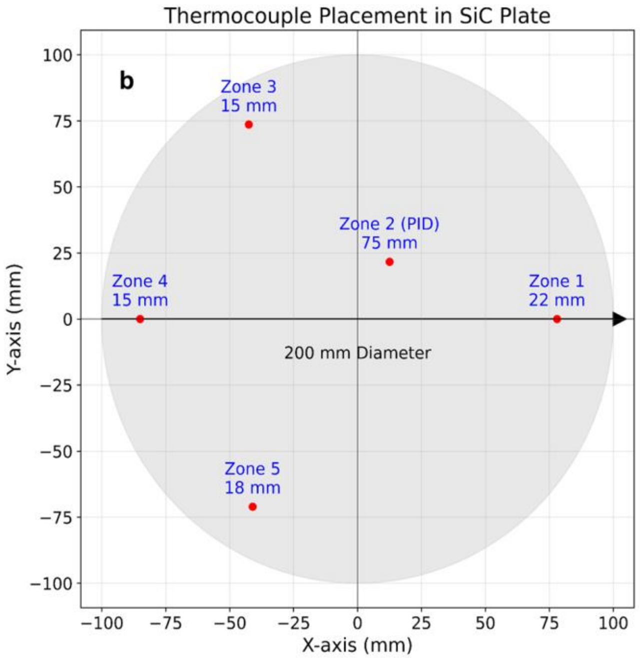
**Purpose:** *To test the back-end calibration of the FTS and evaluate the performance of the prototype ECE components.*

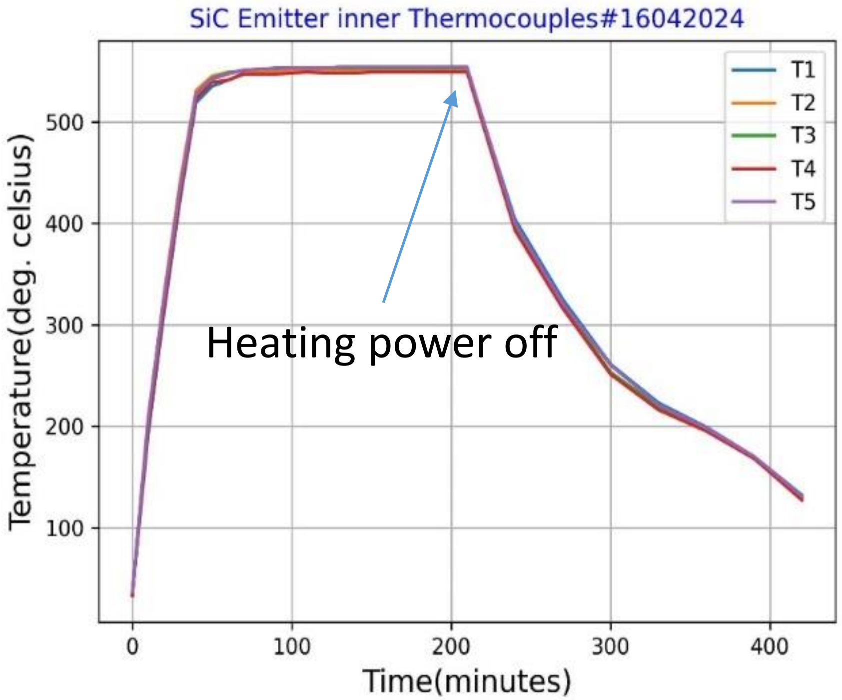
Preliminary Performance Highlights
•Emissive Surface Temperature: 500 °C
•Temperature Uniformity: ±10 °C across surface
•Thermal Equilibrium Time: < 1 hour
•Temperature Stability: ±2 °C over 24 hours

Manufactured by M/s Bhukhanvala Pvt. Ltd. (India)





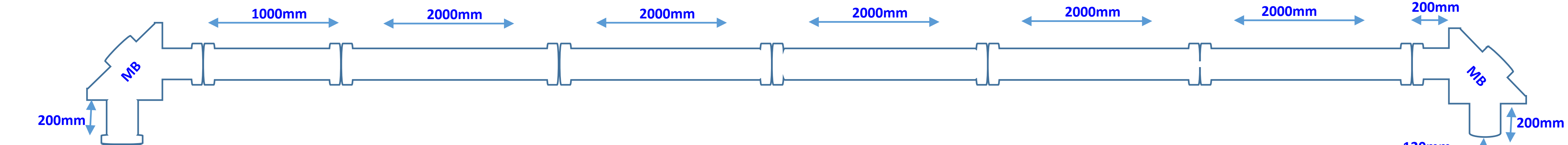



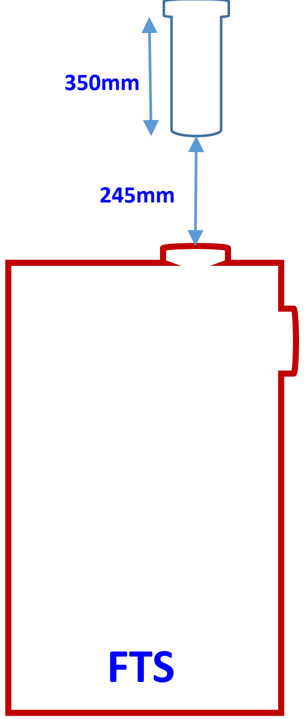



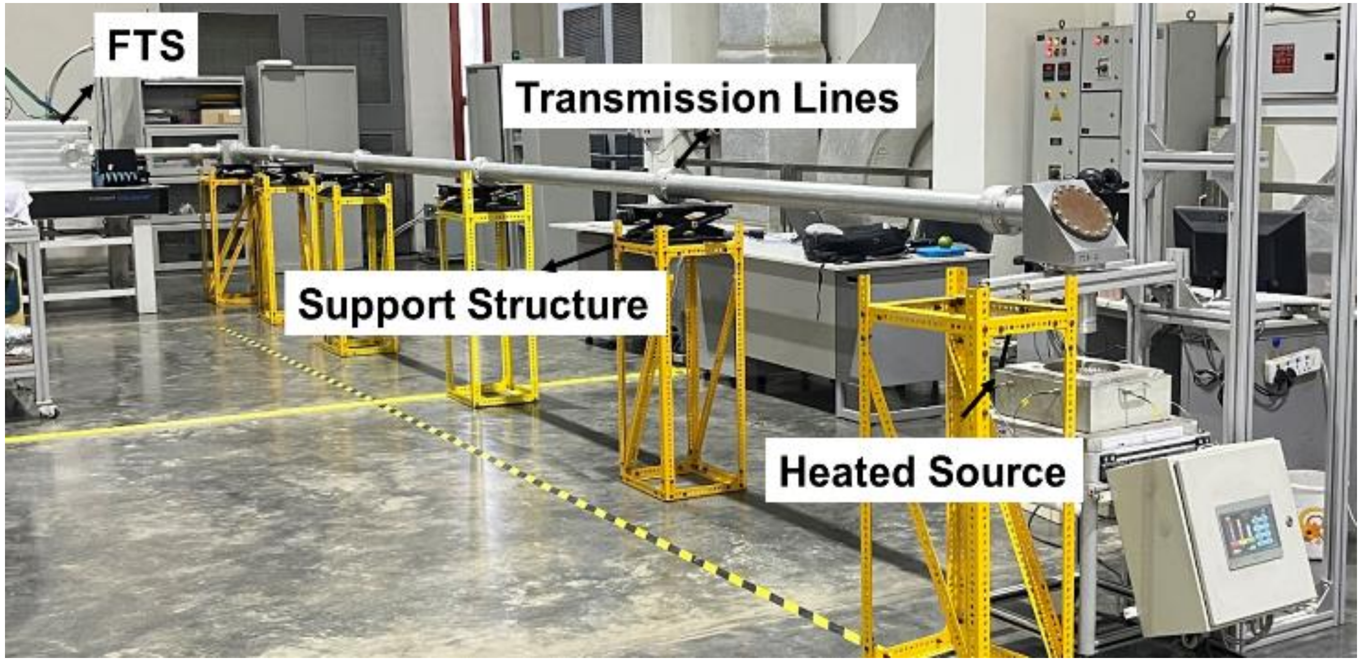

Five thermocouples placed beneath (~8mm) the emitter plate pyramid monitor temperature distribution for uniformity.

# Transmission Line

- Waveguide Material:**Al6061-T6**
- Type: Smooth-walled **circular** waveguide
- Dimensions: ID **72 mm** ,OD 88 mm
- Frequency Range: **70–1000 GHz**
- Integrated Features: Mitre bends, joints, and end flanges for assembly .



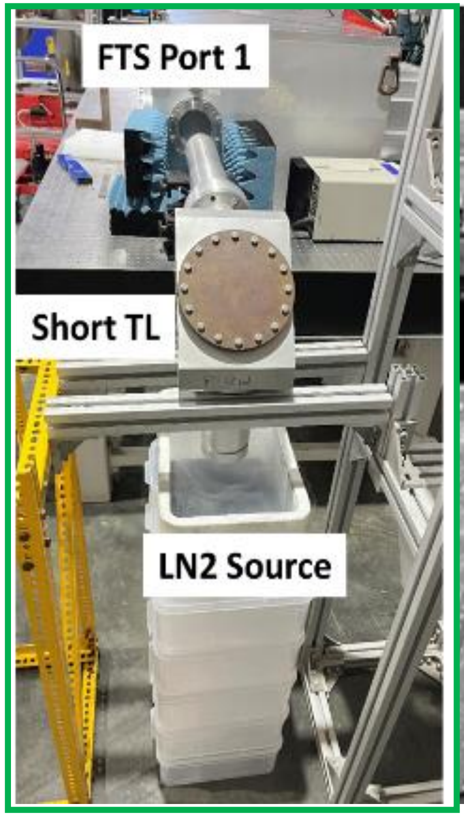



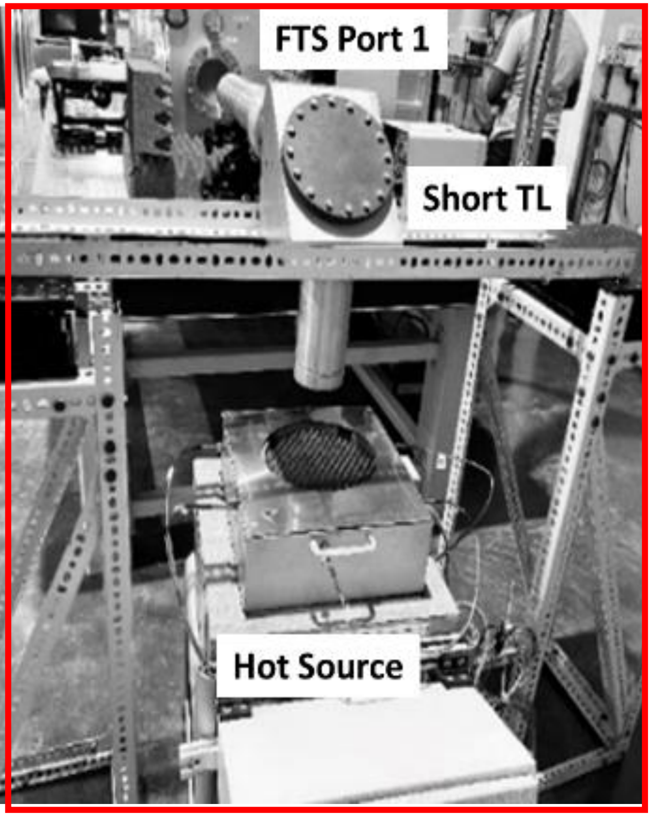



# Experiments

# Back-end Sensitivity

- Sensitivity Measurement (Hot–Cold Method with TK RAM Sources)
- Configuration: 0.5 m waveguide with 90° miter bend
- Aperture: Aligned with FTS focal point
- Source Position: Approximately 120 mm below aperture
- Data Capture: 5-minute interferograms at each temperature

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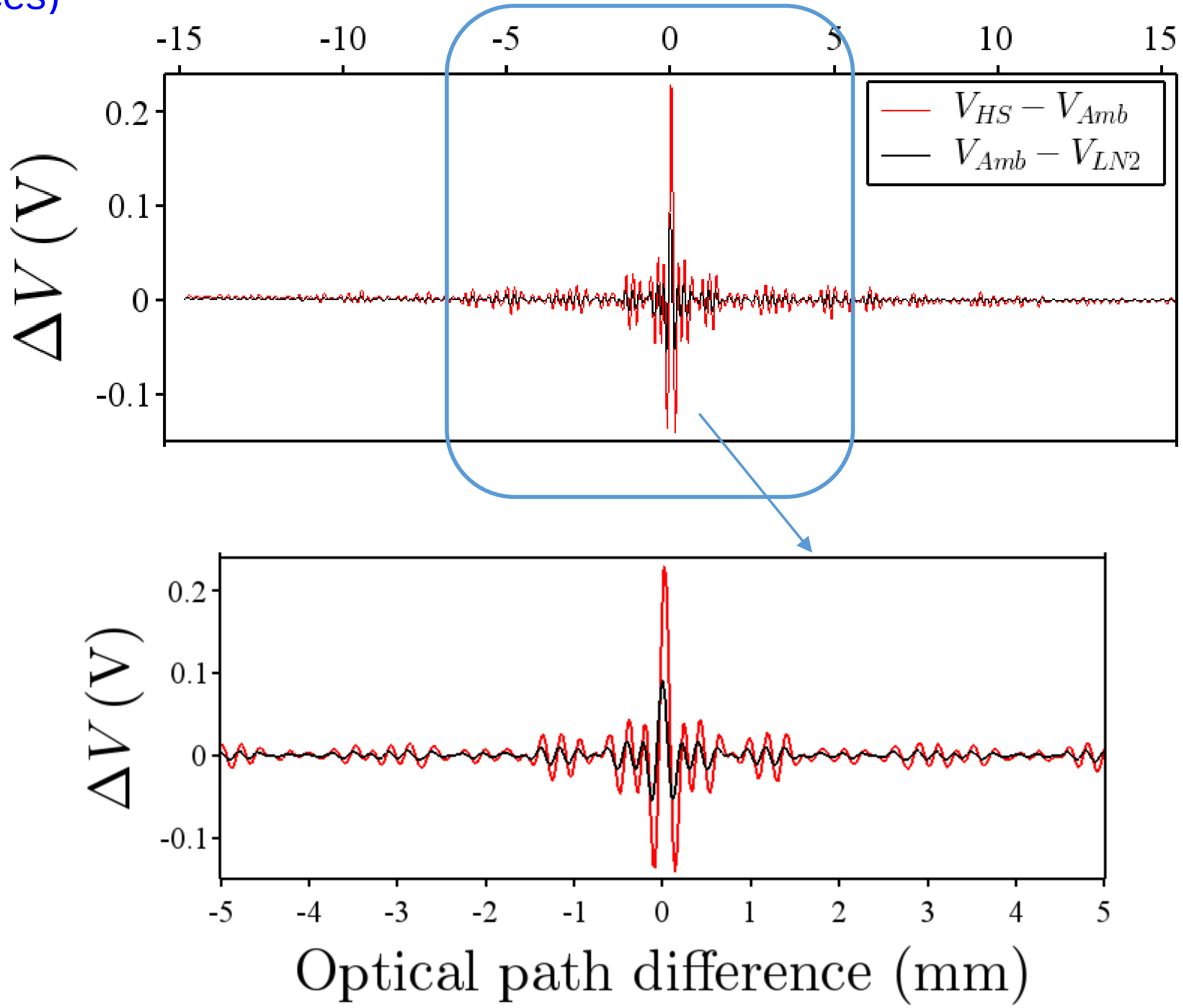
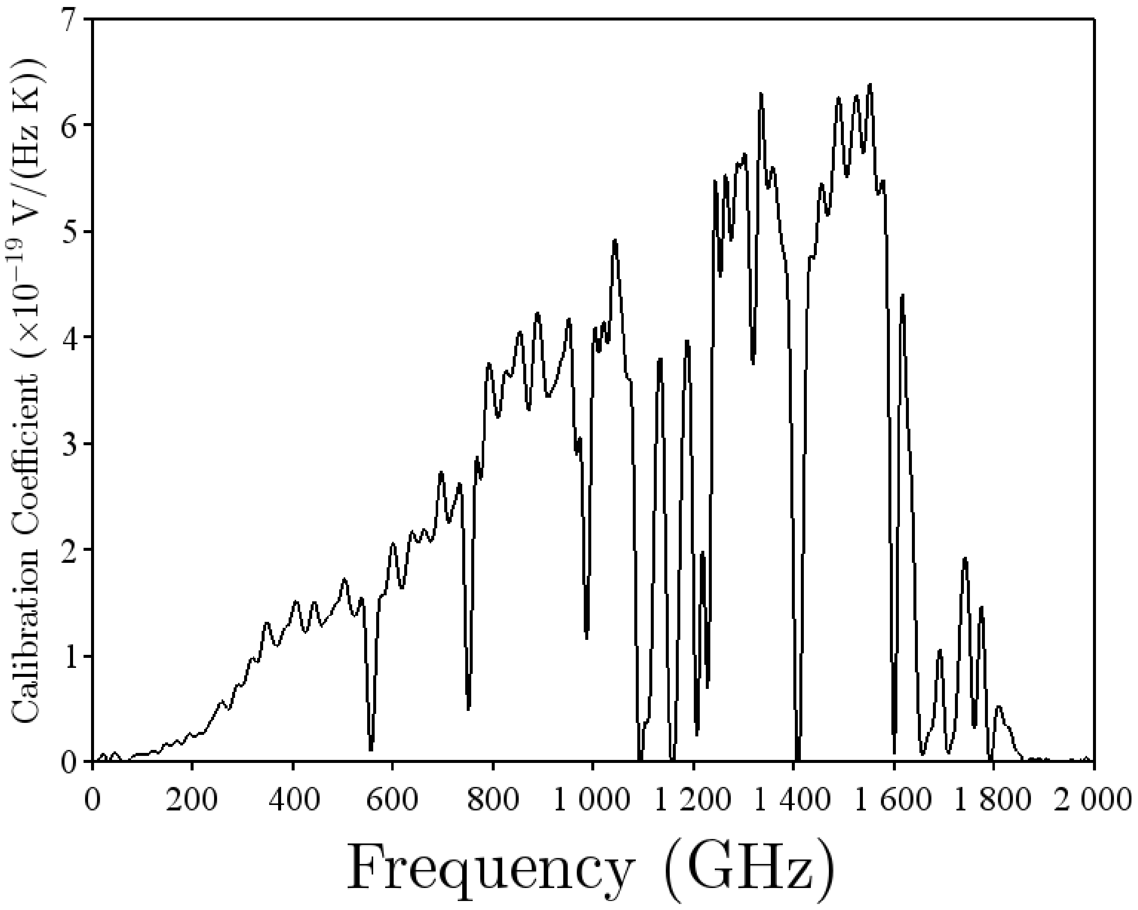


# Back-end Sensitivity

- •Back-end sensitivity extends up to 1.8 THz
- •Clear signatures of water vapor absorption lines
- •Reduced sensitivity below 150 GHz

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# Spectral Characterization of Heated Source

Measurements made with the prototype FTS system:

- Martin-Puplett type interferometer
- Frequency range: up to 1.8 THz
- Frequency resolution / Temporal resolution: ~10 GHz / 10 ms

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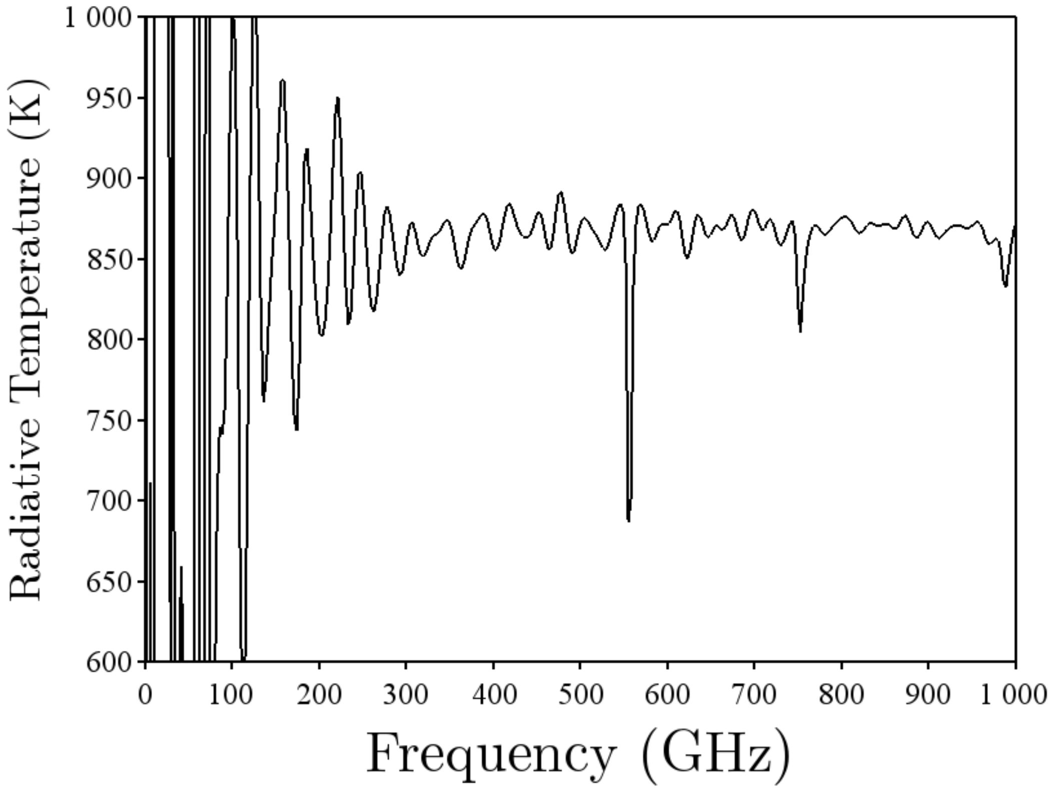
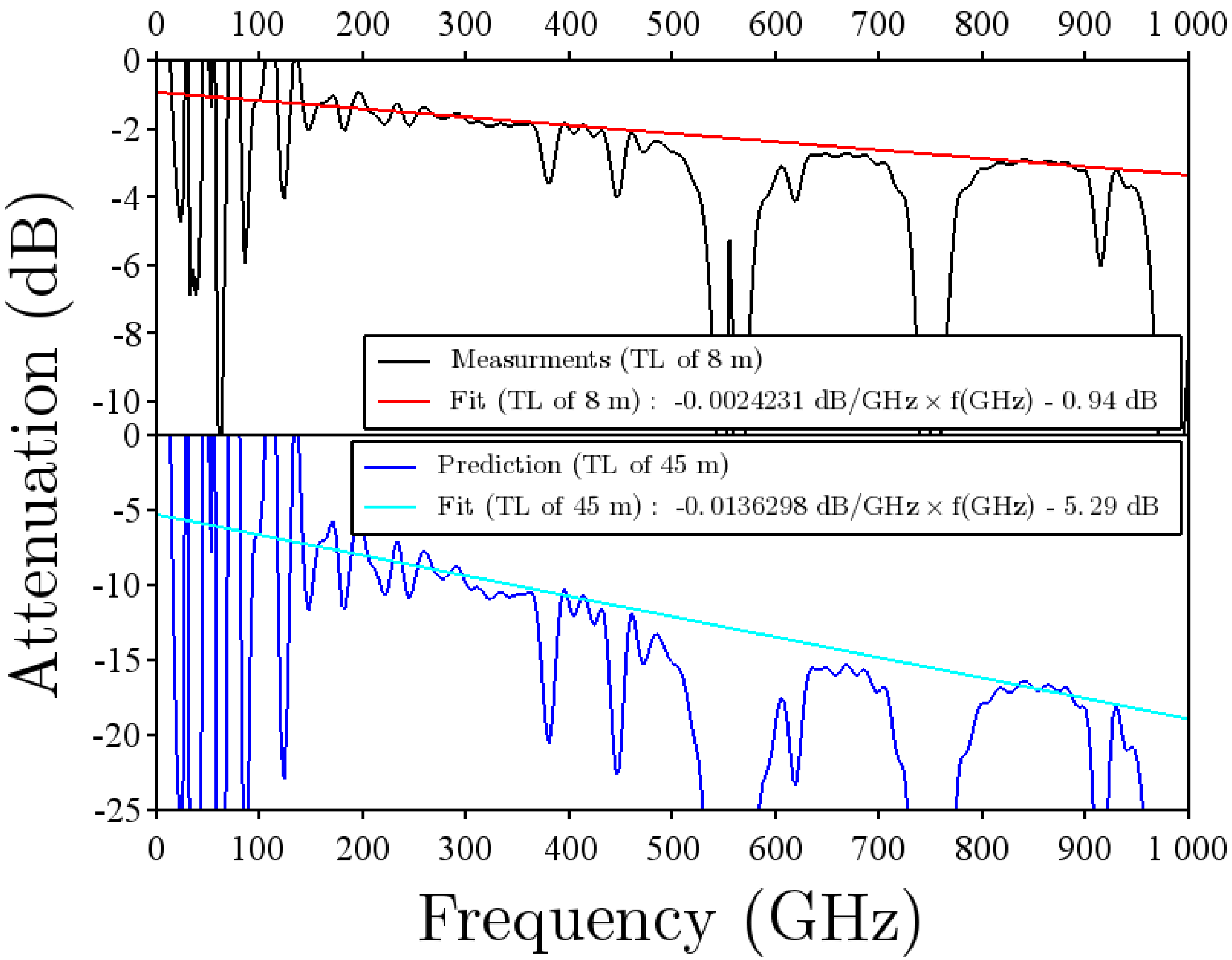
- ❑ Radiative temperature (~873 K) is 50–70 K lower than the physical temperature.
- ❑ Strong variations below 200 GHz likely due to low sensitivity.




The hot source emission spectrum is approximately flat across the 250–1000 GHz frequency range, with an emissivity of nearly 0.9 throughout this band.

# Transmission Line losses

- Reliable attenuation measured up to 1 THz.
- Oscillations below 150 GHz likely arise from low diagnostic sensitivity; further analysis is needed.
- Water vapor absorption lines are evident, indicating system sensitivity to atmospheric effects.




**Estimated loss for 45 m TL :**
Average transmission loss from 100 to 400 GHz: ~ -8.7 dB
Average transmission loss from 400 to 1000 GHz : ~-14.8 dB

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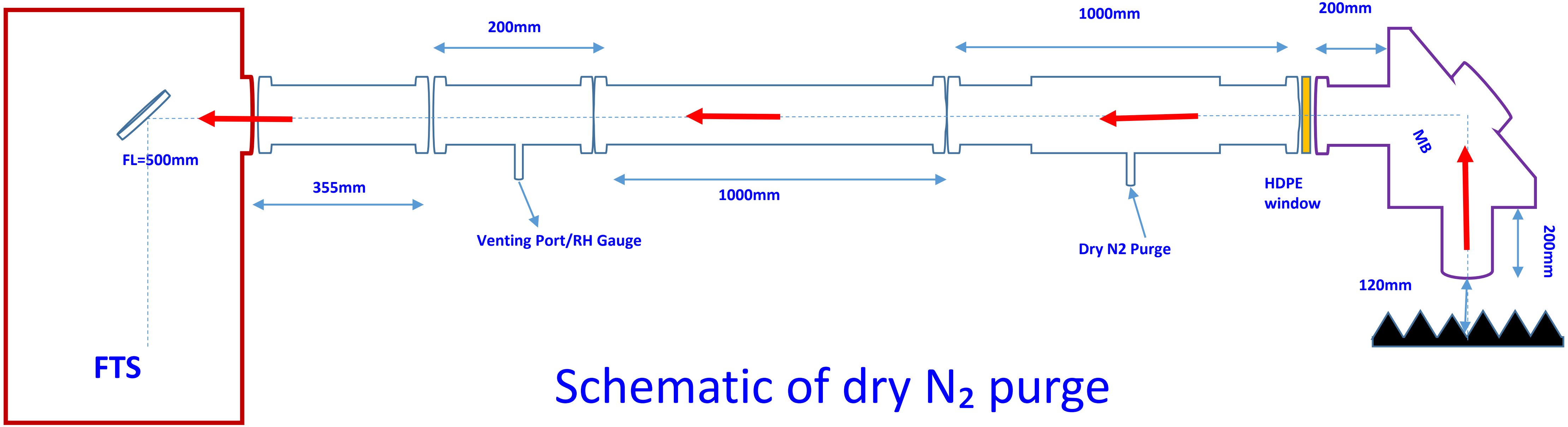
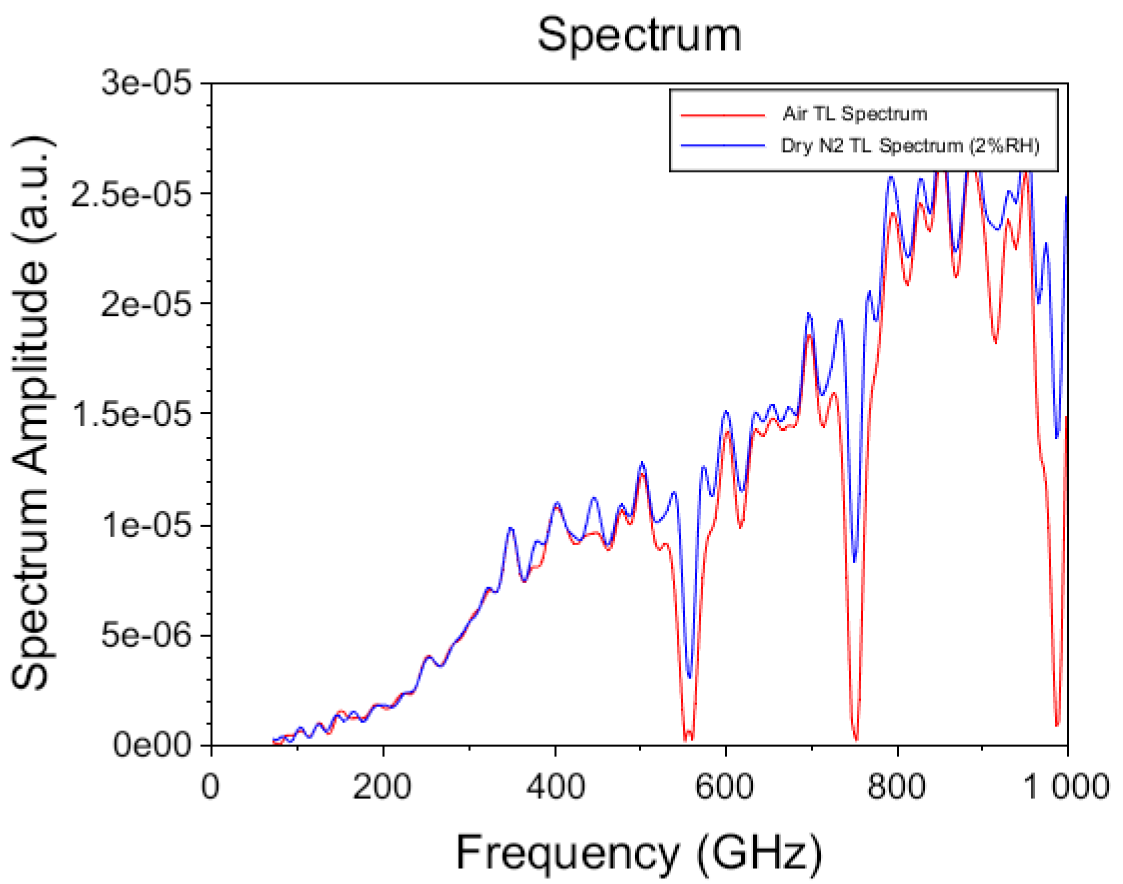
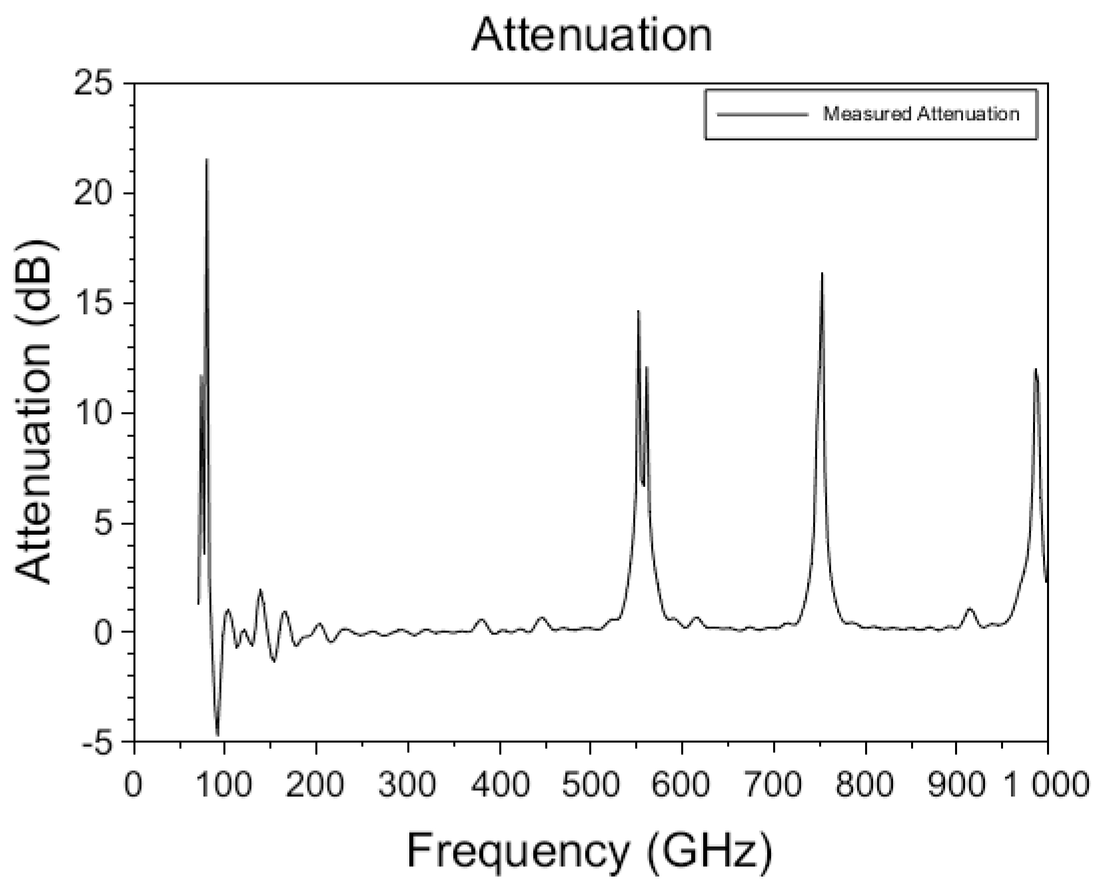
# Effect of dry $N_2$ purge on signal transmission




Schematic of dry $N_2$ purge

# Effect of dry $N_2$ purge on signal transmission



# Summary

- Calibration of the FTS was performed using TK RAM-based blackbody sources at room temperature and liquid nitrogen ($LN_2$).
- The radiation temperature of a high-temperature blackbody source was characterized using the calibrated FTS.
- A preliminary transmission study using ITER-like waveguides (~45 m) yielded:
  - ~-8.7 dB loss in the 100–400 GHz range
  - ~-14.8 dB loss in the 400–1000 GHz range

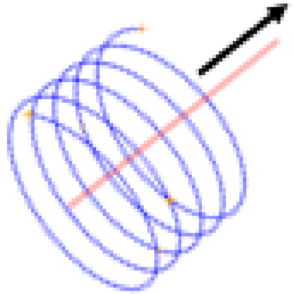
- The measurement process and analysis procedures have been established; future work can focus on quantifying the accuracy, precision, and long-term stability of FTS sensitivity.

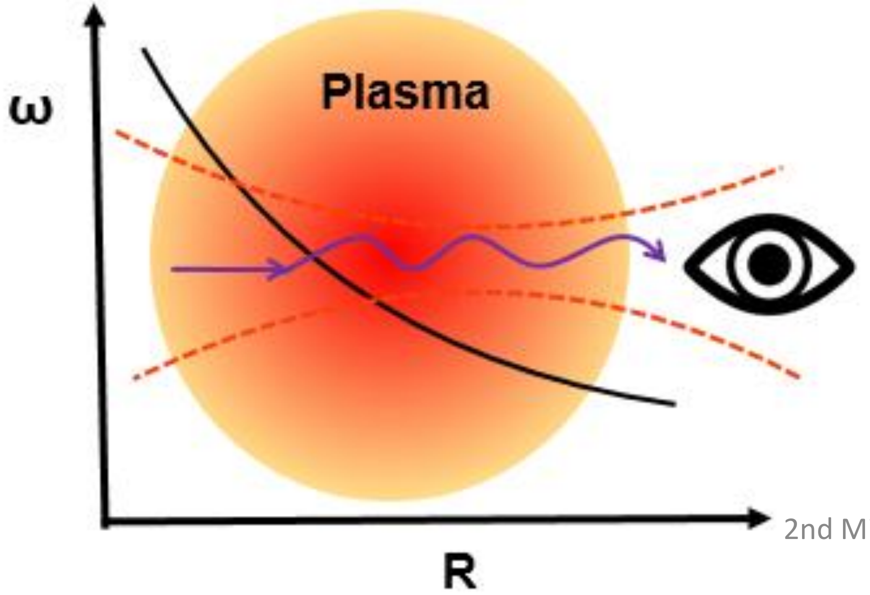
Thank you for your attention!

# Back up slides

# Introduction

- Electrons in a tokamak plasma emit radiation through "Electron Cyclotron Emission (ECE)" as they orbit the confining magnetic field lines.
- ECE **intensity** correlates with **electron temperature** under specific conditions.
- ECE occurs at the frequency of electron gyration and its low harmonics.
- Frequencies are determined by the local magnetic field, precisely known in tokamaks
- Emission frequency relates to a specific position in the plasma due to the known magnetic field.
- Measuring radiation intensity at different frequencies allows the determination of electron temperature at various plasma positions.





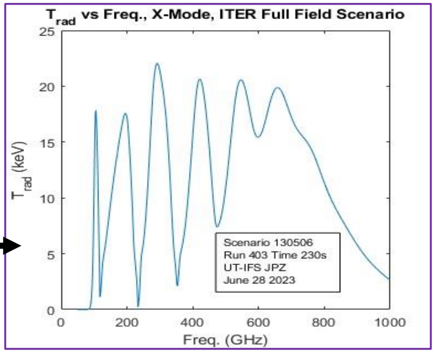

$\omega = neB/\gamma m$

$B \propto 1/R$

$I(\omega) = \frac{\hbar\omega^3}{8\pi^3c^2}\left[e^{\hbar\omega/T_e} - 1\right]^{-1}$

Rayleigh-Jeans limit ($\hbar \ll kT_e$)

$I(\omega) = \omega^2 kT_e/8\pi^3c^2$



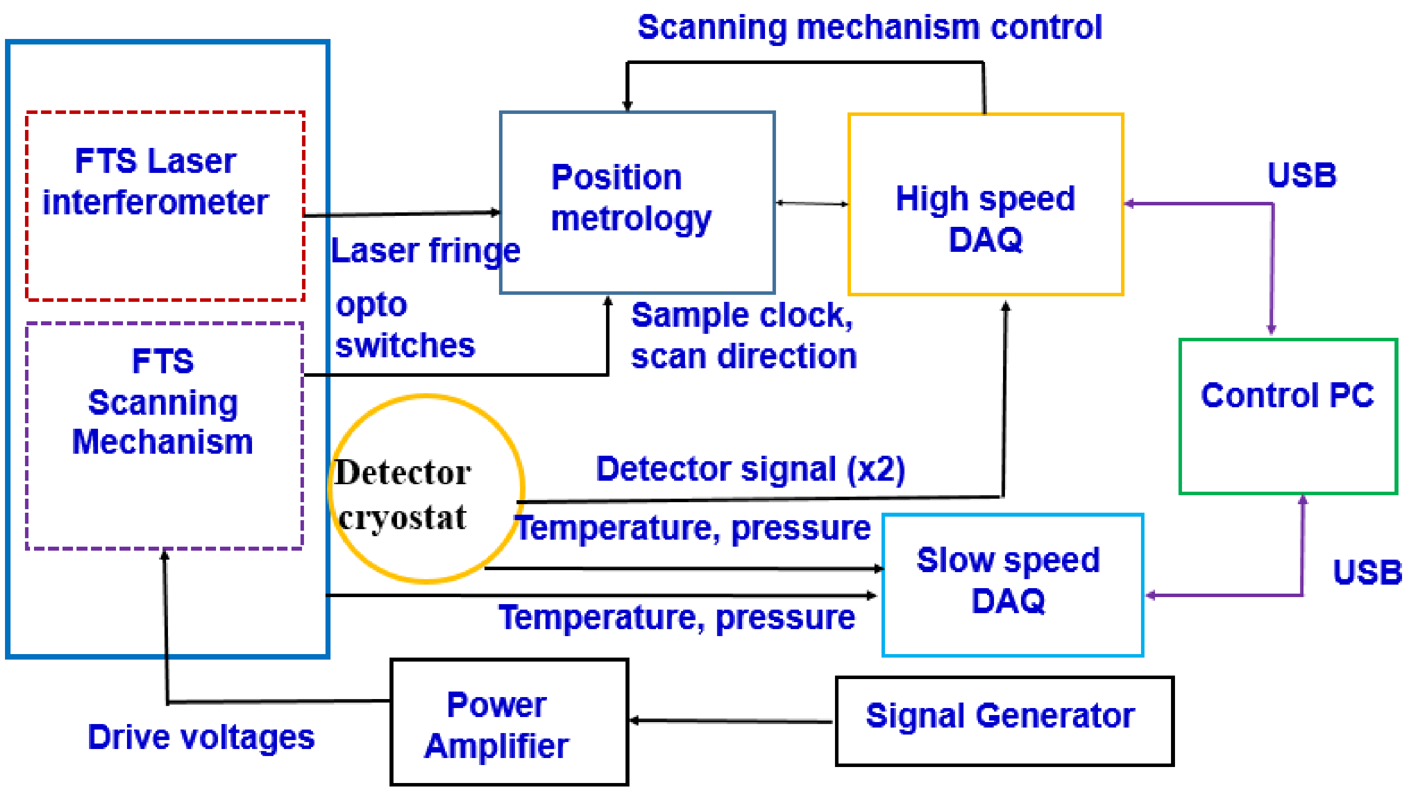

→ $T_e$ Profile

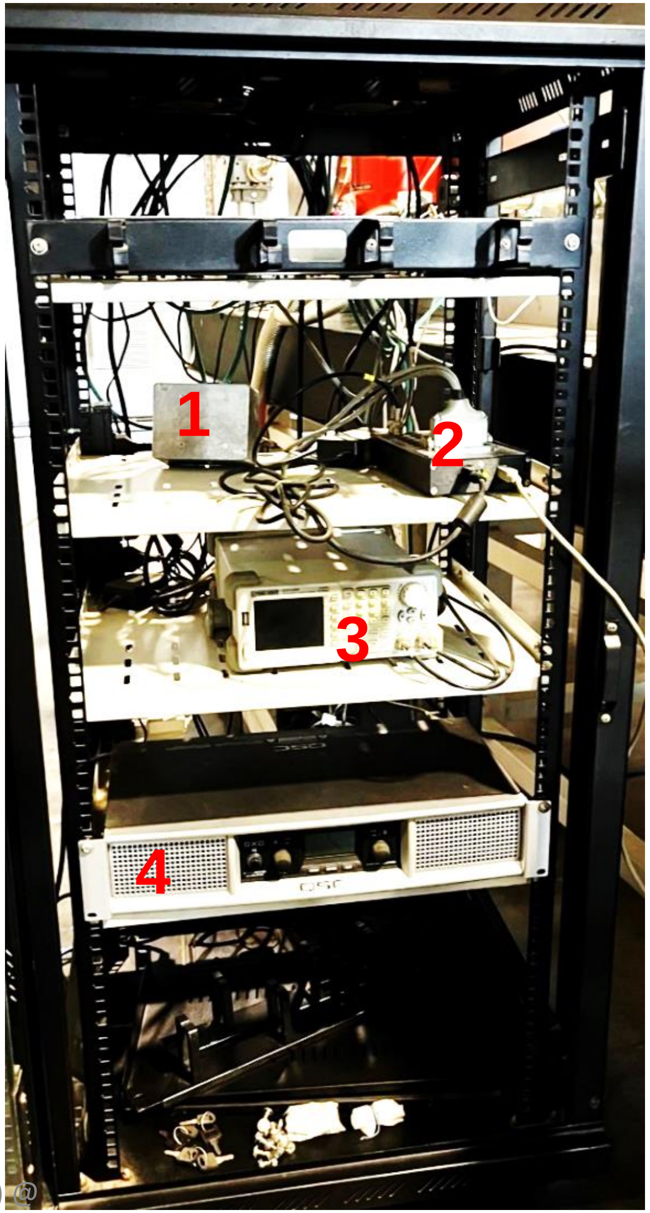


Courtesy: The ECESIM code (developed by M. Austin) was used to generate ECE radiation spectra.

# Data Acquisition system

- Capture and digitize interferogram signals from THz detectors
- Synchronize data with mirror position in fast-scanning FTS
- post-processed spectrum reconstruction




1. Position metrology
2. DAQ
3. Signal Generator
4. Power Amplifier