Phase-sensitive mid infrared frequency comb interferometry for plasma electron density measurements

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Fraunhofer UK

UK Atomic Energy Authority

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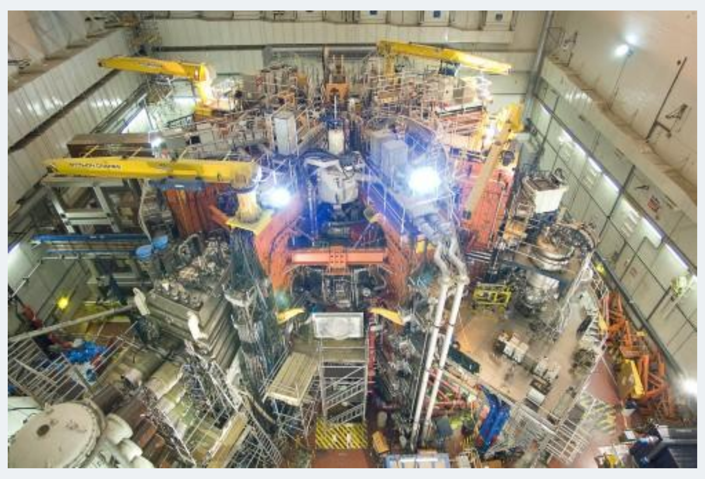
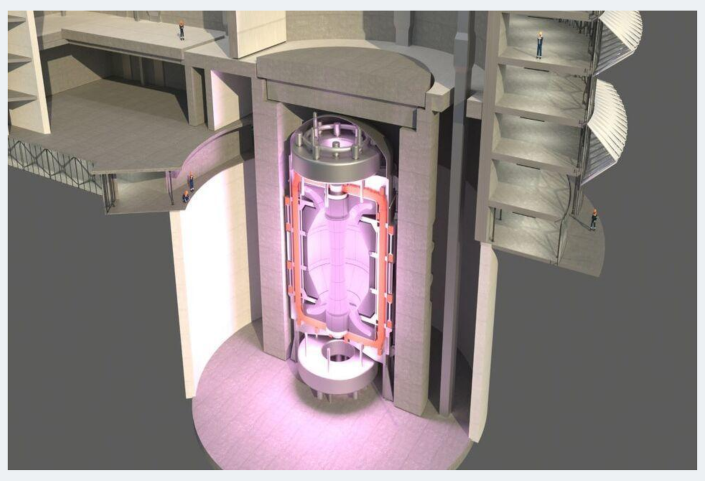
Motivation

- Robust Plasma density monitoring system
- Reduce fringe jumping errors
- Eliminate need for temporal history
- Funded though UKAEA as part of FIP



JET – European research reactor active 1983 - 2023

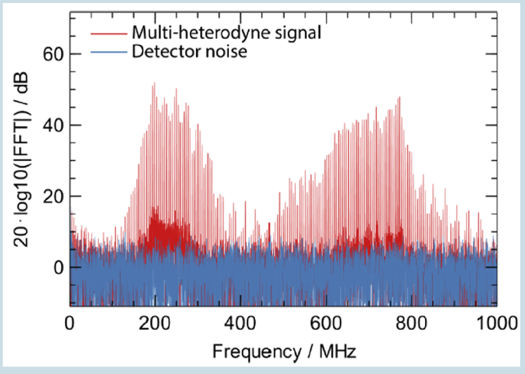
ITER – International research fusion reactor, first ignition 2033

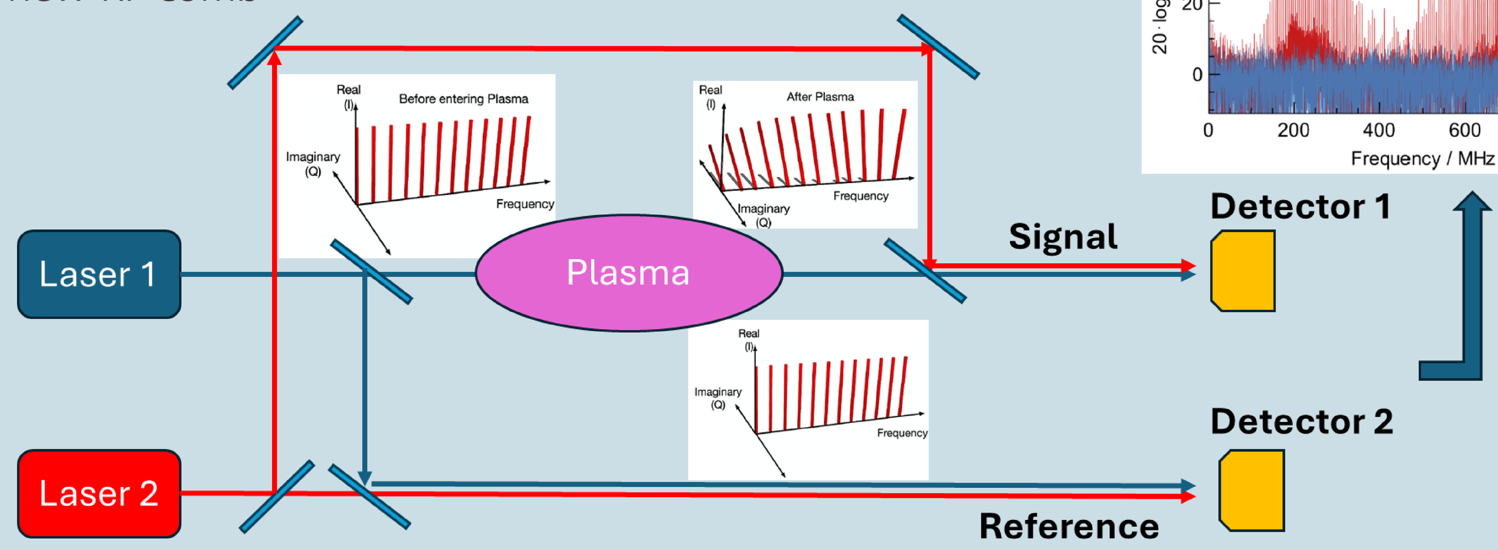


STEP – Uk based fusion power plant opening 2040

Phase sensitive dual comb spectroscopy

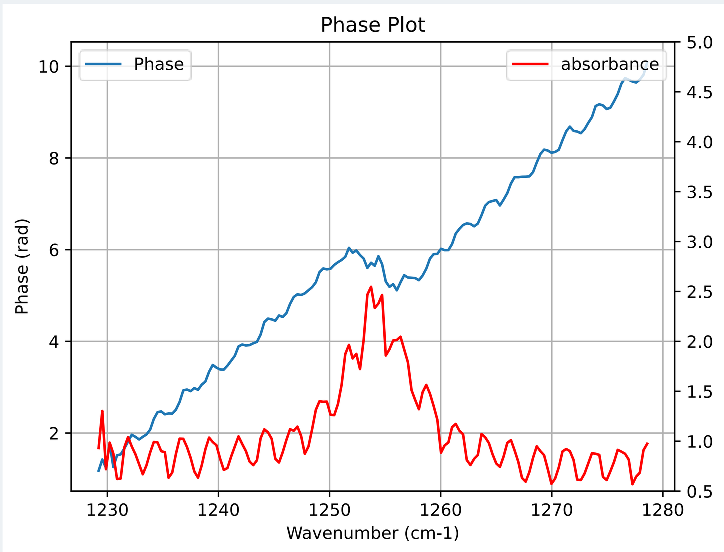
- Consist of equally spaced narrow intense laser lines
- Resolution based on comb tooth density
- Full spectrum acquired simultaneously
- Returns both amplitude and phase information encoded in new RF comb





Phase measurements

- Verification of phase measurements
- Sample with known optical constants (Polypropylene)
- Has absorption feature in wavelength range (8μm)
- Both negative and positive phase gradient



Limits of Detection

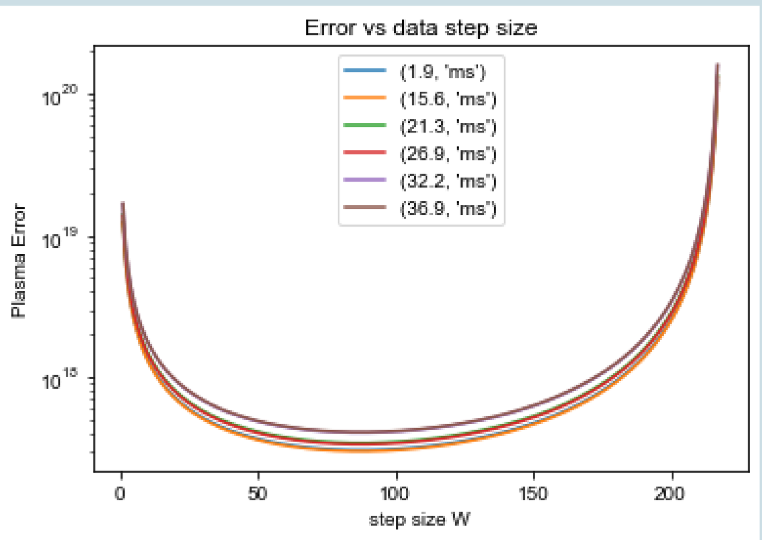
Fringe jump cut off density:
- Density where fringe jump occurs between comb teeth
- For 0.5 cm^{-1} tooth spacing – **1.3x10^{27} m^{-2}**

Plasma cut off density:
- Density where plasma fully reflects incoming light
- For comb centred on 8 µm – **4.4x10^{23} m^{-2}**

Lower limit
- Determined by phase noise and phase drift
- measured experimentally – **10^{17} m^{-2}**
- Stable over 30mins

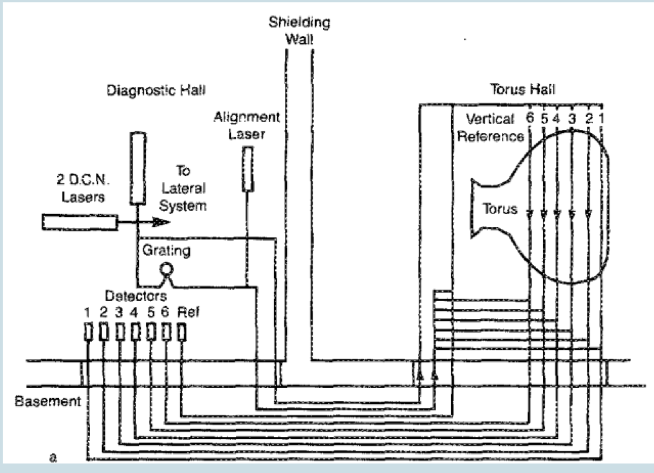
$$\sigma_{plasma} = \frac{\sqrt{2\sigma_{phase}}}{C_1 F_3}\sqrt{(N-W)^2 F_1 + (N-W) F_2}\ [3]$$

Where:
N, W, F_1, F_2, F_3, C_1 are constants
σ_{phase} is Std of phase

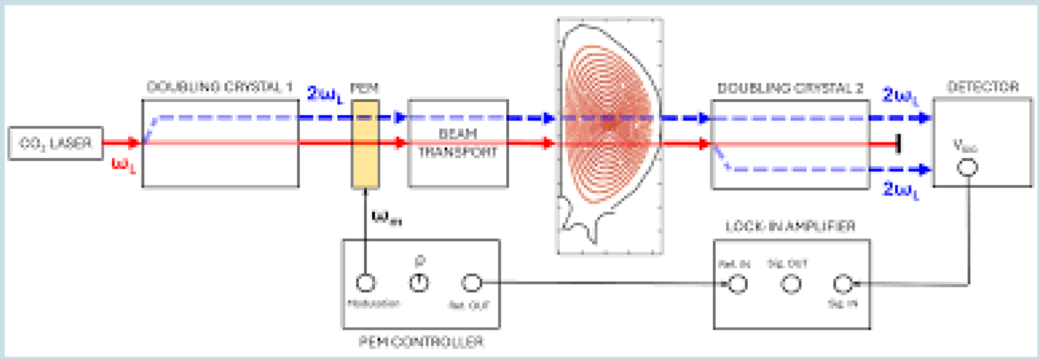


Current methods

- **[1] Far infrared interferometer**
- Used in Jet
- Power – 400 mW CW per laser
- Wavelength - 195 µm
- First installed 1985

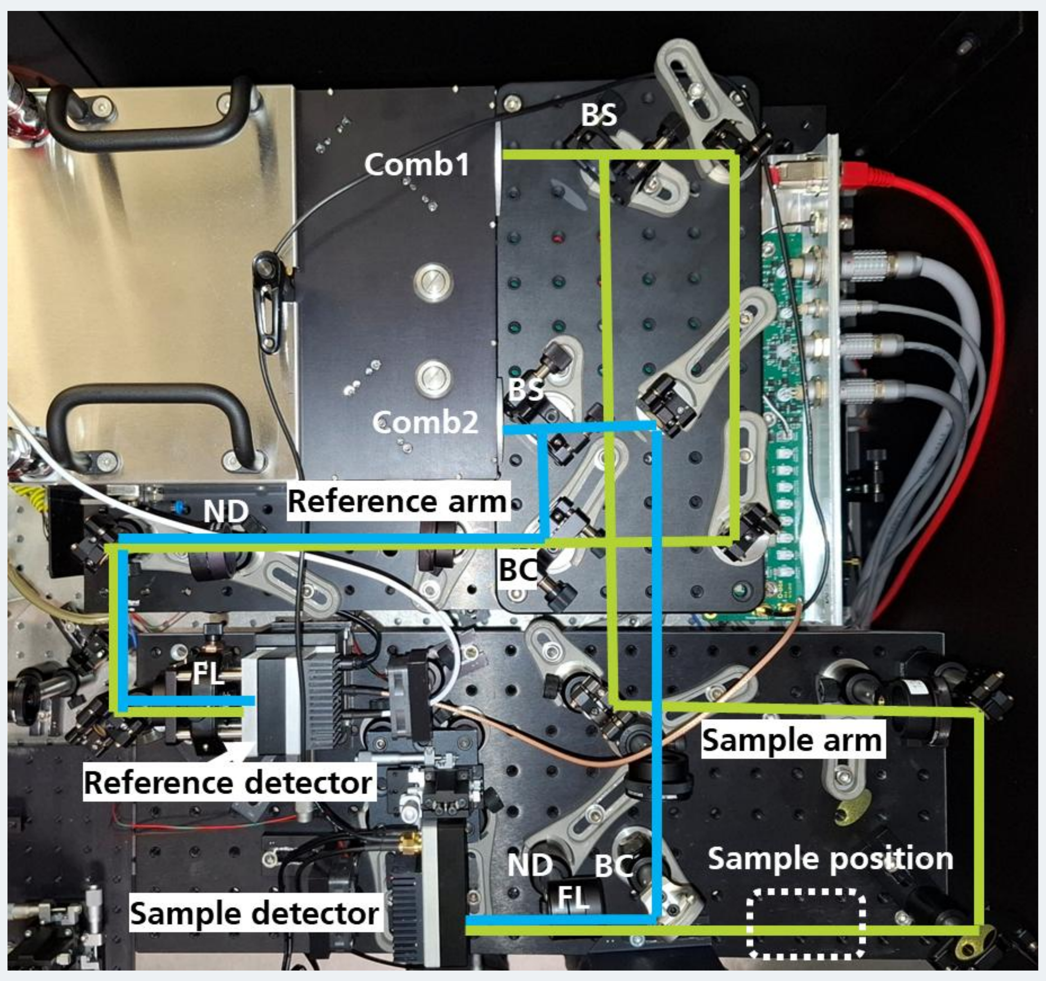


- **[2] Density interferometer Polarimeter (DIP)**
- Used in ITER
- Power – 40 W CW
- Wavelength - 10 µm
- First installed 2022



Optical design

- All components sourced commercially
- QCL based frequency comb source
- 1 ms acquisition time
- 1200 – 1300 cm^{-1} spectral range
- 200 comb lines with 0.5 cm^{-1} resolution
- 250 mw of power



Theory

$$\Phi = \frac{C_1}{f}\int n_e\, ds + C_2 f L\ [3]$$

1st Derivative

- $N_e dS$ is the line integrated plasma density
- L is the change in path length

Taking the Gradient as a function of $-C/f^2$ is equivalent to the line integrated plasma density

$$\frac{d\Phi}{df} = -\frac{C_1}{f}\int n_e\, ds + \frac{1}{c_2} L\ [3]$$

Variable phase verification

robust and precise method for optical phase shift control

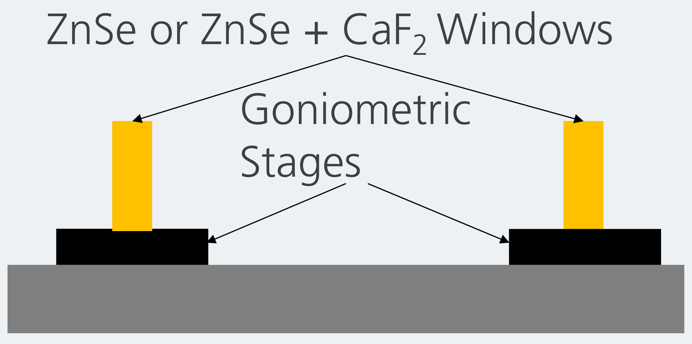
$$\Delta\phi_{total} = \Delta\phi(\alpha) + \Delta\phi(-\alpha) = \frac{4\pi d_0}{\lambda}\left[\frac{n}{\cos\beta} - \left(n + \frac{\cos(\alpha-\beta)}{\cos\beta} - 1\right)\right]\ [4]$$

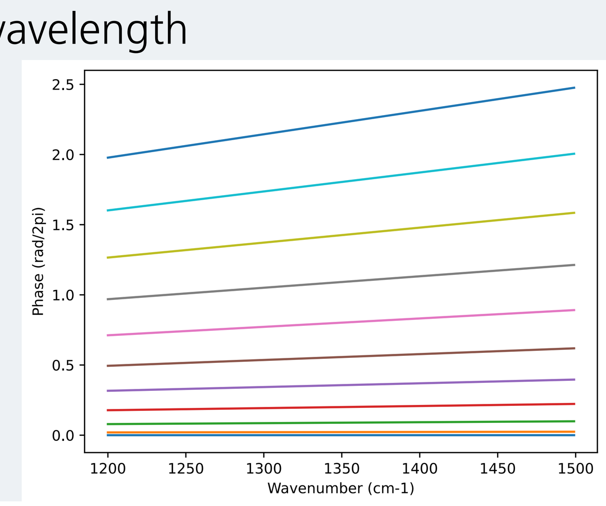
d_0 - plate thickness

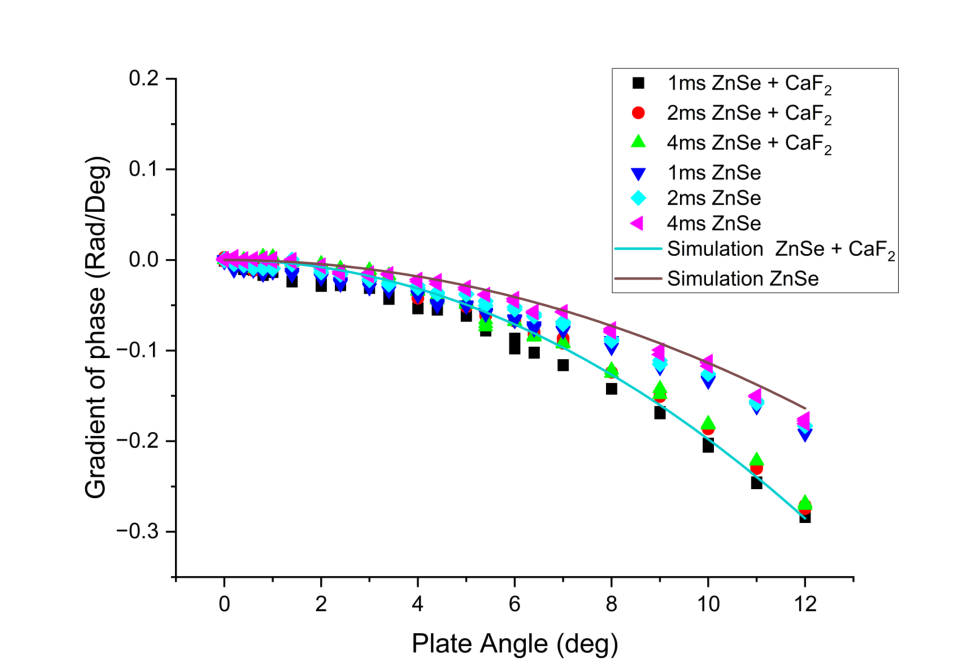
β – internal refraction angle (from Snell's law $\sin\alpha = n\sin\beta$)

n – refractive index of the plate

λ – wavelength







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