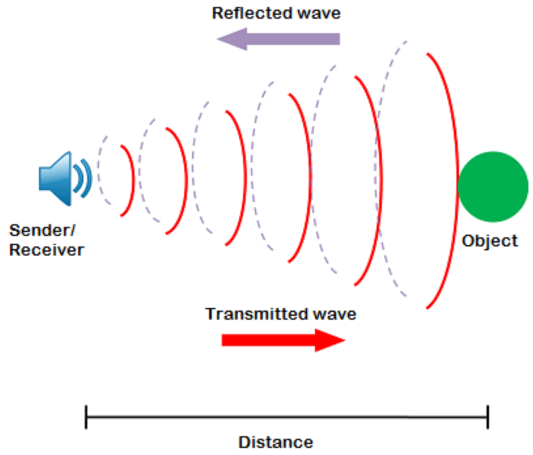
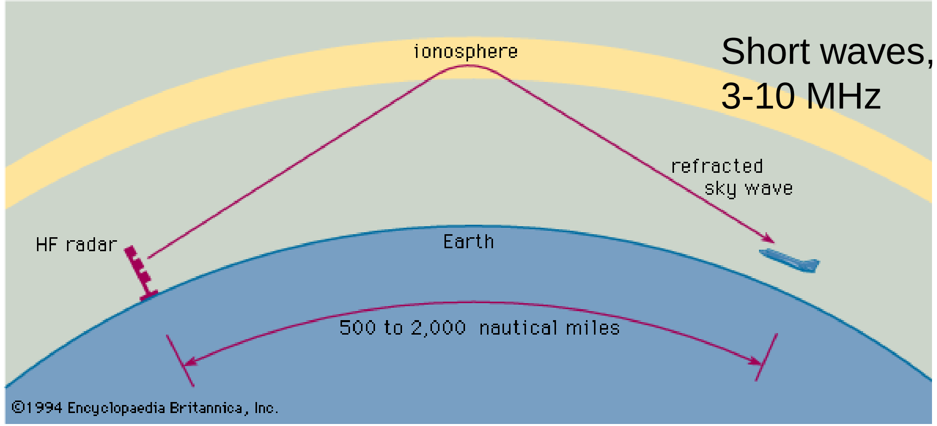
TÉCNICO LISBOA

Reflectometry & interferometry

Reflectometry techniques based on radar principle

"Reflectometry is a radar technique for plasma density measurements using the reflection of electromagnetic waves by a plasma *cutoff*." [Mazzucato, 98]

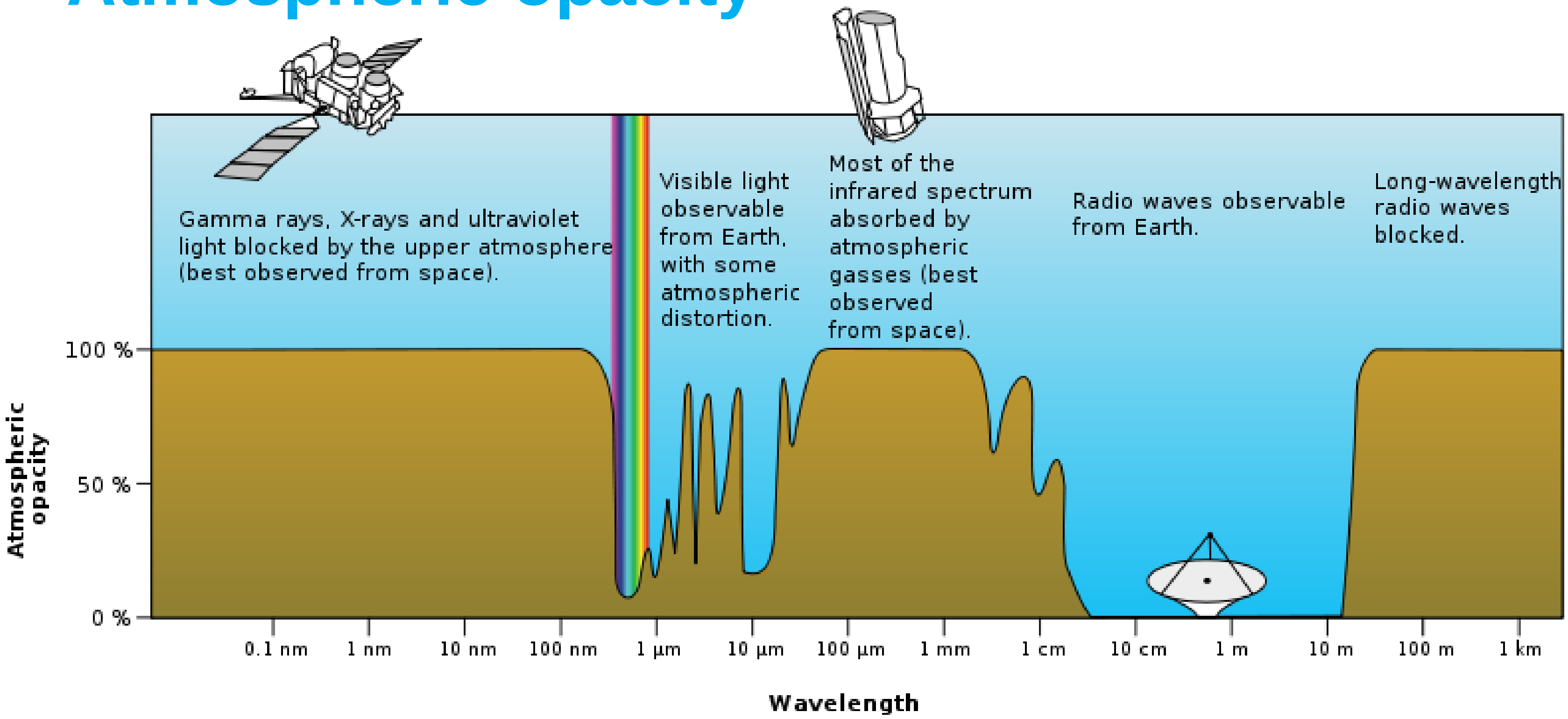




Plasmas modify the wave propagation, examples:

- ❑ Reflection in the ionosphere, used in communications
- ❑ Communications blackout during space reentry

Atmospheric opacity



Microwave diagnostics for plasmas

Microwave diagnostics use electromagnetic waves to obtain plasma information

Electromagnetic waves are remote sensors. Waves can propagate from remote galaxies or to regions of difficult access due to its extreme conditions such as the fusion plasmas

Microwave diagnostics plasma properties are inferred from the effects that the plasma produce in the probing waves

Interferometry and **reflectometry** are two diagnostic techniques based on wave propagation

- ❑ **Reflectometry** (microwaves) operates at the plasma cutoff where reflection occurs
- ❑ **Interferometry** (microwaves or infrared region) operates above the cutoff frequency

Microwave diagnostics for plasmas

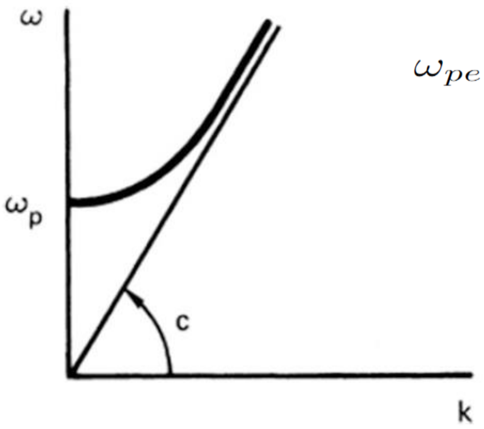
Reflectometry / interferometry diagnostics have been widely used due to its great advantages

- ❑ Minimal access requirements
- ❑ Hardware robustness and flexibility
- ❑ High temporal and spatial resolution

- ❑ Cutoff condition depends on the plasma density (and magnetic field for X-mode)
- ❑ Typical applications of the reflectometry diagnostic are electron density profile and density fluctuation measurements
- ❑ Also allows for plasma rotation measurements (Doppler reflectometry)

Basic principles of waves in plasmas

- Electromagnetic waves propagating in inhomogeneous plasma are reflected at cutoff density layer
- The refractive index (N = c.k/w) decreases with increasing density and vanishes at the cutoff density
- Does not measure non-monotonic profiles of the cutoff frequency



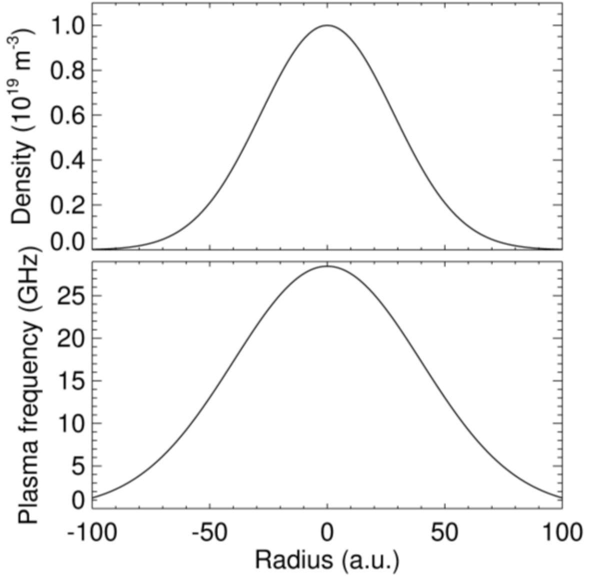
$$\omega_{pe} = \sqrt{\frac{e^2 n_e}{m_e \epsilon_0}}$$

main characteristic frequency of the plasma

$$\omega^2 = \omega_p^2 + c^2 k^2$$

$$N^2 = 1 - \frac{\omega_{pe}^2}{\omega^2}$$

Simplest dispersion relation: O-mode

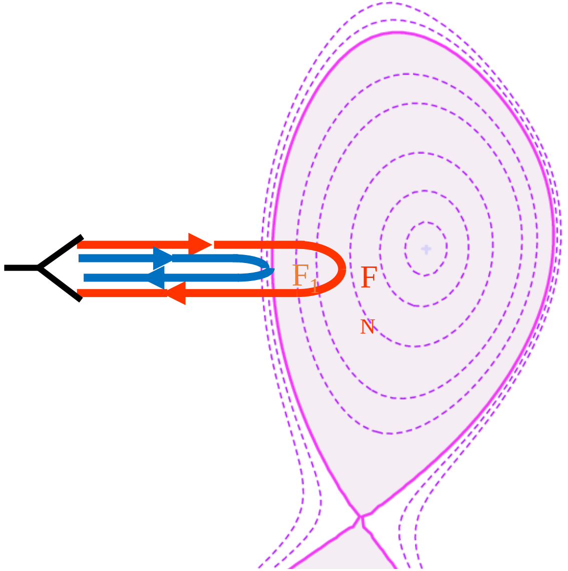


Basic principles of reflectometry

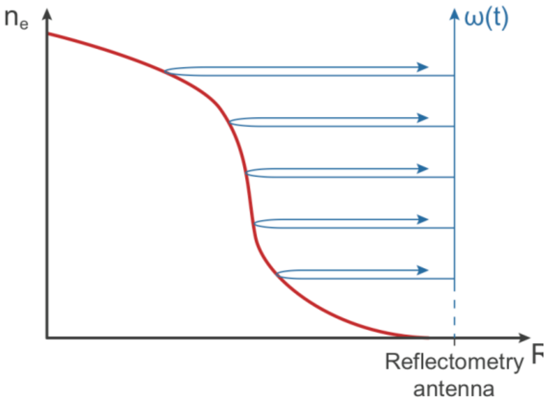
- Signal sent to the plasma being reflected at the cutoff position

$$s_e(t) = A\cos(\omega t)$$

$$s_r(t) = A'\cos(\omega t + \phi)$$



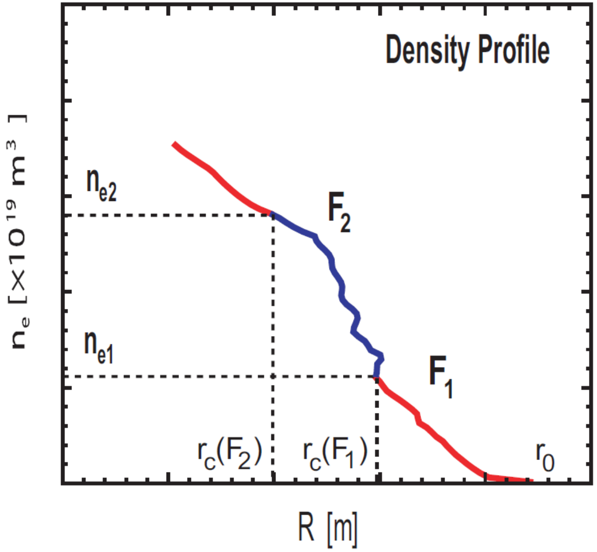
- The reflected wave shows a phase shift ϕ due to the propagation in the plasma
- Electron density at cutoff obtained from wave frequency. Cutoff position derived from integrated time delay due to wave propagation in the plasma
- The phase reflects the propagation of the wave along a path described by a refraction index *N(r)*
- Probing frequency can be swept (profiles) or fixed (fluctuations)



Density profile for O-mode

- Refractive index varies along the plasma according to the density profile
- For O-mode, the phase of the reflected signal can be written as:

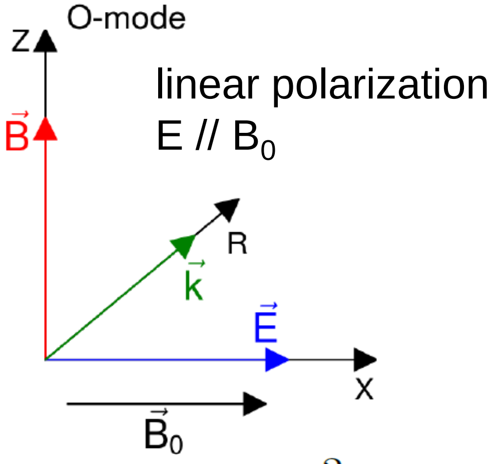
$$\phi(F) = \frac{4\pi F}{c}\int_{x_0}^{x_{co}} N_O(x,F)\mathrm{d}x - \frac{\pi}{2}$$



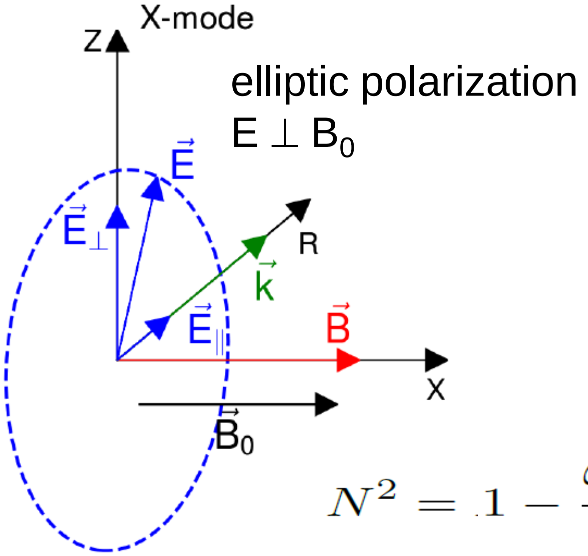
- The phase contains information about the refractive index integrated over the complete propagation path
- Using an inverse Abel transform it is possible to obtain the localization of each plasma layer (accumulated phase shift)

$$x(f_{co}) = x_0 - \frac{c}{2\pi^2}\int_0^{f_{co}} \frac{\mathrm{d}\phi/\mathrm{d}F}{\sqrt{f_{co}^2 - F^2}}\mathrm{d}F$$

Refractive index: O and X propagating modes



$$N^2 = 1 - \frac{\omega_{pe}^2}{\omega^2}$$



$$\omega_{pe} = \sqrt{\frac{e^2 n_e}{m_e \epsilon_0}}$$

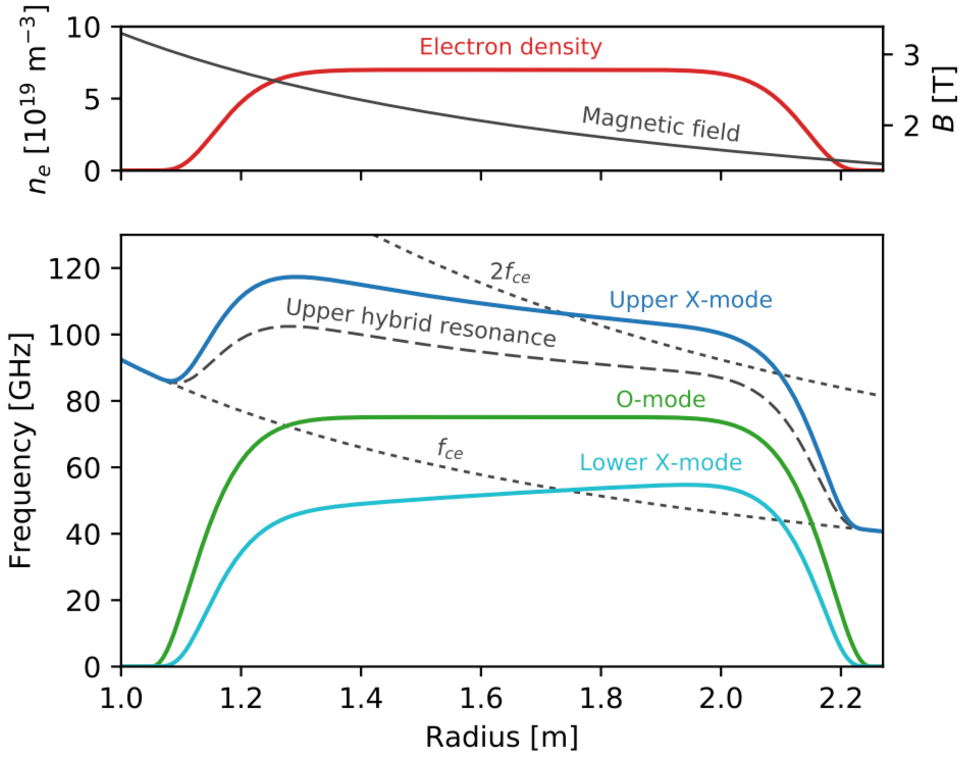
$$\omega_{ce} = \frac{eB}{m_e}$$

$$N^2 = 1 - \frac{\omega_{pe}^2}{\omega^2} \frac{\omega^2 - \omega_{pe}^2}{\omega^2 - \omega_{pe}^2 - \omega_{ce}^2}$$

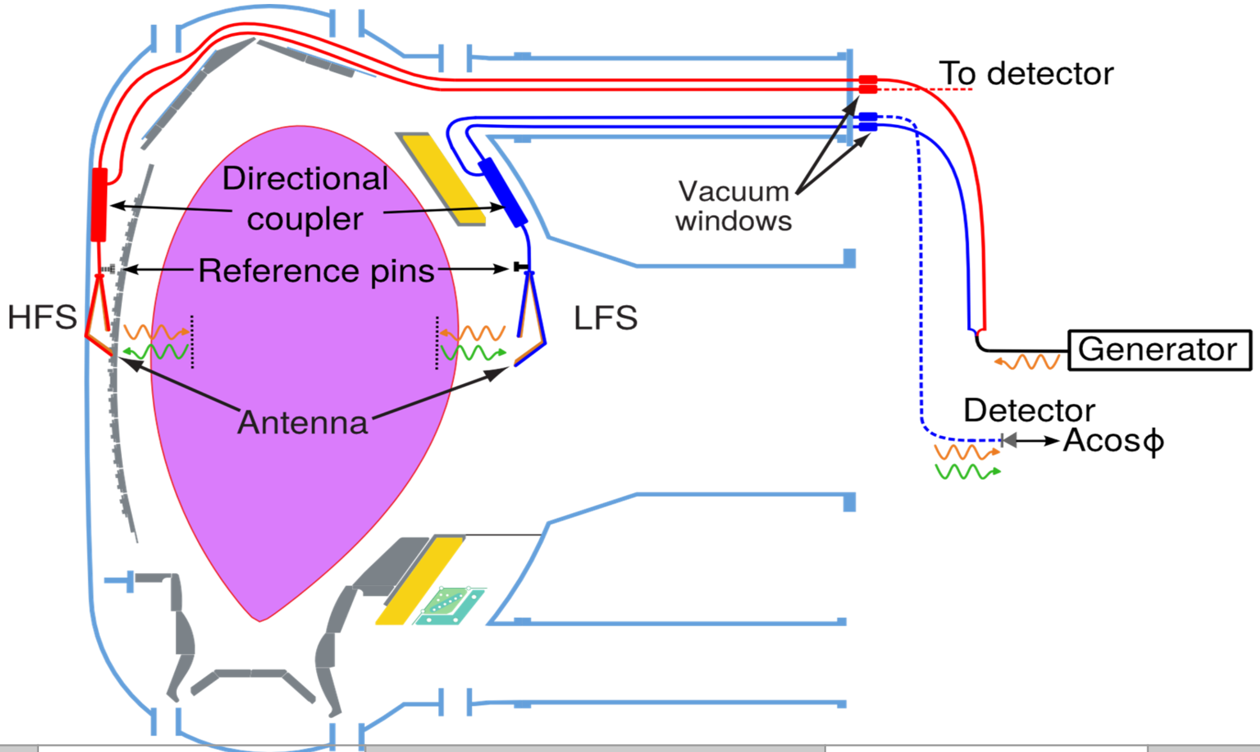
- ❑ Plasmas are in general inhomogeneous and non-stationary in density. In such a complex environment, wave propagation should be treated numerically: **full-wave**
- ❑ Analytic treatment can provide useful expressions in specific situations, for example when the plasma properties change slowly
- ❑ This simplified reality is called the Wentzel-Kramers-Brillouin (WKB) approximation

Electromagnetic access of the reflectometry diagnostic to the plasma

- X-mode offers the advantage of measuring plasma profiles from almost zero densities and flat (even slightly negative) gradients
- O-mode does not depend on B that can be an advantage
- Shallow gradients of the cutoff profile may result in large uncertainties in the position

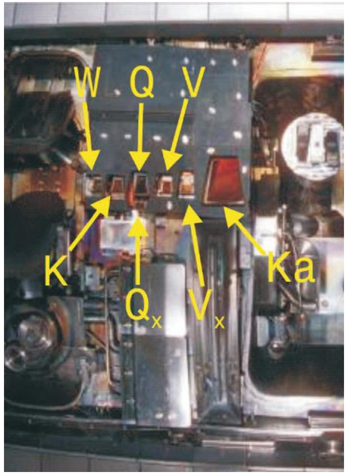


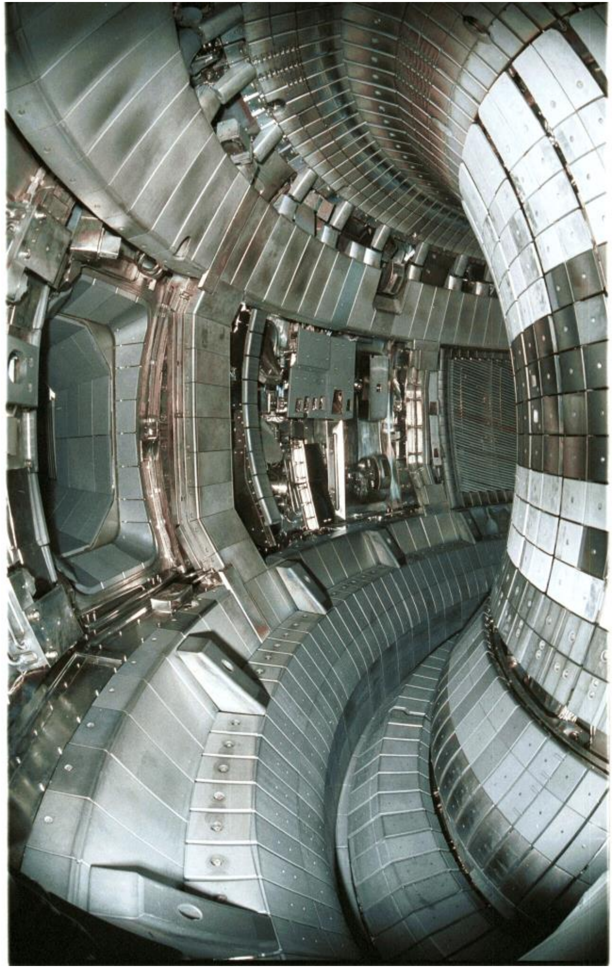
Reflectometer at ASDEX Upgrade

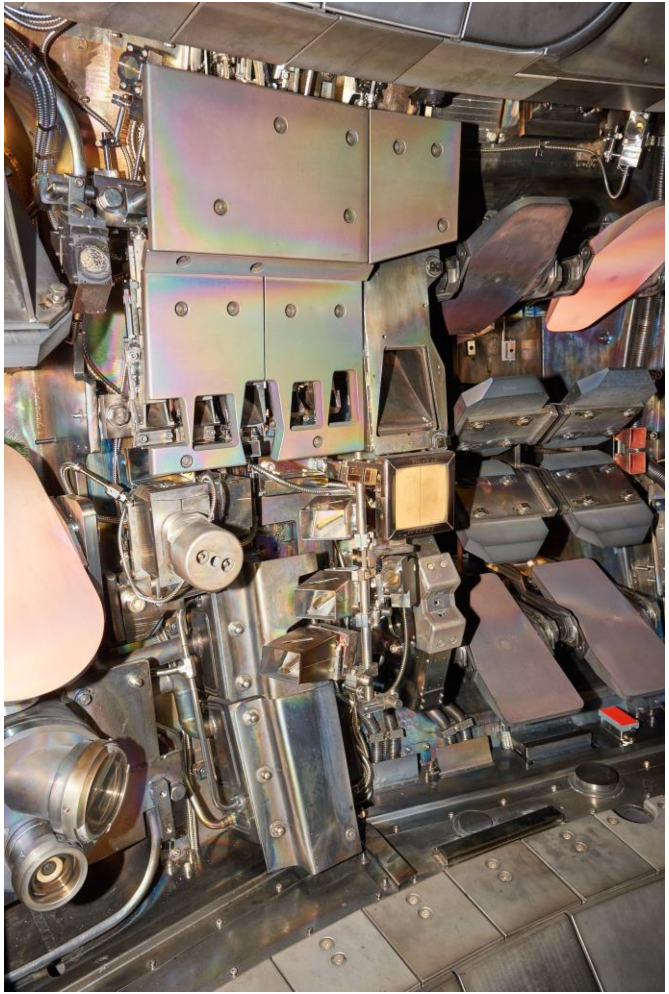


Band	K: 18-24 GHz	Ka: 24-36 GHz	Q: 33-49 GHz	V: 49-72 GHz
Density [$10^{19}m^{-3}$]	0.3-0.8	0.8-1.5	1.5-3.0	3.0-6.4

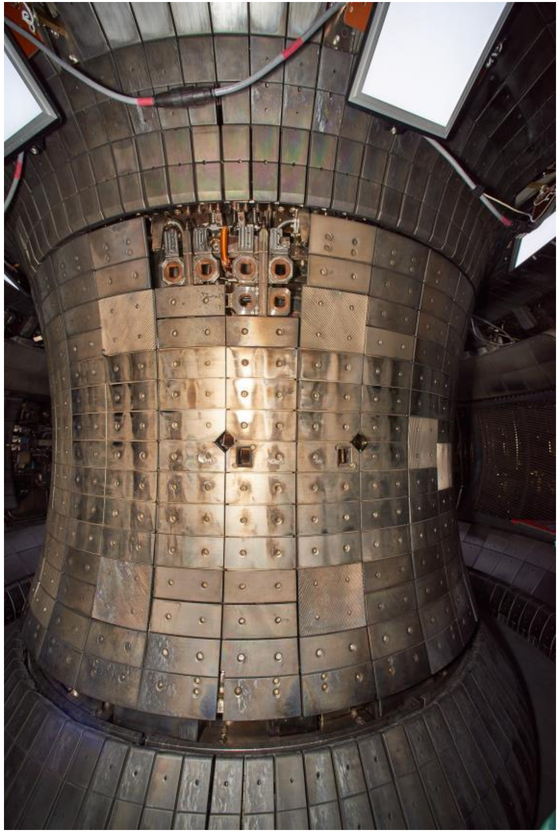
Front end reflectometer channels at LFS

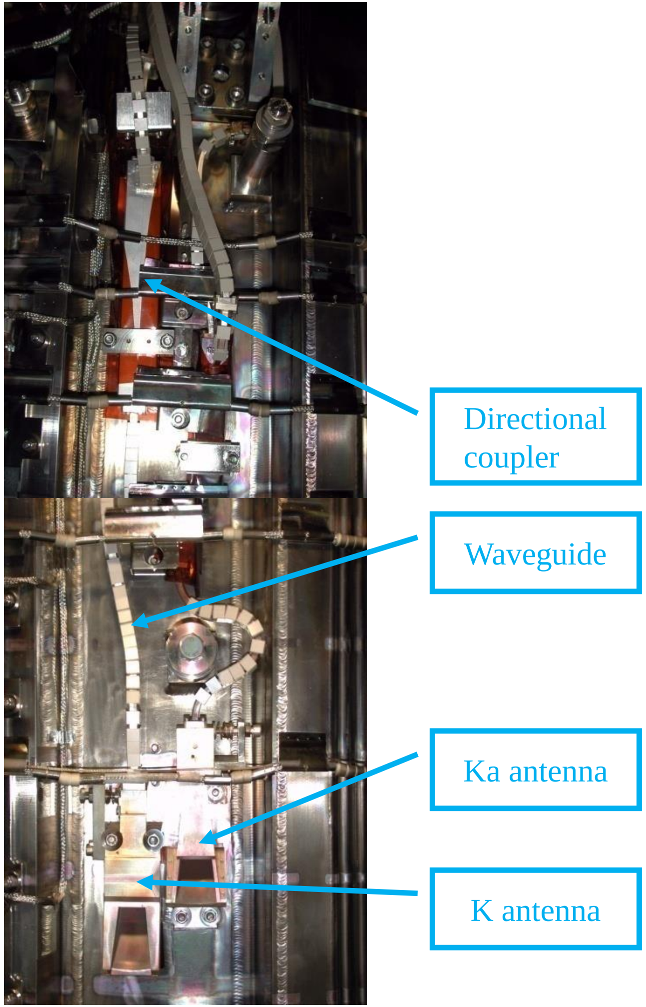




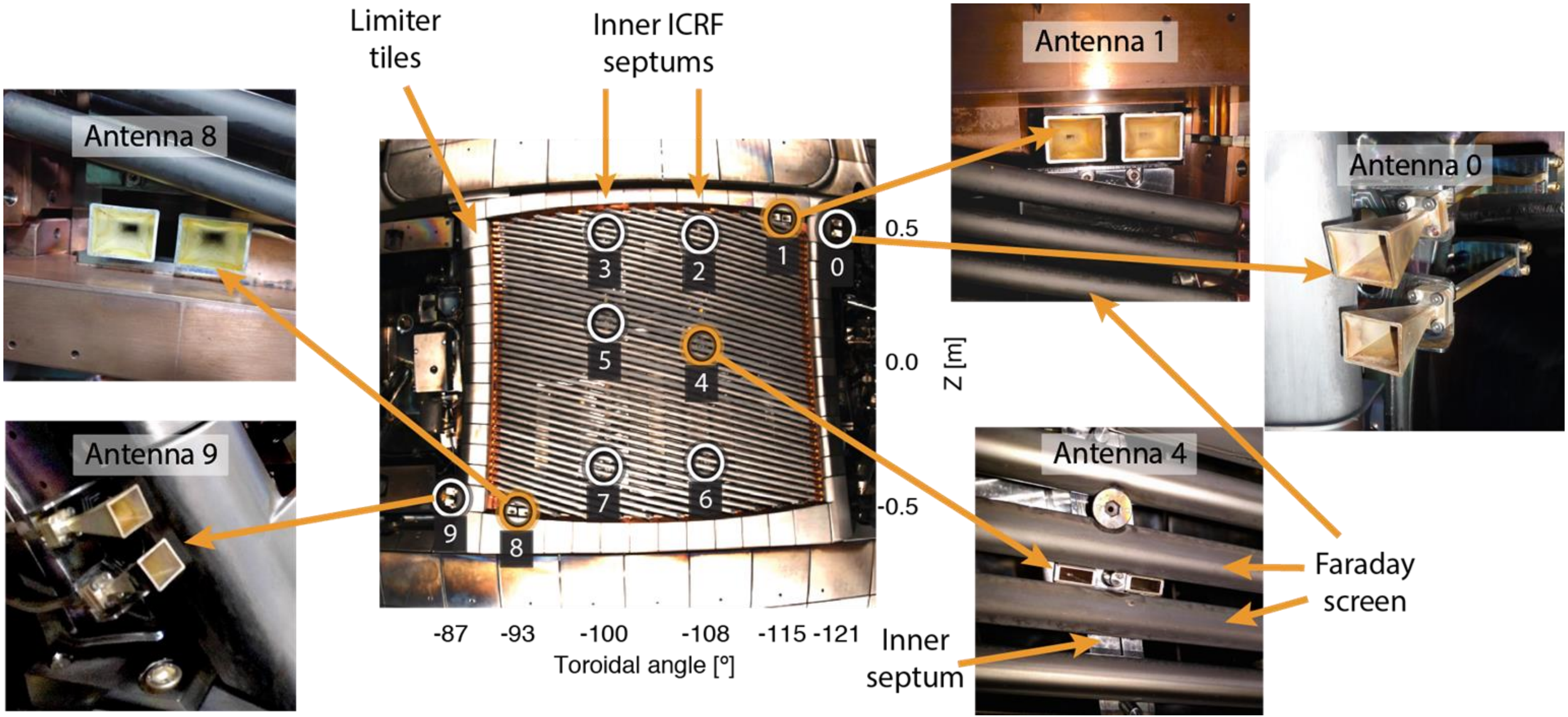


Front end reflectometer channels at HFS



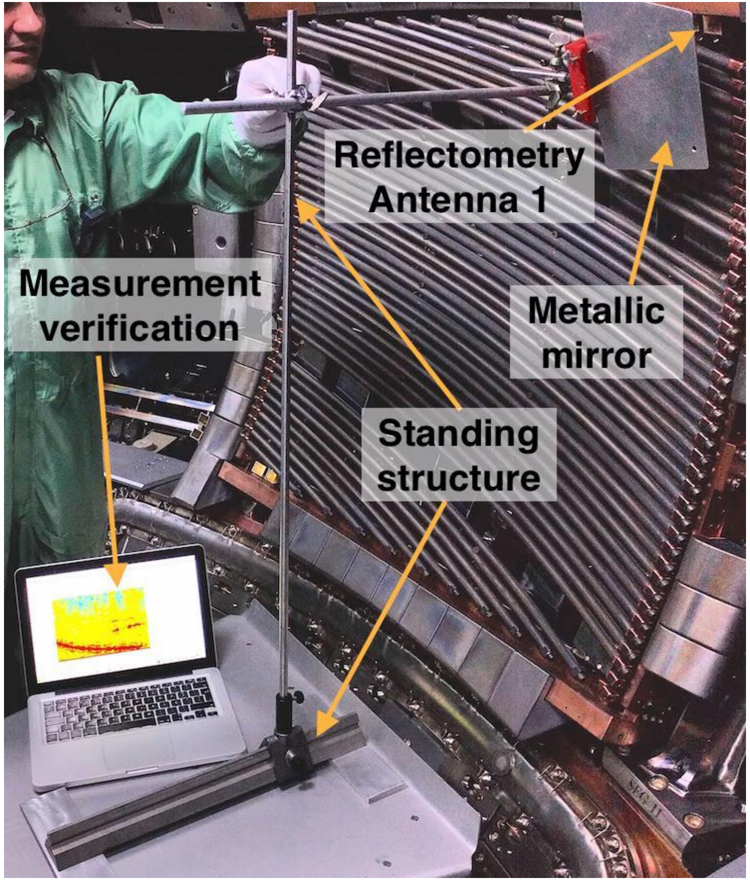


Embedded X-mode reflectometry channels

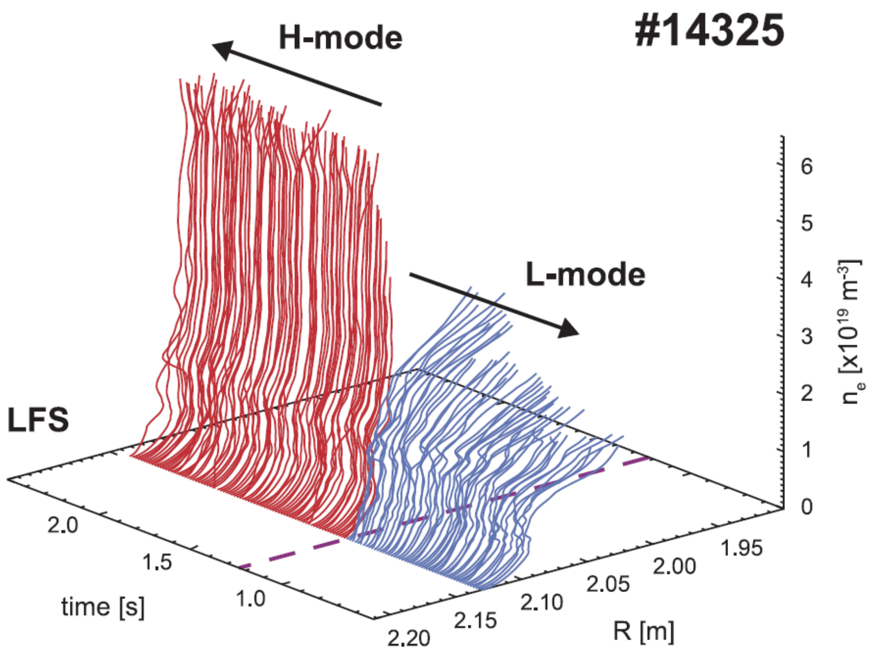


Waveguide calibration setup

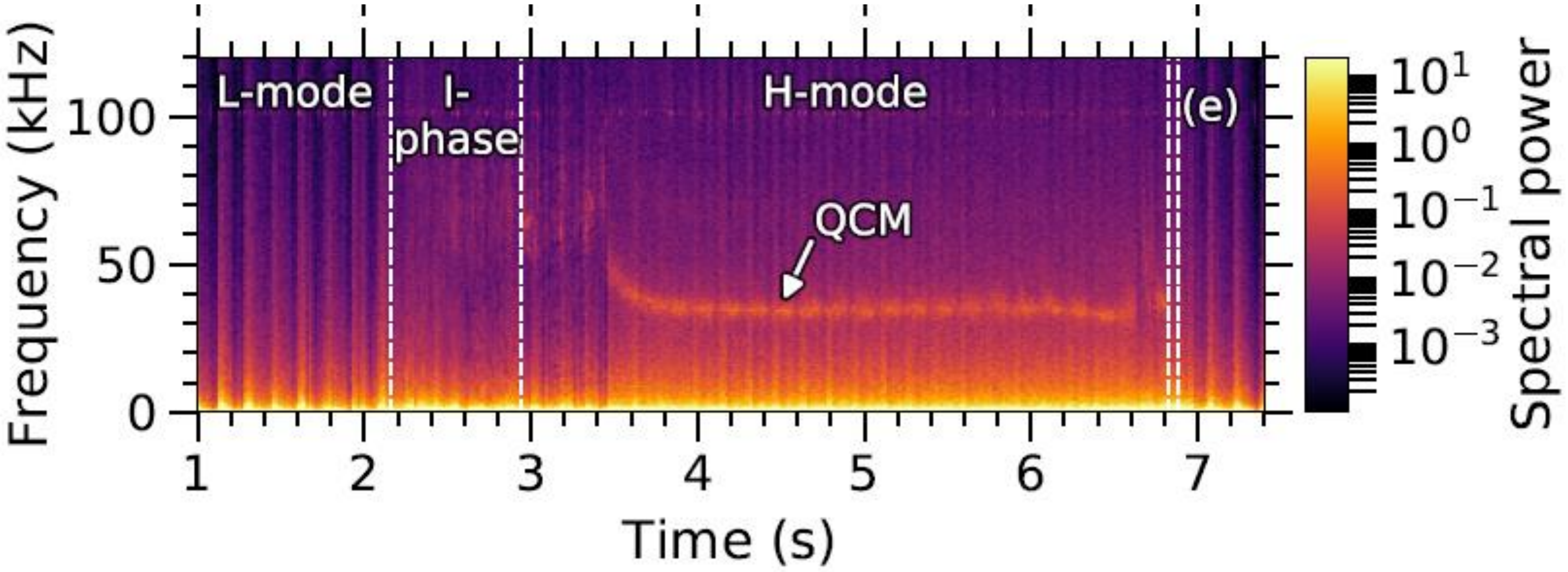
$$\tau = \tau_{wg} + \tau_g$$



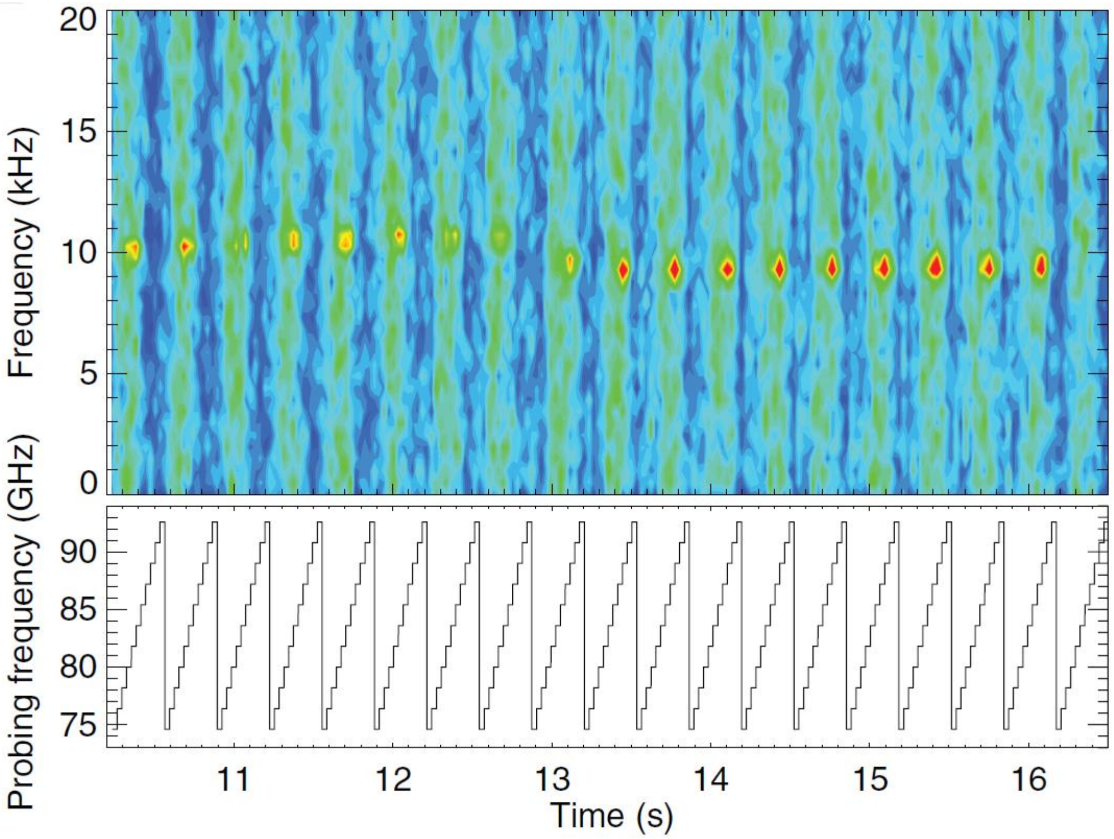
Density profile evolution



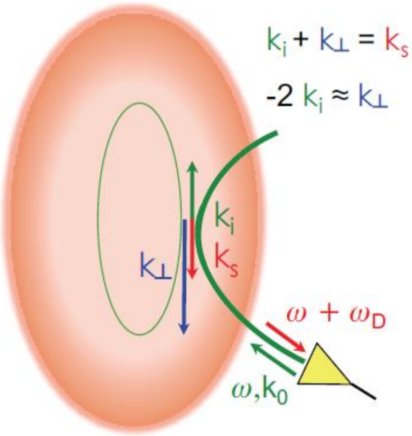
Fixed frequency: density fluctuations

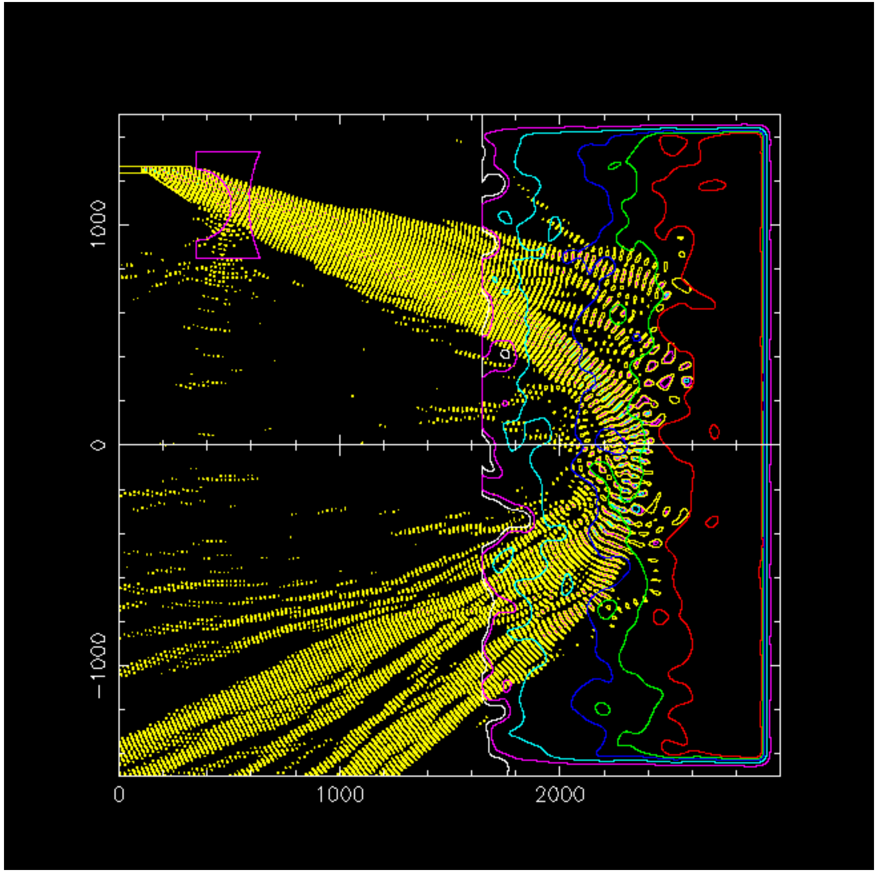


Fixed frequency / hopping



Full-wave simulations

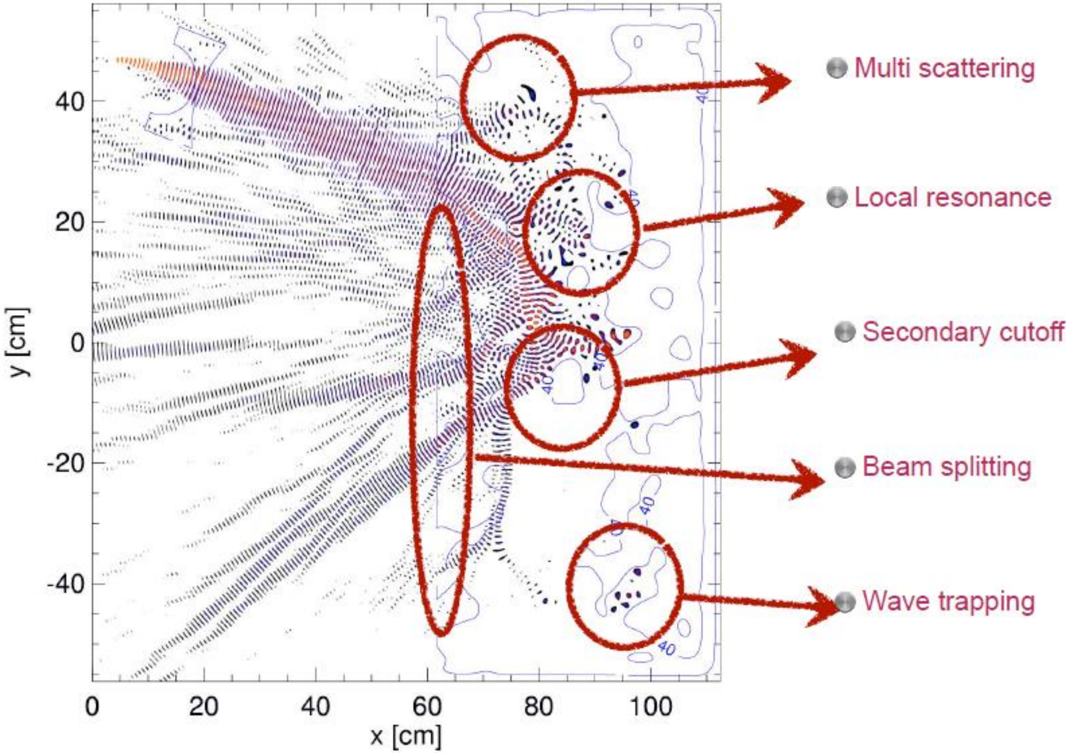




F. Silva

Propagation in plasma is complex

Plasma is extremely complex, non-homogeneous, non-stationary, anisotropic, where waves suffer the effects of turbulence, MHD, Doppler shifts, absorption, tunneling, mode conversion. It requires a numerical full-wave treatment based on a simplified model which retains the fundamental physics



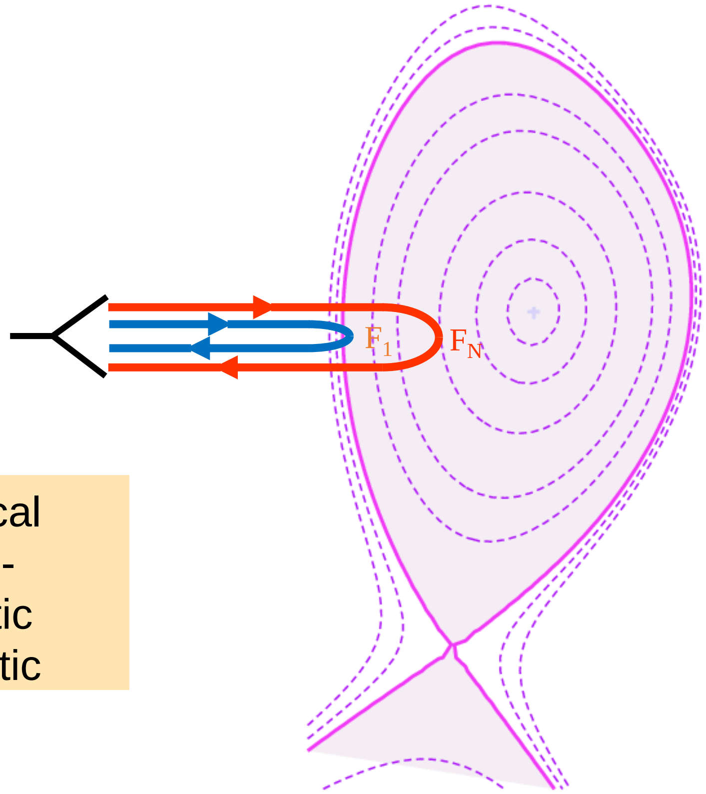
F. Silva

Reflectometry diagnostic system

Microwave system

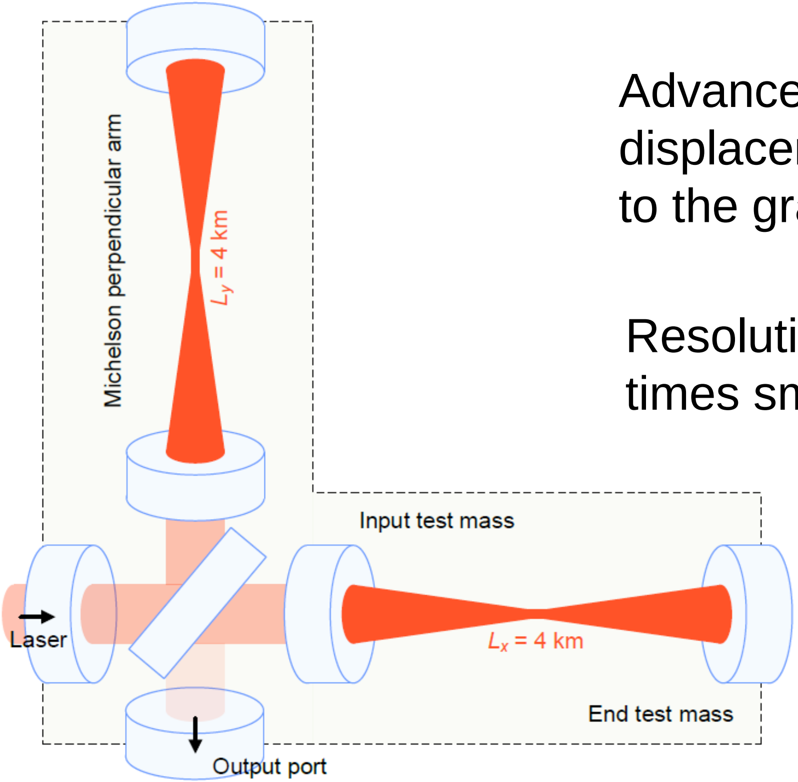
Data processing

Numerical codes - Synthetic diagnostic



Interferometry

Laser Interferometer Gravitational-wave Observatory (LIGO)

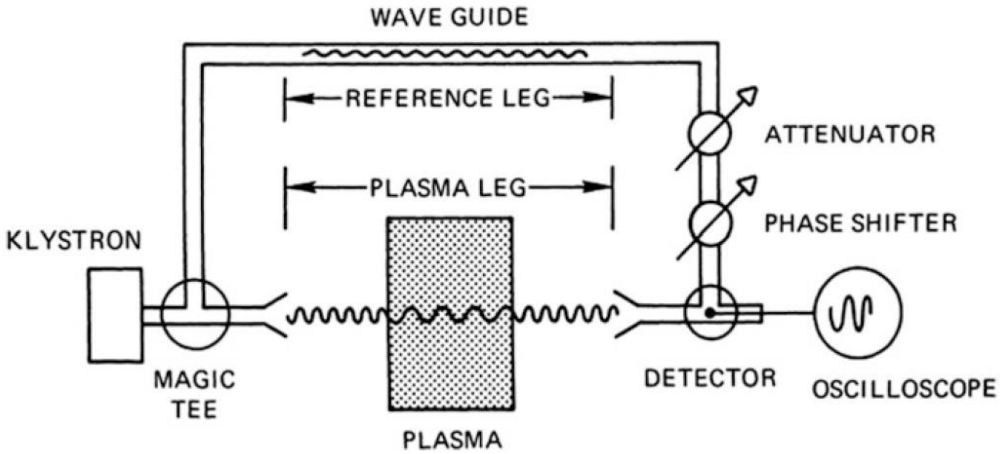


Advanced LIGO measures linear differential displacement along the arms which is proportional to the gravitational wave strain amplitude

Resolution: measures a change in distance 10,000 times smaller than a proton dimension

Interferometer

- Interferometry is a well established technique to measure the plasma average density from the phase shift of the waves transmitted through the plasma
- The variation of the phase with respect to a reference signal used to determine the temporal evolution of the line-averaged density



Interferometer

- Uses probing frequencies larger than the plasma frequency
- For O-mode, the phase shift resulting from the difference between the optical path in vacuum and in the plasma, can be related to the plasma density as

$$\varphi = \frac{\lambda e^2}{4\pi c^2 \epsilon_0 m_e} \int_{z_1}^{z_2} n(z)\, dz$$

- Frequency selected to allow for a reliable determination of the phase (phase variation below 2π but measurable)

Interferometer

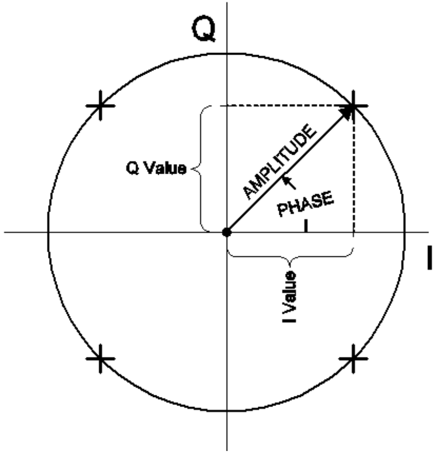
- The simplest technique uses an homodyne detection where the detected signals are proportional to A.cos(ϕ)
- Phase-quadrature detection interferometry allows separate measurements of amplitude and phase through the use of an I/Q detector
- The reference and reflected signal are directly mixed and filtered to obtain the in-phase (I) signal. For the quadrature (Q) signal, the reference is 90º phase shifted, usually by a delay line, prior to mixing and filtering
- The output of the I/Q detector is given by:

$$I = A\cos(\phi)$$

$$Q = A\sin(\phi)$$

$$A(n) = \sqrt{I^2(n) + Q^2(n)}$$

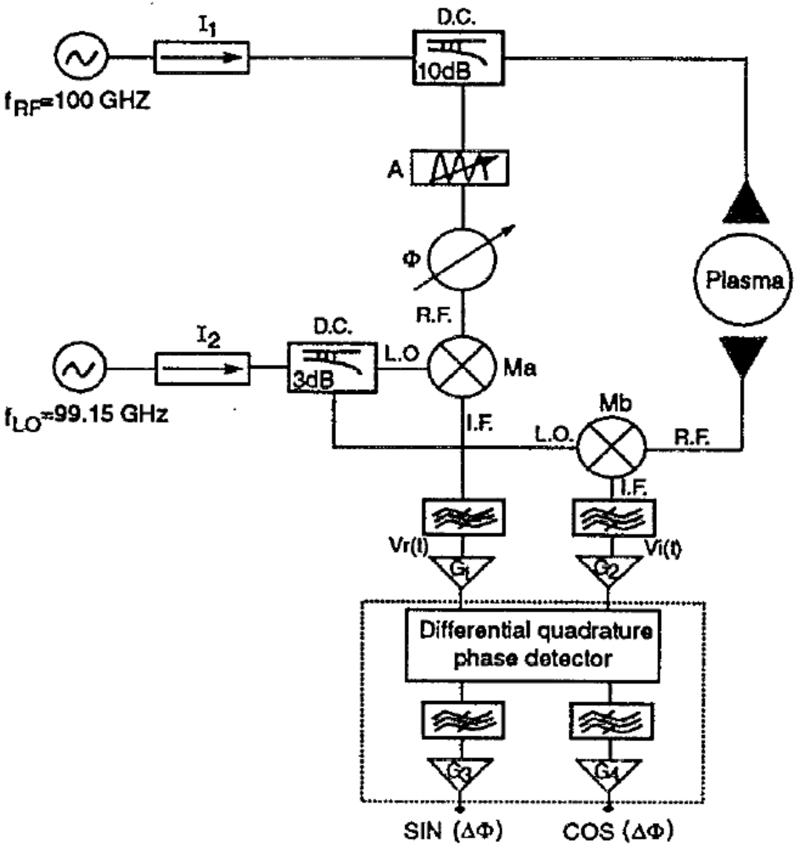
$$\phi(n) = \tan^{-1}\left(\frac{Q(n)}{I(n)}\right)$$



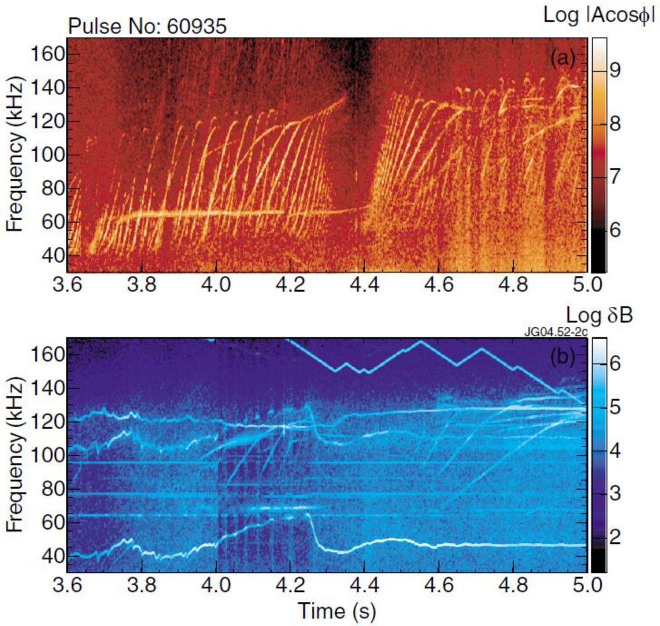
Interferometer at ISTTOK

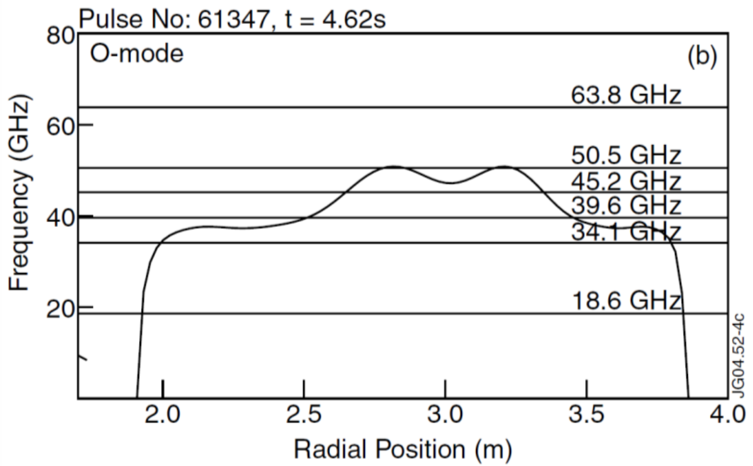
- 100 GHz probing frequency
- Max density: ~1.2×10^{20} m^{-3}
- Local oscillator at 99.15 GHz: signals down converted to the intermediate frequency of 850 MHz
- Microwave mixers translate the frequency of electromagnetic signals

$$\sin(\alpha) \times \sin(\beta) = 0.5[\sin(\alpha + \beta) + \sin(\alpha - \beta)]$$



Fluctuations studies using interferometry





$$N^2 = 1 - \frac{\omega_{pe}^2}{\omega^2}$$

- ❑ The microwave beam propagating through the plasma undergoes a change in amplitude and a shift in phase due to the variation of the refractive index
- ❑ Plasma fluctuations best observed if the microwave beam frequency is just above (by 10%–20%) the critical frequency

Home assignment

- ❑ Estimate the temporal evolution of the line-averaged electron density in ISTTOK
- ❑ Correct possible fringe jumps
- ❑ Study the possible effect of the plasma position on the LAD

IDs:

CENTRAL.OS9_ADC_VME_I8.IF0CS

CENTRAL.OS9_ADC_VME_I8.IF0SN

MARTE_NODE_IVO3.DataCollection.Channel_081 (plasma radial position)

Discharges: 36865, 36869, 36873, 36874, 36886, 36888, 36889, 36890, 36891

Cord length: 17 cm; **Probing frequency**: 100 GHz

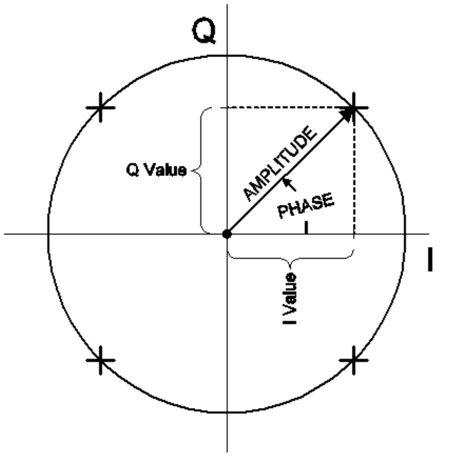
$$\varphi = \frac{\lambda e^2}{4\pi c^2 \epsilon_0 m_e} \int_{z_1}^{z_2} n(z)\, dz$$

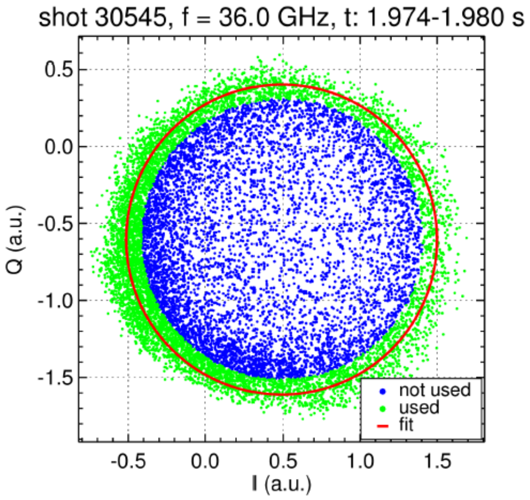
Data analysis

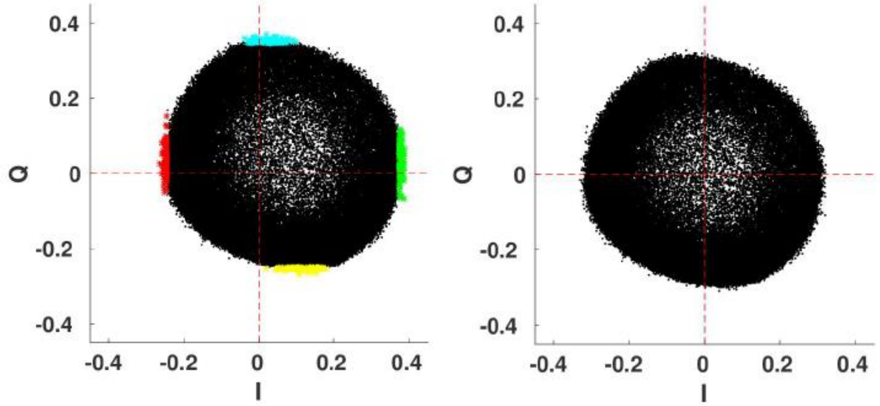
- ❑ Read I, Q signals
- ❑ Remove offsets
- ❑ Estimate the phase
- ❑ Unwrap the phase
- ❑ Calculate the line-averaged density
- ❑ Validate results
- ❑ Validate and discuss every step and give analysis details

Offset removal

- Circular shapes can be clearly identified in I/Q polar plots
- Often centers are shifted from the origin. I / Q signals have offsets caused by electronic hardware which have to be removed to correctly determine the amplitude and phase
- Method: estimate I/Q max and min (**outliers**?)





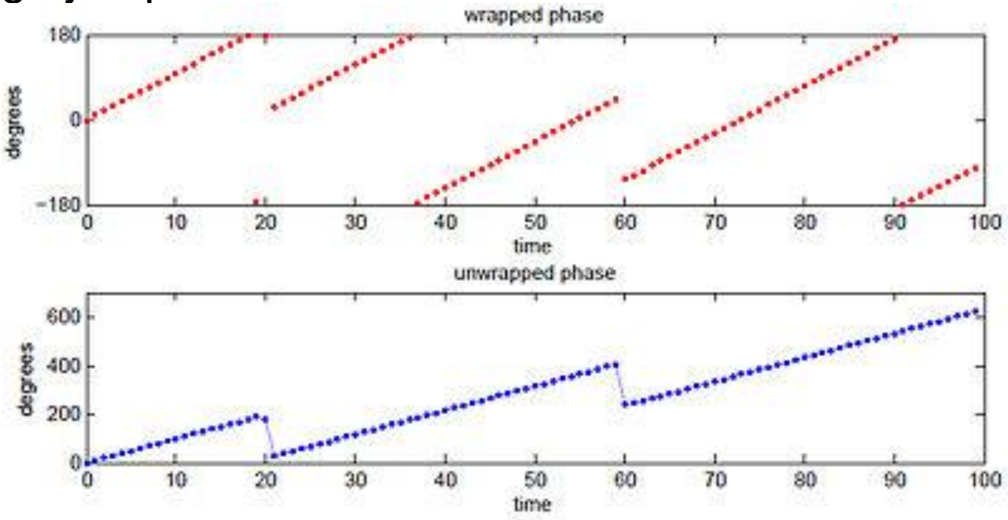


(a) initial data

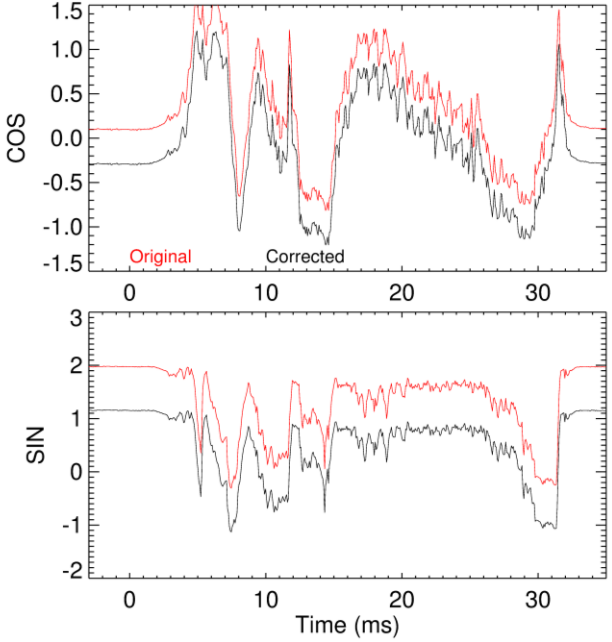
(b) corrected

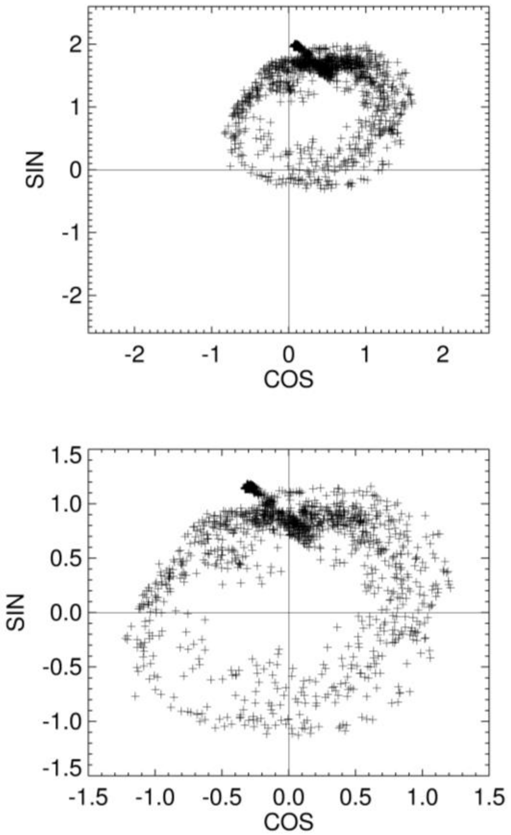
Phase unwrapping

- Phase is constrained to a finite interval $(-\pi, \pi)$, whenever it reaches $\pm\pi$ it wraps back to the other end. For this reason the phase is called wrapped phase
- The continuous phase is called the unwrapped phase. First the differences between consecutive wrapped phase samples are calculated. If $> \pi$, then 2π is added or subtracted to all following phase values. Codes available in Python
- Sometimes fringe jump are difficult to avoid

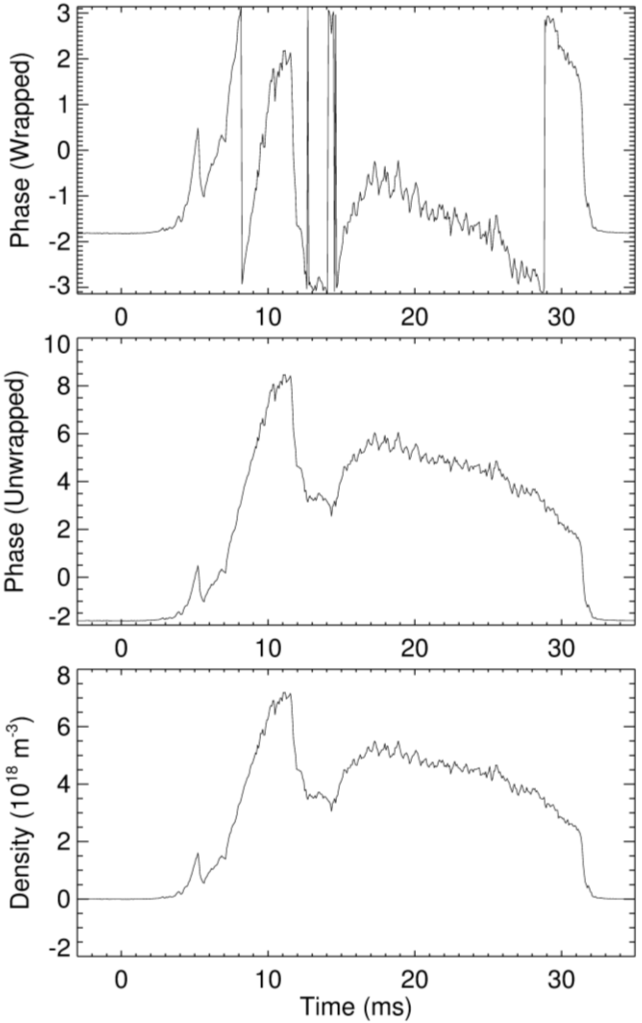


Example from ISTTOK



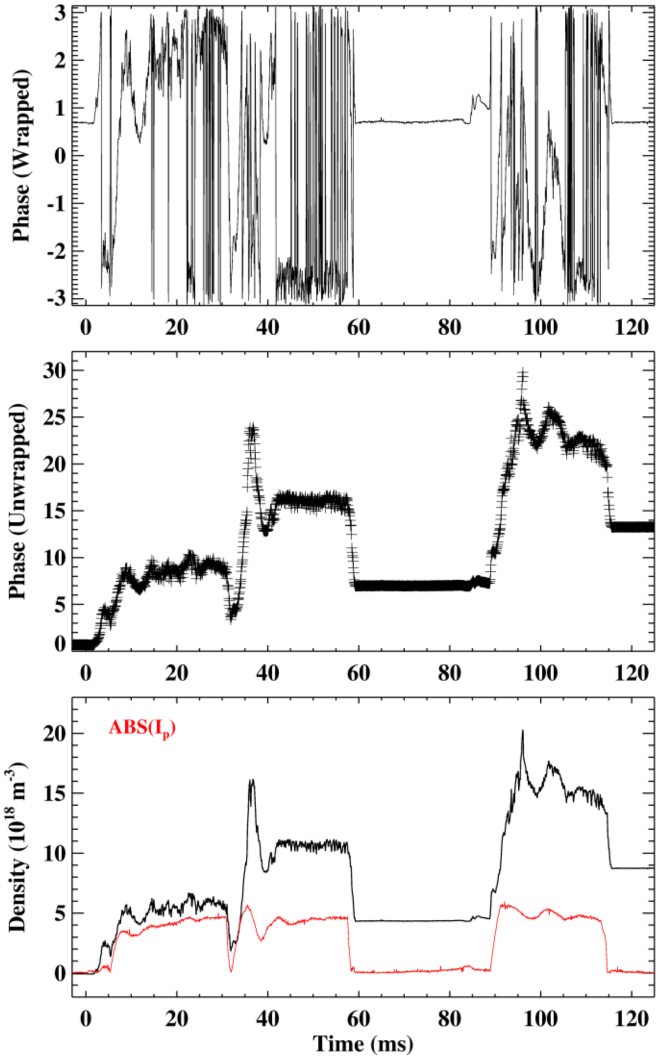


$$\varphi = \frac{\lambda e^2}{4\pi c^2 \epsilon_0 m_e} \int_{z_1}^{z_2} n(z)\, dz$$



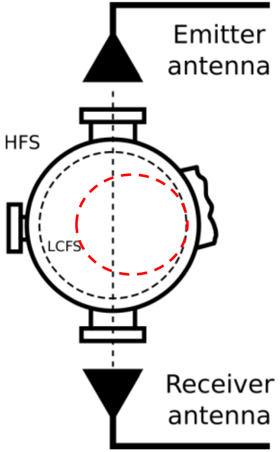
Fringe jump

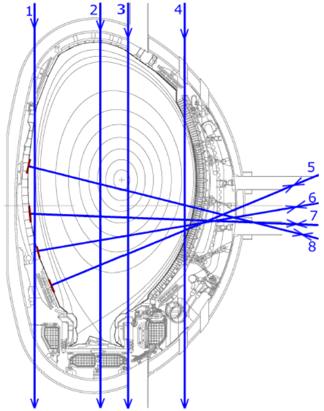
- Ambiguity when phase variation is larger than 2π
- Often fringe jumps have to be corrected manually
- Sometimes jumps are difficult to locate

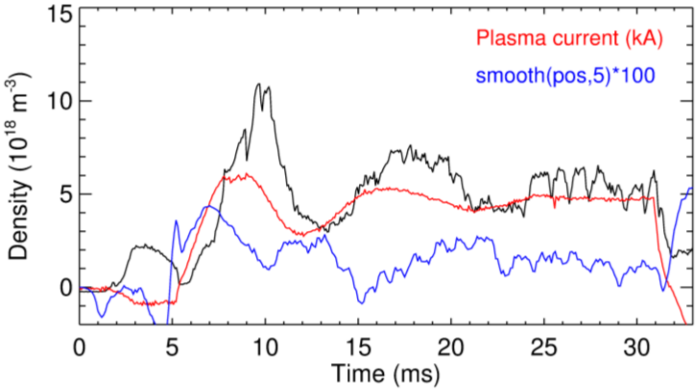


Effect of the plasma position

- Single vertical central cord available on ISTTOK
- Plasma radial movement leads to variations in the line-averaged density. Convolution between evolution of the density and plasma position
- Study the possible effect of a variation in the plasma position (cord length and average density): simply check if changes in position could justify changes in LAD
- Often a complex effect

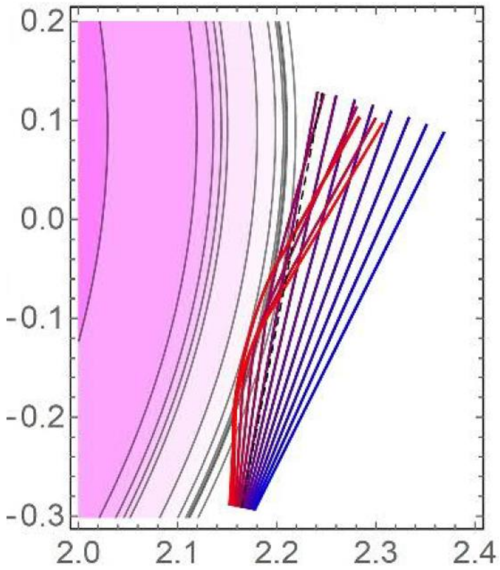


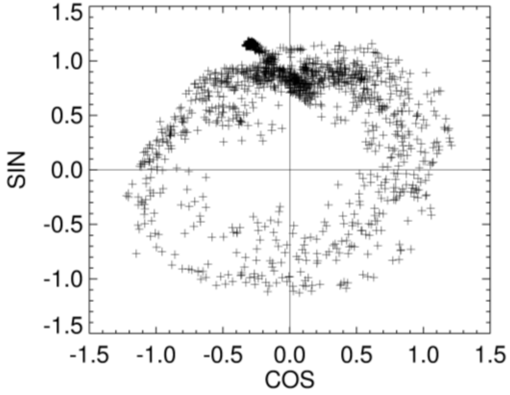




Amplitude

- ❑ Refraction - the beam is diverged
- ❑ Scattering due to turbulence (should be a weak effect)
- ❑ Both lead to a reduction in amplitude
- ❑ Problems at low amplitude
- ❑ Confirm if this is the case





- 25 October, 16:00 - Clarifications + Decision on the research project
- 27 October, 11:30 - Decision on the research project
- Topic to be decided asap, deadline November ~18