The new swept-frequency X-mode reflectometry KG8a diagnostic for density profile measurement on JET

S. Hacquin, L. Meneses, A. Ferreira, A. Fonseca, … *et al* [@]

Associação EURATOM / IST, Centro de Fusão Nuclear,
Av. Rovisco Pais, 1049-001 Lisboa, Portugal

[@] *"Electron Kinetics" Group, EURATOM / UKAEA Association*

• **Outline**

- Principles of reflectometry measurement of the density profile

- Advantages and inconveniences of using the X-mode polarisation

- Characteristics of the KG8a diagnostic

- Determination of the density profile from the KG8a data

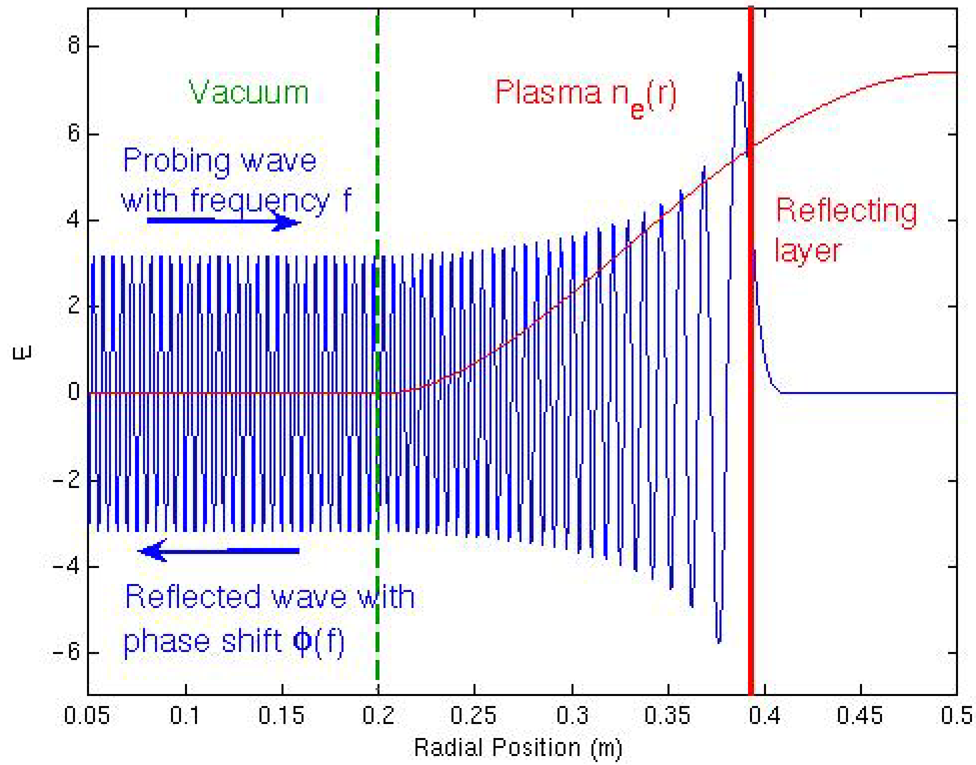
- Expected performances and measurable density range

Principle of reflectometry

The position of the reflecting layer r_c is determined from the measure of the phase shift $\phi(f)$

The spatial resolution depends on the accuracy of the determination of r_c => $\Delta r_c < 1$ cm

The density of the reflecting layer n_c is defined by the probing frequency f => $\Delta n_c = 0$!



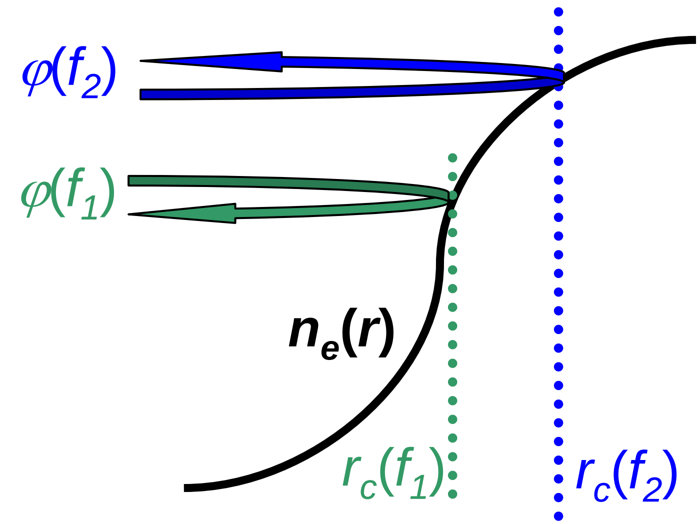
To reconstruct the density profile, the probing frequency has to be swept in order to probe different reflecting layers

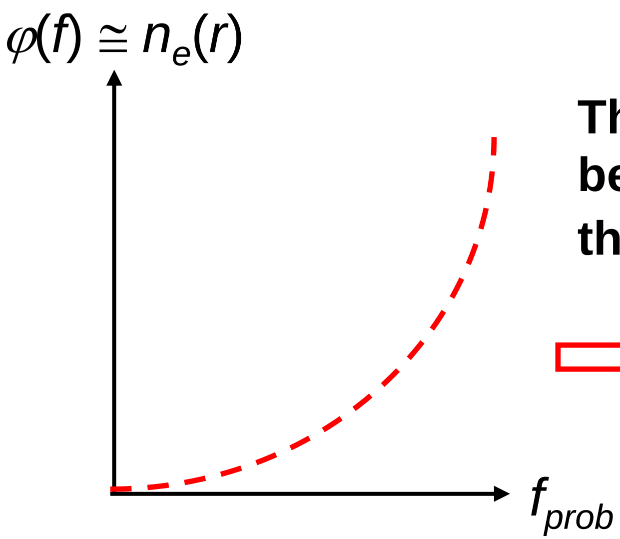
Measurement of the density profile using reflectometry

The position of the reflecting layer $\mathbf{r_c}$ **depends on** the plasma parameters (***n*****$_e$****(*r*)**, …) and **on the frequency *f* of the probing wave**

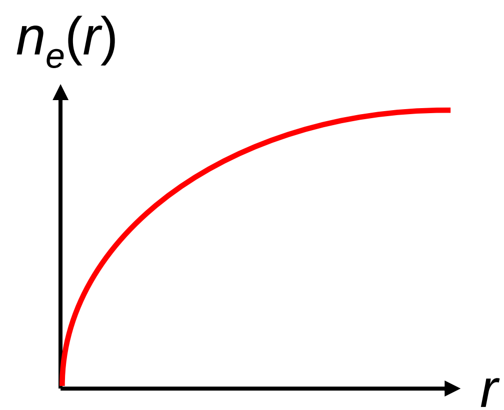
A scan of the density profile $n_e(r)$ requires then a **sweep of the probing frequency *f***

=> Range of $n_e(r)$ measured depends on sweeping frequency range **+ B_0**





The density profile $n_e(r)$ can be numerically inverted from the experimental $\varphi(f)$ curve



Polarisation of the probing wave

O-mode polarisation (E_{prob} // B_0)

- refractive index **depends only on the plasma density**
- probing wave reflected at density layer satisfying $f_{pe}(r_c) = f_{prob}$

=> the plasma edge region cannot be probed since $f_{prob} >> 0$

=> **the edge part of the density profile n_e (r) cannot not be measured !**

X-mode polarisation ($E_{prob} \perp B_0$)

- refractive index **depends on both the plasma density and the magnetic field**
- probing wave reflected when $\boldsymbol{f_{prob} = 0.5 \times [f_{ce} + (f_{ce}^2 + 4 \times f_{pe}^2)^{1/2}]}$

=> the $n_e = 0$ layer is probed when $\boldsymbol{f_{prob} = f_{ce}}$

=> **possibility of measuring the edge part of the density profile n_e (r)**

- requires $B(r)$ to be known & measurable density range depends on B_0 !

Main characteristics of the KG8a diagnostic

X-mode polarisation => influence of B_0 !

Sweeping of the probing frequency in the 50-75 GHz band

- limited density range => **from n_e = 0 up to 2.5 x 10^{19} m^{-3} for B_{edge}=1.8 T**

- continuous sweeping => high spatial resolution (better than 1 cm)

- **fast sweeping rate (in 25 μs)** => high temporal resolution (about 35 μs)

Heterodyne I/Q detection allows measurement of the phase $\varphi(f)$ of reflected wave

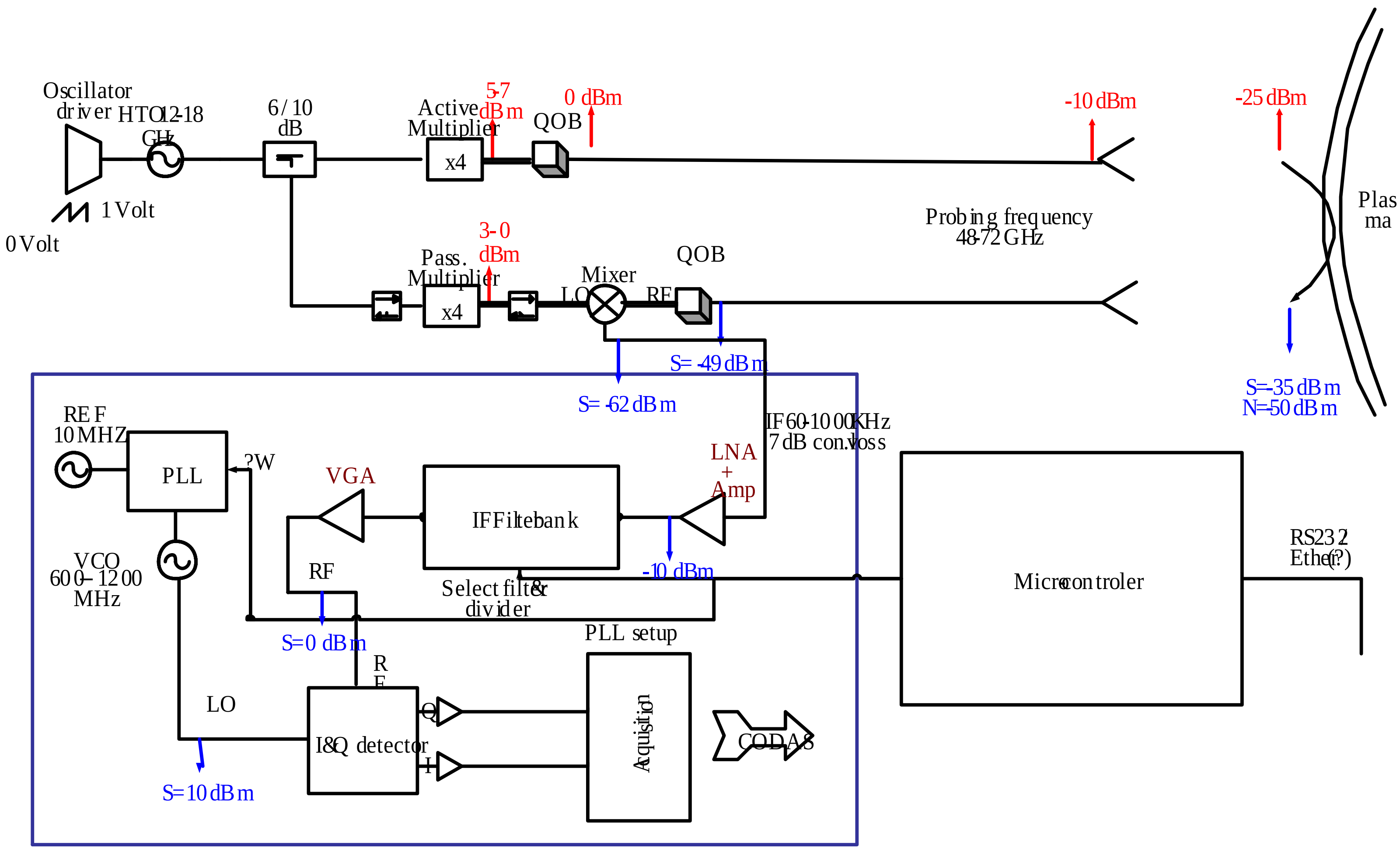
Use of new MWA for good S/N ratio

Acquisition capablities

=> 1024 points per profile with sample acquisition of 40 MHz

=> up to 128 profiles can be acquired per shot

Schematic of the KG8a diagnostic



Reconstruction of the density profile from KG8a data

Data calibration

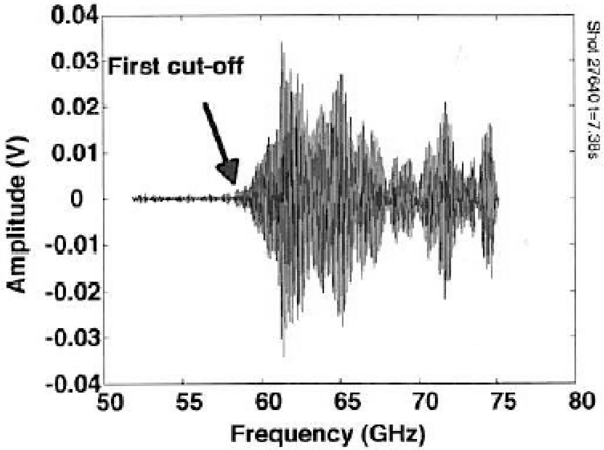
- phase shift in the plasma $\varphi_p(f)$ deduced from $\varphi_{total}(t)$

Detection of the "first fringe" f_0 corresponding:

- to the $n_e(f_0) = 0$ layer and

- to $f_0 = f_{ce}(r_0) = e.(2\pi m_e)^{-1}.B(r_0)$

=> determination of the position r_0 of the plasma edge



Iterative reconstruction of $n_e(r)$

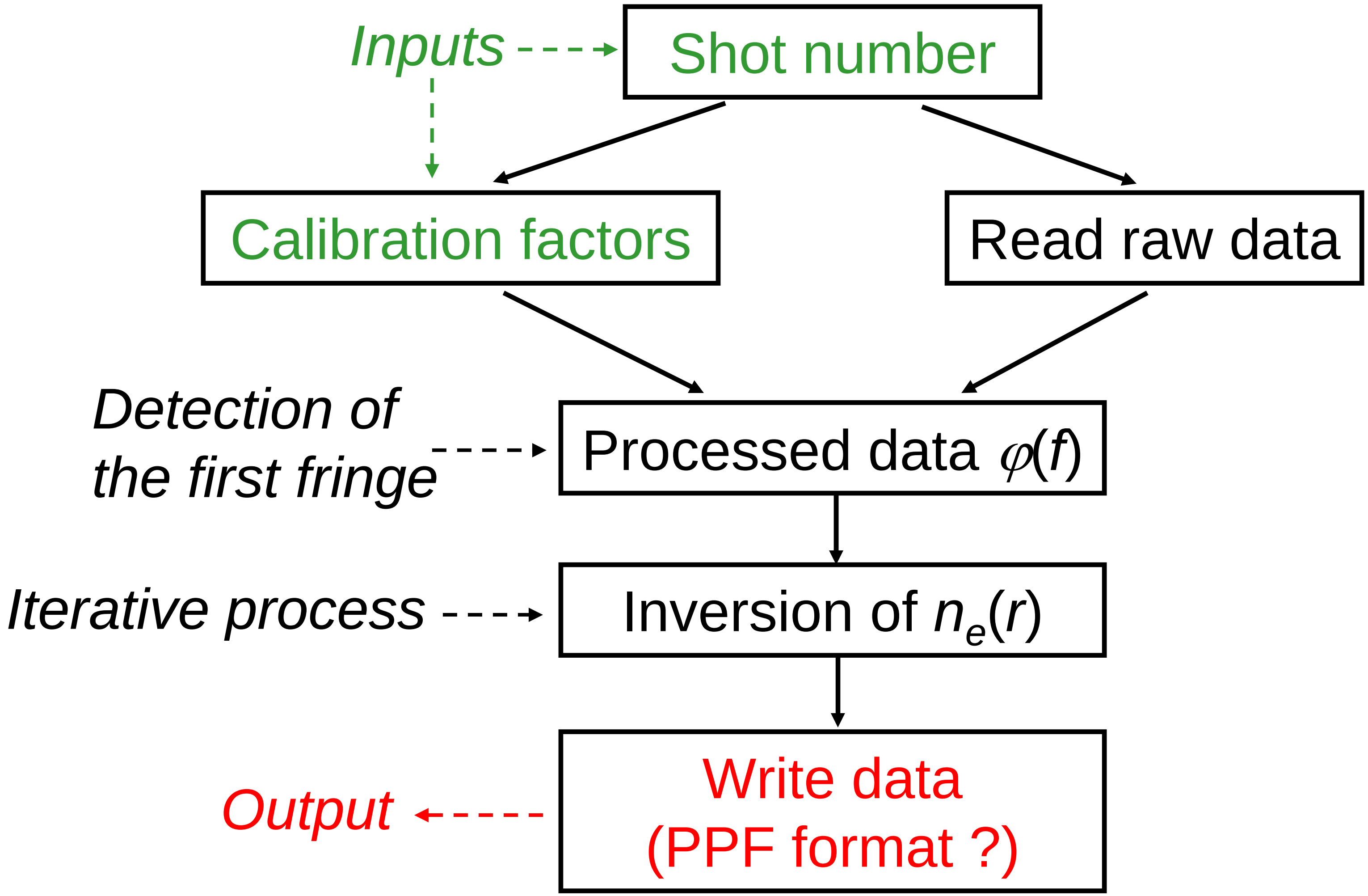
cf. F. Clairet *et al*, *PPCF* **43**, 429 (2001)

1) $\varphi(f) = M[r_c(f)]$ => $r_c(f) = M^{-1}[\varphi(f)]$ (numerical solution only for the X-mode)

2) $n_e(r_c)$ obtained from cut-off relation $f = [f_{ce}(r_c) + (f_{ce}^2(r_c) + 4 \times f_{pe}^2(r_c))^{1/2}]/2$

=> iterative computations of $r_c(f_{i+1})$ and $n_e(f_{i+1})$ for successive probing frequencies

Algorithm for computation of the density profile



Expected performances

Calibration

- consists of determining the frequency of the reflected signal => $\varphi(f)$ from $\varphi(t)$
- 1000 data points will used for determining the phase $\varphi(f)$

=> for a sweeping time of 25 μs, it means that the total time delay of the probing wave has to be known with precision of at least 25 ns !

Precision on $n_e(r)$ measurement

- errors on $B(r)$ given by EFIT could affect the precision of $n_e(r)$ measurement
- uncertainty on the detection of the first fringe $\delta B\ (r_0) = (2\pi\ m_e / e)\ \delta f_0$

=> error on plasma position $\delta r_0 = \delta B\ (r_0) \times dr / dB\ (r_0)$ => $\delta r_0 \sim 3$ cm / GHz

Thermal effects

- relativistic effects should not significantly affects the $n_e(r)$ measurement at the edge
- **during LH heating**, supra-thermal electrons can downshift f_{ce} so that ECE is no longer cut-off and might "pollute" the signal reflected from the cut-off layer

Dependence of the KG8a measurements on B_0

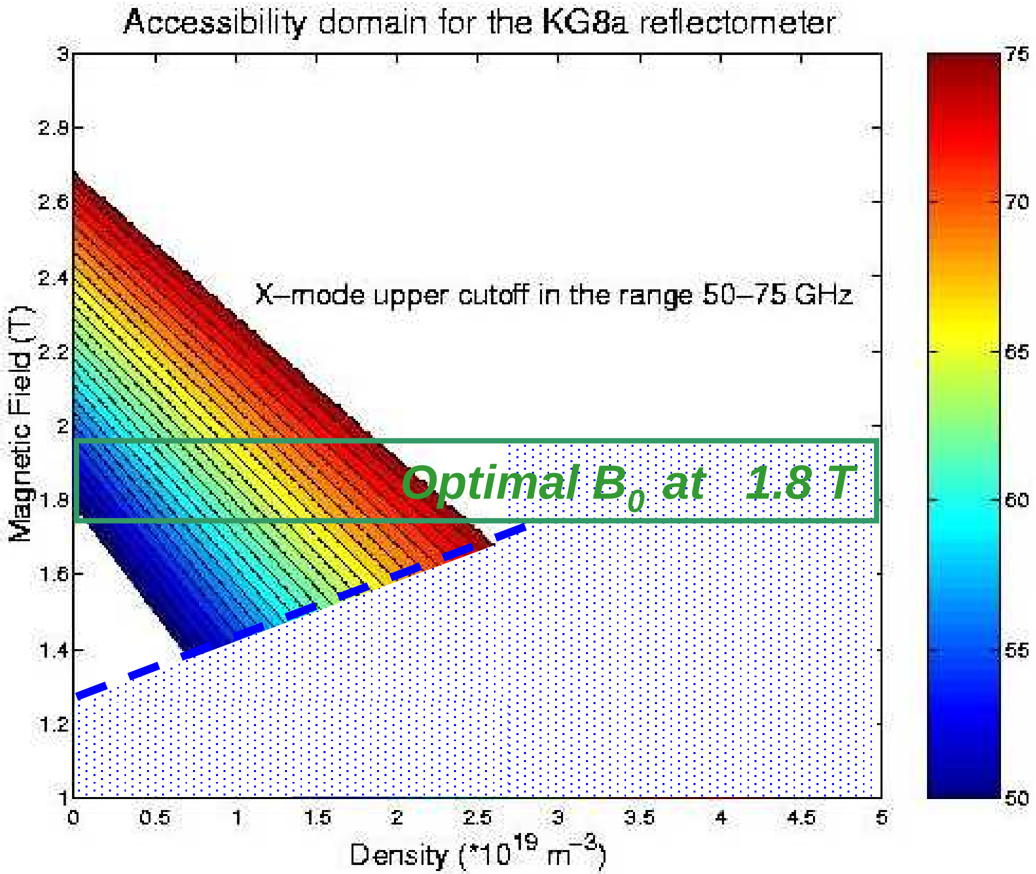
Probing wave reflected when $f_{probing} = 0.5 \times [f_{ce} + (f_{ce}^2 + 4 \times f_{pe}^2)^{1/2}]$

High magnetic field B_0

- measurement of limited density range

Low magnetic field B_0

- $n_e = 0$ layer not measured !
- absorption if $f_{prob} = 2 \times f_{ce}$



Conclusions

The new KG8a reflectometry diagnostic is being installed and should provide its first data during the next JET campaigns (C15-C17)

=> routine density profile measurement with

high temporal (35 μs) and spatial (< 1 cm) resolution

A period of a couple of months might be required in order to debug any hardware or software problems and test the signal calibration and the signal process procedures

=> Routine PPF production is planned after this testing period

Possible future upgrades … if successful !

=> higher memory capacities for more density profiles per shot

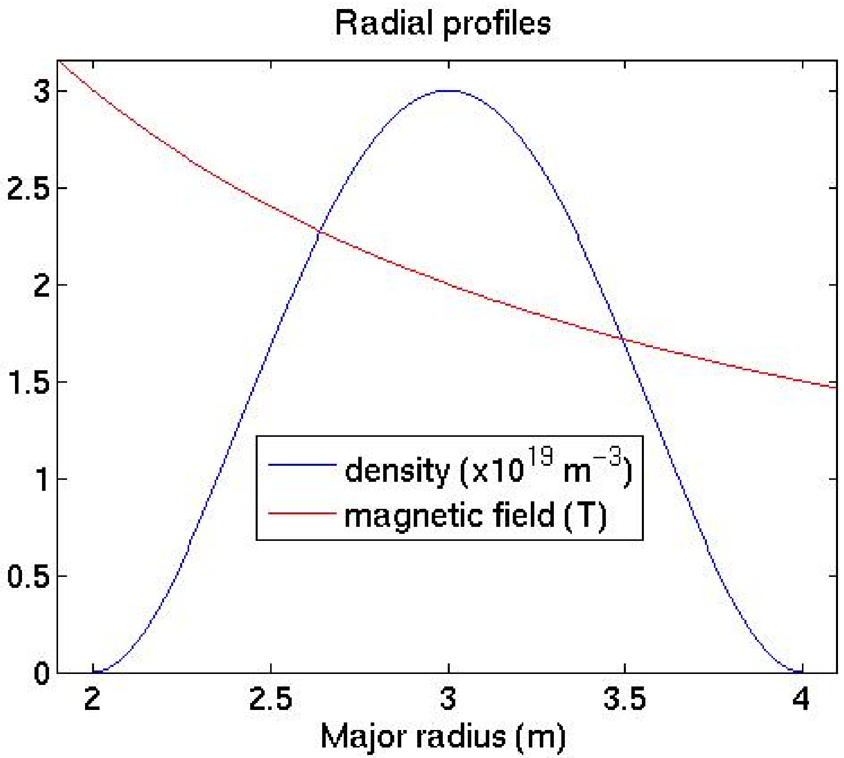
=> **additional frequency band (75-110 GHz) to cover larger density range !**

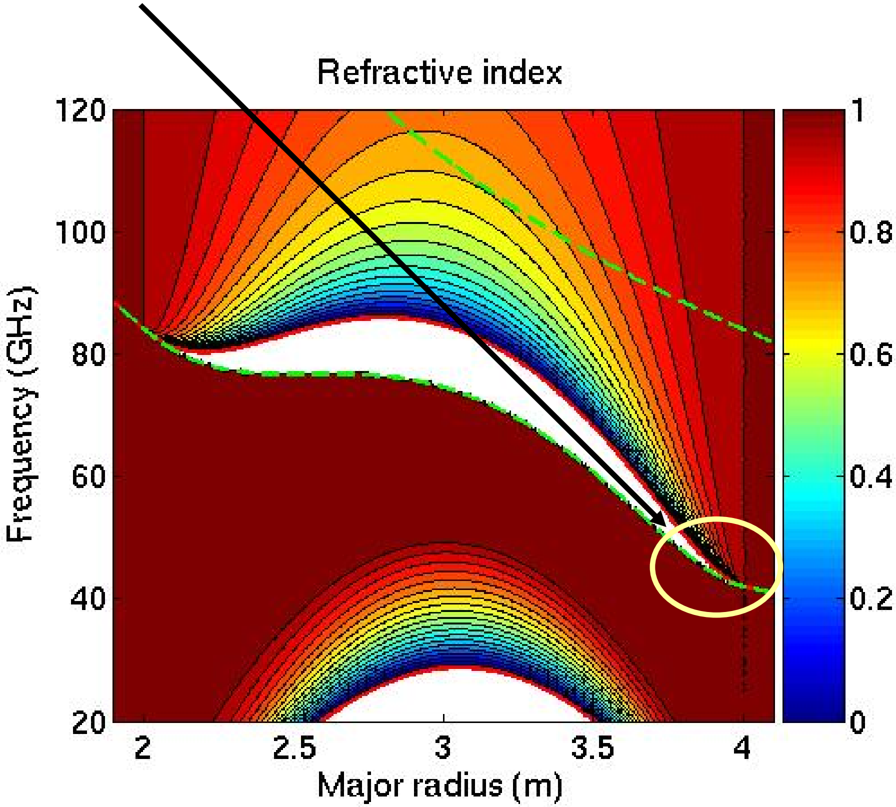
Initialisation problem

Determination of the first fringe

- should be accurate for a good localisation of the $n_e(r_0)$ layer !

- tricky due to proximity of upper cut-off layer and resonance layer !





Initialisation problem

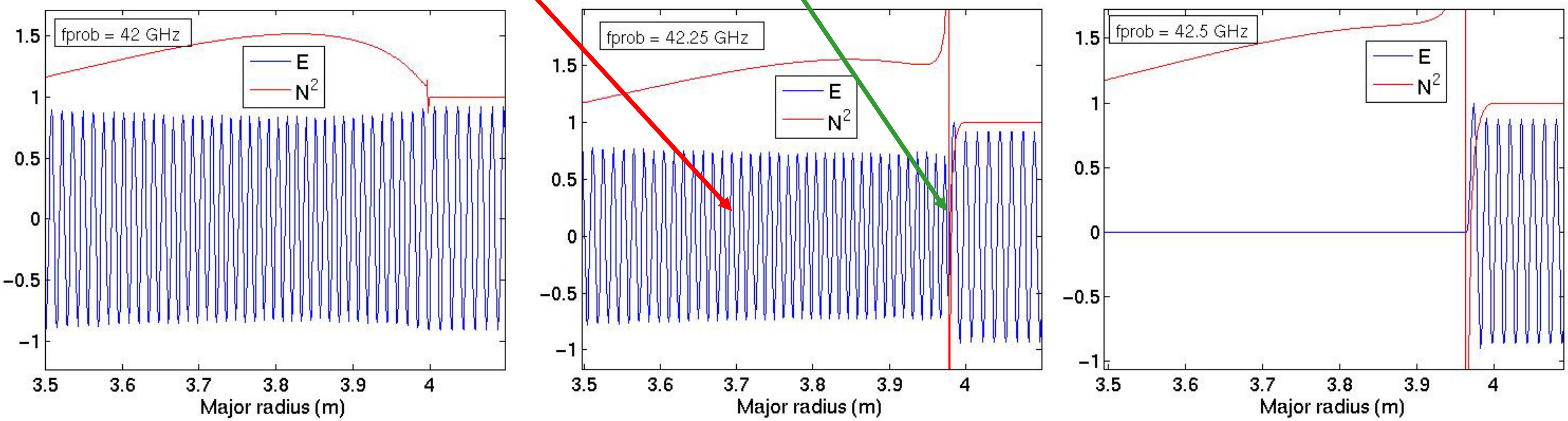
Determination of the first fringe

- full-wave simulations show that, in the vicinity of the first fringe,

part of the probing wave is reflected while

another part propagates by tunnel effect and is reflected by the back-wall

no plasma reflection | *intermediate case* | *reflection at upper cut-off*



- **this induces an error on $\varphi(f_0)$** to be assessed by time-dependent full-wave code

Spatial resolution of the KG8a diagnostic

In H. Bottollier-Curtet *et al*, *Review of Scientific Instruments* **58**, 539 (1987)

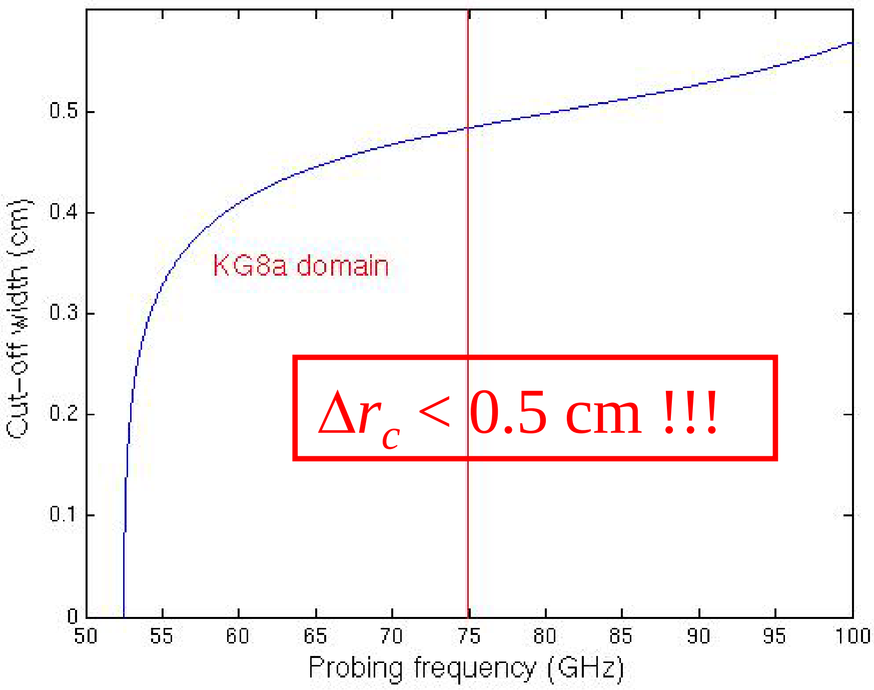
$$\Delta r_c = 1.5 \left(\frac{c}{2\pi f} \right)^{2/3} \left(\frac{dN_X^2(f, r_c)}{dr} \right)^{-1/3}$$

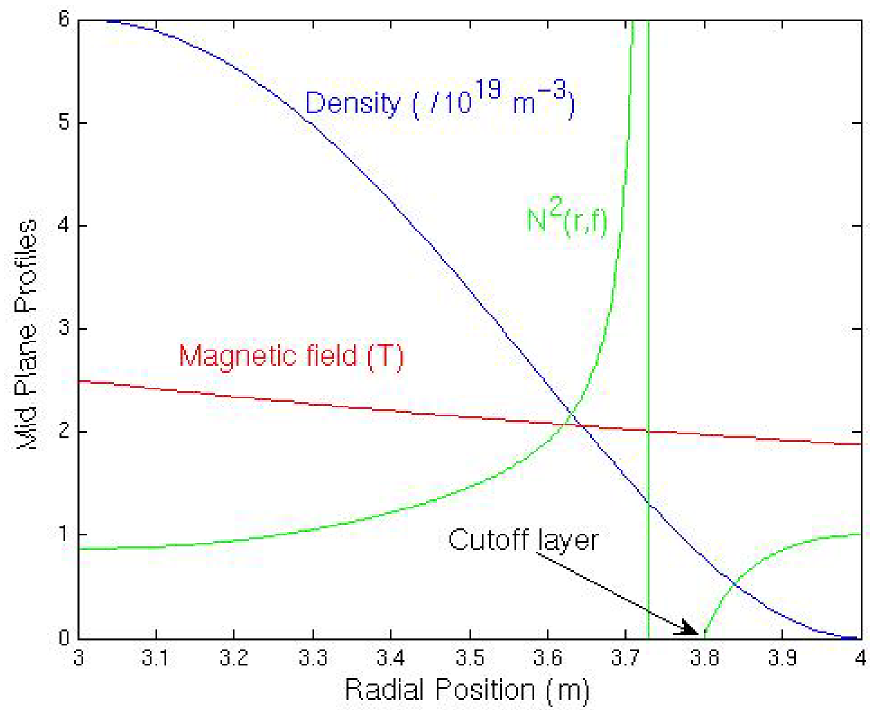
Example for typical JET parameters

=> peaked density profile (L-mode)

=> $B_t \cong 2.5$ T

$$N_X^2(f, r) = function\,(n_e(r),\ B(r),\ f)$$



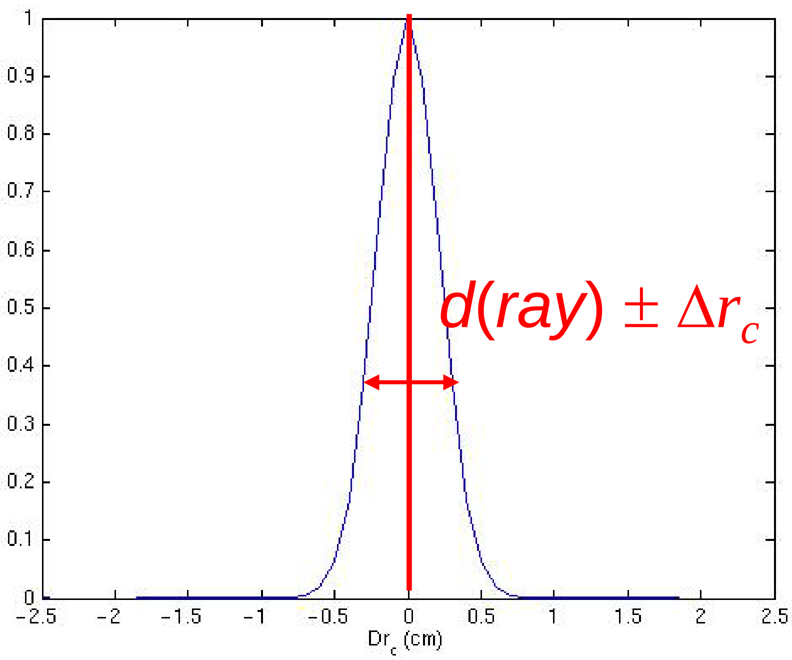


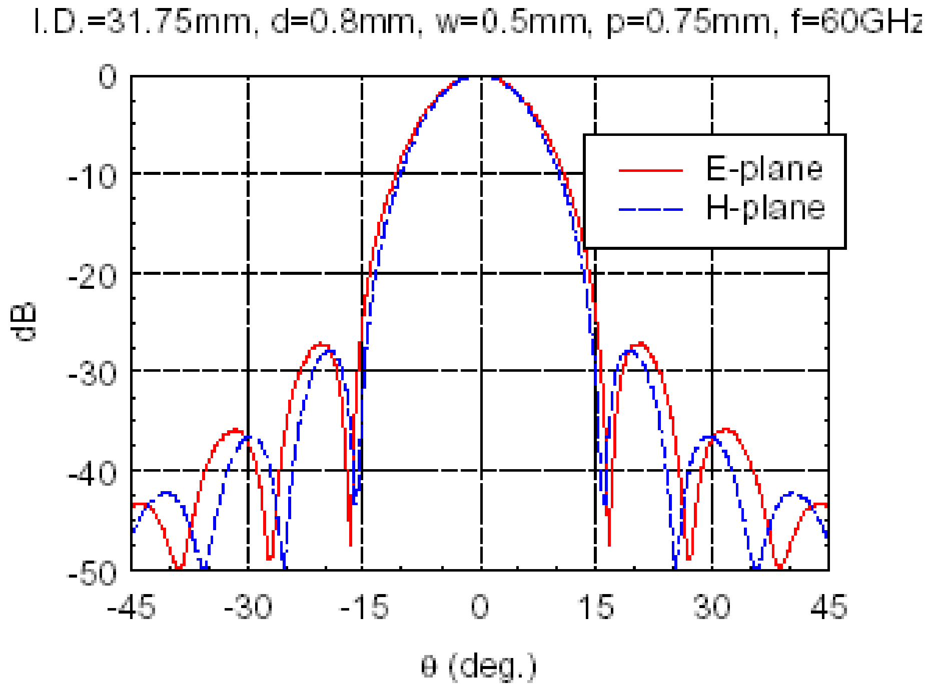
Influence of the antenna radiation pattern

Each ray propagating from the emitting antenna to the receiving one:

- travels a different distance $d(ray)$ which can be determined with a precision $\Delta r_c < 0.5$ cm

- has a different weight $I(ray)$ depending on the radiation pattern of the emitting and receiving antennas





Spatial resolution of the KG8a diagnostic

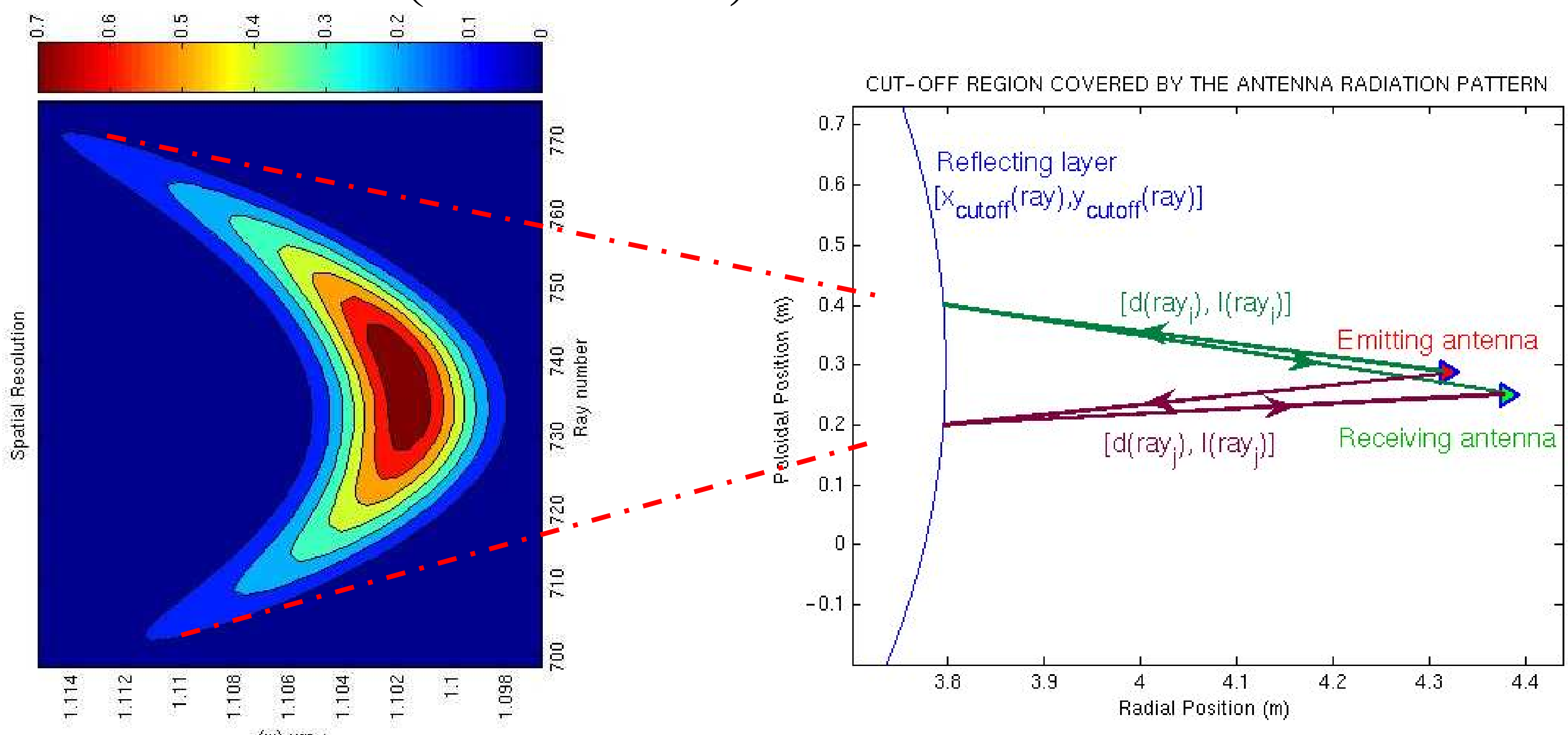
Distribution of the distances travelled by all the rays:

$$dist(r,ray) = I(ray).\exp\left(-\left(\frac{r-d(ray)}{\Delta r_c}\right)^2\right)$$

Each ray is defined by:

- a travel distance *d*(*ray*) $\pm \Delta r_c$

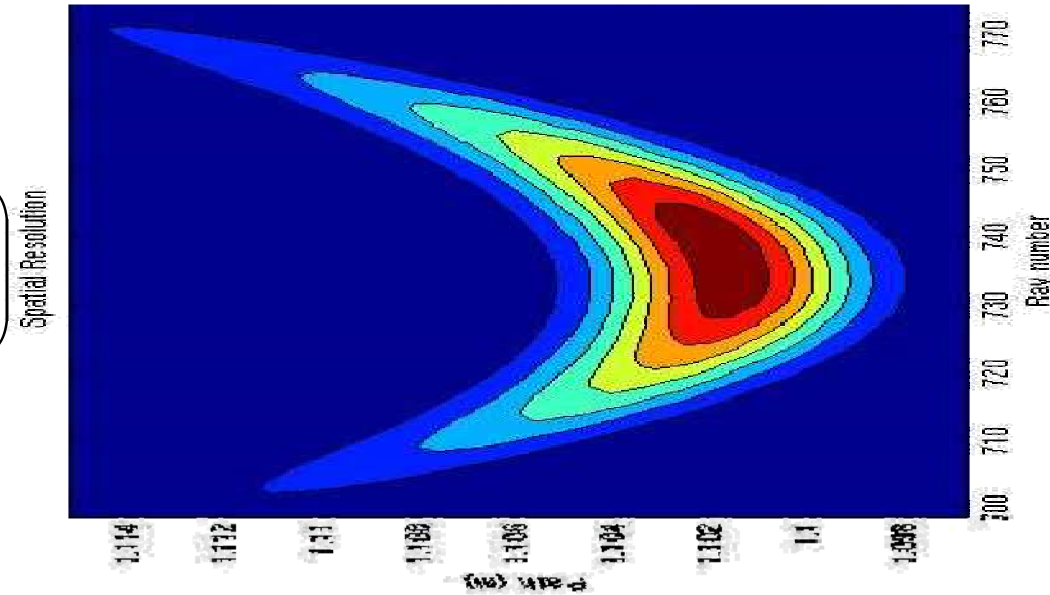
- a weight *I*(*ray*) = *I*(θ_{emit}) x *I*(θ_{rec})



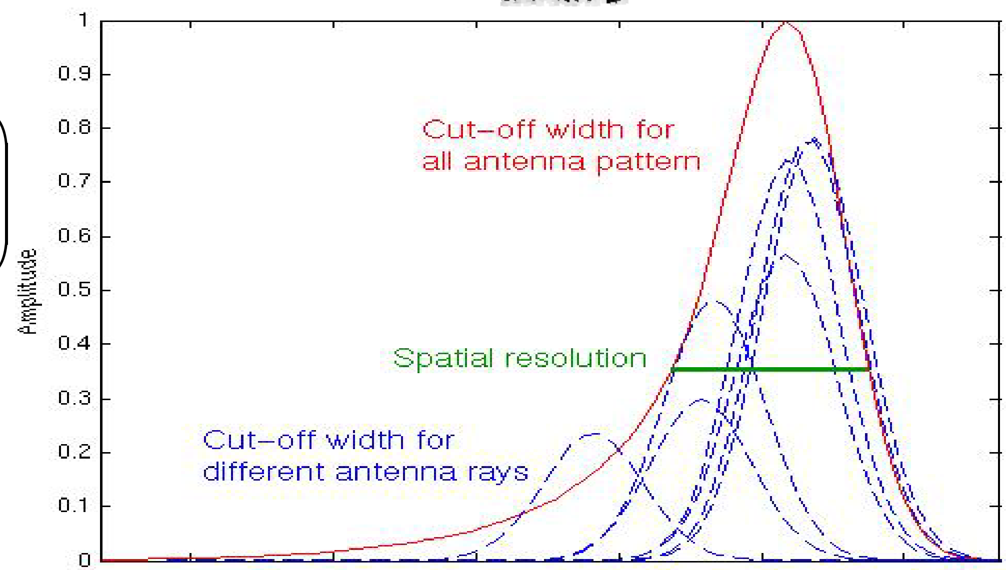
Estimation of the global spatial resolution

Distribution of the various distances for a typical JET geometry

$$dist(r,ray) = I(ray).\exp\left(-\left(\frac{r-d(ray)}{\Delta r_c}\right)^2\right)$$



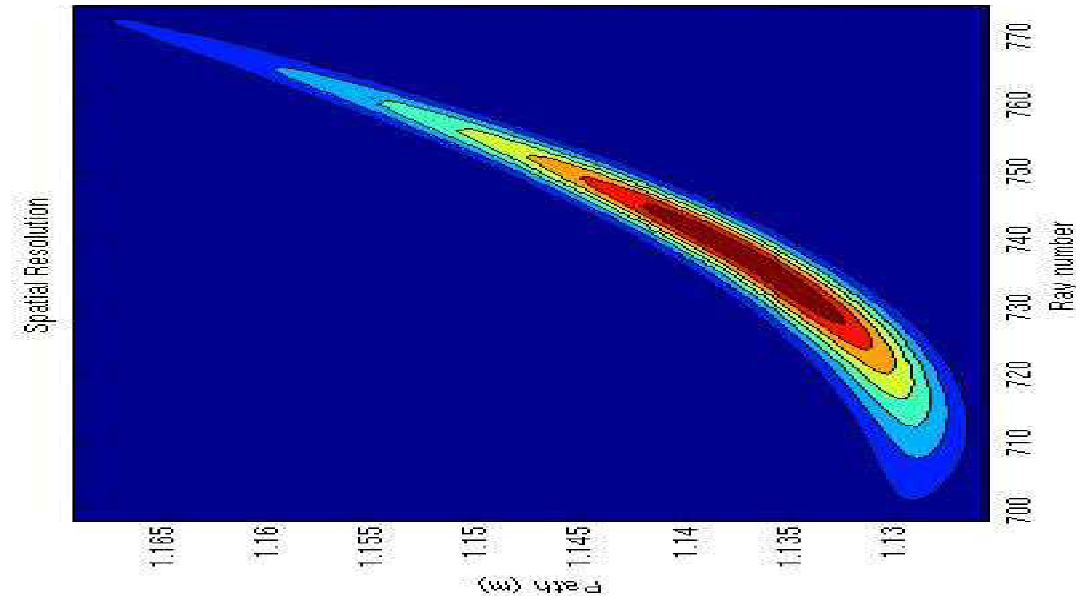
$$\Delta d(r) = \sum_{ray} I(ray).\exp\left(-\left(\frac{r-d(ray)}{\Delta r_c}\right)^2\right)$$

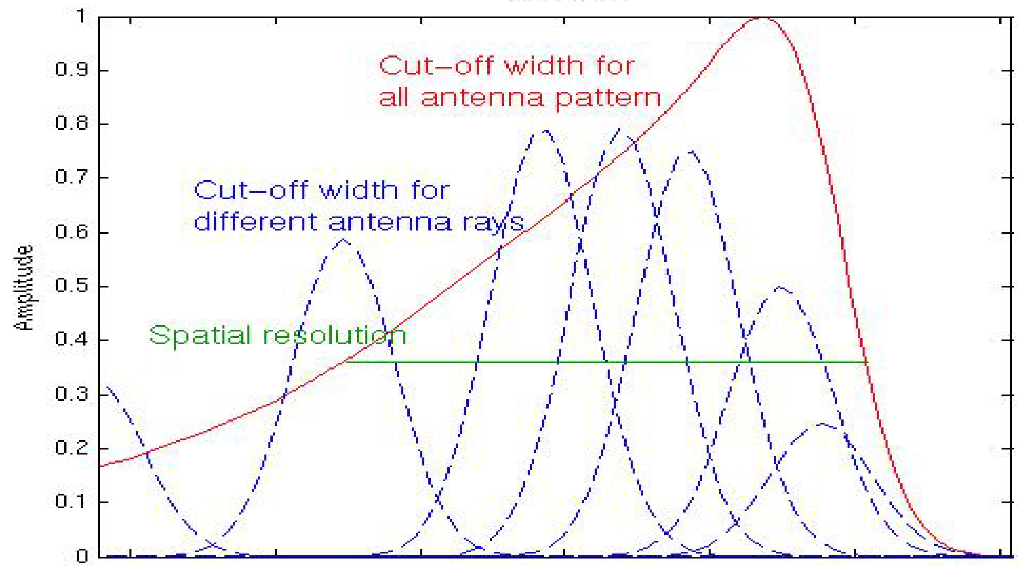


Assuming the plasma mid-plane is centred with the antenna axis, the spatial resolution is about 0.7 cm !

Antenna misalignment with the antenna mid-plane

Broadening of the distribution of the distances travelled by the various rays





For a plasma displacement of about 30 cm with respect to the antenna axis, the spatial resolution gets worse and is about 1.8 cm !

Antenna misalignment with the antenna mid-plane

The spatial resolution remains better than 1 cm
for almost 98% of the JET discharges !!!
(statistic done on more than 1000 shots in 2004 campaign)