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Optimum Beam Diameter for Microwave Reflectometer Measurements

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Abstract

Simulation results of the reflectometer phase and power sensitivity from a two-dimensional physical optics model show that a tightly focused reflectometer beam is most appropriate for fluctuation measurements, while a larger beam diameter appears more appropriate for density profile measurements.

Microwave reflectometry has two diagnostic applications for fusion plasmas. It can be used to measure the electron density profile using swept or multiple microwave frequencies, and it can be used to measure density and magnetic field fluctuations [1]. In many cases the same diagnostic apparatus has been used for both purposes. However there appears to be some uncertainty over the most suitable reflectometer beam diameter for each type of measurement.

For density profile measurements, signal fluctuations due to plasma turbulence are undesirable as they can lead to phase jumps and errors in the profile reconstruction. One approach to minimizing the effects of fluctuations is ultra-fast sweeping of the microwave frequency. Here the whole profile is measured in a time scale short compared to the turbulent fluctuations. While the fluctuations maybe frozen in the temporal domain, the reflection layer can still contain large spatial inhomogeneities - again leading to errors in the mean measured phase.

Now, the question addressed here is whether there is an optimum beam spot size which minimizes the spatial fluctuation effects for the profile measurements, and, whether this is the same optimal beam size for fluctuation measurements.

A two-dimensional (2D) physical optics model of reflectometry is used to study this problem. The results indicate that a narrow or tightly focused beam is better for fluctuation measurements as it gives the maximum phase response over the largest possible range of fluctuation wavelengths, while a large beam diameter is more appropriate for profile measurements as it involves greater averaging of the spatial fluctuations. However these observations arise only from consideration of the phase and power sensitivity, as discussed later there are other experimental factors that may affect the choice of optimum spot size.

The physical optics model was used previously to study the reflectometer's response to coherent modes and turbulence [2,3]. The model is based on the experimental observation that the microwave reflection is highly localized and is dominated by plasma perturbations in the immediate vicinity of the cutoff layer. This allows the reflection layer to be modelled as a thin distorted conducting surface. The Helmholtz integral is then used to calculate the phase and amplitude of the scalar electric field of the reflected microwave beam from this layer.

To study the effect of varying the beam width a simplified geometry can be assumed.The microwave beam is modelled as a paraxial Gaussian beam with a circular cross section and a 1/e amplitude radius of *w* at the reflection layer. The beam is normally incident on the layer and only the normal backscattered signal is considered (the idealized monostatic reflectometer geometry). The receive/transmit antenna is placed beyond the far-field limit of both the fluctuations and the antenna aperture, a condition usually met for the majority of large scale experiments. Also, by normalizing the scattered electric field by the specularly reflected field from a smooth surface (to give a scattering coefficient ρ) the range dependence is removed. Plasma refraction can bend the beams and spread the beam profile, but for this study refraction can be ignored.

The plasma perturbations are modelled as sinusoidal ripples of amplitude *h* and wavelength Λ, aligned along, and moving transverse to the magnetic field lines (i.e. in the poloidal direction).

For normal incidence and backscatter the scattering coefficient is given by [2]:

$$\rho = \frac{-R \int_{-3w}^{3w} exp(-2x^2/w^2)\ \exp\ i(-4\pi\zeta/\lambda)\ dx}{\int_{-3w}^{3w} exp(-2x^2/w^2)\ dx} \qquad (1)$$

x is a transverse distance in the poloidal direction. $\zeta = h\cos(2\pi x/\Lambda + \nu)$ is the reflection layer displacement normal to the mean surface, ν is variable phase, and R is the smooth surface (Fresnel) reflection coefficient. For a perfectly reflecting surface (zero absorption) R = ± 1. The reflected power and phase are then given by:

$$P = \rho\rho^* \qquad (2)$$

$$\phi = \tan^{-1}\left\{\frac{Im\,\rho}{Re\,\rho}\right\} \qquad (3)$$

Figure 1 shows the maximum reflected power (i.e. the effective attenuation) and the reflectometer phase response as a function of the normalized transverse fluctuation wavelength Λ/λ for various fluctuation amplitudes *h*/λ for a focused Gaussian beam with $w/\lambda = 2$. The curves define three distinct wavelength regions:

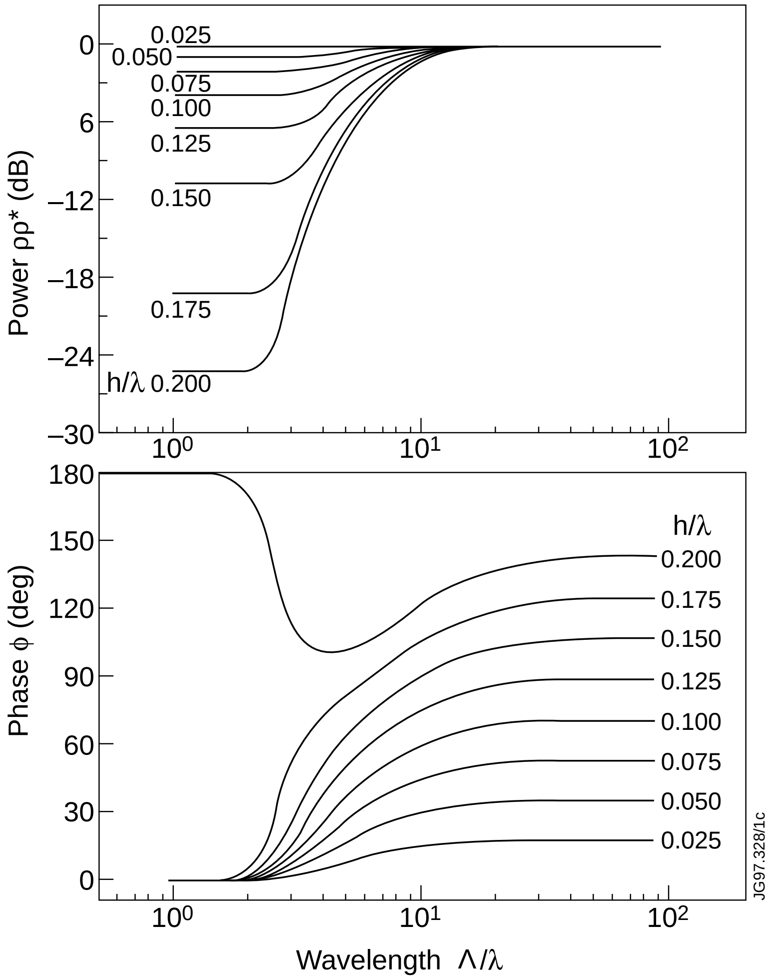

Figure 1: Maximum reflected power (attenuation) and phase response as a function of transverse normalized fluctuation wavelength Λ/λ for various fluctuation amplitudes h/λ with a tightly focused Gaussian beam w/λ = 2

(1) Long fluctuation wavelengths $\Lambda/\lambda > 10\ w/\lambda$: where the attenuation of the reflected signal is zero and the phase response approaches the one-dimensional geometric optics limit $\delta\phi = 4\pi h / \lambda$;

(2) Transition wavelengths where the attenuation and phase response is non-linear, and

(3) Short fluctuation wavelengths $\Lambda/\lambda \leq w/\lambda$: where signal the is strongly attenuated (depending on the fluctuation amplitude) and the phase response is zero.

Figure 2 shows the effect on the maximum reflected power and the phase response of increasing the Gaussian beam radius w/λ with a fixed fluctuation amplitude of $h/\lambda = 0.15$. As the beam width is increased the response curves move linearly to higher fluctuation wavelengths. Therefore, for a reflectometer viewing a broadband turbulent cut-off layer increasing the beam size means that more and more of the fluctuation wavelengths fall into the short wavelength region where their contribution to the total reflected power is attenuated and their phase shift is zero.

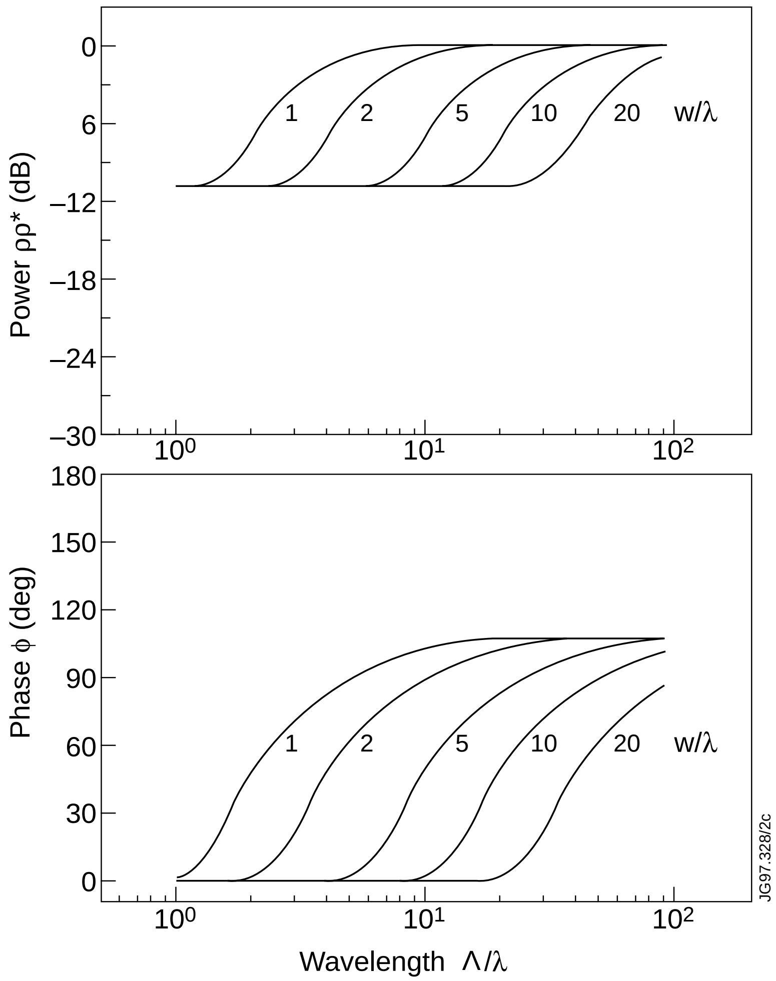

Figure 2: Maximum reflected power (attenuation) and phase response as a function of normalized fluctuation wavelength Λ/λ for various Gaussian beam widths w/λ with a fixed fluctuation amplitude $h/\lambda = 0.15$

So, for profile measurements the reflectometer could be made insensitive to short transverse fluctuation wavelengths by making the beam size as large as possible. Conversely, for fluctuation measurements the beam size should be made as small as possible so as to push as much of the turbulent spectra into the long wavelength region thus extending the wavelength coverage, maximizing the phase response and maximizing the spatial resolution.

The results were obtained for a paraxial Gaussian beam which assumes plane wavefronts across the beam diameter. This may be valid for focused beams, but less so for non-focused beams. Large diameter spot sizes arising from non-focused divergent beams are likely to have curved wavefronts leading to phase incoherency at the spot edges. Curved wavefronts are considered to be coherent across the diameter of the first Fresnel zone, whose radius s_1 is given by [4]

$$s_1 = \sqrt{\frac{\lambda d}{2}}$$

where d is the mean radius of curvature of the phase front. The first Fresnel zone essentially defines the extent of coherent backscatter from the reflection layer [5] and so places an upper practical limit on the optimum spot diameter. Making the spot width w greater than s_1 does not improve the situation for profile measurements as more microwave power is simply lost in incoherent backscatter.

As an example the JET correlation reflectometer operating at 75GHz uses horn antennas with a ploidal dimension of 4cm placed approximately 50cm from the plasma edge. This gives a rough value for the normalized Fresnel radius of s_1/λ of about 8. The actual spot radius at the plasma separatrix w/λ however is closer to 15. This highlights the fact that many diagnostic configurations are not optimized for their respective roles, indeed, for many diagnostics the spot size was not a parameter of great concern during their design.

The choice of a small beam diameter is clearly the optimum for fluctuation measurements, but the Fresnel diameter may not necessarily be the optimum for profile measurements. Although the phase fluctuations decrease with increasing beam diameter, the mean reflected power level also decreases (see figure 12 in [3]) as more power is scattered incoherently into side lobes. This means that the launched power needs to be increased to compensate. The loss of carrier strength due to enhanced scattering (and refractive effects) needs to be weighed against the benefits of greater spatial averaging on an individual experimental basis.

Situations, such as the ITER reflectometers, where the antenna systems will be used for both profile and fluctuation measurements [6], will necessarily involve compromise. The best option may, in fact, be to maximize the returned power and use other means of minimizing the phase fluctuations in profile measurements: Such as temporal averaging, although this presumes that the phase fluctuations behave linearly and will average to zero; or averaging over small steps in the microwave sweep frequency - at the cost of greater phase ambiguity and reduced radial resolution. Such choices however can only be made after a systematic experimental investigation of the effects of beam size on the measured turbulence levels and characteristics.

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