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Sensor for plasma density profile measurement in magnetic fusion machine

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Abstract

A method is presented for the measurement of the electron density in an experimental plasma fusion device by means of microwave reflectometry. Since microwaves with increasing frequency can penetrate deeper into the plasma, it is possible to sample the electron density distribution by frequency-sweep techniques. For the first time the system allows a non-contact measurement of the electron density profile in the outermost region of a magnetically confined plasma without separate calibration. The influence of strong electron density fluctuations of up to 50% with frequencies up to 500 kHz has been eliminated by a fast sweep from 60 to 80 GHz with a sweep time of about 150 µs. In connection with microwave plasma heating experiments at 2.45 GHz, the theoretically predicted dependence of the reflection coefficient of the heating wave on the electron density has been confirmed.

1. Introduction

A possible future energy source is controlled nuclear fusion. Huge amounts of thermal energy can be set free by burning the hydrogen isotopes deuterium (d) and tritium (t) to helium. This thermal energy, in turn, can be converted into electrical energy. As no material walls can sustain the temperatures needed to achieve ignition, a different method of confinement must be found. One possibility is to use strong toroidal magnetic fields in a so-called tokamak (Russian acronym for a toroidal chamber with magnetic coils).

The completely ionized hydrogen isotopes form a plasma of d’, t^+ and e^-, which are held in helical orbits around the magnetic-field lines. A key parameter of a tokamak plasma is the local behaviour of the electron density, indicating the quality of the confinement. The electron density is also a critical parameter for the penetration and absorption of high-power electromagnetic waves, which are used to heat the plasma to fusion-relevant temperatures (of the order of 100 million degrees).

One way of measuring the electron density, also called the plasma density, is microwave reflectometry. Since electromagnetic waves of increasing frequency can penetrate deeper into the plasma until they are reflected, it is possible to sample the electron distribution by frequency-sweeping techniques. Broadband microwave reflectometry has previously been used to measure electron density profiles [1, 2]. In the present work, the range has been extended to the outermost part of tokamak plasmas, which is subject to very strong electron density fluctuations.

2. Principle of the measurement

The phenomenon that electromagnetic waves are reflected by a plasma is well known in the range of radio frequencies. The reflection of radio waves by free charges in the ionosphere is the basis for long-distance short-wave communication. Radio waves of higher frequency simply penetrate the ionosphere and are thus not suitable for long-distance communication. More physically, the influence of a plasma on electromagnetic waves can be understood in terms of the refractive index N, which is defined as the ratio of the wavelength in free space to the wavelength in a medium. If the electron density is increased from zero, the refractive index (for a fixed frequency) will decrease from N= 1 to N= 0 (for a critical density). This density is called the cut-off density; the corresponding frequency is the cut-off frequency. It is important to note that higher cut-off densities correspond to higher cut-off frequencies. In the presence of an external magnetic field as in the case of a tokamak plasma, there are two cut-off frequencies depending on the polarization of the microwave relative to the magnetic-field vector.

Figure 1 illustrates microwave propagation in a tokamak plasma. Figure l(a) (solid line) gives a typical

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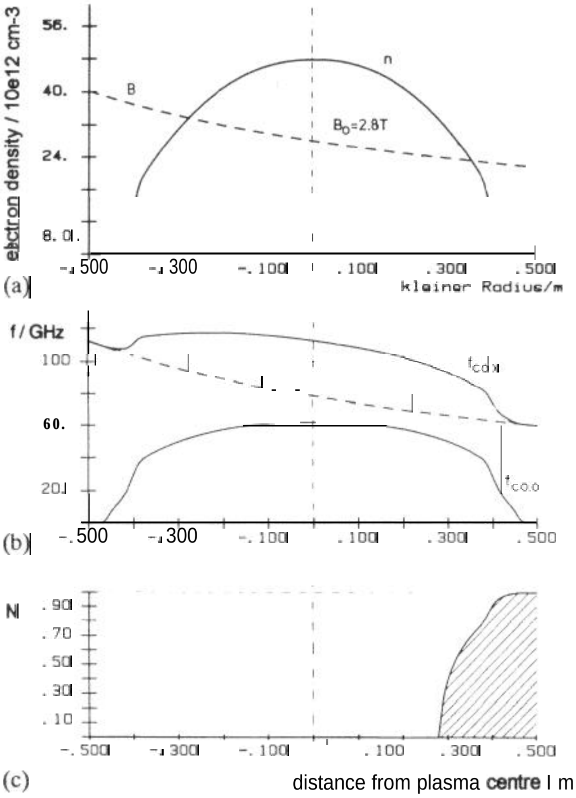

Fig. 1. Microwave propagation in a tokamak plasma: (a) typical electron density distribution *n* and magnetic-field strength ***B*** in the cross section of a tokamak; (b) corresponding cut-off frequencies for the two possible polarizations of microwaves; (c) typical value of the refractive index for a fixed frequency.

electron density profile n(x), with the maximum at the plasma centre and a very low density in the outer part close to the chamber walls. Figure 1(b) shows the corresponding cut-off frequencies for the two possible polarizations. $f_{co.O}$ is the cut-off frequency for a microwave with the E-vector parallel to the static external magnetic field. This polarization is called the ordinary mode, or O-mode. $f_{co.X}$ is the cut-off frequency for a microwave with the E-vector perpendicular to the static external magnetic field. This polarization is called the extraordinary mode, or X-mode. Qualitatively, the cut-off frequency for the X-mode is shifted up by a value depending on the magnetic field in comparison to the O-mode. For this reason the X-mode is used in the present work. The higher frequencies, and the corresponding shorter wavelengths, give a more precise measurement.

Figure 1(c) shows the local dependence of the refractive index N for a given frequency. For a given frequency the hatched area is proportional to the phase shift $\Phi(f)$ of the reflected wave:

$$\Phi(f) = \frac{4\pi f}{c_0} \int_{x_{co}}^{x_a} N(f, n(x), B(x))\, dx - \frac{\pi}{2} \qquad (1)$$

f, frequency of the microwave; c_0, speed of light; N, refractive index; x_{co}, coordinate of the cut-off point; x_a, coordinate of the antenna opening.

The integral gives the number of wave periods from the antenna to the reflection point. $\pi/2$ is obtained in a more detailed calculation, and is caused by the non-metallic character of the reflection at the cut-off point. If $\Phi(f)$ is known for the whole density profile beginning at the very edge of the plasma, the electron density profile n(x) can be calculated by numerical inversion of eqn. (1). To overcome numerical instabilities in existing procedures for the inversion of eqn. (1), a new and fast-converging algorithm has been designed [3]. Experimentally, $\Phi(f)$ can be measured by counting the interference fringes during a broad-band frequency sweep. In contrast to the well-known FMCW radar with fixed objects, the phase shift in a reflectometer is not only caused by the change in the wavelength, but also by a shift of the reflection point in the plasma.

3. Experimental set-up

Figure 2 shows the principle of the set-up. The microwaves from a sweep generator are emitted into the plasma. The reflected signal is mixed in detector 1 with part of the oscillator signal. Changes in the relative phase of the two signals lead to maxima and minima (fringes) in the output signal of detector 1. Detector 2 allows the intensity of the reflected wave to be monitored.

The reflectometer presented here has been installed on the ASDEX tokamak at the Max-Planck-Institute in Garching near Munich. ASDEX's main parameters are: major radius, 1.65 m; plasma radius, 0.4 m; magnetic field at the plasma centre up to 2.8 T. Among other means, the plasma on ASDEX can be heated by microwaves of 2.45 GHz with power levels up to 2 MW. In accordance with a resonance zone in the plasma where the microwave is absorbed, this method is called lower hybrid heating. These waves also allow a toroidal current to be driven in the plasma, a vital condition for a future thermonuclear reactor. The heating waves are coupled to the plasma by a phased array of open-

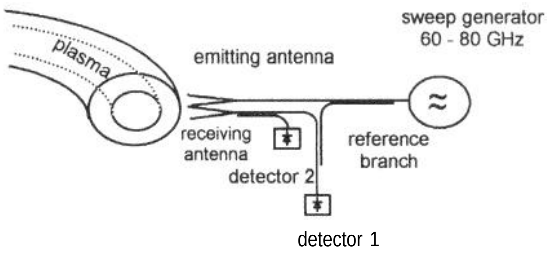

Fig. 2. Principle of the microwave reflectometer.

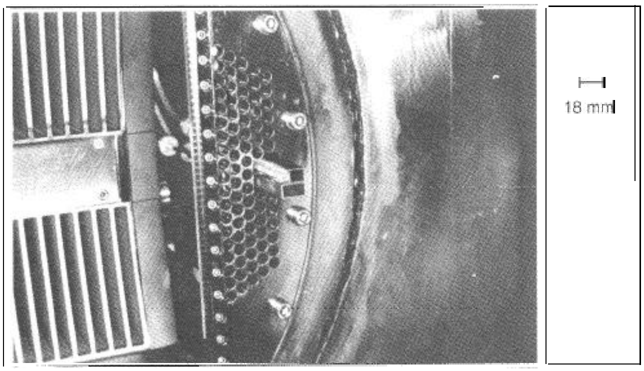

Fig. 3. Microwave born antennae for electron density measurement (centre of the photograph). The open-ended waveguide has not been used in the final configuration. The left of the picture shows part of the phased array antenna (so called grill), which is used to launch up to 2 MW into the plasma by a heating wave at 2.45 GHz.

ended waveguides in a 2 X 24 matrix, the so-called grill antenna. The probing antennae of the reflectometer are installed only 6 cm away from this grill in order to investigate the interaction of the heating wave with the plasma edge (Fig. 3).

The parameters of the reflectometer are:

microwave source:	backward wave oscillator 60-80 GHz
sweep time:	150 μs
antennae:	emitting, horn antenna with 16 mm X 10 mm opening receiving, horn antenna with 8 mm $\times$ 10 mm opening
data acquisition:	10 MHz, 12 bit resolution, 10^6 samples
microwave circuitry:	waveguides

A detailed description is given in refs. 3 and 4.

4. Results and discussion

In first tests with a slow sweep and an expected fringe frequency of 6 kHz, no clear fringe pattern could be seen,. so a phase measurement was not possible. Experiments at a fixed frequency showed that the fringes were blurred out by the strong intensity and phase modulations of the reflected signal (Fig. 4). Similar problems have also been reported in other reflectometers (see, for example, [5]). These strong modulations are caused by plasma density fluctuations, and can be described in a two-dimensional model for the microwave reflection [6]. By reducing the sweep time to about 150 ps, the fringe frequencies were shifted to between 800 kHz and 2.4 MHz. As the bulk of the fluctuations are below 500 kHz, the fringes can clearly be distinguished from the fluctuations.

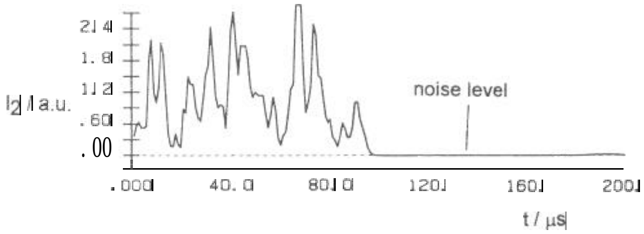

Fig. 4. Intensity of the reflected microwave as a function of time. The strong modulations are caused by electron density fluctuations.

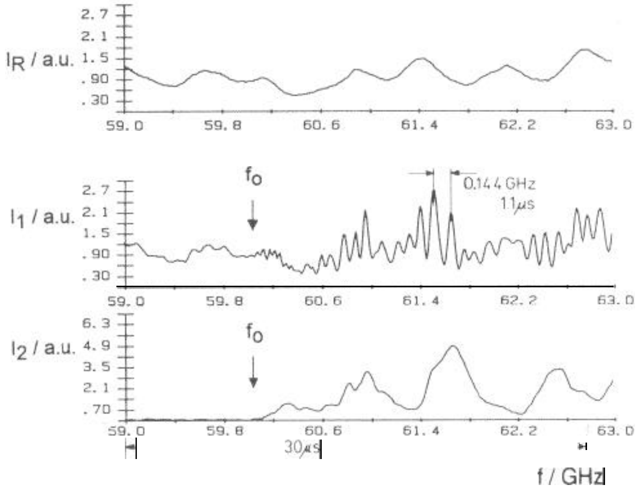

Fig. 5. Raw data during sweep operation: I_R, intensity of the emitted microwave signal; I_1, mixed signal; I_2, intensity of the reflected signal. The reflection begins at f_0, the cut-off frequency at the very edge of the plasma (see Fig. l(b)).

Figure 5 shows the raw data of the first part of a sweep. The upper trace gives the power of the microwave generator, which is a function of frequency. The lower trace shows the intensity of the reflected wave. It is clearly seen that there is only reflection for $f>f_0$ (arrow). f_0 is the cut-off frequency for the X-mode at the antenna mouth (see Fig. l(b)). In a series of experiments the first reflection could be localized within 5 mm from the opening of the antennae. As this sudden onset of the reflection exists only in the X-mode, it is not possible to perform a calibration of the measurement on the first reflection in the O-mode. This allowed, for the first time, electron density measurements with a very high precision by reflectometry, without further assumptions about the edge density profile. The second trace gives the signal of detector 1. The interference fringes are clearly seen, as they are much higher in frequency than the intensity modulations of the reflected signal (lower trace) caused by the electron density fluctuations.

Figure 6 shows the electron density profile from one sweep. Figure 7 shows 3.5 momentary profiles measured in a stationary plasma phase. The scattering of the

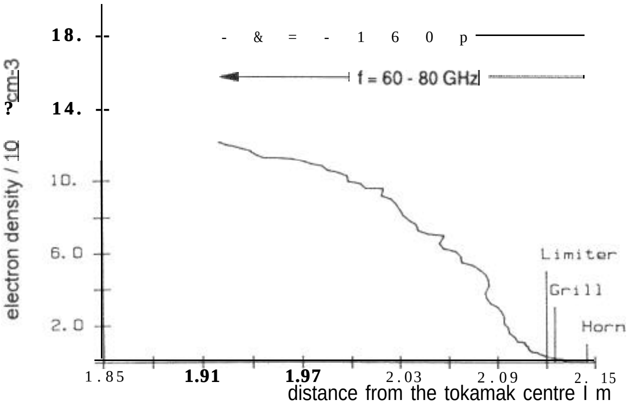

Fig. 6. Electron density profile calculated from one frequency sweep. The positions of the grill antenna, the reflectometer antennae (horn) and of a structure protecting the chamber walls (limiter) are indicated by vertical lines.

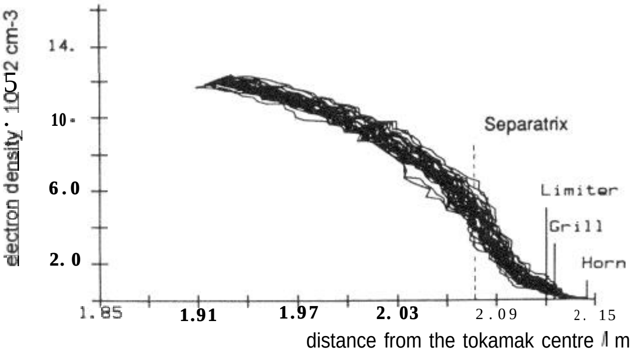

Fig. 7. 3.5 electron density profiles measured in a macroscopically stationary plasma phase. (The separatrix is the theoretical limit between the main and the edge plasma.)

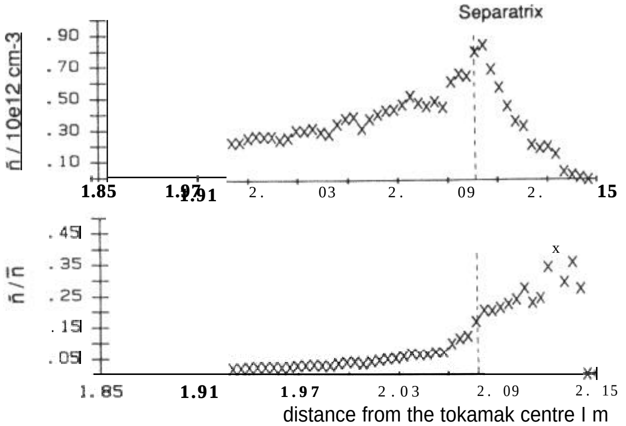

Fig. 8. Absolute and relative levels of electron density fluctuations as calculated from the data shown in Fig. 7. The maximum of the absolute electron density fluctuations coincides with the limit between the main and the edge plasma (the so-called separatrix), as predicted theoretically.

profiles is due to the strong electron density fluctuations. The absolute and relative fluctuation levels, as deduced from these profiles (Fig. 8), are in good agreement with other measurements [7]. To get reproducible profiles it is necessary to average between 10 and 40 measurements.

The most striking results were obtained in connection with plasma heating experiments by means of microwaves at 2.45 GHz. As predicted by theoretical calculations [8], the lowest reflection coefficient at the plasma periphery is achieved for electron densities of $n = 0.5 \times 10^{12}\ \mathrm{cm}^{-3}$ in front of the grill antenna. These are exactly the values measured by the reflectometer. For lower densities, almost all of the power is reflected back to the generator.

This can clearly be seen during experiments where the plasma was moved away from the grill antenna during the application of the heating wave (Fig. 9(c)) [8]. Depending on the exact experimental conditions, the reflection coefficient is kept low even for a large distance of the main plasma from the antenna (Fig. 9(a)). Under these conditions the reflectometer gives a sufficient electron density for a low reflection coefficient (Fig. 10, solid line). Under slightly different experimental conditions, a sudden increase of the reflection coefficient of the heating wave occurs when the plasma is moved away from the heating antenna

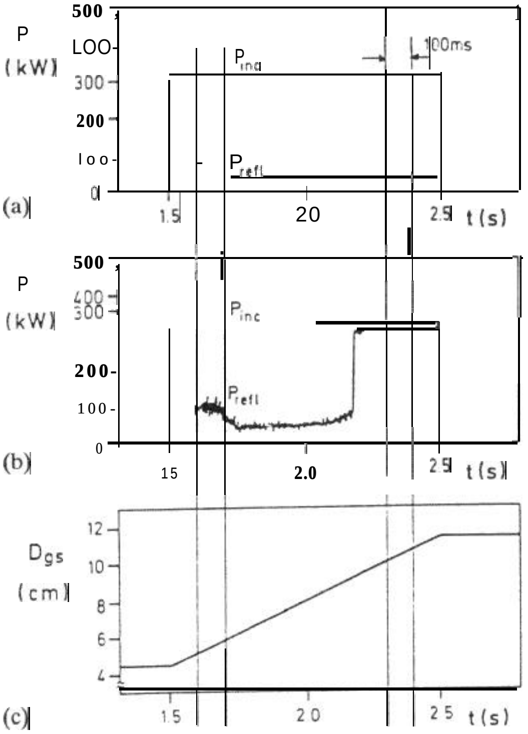

Fig. 9. Reflected power of the heating wave (P_{refl}) at 2.45 GHz in two experiments where the plasma has been moved away from the antenna; P_{inc} is the incident power. Under favourable conditions (trace (a)) a low reflection coefficient can be achieved even for a large distance between the main plasma and the heating antenna (D_{gs} = grill-separatris distance). For the two time windows, the electron density is given in Fig. 10.

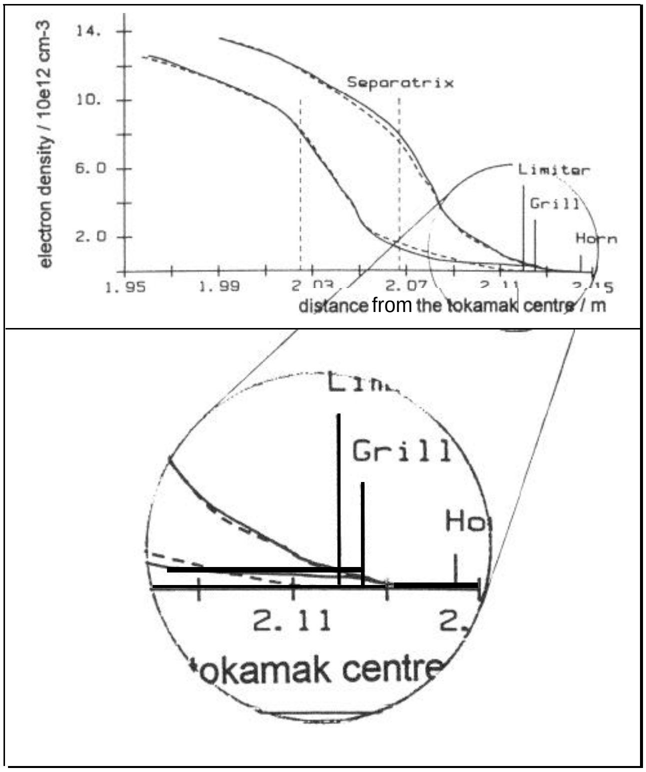

Fig. 10. Electron densities measured for two different positions of the main plasma in two experiments, where the plasma has been moved away from the antenna. Under favourable experimental conditions (solid curve) a sufficient electron density for low reflection of the heating wave (see Fig. 9(a)) can be maintained in front of the grill antenna.

(Fig. 9(b)). In this case, the electron density measured by the reflectometer dropped to very low values (Fig. 10, dashed line).

Thus, it could be confirmed that the heating wave itself can create, under certain experimental conditions, a sufficiently high electron density in front of the grill for good wave coupling. The electrons are probably set free by the ionization of hydrogen gas, which is present in the outer part of a tokamak plasma.

In a different experimental campaign an increase of the fluctuation level [9] and the formation of thermal eddies [10] at the plasma edge during application of the 2.45 GHz heating wave could be confirmed.

5. Discussion and concluding remarks

In the present work, microwave reflectometry is extended to the outermost part of tokamak plasmas, which is subject to strong electron density fluctuations. Using a very fast sweep, it was possible to make reliable measurements of the electron density profile under virtually all plasma conditions. For the first time, the polarization-dependent onset of the reflection in front of very small microwave antennae was used to calibrate the measurement. This gives a very high-accuracy reading even in the outer, low-density region of the plasma. The electron density measurements in the plasma edge allowed the confirmation of the theoretically predicted dependence on the plasma density of the reflection coefficient for microwaves at 2.45 GHz, which are used to heat up the plasma. Further, a detailed study of the influence of these heating waves on the plasma edge could be performed.

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