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Measurement of chord averaged electron density in ADITYA using 100 GHz and 136 GHz interferometers

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Abstract : The time and space-resolved measurement of chord averaged electron density in ADITYA is measured using two channels of 100 GHz and one channel of 136 GHz microwave interferometers using fringe counting technique. The resolution of measurement is $n_e = 2 \times 10^{11}$ cm^{-3} (*i.e*, one tenth of a fringe). The measured density at the central chord is in the range of 3×10^{11} cm^{-3} (plasma current = 3 kA) to 9×10^{12} cm^{-3} (plasma current = 50 kA). In general, the density profile is peaked at the center.

Keywords : Plasma density, tokamak, microwave interferometer.

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1. Introduction

The microwave interferometer technique is a well known method of measuring plasma density. This method gives line averaged electron density along the line of sight through the measurement of the phase shift in the microwave beam due to the plasma. The phase velocity of an ordinarily polarised electromagnetic wave (*i.e.* $E \| B$) travelling through a magnetised plasma depends on the density. At a certain critical density, n_e, the phase velocity become infinite, so electromagnetic waves of a chosen frequency can not propagate any more through the plasma but are reflected. A proper choice of applied frequency is made as long as electron density n_e remains smaller than cutoff density n_c. Interferometry is basically the measurement of the phase change due to the presence of plasma. If the plasma density is nonhomogeneous and has a certain spatial distribution (*i.e.* parabolic) a wave passing through the plasma undergoes varying refractive effects all along its path and may therefore not travel along a straight line. The resulting angle of refraction depends on the chosen frequency, on the values of n_e/n_c, and on the spatial variation of n_e. For this reason the wavelength of the probing beam should be chosen far away from cut-off, *i.e.* as short as possible, but still within the range where the phase changes, due to the presence of plasma, are still detectable. Interferometry may yield density profiles when applied along a number of (parallel) chords. Since line integrated densities are measured, one must unfold the interferometric information, *i.e.* by Abel invertion, to find the local density. Two microwave interferometers at 100 GHz and 136 GHz, with critical density of 1.24×10^{14} cm^{-3} and 2.29×10^{14} cm^{-3} respectively, have been installed in ADITYA to measure the plasma density. In this paper we present the density measurement using fringe counting technique. One of the problem encountered in such a technique is that the decoding of phase shift from the detector signal is not unique, since the signal at the detector has a component proportional to the cosine of ϕ. Therefore, the peak of the electron density can not be detected unambiguously. Hence, we assume that time of plasma current peak is the time of plasma density peak. In future we shall use the unambiguous technique of plasma density measurement using 4 steps stair case modulation of the microwave source power [1]. The total duration of each steps will be of 25 μs. In this method, the staircase repetition rate should be fast compared to the rate at which the phase shifts by a full fringe.

2. Basic principle

An interferometer is in fact used to measure the difference in path length between a reference beam, which is kept constant in path length, and a beam transmitted through the plasma. The path length through the plasma varies because of the change in refractive index, connected with the increase and decrease of the electron density. The phase difference ϕ, between the two beams, caused by the presence of plasma is given by [2].

$$\phi = (e^2 / 2\varepsilon_0 m_e \omega c)\int_0^l n_e(x)dx \qquad (1)$$

For a path length l, the averaged electron density can be written as

$$n_e = (2\theta_0 m_e c / e^2)(\omega\phi / l) \qquad (2)$$

where ω is the source frequency.

For a square law detector the current is proportional to the square of microwave voltage at the diode terminals and thus to the microwave power. Hence, the detector signal, which is the sum of the reference and the transmitted signal can be written as [3],

$$S(t) = (A^2+B^2)/2 + AB\cos(\phi(t)) \qquad (3)$$

where A and B are the amplitude of the signals in the reference and transmitted paths, ϕ is the phase shift due to plasma. By knowing the phase shift ϕ due to the presence of plasma [eq. (3)], the averaged electron density is calculated with the help of eq. (2).

3. Experimental setup

(a) Two channel 100 GHz interferometer :

The schematic of the two channels 100 GHz interferometry setup is shown in Figure 1. Extended Interaction Oscillator (EIO) at 100 GHz with an output of 10.5 W is used and the

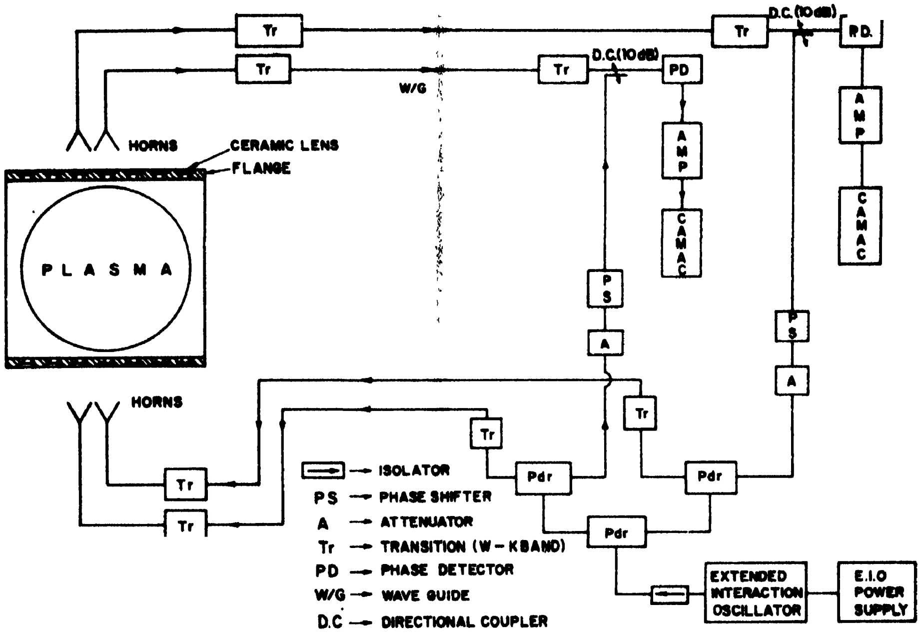

Figure 1. Schematics of the two channel 100 GHz microwave interferometer set up.

output power of the source is divided in two channels by using power dividers. From each channel one output is taken to one of the horns at the bottom port and the other output as reference channel is directly connected to the mixer housed at the top of the cabinet. At the bottom of the cabinet the EIO is housed. The cabinet is situated 6.5 meters away from the plasma center. The receiving horns are placed at the top port of vacuum vessel. The distance between the transmitting and receiving horns is 1.05 m. The horns (beam width = 5 degree) of all the channels are separated radially by 7 cm to each other, hence, there will be cross talks between the channels. Therefore, the machinable ceramic lenses are fitted on the cover flange which focuses the microwave beams and are also used as vacuum windows. The waveguide horns alongwith their supports are isolated electrically from the vacuum vessel and other supporting structures. The loss in W-band (WR-10) waveguide is 5 dB/m and in the oversized waveguide K-band (WR-42) at 100 GHz is 1 dB/m. Therefore, the oversized waveguide (WR-42) of 20 m length is used in plasma path of each channel to reduce the losses in the waveguide paths.

Transitions from W-band (WR-10) to K-band (WR-42) are used for each channel on the either sides of plasma path. The electrical breaks are provided at a regular interval in each channel in the K-band waveguide and their supporting structure to avoid close loop for eddy current. Waveguide type WR-10 is also used for reference channels. The phase detector are made of 10 dB directional couplers, detectors and detector mounts. A fixed attenuator (20 dB) and a variable attenuator (0-30 dB).are connected in reference channel to match the power in both the paths. A variable phase shifter (0-360 degree) are connected in each reference channel to adjust the phase difference to zero between the reference and plasma path before the plasma shot. The difference in the length between the two paths is about 20 meters.

(b) Single channel 136 GHz interferometer :

A single channel conventional microwave interferometer at 136 GHz is also used to measure the central chord plasma density. This measurement will be used in feedback loop of gas feed valve to keep plasma density constant. The source is a Klystron with an output of 115 mW. The transmitting and receiving horns are mounted on the same port, toroidally shifted by 60 mm from the central chord of 100 GHz transmitting and receiving horns respectively. The output of source is first carried by F-band (WR-8) waveguide and then carried by oversized waveguide K-band (WR-42). The returned power is propagated in a similar way.

(c) Data acquisition :

The output of the detector is amplified by using a low noise amplifier (noise figure = 4 dB). The output of the amplifier is fed to CAMAC digitizer through opto-coupler. We use a digitization rate of 40 kHz. The phase shift ϕ and density n_e are computed using eqs. (3) and (2) respectively.

4. Results and discussions

The present set up of microwave interferometers have one 136 GHz interferometer channel for measuring plasma density at the central chord (plasma major radius R = 0.75 m) and two 100 GHz interferometer channels, one at the central chord and the other shifted by 7 cm towards the inboard side of the torus (R = 0.75 m, a = 0.25 m). The plasma density was measured in various discharges with different fill gas pressure, vertical magnetic field, breakdown voltages and current rise rate.

The measured phase shift (fringes) and corresponding density in a typical ADITYA discharge is shown in Figure 2. The detector output of the interferometer is a D.C. voltage. Using phase shifter, which is used in reference path of interferometer, the phase difference between plasma path and reference path is kept zero before the plasma shot. During the plasma shot, plasma comes in between the transmitting and receiving horns of the plasma path and introduces a phase difference. The microwave detector signal varies from 0 degree to 180 degree phase shift. The signal is acquired by Camac data acquisition system with a digitization rate of 40 kHz. Figure 2 shows detector output after a software smoothing 0.1 ms. The chord averaged electron density is obtained by software implementation of eq. (2). The total experimental error in the density measurement is about 10%. Initially, the density increases rapidly, hence, we get fast fringes. From 3 to 6 ms detector output remains constant leading to constant density during this period. After 6 ms, we again get regular fringes. In the falling part of density, we observe very fast fringes leading to sharp fall in the density.

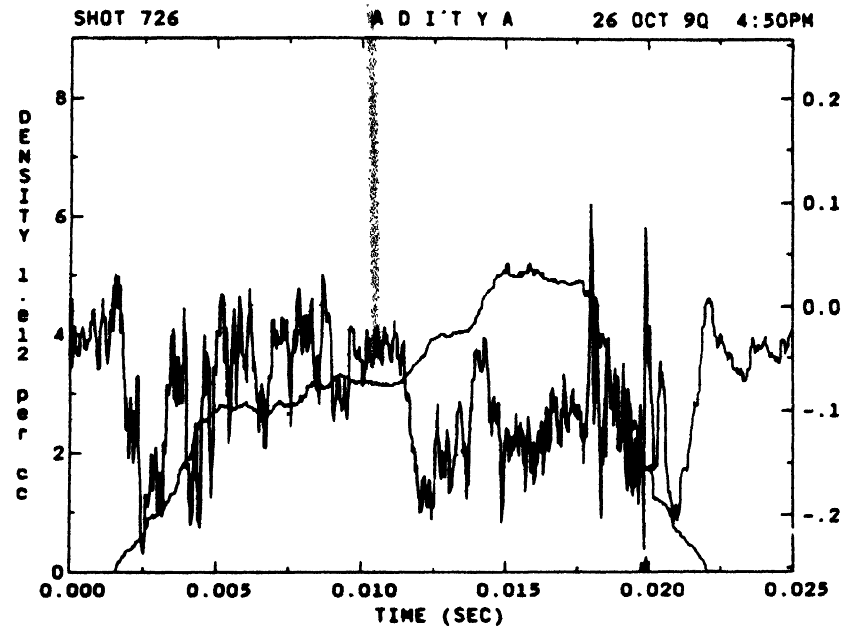

Figure 2. The fringes and the corresponding density as a function of time for a typical ADITYA discharge.

The diagnostic signatures of a typical ADITYA discharge are shown in Figure 3. The starting of plasma current, fringes, electron density, and optical signal are delayed by about 0.5 ms from the applied loop voltage. The resolution of fringe shift is 1/10 of a fringe corresponding to electron density of 2×10^{11} cm^{-3}. In the fringe shift data, the peak of the density can not be detected unambiguously. Therefore, we take the plasma current peak as also the peak of plasma density. It is observed that the plasma current falls very fast (time scale about 1-2 ms) where as the density is typically 2-3 ms longer.

Figure 4 shows peak plasma density and time delay in starting of the density (2×10^{11} cm^{-3}) after switching of ohmic transformer as a function of pressure. Plasma density increases with increasing pressure (left block in Figure 4). The time delay in starting of the density is 0.5 ms for pressure in the range of 8×10^{-5} torr to 1.2×10^{-4} torr. For pressure lower than 8×10^{-5} torr the delay time increases with decreasing pressure. The time delay increases with increasing pressure for pressure exceeding 1.2×10^{-4} torr. The time delay in density behaves just like the time delay in plasma current and optical signal [4].

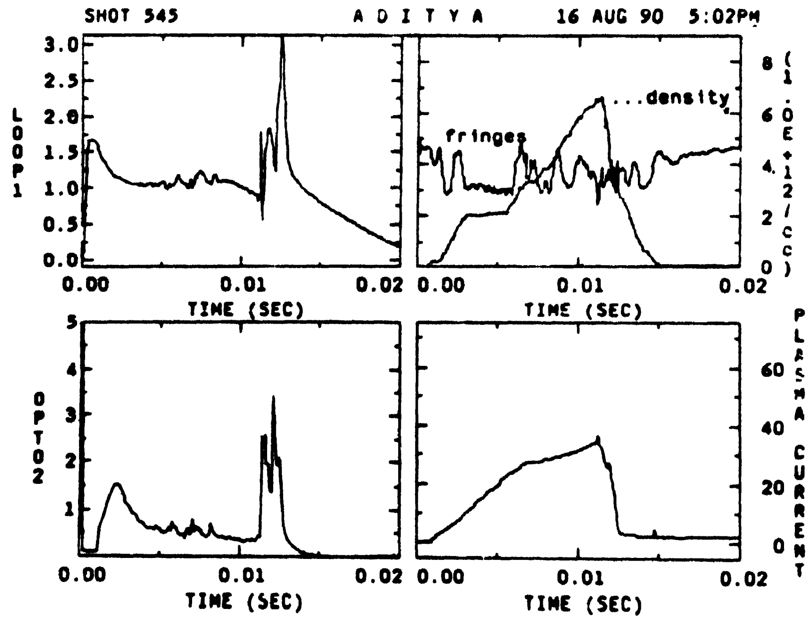

Figure 3. The loop voltage, fringes, plasma density, optical signal and plasma current for a typical ADITYA discharge.

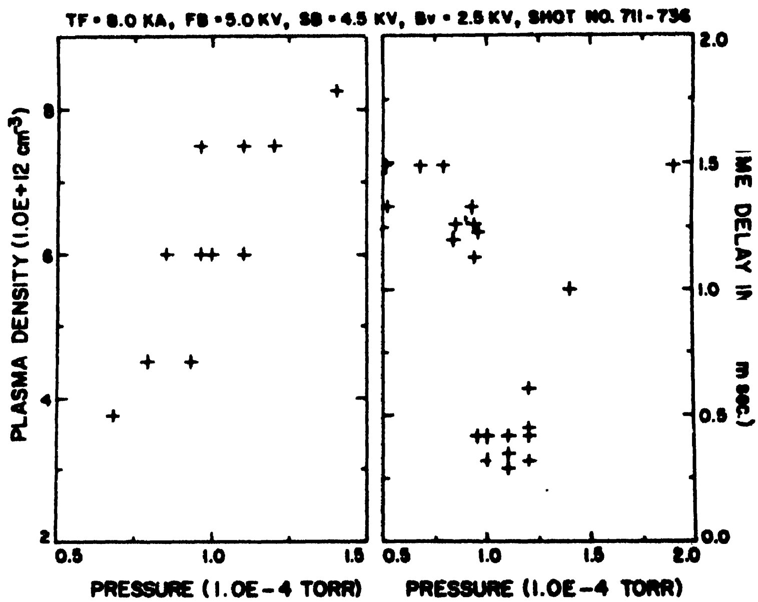

Figure 4. Left block : the average plasma density as a function of fill pressure with constant toroidal magnetic field, loop voltages and vertical magnetic field. Right block : The time delay in starting of the density with respect to loop voltage as a function of fill pressure with constant magnetic field, loop voltage and vertical magnetic field.

Figure 5 shows the plasma density as a function of plasma current for different pressure. Initially the plasma current and plasma density rise linearly. However, with plasma current exceeding 10.0 kA, the behaviour of density rise is different from that of the current. While rise in the plasma current continues, the density build up stops for 3 to 7 ms (Figure 5). The density remains constant upto 25 kA current. After 25 kA current, the density rise is again observed. The above feature has been observed in most of the ADITYA discharges. It may probably be due to shift of the plasma position. However, in the absence of position measurement/control of the current channel, it is difficult to determine the exact cause. In ADITYA shots with plasma current I_p > 10 kA, it is observed that the density duration is greater than the current duration by 1 to 3 ms. This may probably indicate the characteristic residence time of electrons in the torus. Generally, time duration of plasma density matches with the time delay of optical signal (Figure 3).

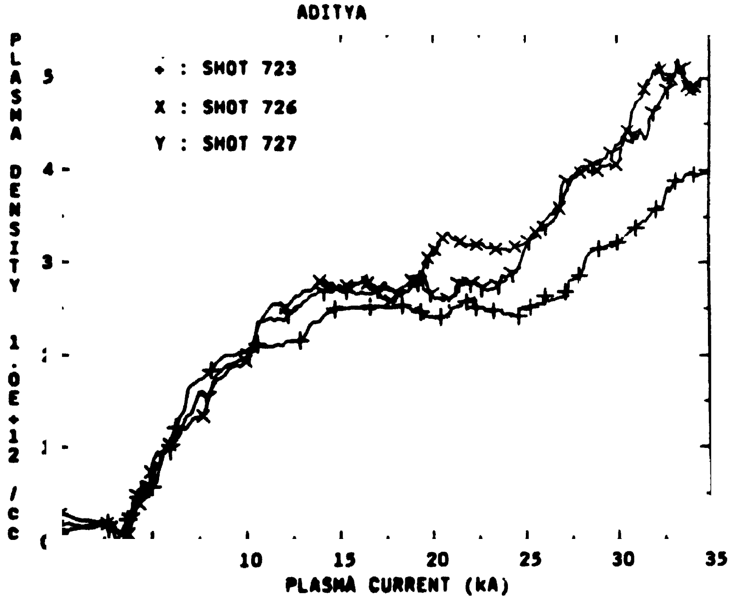

Figure 5. The plasma density as a function of plasma current.

At different initial gas fill pressures, the radial profile of the density are shown in Figure 6. In this, we have used the density measured by two channels 100 GHz microwave interferometer, at the central chord (major radius R = 0.75 m) and a chord shifted by 7 cm towards inboard side from the central chord, and two Langmuir probes placed at the limiter radius, R = 0.5 m and R = 1.0 m but 72 degree toroidally shifted from the limiter. In most of the shots shown in the Figure 6, the plasma density is higher at the central chord (R = 0.75 m) expect one, in which the density is higher at the inboard side of torus (R = 0.68 m). It may indicate shift in the plasma column towards inboard side of torus.

The operation regime of ADITYA has been shown in the conventional Hugill diagram (Figure 7). The lowest $q(a)$ is about 2 and the maximum value of the Murakami parameter

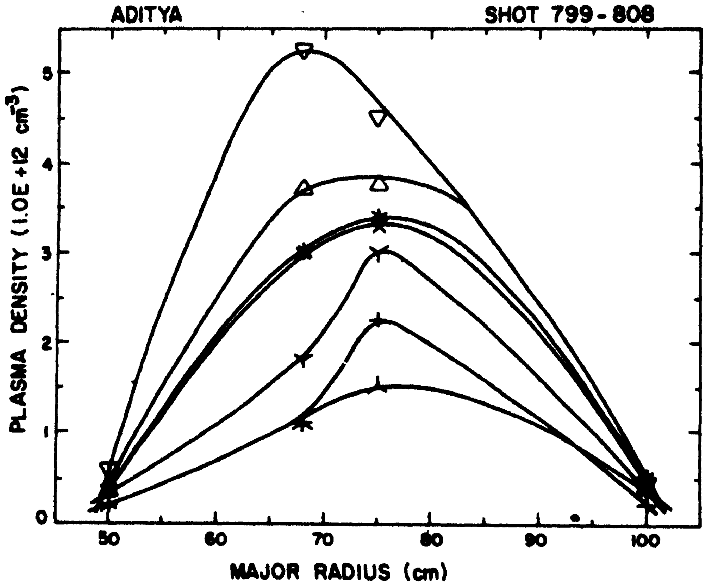

Figure 6. Radial profile of plasma density (two channel of 100 GHz) at major radius R = 0.75 m and R = 0.68 m, and two channels of Langmuir probe at R = 0.5 m and R = 1.0 m, toroidally shifted by 72 degrees from the limiter.

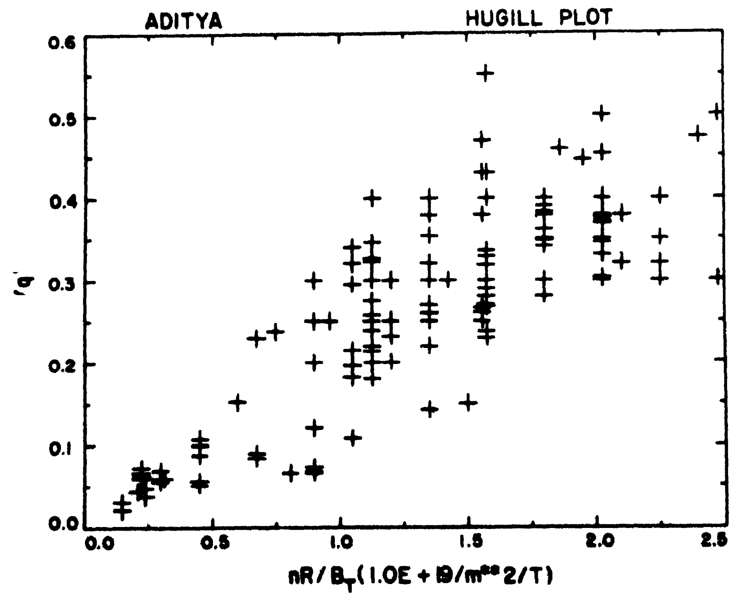

Figure 7. The Hugill plot of normalised plasma density (n_eR/B_T) and normalised plasma current ($1/q$). The boundary lines are not delineated.

(n_eR/B_T) is $2.5 \times 10^{19} m^{-2} T^{-1}$. These experiments were not conducted specifically to determine the limits of ADITYA operation. So far we have not observed any major disruptions and so the boundary between stable and unstable discharges is not delineated in this diagram.

References

[1] D Bora and P K Atrey 1988 *Rev. Sci. Instrum.* 59 2149

[2] M A Heald and C B Wharton 1978 *Plasma Diagnostics with Microwaves* (New York : Wiley) p 121

[3] D Bora, R Jayakumar and M K Vijayashankar 1984 *Plasma Phys. Control. Fusion* 26 853

[4] P K Atrey, S B Bhatt, D Bora, B N Buch, C N Gupta, K K Jain, R Jha, P I John, P K Kaw, A Kumar, V Kumar, S K Mattoo, C Natarajan, H A Pathak, H R Prabhakara, H D Pujara, C V S Rao, D C Reddy, K Sathyanarayana, Y C Saxena, G C Sethia, A Varadharajulu, P Vasu and N Venkataramani 1992 *Indian J. Phys.* 66B 481