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Study of Electron Density and Pressure Profile Behavior in a Tokamak Plasma

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Abstract

Simultaneous determinations of local electron density and magnetic flux surface in a tokamak plasma have been made feasible with multichannel interferometry using a new asymmetric Abel inversion method. This new method takes advantage of interferometry by measuring the electron density profile as a function of time. The derived electron density parameters, such as the total number of electrons, peak density, and the profile shape factor, have been extremely useful in tokamak plasma experiments. In addition, by using measured time-dependent electron temperatures from electron cyclotron emission, similar parameters for the electron pressure can be studied.

In a tokamak plasma, electron density has been measured mainly either by Thomson scattering^{1,2} or interferometry.³⁻⁵ A distinct advantage of multichannel interferometry is that it can measure the electron density profile continuously with excellent time resolution and relative simplicity compared to Thomson scattering. However, in the past a disadvantage resulted from uncertainties in the deduced local density from Abel inversion of the chordal data. A few asymmetric Abel inversion methods^{6,7} were proposed, but extreme caution was needed to interpret the inverted results. Furthermore, often the inverted data from the same line density measurements were significantly different depending on the method used. In order to make interferometric measurements more useful, a reliable inversion method was developed to analyze interferometric data from the Tokamak Fusion Test Reactor (TFTR). In this paper, a summary of different inversion methods is presented, and problems encountered with the old methods and advantages of the new method are discussed. A detailed description of the new asymmetric Abel inversion method and problems of the old methods are given in Ref. 8. The usefulness of multichannel interferometric measurements for various plasma conditions is also demonstrated in this paper. The flux surface and local density calculated with this method can be combined with the measured electron temperature to study the behavior of the electron pressure profile.

In order to determine precise local electron density from interferometric measurements, a self-consistent and reliable inversion method is needed. The new method developed for the TFTR multichannel FIR interferometer⁵ fulfills this need and demonstrates the usefulness of interferometry as an

electron density diagnostic. The inconsistencies among local electron density measurements deduced by the old inversion methods are due to a number of intrinsic problems with each method. These problems include rigid boundary conditions, *ad hoc* assumptions about asymmetry, and intrinsic errors in mathematical algorithms for estimating pathlength. For instance, if the error of the measured line-integral density is small, the errors in local electron density are entirely due to errors in estimating the pathlength. The new method overcomes these problems and provides a reliable local density and flux surface geometry, as described in Ref. 8. The essence of the new method can be summarized as follows: First, the global asymmetries, if they exist, can be treated with the reasonable assumption that the linear distribution of the asymmetry is along the same poloidal flux zone. Second, boundary conditions can be made flexible, since this method does not require zero line densities at both edges of the profile. Third, a self-consistent Shafranov-shifted flux surface can be constructed by iteration (i.e., assume that density has no asymmetry at the center of the flux surface). Finally, inversion on a non circular flux surface can be treated with the aid of magnetic measurements.

The local density and self-consistent flux surface measurements simultaneously determined by this method make possible the calculation of local and global information regarding the electrons. This includes the density profile peakedness ($F_{pe} = n_e(0)/\langle n_e \rangle$) where $n_e(0)$ is the peak electron density and $\langle n_e \rangle$ is the volume-averaged electron density, the peak electron density ($n_e(0)$), total electrons ($n_e(tot)$), and the line-integral density along any

direction. Figure 1 shows a typical time history of various electron density parameters during a neutral beam heating experiment. The upper two traces are F_{ne} and the line-integral density along the horizontal direction. The bottom two traces are $n_e(0)$ and $n_e(tot)$. During the neutral-beam heating phase, broadening of the density profile is observed while the peak density is rising. This profile broadening is a typical characteristic of L-mode discharges. It is noticeable that the time history of the total number of electrons in the discharge does not show sawteeth while all other parameters have clear sawtooth oscillations. This implies that the total number of electrons are conserved during sawtooth oscillations. In order to check the accuracy of the inversion, line integration is performed along the horizontal plane and compared with the measured line-integral densities of the two vertical channels near the center of the plasma. The results are shown in Fig. 1b.

In contrast to the L-mode regime, density profiles in the TFTR Super-shot regime⁹ are highly peaked during the neutral beam heating period. The energy confinement time (τ_E) in this regime is improved by up to three times that of the L-mode regime. These discharges with highly peaked density profiles were obtained with low recycling ($R=0.5$) target plasmas, where R is the wall recycling coefficient. A correlation between F_{ne} and τ_E was found;¹⁰ similar correlations can be found in other tokamaks.¹¹⁻¹³ In a TFTR study, 561 data points were collected for various plasma currents ($I_P = 0.8 - 1.8$ MA) and a wide range of beam heating power ($P_B = 10 - 30$ MW). The F_{ne} for the ohmic target plasma was from 1.6 to 1.8 and the F_{ne} at the time of the maximum stored energy was from 1.2 to 3 during the beam heat-

ing phase as shown in Fig. 2. The discharges with highly peaked density profiles ($F_{ne} > 2.0$) had no sawteeth during the neutral beam heating period and τ_E for these discharges improved in comparison to the less peaked discharges that had sawteeth. Here, the improvement in energy confinement time (τ_E/τ_E^L) for deuterium discharges is depicted as a function of F_{ne} , where the τ_E^L is the L-mode scaling energy confinement time¹⁴ with mass correction ($D^0 \rightarrow D^+$). The regression study showed the energy confinement time is strongly correlated with F_{ne} and is a weak function of beam heating power (P_B) and plasma current (I_P). The weak dependence of τ_E on P_B and I_P was a result of significant correlation between P_B and I_P as F_{ne} was increased. From a multiple linear regression analysis, it was found that $\tau_E = 2.4 \times 10^{-3} F_{ne}^{0.76} P_B^{-0.12} I_P^{0.18}$. The correlation between τ_E and F_{ne} is an interesting empirical scaling relationship.

On the basis of flux surface and local density, it is relatively easy to derive similar parameters for electron pressure using time-dependent electron temperature measurements. In TFTR, the time dependence of the electron temperature profile is measured from electron cyclotron emission (ECE) either by a heterodyne radiometer¹⁵ or a Michelson interferometer.¹⁶ An example of the electron pressure parameters which can be generated is illustrated in Fig. 3. The upper two traces are the magnetically determined total stored energy (E_{tot}) and pressure profile peakedness factor ($F_{pe} = P_e(0)/\langle P_e \rangle$), where $\langle P_e \rangle$ is the volume-averaged electron pressure and the lower two traces are total electron energy (W_e) and central pressure ($P_e(0)$). One interesting observation is the comparison between E_{tot} and W_e during the beam heating period,

as shown in Fig. 3. E_{tot} decreases early in the neutral beam heating phase while W_e increases. From this result, it appears that the ion energy loss is significant.

In summary, the new Abel inversion method developed for TFTR demonstrates the usefulness of multichannel interferometry as an electron density diagnostic. The time-dependent study of various density parameters which can be generated between shots is not only important for tokamak operation but also provides valuable physics insights. A time-dependent study of electron pressure is also possible by combining electron density and temperature on a self-consistent flux surface geometry determined by the new Abel inversion method.

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Figures

FIG. 1. (a) Typical time history of electron density parameters during neutral beam heating phase. The upper two traces are density profile peakedness and horizontal integration of inverted profile and the lower two traces are peak electron density and total electrons. (b) The line-integrated density along the horizontal direction is compared with the measured values of the two vertical channels near the center of the plasma.

FIG. 2. Correlation between F_{ne} and energy confinement time (τ_E) for various plasma currents and beam heating power.

FIG. 3. Typical time history of electron pressure parameters during neutral beam heating phase. The upper two traces are magnetically measured total stored energy and pressure profile peakedness (F_{pe}) and the lower two traces are total electron energy and peak electron pressure.

Figure 1a

Figure 1b

Figure 2

Figure 3