Motional Stark Effect Measurements of the Local ICRH Induced Diamagnetism in JET Plasmas

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Introduction

Measurements of the toroidal magnetic field inside the JET tokamak plasma by means of the motional Stark effect are reported. In the vicinity of the resonance layer ion-cyclotron-resonance-heating (ICRH) generates a population of energetic ions. For the first time the diamagnetic change in the toroidal magnetic field due to these ICRH fast ions has been measured. A magnetic field decrease up to 4% has been observed.

Details of the measurement of the motional Stark effect, the magnitude of which is given by the Lorentz electric field experienced by the neutral beam, are described. The deduction of the toroidal magnetic field from the Stark wavelength splitting is discussed, in particular the involved accuracy which is necessary to resolve toroidal field effects of the order of 0.5%.

The evolution of the thermal plasma pressure - measured independently - combined with the PION-T code simulation of the fast ion pressure [1] agree within an order of magnitude with the measured toroidal field changes and indicate that the contribution of the anisotropic pressure from fast particles to the total pressure increases towards the plasma centre. First applications are presented, including β-increase due to ICRH and the slowing down time of the ICRH fast ions.

Motional Stark Effect

A local measurement of the toroidal magnetic field is obtained from the Doppler shifted Balmer-α emission of the neutral hydrogen or deuterium heating beams due to the Lorentz electric field $\mathbf{E} = \mathbf{v} \times \mathbf{B}$ [2,3]. In the case of hydrogen (or hydrogenic atoms), where the motional Stark effect is linear, this electric field gives rise to a wavelength splitting which is proportional to $|\mathbf{E}|$.

The fully resolved beam emission spectra are observed at four radial plasma positions simultaneously with a time resolution of 50 msec. The positions cover a radial range from $R = 3.0$ m to 3.4 m. The magnetic axis of JET is in the vicinity of 3.10 m, the last closed flux surface lies at 4.10 m. The Stark wavelength splitting is derived from the fully resolved beam emission spectrum by means of a multi-Gaussian fit code. On the basis of the detailed knowledge of the atomic physics involved the code restricts the number of free parameters to the minimum required. As a result, the fit procedure accomplishes an accuracy which allows minute changes of the Stark wavelength splitting and subsequently variations of the toroidal magnetic field of the order of 0.5% to be resolved.

Deduction of the Toroidal Magnetic Field

Fig. 1 shows the correlation between the strength of the Lorentz electric field E_L and the ICRH power. The observed decrease of E_L is attributed to the pressure increase of the plasma causing a diamagnetic drop of the toroidal magnetic field. The toroidal magnetic field is derived from E_L using the following relation

$$E_L = |v|\sqrt{B_{pol}^2 + B_{tor}^2 - \left(\hat{v}_{pol}\, B_{pol} + \hat{v}_{tor}\, B_{tor}\right)^2}\,, \qquad (1)$$

where B_{pol}, B_{tor} and $\hat{v}_{pol}$, $\hat{v}_{tor}$ are the poloidal and toroidal components of the magnetic field and the unit vector $v/|v|$ of the beam velocity respectively. In the JET beam geometry the normal and toroidal velocity components generally form the dominant parts. Since B_{pol} for the discharges considered is at least a factor of 6.5 smaller than B_{tor}, B_{pol} forms only a minor contribution to the total magnetic field and hence to E_L. For that reason B_{pol} is taken from the equilibrium code IDENTC without being concerned about the accuracy of the given poloidal field values.

Several sources of spurious effects which could lead to changes of the Lorentz electric field not correlated with the diamagnetic behaviour of the toroidal magnetic field have to be considered: (A) Variations of the Doppler shift of the beam emission spectrum give an upper limit of $\Delta R < 3$ mm and $\Delta v/v < 0.2\%$ and subsequently $\Delta E_L/E_L < 0.2\%$, which is small enough to be neglected. (B) The effect of the Shafranov shift on the deduced B_{tor}, only if not recognised by the equilibrium code, can be as high as 0.5%. (C) Theoretical investigations [4] show that ICRH current drive only contributes of the order of 0.1% to the total magnetic field, which is negligible compared to the observed Lorentz field variations. (D) The shift of the paramagnetic correction as a consequence of the Shafranov shift generally can be ignored. Besides, this causes a field increase which is opposite to the observed decrease. Thus it can be concluded that the observed changes of the Lorentz electric field can be solely attributed to the diamagnetic decrease of the toroidal magnetic field. This is corroborated by the comparison of B_{tor}, derived from E_L, with the diamagnetic signal (fig. 2).

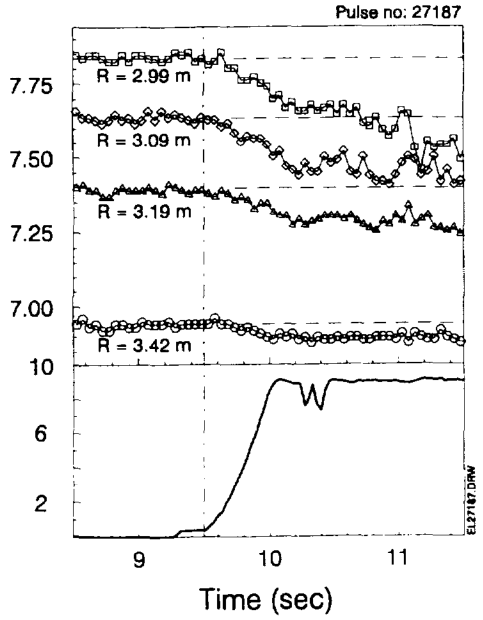

Fig. 1. Correlation between the Lorentz electric field E_L and the total coupled ICRH power P_{ICRH}. The decrease of E_L ranges from 0.5% at 3.43 m to 4% at 2.99 m.

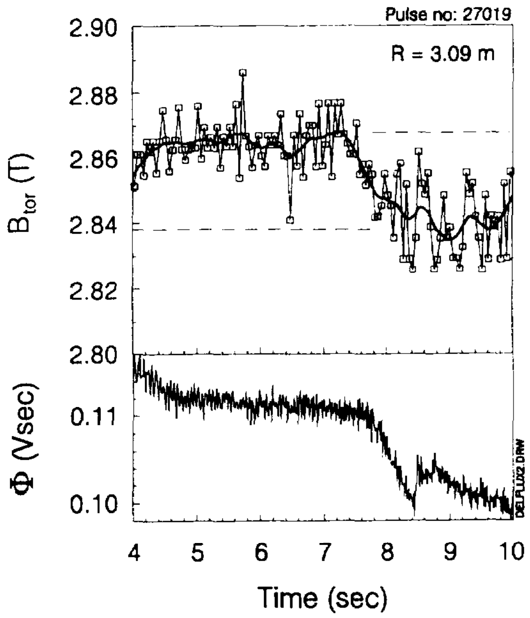

Fig. 2. Evolution of the toroidal magnetic field compared with the poloidal flux (Φ) from the diamagnetic loops. Clearly also Φ drops when the B_{tor} decrease is observed.

ICRH Induced Diamagnetism

The diamagnetic decrease of the toroidal magnetic field is caused by an increasing kinetic pressure in the plasma centre due ICRH. The strength and radial extent of the measured decrease rises with the coupled ICRH power (fig. 3). In the case of ICRH two contributions to the pressure have to be considered, the anisotropic perpendicular fast-ion pressure ($p_{\perp,fast}$) and the thermal pressure (p_{th}). Thus the pressure balance becomes

$$p_{th} + p_{\perp,fast} + \frac{B_{tor}^2}{2\,\mu_0} = \text{const.}, \tag{2}$$

from which the expected B_{tor} evolution is calculated. The fast ion pressure is modelled self-consistently by the PION-T code, while the thermal pressure is derived from electron density and temperature measurements. The so simulated B_{tor} changes agree within an order of magnitude with the motional Stark measurement. Approaching the resonance layer the fast-ion pressure becomes increasingly dominant, until at 2.99 m the thermal component can only account for 25% of the observed B_{tor} drop. Even more detailed features of the measurement can be explained by the simulation, such as the influence of the change of the slowing down time due to a density rise and sawtooth oscillations of the thermal pressure (fig. 4).

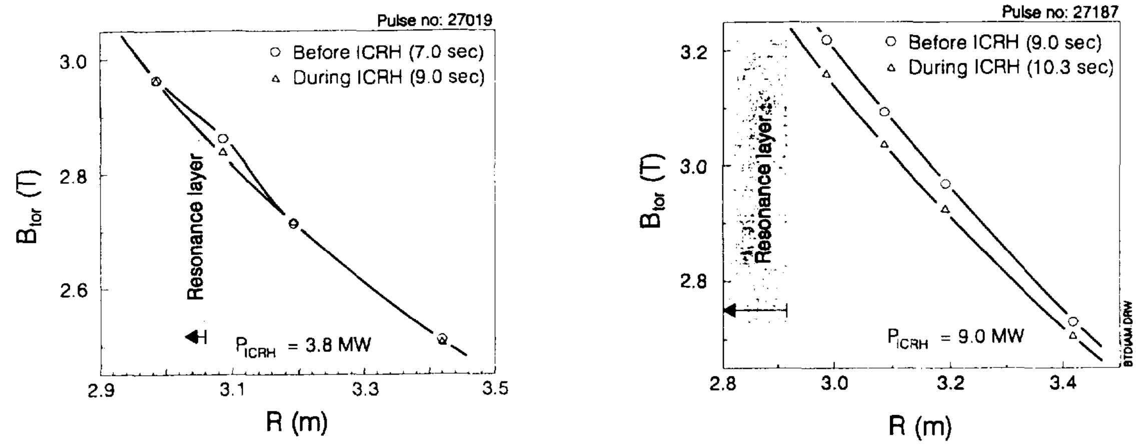

Fig. 3. Toroidal magnetic field vs major radius for time points before and during ICRH. The shaded regions indicate the position of the ICRH resonance layer which moves inboard as the toroidal field drops.

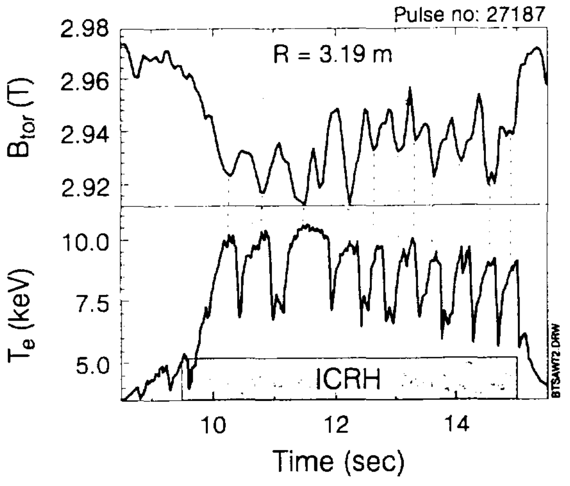

Fig. 4. Oscillation of the toroidal field caused by sawtooth oscillations of the electron temperature.

The β-increase due to ICRH, derived from the relative change of the toroidal field, is shown in fig. 5. The difference between the total, inferred from the motional Stark effect (MSE), and the thermal part must be attributed to the fast ions.

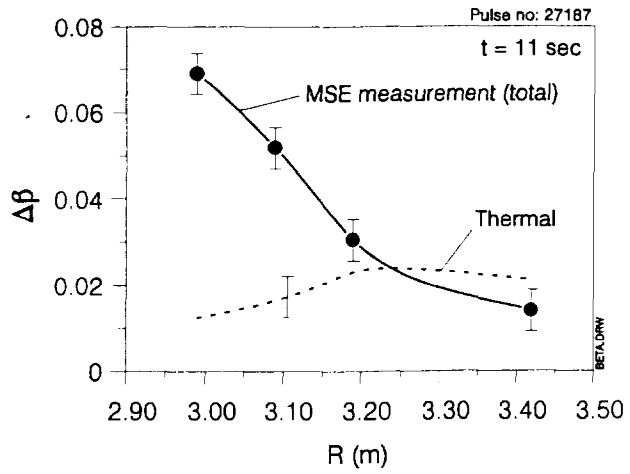

Fig. 5. *β-increase due to ICRH.*

The slowing down time of the fast ions is estimated from the measured rise of the toroidal magnetic field at the position closest to the resonance layer, where the fast ions are dominating, under the assumption that the slowing down time itself changes on a much slower time scale than B_{tor}. This gives a value of (280±101) msec which is in reasonable agreement with the theoretical value of 366 msec.

Summary

Employing the motional Stark effect on the hydrogenic heating beams, a high resolution measurement (of the order of 0.5%) of the internal toroidal magnetic field distribution has been achieved. Additional information given by the beam emission spectrum permits to eliminate spurious effects. The sensitivity of the diagnostic has been demonstrated by resolving "diamagnetic" sawtooth oscillations of the toroidal field. First applications show the potential of the diagnostic in delivering quantitative information important for the understanding of the ICRH process.

References

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