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ABSTRACT

Changes of the toroidal rotation velocity of up to 3×10^4 m/s have been observed during ICRH in JET. The plasma increases its toroidal rotation in the direction of the plasma current. The change in velocity is obtained from the measurement of the Doppler shifted X-ray lines emitted from He-like nickel present in the centre of the plasma. By analysing various heating scenarios and also measuring the fast anisotropic ion energy content of the plasma we conclude the rotation is connected with the creation of fast ions during ion cyclotron resonance heating. Toroidal acceleration of the plasma in connection with MHD-instabilities leading to similar magnitude of rotational velocity is also seen.

1. INTRODUCTION

During ion cyclotron resonance heating, ICRH [1], a toroidal acceleration of the plasma in the direction parallel to the plasma current has been observed in JET. A change in the toroidal rotation velocity of up to 3×10^4 m/s has been measured. The acceleration takes place during the initial heating phase. The velocity is measured from the Doppler shift of a helium-like nickel-line with an X-ray crystal spectrometer [2-4]. The antenna launches a wave spectrum which is

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symmetric with respect to the toroidal wave number so no net toroidal angular momentum is transferred to the plasma.

In the ion cyclotron frequency range, the launched magnetosonic wave can either be absorbed by electrons, by electron Landau damping and transit time magnetic pumping, or by ion cyclotron absorption [5]. The former two damping mechanisms can act either directly by absorbing the magnetosonic wave or after mode conversion to a kinetic wave. Which of these damping processes dominates depends on the plasma composition, frequency, magnetic field strength and wave spectrum. Ion cyclotron absorption can lead to formation of highly energetic and anisotropic ion velocity distributions [6]. This is regularly seen when the heating is applied to minority ion species at high power density. A recent analysis of the diffusion in real and velocity space induced by the wave field predicts that the formation of a high energetic ion distribution during ICRH will lead to toroidal plasma rotation [7].

According to this analysis, the plasma rotation could be caused by an ion current associated with the pump out of high energy ions from the plasma center. When the plasma is accelerated as the RF-power is switched on, the presence of an anisotropic velocity distribution can be confirmed by measuring the difference between the increase of the plasma energy measured with different diagnostics. Here we take the difference between the plasma energy measured with a diamagnetic loop and the plasma energy measured with magnetic coils. By measuring the anisotropic energy content and the plasma rotation for various heating scenarios we observe a correlation between the rotation and the formation of high energy ions.

We have also seen that after the crash of the long sawtooth-free periods obtained during ICRH, so called "monster" sawtooth [8], the plasma is sometimes accelerated anti-parallel to the plasma current. Abrupt reduction of the changes of plasma rotation by MHD-instabilities in beam heated plasmas have been discussed [9]. In this paper we give a summary of the observations of toroidal rotation induced during ICRH ion cyclotron resonance heating of the plasma.

2. EXPERIMENTAL MEASUREMENTS

The measurement of the plasma rotation is performed by observing the Doppler shift of the X-ray spectral line arising from the transition $1s^{2\,1}S_0 \rightarrow 1s2p\,^1P_1$ of helium like nickel. The shift is measured with a high resolution crystal spectrometer viewing along a horizontal line in the torus midplane [2]. The X-rays are diffracted by a Bragg crystal and detected by a position sensitive multiwire proportional counter. The full line profile is measured over a preset time interval (typically 20 ms) with the detector over the 192 channels. The full width at half maximum of the line is typically 10 to 20 channels determined by the Doppler broadening due to the thermal motion of the ions. The line position can be accurately measured by analysing the line profile with a line shape composed by a Voigt profile [4,10] which is a convolution of a Gaussian and Lorentzian component. The accuracy of a line shift measurement, at best ~ 0.3 channels, corresponds to a change of $\sim 7{\cdot}10^3$ m/s in toroidal rotation velocity. This is the lower limit for observation of changes in toroidal rotation velocity. We have also calculated the modification of the nickel X-ray spectrum caused by intensity variations of satellite lines and by the changes of the emissivity profiles along the line of sight for a wide range of electron temperatures. For example, when the electron temperature changes from 2 to 6 keV a line shift of 0.2 channels is obtained, which is below the measurement accuracy in this experiment. The spectrometer is not absolutely calibrated in wavelength with required accuracy [3] so the velocity measurements always represent changes in rotation velocity during the plasma discharge. A decrease in channel number represents an acceleration parallel to the plasma current. The peak position of the line is in general very stable during ohmic discharges and a shift of the line can unambiguously be identified as caused by a change in the toroidal rotation of the nickel ions.

The X-ray spectrometer views the plasma tangentially with an angle of about 37° to the toroidal mid-axis through the horizontal midplane of the torus. The line-of-sight goes through the plasma twice and the emission comes from an extended region of the plasma. However, the emission is weighted towards the centre of the plasma where the electron temperature is sufficiently high to produce and excite helium-like nickel, Ni^{26+}. The intensity of the emission line depends also on the nickel concentration and the electron density. During ICRH the nickel impurity level tends to increase, which facilitates accurate measurements with high temporal resolution. Before the onset of the ICRH, the intensity of the emission is often too low to make accurate measurements. This makes it sometimes difficult to measure the change in plasma rotation. Sometimes a clear change in channel number of the nickel-line is seen as the RF-heating is switched on and sometimes not. Figs. 1 and 2 show two cases. A shift of the peak position of one channel represents a change of the toroidal velocity of $2 \cdot 10^4$ m/s. A sudden toroidal acceleration of the plasma can also be seen in connection with MHD-activity (Fig. 3) which will be discussed later. Such a toroidal acceleration has been seen both with ICRH as in Fig. 3 and without.

The plasma rotation measured with this technique has been compared with charge exchange recombination spectroscopy during neutral beam heating. The two methods show good agreement. However, the latter method cannot be used during RF-heating in the absence of neutral beam injection and in this paper only date from X-ray spectroscopy has been used.

The anisotropic plasma energy content, W_a, of the plasma is measured by taking the difference between the change of plasma energy measured with a diamagnetic loop, W_{dia}, and the change of plasma energy obtained from magnetic equilibrium measurements [11] W_{MHD}, by,

$$W_a = \frac{4}{3}\left(\delta W_{Dia} - \delta W_{MHD}\right). \tag{1}$$

The diamagnetic loop measures the perpendicular plasma energy, $W_\perp$,

$$W_{Dia} \equiv \frac{3}{2} W_\perp . \tag{2}$$

The energy obtained from the magnetic equilibrium measurements, W_{MHD}, is a combination of perpendicular and parallel energy, $W_\parallel$ [11],

$$W_{MHD} = \frac{3}{4} W_\perp + \frac{3}{2} W_\parallel . \tag{3}$$

Since W_a is obtained as a difference between two nearly equal quantities measured with different diagnostics, large errors can be expected. The anisotropic plasma energy becomes significant during ICRH and represents nearly the whole energy content of the minority ions. The change in W_a with time is shown in Fig. 1c. The heating scenario for this discharge #13043 is H minority heating in a ^{4}He-plasma, the plasma current was 1.1 MA, the toroidal magnetic vacuum field 2.19 tesla at R = 2.96 m, RF-frequency 32 MHz. The antennae were phased in the so-called toroidal monopole phasing peaking the toroidal wave number spectrum around zero. From Fig. 1a one can see that the plasma is accelerated toroidally during the RF-power ramp and saturates at about 0.5 s after the coupled RF-power has saturated. It should also be pointed out that when the RF power is switched off a transient further acceleration of the plasma occurs. However, the time resolution of the velocity measurement at the end of the RF pulse is too low and the uncertainty in this velocity determination too large to permit further analysis of this effect.

The discharge #12948 shown in Fig. 2 for which no plasma rotation is seen is characterised by the following parameters: plasma current 5 MA, magnetic field 3.4 tesla, and minority heating of ^{3}He in ^{4}He with a minority concentration of $n_{3He}/n_e = 0.02$. The antennae were also phased in the monopole phasing and the RF-frequency was 35.7 MHz. The anisotropic energy content does not show a significant increase during the onset of the heating, but increases slowly during the discharge and remains much lower than for discharge #13043. In this case the increase in the measured W_a is not due to the energy of the fast ions generated by ion cyclotron absorption but to changes in the internal inductance of the plasma. Such changes are often seen when measuring W_a. A critical study of this signal has therefore to be done by comparing the value of W_a before and after the ICRH. The differences in plasma current, magnetic field and plasma density between the discharges #12948 and #13043 are not important for whether the plasma rotates or not. Plasma rotation connected to the switch-on of ICRH has been observed for all levels of plasma current and magnetic fields. The plasma current and the toroidal magnetic field may affect the level of plasma rotation, but the spread in the observed data is too large to assess the correlation with these parameters.

Acceleration of the plasma anti-parallel to the plasma current can be seen for the discharge #13689 (Fig. 3), which represents ^3He minority heating in ^4He. In this discharge there is a high minority concentration $n_{3He}/n_e \cong 0.07$ and high impurity concentration $Z_{eff} = 4.5$ which gives a high ratio of ^3He to ^4He density. The antennae were phased in the so-called toroidal dipole phasing which peaks the toroidal mode number spectrum around 30. This discharge has previously been analyzed [12] and was found to be a discharge with small anisotropic energy content. In Fig. 3 we show the variation with respect to time of the peak position of the nickel-line, the electron temperature near the plasma centre, the coupled RF-power and W_a. Between t = 46.5 s and 49 s the mean value of the peak position does not change. Thus there is no toroidal acceleration of the plasma during the RF-power ramp, which is consistent with only negligible tail formation. At t = 49.3 s the channel number of the peak jumps to a higher value, corresponding to an anti-parallel acceleration of the plasma. The anti-parallel acceleration of the plasma takes place at the same time as the first sawtooth crash, after the long sawtooth-free period, so called monster-sawtooth.

A plot of the change in channel number versus coupled RF-power is shown in Fig. 4. The range of plasma parameters are: plasma current from 1 to 5 MA, central electron density from $1.5 \cdot 10^{19} m^{-3}$ to $6 \cdot 10^{19} m^{-3}$ and peak electron temperature between 2 keV and 6 keV. Target plasmas of He^3, He^4 and D were used with minority heating of H or He^3. The data points include both limiter discharges and X-point discharges. In the latter the plasma is limited by a magnetic separatrix and in the former by two toroidal belt limiters on the outboard side. Both toroidal dipole and toroidal monopole phasing were used.

The largest change in the velocity seen was $3 \cdot 10^4$ m/s. The discharges with the largest change in rotation were X-point discharges with low density and low plasma current. The data set shown in Fig. 4 represents a set with large scattering and no direct scaling with the RF-power is seen. If the change in plasma rotation is connected with creation of high energy ions, one would expect to see a correlation between the change in toroidal angular momentum and the anisotropic energy content. Instead of multiplying the change in channel number with the axial density and plot this quantity versus W_a, we plot the change in channel number versus $W_a/n_e(0)$ in Fig. 5. A clear correlation between the $W_a/n_e(0)$ and change in channel number can be seen. Although, there are a few discharges with no change in the channel number but with an appreciable value of $W_a/n_e(0)$. There are also some discharges with an appreciable change in the channel number but with negligible value of $W_a/n_e(0)$. These particular discharges were hydrogen minority heating with coupled RF-power between 5 MW and 11 MW which normally gives a significant values of W_a but not for these particular discharges.

It is well known that the presence of MHD-modes in the plasma can slow down toroidal rotation of beam heated plasmas. To investigate whether the former class of exceptions, i.e. discharges with significant W_a but without any change in the rotation, can be explained by the presence of a larger MHD-activity than the other discharges, we compare the amplitude of the n = 1, 2, and 3 modes with the change in channel number of the nickel-line for fixed intervals of $W_a/n_e(0)$. The amplitude of the MHD-modes with toroidal mode number n = 1, 2, and 3 are measured with a set of pick up coils inside the vacuum chamber [13]. We then find that for discharges not affected by MHD there is an appreciable rotation while for all discharges where no rotation is observed, and still with a substantial energy anisotropy, there is a high level of MHD activity. However, the MHD activity does not seem to be able to fully stop the rotation velocity in a few cases.

3. DISCUSSION AND CONCLUSIONS

Changes in the toroidal plasma rotation of up to $3 \cdot 10^4$ m/s are observed during ICRH as compared to before the ICRH pulse is switched on. The plasma is seen to be accelerated in the direction of the plasma current. Plasma acceleration is also seen in conjunction with sawtooth crashes for which the change in rotation velocity is of the same order as the one caused by the ICRH. This makes the correlation between RF-power and other parameters with the induced toroidal rotation more difficult.

The toroidal acceleration caused by RF-heating is seen to be correlated to the creation of fast ions. The data base shows a large scattering of the change of toroidal velocity with coupled RF-power. A more clear correlation is seen when comparing it with the measured anisotropic energy content divided by central electron density, i.e. when correlating the change in toroidal angular momentum with the anisotropic energy content. However, scattering of data is still large. There are large uncertainties in the measured anisotropic energy content. For plasmas with large energy content, the error in the anisotropic energy content becomes larger since it is deduced by subtracting two large quantities. The change in plasmas toroidal momentum is not only expected to depend on anisotropic energy content, but also on plasma current, position of the cyclotron resonance, minority density and species. A few discharges were seen with substantial values of $W_a/n_e(0)$ but no change in plasma rotation. It is found that these discharges have much larger MHD-activity, about 5 times higher. For some discharges a change in the plasma rotation took place as the RF-power was switched on, without any noticeable change in the anisotropic energy content. At a first sight this seems to contradict the correlation with induced toroidal rotation caused by creation of high energy ions. However, for these particular discharges the heating scenario was that of minority heating of hydrogen ($\frac{n_H}{n_e} < 0.03$) with coupled power between 5 and 11 MW. Such discharges are expected to give a significant anisotropic energy content, because minority heating of hydrogen is expected to be the dominating absorption mechanism, which is not always true for He^3 minority heating. Why this is not experimentally seen could be due to error in the measurement of the anisotropic energy which have large uncertainties.

The quantity $W_a/n_e(0)$ is strongly correlated to the change in the electron temperature. An alternative interpretation of the correlation seen in Fig. 5, is that the change in channel number is caused by the change in the electron temperature. However, this is not the case. This can be seen, e.g. by studying the discharge #13689 (Fig. 3) in which the electron temperature increases from 4.5 to 9 keV without any observed changes in the measured channel number.

Neither can the change in channel number be due to the distortion of the velocity distribution of the nickel ions caused by the interaction with high energy minority ions. This distortion occurs only when the velocities of the two ion species are equal. The nickel line is measured at one or two times the thermal velocity of the nickel ions and at this low velocity there is no significant distortion of the velocity distribution.

A possible explanation of this acceleration is given [7] where it is predicted that the wave field causes a pump out of the resonating ions from regions with high power densities. The radial ion current associated with the pump out of resonating ions together with the poloidal magnetic field gives rise to a torque accelerating the interior of the plasma in the toroidal direction parallel to the plasma current. Both the measured direction and magnitude is consistent with the fact that a significant part of the resonating ions are pumped out from the centre during ICRH. The observed acceleration of the plasma induced by ICRH takes place on a timescale comparable to the Spitzer's slowing down time, which is the timescale for tail formation as well as for the radial diffusion induced by ICRH. Therefore, we cannot distinguish whether the radial ion current caused by the depletion of the minority density is due to orbit broadening, which also represents a pump out of ions by the wave field from the centre, or due to spatial diffusion induced by the wave field. The two effects will occur on the same timescale and both contribute to a toroidal acceleration of the plasma. Both processes lead to a toroidal as well as a poloidal rotation of the plasma. The poloidal plasma rotation is expected to be more strongly damped by viscous effects and cannot be seen with the X-ray spectrometer lined up as in the present experiments.

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References

[1] JACQUINOT, J., BHATNAGAR, V., BRINKSCHULTE, H., BURES, M., CORTI, S., COTTRELL, G.A., EVRARD, M., GAMBIER, D., KAYE, A., LALLIA, P., SAND, F., SCHUELLER, C., TANGA, A., THOMSEN, K., and WADE, T., Philos. Trans. R. Soc. London, Ser. A 322, 95 (1987).

[2] BARTIROMO, R., BOMBARDA, F., GIANNELLA, R., MANTOVANI, S., PANACCIONE, L. and PIZZICAROLI, G., Rev. Sci. Instr. 60 (1989) 237.

[3] BOMBARDA, F., GIANNELLA, R., KÄLLNE, E., TALLENTS, G.J., BELY-DUBAU, F., FAUCHER, P., CORNILLE, M., DUBAU, J. and GABRIEL, A.H., Phys. Rev. A37, 504 (1988).

[4] BOMBARDA, F., GIANNELLA, R., KÄLLNE, E. and TALLENTS, G.J., J. Quant. Spectr. Rad. Transfer 41 (1989) 323.

[5] STIX, T.H., Theory of Plasma Waves. McGraw-Hill, New York, 1962.

[6] STIX, T.H., Nuclear Fusion 15 (1975) 737.

[7] HELLSTEN, T., Plasma Physics and Controlled Fusion 31 (1989) 1391.

[8] CAMPBELL, D.J., START, D.F.H., WESSON, J.A., BARTLETT, D.V., BHATNAGAR, V.P., Phys. Rev. Lett. 60 (1988) 2148.

[9] NAVE, M.F.F. and WESSON, J.A., 14th Europ. Conf. on Controlled Fusion and Plasma Physics, Proc. Contributed Papers, p. 1103, Madrid (1987).

[10] BITTER, M., von GOELER, S., HILL, K.W., HORTON, R., JOHNSON, D., RONEY, W., SAUTHOFF, N., SILVER, E. and STODIEK, W., Phys. Rev. Lett. 47 (1981) 921.

[11] CHRISTIANSEN, J.P., CORDEY, J.G. and MUIR, D., Nucl. Fus. 29 (1988).

[12] ERIKSSON, L.-G. and HELLSTEN, T., Nucl. Fus. 19 (1989) 875,

[13] TONETTI, G. et al., Rev. Sci. Instr. 57 (1986) 2087.

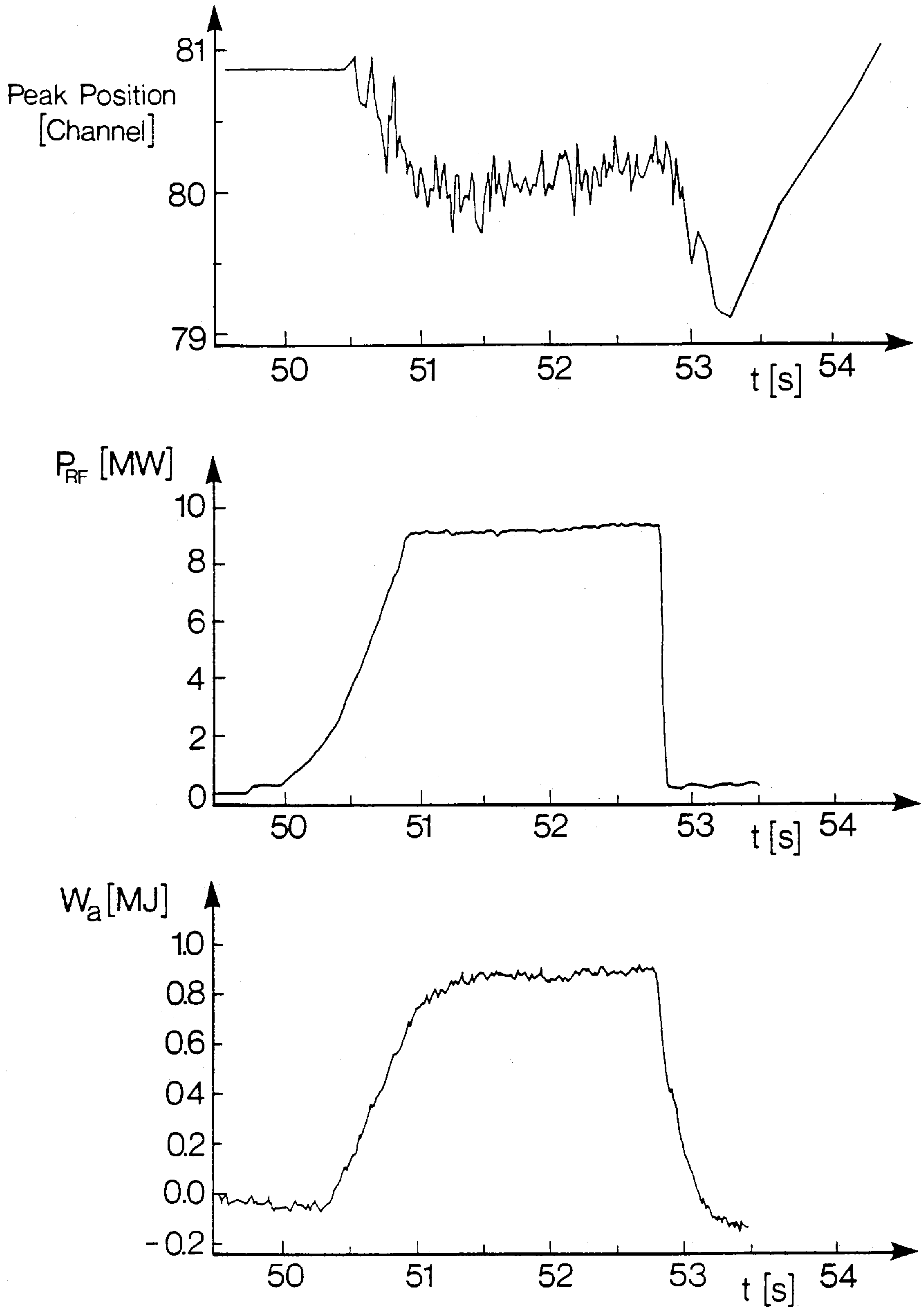

Fig. 1 Peak position of the Doppler broadened nickel line during ICRH versus time (a), coupled RF-power (b), and (c) anisotropic energy content W_a for discharge #13043.

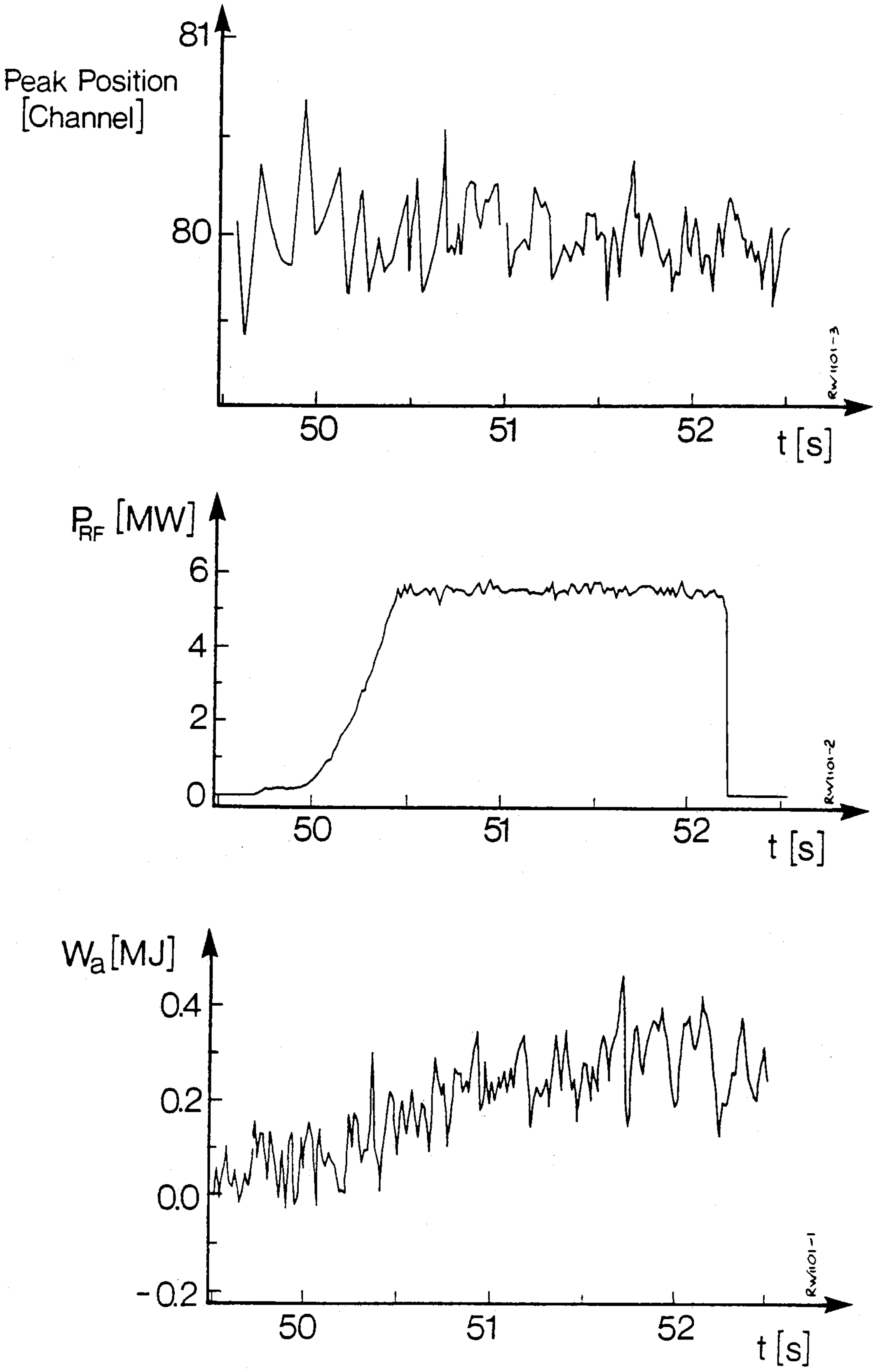

Fig. 2 Peak position of the Doppler broadened nickel line during ICRH versus time (a), coupled RF-power (b), and (c) anisotropic energy content W_a for discharge #12948.

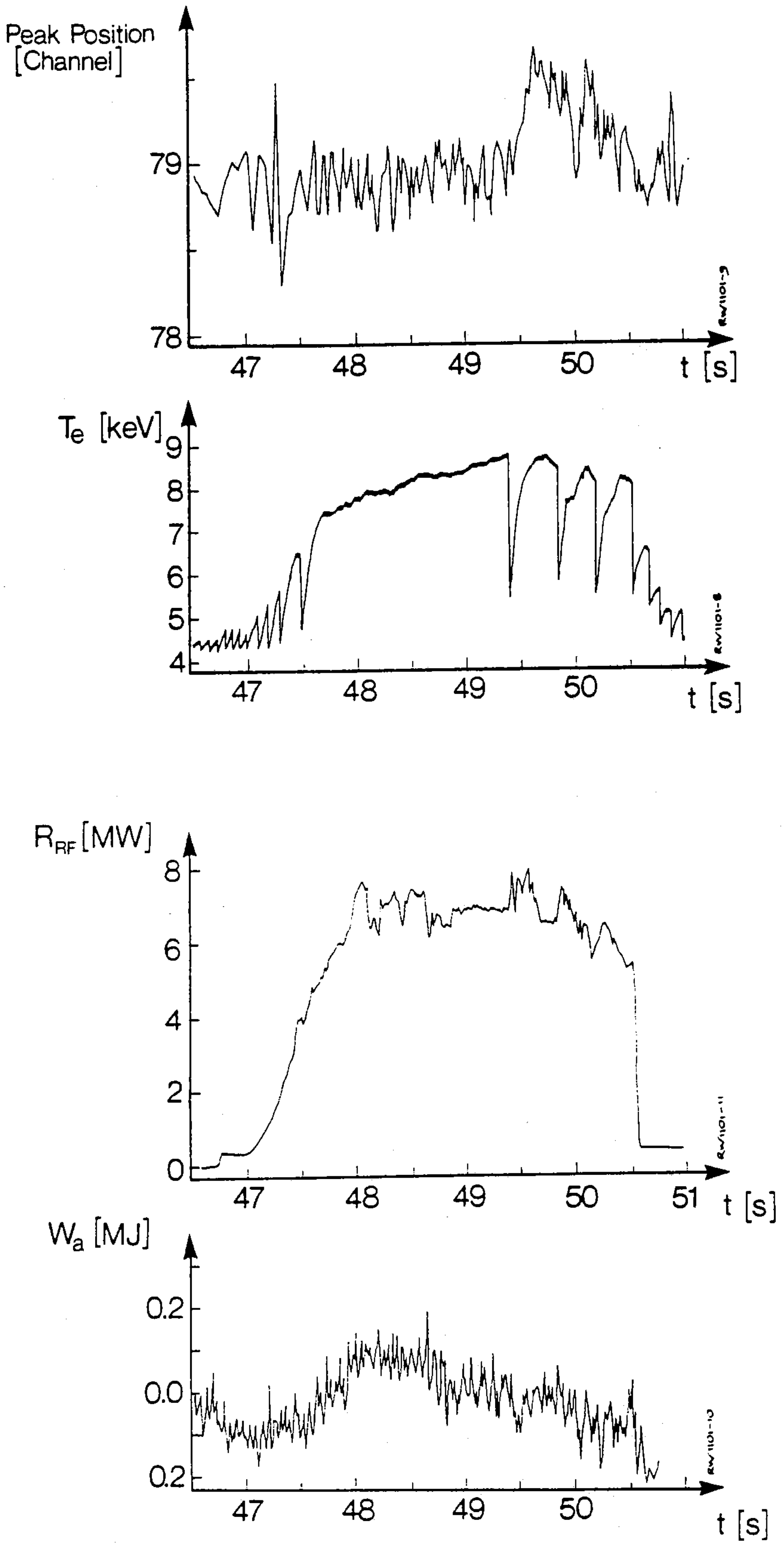

Fig. 3 The time evolution for discharge #13689 of the peak position of the nickel line (a), the electron temperature at the plasma centre (b), the coupled RF-power (c), and (d) the anisotropic energy content W_a.

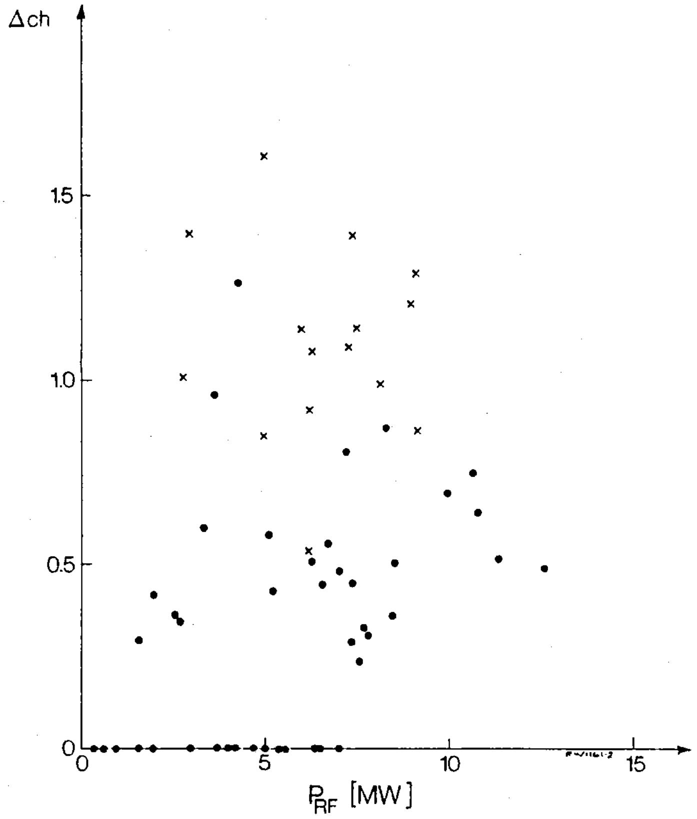

Fig. 4 Change in the channel number of the nickel line versus couples RF-power. (x X-point discharges, • belt limiter discharges).

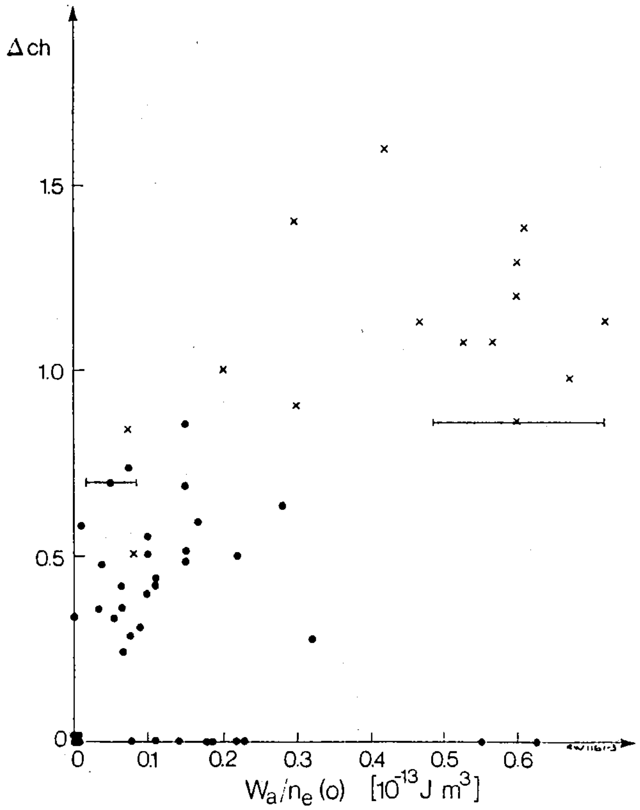

Fig. 5 Change in the channel number of the nickel line versus $W_a/n_e(0)$. (x X-point discharges, • belt limiter discharges).