NEW NONLINEAR EFFECTS OF THE CURRENT-DRIVEN ELECTROSTATIC ION-CYCLOTRON INSTABILITY

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Abstract

The current-driven **e**lectrostatic **i**on-**c**yclotron **i**nstability (EICI) can be excited in a magnetised plasma column by a positively biased circular collector. The EICI is a coherent oscillation of the plasma with a frequency above the ion gyrofrequency. We have investigated various nonlinear aspects of the EICI and of related phenomena in a Q-machine: (i) a strong amplitude and frequency modulation of the EICI by the **p**otential **r**elaxation **i**nstability (PRI); (ii) the formation of sidebands around f_{EICI}; (iii) a decrease of f_{EICI} with the collector current. Our explanation is based on the fact that both instabilities involve space charge double layers, which are periodically created and decaying during one instability period.

1. Introduction

Among the instabilities in a magnetised plasma column, the **e**lectrostatic **i**on-**c**yclotron **i**nstability (EICI) [1,2,3] and the **p**otential **r**elaxation **i**nstability (PRI) [4,5,6] are the best known. Both are excited by an electron current parallel to the magnetic field toward a circular **co**llector (CO), which is inserted into the plasma column perpendicular to the axis. For the PRI, the radius of the CO must be larger than the ion gyroradius so that the ion trajectories can be approximated as one-dimensional. For the EICI, the radius of the CO must be a few ion gyroradii and considerably smaller than the radius of the plasma column. In a certain range of CO radii the PRI and the EICI can be excited simultaneously [7,8]. This leads to an amplitude modulation of the EICI by the PRI, with the amplitude of the latter being much larger than that of the former.

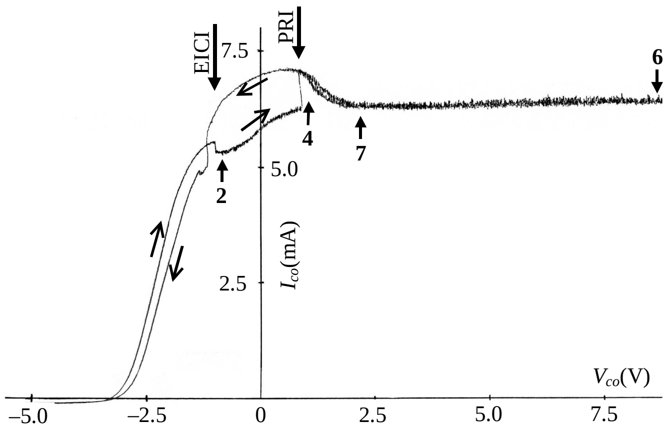

Fig. 1 Typical current-voltage characteristic of the collector with hysteresis. The onsets of the instabilities are indicated by large arrows. The numbers refer to values of V_{co}, where the FFTs shown in Fig. 2, have been taken.

Here we report on a much stronger modulation of the EICI by the PRI, where both instabilities were for the first time observed with comparable amplitudes. This was obtained when the bias of the CO was gradually increased, with the EICI appearing at first, and later the PRI. The EICI frequency was about four times larger than that of the PRI. The modulation not only affected the amplitude but also the frequency of the EICI. This led to the formation of sidebands in the spectrum around f_{EICI} with a frequency difference equal to $\pm f_{PRI}$. Furthermore we found that the frequency of the EICI drops linearly with increasing CO current.

The modulation of the CO current by the PRI can be used to make an estimation of the periodical frequency shift of the EICI, which is concomitant with the formation of sidebands. The obtained results are in qualitative agreement with the measured amplitude and frequency

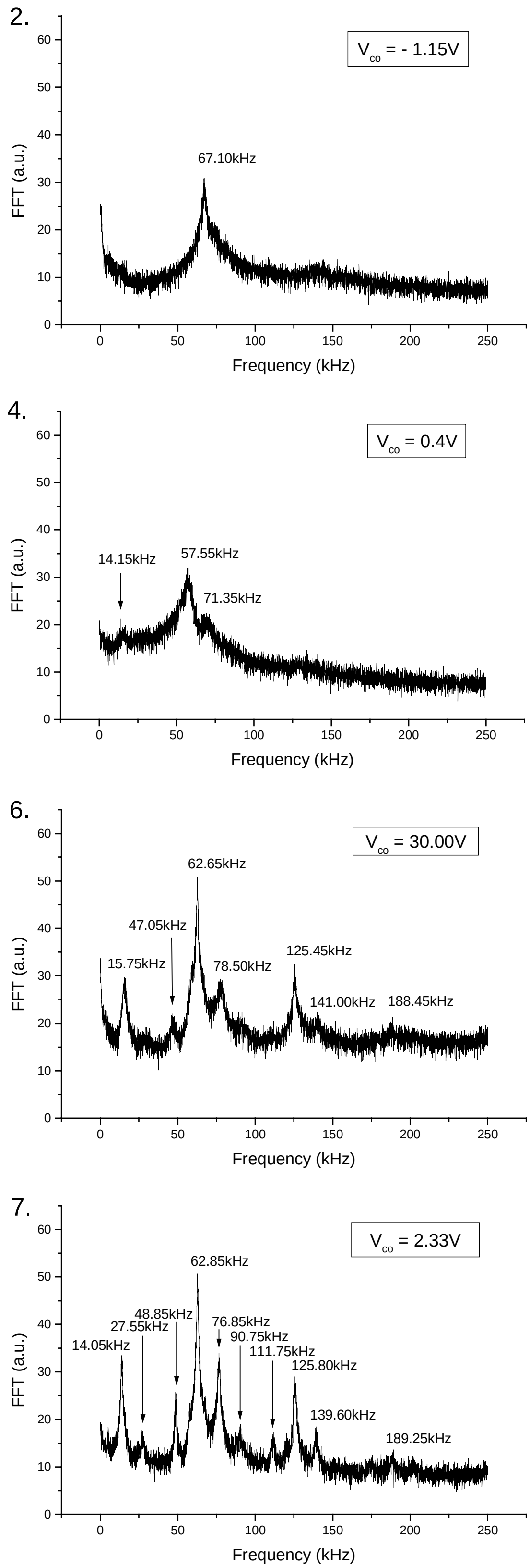

Fig. 2 FFTs of the time series taken at the values of V_{co}, indicated by the numbers in Fig. 1.

modulation of the CO current. In addition, the current-voltage characteristic of the CO (see Fig. 1) shows abrupt jumps when the EICI and the PRI appear, respectively [9].

2. Experimental set-up

The experiments have been performed in the Innsbruck single-ended Q-machine in a potassium plasma, produced by contact ionisation on a 6 cm diameter tungsten **h**ot **p**late (HP), heated to about 2200 K. A circular tantalum limiter, 3.6 cm in front of the HP, reduced the diameter of the plasma column to 3.5 cm. The plasma parameters were: density $10^8 < n_{pl} < 10^9$ cm^{-3}, ion and electron temperatures $T_i \cong T_e \cong 0.2$ eV, background pressure $p < 10^{-5}$ mbar, magnetic field $0.05 < B < 0.2$ T, length of the plasma column $d = 35$ cm. The plasma column was terminated by a heatable tantalum collector (CO) of 1 cm diameter.

3. Experimental results

Fig. 1 shows a typical current-voltage characteristic $I_{co}(V_{co})$ of the CO. Due to the strong magnetic field, the current I_{co} originates from a **c**urrent **c**hannel (CC) with roughly the same diameter as the CO, extending from it toward the HP. The characteristic shows a downward and an upward jump of the current, when first the EICI and then the PRI appear (see large arrows). The numbers indicate the values of the CO bias V_{co}, where times series of the ac component of I_{co} and FFTs of them have been taken (see Fig. 2). The characteristic shows a strong hysteresis around $V_{co} \cong 0$ V. More details about such characteristics can be found elsewhere [10].

The FFTs show that the EICI appears for $V_{co} \cong -1.5$ V, (cf. Fig. 2, FFT #2) with a frequency $f_{EICI} \cong 67$ kHz. For potassium and $B \cong 0.13$ T the ion gyrofrequency is $\Omega_i/2\pi \cong 51$ kHz and the ion gyroradius is $r_i \cong 2.2$ mm. Thus $f_{EICI} \cong 1.3\Omega_i/2\pi$, and the CO radius, normalised to the ion gyroradius, is $R \equiv r_{co}/r_i \cong 2.3$ [7]. This value is very favourable for a strong excitation of the EICI [7].

Around $V_{co} \cong +1$ V (FFT #4), the PRI appears with a frequency around 15 kHz [6]. For increasing V_{co}, the PRI amplitude grows, and from now on the system has two resonances, one at the PRI, one at the EICI frequency. When the PRI amplitude attains the same order of magnitude as that one of the EICI, the interaction between the two instabilities leads to a strong modulation of the latter by the former, not only in amplitude but also in frequency, and consequently also sidebands around f_{EICI} are formed with a frequency $f_{EICI} \pm f_{PRI}$. These can be seen best in the FFT #7 of Fig. 2, showing $f_{EICI} \cong$ 62.5 kHz. The amplitude and frequency modulation is well visible in the corresponding times series. The relative amplitude of the oscillations is between 0.3 to 0.6. The amplitude modulation affects more strongly the negative amplitudes. The upward excursions of the oscillating current are always much less pronounced, sometimes even the positive amplitude seems to be clipped off. A current limitation is a very obvious feature of both instabilities [3,5]. By averaging over the EICI period, the PRI oscillations of I_{co} becomes discernible, showing a current oscillation of ±1 mA. From the time series it turns out that the period of the EICI oscillations in the amplitude maxima of the PRI oscillations is shorter than in the minima by a value of about 4 ms. Thus f_{EICI} is higher than the average value of 62.5 kHz in the amplitude maxima (attaining $f_{EICI} \cong 71.4$ kHz) and lower in the minima (attaining $f_{EICI} \cong 55.6$ kHz).

4. Discussion

From the FFTs of Fig. 2 and from the current-voltage characteristic in Fig. 1, the dependence of the EICI frequency on the time average CO current I_{co} has been determined. Fig. 3 shows this relation, and obviously the EICI frequency drops with the current and is roughly inversely proportional to it. The solid straight line is a linear fit of the experimental data. A decrease of the amplitude and of the frequency with increasing CO current was also found earlier [1,11].

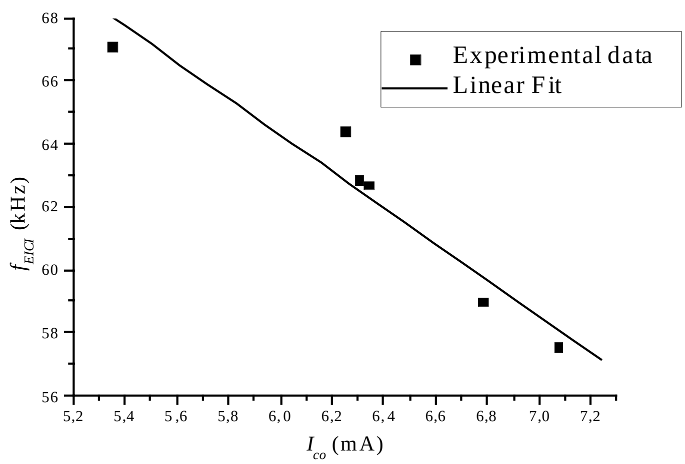

Fig. 3 Decrease of the EICI frequency with the collector current.

The formation of sidebands in the FFTs is concomitant with the observed frequency modulation of the EICI by the PRI. The above mentioned upper and lower frequencies correspond roughly to the sidebands in the FFT #7 of Fig. 2. We assume that the frequency shift in both directions is due to the modulation of the CO current by the PRI. The observed modulation of the EICI frequency between 55.6 kHz and 71.4 kHz corresponds on the linear fit of Fig. 3 to a current oscillation between about 7.5 and 4.8 mA. Although this amplitude is larger than the above mentioned observed oscillation of I_{co}, and although the frequency modulation, seen in the time series is smaller, the trend is obvious.

As for an explanation of the frequency shift in general, we recall the phenomenological model for the mechanism of the EICI as described in [1,2,3,12]. According to Refs. [2,3] (see also [12]), the main feature of the EICI is the periodical expulsion of a group of ions, originating mostly from the region in front of the CO [8], from the CC into the surrounding unperturbed plasma during every maximum of the EICI. In the surrounding plasma these ions describe orbits in the magnetic field with a radius 3 - 5 times larger than the unperturbed ion gyroradii [12]. This ion expulsion occurs because of a periodically created radial electric field at the edge of the CC, which is due to a periodically appearing positive space charge inside it. This space charge is due to the positively biased CO, which draws an electron current, thereby removing the electrons from the CC. The space charge is confined both axially and radially by **d**ouble **l**ayers (DL) [2,3]. The experimental fact that the period of the EICI oscillation is shorter than one ion gyroperiod can be understood by taking into account that the ions are *accelerated* for a part of their gyration by the aforementioned radial electric field. Thus their trajectories are not pure circles [13], and the time they need for leaving and re-entering the CC is smaller than $2\pi/\Omega_i$. Consequently, the strength of this radial field has a strong influence on the EICI frequency: the larger the space charge inside the CC, the higher are the DLs at the edge of it, the stronger is the radial electric field there, the stronger is the radial acceleration of ions, eventually causing a shorter period of the EICI and a higher EICI frequency, and vice versa: whenever the space charge becomes smaller, the period rises and f_{EICI} will drop. And this is exactly the effect which we see here for increasing I_{co}.

So our observation indicates that for increasing I_{co} the space charge inside the CC becomes *smaller*. Indeed there can be found evidence for this presumption since a higher CO current means also a more energetic electron flux towards the CO. Recent findings have shown that there could be a considerable number of impact reactions of the electrons (both excitation and ionisation processes) with a non-negligible background vapour pressure of potassium [10]. Since inelastic collisions like electron excitation and ionisation reactions lead to a loss of kinetic energy of the electrons, on the time average inside the CC a population of low energetic electrons is created dynamically [14]. These in turn cause a reduction of the positive space charge inside the CC and thus to a drop of the periodical radial electric field which is involved in the EICI mechanism. Therefore the EICI period increases and f_{EICI} decreases.

Acknowledgments
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