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LETTER TO THE EDITOR

Positive biasing of plasma in front of LH antennae

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Abstract
It has been shown on tokamak CASTOR by using an emissive Langmuir probe that positive plasma 'biasing' takes place in a radially very narrow layer just at the grill mouth. The effect scales linearly with the power applied. Apparently, this positive biasing results from the charge separation due to the escaping electrons, accelerated by the near field lower hybrid wave effects in this region, along the magnetic field lines (Fuchs V *et al* 1996 *Phys. Plasmas* **3** 4023).

1. Introduction and theoretical background

Lower hybrid waves (LHWs) are commonly used in tokamaks for non-inductive generation of electrical current. This current substitutes the current induced in the plasma by a transformer and in this way it could enable stationary operation of a future fusion tokamak-reactor. However, if an LH power of the order of megawatts is used in big machines, a detrimental effect of parasitic acceleration of edge particles in front of LH launchers (grills) is found. These locally accelerated energetic particles (up to several kiloelectronvolts) can hit a location on a solid surface, which is connected by magnetic field lines with the region of their acceleration in front of the grill mouth. A strongly localized erosion of some elements of the first wall has already been found and the creation of the so called hot spots in locations of the impact of fast particles during LHW launching has already been observed [2–4].

The small tokamak CASTOR enables direct measurements of the plasma as well as of the electric field behaviour just in front of the LH antenna (i.e. directly in the wave–plasma interaction region) by using the Langmuir probe technique. Recently, a well-expressed decrease in the potential of an insulated probe up to -200 V has been observed in a several millimetres radially narrow layer during application of LHWs on this machine [5]. Simultaneous RF measurements of the LHW amplitude, made using the same probe (a 50 Ω coaxial line with an RF detection diode), proved the existence of the LH field in the radial region to be much broader than the layer of potential decrease mentioned above (the strong LH field is found even at radii where no effects of this field on the probe potential have been observed). This fact may be considered as experimental proof that the potential decrease observed is not a result of rectification of the LHW field by the plasma but is a real change in the plasma floating potential. And, because the plasma floating potential is sensitive first of all to the presence of energetic electrons, generation of such supra-thermal locally accelerated electrons upon LHW application can be deduced from this fact.

As these non-thermal electrons (generated by the acceleration mechanism in a radially narrow layer just in front of the LH antenna) escape from the interaction region along confining magnetic field lines, they leave the heavier ions behind. Consequently, the plasma is positively biased, and thus an electrostatic field parallel to the magnetic field lines arises. This field results in the generation of parallel plasma flows, which were theoretically predicted for a variety of parameters (LH power, toroidal grill length) in [6, 7]. Due to the strong radial localization of the effect, significant radial (and poloidal) electric fields are also created during the LHW application, which in turn result in the generation of the consequent plasma flows ($\boldsymbol{E} \times \boldsymbol{B}$ drifts). In addition, probe measurements in Tore Supra indicate that the density fluctuations in front of the LH grill significantly depend on the launched LH power, which may modify the radial plasma transport to the grill mouth [8]. However, the increase in the plasma potential in the interaction region, envisaged by theory, has not been observed up to now.

In this paper, results of the first measurements of the plasma potential in front of the CASTOR LH antenna, obtained by using an emissive Langmuir probe [9], are given. In such a case, if the emissivity (i.e. the temperature) of the probe surface is high enough, the probe floating potential (i.e. the potential of an insulated probe submerged in the plasma) approaches the plasma potential, independent of the fast electron presence. It has been found that the floating potential of the heated probe located near the antenna exhibits, in contrast to the floating potential of the cold probe, a notable positive increase during the LHW phase. As no macroscopic changes in the plasma parameters are observed during the LHW phase, this fact can be considered as the first direct proof of the theory mentioned above: the primary mechanism of the observed effect is the acceleration of electrons in front of the antenna, while the erosion of the first wall might be caused predominantly by ions accelerated due to the charge separation. However, let us note that these fast ions cannot be found by using simple Langmuir probes. Attempts to find these fast ions using a retarding field analyser (RFA) are being made at Tore Supra [8].

The structure of the paper is as follows. The experimental arrangement is described in section 2. In section 3, the character of the probe signals and radial profiles of the floating potential of the cold and heated (to temperature above 2500˚C) probes will be given, together with the dependence of the effect on LHW power. The discussion and summary of the results will be presented in section 4.

2. Experimental arrangement

The tokamak CASTOR is a small device with $R/a = 0.4/0.085$ m (R is the major radius, a is the radius of the poloidal aperture limiter), the confining toroidal magnetic field on the device axis being $B(0) \leqslant 1.5$ T, the plasma current $I_p \leqslant 20$ kA, the density on the axis $n(0) \leqslant 3 \times 10^{19}$ m^{-3} and the operation pulse length up to 40 ms. The LH experiments have been carried out using a three-waveguide grill antenna having a toroidal dimension of 50 mm and working at a frequency of 1.25 GHz. The grill dimension of 160 mm in the vertical direction is comparable with the plasma diameter, and therefore the grill mouth is partially shaped in the poloidal plane with radius 86 mm, see figure 1. The LH power used was varied between 0 and 20 kW, and it was applied in pulses with a length of 3 ms in the quasi-stationary tokamak discharge phase (6 ms after the beginning of the discharge).

The emissive probe is formed by a small loop of a thin tungsten wire with diameter 0.2 mm (heated by dc current), protruding from two, tiny, corundum tubes fixed together with a diameter of 1.65 mm. These tubes prevent the exposure of the other parts of the tungsten wire by the plasma and also protect the feeding Cu conductors carrying the probe heating current. The plane

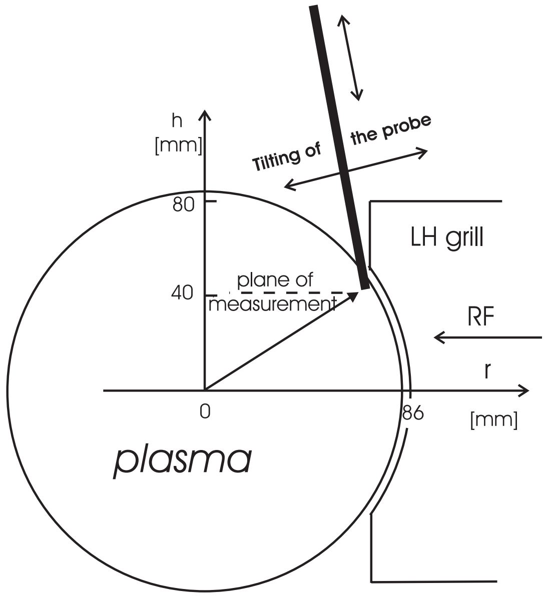

Figure 1. A schematic of the CASTOR small cross-section with the lower hybrid grill (radius of the grill circular shaping 86 mm, aperture limiter radius 85 mm) and the movable Langmuir probe.

of the loop is oriented in the toroidal direction, perpendicular to the small radius (i.e. the loop is placed on one magnetic surface, to assure a high radial resolution). The dimension of the loop exposed to the plasma does not exceed 1 mm in the poloidal direction, while its length in the toroidal direction reaches nearly 1.65 mm (as given by the distance between the centres of the two corundum tubes). A heating dc current of 7A is sufficient to reach a stationary temperature of the tungsten loop, higher than 2500˚C, in less than 1 s (the probe is heated several seconds only, just before and during the CASTOR pulse).

To reach the wave–plasma interaction region just in front of the grill antenna, the emissive probe has been fixed in a spherical joint located in the upper port of CASTOR, more than 500 mm above the grill, see again figure 1. The vertical position of the probe was set by a vertical shift of the probe holder and radial position of the probe simply by tilting the probe holder in the poloidal plane. Due to the low plasma energy in CASTOR and the short pulses (about 15 ms for our measurements) the probe could be moved through the whole interaction region in front of the grill. Because of good pulse repetition, broad radial profiles of the probe floating potential were obtained this way on a shot-to-shot basis. One shot without heating current and one, immediately successive shot, with a dc heating current of 7 A, were performed for every radial position. In the first case, i.e. with the non-emissive probe, the probe floating potential was detected (see the left-hand side of figure 3). In the second case, i.e. with the emissive probe, the plasma potential was detected (see the right-hand side of figure 3). The signals were sampled with a frequency of 1 MHz. All measurements presented below were obtained 20 or 30 mm above the tokamak equatorial plane, toroidally in the grill centre.

3. Experimental results

A typical time dependence of the probe floating potential in the interaction region (here $r = 84.5$ mm) before and during the LHW application (between the 6th and 9th milliseconds) is shown in figure 2. For a better orientation, the floating potential of the cold probe is denoted

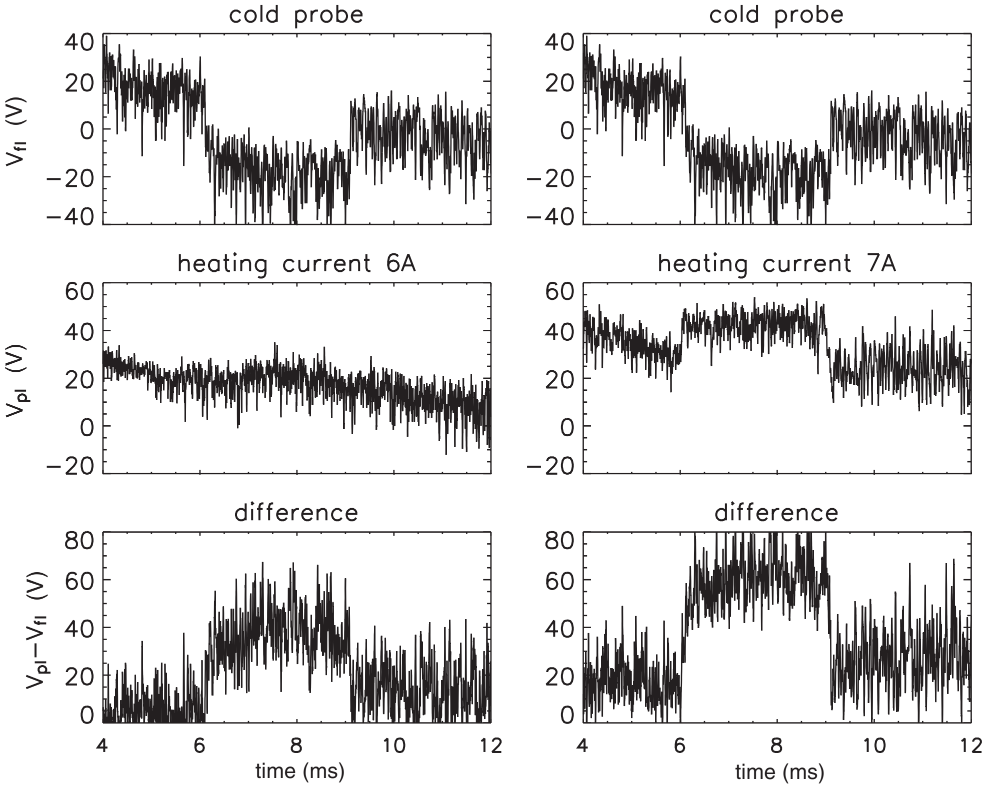

Figure 2. The time dependence of the floating potential of the cold (V_{fl}) and the emissive (V_{pl}) probes with two different heating currents of 6 and 7 A. The LH wave is applied between 6 and 9 ms.

as V_{fl} (floating), and the floating potential of the heated probe as V_{pl} (plasma). However, as to how much this potential can approach the real plasma potential, see e.g. [9]. The importance of sufficient emissivity of the probe surface is demonstrated by comparison of the LHW effect at the heating current values of 6 A (the left-hand side of the figure) and 7 A (the right-hand side of the figure). It may be seen from this comparison that the lower emissivity at 6 A is already sufficient to compensate fully the biasing effect of a small number of fast electrons; however, for approaching the plasma potential, a still higher emissivity is needed. In the lower part of the figure, the difference in the V_{pl} and V_{fl} signals is given, to characterize the effect of the LHW better quantitatively (please take into account the fact that V_{pl} and V_{fl} are measured in two different shots). It may be seen that this difference, corresponding to the value of several electron temperatures in the case of a Maxwellian plasma during the OH phase, is greatly enhanced during the LH phase. It is also important that this enhancement during the LH phase is not only due to the compensation of the negative biasing effect of the parasitic fast electrons generated through the electron emission from the probe, but partially also by the increase of the value V_{pl} itself (at least for the heating current 7 A, see V_{pl} on the right-hand side of the figure), in qualitative correspondence with the theoretical predictions. For a reasonable life time of the tungsten wire, the current value of 7 A has not been exceeded and this value has been used for all other measurements.

Series of cold and emissive probe floating potentials, obtained on a shot-to-shot basis by a radial shift of the probe, are given in figure 3. Measurement has been done 20 mm above the equatorial plane through the radial layer, 10 mm thick, just in front of the grill (the shaped grill

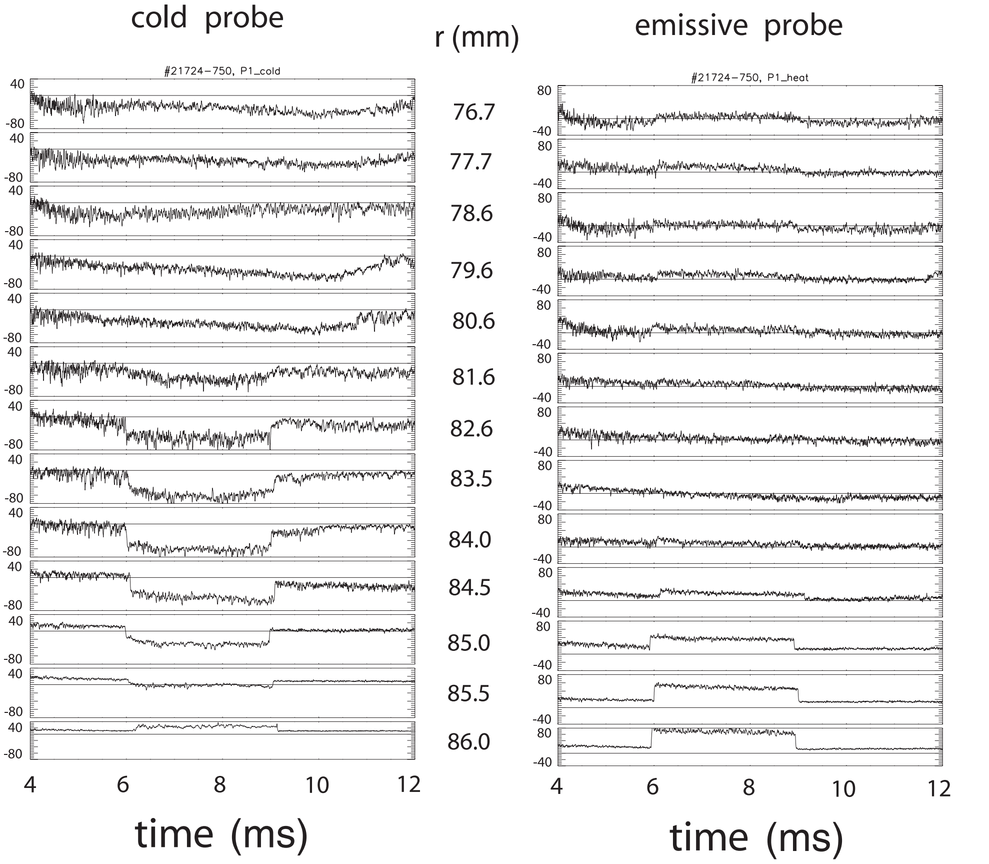

Figure 3. A comparison of the cold (left-hand side) and the emissive (right-hand side) probe floating potentials (in volts) during the OH and during LHW application (between the 6th and 9th milliseconds) on different radii in front of the CASTOR grill.

mouth has a radius of 86 mm). The substantial difference in the signal character for the cold and emissive probes is clearly visible (note also that the ordinate axes in the two series have a mutual shift of 40 V).

The radial profiles of the potentials V_{fl} and V_{pl} in front of the CASTOR grill, obtained from the curves shown in figure 3, are given in figure 4. The profiles have been obtained by averaging of 10^3 samples of a strong fluctuating signal during the OH (diamonds) just before application of the LHW and by averaging of the same number of samples during LHW application (asterisks). The formation of a narrow potential dip ('well') in the V_{fl} profile is clearly visible between the radii of 82 and 85 mm during the LH phase, while, in contrast to this effect, V_{pl} exhibits a certain increase, especially quite near the grill mouth. To judge better the change, when the LHW is applied, the difference, $V_{\mathrm{pl}} - V_{\mathrm{fl}}$, is shown in the figure as well (again, note that corresponding values of V_{fl} and V_{pl} are obtained in two different discharge pulses). It may be seen that, while this difference recalls the case of the Maxwellian plasma deeper in the plasma, it is greatly enhanced just in the 'well' of V_{fl}. As no macroscopic changes in the plasma quality are observed, and a local increase in the electron temperature has been excluded by probe characteristics analysis, the observed enhancement of the difference, $V_{\mathrm{pl}} - V_{\mathrm{fl}}$, must be caused by generation of fast electrons with a corresponding energy (decrease in V_{fl}) and partially also

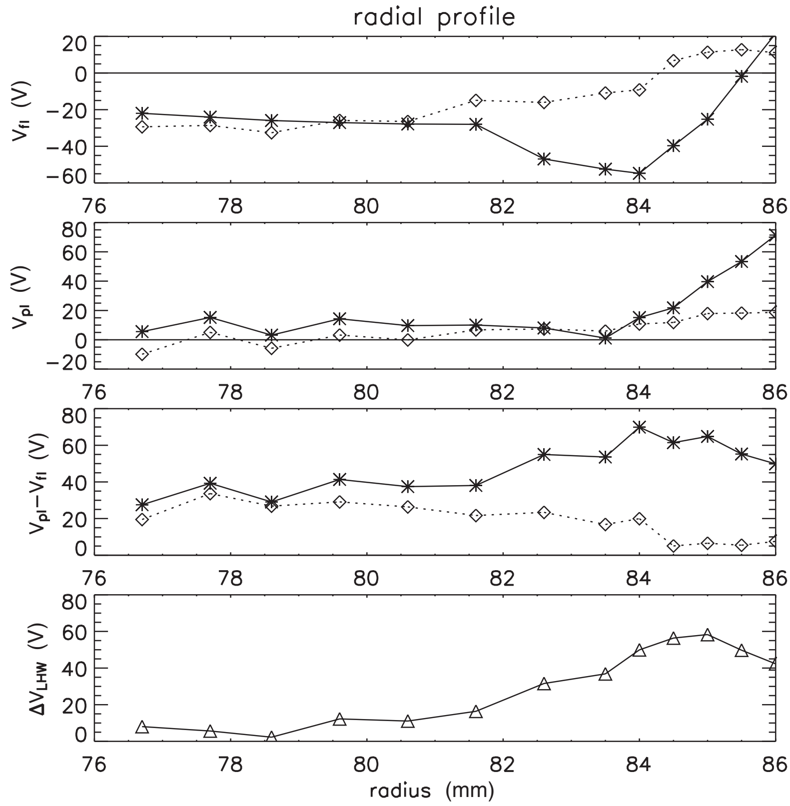

Figure 4. A comparison of the radial profiles of the cold (V_{fl}) and the emissive (V_{pl}) probe floating potentials in the OH (diamonds) and in the LHW (asterisks) discharge phase. The difference between the two potentials, $V_{pl} - V_{fl}$, is also shown. The last trace denoted as V_{LHW} (triangles) is the net change of $V_{pl} - V_{fl}$ due to the LHW with respect to its ohmic value.

by the increase in V_{pl}, due to the escape of these electrons. The net effect, ΔV_{LHW}, of LHW, i.e. the change in the difference, $V_{pl} - V_{fl}$, during the LHW compared with this difference in the OH phase, is shown in the figure as the last trace. It may be seen again that this net effect is concentrated in a radially narrow layer of only several millimetres just in front of the grill.

Figure 5 shows the dependence of the investigated effect on the incident LHW power. All quantities in the figure have the same meaning as in the foregoing figure 4. The power dependence has been measured near the minimum of the V_{fl} potential well (at $r = 85$ mm), in this case 30 mm above the tokamak equatorial plane. It seems that the effect has no power threshold and that the dependence on the power has a linear character. This is in qualitative agreement with theoretical predictions of the increase in the energy of the accelerated electrons with the power launched into the tokamaks.

4. Conclusions

New experimental data concerning the character of the interaction between the LHW and the plasma periphery in front of LH antennae have been obtained using cold and emissive Langmuir probes. The results of the measurements shown above can be summarized as follows:

(i) The measurements with the non-emissive cold probe (i.e. without the probe heating) confirmed the formation of a well on the profile of the floating potential during the

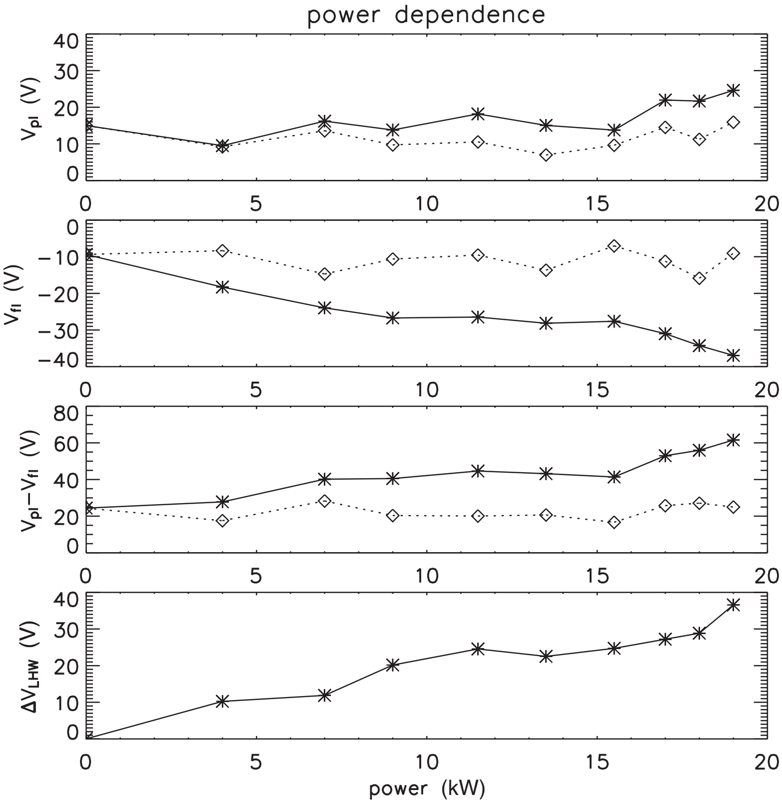

Figure 5. The LHW power dependence of the quantities shown in figure 4, measured by the probe located near the probe floating potential well minimum (at $r = 85$ mm).

LH discharge phase, observed already on the CASTOR tokamak before and explained by the existence of a group of electrons accelerated to the corresponding supra-thermal energies.

(ii) The radial width of this well is less than 4 mm, and its minimum is localized about 2 mm in front of the grill mouth.

(iii) On the other hand, the floating potential of the probe heated to a temperature over 2500°C (i.e. when the probe becomes emissive) exhibits near the grill a notable increase, if the LHW is applied.

(iv) This increase of the emissive probe floating potential is localized still closer to the grill mouth than to the well of the cold probe floating potential. It starts to be observable at a distance of 2–3 mm from the grill and it increases up to the grill mouth itself, maybe due to a continuous decrease in the plasma density up to the grill.

(v) If we consider this measured potential to be the plasma potential, a strong radial electric field of nearly 30 kV m^{-1} will appear in this radially very narrow layer just in front of the CASTOR grill at an LHW power of 20 kW. The shear velocity layer, formed under such an electric field, can result in substantial changes in the transport coefficients in this region due to the $\boldsymbol{E} \times \boldsymbol{B}$ drifts (improvement of the global particle confinement is routinely observed in CASTOR during LHW application, see [10]).

(vi) The dependence of the effect on the LHW power, characterized as the difference between the floating potentials of the heated and the cold probes in the LH and OH plasmas, seems to have a linear character, i.e. still much higher radial electric fields can be expected in front of antennae launching a power of up to several megawatts.

The results obtained can be considered as a direct experimental confirmation of the presence of the locally accelerated electrons in front of LH antennae, already predicted by theory [1, 6, 7]. The escape of these electrons along the magnetic field lines results in the positive plasma biasing, with a possible successive acceleration of plasma ions by the positive charge of the Coulomb separation. These ions might then contribute to the observed erosion of the parts of the first tokamak wall, connected directly by magnetic field lines with the interaction region in front of the LH antenna–grill (as observed already in tokamaks with LH power of the order of megawatts [2–4], where the energy of the accelerated particles can reach values of up to several kiloelectronvolts). The observed effect exhibits a linear dependence on the power, without any visible power threshold, at least within the limits of reproducibility of CASTOR discharge pulses.

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