Contrib. Plasma Phys. **44**, No. 7-8, 635 – 642 (2004) / **DOI** 10.1002/ctpp.200410094

Radially scanned probe measurements in front of the CASTOR lower hybrid antenna

F. Žáček[*1], **V. Petržílka**[1], **M. Goniche**[2], **P. Devynck**[2], and **S. Nanobashvili**[3]

[1] Association Euratom/IPP.CR, Za Slovankou 3, 182 21 Prague 8, Czech Republic

[2] Association Euratom/CEA, Cadarache, France

[3] Institute of Physics, Tbilisi, Georgia

Received 15 April 2004, accepted 15 April 2004
Published online 29 October 2004

Key words Waves, non-inductive current, tokamak, particle acceleration, probes, fluctuations, electric field.

PACS 52.50.Sw

Lower hybrid waves (LHW) are used for non-inductive generation of the electrical current in many tokamaks. However, in addition to the current drive, a parasitic acceleration of particles in front of the antennas takes place if the power is high enough. The small tokamak CASTOR allows to carry out measurements directly in the waves-plasma interaction region, using movable Langmuir probes. This paper investigates fluctuations of the plasma parameters and electrical fields in the radially narrow layer in front of the CASTOR antenna, where a significant drop of floating potential has been observed recently [1]. Significant changes in these quantities have been found during LHW discharge phase.

1 Introduction

RF waves are commonly used in tokamaks for additional plasma heating as well as for non-inductive electrical current drive. However, additionally to the effects expected, the wave-plasma interaction leads sometimes to other effects, especially for RF power high enough. One of these is a parasitic acceleration of particles in the region just in the front of the lower hybrid grills, i.e. in the plasma edge region. The energy consumed for acceleration of such particles is lost for the current drive and moreover, the particles themselves can realize a real danger for those plasma-facing components of the first wall, which are magnetically connected with the region of their generation (an enhanced local erosion of some vacuum vessel component has been already observed e.g. in Tore Supra). According to the theory estimates, the power losses could reach ten percents of the power launched and energy of accelerated particles several keV for LH power on the large tokamaks currently used. Theory suggests a mechanism of the particle acceleration by absorption of higher spatial harmonics in the antenna spectrum [2] and enhancement of this acceleration or even acceleration without presence of the high LHW harmonics by formation of random toroidal electric fields [3]. No experimental assessment of the relative magnitude of these two mechanisms has been done yet.

The presence of accelerated particles has been already demonstrated in tokamaks Tore Supra and JET by observing of ”hot spots” on the material wall [4]. However, direct measurements of local accelerating fields as well as appearance of the accelerated particles in the interaction region in front of the LH grills using material probes is difficult in these tokamaks due to the high plasma energy density. This paper describes such direct measurements carried out in small tokamak CASTOR by means of Langmuir probes. The experiments are briefly described in the following Sec.2, the results of the measurements in Sec.3. In Sec.4 a short summary of the results is given.

* Corresponding author: e-mail: zacek@ipp.cas.cz, Phone: +00-420-286890448 Fax: +00-420-266052907

2 Experimental setup

Tokamak CASTOR (R/a=0.4/0.085m, where a denotes the radius of the poloidal aperture limiter) is a small device with magnetic field $B(0) \leq 1.5T$, plasma current $Ip \leq 20kA$ and density $n(0) \leq 3.10^{19}m^{-3}$. For experiments with LH current drive a three-waveguide grill working at the frequency 1.25GHz (power up to 50kW) is used. The grill mouth with dimension 160mm in poloidal and 50mm in toroidal directions is partially shaped in the poloidal plane (with radius r=86mm), as shown in Fig.1. Two movable double tips probe systems, one with tips separated 3.5mm toroidally and the second separated 3.5mm poloidally, have been used for the measurements. The tips (diameter 1mm, length 1.5mm) are oriented in the radial direction. In the first case, the both tips are located in the same field flux tube and therefore, it is possible to make only limited assessment of the poloidal transport. On the other hand, conclusions about the characteristics of the toroidal electric field (important for the process of the particle acceleration) can be drawn. In the second case, a qualitative assessment of the changes in the poloidal rotation (and correspondingly of the particle radial flux) can be done. Due to the low plasma energy in CASTOR, short pulses (20ms only) and a good pulse repetition, the probes could be moved through the whole interaction region in this device (see also Fig.1, where the situation in the small cross-section is shown). In this way, broad radial profiles of the floating potential and ion saturated current have been obtained on shot-to-shot basis (with a radial resolution given by the tips length 1.5mm). The signals have been sampled with the frequency 1 MHz and stored for the whole discharge duration (32ms).

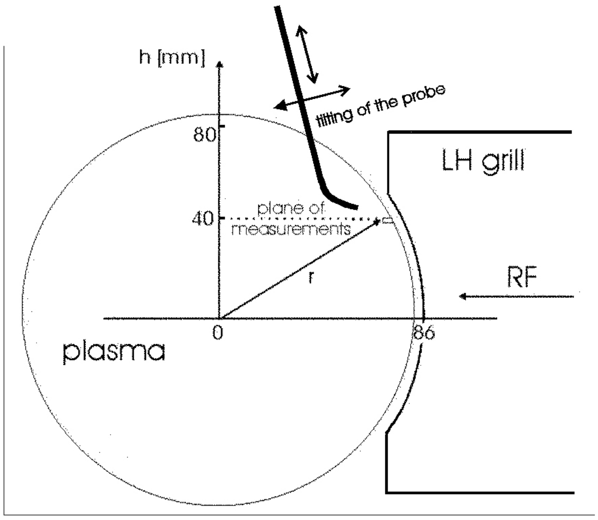

Fig. 1 Layout of the radial probe measurement through the small CASTOR cross-section.

3 Results of the measurements

As it has been already mentioned above, a radially very narrow layer (several mm only), with a dip in floating potential up to -200V (potential ”well”), is observed several mm in front of the CASTOR grill mouth during the LHW application [1]. This dip was interpreted as arising due to the presence of electrons accelerated just in this layer. However, an attempt to find such fast electrons by measurement of I-V probe characteristics did not bring the expected proof. Note also that no similar dip in plasma floating potential is observed far (in toroidal direction) from the CASTOR grill, where only a positive biasing of the peripheral plasma during the LH current drive phase is measured [5] (improvement of the global particle confinement during LHW CASTOR phase is attributed just to this global positive biasing). The measurements discussed below are therefore attended to investigation of changes of the fluctuating plasma and field parameters just in the floating potential dip and in its radial vicinity.

3.1 Toroidal electric field fluctuations

The probe system with the tips placed on the same field line has been used for the measurement of the toroidal electric field. The measurements have been performed 40mm above the equatorial tokamak plane. The LHW has been applied in the time period 10-13ms. For illustration, Fig.2 brings the time courses of the rough floating potential signal V_{fl} measured at five radii through the potential "well". The radial profiles of V_{fl}, evaluated by averaging over $500 \mu s$ in OH (Ohmic Heating) plasma just before (asterisks) and immediately after (diamonds) application of LHW pulse, are given in Fig.3. The formation of the potential "well" deeper than minus 100V during LHW is clearly visible. Note that the maximum of V_{fl} drop (and probably also the maximum of the particle acceleration) is slightly shifted from the grill mouth into the plasma. This is in accordance with measurement done in JET [4b], exhibiting maximum of hot spot brightness at the divertor apron for a grill slightly retracted behind the limiter.

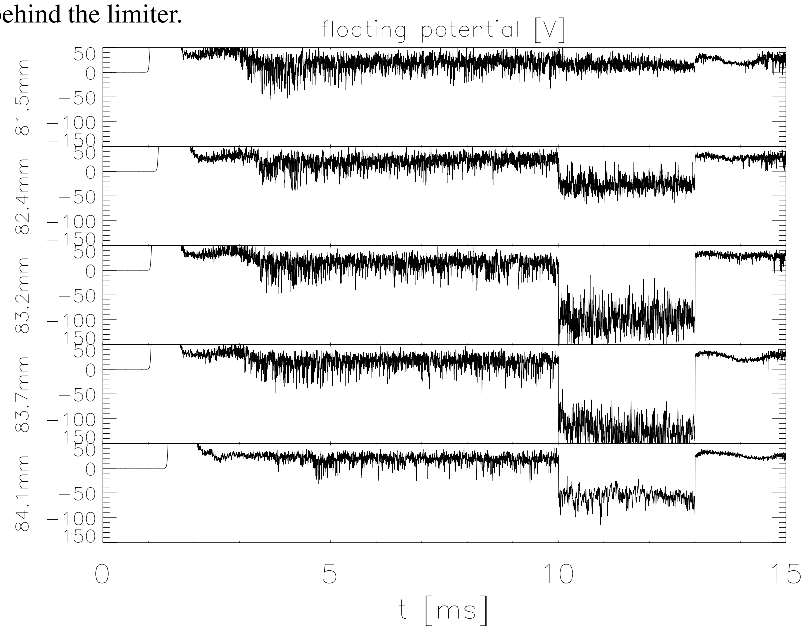

Fig. 2 Time development of the floating potential measured in five radial probe positions through the potential "well".

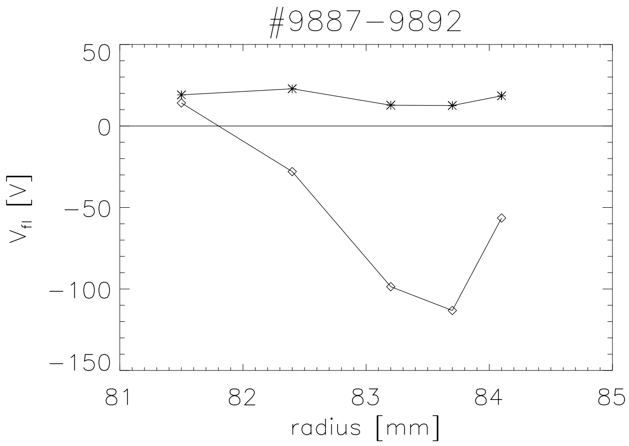

Fig. 3 Radial profiles of the time averaged floating potential in OH (asterisks) and LHW (diamonds) discharge phases (h=40mm, toroidally spaced probes).

In the following, comparison of several characteristics derived from V_{fl} signals just before and just after the beginning of the LHW phase are given at three radii regarding the "well" shown in the Fig.3: r=81.5mm (deeper in the plasma), 83.7mm (place of the maximum V_{fl} drop) and 84.1mm (near to the grill mouth). At first, Fig.4 shows cross-correlation functions [6] of the signals V_{fl} measured simultaneously by the both tips 1 and 2 (located at the mutual toroidal distance 3.5mm). Sets of 500 samples from the time intervals 9.4-9.9ms and 10.1-10.6ms have been used for this analysis (LHW is applied at t=10ms). Fig.5 shows frequency spectra of the signal measured by tip 2, evaluated from the set of 2^{10} samples (8.9-9.924ms and 10.1-11.124ms).

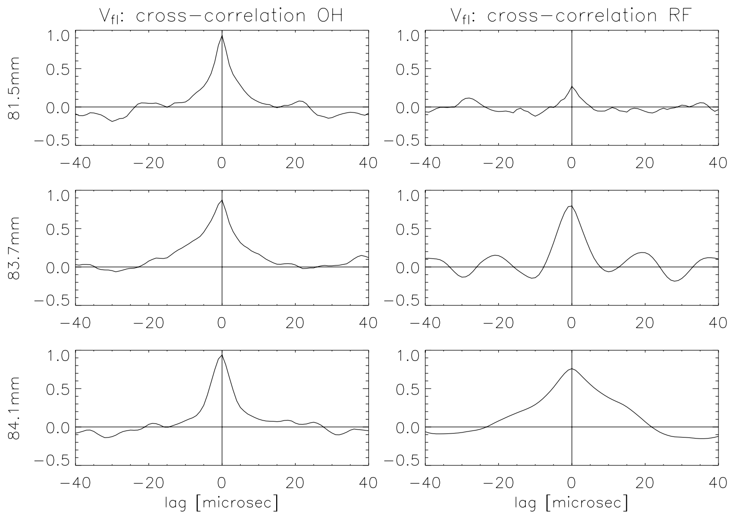

Fig. 4 The cross-correlation functions of the floating potentials measured on the same field line in a toroidal distance 3.5mm. The functions are evaluated at the three probe radii shown and compared for OH and LHW discharge phases.

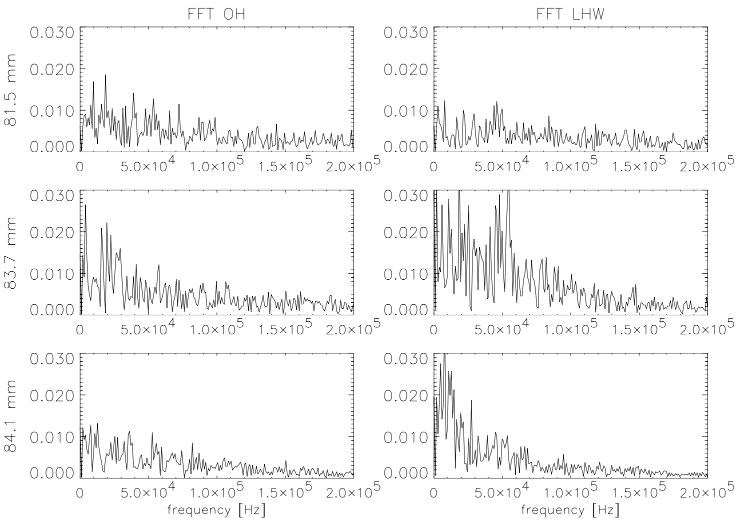

Fig. 5 Comparison of the floating potential frequency spectra for OH and LHW discharge phases. Spectra are evaluated for the same probe radii as given in Fig.4.

Further, Figs. 6,7 concern already the radial dependence of the fluctuating toroidal electric field E_{tor} [kV/m] and its frequency spectra. This field has been calculated from difference of the V_{fl} signals of the both tips. Substantial changes of all these quantities during the LHW application are easy visible. The main differences can be summarized as follows:
(i) the cross-correlation coefficient of the V_{fl} signals reaches for all radial positions a value nearly one during the OH (Fig.4), i.e. practically no measurable toroidal electric field is present in this discharge phase;
(ii) the cross-correlation of the V_{fl} signals is practically zero during LHW phase deeper in the plasma, while it is recovering just at the radius of the V_{fl} ”well” layer;
(iii) together with recovering of the correlation, a certain time shift of the cross-correlation function maximum appears in this radially narrow layer; this fact indicates establishment of a toroidal rotation (with a velocity several km/s) of the plasma fluctuations;
(iv) simultaneously, an expressive long-living frequency component about 50kHz (visible in the cross-correlation function) appears at the radius of the ”well” layer;
(v) this 50kHz component existence is confirmed also directly by FFT analysis of V_{fl} signal, see Fig.5; moreover it may be seen from the figure that 50kHz component is slightly enhanced at all radial positions during the LHW (in contradiction to the OH phase), but it is markedly increased just only inside the ”well” layer (evidently result of a regular poloidal plasma rotation, observed also in W7-AS under ECRH, see [7]);

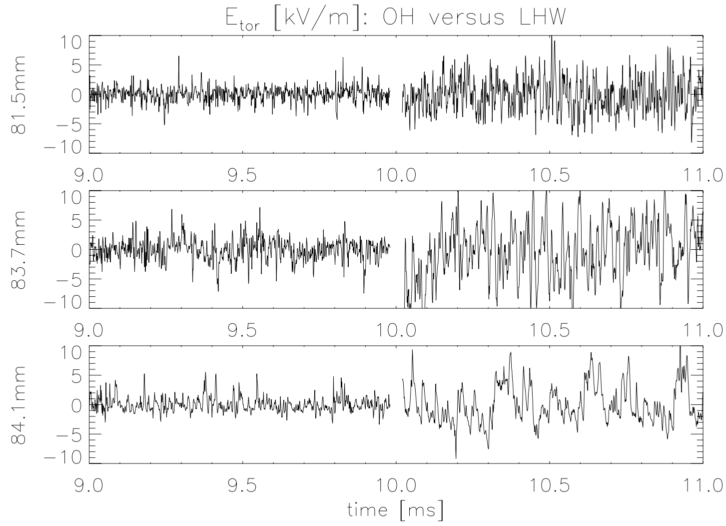

Fig. 6 Comparison of time course of the toroidal electric field for OH and LHW discharge phases, evaluated for the same three probe radii as given in Fig.4.

(vi) amplitude of the toroidal electric field E_{tor} is strongly increased during LHW phase (Fig.6) at all probe radii as expected (see also the point (i) above);
(vii) this amplitude increase during the LHW is caused first of all by a massive enhancement of the low frequency component of the E_{tor} spectrum (spectrum has a character of "white noise" during OH), see Fig.7;
(viii) however, this distinct difference in spectrum is not in any case the most profound in the "well" layer, where the process of acceleration is supposed to take place; this fact could indicate that the fluctuating toroidal electric field, detected in the experiment, participates in the particle acceleration in the very narrow layer in front of the grill mouth and, in this way, it is absorbed there (this would be similar to the absorption of the high LH field harmonics observed in numerical simulations [8] just in a similar very narrow layer close to the antenna).

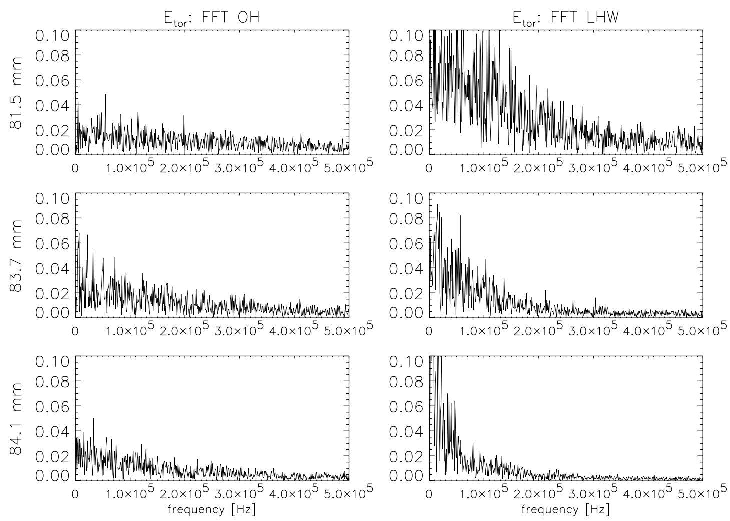

Fig. 7 Comparison of the toroidal electric field frequency spectra for OH and LHW discharge phases. Spectra are evaluated for the same probe radii as given in Fig.4.

3.2 Poloidal rotation and radial transport assessment

The probe system with the tips placed on the same magnetic surface, but poloidally separated by 3.5mm, has been used for this measurements. The measurements reported have been performed 15mm above the equatorial tokamak plane. Fig.8 demonstrates formation of the V_{fl} "well", Fig.9 shows behaviour of the cross-correlation function of the both V_{fl} signals at three characteristic radii (with regard to the "well") before OH and during LHW application. The following can be seen and concluded from these figures:

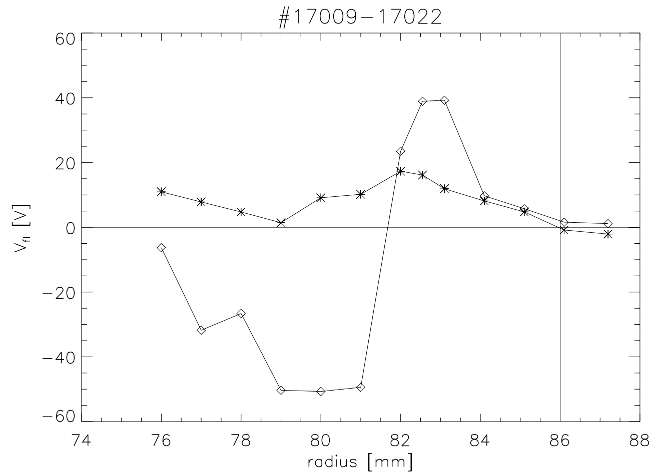

Fig. 8 Radial profiles of the time averaged floating potential in OH (asterisks) and LHW (diamonds) discharge phases (h=15mm, poloidally spaced probes).

(i) there is a stable poloidal velocity shear layer during the OH phase, located between the radius 76 and 80mm; during this OH phase the plasma fluctuations rotate in direction of the electron diamagnetic drift with velocity about 3.5km/s inside the layer, in opposite direction (with a similar velocity) outside the layer;
(ii) the shear layer is evidently shifted more to the periphery during the LHW phase because there is no apparent difference between OH and LHW phase deeper in the plasma, while a substantial difference is observed just in the V_{fl} "well": the sense of the fluctuations rotation is changing with LHW application in this region and the correlation itself is much smaller (quite disappears at radii greater than the "well" radius);
(iii) the observed shift of the shear layer to the grill, as well as increase of V_{fl} close to the grill (see Fig.8), are in concordance with theoretical predictions about an increase of the plasma potential in the interaction region, ensuing from electron acceleration and their successive run out [9].

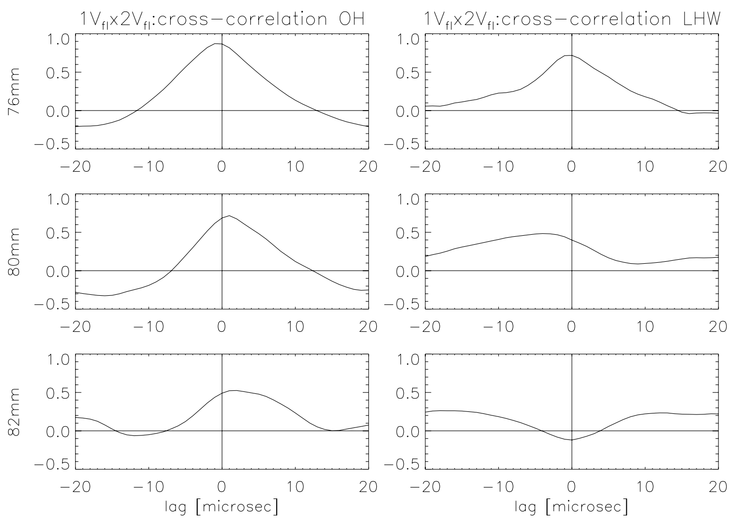

Fig. 9 The cross-correlation functions of the floating potentials measured by two probes placed in a poloidal distance 3.5mm. The functions are evaluated at the three probes radii shown and compared for OH and LHW discharge phases.

The following Figs.10 and 11 bring certain data about the radial particle transport changes. For this purpose only one of the probes (tip 2) is measuring V_{fl}, while the second (tip 1) ion saturated current I_{sat}. The Fig.10 shows comparison of radial profiles of the both quantities time averaged over $500\mu s$, Fig.11 their mutual cross-correlation function for 6 radial probe positions marked in Fig.10. The following main conclusions can be drawn from the figures:

(i) LHW pushes the plasma 1-2mm out of the CASTOR grill (and generally decreases density fluctuation, see e.g. Fig.11 in [5]); such plasma pushing has been already predicted by theory [10] and observed e.g. in ASDEX

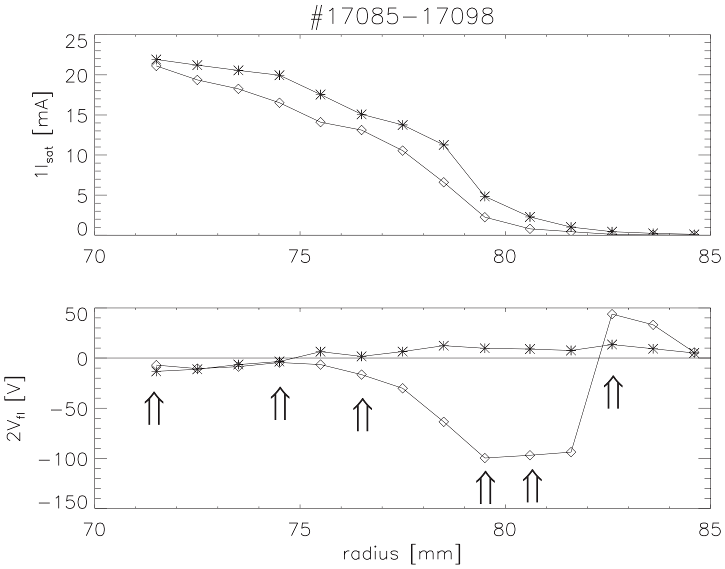

Fig. 10 Radial profiles of the time averaged ion saturated current I_{sat} and floating potential V_{fl} in OH (asterisks) and LHW (diamonds) discharge phases.

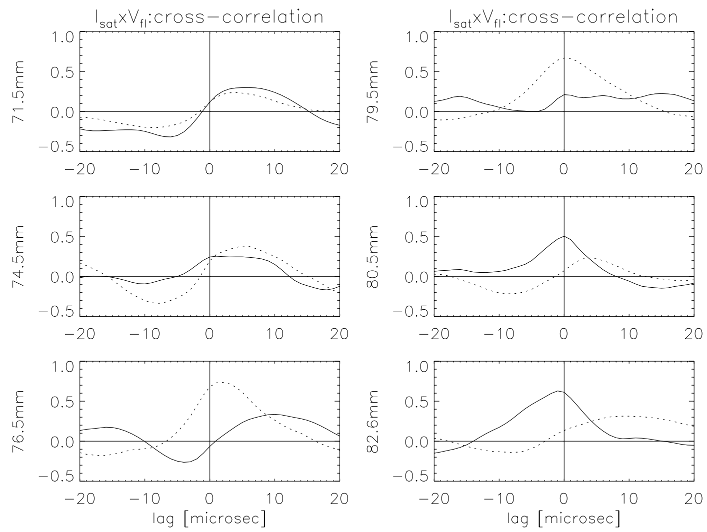

Fig. 11 The cross-correlation function of the ion saturated current I_{sat} and floating potential V_{fl} (measured by two probes separated by a poloidal distance 3.5mm) for 6 radial positions shown in Fig.10 during OH (full lines) and LHW (dotted lines) phases.

device;
(ii) the cross-correlation function (and probably radial transport also) varies substantially with the radius for the both OH as well as LHW discharge phases;
(iii) however, radial dependence of this function differs significantly for OH and LHW: while hardly any difference is observable deeper in the plasma (i.e. no effect of LHW is observed), it acquires totally another character starting with approaching to the potential "well"; a strong effect of LHW on the transport properties just in this region can be deduced.

4 Summary

The local measurements of the plasma floating potential and ion saturated current profiles in front of the CASTOR LH grill have been carried out. Two movable systems, each consisting of two small Langmuir probes located either in toroidal or poloidal direction, enabled to obtain data about the changes of fluctuating toroidal electric field and particles transport, respectively. Substantial differences have been found just in the radially thin layer, where during LHW the steep negative "well" of the plasma floating potential is formed (i.e. just in a supposed region of the electron acceleration).

Acknowledgements This work has been supported by the Czech grant project GA AV 1043101.

References

[1] F. Žáček et al., Proc of 28th EPS Conference on Controlled Fusion and Plasma Physics, Funchal, Portugal, 18-22 June 2001, ECA Vol. **25A**, 325 (2001).
[2] V. Fuchs et al., Phys. Plasmas **3**, 4023 (1996).
[3] V. Petržílka et al., 18th IAEA Conf., Sorrento 2000, paper CN-77 EXP4/07.
[4] a) M. Goniche et al., Nucl. Fus. **38**, 919 (1998), b) K. Rantamaki et al., 30th EPS Conf. on Contr. Fus. and Plasma Phys., Petersburg 2003, P1.189.
[5] Žáček F. et al., Czech. J. of Phys. **51** (2001) 1129.
[6] A.V. Oppenheim, A.S. Willsky, I.T. Young, "Signals and systems", Prentice/Hall Internat., Inc, 1983, ISBN 0-13-811175-8, p. 144.
[7] H.J. Hartfuss et al., Plas. Phys. Contr. Fusion **38**, A227 (1996).
[8] K. Rantamaki et al., Nucl. Fus. **40**, 1477 (2000).
[9] V. Petržílka et al, 29th EPS Conf. on Plasma Phys. and Contr. Fus., Montreaux 2002, P2.105.
[10] V. Petržílka et al., Nucl. Fus. **31**, 1758 (1991).