Studies on ISTTOK during edge electrode biasing assisted AC operation

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Abstract. It has been experimentally established in ISTTOK that edge electrode biasing under appropriated conditions improves particle confinement by reducing radial transport via ExB shear layer formation. In order to understand the influence of electrode biasing on the repeatability and reproducibility of AC operation edge electrode biasing was used during the AC transition of plasma current. The control of the plasma density in the quiescent phase is made just before the AC transition by means of edge polarization leading to a transitory improved of density (30% - 40%). This improvement by itself does not seem to be a sufficient condition to obtain successful AC discharges. By varying the biasing voltage from 120V up to 200 V and operating at higher plasma currents (4.5 kA) it has been possible to increase further the plasma density during the transition. The experimental characterization results have indicated that in spite of the successful increase of density during the AC transition the completion of the AC cycle depends on factors such has machine conditioning (Z effective), operating background pressure (gas puff and wall recycling), and mainly for ISTTOK, on the balance of external magnetic fields matching the transient plasma current formation.

1. Introduction

The operation of ISTTOK in AC type discharges with positive and negative plasma current semi-cycles has been implemented since 1998 [1] while recent upgrades allowed to extend the discharge duration up to 20 full cycles (~50 ms each period). The success of a reproducible AC discharge has been reported to depend on several macroscopic factors such as the level of plasma current, balance of horizontal and vertical magnetic fields (controlling plasma column position), the conditioning of the chamber (impurity content and wall recycling) and gas puff levels. In this paper we present and discuss new results on the characteristic plasma parameters of the AC discharge operated under electrode biasing. By using the heavy ion beam diagnostic we can obtain the radial profile measurements of the $n\sigma(T_e)$ (*nsigma*) quantity being n the electron density and σ the effective electron impact ionization cross section of the probing beam. Details of operation of the HIBD can be found in [2]. The $n\sigma(T_e)$ quantity is measured at 12 radial positions ranging from ($-55 < r < 55$ mm) with a typical spatial resolution of 11 mm. The *nsigma* data can be taken as a proxy for local plasma pressure relative changes. In addition, when combined with data from interferometer it can provide information about average plasma temperature. Also, by assuming density profiles limited by the integral value of plasma density (interferometer) it can give an insight on the electron temperature profile.

ISTTOK is a large aspect ratio limiter tokamak with a toroidal field $B_T = 0.45$ T, major radius R = 460 mm and minor radius r = 85 mm, plasma current Ip = 4-6 kA, electron density n = 3-7 x 10^{18} part./m^3 and central temperature typically around 60-140 eV. During the AC discharges positive bias is applied via a dedicated electrode typically located at r = 70 mm that can be moved between plasma discharges. Positive bias experiments [3,4] have shown that the plasma density can be increased above 30%-40% for a typical polarization time of 1.5-2 ms. During this time the plasma density rises and the plasma temperature drops maintaining the total plasma thermal energy relatively constant. The aim of this work is to use biasing during the AC transition in order to increase the plasma density during the current transition (*Ip* = 0) and study which effect this may have on the reproducibility of the AC cycle.

2. Experimental characterization of AC discharges

A typical *nsigma* evolution for a current limited (4 kA) AC discharge (#40035) is depicted in Fig. 1. In this discharge no bias was applied (reference AC discharge). We can see several cycles of the discharge with increasing of *nsigma* absolute value as the discharge progresses attributed to a better conditioning of the chamber. Transitions are marked by a fast (but not null) drop of *nsigma* during the plasma current inversion.

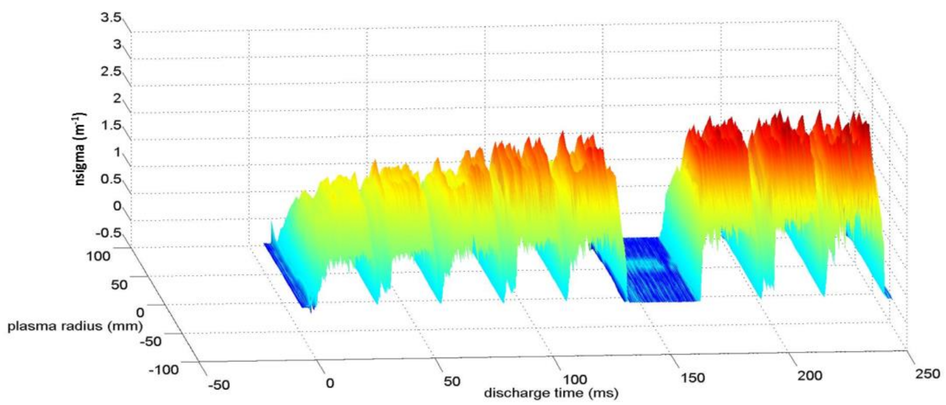


Fig. 1 - Evolution of the *nsigma* profile of a 10 semi-cycle AC discharge. The low signal level at around 140-170 ms corresponds to an unsuccessful negative cycle. The last negative cycle beyond 250 ms was also unsuccessful.

The temporal evolution of the *nsigma* profile and the interferometer line integral are shown in Fig. 2, for a successful AC transition (around 193.7 ms) and for a non-successful AC transition (around 246.5 ms). During the successful AC transition the *nsigma* profile is peaked just before the transition, becomes to a residual value during transition and restarts in the negative cycle, peaked and vertically centred (this scenario evolution is the most commonly observed during successful AC transition). During the transition period when $I_p = 0$ the interferometer density does not vanish ($n \sim 1 \times 10^{18}$ m^{-3}) neither the collected secondary currents by the HIBD. In both cases, *nsigma* is visibly more reduced from its maximum value as compared to plasma density due to the strong cooling down of the plasma during the transition phase. In fig. 2b) it is clearly seen that at the start of the transition phase (end of the positive cycle) the *nsigma* presents a hollow profile starting to form after 245.5 ms. From that moment the *nsigma* profile becomes more hollow and faint while the average density maintains a relatively high value, $n = 3.6 \times 10^{18}$ from 245.8 ms till 246.5 ms. The reason for a hollow *nsigma* profile while the plasma average density remains relatively high is primarily due to a reduction of core temperature. We can observe from the last row in Fig. 2b that there is a residual plasma lasting for about 0.8 ms after the unsuccessful (+/-) transition. The two scenarios presented in Fig. 2 are in general observed for both successful and unsuccessful transitions; when the temperature profile becomes noticeable hollow during the AC transition the following plasma cycle does not normally start and in the few cases it does presents a relatively large vertical offset which direction from equatorial plane depends on direction of the transformer induced electric field.

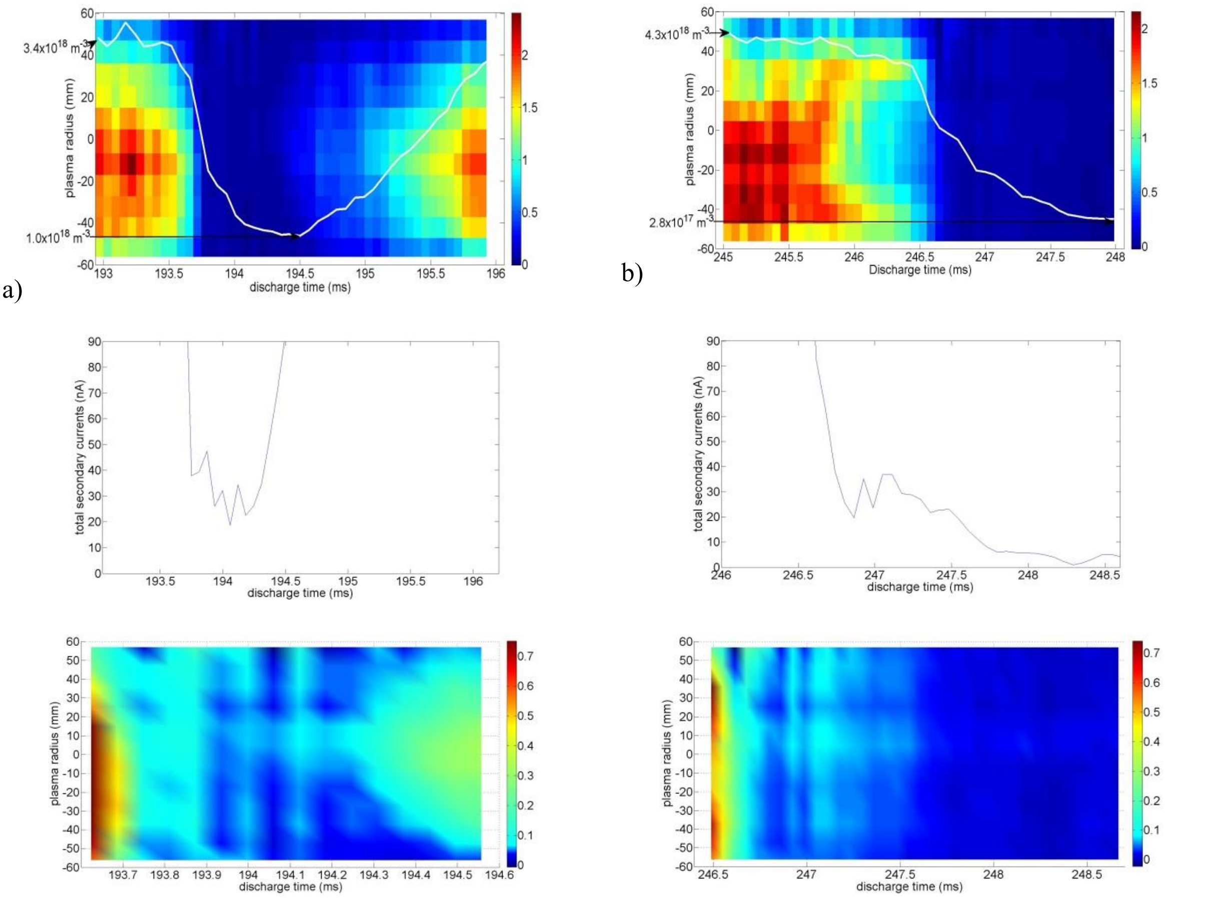


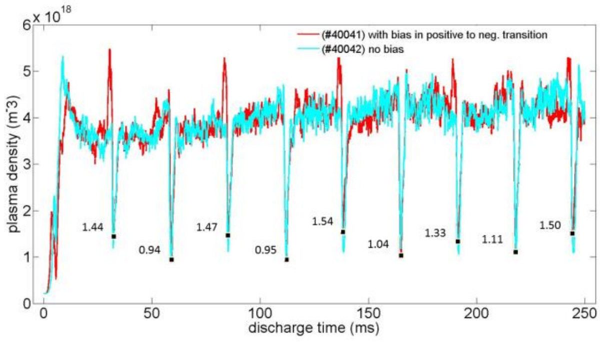
Fig. 2. Column a) successfully AC transition (positive and negative cycle; Column b) unsuccessful AC transition (no negative cycle). In the top row the white line is the normalized interferometer signal and *nsigma* profile is depicted in the background. The middle row shows the total current on the HIBD cells (total secondary ions current). The bottom row shows a close-up of the *nsigma* profile evolution during the AC transition.

2.1. AC discharges at 4kA with electrode bias at 120V

The experiments realized have shown that electrode biasing (positive) at the plasma edge can increase the plasma core density either in the positive either in the negative semi-cycle of the AC discharge. We are interested in studying the effect that the plasma density increase imposed just before the AC transition has on the subsequent cycle. Although several parameters need to be taken into consideration for a successful AC cycle it may be possible that increasing the density just before the transition can help to maintain a successful chain of AC discharges. It is worth to mention experiments with biasing applied during the whole AC transition phase have also been conducted however, due to the strong plasma current and density reduction at Ip = 0 A (loss of rotational transform) no systematically effect was obtained.

In fig. 3, is depicted the interferometer density evolution for two AC successful (consecutive) plasma discharges one with bias and other with no bias for a feedback limited plasma current of I_p = 4 kA. The increase of plasma density due to biasing during the positive to negative transition is clearly seen for the biased discharge. However, the flat-top density of the negative cycle does not seem to have changed between the two cases, achieving the same equilibrium values.

Fig. 3 – Density evolution for two plasma shots (I_p = 4 kA), # 40041 biased and # 40042 unbiased. Density levels during the AC transition are marked for the biased shot (bias pulse is applied only for +/- transition: 120 V, 2 ms duration applied 2ms before AC transition).



2.2. AC discharges at 4.5 kA with electrode bias at 120 V

It is experimentally observed in ISTTOK that when the plasma current limit is increased to beyond 4 kA the success of AC transition is reduced. Several factors can contribute to these observations such as (i) formation and balance of plasma column during transition (a key issue given the reported possible formation of a double opposite current column in similar experiments [5]), (ii) impurity content (as in a normal start-up phase can lead to too much radiation losses) and (iii) plasma resistivity and inductance that can govern the efficiency of current generation and the current decay time. The plasma density and temperature during AC transition could be affecting some of these parameters and consequently determine the course of the subsequent cycle.

We have analysed the AC transition in the case of biased and unbiased discharges at I_p = 4.5 kA for cases (+/-) where the negative cycle has failed to start. Several shots have been realized and Fig. 4 presents some parameters obtained from the experiments.

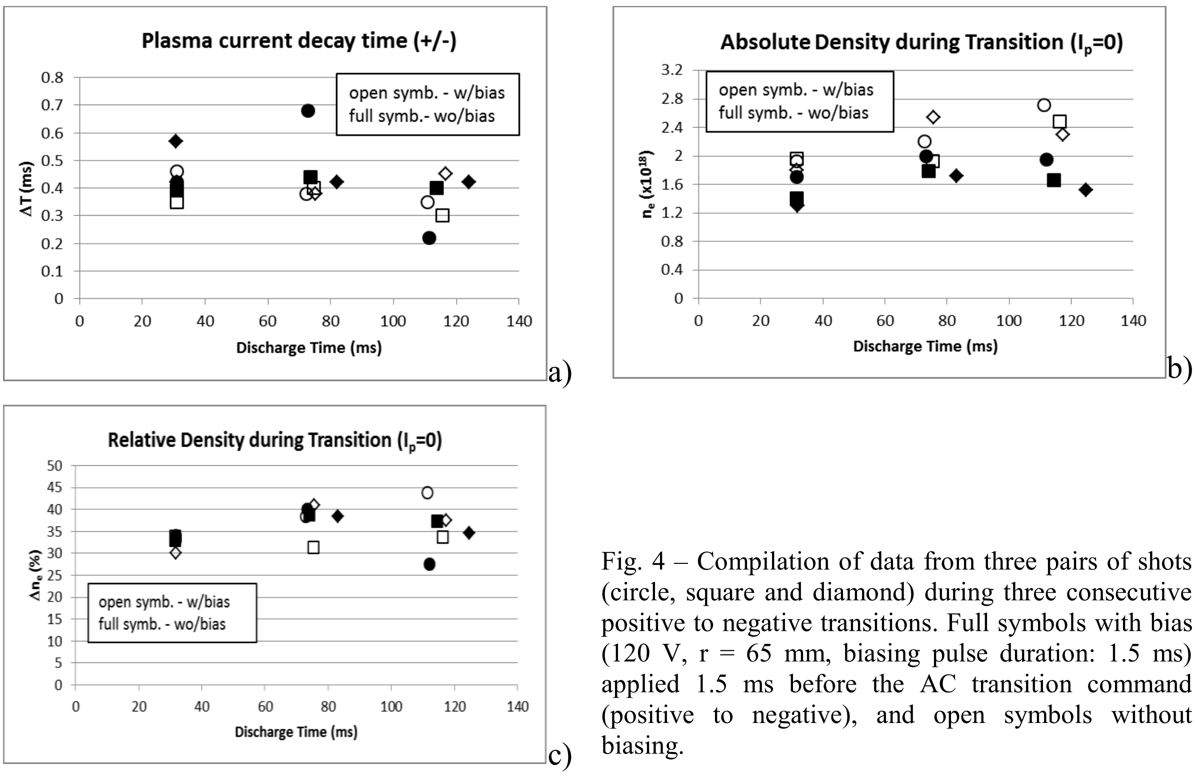


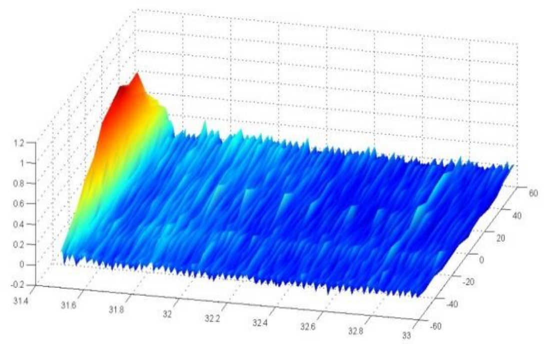
Fig. 4 – Compilation of data from three pairs of shots (circle, square and diamond) during three consecutive positive to negative transitions. Full symbols with bias (120 V, r = 65 mm, biasing pulse duration: 1.5 ms) applied 1.5 ms before the AC transition command (positive to negative), and open symbols without biasing.

There are observable characteristics for biased and unbiased shots. In Fig. 4a is plotted the plasma current decay time. Details on plasma temperature profile changes' during current decay (particularly immediately after biasing switch-off) and MHD activity can lead to some scattering of the characteristic current decay time. However, except for an isolated case (in full circles), this parameter seems to be relatively constant and similar for biased and unbiased shots which could indicate that the plasma resistivity may not be significantly influenced by biasing. Fig. 4b presents the absolute density measured at the AC transition, when $I_p = 0$, where we can see that the biased shots present a higher density during the transition. In Fig 4c it is depicted the relative density at the transition compared to the value just before transition. We may observe that the data covers a range between 30%-40% and there is no distinction to be made between biased and unbiased shots. This can be expected since the characteristic particle confinement time does not change once the biasing is removed just before the transition, as it can no longer influence the plasma edge transport.

3. Background plasma characterization during AC transition at several bias voltages

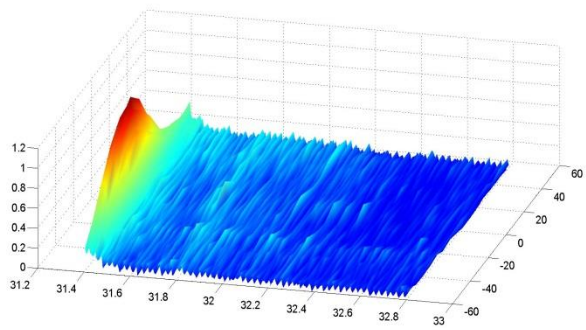
In spite of the increase of density in biased shots during the transition the development of the AC negative semi-cycle for plasma currents of 4.5 kA remained unsuccessful. A closer look into the *nsigma* data (Fig. 5) of a pair of unbiased and biased shots shows that the *nsigma* values of the background plasma just after the positive cycle are slightly higher in the case of the biased shot (#40199) due to the higher density at the transition. In these shots the background plasma apparently presents a quasi-uniform radial distribution for the detected levels of *nsigma*.

a)



Time (ms)

b)



Time (ms)

Fig. 5 – Time evolution of *nsigma* profile during positive to negative cycle transition: a) no biased shot (#40196) and b) biased shot (#40199).

Taking further these experiments a set of discharges with increasing biasing voltage where performed. In these discharges some AC cycles have failed, either positive either negative, and for a proper comparison the data collected was chosen to be only for failed positive to negative transitions (not necessarily occurring at the same time stamp between shots). The data in Fig. 6a) shows similar values as in Fig. 4a) indicating that the bias voltage plays no role in the current decay time (this may be because bias is removed at the time of transition). In Fig. 6b) one can see that when the biasing voltage is increased the peak of maximum density induced by the biasing action starts to occur before the maximum V_{loop} indicating that for increasing biasing voltages the transient effect of increasing the plasma density lasts for less time than the bias pulse duration (1.5 ms). As a consequence, in this particular case of a 1.5 ms biasing pulse duration applied at 1.5 ms before the AC transition, the bias induced increase of plasma density is not maximum at the moment when the AC transition is taking place. In spite of that, as shown in Fig. 6c), the absolute density during AC transition was still increased (except for one case). However the relative density increase in Fig. 6d) shows now a larger dispersion of values. This dispersion increase is attributed to the non-optimization of the time for biasing and bias pulse duration in respect to the command for current inversion. In terms of the discharge global parameters we may say that by increasing the bias voltage the only visible positive effect is the increase of the plasma density during the AC transition.

We may also note that several experiments in ISTTOK have shown the existence of fast electrons or even runaway beams formation at the termination of the plasma discharge [6]. In that case using gas puff during the transition could in principle help to mitigate the runaway beam and eventually develop the subsequent plasma current cycle.

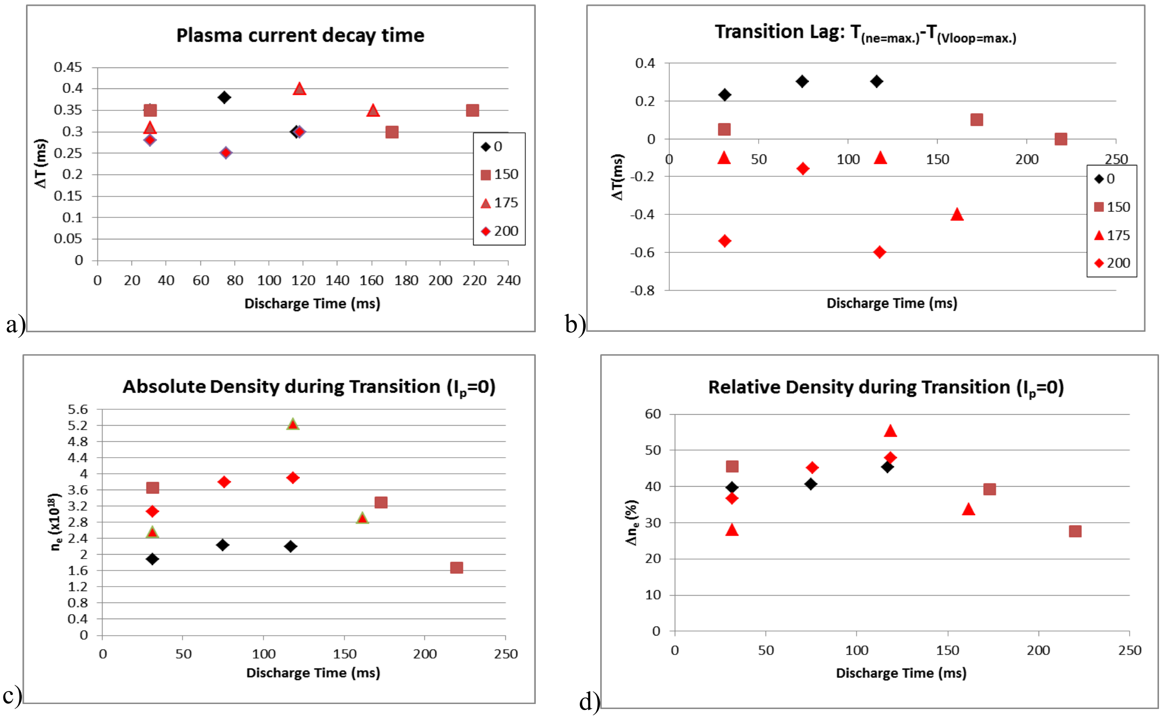
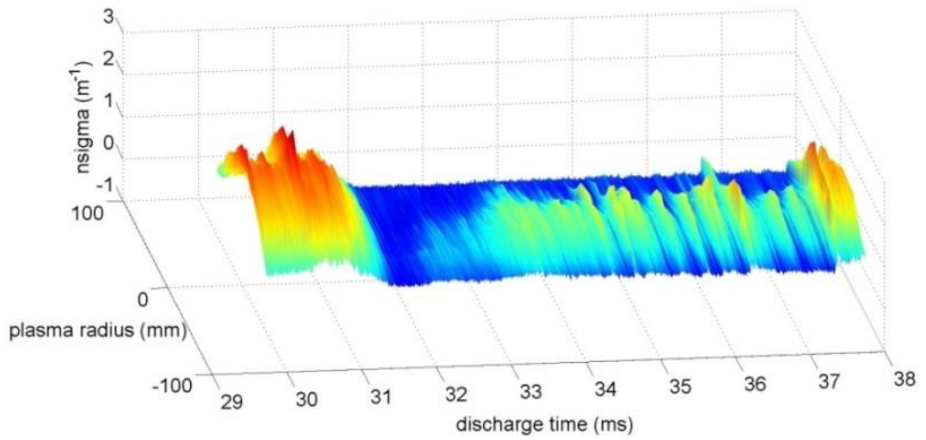


Fig. 6 – Data points concerning the transition cycle from positive to negative (unsuccessful) for a position r = 70 mm of the biasing electrode for four biasing voltages (0 V, 150 V, 175 V, 200 V) and biasing pulse duration 1.5 ms applied 1.5 ms before the AC transition trigger.

Compatible with the present observations it is not to exclude the formation of a flat, or hollow-like plasma distribution just after the transition, that may or not evolve to a full plasma discharge. In Fig 7 it is depicted the AC inversion (+/-) for shot #40264. The negative discharge does not fully develop until the time ~38 ms. It is possible to observe that a plasma located vertically down in the chamber emerges from the quiescent phase after the AC transition, at about 32.5 ms, and evolves while moving towards the centre of the chamber (vertical cord). These observations could be compatible with a scenario of a drift electron current generated by the existing reminiscent electron density at the AC transition and probably also by the pre-ionization electrons (arc discharge between a filament and the vessel) that interacts and ionize the neutrals spreading into some background plasma distribution (initially with no rotational transform). It that case it is expected that the electron drift current would change its vertical position relative to the equator depending on the induced electric field direction.



b)

Fig. 7 - Evolution of *nsigma* at a partial successful AC transition.

For example, in Fig. 8 is depicted the average plasma discharge signals (Fig. 8a) and the corresponding *nsigma* (Fig. 8b) during the start-up phase of a failed positive cycle. Judging from the *nsigma* profile, during the transition it seems that the plasma column is formed on the top half of the chamber but it does not progress to a full plasma discharge. This flipping of position of the quiescent plasma around the equatorial plane with the direction of the induced electric field seems to be in line with the scenario of a drift electron current formation during the AC transition.

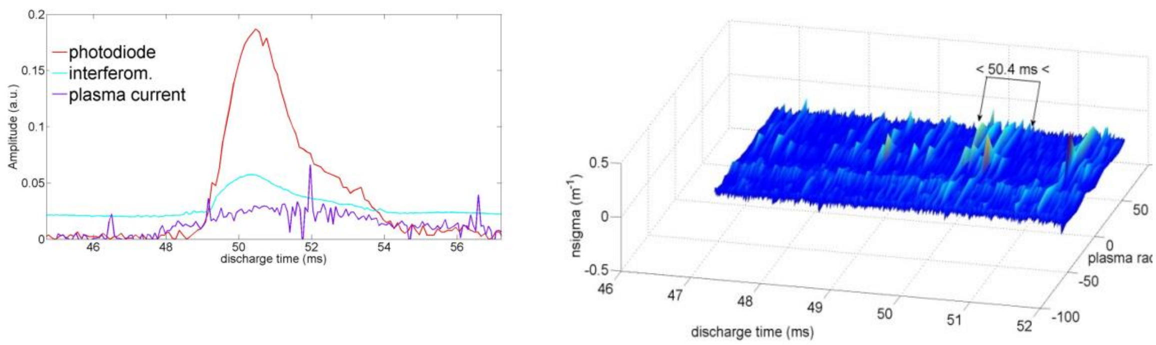


Fig. 8 – Evolution of macroscopic signals (left) and *nsigma* (right) during failed AC transition (+/-) with quescient plasma formed during AC transition.

As already mentioned one factor that can play an important role in the AC transition is the mismatch of the vertical and horizontal fields to sustain the centre position of the plasma column during its development. Although the plasma positioning fields have been optimized for the fully developed plasma discharge there is no systematic optimization yet for the AC transient phase of the discharge.

4. Conclusions

The electrode biasing experiments demonstrate that it is possible to increase the plasma density during the AC transition (when $I_p = 0$) roughly from 30%-40% above of the non-biased cases. It is observed that some background plasma is maintained for up to 0.8 ms after the unsuccessful AC transition which is longer than ISTTOK confinement time (0.3-0.4 ms). The longer plasma life-time beyond the particle confinement time has been attributed to the confinement of the electron drift current by means of the toroidal magnetic field [7]. In ISTTOK the source for the drift current could be the existence of the reminiscent electrons at the AC transition (no rotational transform) and also from the pre-ionization electrons (filament arc discharge). In addition, when the biasing voltage was increased the plasma density at the transition increased as well as observed on both, the interferometer and on the HIBD. In similar experiments it has been reported [5] the formation of two concurrent currents in opposite sense during the AC transition providing thus a mechanism to retain some confinement during the $I_p = 0$ phase. Being that the case, a shallow plasma region may form during the AC transition between the two channels of current located at two different radii. Since the HIBD cord will pass at the centre of the minor radius this scenario would produce a flat or hollow plasma pressure profile with a possible higher current channel intersecting the HIBD cord (consistent with some qualitative observations).

The possible conclusion to take at this stage of experiments is that, in order for the biased induced density increase to be efficient for a successful AC transition it calls for the optimization of the discharge start-up parameters namely, (i) the correct dosing of gas puff in order to avoid the formation of fast electrons that can generate runaway beams and (ii) the careful balance of horizontal and vertical magnetic fields.

Future experiments, including additional edge diagnostics, will be conducted in order to exploit the additional control possibilities above mentioned for obtaining successful AC discharges at higher currents (> 4.5 kA) and to deeper the analysis of the plasma behaviour during AC transitions.

Appendix 1: References

[1] H Fernandes, et al., "Engineering aspects of the ISTTOK operation in a multicycle alternating flat-top plasma current regime", Fusion Engineering and Design Volume 43, Issue 1, October 1998, Pages 101–113, doi:10.1016/S0920-3796(98)00263-4.

[2] A. Malaquias et al., "Inversion methods for the measurements of MHD-like density fluctuations by Heavy Ion Beam Diagnostic", Journal of Instrumentation, Volume 10, September 2015, doi:10.1088/1748-0221/10/09/P0902

[3] C. Silva et al., "Influence of electrode and limiter biasing on the ISTTOK plasma", Plasma Physics and Controlled Fusion, Volume 46, Number 1

[4] R.B. Henriques et al., "Characterization of positive electrode biasing experiments in the tokamak ISTTOK with the Heavy Ion Beam Diagnostic" , Proceedings of the 42nd EPS Conference on Plasma Physics, Lisbon 2015, http://ocs.ciemat.es/EPS2015PAP/pdf/O1.101.pdf

[5] Jianguo Huang et al., "The plasma current profile during current reversal in AC operation of the CT-6B tokamak", Nuclear Fusion, Vol. 40, No. 12, 2000, IAEA, Vienna

[6] V. V. Plyusnin et al., "Characteristics of four-channel Cherenkov-type detector for measurements of runaway electrons in the ISTTOK tokamak", Rev. Sci. Instrum. 81, 10D304 (2010); doi:10.1063/1.3478658.

[7] O. Mitarai, "Stable AC Tokamak discharges in the STOR-1M device", Nuclear Fusion (Letters), Vol. 27, No. 4 (1987)