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EFFECT OF THE TWO-CLOSE-FREQUENCY HEATING TO THE EXTRACTED ION BEAM AND TO THE X-RAY FLUX EMITTED BY THE ECR PLASMA

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Abstract

Multiple frequency heating has been used since the ’90 in ECR ion sources as heating schemes able to improve current intensities especially for highly charged ions. More recently “Two Close Frequency Heating”, where the frequency gap is comparable with the scale-length of the resonance, has been proposed, expected also to be sensitive to the relative waves’ phase relationship. At ATOMKI – Debrecen a dedicated experiment has been carried out for exploring the effects of the combined frequencies and their relative phase-difference in an argon plasma. The second frequency was finely tuned between 13.6-14.6 GHz with respect to the first one (fixed 14.25 GHz). An optimal frequency gap (in terms of Ar^{11+}/Ar^{6+} beam currents ratios) has been experimentally found, in agreement with the theory; the optimal power balance (total RF power was 200 W) between the two frequencies has been determined empirically. A weak but clear effect of the relative phase shift has been observed. Each configuration has been characterized by a multi-diagnostics set-up: HPGe and SDD detectors were used for the X-rays, a RF probe was introduced inside the plasma chamber to detect the radio-emission from the plasma.

INTRODUCTION

Demand from the users of ion beams are continuously motivating the development of ion sources to produce as high current of highly charged ions as possible. Electron Cyclotron Resonance (ECR) Ion Sources (ECRIS) seem to be the best candidates to fulfil the strict requirements in terms of beam intensity, emittance, ion choice, stability, etc [1]. To obtain intense highly charged ion current the ions should be extracted from dense and energetic ECR plasma, having anisotropic distribution of the electrons in the velocity space.

General approach of the way for the improvement is pointed by the scaling laws [2]. Accordingly, higher plasma density is needed to produce higher charge state ions, which requires higher microwave heating power. However in order to still remain below the critical density (to avoid the cut-off of the microwaves), which is scaling with the frequency square the heating frequency and the corresponding magnetic field should be increased, as well.

Milestones in this way are symbolized by different generations of ECRISs. However, the steps between two generations are money- and time-consuming, requiring many investments from cryogenic and radiofrequency engineering sides. Therefore, at a given generation level (where the magnetic field and frequency configuration is determined) tricks were worked out to significantly improve the beam parameters without drastically changing the ECRIS configuration. They are widely applied in the ECRIS committee e.g. gas mixing [3], biased disc [4], fine frequency tuning [5], and two frequency heating [6].

Since the first half of the ‘90 multiple frequency heating has been tested and used as a technic which provides remarkable improvement of the ion source performance by improving the stability of the plasma and by shifting the ion charge state distribution toward the higher charge ones [7]. The first experiments providing promising results were performed applying two far frequencies (e.g. 10 GHz + 14 GHz, 14 GHz + 18 GHz) obtaining two well separated ECR heating zones (Two Far Frequency Heating (TFFH)). The effects were explained by the increase of the ECR heating volumes [8]. However, in 2008 Gammino at al. [9] pointed out a possible “extra” interplay between the two resonant zones having the two frequencies close to each other (Two Close Frequency Heating (TCFH)). Particularly, some kind of “electron surfing” is expected; the electrons that leave the first resonant zone may further accelerated by the second one (two close frequency is needed because the phase randomization of the electrons should not be occurred). The idea was confirmed by numerical simulations showing remarkable variation in electron energy as function of the relative phase difference between the two close frequencies.

Independently of the magnitude of the relative frequency difference (TCFH or TFFH) the importance of the fine tuning at least one of the two microwave frequencies was stated, since strong fluctuation of highly charged ions were obtained by slight tuning of the relative frequency difference [10, 11]. In case of TCFH mode the optimal effect was obtained when the distance between the two resonant layers were close to the Larmor radius of the warm electrons [10].

It was highlighted that the plasma stability and therefore the ion beam stability can be improved by adding an extra

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frequency [12, 13]. Higher net microwave power can be injected to the plasma chamber still maintaining stable plasma conditions at TFH mode therefore, higher current of highly charged ions are reachable.

It was also shown that the instabilities limiting the performance of the ion source is occurred at certain conditions [14] only i.e. at suitably high microwave power and at B_{min}/B_{ecr} ratios higher than 0.75. As a characteristics of the instabilities, events are followed by sudden radio and X-ray emission from the plasma [15, 16]. These kinetic instabilities are caused by the strongly anisotropic distribution of the electrons in the velocity space and are triggered when the transverse velocity of the electrons respect to the magnetic field starts to dominate over the longitudinal one.

One can roughly summarize that the goal is to verify if two frequency heating can help the ionization efficiency of ECR plasma and can suppress the ion beam oscillation caused by the kinetic instabilities in two far and two close frequency operations, as well. However the mechanism and the dynamics of the processes caused by the second frequency are still not known, furthermore many aspects of the TFH have never been tested experimentally: the power balance between the two frequencies and the relative phase difference between them at TCFH mode.

Therefore we designed and arranged a multi diagnostic setup to investigate the behaviour of a 14.25 GHz plasma when an additional finely tuned frequency close to the first one is added. Beside the ion beam properties (current of multiple charged ions), the setup provides information on the warm and hot electron components of the plasma by measuring the hard and soft X-ray rates by the help of High Purity Germanium (HPGe) Detector and Silicon Drift Detector (SDD), as well. Furthermore the plasma generated microwave signals are able to be monitored through a radiofrequency (RF) probe placed inside the plasma chamber and connected to a spectrum analyser operating in GHz ranges. Parameters of the radiofrequency spectra can be used as an indication of stable and unstable plasma conditions.

As a unique feature, two dimensional information on the plasma structure and electron losses are obtained by X-ray pinhole camera. Effect of the relative frequency phase difference and power balance between the two TCF were explored by these diagnostics tools. This experimental campaign with this arsenal of diagnostics tools provides many important information (a complex image) on the nature of the stable, unstable and two frequency heated ECR plasmas. In this paper we are reporting the part of the obtained results which strictly corresponds to the ion source performance (ion beam, volumetric X-ray emission) while the results more deeply corresponds to the ECR plasma dynamics will be published in other papers [17].

EXPERIMENTAL

The dedicated experiment was carried out at the Atomki ECRIS, in Debrecen. This ion source [18] is a 14 GHz, second generation ECRIS. B-minimum trap consists of two room temperature coils and of a NdFeB permanent magnet hexapole. The radial magnetic field measured at the plasma chamber wall is about 1.2 Tesla while the axial magnetic peak fields at the axes of the plasma chamber are 1.26 T at the injection side and 0.95 T at the extraction side, and the minimum value (B_{min}) is 0.39 T. Detailed experimental setup of the whole, complex measurement system together with numerus technical figures and tables for a better understanding, are presented in a separated accompanying paper [19]. Only the main features of the measuring system are summarized in the following paragraphs.

The first 14.25 GHz signal was amplified by a klystron while the second tuneable one (13.6 GHz - 14.6 GHz) was provided by a TWTA. Due to the compactness of the plasma chamber and to the high number of diagnostic tools to be equipped to the ion source it was reasonable launching the heating microwaves through only one waveguide by mixing the two RF signals before the plasma chamber by power combiner. Before the power combiner a phase shifter was inserted into the TWT waveguide line. Both the forwarded and the reflected powers were measured at the closest possible point to the plasma chamber. Argon plasma was generated keeping in most cases the net power ($P_{net} = P_{forwarded} - P_{reflected}$) at fixed 200 Watts. The maximum power was limited by the X-ray imaging system to obtain photos with appropriate signal noise ratios. Gas flow was optimized for middle charged argon ion production.

Two detectors were applied at the injection side, alternatively. SDD was placed at the plasma chamber axis beyond 50 um thick kapton foil for vacuum break, and collimated by a 30 cm long lead cylinder with a 1 mm drilled hole. The CCD X-ray camera made by 1024 x 1024 pixels operational in the range 500 eV – 20 keV was coupled to a lead pin-hole and placed along the axis, facing the chamber from the injection flange. Titanium windows with 9.5 um thickness were used to screen the CCD from the visible and UV light coming out from the plasma. In addition, HPGe detector was placed also on the axis, but at the other (extraction) side of the source beyond the 90-degree analysing magnet, closed to a quartz window. The HPGe was collimated by lead blocks through 3 mm hole in diameter.

RF probe was introduced inside the plasma chamber and connected to an Anritsu Spectrum Analyser in order to detect the radio-emission from the plasma. The sudden radio-emission occurred at the beginning of the unstable plasma regime was used to trigger the signals measured by the HPGe detector, as well. Such an arrangement was allowed to record the temporal spectral composition of the emitted X-ray. So, hard X-ray spectra are able to be recorded close to and at unstable plasma conditions.

Placement of the detectors opened the possibility to extract ion beam from the plasma simultaneously with the usage of the diagnostics tools to take note some representatives of the charge state distribution (Ar^{6+}, Ar^{9+}, Ar^{11+}) at different working points.

Plasma chamber of the ion source was changed by applying dedicated materials for different part of the chamber. Tantalum liner was inserted as lateral wall of the plasma chamber, while the plasma electrode was made of Titanium. Injection plate was adapted to the X-ray imaging: the area of the Al made circle shape injection plate was divided into two regions in the ratio 2:1. The smaller area was used for microwave and gas injection, while the larger part was closed by Al mesh to form closed resonant cavity and to provide transparency for imaging at same time (see the details in [19]).

RESULTS

Response of the ion source to the settings parameters was systematically studied. Presentation of the results in terms of rates of X-ray detectors, and ion beam representatives will follow this structure: (1) effect of the single frequency sweep, (2) effect of the microwave power at selected single frequency, (3) effect of the power balance between two close frequencies (4) effect of the frequency scan at a selected power balance at TCFH mode (5) effect of the phase shift at TCFH mode.

(1) Single Frequency Scan

Figure 1. (a) shows the trend of the representatives of multiply charged ion currents extracted from the ion source as function of the TWT frequency at single frequency heating mode.

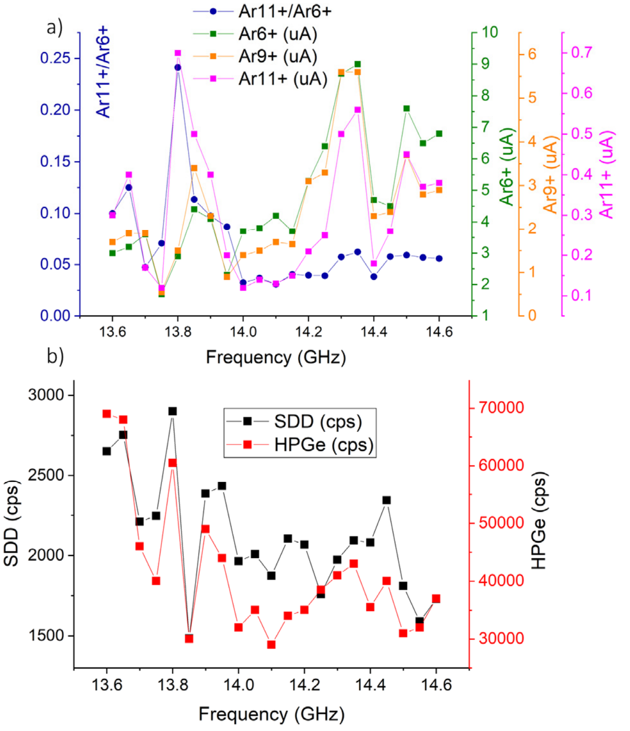

Figure 1: Effect of the single frequency scan to the extracted ion beam and to the plasma emitted X-ray

The net microwave power was always 200W, while the frequency was changed between 13.6 GHz and 14.6 GHz with 50 MHz steps. This fine frequency tuning firmed the nonlinear response of the currents which obtained by many times by many groups. Ar^{11+}/Ar^{6+} ratios (Fig.1.(a)) has maximum at 13.8 GHz and it has a general rising trend with some fluctuation from the higher frequencies toward the lower ones. This trend is also visible on the plots showing the rates of soft and hard X-ray fluxes (Fig.1. (b)).

(2) Power Dependence At Single Frequency

Power dependence were measured at 13.8 GHz being the most promising frequency in terms of Ar^{11+} current and Ar^{11+}/ Ar^{6+} ratios. At microwave power lower than 100 W the measured currents corresponding to different charge states are increasing monotonically (Fig. 2. (a)). Above 100 W nonlinear effect appeared in all the three plots cases. Ar^{6+} and Ar^{9+} currents are decreasing dramatically, while the Ar^{11+} current and the Ar^{11+}/Ar^{6+} ratio start to increase exponentially. There is a quite significant nonlinear jump in the emitted X-rays above 100 W, as well (Fig. 2. (b)).

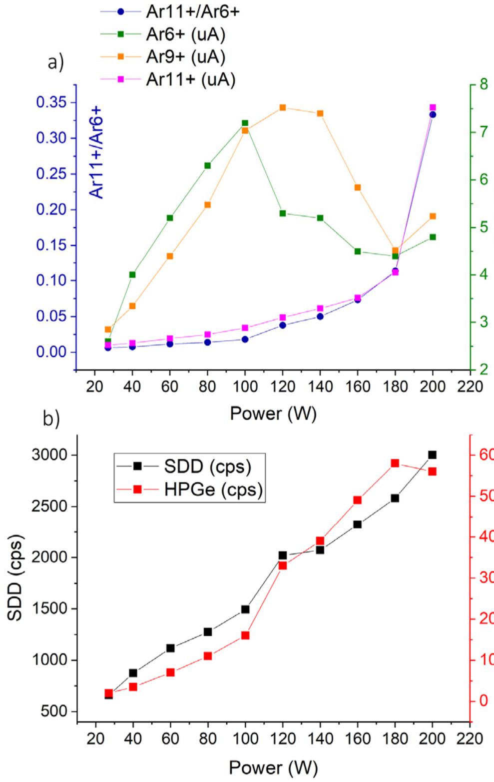

Figure 2: Power dependence of the *extracted ion beam and of the plasma emitted X-ray*

(3) Power Balance At 13.8 GHz And 14.25 GHz

Power balance between the two injected frequencies was investigated at the fixed 14.25 GHz klystron and 13.8 GHz TWT frequencies. Sum of the two power components was kept always at 200 W net power. Figure 3 shows the tendencies as function of the applied TWT power. While the Ar^{6+} and Ar^{9+} currents are decreasing with the amplitude of the TWT power Ar^{11+} and Ar^{11+}/Ar^{6+} are behaves inversely (Fig. 3. (a)). The more dominant of the TWT the higher the emitted hard and soft X-ray fluxes were obtained (Fig. 3. (b)). Instability of the plasma in terms of the plasma emitted RF signals was varying significantly with the power ratios and it was quite low at the 120 W klystron and 80 W TWT power balance case.

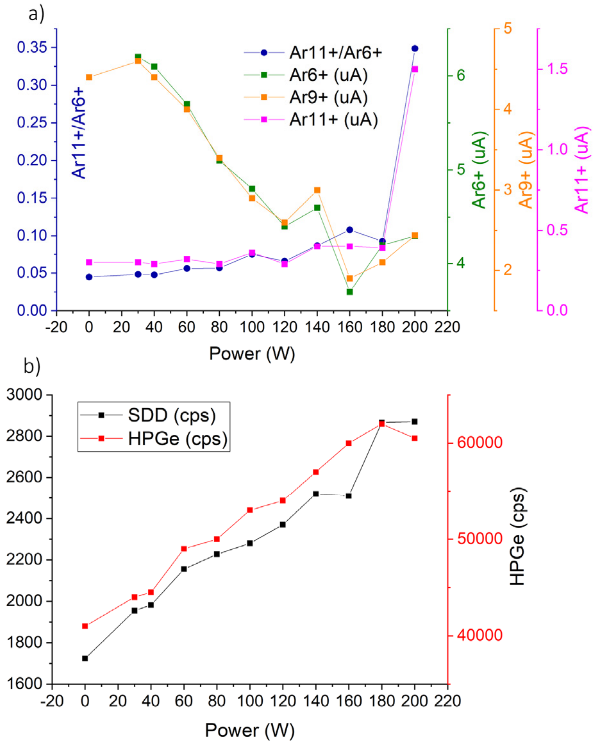

Figure 3: Effect of the power balance between 13.8 GHz and 14. 25 GHz to the extracted ion beam and to the plasma emitted X-ray

(4) Frequency Scan At TCFH Mode

Because stable plasma conditions were found around 120 W klystron and 80 W TWT powers, TCFH was investigated at this power balance, keeping the net power always at 200 W, while changing the TWT frequency between 13.6 GHz and 14.6 GHz with 50 MHz steps.

Currents corresponding to different charge states (Fig. 4. (a)) shows rather different trends than the case of single frequency scan (having minimums and maximums at different frequencies), while the obtained Ar^{11+}/Ar^{6+} ratio behaves very similarly. The two “side peaks” (especially in the 11+ production) located almost symmetrically respect to the main frequency consistent with earlier observations and with TCFH expectations. Both components of the X-ray fluxes (fig. 4. (b)) are decreasing toward the higher frequencies as obtained in single frequency scan case but the overall rate was decreased by about 15 % respect to the single frequency operation mode.

(5) Phase Shift At TCFH Mode

As mentioned in the experimental section our setup provides opportunity to check the effect of the relative phase difference between the two heating microwave. Phase of the klystron related signal was not changed while the TWT signal was phase-tuned finely. The effect was checked at several frequency combinations, at several power balance cases. Significant effect was obtained at 13.8 GHz TWT frequency at a power balance sustaining unstable plasma condition in terms of the plasma emitted RF signals (P_{KLY} = 170 W, P_{TWT} = 30W). About 10 % variation were found in the currents of Ar^{11+}, Ar^{9+} and ratio of Ar^{11+}/Ar^{9+} (see Fig. 5).

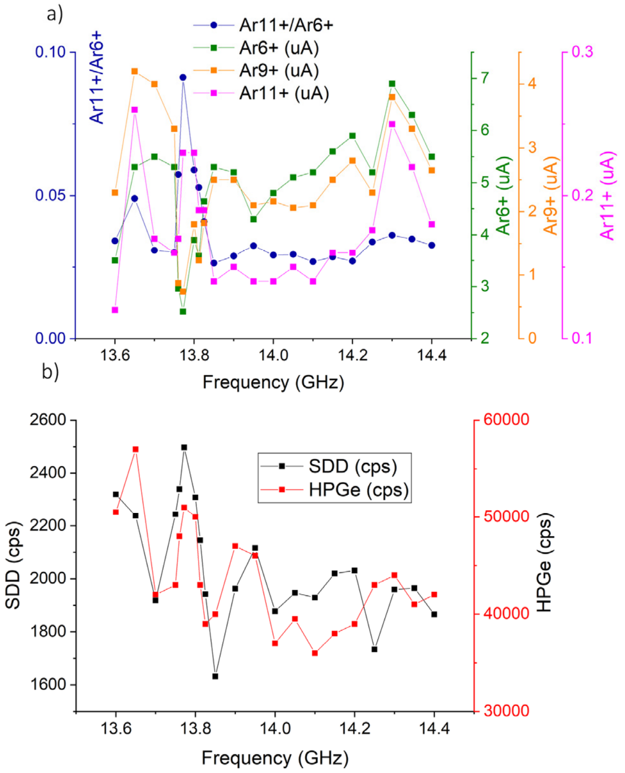

Figure 4: Effect of the frequency scan at TCFH mode to the extracted ion beam and to the plasma emitted X-ray

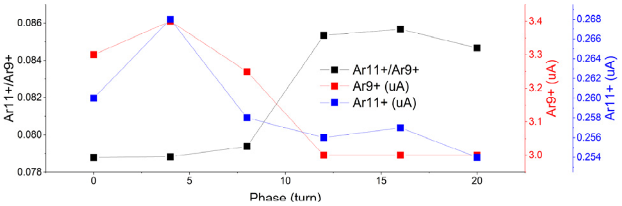

Figure 5: Effect of the relative phase difference at TCFH mode. 20 turns correspond to π phase shift.

DISCUSSION AND OUTLOOK

At single frequency scan the nonlinear behaviour of the emitted X-rays and ion beam intensities as function of the frequency was obtained in accordance with earlier experiments. It can be explained by the ECR heating depends on the excited modes in the plasma chamber, as it was shown in [20]. Due to the applied magnetic field configuration and to the selected frequency range the B_{min}/B_{ecr} ratio was varied from 0.75 – 0.8 (increasing toward the lower frequencies). Tarvainen et al. have shown that kinetic plasma instabilities are triggered always around this configuration [14]. They have controlled the B_{min}/B_{ecr} ratio by tuning the coils current. In this experimental campaign we implemented a different way for the tuning without changing the plasma confinement drastically. The rising trend of the hard X-ray flux toward the lower frequencies can be explained by stronger and more frequent instabilities causing more energetic warm electrons to be lost on the plasma chamber wall and producing Bremsstrahlung radiation. Stronger evidence is expected by analysing the X-ray photos showing the spatial distribution of plasma losses.

Curves corresponding to the power dependence shows nonlinear behaviour (jump in X-ray emission and CSD shift) above 100 W at 13.8 GHz. It could be the sign of the unstable regime appeared above a threshold level. Power balance between the two frequencies affected not only the X-ray flux but also the CSD of the ion beam and the stability of the plasma. Such an aspect of the TFH has never been highlighted.

We could find optimal frequency gap (to produce intense ion beam) between the two frequencies at TCFH mode at both side of the fixed frequency.

As it was predicted by Gammino et al. [9] by controlling the relative phase difference between the TCF the ion source performance was clearly affected. Effect of the phase shift was rather weak (about 10 %). However, the fact of the effect itself is promising. Therefore more detailed investigation of this phenomena is proposed to find probably more suitable plasma conditions having stronger impact on the ion beam parameters.

At each working points presented in this paper radio-emission spectra was recorded. Results are reported in [17]. Furthermore, spectrally integrated [21] X-ray images were also taken at every configuration. After this main characterisation of the source limited number of working points (being interesting some point of view) were selected for further time-consuming investigations. Spectrally resolved (photon counted) images [21] and temporally resolved hard X-ray spectra were acquired in those conditions and will be presented in separated papers.

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