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IMPACT OF THE TWO CLOSE FREQUENCY HEATING ON ECRIS PLASMAS STABILITY

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Abstract

Several experiments have recently demonstrated that plasma instabilities are powerful limiting factors to the flux of highly charged ion beam extracted from ECRIS. One of the methods for damping the instabilities is to feed the plasma in two frequency heating mode. Since the fundamental physical mechanism is still unclear (diffusion in velocity space? additional confinement?), a deeper experimental investigation is necessary, using multi-diagnostics setups. At ATOMKI-Debrecen the effect on the plasma instabilities of an argon plasma in a “Two Close Frequencies” scheme has been explored. Spectra of radio-emission from the plasma have been collected for different frequency gaps and relative power balances. The measurements show the plasma self-emitted radiation comes out from the internal plasma (i.e. around the lower frequency) but the instability damping can be effective for some specific combinations of frequency-gap and power balance. Radiofrequency spectra have been collected simultaneously produced by the instabilities and detected via a microwave diode connected to a plasma-chamber-immersed multi-pin RF probe.

INTRODUCTION

Electron Cyclotron Resonance Ion Sources (ECRIS) are able to produce beams of highly charged ions with high intensity and stability, which are necessary for accelerators, in applied and nuclear physics research.

In order to produce these beams, continuous improvements of the performances of ECR ion sources are needed. For many years these improvements consisted principally in the use of higher power of RF wave heating, and more intense magnetic field, on the basis of the “scaling laws” [1]. More recently, this approach has become more difficult because of the technological limits.

A deeper knowledge of plasma parameters (electron density, temperature and charge state distribution CSD) is thus fundamental: characteristics of the extracted beam (in terms of current intensity and production of high charge states) are directly connected with plasma parameters and structure.

Several experiments have in fact demonstrated that plasma instabilities limit the flux of highly charged ions extracted from ECR ion sources, causing beam ripple, as well [2]. The instability threshold depends principally from the strength of the magnetic field in terms of B_{min}/B_{ECR} and from other parameters as RF pumping power and pressure [3]. Even if many studies have been done, the exact mechanism of turbulent regimes of plasmas is still unknown and a deeper investigation is so necessary.

Plasma kinetic instabilities are characterized by fast RF and X-ray bursts causing performance deterioration of the ECRIS; to overcome this limitation more studies aiming at characterizing in detail this still unknown process and at finding a way for damping the turbulence are required. Some indications say that a key role for damping turbulences may be played by the Two Close Frequency Heating (TCFH).

In this work the experiment that has been done at ATOMKI, Debrecen (Hungary), is presented, where stable and unstable ECR plasmas in a B-min magnetic configuration have been characterized through a multi-diagnostic setup. The characterization has been carried out for the first time in Two Close Frequency Heating (TCFH) mode, through the use of two frequencies with a gap difference of the order of some hundreds of MHz.

It is well known that when the plasma is excited in double (far or close) frequencies, it is possible to observe improvements in the characteristics of the extracted beam. This process is still unknown in detail and here some experimental evidences regarding how the TCFH is able to damp instabilities are presented. Evidences of an increase of the electron confinement inside the “plasmoid region” can be argued from the experimental results.

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EXPERIMENTAL SETUP

Stable and unstable plasma regimes have been characterized through a multi-diagnostic setup, consisting in a collection of non invasive tools that allows unprecedented investigations of magnetoplasmas properties in terms of density, temperature, CSD and inner plasma EM wave emission.

The multi-diagnostic setup includes a multi-X-ray detectors system for X-ray spectroscopy consisting of:

- Silicon Drift Detector (SDD) for plasma density and temperature measurement in soft X-ray domain (Q.E. ~ 1.0÷30 KeV).
- A High-purity Germanium (HpGe) detector for spectral temperature measurement of hard X-ray domain (Q.E. ~ 30÷400 KeV), including time resolved spectroscopy.

The other devices of the multi-diagnostic setup are a spectrometer for the plasma-emitted visible light characterization and a two-pins RF probe.

The RF probe, installed inside the plasma chamber in the injection plate, protrudes through one of the gas input holes. It was connected to a Spectrum Analyzer (SA) in order to detect the plasma emitted EM wave in GHz ranges, which typically characterizes the kinetics instabilities. All instabilities were detected via RF spectra.

Alternatively, the RF probe can be connected with a diode and an oscilloscope in order to obtain the total integrated power emitted from the plasma, using this value as trigger signal for instability signature and to perform time resolved X-ray analysis too.

All diagnostic tools can operate simultaneously with the faraday cup in order to measure the charge state distribution. It has been possible to correlate the plasma parameter with the characteristics of the beam extracted on-line.

More details about the general setup, each tool and its own characteristics are well described in [4].

For the microwave coupling for TCFH a Klystron generator (with a fixed frequency of 14.25 GHz) and a TWT amplifier (with a frequency range 13.6 - 14.6 GHz) were used. Through of a power combiner it has been possible to mix the two frequencies to heat and excite the plasma inside the plasma chamber.

EXPERIMENTAL PROCEDURE

The experimental procedure have been done in different configurations.

At the beginning the system was characterized in single frequency heating mode in order to have some reference configurations. Then, the system has been characterized in TCFH mode in order to study the effect of the second frequency on plasma instabilities, and on its structure. The different configurations are here reported:

- 1FH : frequency scan by TWT only
  13.6 GHz – 14.6 GHz, df=50 MHz @ P=200W
- 1FH : TWT power scan at 13.8 GHz representative frequency, until 200W.
- 2FH : Frequency scan by Klystron 14.25GHz + TWT 13.6GHz – 14.6 GHz, df=50 MHz @ P=200W
- 2FH : Power balance @ total net power 200W, TWT 13.8GHz + Klystron 14.25 GHz

In order to correlate the instability strength of a configuration with other parameters, such as RF power and RF pumping frequency, it is very important to find a quantitative way to define how much a system is unstable. In order to give a quantitative estimation of the strength of the instabilities we introduce the parameter *Is* (Instability Strength).

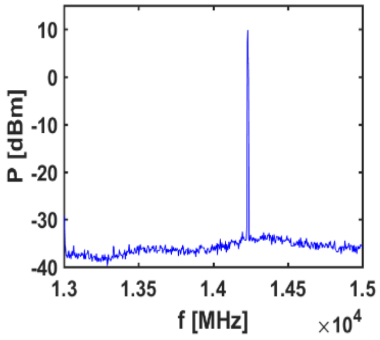
There is a series of issues concerning the quantitative evaluation of the instability strength, and, then, about the eventual correlation of confinement dynamics (plasma vs. losses X-radiation emission) with the *Is* parameter itself.

From the point of view of the *Is* rigorous definition, some (critical) issues still remain open:

a) SA measurements are performed without any temporal resolution, whilst instabilities are by definition fast evolving phenomena whose temporal scale lies in the range of μsec. or shorter; hence, any quantitative evaluation of Is has to cope with integration time of our spectrum analyzer;

b) due to the still not-perfectly known physical mechanism governing the ECRIS instability dynamics, it is difficult to find rigorous quantitative criteria to evaluate *Is*: is more important the total integral of plasma self-generated sub-harmonics or their number? Or their superposition?

In fact, as it is possible to observe in Fig. 1, a stable plasma (Fig. 1-(a)) is characterized by the pumping RF peak only. Whilst unstable configuration can be characterized by a low number of sub-harmonics with a high power in each one (Fig. 1-(b)), or also by a high number of sub-harmonics but at low power (Fig. 1-(c)).



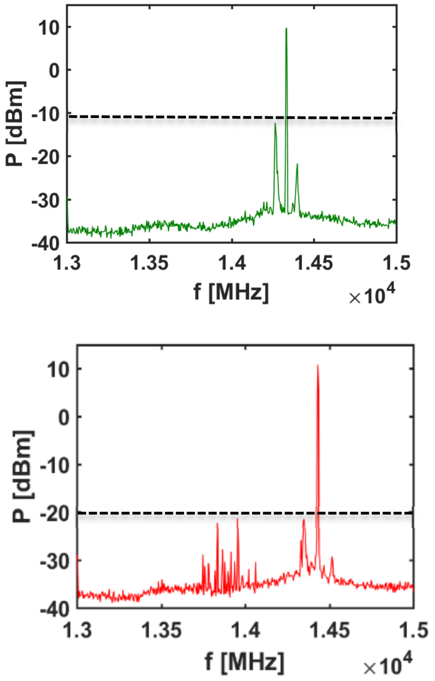


Figure 1: Sequence of SA collected spectra for: (a) stable; (b) unstable but with a small number of sub/up-harmonics at high power; (c) unstable but with a large number of sub-harmonics at low power.

After several attempts, all of them trying to find a significant Is definition able to quantitatively describe what we got from direct observation, our choice was to define Is considering both contributions as follows:

$$Is = \left(\int_{13GHz}^{15GHz} P(f)df - P_{mainpeak}\right) \cdot (1 + w(N_{sub} - 1))$$

where $P_{mainpeak}$ is the integral of the power of the main peak of pumping frequency, N_{sub} the number of sub-harmonics and w a weigth factor.

With this definition, the *Is* parameter has been calculated considering the amplitude (integral of the power) of RF plasma-self emitted signal, once subtracted the main pumping wave contribution; this number has been then multiplied by a factor which takes into account the number of sub-harmonics, N_{sub} with an opportune weight factor w. The weight was calculated in order to give more importance to the total integral of plasma self-generated sub-harmonics than their number.

EXPERIMENTAL RESULTS

In order to validate the Is consistency we made some plots concerning the *Is* behaviour vs RF power, in single and two close heating mode.

The definition of Is resulted to be consistent with the direct observation of the SA recorded spectrum, increasing steadly with the power, as expected.

Details of correlations with other parameters and time resolved X-ray data are commented in [5].

In this work the attention is focused to instability issues only.

RF Spectra in 1FH - Power Scan @ 13.8 GHz

The plot of Is vs. RF power is in Fig. 2, and it displays a clear increase of Is, as expected, but anyway without any evident jump or non-linearity. *Is*>0 condition occurs already at 40 W, and this is consistent with the direct observation of SA recorded spectrum.

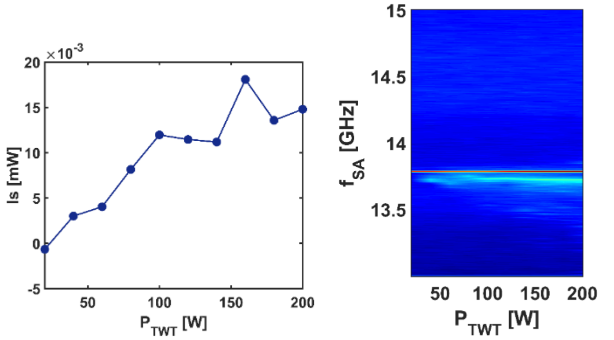


Figure 2: trend of the Is parameter vs. the TWT power, during the single-frequency power scan. On the right, the spectral evolution of the RF probe detected signal vs. the pumping wave power. Sub-harmonics generation is evident already at around 40W.

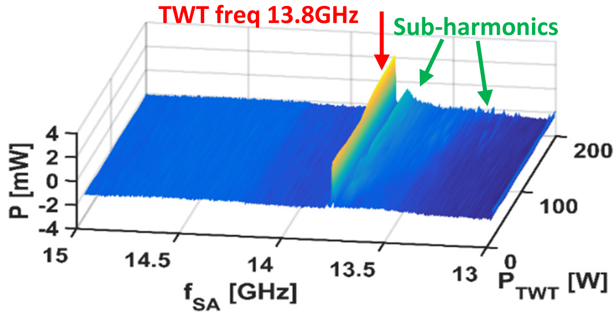


Figure 3: 3D plot of the RF probe detected signal, analysed through the SA. This plot is equivalent to the pseudo-colours plot of Fig. 2-right.

Figure 2-right illustrates the RF probe detected signal via SA analysis, when increasing the pumping wave power: the red line represents the pumping frequency (TWT only @ 13.8 GHz) whilst the green shadows are the sub-harmonics, i.e. the plasma-self generated waves due to the instability onset. It is possible to observe how these additional components become more and more intense and their number increase for higher TWT powers. A "down-shift" of the emitted frequencies is also evident.

Also in Fig. 3 is possible to observe the increase of characteristic sub-harmonic peaks for higher power.

RF Spectra in 1FH - Frequency Scan @ 200W

The trend of Is vs RF frequency displays a frequency-dependent behaviour (see Fig. 4). To the knowledge of the authors, this is the first time the frequency tuning is systematically explored for the instability. Is mirrors the strongest instability at the lowest frequency we used, i.e. 13.6 GHz. Even in this case, this is in agreement with the direct experience, both looking to the raw spectrum and to the general conditions of the source (at 13.6 GHz we obtained the largest high-energy X-ray flux, the largest total X-ray dose, etc.).

This is also consistent to the fact that at 13.6 GHz the source is operated well below the B_{min}/B_{ECR} threshold that is universally considered as the "trigger" for the instability onset. Anyway, the plot shows that the frequency also (and not only the RF power and B_{min}/B_{ECR} value) affects the instability strength.

Looking to this plot, it is more evident why integral only was not enough for evaluating Is. In fact in the case of 13.6 GHz there are a lot number of sub-harmonics, but with low emitted power.

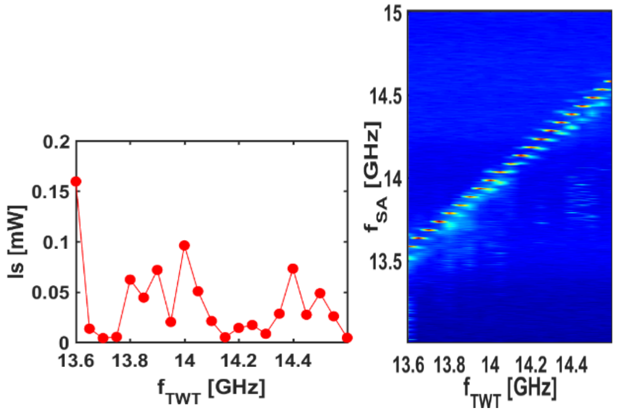


Figure 4: left – trend of Is parameter during the one-frequency scan; right – spectral structures as detected by the SA at different frequencies, during the single frequency scan.

The "drop" below the pumping-frequency (pump. Freq. lies all along the line $y=x$) gives a qualitative indication about the instability strength which is not only related to the amplitude of the "down-chirp" spot, but also to the frequency spread of the self-generated sub-harmonics; This effect has been included in the above mentioned numerical definition of Is.

Another very interesting result is that instabilities generate sub-harmonics for all frequencies of TWT, and some up-harmonics appear for higher frequencies only (in particular, above 14.2 GHz).

These plots demonstrate that despite our definition of Is was difficult, it seems to follow in a reasonable way what happens in the plasma in more or less unstable conditions (depending on the power, magnetic field and frequency).

RF Spectra in 2FH – Frequency Scan @ 200W

The trend of RF spectra vs freq. scan at 2FH plot (Fig. 5) shows first of all that sub-harmonics in double freq. heating mode and in unstable regimes are always at frequencies lower than the lower of the twos.

In TCFH mode up-harmonics disappear totally. This result, compared with the single frequency case, is very relevant: a possible explanation could be that in TCFH a steeper density profile is generated, since TCFH increases confinement and the plasma is more concentrated in the inner-plasmoid.

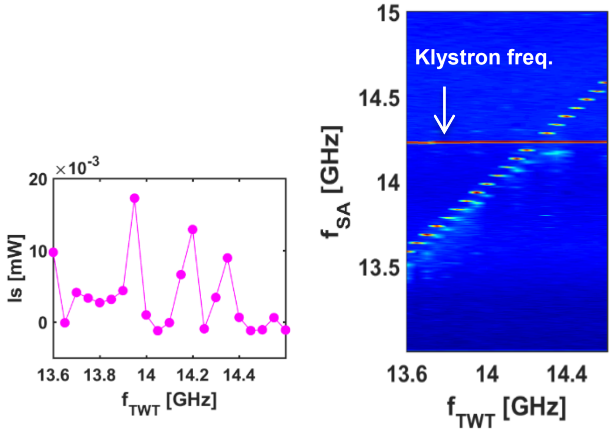


Figure 5: left – trend of Is parameter during the two-frequency scan; right – spectral structures as detected by the SA at different frequencies, during the double frequency scan (Klystron at fixed frequency, TWT varying from 13.6 to 14.5 GHz).

In Fig. 6 we directly compare the *Is* parameter in single frequency and in two close frequencies heating mode: it is possible to observe that the instability strength drops drastically, confirming that the TCFH is able to dump the instabilities.

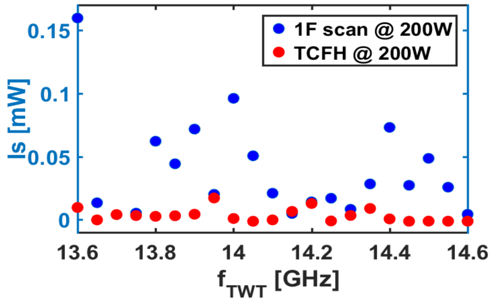


Figure 6: Comparison of the Is parameter for single and double frequency heating, at fixed power. TCFH damps the instability almost over the entire frequency set.

Figure 7 enters more in details about the relevance of the instability damping at 13.8GHz, 200W, which was a very unstable regime. It is clear that this frequency is highly unstable already at low power levels. Anyway, the addition of the second wave, coming by the Klystron, damps the instability even if the total amount of power reaches 200 W

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(120 W by TWT and 80 W by Klystron). That means the instability can be damped by TCFH.

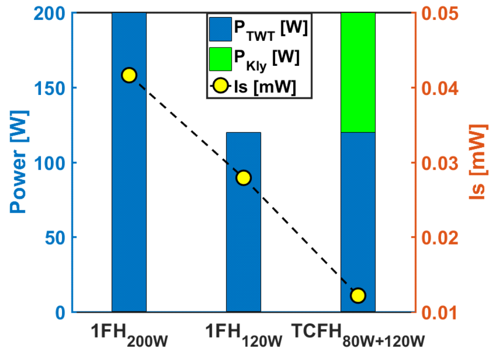

Figure 7: histograms represent the RF power provided in single-frequency or double-frequency mode by the two generators. Yellow dots are the relative Is factor. The combination of two frequencies is in this case more stable than a single one, even if the power is increased of almost a factor 2.

RF Spectra in 2FH – Power Balance @ 13.8 GHz + 14.25 GHz @ 200W

RF spectra vs power balance plot (Fig. 8) shows that instabilities increase very much for higher power of TWT. This result was somehow expected since the TWT frequency 13.8GHz is much unstable due to the fact that B_{min}/B_{ECR} value is closer to the instability threshold than the Klystron frequency.

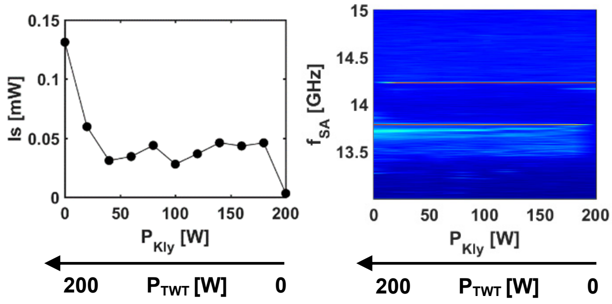

Figure 8: Power Balance scan in case of TCFH: instability strength increases at increasing TWT power, as confirmed by the microwave spectrum depicted on the right.

CONCLUSION AND PERSPECTIVES

The paper reports on an experimental campaign aiming at investigate the impact of TCFH on the plasma stability. At the B_{min}/B_{ECR} values that are typical of the ATOMKI ECRIS, the plasma is prone to kinetic instability development for any frequency we used in the range 13.6-14.5 GHz. The measurements show the TCFH can totally suppress the instabilities if the power balance is suitable. The Is parameter, that has been evaluated to quantitatively provide the strength of the instability, has been directly correlated to operative parameters (RF power and frequency) in single and double-frequency heating modes, showing a significant drop (one order of magnitude) during TCFH operations, at any second frequency.

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