Impact of two-close-frequency heating on ECR ion source plasma radio emission and stability

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Abstract
Experiments have recently demonstrated that kinetic instabilities occurring in magnetoplasma are huge limiting factors to the flux of highly charged ion beams extracted from ECR ion sources. Recently, it has been shown that the two-frequency-heating (TFH) mode has the proven potential to mitigate these instabilities. Since the fundamental physical mechanism of TFH is still unclear, a deeper experimental investigation is necessary. At ATOMKI-Debrecen, the effect on the kinetic instabilities of an argon plasma in a ‘two-close-frequency heating’ scheme has been explored for the first time by using a frequency gap smaller than 1 GHz (i.e. operating in the so-called two-closed-frequency heating mode). A special multi-diagnostics setup has been designed and implemented. In this paper, we will show the data collected by a two-pin, plasma-chamber immersed antenna connected to an RF detector diode and/or to a spectrum analyzer for the detection of plasma radio-self-emission when varying the pumping frequency in single versus double frequency heating mode. Data have been collected simultaneously to the beam extraction and for different frequency gaps and relative power balances. The turbulent regime of the plasma has been tentatively described in a quantitative way, according to the properties of the plasma self-emitted RF spectrum. The measurements show that plasma self-emitted radiation emerges from the internal ECR region every time (i.e. below the lower pumping frequency) but the almost total instability damping can be effective for some specific combinations of frequency-gap and power balance, thus eventually improving the plasma confinement.

Keywords: electron cyclotron resonance ion source, plasma diagnostics, kinetic plasma instability

1. 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 improvement in the performance of ECR ion sources is required. For many years, these improvements consisted principally in the use of higher power RF wave heating and more intense magnetic fields 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: the characteristics of the extracted beam (in terms of current intensity and production of high charge states) are directly connected to 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 [2–4]. The
instability threshold depends principally on the strength of the magnetic field in terms of \(B_{\text{min}}/B_{\text{ECR}}\) and from other parameters such as RF pumping power and pressure [5]. Even though many studies have been conducted, the exact mechanism of turbulent regimes of plasmas is still unknown and a deeper investigation is 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 are required aimed at characterizing, in detail, this still unknown process and at finding a way to damp the turbulence. Some indications say that a key role for damping turbulences may be played by two-close-frequency heating (TCFH) [6], which is a variation of the well-known technique called two-frequency-heating (TFH) that has already proven to be a powerful method for increasing ion beam intensities [7, 8]. Our characterization has been carried out for the first time in TCFH mode through the use of two frequencies with a difference of the order of some hundreds of MHz (instead of >1 GHz as typically done in TFH). This paper describes the results of an experiment carried out at ATOMKI, Debrecen (Hungary), where stable and unstable ECR plasmas in a \(B_{\text{min}}\) magnetic configuration have been characterized through a multi-diagnostic setup. It is well known that when 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, below, we present some experimental evidence regarding how TCFH can be able to damp instabilities. Evidence of an increase of the electron confinement inside the ‘plasmoid region’ can also be argued.

### 1.1. TCFH versus TFH

The use of two frequencies for plasma heating in ECRIS is a well-established method in order to increase the production of, in particular, highly charged ions. Normally, the frequency of the two waves differs by more than 1 GHz, typically 3 or 4 GHz. The role of TFH has also been explored in terms of its impact on instability dynamics, as described in [9, 10]. In these papers, the authors demonstrate that, other than an increase in the beam current and the average charge state, the method is able to provide a stabilizing effect by suppressing the kinetic instabilities. Some qualitative explanations are attempted, inferring, in summary, that probably the interplay between the two waves re-distributes the plasma in real and phase space, reducing the amount of hot electrons that are deemed to support the instability growth. The aim of our article is to investigate the role of double frequency heating of the plasma when the two-frequency gap is consistent with the estimation given by [11], under which the two resonance zones overlap. Hereinafter, this condition (i.e. the overlapping of the two resonance zones) will uniquely define TCFH, thus distinguishing it from classical TFH. From a mathematical point of view, the \(\delta \omega/\omega\) (omega is the heating frequency) condition fulfilling TCFH is given by the following formula:

\[
\frac{\delta \omega}{\omega} \leq \frac{Y}{M^2}
\]  

(1)

where \(M\), in a parabolic mirror, is given by

\[
M = \frac{\pi R^2 \omega}{2(\sqrt{\frac{4 \pi k}{m}}) \left( \epsilon^2 + \epsilon^2 \frac{k}{2 B^2} \right)^{\frac{1}{2}} \left( \frac{2 B}{dz} \right)^{\frac{1}{2}}}
\]

(2)

and \(Y\) depends on the resonant and minimum \(B\) fields. For the estimation in our trap, we use the following parameters due to [11]: \(L = 0.055, \rho = 0.218, Y = 0.1\). In (2), other than the classical physical constants, \(L, \rho\) and \(Y\) are parameters describing the shape of the mirror trap (characteristic length, mirror ratio, etc.), \(Ai\) is the Airy function, \(R\) is the mirror ratio, \(\epsilon\) is the amplitude of the heating electric field (for both the frequencies the amplitude was considered for propagating waves as equal to \(95 \frac{V}{cm}\), \(Bi\) is the resonant field and \(dB/dz\) is the magnetic field gradient at the resonant point.

If we fix the first pumping wave frequency at 14.25 GHz, calculation \(\delta \omega/\omega\) provides ±0.45 GHz. This estimation agrees with the empirical estimation of the resonance thickness, which is also reported in [6], which was used to roughly estimate the frequency gap for simulating the TCFH effect on electron heating. In the paper of Lieberman et al [11], the quasi-linear theory of TFH is used to give a robust explanation of the TCFH consequences on the heating and confinement dynamics. Basically, the authors claim that TCFH can turn the diffusion in velocity space into a four-dimensional process which also enhances the diffusion rate along \(v_t\) by more than a factor of two, even if the total power is just shared among the two frequencies. We will come back to this model later in section 5. The instability dynamically grows or damps according to the competitive balance between the growth and damping rate:

\[
\frac{dE_i}{dr} \approx (\Gamma - \Delta) E_i
\]

(3)

and the growth rate \(\Gamma\) is

\[
\Gamma \propto \frac{N_e \text{hot}}{N_e \text{cold}}
\]

(4)

i.e. it depends basically on the ratio between the number of hot over cold electrons in the plasma, and in particular on the anisotropy of the electron energy distribution function (EEDF). In fact, a more complete relation between the growth rate and the EEDF states that the instability grows for enhanced \(\frac{\partial \rho}{\partial \rho}\). In TCFH, the higher diffusion along \(v_t\) should reduce the growth rate, thus limiting the energy by which the plasma can self-couple to the electromagnetic modes supporting the instability. This is our basic assumption that will be validated by the experimental results below.

### 2. Experimental setup

Stable and unstable plasma regimes have been characterized through a multi-diagnostic setup, consisting of a collection of non invasive tools and detectors which allow unprecedented investigation of the magnetoplasma properties in terms of
density, temperature, CSD and inner plasma EM wave emission [12]. All diagnostic tools can operate simultaneously with the Faraday cup in order to measure the charge state distribution; it has been possible to correlate all the detected plasma parameters with the characteristics of the beam extracted on-line. More details about the general setup, each tool and its own characteristics are given in [13].

Due to the huge amount of data and their relative complexity, we opted for a sequential analysis aimed at focusing on a specific issue at each step. In particular, in this paper we will discuss the plasma self radio-emission since this can be considered as a signature of the plasma instability regime.

The experiment was carried out at the ECR Laboratory of Atomki in Debrecen. The Atomki-ECRIS is a second generation ion source and the basic operation frequency is typically 14.25 GHz, amplified by a klystron. The second tuneable frequency can be provided by a travelling wave tube (TWT) amplifier, with an operating range from 13.6 GHz–14.6 GHz.

The axial magnetic field is 1.26 T (injection), 0.39 T ($B_{\text{min}}$) and 0.95 T (extraction), whilst the radial magnetic field produced by the hexapole and measured at the plasma chamber wall ($R = 29$ mm) is about 1.2 T.

When we use only the klystron fixed frequency (14.25 GHz) the ratio of $B_{\text{min}}/B_{\text{ECR}}$ is 0.76; this value is very close to the ‘critical’ 0.75 value for the instability onset [2, 5]. Operating the source in TCFH mode, the second frequency amplified by the TWT can vary between 13.6GHz and 14.6 GHz resulting in a $B_{\text{min}}/B_{\text{ECR}}$ value ranging from 0.8–0.75. So, it is possible to study what happens when we approach or pass the critical value without changing the axial magnetic field configuration.

The ion source was optimized for middle charged argon ion production while the gas pressure measured at the injection box of the ion source was 2 $10^{-6}$ mbar. The ion beam was extracted from the plasma by a 10 kV extraction voltage.

The diagnostic setup used for the plasma self radio-emission characterization (see figure 1) consists of a two-pin RF probe [14] installed inside the plasma chamber in the injection plate that 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 kinetic instabilities. All instabilities were detected via RF spectra.

The two-pin RF probe was flexible with an outer diameter of 4 mm, a pin length of 3.5 mm and a pin distance of 2 mm (see figure 2).

The SA operated with a frequency span in the range 13–15 GHz with a resolution bandwidth (RBW) of 3 MHz, and a sweep time of 400 ms. By these operative parameters, the ratio between the frequency span and the RBW fixes the number of points in the frequency spectrum. From the latter, it is possible to estimate the temporal baseline the analyzer took in order to perform the FFT with the given RBW, resulting in the ratio between the sweep time and the number of frequency points per spectrum. This number is around 0.7 ms; the sampling in the time domain is instead in the range of tens of ps (it is comparable to the inverse of the bandwidth and, since the bandwidth is 40 GHz, sampling occurs at 1/40 GHz). Alternatively, the RF probe can be connected with a diode and an oscilloscope in order to obtain the time-resolved but totally integrated power emitted from the plasma, using this value as a trigger signal for an instability signature and to perform time resolved x-ray analysis too. A more detailed block diagram can be seen in figure 3. The probe acquisition setup also consists of an RF power limiter, 10 dBm limiting and operating in the range 10–26.5 GHz, and a set of variable attenuators in the dynamical range 3–30 dB.
We calibrated the RF antenna in the standard way, i.e. by measuring the reflection coefficient $S_{11}$ in free space. The $S_{11}$ trend is shown in figure 4.

In the experimental frequency range 13–15 GHz, the $S_{11} < -9.25$ dB condition is satisfied almost everywhere. This condition implies the antenna matching was good. Only for about $f < 13.2$ GHz, the $S_{11}$ parameter becomes $> -9.25$ dB; the experimental data renormalized by this factor did not differ considerably.

We also calibrated all the cables connecting the antenna to the SA. The measured attenuation trend is shown in figure 5, and all experimental data have been renormalized by these factors.

Finally, 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 of 13.6–14.6 GHz) were used. Through a waveguide combiner, it has been possible to transmit the two frequencies to heat and excite the plasma inside the plasma chamber. The detailed scheme of the microwave coupling system to the plasma chamber is illustrated in figure 4 of [13].

3. Experimental procedure

At the beginning, the system was characterized in single frequency heating mode (SFH) in order to collect some reference configurations. Then, the system was characterized in TCFH mode in order to study the effect of the second frequency on the plasma instabilities. The different configurations are reported here:

(a) SFH: TWT power scan at 13.8 GHz representative frequency, from 20 W until 200 W.
(b) SFH: frequency scan by TWT only 13.6–14.6 GHz, at steps of $\Delta f = 50$ MHz, $P = 200$ W.
(c) TCFH: Frequency scan by klystron 14.25 GHz + TWT 13.6–14.6 GHz at steps of $\Delta f = 50$ MHz, total net power 200 W.
(d) TCFH: Power balance at total net power 200 W, TWT 13.8 GHz + klystron 14.25 GHz.

In order to correlate the instability strength of a given configuration with other parameters—such as RF power, RF pumping frequency, SFH or TCFH operations—it is very important to find a quantitative way to establish how turbulent the plasma is. In order to give a quantitative estimation of the instability strength, we introduce here the parameter $I_S$ (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 versus losses x-radiation emission) with the $I_S$ parameter itself. From the point of view of the $I_S$ definition, some (critical) issues still remain open:

- (a) As stated above, frequency spectra were elaborated by the SA with a temporal resolution of around 0.7 ms. That means the signal at each frequency must be considered as an averaged value in the mentioned temporal window; on the other side, instabilities are by definition fast, evolving phenomena whose temporal scale lies in the range of $\mu$sec or shorter; hence, any quantitative evaluation of $I_S$ has to cope with the frequency spectrum evaluation time of our SA.
- (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 $I_S$. A question arises: what is more important, the total integral of plasma self-generated sub-harmonics, or their number? Or their superposition?
In fact, as can be observed in figure 6, a stable plasma is characterized by the pumping RF peak only (figure 6(a)), whilst an unstable configuration can be characterized by a low number of sub-harmonics with high power in each one (figure 6(b)), or also by a high number of sub-harmonics but at low power (figure 6(c)).

After several attempts to try to find a significant $I_S$ definition able to quantitatively describe what we observed directly, our choice was to define $I_S$ considering both contributions, as follows:

\[
I_S = \left( \int_{13 \text{GHz}}^{15 \text{GHz}} \frac{dP(f)}{df} \right) \left( 1 + w(N_{\text{sub}} - 1) \right) \]

where $P_{\text{mp}}$ is the integral of the power of the main peak of pumping frequency, $N_{\text{sub}}$ the number of sub-harmonics and $w$ a weight factor. With this definition, the $I_S$ parameter has been calculated considering the amplitude (integral of the power) of the RF plasma-self emitted signal, once the main pumping wave contribution is subtracted; this number has then been multiplied by a factor which takes into account the number of sub-harmonics $N_{\text{sub}}$ with a proper weight factor $w$. The weight was introduced in order to give more importance to the total integral of plasma self-generated sub-harmonics than their number, so $0 \leq w \leq 1$. It was calculated to find the best value of compromise between these two contributions.

Typically, it is expected that plasma instabilities increase with power [2, 5]. So, in order to try to estimate in a quantitative way the best weight-parameter $w$ to be used hereinafter, we calculated the Pearson coefficient $R$ to evaluate the degree of correlation of $I_S$ versus RF power for different values of $w$ at steps of 0.001.

The plot in figure 7 shows that during the power scaling (case (a) SFH: TWT at 13.8 GHz) the data were very well linearly fitted with almost all the choices of the $w$-parameter (very high correlation with $0.86 < R < 0.9$), even if—strictly speaking—the best agreement was found for $w = 0.1$. The plot, in our opinion, can be interpreted in two ways: on one hand, we have a quantitative estimation of the best $w$, even if only a weakly predominant value was found. On the other hand, the fact that for all the $w$ values the agreement is pretty good, we may conclude that this supports an arbitrary choice.

The direct observation of the SA-recorded spectrum highlights that a consistent analysis of the data cannot be done if we do not take into account the multipeaks of sub-harmonic emission. We decided to use the maximum value obtained $w = 0.1$, in equation (1), in order to estimate the $I_S$ parameter.

4. Experimental results

In order to validate the $I_S$ consistency, we made some plots concerning the $I_S$ behavior versus RF power in single and TCFH mode. The definition of $I_S$ was consistent with the direct observation of the SA-recorded spectrum, increasing steadily with power, as expected. Details of correlations with other parameters (CSD, soft and hard volumetric x-ray measurements) and time-resolved x-ray data are provided in [15]. The two-dimensional space-resolved measurements regarding an x-ray pin-hole camera to study the plasma structure and intensities of electron losses have already been analyzed and will be subsequently reported in a dedicated paper in the near future.
In this work, the attention is focused on instability issues only.

4.1. RF spectra in SFH—power scan at 13.8 GHz

The plot of $I_S$ versus RF power is shown in figure 8, displaying a clear increase of $I_S$, as expected, but without any evident jump or non-linearity.

The $I_S > 0$ condition occurs already at 40 W, and this is consistent with the direct observation of the SA-recorded spectrum. Figure 8 (right) illustrates the RF probe detected signal via SA analysis while increasing the pumping wave power: the red line represents the pumping frequency (TWT only at 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 increases for higher TWT powers. A ‘down-shift’ of the emitted frequencies is also evident. In figure 9, it is also possible to observe the increase of characteristic sub-harmonic peaks for a higher power.

4.2. RF spectra in SFH—frequency scan at 200 W

The trend of $I_S$ versus RF frequency displays a frequency-dependent behavior (see figure 10).

To the knowledge of the authors, this is the first time the frequency tuning is systematically explored for instability. $I_S$ 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 with the fact that at 13.6 GHz, the source is operated well above the $B_{\text{min}}/B_{\text{ECR}}$ threshold that is universally considered as the ‘trigger’ for the instability onset.

Anyway, the plot shows that the frequency (and not only the RF power and $B_{\text{min}}/B_{\text{ECR}}$ value) also affects the instability strength.

By looking at this plot, it is more evident why the integral only was not enough to evaluate $I_S$. For instance, in the case of 13.6 GHz, there is a higher number of sub-harmonics but with a lower emitted power.

The ‘drop’ below the pumping frequency (the pumping frequency lies all along the line $y = x$) gives just a qualitative indication of the instability strength which is not only related to the amplitude of the ‘down-chirped’ 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 $I_S$.

The $I_S$ parameters are shown in table 1, also listing separately the two contributions: (a) the total number of sub-harmonics $N_{\text{sub}}$; and (b) the total power integral of plasma self-generated sub-harmonics $P_{\text{sub}}$. 
For the sake of example, we directly compared the spectra for two configurations: \( f_{TWT} = 13.6 \, \text{GHz} \) (figure 11(a)) and \( f_{TWT} = 14.05 \, \text{GHz} \) (figure 11(b)). In these cases, the vertical axis scale is set in order to highlight the sub-harmonic contributions (thus the pumping frequency peaks saturate).

It is possible to highlight that, even if \( P_{\text{sub}} \) at \( f_{TWT} = 14.05 \, \text{GHz} \) is higher than at \( f_{TWT} = 13.6 \, \text{GHz} \), considering also the number of sub-harmonics \( N_{\text{sub}} \), the \( I_S \) parameter results to be smaller.

At \( f_{TWT} = 13.6 \, \text{GHz} \), in fact, many sub-harmonics are widely spread in frequency, with peaks at a distance of more than 0.5 GHz.

Another very interesting result is that instabilities generate sub-harmonics for all the selected frequencies by the TWT; the emitted radiation is predominantly at lower frequencies than the plasma heating frequency (as also previously measured in [16]), and some up-harmonics appear for higher frequencies only (in particular, above 14.2 GHz—see figure 10). Also, in figure 12, it is possible to observe characteristic sub-harmonic peaks.

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

### 4.3. RF spectra in TCFH—frequency scan at 200 W

The trend of RF spectra versus frequency scan in the TCFH plot (figure 13) shows that sub-harmonics in unstable regimes are always at frequencies below the lowest one of the two.

**Table 1.** Contribution of \( P_{\text{sub}} \) and \( N_{\text{sub}} \) to the \( I_S \) parameter at (single) frequency scan.

| \( f_{TWT} \) [GHz] | \( N_{\text{sub}} \) | \( P_{\text{sub}} \) [mW] | \( I_S \) [mW] |
|---------------------|----------------|----------------|----------|
| 13.60               | 13             | 5.544 2        | 12.751 6 |
| 13.65               | 3              | 1.495 0        | 1.943 5  |
| 13.70               | 2              | 0.753 2        | 0.903 9  |
| 13.75               | 2              | 0.975 0        | 1.170 0  |
| 13.80               | 9              | 4.934 3        | 9.375 2  |
| 13.85               | 12             | 3.517 1        | 7.737 6  |
| 13.90               | 15             | 3.323 0        | 8.307 4  |
| 13.95               | 6              | 1.599 5        | 2.559 2  |
| 14.00               | 5              | 6.675 1        | 10.012 7 |
| 14.05               | 4              | 7.033 5        | 9.846 9  |
| 14.10               | 2              | 1.947 9        | 2.337 5  |
| 14.15               | 2              | 0.687 8        | 0.825 3  |
| 14.20               | 2              | 1.971 4        | 2.365 7  |
| 14.25               | 4              | 1.894 9        | 2.652 8  |
| 14.30               | 2              | 1.157 1        | 1.388 5  |
| 14.35               | 3              | 3.938 0        | 5.119 4  |
| 14.40               | 5              | 4.512 8        | 6.769 2  |
| 14.45               | 5              | 1.516 6        | 2.274 9  |
| 14.50               | 7              | 2.250 8        | 3.826 3  |
| 14.55               | 4              | 2.388 7        | 3.344 2  |
| 14.60               | 2              | 0.607 0        | 0.728 4  |

**Figure 11.** Experimental spectra: (a) pumping frequency \( f_{TWT} = 13.6 \, \text{GHz} \); (b) pumping frequency \( f_{TWT} = 14.05 \, \text{GHz} \).

**Figure 12.** 3D plot of the RF probe detected signal analysed through the SA. This plot is equivalent to the pseudo-colour plot of figure 10 (right). The image was plotted in logarithm colour scale.

In other words, in TCFH mode, up-harmonics disappeared everywhere, for any frequency. If compared with the single frequency case, this result is really relevant. In such a configuration, most of the plasma self-irradiated energy in the RF
domain came from the inner plasmoid regions, i.e. from regions of the plasma where \( B < B_{ECR} \). Also in figure 14, it is possible to observe spectral structures as detected by the SA: it is possible to highlight the two different pumping frequencies and the characteristic sub-harmonic peaks.

4.4. RF spectra in TCFH—power balance at 13.8 GHz + 14.25 GHz at 200 W

The RF spectra versus the power balance plot (figure 15) shows that instabilities increase very much for a higher power of TWT.

This result was somehow expected since the TWT frequency 13.8 GHz is much more unstable due to the fact that the \( B_{\text{min}}/B_{ECR} \) value is closer to the instability threshold than the klystron frequency. Figure 16 is equivalent to the pseudo-colour plot of figure 15 (right), and it is possible to better highlight characteristic sub-harmonic peaks.

4.5. Instability damping by TCFH

In figure 17, we directly compare the \( I_5 \) parameter in single frequency and in TCFH mode: it is possible to observe that the instability strength drops dramatically, confirming that TCFH is able to dump the instabilities.

Figure 18 highlights the instability damping at 13.9 GHz and 200 W, which was a very unstable regime. It is clear that at this operative frequency, the plasma is already highly unstable at low power levels. Anyway, the addition of the second wave, provided by the klystron, damps the instability even if the total amount of power reaches 200 W (120 W by the TWT plus 80 W by the klystron).

This means that the instability can be damped by TCFH, even if the second frequency brings additional RF power into the system.

It is also possible to observe the same experimental evidence of instability damping in the case when the TWT
frequency was 14.5 GHz (figure 19). These results highlight that a key role for damping turbulences and increasing the electron confinement inside the ‘plasmoid region’ is played by TCFH. During the experiment, the characterizations have been carried out only in TCFH mode; in fact, as described in section 2, the second frequency amplified by the TWT can be varied between 13.6 GHz and 14.6 GHz with a maximum difference of the order of 650 MHz between the two frequencies.

In perspective, it would also be very interesting to study these effects in two-far-frequency heating mode (>1 GHz between the two frequencies) using the measuring arsenal shown in this paper, and optionally expand the ranges toward higher RF-frequencies to be detected and toward higher klystron and/or TWT RF-powers, coupled into the plasma. Such a measurement arrangement provides further possibilities to characterize plasma instabilities and makes possible a comparison between the effects of these two different plasma heating modes.

5. Discussion

The data shown, particularly in figure 17, demonstrate that the instability suppression is effective almost over the entire investigated frequency spectrum. We investigated the trends of the $\Delta I_S$ (giving the effectiveness of damping $\Delta I_S = I_S(\text{SFH}) - I_S(\text{TCFH})$) versus the used $\delta \omega$, as illustrated in figure 20. From an analysis of figure 17, it emerges that $I_S$ data are quite scattered versus the TWT frequency. This is due to the frequency tuning effect that is superimposed on the greater or lesser intensity of the instabilities. Therefore, we consider only very unstable regimes in SFH, for which the $I_S$ parameter is high in absolute value in order to see if, under this condition, the instability effects dominate the frequency tuning. With this perspective, the selection is done by looking to those frequencies only featuring a significant variation in the equilibrium state of the plasma (from stable to unstable, and vice versa) when going from SFH to TCFH. A $3\sigma$ level on the fluctuation of $I_S$ in TCFH mode can be inferred as the threshold above where we can consider $\Delta I_S$ versus $\delta \omega$ plot. Under this assumption (the threshold is around 2 mW), a weak but meaningful trend appears in figure 20. That is in
agreement with what was expected by the theory, namely by the estimation of the $\delta \omega$ range over which TCFH should be effective.

We can now enter more into the details of the mechanism underlying the instability damping by TCFH. In summary, the consequences of TCFH on the electron dynamics are:

- The phase space describing the diffusion in velocity space becomes four-dimensional instead of two-dimensional, as with a single frequency.
- As a consequence, the adiabatic barrier limiting electron heating from below is deemed to increase, causing higher diffusion in $E_{\perp}$, i.e. in the perpendicular energy, but also in $E_{\parallel}$, i.e. the parallel energy component.
- As a consequence of higher diffusion in the parallel direction of the particles’ energy, particles scattering into the loss cone are hugely enhanced and become more competitive with collisions (diffusion due to TCFH is more than a factor of two larger than collisions).

Briefly, therefore, it emerges that TCFH plays a relevant role in making the EEDF less anisotropic. This assumption can be investigated in more detail by looking at the theory of TCFH and comparing it to the instability onset conditions. The amount of electrons that is considered to be prone to develop an instability is considered to be dependent on $\frac{T}{T_{\parallel}}$ ratio. In most cases, other authors have found that this amounts to around 1% up to 40% of the global plasma electrons [17].

Estimation of the total amount of electrons that shows a distribution function that is globally prone to develop kinetic instabilities is normally conducted by considering the relation $\frac{R}{R_{\text{rev}}} < 1 - \frac{I_{\parallel}}{I_{\perp}}$. This relation states that by increasing the $\frac{I_{\parallel}}{I_{\perp}}$ ratio, the region of the plasma where the $\frac{\partial (v_i)}{\partial v_i} > 0$ condition is fulfilled (what, in [17], is called the ‘butterfly’ distribution) reduces more and more. Normally, in single frequency heating mode, interparticle collisions represent the main mechanism of electrons scattering in the $v_i$ direction. But TCFH acts right in the mechanism of re-balancing the $\frac{T}{T_{\parallel}}$ ratio since the diffusion coefficient $D_{||}$ due to quasi-linear diffusion is greatly enhanced, scaling as

$$D_{||} = \frac{\Delta E_i^2}{2\eta} \propto \frac{E_{\perp}}{E_{\parallel}}^{\Delta \nu} \left( \frac{\delta \omega}{\omega} \right)^2$$

where $E_i$ and $E_\perp$ are the electric field amplitudes of the first and second wave (label 1 identifies the lower frequency) while $\Delta \nu$ is the velocity jump at the resonance, being $\Delta \nu \propto \delta \omega^{1/2} / \omega$. From the above relation, it follows that quasi-linear diffusion applies only parallel for TCFH. It depends on the ratio between the two electric field amplitudes, meaning that for an unbalance of power on the first frequency (i.e. the inner resonance), the parallel diffusion is enhanced. Strong enhancement is also expected to increase the power of the lower frequency due to the term $\frac{\delta \omega}{\omega}$, but the predominant effect is related to the different coupling of the global RF power, which directly affects the velocity jump $\delta \omega$: it now causes the $\delta \omega$ to scale more than linearly with the RF power itself (i.e. as $\propto \delta \omega^{1/2} / \omega$). These basic assumptions on quasi-linear diffusion are in qualitative agreement with the experimental observations. The most effective damping, in fact, as shown in figures 18 and 19, was obtained when applying an even higher power than single frequency operations, when normally the instability grows non-linearly with the power itself. Despite the fact that the total amount of power was increased by a factor of about two, the $I_{\parallel}$ parameter collapsed.

In addition, figure 20 shows that the damping appears to be more effective, on average, at larger $\frac{\delta \omega}{\omega}$—again in agreement with the increase of parallel diffusion.

In summary, TCFH seems to be able to reduce the regions of velocity space where $\frac{\partial (v_i)}{\partial v_i} > 0$ due to the much more efficient balancing of the $\frac{T}{T_{\parallel}}$ ratio. This argument also helps to provide a reasonable explanation to the spectral structure of the self-emitted radiation when the instability is also active in the TCFH mode. Every time, the emission has been observed to occur at frequencies lower than the lowest of the pumping frequencies. Considering the main claims of quasi-linear theory, the diffusion in parallel velocity is expected to be maximal in the gap between the two pumping frequencies. There, the $\frac{T}{T_{\parallel}}$ ratio should be thus minimal, minimizing the amount of electrons able to support the instability and its related RF emission. As a consequence of the above arguments, the particles losses into the loss cone should also be enhanced in the TCFH mode. This probably explains the only moderate effect provided by the TCFH mode on the ion source’s performance, as referred to in [15].

The TCFH should eventually result in broadening up the islands of stability for an ECRIS, and other techniques could be applied to further boost their performance. Assuming the main action of TCFH is on the enhanced parallel diffusion, the study of plasma confinement and losses during single or double frequency heating mode should be carried out. In particular, it would be interesting to measure fluxes of electrons escaping from the magnetic trap during TCFH since
quasi-linear theory predicts the average energy per particle lost scaling versus the discharge parameters according to the following formula:

\[ E_L = \frac{2}{3} \left( \frac{\delta \omega}{\omega_0} \right)^{1/3} M^{1/4} \Delta v^2. \] \hspace{1cm} (7)

An experimental setup suitable for this purpose should be able to detect energies of electrons lost from the trap and impinging on the plasma chamber walls. The aim of separating electrons from enhanced parallel diffusion from the ones undergoing the instability should be accomplished if energy filtering is possible, for instance via x-ray imaging in photon counting mode. A proper setup has been described in [13] and used for this purpose. Data analysis is still ongoing and the results will be presented soon.

6. Conclusion and perspectives

The paper reports on an experimental campaign aimed at investigating the impact of TCFH on plasma stability. At the \( B_{\text{min}}/B_{\text{ECR}} \) values that are typical of the ATOMKI ECRIS, the plasma is prone to kinetic instability development for any frequency we used in the range 13.6–14.6 GHz. The measurements show that TCFH can almost totally suppress the instabilities if the power balance is suitable. The \( I_S \) 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. In summary, space-resolved soft x-ray analysis is expected in the near future in order to investigate the dynamics of plasma versus plasma losses emission, and to verify how plasma turbulence (described by the \( I_S \) parameter) and TCFH-induced parallel diffusion in velocity space affect plasma confinement and loss dynamics.

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