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MULTI-DIAGNOSTIC SETUP TO INVESTIGATE THE TWO-CLOSE-FREQUENCY PHENOMENA*

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Abstract

While the mechanism is still not fully clear, the beneficial effect (higher intensity of highly charged ions, stable plasma conditions) of the second micro-wave injected to the ECR plasma was observed in many laboratories, both with close and far frequencies. Due to the complexity of the phenomena (e.g. interaction of resonant zones, damped instabilities) complex diagnostic methods are demanded to under-stand its mechanism better and to fully exploit the potential hidden in it. It is a challenging task since complex diagnostics methods require the arsenal of diagnostic tools to be installed to a relatively small size plasma chamber. Effect of the injected second 13.6-14.6 GHz microwave to the 14.25 GHz basic plasma has been investigated by means of soft and (time-resolved) hard X-ray spectroscopy, by X-ray imaging and space-resolved spectroscopy and by probing the rf signals emitted by the plasma. Concerning the characterization of the X radiation, in order to separate the source and position of different X-ray photons special metallic materials for the main parts of the plasma chamber were chosen. A detailed description and explanation of the full experimental setup and the applied non-invasive diagnostics tools and its roles are presented in this paper.

INTRODUCTION

Electron Cyclotron Resonance (ECR) Ion Sources (ECRIS) are able to produce highly charged plasma in their plasma chamber from which positive ions with very different charge states can be extracted and transported to a target or into an accelerator. In order to deliver more and more intense, higher and higher charged ion beams, first a time-stabile, highly ionized plasma has to be generated. By a simplified approach two tasks have to be solved: (1) to inject more and more electromagnetic energy from outside into the plasma on an efficient way and (2) to suppress or decrease those processes (instability, recombination, etc.) which work against the ionization process. The studying the ECR plasma itself for both purposes is thus essential and such investigations have been carried out in many laboratories since the discovery of ion sources of this type.

The ECR groups of two laboratories (Atomki-Debrecen and INFN-LNS Catania) from time to time unify their forces to carry out diagnostics measurements of the ECR plasma for the purposes described above. In an earlier joint experiment [1, 2] a campaign for correlating the plasma density and temperature with the output charge states and the beam intensity for different pumping wave frequencies, different magnetic field profiles was carried out. The results revealed surprisingly very good agreement between warm-electrons density fluctuations, output beam currents and the calculated electromagnetic modal density of the plasma chamber. That experiment was based on the pioneering measurement of this type carried out and published for the first time space-resolved plasma diagnostics measurements by a pinhole X-ray camera [3].

In 2018 a new series of experiment was designed and realized by the collaborating groups. The experiments were carried out in Debrecen, at the Atomki ECRIS Laboratory basing to the Atomki-ECRIS to deliver the necessary plasmas and ion beams.

The main aims were to study these phenomena:

- Exact mechanism of the two-close-frequency heating;
- Role of the 2nd frequency in the suppression of plasma instabilities;
- To obtain volumetric and spatially resolved X-ray emissions from two-frequency plasmas;
- Hard X-ray spectra in unstable regimes;
- Structural changes triggered by instabilities;
- Structural changes when the turbulences are suppressed;

In some of the above goals significant results were obtained, in some others the first promising steps were done. The post-processing of the data is still not finished completely. For the high amount of the material and for the complexity of the results we decided to publish them in three different accompanying papers. The present paper here describes the technical setups of the measurements and shows those technical modifications on the Atomki-ECRIS which were necessary for the investigations. The first part of the results are shown in [4], where an outlook to the history of the two-frequency effect is also presented with references to others' works. The second part of the results, mostly related to the investigation of stable and unstable plasma regimes in single or double frequency operations, is discussed in our third paper [5].

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EXPERIMENTAL SETUP

The X-ray diagnostics measurements were carried out in the ECR Laboratory of Atomki. Debrecen. The Atomki-ECRIS is a classical, room-temperature 2nd generation ion source. Its basic operation frequency is 14.25 GHz supplied by a klystron amplifier. A second frequency can be coupled in by the same WR62 waveguide supplied by a TWT amplifier. The axial magnetic field is 1.26 T (injection), 0.39 T (minimum) and 0.95 T (extraction). The hexapole produced magnetic injection at the plasma chamber wall (R=29 mm) is 1.2 T. The ion source is not connected to accelerator thus it is highly applicable for plasma physics investigations. Further technical and application details are in a summary paper [6].

In order to carry out complex plasma diagnostics we installed and applied a full arsenal of diagnostic tools and methods. Figure 1 shows the simplified drawing of the ECRIS with the applied instruments around it or connected to it. In Table 1 some detailed specifications of the diagnostics tools, are shown.

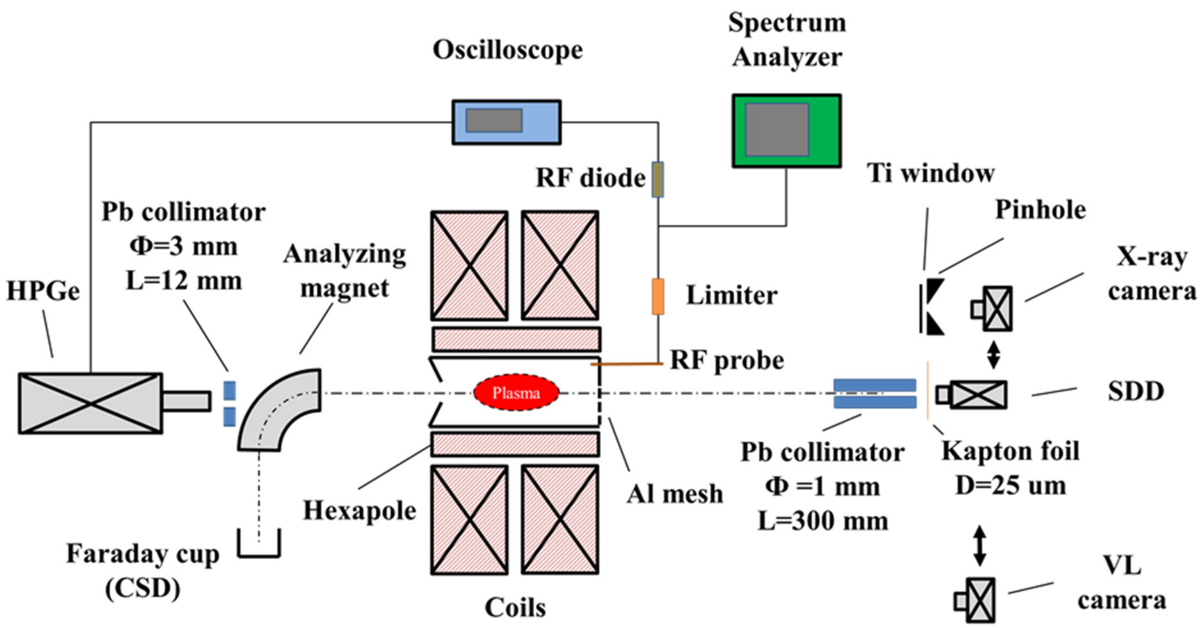

Figure 1: The measuring setup with the ECR plasma in the center.

Table 1. Technical Specifications of the Applied Diagnostics Tools.

Name	Energy range	Type	Resolution	Window	Collimation
Silicon Drift Detector (SDD)	1-30 KeV	XGL-SPCM-8110-CUBE	130 eV	kapton (25 µm, 50 µm) and Be (12.5 µm)	Lead, 300 mm length, 1 mm hole
CCD pinhole camera	1-20 KeV	Andor Ikon	1MP in 13x13 mm	Ti (9.5 µm)	Lead collimation system
Germanium Detector	30-400 KeV	HpGe-D	200 eV	Al	Lead, 12 mm, 3 mm hole
Visible light camera	Several eV	Basler acA2040	4 MP	plexi	-
RF-probe + Spectrum Analyzer	9 kHz – 43 GHz	homemade probe, Anritsu MS2720T SA	from 1 Hz to 10 MHz	-	-

The role of each diagnostics tool is different.

A Silicon Drift Detector (SDD) records x-ray spectra in the 1-30 KeV range. From the spectra electron density and electron temperature can be calculated. A long (300 mm) led collimator with 1 mm hole was used in vacuum conditions to obtain soft X-ray emission only from the plasma region. Cone of view of the detector went through the aperture of the plasma electrode (10 mm) in order to do not detect X-ray photons coming from the metal parts of the chamber.

Alternatively with the SDD detector, a 1 MP CCD pinhole x-ray camera was mounted to the injection side. The pictures taken by the camera give spectral and structural information on the plasma and on the electron losses. By using 2 mm thick pinhole (Φ = 0.4 mm) and extra led

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shieldings, the X-ray picture re-cording was possible in relatively high RF-power operation mode (upto 200 W total incident power). The earlier experiments (see e.g. [7]) were restricted upto several tens of RF-power.

A third alternative at this site is a 4 MP mono-chrome visible light camera. The photos taken from the full plasma or from a selected area contains pho-tons in the eV energy range and thus give information on the low energy component of the electrons energy distribution function (EEDF) exciting visible light transitions of atoms and ions.

The RF probe (mounted into the injection plate of the plasma chamber) together with a Spectrum Analyser (SA) can detect and show the plasma emitted EM waves in the GHz range. In our case the range of interest was 13-15 GHz. If the frequency of the emit-ted wave differs from the original one(s) it could be a sign of instability in the plasma.

The High Purity Germanium (HPGe) Detector is mounted to the straight axial port of the 90 degree analyzing magnet. Its operation range is 30-400 keV. We used it in two different modes. In time integrated mode the spectral temperature of the plasma can be calculated from the raw data. In time resolved mode we triggered its measurements by the sudden RF signals emitted by the unstable plasma to obtain hard X-ray spectra at different time domains corresponding to unstable and stable plasma regimes. Shaping time of the detector is about 5 us.

During all the measurements a middle-charged argon plasma was kept in the ion source with fixed gas dosing valve and with fixed (maximal) magnetic field. Representatives of the charge state distribution of the extracted ion beam (Ar6+, Ar9+, Ar11+) were continuously monitored which gave information on the ionization efficiency and on CSD shift.

ALTERATIONS ON THE ECRIS FOR THIS MEASUREMENTS

The original plasma chamber of the Atomki-ECRIS is made of stainless steel containing Fe, Cr, Ni, Mo and other components which, of course, appear in the X-ray spectra made the analysis difficult in our earlier experiments. To avoid it, after careful selection, we made or covered the three main parts of the chamber with three different metals. Figure 2 and Table 2 show the details. The new injection plate was made of aluminium allowing the mounting the gas tube, the WR62 waveguide and the RF-probe (Fig.2a, from left to right). The lateral wall was covered with 50 m thick tantalum sheet (Fig. 2b). The Al plasma electrode was covered by a 1 mm thick titanium plate (Fig. 3c, after plasma operation).

From Table 2 is obvious that by using these materials when an argon plasma is present, all the characteristic peaks can be well separated by our soft X-ray detectors between 1.49 and 8.14 keV energies (the expected peaks with increasing order are: 1.49, 1.56, 2.96, 3.19, 4.51, 4.93, 8.14 keV). This solution also makes possible a post-processing energy filtering of the x-ray photos taken by the pinhole camera. If so, the origin of the different X-ray photons and also the role of the different part of the plasma chamber can be revealed.

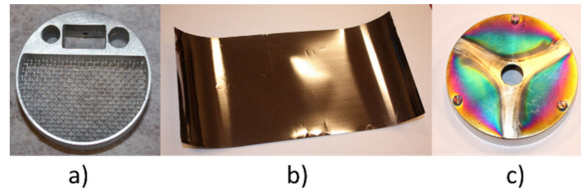

Figure 2: New materials in the plasma chamber. a) Injection plate, aluminum, mesh transparency is 60%. b) Lateral wall is tantalum. c) Plasma electrode covered with titanium.

Table 2: The Most Probable K and L Shell Related Characteristic X-ray Energies From Different Metals.

Part of chamber	Material	K_α (keV)	K_β (keV)	L_α (keV)
Injection plate	Al	**1.49**	**1.56**	-
Lateral wall	Ta	57	65	**8.14**
Plasma electrode	TI	**4.51**	**4.93**	0.45
Plasma	Ar	**2.96**	**3.19**	-

During the measurements the ECRIS was operated at maximum coils' power resulting in an axial magnetic field distribution as it is in figure 3. At klystron-mode operation (f=14.25 GHz) the ratio of B_{min}/B_{ECR} is 0.76 Tesla which is close to the "critical" 0.75 value for the instability onset, as observed by different authors [8, 9]. When operating the source in two-frequency mode the second frequency can be varied between 13.6-14.6 GHz resulting in a B_{min}/B_{ECR} value between 0.75-0.8. Thus one can study what happens when we approach or pass the critical value both up and down direction without changing the axial magnetic field configuration.

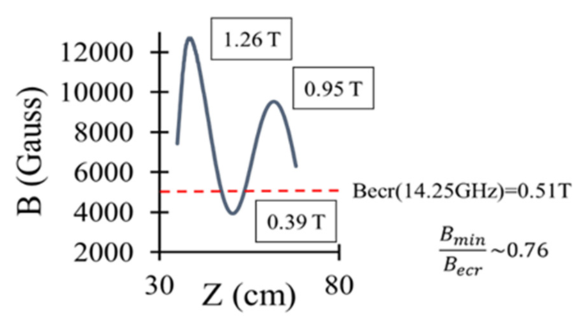

Figure 3: The axial magnetic field distribution of the Atomki-ECRIS at maximum coils fields.

The microwave system was also significantly modified to inject two frequencies and to measure the net incident power with high precision. The plasma chamber size (diameter 58 mm, length 210 mm) of the Atomki-ECRIS is small comparing with most other ECR ion sources and, of

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course, is much smaller than the known experimental fu-sion plasma devices. To use the above mentioned instru-ment arsenal and to install all the measuring tools thus meant a challenge for us and also forced some restrictions and compromises. For the way of studying the two-close-frequency operation mode we decided to use only one waveguide in order not to "occupy" most surface of the in-jection flange. By applying the small size WR62 wave-guide window and two holes for gas injection and for the RF-probe let us to observe more than 60% of the plasma through an aluminium mesh (Fig. 2a). The full micro-wave system is shown in Fig. 4. Both the klystron ampli-fier (14.25 GHz fixed frequency, power max 1000 watt) and the TWTA (13.6-14.6 GHz variable frequency, power max 500 watt) are fed by sweep oscillators. A special com-biner unifies the two amplified signal and forwards them toward the plasma chamber. At the TWTA branch we in-stalled a phase shifter to explore the effect of the phase shift, if any. A broadband frequency circulator was applied to save the amplifiers from damages caused by reflected powers. A cross-guide was mounted as close to the plasma chamber as possible to the simultaneous measurement of the forwarded and reflected rf-powers. This solution made us possible to fix the net power (which is the difference of the two ones mentioned) at a constant value. Then the waveguide system was connected to the plasma chamber through high voltage and vacuum windows (Fig. 4.).

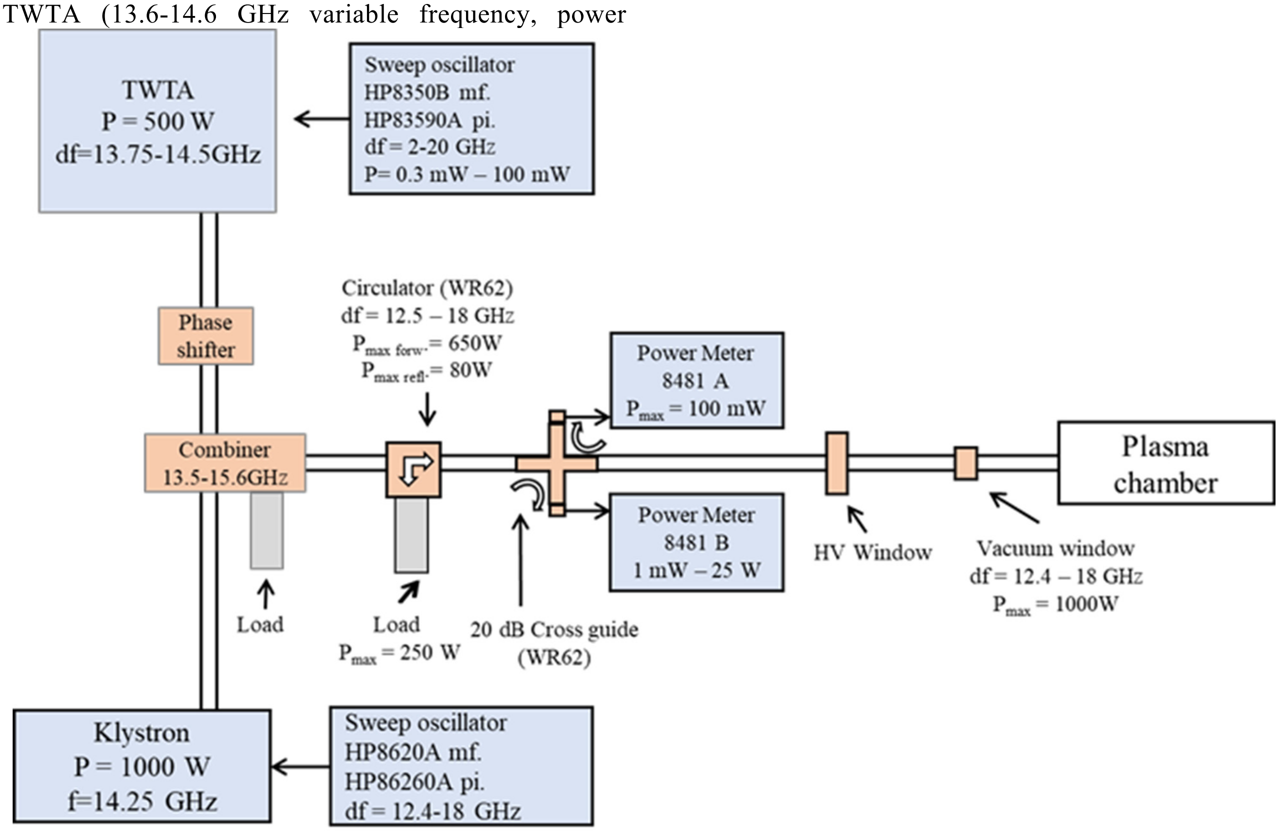

Figure 4: The microwave coupling system to study the two-close-frequency operation mode in ECR ion sources.

TECHNICAL RESULTS

The measurement system described in this paper was as-sembled and tested in two steps (March and June 2018), first part by part and after that in whole. The ECRIS was always operated with argon plasma with fixed gas flow (optimized for middle-charged argon plasma) but without any mixing gas. The coils currents were at maximum. The applied total micro-wave power was varied between 20 and 200 watt. While 200 W is still a "low-power" operation in the world of highly-charged-ECRISs, in the X-ray meas-urement history of this kind of plasma it is a big step for-ward, if we compare with ours earlier settings [3, 2, 7] where we were restricted up to a several tens of watts.

The measuring system operated well, regardless of some smaller technical failures which are unavoidable when working with such complicated setups. By using the silicon drift detector and the long collimator we were able to see only the argon plasma (with tiny titanium peaks from the plasma electrode) in the X-ray spectrum.

The RF-probe together with the Spectrum Analyser rec-orded signals effectively from the plasma in the GHz region. An example is in Fig. 5 where the source was operated in two-frequency mode. Beside the two main (coupled-in) signals one can see fake peaks as well, caused by the power-limiter (inserted before the SA). The limiter be-ing a nonlinear electrical circuit is operating as frequency mixer and produces such fake peaks. Also there

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are signals which are generated in the chamber due to plasma instabilities.

In Fig. 6 we show another example: it is a typical X-ray plasma picture taken by the pinhole camera. Special areas (red quadrants in figure) were selected as ROIs (region of interests) to investigate the count rates in those regions carefully as function of the ion source setting parameters. Areas are corresponding to the plasma region (ROI-2, ROI-3, ROI-4, ROI-8), to the plasma losses on the plasma electrode (ROI-1, ROI-12), to the plasma losses on the lateral wall of plasma chamber (ROI-5, ROI-6, ROI-7), to the whole image (ROI-10), to the background (ROI-9, ROI-11). A comparison with the plasma traces on the extraction electrode (Fig. 2c) is possible and necessary to do.

As mentioned in the Introduction the results of the measurement campaign obtained so far are presented in two other accompanying papers [4, 5].

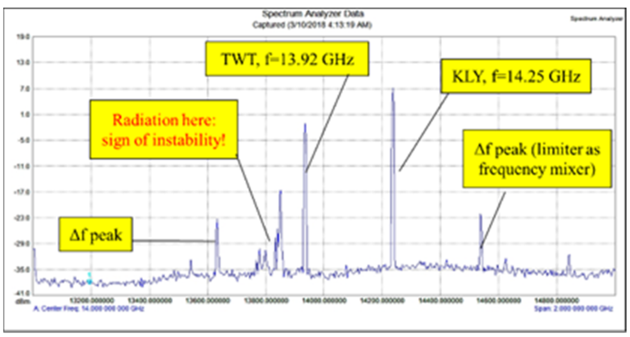

Figure 5: Example of the detected RF-signals emitted by the plasma at coupled 13.92 and 14.25 GHz frequencies.

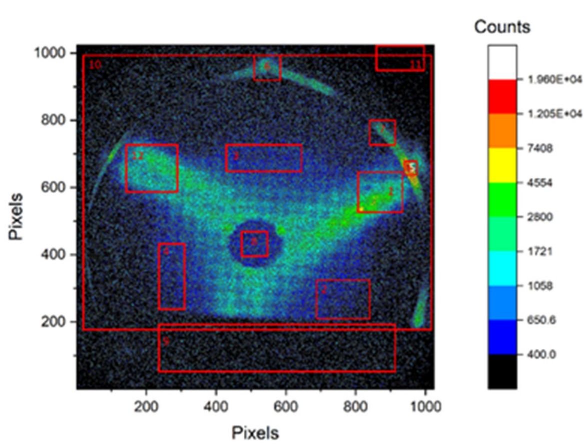

Figure 6: Typical x-ray plasma picture recorded by the pinhole camera. The red quadrants represent the selected ROIs.

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