PRACTICAL COMPARISON OF TWO-FREQUENCY HEATING PHENOMENA IN DIFFERENT ECR ION SOURCES

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Abstract

Plasma heating in electron cyclotron resonance ion sources (ECRIS) with the injection of two microwaves having different frequencies has been studied. An 18 GHz ECRIS installed in the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS) and a 14 GHz ECRIS at the Institute for Nuclear Research (ATOMKI) were utilized for this study. One was operated with the frequencies close together each; the other was tested with the two frequencies being even far from each other. The tendencies of the phenomena at both ECRISs were similar, and the output currents of highly charged ions increased with increasing the sum of two microwave powers.

INTRODUCTION

In order to improve highly charged ion production, the two-frequency heating technique was initiated by ECR pioneers Jongen and Lyneis in Berkeley, and some years later more successfully by Xie and Lyneis, again at Berkeley [1]. Since then, many ECR laboratories have tested this technique. The two-frequency heating technique has several advantages: it is effective for any kind of ion species, it is coexistent with almost all other techniques, and no modification of the existing structure is necessary, except for an additional microwave feeding.

Between 1998 and 2014 numerous experiments were carried out at NIRS; in each experiment a positive effect of the second microwave was demonstrated [2, 3]. Our basic observation concerning the productions of C, Ar, Fe, Ni, Kr, and Xe ions is that when the primary microwave power increases, the plasma shows instability, and it is difficult to keep. When an additional microwave with a different frequency is added in the above situation, the plasma stability is improved at greater microwave power. Our conclusion is that the output current of the highly charged ion beam is proportional to the total power of both microwaves. The dependence on the additional frequency showed fine structure. Since this structure depended on the magnetic field, vacuum pressure, and so on, precise frequency adjustment for the maximum output was required under each condition.

It is considered that the plasma instability of the ECR heating plasma is a 'microscopic instability'; like the velocity space instability. In an ECR ion source for the production of highly charged ions, a great deviation of the electron energy distribution from the Maxwell-Boltzmann distribution and the anisotropy of its velocity distribution may adversely affect the plasma stability [2].

Our group has focused on studying the mixture of two microwaves of which the two frequencies are each close together (close 2f) since 2008 at NIRS-HEC. An interest has arisen as to whether the above-mentioned phenomenon can be demonstrated using a different ion source where the two frequencies are even far apart from each other (far 2f). That is why we installed a 17.75-18.25 GHz microwave system in addition to the 14.3 GHz klystron amplifier of the ATOMKI ECRIS. The argon output currents at various values of the microwave power and frequency were recently studied.

TECHNICAL METHOD

18GHz NIRS-HEC ECRIS

The heavy ion medical accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS) was constructed as the first medical-dedicated heavy-ion synchrotron in 1994. HIMAC has treated more than 10,000 patients as of 2016 [4]. It has also been utilized as a second essential task to operate as a user facility for basic experiments in e.g. physics, chemistry, material science, and other life-science studies. In order to extend the range of available ion species for HIMAC, an 18 GHz ECRIS, named NIRS-HEC, was constructed in 1996. The detailed specifications of NIRS-HEC are described in reference [5].

The primary microwave source is an 18 GHz fixed-frequency Klystron (KLY) amplifier system with a maximum power of 1500 W. The additional source is a travelling-wave tube (TWT) amplifier system with a frequency range from 17.10 to 18.55 GHz and with the maximum power of 1200 W. Since the power stability is important for the reproducibility, both microwave systems have been equipped with power feedback. Pulse operation is available with both microwave sources.

14GHz ATOMKI ECRIS

A multi-purpose ECR ion source has been operating since 1996 at the Institute for Nuclear Research (ATOMKI). The ATOMKI-ECRIS does not serve as an injector for an accelerator; instead, it was designed and has been used for low-energy atomic physics research, for plasma studies and for medical and industrial applications [6,7]. The mechanical and electrical structures of the ATOMKI-ECRIS are not fixed; depending on the actual application goal, it has several configurations. During the present experiment, two external microwave sources are

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coupled to the plasma chamber. A 14.3 GHz fixed-frequency klystron (KLY) amplifier with a maximum output power of 1500 watt and an additional 17.75-18.25 GHz variable frequency TWT amplifier with a maximum power of 500 watt.

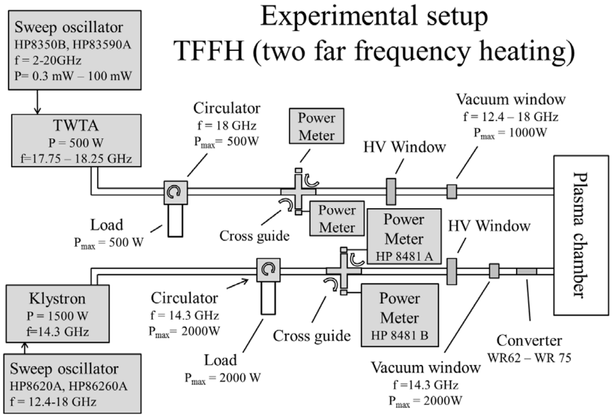

Figure 1: Schematic drawing of the two-frequency heating system at ATOMKI-ECR.

Comparison of the Configurations of NIRS-HEC and ATOMKI-ECR

Table 1 gives the specifications of NIRS-HEC and ATOMKI-ECR. The major differences between both sources are the frequency bandwidth and the maximum power of the additional microwave. The extraction voltages in these experiments were about 20 kV at NIRS-HEC and about 10 kV at ATOMKI-ECR, respectively

Table 1: Specifications of NIRS-HEC and ATOMKI-ECR

	NIRS-HEC	ATOMKI-ECR
Main microwave frequency (GHz)	18.0	14.3
Maximum power (kW)	1.5	1.4
Additional microwave Frequency (GHz)	17.10-18.55	17.75-18.25
Maximum power (kW)	1.2	0.5
Maximum mirror magnetic field at injection side (T)	1.3	1.2
at extraction side (T)	1.2	0.95
Mirror field peak-peak distance (mm)	165	235
Radial magnetic field on the surface of chamber (T)	1.1	1.1
Hexapole magnet length (mm)	200	200
Plasma chamber length (mm)	200	210
Plasma chamber diameter (mm)	61	58
Maximum extraction voltage (kV)	56	30

Figure 2 shows typical geometrical configurations of both NIRS-HEC and ATOMKI-ECR in the experiments. The contours of ECR zones, calculated by TrapCAD [8], are drawn.

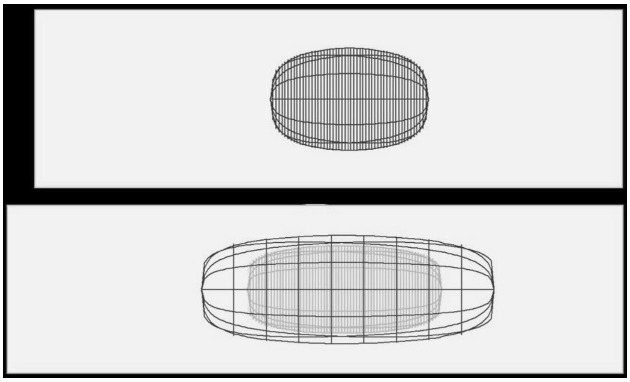

Figure 2: Typical configurations for the plasma confinement of NIRS-HEC (up) and ATOMKI-ECR (down) with the same scale. Left; injection side.

EXPERIMENTAL RESULTS

Production of Ar Ions at ATOMKI-ECR

Experimental data of “far 2f” at ATOMKI were obtained with Ar gas. Initially, the single microwave from KLY was fed, and the operation parameters, i.e., microwave power, amount of gas, magnetic field, extraction voltage, and so on, were optimized. Then, the second microwave from TWT was added and the frequency dependence of TWT was measured. The other parameters were optimised again at the best frequency. This procedure was iterated several times; thus, all parameters were fixed. The typical frequency dependence is shown in Figure 3. The fine structure appeared in this “far 2f” experiment similar to the case of the “close 2f” experiments at NIRS-HEC.

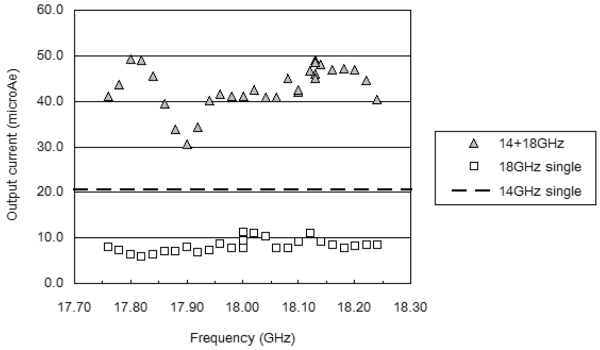

Figure 3: Typical frequency dependence of the output current of Ar^{11+} with the single TWT and the mixture of KLY and TWT. The KLY power was 700 watt; the TWT power was 400 watt.

The microwave power dependences of the output currents of some charge states of Ar ions were measured. The output currents of Ar^{11+} and Ar^{13+} were almost proportional to the power. On the other hand, the dependence of Ar^{7+} and Ar^{1+} were saturated at lower powers. Figure 4 shows an example of the power dependence of the output currents of Ar^{13+}. The square and triangle markers mean the single KLY microwave and two frequency by KLY and TWT, respectively. In this figure, the total power is determined by the sum of the two microwave powers, measured by RF crystal detectors. Since the coupling between a microwave and a plasma depends on the operation parameters, this determination is usually too simple. However, it must be noted that the x axis has an ambiguity: the output current increased with increasing the total power. This characteristic in “far 2f” is also similar to “close 2f” at NIRS-HEC [3, 4].

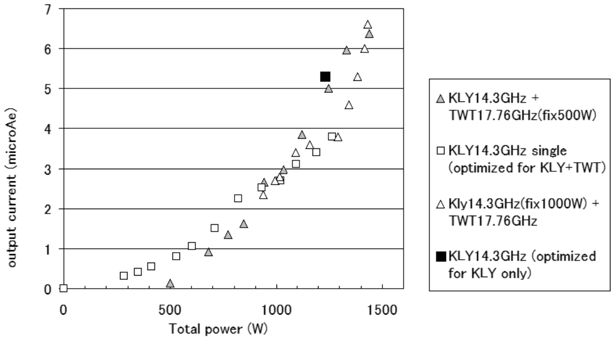

Figure 4: Typical power dependence of Ar^{13+} with the single KLY and the mixture of KLY and TWT.

Since the maximum total power was limited to bellow 1.5 kW (due to the limited cooling capacity), no plasma instability appeared during this measurement. It has not been confirmed that the mixture of two frequencies suppresses the plasma instability and improves the output currents of highly charged ions. If the cooling capacity is improved, it is expected the output currents increase with increasing the total power.

Production of Ar Ions at NIRS-HEC

We tried to observe the plasma instability in the case of “close 2f” at NIRS. The plasma instability strongly depends not only on the microwave power, but also on the vacuum pressure. The increasing pressure provides a stable plasma, and at the same time reduces the output current of highly charged ions. In order to decrease the pressure as much as possible, we carried out a pulse-mode operation, and measured the output currents of the afterglow in this experiment. Because the lower outgas was expected, all operation parameters were optimised for Ar^{13+}. The instability did not appear with the single frequency from KLY or TWT. When the total power increased up to 2 kW, the plasma became instable. This is larger than around 1 kW in the previous cases for Kr and Xe. The maximum output current of Ar^{13+} in the stable region was obtained in the case for the KLY power being 1.15 kW and the TWT power of 0.8 kW. The afterglow also improves the output currents of highly charged ions, as shown in Table 2.

Table 2: Improvement of the Output Currents (eμA) for Ar Ions at NIRS-HEC

Technique		Charge state of Ar ions				
frequency	afterglow	11+	12+	13+	14+	16+
Single	No apply	130	50	21	-	-
Two	No apply	200	116	42	15	-
Two	Add	300	242	118	47	2.3

DISCUSSION

It is usually considered that the plasma instability of ECR heating plasma with a minimum B structure is not magnetohydrodynamic instability called ‘macroscopic instability’, but ‘microscopic instability’ like velocity space instability. Especially, in an ECR ion source for the production of highly-charged ions, a great deviation of electron energy distribution from Maxwell-Boltzmann distribution and anisotropy of its velocity distribution may adversely affect the plasma stability. The additional microwave with a different frequency may cause various modes of waves and also causes unexpected resonant absorptions as an origin of microscopic instability. For example, when the 14 GHz microwave penetrated through the 18 GHz resonance zone which surrounded 14 GHz plasma, the plasma instability grew with increasing 18 GHz microwave power. It is likely that the 14 GHz microwave was disturbed by the dense plasma maintained with 18 GHz microwave. In the case of lower 18 GHz microwave power, a similar phenomena was not appeared. Although the interference in two far discrete frequency microwaves shows the complex phenomena, it is curious that an additional microwave with a well-tuned close frequency supports the stability of plasma. However, we did not observe any conflict or disturbance between the two microwaves. It was guessed that our present experiment at ATOMKI has not reached such conditions.

Although the improvement on the plasma instability was not demonstrated at the ATOMKI-ECR, due to the cooling capacity in the case for Ar, we think that it will appear in the case of a lower gas flow for a higher charge state or heavier ions. The other tendencies of the observed phenomena in the “far 2f” experiment are very similar to the “close 2f” experiments. Both the tuning of the additional frequency and the increasing of the total power are necessary for producing highly charged ions. This similarity between “far 2f” and “close 2f” also suggests that the geometrical configuration is not a dominant parameter for the two-frequency heating.

Many reports pointed the importance of fine tuning of microwave frequency, for example in Ref. [9]. A detailed study on frequency tuning effects was performed by INFN, GSI, and JYFL group [10-13]. Here the emphasis in the explanation was set to the RF properties of the plasma chamber. The authors’ another work also gave similar results for more simple system [14]. On the other hand, a typical ECR ion source has a steep gradient of magnetic field. One percent of frequency change gives almost no spatial difference less than one mm. It suggests that the optimising frequency of additional microwave displays behaviour different from the cavity mode of chamber in the case of two frequency heating technique. From the comparison between the X-ray photographs and spatial distribution of the simulated warm electron component of the plasma, the highly charged ions probably occupy much larger volume around the resonance zone than the ionising electrons [15] and collect cold electrons due to quasi-neutrality. These spatial distributions will be taken into account for the frequency tuning. Our trials to verify the assumption, that the additional frequency controls the anisotropy of the electrons' velocity distribution which may affect the plasma instability, have not been yet confirmed by a computer simulation [3]. Recently Skalyga and Tarvainen group showed the interesting observations and proposed the similar explanation [16, 17].

When NIRS-HEC produced an output current of 42 eμA for Ar^{13+} (Table 2), it was estimated that a total power of 1.5 kW was fed into the 18 GHz ECR zone. Figure 4 shows that 6.6 eμA was obtained at ATOMKI-ECR with a 14 GHz power of 1 kW and an 18 GHz power of 0.5 kW. This big difference is partly caused, of course, by the significant differences between the two ion sources: main frequency, magnetic fields and its peak-peak distance, extraction voltage, plasma chamber material, horizontal slit width of analyser magnet, and so on. That is why the "basic" HCI currents at Atomki-ECR are much lower than at NIRS-HEC. Another difference comes from the geometry of ECR zones. Calculations shown in Figure 2, under the present experimental conditions, the typical diameter, length, volume, and surface area of the ECR zones at ATOMKI-ECR and NIRS-HEC are shown in Table 3. The surface area and volume of ECR zone at 18GHz ATOMKI-ECR are roughly two times larger than that of NIRS-HEC and 14 GHz ATOMKI-ECR. It might cause the decreasing the beam-extraction efficiency towards the magnetic field line.

Table 3: The Geometry of ECR Zones at ATOMKI-ECR and NIRS-HEC

	ATOMKI-ECR		NIRS-HEC
Mirror magnetic field at injection side (T)	1.2		1.3
at extraction side (T)	0.95		1.08
Frequency (GHz)	18	14	18
Diameter (cm)	3.8	3.1	3.5
Length (cm)	10.0	6.6	5.0
Volume (cm^3)	85	36	35
Surface (cm^2)	112	61	51

However, from a practical point of view, at both cases large improvement was observable (to the basic currents) if the microwave power was increased, regardless close-2f or far-2f mode was applied. Considering the above mentioned numerous geometrical differences between the two ECRISs, from these experiments it could not be clearly concluded which combination (near or far 2f) is better or worse. On the other hand, Figure 4 shows a non-linear correlation. We expect it will suggest useful information concerning more detailed coupling between the microwaves and the plasma in order to understand the phenomena. In order to learn how to adapt or to design a source suitable for two-frequency heating, we would like to more precisely measure the power dependence in various cases: mirrored 2f at both ECRISs (near 2f in Atomki, far 2f in NIRS), higher microwave power at Atomki-ECR by improving cooling, etc.

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