TWO-FREQUENCY HEATING TECHNIQUE FOR STABLE ECR PLASMA

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Abstract

Two frequency heating technique was studied to increase beam intensities for highly charged ions. The observed dependences on microwave power and frequency suggested this technique improves plasma stability but it requires precise frequency tuning. Although the mechanism is not clear, a high power travelling tube amplifier is promising for more improvement.

INTRODUCTION

In order to accelerate various ion species for basic experiments in e.g. biomedical and material science, physics and chemistry, two ECR ion sources and one PIG ion source are installed in the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS)[1]. Efforts to extend the range of ion species are continuously devoted, but more intense beams in excess of the present performance are desired for heavier ions like Xe or ions made from solid materials like Sn. In addition, a few carbon-ion radiotherapy facilities plan uses of some different ion species for fundamental researches. Since such experiments will be given a lower priority than the treatment, the diversion of existing hardware is expected. In the case of a typical hospital-specified facility, a charge-to-mass ratio as the injection condition into a linac is around 1/3. It means higher charge state ions are also required. For example, Ar^{13+} is required for some biological experiments.

Feeding RF power into an ECRIS at two frequencies was initiated by ECR pioneers Jongen and Lyneis in Berkeley, and some years later more successfully by Xie and Lyneis again in Berkeley[2]. So-called 'Two-frequency heating technique' has advantages; it is effective for any kinds of ion species, no modification of existing structure is necessary, and it is coexistent with almost other techniques. In early stages of our development, the enhancement of plasma region at different ECR zones was observed by the shapes of visible radiations[3]. The output currents had great dependence on additional microwave frequency[4]. However, the limited maximum power and bandwidth of an additional microwave constricted more detailed experiments.

A travelling wave amplifier system (TWT) recently has a capacity to feed larger power. A TWT with the frequency range from 17.75 to 18.25GHz and the maximum power of 700W was added to an 18 GHz ECR ion source called 'NIRS-HEC' with a krystron amplifier system (KLY) with a maximum power of 1500 W in 2007, then we studied the phenomena of two-frequency heating[5]. Table 1 shows maximum records of output currents of NIRS-HEC without two frequency heating technique. The underlined output currents were obtained with the afterglow technique. The output currents for ion species indicated in Italic have not routinely achieved the intensity requirement. The details of development on NIRS-HEC had been described in Ref. [6]

Table 1: Output Currents of the 18 GHz ECR Ion Source, NIRS-HEC Without Two Frequency Heating Technique

Ion	Ar		Fe	Co	Ni	*Ge*	*Kr*	*In*	*Xe*
m	40		56	59	58	74	84	115	132
q	8	13	9	9	10	28	15	20	21
I (eμA)	1100	20	400	160	100	*50*	*200*	*140*	*200*

DEPENDENCE ON MICROWAVE POWER

Dependence of Plasma Stability on Microwave Power

A beam intensity of highly charge state ions usually depends on the microwave power under a well-optimised condition. However, when the power increases, the plasma shows instability and it is difficult to keep. Figure 1 shows an example of plasma instability in the pulse shape of an extracted beam of Xe^{21+}. The left, centre, and right figures are obtained at the microwave power of 480, 720, and 960 W by KLY, respectively.

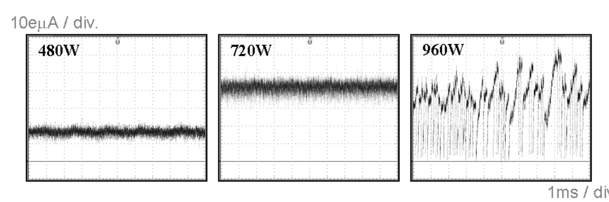

Figure 1: Example of plasma instability in the pulse shape of an extracted beam.

When an additional microwave is added in the above situation, the plasma instability is improved at larger microwave power obtained by the mixture of two different frequency microwaves.

Dependence of Beam Intensity on Microwave Power

Figure 2 shows the dependence of the beam intensity of Ar^{13+} on microwave power. A triangle, rectangle, and

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circular symbols mean a single KLY, a single TWT, and a sum of KLY and TWT, respectively. At first, all operation parameters like the mirror magnetic fields, the gas flows of Ar and O_2, the extraction voltage and distance of electrodes, the biased disk voltage, and so on were optimised by the single KLY. Then the microwave from TWT was added and the frequency of additional microwave was precisely optimised under the fixed conditions. The total of microwave power mostly dominated the beam intensity. It seems that the balance of KLY and TWT is not so effective. 792 W by the single KLY, 802 W by the sum of 602 W KLY and 200 W TWT, and 793 W by the sum of 552 W KLY and 241 W TWT gave almost same currents, 21.0, 17.7, and 19.5 eμA indicated in the dotted ellipse in Figure 2.

At the small KLY power, the measurement value is decreased from the proportional line. It is reasonable that the optimised additional frequency is not suitable for the single operation.

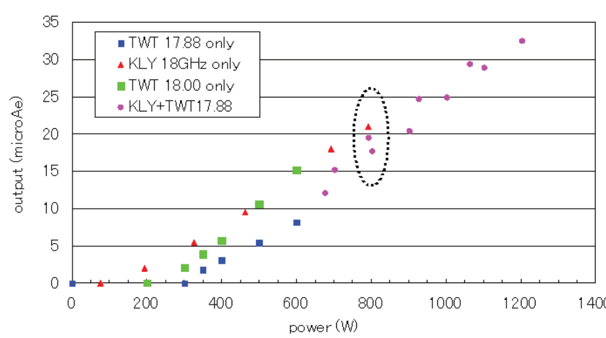

Figure 2: Dependence of beam intensity on microwave power.

DEPENDENCE ON MICROWAVE FREQUENCY

Dependence of Beam Intensity on Microwave Frequency

Figure 3 shows the dependence of the beam intensity of Ar^{13+} on microwave frequency in the same condition as Figure 2. The dependence on the frequency of single microwave by TWT makes a peak at 18 GHz. The result suggests the source was well optimised at 18 GHz. The dependence on the frequency of additional microwave by TWT has some peaks. Figure 2 was measured at 17.88 GHz. It is noted that the mixture of 18GHz KLY and 18GHz TWT gave no improvement and the power exceeded by the power limit by the single KLY also showed instability.

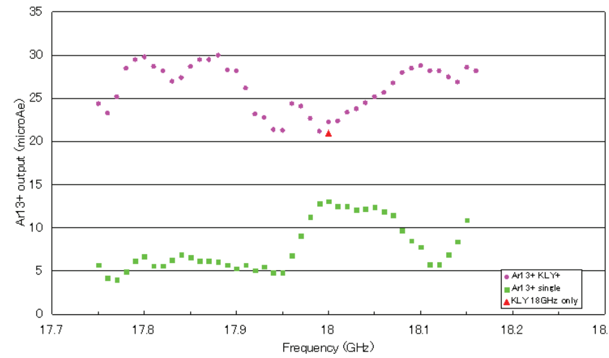

Figure 3: Dependence of the beam intensity on microwave frequency.

When the operation parameters are changed, it is guessed that the coupling efficiency between the microwave and the plasma is changed. It is natural that the optimised frequency of additional microwave is also changed. We searched another optimum condition (B) from the original condition (A) and measure the dependence on microwave power and frequency. Figure 4 shows both of dependences at the condition (A) and (B). The major difference between (A) and (B) was the mirror magnetic field. The mirror field at the extraction side of (B) was about 2.5 % lower than (A). The maximum currents of Ar^{13+} were same as both conditions. However, the optimum frequencies were different at 17.88 GHz for (A) and 18.08 GHz for (B).

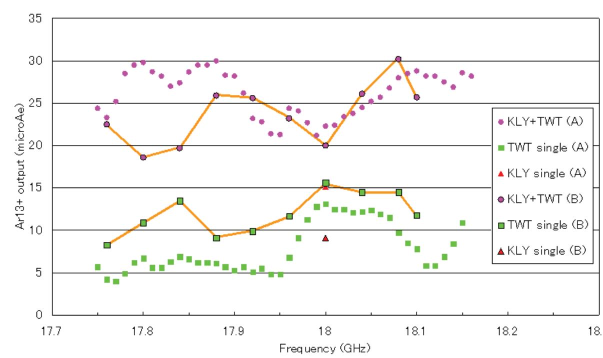

Figure 4: shows both of dependences at the condition (A) and (B).

The dependence on the microwave power under (B) shows the left figure of Figure 5. The large difference from (A) is that the beam intensity of the single KLY were lower than one of the single TWT. It seems that the coupling efficiency of 18GHz KLY microwave and the plasma under (B) decreased from (A) almost 50 %. If this efficiency coefficient is taken account, the tendency is similar as the previous one shown in the right figure of Figure 5.

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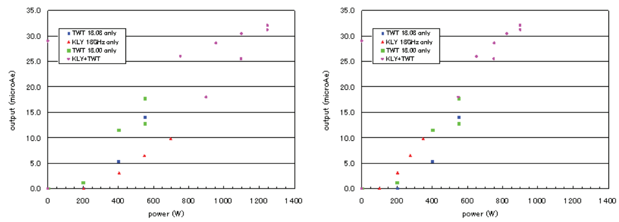

Figure 5: Dependence of beam intensity on microwave power.

In order to obtain better improvement, the larger microwave amplifier with enough wide bandwidth is necessary. Since a few % of bandwidth is required from our experiences, a klystron amplifier is not suitable as an additional microwave amplifier. The performance of a solid state amplifier is increasing year by year, but it still does not have enough cost effectiveness. A travelling wave tube amplifier is only a solution of two frequency heating technique at present. In our situation, the existing 700 W system is not enough for almost cases. So we are developing a new amplifier with a maximum power of over 1 kW. The amplifier will be installed in March 2013.

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.

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. In the future these spatial distributions will be taken into account for the frequency tuning. If it is supposed that the coupling of additional frequency alleviates the deviation and anisotropy and results in the improving the instability, it is expected that optimised multiple frequencies make more favourable condition.

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