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Plasma Response to Amplitude Modulation of the Microwave Power on a 14 GHz Electron Cyclotron Resonance Ion Source

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Abstract. This paper reports the effects of sinusoidal microwave power Amplitude Modulation (AM) on the performance of Electron Cyclotron Resonance (ECR) ion sources. The study was conducted on the 14 GHz ECR ion source ECR2 at the University of Jyväskylä. The klystron output was intentionally altered by a variable frequency sinusoidal amplitude modulation. The average microwave power 350 W was modulated between 530 W and 180 W from 0.011-25 kHz. The integrated x-ray energy, the mass analyzed beam current and the forward and reflected microwave power were measured. The energy integrated x-ray signal responded strongly with low frequency modulation and was no longer observable at approximately 2.2 kHz where the signal strength became solely dependent on the time averaged power. The beam current responded in a similar way but exhibited a strong dependence with magnetic field. Qualitatively, we found source tuning parameters where AM effects were reduced also produced the highest currents of Ne^{8+} in Continuous Wave (CW) mode. Furthermore, these parameters are typically used for optimized beam injection into the K130 cyclotron. The dependence of beam current and the x-ray signal modulation on AM frequency for different magnetic fields are reported. A qualitative interpretation of the results will be given.

INTRODUCTION

For the development of high performance Electron Cyclotron Resonance (ECR) ion sources stronger confinement magnetic fields in conjunction with higher microwave frequency are utilized to improve both the average Charge State Distribution (CSD) peak and the maximum achievable plasma density. In the last decade, superconducting ECR ion sources operating at 24 and 28 GHz are setting the new standard for accelerator facilities operating or under construction. However, at frequencies above 18 GHz, gyrotrons are typically utilized for heating and sustaining the plasma since the small wavelength makes high power CW klystrons and traveling wave tubes impractical. The experiments at the University of Jyväskylä (JYFL) and at Michigan State University (MSU) were motivated by an inherent property of gyrotrons, which exhibit amplitude modulation of the microwave power due to the use of high frequency switching power supplies to generate the required high voltage for the anode. One of our motivations for amplitude modulating the microwave power was to determine if the power ripple from a microwave source such as a gyrotron would affect the resulting beam extracted from an ion source. We hope to gain some insight into characteristic plasma timescales like electron and ion lifetimes. Additionally, intentionally perturbing the plasma with AM may provide guidance for tuning parameters that result in the most stable operating conditions. Following initial preliminary experiments at MSU, a detailed experimental campaign was undertaken at the University of Jyväskylä in May of 2017 to study the amplitude modulation response of the 14 GHz ECR ion source ECR2 [1]. Sinusoidal modulation of microwave power when operating the ECR ion source with four different noble gasses and oxygen were investigated. A small subset of these results using neon gas to generate the plasma are presented in preparation of a more extensive manuscript.

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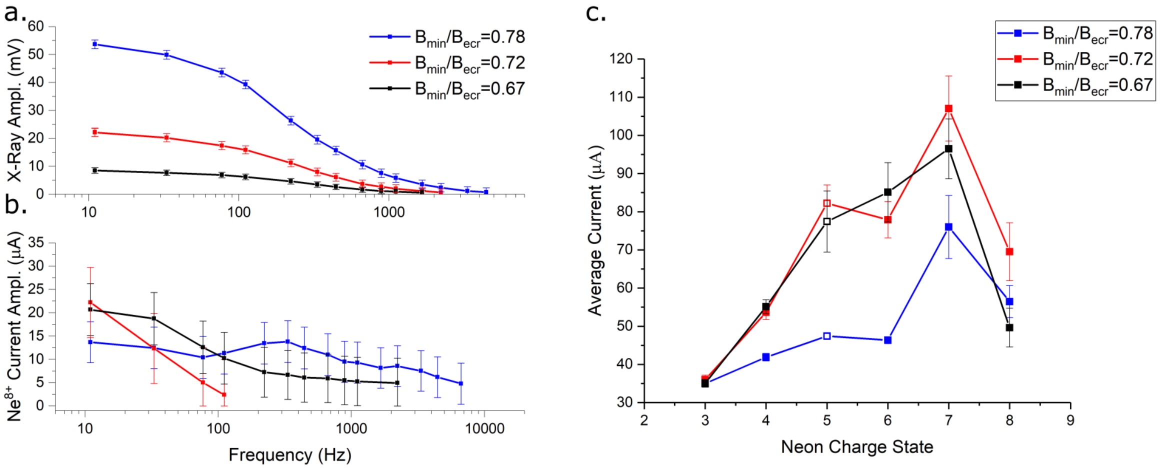

FIGURE 1. X-ray amplitude (a) and Ne^{8+} beam current (b) as a function of applied modulation frequency for three different magnetic fields summarized in Table 1. Neon charge state distributions sampled at 350 W for three different magnetic fields are shown in (c), the lines drawn between points are to aid the reader. Ne^{5+} has artificially more current because it overlaps with O^{4+} and is the reason for a different symbol. The total x-ray emission of the three magnetic fields from B_{min}/B_{ecr} =0.67 to B_{min}/B_{ecr} =0.78 was measured to be: 15.1±0.9, 35.6±1.3, and 88.0±1.4 mV respectively. The average x-ray emission did not depend strongly on modulation frequency and did not change significantly from the value measured at 350 W CW.

EXPERIMENTAL SET-UP AND PROCEDURE

The JYFL ECR ion source is a second generation ECR ion source similar to the AECR-U at LBNL and the ARTEMIS source at MSU [1, 2, 3] The 14 GHz microwave power is generated by a klystron (not a gyrotron). In order to modulate the forward power, the 14 GHz driver oscillator was modulated with a sinusoidal waveform around the average power of 350 W (which was used for all CW results) with a maximum of 530 W and a minimum of 180 W. The modulation frequency was varied from 11 Hz to 25 kHz. In most cases if a frequency was reached where beam current modulation was no longer observable no additional (higher) frequencies were sampled. Care was taken at frequencies below 1 kHz to avoid harmonics of 50 Hz and to increase point density at low frequencies. To best capture the beam current and x-ray modulations we used a distribution of frequencies that increases exponentially. Four parameters were saved simultaneously: forward power, beam current, energy integrated x-rays, and reflected power. Forward and reflected power were sampled at the klystron from power diodes and transmitted through isolation amplifiers. Because the microwave power acts as the agent of change and was an independently controlled parameter we used it as the trigger source for the oscilloscope.

X-rays were measured using a bismuth germanate scintillator crystal located radially in between injection and extraction solenoids coupled with a sodium doped cesium iodide photomultiplier tube operating in current (DC) mode [4]. The scintillator crystal was placed in between radial ports on the ion source and therefore the direct optical path was obstructed by the plasma chamber wall, hexapole magnet, and vacuum chamber. We estimate that the scintillator is sensitive to x-rays above 30 keV. In current mode the scintillator measures x-ray power flux integrated across all energies. The beam currents were recorded on a Faraday cup after mass to charge separation using a current preamplifier operating in high bandwidth mode allowing for a sensitivity up to 200 kHz. Several cycles were sampled on the oscilloscope screen, typically varying from 4-10. Three different magnetic fields were explored and are referred to by their B_{min}/B_{ecr} ratios 0.67, 0.72, and 0.78 respectively. Only one of these fields, B_{min}/B_{ecr} =0.72 was tuned for its unique affect to suppress modulation observed in the beam current, and the other two field were selected in reference to this one.

ANALYSIS AND DISCUSSION

The results and discussion summarized here are only qualitative observations of the preliminary analyses of the subset of data discussed here. We are in the process of preparing a paper that aims to discuss the analysis method of the data in more detail. To quantify the plasma response a sinusoidal fitting function was applied to all four sampled

TABLE 1. The three magnetic fields used in the experiment and some characteristic information.

	Injection (T)	**Minimum (T)**	**Extraction (T)**	**ECR Length (mm)**
B_{min}/B_{ecr} =0.67	1.89	0.336	0.880	118
B_{min}/B_{ecr} =0.72	1.95	0.362	0.924	107
B_{min}/B_{ecr} =0.78	2.01	0.389	0.968	94.6

parameters (forward power, reflected power, energy integrated x-rays, and beam current) as described in detail in [5]. Amplitude values like those plotted in Figs. 1a and 1b are generated from the sinusoidal fitting and correspond to half the peak-to-peak amplitude.

We found that the energy integrated x-ray signal followed the microwave amplitude modulation very closely with a nearly constant time delay of about 0.5 ms in all cases. As shown in Fig. 1a the absolute x-ray value is dependent on the magnetic field as expected following the previously reported trend that higher B_{min}/B_{ecr} ratio produce higher total flux of x-rays on the detector [6]. For the energy integrated x-ray signal, the modulation amplitude decreases smoothly as the modulation frequency increases and disappears for frequencies above 1.3k Hz to 3.3 kHz. Surprisingly we found that the beam current is much more sensitive to amplitude modulation indicating additional plasma mode changes that cannot be observed by measuring x-ray flux only. In some cases the beam current amplitude modulation can be observed to tens of kilohertz and the amplitude does not decline smoothly with frequency. Furthermore, the modulations are strongly dependent on the magnetic confinement configurations and Ne^{8+} is plotted as an example in Fig. 1b. For a field configuration using B_{min}/B_{ecr} =0.72 the amplitude modulation disappeared for frequencies above 120 Hz versus while for other configurations the modulations can extend to kilohertz as in the case of the B_{min}/B_{ecr} =0.78 field configuration. There is also a maximum in modulation amplitude at a frequency of approximately 300 Hz in this case. We have seen similar behavior for all gases used in the experiments and observe maxima for different charge states at various frequency indicating that the charge state distribution is shifting as the modulation frequency is varied.

One interesting observation is that the field minimizing beam current modulation, Bmin/Becr =0.72, also generated the highest CW beam current (Fig. 1c). In addition, the length of the ECR zone at this field is 5.0 times the vacuum wavelength at the driving frequency of 14.056 GHz when determined from solenoid field calculations. The other two fields, B_{min}/B_{ecr} =0.67 and B_{min}/B_{ecr} =0.78 have ECR zone lengths that are 5.6 and 4.4 times the vacuum wavelength respectively. A similar sensitivity to magnetic field was observed on VENUS in 2006 [7] that the authors attributed to the efficiency of microwave coupling. We found that for all field configurations and all gases used in the experiment that the beam current amplitude modulation disappears or is highly suppressed at frequencies above 10 kHz indicating that the power modulation for gyrotron microwave sources should have little effect on the overall performance of the ECR ion source.

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