AN EXPERIMENTAL STUDY OF ECRIS PLASMA STABILITY AND OSCILLATION OF BEAM CURRENT*

O. Tarvainen#, V. Toivanen, H. Koivisto, J. Komppula, T. Kalvas, University of Jyväskylä, Finland
C. M. Lyneis, M. Strohmeier, LBNL, Berkeley, CA 94720, USA

Abstract

The stability of ion beams extracted from ECR ion sources has been studied with the VENUS ion source at LBNL and the 14 GHz A-ECR at JYFL. Oscillations of the beam current in ~ kHz range are characterized with the Discrete Fourier transform. The effect of the ion source tuning parameters on the frequency and amplitude of the oscillations of various charge states is discussed. It was found that double frequency heating affects the oscillation frequency, the biased disc can be used to mitigate their amplitude, increasing B-minimum results to pronounced instabilities and operating the ion source with significantly higher mirror ratio than suggested by ECRIS scaling laws yields the most stable ion beams. It is argued that the observed beam current fluctuations are correlated with plasma processes.

INTRODUCTION

The stability of the ion beams extracted from ECR ion sources is important for accelerators, especially for high power linacs (e.g. FRIB) due to problems arising from fluctuating beam power and spill, medical applications (e.g. carbon therapy) and industrial applications. The stability of ion beams extracted from an ECRIS is determined by two factors; the long-term stability and rapid oscillations of the beam currents on a millisecond scale. This experimental study focuses on the fast oscillations presumably driven by plasma mechanisms.

EXPERIMENTAL RESULTS

The experiments were performed with the superconducting VENUS ECR ion source (see e.g. [1]) at LBNL and A-ECR type 14 GHz ECRIS at JYFL [2]. The temporal behavior of the beam currents for different charge states of oxygen (O^{2+} thru O^{7+}) was recorded with a resistor directly at the Faraday Cup. The VENUS microwave coupling system has both 18 GHz and 28 GHz waveguide antennas, which are used to inject power into the plasma chamber. The VENUS waveguide system has recently been reconfigured to measure cross coupling of 18 and 28 GHz with diode detectors as described in Ref. [3]. This feature was used for monitoring the 28 GHz power coupled out (transmitted) from the chamber through the 18 GHz waveguide port in order to correlate beam current fluctuations with properties of microwave-plasma coupling. The schematic of the experimental setup for VENUS is presented in Fig. 1. The setup used with the JYFL A-ECR is similar with minor exceptions. The beam stability data analysis procedure and experimental results are described hereafter.

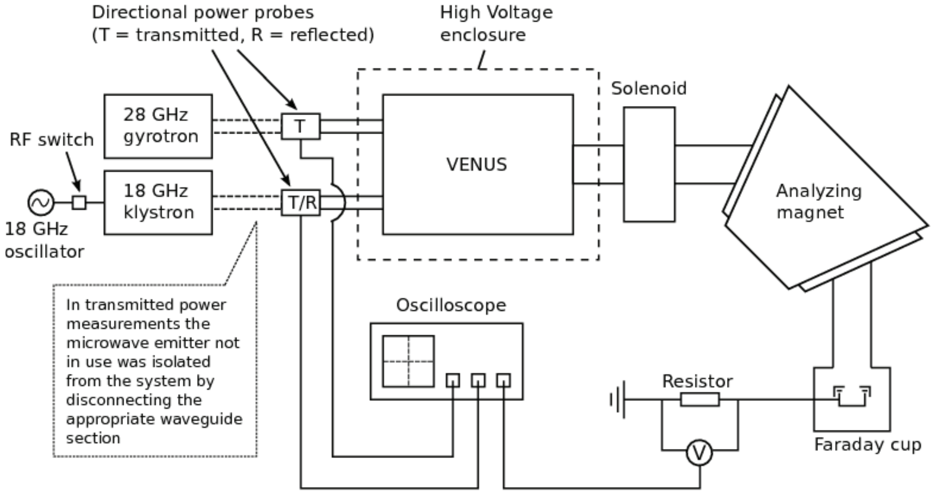

Figure 1: A schematic presentation of the experimental setup used with VENUS.

Data Analysis

The raw signals recorded from the Faraday cup in time domain were transformed to frequency domain with Discrete Fourier Transform (DFT) for further analysis. With VENUS the results were recorded with an oscilloscope (250 kHz sampling rate) and analyzed offline

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olli.tarvainen@jyu.fi

with a Mathematica™ script. A dedicated, LabView-based, measurement and online analysis program [4] was developed for monitoring the beam current stability of the JYFL 14 GHz ECRIS and signals were recorded with a National Instruments data acquisition card. The sampling rate was set to 100 kHz. The given amplitudes correspond to 2σ standard deviation of the time-resolved beam current i.e. rogue points are eliminated by rejecting ~5% of the data points. Frequencies appearing in background, e.g. 50 Hz, and their first harmonics have been eliminated during the analysis. Figure 2 shows a representative example of O^{6+} beam current signal recorded with the JYFL 14 GHz ECRIS together with the corresponding Fourier spectrum. The source was operated with pure oxygen and 650 W of power at 14 GHz resulting to average O^{6+} current of 175 μA and a fluctuation of +8.6 /-12.4 μA i.e. total of 12 % at 860 Hz.

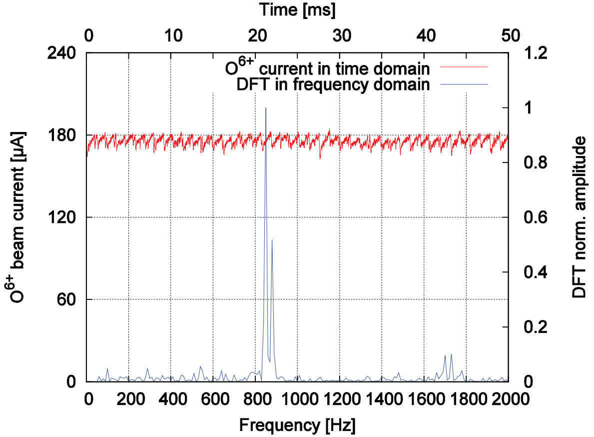

Figure 2: An example of O^{6+} beam current signal and corresponding Fourier spectrum (JYFL A-ECR).

Results

The effect of ion source tuning parameters on the frequency and amplitude of the beam current oscillations has been studied rather extensively and this paper can only summarize the results shortly. Figure 3 illustrates the range of oxygen beam current oscillation (primary) frequencies and amplitudes recorded with the JYFL A-ECR as the source tuning parameters i.e. power, neutral gas feed rate, bias disc voltage and magnetic field were varied. The amplitude of the beam current oscillation varies between 1 - 65 % depending on the tune, the typical value being ~10%. The range of oscillation frequencies is 30 Hz - 1.4 kHz. The corresponding numbers for VENUS are 1 - 25 % and 200 Hz - 6.8 kHz. The lower limit is defined by the duration of the recorded current signal. Beam current monitoring methods applied regularly for the ion source tuning at JYFL fail to detect oscillations at frequencies > 50 Hz due to signal averaging, which highlights the usefulness of the online analysis tool.

It was observed with both VENUS and the JYFL A-ECR that tuning parameters of the ion source affect the characteristics of the beam current oscillations. As an example Fig. 4 shows the amplitude and frequency for O^{6+} beam as a function of power. In the given examples the O^{6+} current increased from 34 μA to 175 μA (A-ECR) and from 190 μA to 980 μA (VENUS) with increasing power. Both, the amplitude and the frequency of the beam current oscillations tend to increase with the power, which has been observed also by Taki et. al. [5].

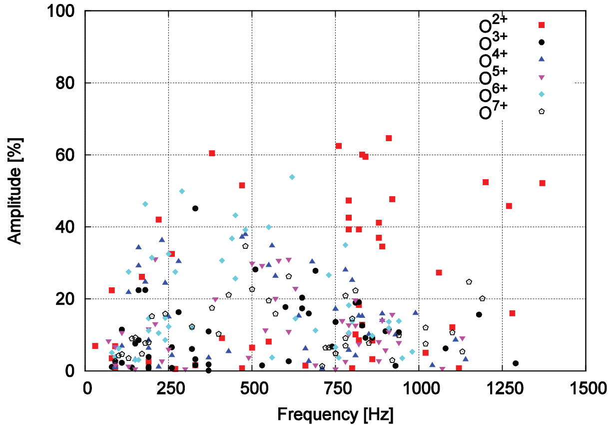

Figure 3: The range of beam current oscillation amplitudes and frequencies (JYFL 14 GHz ECRIS).

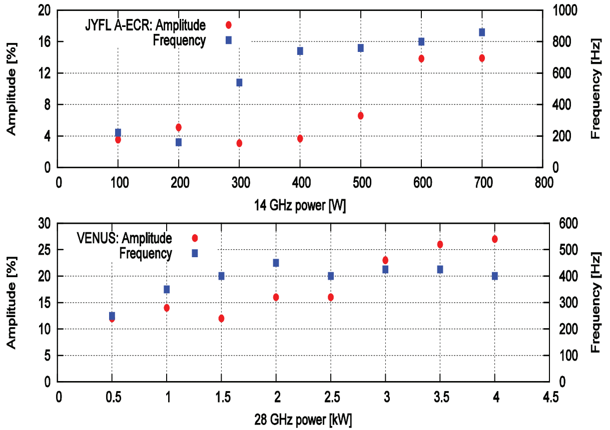

Figure 4: O^{6+} current oscillation as a function of power.

Furthermore, it was observed that (a) the neutral gas pressure had very little effect on the instability characteristics (JYFL A-ECR) although the total extracted current changed by a factor of 2 during the sweep, (b) adjusting the biased disc voltage affects mainly the amplitude of the ripple (VENUS & JYFL A-ECR) offering a tool to mitigate beam current fluctuations and (c) operating the ion sources with a flat magnetic field profile typically yields very unstable beams more than doubling the oscillation amplitude in comparison to magnetic field profiles with steep gradient at the resonance.

The typical charge state dependence of the beam current oscillation amplitude is depicted in Fig. 5. The amplitude of the periodic oscillations is usually observed to increase with the charge state. The ion sources were tuned for O^{6+} in the given example.

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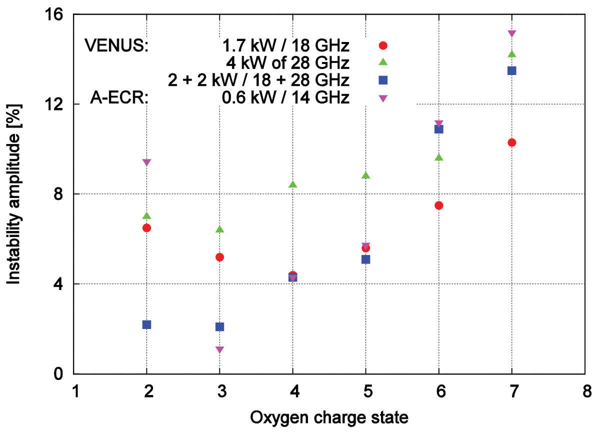

Figure 5: Typical charge state dependence of the beam current oscillation amplitude.

The data in Fig. 5 reveals yet another trend. It was observed that two-frequency heating often improves the stability of the low charge states while the oscillations of high charge states remain virtually unaffected. In the case of oxygen the stability was observed to improve for charge states ≤ 5+ corresponding to M/Q values ≥ 3.2. A representative example of beam current signals of O^{3+} and O^{6+} (measured with VENUS) demonstrating the effect of the secondary frequency is shown in Fig. 6. It is evident that the stabilizing effect is more pronounced for low charge state (O^{3+}).

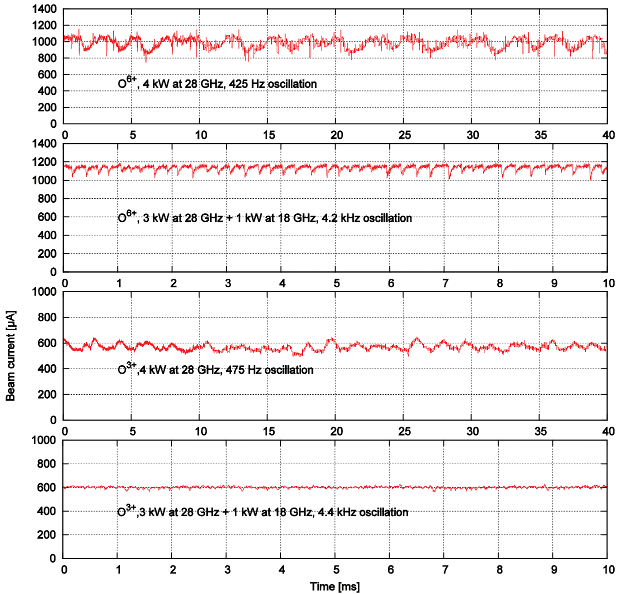

Figure 6: O $^{6+}$and O $^{3+}$ beam current signals in single and double frequency heating modes of VENUS.

Figure 6 demonstrates that also the oscillation frequency of the beam current increases when double frequency heating is applied making it even more difficult to detect the fluctuation with traditional beam current monitoring methods often filtering and averaging the signals. The increase of the beam current oscillation frequency due to double-frequency heating was observed to be significant in the case of VENUS as further illustrated in Fig. 7. The frequency of the periodic oscillations of O^{6+} beam current increases abruptly from ~ 400 Hz to several kHz with increasing power at secondary frequency (18 GHz) added on top of 3 kW at primary frequency (28 GHz). The average O^{6+} beam current was observed to increase from 920 µA (3 kW of 28 GHz) up to 1170 µA corresponding to 1.5 kW of 18 GHz power + 3 kW of 28 GHz. Similar, although not as pronounced, trend was observed also with the JYFL A-ECR operated with 14 + 11.56 GHz. Increasing the power at 11.56 GHz, added onto 500 W at 14 GHz, from 10 W to 200 W the (primary) frequency of the current oscillation increased from 790 Hz to 1.4 kHz.

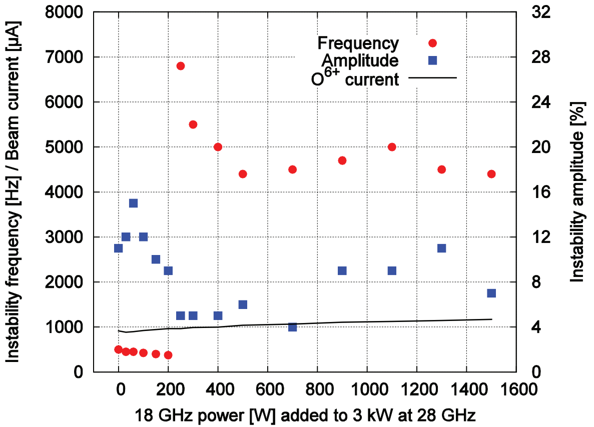

Figure 7: Characteristics of O^{6+} beam current oscillations in double frequency heating mode of VENUS.

For VENUS the most stable setting was found when operating in "high-B mode" i.e. with 18 GHz microwave frequency at field profile optimized for 28 GHz microwave radiation. With the JYFL A-ECR the most stable beams were observed with 11.5 GHz after scaling the injection and extraction mirror ratios to correspond values typical for 14 GHz operation. Table 1 summarizes these observations. The injection, extraction and radial mirror ratios, *R*, are defined as B_{max}/B_{ECR}.

Table 1: Comparison of Beam Current Oscillation Amplitudes for Different Magnetic Field Profiles

Description	$R_{inj}/R_{ext}/R_{rad}$	O^{6+} amplitude [%]
VENUS 1.7 kW / 18 GHz	3.4 / 2.3 / 2.0	**7.5**
VENUS "high-B" 2 kW / 18 GHz	5.3 / 3.3 / 3.5	**2.2**
JYFL A-ECR 300 W / 14 GHz	4.2 / 2.0 / 2.2	**12.1**
JYFL A-ECR 300 W / 14 GHz	3.7 / 1.7 / 2.2	**3.8**
JYFL A-ECR 300 W / 11.5 GHz	4.3 / 2.0 / 2.7	**3.1**

DISCUSSION

Changing pattern of beam current oscillations with the ion source settings (at constant total extracted current) suggests that the mechanisms driving the fluctuations are plasma effects. The contributions of the extraction region (plasma meniscus) and beam optics, which are unknown at this time, are a subject of a further study. Evidence of plasma oscillations, synchronized with the beam current fluctuations of VENUS, was observed with dual-port diagnostics studying temporal behaviour of the transmitted and reflected power signals [3]. Figure 8 shows an example of O^{6+} current and transmitted power signal, measured with 4 kW forward power at 28 GHz. The transmitted power and extracted beam current oscillate in phase at 425 Hz suggesting that the plasma properties affecting the microwave coupling and plasma oscillations are linked together. Furthermore, it was observed with 18 GHz that reflected and transmitted powers oscillate in phase i.e. peak of transmitted power corresponds to peak of reflected power. The high frequency ripple of the transmitted power at ~ 40 kHz is due to gyrotron power supply.

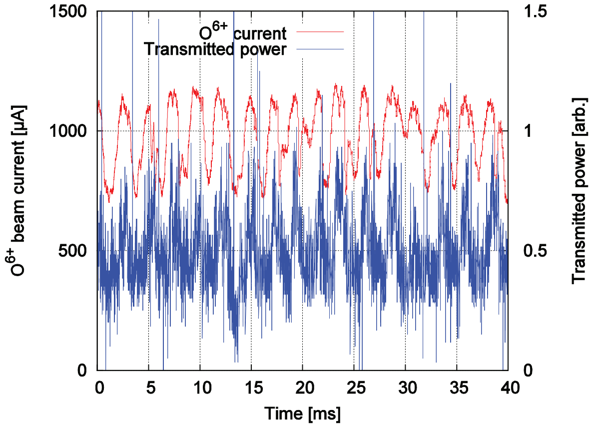

Figure 8: O^{6+} current and 28 GHz transmitted power exhibiting oscillations at 425 Hz. The forward power was observed to fluctuate only at ~ 40 kHz frequency.

Identifying mechanisms causing perturbations of the beam current is challenging. Instabilities are often categorized to (1) kinetic instabilities stemming from the anisotropy of the electron energy distribution function (EEDF) (see e.g. [6,7]) and (2) MHD instabilities driven by the topology of the magnetic field (see e.g. [8-10]). Anisotropic EEDF is prone to kinetic electron cyclotron instabilities. The threshold for the onset of the instability depends on the ratio of the hot electron density to the cold electron density and the difference in their respective temperatures. The existence of kinetic instabilities in ECRIS plasmas has been confirmed by measuring bursts of electrons and bremsstrahlung during the afterglow [11]. MHD-instabilities can lead to observable fluctuation of particle losses e.g. beam current. MHD instabilities are effectively suppressed in minimum-B confinement structures in which the magnetic field increases in radial direction i.e. $\partial B/\partial r \geq 0$ corresponding to concave curvature of the field lines. The superposition of solenoid and sextupole field does not fully satisfy the given condition. The configuration is prone to MHD instabilities in the spatial region where the radial increase of the sextupole field does not overcome the radial decrease of the solenoid field i.e. plasma confined by the field lines intercepting the surface defined by the "minimum-B ring". This region is depicted in Fig. 9 in which the cross section where $\partial B/\partial r$-value is negative has been plotted for the JYFL A-ECR at the plane exactly between the solenoids. Also the ECR-surface is depicted in the figure in order to show that the cross-sectional area where MHD-stability condition is not fulfilled is about 4.5 % of the area defined by the resonance zone. In 3D the minimum-B surface defines nearly ellipsoidal volume prone to MHD-instabilities. It is emphasized that the value of $\partial B/\partial r$ is small enough for diamagnetic effect to shift the minimum-B depending on the spatial distribution of electrons and their energy.

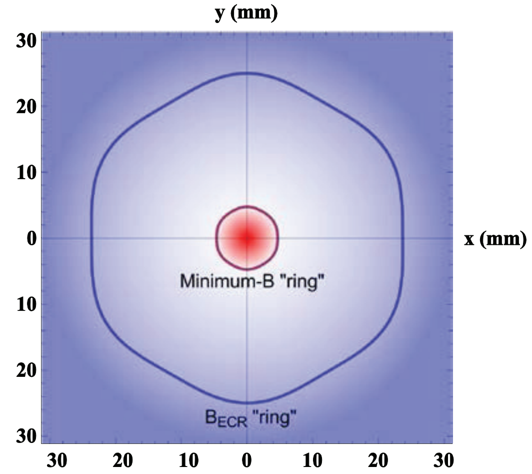

Figure 9 : Magnetic field curvature (JYFL A - ECR) at the plane between the solenoids. Red indicates $\partial B/\partial r < 0$, blue $\partial B/\partial r \geq 0$. The minimum -B "ring" and ECR- surface are shown with solid lines.

The magnetic field topology alone does not guarantee the appearance of MHD instabilities. The condition for magnetohydrodynamically "quiet" plasma can be written as *particle pressure* << *magnetic pressure* i.e. $n_e kT_e << B^2/2\mu_0$ where the left hand side corresponds to the energy content of plasma (in J/m^3). This implies that (a) similar to kinetic instabilities the onset of MHD instabilities depends on the heating rate of electrons and (b) increasing the magnetic field strength i.e. operating the ion source in "high-B mode" [12] allows one to reach higher plasma density without suffering from instabilities or, alternatively, to mitigate instabilities at given plasma density. In practice it has been observed that magnetic mirror confinement structures start exhibiting MHD instabilities when the particle pressure reaches ~ 1% of the magnetic pressure [13].

The increase of the beam current oscillation frequency with microwave power suggests that the fluctuation

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mechanism is related to the rate of energy transfer to plasma electrons. On the other hand, the decrease of the beam current oscillation amplitude at high mirror ratio suggests that the magnetic field configuration plays a crucial role. In this view it is especially important to increase the radial field to minimize the volume where the radial decrease of the solenoid field overcomes the radial increase of the sextupole field. Dedicated experiments addressing this point could be conducted in the future with the VENUS ion source operating at 18 GHz. MHD-instabilities could be presumably eliminated by developing an ECRIS based on a true minimum-B configuration, e.g. the proposed ARC-ECRIS reviewed in Ref. 14.

In this study the focus has been in understanding the nature of the instabilities and the examples shown do not represent the optimum stabilities that can be achieved with careful tuning of VENUS or the JYFL A-ECR. Our future plans include measuring the effect of beam current stability on the transmission of the beam line and cyclotron at JYFL [15], studying the distribution of beam current oscillations in the beam, studying the stability of heavier element beams and correlating the beam current oscillations with plasma instabilities through different diagnostics.

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