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Title: Transverse distribution of beam current oscillations of a 14 GHz electron cyclotron resonance ion source

Year: 2014

Version:

Please cite the original version:

Tarvainen, O., Toivanen, V., Komppula, J., Kalvas, T., & Koivisto, H. (2014). Transverse distribution of beam current oscillations of a 14 GHz electron cyclotron resonance ion source. Review of Scientific Instruments, 85(2), Article 02A909. https://doi.org/10.1063/1.4826539

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Citation: Review of Scientific Instruments **85**, 02A909 (2014); doi: 10.1063/1.4826539
View online: http://dx.doi.org/10.1063/1.4826539
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/85/2?ver=pdfcov
Published by the AIP Publishing

REVIEW OF SCIENTIFIC INSTRUMENTS **85**, 02A909 (2014)

Transverse distribution of beam current oscillations of a 14 GHz electron cyclotron resonance ion source[a)]

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(Presented 11 September 2013; received 6 September 2013; accepted 2 October 2013; published online 28 October 2013)

The temporal stability of oxygen ion beams has been studied with the 14 GHz A-ECR at JYFL (University of Jyvaskyla, Department of Physics). A sector Faraday cup was employed to measure the distribution of the beam current oscillations across the beam profile. The spatial and temporal characteristics of two different oscillation "modes" often observed with the JYFL 14 GHz ECRIS are discussed. It was observed that the low frequency oscillations below 200 Hz are distributed almost uniformly. In the high frequency oscillation "mode," with frequencies >300 Hz at the core of the beam, carrying most of the current, oscillates with smaller amplitude than the peripheral parts of the beam. The results help to explain differences observed between the two oscillation modes in terms of the transport efficiency through the JYFL K-130 cyclotron. The dependence of the oscillation pattern on ion source parameters is a strong indication that the mechanisms driving the fluctuations are plasma effects. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4826539]

I. INTRODUCTION

The temporal stability of ion beams extracted from ECR ion sources is important for high power accelerators and their applications, e.g., medical treatments.[1] The stability of the ECRIS beams can refer to long-term stability and rapid oscillations of the beam currents on a millisecond (kHz) scale. The long term trends are usually associated with the surface conditions of the plasma chamber, i.e., outgassing and accumulation of contaminants, which affect the plasma properties and performance of the ion source. The work presented here concentrates on the periodic beam current oscillations in the millisecond scale, which are presumably driven by plasma instabilities.

A brief summary of previous work on ECRIS beam current oscillations is given in Ref. 2 (and references therein). It is reported there that the beam current oscillations are preserved in the low energy beam transport (LEBT) section of the JYFL 14 GHz ECRIS[3] but vanish after the JYFL K-130 cyclotron.[4] Furthermore, it is shown that the transmission efficiency through the cyclotron depends on the frequency and amplitude of the beam current oscillations in the LEBT section. The purpose of this work is to study the distribution of the temporal beam current fluctuations across the beam profile affecting the beam transport.

II. EXPERIMENTAL SETUP AND PROCEDURE

The experiments were performed with the A-ECR type JYFL 14 GHz ECRIS. The temporal characteristics of oxygen beams (charge states O^{3+}–O^{7+}) were recorded with a Faraday cup, located downstream from the M/Q analysis magnet and divided into 16 sectors. Figure 1 shows the relevant section of the JYFL 14 GHz ECR ion source LEBT and the configuration of the sector Faraday cup. The diameter of the cup is 45 mm with each sector covering $\frac{1}{4}$ circle and 5 mm radial distance. The oxygen ion beams were focused into the cup, i.e., the total beam current was maximized, by tuning the three solenoids, the dipole magnet, and two sets of xy-steering magnets. The 20 mm collimator is at the focal plane of the dipole magnet. The electron suppression voltage of the cup was set to –50 V. Due to the structure of the cup it is not guaranteed that the secondary electrons produced by the incident beam are forced back to the very same sector. However, sweeping the suppression voltage from 0 to –50 V did not change the beam temporal characteristics recorded from each sector.

The currents from the 16 sectors were measured across 100 kΩ shunt resistors. The measurement board was configured to alternatively combine all sectors and measure the total current across a 10 kΩ resistor. The capacitance of each sector and the adjacent cables was measured to be 90–130 pF. Thus, the –3 dB cut-off frequency, $f_{cut\text{-}off} = 1/(2\pi RC)$, of each individual channel and all the parallel sectors combined is 12.2 kHz and 7.7 kHz, respectively. A dedicated measurement and online analysis program[2] was used for monitoring and recording the beam currents with a National Instruments data acquisition card (16-bit USB-6255). The current signals were transformed to frequency domain with Discrete Fourier Transform (DFT). The sampling rate was set to 20 kHz corresponding to a 10 kHz Nyquist limit for the DFT. Since the frequency of the beam current oscillations measured with the JYFL 14 GHz ECRIS are typically below 1.5 kHz, the measurement setup and sampling rate are adequate for the purpose. The reported oscillation 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. The acquisition time for measuring the temporal characteristics of the beam was 1 s. During the

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[a)] Contributed paper, published as part of the Proceedings of the 15th International Conference on Ion Sources, Chiba, Japan, September 2013.

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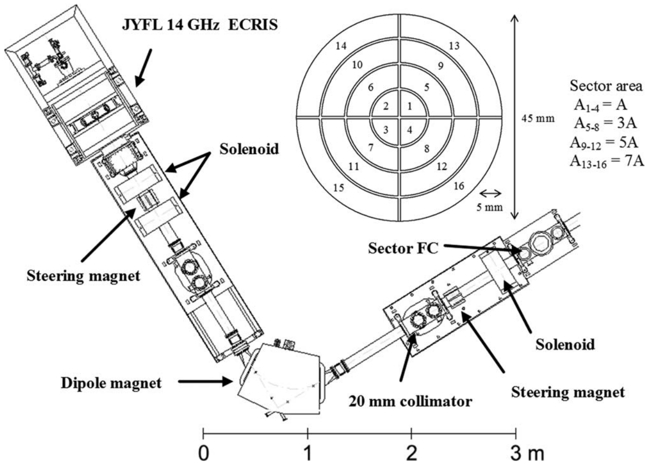

FIG. 1. The LEBT of the JYFL 14 GHz ECRIS and the configuration of the sector Faraday cup (FC).

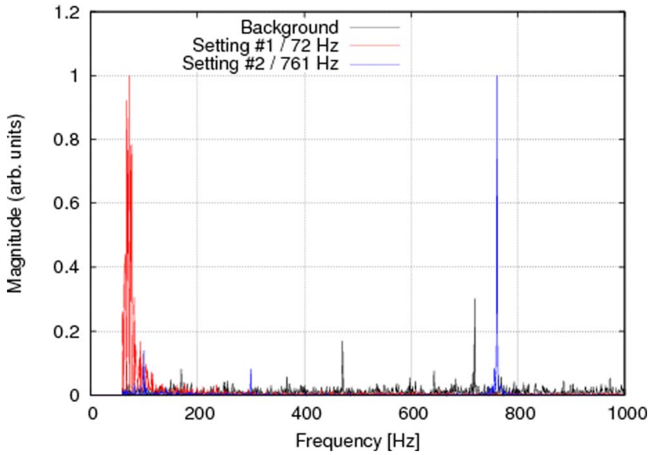

FIG. 2. Normalized frequency power spectra of the two beam current oscillation "modes." O^{6+} beam is used as an example.

analysis several shots were combined to eliminate the effects of random fluctuations.

III. RESULTS AND DISCUSSION

The beam current oscillation frequency and amplitude depend on the ion source settings. Two oscillation "modes" with rather different characteristics are observed with the JYFL 14 GHz ECRIS; one with frequencies below 200 Hz and another with frequencies of 300 Hz–1.3 kHz. The higher frequency "mode" is typically achieved with low neutral gas pressure and strong solenoid magnetic field ($B_{min} > 0.75 B_{ECR}$) and it often corresponds to better transmission through the K-130 cyclotron.[4]

The ion source settings used for this study were chosen to correspond to these two oscillation "modes." The settings for the given examples representing typical results are (a) setting #1: microwave power $P_{rf} = 450$ W, axial magnetic field strength $B_{inj} = 2.03$ T/$B_{ext} = 0.95$ T/$B_{min} = 0.34$ T and neutral O_2 pressure $p = 6.1 \times 10^{-7}$ mbar and (b) setting #2: $P_{rf} = 390$ W, $B_{inj} = 2.08$ T/$B_{ext} = 0.98$ T/$B_{min} = 0.38$ T and $p = 3.3 \times 10^{-7}$ mbar. Typical magnetic field and pressure in normal operation are close to setting #2, i.e., the beam current oscillations are often in the range of 0.3–1.3 kHz. The extraction voltage was kept constant at 10 kV. Figure 2 shows the normalized frequency power spectra for the two cases. The primary frequencies of the current oscillations are 72 Hz and 761 Hz. The background spectrum is shown to demonstrate that the frequencies correspond to beam current oscillations. The data are measured with O^{6+} beam from all of the sectors combined. The corresponding beam currents are 208 μA and 244 μA, respectively. Frequencies below 60 Hz are excluded to suppress the 50 Hz line frequency and remove the DC component.

The transverse distribution of the beam current oscillations is demonstrated in Fig. 3 showing the normalized current densities and 2σ-amplitudes recorded from each sector. The oscillation amplitudes are given as percentage values of the average current collected by each sector due to different active areas. Charge states O^{4+}–O^{7+} are chosen for the display because the focusing power of the solenoid in front of the sector cup is sufficient for >90% capture into the cup for these beams. The given beam current intensities and oscillation amplitudes have been obtained by combining data from 50 individual samples, each of them consisting of 1 s of recorded signal from the Faraday cup. The data in Fig. 3 imply that the temporal fluctuations of the beam current

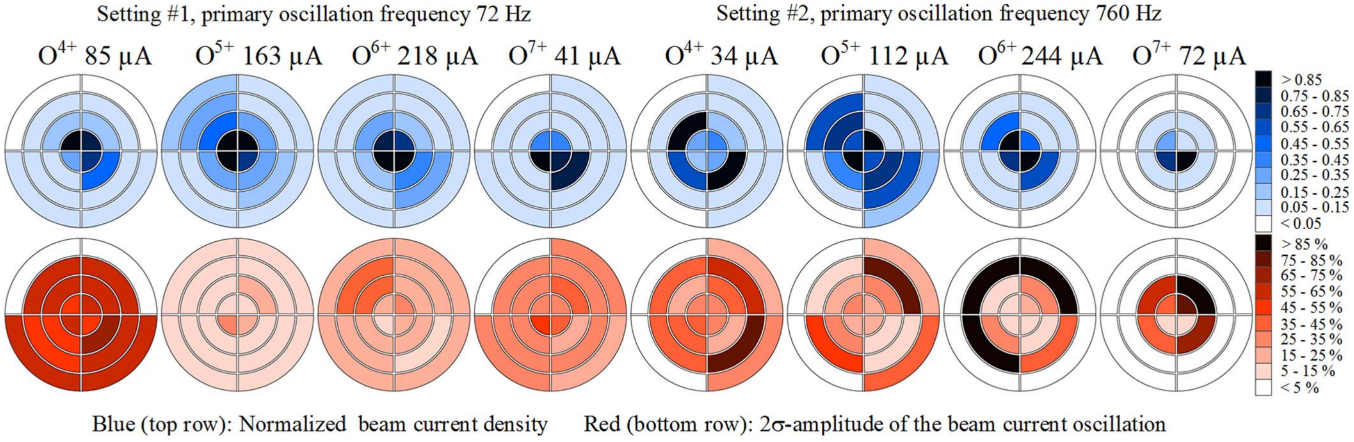

FIG. 3. Normalized current densities (top) and 2σ-amplitudes of the beam current oscillation (bottom) for O^{4+}–O^{7+}. Ion source is tuned for O^{6+} in both cases.

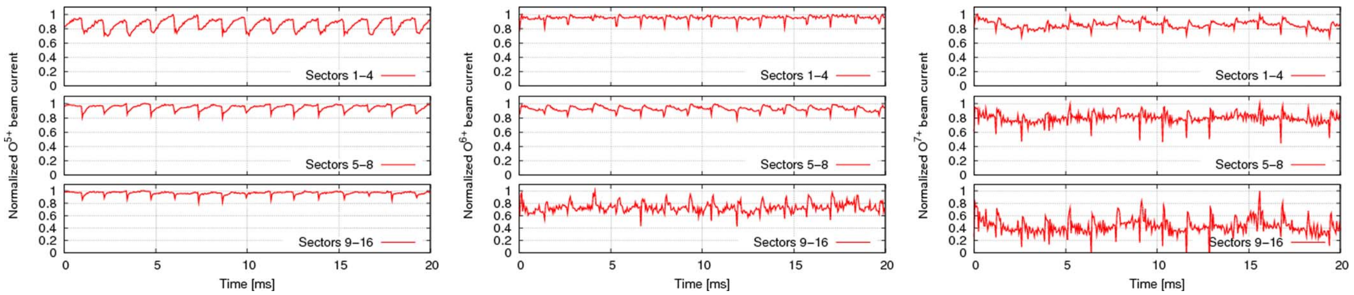

FIG. 4. An example of typical temporal current signals (normalized) of O^{5+}-O^{7+} in sectors 1-4, 5-8, and 9-16 combined. The current oscillates at 760 Hz. Sampling rate is set to 250 kHz/channel.

are distributed across the beam profile somewhat differently in the two oscillation "modes." It was consistently (Fig. 3 is an example) observed that the low frequency oscillations are distributed almost uniformly while in the high frequency "mode" the core of the beam carrying most of the current oscillates with smaller amplitude than the peripheral parts of the beam. The distribution of the oscillations was not observed to depend strongly on the charge state. The fact that the core of the beam oscillates less than the periphery probably contributes to the fact that the transmission through the JYFL K-130 cyclotron has been observed to be better in the high frequency oscillation "mode." This is because the halo of the beam is collimated in the LEBT and subsequent acceleration, which mitigates the beam current oscillations.

Representative examples of the (normalized) temporal current signals of charge states O^{5+}–O^{7+} recorded in the high frequency oscillation "mode" from the sectors covering different radii of the beam spot (sum of sectors 1-4, 5-8, and 9-16, respectively) are shown in Fig. 4. All charge states were observed to exhibit "sawtooth" type behavior, i.e., an abrupt drop and slower recovery of the current throughout the transverse profile of the beam at the oscillation frequency (760 Hz in the given example). However, there are clear differences between the charge states as well. As demonstrated in Fig. 4, the currents of the highest charge states reach a local maximum as they recover from the drop. The effect is pronounced at the peripheral parts of the beam. The timescales of the abrupt drop and the subsequent maximum are similar to those observed in the afterglow[5,6] of ECRIS plasmas.

The results presented in this paper are not intended to correlate the beam current oscillations with the temporal stability of the plasma. The presented study is, nevertheless, necessary for understanding the nature of the oscillations and their impact on the transport of highly charged ion beams extracted from ECR ion sources. It is concluded that the temporal characteristics of the beam and in particular the distribution of the beam current oscillations probably affect the efficiency of the LEBT and subsequent acceleration. The temporal and spatial patterns of beam current oscillations changing with the ion source settings are strong indications that the mechanisms driving the fluctuations are plasma effects.

ACKNOWLEDGMENTS

This work has been supported by the EU 7th framework program "Integrating Activities – Transnational Access," Project No. 262010 (ENSAR) and by the Academy of Finland under the Finnish Centre of Excellence Program 2012-2017 (Nuclear and Accelerator Based Physics Research at JYFL). O.T. thanks Magnus Ehrnrooth foundation for financial support.

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