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Author(s): Tarvainen, Olli; Kalvas, Taneli; Koivisto, Hannu; Komppula, Jani; Kronholm, Risto; Laulainen, Janne; Izotov, I.; Mansfeld, D.; Skalyga, V.

Title: Kinetic instabilities in pulsed operation mode of a 14 GHz electron cyclotron resonance ion source

Year: 2016

Version:

Please cite the original version:

Tarvainen, O., Kalvas, T., Koivisto, H., Komppula, J., Kronholm, R., Laulainen, J., Izotov, I., Mansfeld, D., & Skalyga, V. (2016). Kinetic instabilities in pulsed operation mode of a 14 GHz electron cyclotron resonance ion source. *Review of Scientific Instruments*, 87(2), Article 02A701. <https://doi.org/10.1063/1.4931711>

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Citation: [Review of Scientific Instruments](#) **87**, 02A701 (2016); doi: 10.1063/1.4931711

View online: <http://dx.doi.org/10.1063/1.4931711>

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Kinetic instabilities in pulsed operation mode of a 14 GHz electron cyclotron resonance ion source

O. Tarvainen,^{1,a)} T. Kalvas,¹ H. Koivisto,¹ J. Komppula,¹ R. Kronholm,¹ J. Laulainen,¹ I. Izotov,² D. Mansfeld,² and V. Skalyga^{2,3}

¹*Department of Physics, University of Jyväskylä, 40500 Jyväskylä, Finland*

²*Institute of Applied Physics, RAS, 46 Ul'yanova St., 603950 Nizhny Novgorod, Russian Federation*

³*Lobachevsky State University of Nizhny Novgorod (UNN), 23 Gagarina St., 603950 Nizhny Novgorod, Russian Federation*

(Presented 27 August 2015; received 20 August 2015; accepted 4 September 2015; published online 28 September 2015)

The occurrence of kinetic plasma instabilities is studied in pulsed operation mode of a 14 GHz A-electron cyclotron resonance type electron cyclotron resonance ion source. It is shown that the temporal delay between the plasma breakdown and the appearance of the instabilities is on the order of 10–100 ms. The most important parameters affecting the delay are magnetic field strength and neutral gas pressure. It is demonstrated that kinetic instabilities limit the high charge state ion beam production in the unstable operating regime. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4931711>]

I. INTRODUCTION

Electron cyclotron resonance ion source (ECRIS) plasmas are prone to kinetic instabilities arising from the anisotropy of the electron velocity distribution (EVD). The most critical parameter affecting the occurrence of the instabilities has been shown to be the (solenoid) magnetic field strength, which defines the threshold between stable and unstable operating regimes, while the microwave power and neutral gas pressure affect the repetition rate of the periodic instabilities in continuous (cw) operating mode.¹ It has been shown recently that the instabilities restrict the parameter space available for optimizing the extracted currents of high charge state ions in cw operation of minimum-B ECR ion sources.^{1,2} This is further illustrated in Fig. 1 showing examples of temporally averaged (normalized) beam currents of He²⁺, O⁷⁺, and Ar¹⁴⁺ extracted from the JYFL 14 GHz ECRIS³ when sweeping the magnetic field strength, indicated by the B_{\min}/B_{ECR} -ratio, across the transition from stable to unstable operating regime. In this paper, we focus on studying the kinetic instabilities in pulsed operation of ECRIS (excluding afterglow instabilities⁴). Measurement of the temporal delay between plasma ignition and the appearance of the instabilities with varying source parameters allows determining the characteristic time scale required to create significant anisotropy of the EVD.

II. EXPERIMENTAL SETUP AND PROCEDURE

The experimental data were taken with the room-temperature A-ECR type JYFL 14 GHz ECRIS.³ The pulsing of the microwaves was realized with a RF-switch controlling the input signal of the klystron amplifier. The transistor-

transistor logic (TTL) signal driving the switch was used as a trigger for the data acquisition consisting of current measurement from the biased disc across 1 k Ω resistor, a Bismuth germanate (BGO) scintillator coupled with a Na-doped CsI photomultiplier tube (PMT) and m/q -resolved measurement of the extracted beam currents with a Faraday cup. The bias disc current was recorded in order to determine the delay⁵ between the leading edge of the microwave pulse and the plasma breakdown. The scintillator was used for detecting periodic bursts¹ of wall bremsstrahlung generated by energetic electrons expelled from the magnetic confinement as a result of the kinetic instabilities. The experimental setup is shown schematically in Fig. 2.

All experimental data described hereafter were taken with oxygen plasmas using 0.25 Hz pulse frequency with 50% duty factor, i.e., 2 s microwave ON/OFF time. The temporal delay between the plasma breakdown and the appearance of the kinetic instabilities was measured as a function of the most important source tuning parameters, i.e., (solenoid) magnetic field strength, microwave power, and neutral O₂ pressure. The biased disc voltage was kept constant at –90 V throughout the experiments. A 10 kV extraction voltage was applied when recording the beam currents from the Faraday cup. Fig. 3 shows an example of the diagnostics signals and clarifies the temporal sequence of the microwave pulse, plasma ignition, and appearance of the instabilities.

III. RESULTS AND DISCUSSION

Figure 4 shows the delay between plasma breakdown and the appearance of the instabilities as a function of the magnetic field strength (above the instability threshold) measured with different microwave powers ranging from 300 to 600 W (typical for cw operation of the JYFL 14 GHz ECRIS) pulsed at 0.25 Hz. In the given example, the neutral O₂ pressure measured with an ionization gauge located in the radial port of the plasma chamber was $2.5 \cdot 10^{-7}$ mbar. It is evident

Note: Contributed paper, published as part of the Proceedings of the 16th International Conference on Ion Sources, New York, New York, USA, August 2015.

^{a)}olli.tarvainen@jyu.fi

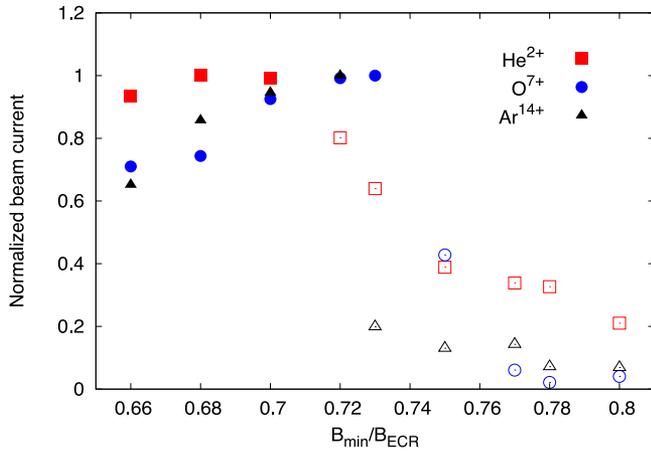


FIG. 1. Normalized temporally averaged currents of He²⁺, O⁷⁺, and Ar¹⁴⁺ ion beams in cw mode as a function of the B_{\min}/B_{ECR} -ratio. Solid symbols correspond to stable and open symbols to unstable operating regime.

that instabilities appear faster with increasing B_{\min}/B_{ECR} -ratio. Moreover, at weaker magnetic fields the onset of the instabilities is temporally more randomized, which is indicated by increasing standard deviation of the measured delay. The effect of the microwave power is insignificant, i.e., the error bars overlap in most cases.

The effect of the neutral gas pressure on the appearance of the instabilities is presented in Table I showing the temporal delay between the plasma breakdown and the onset of the periodic instabilities at three neutral gas pressures. The microwave power and magnetic field strength were kept at 400/600 W and $B_{\min}/B_{\text{ECR}} = 0.8$, respectively. Increasing the neutral gas pressure delays the appearance of the instabilities. Furthermore, it was observed again that the delay is insensitive to the microwave power.

All of the observed trends can be explained qualitatively by the parametric dependencies of the volumetric instability growth and damping rates, γ and δ .⁶ The growth rate is proportional to the magnetic field strength through the

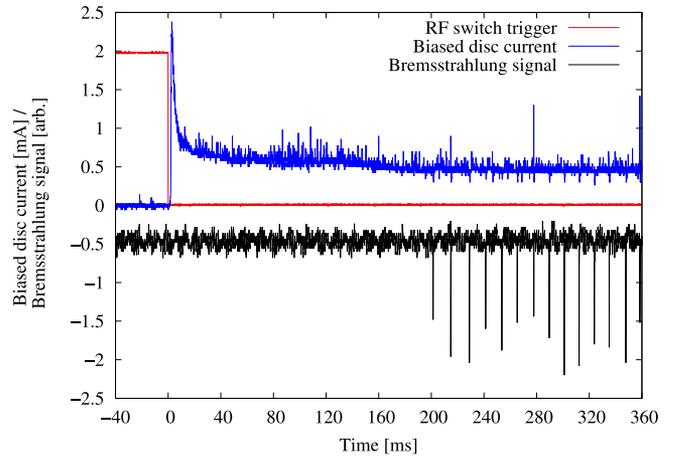


FIG. 3. An example of the diagnostics signals. (i) The microwave pulse is applied at $t = 0$ (trigger signal to 0 V), (ii) the biased disc current exhibits an ignition transient reaching maximum at $t \approx 6$ ms, and (iii) periodic kinetic instabilities (negative spikes) appear at $t \approx 200$ ms. The bremsstrahlung signal has been shifted vertically by -0.5 units to allow viewing the zero level of the RF switch control voltage.

(local) electron cyclotron frequency and the level of EVD anisotropy. The damping rate is determined by collisional absorption of the (instability) wave energy and external (wall) losses. Kinetic instabilities occur when $\gamma > \delta$. In the very beginning of the plasma breakdown, the neutral gas pressure is high and the development of the anisotropy of the EVD is hindered by high inelastic collision rate. The (temporal) transition from the stable to the unstable operating occurs when the anisotropy of the EVD reaches a certain level with increasing hot electron density and/or the inelastic collision rate of the electrons becomes too low to dissipate a sufficient fraction of their energy. Hence, the temporal delay between the plasma breakdown and the appearance of the instabilities is determined by the stochastic heating rate of electrons, which is affected by the average gradient of the magnetic field at the resonance (proportional to B_{\min}/B_{ECR} -ratio²), and the neutral gas pressure. The results are consistent

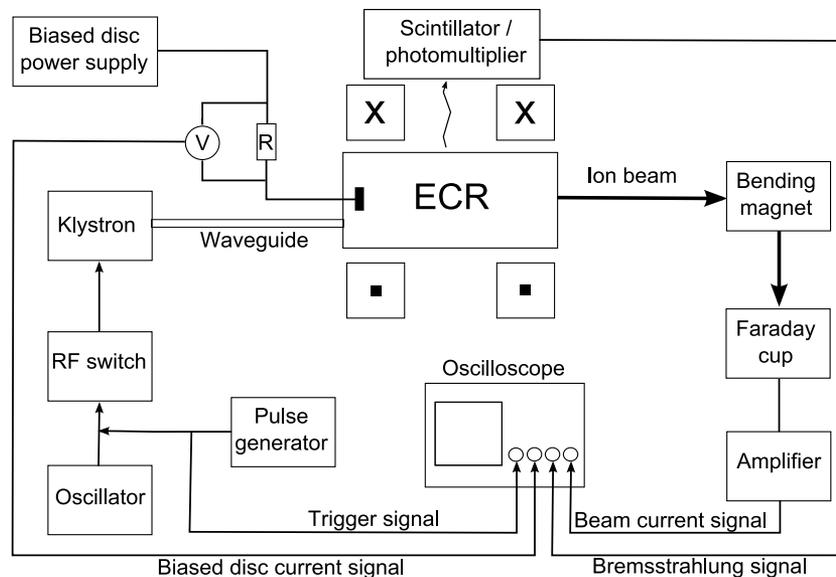


FIG. 2. Schematic presentation of the experimental setup.

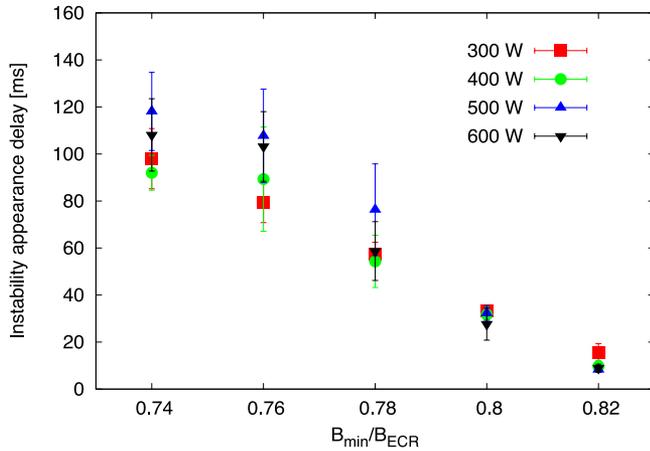


FIG. 4. The delay between plasma breakdown and appearance of the instabilities as a function of the B_{\min}/B_{ECR} -ratio with several microwave powers. The error is calculated as a standard deviation of $N = 20$ samples (microwave pulses).

with earlier studies^{7,8} demonstrating, through diagnostics of bremsstrahlung emission and diamagnetism, that the magnetic field strength is the dominant factor defining the ECRIS plasma energy content and that it takes on the order of 10–100 ms to develop the hot electron population in terms of density and maximum energy.

Finally, it is demonstrated in Fig. 5, showing the beam current signals of O^{6+} recorded in pulsed operating mode (10 kV extraction voltage), that kinetic instabilities limit the high charge state ion beam production in the unstable operation regime. The data obtained in stable regime ($B_{\min}/B_{\text{ECR}} = 0.68$) show that the steady-state beam current of approximately $160 \mu\text{A}$ is reached in ~ 60 ms. In unstable regime with $B_{\min}/B_{\text{ECR}} = 0.74$, the instabilities appear at 96 ms (marked by vertical line) and cause the beam current to drop significantly from the value of approximately $190 \mu\text{A}$, reached within the first ~ 60 ms. Increasing the B_{\min}/B_{ECR} -ratio to 0.8 causes the instabilities to appear at 23 ms, i.e., the beam current never reaches a saturation value. The exact delay between the plasma breakdown and the appearance of the instabilities varies slightly from pulse to pulse. In the given example, the standard deviation ($N = 20$ samples) for $B_{\min}/B_{\text{ECR}} = 0.74$ and $B_{\min}/B_{\text{ECR}} = 0.8$ is 13 ms and 2 ms, respectively. As soon as the kinetic instabilities appear, the average current remains only moderate and fluctuates significantly. The fluctuation is periodic with a repetition rate of 320–360 Hz ($B_{\min}/B_{\text{ECR}} = 0.74$)/1.4–1.9 kHz ($B_{\min}/B_{\text{ECR}} = 0.8$). The data in Fig. 5 support the conclusion² that kinetic instabilities limit

TABLE I. The delay between plasma breakdown and appearance of the instabilities at different neutral gas pressures and microwave powers with $B_{\min}/B_{\text{ECR}} = 0.8$.

Pressure (mbar)	$2.5 \cdot 10^{-7}$	$4.1 \cdot 10^{-7}$	$6.0 \cdot 10^{-7}$
Delay (ms) (400 W)	32 ± 3	56 ± 10	79 ± 20
Delay (ms) (600 W)	28 ± 7	58 ± 13	74 ± 22

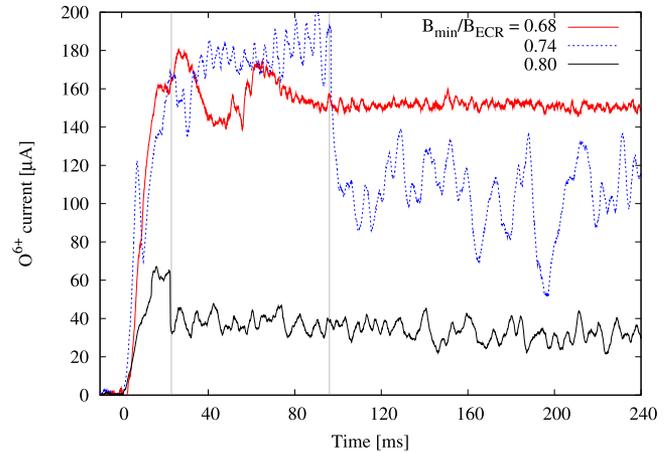


FIG. 5. O^{6+} ion beam current measured at different B_{\min}/B_{ECR} -ratios (400 W/ $2.5 \cdot 10^{-7}$ mbar). Microwave pulse is applied at $t = 0$. The data obtained at $B_{\min}/B_{\text{ECR}} = 0.68$ represent stable operating regime. Instabilities appear at 96 ms for $B_{\min}/B_{\text{ECR}} = 0.74$ and at 23 ms for $B_{\min}/B_{\text{ECR}} = 0.80$ (marked with vertical lines). The appearance of the instabilities was observed by detecting bursts of bremsstrahlung.

the parameter space available for the optimization of high charge state currents extracted from ECR ion sources. Due to the instabilities, the optimum B_{\min} -field in single frequency heating mode is often $\leq 0.8B_{\text{ECR}}$ (see Fig. 1), which is the value suggested by the semiempirical scaling laws guiding the design of modern ECRISs.

ACKNOWLEDGMENTS

This work has been supported by the EU 7th framework program Integrating Activities—Transnational Access, Project No. 262010 (ENSAR), and the Academy of Finland under the Finnish Centre of Excellence Program 2012–2017 (Nuclear and Accelerator Based Physics Research at JYFL) and researcher mobility Grant Nos. 285999 and 285895.

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