ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-TUD1

TIME-RESOLVED MEASUREMENT OF ION BEAM ENERGY SPREAD VARIATION DUE TO KINETIC PLASMA INSTABILITIES IN CW AND PULSED OPERATION OF AN ECRIS

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Abstract

The energy spread of ion beams extracted from Electron Cyclotron Resonance (ECR) ion sources is influenced by plasma conditions such as the plasma potential, and effects taking place in the beam formation region. Kinetic plasma instabilities have a significant impact on the plasma properties, and consequently on the ion beam energy spread. We present experimental results of time-resolved energy spread behaviour when kinetic plasma instabilities are present in CW and pulsed operation of the JYFL 14 GHz ECR ion source. It is shown that the instability-induced energy spread variation corresponds to a momentary plasma potential increase up to several kV from the steady-state value of 5–30 V. The method for measuring the time-resolved energy spread variation is presented, and the consequences of the energy spread and the underlying plasma potential variation for ECRIS operation are discussed.

INTRODUCTION

Energy spread is a relevant parameter when assessing the quality of ion beams produced with ECR ion sources, both for the beam transmission considerations and the eventual application the beam is used for. Recently, a comprehensive simulation and experimental study has been performed to determine the influence of different factors on the energy spread of ion beams extracted from ECR ion sources [1]. The study concludes that with stable plasma conditions the electrostatic focusing effects taking place during beam formation, i.e. extraction geometry and plasma beam boundary, are the dominant factors determining the beam energy spread, and exceed the contributions from magnetic field induced beam rotation, ion temperature and plasma potential.

ECR-plasmas are prone to kinetic instabilities driven by the anisotropy of the electron velocity distribution (see e.g. [2, 3]). The onset of the instability is characterised by a sudden expulsion of electrons from the plasma, resulting in a strong increase in net positive charge in the plasma volume as the heavier and less mobile ions are left behind. As a consequence, the plasma potential experiences a significant momentary (a few μs) increase, until the situation is balanced by the losses of positive ions, which restores the plasma quasi-neutrality. Because the potential has a spatial profile, this leads to a significant increase in the longitudinal energy spread of the extracted beam during the instability event.

The growth rate and broadly speaking the trigger point for the onset of the instabilities is determined by the ratio of the hot and cold electron densities in the plasma [4, 5]. As such, the instabilities can occur both in CW and pulsed operation of ECRIS. In CW operation the plasma heating and confinement leads to build-up of the hot electron population, until a threshold is reached resulting to the instability onset. In pulsed operation, following the switch-off of the plasma heating microwaves, the loss rates of the hot and cold electron populations are different as the plasma decays. The hot electrons are better confined by the magnetic trap compared to the more collisional cold electrons, hence the ratio of hot to cold electrons increases as the plasma decay progresses, eventually leading to the trigger point for the instability [6]. Several instability events can be observed during the plasma decay.

Previous studies [3, 7] have shown that the plasma potential can reach values in excess of 1 kV during a kinetic instability event, i.e. two orders of magnitude higher than the 5–30 V values typically measured in stable plasma conditions [1, 8, 9]. Consequently, in the presence of kinetic instabilities the plasma potential becomes the dominating contributor to the longitudinal energy spread of the extracted beam. As such, temporally resolved measurement of the energy spread allows determining the plasma potential during the instability. A proof-of-principle of this approach has been demonstrated for CW operation in Refs. [3, 7], where the magnetic spectrometer of an ECRIS was utilized as an ion energy analyzer. Here, this work is expanded to pulsed ECRIS operation, studying the properties of the kinetic instabilities during the plasma decay following the microwave switch-off where the instabilities are stronger than in the CW mode.

The following section describes the experimental setup to measure the variations in ion beam energy spread (and plasma potential) during the plasma instabilities. The experimental results section collates the main observations in CW operation from earlier measurement campaigns [3, 7],

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and complements them with new results in pulsed operation with varied ECRIS magnetic field. Finally, the results and their implications for ECRIS operation are discussed.

EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup to study the ion beam energy spread variation in pulsed operation is presented in Fig. 1. All measurements presented in this paper were performed on the JYFL 14 GHz ECR ion source [10]. A dedicated computer was used to control the measurement procedure and for data acquisition through a Picoscope 5000-series digital oscilloscope. The computer communicates with the signal generator driving the klystron to control the microwave pulse pattern. The klystron output power monitoring signal is used to trigger and synchronize the data acquisition to the trailing edge of the microwave pulse. The computer also controls the power supply of the dipole magnet to vary the dipole B field, which was monitored with a Hall probe. The beam current downstream from the dipole was measured with a Faraday cup through a SRS SR570 transimpedance amplifier (TIA). The ion source potential was monitored with a high voltage probe to ensure it doesn't vary during the measurement.

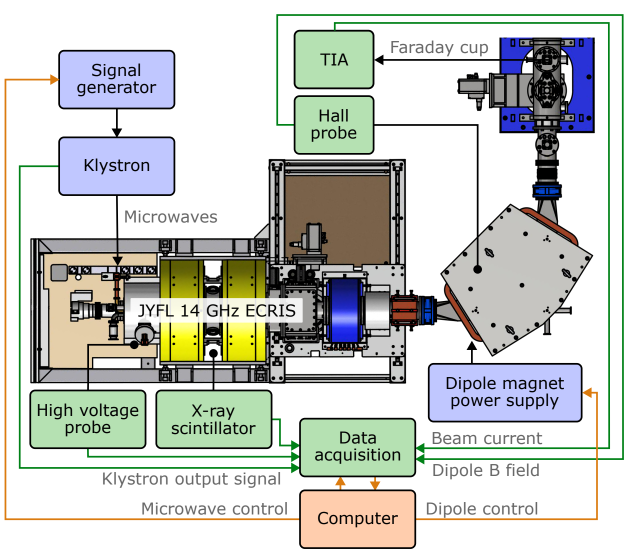

Figure 1: A schematic of the experimental setup.

A BGO x-ray scintillator coupled with a photomultiplier tube was used to monitor the x-ray emissions from the ion source plasma. Sudden bursts of x-rays are a well-established indication of kinetic plasma instabilities [2, 3], and the x-ray diagnostic was used to verify that the observed variations in the beam current during plasma decay are caused by the onset of these intabilities. Figure 2 shows an example of simultaneously measured He^+ beam current and x-ray signal following the microwave switch-off, demonstrating the correlation between the sudden discontinuities in the beam current (a sharp peak followed by a dip as the plasma recovers from the instability) and the instability-induced x-ray bursts.

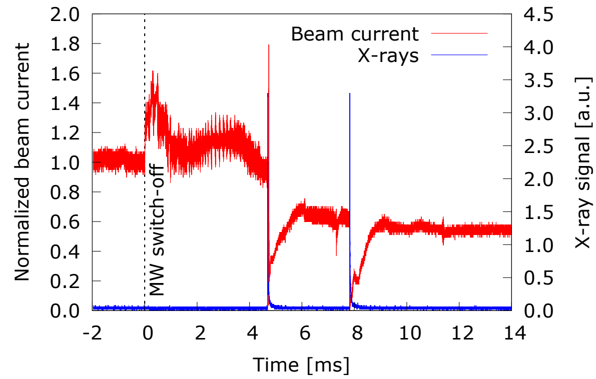

Figure 2: An example of the correlation between the $^4He^+$ beam current and the instability-induced x-ray bursts following the microwave switch-off at $t = 0$.

The measurement procedure is based on recording the temporal evolution of the beam current following the microwave switch-off, i.e. during the plasma decay, at different dipole magnetic fields, effectively scanning the B field region around the magnetic field value that corresponds to the steady-state magnetic rigidity of the ion species of interest. These individual (t, I_{beam}) traces are then combined to create a three dimensional $(t, B_{dipole}, I_{beam})$ colormap plot. This is demonstrated in Fig. 3. The sudden increase of the plasma potential at the onset of a plasma instability event causes a corresponding increase in the energy spread of the extracted ions. As such, the ions of a given species are "spread" momentarily to higher dipole B field values, forming distinct lines in the $(t, B_{dipole}, I_{beam})$ plot, as the dipole magnet acts as an energy analyzer and the timing of the instability events from pulse-to-pulse is very repeatable. The increase in the relative energy spread $\Delta E/E$ can be determined using the dipole field value of the beam before the instability, B_0, and the field value at the maximum extent of the spreading, B_{max}, as $\Delta E/E = \left(B_{max}^2 - B_0^2\right)/B_0^2$. It was verified by careful monitoring of the ion source potential that the extraction voltage remains unchanged during the instability event, and thus the increase in the beam energy spread is dictated by the increased plasma potential. As the plasma potential before instability is much lower than the source potential, the increase in plasma potential can be estimated as $\Delta V_p = (\Delta E/E)V_s$, where V_s is the ion source potential. The experimental procedure and data analysis was automated with a custom Python based program [11].

The duration of the instability-induced beam current variations (peaks) observed during the plasma decay in a single temporally resolved current measurement is in the order of microseconds (see subplots (a)-(c) in Fig. 3), which agrees well with the time scales reported also for the CW operation [3, 7]. The delay time from the microwave switch-off to the onset of the instability is very repeatable in consecutive measurements, with variation within ±0.5 ms (see the right side subplot in Fig. 3).

The onset of kinetic instability influences the whole plasma ion population. This gives freedom in choosing

26th Int. Workshop Electron Cyclotron Resonance Ion Sources ECRIS2024, Darmstadt, Germany JACoW Publishing
ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-TUD1

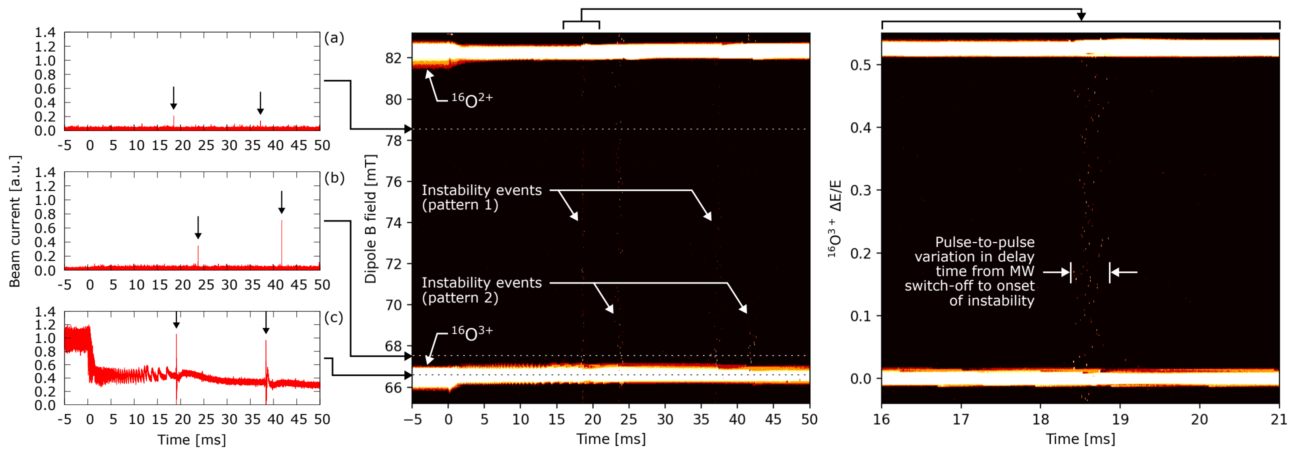

Figure 3: An example of the analysis of $^{16}O^{3+}$ beam with $B_{min}/B_{ECR} = 0.67$ during the first 50 ms of the plasma decay following the microwave switch-off at $t = 0$. Instability events are observed to take place at four discrete times: 18.6 ms, 23.6 ms, 37 ms and 42 ms. These represent a combination of two distinct instability patterns exhibited by the individual plasma decays, as is seen from the individual traces (a)-(c), each of which only show two instability events.

the extracted ion species for the studies. Especially, this provides the possibility to choose such an ion species that is well separated in dipole B field (i.e. in the q/m spectrum of extracted ions) from the neighboring species at higher magnetic field values. This separation can be considered as the most significant challenge of this method. If the beam energy spread increase causes a dipole field shift larger than the separation between consecutive ion species, the beam currents of these species overlap during the instability event, and it is not possible to determine the absolute value of the energy spread increase. In these cases only lower limit estimates for the energy spread increase can be obtained. Such situation is demonstrated in Fig. 3; out of the four observed instability events, only in the last one neighboring ion species do not overlap. This point is especially relevant, if impurity elements are present in the plasma which will further limit the available dipole B field regions. Also, during the instability event the ion optics in the beam line are no longer optimal which does impact the transmission efficiency of ions from the ion source to the Faraday cup.

As previous studies have shown (see e.g. Refs. [2, 3]), the plasma confining magnetic field has a significant impact on the occurrence and characteristics of the kinetic instabilities in CW mode. As such, the pulsed operation results presented here focus on the effect of the ECRIS magnetic field on the instability-induced change observed in the energy spread of extracted ion beams during the plasma decay. The measurements were performed with oxygen plasma (4×10^{-7} mbar plasma-off oxygen partial pressure), 300 W of microwave power pulsed at 1 Hz with 50 % duty factor, −70 V biased disc voltage and 10 kV beam extraction. The magnetic field, characterized with the B_{min}/B_{ECR} ratio, was varied between 0.63 and 0.81. The magnitude of the energy spread increase of $^{16}O^{3+}$ and the corresponding increase in plasma potential were determined, as well as the delay time from the microwave switch-off to the onset of the first plasma instability.

$^{16}O^{3+}$ was chosen instead of $^{16}O^{2+}$ or $^{16}O^{+}$, which would have larger separation in dipole B field, because they would have required lowering the extraction voltage, resulting to worse transport efficiency through the low energy beamline.

EXPERIMENTAL RESULTS

CW Operation

The first temporally resolved results for energy spread and plasma potential variations due to kinetic plasma instabilities, measured with the method described here, were published in Ref. [3] and later expanded in Ref. [7]. In these experiments the energy spread variation was studied with helium, oxygen and argon plasmas. The ECRIS was operated in CW mode with strong solenoid field to drive the plasma into unstable regime. In all cases an increase in energy spread was observed at the onset of kinetic instability. An energy spread increase of up to 15 %, corresponding to plasma potential increase of 1.5 kV at 10 kV source potential, was measured. However, in all studied cases the measured change was limited by the overlap with neighboring ion species in the q/m spectrum, and thus only lower limit estimates were obtained. Regardless, these results show that the magnitude of plasma potential increase during the instabilities can be significant. In addition, an increase in impurities, e.g. carbon, was observed in the q/m spectrum following the instability events. These were attributed to the adsorption/sputtering from the plasma chamber walls by the energetic ions expelled by the increased plasma potential.

Pulsed Operation

The results of the pulsed operation experiments are presented in Fig. 4. Figure 4(a) shows the relative energy spread of $^{16}O^{3+}$, and the corresponding plasma potential, during the instability-induced transient with varied ECRIS magnetic field. Up to $B_{min}/B_{ECR} = 0.74$ the plasma re-

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mains stable during the microwave pulse. In these cases the increase in energy spread during the plasma decay instability is ≥51 %, implying that the plasma potential momentarily reaches values ≥5.1 kV. Unfortunately, these are only lower limit estimates, as the actual values are obscured by the overlap with the adjacent $^{16}O^{2+}$ beam, which was revealed during the offline data reconstruction. With higher B_{min}/B_{ECR} values the plasma becomes unstable already during the microwave pulse, and significantly lower energy spread variations are measured during plasma decay; 15 % (1.5 kV plasma potential) with $B_{min}/B_{ECR} = 0.77$ and 4 % (0.4 kV) with $B_{min}/B_{ECR} = 0.81$. This implies that the instabilities provide a channel for the plasma to expel energy during the microwave pulse, which then mitigates the energy released in instability events during the plasma decay.

Figure 4(b) presents the delay time from microwave switch-off to the occurrence of the first instability event during the plasma decay. It is seen that the delay decreases with increasing B_{min}/B_{ECR} ratio. This behavior agrees with the results obtained from other kinetic instability experiments, where the onset of instabilities has been studied in pulsed operation using x-ray and microwave emissions from the ECRIS plasma [6], and is associated with the increased density and anisotropy of the hot electrons due to enhanced heating with lower magnetic field gradients at higher B_{min}/B_{ECR} values. The fact that the decrease in delay time continues when the plasma becomes unstable during the microwave pulse implies that the instability onset is driven by the ratio of hot to cold electron densities, not the actual plasma energy content.

Multiple consecutive instability events are typically observed during the plasma decay. Furthermore, certain discrete patterns of instability onsets are identified when consecutive microwave pulses are compared. This is seen in Fig. 3, where subplots (a) and (c) show one pattern and subplot (b) a different one. These patterns are combined in the colormap plot, giving the illusion that the plasma exhibits four instabilities during the first 50 ms of the plasma decay, when in reality each individual decay only has two instability events. It was also observed that consecutive events tend to become weaker as the decay progresses, in terms of beam intensity and $\Delta E/E$ variation.

DISCUSSION AND CONCLUSIONS

The experimental results presented here show that kinetic instabilities lead to drastic momentary increase in plasma potential and energy spread of the extracted beam both in CW and pulsed operation of ECRIS. The results obtained so far show that this plasma potential increase can be in excess of 5.1 kV, which is an immense increase from the typical values of some tens of volts measured for stable plasmas. It is emphasized, that this value is still a lower limit estimate for the potential increase, as the actual absolute values still remain elusive due to the overlap issue associated with this measuring technique.

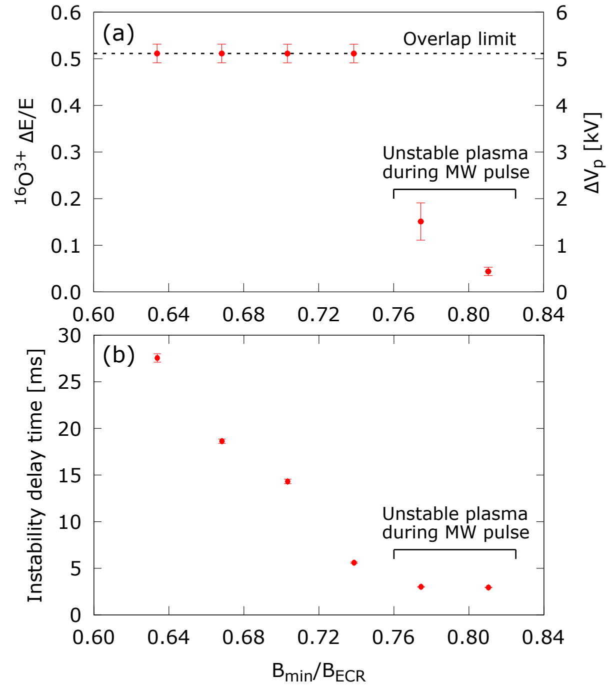

Figure 4: (a) The measured $\Delta E/E$ of $^{16}O^{3+}$ and the corresponding plasma potential increase during instability event with varied ECRIS magnetic field. The dashed horizontal line denotes the maximum $\Delta E/E$ that can be measured until the results are obscured by an overlap with the next ion species. (b) The measured delay time from the microwave switch-off to the appearance of the first instability event during the plasma decay.

The significant increase in plasma potential during the instabilities has consequences for ECRIS operation. Especially in CW operation the instability disturbs the plasma confinement, which consequently disturbs the ion production leading to degraded beam performance, especially for the high charge states. The increased plasma potential also expels high energy ions from the plasma to the chamber walls. This can have at least two undesired consequences; firstly, the flux of energetic ions cause adsorption of impurity elements from the walls, which are then ionized in the plasma, leading to beam impurities. This effect, and the consequent impact on the efficiency of ECRIS charge breeders, has been reported in Refs. [12, 13]. Secondly, the increased sputtering by the energetic ions can lead to chamber erosion. In Ref. [14] structural chamber degradation due to heavy sputtering and metal coating of extraction system insulators was reported following a six month period of pulsed afterglow operation of the GTS-LHC ECRIS with argon plasma. In the experiments presented here instability events were observed in pulsed operation with all ECRIS settings, which implies that these effects can be always present when ECRIS is operated in pulsed mode.

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