STUDIES OF ECRIS ION BEAM FORMATION AND QUALITY AT THE DEPARTMENT OF PHYSICS, UNIVERSITY OF JYVÄSKYLÄ*

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Abstract

During the last couple of years a lot of effort has been put into studies concerning the ion beam formation and beam quality of electron cyclotron resonance ion sources (ECRISs) at the Department of Physics, University of Jyväskylä (JYFL). The effects of microwave frequency fine tuning on the performance of JYFL 14 GHz ECRIS have been studied with multiple experiments in collaboration with INFN-LNS (Instituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud). Also, a number of measurements have been carried out to study the effects of space charge compensation of ion beams on the beam quality. In order to proceed further with these studies, a modified version of the beam potential measurement device developed at LBNL (Lawrence Berkeley National Laboratory) is under development. Simulations are used to study the possibility to improve the beam quality by biasing the beginning of the beam line upstream from m/q separation. With high voltage biasing the beam energy could be increased temporarily over the limit of the injection system of the accelerator. Latest results and current status of these projects will be presented and discussed.

INTRODUCTION

Improving the performance of ion sources is crucial for the future of accelerator facilities. However, increasing the amount of produced ion beam is not enough, as the beam quality determines what fraction of the beam can be utilized by the experiments. In addition, with high beam currents many of the beam quality problems, such as space charge effects, are more pronounced.

At JYFL a significant amount of effort has been put into understanding better the underlying problems of the beam quality, both at the ion source and during the beam transport. The effects of microwave frequency on the phenomena inside the ion source plasma chamber and on the formation of the ion beam and its consequent characteristics have been studied in collaboration with INFN-LNS. The space charge effects play an important role in the high beam current section between the ion source and the analyzing magnet. Possibilities to mitigate these effects have been studied from multiple points of view. One is enhancing the degree of the space charge compensation by decreasing the charge density during the transport by introducing electrons, the other is by altering the beam starting conditions, like energy.

FREQUENCY TUNING

By feeding microwaves into the plasma chamber of an ECR ion source it is possible to excite electromagnetic field structures, or modes, inside the chamber. If the microwave frequency is around 14 GHz, like with JYFL 14 GHz ECRIS, and the chamber has typical ECRIS plasma chamber dimensions, these modes only have separation in the order of some MHz [1]. Thus only a slight change in the feeding frequency can significantly alter the electric field structure inside the plasma chamber. It is not clear how the situation changes when the chamber is filled with plasma. However, if the clear mode structure remains, it should have an influence on the characteristics of the produced ion beam [2].

The measurements were conducted by setting a constant microwave power output and varying the frequency between 14.050 and 14.135 GHz, the normal operation frequency being 14.085 GHz. At the same time, the ion source

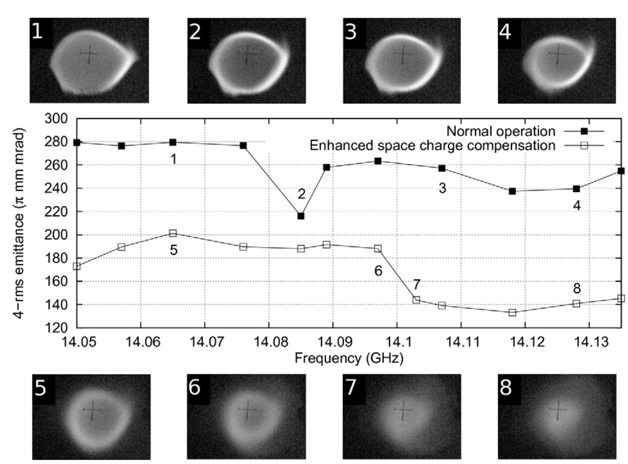

Figure 1: 4-rms emittance of Ar^{9+} with and without enhanced space charge compensation and beam viewer images at selected frequencies.

* Work supported by the Academy of Finland and Nyyssönen foundation. LNS team acknowledges the support of the INFN Strategic Project NTA-HELIOS.

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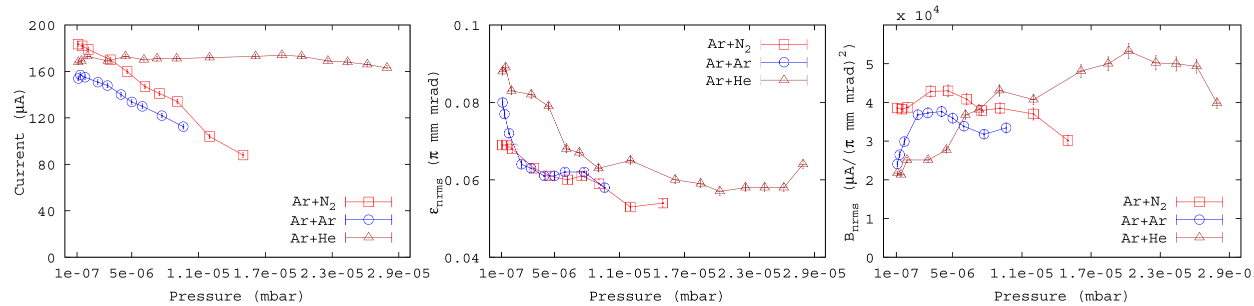

Figure 2: The current, emittance and brightness values of Ar^{8+} as a function of beam line pressure with different gas species injected into the beam line.

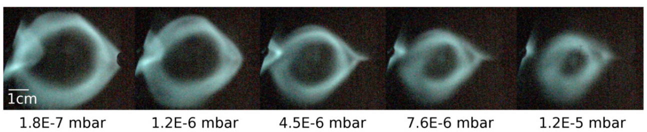

Figure 3: The beam viewer image of Ar^{8+} with various beam line pressures. N_2 as feeding gas. Part of the N^{3+} beam can be seen at the left edge of the viewer plate.

and beam parameters were recorded. In this article the focus is on the beam quality issues. A more complete presentation of the studies can be found in reference [3].

It was observed that the reflected power from the plasma chamber had a clear oscillating behavior which is caused by the wave guide system (see ref. [3]). These oscillating power fluctuations affected the measured beam currents and bremsstrahlung emission, making it difficult to see any underlying phenomena coming from possible mode variations. However, it was observed that the beam emittance exhibited clear variations with varied frequency which did not follow the power fluctuations. These variations correlated with changes in the beam profile and the effects were further strenghtened when additional enhancement of space charge compensation was introduced into the system (see next chapter). An example of the behavior is presented in Fig. 1. These changes in the emittance and profile were reflected in the beam transmission through the injection line and JYFL K-130 cyclotron. Compared to normal operation frequency, relative differencies of up to tens of percent were seen in the transmission efficiency.

SPACE CHARGE COMPENSATION

An extensive series of studies have been performed to study the effects of space charge compensation of ion beams on the beam quality. A more complete presentation of the method and results can be found in reference [4].

Enhancement of space charge compensation was achieved with neutral gas injection into the beam line section between the JYFL 14 GHz ECR ion source and its analyzing magnet. In this section all the ion species produced by the ion source are still present, yielding high total beam currents in the order of a few milliamperes. The ions in the beam interact with the neutral gas atoms and molecules, and the consequent ionization produces slow electrons and ions. The ions are repelled away and the electrons are trapped in the beam potential. The effective charge density of the resulting plasma is lower than the charge density of the original ion beam leading to a decrease in the beam potential. As a result, the radial electric field inside the grounded beam pipe is decreased, which weakens the undesired space charge blow up of the ion beam.

A significant reduction of beam emittance was achieved with this method. The measurements were conducted using helium, nitrogen and argon as feeding gases. With heavier gases (N_2, Ar) the drop of the emittance was steeper with increasing beam line pressure. This is explained with the fact that the ionization cross section in ion-atom collisions increases with the target atom element number [5].

The added neutral gas increases beam losses mainly via charge exchange reactions. It was observed that helium yields the least amount of losses and nitrogen the greatest, argon falling in between. This result is in a good agreement with the theory, which states that the charge exchange cross section decreases with increasing ionization potential [6, 7]. Even though the beam losses increased, the strong decrease in emittance leads to a substantial increase in the beam brightness, which exhibits a clear maximum in the 10^{-6} mbar or low 10^{-5} mbar region. An example of the beam current, emittance and brightness behavior is presented in Fig. 2.

The ion beam profile was measured after the analyzing magnet with a potassium bromide scintillation screen. It was observed that the beam size decreased considerably as the beam line pressure was increased (see Fig. 3). This is a strong indication of the enhancement of space charge compensation. As a further indication of this, no clear emittance decrease was seen when the gas was injected into the beam line section downstream from the analyzing magnet, where the beam current is significantly lower and the space charge effects much weaker. Measurements were conducted with varying ECRIS parameters and tunings, excluding the possibility that the observed phenomena originate from the ion source.

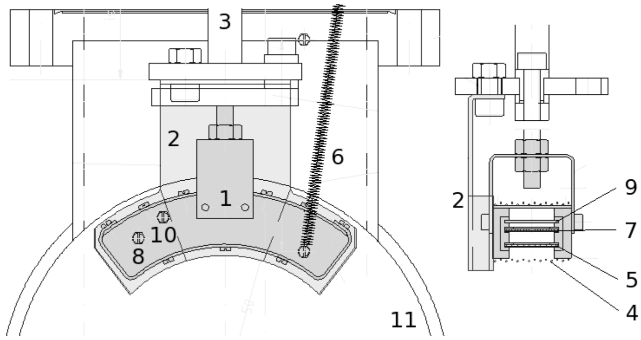

Figure 4: Schematics of the beam potential device. The device (1) is protected from primary beam ions with a cover plate (2) and can be retracted with a pneumatic actuator (3). (4) is the isolation mesh, (5), (7) and (9) are the retardation mesh, bias mesh and current reading plate with feedthroughs (6), (8) and (10). (11) is the vacuum chamber walls.

The improvement on the beam quality led to higher transmission efficiency through the injection line and the JYFL K-130 cyclotron. Unfortunately, because of the increased beam losses, this method does not offer a significant increase in the current of accelerated ion beam. If the beam losses can be decreased, these studies show that enhancement of space charge compensation can be a powerful tool to improve the quality of heavy ion beams on a practical level. Current studies aim to introduce compensating electrons into the beam line using other methods than gas feeding.

Beam Potential Measurement Device

In order to better quantify the changes in the space charge compensation, a device capable of measuring the beam potential is needed. It was decided to construct such an device based on the model developed at the Lawrence Berkeley National Laboratory [8], modified to better suit the beam line configuration at JYFL.

The working principle of the device is based on the determination of the energy of the ions which are produced via ionization of the rest gas. Initially these ions are practically at rest and are accelerated by the beam potential, thus having energy directly proportional to it. The device consists of a series of meshes. The first is used to isolate the device from the beam potential, a retardation voltage is applied to the second and the third is negatively biased to stop electrons. After the third mesh a plate exists for current measurement. The retardation voltage is ramped up linearly as the ion current is measured from the plate. When the current disappears, i.e. no ions reach the plate, the potential of the retardation mesh equals that of the beam potential. A schematic of the device is presented in Fig. 4. The device is constructed and is currently under testing.

HIGH VOLTAGE BIASING OF THE INJECTION LINE

Increasing the extraction voltage of an ion source mitigates the space charge effects, leading to improved beam quality. Also, if the ion source extraction is space charge limited, the increased voltage also leads to increased beam currents. However, the injection structure of the JYFL K-130 cyclotron sets severe limitations to the maximum ion beam energies coming from the ion sources, limiting the typical extraction voltages to values around 10 kV. One possible way to overcome these limitations would be to increase the beam energy only temporarily. The advantages of increased extraction voltages would be acquired at the beginning of the beam line where the beam currents are highest, thus yielding the strongest effects. After the m/q separation the beam would be slowed down making it possible to feed it into the accelerator. This would be done by biasing the first section of the beam line to negative high voltage, creating increased potential difference at the ion source extraction acceleration gap. After the analyzing magnet the beam line would return to ground potential through a lens structure providing additional beam focusing and adjustment.

A set of simulations have been carried out to study the effects of slowing down the beam with a simple cylindrical Einzel lens configuration. The simulations have been carried out with IBSIMU, a three-dimensional simulation software for charged particle optics [9]. The simulations indicate that such a system does not significantly increase the beam emittance or distort the beam shape. These results make this approach for beam quality improvement very promising. However, more studies are still needed to cover all aspects of the project.

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