THE BERKELEY 88-INCH CYCLOTRON INJECTOR SYSTEM

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Abstract

The 88-Inch Cyclotron is a sector-focused cyclotron fed by two Electron Cyclotron Resonance (ECR) high-charge-state ion sources, the double-frequency (14 GHz and 10 GHz) driven AECR-U and the 6.4 GHz LBL ECR ion sources. The two high performance ECR ion sources enable the 88-Inch Cyclotron to accelerate beams of ions as light as hydrogen and as heavy as uranium. Record high charge states and beam intensities are provided by the AECR-U ion source.

However, for the search of new super-heavy elements in low cross section experiments even higher ion beam intensities are required. Therefore, we are concentrating our effort to improve the beam line transmission of our current injection system. Systematic ion beam emittance measurements of the AECR-U injector ion source were performed in order to create a consistent set of data, which can be used for the ion beam simulations. The measured values were used as input for ion optics simulations of the injection line.

These studies are also of importance for the new ultra-high field superconducting ECR ion source VENUS, which is currently under construction [1].

1 INJECTOR ION SOURCES

A detailed description of the two 88-Inch Cyclotron ECR injector ion sources can be found elsewhere [2,3]. The LBL ECR (6.4 GHz) was built in 1982 and is mainly used for light and medium charge state heavy ion beams. The AECR-U (14 and 10 GHz) is used for the more challenging beams: intense medium (e.g. Kr^{19+}) and low intensity high charge state heavy ion beams (e.g. Xe^{38+}, Bi^{41+}). Therefore, this paper focuses on the injection line of the AECR-U ion source.

1.1 The AECR-U Ion Source Performance

The AECR-U ion source started operation in 1990, but was substantially upgraded to the current AECR-U in 1996 [4]. Microwaves of two frequencies, 14 and 10 GHz drive the AECR-U plasma. Six radial slots provide additional pumping of the plasma chamber, which improves the stability and high charge state performance of the ion source. The radial slots also provide easy oven access to the plasma chamber. Up to three different metal ions can be produced with the AECR-U at the same time with two different oven types. Table 1 lists some of the high charge state ion beams produced by the AECR-U ion source. The highest charge state accelerated with the 88-Inch Cyclotron was U^{64+}, which is the highest charge state ion extracted from an ECR ion source world-wide [4].

Ion	I[eμA]	Ion	I[eμA]
Ar^{13+}	120	Ca^{11+}	225
Ne^{6+}	260	Ca^{19+}	0.25
Ne^{9+}	110	Co^{13+}	113
Ar^{17+}	2	V^{12+}	90
Ar^{18}	0.12	Au^{36+}	13
Kr^{19+}	75	Au^{46+}	1
Kr^{28+}	2	Bi^{25+}	85
Xe^{26+}	51	Bi^{50+}	0.15
Xe^{36+}	1	U^{31+}	25
Xe^{38+}	0.25	U^{50+}	0.5

Table 1. A few high charge state ion beams produced by the LBNL AECR-U (currents measured after the analyzing magnet).

2 THE AECR ION SOURCE HORIZONTAL AND AXIAL CYCLOTRON INJECTION LINE

A layout of the horizontal and axial injection line is shown in Fig. 1. The source has an accel-decel extraction system and normally operates between 10 and up to 15 kV extraction voltage, with the puller electrode up to –8 kV (source–puller distance 3.4 cm).

The first Glaser lens (magnetic solenoid with iron return yoke) focuses the ion beam through the first slits into a Faraday cup. After the first Faraday cup, a set of 6 attenuation meshes allows attenuation of the beam for tuning purposes of the beam lines after the cyclotron. The 6 meshes have attenuation factors of about 2, 4, 11, 150, 400 and 800. Any combination of these meshes can be inserted in the beam line. The beam emittance is somewhat effected by the attenuators and increases about a factor of 2 when an attenuator is inserted.

A 90-degree bend magnet analyzes and refocuses the ion beam through a second set of slits on to the second Faraday cup (with a secondary electron suppression of -150V). The 90-degree bending magnet provides a mass resolution of $m/\Delta m=50$ at the typical slit opening of 12mm. It is approximately double focusing with edge angles of 26.6 degrees and has a vertical gap of 76mm. The vertical waist is about 30 cm further downstream from the horizontal waist.

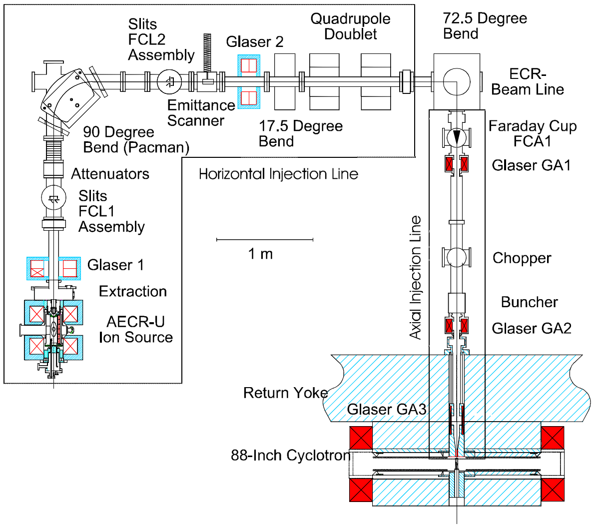

Fig. 1: Layout of the horizontal and axial injection line. The horizontal section is rotated 90º in the Figure.

About 30 cm after the horizontal waist a new emittance scanner device has been installed in order to investigate the ion-optical parameters of the AECR-U injection beam line into the 88-Inch Cyclotron [5]. An electrostatic-deflection-type emittance scanner has been chosen to allow fast on-line measurements while tuning the ion beam through the cyclotron. It allows very fast data sampling (a scan takes between one and two minutes depending on the resolution). The emittance data presented below (see section 3) are measured at the above mentioned location.

After the analyzing system the ion beam is transported through a short matching section for the axial injection line, consisting of a second Glaser lens, a 17.5-degree bend, a quadrupole doublet and a 72.5-degree magnet. Subsequently the axial line consists of three Glaser lenses and a fundamental and first harmonic buncher system. Two electrostatic plates enable chopping (1 µsec rise time) of the cyclotron injection beam. An electrostatic mirror finally bends the ion beam into the cyclotron midplane.

3 EMITTANCE MEASUREMENTS

Systematic ion beam emittance measurements in both the horizontal (xx') and vertical plane (yy') were performed for a wide range of ions [6]. The dependence of the xx' emittance values for helium and charge state distributions of oxygen, krypton and bismuth on the mass to charge ratio M/Q is shown in Fig 2. A similar dependence was measured for the vertical plane. The emittance values for a particular charge state distribution were measured at the same plasma condition, only the settings for the Glaser lens and the analyzing magnet were changed. The emittance decreases systematically with increasing mass. Within a charge state distribution for a particular element the measured emittance decreases for higher charge states.

These results are consistent with the model that highly charged ions are created closer to the center of the ECR plasma, where hot electrons are confined. The low charge state ions can be produced at the outer shell of the ECR plasma and therefore have higher emittance values. This is also in agreement with the observation, that the extracted currents for high charge state ion currents decrease less than the low charge state ions after reduction of the extraction hole diameter [7].

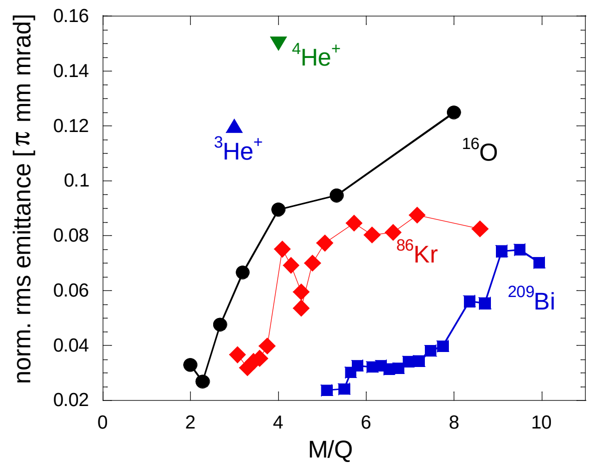

Fig. 2: Comparison of emittance values for different masses and charge states.

The emittance values are approximately independent of current at the medium ion beam intensities as used in Fig. 2 (e.g. 300 eµA of He^{+}, 300 eµA of O^{6+}, 60 eµA of Kr^{19+}, 40 eµA of Bi^{29+}). The predominant factor on the beam emittance is the plasma condition. For instance, the normalized rms emittance values were measured to be .067, 0.64, 0.065, 0.058 π·mm·mrad at total extracted currents of 0.75, 0.86, 1.2 and 2 mA, delivering 10, 52, 108 and 145 eµA of Ar^{9+} at 15 kV extraction voltages. The emittance values changed less than 10% over the mentioned intensity range, the lowest emittance was actually measured at the highest current in this case. On the other hand, the ion beam emittance can easily change a factor of 2 or 3 at comparable ion beam intensity for unstable plasma conditions (see Fig. 3, note the different scales in the x and x' axis). This makes the emittance scanner an extremely useful ion source tuning aid and important step in our goal to improve the overall ion beam transmission. Fig. 3 shows an example of two different ion source tunes of $^{86}Kr^{19+}$ at comparable currents and power levels. The influence of the plasma stability on the ion beam emittance can be clearly seen. The Faraday Cup readings for both tunes are similar, only the emittance measurement indicates the presence of plasma instabilities.

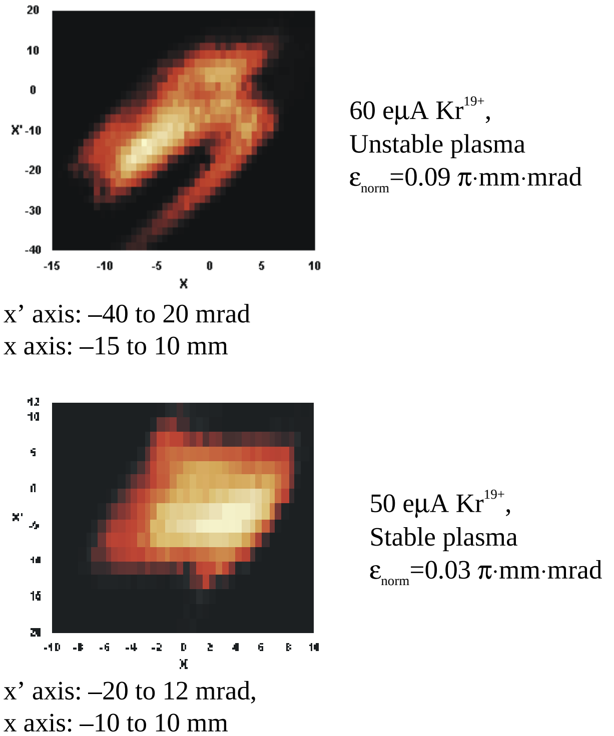

Fig. 3 Measured emittances for two different ion source tunes for high intensity Kr^{19+} beams.

4 INJECTOR LINE OPTICS

With the measured ion beam emittances as input the ion beam optics was investigated. Fig. 4 shows the transverse beam envelope calculated with TRACE3D [8], which includes first order space charge effects. The two most critcal points of the beam line are circled in Fig. 4. At the 72.5 degree magnet the ion beam has to be focused strongly in the vertical plane to achieve a round and small divergence beam after the magnet. This gets more difficult for higher beam intensities. Furthermore, the gap of the bending magnet is too small for the beam size at higher intensities (we are planning to upgrade this magnet). At the entrance of the electrostatic mirror the beam has to be strongly focused to match the cyclotron acceptance. High intensity ion beams become too large inside the last two Glaser lenses. The transmission through the axial line can only be improved at higher injection voltages as demonstrated in Fig. 5. At 15 kV injection energy (current limit for the ion source) the overall transmission through injection line improves up to 30%.

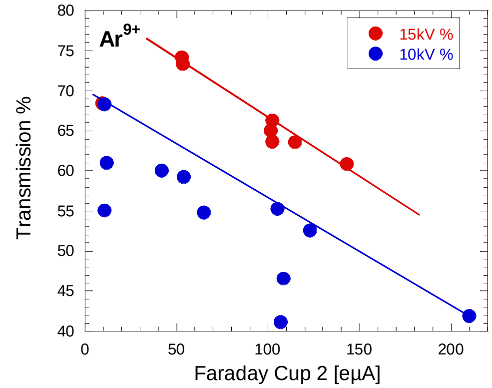

Fig. 5. Ion beam transmission through the cyclotron external injection line for 10 and 15 kV injection energy.

The beam line of the new superconducting source VENUS, which is currently under construction, is being build for up to 40 kV extraction voltages. Studies are currently done to study the ion beam centering in the cyclotron at these higher injection voltages.

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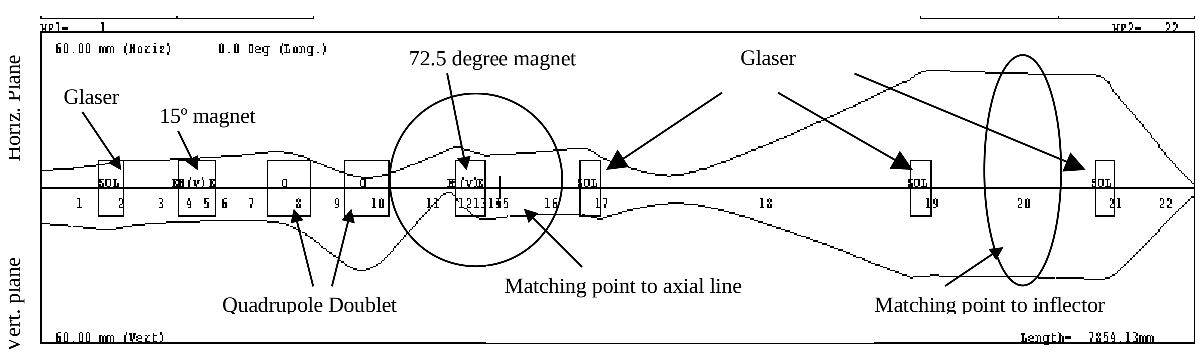

Fig. 4. A 60 eμA Kr^{19+} ion beam envelope through the 88-Inch cyclotron Injection line.