NEW EXTRACTION DESIGN FOR THE JYFL 14 GHz ECRIS*

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Abstract

A new extraction system has been designed and constructed for the JYFL 14 GHz ECRIS at the Department of Physics, University of Jyväskylä (JYFL). The goal of the new design was to improve the performance of the ion source and increase the transmission efficiency of the low energy beam transport and the accelerator by being able to handle higher beam currents, yield better beam quality and offer more tuning flexibility. The design is based on simulations with the IBSimu code. The suitability of the code for this task was verified by simulating the old extraction system resulting to good agreement between simulations and measurements. The new design, simulations and the first experimental results are presented.

INTRODUCTION

In order to improve the "ion source-to-target" performance at JYFL (Department of Physics, University of Jyväskylä), the low energy beam transport (LEBT) section of the beam line from the JYFL 14 GHz ECRIS [1] to the K-130 cyclotron will be upgraded in intermediate steps. The first section of the JYFL LEBT is presented in Fig. 1. Designing and constructing a new extraction system for the JYFL 14 GHz ECRIS is the first step of the project. This upgrade aims to make the ion source extraction more flexible and offer better ion beam starting conditions to facilitate further beam line modifications. Better beam quality and overall performance of the ion source, especially with high extracted total beam currents, are also desired.

SIMULATIONS

The new extraction system was designed by computer simulations with the IBSimu code [2] developed at JYFL. The code is capable of modeling extraction of multiple ion species in the presence of external magnetic field and strong space charge, which are the conditions normally present with ECR ion sources. However, the positive plasma model used by the code does not exactly match the complicated plasma conditions of ECR ion sources, a feature that has proven challenging for simulation codes. To study the feasibility of the code for ECRIS conditions the old extraction geometry was first modeled with IBSimu and the results were compared with measurements.

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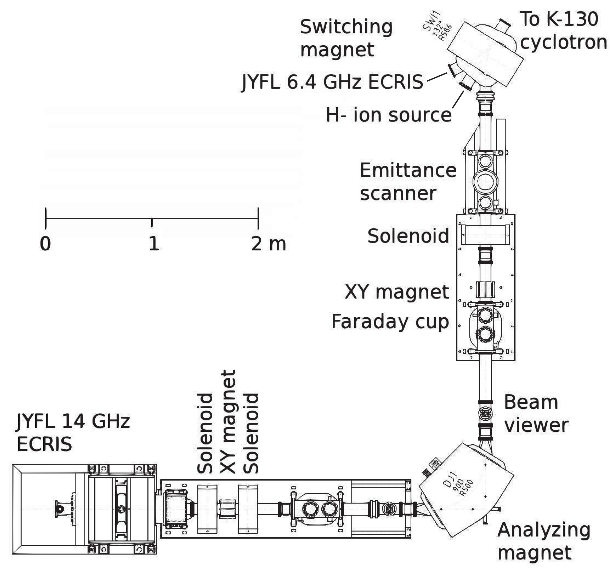

Figure 1: First section of the JYFL LEBT beginning from the JYFL 14 GHz ECRIS.

Old Extraction Design

Figure 2 shows simulation result of the original extraction geometry of the JYFL 14 GHz ECRIS with 1 mA of argon beam and optimum tuning. The beam includes charge states 1+ to 16+ with their ratios taken from measured charge state spectrum. Charge states 17+ and 18+ are omitted due to negligible beam currents. According to the simulations, the extraction system is barely able to handle the extracted beam. The outermost parts of the beam are collimated at the puller face and at the last grounded electrode of the Einzel lens. The beam exiting the extraction ($x = 0.525$ m in Fig. 2) is large, about 65 mm in diameter (FWHM of the profile) and rather divergent with maximum half-axis divergence of about 60 mrad. These values match well with the (64 ± 1) mm diameter and (60 ± 10) mrad half-axis divergence measured at the same location after the extraction with identical settings.

Increasing the current extracted from the plasma increases the simulated beam size due to space charge growth, leading to increased beam losses and a substantial drop in transmission through the extraction region (see Fig. 3). As a consequence, the total beam current leaving the extraction remains roughly constant at the level of $\sim$1 mA but the beam quality and profile are degraded. These results agree well with the experimental observation of degraded beam transmission with high total extracted currents in excess of 1 mA [3]. The collimation of the beam has been

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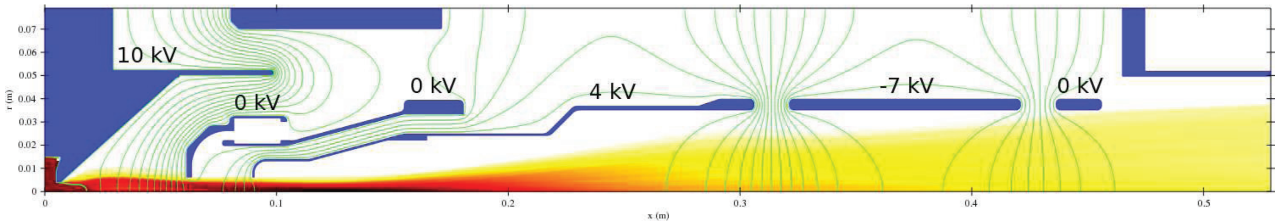

Figure 2: Simulation result (logarithmic trajectory density) for the old extraction system with 1 mA of argon beam, charge states 1+ . . . 16+, tuned for optimum performance. From left to right, plasma electrode (10 kV), puller electrode (0 kV), grounded puller holder, deceleration electrode (4 kV), Einzel electrode (-7 kV) and Einzel ground electrode.

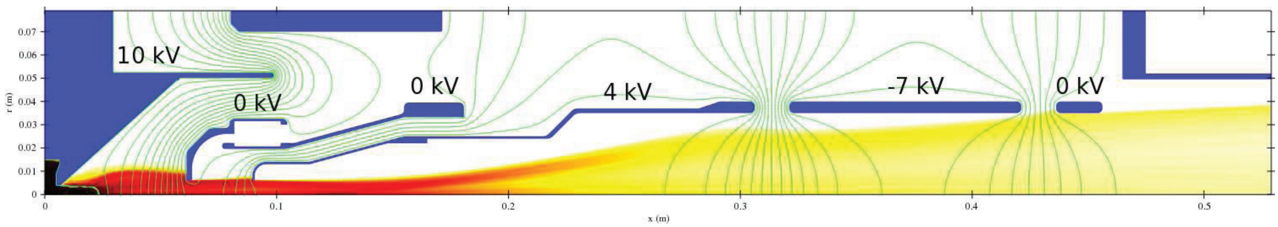

Figure 3: Simulation result for the old extraction system with 3.0 mA of argon beam with same settings as in Fig. 2. Varying electrode voltages shifts beam losses between electrodes, leading no insignificant improvements in the extracted beam.

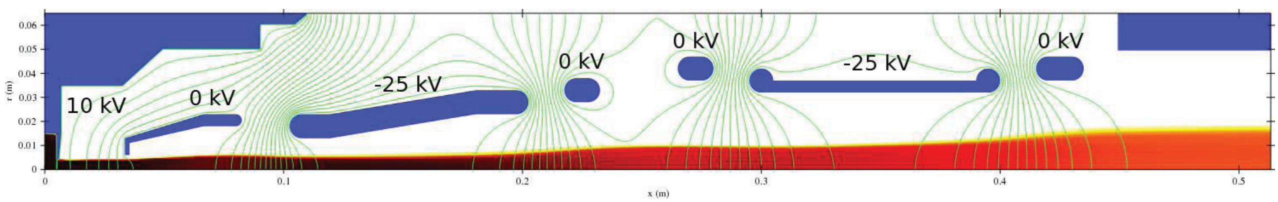

Figure 4: Simulation result for the new extraction system with 1.5 mA of argon beam, charge states 1+ . . . 16+, tuned for optimum performance. From left to right, plasma electrode (10 kV), puller electrode (0 kV), first Einzel (-25 kV), Einzel lens ground electrodes, second Einzel (-25 kV) and Einzel ground electrode.

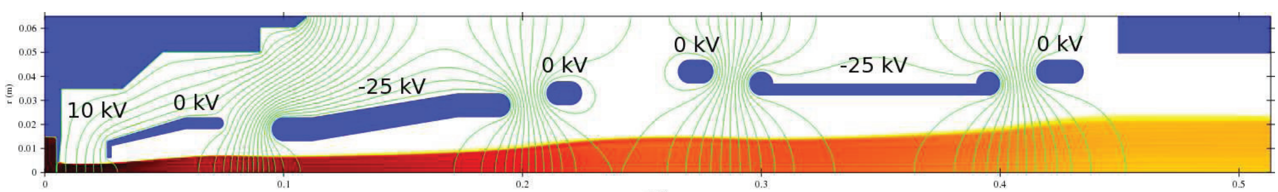

Figure 5: Simulation result for the new extraction system with 3 mA of argon beam with same settings as in Fig. 4.

verified by inspecting the puller face, which shows clear evidence of beam bombardment.

The main limitation of the JYFL 14 GHz ECRIS extraction is the low source potential, normally around 10 kV, dictated by the cyclotron injection. Hence, the beam energies are relatively low and the space charge effects are strong, i.e. slowing the beam further is undesirable. The old extraction design includes a decelerating positive electrode (see Fig. 2), use of which is inevitable in order to achieve reasonable extracted beam currents. However, this leads to emittance growth and decrease of beam quality. Also, the single accelerating Einzel lens, operated at low voltages (below extraction voltage) due to lens geometry limitations (high voltage sparking), can not provide enough focusing power to handle the diverging beam.

In the old extraction geometry the plasma electrode has a strongly conical shape, as shown in Figs. 2 and 3. As a result, the acceleration gap length between the plasma and puller electrodes increases towards the optical axis. This leads to weakening of the electric field at the extraction aperture and subsequent decrease in the Child-Langmuir limit for the maximum space charge limited current.

New Extraction Design

In the new design the decelerating electrode is removed and the beam transport is optimized with two accelerating

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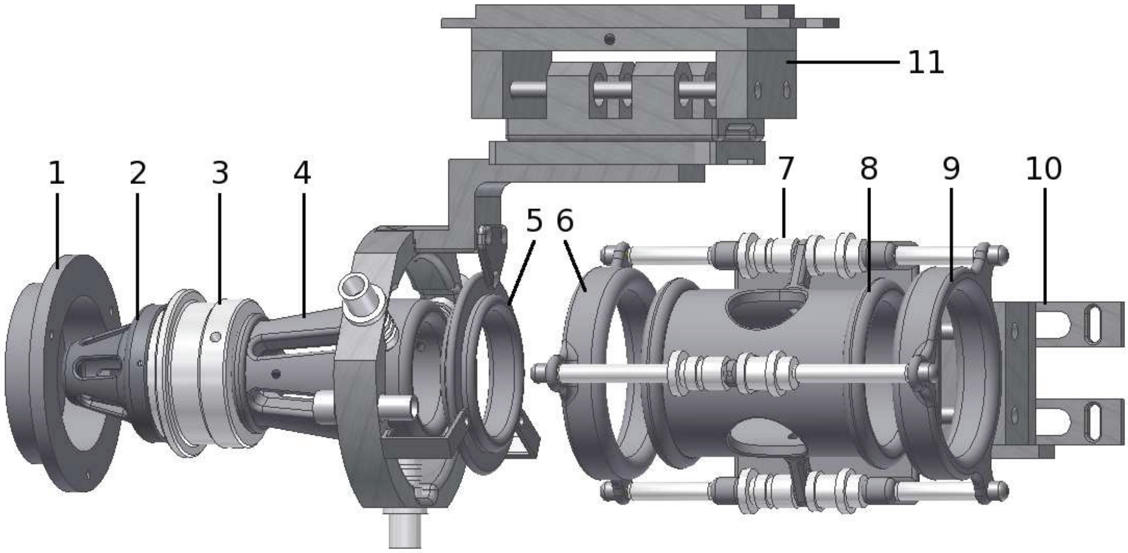

Figure 6: The new extraction system with a plasma electrode (1), a puller electrode (2) and two Einzel lenses (2-5 and 6-9). Macor and alumina are used as insulating materials (e.g. 3, 7). Lense positions can be varied independently (10, 11).

Einzel lenses to provide enough focusing power and flexibility. Accelerating Einzel lenses are more challenging to design than decelerating ones due to higher operating voltages but they offer clear advantage for low energy beams, as the energies of ions passing through the lens are not reduced below their initial values, which would increase the space charge effects. Also, unlike decelerating Einzel lenses, the accelerating ones do not act as electron collectors reducing the space charge compensation degree of the ion beam. Compared to decelerating Einzel lenses, the accelerating ones cause less spherical (smaller beam size inside lens) and chromatic (decreased $\Delta E/E$ inside lens) aberrations [4].

As the flexibility of the extraction system and extracted beam properties are very important features for the future LEBT upgrades, both Einzel lenses were designed to be movable. The puller electrode was designed to be part of the first Einzel lens, replacing the first grounded electrode, to simplify the design and to provide adjustable acceleration gap length.

To improve the electric field structure at the acceleration gap the new design includes an almost flat plasma electrode. To achieve this the extraction aperture position was shifted 12 mm outwards. The magnetic iron ring surrounding the extraction was modified to match the magnetic field maximum at the new aperture location.

Simulation results of the new extraction design for 1.5 mA and 3 mA argon beams are shown in Figures 4 and 5. The results implicate that the new design is capable of handling considerably higher beam currents than the old one and still provide good beam quality and small beam spot size. The beam diameter (FWHM of profile) and maximum half-axis divergence after the extraction (at $x = 0.513$ m in Figs. 4 and 5) are 32.5 mm and 40 mrad for the 1.5 mA case and 45 mm and 60 mrad for the 3 mA case. The performance of the new design with different acceleration voltage was studied by varying the source potential between 8 – 18 kV. Good results were achieved and no notable performance degradation was observed even with highest voltages. The simulations were performed with full space charge (worst case scenario) and the space charge compensation effects were evaluated by altering the total extracted beam current.

Table 1: Transmission results with old and new extraction systems (ES). I_{ECR} and I_{ACC} are beam currents measured after the ECRIS and the cyclotron (in μA), T the transmission efficiency (in %) and $\epsilon_{\text{rms}}^{\text{norm}}$ the normalized 1-rms emittance (in mm mrad).

Beam	ES	I_{ECR}	I_{ACC}	T	$\epsilon_{\text{rms}}^{\text{norm}}$
$^{40}Ar^{8+}$	Old	90	2.3	2.6	0.127 ± 0.004
$^{40}Ar^{8+}$	Old	138	3.1	2.3	0.126 ± 0.004
$^{40}Ar^{8+}$	Old	170	3.6	2.1	0.095 ± 0.003
$^{40}Ar^{8+}$	New	84	3.7	4.4	0.101 ± 0.004
$^{40}Ar^{8+}$	New	102	4.1	4.0	0.097 ± 0.003
$^{40}Ar^{8+}$	New	132	6.0	4.6	0.053 ± 0.002
$^{40}Ar^{8+}$	New	187	7.4	4.0	0.074 ± 0.003
$^{84}Kr^{16+}$	Old	31	1.6	5.0	-
$^{84}Kr^{16+}$	Old	60	2.6	4.3	-
$^{84}Kr^{16+}$	Old	30	1.6	5.3	-
$^{84}Kr^{16+}$	New	40	3.1	7.8	-
$^{84}Kr^{16+}$	New	30	3.1	10.3	-

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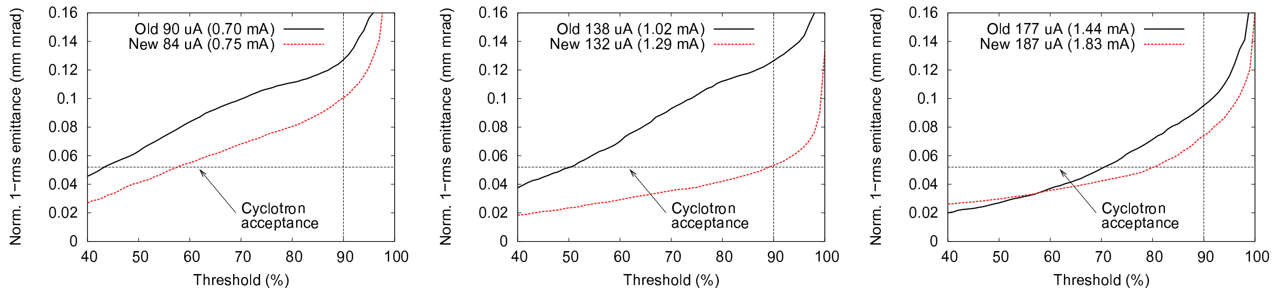

Figure 7: Emittance threshold analysis of $^{40}Ar^{8+}$ for various beam currents. Total extracted current in parenthesis. The 90 % threshold value, used for emittance comparisons, and the K-130 cyclotron acceptance (0.052 mm mrad) are indicated with dashed lines.

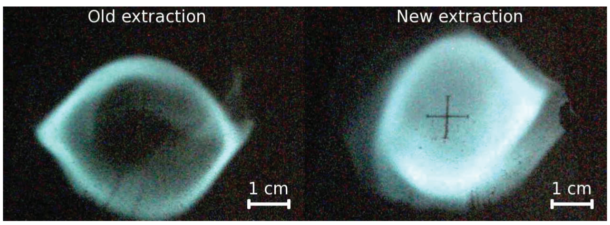

Figure 8: $^{40}Ar^{8+}$ profiles measured after mass separation with old and new extraction designs. Total extracted beam ∼1 mA and mass separated beam current ∼130 μA in both cases.

FIRST RESULTS WITH THE NEW EXTRACTION DESIGN

The mechanical design of the new extraction system is presented in Fig. 6. The performance of the new extraction was tested by running a series of transmission measurements for $^{40}Ar^{8+}$ and $^{84}Kr^{16+}$. The results for both systems are presented in Table 1. For $^{40}Ar^{8+}$ the total transmission through the cyclotron averaged over the data points in Table 1 increased from 2.3 % to 4.2 %. The average transmission of the LEBT increased from 23.0 % to 32.8 % and the transmission of the K-130 cyclotron from 10.0 % to 12.9 %. For $^{84}Kr^{16+}$ the total transmission increased from 4.9 % to 9.0 %. The new extraction yields lower emittance values, as shown in Table 1, indicating better beam quality. The emittance threshold analysis, presented in Fig. 7, shows that with the new extraction a higher fraction of the beam particles are within a given emittance, accounting for the improved transmission.

Figure 8 shows comparison of typical $^{40}Ar^{8+}$ beam profiles measured with KBr scintillation screen after the mass separation (see Fig. 1). The beam profiles measured with the new extraction system tend to be more uniform compared to the beams measured with the old extraction, however still exhibiting some degree of hollowness. This indicates that phenomena outside the extraction region, such as the magnetic solenoid focusing scheme before mass separation and the initial ion disribution extracted from the plasma, still contribute to the hollowness.

DISCUSSION

The new extraction system has been designed, constructed and installed successfully. The first tests and delivered ion beams show improved performance compared to the earlier system. In the presented measurements the optimum performance was achieved with lower Einzel lens voltages than used in the simulations, usually around -10 . . . -15 kV. This can be related to the space charge compensation present in the extraction region, leading to decrease in the required focusing power. Also, the matching of the extraction to the following beam line ion optics plays an important role in determining the lens voltages. As the operation experience increases the matching of the new extraction system to the existing beam line optics is expected to improve, leading to a further improvement in the overall performance of the ion source, LEBT and the cyclotron.

REFERENCES

[1] H. Koivisto, et al., Nucl. Instrum. Meth. Phys. Res. B 174, 379-384 (2001).

[2] T. Kalvas, et al., Rev. Sci. Instrum. 81, 02B703 (2010).

[3] H. Koivisto, et al., Rev. Sci. Instrum. 79, 02A303 (2008).

[4] H. Liebl, Applied Charged Particle Optics, Springer, 2008 (ISBN: 978-3-540-71924-3).

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