COMPARISON OF EXTRACTION AND BEAM TRANSPORT SIMULATIONS WITH EMITTANCE MEASUREMENTS FROM THE ECR ION SOURCE VENUS[*]

D. Winklehner[#], D. Todd, LBNL, Berkeley, CA 94704, USA

D. Grote, LLNL, Livermore, CA 94551, USA

D. Leitner, J. Benitez, M. Strohmeier, LBNL, Berkeley, CA 94704, USA

F. Aumayr, Vienna University of Technology, Vienna, Austria

Abstract

The versatility of ECR (Electron Cyclotron Resonance) ion sources makes them the injector of choice for many heavy ion accelerators. However, the design of the LEBT (Low Energy Beam Transport) systems for these devices is challenging, because it has to be matched for a wide variety of ions. In addition, due to the magnetic confinement fields, the ion density distribution across the extraction aperture is inhomogeneous and charge state dependent. In addition, the ion beam is extracted from a region of high axial magnetic field, which adds a rotational component to the beam. In this paper the development of a simulation model (in particular the initial conditions at the extraction aperture) for ECR ion source beams is described. Extraction from the plasma and transport through the beam line are then simulated with the particle-in-cell code WARP. Simulations of the multispecies beam containing Uranium ions of charge state 18+ to 42+ and oxygen ions extracted from the VENUS ECR ion source are presented and compared to experimentally obtained emittance values.

INTRODUCTION

The superconducting Versatile ECR ion source for NUclear Science (VENUS) [1, 2], was developed as the prototype injector for the Facility for Rare Isotope Beams (FRIB) and as injector ion source for the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory [3, 4]. Like most ECR ion sources VENUS operates in a minimum B field configuration which means that a magnetic sextupolar field for radial confinement is superimposed with a magnetic mirror field for axial confinement. Consequently:

- Ions are extracted out of a region with high axial magnetic field (in VENUS typically 2 T) which then continuously decreases as the ions move along in axial direction, adding a rotational component to the beam.
- Due to the sextupolar field, the total magnetic field inside the source is not rotationally symmetric and thus the spatial distribution of ions at extraction resembles a triangle rather than a circle. This is also confirmed by beam imaging of single- or few-species ion beams (e.g. Figure 1) [4].

Furthermore, the extracted beam often consists of more than 30 different ion species with different mass-to-charge ratios which makes modeling even more complicated. At the moment, several groups are developing versatile extraction codes that are able to handle the complex initial conditions presented by ECR ion source plasmas. The main goals are:

- To better understand the underlying plasma physics that leads to these initial conditions.
- To create a design tool for future ECR injection systems.

The work described here represents the current status of a long-term effort to create a highly adaptable, advanced simulation code utilizing the well-established PIC (particle-in-cell) code WARP [5].

Figure 1: Tantalum imaging of a triangular He$^+$ beam, 80 cm after extraction [4].

Many of the issues regarding the extraction simulation and the beam transport through the beam line have been addressed in earlier work by D. Todd et al. [4, 6] and will be reviewed briefly in the following sections respectively. Results of a Uranium beam simulation using an improved way to obtain the initial conditions will then be presented and compared to emittance measurements.

SIMULATIONS

The simulation of a multispecies ion beam from plasma extraction to the position of the diagnostics box can be divided into three separate simulations (see Figure 2), each employing different simulation methods which are discussed in the following subsections.

Initial Conditions

(See Figure 2, region I: Inside the plasma) The initial particle spatial- and velocity-distributions of each species on the plasma side of the extraction simulation are a vital part of any extraction simulation. These initial conditions are not known for ECR plasmas and are subject to debate. Different approaches exist, including:

- Considering effects within the plasma such as negative potentials forming along the axis which would increase the density of highly charged ions near the axis [7, 8]
- Requiring the ions to be created at points inside the source which a.) exhibit higher or equal magnetic flux density than the extraction region and are b.) connected to the aperture via a field line, along which the ions can travel [9].
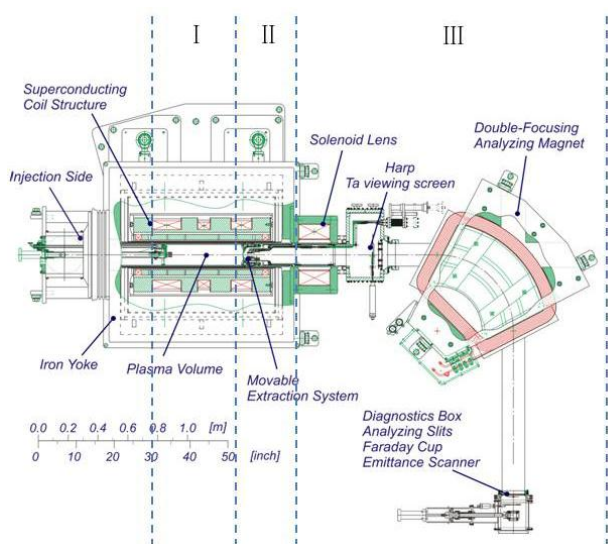

Figure 2: Layout of VENUS and its beam transport system. Initial conditions, extraction simulation and beam line transport correspond to regions I, II and III respectively.

For this work, a semi-empirical approach was taken: VENUS, similar to most ECR ion sources, operates with a negatively biased metal plate (biased disk) on the injection side of the source to enhance the flux of low energy electrons into the plasma. The biased disk is kept at a voltage of -50 V to -100 , thus providing the ions with enough kinetic energy to sputter the surface. As seen in Figure 3, upper left, this disk exhibits two kinds of sputter-marks:

- A large triangular discoloration: Plasma marks which match the magnetic field lines crossing the ECR resonance zone.
- A smaller triangle of about 4 mm height that is etched deeply into the disk and seems to have sharp edges.

The same discoloration can be found on the extraction plate (see Figure 3, upper right) and seeing how the smaller, brighter triangle on the extraction plate fills the

extraction aperture completely, one could presume that ions are extracted evenly distributed over the whole surface of the aperture. This, however, contradicts the triangular beam cross-section image seen in Figure 1 as well as emittance measurements indicating that higher charge states are emitted from a "virtual" extraction aperture of smaller size than the actual one [10]. Clearly, requiring ions to be created on the ECR resonance surface and following field lines to the extraction aperture alone is not enough.
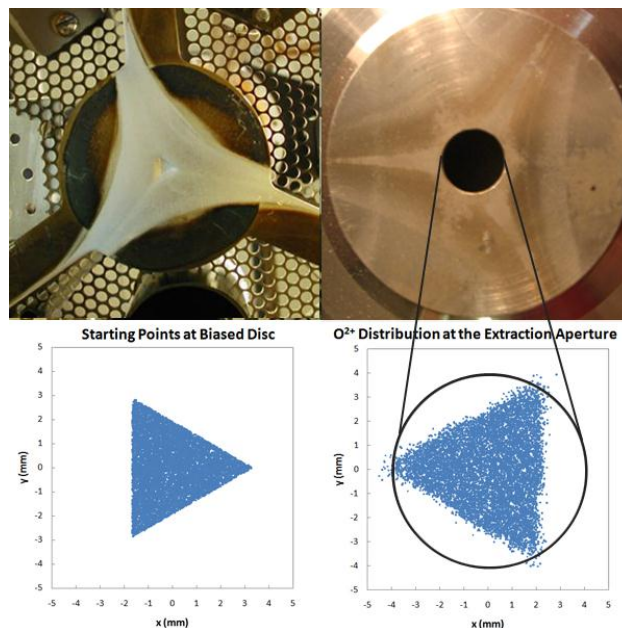

Figure 3: Sputter marks on biased disk (upper left), marks on extraction aperture (upper right), initial particle distribution on biased disk matching sputter marks (lower left) and particle spatial distribution after tracking through the source, shortly before extraction aperture (lower right).

So the small sputtered triangle on the biased disk was examined further. The small triangle's depth and sharp edges indicate a higher ion density near the axis and also give rise to the assumption that "collisions which cause radial diffusion must be a secondary effect between the resonance zone and the biased disk" [6]. Because the ions are cold (a few eV) resulting in small Larmor radii it is reasonable to assume that they mainly follow the magnetic field lines. In addition, there is no reason why the direction towards the biased disk should be preferred, thus it can be argued that a similar ion beam distribution can be found on the extraction side of the source.

The initial (and direct) approach for producing the starting conditions for the sheath extraction simulation was the following: Ions are randomly distributed on a triangle corresponding to the sputtered triangle and given a random velocity corresponding to a Boltzmann distribution with a peak temperature of 2 eV. Subsequently, these ions are tracked through the magnetic field of the source to the extraction aperture by means of a Leapfrog algorithm. Collisions are neglected assuming low plasma

density and small Larmor radii. However, obtaining a statistically relevant number of ~10000 ions per species (~30) is a very time-consuming process and so an alternative (faster) method has been developed.

In this alternate method, particles are still initialized the same way, but instead of tracking them through the source, each particle's respective gyro-motion guiding-centre is calculated and only the field-line originating at that point is tracked through the source. At the respective end-point, an appropriately scaled Larmor radius is applied and the particle is put on a random point on a circle with this scaled radius around the guiding-centre. Because travelling through the source's magnetic field leads to a shift from the ion's transversal velocity to the longitudinal velocity component, velocities are recalculated from the scaled Larmor-radius in the end. As an example, starting points at the biased disk as well as the derived (spatial) initial conditions at the extraction aperture for O^{2+} can be seen in the lower part of Figure 3. Testing both methods against each other with selected ion species showed very good agreement.

One of the limitations of this model for the initial conditions at the plasma interface is that it assumes the same initial spatial distribution of the ions at the bias disk for all charge states. As this assumption might not be valid for the highest charge states the model might need further refinement.

Extraction Simulation

(See Figure 2, region II: The extraction system) WARP includes both a two-dimensional, axially symmetric plasma sheath extraction model similar to IGUN [11] and a three-dimensional sheath extraction model comparable to KOBRA [12]. In order to allow for sufficient resolution at the plasma sheath while keeping the simulation time reasonable, the following two-step approach has been taken:

1. An axially symmetric beam with the same species parameters, currents and energies as the triangular beam is extracted using the two-dimensional model. The beam is tracked through the simulation several times, until a relaxation of the combined potential of applied fields and self-fields has been reached.
2. The obtained potential is stored and used as an applied field in the second step, where the beam is initialized with the obtained triangular particle distributions and the simulation is run in three-dimensional mode.

Previous tests against a full 3D simulation have confirmed the validity of this approach [4].

Beam line Transport Simulation

(See Figure 2, region III: The beam line) Since the longitudinal velocity in the remaining beam line is much higher than the transverse, a two-dimensional Poisson solver can be used to simulate the beam line transport (slice mode). The longitudinal self-fields are neglected but the motion through the three dimensional analyzing magnet fields is simulated [4].

The beam-influencing components in the beam transport simulation are (see Figure 2):

- The solenoid field of the source
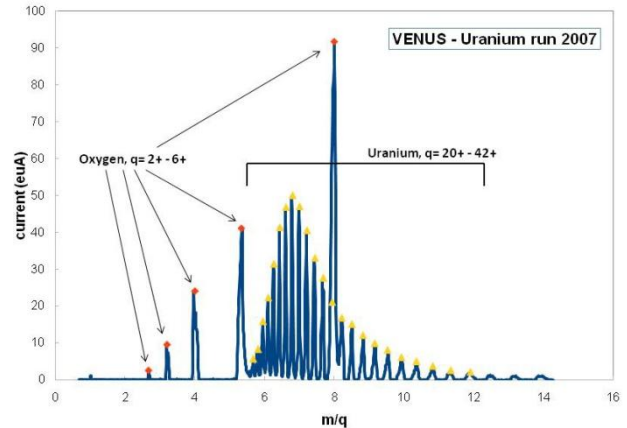- The solenoid lens
- The dipole analyzing magnet

Figure 4: Spectrum of a Uranium beam from VENUS used for the initial species and current distribution in the extraction simulation.

RESULTS

One of the most important beams for FRIB are high intensity medium charge state uranium beams [13]. Uranium beam data from VENUS is thus available and benchmarking this data against simulations is of particular interest. This simulation was run with 28 different ion species, namely Oxygen (as support gas) with charge states 2+ to 6+ and Uranium with charge states 20+ to 42+. The species distribution and respective currents in $e\mu A$ were obtained from the VENUS spectrum which was optimized for U^{35+} as shown in Figure 4. The key initial parameters of the simulation are listed in Table 1. While source and puller voltages, drain current and magnetic fields are known, the other parameters have to be chosen due to the theoretical model of ECR plasmas. Choosing these initial parameters differently can change the simulation and will have to be studied in more detail. The total drain current of 1 mA (as opposed to the measured beam drain current of 1.6 mA) was chosen due to its rather good plasma meniscus and reasonable simulation time and is believed to be close enough to the real current to do a cautious comparison of the results.

Table 1: Initial simulation parameters (E_{kin} is added to the longitudinal Temperature in order to account for pre-sheath acceleration and the current distribution from the spectrum is normalized to the total drain current)

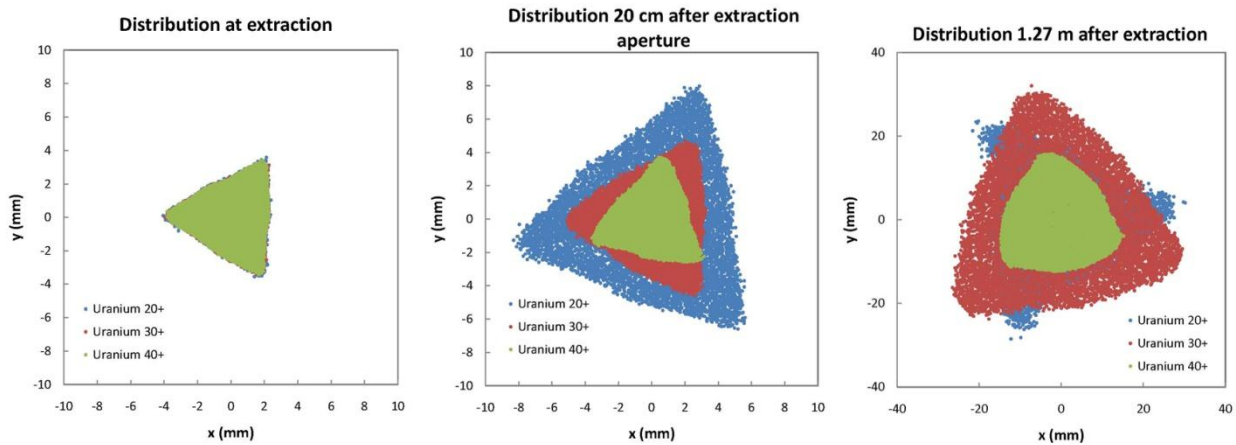| Parameter	Value
Ion mean Temperature	2 eV
Uranium E_{kin} (longitudinal)	~3 eV
Electron Temperature (in sheath)	5 eV
Source Voltage	20 kV
Puller Voltage	-2 kV
Total drain current	1 mA
Max. mag. flux density at extraction	2.1 T

Figure 5: Spatial distributions for U^{20+}, U^{30+} and U^{40+} at the extraction aperture (left), 20 cm after (middle) and 127 cm after (right). Note the different scale for x and y in the last plot, this is the z-position right before the analyzing magnet (the third simulation was done with a neutralization of 70% and the focusing magnet was set for U^{36+}, hence the over-focusing of U^{20+}).

Results from Simulations

The influence of the source solenoid on the extraction end can be seen in Figure 5. The spatial distributions of three different charge states of Uranium (q = 20+, 30+ and 40+) are plotted before extraction and 20 cm after the extraction aperture (where the particles are handed over to the beam line transport simulation) as well as shortly before the dipole magnet. A noticeable difference in rotation and focusing for different charge states can be seen. Emittances for U^{30+} to U^{40+}, both horizontal and vertical, are plotted in Figure 6 for different levels of neutralization due to rest gas ionization in the beam line (0%, 70%, 80% and 90%). Surprisingly it was experimentally observed that although the beam is not pulsed, the extracted ion beams are not fully neutralized [14]. Therefore different neutralization levels were tested in the model.
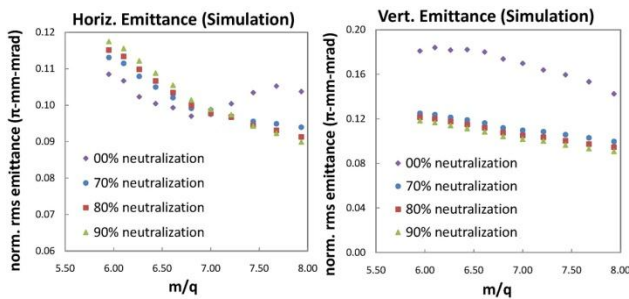

Figure 6: Comparison of horizontal and vertical emittances for U^{20+} to U^{40+} for different neutralization factors.

As expected, Figure 6 generally shows a decrease of emittance with increasing neutralization. The horizontal emittances show additional structures which can't be explained at this moment and will be further investigated.

Comparison to emittance measurements.

The experimental data were taken with Allison type emittance scanners [15] at the position labeled "Diagnos-

tics Box", seen in Figure 2. Figure 7 shows a comparison of U^{36+} phase space plots between experiment and simulation. Though there is no 1:1 resemblance, certain features (like the region of maximum beam current) seem to be reproduced by the simulations and the overall size of the phase space plots is in good agreement.
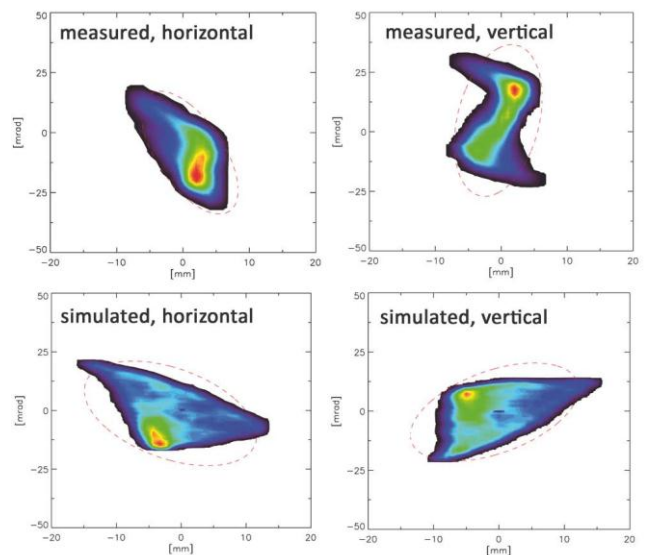

Figure 7: Comparison of U^{36+} phase space plots 3.3 m after extraction and after the analyzing magnet (position of the diagnostics box). The simulation was done with 70% neutralization and optimal focusing for U^{36+}.

Figure 8 shows horizontal and vertical emittances from the simulation compared to measurements. The trend of increasing emittance for decreasing m/q is clearly seen in both simulation and measurement. The overall higher emittances in simulation can be attributed to slightly off initial assumptions about e.g. ion temperature, electron temperature or the radial density distribution of the ions.
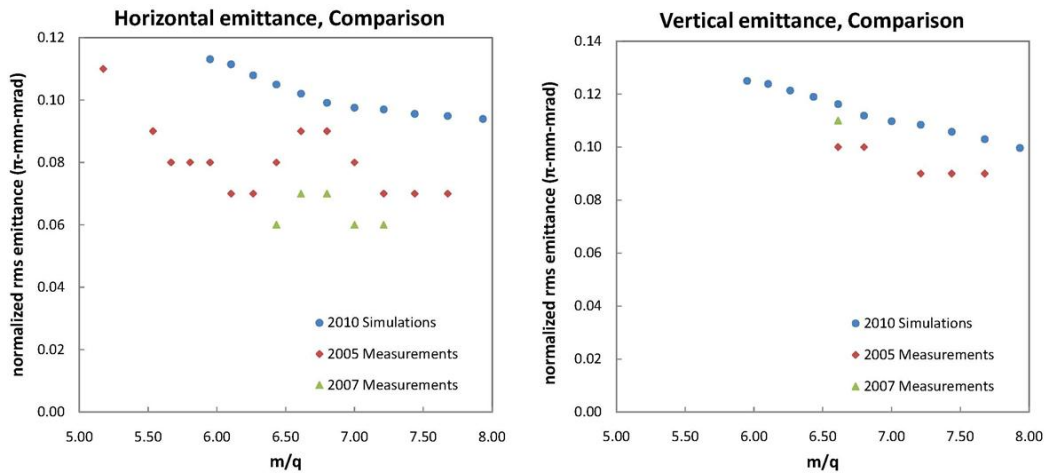
Figure 8: Comparison of emittances for U^{30+} to U^{43+} obtained by simulations and by experiment. Simulations were run with 70% neutralization.

CONCLUSION

The status of the efforts to create an adaptable simulation code for beam extraction from an ECR ion source using WARP has been presented. It is now possible to simulate multispecies beams with more realistic initial particle distributions and a high number of species in 3D mode with a high grid resolution. Emittance values are reproduced within reasonable margins by the simulations. Future work will aim to better understand the physics leading to the initial conditions and beam neutralization.

ACKNOWLEDGEMENTS

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