PLASMA-TO-TARGET WARP SIMULATIONS OF URANIUM BEAMS EXTRACTED FROM VENUS COMPARED TO EMITTANCE MEASUREMENTS AND BEAM IMAGES *

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Abstract

This work presents the latest results of an ongoing effort to simulate the extraction from ECR ion sources and the Low Energy Beam Transport (LEBT). Its aim is to help understand the influence of parameters like initial ion distributions at the extraction aperture, ion temperatures and beam neutralization on the quality of the beam and to provide a design-tool for extraction- and transport-systems. Simulations of multispecies beams (Uranium of charge state 15+ to 42+ and Oxygen) 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" – 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 [5].

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. The work described here represents the current status of a long-term effort to create a highly adaptable, advanced simulation script utilizing the well-established particle-in-cell (PIC) code WARP [6].

SIMULATIONS

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. (e.g. [5, 7]) and will only be reviewed briefly here.

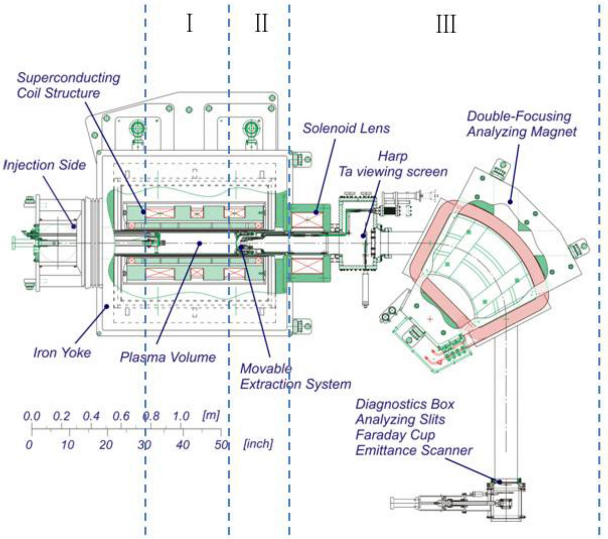

Figure 1: VENUS source and LEBT layout.

Initial Conditions

(See Figure 1, region I: Inside the plasma) For this work, a semi-empirical approach to obtain initial conditions on the plasma side of the extraction simulation was taken: VENUS's biased disk on the far side of the source is kept at a voltage of -50 V to -100V, thus providing the ions with enough kinetic energy to sputter the surface. A triangle with sharp edges was found to be etched into the disk, showing the spatial distribution of the ion beam on the injection side of the source. 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. To obtain the initial conditions the following recipe was used for each species: 10000 ions are randomly distributed on a triangle corresponding to the sputtered triangle and are given a random velocity corresponding to a Boltzmann distribution with a peak temperature of 2 eV. Then, each particle's respective gyro-motion guiding-centre is calculated and 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

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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. A detailed description of the method can be found in [8] and the references therein.

Extraction

(See Figure 1, region II: The extraction system) WARP includes both a two-dimensional, axially symmetric plasma sheath extraction model similar to IGUN [9] and a three-dimensional sheath extraction model comparable to KOBRA [10]. 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 [5].

Beamline Transport

(See Figure 1, 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 [5]. The beam-influencing components in the beam transport simulation are (see Figure 1):

- The solenoid field of the source
- The solenoid lens (Glaser-lens)
- The dipole analyzing magnet

Table 1: Simulation parameters

Parameter	Value	
Total extracted current	1.6 emA	4.6 emA
Ion mean Temperature	2 eV	2 eV
Uranium Ekin (longitudinal)	~3 eV	~3 eV
Electron Temp. (in sheath)	5 eV	5 eV
Source Voltage	20 kV	22 kV
Puller Voltage	-2 kV	-3 kV
Bmax at extraction	2.1 T	2.1 T
Extraction Aperture ↔ Puller	31.5 mm	21.6 mm

RESULTS

One of the most important beams for FRIB are high intensity medium charge state uranium beams [11]. Uranium beam data from VENUS is thus available and benchmarking this data against simulations is of particular interest. Two simulations are compared to each other and to experimental results: 1.6 emA and 4.7 emA total extracted current. The respective species distributions and currents in eμA were calculated from experimentally obtained VENUS spectrums. The key initial parameters of the simulations are listed in Table 1.

Simulation Results

Figure 2 shows a typical horizontal beam envelope plot for a multispecies Uranium beam simulation.

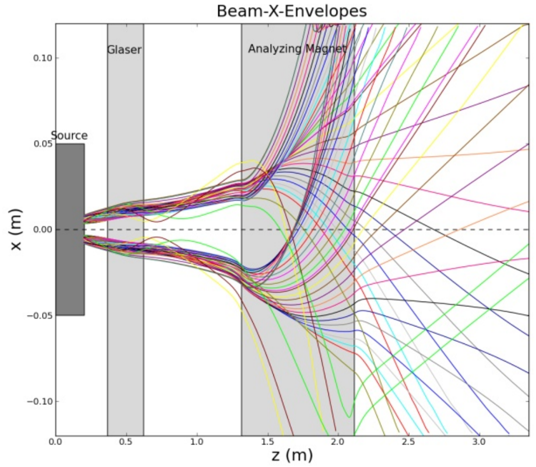

Figure 2: Horizontal beam envelopes (1-rms) of a 4.6 mA Uranium beam, optimized for q = 35+. Note the 'warping' of coordinates to simulate the bend. Different focusing and bending of different species is clearly seen.

Figure 3-Figure 5 show simulation results comparing different neutralization levels and extracted currents. The magnetic emittance displayed for comparison was calculated according to [12] by

$$\varepsilon_{mag}^{xx'-rms-norm} = 0.032 \cdot r^2 \cdot B_0 \cdot \frac{1}{M/Q}.$$

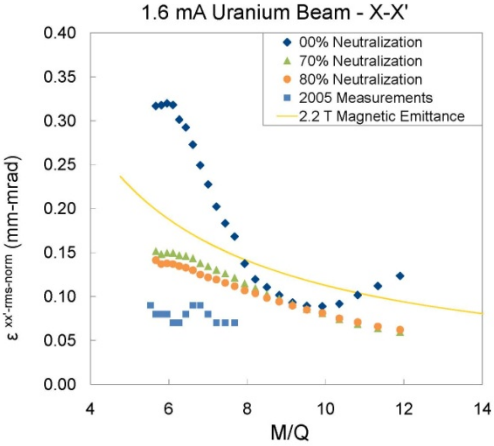

Figure 3: 1.6 mA Uranium run. Comparison of horizontal emittances for different neutralization levels in simulation with a measurement series from 2005.

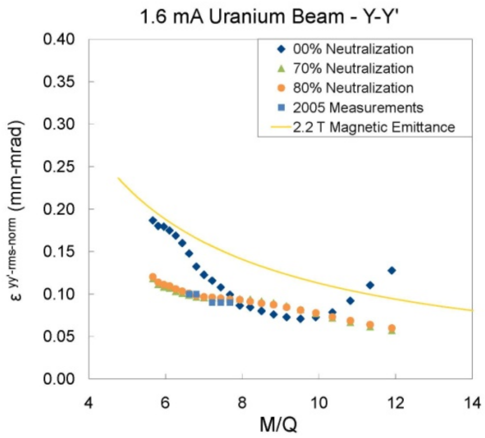

Figure 4: 1.6 mA Uranium run. Comparison of vertical emittances for different neutralization levels with a measurement series from 2005.

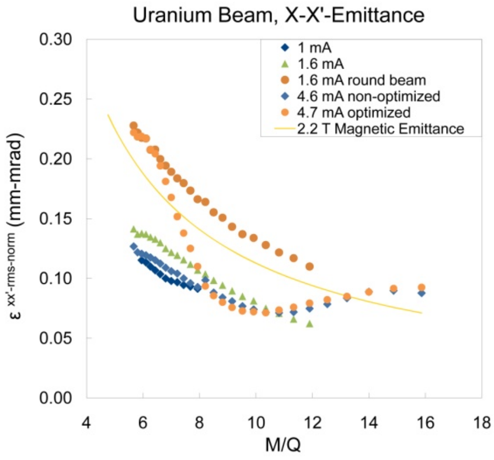

Figure 5: Comparison of horizontal emittances for simulations using different total extracted currents and beam shapes (triangular where not noted otherwise). All simulations were run with 80% neutralization.

Discussion

As seen in Figure 4, the vertical emittances produced by the simulations fit well with the measured values. The offset in horizontal emittance could be a result of one of the following:

- Not all species were included into the 1.6 mA simulation due to computer memory issues,
- For simplification, the size and shape of the initial triangles was set the same for all species.
- Initial conditions like ion and electron temperatures were 'guessed'.

All of the above will be subject to further systematic analysis. In Figure 5, an emittance minimum can be observed in the region of m/q = 9 for the 4.7 mA beam. This might prove useful when it comes to the acceptance of the accelerator subsequent to an ECRIS and will also be investigated further.

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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