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Simulation and beam line experiments for the superconducting ECR ion source VENUS*

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Abstract. The particle-in-cell code Warp has been enhanced to incorporate both two- and three-dimensional sheath extraction models giving Warp the capability of simulating entire ion beam transport systems including the extraction of beams from plasma sources. In this article we describe a method of producing initial ion distributions for plasma extraction simulations in electron cyclotron resonance (ECR) ion sources based on experimentally measured sputtering on the source biased disc. Using this initialization method, we present preliminary results for extraction and transport simulations of an oxygen beam and compare them with experimental beam imaging on a quartz viewing plate for the superconducting ECR ion source VENUS.

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I. Introduction

The superconducting electron cyclotron resonance (ECR) ion source VENUS (Versatile ECR for NUclear Science) and its accompanying transport system were developed as the prototype injector for a next generation rare isotope accelerator in the United States[1]. A crucial part of this research is the development of a highly adaptable, advanced simulation code to serve as a design tool for future sources and accelerators. For this purpose, the established particle-in-cell code Warp[2] was chosen due to its wide-ranging applicability and it has been enhanced with a three-dimensional beam extraction model in order to simulate sheath extraction from asymmetric plasma. This three-dimensional extraction model is a necessary feature as triangular beam cross-sections have been measured immediately after extraction for various ECR sources[3,4]. The triangular beam cross-section arises as a result of ion beam extraction from the ECR plasma's characteristic triangular plasma face. Further complicating both beam simulation and analysis is the fact that the extraction of this triangular beam takes place near the peak of a strong axial magnetic field which falls to zero soon after extraction, introducing rotation to the extracted beam based on ion mass-to-charge ratio. Typical extracted heavy ion beams are composed of upwards of thirty ion species whose effects must be taken into account in simulation.

A brief introduction to the Warp code and the added plasma sheath extraction models is given in the following section. Setting initial conditions for these simulations is crucial, and a novel method of deriving these conditions from experimentally measured sputter marks within the source is described in Section III. Using this initialization procedure to simulate the extraction and transport of an oxygen beam from VENUS, we present preliminary configuration space comparisons between experiment and simulation in Section IV.

II. Extraction Model

The Warp code was originally developed for use in the field of heavy ion fusion where it has been utilized successfully in both the design and analysis of beam transport systems[5]. Since that time the code has been applied to diverse problems such as non-neutral plasmas[6] and electron cloud physics[7]. In recent years Warp has been further enhanced by adding a two-dimensional, axially symmetric plasma sheath extraction simulation allowing Warp to model symmetric extraction systems. This extraction model is based on the work of Self[8] and is similar to the implementation in IGUN[9] against which the Warp plasma sheath model was benchmarked. We have recently also added a three-dimensional sheath extraction model similar to those found in KOBRA[10] and other codes[11]. Both the two- and three-dimensional models assume space charge compensation due to a Boltzmann distribution of electrons. Successive iterations of ion tracking through applied fields while applying the electron distribution's effects leads to an equilibrium solution.

We have benchmarked the three-dimensional sheath extraction simulation against other two-dimensional extraction codes by simulating the extraction of multi-species, axially symmetric beams. However, agreement between the two cases is only achieved when mesh sizes perpendicular to the extraction axis in the three-dimensional case were decreased approximately a factor of five times compared to mesh sizes in the axially symmetric case. This mesh density increase leads to computational arrays that have two orders of magnitude more nodes and are therefore much more memory intensive. Additionally, particle numbers must increase drastically in order to maintain sufficient density statistics on the mesh, and as upwards of thirty ion species are present in a typical ECR-extracted heavy ion beam, memory requirements can grow prohibitively large.

In order to improve both beam statistics and simulation solution time, we have begun exploring a method of using the solved electrostatic potential from an axially symmetric, two-dimensional extraction simulation as an applied field for particle tracking of an asymmetric initial particle distribution. Reasonably good agreement has been found in comparisons of this method with full three-dimensional simulations as only a slight difference in beam size and rotation is found between the two when comparing beam properties shortly after extraction. Therefore we are using this approximation to compare density distributions between experiment and simulation in this paper.

III. Initial Conditions

Any simulation of the extraction of ions across a plasma sheath requires ion initial conditions on the plasma side of the sheath. For ECR plasma, these initial conditions are not known nor even agreed upon in the general case as theories are present in the literature concerning effects within the plasma such as negative potentials on axis and increased density of highly charged ions near the axis[12]. Since no experimental measurement of the distribution at the extraction aperture exists, we have developed a semi-empirical model based on other experimental evidence within the source.

A common starting point for the generation of initial conditions for extraction is magnetic field tracing through the source. ECR ion sources rely on the resonant heating of electrons by microwaves in an applied magnetic field in order to collisionally ionize both neutrals and ions within the plasma. This resonant heating occurs when the electrons cross a closed shell of constant magnetic field magnitude where the electron's cyclotron frequency matches the applied heating microwave's frequency. In the energy range most important to ionization processes (up to 10 keV), electrons inside VENUS are tightly bound to magnetic field lines. When magnetic field lines passing through the resonance zone are traced on field maps from VENUS, these lines can be separated into two categories as shown in Figure 1: those with ends terminating at the axial ends of the source and those with one end terminating on the outer wall of the source. The distribution of field lines that terminate on the extraction aperture is in good agreement with the plasma marks found on the extraction aperture, as can also be seen in Figure 1.

However, when Boltzmann-distributed ions are tracked through the source fields, the constant density distribution across VENUS' 4-mm-radius aperture shown in Figure 2 results and therefore cannot serve as an initial condition capable of producing a triangular beam. It should be noted that a higher density edge is present in the distribution at the aperture shown in Figure 2 though without a larger aperture, this feature would not be seen in beams extracted from VENUS.

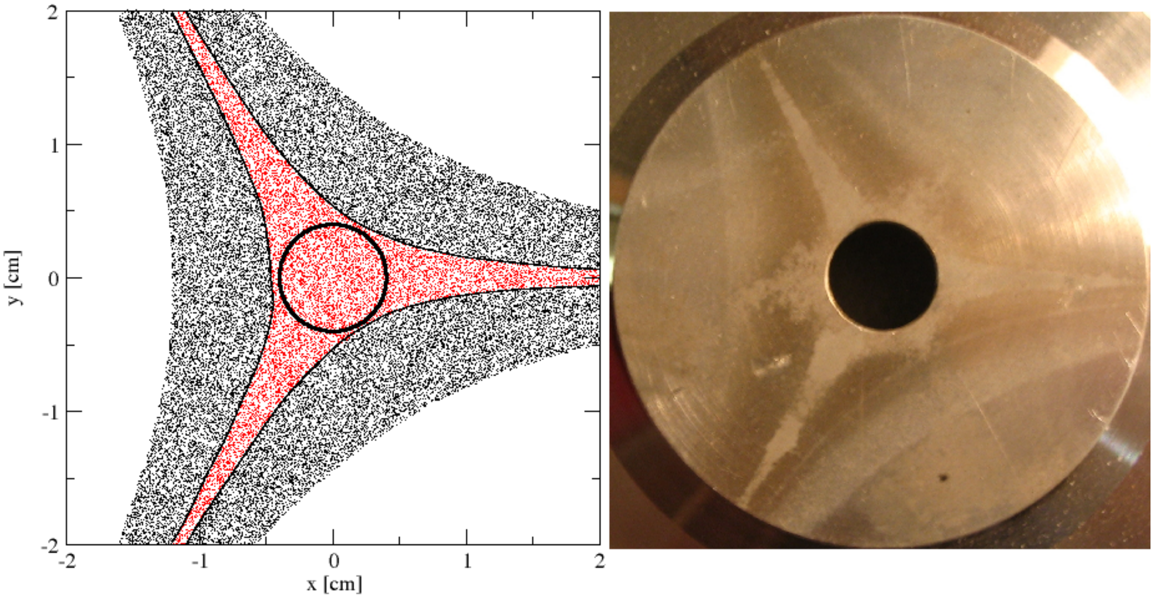

Figure 1. Terminal points on the extraction plane of VENUS magnetic field lines passing through the 28 GHz resonance zone are plotted on the left. Those that terminate on the wall are plotted in black with those terminating on the biased disc at the opposite end of the source in gray. A line separating the two regions has been plotted to aid the eye. A photograph of the VENUS extraction aperture is shown on the right with the same scale. Note that the extraction aperture was rotated 60 degrees and run for a short period resulting in the rotated, lighter markings.

The biased disc is located directly opposite the extraction aperture and it, too, has characteristic plasma marks which reproduce well in simulation. However, in addition to these markings on the VENUS biased disc, another much smaller triangle is present that is deeply etched into the disc as shown in Figure 3. This triangle has approximately a 4 mm height, has very sharp edges, and has what appears to be a constant depth. Under normal operation in the VENUS source, the biased disc is kept in the range of -50 to -100 volts, and this voltage is sufficient to provide plasma ions with enough kinetic energy to sputter the biased disc's aluminum surface. Similar triangle etching can be found in all ECR sources with biased discs.

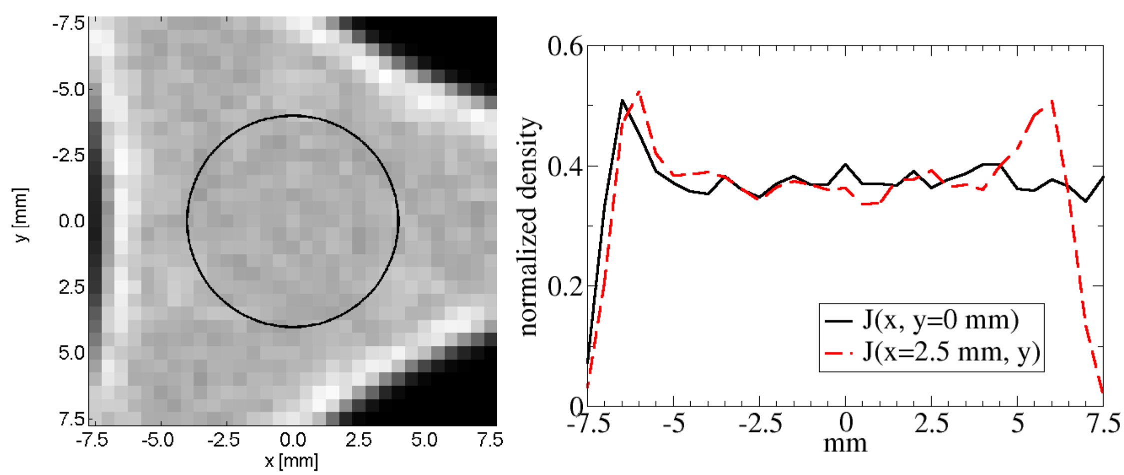

Figure 2. Simulated particle density at the extraction plane, left, and two line scans, right. The size of the VENUS extraction aperture is plotted for reference.

Though the reason for the triangular shape of the sputtered mark on the disc must be due to the applied magnetic fields, its size is not well-understood at present. However, this mark's depth and sharp edges indicates that there is a distinct difference between the sputtering ions and those responsible for the plasma marks on the remainder of the biased disc and the extraction aperture. This sharp edge further indicates that collisions which cause radial diffusion must be a secondary effect between the resonance zone and the biased disc. Therefore, we assume that part of the population of ions that sputters the biased disc is moving in the opposite direction, toward the extraction electrode, and follows field lines in this direction with little scattering as well. Tracing magnetic field lines from the etched triangle on the biased disc in VENUS produces a triangular distribution at the extraction electrode which is smaller than the electrode aperture, as shown in Figure 3. Ions traveling along these field lines, then, would be expected to produce beams with triangular cross-sections, as observed experimentally.

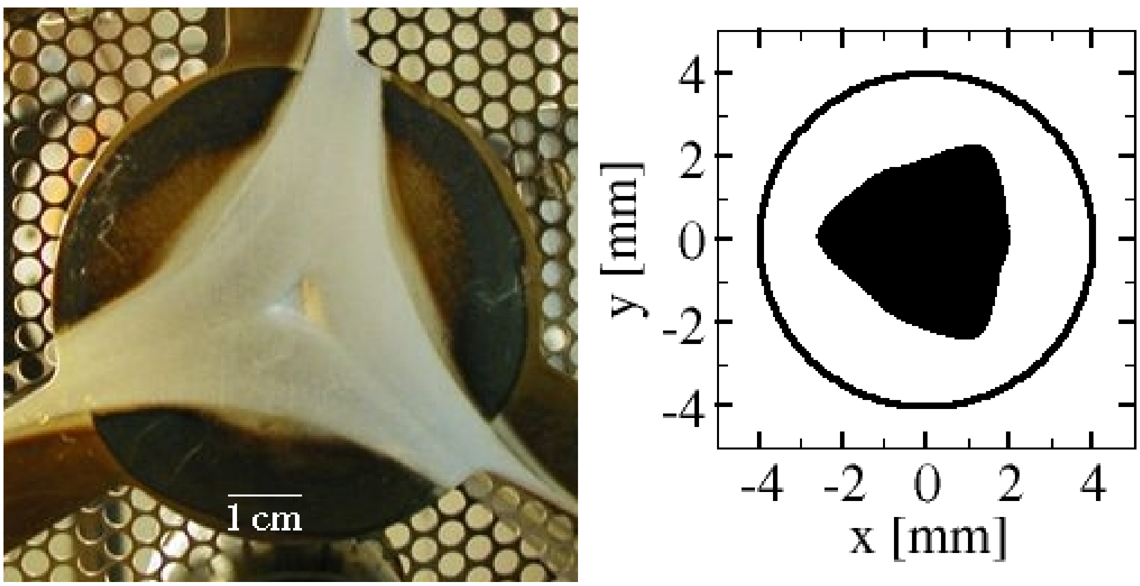

Figure 3. Characteristic plasma markings are found on the biased discs of the VENUS. Field line tracing from this triangular mark to the extraction aperture gives a distribution that easily passes through the 4-mm-radius aperture, as shown on the right.

In order produce an initial distribution for simulation from the bias disc sputtering, we initialize a constant density of ions in a triangle at the biased disc with a Boltzmann energy distribution. The ions are then tracked, without collision, through the applied magnetic field to near the extraction aperture and serve as an initial distribution for the sheath extraction model.

IV. Experimental Comparision

Using this initial distribution for extraction and transport we have performed a simulation of a 3.4 mA oxygen beam extracted from VENUS. In order to compare simulation with experiment, we have installed a quartz viewing screen 2.2 m after the transport system's analyzing dipole and 3.9 m after extraction. The only other optical element in the system is a solenoid lens located before the dipole and centered 0.49 m after extraction.

The plots in Figure 4 show the images of the 293 μA O^{7+} beam as seen on the quartz viewing screen. Next to this plot in Figure 3 is a current density plot from simulation. Both the simulation and experimentally measured beams have near-constant densities across their bulk, however the simulated beam is considerably larger than the experimentally measured beam.

In addition to oxygen, some residual carbon was present in the extracted beam. Figure 5 shows experimental and simulation results for the 86 μA of C^{4+}. For this beam the experimental beam has a hollow distribution and this is replicated in the simulation even though the simulation was started from a constant density, triangular distribution.

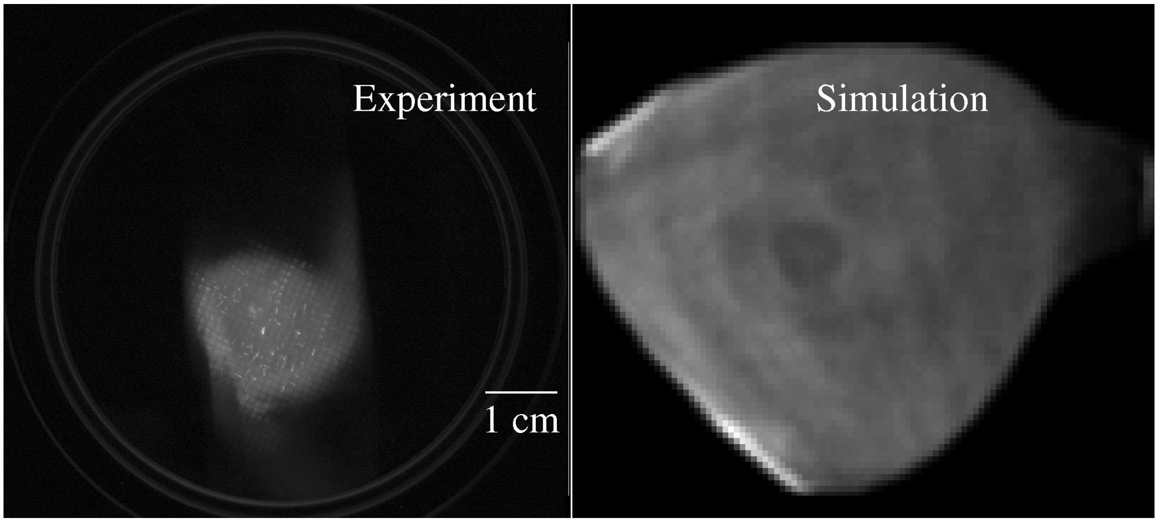

Figure 4. Experimentally imaged O^{7+} beam, left, and the intensity plot from simulation on the right plotted on the same scale.

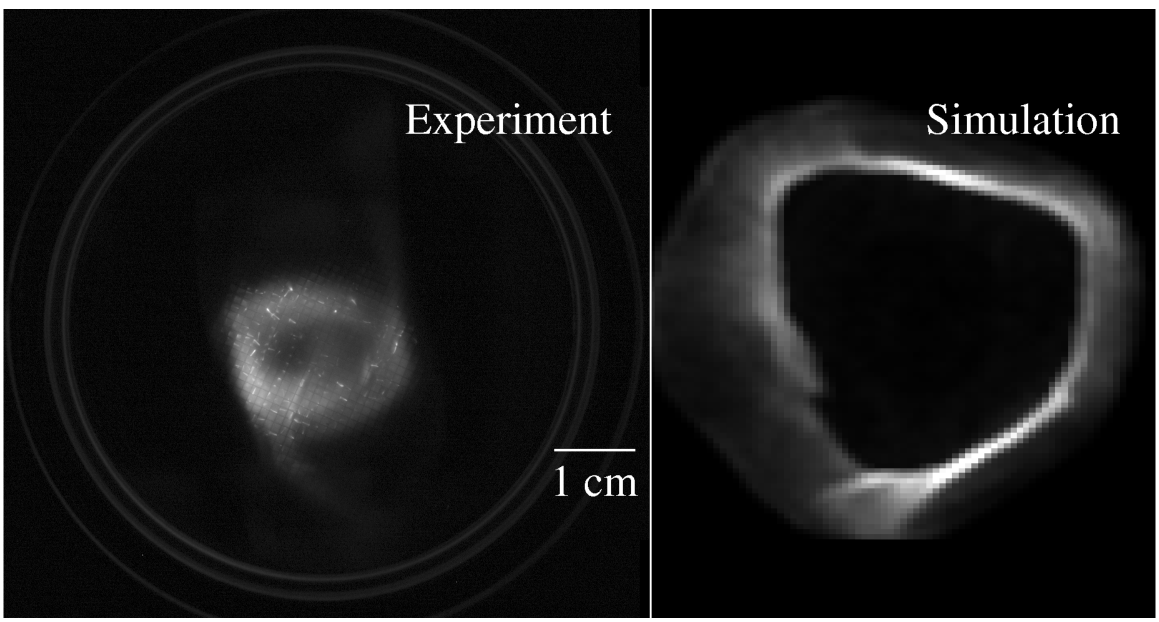

Figure 5. Experimentally imaged C^{4+} beam, left, and intensity plot from simulation plotted on the same scale, right.

Some of the difference in beam size between simulation and experiment for this preliminary beam might be reduced through the adjustment of space charge neutralization along the simulation. Further studies are planned in the near future to determine the degree of neutralization in the VENUS transport system. In addition, more viewing ports will be added to the beam line to enhance the ion beam diagnostics.

Acknowledgements

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