PARTICLE-IN-CELL SIMULATIONS OF THE VENUS ION BEAM TRANPSORT SYSTEM*

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Abstract

The next-generation superconducting ECR ion source VENUS serves as the prototype injector ion source for the linac driver of the proposed Rare Isotope Accelerator (RIA). The high-intensity heavy ion beams required by the RIA driver linac present significant challenges for the design and simulation of an ECR extraction and low energy ion beam transport system. Extraction and beam formation take place in a strong (up to 3T) axial magnetic field, which leads to significantly different focusing properties for the different ion masses and charge states of the extracted beam. Typically, beam simulations must take into account the contributions of up to 30 different charge states and ion masses. Two three-dimensional, particle-in-cell codes developed for other purposes, IMPACT and WARP, have been adapted in order to model intense, multi-species DC beams. A discussion of the differences of these codes and the advantages of each in the simulation of the low energy beam transport system of an ECR ion source is given. Direct comparisons of results from these two codes as well as with experimental results from VENUS are presented.

INTRODUCTION

Electron cyclotron resonance (ECR) ion sources have long been used in the production of high-quality, highly charged ion beams. The push for more current and higher charge states has led to the design of superconducting ECR ion sources. The VENUS ion source at the Lawrence Berkeley National Lab is the most advanced of these next-generation ECR ion sources[1,2].

The VENUS transport system (Figure 1) is composed of a solenoid lens, a double-focusing analyzing magnet, and both a horizontal and vertical emittance scanner for beam analysis. Continuous wave (CW) beams are extracted via a movable accel-decel extraction system through an 8mm diameter source aperture. Typical extraction voltages are between 20-30kV with the negatively biased puller electrode maintained between -1 and -5kV.

This extraction system is located in a region where the magnetic field is peaked at up to three Tesla, and this field decreases to zero over the first forty centimeters of beam travel. This fringing field introduces transverse emittance growth and a rotation of the beam due to canonical angular momentum conservation. The amount of induced rotation varies depending on the magnetic rigidity of the constituent ions, and therefore varies considerably for the typical beams produced by VENUS which are composed of upwards of thirty ion species.

The beam is transported from this region through a solenoid lens and analyzing magnet that have been designed to transport large diameter beams without the creation of a waist before the bend. Avoiding a waist and keeping the beam diameter large reduces space charge effects along the beam transport system. However, the conveyance of large diameter beams through a sector magnet requires a large gap. This large gap leads to beam aberration due to fringing fields. Corrective measures have been taken with the VENUS magnet by shaping the pole faces in such a manner as to introduce aberration-countering sextupole moments to the beam[3].

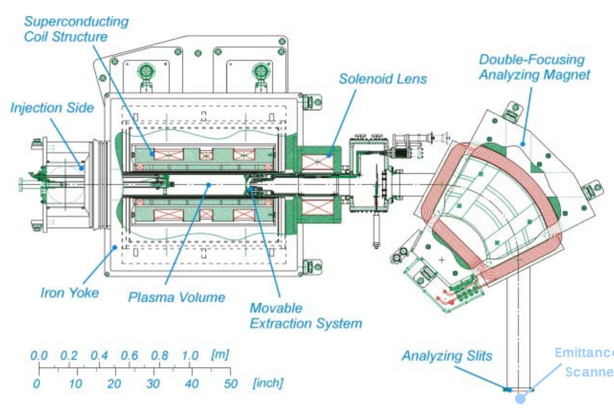

Figure 1: Mechanical layout of VENUS and its accompanying transport system.

Taking all of these effects into account when trying to understand the resulting delivered beam provides a formidable challenge. To aid in the understanding of these complexities a concentrated simulation effort was initiated at LBNL in parallel with the development and testing of the VENUS ion source. In order to be useful, a computer model must be capable of taking into account the dynamics of all relevant beam species in the beam and also allow for a full treatment of space charge effects along the transport system. Due to its dominant fringing fields and complicated pole design, the magnet must be modeled three-dimensionally and allow for a realistic handling of dispersion effects through the magnet. A further requirement is imposed that the simulations be dynamic enough to serve as a design tool in future projects such as the proposed Rare Isotope Accelerator. Therefore, it is necessary that the simulation tool not only accurately model one system, but that it also easily adapt to allow for relatively rapid testing during the design phase.

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Two simulation programs have been enhanced for this purpose, have undergone benchmarking against one another, and are now beginning to be used in comparison with experimental results from VENUS. This paper gives a brief description of the codes as they apply to ECR beam transport as well as a discussion of the testing undergone in benchmarking the codes against one another. Finally, initial results comparing the results of simulation with experimental measurements are given.

SIMULATIONS

From a simulation point of view the most challenging regions of the VENUS transport system are the extraction region and the analyzing magnet. Near the extraction region the beam has its smallest diameter and it is undergoing acceleration from thermal velocities in the plasma to transport velocities over distances of a few centimeters. The small size of the beam coupled with its low velocity, produces a region where the beam is strongly space charge dominated. The dynamics in this region are further complicated by the presence of the fringing field from the extraction solenoid.

Particle-in-cell (PIC) methods were chosen for the simulation of the VENUS system due to their well-demonstrated ability to model systems of large numbers of particles and rapidly solve the associated field equations through the use of a solution mesh. Two pre-existing PIC codes, IMPACT[4] and WARP[5], have each been enhanced in order to model the VENUS beam transport system from extraction to analysis in one self-contained code.

Though IMPACT and WARP are both PIC codes, their methods of solving field equations and handling particle dynamics vary greatly. WARP allows for a fully-three dimensional treatment of the source region while IMPACT requires cylindrical symmetry of electrostatic elements, but can solve the Poisson equation in three-dimensions via a cylindrical series expansion. IMPACT has incorporated a solver to model the formation of the plasma extracting surface while WARP requires the assignment of the surface shape. IMPACT uses a map-based, leap frog approach to move particles through the system while WARP relies on direct integration of the equations of motion. Both codes use Frenet-Serret coordinate system in the treatment of bends which defines the global z-axis to be along the axis of the beam transport system. Multi-processor parallelization can be employed by each code providing improved statistics through the use of more macroparticles. For improved speed, Warp allows for an additional two-dimensional mode of operation which neglects beam self-fields in the z-direction and only solves the Poisson equation in the transverse dimensions.

The two codes have been enhanced in parallel in order to allow for benchmarking between the codes prior to simulation of the VENUS system. Further, the development of both codes together allows for the application of the simulation whose strengths best match a given problem. For example, WARP's lack of a cylindrical symmetric requirement in the source region allows for the investigations of the effects of mechanical misalignment of the electrostatic elements within a source.

Comparisons of the codes both in modeling the source region and the transport of beam through the analyzing dipole show very good agreement[6]. Both field solution and beam analysis compare very well in the extraction region where the beam is most rapidly changing. As expected, differences between the codes appear when comparing the two- and three-dimensional solutions through the dipole. These differences are small for 25keV proton beams with currents less than 10mA, and appear near waists where space charge defocusing is enhanced.

FIRST COMPARISONS WITH EXPERIMENT

One of the more simple beams that can be generated by VENUS is an oxygen beam. The charge spectrum in Figure 2 shows a 1.4mA oxygen beam that was produced and transported through the analyzing magnet with nearly 100% transmission. Such beams are generated by running VENUS at very low power and are primarily composed of the eight oxygen charge states and hydrogen. It should be noted that the O^{8+} and H_2^+ are indistinguishable with the same mass-to-charge ratio.

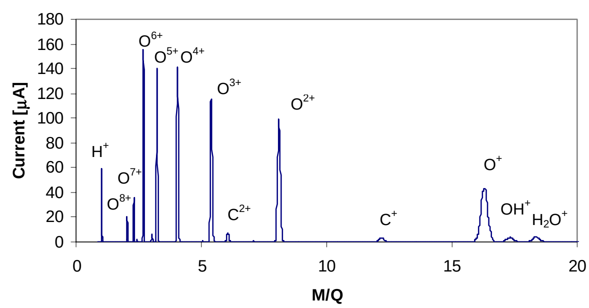

Figure 2: Experimental current spectrum of a oxygen/hydrogen beam produced by VENUS used for comparison with simulation.

The oxygen and hydrogen beam currents shown in Figure 2 are used as a test case for comparison with simulation. The first 0.25m of beam travel using these currents is shown in Figure 3. For simplicity the beam is started from a flat emitting surface and has zero initial transverse velocity. The differences in gyromagnetic wavelength of the various ion species can be seen clearly in Figure 3. These differences result in virtual object points for the respective species that vary depending on their magnetic rigidity.

The continued transport of the beam through the analyzing dipole is shown in Figure 4. As can be seen in the figure, ion species with a greater (lower) magnetic rigidity are seen to leave the simulation at positive (negative) horizontal position.

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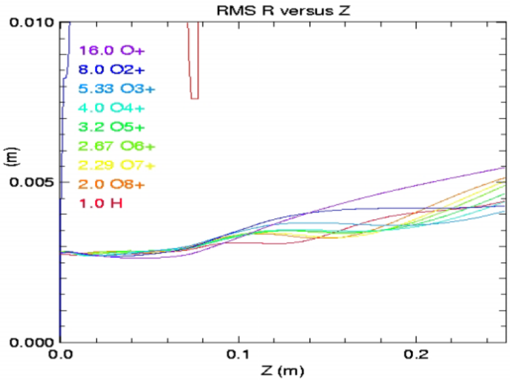

Figure 3: Simulation of the extraction of oxygen/hydrogen beam from VENUS. Radial rms size is plotted as a function of longitudinal distance for each species present.

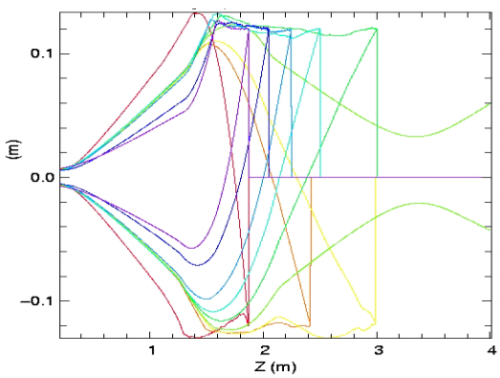

Figure 4: Horizontal edges of each simulated species is plotted as a function of longitudinal length through the analyzing magnet when set to transport O^{6+}.

Through the dipole and along the drift regions, there is some question as to the level of beam neutralization that is present. This neutralization can occur due to the introduction of electrons into the beam as a result of collisions of beam ions with the walls or with background neutrals. Simulations of other transport systems indicate that significant space charge neutralization is necessary to match simulation results with experimentally measured transport[7]. In the VENUS transport system the entire beam line is maintained at pressures below 10^{-7} Torr, therefore neutralization due solely to collisions with neutrals would seem to require very long electron confinement times. Collisions with the walls could liberate a significant electron population, but simulations indicate that wall collisions occur primarily within the analyzing magnet field and liberated electrons would have difficulty leaving this field to neutralize drift regions.

As a rough test of the level of neutralization along the beam line two transport extremes were tested in the simulations. Using the output beam from Figure 3 as an initial condition, simulation of beam transport through the analyzing magnet is performed either with full current or the total beam current set to zero. Figure 5 shows the locations of the vertical and horizontal waists relative to the emittance scanner and compares these with experimental waist locations extrapolated from emittance measurements.

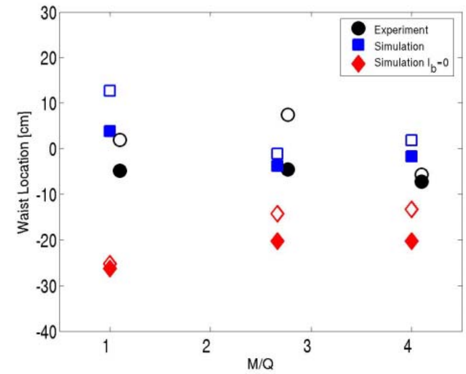

Figure 5: Waist location relative to emittance scanners is plotted versus mass-to-charge ratio. Filled symbols represent horizontal waists and hollow vertical. The experimental results have been offset slightly for clarity.

As expected, the presence of space charge acts to move the waist downstream, though it seems a surprising amount for relatively low-current beams (1.4mA total). The approximate shift of the waists when including space charge is 0.25m for each species. These results indicate that only that the inclusion of space charge along the transport system is necessary the beam waist to shift downstream to where they are found experimentally.

CONCLUSION AND FUTURE WORK

The simulation tools IMPACT and WARP have been tested against one another in the modeling of the VENUS transport system and are in the first stages of comparisons with experiment. The simulation results indicate that little neutralization is taking place along the beam transport system, though this will need to be investigated in more detail. Further, investigations into the effects of temperature and the shape of the plasma surface on beam transport properties will be performed before moving on to beams of higher current and more species.

REFERENCES

[1] D. Leitner, C.M. Lyneis, S.R. Abbott, Nucl. Inst. Meth. B, in press.
[2] D. Leitner and C.M. Lyneis, these proceedings.
[3] M. Leitner, et. al, Proc. 15th Inter. Workshop on ECR Ion Sources, June 12-14, 2002, Jyväskylä, Finland.
[4] J. Qiang, R.D. Ryne, S. Habib, V. Decyk, J. Comput. Phys. 163 (2000) 434.
[5] A. Friedman, D.P. Grote, I. Haber, Phys. Fluids B 4 (1992) 2203.
[6] J. Qiang, D. Leitner, D.S. Todd, these proceedings.
[7] T. Thullier, et. al, Proc. 16th International Workshop on ECR Ion Sources, Sept. 26-30, 2004, 4