Application of 3D code IBSimu for designing an H^-/D^- extraction system for the Texas A&M facility upgrade

T. Kalvas*, O. Tarvainen*, H. Clark†, J. Brinkley† and J. Ärje*

*Department of Physics, University of Jyväskylä, Jyväskylä 40500, Finland
†Texas A&M University, Cyclotron Institute, College Station, TX 77843, USA

Abstract. A three dimensional ion optical code IBSimu is being developed at the University of Jyväskylä. So far the plasma modelling of the code has been restricted to positive ion extraction systems, but now a negative ion plasma extraction model has been added. The plasma model has been successfully validated with simulations of the Spallation Neutron Source (SNS) ion source extraction both in cylindrical symmetry and in full 3D, also modelling electron beam dumping and ion beam tilt. A filament-driven multicusp ion source has been installed at the Texas A&M University Cyclotron Institute for production of H^- and D^- beams as a part of the facility upgrade. The light ion beams, produced by the ion source, are accelerated with the K150 cyclotron for production and reacceleration of rare isotopes. The extraction system for the ion source was designed with IBSimu. The extraction features a water-cooled puller electrode with a permanent magnet dipole field for dumping the co-extracted electrons and a decelerating Einzel lens for adjusting the beam focusing for further beam transport. The ion source and the puller electrode are tilted at 4 degree angle with respect to the beam line. The extraction system can handle H^- and D^- beams with final beam energies from 5 keV to 15 keV using the same geometry, only adjusting the electrode voltages. So far, 24 μA of H^- and 15 μA of D^- have been extracted from the cyclotron.

Keywords: ion source, negative hydrogen, plasma sheath, simulation, ion beam, cyclotron
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INTRODUCTION

The use of computer simulations has become a standard procedure of designing ion optical systems. Many specialized codes exist with capabilities for modelling positive ion plasma extraction problems in two [1, 2] and three dimensions [3]. For negative ion plasma extraction there exists fewer codes ([4] for example), most of them capable of 2D modelling only. The lack of available three dimensional codes for negative ion extraction causes difficulties because negative ion sources are often equipped with magnetic dipole filter fields, which often protrude to the extraction and furthermore the co-extracted electrons are usually deflected using magnetic fields. The application clearly calls for three dimensional simulation. Fortunately, work has been done to develop simplified models for negative ion plasma extraction [5], which can be extended to 3D.

The Ion Beam Simulator, IBSimu, is a program for three dimensional ion optics [6]. The development of IBSimu, was started at LBNL in 2004 for designing a slit-beam plasma extraction system for a neutron generator [7]. The development of the code has been continued at the University of Jyväskylä, Department of Physics (JYFL) with a drive to making the code modular and suitable for many different types of problems.

The code has been published as open source [8] to be used by the community and it has been benchmarked against other codes used for extraction ion optics. IBSimu has been applied to designing an H^+ grid triode extraction, several neutron generator accelerators, slit-beam extraction for diagnostic neutral beams [9], modelling of ECR ion source extraction, designing an $E\times B$ filter for diagnostics and many other problems. The code has only had a plasma sheath model for positive ion extraction, but recently also a negative ion plasma extraction model, which is described in this article, has been developed.

The ongoing facility upgrade for the Texas A&M University Cyclotron Institute aims at extending the reasearch possibilities with stable beams and adding rare ion beam capabilities [10]. This is done by re-activating the K150 cyclotron to deliver high intensity light particle and heavy ion beams. These beams will be used for production of rare isotopes in the targets of light and heavy ion guides for reacceleration with the K500 cyclotron. As a part of the upgrade project, a filament-driven multicusp ion source has been installed for injecting H^- and D^- beams into the K150 cyclotron. The extraction system for the ion source has been designed using IBSimu. This paper reports the development work done for the H^-/D^- project.

SHEATH MODEL FOR NEGATIVE ION EXTRACTION

It is assumed that the extractable negative ions, which are either volume or surface produced, are born in the plasma electrode (wall) potential. These charges form a potential well and counteract the formation of a saddle point at the extraction. The non-existence of the saddle point is supported by the observed good emittance from H^- ion sources. The negative ion plasma extraction model in IBSimu is based on these assumptions and on the existence of an equipotential surface between the bulk plasma and the extraction, where the potential $U = U_W = 0$ V. The potential deviates from zero going into the bulk plasma due to the plasma potential and towards the extraction due to the acceleration voltage. This potential structure causes positive ions from the bulk plasma to be accelerated towards the extraction, having energy eU_P at the zero potential. These ions propagate until they are reflected back to the plasma by the increasing potential in the extraction. The potential well acts as a trap for thermal positive ions. The negative ions and electrons are accelerated from the wall potential towards the bulk plasma and more importantly towards the extraction. Schematic view of the potential structure of the negative ion extraction is shown in figure 1.

The negative ion plasma extraction implementation in IBSimu follows the guidelines of references [4] and [5]. The simulation starts at the plasma electrode potential, where the extracted negative ion and electron beams originate from. The volume between the bulk plasma and this boundary is not simulated, only the flux of directed positive ions is taken in account. The negative particle beams are defined by setting current density, initial drift energy and temperature values. The beams are propagated by standard ray-tracing techniques, using Runge-Kutta integration of the Lorentz force taking into account the electric and magnetic fields. The charge of the beams is deposited on a space charge density mesh during the calculation. The electric field is calculated from a solution of the Poisson equation, using the space charge of the negative beams

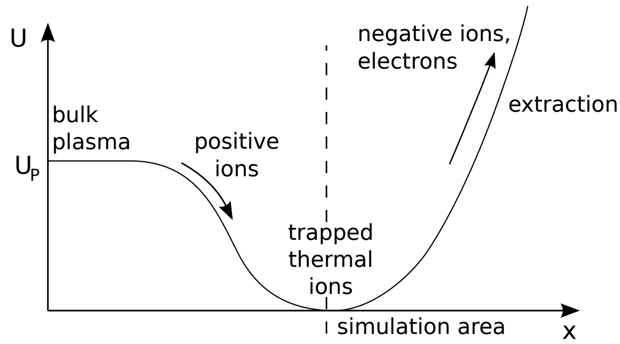

Figure 1. Potentials in a negative ion source: Potential drops from positive plasma potential of bulk plasma to wall potential and raises then again going towards the extraction. Simulations model the area starting from wall potential.

from the previous round of the so-called Vlasov iteration. Positive space charges are taken into account using analytic formulations presented below. The resulting non-linear Poisson equation is solved using Newton-Raphson iteration. The electric field for the first iteration round of the simulation is acquired by setting zero space charge density and forcing $U = 0$ V inside the estimated plasma volume and solving the resulting Laplacian. The Vlasov iteration described here is a standard method for producing self-consistent solutions of space charge dominated problems. The Poisson equation describing the system is

$$\nabla^2 U = -\frac{\rho}{\varepsilon_0}, \tag{1}$$

where $\rho = \rho_{\mathrm{rt}} + \rho_{\mathrm{f}} + \rho_{\mathrm{th}}$. Here ρ_{rt} is the space charge density of negative particles from ray-tracing, ρ_{f} is the space charge of fast positive ions and ρ_{th} is the space charge of trapped positive thermal ions.

The model allows several different negative ion species to be extracted from the ion source and also many positive ion species to be used as background plasma. Each of the thermal ion species has a separate Maxwellian velocity distribution with the associated space charge distribution

$$\rho_{\mathrm{th}} = \rho_{\mathrm{th0}} \exp\left(\frac{-eU}{kT_i}\right), \tag{2}$$

where ρ_{th0} is the space charge density of the thermal ion species at the wall potential and T_i is the corresponding thermal ion temperature. The fast ions are decelerated and turned back to plasma by the extraction voltage. The space charge distribution of the fast ions is defined by the virtual cathode formation and it is

$$\rho_{\mathrm{f}} = \rho_{\mathrm{f0}} \left(1 - \frac{eU}{E_i}\right), \tag{3}$$

at $U < E_i$ and zero otherwise. Here ρ_{f0} is the space charge density of fast ions at the wall potential and E_i is the corresponding kinetic energy, which should be around eU_{P} as the particles are flowing from the bulk plasma. The amount of particles and at least one energy (thermal or directed) must be given by the user for all particle types. The quasi-neutrality of the plasma requires $\rho_{\mathrm{rt}} + \rho_{\mathrm{f}} + \rho_{\mathrm{th}} = 0$ at $U = 0$ V. Otherwise the parameters can be freely selected.

In case of modelling a typical negative ion extraction with a dipole magnetic field in 3D, one problem in the model needs to be addressed: the ray-traced particles will deflect already inside the plasma. This is an unphysical artefact of the simulation and occurs because the particle collisions and cross field diffusion are not being modelled. In reality the ions and electrons are highly collisional and move diffusively until they are accelerated by the extraction electric field. In the simulations this is achieved by suppressing the magnetic field at potentials less than some threshold value given by the user. This threshold defines a boundary between the plasma volume, where ions and electrons are collisional and the extraction volume, where collisions don't happen anymore. In most cases the threshold value should be around 1–20 V as this corresponds to the energy range with typical plasma densities where collisional properties become negligible. The physically correct threshold value is hard to estimate accurately, but it isn't relevant in this context as the ion optics is not very sensitive to the parameter in most cases.

PLASMA MODEL VALIDATION

The plasma model was tested using the widely simulated and thoroughly published extraction of the SNS ion source [11, 12]. The simulations were made using published data about the geometry, magnetic field and electrode voltages of the SNS extraction. Therefore the simulated system might not be exactly identical to the existing extraction, but care has been taken to make it as representative as possible. Many simulations were run with different parameters both in cylindrical symmetry and full 3D to be able to compare to different published results. Examples of cylindrical simulations with different plasma densities are shown in figure 2.

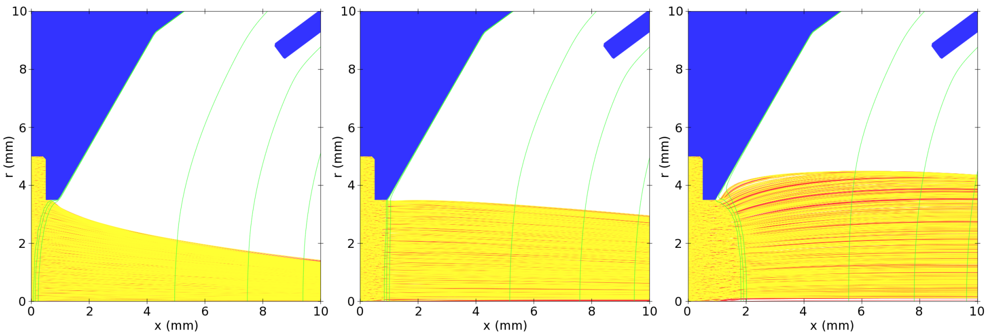

Figure 2. Simulations of plasma meniscus formation on the SNS ion source with different plasma densities. In the center the current density $J = 50$ mA/cm^2, which is optimal for aberration free extraction with the electrode voltages used. On the left $J = 20$ mA/cm^2, which is too small for optimal extraction and on the right $J = 100$ mA/cm^2, which is too large. Electode voltages were kept at values shown in figure 3.

The results show some deviation from previously published simulations, but this is to be expected because of slight differences in the problem definition and because the new simulations feature capabilities which don't exist in the previously used plasma models.

The most important new phenomenon modelled is the unsymmetric increase of negative space charge near the plasma meniscus resulting from the electrons, which are deflected by the electron dump magnetic field. This leads to an unsymmetric plasma meniscus, which affects the optimal tilt angle of the ion source. The biggest difference between the experimental and simulated emittances is that the simulated distributions are much more aberration-free (see [11] for experimental emittance plots). This can also be seen in the emittance value. An example of three dimensional simulations is shown in figures 3 and 4.

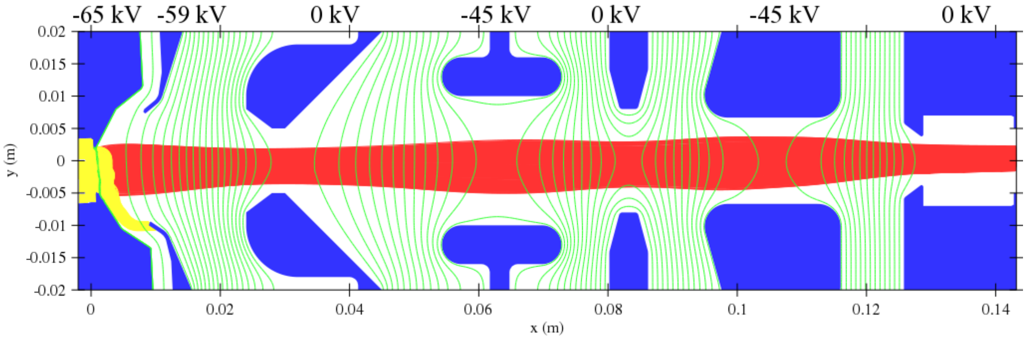

Figure 3. Simulation of the SNS ion source extraction in 3D with 38 mA extracted H^- (red) and 230 mA e^- (yellow) deflected by the magnetic filter.

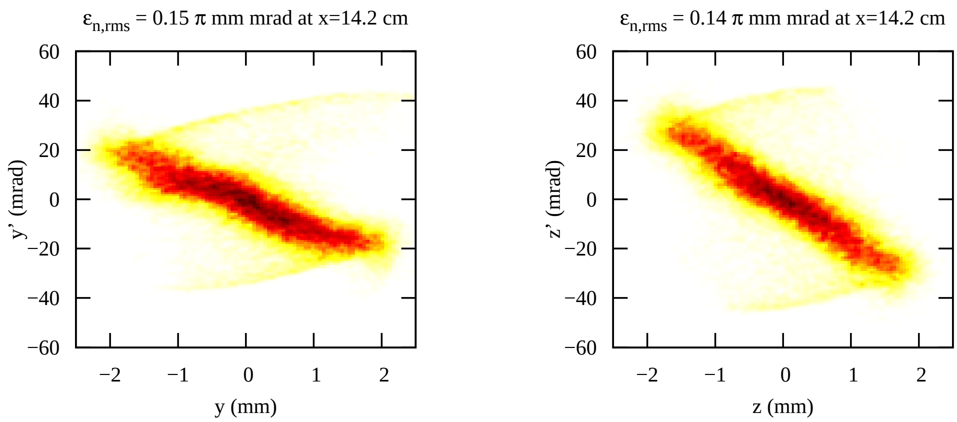

Figure 4. Transverse emittance plots from the 3D simulation shown in figure 3.

Overall, the results achieved with the new negative ion extraction model in IBSimu are consistent with earlier studies and experimental observations from the SNS ion source. This suggests that the plasma model is reasonable.

DESIGN OF NEGATIVE ION EXTRACTION

A filament-driven cesium-free multicusp ion source was installed at the Texas A&M University Cyclotron Institute for production of H^- and D^- beams. The source requires an extraction system capable of extracting up to 1 mA of ion beam and transporting it to the next focusing element of the beam line with low emittance growth. The energy of the ion beam has to be variable from 5 to 15 keV. The extraction system has to be also able to deflect tens of milliamps of co-extracted electron beam into an electron dump. This extraction system was designed using IBSimu.

A dominant feature of a negative ion extraction system is the dumping of the co-extracted electrons. There are several ways of dealing with the electrons. One possibility is to have a transverse magnetic field at the extraction aperture and a separate dumping electrode before the actual puller electrode for dumping the electrons at low energy for decreased power dissipation problems. The ion beam will be deflected by the magnetic field, which is corrected by having the ion source at a small angle with respect to the rest of the beam line [13]. This method is especially beneficial with high-intensity, high-voltage extraction systems.

Another possibility is to have two anti-parallel dipole fields later in the extraction. The first dipole field is used to deflect the electrons to a beam dump and behind this the second dipole field is used to correct the angle of the ion beam. This will cause an offset to the beam axis, which is dependent on the beam energy, but in many cases this is easy to correct mechanically or by using active magnetic elements [14].

In our case, the filter field of the ion source protrudes to the extraction area and thus there will be a tilt in the ion beam regardless of the dumping method. Therefore the tilted ion source method was chosen. The dumping magnetic field was oriented anti-parallel to the filter field to minimize the magnetic field strength at the extraction aperture for minimal interference to the slow particles accelerated from the plasma. The dipole field was constructed using 10 6.35 mm cube SmCo magnets for a maximally flat magnetic field in the transverse direction to minimize emittance growth. The magnetic field peak strength is 32 mT and the FWHM length of the peak is roughly 24 mm. The magnets were integrated in the water cooled puller electrode, engineered to handle the electron beam power.

For the ion beam to tilt to the same angle in the magnetic field regardless of the final energy, the beam energy at the puller electrode has to be fixed. This is done by having the power supply for the puller electrode in the ion source potential. In this case a puller to plasma electrode voltage difference of 6 kV was chosen. After the puller electrode the beam is accelerated to the final energy while the focusing is adjusted using a decelerating Einzel electrode between the puller and the ground electrode. A series of simulations was made in 2D (axially symmetric) to design the extraction electrode geometry and potentials and to check for the sensitivity of simulations to the plasma model parameters. Because of some uncertainty in the plasma parameters and the source performance, the gap between plasma and puller electrodes was made adjustable.

For finding the optimal tilt angle and the center of rotation three dimensional simulations were done. The 3D magnetic field was modelled using Radia3D [15] and the field data was imported into IBSimu. The same plasma model parameters were used as in 2D with the exception of the magnetic field suppression added for $U < 8$ V. The optimal tilt angle for hydrogen was observed to vary from 4.1° to 4.9° with changing final beam energy because the magnetic dipole field is still nonzero at the Einzel lens. The variation of the tilt is so small that the tilt was made fixed. The beam deflection can be corrected by a xy steering magnet which is installed on the beam line after the extraction. A simulation of the optimized three dimensional extraction is shown in figure 5.

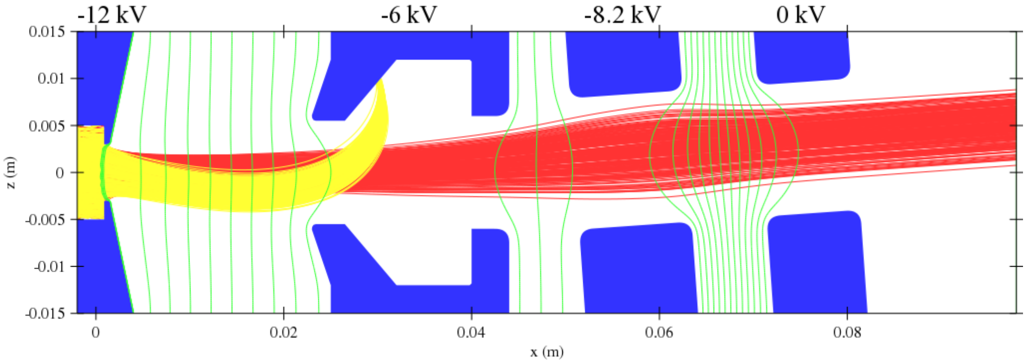

Figure 5. Three dimensional simulation of the extraction system with 1 mA H^- beam accelerated to 12 keV final energy. Co-extracted 25 mA electron beam is dumped inside the puller electrode. Ion beam exits the simulation at 74 mrad angle.

The extraction system is capable of handling both H^- and D^- beams with the same electrode configuration using roughly the same voltages. This is possible because the change in beam bending between the ion species isn't proportional to $\sqrt{2}$ as it should if only the mass would change, but it is less than half of this. There are several reasons for this. One of the reasons is that the electron beam is deflected by the residual filter field of the ion source into $-z$ direction (see figure 6). The electron beam makes a local negative space charge cloud, which pushes the ion beam to $+z$ direction. This effect is magnified with deuterium extraction because the electron-to-ion ratio is higher. Also, the plasma boundary is concave with deuterium because of lower plasma density, which causes the electron beam to deflect more into $-z$ direction amplifying the first effect. This feature makes it possible to change between H^- and D^- beams easily, minimizing the downtime of the facility. It is also a good example of features that are very difficult to model without three dimensional ion optical codes with plasma modelling capabilities.

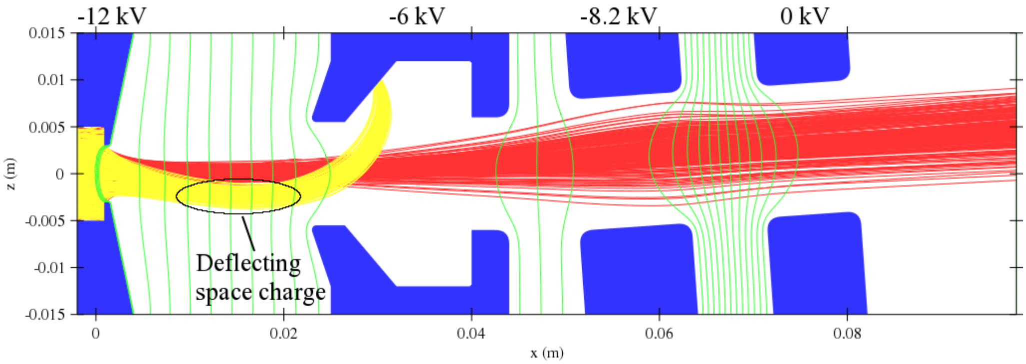

Figure 6. Three dimensional simulation with 0.3 mA D^- extracted with the same electrode voltages used as with hydrogen. Beam exits the simulation at 66 mrad angle.

EXPERIMENTS

The ion source was installed on the injection line of the K150 cyclotron at Texas A&M. The beam line was equipped with a vacuum chamber for housing the extraction, a fine tuning xy steering magnet and three 1000 l/s turbo pumps (see figure 7). The chamber has an electron suppressed Faraday cup for measuring ion current. The electron currents are measured from the puller electrode. At the end of the chamber there is an Einzel lens for focusing the beam to the next ion optical element in the injection line, which is shared with an ECR ion source. The cyclotron inflector is located roughly 6 meters from the ion source.

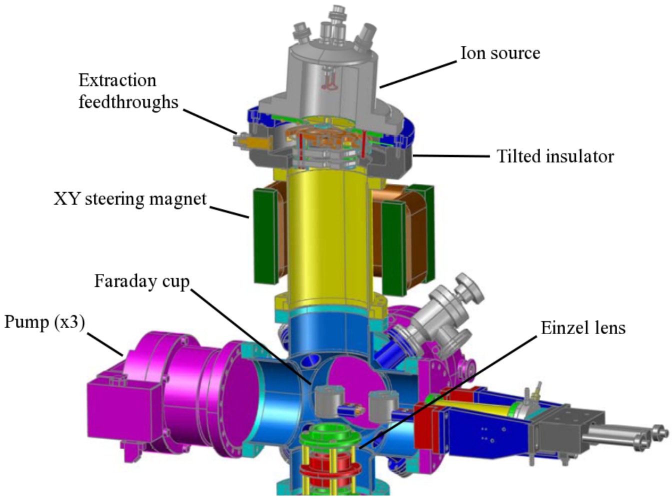

Figure 7. CAD visualization of the ion source, extraction system, pumps, diagnostics and the first beam tuning elements. The next Einzel lens used for focusing is roughly 1 m below the extraction chamber.

The extraction of the ion source proved to function as predicted by the simulations made for both H^- and D^-. The optimal transmission to the first Faraday cup was found very close to the simulated electrode voltages. Also the deuterium beam angle was observed to behave as in the simulations. The H^- current of 1 mA on the first Faraday cup was reached with an arc current of 12.7 A at the arc voltage of 100 V. The e^-/H^- ratio was around 25. For D^- 285 μA was measured on the first cup with 10 A, 100 V arc. The e^-/D^- ratio was about 87. Beam currents of 25 μA of H^+ and 15 μA of D^+ have been extracted at energies of 30 MeV and 20 MeV respecively from the cyclotron with stripping extraction and measured from the first Faraday cup outside the cyclotron.

Overall, the experimental work done with the ion source extraction shows that the design process has been successful.

FUTURE WORK

At the University of Jyväskylä we are starting a project for building a filament driven multicusp H^- ion source to be used on the pelletron accelerator of the laboratory. During this project there will be possibilities for further experimental validation of the sheath model by traditional diagnostics methods including Faraday cup measurement and beam profile determination with Kapton foils. Further development of the code is planned to be done using this data.

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