Deviation of H^- beam extraction simulation model

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Abstract. Negative hydrogen ion source extraction system development is dependent on accurate and fast simulation methods for modelling the behaviour of ion and electron beams. Traditionally this type of work has been done using ray-tracing extraction codes, such as IBSimu. The plasma extraction model in IBSimu has been observed to under-estimate the charge density near the plasma sheath, leading to incorrect prediction of the current at which the system produces the optimum emittance. It is suspected that this deviation results from the approximations made by the model, neglecting the magnetic field and collisional effects near the sheath region. Results and comparisons to simulations are presented for three ion sources, for which two show similar variation and one is more accurately modelled. Conclusions with the currently available data can not be made and therefore further experimental and simulation campaigns to study the effect are suggested.

INTRODUCTION

Development of negative hydrogen ion extraction systems is a challenging task. The extraction system should typically produce a maximum amount of ion beam with a minimum emittance while also deflecting the co-extracted electrons to an electron dump capable of handling the beam power. In most cases the development of new systems is started as a purely computational effort, but in the end on most extraction systems the experimental iteration and feedback from experiments to modelling is needed as the last stage of development because none of the computational tools have 100 % predictive power.

Typically the development process is driven by computational modelling with tools including so-called plasma modelling codes, especially Particle-In-Cell Monte Carlo Collisions (PIC-MCC) codes such as ONYX [1] and KEIO-BFX [2]. These are the most accurate options that represent the reality, but on the other hand they are very slow with computation times of a single calculation being in the order of days to weeks on a cluster of computers. Often faster options for modelling extraction systems are needed as the development is an iterative process, where the next modification on the design is based on results received from previous simulations. A typical choice is to use so-called extraction codes, such as the IBSimu [3], nIGUN [4] or Kobra-INP [5]. These codes make stronger approximations of the physical processes taking place but on the other hand are much faster, allowing solution of a single calculation in hours on a desktop computer. In this paper the model used in the plasma extraction code IBSimu is presented and results produced by the simulations are compared to experiments for three different ion sources.

PLASMA MODEL

To make the negative ion extraction solvable quickly, one needs to make several approximations on the physical processes affecting the particles in the plasma and the beam. In the IBSimu code, the model used for the negative hydrogen ion extraction [6] is based on an approximation assuming that there exists an equipotential surface somewhere near the extraction aperture, which has the potential of the plasma electrode defined as 0 V. This surface acts as a definition plane for the flux of negative particles, the H^- and electrons, which are ray-traced by integrating the equations of motion based on Lorentz force $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$. Each of the calculated particles represents a cloud of real particles and is given a weight defined as current I carried by the particle. The ray-traced particles are given an initial kinetic energy E_0 and the effects of the magnetic field on particle trajectories are suppressed in regions, where

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the potential ϕ is less than some predefined limit ϕ_{sup}. This suppression has to be done in order for the particles to populate the sheath uniformly as proper modelling of the particle transport in the plasma would require taking in account the collisional processes, which would break the plasma model. This approximation is especially strong for electrons typically having gyroradii of the order of tens or hundreds of micrometers (with ~ 0.1 eV energies in magnetic fields around 10 mT) and experiencing diffusive motion. The difference between the reality and the simulation is depicted in fig. 1.

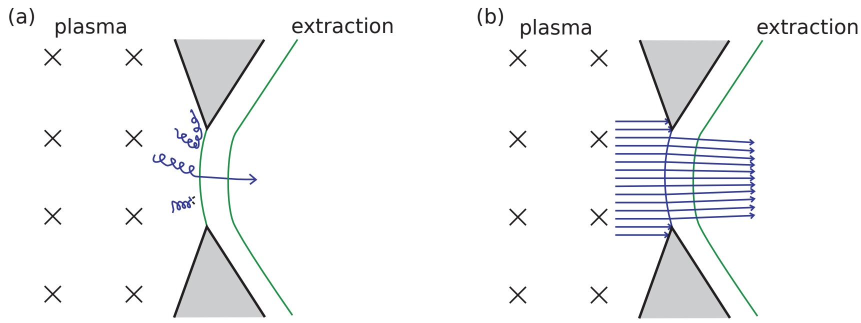

FIGURE 1. Illustration of the difference of the electron trajectories in (a) reality and (b) the simulation.

The model described allows fast self-consistent solution of potential with Poisson equation

$$\nabla^2\phi = -\frac{\rho}{\epsilon_0} = -\frac{\rho_{\mathrm{H}^-} + \rho_e + \rho_f + \rho_{th}}{\epsilon_0}, \tag{1}$$

where the charge density ρ consists of four components, the ray-traced ions ρ_{H^-}, electrons ρ_e and the analytically defined charge densities for compensating positive ions. The positive ions consist of fast particles originating from plasma potential ϕ_P with charge density

$$\rho_f = \rho_{f0}\left(1 - \mathrm{erf}\left(\frac{\phi}{\phi_P}\right)\right) \tag{2}$$

and thermal particles trapped in the potential well of the sheath region with charge density

$$\rho_{th} = \rho_{th0}\exp\left(\frac{-e\phi}{kT_p}\right), \tag{3}$$

where T_p is the temperature of the positive ions. The fraction of fast compensating particles $R_{ff} = \rho_{f0}/(\rho_{f0} + \rho_{th0})$ can be defined, but the total compensating charge density $\rho_{f0} + \rho_{th0}$ must equal the negative charge density at $\phi = 0$ to fulfill the plasma quasineutrality.

Collisional processes are neglected for the negative extracted particles so it is possible that the charged particle densities near the plasma sheath are under-estimated by the model. This is suspected to take place especially for electrons, but may also happen to ions. One of the ways to implement a correction to this deviation is to use a correction factor, which simply multiplies the negative charge density from the ray-tracing algorithm at the region, where the potential is under a predefined limit, for example $\phi < 2\phi_P$ as is done in this paper, and also corrects the densities of the compensating positive particles to maintain quasineutrality. For electrons the correction is known as electron density coefficient R_{ec} and for ions as ion density coefficient R_{ic}. In this paper the ion density coefficient is assumed to be 1, but is presented here for completeness, nevertheless. If we assume that the initial energy is negligible, we can estimate that the velocity of particles is given by $v = \sqrt{2qU/m}$, thus the total negative charge density near the sheath is

$$\rho_{\mathrm{tot}-} = \rho_{\mathrm{H}^-} + \rho_e = \frac{J_{\mathrm{H}^-}}{v_{\mathrm{H}^-}} + \frac{J_e}{v_e}, \tag{4}$$

where J_{H^-} and J_e are the ion and electron current densities respectively. The v_{H^-} and v_e are the corresponding velocities. If we now note that the current densities near the sheath differ from the observed current densities, which are marked with an asterisk (*) as

$$J_{\mathrm{H}^-} = R_{ic}J^*_{\mathrm{H}^-} \tag{5}$$
$$J_e = R_{ec}J^*_e, \tag{6}$$

we can write the total charge density as

$$\rho_{\mathrm{tot}-} = R_{ic}\frac{J^*_{\mathrm{H}^-}}{v_{\mathrm{H}^-}} + R_{ec}\frac{J^*_e}{v_e} = \frac{J^*_{\mathrm{H}^-}}{\sqrt{2qU}}\left(R_{ic}\sqrt{m_{\mathrm{H}^-}} + R_{ei}R_{ec}\sqrt{m_e}\right), \tag{7}$$

where R_{ei} is the observed electron to ion ratio I_e/I_{H^-}, which equals the ratio of current densities J_e/J_{H^-} if no collimation takes place as both extracted particle species uniformly fill the extraction aperture. With this assumption it is also convenient to use effective H^- current instead of total charge density:

$$I_{\mathrm{eff}} = R_{ic}I_{\mathrm{H}^-} + R_{ec}I_e\sqrt{m_e/m_{\mathrm{H}^-}}. \tag{8}$$

The total correction factor R_{tc} for the space charge is the ratio of charge density near the sheath to the observed charge density

$$R_{tc} = \frac{\rho_{\mathrm{tot}-}}{\rho^*_{\mathrm{tot}-}} = \frac{R_{ic}\frac{J^*_{\mathrm{H}^-}}{v_{\mathrm{H}^-}} + R_{ec}\frac{J^*_e}{v_e}}{\frac{J^*_{\mathrm{H}^-}}{v_{\mathrm{H}^-}} + \frac{J^*_e}{v_e}} = \frac{R_{ic} + R_{ei}R_{ec}\sqrt{m_e/m_{\mathrm{H}^-}}}{1 + R_{ei}\sqrt{m_e/m_{\mathrm{H}^-}}}. \tag{9}$$

EXPERIMENTAL RESULTS AND COMPARISONS

Pelletron Light Ion Source

The Pelletron Light Ion Source, PELLIS is a filament-driven volume production ion source intended for production of continuous low-emittance negative hydrogen ion beams of less than 100 µA at 10 keV. The source has a ⌀2 mm plasma aperture and the extraction system is optimized to cause only minimal beam aberrations. The source therefore provides a good case for acting as a benchmark for plasma extraction codes in addition to its intended task. The ion source and the first experimental results are described in detail in reference [7]. Here additional experimental results measured are presented. The H^- beam was measured with a Faraday cup at 195 mm from the plasma electrode and the electron current was determined from the electron dump power supply drain. The emittance was measured with an Allison scanner at 169 mm from the plasma electrode. The emittance data was processed by correcting amplifier bias and filtering by thresholiding to contain 95 % of the beam. All the measurements presented here were measured with 1.8 A electromagnet filter current (corresponding to about 5 mT field at extraction aperture and 12 mT at the peak), which is the optimum field for H^- production at 0.58 Pa pressure.

In fig. 2(a) the electron ion ratio is presented as a function of arc current. The ratio changes from ~10 to ~150 as the ion source pressure changes from 0.85 Pa to 0.28 Pa respectively. The measurement of emittance as a function of H^- current at the pressure of 0.58 Pa and puller electrode to plasma electrode voltage of 5 kV is presented in fig. 2(b) with a solid line. The H^- current in the measurement is varied by adjusting the filament heating current, which changes the arc current and therefore also the plasma density. Other operational parameters were kept constant. The behavior of emittance shows a typical shape for this type of measurement with an optimum at about 38 µA. This optimum corresponds to the optimal meniscus shape for beam formation. At lower or higher arc currents the plasma meniscus becomes convex or concave respectively, causing the beam emittance to grow. The same situation is simulated with IBSimu using plasma parameters well-known for this type of ion sources ($\phi_P = 5$ V, $T_t = 0.5$ eV, $T_p = 0.5$ eV, $R_f = 0.5$, $E_0 = 3$ eV and $R_{ic} = 1$) [8], the measured electron ion ratio of 20, varying emission current densities and R_{ec} values of 1, 3 and 5. It can be seen that the simulation model seems to under-estimate the charge density near the plasma sheath as the best matching emittance curve is produced with with $R_{ec} = 3$.

The emittance curve measurement was repeated for four different pressures. The data is shown in fig. 3(a). For each pressure there is a minimum emittance at a certain H^- current. The location of the optimum shifts to higher currents with increasing ion source pressure. This effect is assumed to take place because the plasma sheath shape and location is mainly dependent on the charge density in the proximity of the sheath and not dependent on the particle type. With high pressure the electron to ion ratio is lower, which moves the the optimum towards higher ion current when comparing to lower pressure operation. If the H^- equivalent current (eq. (8)), which is proportional to charge density near the sheath region, is used on the x-axis instead of H^- current the optimum is expected to be located at the same position for all four cases. This condition is fulfilled in two noteworthy conditions: Firstly, if the fitted $R_{ec} = 3$ value is used for the 0.58 Pa case and $R_{ic} = 1$ for all cases, one achieves the matching condition with R_{ec} values of 1.8, 2.2 and 5.0 for the 0.28 Pa, 0.44 Pa and 0.85 Pa cases respectively, as is shown in fig. 3(b). It is understandable that

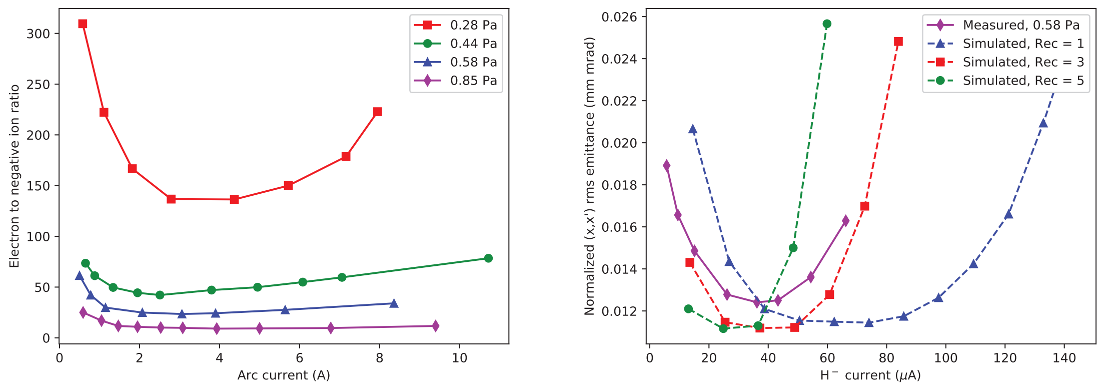

FIGURE 2. (a) The measured electron ion ratio as a function of arc current for four different ion source gas pressures and (b) the normalized rms emittance as a function of ion current for a measurement at 0.58 Pa and simulations using three values of electron density coefficient.

the electron density coeffcient becomes higher with higher pressure as the pressure does effect the electron diffusion and collisions in the plasma. The second case which also produces a match if both R_{ec} and R_{ic} are equal to 1. This is somewhat unbelievable as an explanation to the observations as it would mean that there is no difference in the behaviour of electrons and ions near the plasma sheath. Fitting the simulations to the experimental results can be be done with the R_{ec} values mentioned above if $R_{ic} = 1$, with a single total density coefficient $R_{\mathrm{tc}} = 1.6$ or any combination of R_{ec} and R_{ic} providing the same total effect according to eq. (9).

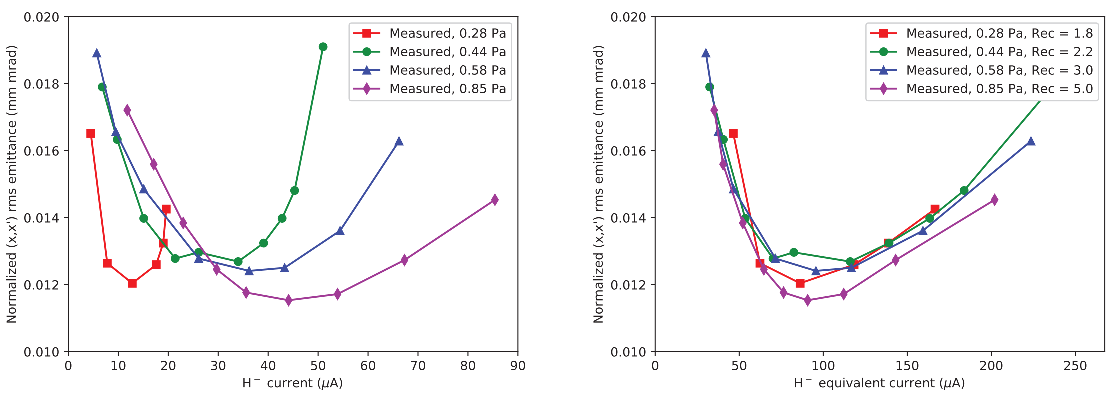

FIGURE 3. (a) The measured normalized rms emittance as a function of ion current for four different ion source pressures. (b) The same data presented as a function of H^- equivalent current.

One well-known phonomenon effecting the ion density coefficient is the stripping loss of H^-. The PELLIS ion source was modelled using Direct Simulation Monte Carlo technique [9] to estimate the hydrogen molecule density distribution in the system. According to the simulation the pressure drops from 0.5 Pa to 0.05 Pa in about 10 mm, which results in stripping loss of about 10 %. The stripping loss is therefore only slightly effecting the ion charge density and will only have a minor contribution to R_{tc}. This affect is not taken in account in the simulation presented here.

If the charge density coefficient is used the simulations reproduce the emittance and phase space distributions as a function of H^- current well, not only for a single puller to plasma electrode voltage but for a range of voltages from 4 kV to 7 kV.

CERN Linac4 ion source

The CERNs Linac4 radiofrequency ion source is a state-of-the-art cesiated ion source for production of 45 keV H^- ions with an intended purpose of being the future main injector for CERNs accelerator chain. The source aims to produce 50 mA, 600 µs pulses of H^- with normalized rms emittance of 0.25 mm mrad or less [10]. The ion source extraction and electron dumping has gone through several revisions during the development [11, 12]. The recent versions of the extraction are capable of producing 50 mA H^- beam with emittance within the specification according to the simulations. Unfortunately the emittances measured with a slit and grid emittance meter show that the emittance at high current levels is underestimated by the simulations if $R_{tc} = 1$ (and other plasma model parameters being $\phi_P = 7.5$ V, $T_t = 0.5$ eV, $T_p = 1$ eV, $R_f = 0.5$, $E_0 = 5$ eV and $R_{ic} = 1$). First it was thought that the difference in emittance could be a result from the plasma model failing to reproduce the surface produced H^- component. This was later shown to be highly unlikely as emittances and phase space distributions close to the plasma sheath produced by backtracking the particle distributions from emittance measurements are almost identical in cesiated and uncesiated conditions.

If the experimental emittance measurement data as a function of H^- current is compared to simulations it can be noticed that the deviation is very similar to the observations made with the PELLIS: In simulations, with charge density coefficient of unity, the optimum emittance produced by the extraction system is located at a higher current compared to the experimental result. By redoing the simulations with $R_{tc} = 1.5$ a much better fitting to experiments is achieved. The measurements and simulations are shown in fig. 4 for the IS03b version with a ⌀5.5 plasma aperture. Again the question arises on why is this factor needed? If it is thought that the effect is completely due to error in modelling the electron transport, the difference should result from a difference in electron charge density. To produce the same total effect of $R_{tc} = 1.5$ the electron density factor $R_{ec} = 10$ should be used as the electron to ion ratio in this case was 2.5. This seems unbelievable as an explanation to the factor as it is very high to be really a physical effect (a difference in real electron density). As direct experimental measurement of particle densities are not possible, the densities from IBSimu modelling should be compared to PIC simulation of the Linac4 source to gain understanding of the physical processes contributing to this observed difference between the simulations and the experiments.

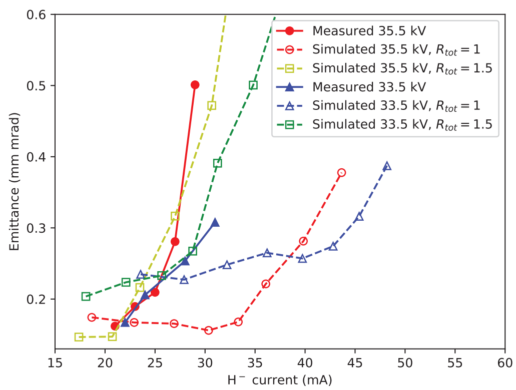

FIGURE 4. The measured normalized rms emittance as a function of ion current for CERN Linac4 IS03b ion source with a ⌀5.5 plasma aperture.

Spallation Neutron Source ion source

The Spallation Neutron Source at Oak Ridge National Laboratory uses a cesiated internal antenna radiofrequency-driven ion source for production of pulsed 60 Hz, ~1 ms H^- beams at 65 keV with typical beam current of roughly 35–40 mA. The beam emittance produced by the source and the double einzel extraction system has been measured as a function of the H^- current and compared to simulations using charge density coefficient of unity (and other plasma model parameters being ($\phi_P = 15$ V, $T_t = 2$ eV, $T_p = 0.5$ eV, $R_f = 0.5$, $E_0 = 2$ eV and $R_{ic} = 1$) [13, 14]. The comparison is shown in fig. 5. In the SNS simulations the optimum is at a lower current compared to the measurements. This is the opposite to the two previous cases. Therefore, it can be concluded that the error in the simulation is not systematic, but is somehow dependent on the ion source. As discussed already before one feature that obviously affects the space charge close to the plasma sheath is the magnetic field. In the SNS ion source case the electrons are dumped immediately after the sheath by a strong magnetic field, causing the local electron density to be increased. The dumping takes place outside the plasma and therefore it can be accurately calculated by extraction codes.

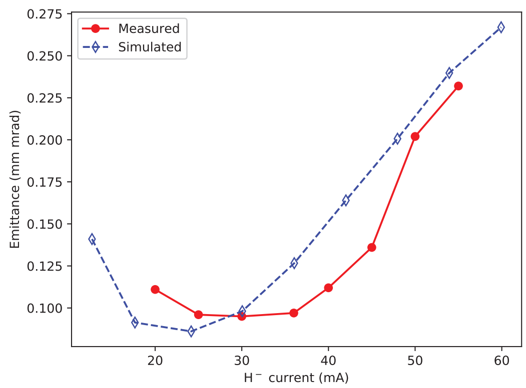

FIGURE 5. The measured normalized rms emittance as a function of ion current for SNS ion source.

CONCLUSIONS AND OUTLOOK

This study presents more questions than it can answer. It is can be seen that in some cases the simulations seem to under-estimate the negative charge density in the proximity of the plasma sheath. Why this happens is not clear at all. It was presented that this might be related to the diffusive transport of electrons in the filter field of negative hydrogen ion sources. This would make the magnitude of the error dependent on the magnitude of the magnetic field and the ion source pressure. The magnitude of the transverse magnetic fields in the studied ion sources is presented in the fig. 6. It can be seen that the cases where the charge density was under-estimated have fields in the 5–10 mT range and decreasing towards the extraction, while in the SNS ion source in which the simulations match better have a field of 50 mT and increasing. One would expect that a higher field would produce a larger error in the charge density. The observed effect goes in the opposite direction. It might be that the electron dumping and highly curved electron trajectories near the sheath mask the possible error in the sheath modelling in the SNS case. Unfortunately no comments can be made about the effect of pressure as no information about the ion source pressures, except for the PELLIS, was available for this study.

Obviously more experiments are needed to reach a conclusion for the study of the space charge under-estimation. A possible source of data for this study are the TRIUMF-type filament-driven ion sources in which the dumping of electrons also takes place very close to the plasma sheath, but with a lower magnetic field compared to the SNS ion source. The field for the TRIUMF-type ion source in Jyväskylä is also plotted in fig. 6 for reference. This source is very similar to the PELLIS source but with a dumping field more like in the SNS ion source. Hopefully the source can be used to probe the effect. It has also been planned to make more experiments with the PELLIS ion source taking advantage of the adjustable magnetic field. The Linac4 ions source will be used to study the effect as the requirements of the Linac4 project have not yet been completely fulfilled. Also the Rutherford Appleton Laboratory RF H^- ion source extraction development [15] is made with the model presented here and would therefore benefit from accurate predictions.

The main suspect for the charge density under-estimation effect is the neglect of the magnetic field and collisional processes near the sheath. It is also possible that the effect is a result of the other fundamental approximations made by the model. A way to evaluate the validity of the approximation is to make comparisons against results from PIC codes, which include more physics and are capable of providing data that could be used for the evaluation, such as potential maps, particle densities, fluxes and reaction rates. Another possibility to study and improve the plasma model is to implement other negative ion extraction models from the literature, such as one presented by Whealton [16]. It is also

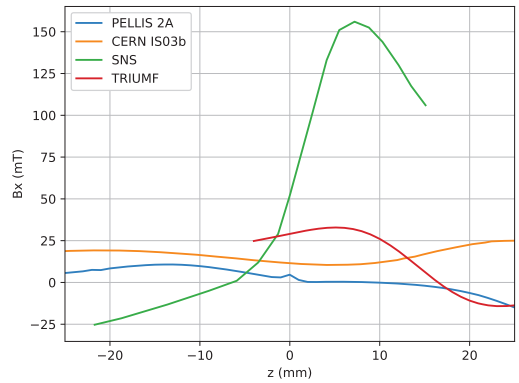

FIGURE 6. The magnetic fields on the axes of PELLIS, CERN IS03b, SNS and Jyväskylä TRIUMF-type ion sources. The plasma electrode is located at $z = 0$ in each case.

worth studying expanding the current model by using a collisional analytic model [17].

ACKNOWLEDGMENTS

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