Ion beam emittance from an ECRIS

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Simulation of ion beam extraction from an Electron Cyclotron Resonance Ion Source (ECRIS) is a fully 3 dimensional problem, even if the extraction geometry has cylindrical symmetry. Because of the strong magnetic flux density, not only the electrons are magnetized but also the Larmor radius of ions is much smaller than the geometrical dimension of the plasma chamber ($\varnothing 64 \times 179$ mm). If we assume that the influence of collisions is small on the path of particles, we can do particle tracking through the plasma if the initial coordinates of particles are known. We generated starting coordinates of plasma ions by simulation of the plasma electrons, accelerated stochastically by the 14.5 GHz radio frequency power fed to the plasma. With that we were able to investigate the influence of different electron energies on the extracted beam. Using these assumptions, we can reproduce the experimental results obtained 10 years ago, where we monitored the beam profile with the help of viewing targets. Additionally, methods have been developed to investigate arbitrary 2D cuts of the 6D phase space. To this date, we are able to discuss full 4D information. Currently, we extend our analysis tool towards 5D and 6D, respectively. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4934210>]

INTRODUCTION

The extraction from an ion source determines the ion beam quality. Shrinking of the phase space is not possible without acceleration or cooling. Whereas the extraction process is well understood since the 1970s for electron guns,¹ or for ion sources extracting from a cold plasma,² the extraction from ion sources using a magnetic field for confinement is still under discussion. This concerns at least Penning ion sources (PIG), Duoplasmatron Ion Sources (DPIs), and Electron Cyclotron Resonance Ion Sources (ECRISs). Depending on the magnetic flux density and on the charged particle energy within the plasma, electrons are magnetized for PIG and DPIS. ECRIS has typically an even stronger magnetic field such as high that ions become magnetized as well. Magnetized means that the Larmor radius becomes smaller than the geometrical dimensions of the plasma chamber. This fact distinguishes the simulation process between different ion sources. The paper first describes the details and results of beam profile measurements carried out with the GSI ECRIS years ago. Then, our recent computer simulations try to explain and make understandable the experimental observations.

EXPERIMENTAL EXPERIENCES

All experiments have been made using a Compact source A Plusiers Resonances Ionisantes Cyclotron Electroniques (CAPRICE) ECRIS. The ion source has two coils for the mirror field and a special permanent magnet arrangement for

the hexapole magnet. The mirror field can reach 1.2 T on axis. This is almost the value of the hexapolar field at the inner radius of the plasma chamber. Different gases for the discharge are fed to the plasma chamber by two different valves. To heat the electrons, a 14.5 GHz klystron is used.³ Traces inside the plasma chamber and the three loss lines on the extraction electrode and on the injection side indicate that diffusion in this case can be neglected. All traces are relatively sharp limited, indicating a strong confinement. To extract the ion beam, we are using a single-hole (diameter 10 mm) accel-decel electrode system. The extraction gap width between the plasma electrode and the negative screening electrode can be adjusted online but is in the order of 30 mm.

The source is operated in dc mode to avoid any space charge effect along the beam line. Our beam is space charge compensated to a very high degree after a few ms.⁴

Measurements of beam profiles using viewing targets along the ECRIS test beam line EIS⁵ have shown the following behavior: directly behind the ECRIS ground electrode of the extraction system, the different charge states can be distinguished from each other by the different focusing strengths for the different mass to charge ratios (m/q) within the extraction region.

50 cm downstream, the ground electrode a magnetic solenoid is used to focus the ion beam. Different m/q ratios will be focused differently and therefore the beam becomes partly separated. Interesting is the fact that each m/q ratio showed a similar profile, starting from m/q equal 1 up to the heaviest particles. With increasing focusing strength, the profile always starts with a hollow ring, three azimuthal fractions of that ring become stronger focused and cross the optical axis earlier than the residual of the beam. Especially, this effect should be possible to simulate if the correct model is used.

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A quadrupole singlet for vertical focusing is used in front of a dipole magnet, which separates the different m/q . A third viewing target is installed behind the dipole. Again, a structure can be seen on that target, which could be explained by an energy dependence or a momentum spread.

The figures of these three viewing targets have been published already 10 years ago,⁶ but up to now an explanation for that behavior is missing.

It should be pointed out that viewing targets show the real profile instead of the integrated quantity provided by wire grid harps. Emittance measurements using a slit grid device or similar devices (Allison scanner) do have a similar problem, namely, the integration of all particles perpendicular to the direction of measurement. To improve this situation, the old pepper pot technique has been re-introduced to the community.⁷

Behind the dipole two chopper plates with a fast power supply can be used to apply a voltage within 1 μ s to these electrodes to change the dc beam, coming from the source, to a pulsed beam usable for the Radio Frequency Quadrupole (RFQ) accelerator.

SIMULATION

The simulation process for ECRIS differs slightly from the simulation of other ion sources: we do assume that electrons and ions are strongly magnetized. Therefore, collisions have a different influence on the particles compared to the conditions found in an electro static plasma. Drifts and diffusion processes need to be considered under the assumption of modified plasma parameters. We do believe that the particle history within the plasma is essential to solve the trajectory coordinates. To get the correct initial coordinates, we have simulated the electron movement within the plasma, including the heating process of electrons, caused by the 14.5 GHz rf. After a pre defined time (200 ns), the electron is stopped and this final spatial coordinate of the electron is used as starting point for an ion⁴ trajectory.

We distinguish four different classes for acceleration of electrons: cold electrons ($E \leq 0.2$ keV), an intermediate electron energy ($0.2 \text{ keV} < E \leq 3$ keV), a warm electron energy ($3 \text{ keV} < E \leq 10$ keV), and a hot electron distribution ($E \geq 10$ keV). The energy distribution in these classes depends on the history of each electron during the heating process. These four groups of electrons occupy partly different spatial positions as it comes from TrapCad simulations. It means by using any of these groups (i.e., by energy filtering of electrons) for further simulations, we can study the effect of the (starting)

FIG. 1. Beam profile showing the influence of initial energy on the ion beam. Left: cold ions; right: hot ions (last line in Table I).

TABLE I. Extraction efficiency.

Electron energy (keV)	Generated ions	Extracted	
		Cold ions (%)	Hot ions (%)
≤ 0.2	117.202	13.7	...
0.2-3	808.101	15.3	...
3-10	543.682	13.7	...
≥ 10	134.979	11.1	29.3

ions positions to the extraction. Starting energies of ions have been kept small and constant for all four cases. In a second simulation, we changed the initial energy of ions to investigate the influence of plasma temperature on the extracted beam.

Whereas the influence of starting location seems to be less strong, the initial energy distribution has a stronger influence on the ion trajectory, see Fig. 1. One reason that the influence of starting positions seems less effective is that obviously we cannot extract all the ions starting from electron's locations. Preliminary calculations showed that only 10%-26% of ions could be extracted (depending on the energy class of electrons) and mostly those ions are extracted (by neglecting collisions, as mentioned) whose associated magnetic field line goes through the extraction hole. The verification of this assumption needs further careful experimental and simulation studies. In any case, we have found that ions with higher energy (several eV ion temperature) can be extracted more easily than cold ions, see Fig. 1 and Table I. For diagnosis of simulation results, a similar problem arises as in the real experiment: the number of particles is too small to provide an acceptable resolution. Integrating all particles in the perpendicular direction improves the number of particles but may hide structures in phase space.⁴

With the assumption about the plasma that each trajectory might have another path, therefore, $\int \mathbf{B} ds$ might be different for each trajectory. This is shown in Fig. 2. If $\int \mathbf{B} ds \neq 0$, trajectories will be tilted.

2D sub-spaces of the 6D phase space can be separated from each other under certain conditions. In case of coupling between these planes (see Fig. 3), their separation is not justified any more and, therefore, other visualization methods are necessary by all means. We use a new software tool⁸

FIG. 2. $\int \mathbf{B} ds$ ranges from 0.09 Tm to 0.15 Tm for each extracted trajectory along the longitudinal coordinate for CAPRICE. Different initial longitudinal starting conditions are shown in different colors.

FIG. 3. Visualization of the coupling of the longitudinal phase space with the horizontal coordinate (left) and the vertical coordinate (right). Note the visible wings.

FIG. 4. Visualization scheme for a 4D space. A cube with the 3D coordinate system r' , ϕ , and ϕ' is moved stepwise in r direction.

that can help to visualize hyper-surfaces (i.e., volumes) in 4D (radius r , azimuthal angle ϕ , and the two velocities r' and ϕ') through evaluation of specific intersections. One possible visualization is shown in Fig. 4. While generating these 4D data, it is important to have enough statistics in order to get a smooth distribution, see Table II. It is planned to expand this diagnostics to 6D, which might be necessary if strong magnetic fields are present. To generate the 4D data, the resources

TABLE II. Required resources.

Electron energy (keV)	Tetrahedrons	4D points
≤ 0.2	878.264	701.176
0.2-3	2.447.999	1.680.141
3-10	2.058.702	1.426.831
≥ 10	756.765	621.184

listed in Table II have been used. For the 6D evaluation, these numbers will increase drastically.

CONCLUSION

Extraction of an ion beam from a magnetized plasma behaves differently as the extraction from an electro static plasma. Coupling between different planes of the 6D phase space prevents separation of 2D sub-spaces. Extended diagnostics are required to measure and to visualize the resulting 4D and the 6D phase space.

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