STUDY ON SPACE CHARGE COMPENSATION OF LOW ENERGY HIGH INTENSITY ION BEAM IN PEKING UNIVERSITY*

S. X. Peng[1, †], A. L. Zhang[1, 2], H. T. Ren[1], T. Zhang[1], J. F. Zhang[1], Y. Xu[1], J. M. Wen[1], W. B. Wu [1], Z. Y. Guo[1], J. E. Chen[1,2]
[1]State Key Laboratory of Nuclear Physics and Technology & Institute of Heavy Ion Physics, School of Physics, Peking University, Beijing, China
[2]University of Chinese Academy of Sciences, Beijing, China

Abstract

To better understand the space charge compensation processes in low energy high intensity beam transportation, numerical simulation and experimental study on H^+ beam and H^- beam were carried out at Peking University (PKU). The numerical simulation is done with a PIC-MCC model [1] whose computing framework was done with the 3D MATLAB PIC code bender [2], and the impacts among particles were done with Monte Carlo collision via null-collision method. Issues, such as beam loss caused by collisions in H^+, H^- beam and ion-electron instability related to decompensation and overcompensation in H^- beam, are carefully treated in this model. The experiments were performed on PKU ion source test bench. Compensation gases were injected directly into the beam transportation region to modify the space charge compensation degree. The results obtained during the experiment are agree well with the numerical simulation ones for both H^+ beam [1] and H^- beam [1]. Details will be presented in this paper.

INTRODUCTION

The space charge compensation occurred by tapping opposite polarity of the particles could come from the secondary particles produced by gas ionization or supplied by specific device. For gas ionization, it takes time for a particle of the beam to produce a neutralizing particle on the gas. It is expressed as,

$$\tau = \frac{1}{\sigma_i n_g \beta_B c} \tag{1}$$

where σ_i is the ionization cross section of the incoming particles on the gas and n_g is the gas density in the beam line. The gas space charge compensation only applies to those beam whose pulse length is longer than τ, for example CW beam or long-pulse beam. For those short pulsed beam, the opposite polarity of the particles should be initiatively provided and sustained by specific device without transient time limit, such as Electron Volume [3] and Gabor Lens [4]. In this paper, we will focus on the space charge effect and space charge compensation of CW beam and long-pulse beam. Study on space charge compensation can help us to understand the processes during the compensation and guide accelerator design. Experiment research as well as numerical simulation are complementary ways on this study. To simulate the process of space charge compensation within an ion beam, the space charge effect should be treated by taking into account either through a linear analytical model or by treating the beam fully three-dimensional through particle-in-cell (PIC) methods. At PKU, a Monte Carlo collision (MCC) [5] package including the null collision method has been developed as an addition to the usual PIC charged particle scheme. This PIC-MCC code done with 2D MATLAB code has been used to simulate the space charge compensation of H^+ beam. The simulation results had a good agreement with the experimental ones when dealing with Ar compensating H^+ beam [1]. Recently, this PIC-MCC simulation code was improved to 3D model and had been used in the H^- beam after considering the difference of positive and negative ion beams [2]. Again, the results obtained by H^- beam experiment were coincident well with the numerical results. Space charge effect and space charge compensation, and experiment and simulation of space charge compensation will present in the paper.

SPACE CHARGE EFFECT

Space charge is the most fundamental of the collective effects whose impact generally is proportional to the beam intensity. The defocusing force of space charge effect will lead to emittance growth ($\Delta\varepsilon_{rms}$) [5]. It can be expressed by the generalized perveance K,

$$\Delta\varepsilon_{rms} = \sqrt{\varepsilon^2_{rms,final} - \varepsilon^2_{rms,start}} = \sqrt{\frac{<X^2>K\Delta W_{nl}}{8}} \tag{2}$$

Here X is the position of the ions in the beam, ΔW_{nl} is the normalized non-linear field energy which mainly determined by the density distribution of the ion beam. The generalized perveance K, a dimensionless parameter, is defined as,

$$K = \frac{qI}{2\pi\epsilon_0 m_0 c^3 \beta^3 \gamma^3} \tag{3}$$

The perveance K refers to the magnitude of space-charge effects in a beam, and it will largely determine the particle trajectories in drift region. In equation (3), I is the density of the beam, while we approximate that $\Delta W_{nl} \propto I$, from equation (1) we get $\Delta\varepsilon_{rms} \propto I$, which means the emittance growth is proportional to beam current.

Figure 1 showed the perveance K under different energy in several high current projects [6]. As shown in Fig. 1, in low energy region (100 keV) the perveance K is 5×10^{-3}, five orders higher than that in the high energy region (100 MeV). From equation (1) we know that $\Delta\varepsilon_{rms}$ is proportional to $\sqrt{K}$. This means the emittance

---

*Work supported by the National Natural Science Foundation of China (11575013, 11305004)

†E-mail address: sxpeng@pku.edu.cn.

ISBN 978-3-95450-178-6

growth $\Delta\varepsilon_{rms}$ caused by space charge effect in low energy is hundreds times larger than it in the high energy region. Therefor the following discussion will focus on the low energy part of accelerator.

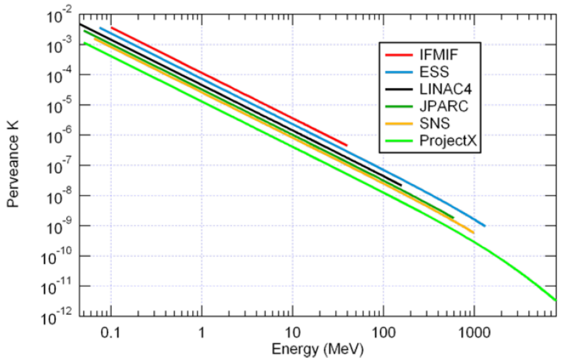

Figure 1: The perveance K under different energy in several projects [6].

Low energy beam transportation (LEBT) is a beamline that connects ion source and the accelerating structure whose energy is usually tens kV to hundreds kV. Emittance growth will be the significant problem according to Figure 1 and equation (2). The space charge in LEBT of the high intensity accelerators should be compensated carefully.

SPACE CHARGE COMPENSATION

The most common way for space charge compensation in low energy parts of accelerator is gas ionization, and the gas could come from residual gas or initiatively injecting. Figure 2 is an example [7]. When a proton beam is propagating through the gas of the beam line, the proton beam will ionize the molecules of residual gas or injected gas within the vacuum pipe, the electrons will be absorbed to the beam core while the ions are expelled from the beam core, this results that the beam will be neutralized, it's so called space charge compensation.

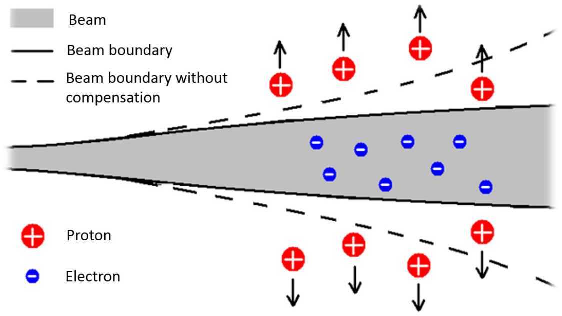

Figure 2: Proton beam compensated with gas ionization [7].

The space charge compensation can be particularly different from each other under different electromagnetic environment. The ions that generated within an ion source body are formed as an ion beam through a beam extraction system. When an extraction electric field applied on the ion source, the wanted sign particles will be extracted from the plasma while the opposite charge particles will be decelerated and reflected towards the plasma. To avoid the compensating particles lost towards the ion source, an accel-decel extraction system has to be used in GSI [8]. The experimentally observed beam profiles using viewing targets and the simulation using the three-dimensional 3D simulation code KOBRA3-INP [9] have a good agreement. Figure 3 showed a simulation result concentrating on magnetic field line and extraction aperture from KOBRA3-INP.

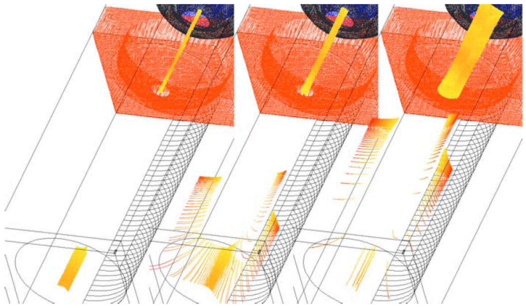

Figure 3: Magnetic field lines going on different radius through the extraction aperture:1 mm, 2 mm, and 6 mm [9].

Once the beam is extracted from the ion source, it has to be transported and matched by the low energy beam transportation (LEBT) to the first accelerating structure such as a RFQ. The focus can be done with electrostatic or magnetic elements [10].

Electrostatic LEBT mainly consists of axisymmetric electrostatic focusing components. The lenses are affecting the beams by the electric field they generated so to adjust the beam transmission parameters to achieve the goal of matching the beam emittance with the cavity acceptance. The electrostatic LEBT is compatible with fast beam chopping as there is no transient time for the space charge compensation. The beam is propagating in electrostatic LEBT without any space charge compensation because the neutralizing particles are repelled by the electric field induced by the focusing elements. The injector developed by PKU for the DWA (Dielectric Wall Accelerator) [11] is a typical electrostatic injector, which consists of an ion source and a 20 cm six electrodes LEBT. The SNS (Spallation Neutron Source) injector shown in Figure 4 is composed by an H$^-$ ion source with a 12 cm long electrostatic LEBT equipped with two Einzel lenses.

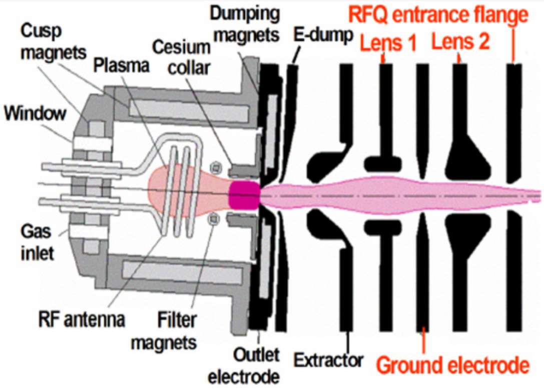

Figure 4: The electrostatic LEBT of SNS [12].

Nowadays, it is commonly accepted that an optimal LEBT for high current accelerator applications consists of focusing solenoids with space charge compensation. Such magnetic LEBT is spark free and low sensibility to beam loss, and beam diagnostics and mass separation can be easily inserted. However, the pulse rise time in magnetic LEBT which dominated by the transient time of the space charge compensation should be no shorter than hundreds of μs. Two-solenoid Magnetic LEBTs have been successfully used for high current (>100 mA) proton beam [13, 14]. Figure 5 showed a schematic view of the designed two-solenoid magnetic LEBT in SNS. It consists of solenoids S1 and S2 that focus the H^- beam into the RFQ entrance at the right, separated by 50 cm used for pumping and beam diagnostics.

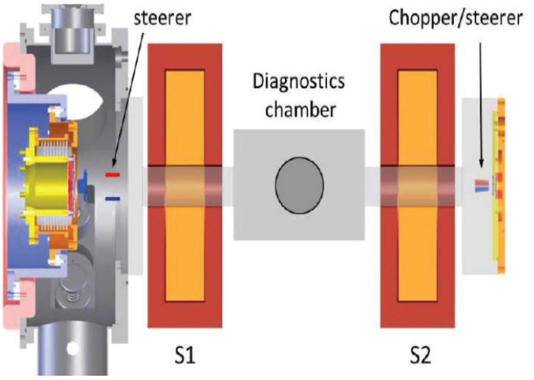

Figure 5: The two-solenoid magnetic electrostatic LEBT of SNS [15].

SIMULATION FOR SPACE CHARGE COMPENSATION

Simulation codes can take space charge compensation into account either by a linear analytical model (as for example presented in Reiser [16]) or by treating the beam fully three-dimensional through numerical simulation methods [1]. The original analytical formula about space charge compensation was presented in 1968 by Nezlin M V [17]. Then, in 1977 Gabovich published a detailed review article on the processes involved in compensation and decompensation of positive and negative high intensity ion beams considering dynamic and decompensation of the ion beams as well as collective processes in the beam plasma [18]. With the development of computer technology, numerical simulation becomes more and more reliable. Numerical simulation codes for space charge compensation had been developed in many lab, such as WARP [19] developed in Lawrence Berkeley National Laboratory (LNBL), SOLMAXP [20] which were developed at CEA/Saclay, and IBSimu [21] 3D simulation code developed at CERN. However, the collisions in those codes are not calculated accurately enough. At PKU, a PIC-MCC code concentrated on collisions had been developed in PKU. Beam loss and instability caused by collisions were careful treated within this code. Its scheme of PIC-MCC simulation is shown in Figure 6. This is similar to the input/output routines of any other numerical tool.

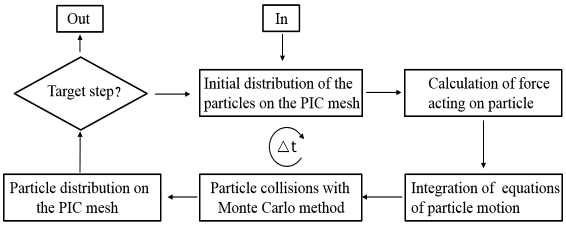

Figure 6: Scheme of the PIC-MCC simulation in PKU.

In order to verify the PIC-MCC model, experiments were performed on PKU Ion Source Test Bench. Figure 7 is a photo of this bench [22]. It consists of a set of microwave system, the permanent magnet 2.45 GHz ECR ion source, a tri-electrode extraction system, and a beam diagnostic section with a Faraday Cup (FC1) that integrates a set of slit-grid emittance measurement device. Compensation gas is injected in the same section of FC1. Mass Flow Controller was used to control the compensation gas flow.

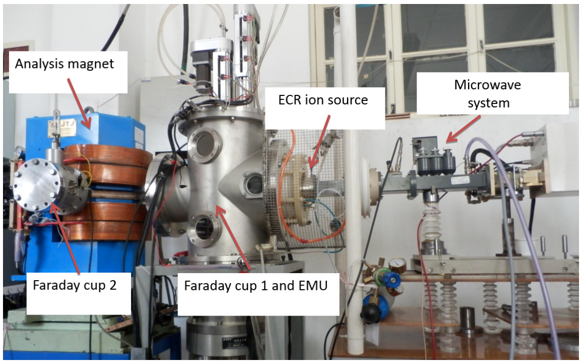

Figure 7: Skeleton diagram of PKU ion source test bench [22].

COMPARISON OF EXPERIMENTAL RESULTS AND SIMULATION ONES ON SPACE CHARGE COMPENSATION

H^+ Beam Results

The PIC-MCC model for H^+ beam is concentrate on the scattering effect which can cause particle loss. Collisions in the simple hydrogen model are,

(1) $H^+ + Ar \rightarrow H^+ + Ar$ (Elastic Scattering)
(2) $H^+ + Ar^+ \rightarrow H^+ + Ar^+$ (Electromagnetic Scattering)
(3) $H^+ + Ar \rightarrow H^+ + Ar^*$ (Excitation)
(4) $H^+ + Ar \rightarrow H^+ + Ar + e$ (Ionization)
(5) $H^+ + e^- \rightarrow H^+ + e^-$ (Electromagnetic Scattering)
(6) $H^+ + H_2 \rightarrow H^+ + H_2$ (Elastic Scattering)
(7) $H^+ + H \rightarrow H^+ + H$ (Elastic Scattering)
(8) $H^+ + H^+ \rightarrow H^+ + H^+$ (Electromagnetic Scattering)

The ionization and electromagnetic scattering (2), (3), (4), (5), (8), is included in the part of PIC. (1), (6), (7) should be calculated with MCC. Null collisions method is used to reduce the computational work.

Experiment of the space charge compensation using Ar in H^+ beams is presented in this paper. Ion beams were transported through 300 mm of drift section under various vacuum conditions. The simulation result is shown in Figure 8. Comparisons between the 2D PIC-MCC simulations (Figure.9) and the experiment showed the numerical results had a good agreement with the experiment. By studying the scattering effect, we found out an appropriate compensation circumstance to get the best efficiency in Low-energy Beam Transport.

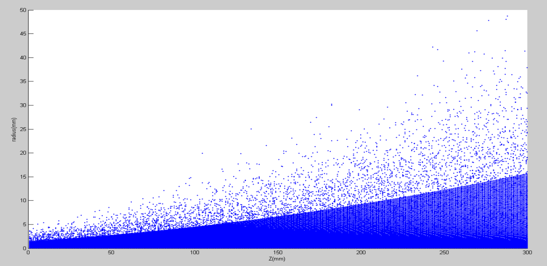

Figure 8: 2D simulation result for H^+ beam. (compensate with 0.05sccm Ar.)

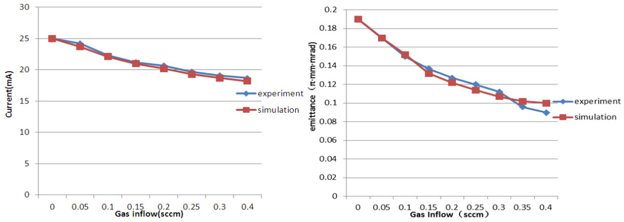

Figure 9: Current (left) and emittance (right) comparison between experiment and simulation for H^+ beam.

H^- Beam Results

The 2D PIC-MCC was improved to simulate the space charge compensation of H^- beam in PKU. The biggest difference between compensation of positive and negative ion beams are the masses of the electrons and ions produced by gas ionization. In a negative ion beam, the space charge effect is neutralized by heavy positive ions while positive beam is neutralized by light electrons. The results are that the negative beam maybe overcompensated because the ion is harder to be moved than the electrons. Experiments were done at PKU ion source test bench. Compensation gas He and Ar were injected directly into the beam transport region to modify the space charge compensation degree.

Processes in H^- beam compensated with Ar are,

$$(1)\ H^- + Ar \rightarrow H^- + Ar^*$$
$$(2)\ H^- + Ar \rightarrow H^- + Ar^+ + e$$
$$(3)\ H^- + Ar \rightarrow H^+ + Ar^+ + 3e$$
$$(4)\ H^- + Ar \rightarrow H^+ + Ar + 2e$$
$$(5)\ H^- + Ar^+ \rightarrow H^+ + Ar^+ + 2e$$
$$(6)\ H^- + H_2 \rightarrow H^- + H_2^*$$
$$(7)\ H^- + H_2 \rightarrow H^- + H_2^+ + e$$
$$(8) H^- + e \rightarrow H^+ + 2e$$

Simulations were done with the 3d particle-in-cell [23] code bender. The code provides three solvers for Poisson's equation: a 3d finite-difference Poisson solver which allows handling of boundary conditions on arbitrary geometric objects, an r-z finite-difference solver and a solver using a Fast Fourier Transform. Collisions are handled via the null-collision method. The residual gas is assumed as an ideal gas at constant temperature and pressure.

The 2D PIC-MCC was improved to a 3D MATLAB PIC-MCC code. Figure 10 showed an example of the 3D simulation result of H^- beam transport 50 mm to faraday cup. In this case, the beam focal point, the electron temperature is 10.8 eV, the max electron density on axis is about 5.8×10^{15} m^{-3}, the Debye length is about 1.7 mm and the plasma frequency is about 2.7 GHz.

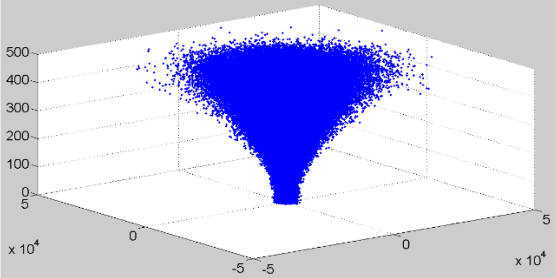

Figure 10: Simulation for H^- beam transport 50 mm to faraday cup. (x, y label represents the PIC meshgrid, z is the time step.)

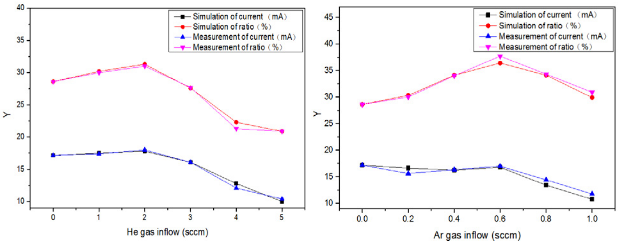

Figure 11: Simulation and experiment comparison on current and ratio for H^- beam.

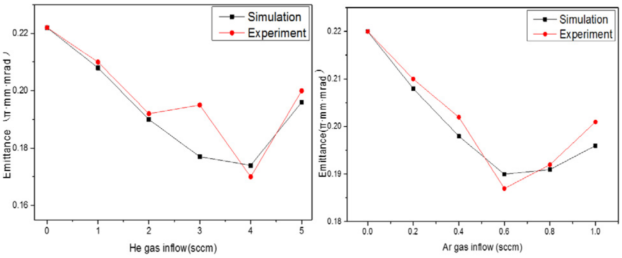

Figure 12: Simulation and experiment comparison on emittance for H^- beam. The minimum emittance is the location where it is believed the space charge compensation is optimum. For He 4 sccm, while for Ar is 0.6 sccm.

Figure 11 showed that the simulation results of current of H^- and ratio of H^- to total beam current have good agreement with the experimental ones. Emittances are calculated and compared in Figure 12. Both He and Ar can reduce the space charge effect in H^- beam transportation. However, to get the best emittance result more than 6 times He inflow (4 sccm) is needed than Ar (0.6 sccm). The simulation results agrees well with the experiments and it will help us to find a good compensation circumstance to avoid the decompensation and overcompensation region in H$^-$ beam.

SUMMARY

In this paper we reviewed the space charge compensation in LEBT. Until now, the beam dynamics simulations of LEBTs have been done with particle tracking codes. The PIC-MCC code developed in PKU had been used to model the space charge compensation, and it has a good agreement with the experiment which was performed on PKU ion source test bench. The simulation result agrees well with the experiments. That helps us to understand the process during the compensation in H$^+$ beam and H$^-$ beam, and guides us to find a good compensation circumstance to improve the transmission efficiency for LEBT. It has been demonstrated that numerical simulation code PIC-MCC developed in PKU can be used for injectors design of high intensity accelerators.

REFERENCES

[1] A. L. Zhang *et al.*, "Simulation study of space charge compensation in low energy beam transport"*, In proceedings of CPAC'14,* Wuhan, China, 2014, AT007.

[2] A. L. Zhang *et al.*, "Study on space charge compensation in negative hydrogen ion beam", *Review of Scientific Instruments,* 2016, 87(2): 02B915.

[3] V. Shiltsev et al., "The use of ionization electron columns for space-charge compensation in high intensity proton accelerators", AIP Conf. Proc. 2009, 1086(FERMILAB-CONF-08-395-APC): 649-654.

[4] O. Meusel et al., "Low energy beam transport for HIDIF". Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2001, 464(1): 512-517.

[5] N. Chauvin et al., "Simulation and measurements in high intensity LEBT with space charge compensation", 2012.

[6] J. Struckmeier et al., "On the stability and emittance growth of different particle phase-space distributions in a long magnetic quadrupole channel", 1984.

[7] P. N. Lu, "Researches of space charge compensation in low-energy-high-intensity ion beam and emittance measurement in high-power ion beam", Peking University (Nuclear technology and application) Master, 2012 :6-7.

[8] P. Spädtke, "Sophisticated computer simulation of ion beam extraction for different types of plasma generators", Review of Scientific Instruments, 2004, 75(5): 1643-1645.

[9] P. Spädtke, "TINSCHERT K, LANG R, et al., "Prospects of ion beam extraction and transport simulations (invited)", Review of Scientific Instruments, 2008, 79(2): 02B716.

[10] S. X. Peng et al., "Review on low energy high current ion injector", Journal of Anhui Normal University (Natural Science) Vol.37, No.3, May, 2014: 205-211.

[11] S. X. Peng *et al.*, "Proton injector acceptance tests for a Dielectric Wall Accelerator (DWA): Characterization of Advanced Injection System of Light Ions (AISLI)", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* 2014, 763: 120-123.

[12] R. Keller *et al.*, "Design, operational experiences and beam results obtained with the SNS H$^-$ Ion source and LEBT at Berkeley Lab", *Lawrence Berkeley National Laboratory,* 2002.

[13] M. P. Stockli, T. Nakagawa, "Ion injectors for high-intensity accelerators", *Reviews of Accelerator Science and Technology*, 2013, 6: 197-219.

[14] N. Chauvin *et al.*, "Source and injector design for intense light ion beams including space charge neutralization", *Proc. of LINAC*, 2010, TH302.

[15] B. X. Han *et al.*, "Physics design of a prototype 2-solenoid LEBT for the SNS injector", *Proceedings of the 2011 Particle Accelerator Conference*. 2011: 1564-1566.

[16] M. Reiser, "Theory and design of charged particle beams", *John Wiley & Sons*, 2008:120-124.

[17] M. V. Nezlin, "Plasma instabilities and the compensation of space charge in an ion beam", *Plasma Physics*, 1968, 10(4): 337.

[18] M. D. Gabovich "Ion-beam plasma and the propagation of intense compensated ion beams", *Soviet Physics Uspekhi*, 1977, 20(2): 134.

[19] D. P. Grote *et al.*, "The warp code: modeling high intensity ion beams", *Lawrence Berkeley National Laboratory*, 2005.

[20] R. Duperrier, "HIPPI 2008 Annual Meeting", CERN, Meyrin, 2008.

[21] C. A. Valerio lizarraga *et al.*, "Negative ion beam space charge compensation by residual gas", *Physical Review Special Topics Accelerators and Beams*, 2015, 18(8): 080101.

[22] H. T. Ren *et al.*, "Milliampere He2+ beam generator using a compact GHz ECRIS", *Science China Physics*, Mechanics and Astronomy, 2013, 56(10): 2016-2018.

[23] V. Vahedi and M. Surendra. "A Monte Carlo collision model for the particle-in-cell method: applications to argon and oxygen discharges.", *Computer Physics Communications* 87.1–2 (1995), pp. 179–198.

ISBN 978-3-95450-178-6