Space Charge Modeling for Negative Ion Beam Transport: A PIC Study

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Introduction

- Multi beam group based negative ion sources are being developed for neutral beam injectors (NBIs) in fusion reactors. The ions are extracted and accelerated as beamlet bunches/ beam groups from the source using electrostatic accelerators, and then neutralized and transported to the reactor[1].
- However, during the transport (i.e., before neutralization), the beam groups interact in the transverse direction due to their space charge (SC), deteriorating the quality of the beam (i.e., bad optics and derailed beam steering), thereby reducing effective power transport across the beamline.
- The SC interaction (Electrostatic Repulsion) of beam groups is observed experimentally in the ROBIN ion source. The repulsion between beam groups is observed to be dependent on the longitudinal charge density i.e., the ratio of beam current to beam velocity[2].

$$\frac{dQ_{beam}}{dz} = Nq = \frac{I_{beam}}{V_{beam}} \quad \text{------------ 1}$$

- The goal of this work is to develop a realistic beam transport model to investigate the role of SC interactions during transport, as well as to establish a correlation between SC interactions and accelerator parameters to optimize transport in large-scale NBIs.

[1] Graceffa, J., et al. "Assembly process of the ITER neutral beam injectors." Fusion Engineering and Design 88.9-10 (2013): 2029-2032.

[2] Dash, Sidharth, et al. "Probing into space charge interactions of negative ion beams through imaging diagnostics." Journal of Instrumentation 20.07 (2025): C07054.

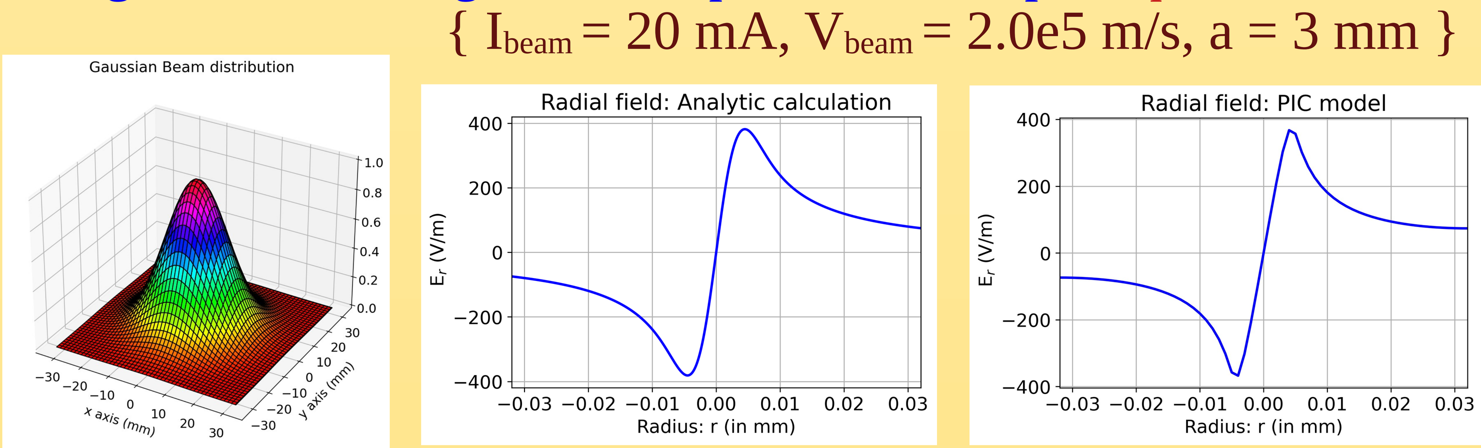
Methodology and modeling

- A 3D rectangular simulation domain (128 x 128 x 512 mm^3) with Dirichlet injection and Neumann exit boundary conditions is considered for modeling the beam transport using the IBSimu software package[3].
- The space step Δx is set at 1 mm ($\Delta x < \lambda_D$:debye length), and the time step $\Delta t < 5$ ns is considered for the simulation, satisfying the Courant-Friedrichs-Lewy (CFL) condition[4].
- The beam parameters like emittance, electrostatic potential, and electric field profiles, are tracked spatial-temporally to quantify the impact of the SC interactions. The beam velocity is in the range ~ 10^5-10^6 m/s, diminishing the effect of the magnetic field.
- Two tilted ($\theta = 1^o$) beams (top and bottom) having Gaussian transverse (x-y axes) and a uniform longitudinal (z-axis) particle distribution are injected simultaneously into the domain.
- The radial electric field due to a Gaussian transverse particle distribution under the rigid beam approximation is[5]:

$$E(r) = \frac{Nq}{2\pi\epsilon_o r}\left(1 - \exp\left(\frac{-r^2}{a^2}\right)\right) \quad \text{------------ 2}$$

- The benchmarking is performed using the analytic solution of this electric field equation (equation 2) and PIC simulation of a single beam, setting the beam parameters as per equation 1.

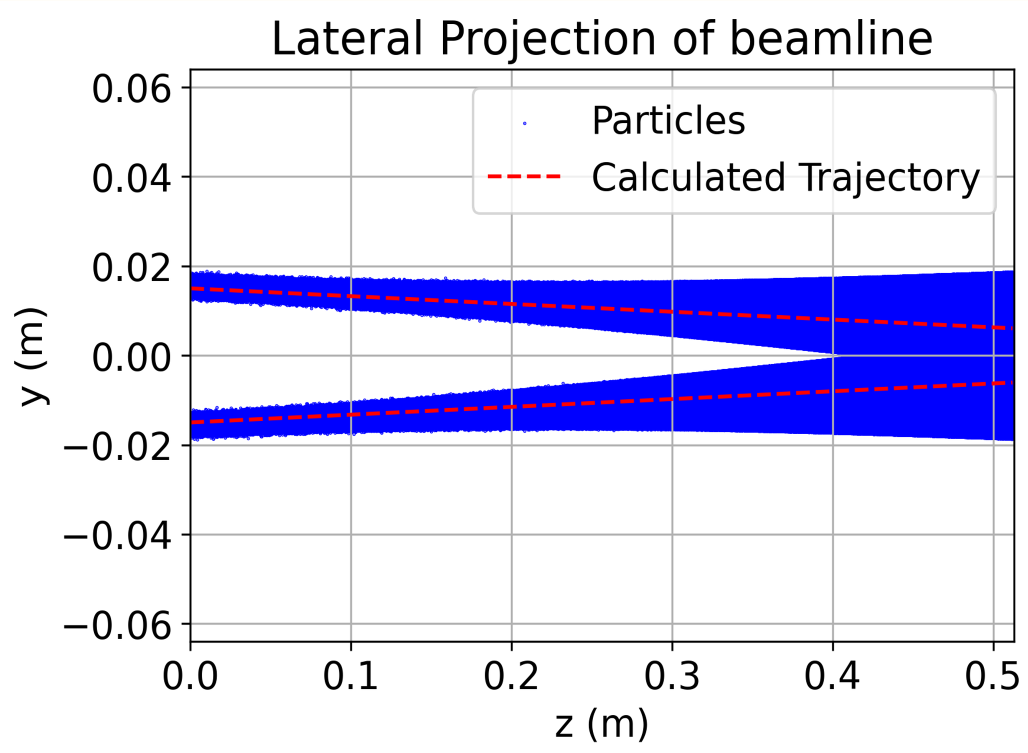
{ I_{beam} = 20 mA, V_{beam} = 2.0e5 m/s, a = 3 mm }



[3] Kalvas, Taneli, et al. "IBSIMU: A three-dimensional simulation software for charged particle optics." Review of Scientific Instruments 81.2 (2010).

[4] Valerio-Lizarraga, Cristhian A., Ildefonso Leon-Monzon, and Richard Scrivens. "Negative ion beam space charge compensation by residual gas." Physical Review Special Topics—Accelerators and Beams 18.8 (2015): 080101.

[5] Gsponer, Andre. "Physics of high-intensity high-energy particle beam propagation in open air and outer-space plasmas." arXiv preprint physics/0409157 (2004).



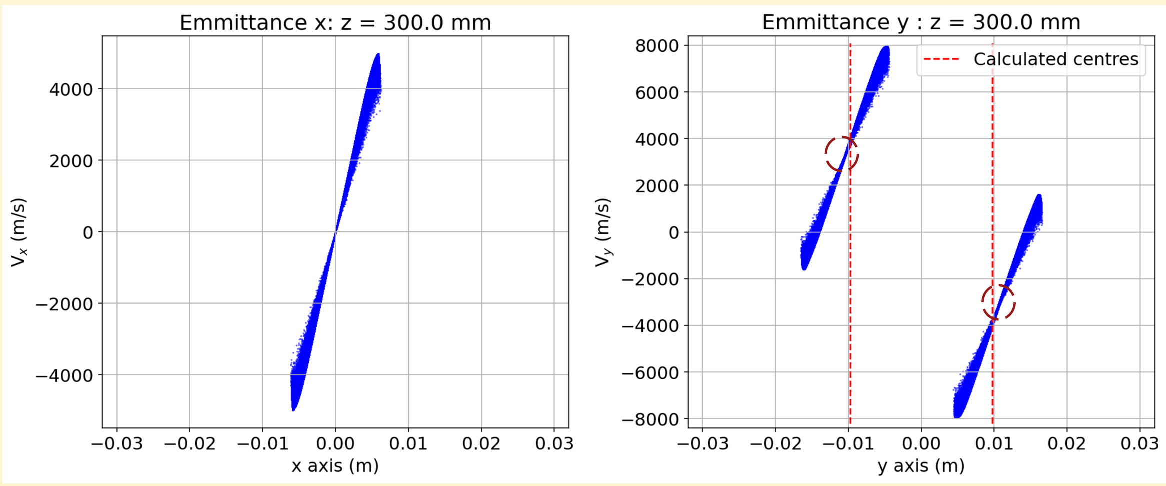
- The scatter plot for a lateral projection of the two merging beams propagating downstream with parameters:

I_{beam} = 12.6 mA, V_{beam} = 2.09e5 m/s

- The actual calculated parameters from the CL law for an extraction potential of 6 kV and acceleration potential of 15 kV, radius 4 mm, and gap 3.5 mm i.e., $I_{beam} > 100$ mA, and V_{beam} >2e6 m/s, has both been scaled down to maintain the charge density ~ 1e-7 C/m .

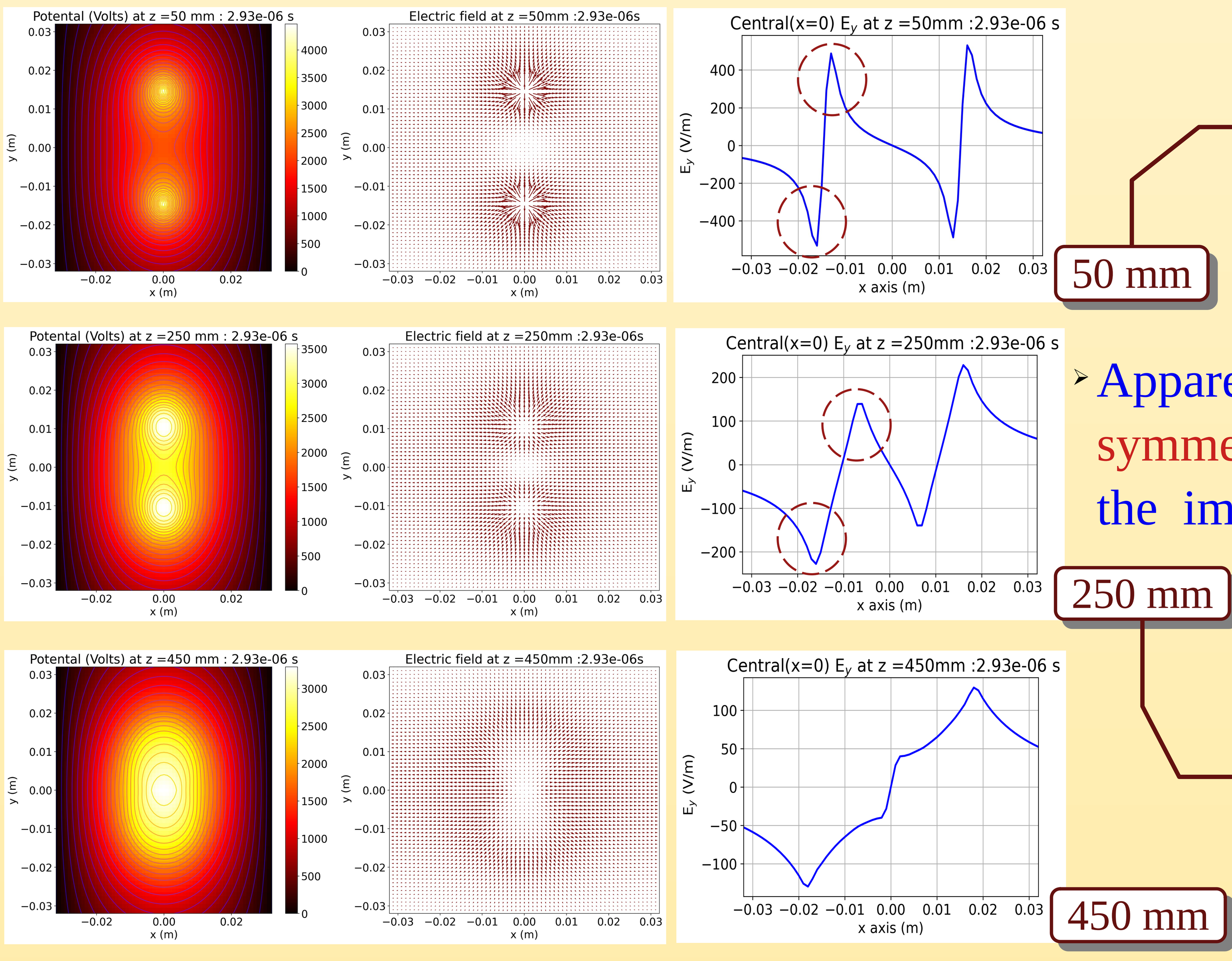
Results and Discussions

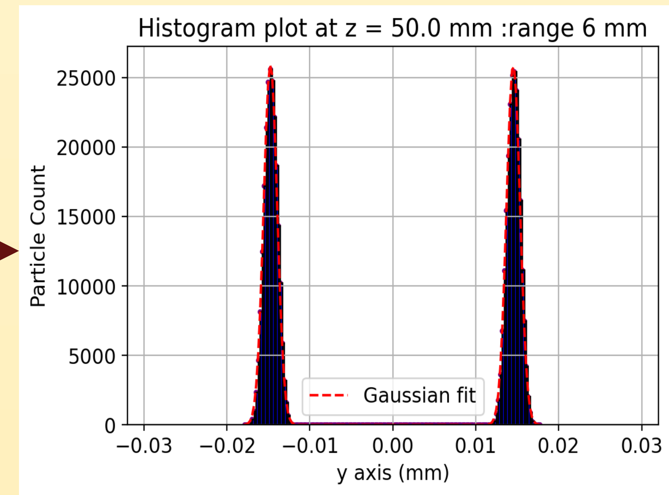
Trace Space Distribution along x and y axis



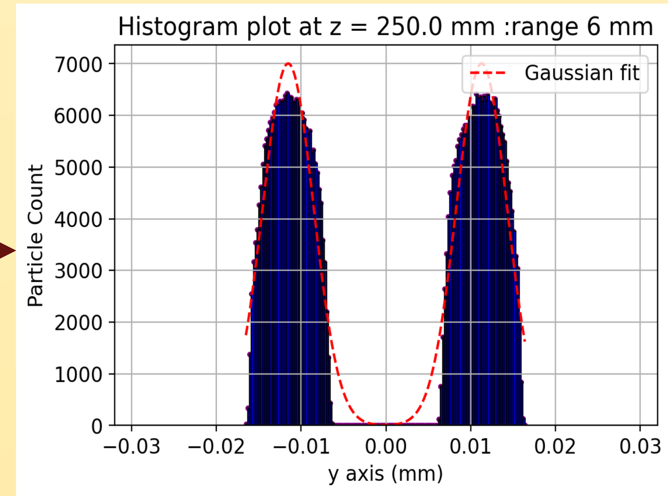
- The asymmetry in beam spread, electric potential and field profiles observed in the y (vertical) direction indicates the impact of SC interactions: additional spread in the outboard side and less spread in the inboard side.
- The central position of beams (top and bottom) seems shifted vertically when compared with the position calculated due to the introduced tilt in distributions.

Evolution of Transverse Electric Potential and Field Profiles During Transport

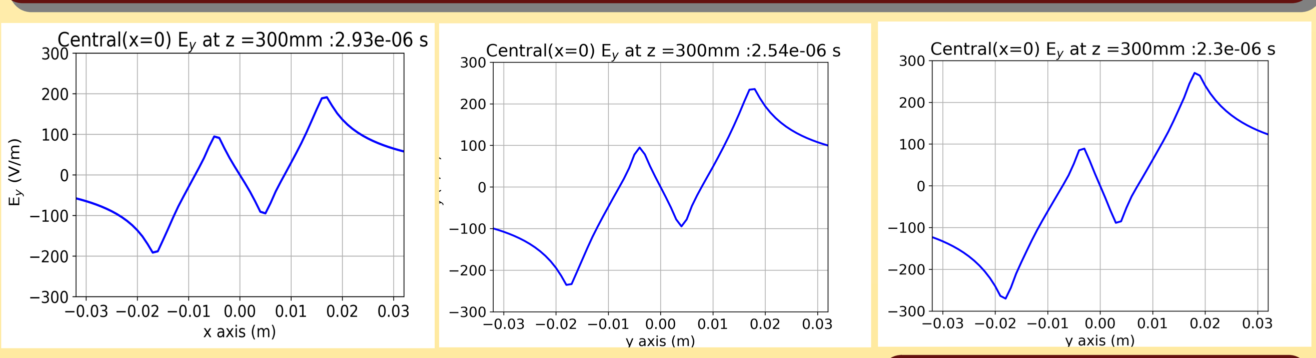




- Apparent skewness (deviation from symmetric Gaussian) is observed under the impact of SC interactions.



Tracking Field with Rise in Beam Charge Density



I_{beam} = 12.6 mA, V_{beam} = 2.09e5 m/s	I_{beam} = 16.4 mA, V_{beam} = 2.14e5 m/s	I_{beam} = 20.8 mA, V_{beam} = 2.19e5 m/s

- The vertical electric field profiles at 300 mm, mimicking the conditions of U_{ext}(Extraction Voltage) rise (6, 7, 8 kV), calculated using the Child's Langmuir law, and scaled down.
- The longitudinal charge density is kept similar to the ROBIN ion source parameters (i.e., ~ 10^{-7} C/m), where the SC forces play a more dominant role during the beam transport.

Conclusion and future work

- When two beams having Gaussian transverse distribution travel to merge, the beam-beam SC field (electric field, E_r) alters their transverse profiles. This SC interaction distorts the otherwise symmetric Gaussian shape, making the distribution appear skewed.
- The skewness rises with the beam charge density (**$Nq = I_{beam}/ V_{beam}$**), which ultimately is controlled by the accelerator parameters (Extraction and Acceleration potentials) .

In Process:

- The incorporation of space-charge (SC) neutralization into the simulation using a Monte-Carlo algorithm is currently in progress. The simulation model will be further extended to investigate real experiments in the ROBIN ion source.