ANALYSIS OF BACKGROUND PLASMA BEHAVIOR UNDER EXTERNAL FIELDS IN THE LOW ENERGY BEAM TRANSPORT SECTION OF LIPAC

[1]T. ITAGAKI, [1]T. AKAGI, [2]N. CHAUVIN, [3]L. BELLAN, [4]F. CISMONDI, [1]K. MASUDA, [4]H. DZITKO, [5]Y.CARIN

[1]QST-Rokkasho, Aomori, Japan
[2]CEA Paris-Saclay, Gif sur Yvette, France
[3]INFN, Legnaro, Italy
[4]Fusion for Energy, Garching, Germany
[5]IFMIF/EVEDA Project Team, Aomori, Japan

Email: itagaki.tomonobu@qst.go.jp

1. BACKGROUND

The International Fusion Materials Irradiation Facility (IFMIF) is an accelerator-driven intense neutron source using D-Li nuclear reaction for irradiation of potential candidate materials constituting a fusion DEMO reactor, and now the Engineering Validation and Engineering Design Activity (EVEDA) phase is ongoing under the Broader Approach (BA) agreement between Japan and the EU[1]. The Linear IFMIF Prototype Accelerator (LIPAc) is under commissioning progressively in several phases in Rokkasho, Aomori, Japan. The mission of LIPAc is to validate the acceleration of a deuteron beam of 125 mA to 9 MeV in continuous wave (CW) mode. A commissioning phase of the LIPAc called “Phase B+ has been held in 2021-2024, whose main objective was to validate the deuteron beam acceleration by RFQ up to 5 MeV at a high-duty cycle and to characterize the beam. The main outcomes of Phase B+ stage 1 (pilot beams using proton/deuteron beam) were reported at FEC2023[2], and the outcomes of whole the Phase B+ is to be reported in FEC2025[3]

An injector composed with an ECR ion source, and a low energy beam transport (LEBT) line is on the top of LIPAc beam line. Figure 1 shows the configuration of LIPAc injector. The LEBT is mainly composed with two solenoid lenses (SOL1, 2) with steering magnets (ST1, 2) to guide and focus the beam up to the RFQ entrance, a beam stopper (FC), an emittance measurement unit (EMU), and an electrostatic chopper to kick the beam vertically for short-pulsed operations. Accurate prediction of beam behaviour in the injector is crucial for safe commissioning without critical beam losses since it dominates the accuracy of beam prediction of whole the LIPAc. Background plasma in LEBT, generated by ionization of residual gas or secondary electron from beam loss, affects the beam by neutralizing its space charge force. This effect, known as space charge compensation (SCC) [4], is significant due to the high beam density in there. This study is devoted to a simulation and an analytical modelling of a part of plasma behaviour to enable accurate beam prediction.

2. SIMULATION FOR SCC IN LIPAC LEBT

To understand the effects of external fields on the plasma and the SCC in the LEBT, we performed a three dimensional particle-in-cell simulation to simulate details of the plasma behaviour of during whole transient and steady state since its analytical models are still limited like ones assuming steady state of a beam in a drift space without any external fields[5]. The simulation used the estimated profile of the proton beam from Phase B+ stage 1 commissioning. The total extracted beam current was 22 mA, including its 30 % H_2^+ subcomponent beam, under a background H_2 gas pressure of 1.2×10^{-5} mbar. Fields on SOL1,2 centres are 0.185 and 0.217 T. The simulation tracked the “kicked” beam using the chopper for 200 μs to reach a steady state, followed by 100 μs after the chopper was turned off. Electrons and H_2^+ ions from gas ionization by beam-gas collisions are used as background plasma particles, and secondary electrons from beam loss are not included in this case for simplicity.

3. RESULTS AND DISCUSSION

Figure 2 shows the simulation results including the line density distributions normalized to that of injected proton beam along the beam axis under steady state with the chopper being on as Figure 2(a) and off as Figure 2(b). When the chopper is on, the background plasma particles in the drift space around the chopper are removed as seen in Figure 2(a), and the solenoid lenses spatially limited the chopper’s effect with their plasma confinement effect. After the chopper turned off, around the chopper, the beam is defocused by its space charge force until the background plasma fulfilled and this will dominates rise time of effective beam pulse. Changes of the background electron density in the drift space at the upstream side of the first solenoid between Figure 2(a) and (b) indicates some remaining leakage path through the solenoid. Figure 3 shows time evolution of the SCC rate along the beam axis obtained from ratio of line density of charge in background plasma to that in the beams, with 15 us step after chopper turned off from the steady state shown in Figure 2(a). The 0 % case in Figure 3 means no SCC effect so that the beam is fully exposed to its own space charge force. Since the estimated rising rate of the neutralization is around 2 %/us due to the ionization and smaller than the result seen in Figure 3, we speculated that there would be some leakage through the axis of the solenoid where its radial field is so small that it cannot reflect electrons.

We tried to estimate the radius of this leakage channel based on the relationship between the magnetic and electrostatic fields. The additional rising rates due to electron flow from each side were estimated and found to be in reasonable agreement with the simulation results shown in the Figure 3.

4. SUMMARY

The particle-in-cell simulation was performed to understand the time-transient behaviour of the background plasma and the SCC effect in the LIPAc LEBT. The simulation showed that the chopper removes background plasma significantly, while solenoids limit its effect, and this impacts on SCC. Electron leakage through solenoids was observed when the chopper was off. These knowledges about characteristics of background plasma and SCC provide the essential understanding for the accurate beam prediction in the next LIPAc beam commissioning phase so called "Phase C" and promise it to be safe and successful.

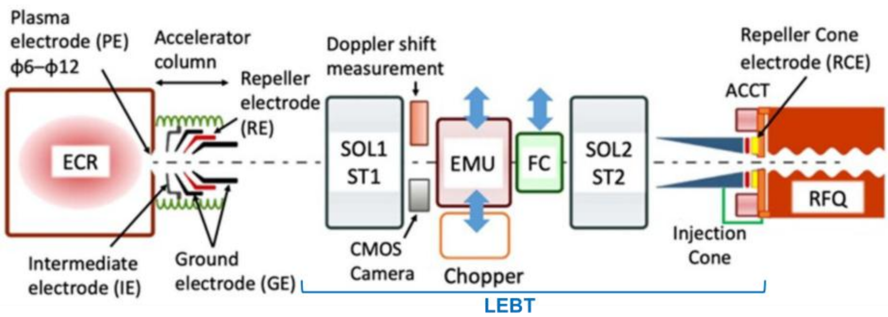

Figure 1. Configuration of LIPAc Injector

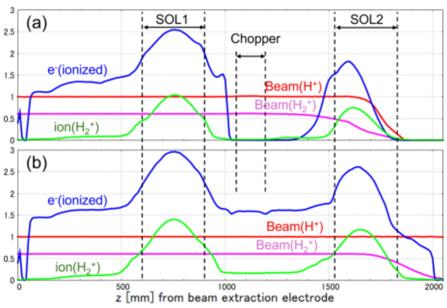

Figure 2. Linear number density of charged particles in the simulation under steady state with chopper is (a) turned on, and (b) turned off.

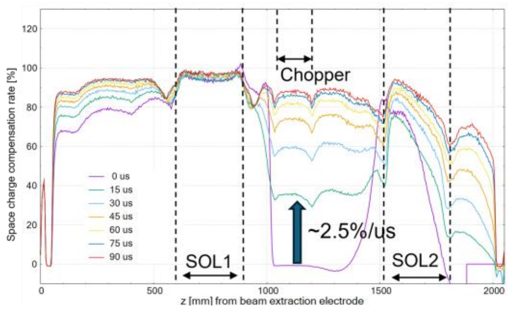

Figure 3. Time evolution of SCC rate along beam axis after the chopper turned off from the steady state of chopper turned off.

REFERENCES

[1] Y. Carin, et al., Overview of Achievements of the IFMIF/EVEDA Project, proceedings of FEC2023, IAEA-CN-316-1681 (2023).

[2] K. Masuda, et al., Beam Commissioning of Linear IFMIF Prototype Accelerator (LIPAc) Toward High-Duty Operation at 5 Mev, 125 mA D+, 29th IAEA Fusion Energy Conference (FEC2023), TEC-FNT/P1-1741.

[3] T. Akagi, et al., Accomplishment of High Duty Cycle Beam Commissioning of Linear IFMIF Prototype Accelerator (LIPAc) at 5 MeV, 125 mA D+, 30th IAEA Fusion Energy Conference (FEC2025)

[4] N. Chauvin, et al., Transport of intense ion beams and space charge compensation issues in low energy beam lines, Rev. of Sci. Instrum. 83, 02B320 (2012).

[5] D.Winklehner and D.Leitner, A space charge compensation model for positive DC ion beams, JINST 10 (2015) T10006.