Analysis of Background Plasma Behavior Under External Fields in the Low Energy Beam Transport Section of LIPAc

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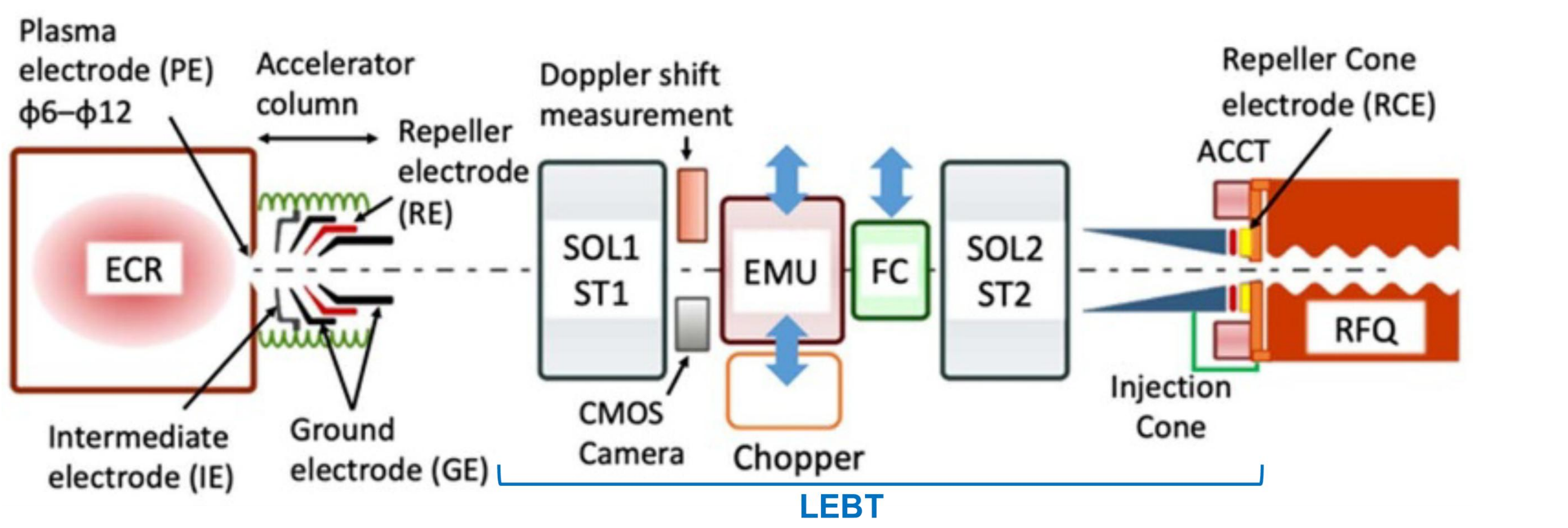
ABSTRACT

- Background plasma behaviour in the low energy transport (LEBT) section of the LIPAc is analysed with 3-dimensional particle-in-cell simulation.
- The simulation showed characteristic effects under external fields in the LEBT.
- The electron leakages through a solenoid lens is roughly estimated theoretically and compared to the simulation results.
- Results of experiments still has a mysterious transient motion of beam pulse shape not shown in the simulations, while saturated state is roughly reproduced.



Configuration of LIPAc Injector

Electrostatic / magnetostatic elements in the LIPAc LEBT:

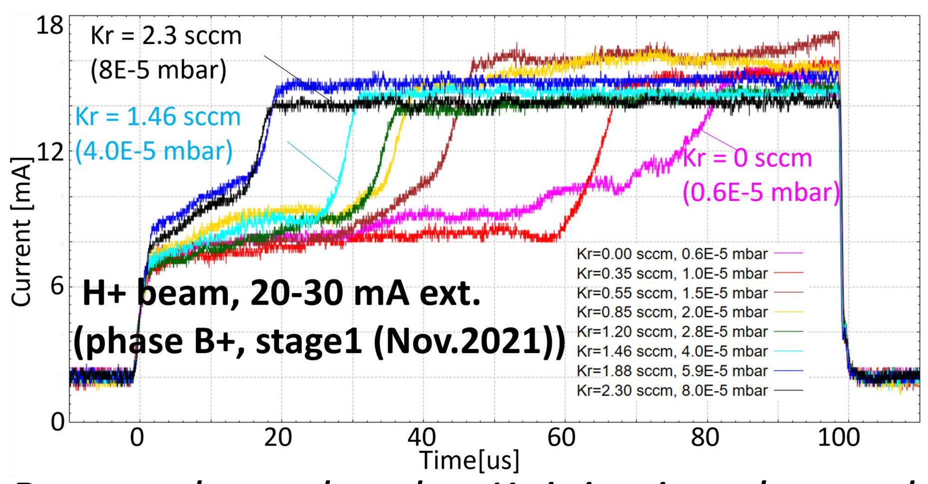
- A positive biased chopper electrodes to kick the beam except the required pulse
- Two solenoid lenses (SOL1, 2) to focus the beam for beam injection to the RFQ

BACKGROUND

- The Linear IFMIF Prototype Accelerator (LIPAc) is under commissioning progressively in QST-Rokkasho. The mission of LIPAc is to validate the acceleration of a deuteron beam of 125 mA to 9 MeV in continuous wave.
- Beam optics in LIPAc LEBT is largely affected by the background electron plasma behavior due to its space charge compensation (SCC) effect, so that its accurate prediction is important for the progress of the project.
- The background electron plasma behavior in LEBT section of intense ion beam accelerators are still not well understood so that it needs to be investigated, especially the effect of external electrostatic and magnetostatic fields to the electron plasma.

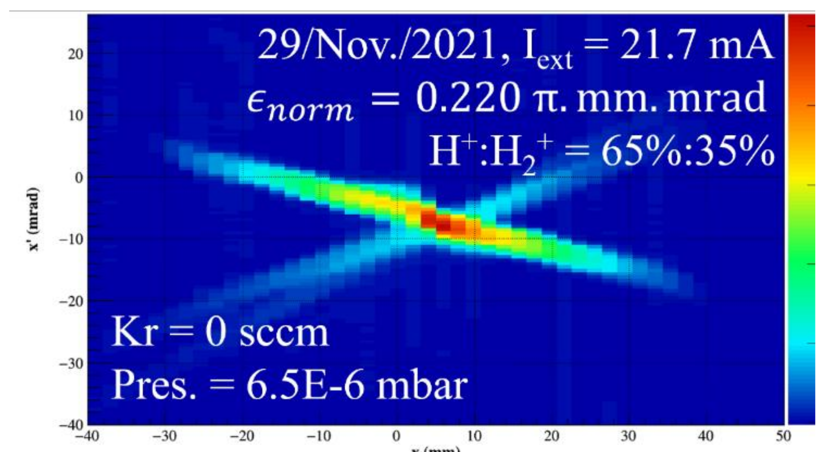
Requirements for the LIPAc injector

	D+	H+
Beam energy (keV)	100	50
Beam current (mA)	140	70
RMS emittance (π mm mrad)	<0.25 (0.3 acceptable)	<0.25 (0.3 acceptable)
Operation mode	pulse/CW	Pulse



Beam pulses related to Kr injection observed in the LIPAc commissioning in 2021.

Beam pulse shape largely affected by the background gas state due to the SCC effect.



Extracted beam profile measured on the EMU.

Initial beam profile is estimated from with another tracking code using a model of saturated SCC state in drift tube.

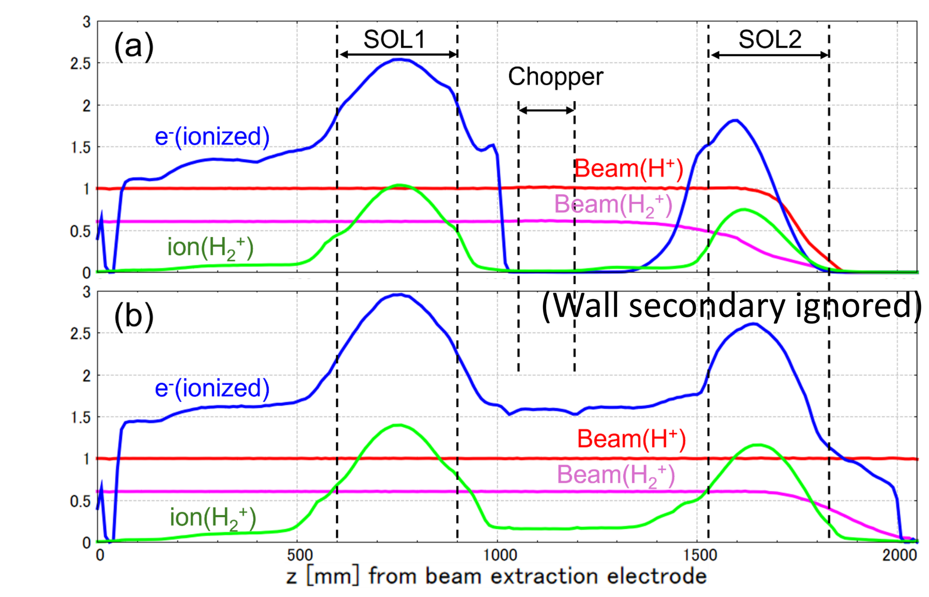
METHODS

Particle in cell (PIC) simulation

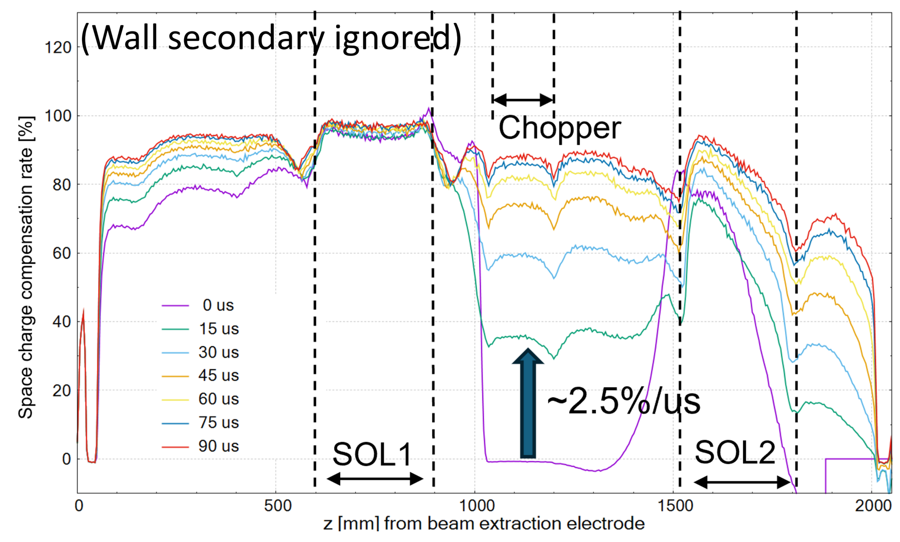
- Gas ionization and wall secondary emission by beam collisions are considered.
- The simulation is done up to saturated situation(200 us) under chopper-on. After that the chopper turned off and simulated 100 us as pulse width.
- For simplicity, detail investigation of simulation result are focused on the case without wall secondary emission.

Particles and reactions included in the simulation

Particles	Particle source	Reactions
H^+, H_2^+	Beam extraction	$H^+ + H_2$ gas → H_2^+(ionization) + e^-(ionization) $H_2^+ + H_2$ gas → H_2^+(ionization) + e^-(ionization)
e^-, H_2^+(optional)	Background gas ionization	H^+ + wall → e^-(wall secondary, SEY = 1.3)
e^-(optional)	Secondary emission from beam pipe wall	H_2^+ + wall → e^-(wall secondary, SEY = 2.6) (SEY: secondary emission yield)



Linear number densities in the simulation under steady state with chopper is (a) turned on, and (b) turned off.



Time evolution of SCC rate along beam axis after the chopper turned off.

Contribution of the electrons from gas ionization are estimated as 2.0%/μs so that the rest 0.5%/μs comes from axial electron flow-in to the chopper region

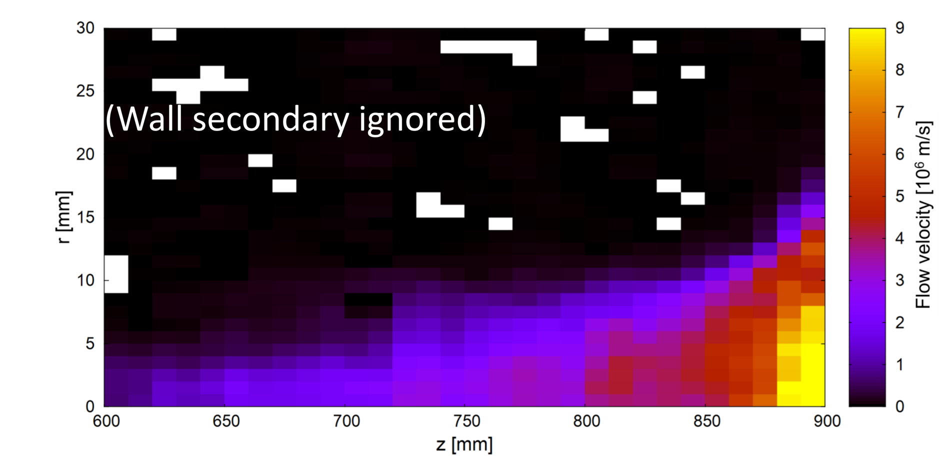
OUTCOME

Characteristic features of background electron plasma

- Working chopper absorbed electrons between solenoids.
- Background plasma is confined by the solenoid fields and SCC rate is almost stable. This indicates that the space charge is almost fully compensated.
- Electron flow to the chopper region after the chopper-off was indicated. Its theoretical estimation showed good agreement with the simulation result.

Experimental result and comparison to the simulation

- Beam current at the end of pulse was reproduced, but the transient region.
- The two-stepped shape of the experimental results related to the gas state. Comparison between the results of experiment and simulation indicates coupled situation about electron sources with different time scales.



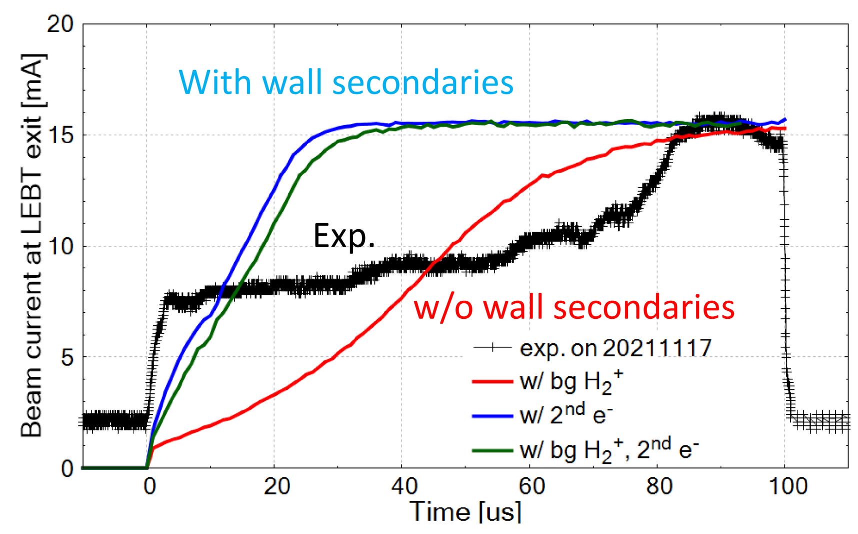
Axial frow velocity distribution simulated in the 1st solenoid

most part of electrons are still trapped by the magnetic field, except the solenoid axis.

Estimated area of leak path through SOL1

$$\pi r_0^2 \approx \frac{4\pi m_e}{e^2 B_0^2}\left(\frac{m_e u_e^2}{2} + e\Delta\phi\right) \approx 0.23\ \mathrm{mm}^2$$

Neutralization around the chopper by electron flux through the SOL1 ≈ 0.27 %/us



Comparison of the RFQ injection beam pulse between the experiment and simulations.

CONCLUSION

- Beam current at the end of pulses were well reproduced.
- The obtained knowledges about the LEBT background plasma and SCC promise the next phase of the LIPAc commissioning to be successful:
  - ➢ The chopper absorbed plasma in the surrounding drift region, that is limited by the solenoid lenses, though indicating some electron leakage through the solenoid still be there.
- To reproduce the strange two-stepped transient beam shape, further investigation of the background plasma behavior is needed. E.g. change of electron temperature, with considering Coulomb collisions, under two different sources (gas ionization and wall secondaries) exists.
  - ➢ 1D simulation with thermal electron flow model is under development.

1-dimensional model under development

Expecting fast time-tracking of density, flow, temperature of background electron plasma

Equation of continuity: $\frac{\partial}{\partial t} n_e(z,t) = (1-r) g_e - \frac{\partial}{\partial z}(n_e u_e)$

Equation of motion: $m_e n_e \frac{\partial}{\partial t} u_e(z,t) = e n_e \frac{\partial}{\partial z}\phi - \frac{\partial}{\partial z}(n_e k_b T_e) - m_e n_e u_e \frac{\partial}{\partial z} u_e$

Energy conservation: $n_e k_b \frac{\partial}{\partial t} T_e(z,t) = \mathcal{E}_{cc}(n_e) + \mathcal{E}_{ge} + \mathcal{E}_{pe}(\phi) - \left(\frac{1}{2} m_e u_e^2 + \frac{3}{2} k_b T_e - e\phi\right)\frac{\partial}{\partial z}(n_e u_e)$

Loss rate of produced electrons: $r(z) = \exp\left(-\frac{e\phi}{k_b T_e}\right)$

g_e : electron production rate; $\mathcal{E}_{ge}$: Initial kinetic energy of produced electrons

$\mathcal{E}_{cc}$: Energy transfer from beam by Coulomb collisions; $\mathcal{E}_{pe}$: Potential energy of electrons where they produced

ACKNOWLEDGEMENTS

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