HB2016—57th ICFA Advanced Beam Dynamics Workshop
on High-Intensity and High-Brightness Hadron Beams

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H- Beam Dynamics Study of a LEBT in XiPAF Project with the WARP code

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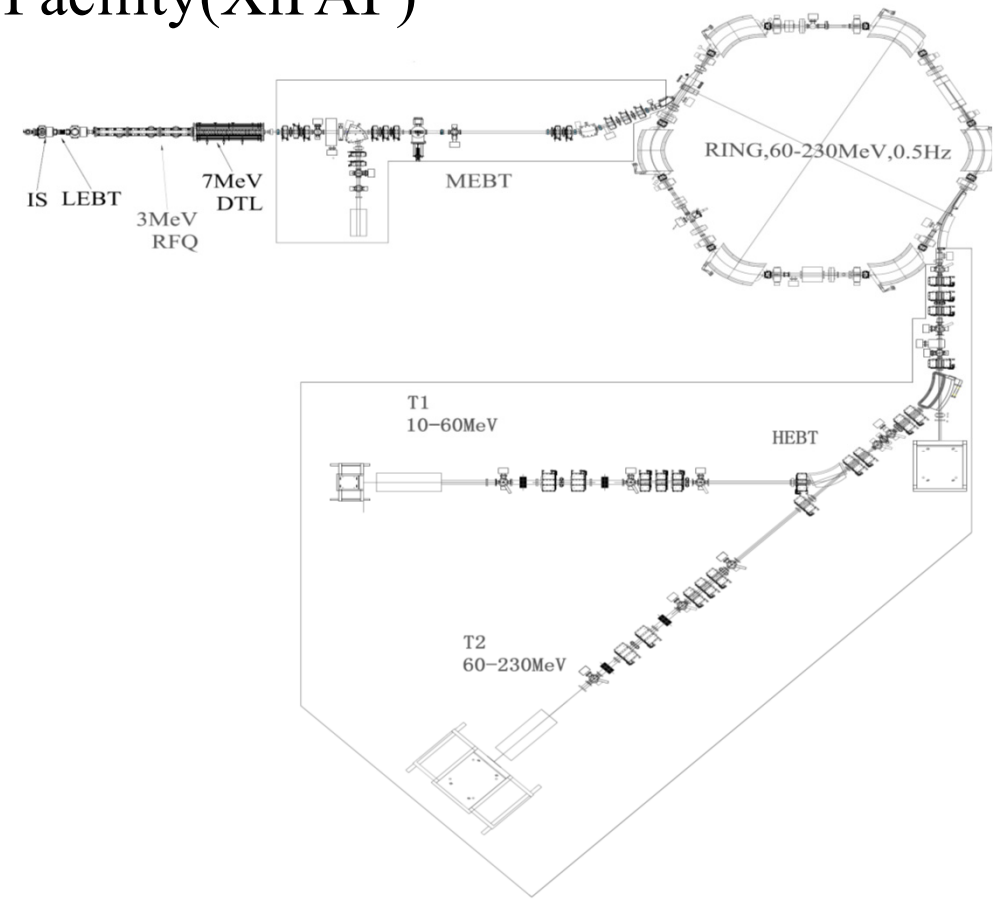
- Introduction
- Simulation Method
- Dynamics Simulation Results
- Conclusion

Introduction of XiPAF

Xi`an Proton Application Facility(XiPAF)

Parameter	Injector	Synchrotron
Ion type	H^-	Proton
Output energy (MeV)	7	60~230
Peak current (mA)	5	
Repetition rate (Hz)	0.1~0.5	0.1~0.5
Beam pulse width	10~40μs	1~10s
Max. average current (nA)	100	30
Flux (p/cm^2/s) (10×10cm^2)		10^5~10^8



S.X. Zheng et al. "Design of the 230 MeV proton accelerator for Xi'an Proton Application Facility", HB2016

Introduction of XiPAF

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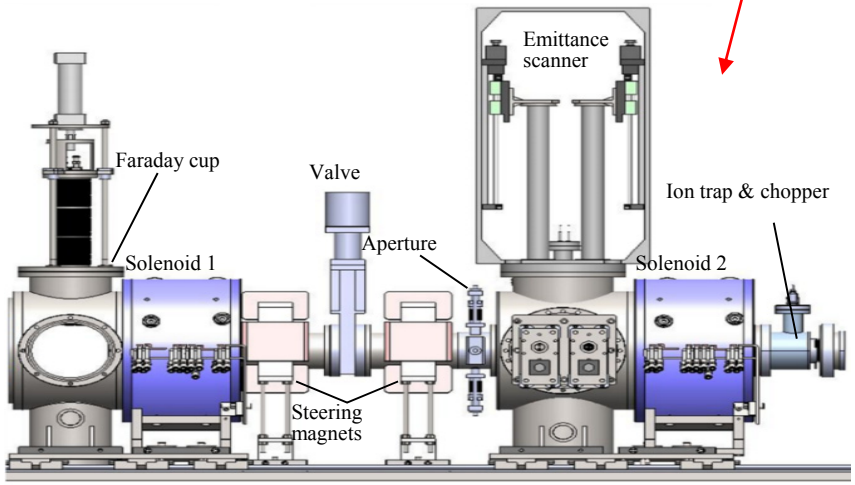

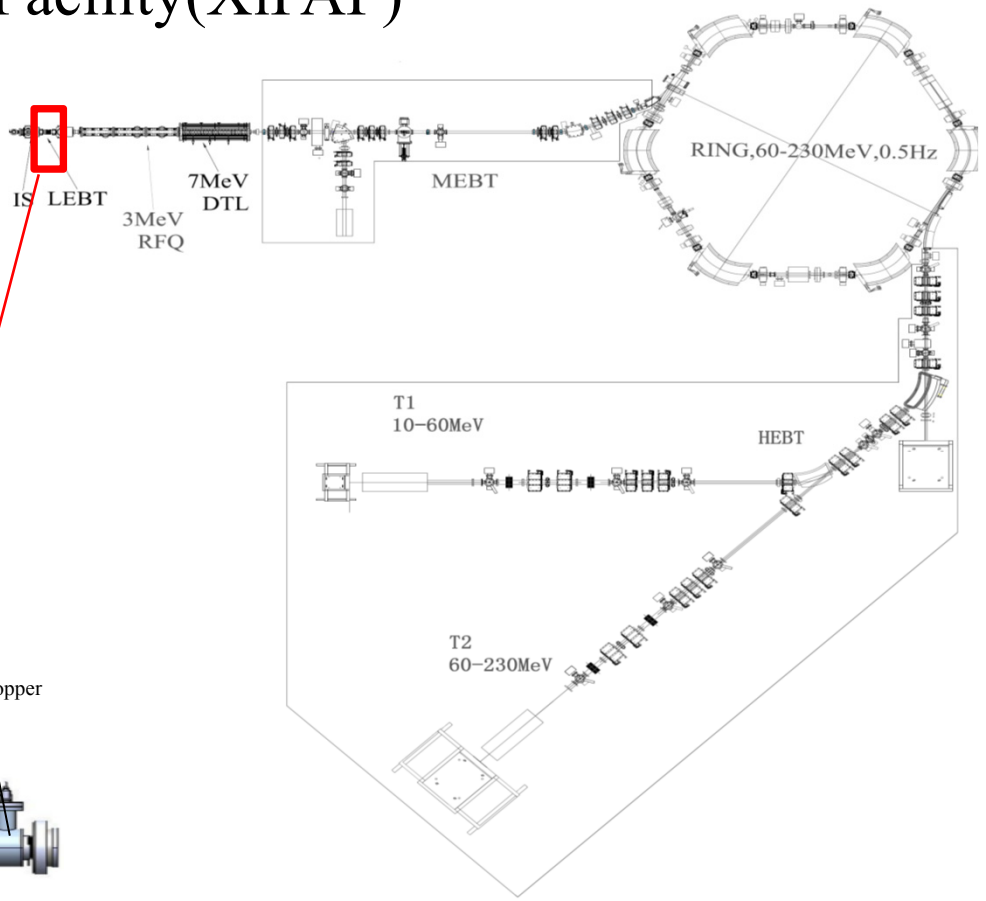

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Introduction of LEBT

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LEBT Design:

Exit of the ion source	
Particle species	H-
Particle energy	50keV
Peak current	10mA
Pulse width	1ms
α	0
β	0.065 mm/mrad
Normalized RMS emittance	0.2π mm• mrad

Entrance of the RFQ	
Particle species	H-
Particle energy	50keV
Peak current	6mA
Pulse width	40 μ s
α	1.052
β	0.0494mm/mrad
Normalized RMS emittance	0.2π mm• mrad

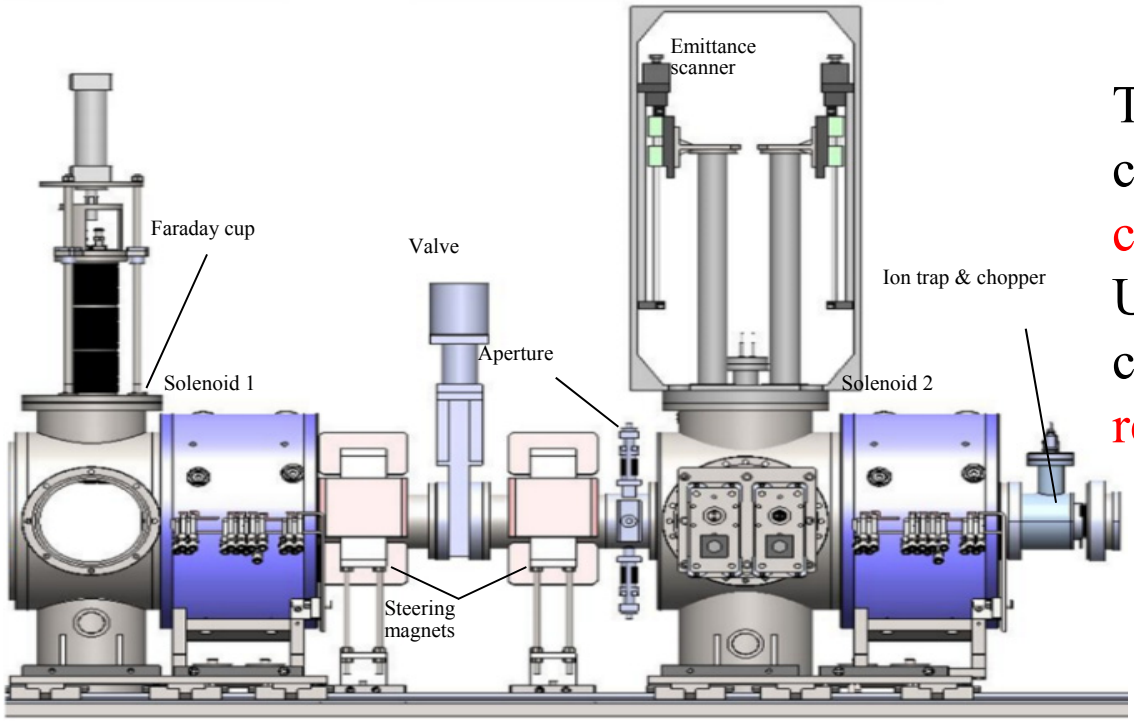
Requirement:

1. Matching of the beam Twiss parameters
2. Decreasing of the beam peak current
3. Decreasing of the beam pulse width

Introduction of LEBT

LEBT Design:

The LEBT length is about 1.7m. It is composed of two solenoids, a Faraday cup, two steering magnets, an adjustable aperture, an emittance scanner, ion trap & chopper and the vacuum systems.



The dynamics design has been carried out with Tracewin code.

Under the 85% space charge compensation assumption, the requirement is achieved.

Introduction of Warp code

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The motivation of Warp code simulation:

1, the relationship of the degree of SCC and the residual gas parameters (pressure, type) is unknown.

Beam transportation

Time control of chopper

2, the relationship of the build-up time of SCC and the residual gas parameters (pressure, type) is unknown.

Introduction of Warp code

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- Warp is a extensively developed open-source particle-in-cell code designed to simulate charged particle beams with high space-charge intensity.
- Warp was first developed by Alex Friedman in the 1980s at LLNL following a Livermore Lab model of steerable compiled code modules linked to an interpreter(https://sites.google.com/a/lbl.gov/warp/home).

There are many physics models integrated into Warp code. Considering the interaction between the beam and the residual gas in the LEBT, the relationship of the space charge compensation and the residual gas can be studied with the help of Warp code simulation.

All the simulations are based the LEBT design parameters.
Guidance on the LEBT commissioning in the future.

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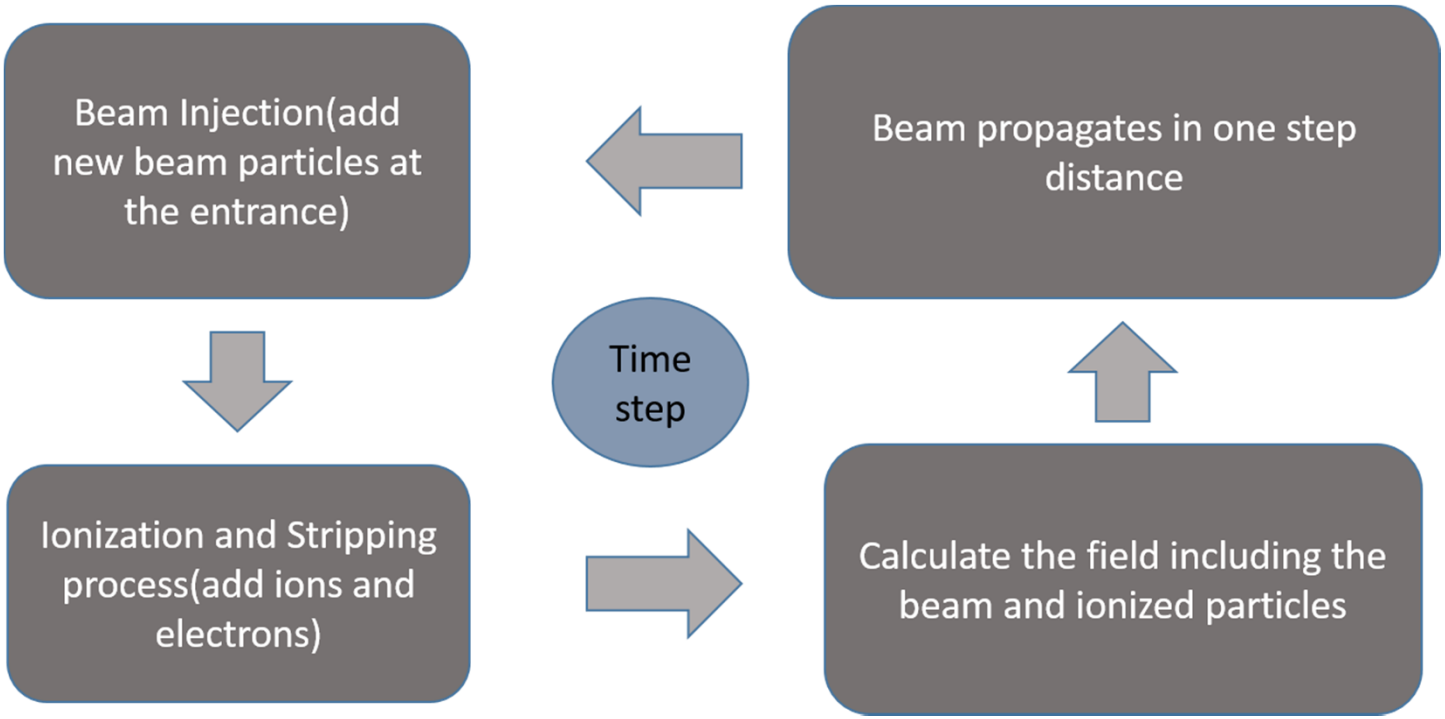
Simulation Process



Simulation Model

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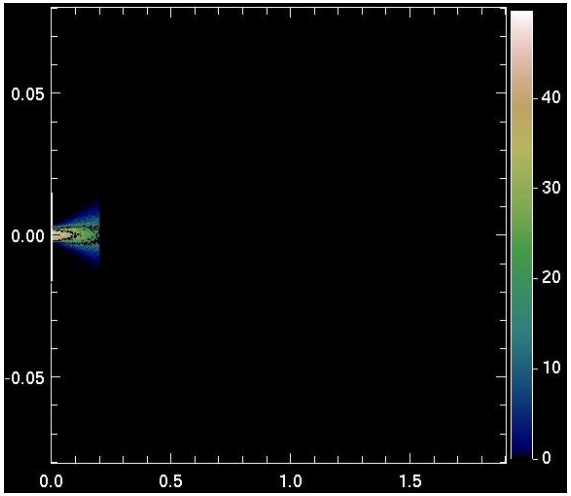
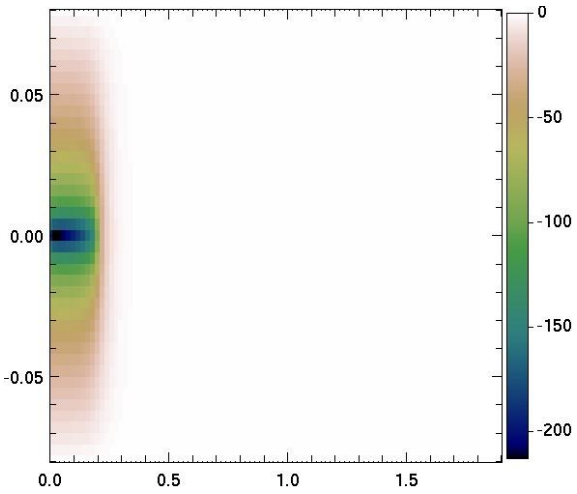
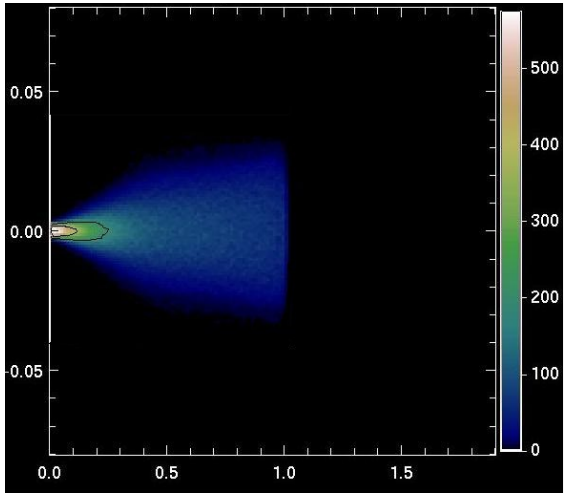
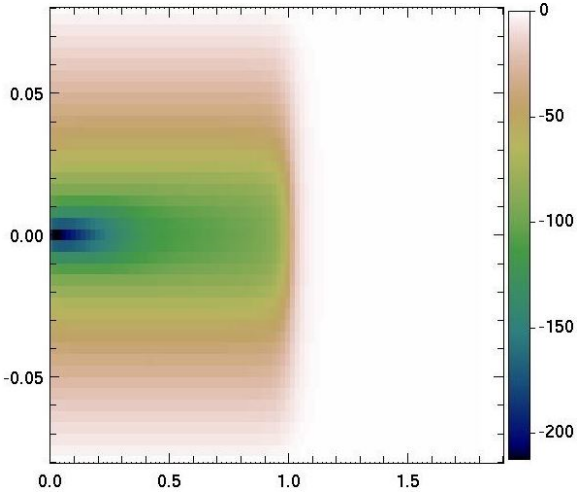
t=65ns



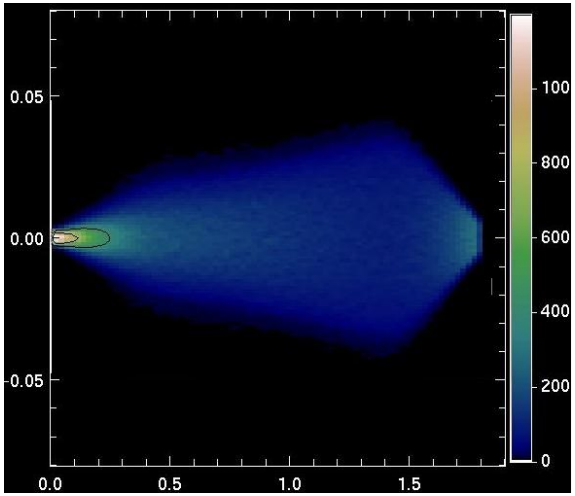


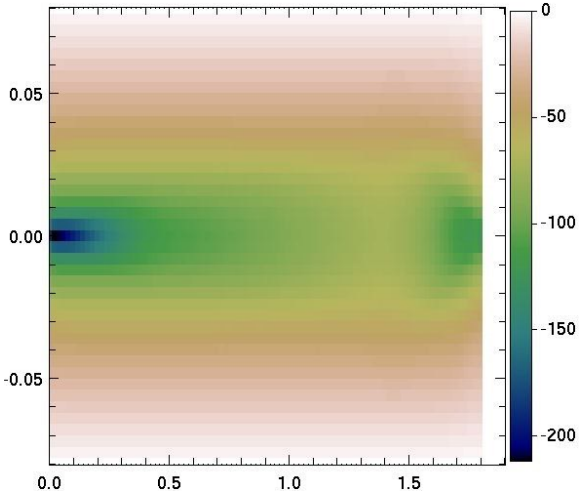
t=323ns





t=582ns





Simulation Model

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Space Charge Compensation Time: $$\tau = \frac{1}{n_g \cdot \sigma \cdot v_b}$$

Space Charge Compensation Degree: $$\eta = 1 - \frac{\emptyset_{scc}}{\emptyset_{beam}}$$

Beam particle interaction with residual gas

ionization $$H^- + X \rightarrow H^- + X^+ + e$$

stripping $$H^- + X \rightarrow H + X + e$$

Simulation Model

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Simulation Setup

50keV H- cross section data

gas	ionization (1e-16)cm^2	stripping (1e-16)/cm^2
H2	4.45	6
N2	9.77	12
Ar	10.18	15

Simulation area: R=80mm H=1800mm

Field calculation mesh size: 2mm*2mm*20mm

Time step: 6.46ns

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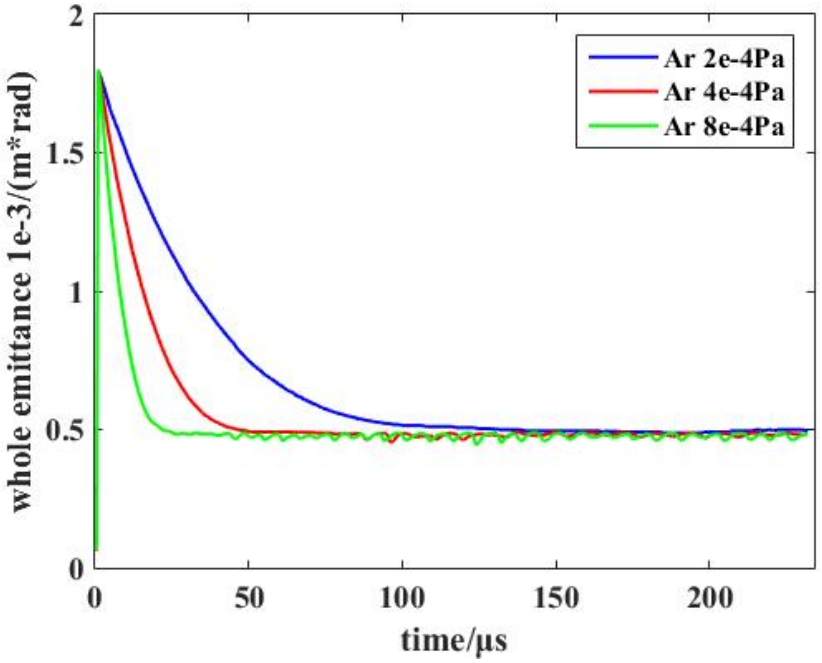
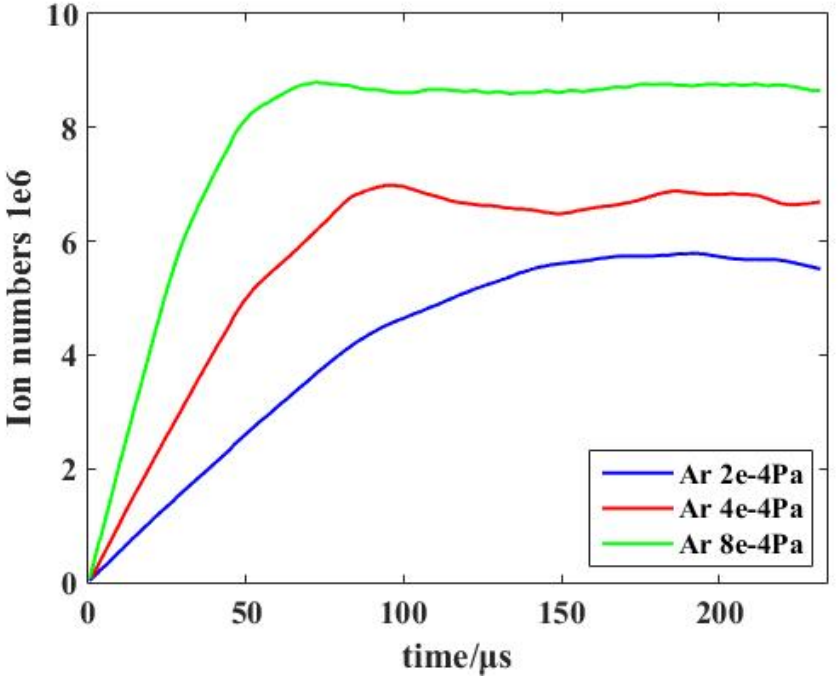
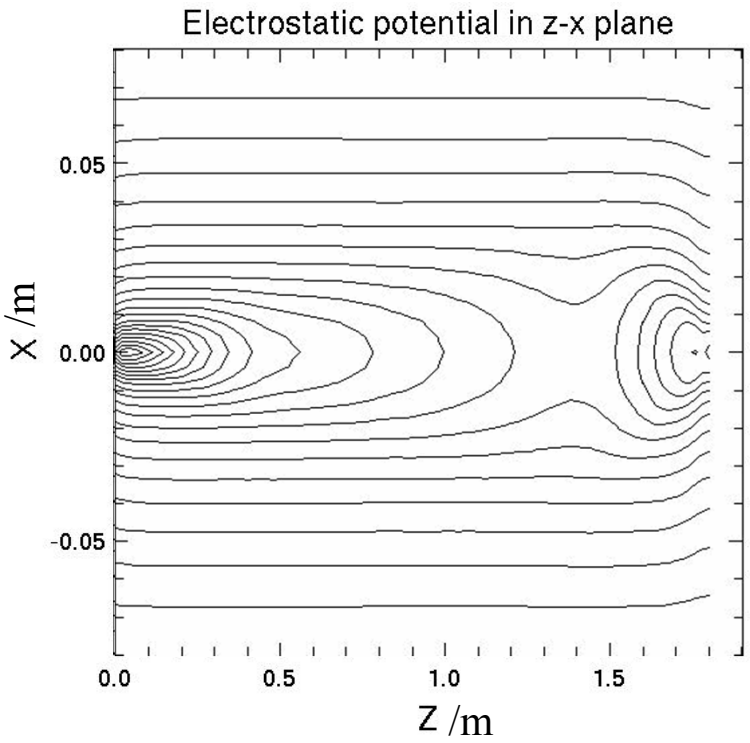
Simulation Results

Argon gas injection in three different pressure:

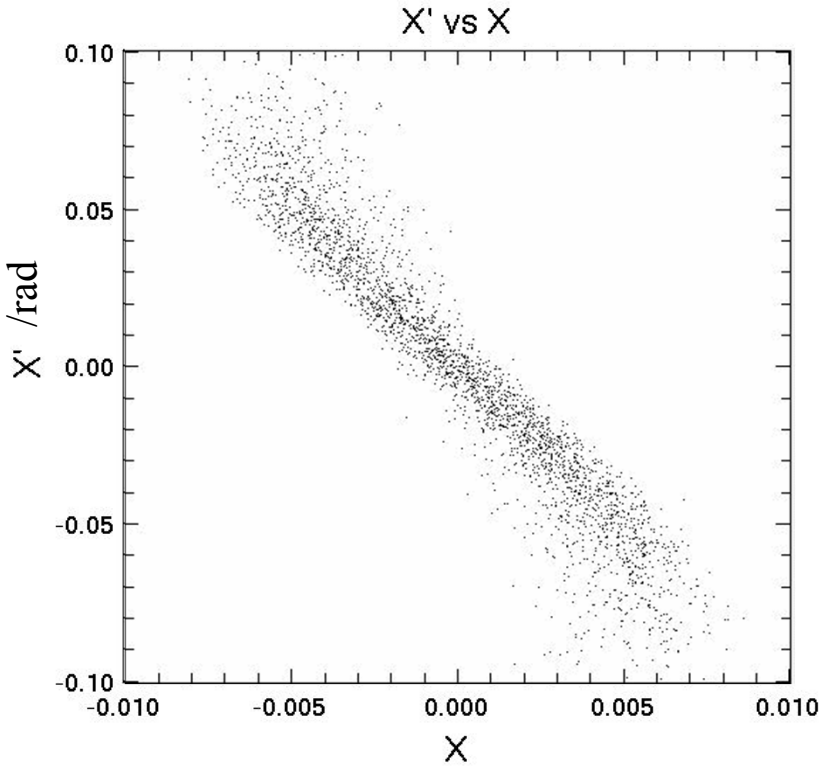




Simulation Results



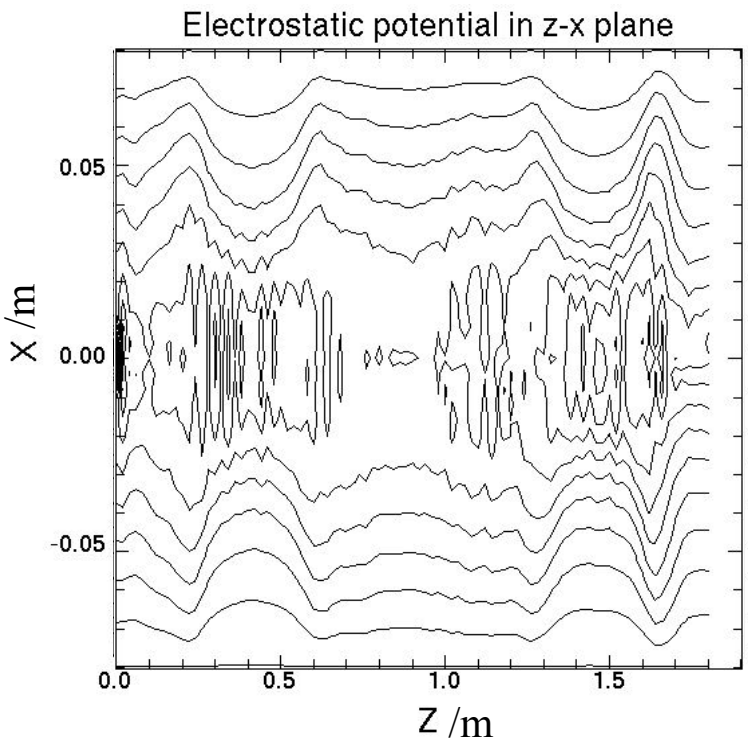
(electric potential in the LEBT simulation area)



(beam phase space in x direction at the LEBT exit)

Argon gas injection: the gas pressure is 4e-4Pa;
the time of beam transportation is 232.6μs

Simulation Results



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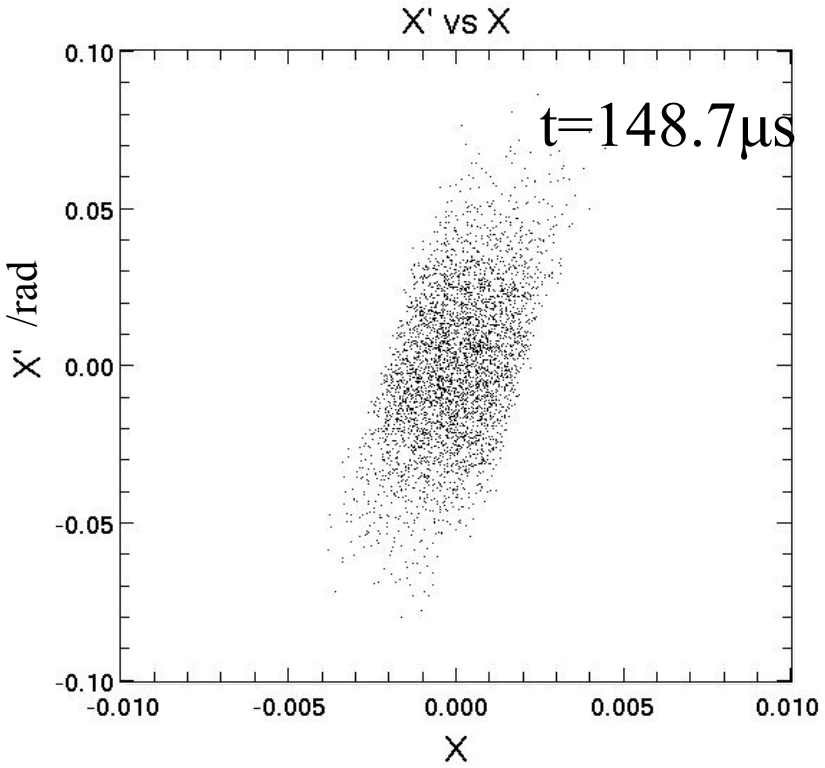

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Simulation Results

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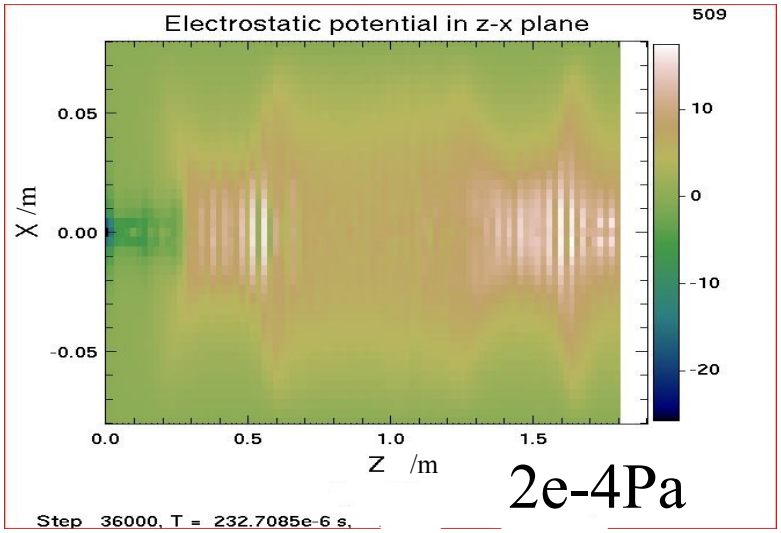
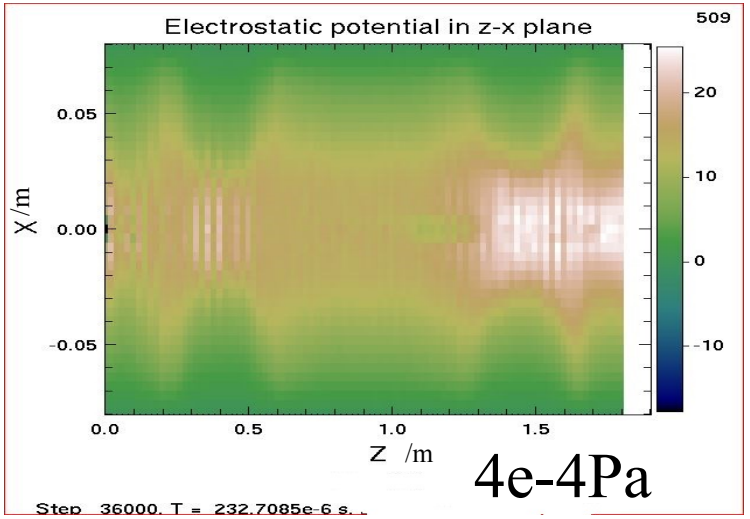
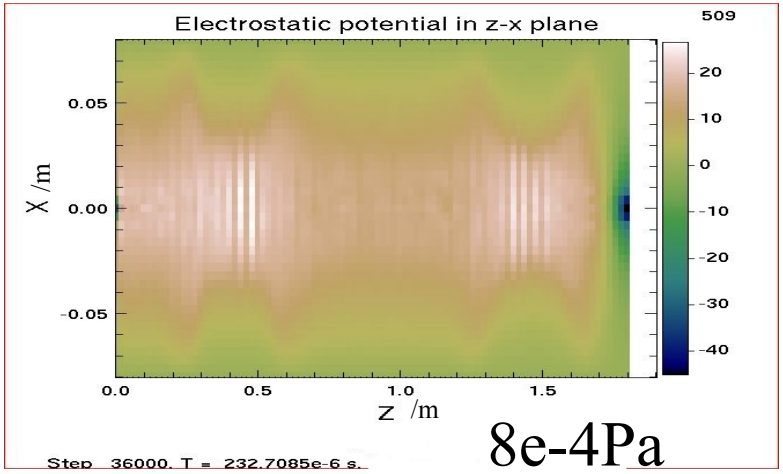
Argon gas injection in three different pressure:



2e-4Pa



4e-4Pa



8e-4Pa

All cases are over compensated, the pressure needs to be smaller than 2e-4Pa to reach ~85% SCC.

Simulation Results

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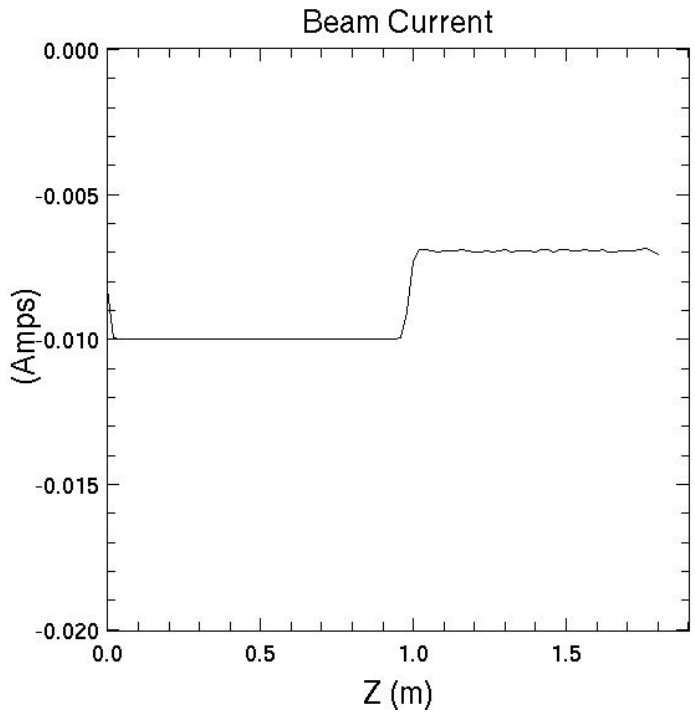
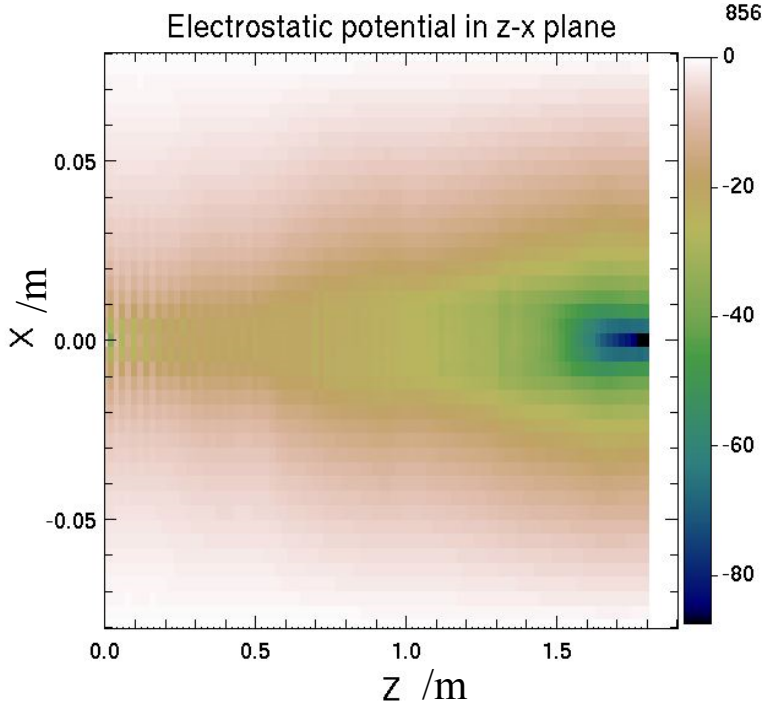
Ar gas pressure=3.5e-5Pa

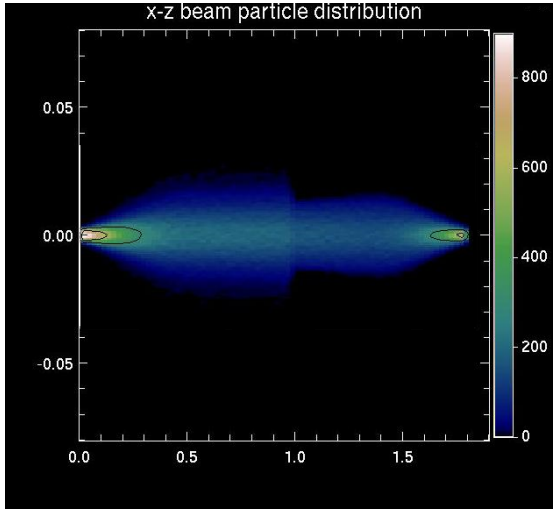


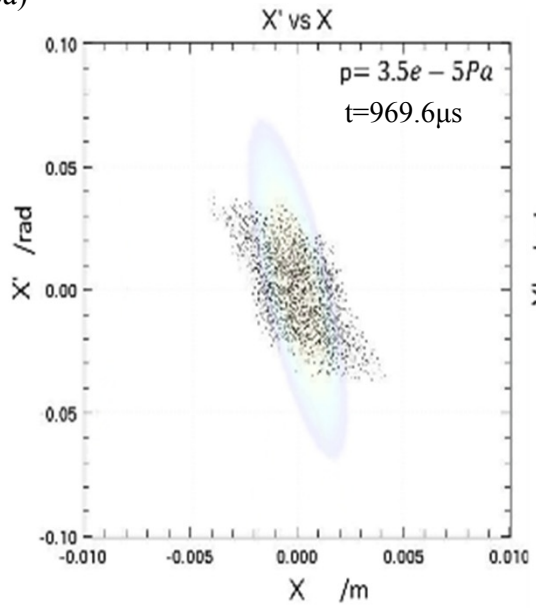


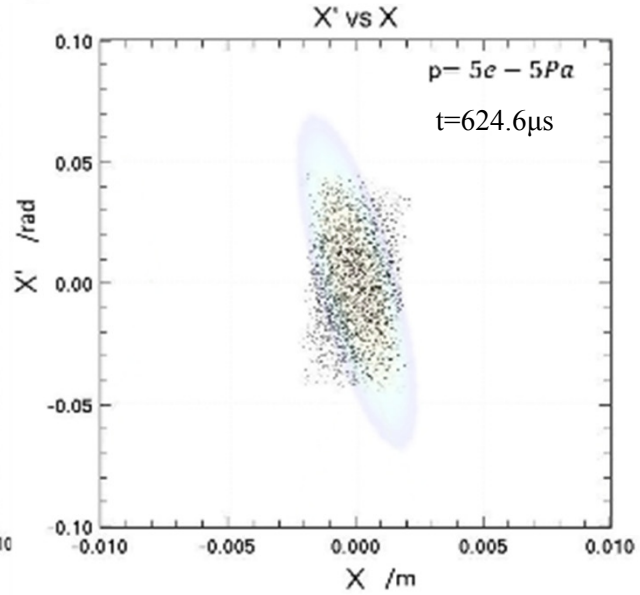
- the beam peak current at the exit is about 7mA
- the potential trap in the central area is about -30V
- the SCC degree is about 70%

Simulation Results

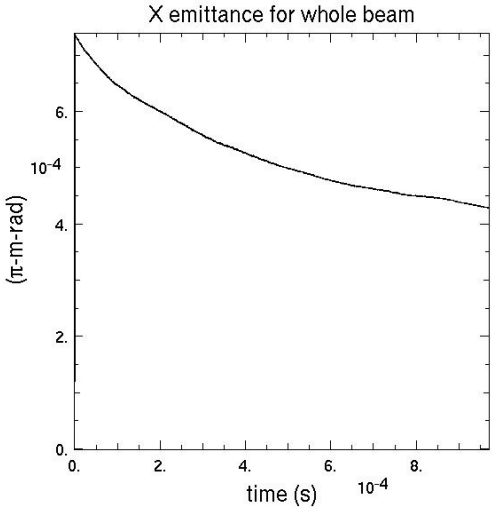
(beam envelop at t=969.6, pressure=3.5e-5pa)







(phase space at the LEBT exit, the shadow represents the acceptance of the RFQ)



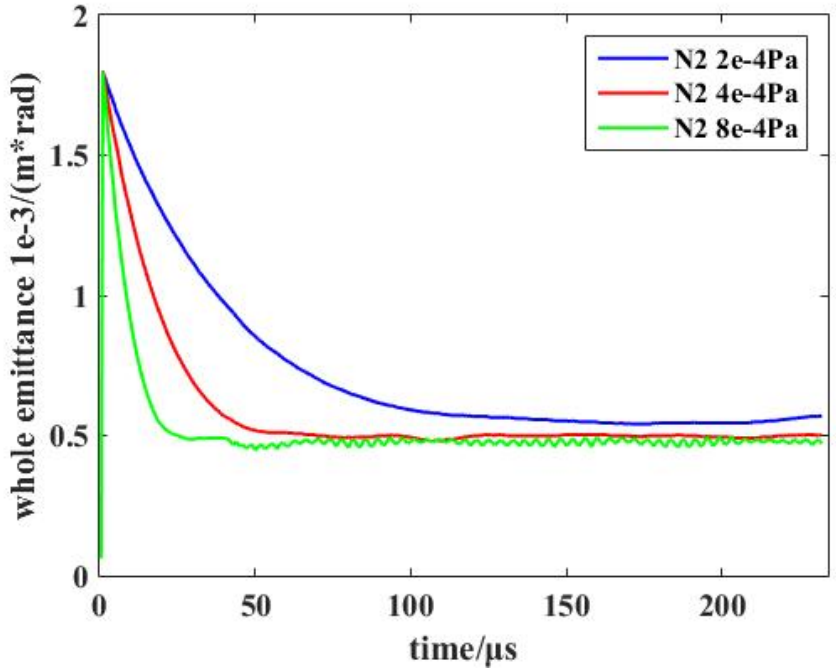
Argon gas injection:

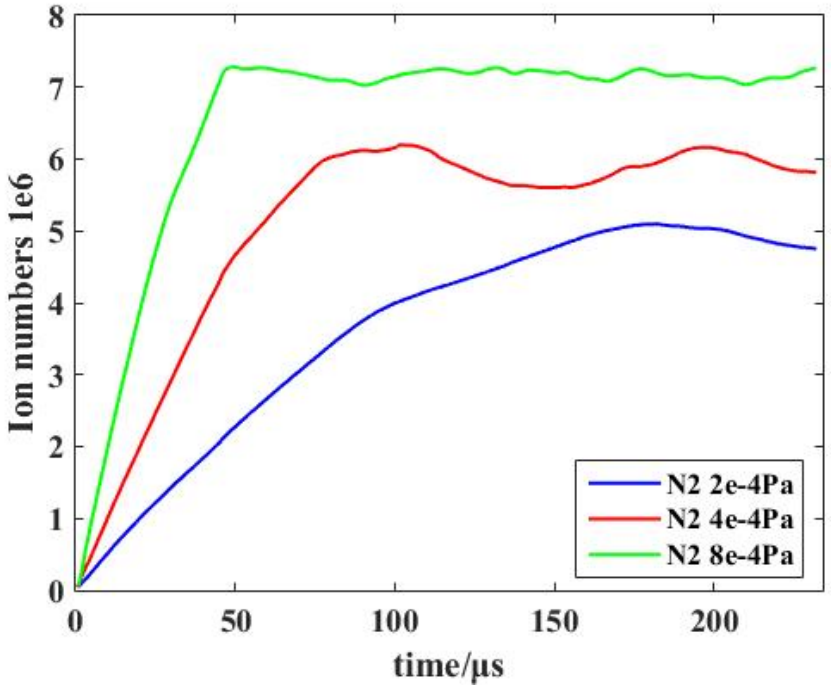
pressure range 3.5e-5Pa~5e-5Pa

SCC build-up time > 800μs

Simulation Results

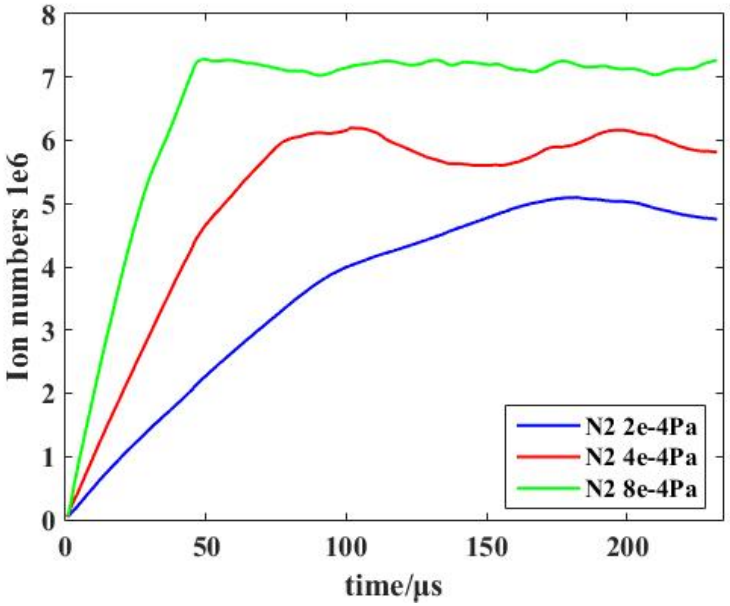
Nitrogen gas injection in three different pressure:

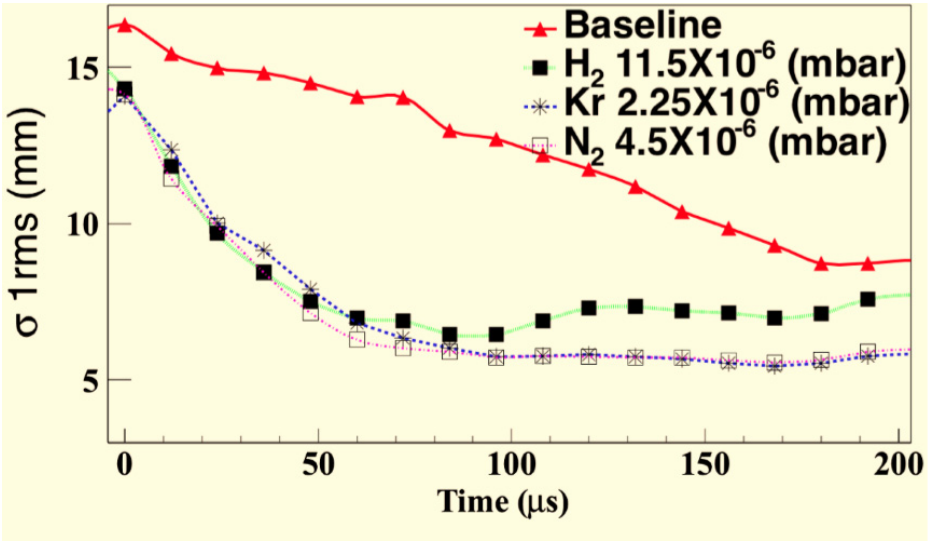




Simulation Results

Nitrogen gas injection in three different pressure:

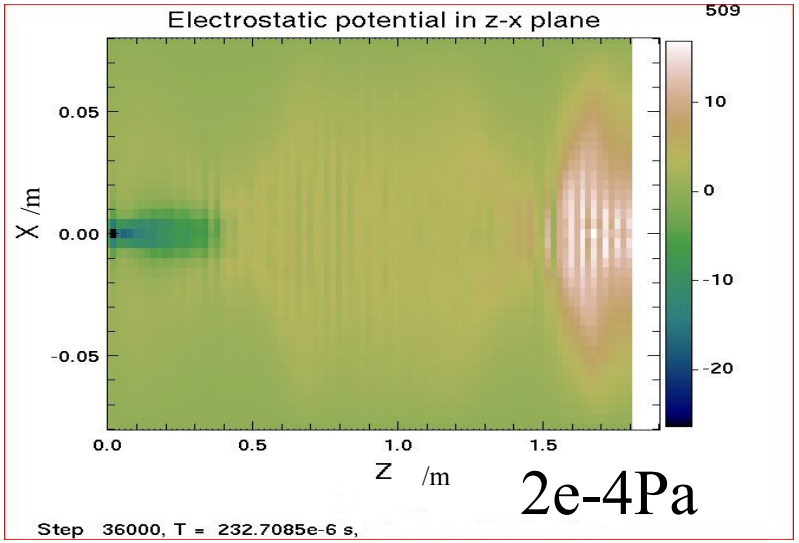




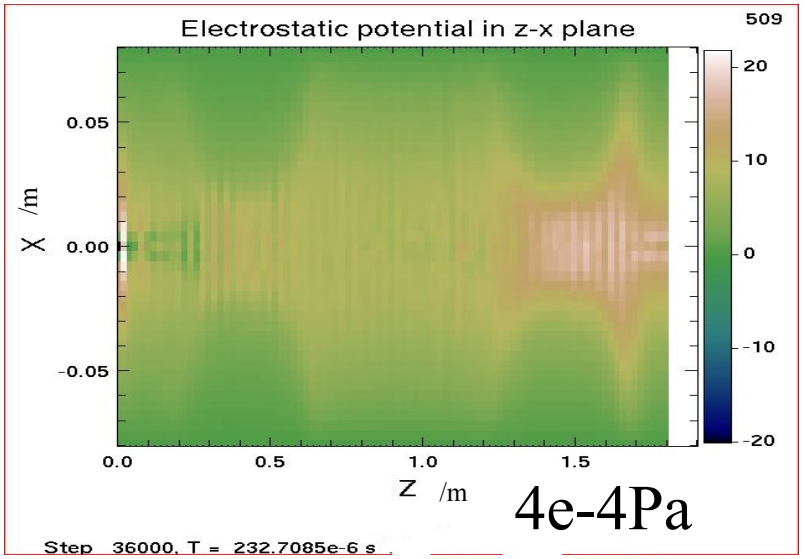
Valerio-Lizarraga C A et al. "Negative ion beam space charge compensation by residual gas[J]. Physical Review Special Topics-Accelerators and Beams, 2015

Simulation Results

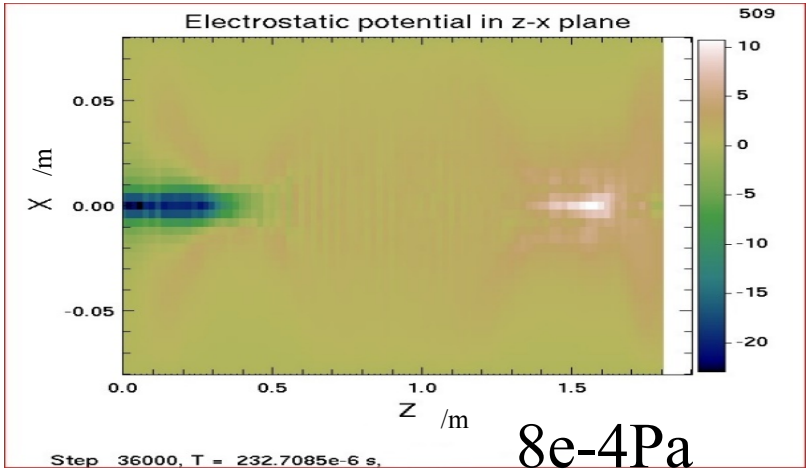
Nitrogen gas injection in three different pressure:



2e-4Pa



4e-4Pa

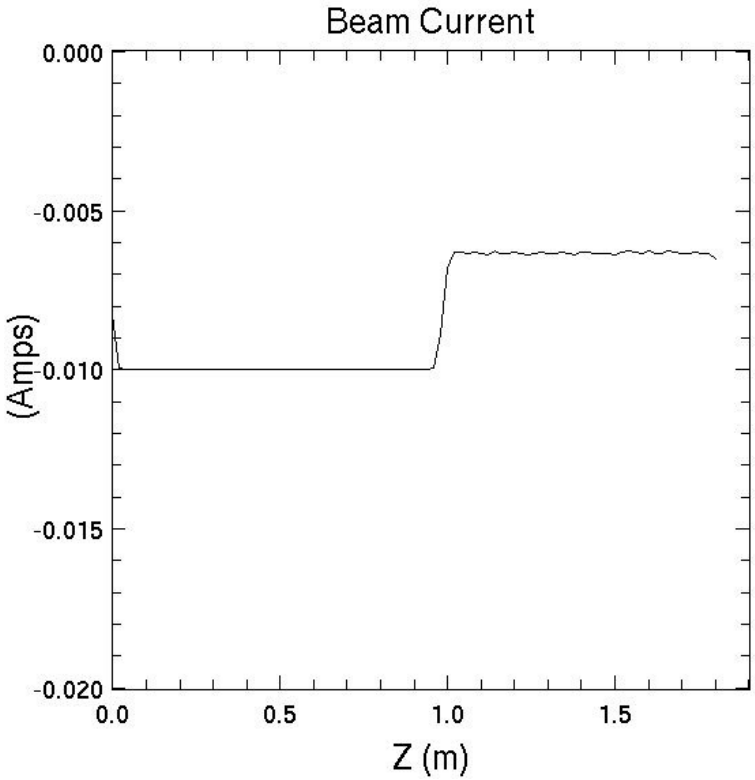


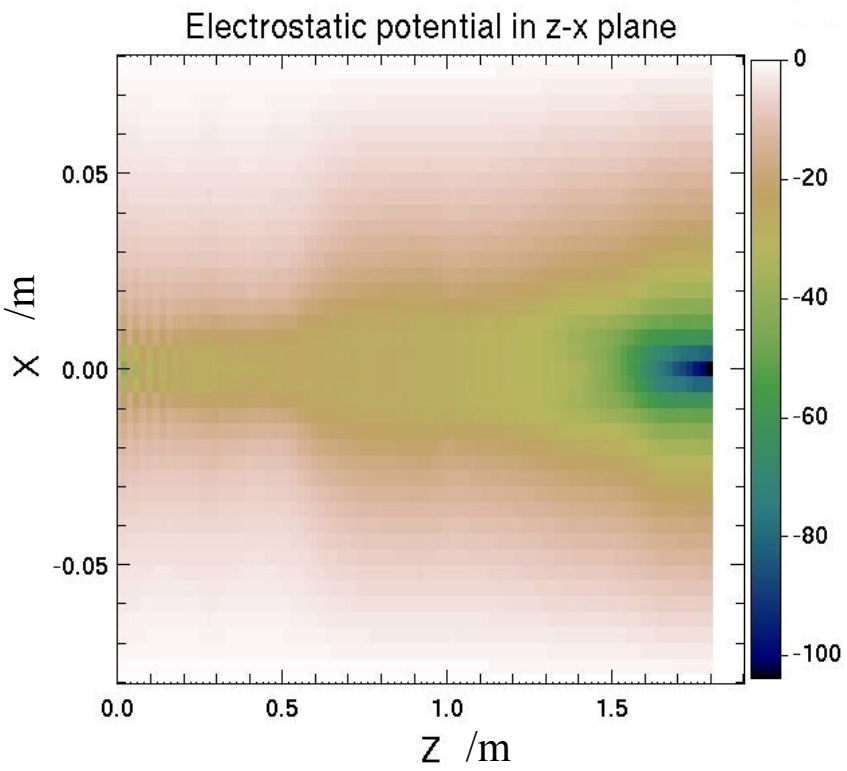
8e-4Pa

All cases are over compensated, the pressure needs to be smaller than 2e-4Pa to reach ~ 85% SCC.

Simulation Results

N2 gas pressure=5e-5Pa

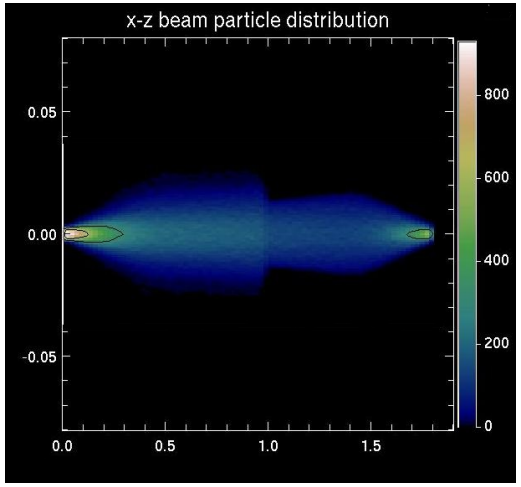


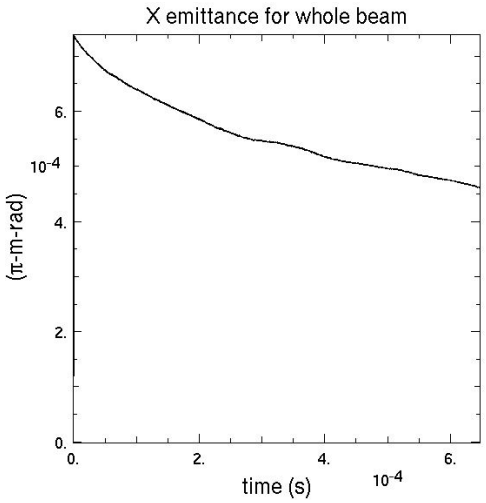


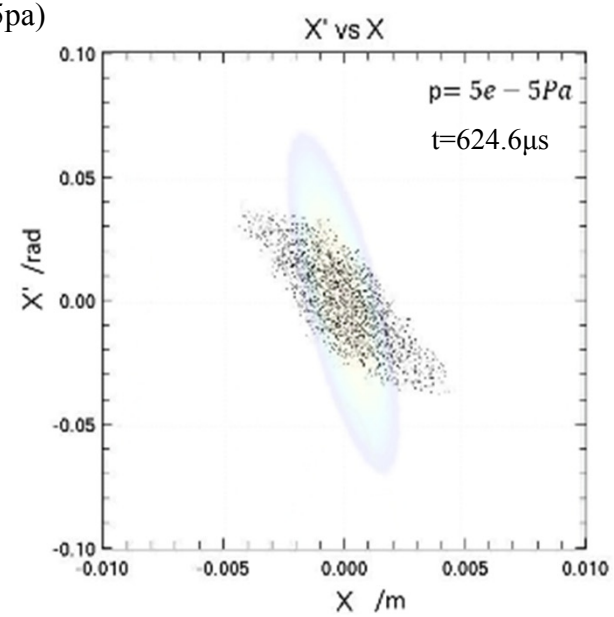
- the beam peak current at the exit is about 6mA
- the potential trap in the central area is about -30V
- the SCC degree is in the central area about 70%

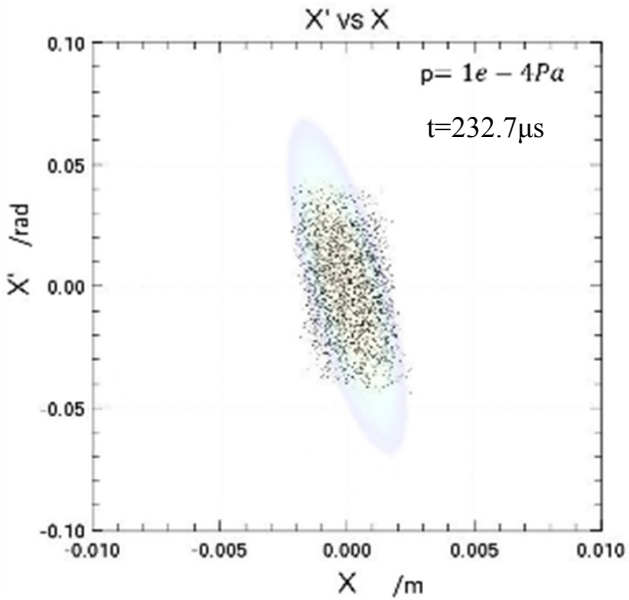
Simulation Results

(beam envelop at t=624.6μs, pressure=5e-5pa)









(phase space at the LEBT exit, the shadow represents the acceptance of the RFQ)

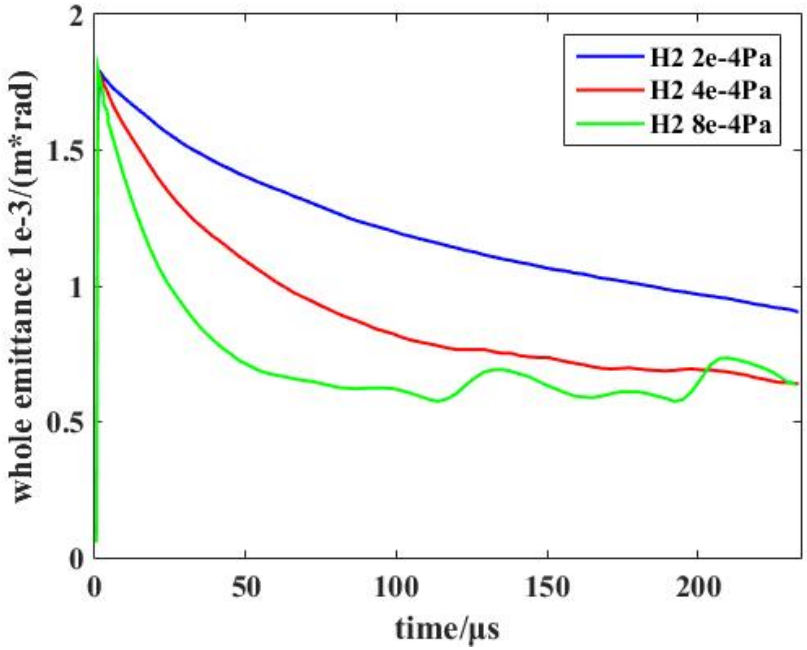
Nitrogen gas injection:

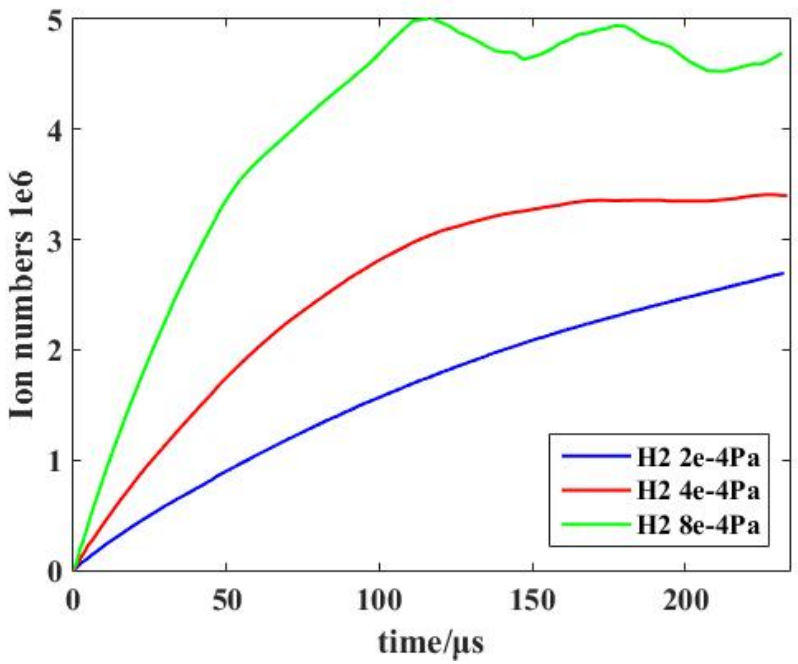
pressure range 5e-5Pa~1e-4Pa

SCC build-up time > 600μs

Simulation Results

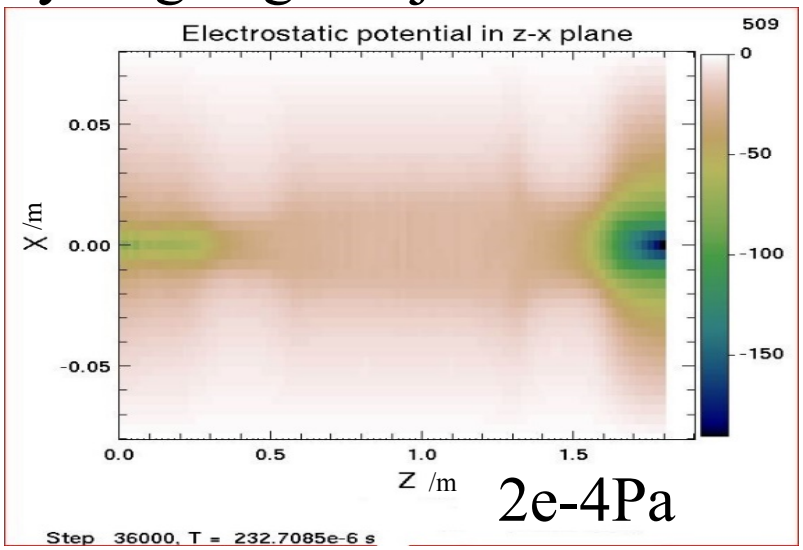
Hydrogen gas injection in three different pressure:



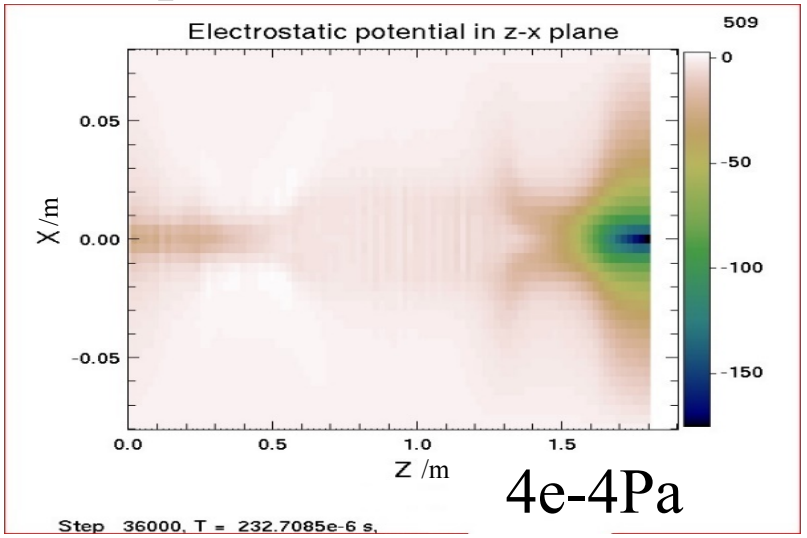


Simulation Results

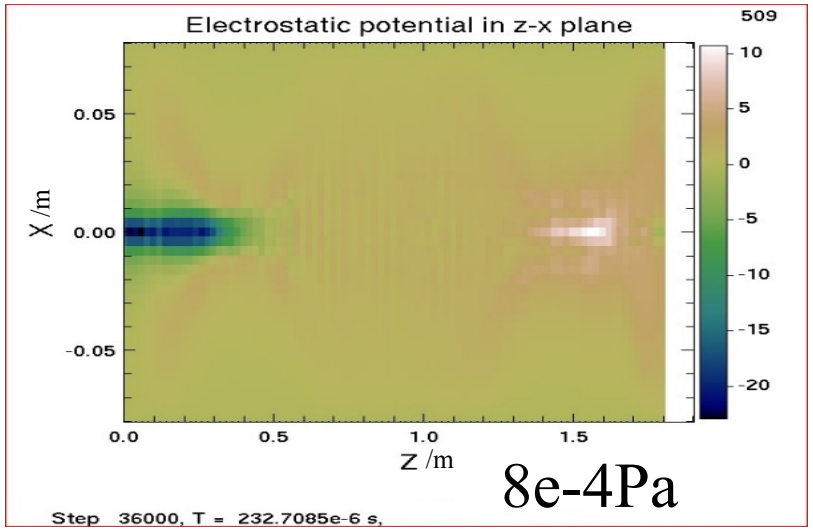
Hydrogen gas injection in three different pressure:



2e-4Pa



4e-4Pa

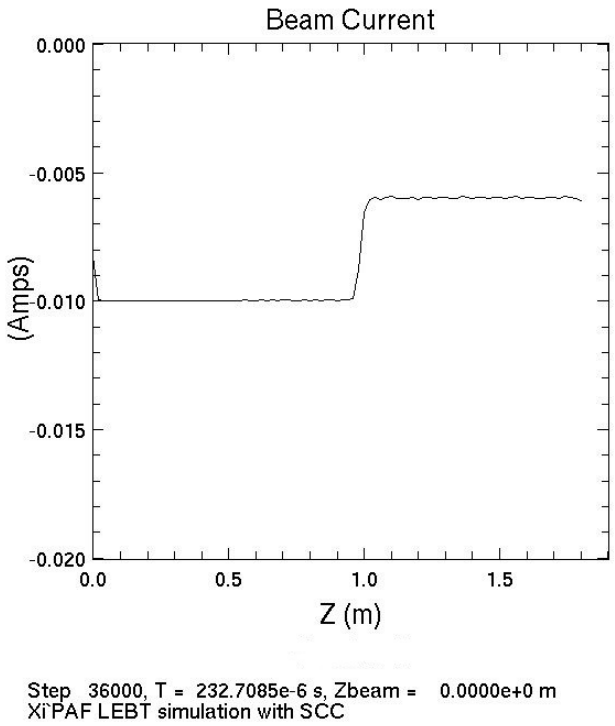


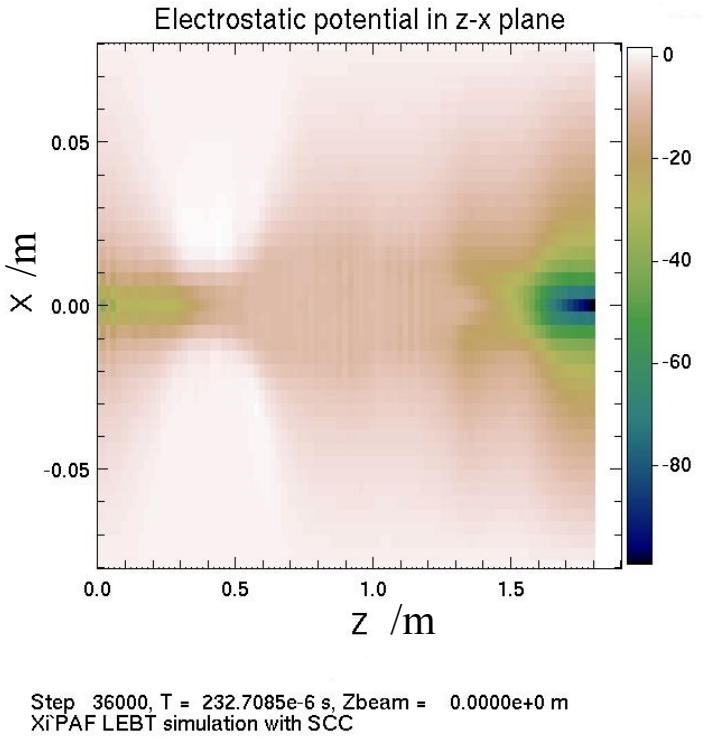
8e-4Pa

At 2e-4Pa, the degree of SCC is too small. At 8e-4Pa, it is near to 100% SCC. To reach ~ 85% SCC, the pressure needs to be close to 4e-4Pa.

Simulation Results

H2 gas pressure=3.5e-4Pa

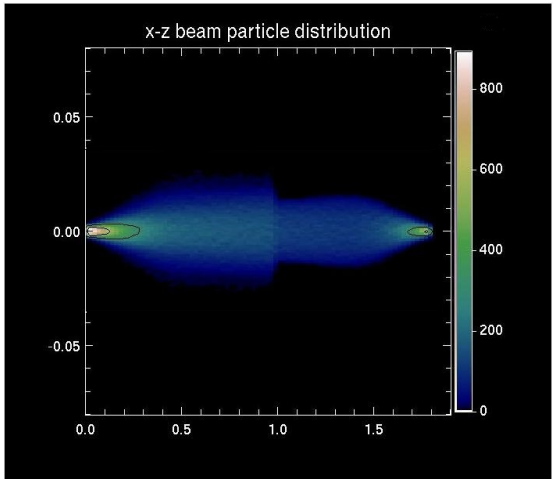


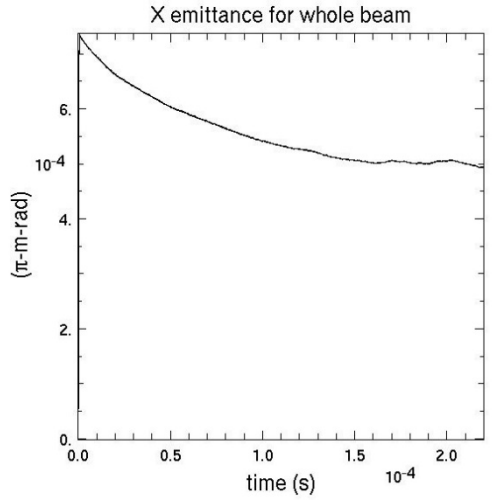


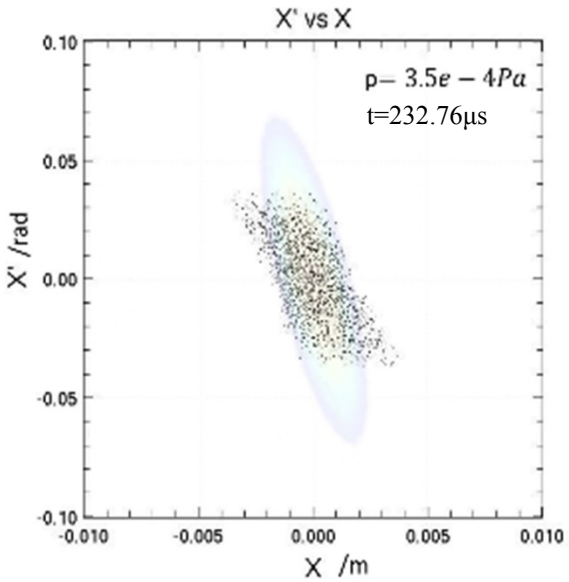
- the beam peak current at the exit is about 6mA
- the potential trap in the central area is about -20V
- the SCC degree in the central area is about 80%

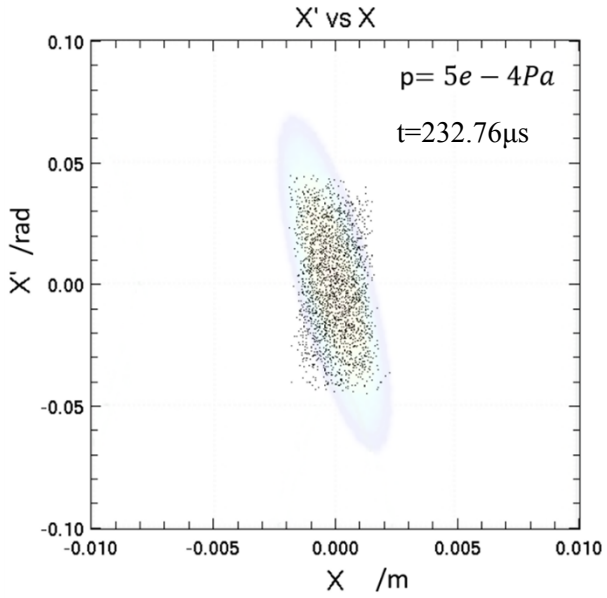
Simulation Results

(beam envelop at t=232.7μs, pressure=3.5e-4pa)









(phase space at the LEBT exit, the shadow represents the acceptance of the RFQ)

Hydrogen gas injection:

pressure range 3.5e-4Pa~5e-4Pa

SCC build-up time > 180μs

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Conclusion

The relationship of space charge compensation and the residual gas has been studied with the WARP code. The simulation shows that the degree of SCC increases as the gas pressure increasing, while the build-up time of SCC decreases.

Guidance on the LEBT commissioning of XiPAF in the future:

1)the pressure range of the injected argon gas is $3.5\sim5\times10^{-5}\ Pa$, ~800μs beam pulse needs to be chopped at the beam head and the radius of aperture should be smaller;

2) the pressure range of the injected nitrogen gas is $0.5\sim1\times10^{-5}\ Pa$, ~600 μs beam pulse needs to be chopped at the beam head;

3) the pressure range of the injected hydrogen gas is $3.5\sim5\times10^{-4}\ Pa$, ~150 μs beam pulse needs to be chopped at the beam head.

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Thanks for your attention!