H- BEAM DYNAMICS STUDY OF A LEBT IN XIPAF PROJECT WITH THE WARP CODE

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Abstract

The 7 MeV H- linac injector of Xi`an Proton Application Facility (XiPAF) is composed of an ECR ion source, a Low Energy Beam Transport line (LEBT), a Radio Frequency Quadrupole accelerator (RFQ) and a Drift Tube Linac (DTL). The 1.7 m-long LEBT is used for matching a 40 μs pulse width 6 mA peak current beam to the entrance of the RFQ accelerator. The peak current and pulse-width of the 50 keV H- beam extracted from the ion source is 10 mA and 1 ms respectively. In the LEBT, an adjustable aperture is used for scraping the peak current of the beam to 6 mA, and an electric chopper is used for chopping the beam pulse width to 40 μs. These elements make the space charge compensation problem more complicated. A careful simulation of the space charge compensation problem of the H- beam has been done by considering the beam particles interacting with the residual gas with the help of WARP PIC code. To achieve the requirements of the LEBT in XiPAF, the type and pressure of the residual gas is given according to the simulation results.

INTRODUCTION

Xi`an Proton Application Facility (XiPAF) is a new proton project which is located at Xi`an City, Shanxi Province of China. This facility is being constructed for single-event-effect experiments. It provides proton beam with the maximum energy of 230 MeV. The accelerator facility of XiPAF mainly contains a 7MeV H- linac injector and a proton synchrotron accelerator. The 7 MeV H- linac injector of Xi`an Proton Application Facility (XiPAF) is composed of an ECR ion source, a Low Energy Beam Transport line (LEBT), a Radio Frequency Quadrupole accelerator (RFQ) and a Drift Tube Linac (DTL). The H- beam current extracted from the ECR source is 10 mA. The space charge effect of this intense beam makes a huge impact on the beam transport. In general, the 50 keV H- beam ionizes the residual gas and traps the positive ions. This process named SCC (space charge compensation) decreases the space charge effect greatly. In the LEBT design of XiPAF, the degree of SCC is assumed as 85% [1]. With the help of WARP PIC code, the residual gas ionization and stripping process is added into the H- beam dynamics simulation. This more accurate simulation is expected to provide guidance for the LEBT commissioning in the future.

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LEBT DESIGN

The actual length of the LEBT is about 1.7 m. With the beam waist as the entrance, the length of the beam dynamics simulation is 1.8 m. Figure 1 shows the layout of the LEBT. The LEBT is used to match the beam between the exit of the ion source and the entrance of the RFQ accelerator. Table 1 shows the symmetric beam parameters at the exit of the ion source and the acceptance of the RFQ accelerator. The Twiss parameters at the exit of the ion source are estimated to be α=0 and β=0.065 mm/mrad.

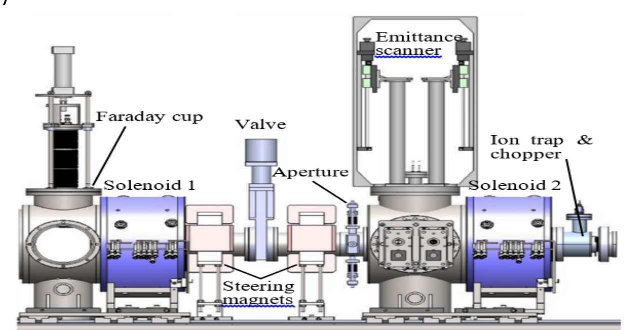

Figure 1: Layout of the Low Energy Beam Transport line (LEBT) of XiPAF.

Table 1: Beam Parameters Requirement

	ECR exit	RFQ entrance
Particle species	H-	H-
Particle energy	50 keV	50 keV
Peak current	10 mA	6 mA
Pulse width	1 ms	40 μs
α	0	1.052
β	0.065 mm/mrad	0.0494 mm/mrad
Normalized RMS emittance	0.2 π mm• mrad	0.2 π mm• mrad

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The LEBT is mainly composed of two solenoids, an adjustable aperture and an electric chopper. The aperture is used to decreasing the peak beam current. It can decrease the beam emittance as well. The chopper is used to chop the long beam pulse to 40 µs [1].

SIMULATION MODEL

The residual gas molecules in the vacuum area of the LEBT are ionized by the 50 keV negative hydrogen beam particles. The secondary electrons are expelled from the beam area by the space charge force. And the secondary ions are trapped by the beam potential trap. The beam potential trap is decreased as the number of trapped ions increases. This is called Space Charge Compensation (SCC). The space charge compensation time is determined by the residual gas type, the density of gas molecules (n) and the speed of the beam particles (v_{beam}), as given in Eq. (1). σ is the ionization cross section, which is determined by the gas type and the kinetic energy of the beam particles. While there is no available data for negative hydrogen beam, the ionization cross section data for 50keV proton is used in the following simulation [2].

$$\tau = \frac{1}{n \cdot \sigma \cdot v_{beam}} \quad (1)$$

As the ionization continues, the beam potential trap decreases gradually and the secondary ions start to move out of the beam area. At last, there is a balance between the loss and production of the secondary ions. Then, the space charge compensation reaches stable [3]. The degree of space charge compensation is defined as Eq. (2), where ϕ_{beam} is the beam potential created by the non-compensated beam, and ϕ_{scc} is the beam potential created by the compensated beam.

$$\eta = 1 - \frac{\phi_{scc}}{\phi_{beam}} \quad (2)$$

The electrons of the negative hydrogen beam particles can be stripped off by the residual gas molecules. Only one electron stripping process is considered in the following simulation, as given in Eq. (3), where X represents for different gas molecules.

$$H^- + X \rightarrow H + X + e \quad (3)$$

WARP code has been developed to model high current and high brightness beams for heavy-ion inertial fusion studies [4]. It is an open source code and has many models including all sections of particle accelerator. There are many Monte Carlo modules available including the residual gas ionization and stripping process. The code has been cross-checked with Tracewin code. In the H- dynamics simulation with space charge compensation, a very simple and direct method has been proposed. This simulation method is divided into four steps at each time step, as shown in Figure 2.

1, the H- beam particles are injected at the entrance of the simulation area (z=0 m) with the same parameters as the ion source exit.

2, the secondary electrons and ions are added into the simulation area by the Monte Carlo module. The density of those new secondary particles is determined by the cross section data, the density of the residual gas and the density of the beam particles. A uniform distribution of the gas particles is assumed.

3, the space charge induced electromagnetic field is calculated by solving the Poisson equation ($\nabla^2\emptyset = -\rho/\varepsilon$). ρ is the density of the charge, which is contributed by all the charged particles (including the beam particles and the secondary particles, which is produced in this time step or left before this time).

4, beam transports for one step time considering the solenoids magnetic field together with the field calculated in step 3.

The simulation is a cycle composed of above four steps. It won`t stop until the beam transportation time equals to the required value. The simulation volume is one cylinder with the radius of 80 mm and height of 1800 mm. All kinds of particles out of this area will be not concerned. The cross section data used in the simulation is given in Table 2 [5] [6]. Because of the large simulation time cost, the time step is set to 6.46 ns, and the mesh size of the LEBT area is 2 mm*2 mm*20 mm. The number of the injected macropartilces is 4×10^3 for each time step. The typical number of the beam macroparticles tracked in the simulation area is about 5×10^5.

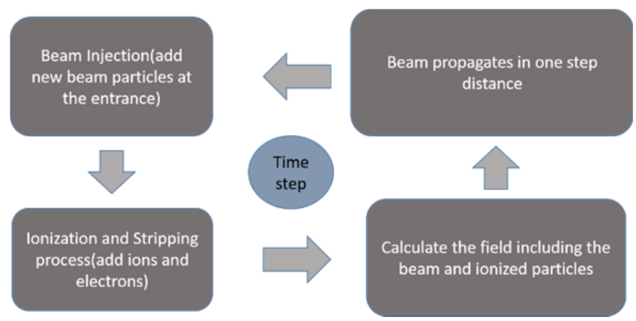

Figure 2: Diagram of simulation flow.

Table 2: Cross Section Data for 50keV H- Beam

Gas type	Ionization(1e-16/cm^2)	Stripping(1e-16/cm^2)
Ar	10.18	15
N2	9.77	12
H2	4.45	6

SIMULATION RESULTS

According to Eq. (1) and Eq. (2), the space charge compensation is closely related to the residual gas type and pressure. Ignoring the aperture, the simulation results with only argon gas injection are below.

The argon gas molecule is ionized into Ar^+ and an electron. Before the space charge compensation reaching stable, almost all of the Ar^+ particles are trapped by the beam potential. The number of Ar^+ particles is proportional to the beam transportation time [2]. This is the space charge compensation buildup process. The time is called SCC buildup time. Figure 3 shows the SCC buildup process with different gas pressure. The left plot

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shows the total emittance (the emittance is the same in x and y direction for the symmetric beam) related to the beam transportation time. The right plot shows the ion numbers related to the beam transportation time.

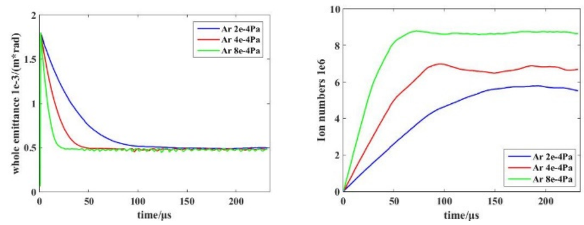

Figure 3: Total emittance vs beam transportation time (left) and ion numbers vs beam transportation time (right).

Before the space charge compensation built up, the beam phase space at the exit of the LEBT changes with the beam transportation time. This unstable beam needs to be chopped and the chopped beam pulse width must be larger than the buildup time. Figure 4 shows several beam phase spaces (at the exit of LEBT) in x direction.

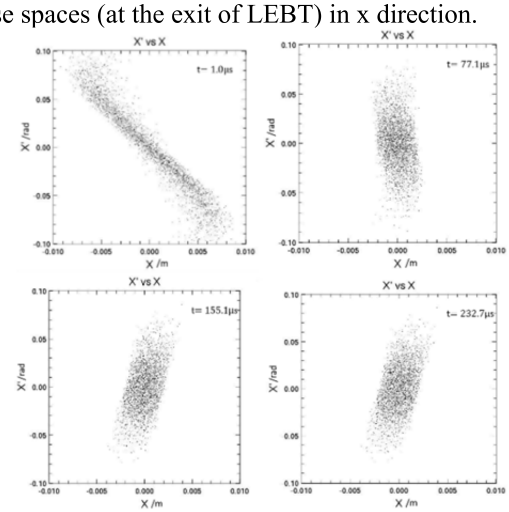

Figure 4: beam phase spaces (at the exit of the LEBT) in x direction at different time (gas pressure of 2e-4 Pa).

After the space charge compensation built up, the beam reaches stable. The degree of the space charge compensation is calculated by Eq. (2). Figure 5 shows the potential map in the LEBT with different pressure.

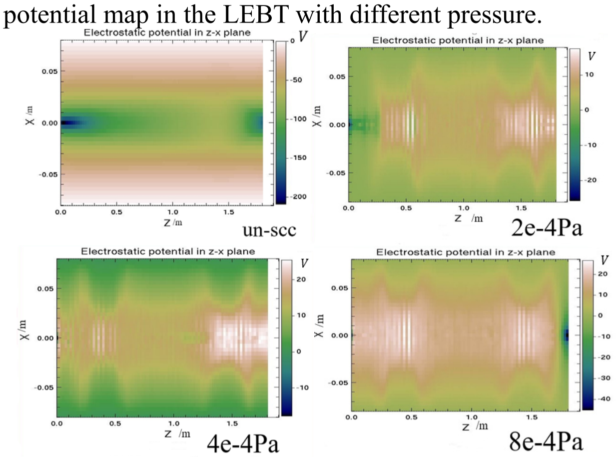

Figure 5: potential map in the LEBT (at t=232.1 µs, un-scc means there is not space charge compensation).

Because of the magnetic field of the two solenoids, the potential at the entrance and exit area of the LEBT changes a lot in the transverse directions. Focusing on the middle area of the LEBT, the degree of space charge compensation is ~105%, ~115% and ~120% for 2e-4 Pa, 4e-4 Pa and 8e-4 Pa respectively. The SCC buildup times are ~25 µs, ~60 µs and ~150 µs for 2e-4 Pa, 4e-4 Pa and 8e-4 Pa gas pressure respectively.

Those simulation results above are based on a simple LEBT model with only two solenoids. Considering the aperture between the solenoids, the simulation results changes as the beam current decreased after the aperture. The radius of aperture is 13.4 mm, and the results are below.

Argon gas injection: Figure 6a, 6b, 6c shows the results with the pressure of 3.5e-5 Pa at time=969.6 µs. The beam current after the aperture is about 7 mA. According to the phase space results, a bigger focusing force is needed to match the beam into the RFQ accelerator. Figure 6d shows the beam phase space in x direction at 5e-5 Pa pressure and t=624.6 µs. A smaller focusing force is needed and the beam current is also about 7mA at the LEBT exit. These simulation results suggests that with the pressure range of $3.5{\sim}5 \times 10^{-5}\,Pa$ for the injected argon gas, ~800 µs beam pulse needs to be chopped at the beam head and the radius of aperture shall be smaller.

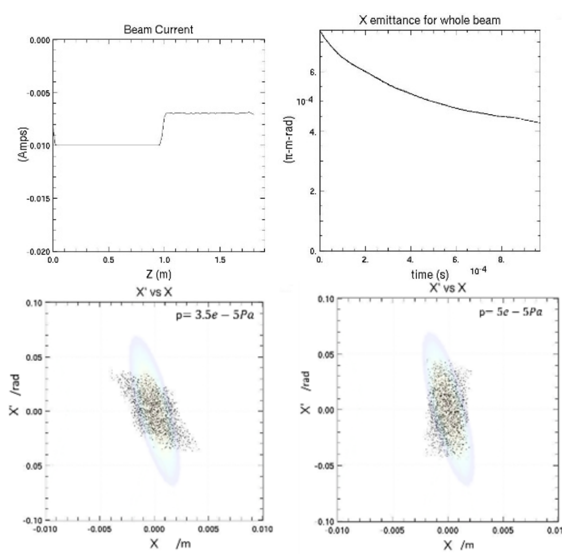

Figure 6: Simulation results at 3.5e-5 Pa and t=969.6 µs. (a. beam current (left top); b. total emittance (right top); c. phase space (left bottom); d. phase space at 5e-5 Pa pressure (right bottom) and at t=624.6 µs; the shadow in phase space plot represents the RFQ acceptance)

Nitrogen gas injection: Figure 7a, 7b, 7c shows the results the pressure of 3.5e-4 Pa at time=624.6 µs. The beam current after the aperture is about 6 mA. A bigger focusing force is needed to match the beam into the RFQ accelerator. Figure 7d shows the beam phase space in x direction at 1e-4 Pa pressure and t=232.7 µs. It meets the RFQ acceptance requirement and the beam current is also about 6 mA at the exit of the LEBT. These simulation results suggests that the pressure range of the injected

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nitrogen gas is $0.5{\sim}1 \times 10^{-5}\,Pa$, ~600 μs beam pulse needs to be chopped at the beam head.

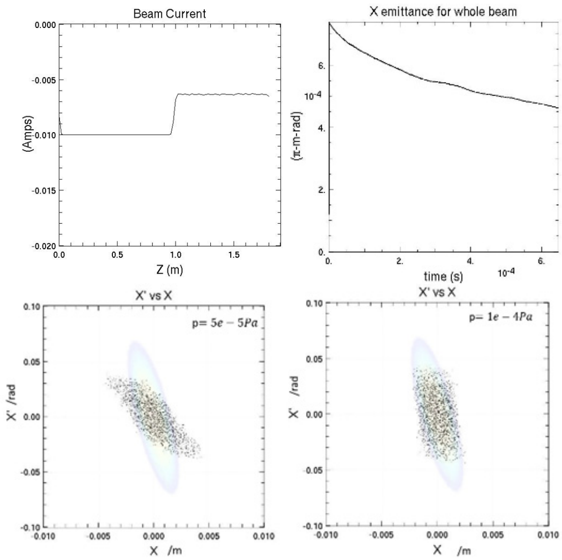

Figure 7: Simulation results at 5e-5 Pa and t=646.6 μs. (a. beam current (left top); b. total emittance (right top); c. phase space (left bottom); d. phase space at 1e-4Pa pressure and at t=232.7 μs(right bottom); the shadow in phase space plot represents the RFQ acceptance).

Hydrogen gas injection: Figure 8a, 8b, 8c shows the results the pressure of 3.5e-4 Pa at time=232.7 μs. The beam current after the aperture is about 6 mA. A bigger focusing force is needed to match the beam into the RFQ accelerator. Figure 8d shows the beam phase space in x direction at 5e-4 Pa pressure and t=232.7 μs. A smaller focusing force is needed and the beam current is also about 6 mA at the LEBT exit. These simulation results suggests that the pressure range of the injected hydrogen gas is $3.5{\sim}5 \times 10^{-4}\,Pa$, ~150 μs beam pulse needs to be chopped at the beam head.

CONCLUSION

This paper presents a simple and direct space charge compensation simulation method with WARP PIC code. With the design parameters of a LEBT in XiPAF project, H- beam dynamics has been studied by adopting this simulation model. Without the aperture, the space charge compensation with argon gas is simulated. The space charge compensation build-up time is about ~25 μs, ~60 μs, ~150 μs for 2e-4 Pa, 4e-4 Pa and 8e-4 Pa, while the degree of space charge compensation is ~105 %, ~115 % and ~120 % respectively. Adding the aperture, the beam dynamics simulations for the negative hydrogen have been carried out via injecting hydrogen, nitrogen and argon gas separately. To achieve the requirements of the design of the LEBT in XiPAF, the simulation results suggest: 1) the pressure range of the injected argon gas is $3.5{\sim}5 \times 10^{-5}\,Pa$, ~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

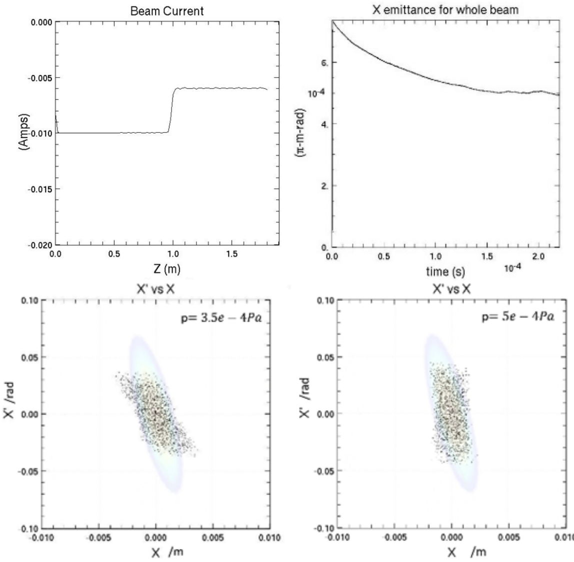

Figure 8: Simulation results at 3.5e-4 Pa and t=232.76 μs. (a. beam current (left top); b. total emittance (right top); c. phase space (left bottom); d. phase space at 5e-4 Pa pressure and at t=232.7 μs(right bottom); the shadow in phase space plot represents the RFQ acceptance)

nitrogen gas is $0.5{\sim}1 \times 10^{-4}\,Pa$ and ~600 μs beam pulse needs to be chopped at the beam head; 3) the pressure range of the injected argon gas is $3.5{\sim}5 \times 10^{-4}\,Pa$, ~150 μs beam pulse needs to be chopped at the beam head. These results will provide guidance for the LEBT commissioning in the future.

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