SPACE-CHARGE COMPENSATION IN LOW ENERGY BEAM LINES

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Abstract

The dynamics of a high intensity beam with low energy is governed by its space-charge forces which may be responsible of emittance growth and halo formation due to their non-linearity. In a low energy beam transport (LEBT) line of a linear accelerator, the propagation of a charged beam with low energy causes the production of secondary particles created by the interaction between the beam and the background gas present in the accelerator tube. This phenomenon called space-charge compensation is difficult to characterize analitically. In order to obtain some quantitative values to characterize the space-charge compensation (or neutralization), numerical simulations using a 3D PIC code have been implemented.

INTRODUCTION

Since many years, the interest for high power accelerators has increased. These devices are essential in different domains like injection for high energy colliders (Linac4), production of exotic nuclei (Spiral2), production of neutrons by spallation (SNS, ESS) or by a deuterium beam (IFMIF). They can be used as ADS (Accelerator Driving System), like the linear accelerator MYRRHA launched by the European Commission. It consists in driving a nuclear reactor with a 2.4 MW proton beam that is sent to a spallation target to create neutrons which feed the sub-critical core [1].

In linear accelerators, the beam extracted from an ion source first propagates in a low energy beam line followed by a radiofrequency quadrupole (RFQ) and accelerating structures. The aim of the LEBT is to transport and optimize the injection of the beam into the RFQ, providing, at the RFQ entrance, a beam with matched Twiss parameters.

Some simulations of beam transport in a LEBT have been performed. We have specifically simulated the MYRRHA LEBT in order to compare these numerical results with experimental data measured on the same line.

BEAM DYNAMICS

Space Charge

The space-charge force has two components that are in competition. The first component corresponds to an electrostatic repulsion force which tends to defocus the beam and the second one corresponds to a magnetic force that tends to focus it.

At low energy, the beam dynamics is dominated by the space-charge field, which is auto-induced by the beam. The beam transport is particularly challenging because of the non-linearity of the space-charge forces which may cause emittance growth and beam losses.

Space Charge-neutralization

At low energy, the beam particles ionizes the gas present in the line. This gas mainly comes from the source and beam pipe outgassing or can be intentionally injected.

The particles created by ionization (ions & electrons) are confined or repelled by the space-charge field according to their charge sign. The progressive accumulation of particles which charge sign is the opposite of the beam contributes to the space-charge neutralization.

This phenomenon depends on the beam distribution, is time-dependent and is spatially partial. An interesting quantity is the characteristic time of compensation which can be defined by:

$$\tau_{SCC} = 1/\sigma n \beta c \tag{1}$$

with σ is the ionization cross section, n is the gas density and βc is the velocity of the beam. It corresponds to the time it takes for the beam to produce by ionization as neutralizing particles as there are charged particles in the beam.

Some analytical models allow to obtain orders of magnitude of the space-charge compensation degree and its establishment time but it is necessary to have more precise results. That's why we use numerical simulations taking into account the physical processes in the LEBT in order to get quantitative values of these quantities.

SIMULATION FRAMEWORK

Description

WARP is the code used for our simulations of beam transport in LEBT. It is an open-source PIC (Particles In Cell) code implemented in LBNL which is designed to simulate charged particles beams in space-charge neutralization regime [2]. It is a self-consistent code.

In our case, we use a multigrid Poisson Solver. To realize the simulation, we must enter some physical quantities:the initial beam distributions, the nature and pressure of the gas present in the line, the reactions (ionization, secondary electrons emission, collisions...), the line geometry, the external fields maps and the boundary conditions.

Algorithm

At each time step, the method is the following:

1. Assignation: the charge density ρ is assigned at each node of the grid.
2. Field integration: the potential is calculated from the charge density by solving the Poisson equation. The field is obtained by derivation of the potential.

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3. Field interpolation: the forces acting on the particles are evaluated from the values of the fields E and B obtained on the grid nodes.
4. Particle pusher: the velocity and the position of the particles are obtained by integration of the equations of motion.
5. Collision: simulations of collisions between macroparticles are realized via a Monte-Carlo algorithm.

SIMULATION RESULTS

We have simulated the LEBT of the MYRRHA accelerator whose scheme is presented in Fig. 1. The beam focusing is achieved by two solenoids. The Table 1 shows the input parameters of the simulation. The simulation time is higher than T_{SCC}(5.8 µs) in order that the system reaches the steady-state, indeed when the number of neutralizing particles doesn't evolve anymore.

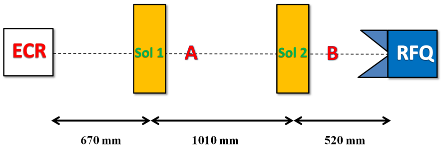

Figure 1: MYRRHA LEBT with diagnostics located at points A and B.

Table 1: Main Simulation Parameters

Simulation parameter	Type or values
Beam species	Protons
Beam intensity	7.9 mA
Beam energy	30 keV
Magnetic field in solenoid 1	0.17 T
Magnetic field in solenoid 2	0.19 T
Gas	Ar @ 6.4x10^{-5} hPa
Simulation time	30.0 µs

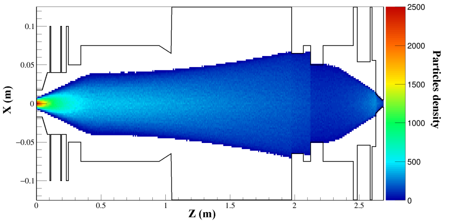

Figure 2: Proton beam at time t = 1.5 µs.

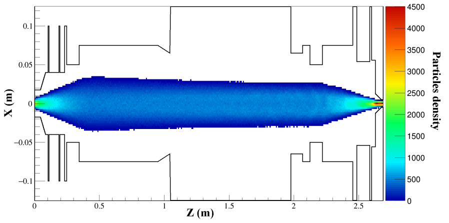

Figure 3: Proton beam at time t = 30.0 µs.

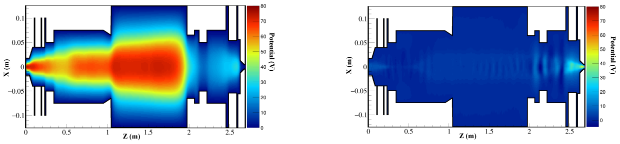

Figure 4: 2D section in plane z0x of the space-charge potential at time t=1.5 µs and t=30.0 µs.

We starts the simulation at z = 107 mm from the puller electrode of the source extraction system. Figure 2 shows the proton beam propagating in the LEBT at time ($t < T_{SCC}$). Fig. 3 shows the beam propagating in the LEBT at steady-state. We can see the effect of space-charge compensation: as time increases, the electrons are trapped by the positive potential induced by the proton beam and they contribute to reduce the transverse dimension of the beam. It acts as a focusing effect evolving in time. The space-charge potential is an important parameter to calculate the space-charge neutralization. In Fig. 4 we see the potential induced by all the particles in the line in plane zOx at different time steps. From that, we deduce the decrease of the potential due to the electrons that are trapped by the positive potential of the beam. In order to calculate the space-charge compensation yield η, we use the following method at different time steps t of the simulation:

1. One calculates the potential created only by the protons beam without space-charge compensation (uncompensated beam): $\phi_0(t, x, y, z)$
2. The potential created by all the particles (protons, ions & electrons) in the line (compensated beam) $\phi_C(t, x, y, z)$ is an output of our simulations
3. One makes the ratio between this two quantities: $\eta(t, x, y, z) = 1 - \frac{\phi_C(t,x,y,z)}{\phi_0(t,x,y,z)}$

In Fig. 5 the space-charge compensation map in steady-state is represented in the plane zOx. We can see that the compensation is not uniform in space. It is higher in the solenoids because the electrons are confined by the magnetic field of the solenoids. At the entrance and at the end of the LEBT, the low compensation is induced by the important electrons losses on the walls.

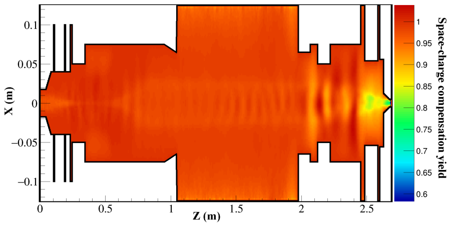

Figure 5: 2D section in plane zOx of the space-charge compensation map.

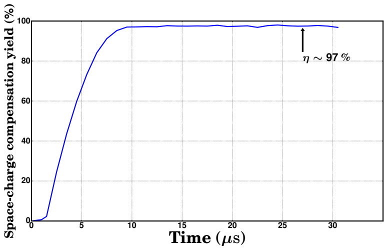

Figure 6: Time-volution of the space-charge neutralization yield.

The Fig. 6 shows the time evolution of η along the beam axis calculated between the two solenoids. The value of η in steady-state is $\sim$ 97 %.

EXPERIMENTAL LAYOUT

Experimental Setup

In February 2016, we took part to experimental activities on the MYRRHA LEBT which is currently in operation at LPSC in Grenoble.

In order to collect data to characterize the space-charge neutralization as a function of different parameters, we can independently vary the magnetic field in the two solenoids, the nature of the injected gas and its pressure.

We measure the beam intensity with a Faraday cup and the transverse beam distribution in the two planes (x-x') & (y-y') with two Alisson-Scanner [3] that can be placed at point A and at point B of Fig. 1. This experimental framework can easily be simulated in order to compare experimental data with simulations results.

Preliminary Results

In this section, we present the pressure dependency of the space-charge compensation by studying the beam emittance and its transverse beam dynamics. In Fig. 7 we have plotted the beam emittance (measured in A) as a function of the gas pressure for argon.

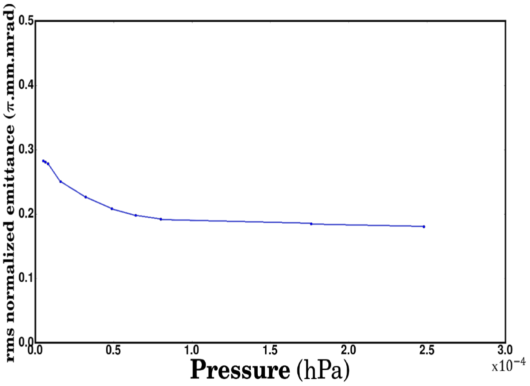

Figure 7: Normalized emittance of protons beam as a function of the Ar-pressure.

In this case, we see that the increase of the pressure is responsible of a significant decrease of the emittance.

Then, we show the horizontal beam distribution (measured in A) in two different cases. The experimental parameters are the following: the beam energy is 30 keV, the beam current is 10 mA, the magnetic field in the first solenoid is 0.21 T and the gas injected in the line is helium. The unique difference between the case a and the case b is the gas pressure in the beam line. In case a, it is 2.3x10^{-4} hPa and in case b 1.2x10^{-3} hPa. So, due to the increase of the gas-pressure injected in the line, the beam goes from divergent to convergent. These first results show the pressure dependency of the space-charge neutralization (see Figs. 8 and 9).

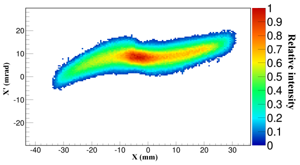

Figure 8: Beam distribution in phase space (case a).

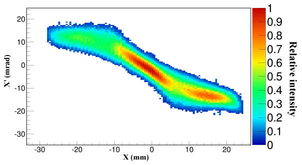

Figure 9: Beam distribution in phase space (case b).

CONCLUSION & OUTLOOK

Beam dynamics simulation in a LEBT with space-charge neutralization with a 3D PIC Code has been achieved. Some experimental results have been obtained on the MYRRHA LEBT that show the pressure dependency of the space-charge neutralization.

In a near future, we will simulate the MYRRHA LEBT in the same conditions as in the experiences. Next, some physical phenomenon like secondary electrons emission from the wall, ionization by the electrons and the pressure gradient in the line will be added in the simulations. Then, other LEBT (IFMIF, FAIR Proton-Linac) will be simulated.

For the experimental part, beam distributions at the end of the line will be measured with an Allison-scanner as well as the space-charge neutralization with a 4-grid analyzer.

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