SPACE CHARGE COMPENSATION IN LOW ENERGY PROTON BEAMS*

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Abstract

High-power accelerators are being studied for several projects including accelerator driven neutron or neutrino sources. The low energy part of these facilities has to be carefully optimized to match the beam requirements of the higher energy parts.

In this low energy part, the space charge self force, induced by a high intensity beam, has to be carefully controlled. This nonlinear force can generate a large and irreversible emittance growth of the beam.

To reduce the space charge (SC), neutralization of the beam charge can be done by capturing some particles of the ionised residual gas in the vacuum chamber. This space charge compensation (SCC) regime complicates the beam dynamics study. Modelling the beam behavior in such a regime would be a significant contribution to the development of high intensity accelerators.

INTRODUCTION

In the low energy part of an accelerator, a high intensity beam is space charge dominated. Such a beam can be transported in a neutralization regime using the charge of the ionized residual gas. This regime occurs naturally when the beam propagates through a residual gas. Gas ionization takes place inside the beam and produces electrons and positive ions. For positive beams, electrons are trapped as long as the SC is not fully compensated.

As many experiments show [1], the beam charge is not always fully neutralized. Inside a Low Energy Beam Transport line (LEBT), the time dependent SCC is not necessarily homogeneous in space. These conditions contribute to emittance growth induced by non-linear forces and may lead to particle losses.

The knowledge of such regime is important to predict the optical qualities of the transported beam.

In this paper, we first describe a code CARTAGO for SCC modelization. This PIC code simulates the SCC mechanism during the transient and steady state regimes. We then present a numerical investigation of the SCC behavior for a continuous (DC) and a bunched (AC) proton beam through a drift section.

This work is a part of the theoretical and experimental work for the IPHI project [2].

CARTAGO ALGORITHM

Cartago is a beam dynamics simulation code including the effect of the non linear SCC. The scheme used to simulate the beam and plasma dynamics is composed of four basic parts (Fig.1):

Part1 At each time step, new particles produced by gas ionization are added according to the angular end energy differential cross section [3]. The beam is defined by a particle cloud carrying the main current.

Parts2&3 The charge distribution, is obtained in a 1D mesh (r) with a PIC scheme. The Poisson equation is solved with the grid by integration of the Gauss law. Forces extracted from the resulting potential, are applied to particles via the step by step "leap frog" scheme [4]. This scheme allows to integrate the equation of motion including the SC calculation.

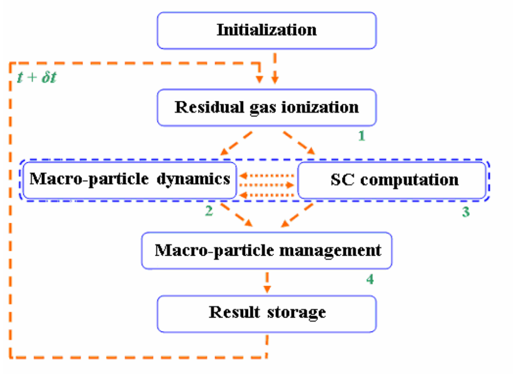

Figure 1: Cartago algorithm

Part4 The residual gas plasma evolves taking into account the ionization intensity and the extend of the particle losses. This macro-particle system is simulated by using a "chained lists" method [5]. Every particle species is classified on separated lists. The size of each list increases when adding ionized particles, and decreases if some particles are lost on the vacuum chamber walls. Having roughly an idea of the plasma time scale stabilisation [6], and estimating the size for these lists for this moment, we deduce the number of macro-particles generated at every time step. Using this method, we simplify the Read Access Memory management during the computation.

Typical outputs of Cartago are electrostatic field, potential and radial distributions of the studied species. For further information, particle clouds may also be investigated at each time step. The SCC degree at a given azimuth of the beam direction is defined by:

$$\tau(t) = 100 \cdot \left(1 - \frac{\int_0^{r_{beam}} r \cdot \left\| \vec{F}_{SC\_C}(r) \right\| \cdot \rho(r) \cdot dr}{\int_0^{r_{beam}} r \cdot \left\| \vec{F}_{SC}(r) \right\| \cdot \rho(r) \cdot dr} \right), \quad (1)$$

where $\vec{F}_{SC}$, $\vec{F}_{SC\_C}$ and ρ are respectively SC forces of the initial beam, forces in presence of the SCC and the beam distribution. This SCC degree gives the average reduction of the force acting on the beam. It is 0 if no compensation and 100 if the SC is fully compensated.

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SCC OF A DC RIGID BEAM

In this section, the study is restricted to a drift region with a 3 cm constant beam radius. The proton beam (95 keV, 100 mA) is uniform, cylindrical and rigid.

The residual gas consists of H_2 molecules at 3.8 10^{-4} hPa and 300 K. We assume that the only source of secondary charges is the gas ionization. The drift radius is 0.1 m.

We studied the SCC of this particular beam during 20 µs. The SCC degree reaches 99% and still increasing very slowly (Fig.2.a). This result gives a good agreement with our expectation. With these beam and gas parameters, ionization dominates all beam-plasma interactions which favours continuously the SCC.

First studies of some other Coulomb collisions show that the SCC degree at the steady state is lower than 100% if we include only the beam-electron Coulomb scattering.

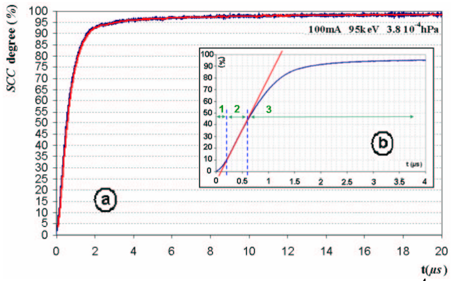

Figure 2: SCC of a rigid beam at 3.8 10^{-4}hPa.

Before reaching the steady state regime, we can divide the SCC transient phase (up to 4 µs) into 3 stages (Fig.2.b).

The stage 1 is characterized by a slow SCC evolution. The ions are not immediately repelled (heavy particles created without initial energy) (Fig.3.a). This point will have an important effect on the bunched beam neutralization.

In the stage 2, the ions are lost at a constant rate. This condition makes the SCC evolution similar to the classical description proposed in [5]. By measuring the second stage slope (Fig.2.b), we find the same value of the SCC time scale (T_{SCC} = 1 µs) as given by:

$$T_{SCC} = (\sigma_i \cdot n_g \cdot v_f)^{-1}, \qquad (2)$$

where v_f (m/s), n_g (m^{-3}), σ_i (m^2) are respectively the beam velocity, the gas density and the ionization cross section.

During the stage 3, the negative charge compensates gradually the positive charge beginning by the beam centre. This particular evolution implies a non linear SC field (Fig.3.c). The emittance growth of a transported beam will depend on the amplitude of this non-linearity.

The hollow electron density (Ne) is due to the fact that each electron gets some orbital kinetic moment at the creation. This gives to the radial electron oscillation an elliptical trajectory and reduces the total electron density near the beam centre [7].

SCC OF A TRANSPORTED DC BEAM

We study in this section the beam transport in a drift section of 0.25 m without longitudinal SC effects. We consider, at the drift entrance, a uniform proton beam (95 keV, 100 mA) with ε_{rms}=0.2 π.mm.mrad the rms normalized emittance. The Twiss parameters are α=-2 and β=1.74 mm/π.mrad (Fig4.a). Gas pressure is 3.8 10^{-4} hPa.

This beam is then transported through the drift section in a time dependent SCC regime.

At the beginning of the simulation, the radial SC force of the uniform beam is linear. The head of the beam propagates then through the drift without emittance growth (Fig.4.b).

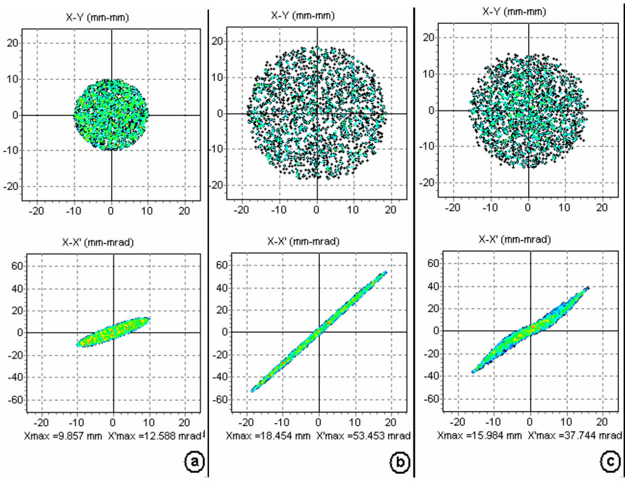

Figure 4: Beam profile and emittance, (a) at the drift entrance, at the drift exit (b) at 58 ns, (c) at 600 ns.

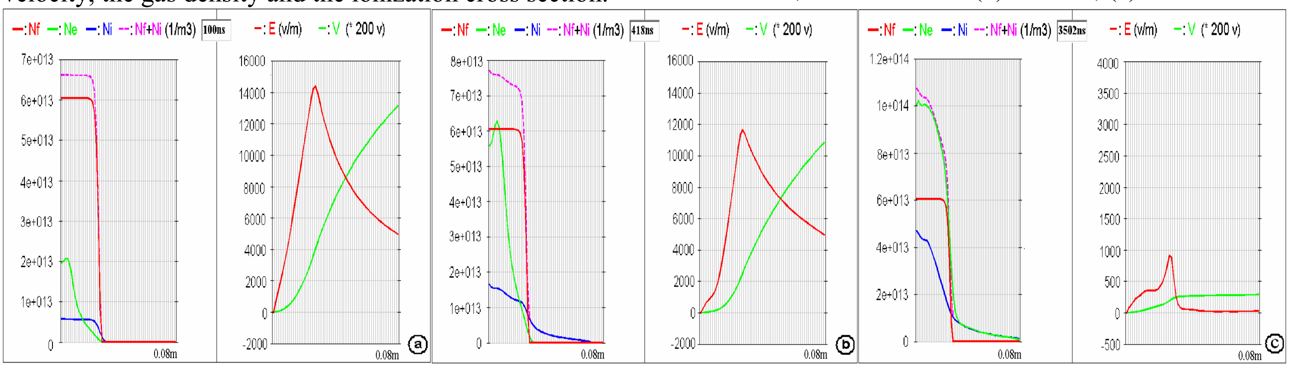

Figure 3: Radial distributions Nf (beam), Ne (electrons), Ni (ions), electrostatic field E and potential V, (a) at 0.1 µs, (b) at 0.4 µs, (c) at 3.5 µs.

When the residual gas is being ionized, the resulting SC force becomes non-linear. This non-linearity is verified, for example at 600 ns (Fig.4.c), when the normalized beam emittance reaches 0.3 π.mm.mrad.

With the same evolution showed in Fig.2.a, SC is nearly compensated at about 10 µs inside the whole drift.

Figure 5 gives the relative emittance growth at the drift exit as a function of the SCC degree.

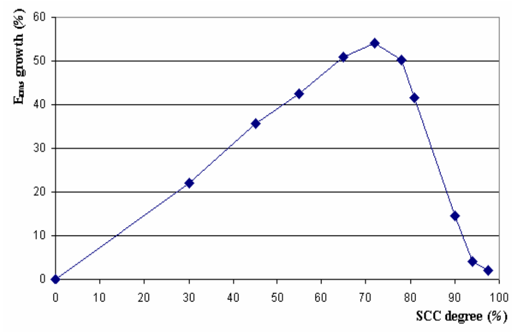

Figure 5: The emittance growth at the drift exit vs. the SCC degree.

When the SC is entirely compensated, the beam transport conditions become similar to the case of linear transport with 0 mA. The emittance of the uniform beam is then conserved inside the whole drift.

SCC OF A BUNCHED BEAM: THE CASE OF THE IPHI MEBT

We study in this section the SCC of a bunched beam using the same parameters of the studied DC rigid beam but at 3 MeV. The bunch length and frequency are respectively 60° and 352 Mhz [2].

At a given azimuth, the electrons see successively the focusing forces induced by the proton bunch, followed by a drift time between bunches. The forces induced by the passage of a bunch have been studied by several authors [8]. Assuming that SC force results only from the beam charge, a criterion for electron stability and accumulation has been established:

$$f_{RF} > (f_{RF})_c = \frac{r_e \cdot u \cdot c}{2 \cdot e} \cdot \frac{I_f}{b^2} \quad , \qquad (3)$$

where u and r_p are respectively the atomic unit mass and the classical electron radius; I_f, b, f_{RF} are respectively the beam current, radius and frequency.

Using only the beam SC, we verified that results obtained by the Cartago code correspond to the stability criterion (Eq.3). The electrons are being accumulated and SC is compensated for frequencies greater than 17.17 MHz.

In the second part of the bunched beam study, we include ions and electrons in the SC computation. The SCC evolution of the bunched beam is showed in figure 6.

The SCC final degree is about 13%. The result is nearly the same at 3.8 10^{-5} hPa, but the rise time is 10 times longer.

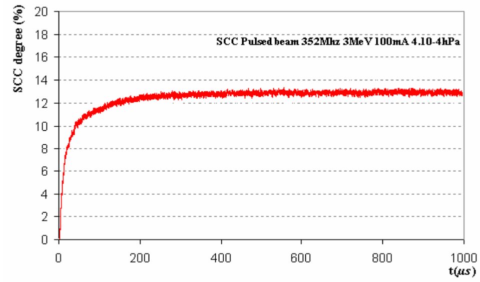

Figure 6: SCC of the bunched beam at 3.8 10^{-4} hPa

In the particular case studied, the SCC and consequently the beam dynamic become stables after ~0.2 ms. This rise time is important for the commissioning where pulsed beams will be used to tune the machine for the CW regime. It may also be a problem for pulsed machines.

CONCLUSION AND PERSPECTIVES

Numerical investigations of SCC evolution in a drift section have been realized. The study, in the case of a rigid beam, verifies that space charge can be fully neutralized when the ionization is the only effective process. The transient regime study is in good agreement with theoretical expectations [3,6,7].

The emittance growth during the transient regime is computed from the transport of a continuous beam.

Theoretical study of a bunched beam, with some specifics hypotheses [8], successfully compare with numerical results. When including the full SC (beam, e^- and ions), the numerical study shows that the bunched beam SC is partially neutralized after a relatively long rise time.

Special effort is presently made to understand and to introduce other collision processes. To take into account the longitudinal effects, the Poisson solver is being modified. Specific SCC measurements in the IPHI LEBT line are planed this year. They will be compared with Cartago predictions.

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