SPACE CHARGE NEUTRALIZATION AND ITS DYNAMIC EFFECTS

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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. This contribution aims to modelize the beam behavior in such regime and to provide criteria to the linac designer to estimate the neutralization rise time and the neutralization degree.

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Work supported by the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395).

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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. This contribution aims to modelize the beam behavior in such regime and to provide criteria to the linac designer to estimate the neutralization rise time and the neutralization degree.

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. This particular space charge regime can not build up in radio frequency cavities because the high electrical fields (several MV/m) eject the ionization products away from the beam axis.
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 propose several basic rules to estimate the relative impact of the space charge neutralization on the different sections of a high intensity linac. We also develops an approach based on PIC simulations to modelize with a significant refinement this regime (non linearity, rise time).

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A NEUTRALIZATION LEVEL DEFINITION

Considering only the ionization process, the DC beam tends to a full neutralized state [2]. To quantify the neutralization degree, several proposals can be found in the litterature: the relative charge, the relative beam potential. We propose to use the following formula :

$$\begin{aligned} D_n(t) &= 1-\gamma^2 \frac{\int_0^{r_b} rE_r(r,t)\rho(r,t)dr}{\int_0^{r_b} rE_r(r,0)\rho(r,0)dr} \\ &= 1-f(t) \end{aligned} \quad (1)$$

where E_r is the radial electrical field, ρ the beam radial distribution and γ the Lorentz factor. This factor $f(t)$ is then directly usable in the envelop equation.

THE NEUTRALIZATION RISE TIME

The neutralization rise is the elapsed time from the beginning of the beam pulse to the instant when the system is stable. The system is assumed stable when the source terms are equal to the loss terms in the equations which lead the production of the particles in the system. It is equivalent to the time when the particles which were repelled to the pipe (H_2^+ for a proton beam) during the transcient, are not any more.
It means that the defocusing kick for these particles provided by the beam is compensated. This point is very important to understand the bunched beam case: an equivalent kick doesn't mean that you provide an equivalent charge density. But it means that the rise time for the DC and the AC case should be the same. In a first and good approximation, the rise time for a DC beam can be computed with the following classical expression:

$$\tau_n = \frac{1}{\sigma N_{gas} \beta c} \quad (2)$$

with σ is the ionization cross section, $N_{gas} = P/kT_{room}$ is the gas density and β the reduced beam velocity. The formula 2 is valid for $\chi = N_{beam}/N_{gas} \ll 1$ with N_{beam} the density of the beam. This is the minimum time to produce a neutralizing charge equivalent to the beam charge. If we plot the neutralizing charge provided in a drift by a DC and an AC beam ($T/6$) during one period T with the same current, we will find the behaviour illustrated by the figure 1. After one period, this figure shows that the same number of neutralizing charge has been provided to the system.

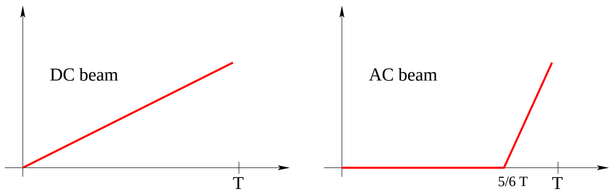

Figure 1: Neutralization charge build up during one bunch period T for a DC beam and a bunched beam with a length equal to $T/6$.

If we compute the transverse kick for a uniform bunched beam:

$$\dot{x} = \int_0^T F_x \frac{dt}{m} \tag{3}$$

with a linear field provided by the neutralizing charge (”DC” beam) between bunches:

$$E_x = -\frac{\rho_b L_b \sigma N_{gas} c}{2\varepsilon_0 \lambda} x n \tag{4}$$

and when the beam is present with a bunch length equal to L_b:

$$E_x = \frac{\rho_b}{2\varepsilon_0} x \left(1 - \frac{L_b \sigma N_{gas} c}{\lambda} n\right) \tag{5}$$

with n the elapsed number of periods, ε_0 the vaccuum permitivity and ρ_b the charge density of the beam. Solving for $\dot{x} = 0$, we find that the number of periods is similar to the DC beam case. The achieved compensation at the equilibrium is:

$$D_n(t \gg \tau_n) = \frac{L_b}{\beta\lambda} \tag{6}$$

STABILITY ISSUE FOR BUNCHED BEAMS

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 [3]. Assuming that SC force results only from the beam charge, a criterion for electron stability and accumulation has been established:

$$\Lambda = \frac{f_c}{f_b} < 1 \tag{7}$$

with:

$$f_c = \sqrt{\frac{r_e \cdot c}{2e \cdot m_p(m.a.u.)} \cdot \frac{I_b}{\beta R^2}} \tag{8}$$

where m_p is the proton mass in mass atomic unit, r_e the classical electron radius; I_b, the beam current, and R the beam radius.

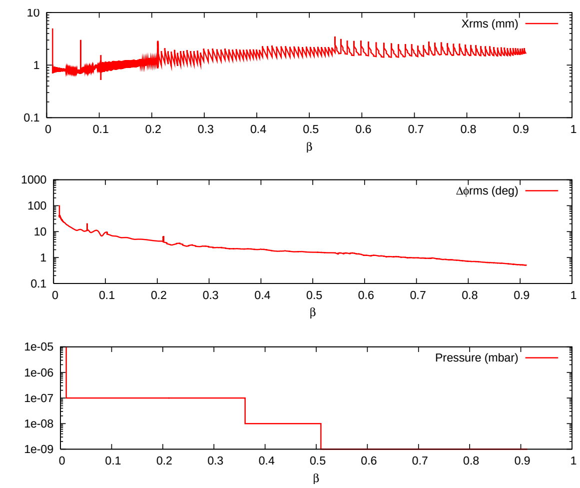

Figure 2: Evolution of the rms beam size in the transverse and longitudinal plane and the pressure of the residual gas in the ESS linac.

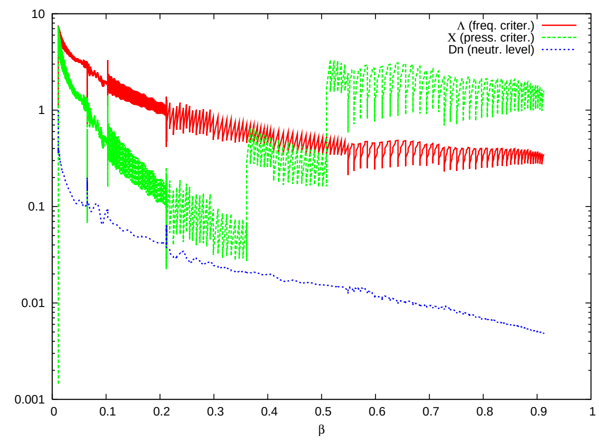

Figure 3: Behaviour of the neutralization level, the frequency criterion Λ and the pressure criterion χ in the ESS linac. .

APPLICATION TO THE ESS LINAC

To illustrate the usefullness of the previous criterions, we propose to calculate them in respect to the ESS linac length taking into account the evolution of the relevant parameters. Doing that, we should be capable to identify sections in which neutralization can play a significant role. This linac has been designed for a peak current of 60 mA [5]. The figures 2 show the evolution of several parameters. In the figure 3, we plot the behaviour of the neutralization level, the frequency criterion Λ and the pressure criterion χ. It appears that if the high energy section is weakly dependent on the input distribution, the neutralization is mainly a front end issue. This point is especially true for $\sim$ one ms pulsed machine as the rise time in the high energy section tends rapidly to several seconds.

PIC MODELIZATION APPROACH

Beam dynamics in LEBT lines are usually simulated with full space charge with a weighting or without space charge assuming a perfect neutralization. The previous sections showed that the bunched beam case requires a additional weighting of the space charge force. But experiments and some theoretical analysis showed that the situation is more complex. It has been observed that the beam charge may be partially compensated in a LEBT line [1]. The neutralizing distribution is not similar to the beam one. This may lead to an emittance growth.
To enhance the modelisation of the effect of the neutralization on the beam properties, we develop a PIC code with the time as independent parameter [4]. For each time step, several species are transported taking into account the dynamic ionization process. We cross-checked the PIC code for different cases. The figure 4 shows a XY simulation for a H^+ DC beam in a drift. It appears to be in a good agreement with the theoretical work of Fleury [2] and experiments made at Saclay [6]. The figure 5 illustrates the same simulation for a H^- DC beam. Due to the trapping of H_2^+ and their high mass compared to electrons, the neutralization pass through an overcompensated regime and tends to 100% with an excess. This behaviour has been observed experimentally by Baartman [7]. We also checked the formula 6. The figure 6 shows that the rise time is independ of the bunch length and that the neutralization degree at the equilibrium verify the equation 6. We also simulated the impact of the initial energy of the ionization products. For proton beams, the initial energy of the electrons induced a larger rise time because it is more and more difficult to compensate the weak potential well at the end of the process. The conservation of the kinetic orbital moment makes that the trajectories of the electrons are elliptical. The consequence is a poor electron density around the axis. During the transcient, the field is then more and more non-linear and its amplitude decreases. It produces a maximum emittance during the transcient and a significant mismatch (see figure 7).

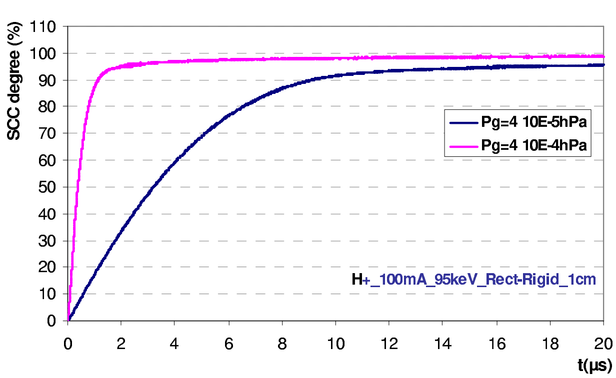

Figure 4: Evolution of the neutralization degree for a H^+ beam with 100 mA, 95keV, 4.10^{-4}hPa and 4.10^{-5}hPa.

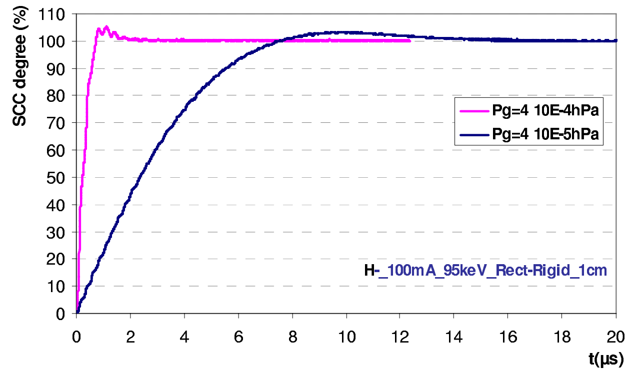

Figure 5: Evolution of the neutralization degree for a H^- beam with 100 mA, 95keV, 4.10^{-4}hPa and 4.10^{-5}hPa.

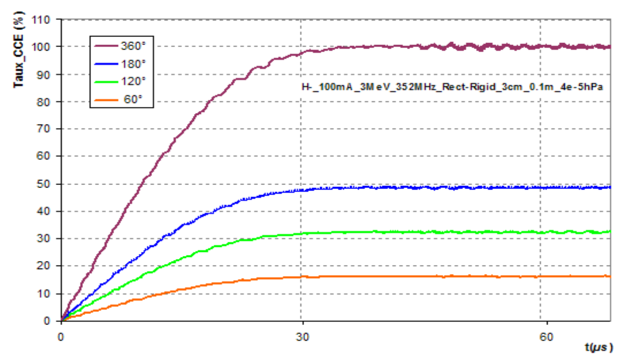

Figure 6: Evolution of the neutralization for a H^+ bunched beam for different bunch length (0.1 A, 95keV, 4.10^{-5}hPa).

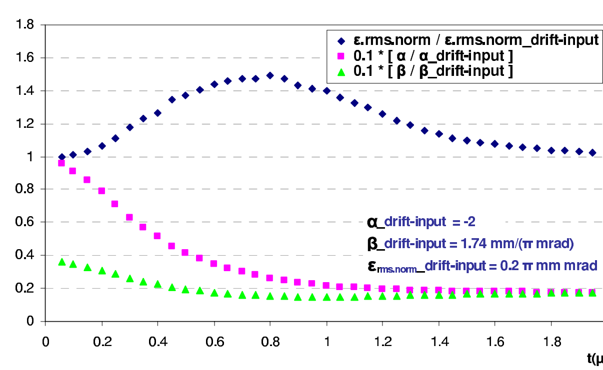

Figure 7: Relative evolution of the twiss parameter in a drift during the transcient for a H^+ beam with 100 mA, 95keV, 4.10^{-5}hPa.

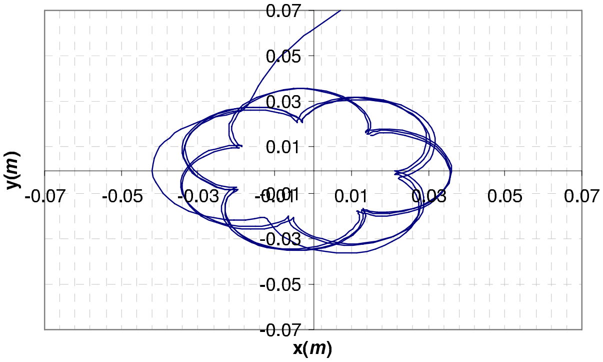

Figure 8: Typical ion trajectory at the center of the solenoid.

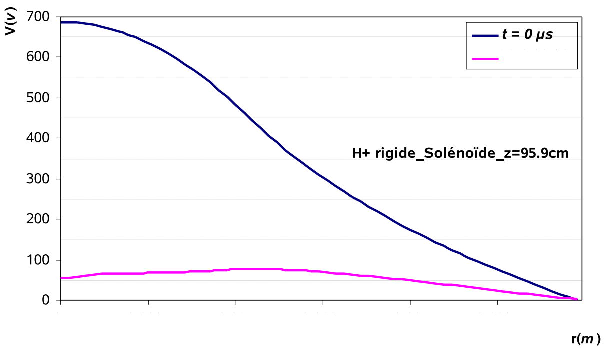

Figure 9: Beam potential well at the beginning (blue) and at the steady state (pink).

COUPLING WITH A SOLENOID

In this section, we test the impact of a solenoid on the dynamic of the system with the neutralization background. It is observed that e^- are longitudinally ejected from the extremities of the magnet. It is due to the magnetic gradient ($F_z \propto q\rho^2\dot{\theta} \cdot \partial B_z/\partial z$). A new behaviour is also observed for the ions. For instance, at the center of the magnet, once they are created, they start to be repelled but, rapidly, their trajectory is curved by the solenoidal field and they go back in the beam. This typical behaviour is illustrated by the figure 8. The resulting distributions at the equilibrium produced a strong nonlinear field. For instance, at the center of the system, the beam is overcompensated near the axis and partially compensated in the halo region (see figure 9).

EXPERIMENTAL COMPARISONS

To make experimental comparisons, we simulated the first part of the IPHI LEBT [8]. This simulation couples different components: of the system: external fields (extraction system, solenoid), image effects (faraday cup at exit, variable aperture pipe) and multispecies motion feed by the ionization. The figure 10 shows a schematic view of this part of the LEBT. The AXCEL code [9] is used to produce the input beam parameters. The figure 11 shows at

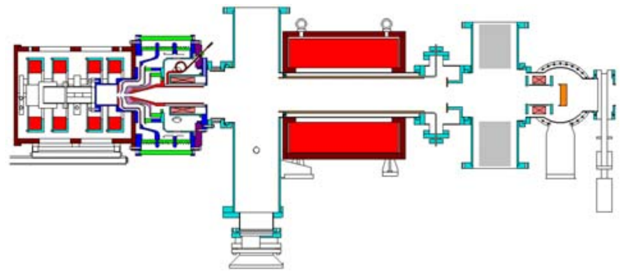

Figure 10: Schematic view of the simulated part of the LEBT.

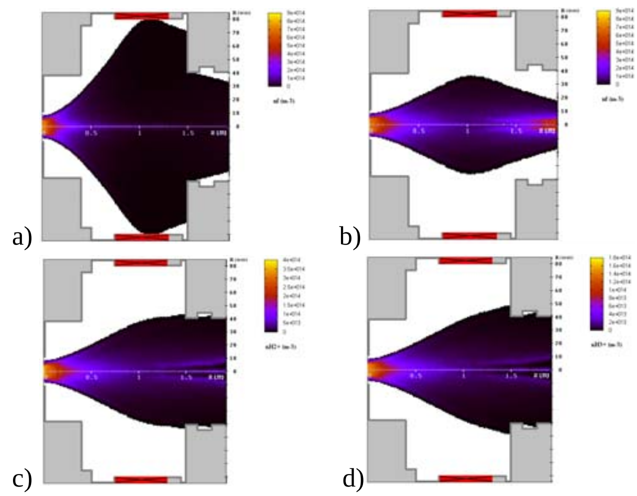

Figure 11: Distributuon for the protons at 1μs in a), at 6μs in b), for the H_2^+ in c) and the H_3^+ in d) at the equilibrium.

several times the distribution for the different species (protons, H_2^+ and H_3^+) which have computed with the code to take into account the full space charge. This last condition is important to be capable to compare the measured transmission with the faraday cup at the exit of the section (see figure 12).

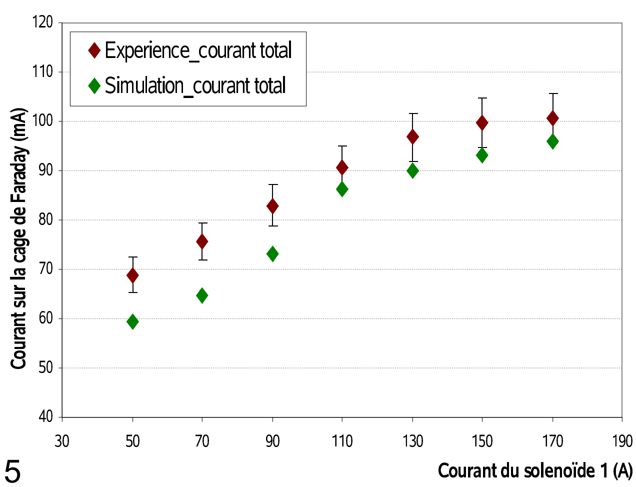

Figure 12: Measured and simulated transmission for different solenoid current..

CONCLUSION

We proposed for the linac designer basic rules to estimate the rise time and the level of compensation in respect to the linac characteristics. It is shown that neutralization is mainly a front-end issue meanwhile the high energy section is weakly dependent on the input distribution coming from the injector. For H^- beams, the rise time and the neutralization level may be computed with simple formulae. The H^+ beam case is more difficult because the possibilities to loose the electrons and to keep a part of the ions are numerous (initial energy of e^-, large mass for ions, heating of the e^- by the beam,...). These few rules are valid in a simple thin drift, to take into coupling induced by electromagnetic elements and the pipe, an approach based on PIC simulations is proposed.

Several experimental comparisons with the developed code have been made and are encouraging but we need to accumulate more data to estimate the errors and to perform good emittance measurements.

It is planned to enhance the present features of the code to include the surface emission process to take into account the secondary electrons. To speed up the computations, a parallelization of the code is also planned.

ACKNOWLEDGMENTS

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