SELF-CONSISTENT EFFECTS OF SPACE CHARGE COMPENSATION ON INTENSE ION BEAMS

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Abstract

It is usually assumed that beams are partially space charge compensated for the design of high intensity, low energy beam transport. Such continuous beams are confined in space by means of magnetostatic lenses, the transverse matching into the RFQ accelerator being achieved with solenoids. Along this low energy transport, beam neutralization is kept almost constant, but severe problems can appear at the entrance of the RFQ where longitudinal bunching takes place. The electric field pulls out the neutralizing electrons, leading to a redistribution of the charged particles. We analyze theoretical solutions of this phenomenom in a self-consistent approach in view of minimizing emittance growth and halo development that could result.

1. Introduction

High perveance proton sources are needed to produce intense beams for industrial projects like TRISPAL.

In the low energy part of the accelerator machine the transport of such beams is critical up to kinetic energies of a few MeV, because the beams are space charge dominated.
It was proposed for a long time to transport such proton beams in a charge compensated regime, where the protons are neutralized by trapped electrons.

This well known effect occurs naturally when the residual gas pressure is relatively high as it is the case after the ion source, even if the gas flowing from the source is pumped out efficiently.

The protons ionize the molecules of the residual gas and produce electrons which are trapped in the collective potential well of the beam.

As this was observed in many experiments [1–3], the beam tends to be partially neutralized, depending on characteristic parameters and vacuum pressure.

This is often a favorable situation since the transported beam current can be enhanced correlatively, and this saves power for the external restoring forces which insure the confinement of the beam; the companion electrons screen the primary beam, diminishing the net defocusing force due to coulombian repulsion and participate to the confinement of the whole beam.

But these time dependent mechanisms of neutralization are not necessarily homogeneous in space: they can produce axi or non-axisymetric instabilities which contribute by non-linear effects to energy redistribution into the beam. This drives the density to a more or less steady profile [4].

Emittance degradation and particle losses in the low energy part of the machine are a real concern for machine designers, it is thus important to be able to predict the optical qualities of the beam and emittance growth.

This is why transport must be simulated using a refined and a self-consistent description.

In this paper, we first describe the system from relevant parameters and time scales of the model that depend on physics: we then derive a set of self-consistent equations for a 1D1/2 model. After analyzing theoretical solutions, we draw conclusions for future studies.

2. Model and hypotheses

We consider a cylindrical DC beam with parameters:
T_0 =100 keV, I_0 = 100 mA, S_0 = 1 cm^2 (R_0 ~5 10^{-3} m).
The study is restricted to a region surrounding a waist where external confinement can be absent. Magnetic focusing is assumed ahead and behind this region; mechanical walls are absorbent and grounded.

• The primary beam (p) is assumed cold, hence its phase space distribution function has the following expression:

$$f_p(r,\mathbf{v},t)= n_p\ \delta(\mathbf{v}-\ \mathbf{v}_p) \qquad (1)$$

where **v** is reduced to the axial velocity v_p; with our parameters n_p = 1.4$10^{15}$ m^{-3}.

• The residual gas (g) mainly consists of hydrogen molecules (H_2 at about 10^{-3} hPa) which are considered at rest compared to the other moving species. With these parameters n_g = 3.5$10^{19}$ m^{-3}.

Physical processes. We assume that the only source of secondary charges is the gas ionization:

$$\underset{1}{p} + \underset{2}{H_2} \rightarrow p + \underset{3}{H_2^+} + \underset{4}{é} \qquad (2)$$

and the generated plasma is composed of four species where 1, 2 are the primary species and 3, 4 are the secondary ones.

From the processus (2), we can estimate the electron density variation versus time:

$$\frac{dn_e}{dt} = \sigma_i n_g n_p v_p \qquad (3)$$

and deduce an approximate neutralization time scale.

$\tau_N = (\sigma_i\ n_g u_p)^{-1}$ assuming that the density n_g and n_p are near constants [5]. With our parameters, $\tau_N\ \geq 330$ *ns.*

We consider that elastic scattering cross section at large energy transfer is small compared to the the ionization one, it is thus assumed that residual gas depletion is inexistent ahead of the beam at any time scale of our study provided:

$$n_i\ \leq\ n_p\ <<\ n_g$$

The radial potential ϕ of a primary beam with a parabolic density profile ρ can be deduced from the Poisson equation:

$$\frac{1}{r}\frac{\partial\phi}{\partial r}(r\frac{\partial\phi}{\partial r}) = -\frac{\rho(r)}{\varepsilon_0} \quad (4)$$

Supposing that this potential vanishes on the wall of the vacuum chamber, we obtain the following expressions:

$$\phi(r) = \frac{3\rho_0 R_0^2}{16\varepsilon_0}(1-\frac{4r^2}{3R_0^2}(1-\frac{r^2}{4R_0^2})+\frac{4}{3}Ln(\frac{r_c}{R_0^2})) \quad (5)$$

for $R_0 \leq r \leq 0$ and,

$$\phi(r) = \frac{\rho_0 R_0^2}{4\varepsilon_0}Ln(\frac{r_c}{r}) \quad (6)$$

for $R_0 \leq r \leq r_c$

This global potential is attractive for the electrons as long as the total neutralization is not reached. In the same time the secondary ions are continuously expelled transversally.

At equilibrium, the ion radial flux balances their creation while electrons are confined in the potential well.

Since electrons are more mobile than ions, electron dynamics will govern this potential: a test electron gaining some energy will escape the well if the potential well is not deep enough. It is exactly as if it evaporates.

When evaporation balances creation a dynamic equilibrium seems to exist. To understand this balance, let us assume for instance that potential depth decreases for some reason; evaporation is then eased and the ions will be expelled slower to the wall, then the ion flux will start to decrease. While electron density decreases, ion density increases and the total potential will return to its previous value.

Secondary particle dynamics. In a first stage, the ionization of the residual gas by primary protons is only taken into account as the main inelastic process. But charge exchange, excitation and dissociation processes will be included in a second stage to interpret more refined experimental results.

Potential of the electrons: once equilibrium is reached, the continuity equation applied to ions gives:

$$n_i = R_0 v_p \sigma_i n_g n_p \sqrt{\frac{m_i}{8e\phi(R_0)}} \quad (7)$$

where $\phi(R_0)$ is the potential at the border of the beam, and is also the minimum energy of the electrons which evaporate. The relation (7) shows that the knowledge of the energy spectrum of the ions leads to the estimation of R_0 and $\phi(R_0)$.

For a partially neutralized beam, the typical value is $\phi(R_0) \cong 20$ V.

Screening effects: To estimate the screening effects we assume that the beam is quasi-neutralized, $n_e \# n_p$ so we can calculate the Debye length:

$$\lambda_d = \sqrt{\frac{\varepsilon_0 T_e}{n_e e^2}} \cong 10^{-3} \text{ m.}$$

This estimation of the Debye length value shows that screening effects will not prevent an external electrostatic field from expelling rapidly the trapped electrons.

Velocity distribution functions of the secondaries:

Experimental data and theoretical calculations for the total and differential cross sections can be found in Refs. [6–9].

It comes out that:

- the primary protons have negligeable deviation from incident trajectory and their velocity is almost unaffected,
- the secondary ions have a recoil energy less than 10 eV,
- the electrons created by ionization have energies picked at 0 eV but 50% of them have energies higher than 18 eV.

Usually, it is admitted that both ions and electrons are created at rest, this corresponds to the double differential cross section:

$$\frac{d\sigma_i}{dE_e d\theta d\varphi} = \sigma_i \delta(p_e) \quad (8)$$

where p_e represents the momentum of electrons created at energy E_e and with no energy transfer taken into account.

In our model, we take some more realistic initial condition: ions are still created at rest but electrons have a mean energy of about 10 eV. As mentionned before, the differential cross section is then:

$$\frac{d\sigma_i}{dE_e} = \frac{\sigma_i}{T_e}\exp(-\frac{E_e}{T_e}) \quad (9)$$

and their velocities are distributed as a maxwellian distribution function with a temperature T_e. This temperature will be an adjustable physical parameter which can be checked by experiment.

Relaxation time: the velocity distribution function of the secondary particles is driven to thermodynamic equilibrium by the binary collisions: e-e collisions drive the distribution to a maxwellian, while e-i and e-g collisions participate essentially to the isotropisation of the velocities. The relaxation time is then expressed by

$$\tau_e^{e/e} \approx \frac{3.5 10^{11}}{\Lambda n_e} T_e^{3/2} \quad (10)$$

where Λ is the Coulomb logarithm.

With $\tau_e^{e/e} = 3ms >> \tau_N$ one can conclude that neutralization equilibrium is reached well before electrons are thermalized.

3. System of equations

The system of equations for the different species can be resumed as follows:

- for the electrons

$$\frac{df_e}{dt} = C_e^{iz}(f_e)$$

where $C_e^{iz}(f_e)$ is the collision operator and can be calculated from the continuity equation by:

$$C_e^{iz}(f_e(r, v_r, v_\theta)) = n_g n_p(r) v_p \frac{d\sigma_i}{dv_r dv_\theta} \quad (11)$$

This gives the number of electrons of velocity (v_r, v_θ) created per unit volume in the phase space and per second.

From the relation (11) it is easy to derive the final form:

$$\frac{d\sigma}{dv_r dv_\theta}_i = \frac{\sigma_i m_e}{2\pi T_e^{iz}}\exp(-\frac{m_e(v_r^2+v_\theta^2)}{2T_e^{iz}}) \quad (12)$$

- for the ions

$$\frac{df_i}{dt} = C_i^{iz}(f_i)$$

where $C_i^{iz}(f_i)$ is the collision operator and can be calculated by the same expression as (9) to give:

$$\frac{d\sigma_i}{dv_r} = \sigma_i \delta(v_r) \qquad (13)$$

We obtain finally at stationnarity [12]:

$$v_r \frac{\partial f_e}{\partial r} + \frac{e}{m_e}\frac{\partial \phi}{\partial r}\frac{\partial f_e}{\partial v_r} =$$

$$n_g n_p(r) v_p \sigma_i \frac{m_e}{2\pi T_e^{iz}} \exp\left(-\frac{m_e(v_r^2 + v_\theta^2)}{2T_e^{iz}}\right) \qquad (14)$$

$$v_r \frac{\partial f_i}{\partial r} - \frac{e}{2m_p}\frac{\partial \phi}{\partial r}\frac{\partial f_i}{\partial v_r} = n_g n_p(r) v_p \sigma_i \delta(v_r) \qquad (15)$$

$$\Delta\phi(r) = -\frac{e}{\varepsilon_0}(n_p(r) + n_i(r) - n_e(r)) \qquad (16)$$

$$\phi(r_c) = 0$$

For the closure of the system, we suppose that f_i *and* f_e are not correlated, but the two kinetic equations are coupled by the Poisson equation. For the boundary conditions, we take absorbent walls. This complete set of equations is to be solved by numerical techniques.

Conclusion

A space charge neutralization may be needed to keep small the emittance degradation in a transport system made of magnetic lenses.

But this can be done only in a some dynamical equilibrium between the present charge species, where the degree of neutralization is kept near a constant value.

If this equilibrium cannot be maintained, a proton density redistribution will happen when the beam enters into the RFQ; the electrons participating to the self-confinement will be rapidly released by the electrostatic field.

In this case, the adiabatic matching and bunching into the RFQ might fail.

It is too early, at this stage of the study to draw definitive conclusions related to our concern.

But we saw that the study of the dynamics of the companion electrons is essential to understand the mechanisms of the equilibrium during the transport, and the rapid decompensation at the entrance of the RFQ.

We derived a 1D1/2 model close to reality since it represents a cylindrical beam which is transported in an axisymetric magnetic system.

The assumed parameters like T_e and $\phi(R_0)$ and the density profile will be measured experimentally to refine the initial conditions and hypothesis.

The numerical simulations that we are presently carrying out, will provide the density profile of the protons and electrons at equilibrium.

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