SPACE CHARGE NEUTRALIZATION OF MODULATED ION BEAMS⁺

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Abstract

In order to minimize focusing gradients and particle losses in accelerators and transport systems it is highly desirable to conserve a sufficient degree of space charge neutralization throughout the whole system whenever this is possible. Especially for bunched beams it is quite unclear how an uncompensated beam can be neutralized within a time scale of nanoseconds or microseconds. For a better understanding of the neutralization process we have started a theoretical and experimental program to investigate the influence of the beam parameters like energy, ion current, and distance of the bunches on the compensating electron distribution and the influence of the compensation on the ion beam itself.

Introduction

An ion beam passing through residual gas in an accelerator system ionizes the neutral atoms. The produced electrons accumulate in the space charge potential of the positive ion beam and neutralize the positive space charge. The positive residual gas ions are accelerated to the beam pipe wall[1,2,3,4]. The lower limit of the time necessary to neutralize the positive space charge of the beam is simply given by

$$t = 1/(\sigma_i v n_r)$$

Here σ_i is the ionization cross section, v is the beam velocity and n_r is the particle density of the residual gas. For residual gas pressures in the region of 10^{-6}-10^{-7} mbar and ion energies of some keV the time t is in the order of milliseconds. Due to electron losses the build-up time can be in fact much longer and a full neutralization can not be achieved. The final degree of compensation is given by the dynamic equilibrium of electron production and loss.

One reason for electron losses can be seen from the differential ionization cross section $\sigma_i(E)$ with respect to the energy E of the produced electrons[5] (E_i is the ionization energy)

$$\sigma_i(E) \sim 1/(E_i + E)^2.$$

Only electrons with kinetic energies below the value of the actual space charge potential can contribute to the neutralization process.

Another reason is given by longitudinal electron losses depending on the boundary conditions and fields (magnetic and electric fields).

The remaining electrons are heated by several processes, which leads via the thermalization of the electron velocity distribution due to electron-electron collisions to another loss channel.

Though the initial electron velocities are mainly in beam direction, experiments have shown that the mean electron velocity is zero resulting in an uncompensated beam current[4].

Especially the electron heating by the beam is not well understood. Coulomb collisions only lead to heating rates which are too small to explain partial compensation measured in experiments with dc beams. Possible additional heating mechanism are the two-stream instability[6] as well as fluctuations of ion current due to ion source instabilities, instabilities of the 'secondary plasma'[7] or charge density fluctuations of the beam ions[8].

Bunched beams

All what has been stated in the previous chapter still holds for modulated and bunched beams. But there are a lot of restrictions which lead to a longer build-up time as well as a lower rate of space charge compensation.

In the case of dc beams with an uncompensated current a 'stationary' cloud of electrons staying inside the beam contribute to the neutralization of the space charge potential, thus leading to a compensation of macro pulses within milliseconds and therefore only the head of the pulse remains uncompensated. In the extreme case of bunched beams with great distances between the bunches compared to the dimensions of the surrounding structure (i. e. the axial potential is zero between the bunches) only the electrons accumulated in the threedimensional potential and travelling with beam velocity can do the business. Therefore each bunch has to produce its own electrons and subsequent bunches can not share electrons produced earlier. In this case a millisecond rise time can not be tolerated, because a 10 keV

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proton beam e.g. would have to go some meters to get neutralized.

In a mixed case with non zero potential between the bunches and appropriate longitudinal boundary conditions, electrons also will travel back and forth, forming a 'stationary cloud' which contributes to the neutralization of subsequent bunches.

A simple estimation can show that one expects smaller neutralization rates and slower rise times for bunched beams than for dc beams.

An electron created with zero energy in the bunch center will only be captured, if the axial potential depth (expressed in eV) of the bunch exceeds the kinetic energy of an electron with bunch velocity. In the case of distant bunches and due to the fact that most of the electrons are created with small energies this leads to the conclusion that the bunch potential can be lowered only to this value.

In this case the potential of an infinite beam still holds for the depth of the threedimensional potential $\Delta\varphi$

$$\Delta\varphi = \frac{I}{4\pi\varepsilon_0 v} \left(1 + 2 \ln \frac{R}{a} \right). \qquad (1)$$

Here v is the beam velocity, I the beam current, R the beam pipe radius and a the radius of a uniformely charged beam. All electrons created in the moving frame of the bunch with velocities exceeding v_{crit} can not be accumulated. v_{crit} is given by

$$v_{crit} = \sqrt{\frac{2\, e\, \Delta\varphi}{m_e}} \qquad (2)$$

with the unit charge e and the electron mass m_e. In the laboratory frame this means that only electrons produced with initial velocities v_{init} which satisfy the vectorial equation

$$| v_{init} - v | \le | v_{crit} |$$

will stay within the bunch potential. In fact v_{crit} of course can be much smaller depending on the location of the electron production.

Since most of the electrons are created near zero energy a substantial rise of the build-up time and drop of the rate of neutralization will occur when v equals v_{crit}. Combining equation (1) and (2) and introducing T (in eV) as the kinetic energy per atomic mass unit m_i of the ion beam gives

$$T^{3/2} \le \frac{I\left(1 + 2 \ln \frac{R}{a} \right)}{5.66\, \pi\, \varepsilon_0 \sqrt{e}} \frac{m_i^{3/2}}{m_e}. \qquad (3)$$

T as a function of the beam current I for different ratios of R/a is given in figure 1 indicating that only for beam energies below an upper limit given by eq. (3) electrons with initial energies near zero can be accumulated in the bunch.

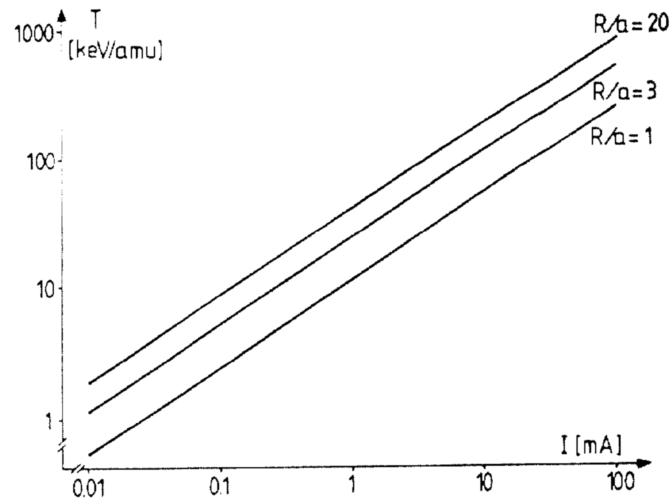

Fig. 1 Upper limit for the kinetic energy of a bunched beam capable to capture zero energy electrons vs. ion current for different values of R/a

The electron cloud formed in the case of closer bunches can compensate the beam to a degree, which depends on the heating of the electrons and the longitudinal boundary conditions.

In the case of closer bunches the threedimensional potential depth is lowered in longitudinal direction thus decreasing the amount of created electrons with the correct initial velocity to be captured in the bunch potential. On the other hand stable electron trajectories are allowed in the transverse potential well for electrons not travelling with the bunch. The so formed 'electron cloud' can compensate the bunched beam only to a lower degree compared to a dc beam, because the electrons are axially not confined in the bunches and because of the strong heating of the electrons by the time variing bunch potential.

The potential of a bunched beam can be approximated with a model using a charge density ρ of the beam given by

$$\rho(z,t) = \rho_0 \left(1 + \cos(\omega t - kz) \right) \qquad \text{for } r < a$$

with $\rho_0 = I_b / v\pi a^2$, $k = \omega / v$. Here I_b is the mean ion current, ω and k the frequency and the wave number of the bunched beam. The beam potential $\varphi(r,z,t)$ inside a beam pipe with radius R can be solved analytically giving

$$\varphi = \varphi_0 (2 \ln R/a + (1 - r^2/a^2)) + \tilde{\varphi} \cos(\omega t - kz)\,(1 - a_3 I_0(kr))\,;\, r < a$$

$$\varphi = \varphi_0 (2 \ln R/a) + \tilde{\varphi} \cos(\omega t - kz)\,(a_1 K_0(kr) - a_2 I_0(kr))\,;\, r > a$$

with $\varphi_0 = \rho_0 a^2/4\varepsilon_0$, $\tilde{\varphi} = \rho_0/\varepsilon_0 k^2$,

$$a_1 = I_1/(I_1K_0+I_0K_1)\Big|_{r=a} \qquad a_2 = a_1K_0/I_0\Big|_{r=R}$$

$$a_3 = a_2 + a_1K_1/I_1\Big|_{r=a}$$ and I and K as modified Bessel functions.

The difference $\Delta\Psi$ between maximum and minimum potential on the beam axis comes out to be

$$\Delta\Psi = 2(1-a_3)\tilde{\varphi}.$$

$\Delta\Psi/\varphi_0$ depending on the geometrical parameters of the beam is shown in fig. 2.

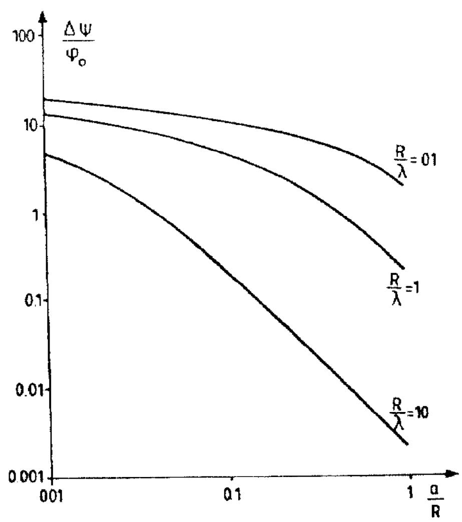

Fig. 2 Normalized axial potential depth $\Delta\Psi/\varphi_0$ for different geometric relations of R, a, $\lambda = 2\pi/k$.

Based on the potential φ given above a particle code has been developed capable to evaluate the trajectory of electrons in the self fields of the bunches together with external magnetic and electric fields. The intention is especially to look how an electron is affected by different boundary conditions.

Fast Neutralization of Bunched Beams

It is highly desirable to obtain a neutralization of high current low energy bunched beams in a time scale of at least less than a microsecond. Obviously this can not be done by residual gas ionization in a pressure range of 10^{-5} - 10^{-7} mbar.

By increasing the neutral gas density to high values compared with the ion density (10^8-10^9/cm^3) in a gas cell the collision rates for sure are increased, but the rise time for the neutralization process is limited by the escape time of the residual gas ions, which is about 1 µsec[9]. This method therefore can be applied to long pulses or to dc beams of course. Charge exchange of the ions must be considered especially in heavy ion accelerators. Another solution may be stripper foils with the same drawback.

Neutralization in a preformed plasma may be better especially if the plasma is connected to an external electron source. In this case even rise times in the order of nsec can be attained[10].

Experiments with bunched beams have been done by using a Gabor plasma lens with a high electron density (10^8-10^9/cm^3) inside. The results[11] have shown that even a higher electron density is necessary to provide neutralization within nanoseconds.

Experiments

We have already started to set up an experiment with bunched beams starting with low bunching frequencies of kHz in order to make use of diagnosis like energy analyzers of the residual gas to measure the actual potential of the beam bunches[3] and Langmuir plasma probes. Our new developed electron source[12] (1 keV, 1 µA) acting as a transverse probe to evaluate the space charge potential of dc-beams together with a fast faraday cup may as well be a good tool in the bunched beam case if the frequency is moderate (kHz).

The beam is provided by a Duopigatron ion source delivering some mA Ar^+ and He^+ beams up to an energy of 30 keV. Within this energy and current range it should be possible to verify the strong dependence of rise time and neutralization rate from the ion energy predicted by theory. Two solenoids actually built to be used in an experiment with dc beams to look at neutralization in external magnetic fields[13] can be used easily as Gabor lenses. Emittance growth of the beam probably occurring due to partial compensation will be measured by our slit-wire system. First results will be expected during the year.

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