NEUTRALIZATION OF THE BEAM SPACE CHARGE IN ELECTRON STORAGE RINGS

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Abstract

Presented are theoretical results concerning the stability conditions of ion confinement in pulsed electron beams. On the basis of the kinetic description of ion core formation, the composition of the core is established and the multiply charged ions density dependence upon the residual gas pressure is estimated. The influence of ion drift and clearing is also discussed. The results of simulation of the self-consistent ion drift in dipole magnets are presented.

1. INTRODUCTION

An efficient performance of storage rings in scientific research and industry applications is determined by the intensity and brightness of the beams. However, with a growing intensity the collective effects start to play an increasingly significant role and finally limit the beam intensity. One of the prime importance effects is connected with a confinement of positive ions occurring due to ionization of residual gas atoms by the circulating beam.

There are two groups of ion driven effects. The first of them occurs due to the presence of additional (to residual gas) scattering centres inside the beam. This leads to the enlargement in transverse beam dimensions and enhances loss rates. This group of effects depends on the density of ions. The second group is associated with the presence of a positive charge in the beam, γ^2 times more effective than the entire beam space charge. The second group depends on the charge density of ions. It is worth noting that the density of ions can differ from that of the ion space charge.

The aim of this report is to present characteristics of the ion core confined in negative pulsed beams, and, in particular, to specify their dependence on the beam parameters and the vacuum conditions.

2. EQUILIBRIUM OF IONS

Let us start with the following definitions: $\eta = \mathbf{qn_i/n_b}$ is the neutralization factor ($\mathbf{qn_i}$ is the ion charge density; $\mathbf{n_b}$ is the beam density averaged over the period of the bunch sequence); $\zeta = \mathbf{n_i/n_b}$ is the relative density of the ion core; $\mathbf{G=2\pi R_0 n_b}\lambda^2$ is the parameter proportional to the beam intensity ($\mathbf{R_0}$ is the classical ion radius, λ is the space period of a bunch train).

2.1 Threshold current

Threshold current of ion trapping $\mathbf{I_0}$ depends on the initial ion energy $\mathbf{E_0}$ [1]:

$$\mathbf{I_0 = E_0 c/e}. \tag{1}$$

At room temperature ($\mathbf{E_0=0.03eV}$) the threshold current is about 1 mA. The upper "initial energy limit" of the neutralization factor responds to the beam current **I** as

$$\eta_{\mathrm{iel}} = (1 - \mathbf{I_0/I}). \tag{2}$$

2.2. Upper limit

The equilibrium upper limit of the neutralization factor can be derived from the self-consistent ion core dynamics in a sequence of cylindric uniform electron bunches of radius **a** [1]:

$$1 = 2\xi(2/\eta G)^{1/2}/(1-\theta)\cdot F\{[((1-\xi^2)/\theta + 2\eta\ln\xi)/2\eta]^{1/2}\} \tag{3}$$
$$\xi = 1 - [(1-\eta\theta)/(1+\eta\theta)]\cdot\{1-\cos[G\theta(1+\eta\theta)/4]\}.$$

Here $F(\mathbf{x})$ is the Dawson function; $\theta = \mathbf{l_{bunch}}/\lambda$ is the inverse bunching factor.

The region of the ion core existence for both the round beam and the flat one is plotted in Fig.1. As one can see, the neutralization factor does not exceed unity and decreases when the bunching factor increases.

2.3. Ion eliminating geometry

From expressions (2) and (3) we obtain the geometrical conditions eliminating ion trapping:

$$(\lambda/a)^2 > Mc^2/(2E_0). \tag{4}$$

For room temperature ions we have

$$\lambda/a > 1.25\cdot10^5\cdot A^{1/2}; \tag{5}$$

Here **A** is the atomic number of the ions. For the heaviest possible gas in the vacuum chamber, i.e., - argon, **A=40** - and for the Gaussian transverse density shape the estimate

$$\lambda/\sigma > 1.8\cdot10^6 \tag{6}$$

is in agreement with the experimental data obtained on ADONE [2] and KEK [3] machines:

$$\text{ADONE}\quad \lambda/\sigma = 4.7\cdot10^5 \tag{7}$$
$$\text{KEK}\quad \lambda/\sigma = 7.6\cdot10^5$$

Therefore, elimination of ions from the beam needs a gap in the bunch train of about a kilometer per milimeter of the beam thickness.

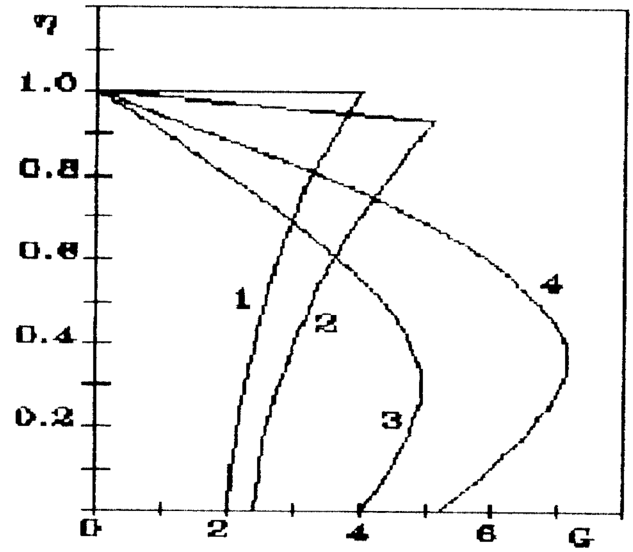

Fig.1. Equilibrium regions for flat (curves 1 and 2) and round (curves 3 and 4) beams. $\theta=0.2$ for 2 and 4 and $\theta=0.001$ for 1 and 3 curves.

3. STEADY STATE DENSITY OF ION CORE

Investigation of the dynamics of ions has enabled us to obtain the upper limit of ion density. Dependence of the steady state core density on the gas pressure inside a vacuum chamber has been obtained established on considering the kinetics of ion product, confinement and loss.

3.1 Kinetic model

We choose the following model. A continuous cylindric beam of radius a and of uniform density propagates through the gas of density n_o. The primary ionization of ions of (q-1) ionization level produces ions of q level (q=0 referred to the neutral gas). These ions are eliminated either by further ionization or by increasing their transverse amplitudes above the beam radius causing by the short range Coulomb field of the beam electrons. Following this model and assuming small frequency of electron-ion collisions, we have obtained a chain of single-particle Belyaev-Budker kinetic equations:

$$<\sigma_h\delta>_q d(Ed\phi_q/dE)/dE=-\sigma^{(q+1)}\zeta_q\phi_q+\sigma^{(q)}\zeta_{q-1}\phi_{q-1} \quad (8)$$

$$0<E<qE_m;\ E_m=G(\lambda/a)^2(1-\eta)/2;$$

$$\eta=\Sigma q\zeta_q.$$

Here $\phi_q=\phi_q(E)$ and $\phi_q(E)=1$, $\phi(E)$ is the source function, $<\sigma_h\delta>$ - is the averaged over scattering angles elastic Coulomb cross section σ_h multiplied by the energy gain per single collision δ, Z is the charge number of the ion nucleus; m_e, M are the rest masses of electrons and ions, resp.; r_o is the classical electron radius.

3.2 Dynamics & kinetics

Taking into account both dynamics and kinetics one can write the neutralization factor as:

$$\eta=\eta_{dyn}(1-I_o/I)/(1+F^*/N_o) \quad (9)$$

There $N_o=n_o\pi a^2$; F^* is a function of microscopic residual gas characteristics. The plot of η/η_{dyn} versus hydrogen density is given in Fig.2.

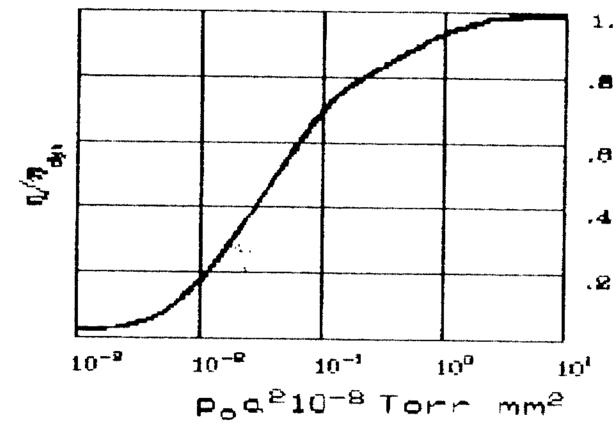

Fig.2.

3.3 Heavy gases (Z>1)

Heavy gases can produce multiply-charged ions. The chain of kinetic equations (8) enables us to establish (numerically, at least) the distribution of ions over the ionization levels.

i) At the limit of the high residual gas density ($n_o/n_b>>1$) we have

$$\zeta_q/\zeta_{q-1}=\zeta_1/\zeta_o<<1;\ \zeta_1/\zeta_o=1/\zeta_o<<1 \quad (10)$$

The neutralization factor is close to its upper limit ($\eta=1$ for the continuous beam) and is independent of the gas density. The ion core consists of single-charged ions creating negligible extra gas density inside the beam.

ii) The low density of residual gas ($n_o/n_b<<1$)

In this case we have

$$\zeta_q/\zeta_{q-1}=\sigma_q/\sigma_{q-1}=1;\ \zeta_Z/\zeta_{Z-1}>>1. \quad (11)$$

The partial densities of ions of charge up to Z-1 are low and approximately equal each other and to that of the neutrals. Most of the core ions are the bare nuclei and their density

$$\zeta_Z=\zeta_o\nu_B\sigma_1 mc^2/(2Z<\sigma_h\delta>_Z, \quad (12)$$

where $\nu_B=N_b r_o$ is the Budker parameter, exceeds that of the residual gas. The neutralization factor is Z times the density $\eta=Z\zeta_Z$.

4. MAGNETIC FIELD AND CLEARING ELECTRODES

The balance of ions is described by the following equation:

$$df/dt + div(Vf) = F_S. \quad (13)$$

where V is the (drift) velocity of ions: $F_S=n_b\sigma_i n_o c$ is the ion production rate; f=f(x,y) is the ionic density. In the beam orbit between two clearing stations equation (13) yields:

$$f(x,y) = n_b\sigma_i n_o c\cdot y / V_y(x) \quad (14)$$

Inside the beam there exist two ion counterflows. If their velocities equal each other (e.g., inside a non-gradient dipole magnet), the ion density is a constant along the orbit but its transverse shape differs from that of the beam

$$f(x,y) = f(x) = n_b\sigma_i n_o c\cdot Y / V_y(x). \quad (15)$$

where Y is the distance between the clearing electrodes.

4.1. Simulation

As it may be shown, the drift velocity of ions in the uniform magnetic field is determined by the electric field value in the centre of the Larmour disk (assuming the radius of the disk much smaller than the beam width):

$$V = c\cdot[E\cdot B] / B^2 \quad (16)$$

This fact encouraged us to develop a simulating code. Some results of the core self-consistent drift are listed below:

i) the ion drift velocity depends on the ion density

$$V = V_{beam}(1-\eta) \quad (17)$$

ii) the ion core behaviour depends on the sign of voltage applied to asymmetric clearing electrodes. Positive voltage applied to the electrode rejects the ions as it is shown in Fig.3.

5. CONCLUSIONS

If there is no extraction, then the characteristics of the ion core depend on the relative density of neutrals $\zeta_0=n_0/n_b$. In case of $\zeta_0>>1$, the neutralization reaches its upper limit and is irrelevant to the residual gas density. In other case, $\zeta_0<<1$, the neutralization is lower than the upper limit. The ion core is formed by stripped nuclei whose density exceeds that of neutrals. The core density depends on the residual gas density linearly. The transverse shape of the core is similar to that of the beam. These results are also valid for the ion motion along the vector of the magnet field.

In the presence of clearing electrodes the transverse shape of the core differs from that of the beam: viz., the core density is inversely proportional to the drift velocity. Based on the results obtained we are able to explain the data presented in [4], where the ion drift velocity is observed significantly lower than that of the empty beam and greater than the thermal one. The effect of ion rejection by the clearing electrode has been observed on the Kharkov H-100 storage ring [5].

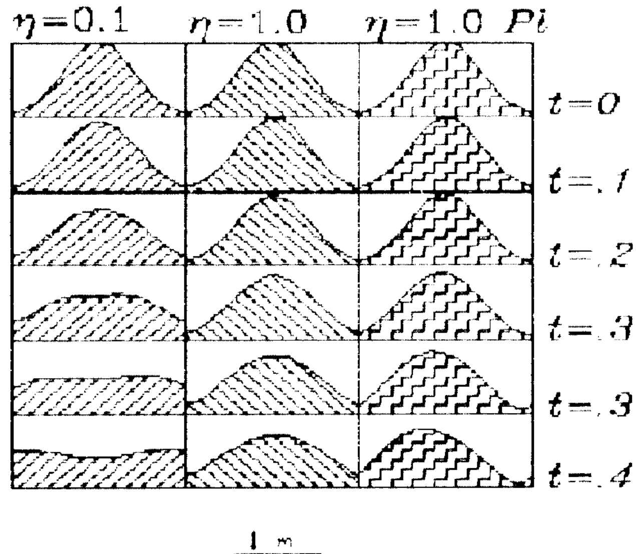

Fig.3. Evolution of the bi-gaussian ion cloud. The beam current is 200 mA; The transverse dispersion $\sigma=1$ mm. In the right column positive potential applied at the right border. Time *t* is in msec.

5. REFERENCES

[1] E.Bulyak, "The ion storage in the intense pulsed electron beams", KFTI, Kharkov, USSR, Ph.D. Dissertation, 1988.

[2] M.E.Biaggini, S.Guiduchi et al, "Observation of Ion Trapping at ADONE", Proc. 11 Int. Conf on High Energy Accelerators, Geneva, 1980, pp 687-692.

[3] S.Sakanaka, "The Stability of Ions in Partially Filled Mode Operation in the Electron Storage Ring", KEK Preprint 86-17, 1986.

[4] Y.Miyahara, "Experimental and Theoretical Studies of the Longitudinal Motion of Trapped Ions in an Electron Storage Ring", Part. Accel., vol.28, pp 113-118, 1990.

[5] P.Gladkikh and A.Shcherbakov, "The Longitudinal Motions of Ions in Electron Storage Rings", Journ.Tech.Phys., Letters, vol.11, issue 24, pp 1509-1511, 1985.