ION CLEARING METHODS FOR THE ELECTRON STORAGE RING

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Abstract

Presented is the survey of the methods of clearing the electron beams from positive ions that limit the beam performance. Considered are: the clearing electrostatic electrodes (CE), a gap in the bunch train (GT), and beam shaking (BS). For the CE method the analytical expressions describing the longitudinal, vertical and horizontal shapes of the core density are presented. As it shown for the GT method, the initially neutralized beams require wider gaps for their clearing. The stability islands for the finite density core are wider than that for a single ion and may overlap for the short gaps. For all methods the density of the remaining ions is estimated as well as its dependence upon the density and composition of the residual gas. Influence of each clearing method on the beam dynamics is also discussed.

1 INTRODUCTION

As it is well known, positive ions of the residual gas confined in electron beams of the storage rings may affect the beam performance by: (i) increasing the density of the gas in the orbit; (ii) nonlinear shift in the betatron tunes; (iii) nonlinear resonances of the betatron oscillations; (iv) electron-ion instabilities, etc. [1].

In the present paper we briefly survey methods to remove ions from a beam, i.e. :

use of the clearing electrodes (CE);
create the gap in bunch train (GT);
use beam shaking (BS).

Particularly we consider the first two methods the most applicable.

2 PHYSICAL BACKGROUNDS

We use the beam with round cross section of the radius a and uniform density n_b that circulates along the orbit of the length L as a model for considering physics of the methods. The average number of electrons per unit of the orbit length is $N_b = \pi\, a^2 n_b$. This beam circulates in a vacuum chamber that contains the gas with the following parameters: the density n_0, the mass of the molecule M, and the ionization cross section σ_i. Also assume that the bunch passing frequency significantly exceeds the ion frequency ω_i, so the ions expose to a continuous beam (or a macrobunch for GT method) with the average density n_b.

2.1 Clearing Electrodes

This method is based on the extraction of the ions by the transverse electrical field. The ions come into a clearing station due to the longitudinal (along the orbit) drift in crossed fields -- the electrical one of the beam and the magnetic field B in a bending magnet. The longitudinal density of the ion core is [2]

$$N_i = \eta N_b = \frac{4\varepsilon_0 n_0 \sigma Y B a}{e} \Psi(y_{min}, D) \qquad (1)$$

$$y_{min} \equiv \frac{x_{min}}{a}(1+D)$$

$$\Psi(y, D) \equiv (1+D)\left\{ \log\left[\frac{1+\sqrt{1-y^2}}{y}\right] - \sqrt{1-y^2} \right\}$$

where D is a parameter determined by the beam intensity and the mass of an ion:

$$D \equiv \frac{N_b M}{2\pi\varepsilon_0 a^2 B^2}; \qquad (2)$$

Y is the distance between the consecutive clearing stations. For the adopted model x_{min} is determined from the condition of equality the ion core density to the beam's $n_i = n_b$ [2].

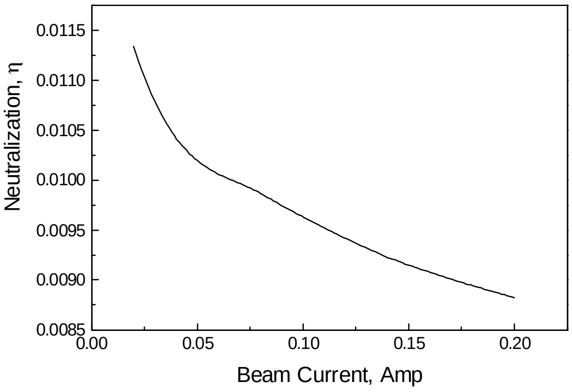

Fig.1. Dependence of the neutralization of the beam by the molecular nitrogen ions on the beam current for the ISI-800 ring.

For the typical synchrotron light source provided with the clearing stations placed at the magnet ends the CE method yields residual neutralization of about few percent. Fig. 1 represents dependence of the neutralization factor on the beam current for the project ISI-800 [3]. The residual ions are localized in the vicinity of the orbit, where the drift velocity is small (see Fig. 2).

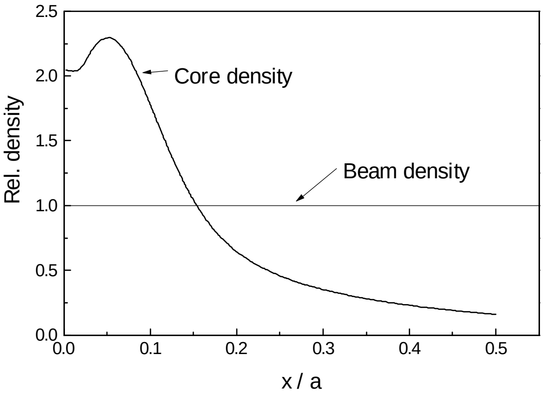

Fig. 2. The relative core density in the median plane within the bending magnets of the ISI-800 at the beam current of 100 mA.

2.2 Gap in Bunch Train

The following is the essence of this method. Injection of a beam is performed in a way that leaves a number of consecutive RF buckets empty. Thus, the ions experience periodic attractive (the force of partially neutralized electron macrobunch) and repulsive (the self force of the ion core) forces. Length of the empty part of a beam is chosen to provide unstable ion motion the working intensity of a beam. The stability of a single ion (the ion core of zero density) was estimated in [4, 5]. As it was shown, the stability of an ion in the beam of a definite geometry is determined by the ion mass and the beam density. A real beam could confine the dense ion core before reaching the unstable conditions. It could trap ions during the beam injection (when the beam density is below the unstable limits) or in operating cycle (when the beam density approaches the unstable limit from the above). Based on that we evaluate stability conditions for the ion core of definite density.

We consider the following model: Macrobunches of the length L_t (the train of bunches) and the longitudinal electron density N_t filled with ions of density N_i ($\eta_t = N_i / N_t$). The problem is to establish the length of the gap G between consecutive macrobunches that corresponds with the ion stability limit. The following relations are obvious:

$$L = L_t + G; \;\; N_b = N_t L_t / L; \; \eta = \eta_t L / L_t. \tag{3}$$

The single ion stability conditions ($\eta = 0$, comp. [4, 5]) for the round and the flat beam model (b is the beam width, $b > a$) have the form:

$$G(\nu, \eta = 0) = \frac{k}{\pi\sqrt{\nu}} \cot\left[\frac{\pi}{2}\left(\sqrt{\nu} - q\right)\right] \tag{4}$$

where k=1 for the round beam and k=2 for the flat one; q is the integer part of $\sqrt{\nu}$ and corresponds to the number of the ion oscillation within the bunch train;

$$\nu_{flat} = \left(\frac{L_t}{a}\right)^2 \frac{a}{b} \frac{N_t R_i}{\pi},$$

$$\nu_{round} = \left(\frac{L_t}{a}\right)^2 \frac{2 N_t R_i}{\pi^2};$$

R_i is the classical ion radius.

The stability islands in the (ν, η_t) plane are depicted in Fig. 3. As it appears from the picture, the maximum ion density decreases if the island number q increases. The decrease is rather sufficient for the large machines with dense beams. For example, for the ESRF in one third mode of operation (see [5]) the beam current 10-100 mA covers the stability islands of q=10..30 for the singly ionized CO or N_2. The maximal neutralization factor does not exceed fractions of a percent: $\eta < 0.004$ (Fig. 4).

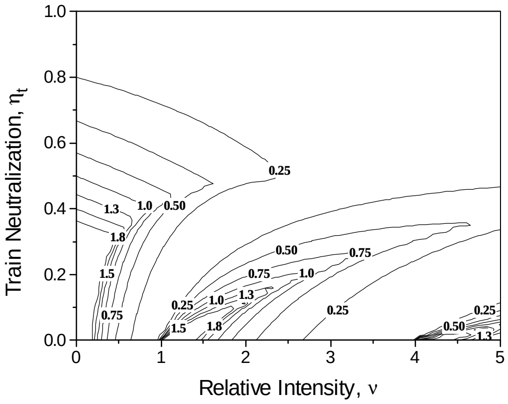

Fig. 3. The stability islands of q=0,1,2 for the flat beam model. Figures in the curves represent the relative gap length G/L_t.

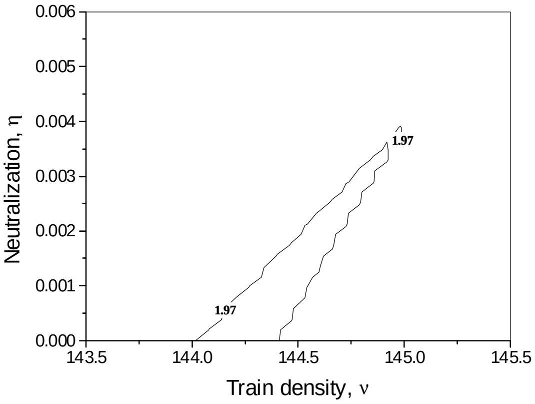

Fig. 4. The stability island for q=12, G/L_t=2, the flat beam model.

Inside a stability island the ion core density reaches its maximal value (island's upper border) under the 'bad vacuum' ($n_0/n_b > 1$) condition. Further ionization of the confined ions under 'the good vacuum' ($n_0/n_b << 1$) condition leads to the state when the density of each ionization rate will be approximately equal to that of the neutral gas (under the assumption that at least the bare nuclei are unstable).

2.3 Beam Shaking

This method consists of driving the transverse oscillations in the ion core. The effective density of the ions n_{ef} oscillating with the amplitude D then decreases:

$$n_{ef} = n_i \frac{a}{\pi D}; \qquad (5)$$

$$D/a >> 1.$$

These oscillations are driven by the beam. There two ways of driving the ion oscillations. The first one consists of shifting the part of the beam orbit by the interval D, in the time frame less then the neutralization time τ:

$$\tau^{-1} = c\,\sigma\, n_0$$

The main problem is in creating the significant shift $D/a >> 1$.

The second way consists of creating the continuous harmonic coherent oscillations of the beam with the small amplitude. It is necessary to maintain the resonance condition:

$$\omega_i = c\sqrt{2\pi R_i n_b} \approx |p - Q| c/L, \qquad (6)$$

where Q is the betatron number; p is the nearest to Q integer

As it follows from (6) the efficiency of the method varies with the changes in the beam current. It is possible to remove the ions from the beam completely (comparing to the first way). The disadvantage of the second way is in exciting the coherent oscillations in the beam.

3 COMPARISON OF THE METHODS

3.1 Use of Clearing Electrodes

The ion core density depends on the density of the gas in a vacuum chamber. The residual ions are located in the near-to-axis region. The additional focusing is mostly nonlinear, the potential function of the ion core is similar to the logarithmic one. This extra focusing force enlarges the betatron frequency band in the electron beam and stabilizes the beam against the transverse coherent instabilities. Clearing stations change the chamber impedance.

Dependence of the core density on the beam current is weak. This method can control the core density by switching off some of the clearing stations.

This method is mostly applicable for the compact storage rings because the clearing stations have to be inserted with a few meter spacings.

3.2 Gap in Bunch Train

This method completely removes ions between the stable islands. Within these islands the ion core density depends on the pressure of the residual gas. The transverse density shape of the ion core is about the same as of the beam, thus impact of the nonlinear force is smaller than that for the CE. Dependence of the core density upon the beam current is craggy. The ‘resonant’ effects during the beam life time may occur. The method requires specific beam filling that leaves part of the RF buckets empty. The double periodicity of the beam asymmetrically loads the RF-system of the ring. Efficiency of this method increases with the increase in the circumference of the ring.

3.3 Beam shaking

This method requires dedicated devices to drive the beam, and may trigger the coherent transverse instabilities. The beam performance (the density, the stability in time) decreases. The method can be applied during the beam injection and ramping up to the operation energy.

4 CONCLUSION

The considered clearing methods were applied on some machines and proved their ability to remove ions from the electron beams. Their applicability mainly depends on the machine circumference. The first two methods seem to be the most effective. The use of CE could help to obtain the maximal number of electrons in the orbit, the GT method is preferable for the big machines to reach the high bunch density.

All of the considered methods do not cover the whole spectrum of clearing ways, ranging from the ‘surgical’ usage of positrons instead of electrons to the exotic electron-ion instability. It is worth to mention that in any case the residual density of ions responds upon the density of the gas in a vacuum chamber.

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