ION DRIVEN EFFECTS IN THE INTENCE ELECTRON BEAM CIRCULATING IN STORAGE RINGS

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1. INTRODUCTION.

Ion-driven effects in electron beams impose severe limitations on performance of storage rings [1]. These effects are much similar to the well-studied effects of the beam space charge. Most effects caused by the entire charge of the beam can be calculated by commonly used codes, e.g., BeamParam and ZAP [2]. We make an attempt to survey briefly in this report the scaling coefficients of the ion-driven effects related to those of the beam charge. The ion core confined by the electron beam is described by the neutralization factor η equal to the relative ion core charge:

$$\eta = \frac{\sum_{q=1}^{Z} qN_q}{N_b}$$

Here N_q is the number of ions within the beam per its unit length; N_b is the number of electrons per beam's unit length ($N_b=j/ce$, j is the beam current); Z is the charge of the ion nucleus.

Besides we use the relative density of the ion core ζ:

$$\zeta = \frac{\sum_{q=1}^{Z} N_q}{N_b}$$

We suppose that the transverse density distributions in both the beam and the core are the same and the ion core is coasting (the core density is homogeneously distributed along the beam orbit). The electron beam is considered consisting of bunches that occupy $1/B$ part of the orbit length (B is the bunching factor). So, the main ion-driven effects with their scaling to similar effects of the beam are discussed below.

2. TUNE SHIFTS

2.1. Incoherent betatron tune shifts

The incoherent shift of the betatron tune Q_u caused by the core is positive:

$$(Q_u-Q_{u0})_{ion}=-(Q_u-Q_{u0})_{beam}\eta\gamma^2/B, \qquad (1)$$

where $u=(x,z)$.

While the tune shift induced by the beam space charge is negligible, the shift caused by ions is significant ($\eta\gamma^2/b>>1$). It is worthy of note that this shift is essentially nonlinear. For the elliptical beam cross section with the normal density distribution the shift is:

$$Q_u = Q_{u0} + \frac{N_i r_0 R^2}{Q_{u0}\gamma^2}\int_0^\infty \frac{\exp\left(-\frac{J_x}{Q_{x0}\left(2\sigma_x^2+t\right)}-\frac{J_z}{Q_{z0}\left(2\sigma_z^2+t\right)}\right)}{\sqrt{\left(2\sigma_x^2+t\right)\left(2\sigma_z^2+t\right)}\left(2\sigma_u^2+t\right)}\,\mathrm{d}t$$

Thus for the round gaussian beam it is:

$$Q_u = Q_{u0} + \frac{N_i r_0 R^2}{Q_{u0}\gamma}\,\frac{1-\exp\left[-\frac{1}{2\sigma^2}\left(\frac{J_x}{Q_{x0}}+\frac{J_z}{Q_{z0}}\right)\right]}{\left(J_x/Q_{x0}\right)+\left(J_z/Q_{z0}\right)} \qquad (2)$$

Here J_u is the square of the betatron amplitude.
Betatron amplitude vs. its tune is plotted in Fig. 1.

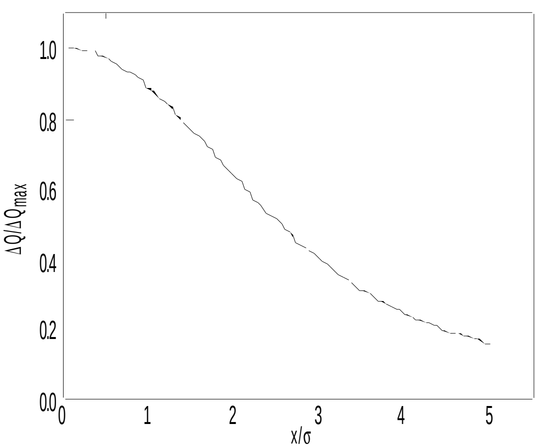

Fig. 1. Q shift vs. amplitude (square root of J over σ).

As it can be seen from Fig.1, the ion tune shift is sufficiently nonlinear at large aplitudes of oscillations. Therefore the periferal beam particles will experince nonlinear oscillations. The maximum in the tune shift at the beam axis (J=0 in (2)) is equal to the maximum value of the tune spread. Major part of the tune spread in electron beams causing the Landau damping is due to trapped ions.

2.2. Tune shifts due to the beam environment

These shifts are much smaller than the beam's and negligibly smaller than those described in 2.1. So, the incoherent tune shift due to reflection in the conducting vacuum chamber walls is smaller than that due to the beam charge by a factor of $-\eta/B$. Reflection of the ion current in ferromagnetics does not take place because of a zero average longitudinal velocity of ions.

2.3. Coherent tune shifts

The ion core is at rest when the beam experiences small coherent betatron oscillations. Hence the coherent betatron shifts are equal to the incoherent ones (2) and are dominant.

3. INCREASE IN BEAM LOSSES AND EMITTANCE

Trapped ions contribute the additional density to the residual gas. The results in the increase of gas pressure in the beam. The influence of the ions is proportional to their density n_i.

$$n_i(\varepsilon_x, \varepsilon_z) = \zeta n_b = \frac{4j\zeta}{\pi Rce}\left(\frac{Q_x Q_z}{\varepsilon_x \varepsilon_z}\right)^{1/2} \qquad (3)$$

where ε_u is the beam emittance.

The transverse emittances can be derived from the set of algebraic equations:

$$\begin{cases} \varepsilon_x = \varepsilon_{rad} + V(n_0 + n_i) / Q_x \\ \varepsilon_z = V(n_0 + n_i) / Q_z + \kappa \varepsilon_x \end{cases} \qquad (4)$$

$$V = \frac{12\pi^3 r_0 R^2 Z^2 \ln\left(181.5 \cdot Z^{-1/3}\right)}{\gamma^5 I_2} \qquad (4a)$$

$$\varepsilon_{rad} = \frac{55}{32\sqrt{3}} \frac{\hbar}{m_e c} \gamma^2 \frac{I_5}{I_2(1 - I_4/I_2)} \qquad (4b)$$

where κ is the coupling factor; I_p are the radiation integrals of the ring.

As it can be seen from (4a)-(4b) the radiation part of the horizontal emittance increases with energy as γ^2 while the 'gas' part decreases as γ^{-5}. Therefore, at high energies the beam emittance is not increased by the ions and the residual gas as well. The trapped ions cause increase in the gas density (3) and the ensuing losses of the beam particles.

4. ION-DRIVEN TRANSVERSE RESONANCES

The forces due to the space charge of the ion core can not only shift the working point (Q_x,Q_z) of the ring towards resonant stop-bands but also drive the specific resonances. These resonances are similar to the crossing beam resonances being studied intensively . The resonances due to the ion core forces are not so complicated for investigation because of the coasting nature of the core. As it has been shown in [3], the ion core drives the nonlinear difference resonances

$$2|mQ_x - nQ_z| << 1, \qquad (5)$$

These resonances capture the peripheral beam particles. The 'transverse energy' of these particles is the constant of motion:

$$E_\perp \equiv J_x Q_x^2 + J_z Q_z^2 = const \qquad (6)$$

It leads to the occurence of halo around the beam and can cause the 'resonant' increase in the beam losses when the halo tails reach the aperture of the ring. These resonances may be harmful for the machine with the low-energy multiple injection, where the injected beam with a large amplitude experiences the nonlinear forces due to the ions confined by the circulating beam. Especially it concerns the rings with Q_z<Q_x. Increase in a value of the relation

$$\frac{\sigma_x}{\sigma_z} \cdot \frac{Q_x}{Q_x}$$

will lead to enlarging of halo. A sketch of the beam cross section experiencing the difference resonance is presented in Fig.2.

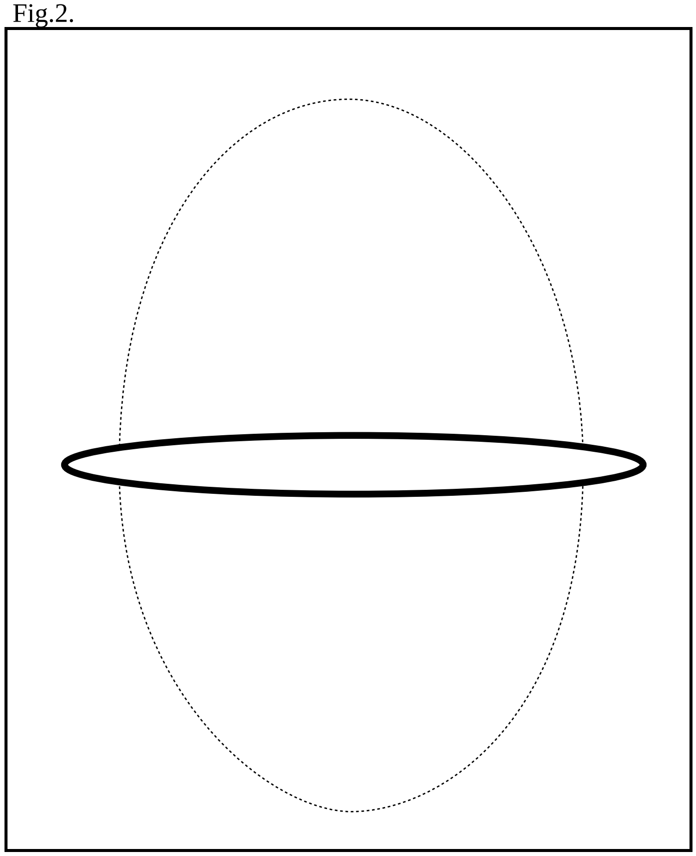

Fig. 2. Solid line represents the beam envelope, dotted line -- the halo envelope.

6. ELECTRON-ION INSTABILITY

This instability of the relative oscillations of the beam and the core is similar to the proton-electron or the antiproton-ion ones. The main difference between them consists in the bunching of the electron beams. This instability is the only known ion driven effect dependent upon the longitudinal bunch shape. The instability of the space modes has the lowest threshold [4]. The hydrodynamic theory for the round homogeneous bunch shows that the threshold is determined by the maximum in the bunch density:

$$\max(n_{bunch}) = \frac{\gamma\left(p^2 - Q^2\right)}{4\pi r_0 R^2} \tag{7}$$

p=1,2,...; $p>Q$

The increment has its largest value in the vicinity of the threshold and is proportional to the square root of the ion density:

$$\delta = \frac{\gamma c\left(p^2 - Q^2\right)}{R^2 r_0 n'_{bunch}} \left(\frac{r_p n_i}{4\pi A}\right)^{1/2} \tag{8}$$

Here $n'_{bunch} \equiv \mathrm{d}\, n_{bunch}/\mathrm{d}\,\vartheta$, r_p is the classical proton radius; A is the ion mass number.

This phenomenon is poorly known. Experimental observations show pulsation in the beam dimensions and none additional beam losses [4].

5. CONCLUSION

The most harmful ion-driven effects among listed above are the nonlinear tune shifts and resonances especially for the rings with the multiple low energy injection. The tune spread caused by ions increases the Landau damping which stabilizes the coherent transverse instabilities. It is essential to choose properly the working point and strength of the multipole lenses such as the octupoles. Some ion-driven effects need to be studied more extensively.

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