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THE CHARGE-EXCHANGE INSTABILITY IN INTENSE ION BEAMS

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The charge-exchange vacuum instability can occur in an intense heavy-ion beam in an accelerator or a storage ring. The instability increment is proportional to the total ion current, to the total cross section of the ion charge-exchange on remanent gas atoms and to the coefficient which determines the atom output into the vacuum chamber from a single beam ion incident on a wall of the vacuum chamber. The instability involved is shown to limit the total heavy-ion current that may transverse the vacuum chamber cross section.

In the last few years, increases of proton and electron intensity in accelerators and storage rings have resulted in a number of new effects, such as a local rise of pressure due to stimulated desorption owing to ion (electron, photon) bombardment of the vacuum-chamber wall.[1,2] Here the ions are produced from ionization of remanent gas molecules by the charged-particle beam. Proton beam loss (or partial loss) occurs not by beam scattering on remanent gas atoms, but by interactions between protons and the cloud of captured electrons.[3]

The acceleration and stacking process of intense ion beams meets a more complicated problem caused by a large ion charge-exchange cross section on remanent gas atoms and large coefficients of desorption and material atomization of the vacuum-chamber walls.

If a single ion changes its charge value through interaction with a remanent gas atom, it will lose stability and hit the vacuum-chamber wall. Local evaporation and atomization of a part of wall material will occur at the location of incidence. Let us denote by η the number of wall-material atoms incident into the vacuum chamber due to a single ion striking the wall. We divide these atoms into two groups. The first group are gaseous combinations which spread throughout the whole volume of the vacuum chamber. The lifetime of these atoms is determined by the vacuum pumping speed and is, from our point of view, long. The second group are atoms with lifetime determined by the time interval necessary to reach a surface and immediately stick to it. Ions moving in the chamber will interact with these atoms, resulting in additional beam loss which will strike the vacuum-chamber wall, bringing about the appearance of new groups of atoms.

To analyze this problem we use the relation

$$\frac{dn^+}{dt} = -n^+ \cdot \sigma(v)v(n_1 + n_2), \qquad (1)$$

where n^+ is the ion density in the beam; v is the ion velocity along the chamber axis; n_1 and n_2 are the density of atoms spread in the vacuum chamber of the first and second groups. Correspondingly $\sigma(v)$ is the total ion charge-exchange cross section on atoms scattered in the chamber. In Eq. (1), we disregard the weak dependence of charge-exchange cross section on the atomic number of the scattering atoms.

Let us integrate Eq. (1) over the vacuum-chamber cross section. The left-hand side gives

$$\int \frac{dn^+}{dt} dS = \frac{dN^+}{dt} = -\frac{dN}{dt}, \tag{1b}$$

where N^+ is the linear ion density in the beam, and N is the linear density of ions escaping the beam.

In carrying out the integration of the right-hand side of (1), we assume that the directions of the atoms after collision are close to the normal to the chamber surface. However, the first atom group "forgets" the conditions of the collision out and fills up the chamber volume uniformly. Therefore, $n_1 = \eta_1 \cdot N/S_c$ and the integral over the cross section of the first term on the right-hand side of Eq. (1) gives $-n^+ \cdot \sigma(v) \cdot v \cdot \eta_1 N(S_b/S_c)$. Here S_b and S_c are the cross-sectional area of the beam and the chamber, respectively.

The second group of atoms interact with the beam during a limited time, which is approximately determined by the transit time of an atom through the ion beam, i.e., $\tau_a \simeq S_b^{1/2} \cdot v_a^{-1}$, where v_a is the mean atom velocity. Then, $n_2 = [N(t) - N(t - \tau_a)] \cdot \eta_2 \cdot S^{-1}$ where $S < S_b$ is the total area occupied by atoms and ions of the beam.

Integration over the area of the chamber cross section gives

$$-\int n^+ \cdot \sigma(v) \cdot v \cdot n_2 \cdot dS = -\eta_2 \cdot [N(t) - N(t - \tau_a)] \cdot \sigma(v) \cdot v \cdot n^+.$$

Finally we have

$$\frac{dN}{dt} = n^+ \cdot \sigma(v) \cdot v\{\eta_1 \cdot S_b \cdot S_c^{-1} N(t) + \eta_2 \cdot [N(t) - N(t - \tau_a)]\}. \tag{2}$$

Let us seek a solution for $N(t)$ of the form

$$N(t) = N_0 \exp \omega t. \tag{3}$$

Substituting Eq. (3) into Eq. (2), we find a characteristic equation that determines ω

$$\omega = n^+ \cdot \sigma(v) \cdot v\{\eta_1 \cdot S_b S_c^{-1} + \eta_2[1 - \exp(-\omega\tau_a)]\}. \tag{4}$$

We denote the roots of Eq. (4) by ω_k. From (4), ω_k is in the interval

$$\omega_{\min} < \omega_k < \omega_{\max}, \tag{5}$$

where

$$\omega_{\min} = n^+ \cdot \sigma(v) \cdot v \cdot \eta_1 \cdot S_b S_c^{-1} > 0$$
$$\omega_{\max} = n^+ \cdot \sigma(v) \cdot v \cdot [\eta_2 + \eta_1 \cdot S_b S_c^{-1}] > 0. \tag{6}$$

It follows from Eqs. (5) and (6) that $\omega_k > 0$ and, therefore, the ion beam plus vacuum-chamber wall system is unstable with increment ω_k.

Let introduce a characteristic time τ over which the system exists without noticeable increase of ion loss. Then the existence condition of the system (stable) takes the simple form

$$\omega_k \cdot \tau \leq 1. \tag{7}$$

Thus the problem reduces to the solution of an algebraic equation and to checking the validity of the condition (7).

At the same time, one can get simple analytical expressions for permissible values of η_1 and η_2 without solving Eq. (4). To this end, let us convert the inequality (7) into an equality and replace ω in Eq. (4) by $\omega_k = \tau^{-1}$. Then the equation of the curve separating the stability region from instability in the plane $\eta_1\eta_2$ takes the form

$$1 = N^+ \cdot \sigma(v) \cdot \{\eta_1 \cdot S_c^{-1} + \eta_2 \cdot S_b^{-1} \cdot [1 - \exp(-\tau_a/\tau)]\}. \tag{8}$$

Here $N^+ = n^+ \cdot v \cdot \tau S_b$ is the total ion flux through the vacuum-chamber cross section during time τ. From Eq. (8), one can obtain a stability condition in the form of two inequalities

$$N^+ \cdot \sigma(v) \cdot \eta_1 \leq S_c \cdot \sin^2 \varphi \tag{9}$$

$$N^+ \cdot \sigma(v) \cdot \eta_2 \leq S_b \cdot [1 - \exp(-\tau_a/\tau)]^{-1} \cos^2 \varphi. \tag{10}$$

In Eqs. (9) and (10), φ is the mixing angle providing Eq. (8) is exactly fulfilled. Thus

$$\varphi = \mathrm{arctg}\{\eta_1 \cdot \eta_2^{-1} \cdot S_b \cdot S_c^{-1} \cdot [1 - \exp(-\tau_a/\tau)]^{-1}\}^{1/2}$$

For parameter estimates with heavy ions, let us assume $\varphi \simeq \pi/4$ and $\tau_a \simeq 10^{-4}$ sec.

It should be cautioned in advance that there is practically no both single-valued spallation-process theory and reliable experimental data. Measured values of η (measurements made using fission fragments) vary within a range of tens to hundreds of thousands units versus experimental conditions.[4] To estimate the spallation coefficient of wall material, the isolated grain model which gives quantitatively correct results within the 1 MeV/nucleon energy range,[4] can be used.[5]

Let us denote the specific energy loss of ion in the wall material by dE/dx. The minimum energy necessary for spalling of one grain with diameter $2R$ from the wall material is

$$E_{\min} \simeq \frac{4}{3} \cdot \pi R^3 N_1 \cdot V_0 = \eta_2 \cdot V_0, \tag{11}$$

where N_1 is the atomic density of wall material and V_0 is the binding energy of wall material ($V_0 \simeq 2$ to 3 eV). If the ionization energy loss of the ion in the course of flight through single grain is large and the size of the grain is small, so that the inequality

$$\frac{1}{3} \cdot \frac{dE}{dx} \cdot \delta \geq E_{\min} \tag{12}$$

is true, full evaporation occurs.

In Eq. (12) δ is the mean path of the ion in wall material and the coefficient 1/3 corresponds to the assumption that this fraction of the energy is transferred to the atomic lattice. Then, assuming $\delta \simeq 2R$, we find from Eqs. (11) and (12)

$$\eta_2 \simeq \frac{R}{V_0} \cdot \frac{dE}{dx}. \tag{13}$$

For high-energy heavy ions ($\simeq 100$ MeV/nucleon) in targets of dense material (Pb, W), we have $dE/dx \simeq 10^{12}$ eV/cm. Substituting into Eq. (13) $R = 20 \cdot 10^{-7}$ cm, $V_0 = 2$ eV, we find $\eta_2 = 10^4$. At energies about 1 MeV/nucleon, Eq. (13) gives values of η_2 close to those experimentally observed ($\simeq 10^3$).

In conclusion, let us consider the compatibility of the stability conditions with the parameters of drivers for heavy-ion thermonuclear fusion.[6,7†] In these designs, 10 to 20 GeV/nucleus rf linacs for Bi^{+2} ions with current $\simeq 0.15$ A and acceleration time $\simeq 6 \cdot 10^{-3}$ s and storage rings with circulating current $\simeq 15$ A are used. The ion charge-exchange cross section is taken to be $\sigma = 10^{-17}$ cm^2. For the linac, we need $N^+ = 2.7 \cdot 10^{15}$ ions and for each storage ring $N^+ = 5.4 \cdot 10^{17}$.

Then assuming in Eq. (9) and (10) $\varphi = \pi/4$, $\eta_2 = 10^4$, $\tau \cdot \tau_a{}^{-1} = 60$, we find from Eq. (10) for the beam cross section; for linac $S_b \geq 10$ cm^2, and for storage rings $S_b \geq 2 \cdot 10^3$ cm^2.

These conditions are very difficult especially, for storage-ring systems. It is evident that a time decrease by a factor 5 for linac and a decrease by a factor 500 for storage rings will be desirable.

It should be pointed out that the condition (9) gives a difficult limitation for η_1: for the linac $\eta_1 \leq 200$ at $S_c = 10$ cm^2 and for the storage ring $\eta_1 \leq 4$ for $S_c = 40$ cm^2.

This example shows that if experiments confirm these large coefficients η_1 and η_2, the effect under consideration may markedly affect the choice of the parameters of heavy-ion drivers.

REFERENCES

1. E. Fisher, *J. Vac. Sci. Technol.*, **9,** 1203 (1972).
2. G. E. Fisher and K. A. Mack, *Ibid.*, **2,** 123 (1965).
3. E. Fisher, CERN Report CERN-ISR-VA/72-39 Geneva, 1972.
4. I. A. Baranov *et al.*, *ZhETF*, **51,** 2457 (1981).
5. A. Goland and A. Paskin, *J. Appl. Phys.*, **36,** 3645 (1965).
6. P. R. Zenkevich *et al.*, ITEP Preprint **64,** 1981.
7. R. Bock, GSI Rpt GSI-82-8, 1982, p. 50.
8. L. W. Jones, Lawrence Berkeley Laboratory Rpt. LBL-103-01, 1980, p. 294.

† The first indication of a possible problem of large beam losses for thermonuclear drivers seems to be contained in Ref. 8.