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SHAKING OF PARTICLE BEAMS TO REMOVE NEUTRALIZING IONS*

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Introduction and Summary

Positive ions produced through ionization of the residual gas by the electron beam in an accelerator or storage ring can be trapped in the potential well of the beam and produce focusing forces on the beam that can shift the betatron frequency onto a resonance or stimulate other beam-dynamics effects. At low beam intensity the ions can be removed by means of the electric field imposed by clearing electrodes; however, at high intensity clearing electrodes can become ineffective when the local field of the beam is greater than that imposed by the electrodes or even harmful because of electromagnetic interaction between the beam and the electrode system. The ions can be removed also by letting them coast to the walls in the interval during an empty gap in the beam[1], but the length of the necessary gap in many cases is impractical. In this paper a new method, called "beam shaking", is proposed for removing the neutralizing ions by inducing increasingly larger amplitudes of ion oscillation about the beam until they are driven to the walls.

Beam Shaking, General Features

The positive ions produced by ionization of the residual gas by an electron beam move under the combined action of the local electric and magnetic fields. The dominant field in a high-intensity, large-radius machine can be the coulomb field produced by the electron beam. In a round metal vacuum chamber of radius R, the electric potential produced by a beam of I amperes uniformly distributed within a beam radius b and centered a distance d along the (transverse) x-axis from the center of the pipe is described on the x-axis by the function V(x,d) (in units of volts):

$$V(x,d) = \begin{cases} -\dfrac{30I}{\beta}\left[1-\dfrac{(x-d)^2}{b^2}+2\ln\dfrac{R^2-xd}{bR}\right], \\ \qquad \text{for } |x-d| < b \text{ (within the beam)} \quad (1a) \\ -\dfrac{60I}{\beta}\ln\dfrac{R^2-xd}{R|x-d|}, \text{ for } |x-d| > b \\ \qquad \text{(outside the beam)} (1b) \end{cases}$$

where βc is the velocity of the electrons in the beam.

The potential at the wall $V(\pm R,d)$ is zero. At the center of the beam $V(d,d) = -30I/\beta[1 + 2\ln(R^2-d^2)/bR]$. We note that the potential difference between the beam and the wall decreases when the beam moves from the center of the chamber, but only by the relatively small amount $60I/\beta \ln(1 - d^2/R^2)$. The positive ions in the chamber tend to oscillate in the coulomb well between the turn-around points corresponding to the total energy (kinetic plus potential) with which it was formed. An ion formed by an ionization event in the electron beam is born with negligible kinetic energy and ordinarily is trapped to oscillate within the beam, always within its original radius to the beam center.

Now if the beam is suddenly moved sideways, an ion instantaneously finds itself at a new potential, but with its old kinetic energy, and thus begins to oscillate at a total energy equal to the sum of the old kinetic and new potential energies. If the change in potential energy is positive, the total energy of the ion is raised, and it begins to oscillate with larger amplitude. It is obvious that repeated movements of the beam in this manner can increase the amplitude of the ion until it can reach the wall and be lost. Even if the amplitude is not enough to let the ion reach the wall, an increased amplitude can serve to decrease significantly the average neutralization of the electron beam. "Beam shaking" is the term used to describe motion of the beam that will tend to increase the amplitude of the ion motion, such as to drive the ions into the wall or merely to reduce beam neutralization by diluting the ion density within the electron beam.

Programmed Beam Shaking

If the details of the ion motion are sufficiently well known, it is possible to remove the ions with just two "shakes" of the beam. Consider, for example, the situation in which the electron beam is initially centered in a round metallic vacuum chamber 8 times larger than the beam. Let us follow the changes in ion energy as the beam is switched from the center to +R/2 and then to -R/2 on the x-axis, as illustrated in Figures 1a, 1b, and 1c. A singly-charged ion born in the beam is somewhere in the cross-hatched area of Figure 1a, where the potential energy is (-140 ± 15) I/β electron volts. (We are ignoring the potential due to the positive ions). When the beam position is abruptly moved to R/2, the potential energy of the ions is raised by about 113 I/β and the ions are transformed to the cross-hatched area on Curve 2 in Figure 1b. The ions then proceed to oscillate across the new potential well (Curve 2) in the region bounded by horizontal dashed lines, where the total ion energies are in the range (-27 ± 15) I/β electron volts.

If the next switch of the beam from x = R/2 (Curve 2) to X = -R/2 (Curve 3) is delayed about 1/4 ion-oscillation period, when the ions will be oscillating through the beam and have their maximum kinetic energies, the gain in ion energy will be optimal. For an ion at R/2 its increase in potential energy due to the beam switch is 124 I/β, and its total energy becomes (+97 ± 15) I/β, so that it is sure to strike the wall and thus be removed within a half ion-oscillation period.

Random Beam Shaking

If the oscillation period of the ions is not known or if there is a variety of ions present, a programmed method of shifting the beam at the optimal time of greatest ion kinetic energy may not be workable. However, a method of shifting the beam at random times also can be effective in raising the ions to escape energy.

Consider Figure 1c again; the cross-hatched area extending up into the positive energy region is the locus of the energy region of Curve 2 (Figure 1b) between (-27 ± 15) I/β transformed by the shift in the beam from x = +R/2 to x = -R/2. Note that each point in the positive x-region is raised in energy while each point in the negative x-region is lowered. If the beam

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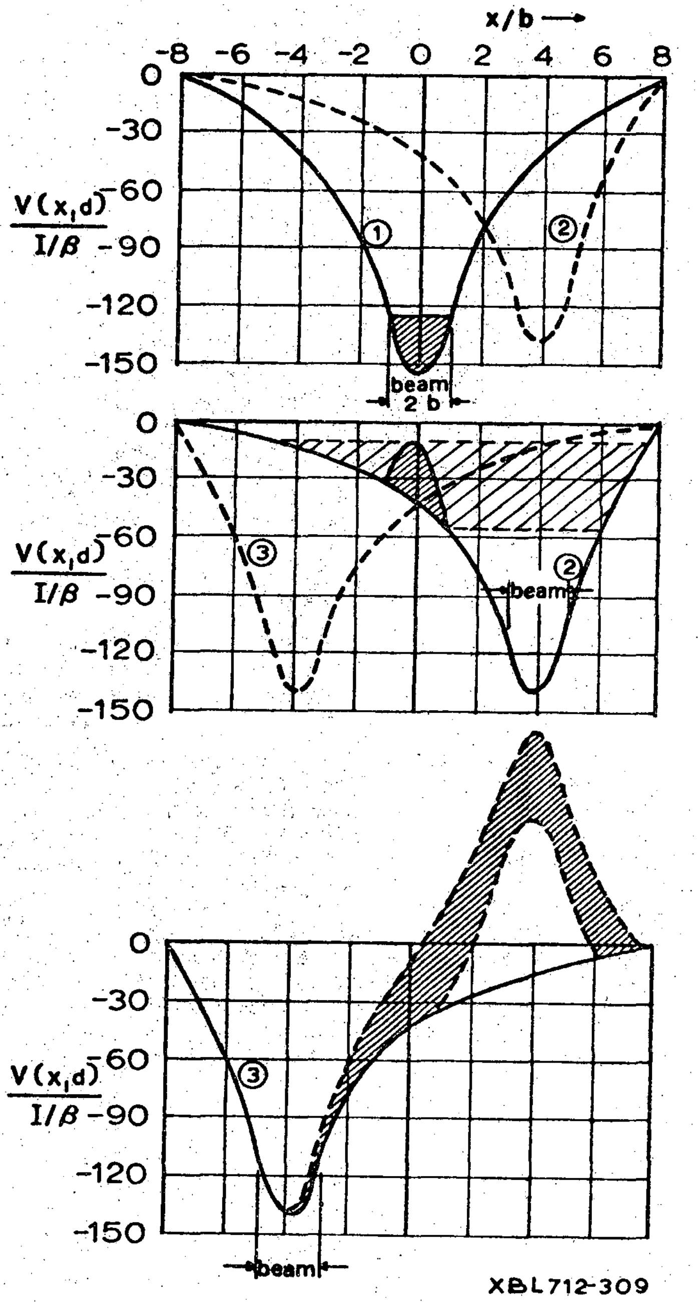

Figure 1. Successive steps in beam shaking.

(1a) Ions formed inside the beam have energies and movement shown within the cross-hatched area on potential curve 1.

(1b) Beam displacement to R/2 moves ions up in total energy to small cross-hatched area on curve 2. Ions then oscillate over the wider cross-hatched area.

(1c) Beam displacement to -R/2 transforms ion energies to cross-hatched area of curve 3. Those lifted to positive energies will be lost to the wall within a half oscillation period.

switch occurs at a random time, the probability that an ion will increase its total energy is equal to the fraction of its period that it is in the positive x-region. For an ion of -30 I/β total energy, e.g., this probability is about 60%, so that even with a random switch time there is a good probability that an ion of this energy or less will be "pumped" upward in total energy. Repeated switches of the beam position between $\pm R/2$ will thus produce a random walk of the ion energy up toward energies of escape. The typical step in this random walk is about 100 I/β, so that only a small number of steps should be sufficient for raising the energy of most of the ions by the 150 I/β typically needed for escape to the walls. It is worth noting that ions having total energies between 0 and -22.5 I/β spend less than 50% of their time in the positive x-region of curve 2, so that a random beam shift is likely to lower their energies. However, this energy band is narrow relative to the typical energy step and thus will eventually be skipped over.

This discussion of the ion motion in the x-direction has neglected the motion in the other transverse direction and also the effect of a magnetic guide field. Although these matters complicate the details of the ion motion, the energetics of the interaction are qualitatively unchanged. The magnetic field, if strong enough, serves to limit the ion motion to helical paths parallel to the flux lines. If one arranges the direction of the beam shaking to be parallel to the magnetic field, the effect of the field is beneficial in that it serves to limit the motion in the other transverse direction.

The oscillation period of an ion in the potential of equation 1 is somewhat laborious to evaluate. When the ion is formed inside the beam centered in the chamber ($d = 0$), the period T is given by

$$T = \frac{2b}{c}\,\frac{\pi}{\sqrt{2}}\left[\frac{Mc^2\beta}{30IZ}\right]^{1/2} . \qquad (2a)$$

When the ion is oscillating with an amplitude appreciably greater than the beam radius b, the period is given approximately by

$$T = \frac{\left[x_1 - x_2\right]}{c}\sqrt{\pi}\left[\frac{Mc^2\beta}{30IZ}\right]^{1/2} \qquad (2b)$$

where x_1 and x_2 are the maximum displacements in the $\pm$ directions. Mc^2 is the rest mass of the ion, (in electron volts) and Z is its charge state. For example, for a N_2^+ ion oscillating within a 100 ampere relativistic electron beam of 1 cm radius, the period is about 1/2 microsecond. When the ion oscillates out to $\pm$ 8 cm from the center of the beam, the period is about 3 microseconds.

Production of Transverse Beam Motion

Moving the beam abruptly and holding it in the displaced position as required in this beam shaking technique can be accomplished in a variety of ways. The requirements are that it be done both in a time much shorter than the ion period and in a way that does not produce appreciable collective oscillation of the beam.

An easy way to perturb the closed-orbit into a sinusoidal path about the normal closed-orbit is by means of a single dipole magnet situated anywhere along the orbit. If this magnet can be switched on in a time much longer than the circulation period of the beam but much shorter than the ion period, the beam will adiabatically move sideways without collective oscillation and thus induce the desired motion in the ions. Such motion can be used to drive out the ions in the regions of the maxima in the sinusoidal closed-orbit. Another such distorting magnet situated an odd number of quarter betatron wave lengths from the first can subsequently be used to produce maxima in the perturbed closed-orbit where the first magnet had "zeroes". However, the use of this simple, single-magnet method of distorting the closed-orbit can be used only when the beam circulation period is much, much shorter than the ion oscillation period.

A more generally applicable method of suddenly displacing the beam sideways without producing collective oscillation is the use of two kicker magnets separated by an integral number of half betatron wave lengths. After magnet number one is switched on, electrons passing through this magnet follow a sinusoidal trajectory about the previous closed-orbit. If the second magnet is placed at the last "zero" in this sinusoidal path before one complete revolution of the machine, and if the second magnet is turned at the time when the first perturbed electrons reach it and in such a manner as to cancel the effect of the first magnet, then no dilution of beam emittance will occur because the closed-orbit of the machine will lie along the path taken by the central beam particle -- i.e., along the sinusoidal trajectory between the two kicker magnets over most of the machines circumference and along the old, unperturbed central closed-orbit for the remaining small section of the machine.

A second pair of kicker magnets shifted 90° in betatron phase will complement the first pair by having large amplitudes in the distorted closed-orbit where the first pair produced zeroes. Similarly, a third pair could help clean up the small portions of the circumference (between the kicker pairs) where the closed-orbit was undistorted.

Obviously, there are infinite number of kicker magnet distributions which will do an equivalent job of suddenly shifting the beam in a transverse direction. The use of kicker pairs is conceptually the easiest, but sensitive to the exact betatron tune. The use of kicker triplets is more flexible and allows compensation for changes or ignorance in the betatron tune and for limitations in available positions for the kicker magnets.

Conclusions

The scheme to remove neutralizing ions from the circulating beam in an accelerator or storage ring by the method of beam shaking seems feasible and practical for machines with vacuum apertures considerably larger than the size of the beam. The method was described as applying to the removal of positive ions from electron beams, but it can be applied also to the removal of electrons or negative ions from beams of positive particles. It can in principle apply also to the removal of neutralizing ions from non-circulating beams, such as in a high-intensity or a dc linear accelerator.

References

1. J.M. Peterson, Proceedings of the 6th International Conference on High Energy Accelerators, CEAL-2000, 1967; see remarks on p. 233.

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