INVESTIGATION OF BUNCH-GAP EFFECTS FOR CURING ION TRAPPING IN ENERGY RECOVERY LINACS

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Abstract

Production and accumulation of ions in the beamlines of energy recovery linacs (ERLs) may cause degradation of their beam performance. We investigated the effects of bunch gaps as a possible measure to prevent ion accumulations. It was shown that considerable stopbands for the ion motions can be introduced by short bunch-gaps, while keeping transient voltages small in the injector cavities. The transient voltages can be reduced further using a feedforward compensation. In addition, a method of beam-size modulation is proposed as a possible alternative measure.

INTRODUCTION

The ionization of residual-gas molecules can lead to accumulation of ions in the beamlines of accelerators. Problems due to ion trapping have been observed in many storage rings [1]. In future energy recovery linacs (ERLs) for highly-brilliant synchrotron light sources, the accumulation of ions may lead to large betatron phase errors [2] or to fast ion instabilities [3]. Therefore, it is important to prepare effective measures to avoid the accumulation of ions.

In many storage rings, introduction of bunch gaps [4] in stored beams has been found to be very effective in avoiding problems caused by ions. This method will also work effectively for ERLs, however, the bunch gaps can cause such harmful effects as transient voltages in the injector cavities. Therefore, the potential problems should be investigated carefully. The effects of bunch gaps in ERLs was discussed in [2]. It was predicted that both the clearing gaps of about 31 μs and of about 2 ms will cause very harmful beam-loading effects, therefore this method did not seem promising.

In this paper, we investigate further the bunch-gap effects in other cases where the gaps are much shorter. We discuss the stability of ions under the short bunch-gaps, and estimate transient voltages in the injector cavities. We also investigate the compensation of the transient voltages using a feedforward technique. Note that the other problems, such as the transient voltages in a buncher or in a gun high-voltage, are left for future study.

STABILITY OF ION MOTIONS UNDER BUNCH GAPS

The ERLs will typically be operated at a bunch repetition frequency of 1.3 GHz with a typical bunch charge of 77 pC. Under such conditions, the critical mass for the ion motion is less than one, for typical beam sizes, therefore produced ions are expected to be trapped in the electron beams.

Suppose that we introduce gaps (empty buckets) in the beams of an ERL, as illustrated in Fig. 1. We assume that the gaps are repeated regularly at a repetition period of T_p with a gap duration of T_g. We denote the corresponding numbers of rf buckets as n_p and n_g, respectively. Using linear approximation for the focusing forces imposed on the ions due to bunch passages, the horizontal (x-) motion of ions are described by a transfer matrix:

$$M_x = \begin{pmatrix} 1 & \tau_b \\ 0 & 1 \end{pmatrix}^{n_g} \left\{ \begin{pmatrix} 1 & \tau_b \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -a_x & 1 \end{pmatrix} \right\}^{n_p - n_g} . \quad (1)$$

Here, a_x is the kick parameter which is given by

$$a_x = \frac{2 r_p c}{\beta \sigma_x (\sigma_x + \sigma_y)} \frac{N_b}{A/Z}, \quad (2)$$

τ_b is the time between bunches, N_b is the number of particles per bunch, A is the mass number of an ion, Ze is the charge of the ion, e is the elementary charge, r_p is the classical proton radius, c is the speed of light, βc is the beam velocity, and σ_x and σ_y are the horizontal and the vertical beam sizes, respectively, assuming Gaussian distributions. A similar equation holds for the vertical (y-) motion. The motion of the ion is stable when $|\mathrm{Tr}(M_x)| < 2$ and $|\mathrm{Tr}(M_y)| < 2$.

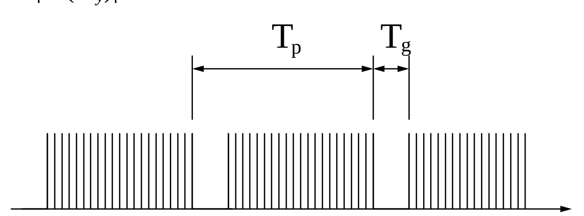

Figure 1: Illustration of bunch gaps.

Figure 2 shows the stability of ion motions for various combinations of the beam size (σ) and the ion mass number (A). We can see that the ion motions tend to be unstable in a low repetition case (Fig. 2(b)) of bunch gaps as compared to those in a high repetition case (Fig. 2(a)). However, we can still expect considerable ion-clearing effect in the high repetition case for typical beam sizes of 10-100 μm.

Even when singly-charged ions (mass number A, charge number Z = 1) are stable and trapped, they experience multiple ionizations, resulting in a change in A/Z. If the multiply charged ions drop into unstable bands, they are cleared. In such cases, the density of the singly-charged ions under equilibrium is given by

$$d_i = d_m \frac{\sigma_i}{\sigma_i^{++}} \sqrt{1+\left(\frac{\sigma_x}{\sigma_x^i}\right)^2} \sqrt{1+\left(\frac{\sigma_y}{\sigma_y^i}\right)^2}, \qquad (3)$$

where d_m is the molecular density of residual gas, σ_i and σ_i^{++} are the cross sections of single- and double-ionizations, respectively, and σ_x^i and σ_y^i are the r.m.s. sizes (assuming Gaussian distributions) of the ion cloud, respectively. Because the density of ions becomes comparable to the molecular density, low vacuum pressure is very important for reducing the ion density using bunch gaps.

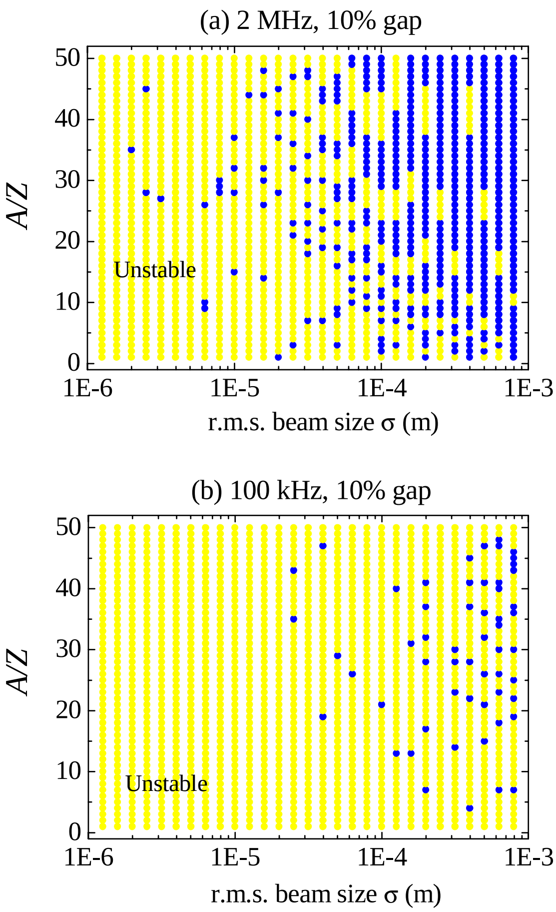

Figure 2: Stability of the ion motions under the bunch gaps. Blue and yellow dots indicate stable and unstable conditions, respectively. Abscissa: beam size (r.m.s.), ordinate: mass number (A) per charge number (Z) of ions. Assumed 10% ratio of the gap, bunch charges of 77 pC/bunch, and equal beam sizes for the horizontal and the vertical distributions. Repetition frequencies of the gaps are: (a) 2 MHz, and (b) 100 kHz.

TRANSIENT RF VOLTAGES IN INJECTOR CAVITIES

When we introduce the bunch gaps, they can induce transient voltages in several key components of the ERL. Among them, a transient voltage in the superconducting (SC) main linac can be avoided if we choose a repetition frequency of the gaps at an integer times the revolution frequency of the recirculation pass [2]. Other important effects are the transient voltages in injector SC cavities, in a buncher, and in a gun high voltage. We discuss the first effect here.

An rf voltage in the injector cavities is given by the superposition of voltages induced by a generator and by a beam. The beam-induced voltage is governed by two processes [5]: (i) every bunch-passage induces a voltage change by $-2k_0 q_b$, where k_0 is the cavity loss factor of the fundamental mode and q_b is the bunch charge, and (ii) after time t, the phasor voltage changes according to the relation,

$$\tilde{V}(t) = \tilde{V}(0) \exp\left(-\frac{t}{T_f}\right) \exp\left(j \frac{\tan\psi}{T_f} t\right), \qquad (4)$$

where T_f is the filling time of the cavity, and ψ is the cavity tuning angle.

Figure 3 shows an example of calculated transient voltages in the injector cavities. We temporarily assumed that the injector comprises five two-cell cavities, having R_{sh}/Q of 200 Ω each (definition: $R_{sh} \equiv V_c^2/P_c$). The external-Q of the cavities and the total rf voltage were assumed to be 5×10^4 and 5 MV, respectively. On-crest acceleration with zero tuning angle was assumed. It can be seen that the peak-to-peak variation in the rf voltage (in amplitude) is about 0.4% of the total voltage under a 2-MHz repetition, 10% bunch-gap. This variation may be acceptable, or it can be reduced further by using a compensation method. On the other hand, if we assume a 10% bunch-gap at a repetition of 100 kHz, the peak-to-peak voltage variation amounts to 8.1%, which is not acceptable. Thus, the bunch gaps at high repetition rate have advantage in reducing the bunch-gap transients.

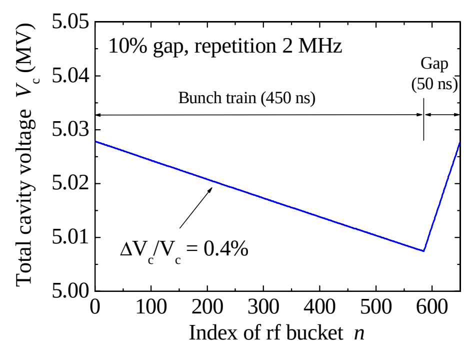

Figure 3: Transient voltage in the injector cavities. Assumed are a total voltage of 5 MV, a beam current of 100 mA, and a 10% bunch-gap at a repetition frequency of 2 MHz.

When the filling time is much longer than the gap period (T_p), the peak-to-peak amplitude variation of the rf voltage is approximately given by

$$\frac{\Delta V_c}{V_c} \approx \frac{\omega_0 (R_{sh}/Q) q_b}{2V_c} \frac{n_g (n_p - n_g)}{n_p}, \qquad (5)$$

where V_c is the total cavity voltage, and ω_0 is the resonant frequency of the cavity, respectively. Under on-crest acceleration with zero tuning angle, there is no transient changes in the rf phase. It should be noted that a high rf voltage with low R_{sh}/Q cavities is desirable for reducing the transients. In this respect, we anticipate that the transients will be more severe in a normal-conducting buncher cavity.

COMPENSATION OF TRANSIENT VOLTAGES

The bunch-gap transients in the injector cavities can be reduced using a feedforward compensation technique. This scheme has been investigated for the KEK B-factory [6], although it has not been needed in operations so far. In the case of on-crest acceleration with zero tuning angle, one can compensate the rf-amplitude transients by changing the generator power appropriately. The rf voltage $V(t)$ in a cavity follows the equation,

$$\frac{d^2V}{dt^2}+2\lambda\frac{dV}{dt}+\omega_0^2V=2k_0\frac{di}{dt}, \tag{6}$$

with

$$i=i_b+i_g, \tag{7}$$

where i_b and i_g are the drive currents due to beams and to the generator, respectively, and $\lambda \equiv 1/T_f$. We assume the solutions in the form,

$$V(t)=\tilde{V}(t)e^{i\omega t}, \text{ and } i(t)=\tilde{i}(t)e^{i\omega t}, \tag{8}$$

where $\tilde{V}(t)$ and $\tilde{i}(t)$ are the complex amplitudes which vary slowly as compared to the rf frequency (ω). We then obtain an approximate equation,

$$k_0\tilde{i}(t)=\frac{d\tilde{V}(t)}{dt}+\lambda(1-i\tan\psi)\tilde{V}(t)\ . \tag{9}$$

To keep the constant rf voltage of V_{c0}, the generator voltage should be changed as

$$\tilde{V}_g=V_{c0}-\tilde{V}_b, \tag{10}$$

where $\tilde{V}_b$ is the beam-induced voltage. The required generator current is given by

$$\tilde{i}_g(t)=\frac{1}{k_0}\frac{d\tilde{V}_g(t)}{dt}+\frac{\lambda}{k_0}\tilde{V}_g(t), \tag{11}$$

where we have assumed $\psi = 0$. The generator power needed is then given by

$$P_g(t)=\frac{R_{sh}}{16\beta_c}\left|\tilde{i}_g(t)\right|^2, \tag{12}$$

where β_c is the coupling coefficient of the cavity.

Figure 4 shows a typical estimation of the generator power (per cavity), which is required for compensating the transient voltage given in Fig. 3. For 100-mA, CW beams, the required generator power is 100 kW/cavity, while with 10% gaps at a repetition frequency of 2 MHz, a maximum power of 112 kW/cavity is needed for the compensation.

In real rf systems, the bandwidth of the generators is limited, which results in deviations in the voltage compensation. Rough estimations indicate that the remaining peak-to-peak voltage variations will be about 0.24% and 0.09%, respectively, for the generator bandwidths of 4 MHz and 10 MHz, while the variation is 0.4% without the compensation. Therefore, a wide bandwidth of 4-10 MHz, or wider, will be needed for the compensation in the cases considered above.

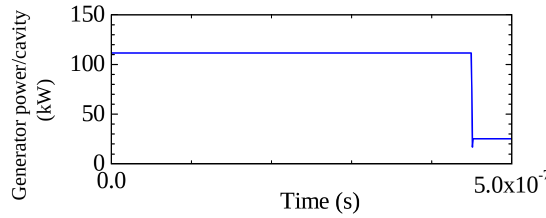

Figure 4: Generator power required for compensating the bunch-gap transient, given in Fig. 3. Per one cavity of the injector. Assumed rf voltage of 1 MV/cavity, a gap ratio of 10%, a gap repetition of 2 MHz, and a beam current of 100 mA.

BEAM SIZE MODULATION

As an alternative measure for preventing the ion trapping, we suppose to modulate the beam sizes regularly, as illustrated in Fig. 5. To carry out such a modulation, we need to modulate the spot sizes of a drive laser light for the photocathode gun by some means. The modulation in the focusing forces causes the stopbands of the ion motions. Figure 6 shows the calculated stability of ions under a typical modulation condition.

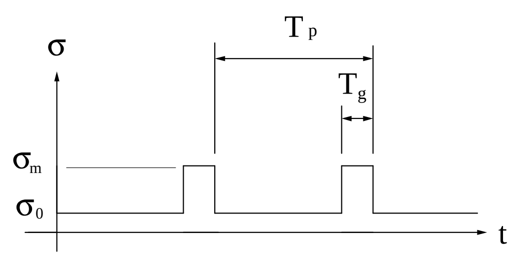

Figure 5: Concept of beam-size modulation.

Comparing Fig. 6 to Fig. 2(a), we can see that the beam-size modulation is less effective than the bunch-gap method at the same modulation frequency and gap ratio. However, this method has an advantage that it is free from transient beam-loading effects. A potential drawback is that this method may cause harmful effects on users' experiments. A possible solution for this problem is supplying gate signals for users' experiments, which can be used to inhibit data acquisition while beam sizes are large.

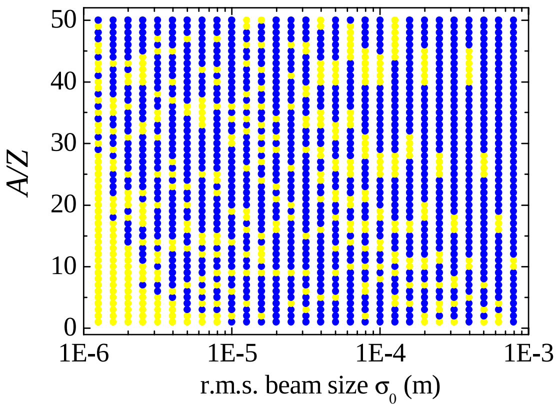

Figure 6: Stability of ion motions under the beam-size modulation. Assumed beam-size ratio (σ_m/σ_0) of 2, the time ratio (T_g/T_p) of 10%, a repetition frequency of 2 MHz, and a beam current of 100 mA.

CONCLUSIONS

As a possible cure for the ion trapping in ERLs, we investigated the introduction of bunch gaps in the cases of high repetition frequencies. Under a typical condition of 10% gap at a repetition frequency of 2 MHz, we can expect considerable ion-clearing effect. The voltage transients in the injector cavities are typically estimated to be 0.4% (peak-peak) at a beam current of 100 mA, which is not too large. The voltage transients can be reduced further using a feedforward compensation with realistic requirements for the generator. If the other problems, of voltage transients in the gun high-voltage and in the buncher, can be resolved, the bunch gaps can be a strong candidate for curing ion trapping.

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