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BUNCH SHAPE OSCILLATION CONTROL IN RF TRAPPING

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Abstract

The bunch formation produces generally an oscillatory time-behaviour of the longitudinal charge density, which is reproduced synchronously in the coherent self-field. The resulting beam behaviour, caused by the space-charge feedback, tends to convert single-peaked bunches into double-peaked ones (as seen on a sum pick-up electrode). It is analysed with the energy spread of the unbunched beam, the beam intensity, and the particle distribution as parameters. For given values of these parameters a theoretical shape of the RF voltage rise V(t) is then obtained by successive approximation, which minimizes bunch shape oscillations without reducing the high trapping efficiency (> 90%). This V(t) (one to five per cent of V_{max} for t = 0) imposes operation under very heavy beam-loading conditions. Experimental results, obtained after the corresponding improvement of the systems performance, are presented and compared with the bunch shapes obtained, for equal trapping efficiencies, with an iso-adiabatic voltage rise.

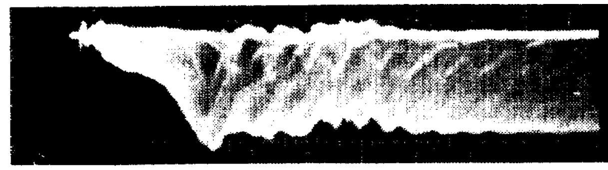
Introduction

The RF trapping in the PSB was designed to work with an iso-adiabatic voltage rise[1] and a relatively large injected beam energy spread ($\Delta E_L \approx \pm 150$ keV). The main feature of such a trapping is the constancy of the shape of the RF voltage V(t) regardless of the injected beam conditions, i.e. V(t) is the same for any $\Delta E_L \leq (\Delta E_L)_{max}$.[1] Space-charge effects were estimated by means of a multiparticle computation.[2] No modification of the iso-adiabatic voltage rise was found to be necessary, except for an increase of max V(t) by about 20% to compensate the reduction of the effective bucket area.[2] The iso-adiabatic voltage rise was thus expected to be optimal for injected beams with widely differing energy spreads, intensities, and charge density distributions.[1,2]

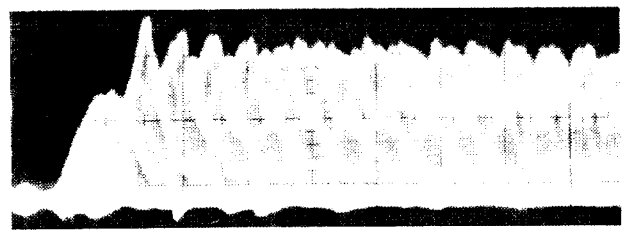
These expectations were not borne out experimentally. Typical PSB wide-band Σ-pick-up electrode signals (proportional to the instantaneous longitudinal charge density) are shown in Fig. 1. From the envelope of these signals it can be seen that the bunch centre density does not always grow monotonically, and that the bunch shape at the end of trapping is not always close to a stationary shape appropriate for the subsequent acceleration. While one can possibly ascribe some of this discrepancy to the statistical nature of the prediction (Table 1 of Ref. 1, § 3 of Ref. 3), a further study of the present case appeared warranted. It was therefore decided to analyse the dynamics of RF trapping with more details than those considered during the design state.[1,2]

Outline of theory

In order to reproduce the bunch formation mechanism during RF trapping, a mixed analytical-numerical method of analysis had to be developed, because the purely numerical one, based on multiparticles[2], did not yield the necessary information. Owing to editorial space limitations, only an outline of the reasoning can be given, the details having been described elsewhere.[3] The starting point is the assumption that RF trapping in the presence of space charge can be described by Hamiltonian equations involving a collective self-field

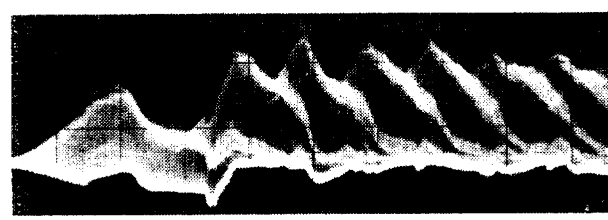


0.2 msec/div; $\Delta E_L \approx \pm 150$ keV
(vertical polarity inversed)



0.2 msec/div; $\Delta E_L \approx \pm 90$ keV

0.2 msec/div; $\Delta E_L \approx \pm 60$ keV



0.1 msec/div; $\Delta E_L < \pm 60$ keV

Fig. 1 Σ-signal for different ΔE_L. The irregularities in the base-line are due to imperfections of the base-line restoration electronics.

term. On a magnetic flat-top this form of equation implies the invariance of the phase area defined by a closed contour C in the $(\Delta E, \phi)$-plane. The bunch formation under the influence of a time-variable RF voltage V(t), starting from the initial value $V(t_0) = V_0$, can be described by means of the time-evolution of a closed contour C(t) from an initial contour $C(t_0) = C_0$. If the RF trapping starts from an unbunched beam, the contour C_0 is a rectangle of width $\Delta\phi = 2\pi$ radians and height 2 ΔE_L keV. In the case of negligible space charge the evolution of the contour C(t) is found in a straightforward manner, by integrating numerically the single-particle synchrotron equations.

In the case of a sufficiently weak but non-negligible space charge, the time-dependent collective self-field $\varepsilon(\phi, t)$ can be determined in a self-consistent manner by a method of successive iterations, using the already known (i.e. previously computed) space chargeless case as an initial approximation. The convergence is assured by the smallness of $\varepsilon(\phi, t)$.

Furthermore, it turns out that if the charge density is assumed to be constant inside C_0, the equations defining $C(t)$ become independent of the particle motion inside $C(t)$, i.e. the evolution of the bunch envelope in the $(\Delta E,\phi)$-plane becomes independent of the internal bunch dynamics. Applying standard sensitivity methods (see, for example, Radanovic[4]), it is found that small deviations of the charge distribution function from a constant one have a weak effect on the evolution of $C(t)$.

When the collective space-charge field $\varepsilon(\phi,t)$ is rigorously self-consistent and the bunch area, defined by the contour $C(t)$, does not have an invariant (stationary) form with respect to the total longitudinal focusing field, then $\varepsilon(\phi,t)$ has necessarily an oscillatory time-dependence which is in precise synchronism with twice the rotation frequency of $C(t)$ in the phase plane. Since the total focusing field depends non-linearly on ϕ, this synchronism corresponds to the necessary conditions of what is called in non-linear dynamics (see, for example, Malkin[5]) an internal resonance. Moreover, since the equations which describe $C(t)$ are Hamiltonian, this non-linear resonance is not asymptotically stable, i.e. it is inherently undamped. Filamentation, which may lead to a stationary bunch envelope $\bar{C}$ with a reduced phase plane charge density, needs a longer time than that available during RF trapping.

The main effect of a weak resonance consists in producing two bulges in the contour $C(t)$ and thus reducing the maximal longitudinal charge density, or in other words, converting single-peaked bunches into double-peaked ones (Fig. 2). Under conditions of a stronger resonance the "main" bulges of $C(t)$ release some secondary ones, which might give rise to Σ-electrode signals looking like satellite bunches (Fig. 3).

The internal non-linear resonance was found on the basis of purely theoretical considerations, although the impetus for the study originated from experimental evidence (Fig. 1). Satellite bunches were observed in the PSB both during trapping (Fig. 4a) and acceleration (Fig. 4b).[6] These observations do not, however, constitute compelling evidence that the mechanism examined theoretically is actually operating in the PSB. A direct experimental test is needed to establish a causal link between the theory and the behaviour shown in Fig. 1.

Experimental test

From Fig. 1 it can be seen that an improvement of the bunch evolution is readily observable when $\Delta E_L \approx \pm 90$ keV, provided an appropriate RF voltage rise $V(t)$ can be found. According to the theory just described, the resulting $V(t)$ is dependent on the injected beam intensity N. Two shapes of $V(t)$ computed on this basis and appropriate for $\Delta E_L = \pm 100$ keV, N = negligible and $N = 2.5 \times 10^{12}$ protons/ring, respectively, are shown in Fig. 5. The details of these computations will be described separately. In both cases the minimum RF voltage $V(t_0) = 0.5$ kV turned out to be lower than that used with the iso-adiabatic voltage rise $[V(t_0) = 1\text{ kV}]$. The power part of the RF system had therefore to be modified for the test.

The low intensity results (negligible space charge, $N = 10^{11}$), used for over-all checking purposes, are shown in Figs. 6 to 8. No systematic machine optimization was attempted, in spite of the presence of a significant radial position error (curve c, Fig. 7), because the evolution of central bunch density was influenced in the right direction (Fig. 8) and the trapping efficiency was $\geq 95\%$ (curve a, Fig. 7).

The high intensity results (close to nominal space charge, $N = 2.3 \times 10^{12}$) are shown in Figs. 9 to 11. Contrary to the low intensity case, there appeared on the cavity gap voltage an amplitude modulation at about twice the coherent synchrotron frequency (Fig. 9c). The amount of amplitude modulation visible in Fig. 9c is known to lead to non-negligible single-particle parametric resonance effects[7], estimated during the design of the PSB. If the trapping test is to be unambiguous, the amplitude modulation must be reduced by modifying the power part of the RF system further. After this modification, involving roughly the halving of the cavity impedance and of its Q (Figs. 9d and 9e), the cavity gap voltage became acceptably smooth (Fig. 9b). The resulting trapping efficiency was $\geq 95\%$ (Fig. 10a) with a nearly monotonically increasing bunch centre density (Fig. 11). The observed residual radial beam position error turned out to be larger than in the case of a low intensity beam (compare Fig. 10c to Fig. 7c). The cause of this increase was not investigated. Later tests have shown that it had purely technological causes.

Since the PSB can be operated with independent settings of the RF system in the four rings, the same linac beam was injected into another ring, where the RF voltage rise was the normally used iso-adiabatic one. The resulting simultaneously recorded Σ-electrode signals are shown in Fig. 12. The lower accelerated intensity ($N \approx 1.6 \times 10^{12}$) in the ring with the iso-adiabatic voltage rise is due to a less carefully adjusted multiturn injection. The trapping efficiencies in the two rings are about the same, but the improvement of the bunch shape evolution, compared to the iso-adiabatic voltage rise, is clearly visible.

Conclusion

High efficiency RF trapping with improved bunch shapes matching to the subsequent acceleration can be obtained by deviating from the iso-adiabatic voltage rise. In the absence or the presence of a weak but non-negligible space charge, the modified RF voltage rise $V(t)$ can be computed by means of a theory which includes the existence of an internal non-linear space-charge-induced resonance. The computed $V(t)$ depend on the energy spread of the injected beam, the beam intensity, and more weakly on the phase plane charge distribution. The effectiveness of the improvement is also subject to the accurate reproduction of the $V(t)$ programme on the cavity gap voltage.

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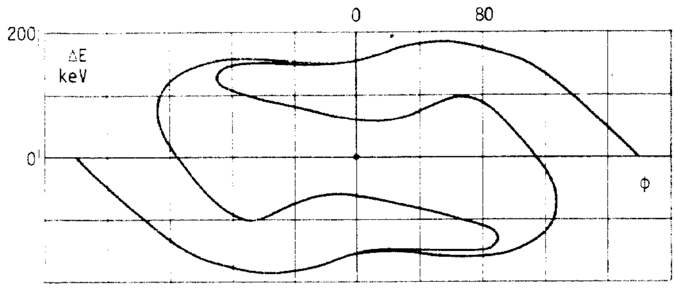


Fig. 2 Computed bunch envelope in the presence of a weak space charge. Effect of a weak internal resonance: two bulges result from a decrease of central density.

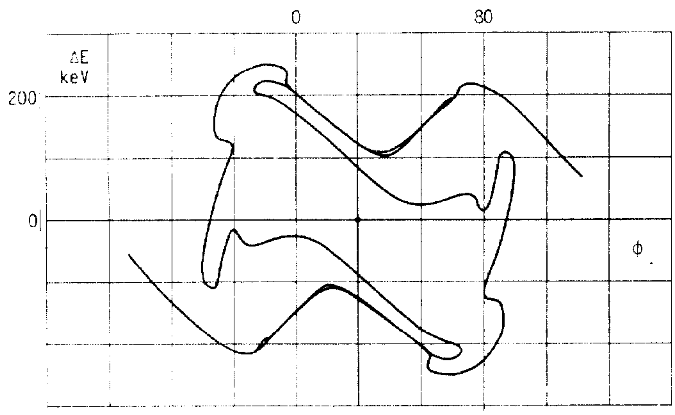


Fig. 3 Computed bunch envelope in the presence of a weak space charge. Effect of a stronger internal resonance: secondary bulges give rise to satellite bunches.

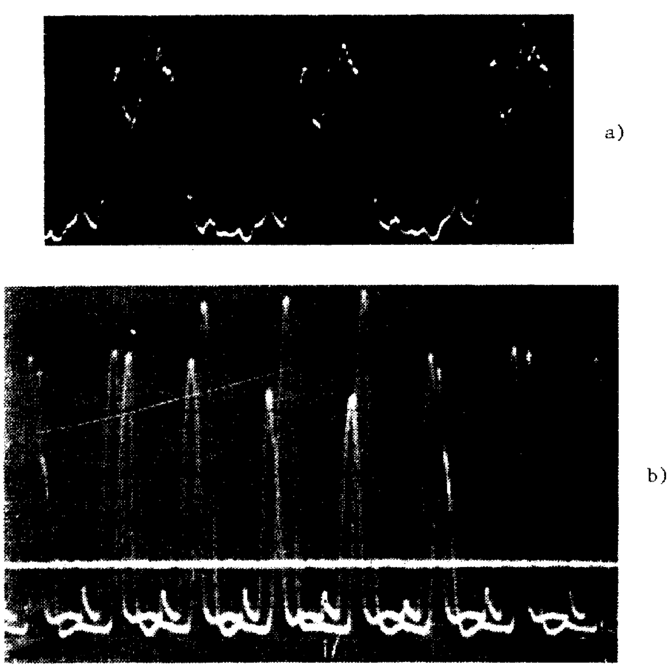


Fig. 4 Observed satellite bunches during trapping and acceleration.

a) During trapping, 0.1 μsec/div.
b) Near end of acceleration, 0.1 μsec/div. Two separate PSB pulses are superimposed.

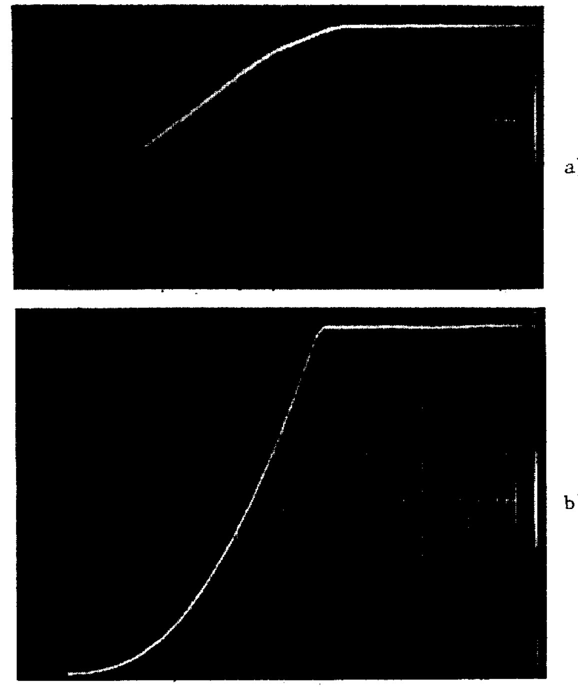
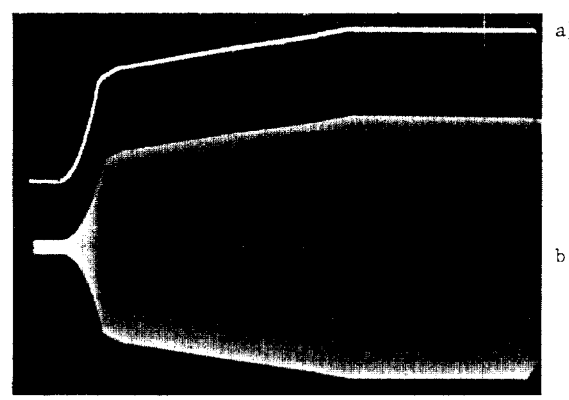


Fig. 5 Theoretically determined PSB RF voltage programmes for $\Delta E_L = \pm 100$ keV.

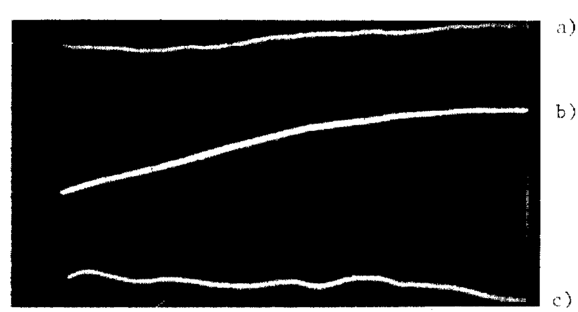
a) Negligible space charge, 0.5 msec/div.
b) Nominal space charge, 0.1 msec/div.



1 msec/div.

Fig. 6 Negligible space charge.

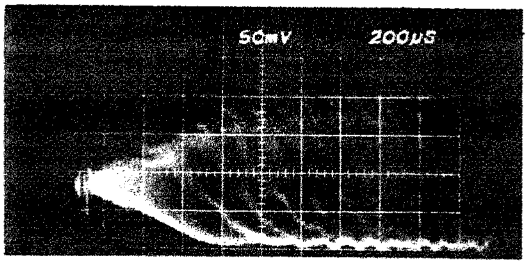
a) Input signal to RF power stage.
b) RF voltage at cavity gap.



5 msec/div.

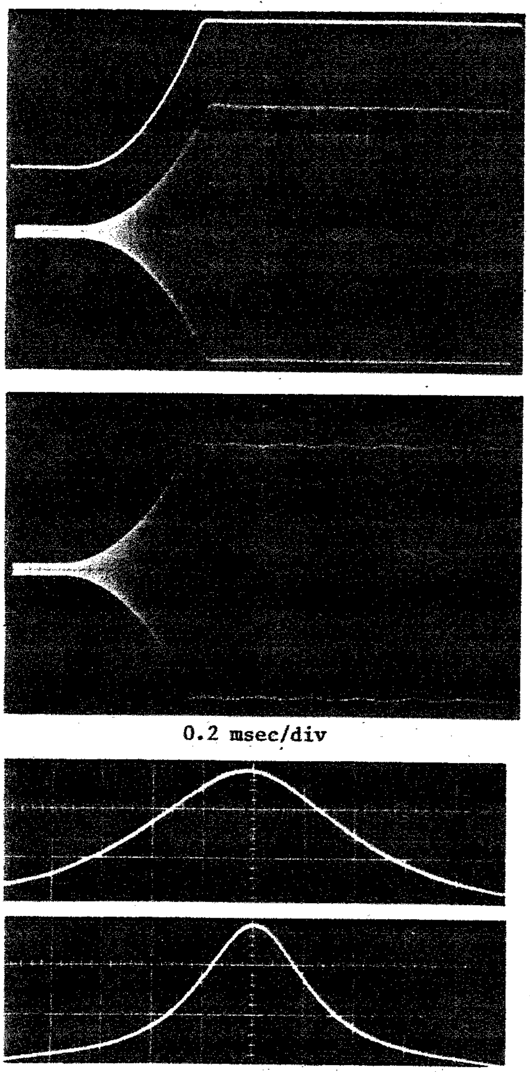
Fig. 7 Negligible space charge.

a) Beam current.
b) RF frequency programme.
c) Mean radial beam position error.



200 µsec/div

Fig. 8 Negligible space charge wide band Σ-electrode signal.



a)

b)

c)

0.2 msec/div

d)

e)

3 MHz 100 kHz/div

Fig. 9 N = 2.3 × 10^{12} (close to nominal space charge).

a) Input signal to RF power stage.
b) RF voltage at cavity gap with reduced cavity impedance.
c) RF voltage at cavity gap with normal cavity impedance. Evidence of beam loading.
d) Frequency response of cavity with reduced impedance.
e) Frequency response of cavity with normal impedance.

a)

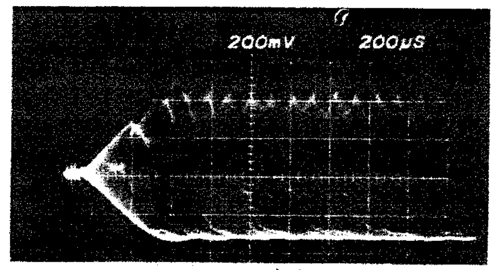
b)

c)

5 msec/div

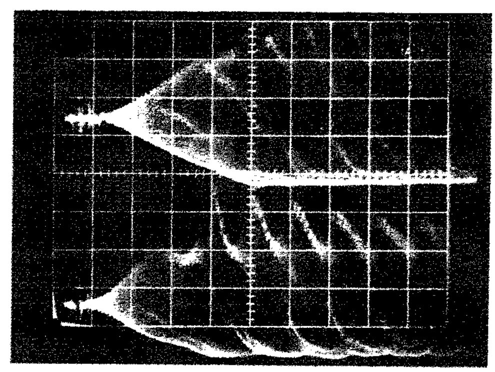
Fig. 10 N = 2.3 × 10^{12} (close to nominal space charge).

a) Beam current.
b) RF frequency programme.
c) Mean radial beam position error.



200 µsec/div

Fig. 11 N = 2.3 × 10^{12} (close to nominal space charge). Wide band Σ-electrode signal.



a)

b)

100 µsec/div

Fig. 12 Comparison of the effect of two different V(t) on bunch evolution. Simultaneous trapping in two separate PSB rings. ΔE_L = ±100 keV

a) V(t) computed theoretically for N = 2.5 × 10^{12}, (minimizing internal non-linear resonance), experimentally N = 2.3 × 10^{12}.
b) V(t) derived from the iso-adiabatic trapping theory, normally used for any N. Experimentally N = 1.6 × 10^{12}.

Acknowledgement

The implementation of the modified RF voltage programmes and the minimization of RF frequency and radial beam position errors via the control computer were carried out by P. Heymans.