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Longitudinal phase-space coating of beam in a storage ring

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ABSTRACT

In this Letter, I report on a novel scheme for beam stacking without any beam emittance dilution using a barrier rf system in synchrotrons. The general principle of the scheme called longitudinal phase-space coating, validation of the concept via multi-particle beam dynamics simulations applied to the Fermilab Recycler, and its experimental demonstration are presented. In addition, it has been shown and illustrated that the rf gymnastics involved in this scheme can be used in measuring the incoherent synchrotron tune spectrum of the beam in barrier buckets and in producing a clean hollow beam in longitudinal phase space. The method of beam stacking in synchrotrons presented here is the first of its kind.

1. Introduction

With the recent surge in worldwide interest in the *beam intensity frontier*, high intensity beam stacking in synchrotrons without any emittance dilution has become very important. Several decades of research have resulted in many novel methods of beam accumulation in storage rings [1–7]. However, during the Tevatron collider operations at the Fermilab between 2000 to 2011 none of the previously developed beam stacking methods could be used in the Recycler Ring [8], a permanent magnet 8 GeV storage synchrotron, which exclusively used *barrier radio-frequency* (rf) systems [9,10] in all of its beam manipulations. For this reason and in order to support luminosity upgrades [11] new methods needed to be developed for beam operation [12,13].

The barrier rf systems were introduced to modern accelerator technology by Griffin et al. [9] in 1983 and the flexibility they provided in the handling the beam with very complex bunching formats, like that demonstrated in longitudinal momentum mining [14], has opened up new prospects in beam dynamics not possible with conventional harmonic rf systems. Over the past decade, substantial experimental and theoretical progress has taken place in the field of barrier rf systems because of their important role in the Fermilab Recycler Ring [12–16], induction accelerator at KEK [17], R&D effort at CERN and BNL [18] and the proposed future NESR facility at GSI [19]. Despite these developments, not enough attention was given on improving beam stacking using barrier rfs. In the case of the Recycler, the antiproton beam was accumulated by repeated beam transfers from the Pbar source and cooled throughout the beam accumulation. It was imperative to keep the emittance of the cooled beam intact during the rf manipulations needed during beam stacking. All of the previously adopted beam accumulation techniques [12,13] encountered difficulty in preserving longitudinal emittance.

In this Letter, we demonstrate a novel beam accumulation scheme called "longitudinal phase-space coating" (LPSC) [20]. The phase space density of the initial beam is held unchanged and the emittance dilution for the newly arrived beam kept minimal. The physics concepts, an experimental demonstration and some spin-off applications of the scheme are presented.

2. Formalism of LPSC

The Hamiltonian for the synchrotron motion of a particle in a barrier bucket made of an arbitrary rf wave form $V(t)$ can be written as [15],

$$H(\Delta E,\tau)=-\frac{\eta}{2\beta^2 E_0}\Delta E^2-\frac{e}{T_0}\int_0^{\tau} V(t)dt \qquad (1)$$

where the quantities E_0, ΔE, e, η, T_0 and β represent synchronous energy, energy offset from E_0, electronic charge, phase slip factor, revolution period and the relativistic velocity of the particle, respectively. The time difference between the arrival of the particle and that of a synchronous particle at the center of the rf bucket is denoted by $-\tau$. The second term in Eq. (1) represents the potential energy of the particle. In the absence of non-linear forces like *intra-beam scattering* and/or *synchro-betatron coupling*, a particle will continue to follow the contour of a constant Hamiltonian

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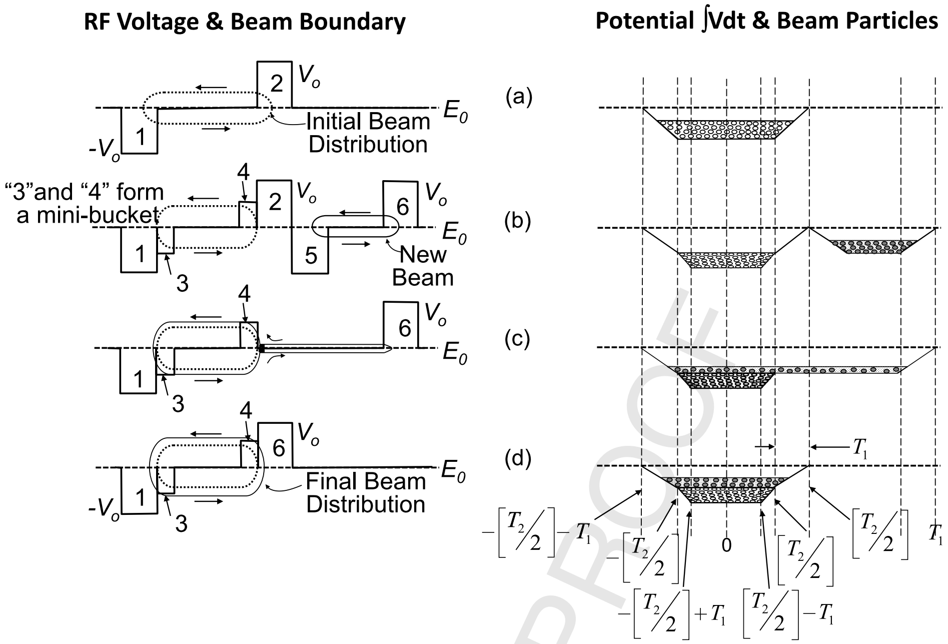

Fig. 1. Schematic view of LPSC. (a) Initial beam, (b) initial beam in a mini-barrier bucket and the new injection, (c) a stage of coating after removal of barrier pulses "2" and "5", and (d) after coating. The voltage wave forms (solid lines) and direction of the synchrotron motion are also shown on the left half of the figure.

in an rf bucket performing synchrotron oscillations. The maximum energy offset $\Delta E_{\rm Max}$ of a particle during its synchrotron motion is related to its penetration depth $T_{\rm Max}$ into the barrier, and is given by,

$$\Delta E_{\rm Max} = \sqrt{\frac{2e\beta^2 E_0}{|\eta| T_0}\left|\int\limits_{T_2/2}^{T_2/2+T_{\rm Max}} V(t)dt\right|}, \tag{2}$$

assuming rf pulses are antisymmetric with respect to the center of the bucket. T_2 denotes the gap between positive and negative pulses that forms a barrier bucket. In the case of rectangular barrier pulses one can replace the integral in this equation by $V_0 T_{\rm Max}$ where V_0 represents maximum of rf pulse height. Further, any rectangular barrier bucket can be treated as a combination of multiple buckets, one inside the other, like a *matryoshka doll*, so that one of the inner buckets confines all of the particles below $\Delta E_{\rm Max}$. The principal goal of the new stacking scheme is to isolate all the particles below a certain maximum energy spread using an inner barrier bucket (*mini-barrier* bucket). The maximum potential energy of the particles in the mini-bucket is set at the same level as the minimum potential energy of the newly injected beam and coat the new beam on top of the isolated beam. The coating takes place in $(\Delta E, \tau)$-space. The particles in the mini-bucket will be left undisturbed throughout the stacking.

Fig. 1 provides an insight into the coating mechanism. A schematic view of the rf wave-forms with the beam phase space boundary and the beam particles in the corresponding potential well for a storage ring operating below transition energy are shown. Before the transfer of a new beam, a mini-bucket made of two barrier pulses "3" and "4" is opened adiabatically to isolate the initial beam, as shown in Fig. 1(b). The mini-bucket isolates particles in a phase space area $\varepsilon_m = 2(T_2 - 2T_m)\Delta E_m + 4T_0|\eta|\Delta E_m^3/[3\beta^2 E_0 e V_m]$. The quantities T_m, ΔE_m and V_m represent pulse width, bucket height and pulse height for the mini-bucket, respectively. Subsequently, a new beam is injected in a separate barrier bucket made of rf pulses "5" and "6". For simplicity, the parameters of barrier pulses "5" and "6" are chosen same as those of "1" and "2", respectively. The rest of the beam stacking involves adiabatic and simultaneous removal of the barrier pulses "2" and "5". Thus, the injected beam particles start slipping along the newly formed contours of constant Hamiltonian around the mini-bucket as depicted in Fig. 1(c). Eventually, the rf pulse "6" is moved to the location of "2" adiabatically to complete the coating process as shown in Fig. 1(d).

3. Experimental demonstration

We have demonstrated the above beam stacking scheme in the Recycler which operated below the transition energy of 20.27 GeV with $T_0 = 11.12$ μsec. The Recycler barrier rf system was capable of providing pulses of any shape with amplitudes up to ∼2 kV [10] and had a versatile LLRF [16]. The 2D-particle tracking simulation code ESME [21] was employed to validate the scheme and to establish the rf manipulation steps. Subsequently, the beam experiments were carried out as proof of principle demonstration.

Fig. 2 shows simulated beam particle distributions in the longitudinal phase space along with the barrier rf pulses. An initial beam of ∼125 eV s was populated in a barrier bucket of total area 250 eV s with pulse width $T_1 = 0.91$ μsec, $T_2 = 5.89$ μsec and $V_0 = 1.93$ kV at clock time = 0 sec. A new beam of about 7 eV s was injected after confining 108 eV s of the initial beam. The parameters of the mini-barrier bucket were $T_m = 0.25$ μsec, $(T_2 - 2T_m) = 5.4$ μsec, $V_m = 1.93$ kV and $\Delta E_m = 9.41$ MeV as shown in Fig. 2(b). There are an infinite number of ways of selecting the parameters for a mini-bucket of phase space area of 108 eV s. The principal idea is that the mini-bucket must isolate the entire initial beam or some part of it. The rest of the beam coating was performed as depicted in Fig. 1. In the simulations, the width of the barrier pulses separating the initial and the new beam were reduced symmetrically to the "unstable point" (see Fig. 2(b)), keeping the newly arrived beam undisturbed. To complete the coating, the right-most barrier pulse was moved adjacent to the mini-barrier bucket as in Fig. 2(d). The simulation showed that the final emittance of the beam was about 132 eV s with a negligible emittance dilution. Repeating the steps shown in Figs. 2(b) to 2(d) one can perform multiple coatings. The simulations clearly showed that the emittance preservation in this scheme depends on the iso-adiabaticity of the rf manipulation. An initial distribution

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