BARRIER RF SYSTEMS IN SYNCHROTRONS*

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Abstract

Recently, many interesting applications of the barrier RF system in hadron synchrotrons have been realized. A remarkable example of this is the development of longitudinal momentum mining and its implementation at the Fermilab Recycler for extraction of low emittance pbars for the Tevatron shots. At Fermilab, we have barrier RF systems in four different rings. In the case of the Recycler Ring, all of the RF manipulations are carried out using a barrier RF system. Here, I review various uses of barrier RF systems in particle accelerators including some new schemes for producing intense proton beams and possible new applications.

INTRODUCTION

About twenty years ago, at the early stages of the Tevatron project at Fermilab [1] it was realized that one can increase the antiproton stacking rate by >10% if the antiproton bunch length in the Fermilab Debuncher (of circumference 505.28 m) is matched to the circumference of the Accumulator (474.06 m). Also, at the time of extraction of the antiproton beam from the Accumulator it was desirable to use an RF system with harmonic number h = 2 with one of its bucket suppressed. These requirements lead to invention of barrier RF systems [2]. Since then, many more versatile barrier RF systems have been built and are in use at various hadron facilities [3]. In this paper I review various uses of the barrier RF systems with emphasis on some recent applications.

A barrier RF system is nothing more than a broad-band RF system comprising of ferrite loaded RF cavities with RF wave forms generated using solid state wide-band power supplies. One can also generate some specific wave forms using fast switches [4].

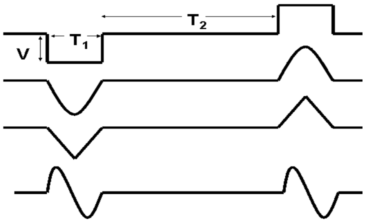

Figure 1: Possible forms of barrier RF wave forms.

There are various forms of barrier wave-forms in use. Figure 1 shows some typical wave forms used in synchrotron rings. As a particle circulates around a storage ring with barrier RF system on, it will not see any RF voltage for most of the time. However, it gets accelerated or decelerated whenever it encounters an RF wave. Depending upon whether the synchrotron is above or below *transition energy* these waves can be used to produce a gap in the beam or to form a long bunch. A comprehensive review of particle dynamics in storage rings with barrier buckets is available in literature [5].

BARRIER RF SYSTEMS AT FERMILAB

There are many barrier RF systems in use at Fermilab synchrotrons *viz*., antiproton Accumulator, Debuncher [1], Recycler [6] and very recently in the 150 GeV Main Injector(MI)[4]. Each one of them has specific application. The barrier RF system in the antiproton Debuncher is historically the first barrier system in use. Ever since its installation this system is used as a gap preserving RF for antiproton stacking. Among all of the above the one used in the Recycler is most versatile [7] barrier system. Table 1 summarizes the properties of these barrier RF systems.

Table 1: Barrier RF systems at Fermilab

RF system & Use	**Ferrite Type (Cavity Dimension)**	**Properties (Power, V_{peak}, R_{shunt}, Band-width, Power Amplifiers)**
Debuncher – Gap preserving	MnZn+NiZn (~ 1 meter)	2.4kW, 700V, 104Ω, 10kHz-10MHz,IFI3100S [1,2]
Accumulator – Ion clearing	MnZn+NiZn (~1 meter)	100W, 70V, 50Ω, 10kHz-10MHz, ENI2100 [1,2]
Recycler – Main and only RF system	Ceramic Magnetics MN60, CMD10 (~1 meter)	4×3.5kW, 4×500V, 4×50Ω , 10kHz-100MHz, Amplifier Research Model 3500A100 [6]
MI – Stacking Studies	Finemet®core (~0.75 meter)	150kW, 10kV, 500Ω Fast Switch [4]
MI – Damper Cavities	MnZn+NiZn (~1 meter)	3×3.5kW, 3×500V, 3×50Ω , 10kHz-100MHz, Amplifier Research Model 3500A100 [4]

APPLICATIONS OF BARRIER SYSTEMS

There are a number of un-explored applications of barrier RF system. In this section I will try to summarize a few of them.

Longitudinal Momentum Mining

Very recently, I have developed a new scheme [8] for selectively isolating high density low longitudinal emittance beam particles in a storage ring from the rest of the beam without emittance dilution. We called this method *longitudinal momentum mining*. The general principle of the longitudinal momentum mining is illustrated using potential diagrams in Figure 2. 2D-multiparticle beam dynamics simulations applied to the Recycler convincingly validate the concepts and feasibility of the method. This method has been successfully demonstrated with beam experiments in the Recycler.

In the figure 2, the quantities T_1 and T_2 represent barrier pulse width and pulse gaps, respectively. V_0 is the pulse height and ΔE and τ are, respectively, coordinates representing the energy relative to synchronous particles and time relative to the center of the barrier bucket.

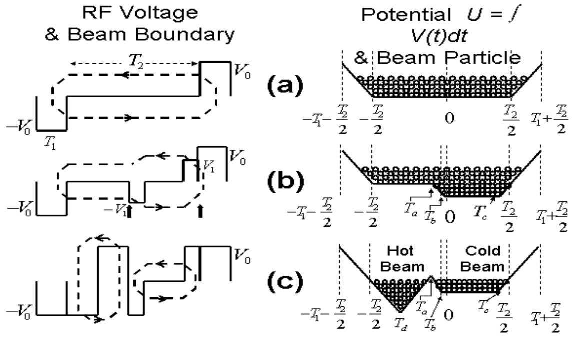

Figure 2: Schematic view of the longitudinal momentum mining using barrier buckets. Barrier RF voltage (solid-lines) and beam particle boundary in $(\Delta E, \tau)$-phase space (dashed line) are shown on the left. The cartoons on the right show the potential well and the beam particles in it. (a) The initial distribution, (b) after confining particles with low energy spread in a deeper well and (c) after isolating particles with high and low energy spreads.

Over the last few months we have fully implemented this scheme for antiproton extraction from the Recycler for Fermilab collider operations. For collider use, the cold beam is sliced further up to nine 6 eVs bunches using additional barrier buckets. And finally, each such bunch will be divided further into four 1.5 eVs bunches using 2.5MHz buckets before transfer to the Tevatron *via* the MI. Operational schemes have been implemented for 4-36 bunch (in multiple of 4 bunches) transfers from the Recycler. Figure 3 shows typical cavity fanback signals and wall-current monitor data taken during 12 bunch transfer to the Tevatron.

For a beam with initial longitudinal emittance of 34 eVs with a Gaussian beam energy distribution we have predicted about 62% of the beam to be mined in 18 eVs. Experimentally we were able to mine about 53% of the beam, indicating that the cold pbars in the Recycler are not perfect Gaussian in energy coordinates.

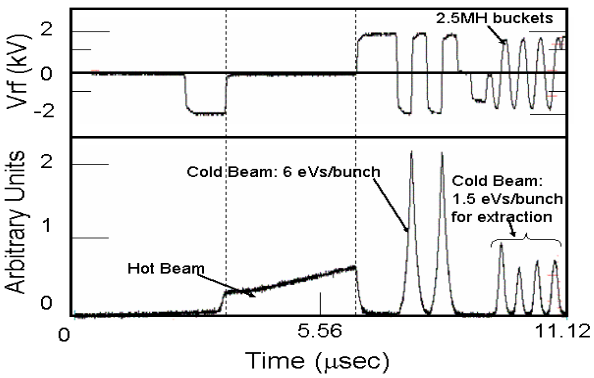

Figure 3: Recycler cavity fanback and wall current monitor signals for anti-proton unstacking for the ppbar collider operation.

Beam Cooling in Segments

In the Recycler it is highly essential to cool the newly injected hot antiproton beam using stochastic cooling technique and the rest using electron cooling techniques [9]. With the help of the barrier RF system, maintaining two super bunches of different emittances has become a trivial task. Once these two bunches are cooled optimally they need to be merged. We have developed a scheme to merge two stacks nearly adiabatically with minimum emittance dilution [10].

Production of Intense Beam in Accelerators

Accelerator based neutrino programs around the world demand very high intensity hadron beams on the neutrino targets. The barrier RF system can be of great help here. In this section I list a few potential techniques that are being explored at Fermilab to produce high intensity proton beam in the MI using barrier systems.

1. Barrier Flip-Flop [11]

A novel concept for doubling the beam intensity has been proposed [11]. A schematic view illustrating the principle of the method is shown in Figure 4 for a synchrotron which operates below its transition energy. After injection of 1st and 2nd bunches in a barrier bucket (Fig. 4(a)) the region between barrier pulses is replaced by a linear voltage ramp as shown in Fig. 4(b). Then, the bunches undergo rotation in the $(\Delta E, \tau)$-phase space as shown in Fig.4(c). Subsequently, the steps 4(d)-4(f) are followed, resulting in the final beam distribution. Our 2D simulations showed that the emittance dilution from step 4(a) to 4(f) is at the level of few percent.

We have conducted beam experiments using Recycler barrier RF systems. Two 1.6 μsec long batches were injected in the barrier bucket and compressed following the method outlined here. Finally, the compressed bunches are transferred to the MI and captured in 53 MHz buckets. In our experiments we did not see any noticeable longitudinal emittance growth.

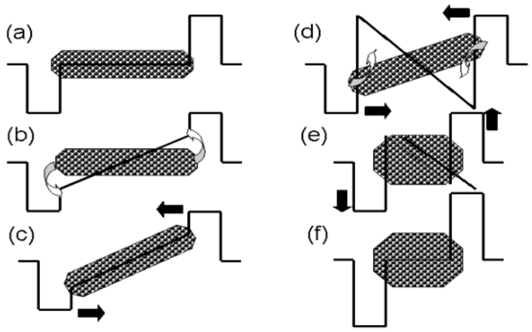

Figure 4: Schematic view for flip-flop method of beam compression using barrier RF system. The horizontal arrows show direction of barrier pulse motion and the vertical one show pulse height adjustments.

2. Adiabatic Compression [12]

One can double the proton beam intensity by injecting two batches of proton beam at injection energy between two barrier pulses and compress them adiabatically to half of its original size. In our experiments in the Main Injector, the compressed beam is recaptured in 53MHz buckets with resulted twice the bunch intensity and accelerated to 120 GeV.

3. Momentum Stacking [13]

In this scheme one injects multiple bunches, one following the next, below the half energy spread of the bunch, between a stationary barrier and a moving barrier close to the latter as shown in Fig. 5. The first bunch gets accelerated by the moving barrier and gets out of the way of the second injection and so on. At Fermilab MI we are seriously pursuing this method to double the MI beam intensity.

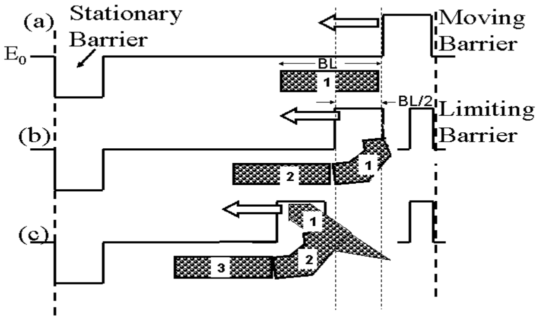

Figure 5: Schematic view of momentum stacking.

There are a number of other applications of barrier systems being explored around the world. Broad-band RF system as dampers [14] produce ion-clearing gaps in storage rings, induction acceleration [15] etc.

POTENTIAL WELL DISTORTION

It is important to note that every barrier RF system has intrinsic shunt impedance. As a result of this, cavity beam loading is an issue even in the barrier RF system. Recently, we have reported on the first observation of potential well distortion [16] of barrier beam in hadron ring. This effect certainly makes the acceleration of super-bunches in synchrotrons [15] more difficult than originally thought and it is highly essential to develop a beam-loading compensation system as an integral part of barrier RF system used for any high intensity operation.

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