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Isolated Bucket RF Systems in the Fermilab Antiproton Facility

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Introduction

In the Fermilab $\bar{p}p$ colliding beam facility[1] antiprotons are to be collected in an accumulator ring where the injection/extraction orbit length and rotation period are the same as those of the Booster Ring at T = 8 GeV, namely 474.19 m. and 1.59 x 10^{-6} sec. Prior to injection into the Accumulator ring the momentum spread of the antiprotons is reduced by mismatched bunch rotation in a slightly larger Debuncher ring with circumference[2] 505.28 m and rotation period (8 GeV) 1.695 x 10^{-6} sec. Several of the beam manipulations in these rings are facilitated by rf systems capable of applying a longitudinal accelerating field for only part of each rotation period. The accelerating field is "suppressed" for the remainder of the rotation period. The concept of "suppressed bucket" is not new,[3] but the use to which they are put in this project is unique. Fig. 1a is a sketch of a voltage function of time which, when developed on an accelerating gap, would provide such a field. T_o is the synchronous particle rotation period and the voltage is a single complete sinusoid of period T_{rf}. The period T_{rf} can be related to the rotation period by the expression $T_o = hT_{rf}$, where h > 1 but h need not be an integer. The repetition period of the isolated wave can be precisely T_o (stationary) or it may differ slightly from T_o (moving). Furthermore, the wave need not be sinusoidal as shown or even symmetric about some center point. It must only span some region T_{rf} and it cannot have a dc component. Practical considerations indicate that the wave should be reasonably smooth so that the Fourier spectrum is not excessively broad.

The voltage wave of Fig. 1a, repeated with period T_o and applied to an accelerating gap in a ring operating above transition, would create an isolated bucket indicated by the separatrices shown in Fig. 1b. Particles trapped within the bucket would execute normal synchrotron phase oscillations and particles initially outside of the bucket would move on orbits which are displaced in momentum around the bucket as shown.

Gap Preservation

Initial momentum reduction of antiprotons is to be done by injecting 82 narrow antiproton bunches spaced 5.614 m. apart into large rf buckets at harmonic number[2] 90 (53.105 MHz) in the 505.28 m Debuncher ring. A gap in the injected beam of 8 rf wavelenghts or 44.91 m (150.6 nsec) will exist initially. During the early stages of bunch rotation the bunches are contained completely within the h = 90 buckets so the gap is preserved. During the late stages of momentum reduction the bunches are adiabatically debunched by lowering the rf voltage to a very small value and finally removing it entirely.

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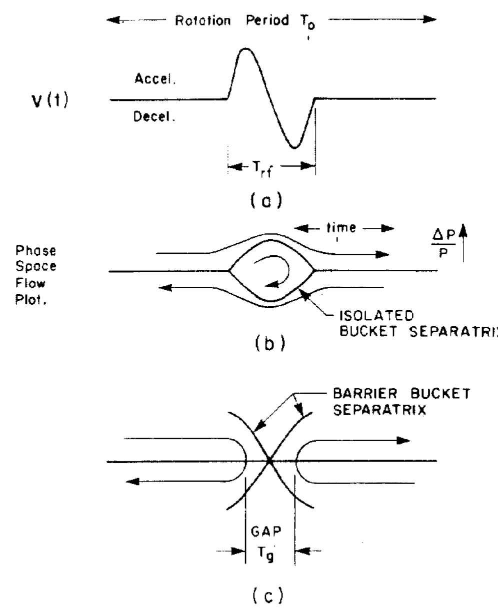

Fig. 1 a) Isolated sinusoidal voltage excursion of period less than rotation period T_o. b) Phase space particle flow plot if voltage of part a is applied to a gap with the phase shown, in a ring operating above transition. c) Phase space flow plot if polarity of accelerating field is reversed. A gap is preserved in the flow if the bucket height is sufficiently large.

Since the beam is required to remain in this ring for several seconds for stochastic betatron cooling,[4] off-momentum particles would drift longitudinally and fill the gap before extraction. The Accumulator ring into which the antiprotons are to be injected has a smaller circumference, equivalent to h = 84, so about nine percent of the antiprotons will be lost upon transfer unless the gap is preserved.

A gap in the Debuncher charge distribution could be preserved by applying an rf voltage at h = 1 (589.9 kHz) and establishing a single bunch somewhat shorter than the stationary bucket length. This procedure would create a nonuniform momentum distribution with an increase in momentum spread at the bunch center. The small momentum spread at the ends of such a bunch would have an adverse effect on the betatron cooling and the enlarged momentum spread at the center would defeat somewhat the preceeding effort to lower the momentum spread. A better solution can be obtained by using an isolated "barrier bucket".

If the phase of the isolated voltage wave applied to an accelerating gap is reversed from that shown in Fig. 1a, so that higher momentum particles are decelerated upon entering the bucket region, the separatrices no longer form a closed region, but they appear back-to-back as shown in Fig. 1c. Higher momentum particles within the barrier region follow normal trajectories and are returned to the field free region with negative incremental momentum. On the later time side of the separatrix region the lower momentum particles move into the bucket and are similarly returned to the field free region with higher momentum. In this way a gap, T_g, is preserved in the phase space distribution while the normal momentum spread and charge migration rate are preserved in the field free region.

If the isolated voltage wave is essentially sinusiodal the standard expressions for bucket height, bucket area, and synchrotron phase motion apply within the bucket. The period of the applied rf wave is one quarter of the rotation period or 424 nsec (f = 2.36 MHz). Since it is required to preserve a gap of 150 nsec, particles are allowed to travel on orbits which extend 137 nsec, or 2 radians into each end of the rf half-buckets. The required bucket height ΔE_b can be related to the energy ΔE of particles on these maximum incursion trajectories by the expression

$$\Delta E = \Delta E_b \sin\frac{\phi}{2} = 0.841\ \Delta E_b \tag{1}$$

where, $\phi = \pi - 2$.

The energy spread of the antiprotons after debunching[2] is about ± 9.1 MeV ($\pm 2\sigma$). The required bucket height becomes 10.8 MeV and the peak voltage can be calculated directly

$$\Delta E_b = \left(\frac{2E_s V}{\pi h \eta}\right)^{1/2} = 10.8 \times 10^6\ \text{eV} \tag{2}$$

$E_s = 8.9\times10^9$ eV, $h = 4$, $\eta = 1/\gamma_t^2 - 1/\gamma^2 = 0.006$.

$$V_{peak} = \frac{\pi h \eta \Delta E_b^2}{2E_s} = 492\ \text{volts} \tag{3}$$

At this voltage the sychrotron phase oscillation period for particles within the bucket is ~ 0.13 sec. and particles with momentum deviation of 1 σ require about 0.42 sec. to transverse the field free region.

The gap will appear as a pulse of current passing through the stochastic cooling pick-ups with repetitation period T_o, so it will have Fourier components in the 2-4 GHz frequency range which could adversely affect the cooling. Fortunately, because of the smooth sides of the pulse, resulting from curved trajectories within the bucket and a roughly Gaussian momentum distribution of charge, the Fourier components fall off with harmonic number almost as n^{-3}. At 2 GHz n = 3400, so signals resulting from the gap are of order $10^{-9}N/T_o$ (N = number of antiprotons) whereas the stochastic signal is of order $N^{1/2}/T_o$. For $N = 10^9$ the ratio of stochastic signal to gap induced noise is of order $10^4 - 10^5$ so no adverse effect is expected. Because of the relatively long periods during which particles remain in the field free region, stochastic cooling of the betatron motion can proceed normally in the 2-4 GHz band.

Accumulator RF Unstacking

After collection, stacking, and cooling, a dense core of about 4.5×10^{11} antiprotons with roughly Gaussian distribution will be stored in the accumulator ring.[1] The peak density and standard deviation will be 10^5/eV and 2 MeV respectively. Single bunches of about 8×10^{10} $\bar{p}$s must be rf captured at the core center and accelerated (rf unstacked) about 140 MeV to the extraction orbit. The ring is characterized by a rotation period at 8.9 GeV of $T_o = 1.59 \times 10^{-6}$ sec and $\eta = \gamma_t^{-2} - \gamma^{-2} = 0.02$. At the core center 8×10^{10} $\bar{p}$s occupy a phase space of about 1.5 eV sec. At harmonic number one (629 kHz) an rf voltage of only 2 volts is required to establish a stationary bucket of area 1.5 eV sec. At a synchronous phase angle of 20 degrees, the voltage must be raised to 8 volts and the accelerating voltage is 2.8 volts. The voltage must be maintained at this level during unstacking through the "tail" of the accumulated stack so acceleration to the extraction orbit requires 60-80 seconds.

By using an isolated bucket, Fig. 1b, at h = 2 higher voltage is required and rf unstacking of a single bunch can proceed more quickly. At h = 2 and ϕ_s = 20 degrees the moving bucket is established by applying 72 volts, and acceleration to the extraction orbit requires only 11 seconds. Because of the many Fourier components required to create the required voltage wave, the accelerating structure is, of necessity, a broad-band low impedance device and, as such, it is not likely to contribute to beam induced instabilities inherent in low momentum spread stored beam situations.

Isolated Bucket Hardware

Electronic generation of the waveform of Fig. 1a is a straightforward low level electronics problem involving phase-lock loops, linear gates, etc. Different applications require different techniques and no attempt will be made here to describe any single system. Of more interest are the techniques required to develop relatively large amplitude signals on accelerating gaps.

The Fourier spectrum of an isolated unit amplitude sinusoid of period T_{rf} on a T_o period where $T_o = hT_{rf}$ is

$$u(t) = \frac{2h}{\pi}\sum_{n=0}^{\infty}\frac{\sin n\pi/h}{h^2 - n^2}\ \sin n\omega t \tag{4}$$

The rotation frequency of the Debuncher ring is 590 kHz ($T_o = 1.69 \times 10^{-6}$ sec) and at h = 4 the fundamental amplitude is 0.12. The maximum required amplitude is 0.27 at n = 3. For harmonics much larger than h the harmonics decrease in amplitude like n^{-2}. The 10th harmonic, 5.9 MHz has amplitude 0.03. A very acceptable wave can be generated using a system which can reproduce 10 harmonics with minimal amplitude and phase distortion. The usable bandwidth of each component in the system should extend at least an octave above and below the required range of Fourier components. Ideally the synthesized signal is amplified by a broadband power amplifier and delivered to a nearly resistive load of constant amplitude over the entire required bandwidth. The load must, of course be the beam accelerating structure.

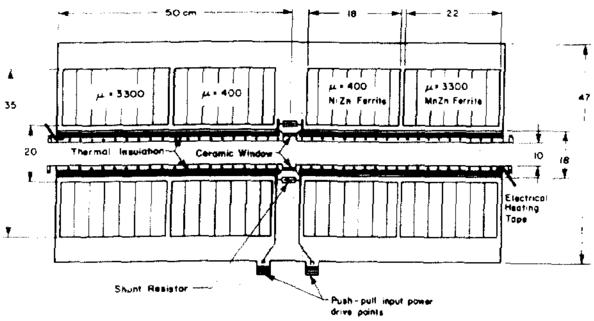

Fig. 2 Double ended ferrite loaded broadband accelerating structure. Beam pipe can be baked in situ for vacuum clean-up.

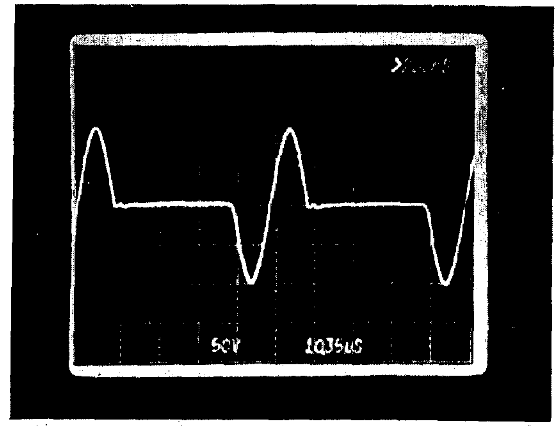

Fig. 3 Isolated bucket sinusoidal waveform for $h = 4$ developed on prototype accelerating structure. Base period is 1.7×10^{-6} sec and peak voltage 100 volts.

The accelerating structure consists of a assembly of enclosed ferrite rings which create an impedance large with respect to ~ 52 ohms over the required frequency range. The rings encircle the beam pipe and a low capacitance ceramic gap couples the devleoped field to the beam. When shunted with a 50 ohm resistor, the assembly provides the required (nearly) constant resistance. Because of the very low fundamental frequency some of the ferrite must be high μ_r MnZn ferrite. Since this ferrite becomes very lossy above about 1 MHz it must be augmented with additional rings of NiZn ferrite to extend the high impedance range above 10 MHz. If sufficient NiZn ferrite is to be included so that the impedance is acceptably high at around 1 MHz then the system will become parallel resonant around 4 MHz and the subsequent series resonance could force the impedance to an unsuitably low value within the operating range. Fortunately the presence of the MnZn ferrite, which at 8-10 MHz is very lossy, lowers the system Q sufficiently so that the impedance excursions at resonances are muted and the impedance remains relatively high and almost real. Fig. 2 shows such a structure. In this case two ferrite assemblies are coupled to one gap which is loaded with ~ 104 ohms. The two sides of the gap are driven in push-pull mode by separate amplifiers. The impedance presented to each amplifier varies from $51.5 \angle 8^\circ$ at 600 kHz to $47 \angle -2^\circ$ at 10 MHz. If each side is driven at $h \approx 4$ with peak voltage of 250 volts the shunt resistor must dissipate 312 watts. The rf flux in various parts of the ferrite can be calculated for each harmonic and these peak fields are about 5 Gauss for each of the first four harmonics, so power dissipation in the ferrite is negligible. The structure shown meets the requirements of the barrier bucket system described above.

The power to be delivered to the load is reduced by the factor h from that which would be delivered by a continuous wave of the same amplitude. Therefore the peak current and voltage capability of the amplifier operating into a fixed load may become more important than the power delivery capability. The group delay of the amplifier must be approximately constant over the required bandwidth and this is especially important at the low frequency end where the Fourier components are large and small relative phase shifts introduce large distortions.

Unfortunately, tests of many commerical broadband amplifiers reveal that design concessions have frequently been allowed in the group delay in order to provide constant amplitude at different frequencies over the specified bandwidth. Many amplifiers are designed to be used with no retuning, but complex wave forms have not been given serious consideration. One commercial amplifier has been located (specified bandwidth 12 kHz-12MHz) capable of delivering ±125 volts to a 50 ohm load with acceptable phase integrity and harmonic distortion. Four such amplifiers, coupled through high power broadband power combiners can produce the required 250 volts for excitation of one input of the accelerating structure.

A preliminary accelerating structure similar to one half of that shown in Fig. 2 has been assembled, with an insufficient quantity MnZn ferrite. This requires the real shunt resistance to be lower than the design value. The structure was driven in the $h = 4$ mode ($T_0 = 1.69\mu$sec) at a level of ±100 volts. The isolated bucket wave is shown in Fig. 3. In other tests the combined signals from two amplifiers have been delivered to a 50 ohm load with acceptable results so there is apparently no serious problem associated with the development of isolated buckets or barriers of the amplitude required.

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