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FERMILAB-FN-0746

A New Scheme for Momentum Mining of Beam Particles in a Storage Ring

Application to the Fermilab Recycler

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Submitted to Fermilab Publications on March 15, 2004

Abstract:

Here I propose a new scheme for selectively isolating low momentum particles in a storage ring. I discuss the method as a specific application to momentum mining of antiprotons in a cooled stack at the Fermilab Recycler Ring. The scheme is extended to extract 36 anti-proton bunches of equal intensities and of equal longitudinal emittance for the Fermilab proton antiproton collider operation. The results of step-by-step multi-particle beam dynamics simulations convincingly support the feasibility of the technique. I have demonstrated the technique with beam experiment, and the method has been successfully used in extraction of anti-protons from the Recycler. The method presented here is first of its kind.

I Introduction

Fermilab has planned to use the Recycler [1, 2] as the main antiproton storage ring for future proton-antiproton collider operations. This will be achieved in two phases. In the first phase, about 200E10 antiprotons will be stacked and cooled using the stochastic cooling to ≈ 100 eVs longitudinally and ≈ 10π-mm-mr transversely [3]. In the second phase, electron cooling will be added and the anti-proton stack size is expected to be in excess of 600E10. The longitudinal emittance of the cooled beam is expected to be less than 54 eVs. In both cases, the stored cooled beam will be transferred to the Tevatron *via* the Main Injector for proton-antiproton collider operation. The beam stacking in the Recycler and transfer to the Tevatron comprises of complicated sets of RF manipulations [4]. It is highly essential to maintain the emittance of the beam through-out the chain of the RF manipulations.

The antiproton extraction from the Recycler to the Main Injector takes place in nine transfers of groups of four 2.5MHz bunches each, with a total of thirty six bunches. The longitudinal emittance of these bunches from the Recycler needs to be ≤1.5 eVs. In the Main Injector the beam will be accelerated from 8 GeV to 150 GeV for each injection with a harmonic transfer of the beam from 2.5 MHz buckets (h=28) to 53 MHz buckets (h=588) adopting one of the methods described in references 5 and 6. Eventually, the bunches are transferred to 53MHz buckets of the Tevatron.

For the best performance of the Tevatron collider operation, it is desirable to have same intensity and emittance for all thirty six bunches from the Recycler. To achieve this goal, I present, here, a novel method of RF manipulation that I call "longitudinal momentum mining", which allows one to capture selectively only the high density low longitudinal emittance beam for the collider use and preserve the unused high momentum antiprotons for further cooling and future use. The method developed here is quite a general technique and is first of its kind. The details are given with the application to the Fermilab Recycler ring as an example.

I discuss the principle of longitudinal momentum mining in Section II. Theoretical simulations using the multi-particle beam-dynamics code ESME [7] for the momentum mining are described in Section III. Results of the beam experiment are presented in section IV. And finally, I make some comments on future improvements.

II Longitudinal Momentum Mining in a Storage Ring

Anti-proton beam stored in the Fermilab Recycler ring is characterized by its momentum spread "$\Delta \hat{E}$" about its nominal energy and a characteristic transverse emittance. In the absence of synchro-betatron coupling these two quantities can be varied independent of each other. If the beam is cooled using the stochastic cooling technique, the energy distribution resembles a gaussian distribution with the lower momentum particles being closer to the peak region, and high momentum particles away from the peak. In the case of cooling using electron beam, the beam particle distribution is still gaussian in its phase space. It is highly advantageous to isolate the high density particles with low momentum spread from the high momentum particles and use only the former for collider operation and reserve the rest for further cooling and use them later.

By "momentum mining" in the Recycler ring, we mean, a method of selectively isolating the beam particles in the low momentum region from the rest of the momentum distribution without any emittance growth. The antiproton storage rings around the world have adopted what I call "transverse momentum mining" for extracting the beam from a cooled stack. For example, in the antiproton Accumulator ring at Fermilab, the beam particles (in h=1 system) are captured adiabatically in buckets of sinusoidal rf wave with h=4 and of bucket area smaller than the total beam area. Then the beam particles in h=4 buckets are pulled out from the main stack transversely by accelerating them [8]. Once they are completely outside of the h=1 distribution they are extracted using electro-static kickers. The shortcoming of this method is that, at the time of separating the low momentum particles from the original distribution, disturbance of the rest of the distribution is inevitable. Consequently, one expects longitudinal emittance growth. As a result of this, if the beam extraction is carried out multiple times, then the later extractions will have lesser particle density for the same phase-space area. In the method I have proposed here, the particle mining is carried out longitudinally using barrier buckets and the expected emittance dilution is minimal.

In the past, proton mining using dual frequency amplitude modulation has been proposed [9]. The theory is applied to the problem of parasitic extraction of protons from a circulating beam in a high energy hadron accelerator for crystal extraction. This method in many respects is very similar to the transverse mining method mentioned earlier.

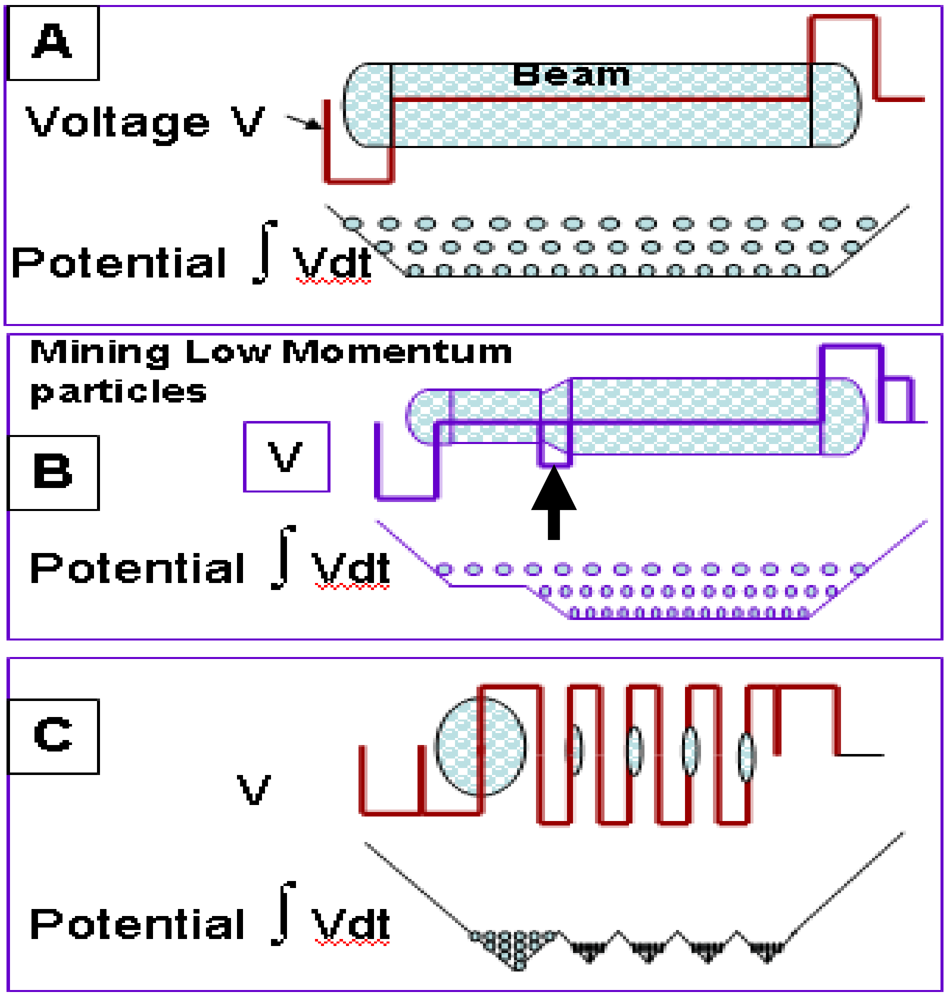

Figure 1: Schematic view of "longitudinal momentum mining" using barrier buckets. Barrier rf voltage and beam particle distribution in ($\Delta E,\Delta t$)-phase space are shown (top) in each of the three pictures. The bottom picture shows potential well and beam particles in it. (A) the initial distribution, (B) after dropping low momentum particles in a deeper well and (C) capturing in smaller barrier buckets and high momentum particles in a bigger barrier bucket.

The principle of "longitudinal momentum mining" is illustrated schematically in Figure 1. The initial phase-space distribution of the beam particles in a rectangular barrier bucket and the distribution in the corresponding potential well are shown in Figure 1A. The first stage of longitudinal momentum mining is to grow a bucket in the barrier bucket region as shown in Figure 1B and allow beam particles to drift into the deeper region of the potential well. Or, one can grow a negative pulse at the right hand side of left-most rf pulse and move adiabatically to a location indicated by an arrow in Figure 1B. By this technique, one will be able to populate low momentum particles in the right side region of the potential well and the high momentum particles will be executing synchrotron oscillations almost freely. Then, the required numbers of constant emittance smaller barrier buckets are opened to capture low momentum particles and a larger bucket for trapping high momentum particles. This situation is shown in Figure 1C.

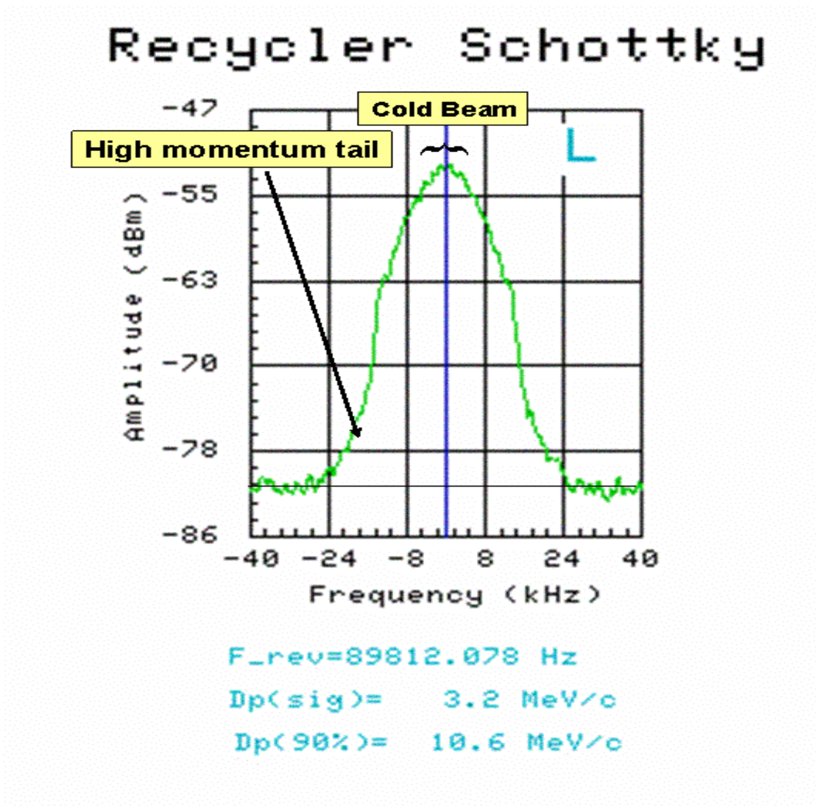

Figure 2: A typical Schottky spectrum of beam particle in the Recycle Ring. Regions of high and low momentum particles are indicated.

A typical Schottky frequency spectrum of the beam particles in a barrier bucket is shown in Figure 2. The synchronous energy of the Recycler at Fermilab is about 8.938 GeV. The regions of high and low momentum particles are also indicated in the Figure. The energy spread of the cold beam with longitudinal emittance of about 100 eVs when spread by about 8.67 μsec around the Recycler is expected to be about ±5.7 MeV. For a fixed beam area ε_l, the energy spread $\Delta \hat{E}$ and the barrier bucket spacing T_2 are related according to [10],

$$\varepsilon_l = 2T_2 \Delta \hat{E} + \frac{8\pi|\eta|}{3\omega_o \beta^2 E_o eV_{rf}} \left[\frac{\Delta \hat{E}}{2}\right]^3 \qquad (1)$$

where,

$$\Delta \hat{E} = 2\sqrt{\frac{2\beta^2 E_0}{|\eta|} \frac{eV_{rf} \hat{T}_1}{T_0}} \qquad (2)$$

In equations 1 and 2, the quantities η, E_0, T_0 and V_{rf} are respectively, slip-factor of the synchrotron, synchronous energy of the beam, the revolution period of the charged particle and peak rf voltage of the rectangular barrier pulse. $\hat{T}_1$ is a measure of beam penetration in the barrier. The quantities ω_0 and β are angular revolution frequency of the beam particles and the ratio of the beam velocity to that of velocity of light, respectively.

By using the method proposed here, one can choose bunches from the low momentum region with small longitudinal emittance and the energy spread according to the equations 1 and 2, respectively. The beam in the Recycler is stored in barrier buckets in different segments longitudinally and hence the method of momentum mining used for the Accumulator ring is highly inefficient and cannot be used without much modification to the RF system of the Recycler.

III Theoretical Simulations of Unstacking of Cooled Antiprotons in the Recycler

Beam dynamics simulations have been carried out for two unstacking scenarios. I assume that the final anti-proton bunches extracted from the Recycler need to have emittance ≤1.5 eVs each [2] and of equal intensity. In the first scenario, the total longitudinal emittance of the antiproton stack is assumed to be ≤54 eVs. The goal here is to divide the stack into nine equal parts and extract each part in succession into the Main Injector as four 2.5MHz bunches. This gives a total of 36-bunches with longitudinal emittance ≤1.5 eVs each (i.e.,1/36th of the initial longitudinal emittance of the stack). In the second scenario, the longitudinal emittance of the anti-proton stack is assumed to be in excess of 54 eVs. This method allows us to extract 36 bunches with longitudinal emittance ≤1.5 eVs bunches to the Main Injector and trap the unused high momentum particles in a separate bucket.

All RF manipulations in the Recycler are performed using rectangular barrier buckets. The maximum available RF voltage is 2kV. Table I lists the Recycler machine and beam parameters used in the simulations.

Table I: The Recycler machine parameters.

Parameters	**Values**
Mean Radius of the Recycler	528.3019 meters
Nominal γ_T	19.9678
Beam Energy E_0 (Momentum)	8.938 GeV (8.889 GeV/c)
Maximum RF voltage for the barrier buckets	2 kV
Slip Factor η	-0.0085
Revolution Period T_0 Revolution Frequency f_0	11.13 μsec 89.812 kHz
Length of the cooled barrier bucket	≈ 1.6 μsec,
Longitudinal Emittance With Stochastic cooling With electron cooling	 ≈100 eVs@200E10 ≤54 eVs@620E10[A]
Required Longitudinal Emittance at Extraction	≤1.5 eVs /2.5 MHz bunch

[A]The Run II upgrade plan [1] anticipates the final antiproton bunch intensity at collision point in the Tevatron to be 130E9/bunch. By taking into account the acceleration and transfer efficiencies, the initial anti-proton bunch intensity at the time of extraction from the Recycler is estimated to be about 170E9/bunch (David McGinnis, private communications, September 2003)

A. Antiproton Stack ≤54 eVs:

At the start of unstacking process, the length of the cold antiproton stack distribution is established by the requirements of stochastic /electron cooling system. If the beam is in one or several segments they will be merged and beam is stretched to about 8.5 μsec (450 buckets of 53MHz type) adiabatically in about 50 sec. Figure 3A shows the phase-space distribution of the stretched distributions of the antiprotons. The dotted lines show the barrier bucket boundary. The azimuthal projection and the energy spectrum of the antiproton distribution are shown in Figure 3B and 3C, respectively. The predicted energy spread and rms spread are about 3.2 MeV and 1.37 MeV, respectively. After the stretched beam distribution reaches equilibrium, nine equally spaced back-to-back barrier buckets with 950 nsec width each are developed adiabatically to make nine bunches of equal intensity. The emittance of each bunch will be ≤6 eVs (like the first eight bunches in Figure 4A). The amount of final stretch (see Figure 3A) depends on the choice of the size of barrier buckets to be used to divide the stack into nine equal parts. The minimum area of each bucket should be larger than 1/9th of the total beam area of the stretched distribution to get nine bunches.

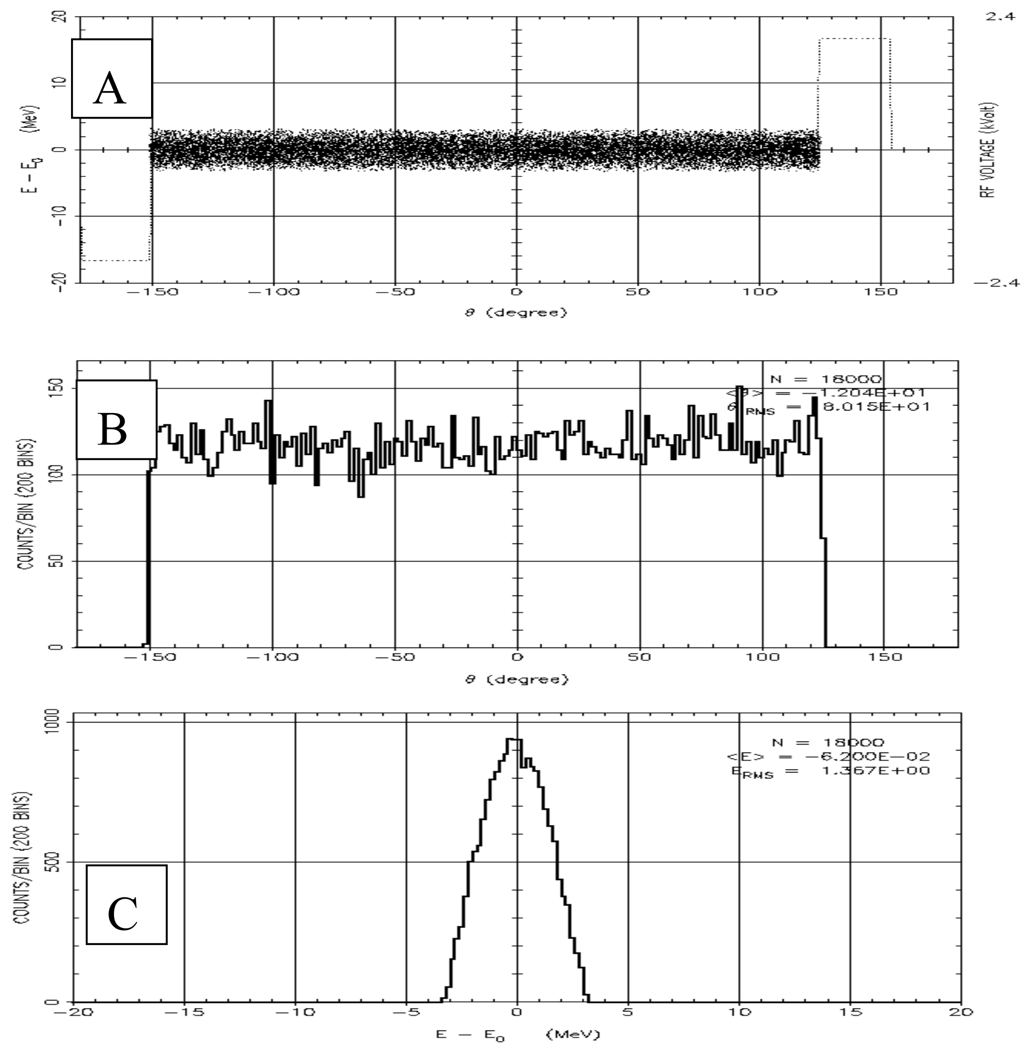

Figure 3: ESME simulations for (A) ($\Delta E, \Delta\theta$) distribution of 54 eVs antiprotons in the Recycler stretched to about 8.5 μsec, (B) θ- projection for the distribution shown in "A". (C) The predicted energy spectrum of the beam particles.

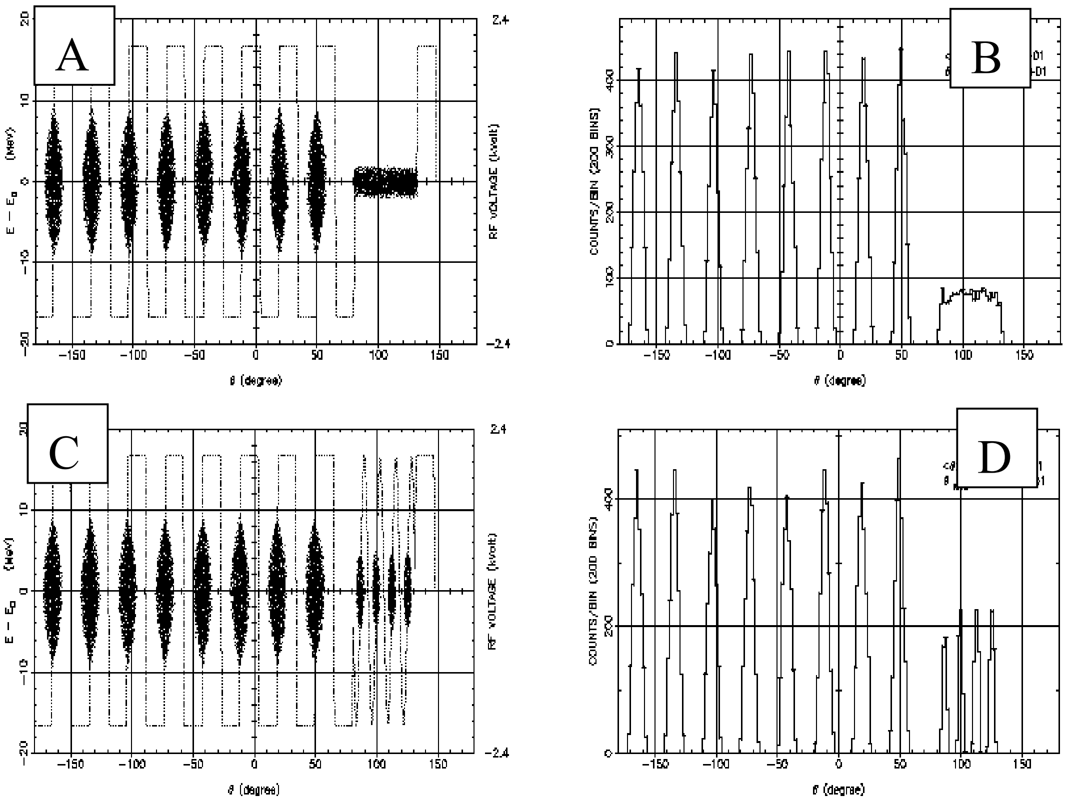

Figure 4: Simulated phase space distribution of the beam particles at different stages of unstacking (A) nine 6 eVs bunches with the ninth bunch in the extraction region and after growing it by 1.6μsec (B) θ projection of "A", (C) after growing four 2.5 MHz bunches for injection to the MI for collider shots (D) θ projection of "C".

Once the nine bunches are formed, the barrier bucket used for confining the initial beam distribution shown in Figure 3A (two pulses of 2 kV height and about 0.906 μsec wide each) is turned off. This helps us to provide extra azimuthal space in the Recycler for further RF manipulations for beam extraction. At this stage, the last bunch will be moved slowly to extraction region and is stretched by 1.6 μsec to develop four 2.5MHz buckets iso-adiabatically as shown in Figure 4. The total azimuthal length required for the beam extraction is about 2.45 μsec which includes the kicker rise time and fall time. By repeated application of this method we can divide a 54 eVs distribution into thirty-six equal parts of 1.5 eVs bunches in about 492 seconds.

Table II. Time required for various RF manipulations for unstacking the beam with ≤54 eVs in equal nine parts and ready for transfer to the Main Injector for Tevatron collider operation.

Description of RF Manipulations	**Time in sec**
Adiabatic slicing of the original beam distribution	
Growing 1.6μsec wide distribution to 8.5μsec wide distribution	50
Slicing the distribution into nine equal parts	10
Total time	**60**
Preparation for final antiproton transfer to the Tevatron	
Cogging the 9th distribution to extraction region	10
Stretching the 9th distribution by 1.6μsec	20
Growing four 2.5MHz bunches adiabatically	8
Cogging rest of the eight bunches in the barrier buckets to as close to the extraction region as possible	10
Total time (this will be repeated nine times per Tevatron store)	**48**

The time required for various stages of the RF manipulation for this scenario are listed in Table II. The time required for preparing nine equal parts from the initial cooled beam is about 60 sec which will be performed once per Tevatron store. Each of the subsequent steps of preparing 2.5 MHz bunches need about 48 sec and will be repeated nine times for one Tevatron store.

It should be noted that, in practice, the beam particles in back-to-back barrier buckets shown in Figure 4 have very large synchrotron frequency and are less prone to external disturbances. On the other hand, the stretched beam distribution (i.e., 8.5 μsec long) shown in Figure 3, is prone to disturbances like MI magnet HEP ramps. The simulation carried out here does not take into account any such external disturbances.

B. Antiproton Stack with Longitudinal Emittance >54 eVs:

Extracting 36 bunches of antiprotons at 1.5 eVs each from a stack with longitudinal emittance larger than 54 eVs is a little bit more complicated. In this case, the cooled beam distribution is stretched to the maximum available length around the ring while allowing gaps for beam extraction. The optimum length for this distribution is found to be about 8.68 μsec.

Figures 5-8 display the simulated anti-proton distributions in *(ΔE,Δθ)*-phase space for all beam RF manipulations corresponding to the initial longitudinal emittance of 100 eVs. After stretching the distribution (see Figure 5A), a pair of RF pulses are developed as shown in Figure 5B. The RF pulse heights are chosen to be about 0.7 kV. The RF pulse on the left side is moved adiabatically to shovel low momentum particles to the right side of the distributions as shown Figure 5C. In this configuration, the low momentum particles are confined to about 6.14 μsec and only the high momentum particles will be executing synchrotron oscillations in the entire 8.68 μsec. The minimum synchrotron oscillation period for the particles for the beam distribution in 5A is about 3 sec. We have allowed about 25 sec to go from distribution 5B to 5C. Subsequently, nine 6 eVs buckets are opened as shown in Figure 6A. The RF pulse width and heights for these buckets is selected to be 340 nsec and about 0.7 kV, respectively. The nine barrier buckets will occupy about 6.14 μsec of the Recycler circumference. After holding the distributions for 10 sec the barrier pulses used for shoveling the low momentum particles are turned off in 5 sec. Now a bigger barrier bucket is opened slowly with total bucket area of 46 eVs (pulse height =0.9 kV and width =1.27 μsec). This bucket is intended to trap the high momentum particles which can not be captured by the other nine barrier buckets of smaller bucket area. The simulation results shown in Figure 6C indicate that the phase space distribution of the high momentum particles is quite uniform. The time required for trapping high momentum particles is about 5 sec.

After capturing the high momentum particles in the big bucket, the heights for all buckets have been increased simultaneously to 2 kV. The area of the fully grown buckets used for low momentum particles is about 10 eVs and the half bucket height is about 11 MeV, whereas the area of the bucket reserved for trapping the high momentum particles is about 72 eVs and the bucket height is about 21.6 MeV, well below the design momentum acceptance of the Recycler, 1% [2]. The rest of the beam extraction process shown in Figures 7 and 8 are almost identical to the one described in section IIIA. These sequences of RF manipulations guarantee the selection of low momentum particles for collider operation and high momentum particles to be retained in the Recycler for later cooling and use.

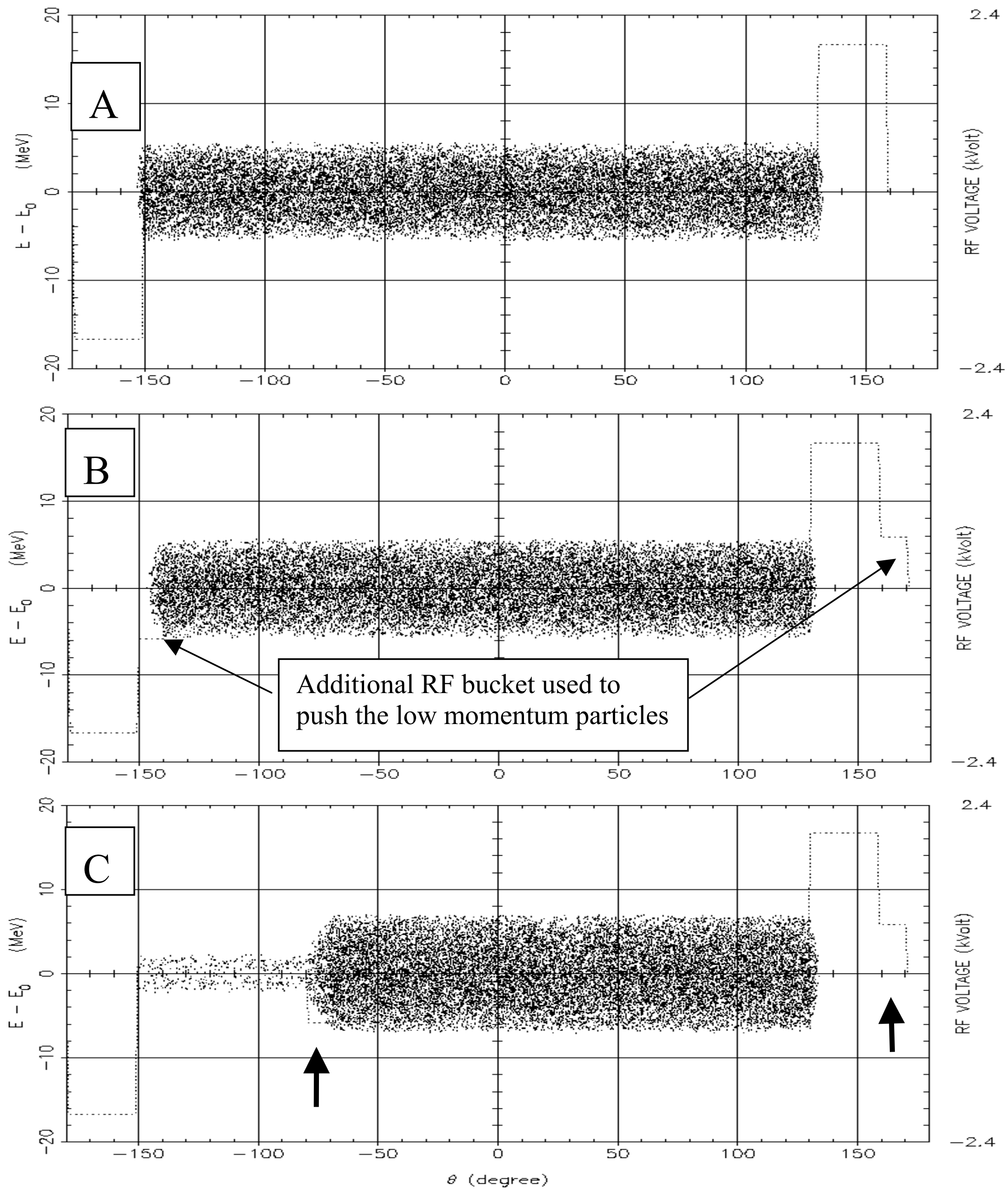

Figure 5: The simulated distribution of 100 eVs anti-protons (A) Stretched to 8.68 μsec. (B) Growing an additional bucket to push the low momentum particles to region of interest in the barrier bucket, (C) After all low momentum particles migrate to the region of interest. The final locations of the smaller rf pulses are indicated by arrows. For other details see caption for Figure 3.

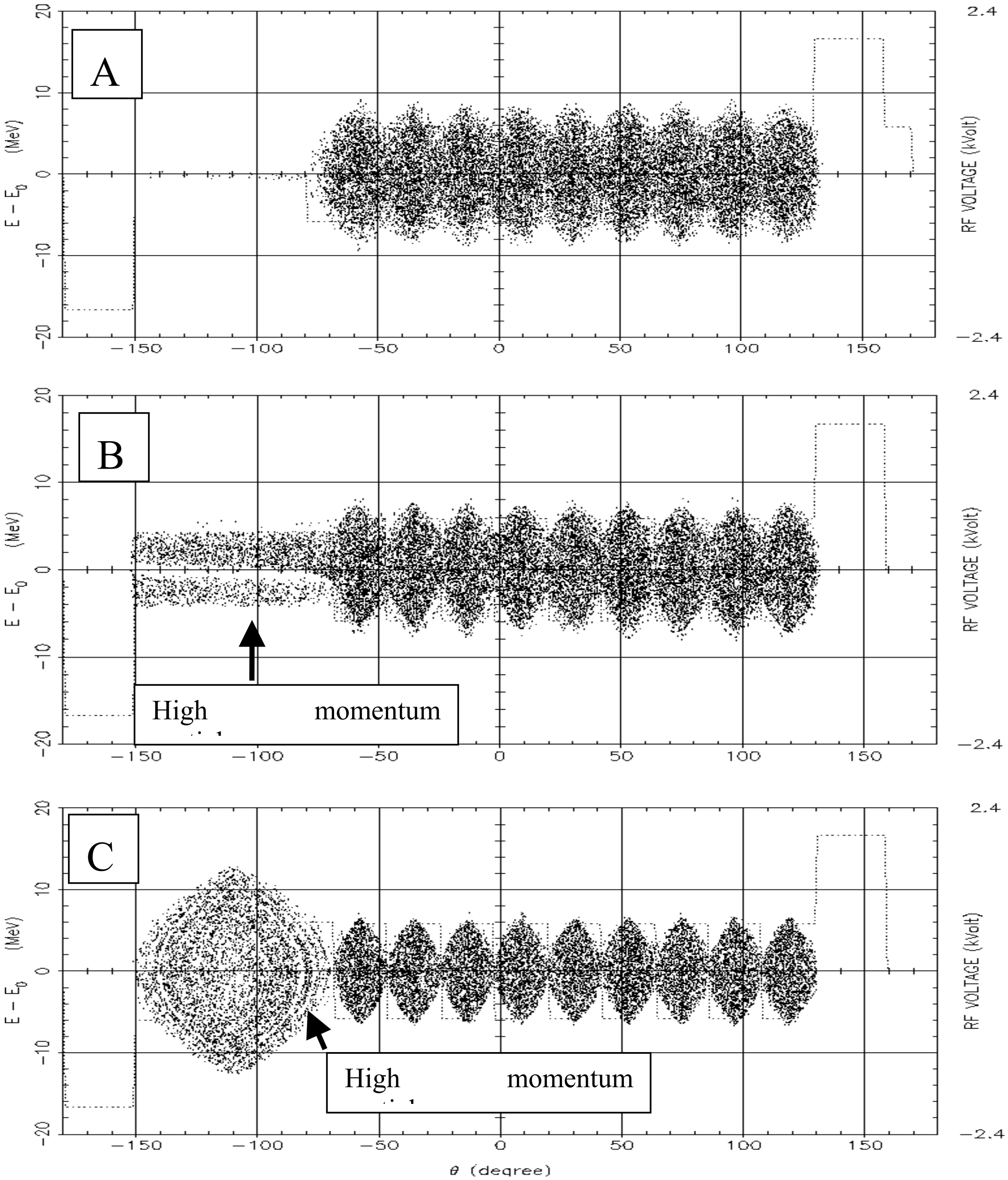

Figure 6: Continuation of RF manipulation from Figure 5. (A) After adiabatic beam capture in nine 6 eVs bunches. (B) After removing the barriers indicated in Figures 5B and 5C, (C) after opening the barrier for capturing the high momentum particles. For other details see caption for Figure 3.

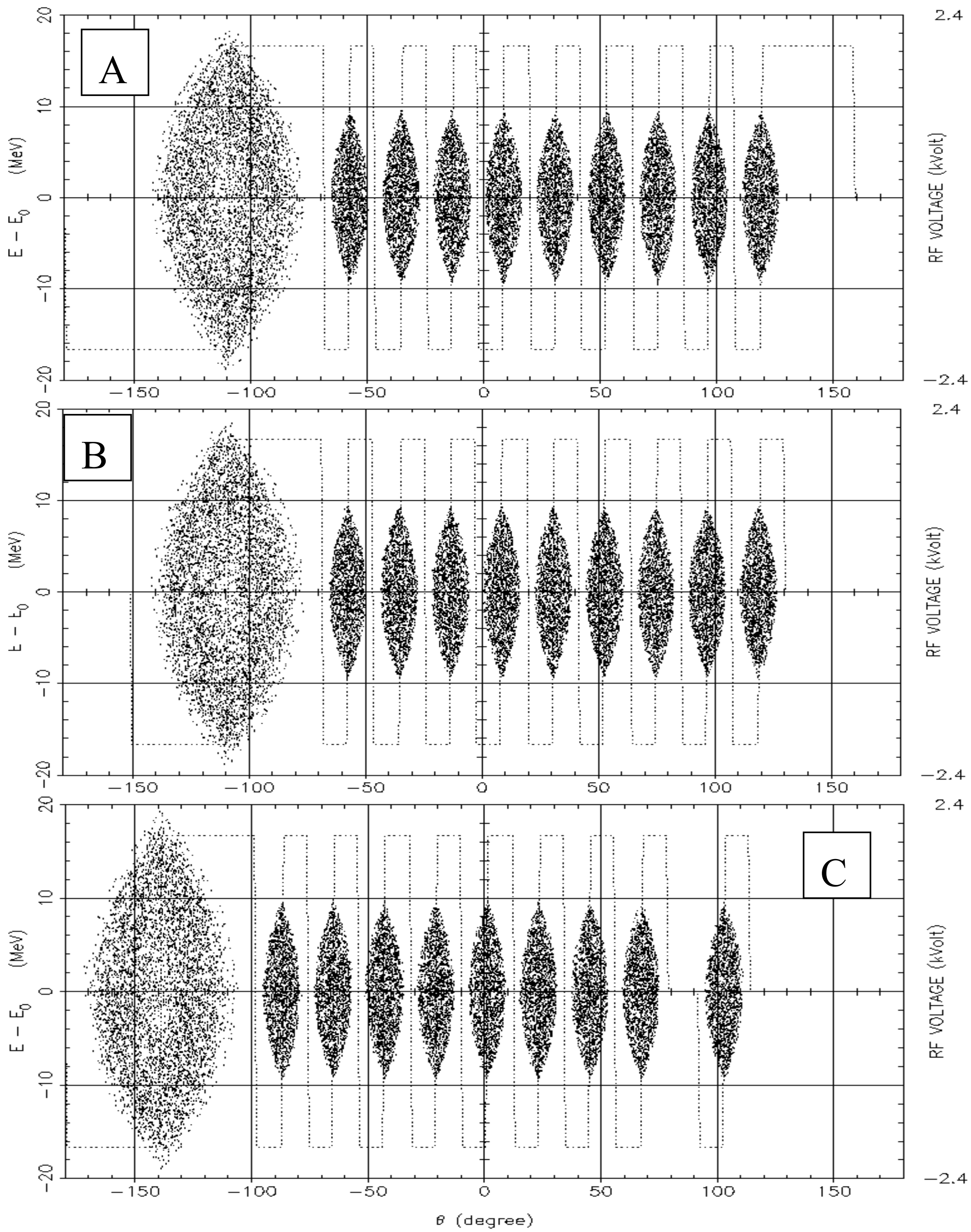

Figure 7: Continuation of RF manipulation from Figure 6. (A) After increasing the bucket area containing 6 eVs anti-protons and high momentum anti-protons to their full values (B) After removing the barriers bounding the initial beam distributions shown in Figure 5A. (C) After bringing the 9th bunch to extraction region keeping the remaining undisturbed. For other details see caption for Figure 3.

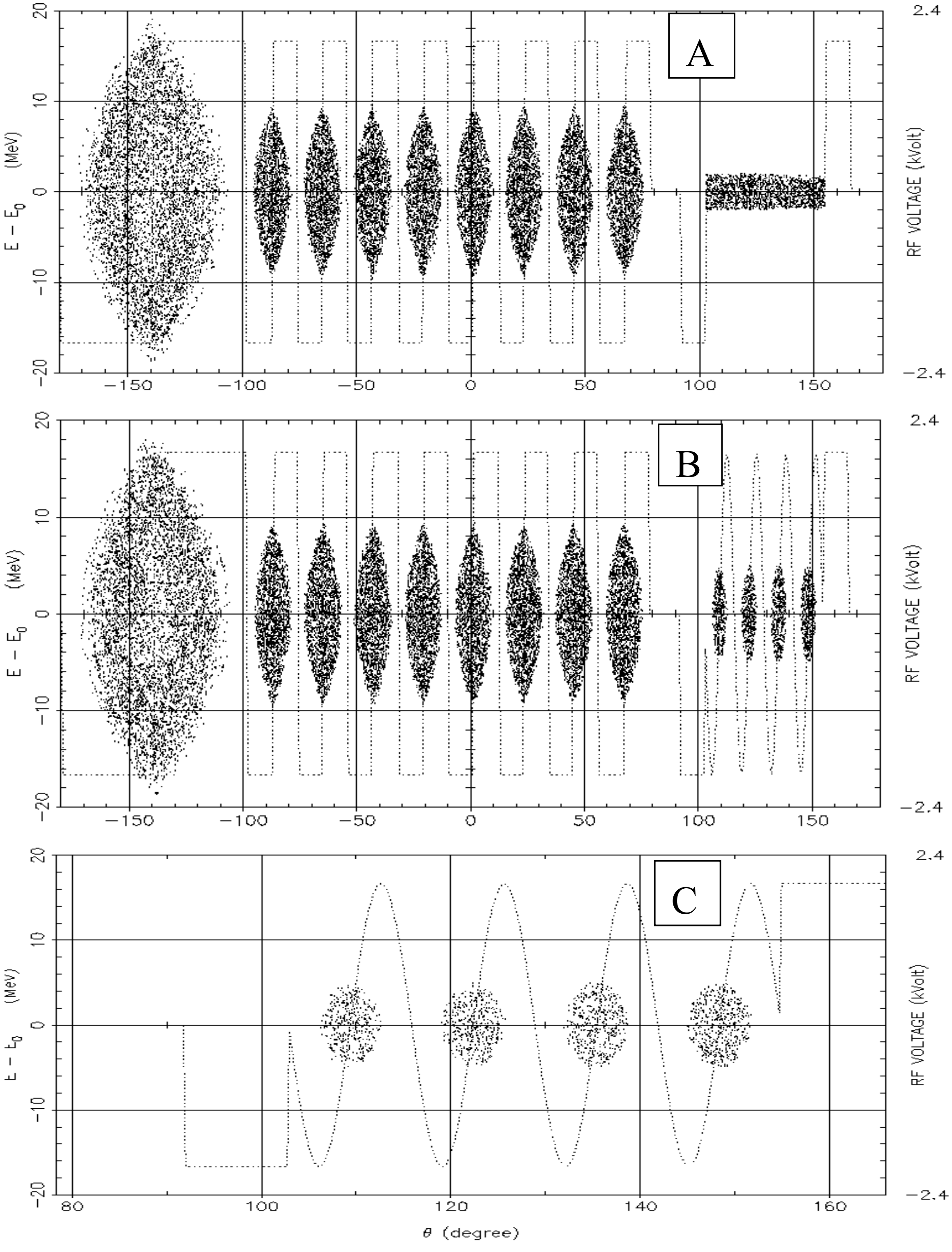

Figure 8: (A)After growing the transfer bucket, (B) producing the 2.5MHz bunches. (C) four 2.5MHz bunches of 1.5 eVs each in the transfer region. For other details see caption for Figure 3.

Table III. The time interval for RF manipulations for unstacking 1.5 eVs bunches from 100 eVs anti-proton stack.

Description of RF Manipulations	**Time in sec**
Adiabatic slicing of the original beam distribution	
Stretching 1.6μsec wide distribution to 8.68μsec wide distribution	90
Shovel low momentum particles	15
Slicing the distribution into nine equal parts	10
Trap high momentum particles	5
Increase barrier RF voltages to 2 kV	4
Time required for reaching equilibrium	28
Total time	**152**
Preparation for final antiproton transfer to the Tevatron	
Cogging the last distribution to extraction region	10
Stretching the last distribution by 1.6μsec	20
Growing four 2.5MHz bunches adiabatically	8
Cogging rest of the eight bunches	10
Total time (this will be repeated nine times per Tevatron store)	**48**

Table III lists the time taken for each of the processes described here. Care was taken to perform isoadiabatically every stage of the RF manipulation in the simulation. The time required for the momentum mining is about 152 sec. The rest of the RF manipulations take same amount of time as in the case of 54 eVs beam stack.

These simulations are not limited to the final 2.5 MHz bunches of 1.5 eVs emittance each. For example, if we want to inject 2.5 MHz bunches of 1 eVs each to the Main Injector, then one needs to open nine barrier buckets of 4 eVs each and trap the high momentum particles in a bucket using similar RF manipulations shown in Figures 5-8. In this case, the presently used bucket sizes many not be optimal.

IV Beam Studies

Experiment has been carried out to investigate the method developed in Section III using protons in the Recycler. The existing Recycler RF system [11,12] is quite adequate to do the beam experiment. The Recycler LLRF [12] has eight independently controllable arbitrary wave generators (ARB) which can be fed with different RF wave-forms. I used seven of the eight ARBs in our experiment (one of them is reserved as beam injection and extraction synchronization marker). Each ARB is 256 channels wide (with bin width of 18.935 nsec/channel i.e., a 53 MHz bucket long).

About 170E10 protons of longitudinal emittance ~130 eVs are injected into a rectangular barrier bucket of width 3 μsec and a total bucket area of about 158 eVs. The goal of the experiment was to mine 54 eVs low momentum protons out of the main stack into nine 6 eVs bunches of equal intensity and capture the remainder in a bigger bucket. Then, slice a 6 eVs bunch into four bunches of 1.5 eVs each with equal intensity in a designated extraction region.

The procedure adopted here for momentum mining is essentially the same as that described in Section IIIB. The initial distribution has been stretched by about 8.67 μsec in about 75 sec adiabatically using "slow" cog rate[i] of LLRF controls [12]. Subsequently, two RF barrier pulses are developed to populate the low momentum particles to one side of the distribution. Fifty seconds later, nine barrier buckets of bucket area of 6 eVs each were opened by raising the barrier pulse height to about 0.7 kV at nearly logarithmic rate in about 5 sec. The barriers used to isolate the low momentum particles are turned off after 5 sec and a 2.5 μsec wide barrier bucket of pulse height 1 kV was developed to trap the rest of the beam. The area of this bucket was chosen to be about 56 eVs. Once all the protons were trapped in the barrier buckets (in approximately 20 sec) the pulse heights for all barrier buckets were raised to 2kV in about 3 sec. To transfer the beam to the Tevatron each of the 6 eVs bunches was pulled to extraction region and stretched further adiabatically in about 20 sec and four 2.5MHz bunches were produced.

The wall current monitor data for the initial and stretched beam particle distribution (bottom trace) and the corresponding RF wave form (top trace) are shown in

[i] The present Recycler LLRF control system allows three different cog-rates for RF manipulations: "slow", "medium" and "fast" rates, respectively corresponding to about 2.74 deg, 8.08 deg and 5100 deg phase slippage /sec. Note that total phase slippage per revolution is 360 deg.

Figures 9A and B. (Note that the wall current monitor data and the rf wave forms shown in figures do not align with each other, because, there is about 300 nsec delay between these two traces which is an artifact of cable delay). Figure 10A shows the data after momentum mining the low emittance beam in nine buckets and the rest in one bucket. The final stage of splitting of 9th bunch into four 2.5MHz bunches is shown in Figure 10B.

Table IV: The results of emittance and intensity measurements for the data shown in Figure 9.

Description	**Bunch**	**97.5% Bunch Length (nsec)**	**95% Longitudinal Emittance (eVs)** [A]	**Beam Intensity (x E10)**
Beam before Unstacking Bunch length before stretching		3070(barrier spacing) 630(left penetration) 750(right penetration)	127±13	170±4
Beam After momentum mining				
Bucket with high momentum particles	1	2470	71±7	58±2
Buckets with low momentum particles (average for nine bunches)	1-9	535±26	7.2±0.6/bunch	12.4±0.3/bumch
		Total	**136**±7	**170**±4
Beam in transfer Region				
2.5MHz Bunches	1-4	260±20	2.3±0.2	3.1±0.1

[A] The overall error in the measurement is ≈20% for the beam in stretched distribution and ≈10% for the beam in back-to-back barrier buckets and in the 2.5MHz buckets.

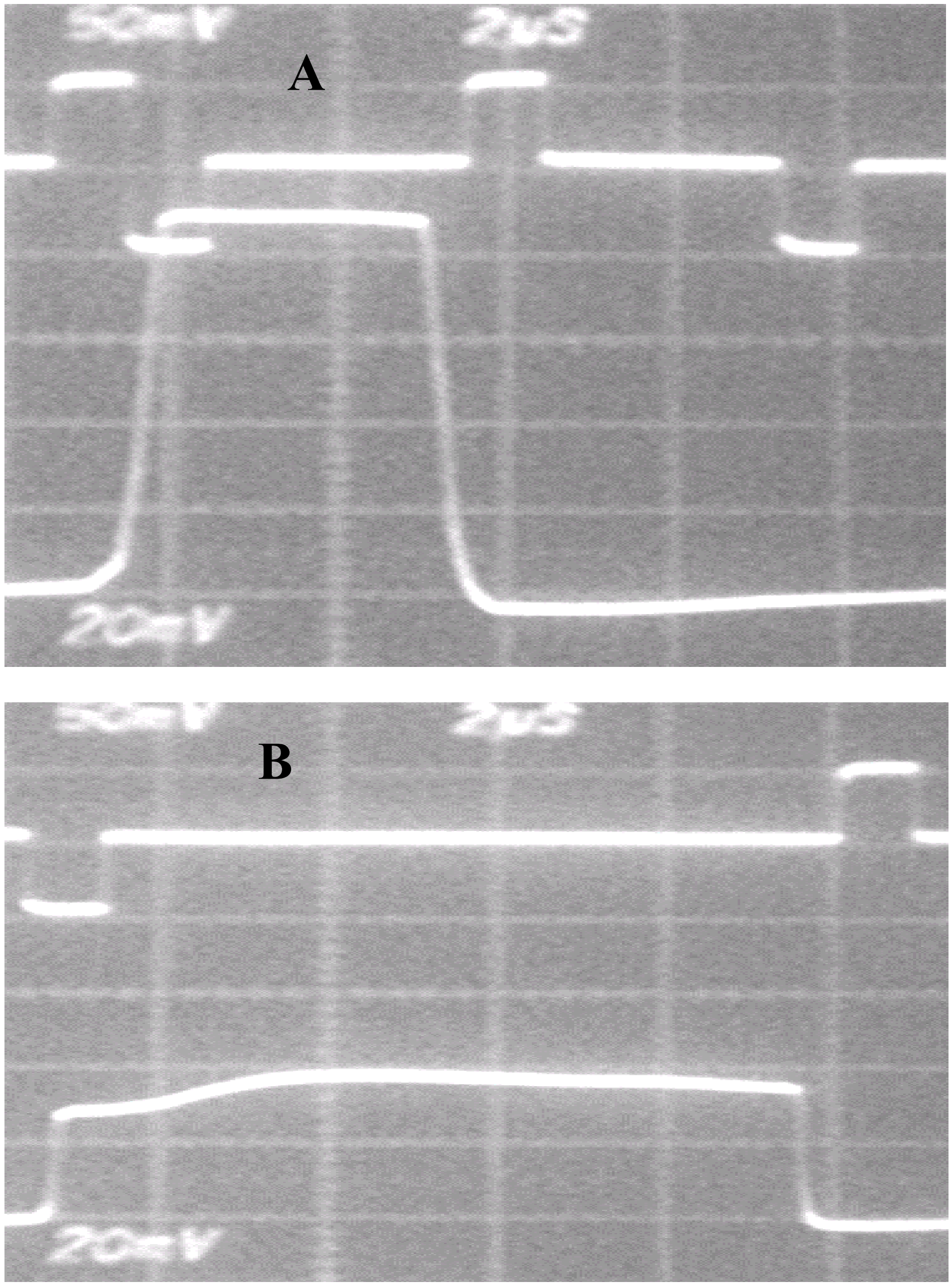

Figure 9: Fan-back signals for barrier bucket wave forms (top traces) and the corresponding line-charge beam distributions measured using a wall current monitor in the Recycler for, (A) initial, 3 μsec long distribution. (B) after stretching the distribution to 8.67 μsec.

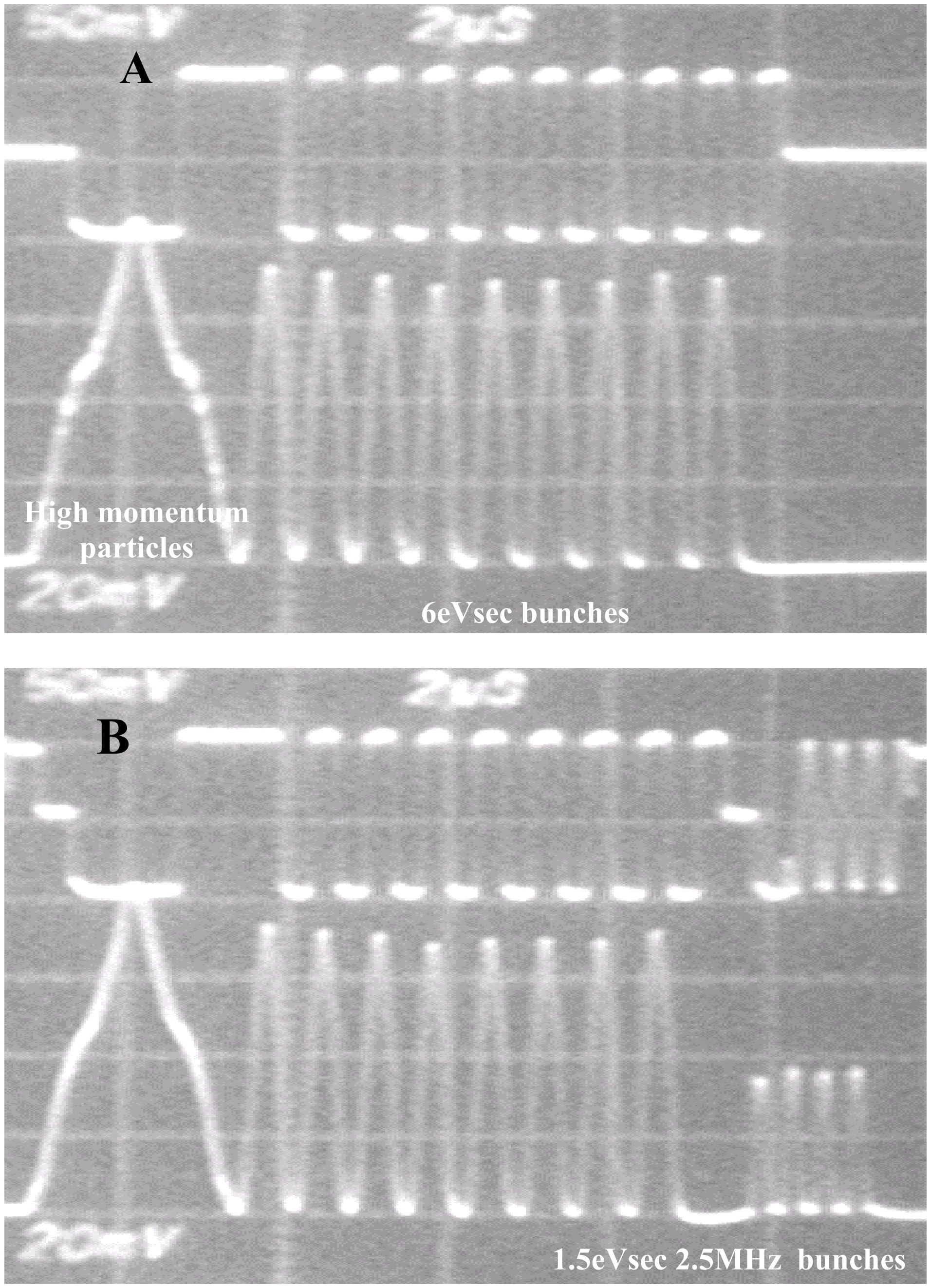

Figure 10: Continuation from Figure 9. (A) After momentum mining. The first bunch from the left is formed out of high momentum particles of the original stack. The next nine bunches are made of low momentum particles. (B) After forming 2.5MHz bunches from the 9th bunch from distribution "B". At this stage the 2.5MHz bunches are in extraction region.

The measured longitudinal emittance and the relative bunch intensities are listed in Table IV. The errors on the longitudinal emittance listed in the table are mainly from the uncertainties in estimating beam penetration in the rectangular barrier pulses. The other sources of errors which are not accounted for in Table IV come from, 1) assuming ideal rectangular RF barrier wave form in calculating the longitudinal emittance using the formulae given in section II. The RF wave forms used here are not perfect rectangular barrier pulses. 2) The amplitude of the RF voltage V_{rf} is not known to better than about 5% at 2kV and the uncertainty is larger at lower amplitudes and 3) the Recycler lattice parameters. Therefore, we assign about 20% error in the final measured emittance. However, the measured emittances at different stages of the RF manipulation give information about relative emittance growth if any is seen.

The data show that within the measuremental errors we see little longitudinal emittance dilution throughout the momentum mining carried out here. For example, from the initial distribution (with emittance of 127±13 eVs) to the end of creating nine smaller bunches for low momentum particles and one larger bunch for high momentum particles (with total emittance of 136±7 eVs), we do not observe emittance growth. However, from the measurement results shown in Table IV, we see that 7.2±0.6 eVs/bunch and 2.3±0.2 eVs/2.5MHz bunch, instead of 6 eVs/bunch and 1.5 eVs/2.5MHz bunch, respectively. Thus, we ended up with about 20% and 50% larger emittance than we intended to get. This longitudinal emittance growth seen in the experiment is attributed to two known reasons. The first one is the effect of the Main Injector high energy acceleration ramps on the longitudinal emittance of the Recycler beam. During this experiment, the Main Injector magnets were ramping to provide beam to the Tevatron and to the Anti-proton production facility. We had only partially commissioned Main Injector ramp correction system in the Recycler. This contributed significantly to the longitudinal emittance growth for the beam in the barrier buckets and in the 2.5MHz buckets. The second reason is that in the present barrier RF system of the Recycler Ring, the base-line between any barriers is not perfectly at zero voltage. We found that even 1% variation is sufficient to produce significant distortion in the line-charge distribution. Further, the higher order Fourier components [13] and potential well distortion due to beam loading effects seen recently [14], contribute to further emittance dilution.

IV Summary

I have proposed here a novel method for selectively isolating low momentum particles and extracting equal longitudinal emittance beam out of a Recycler anti-proton stack. First, I illustrated the scheme using multi-particle beam dynamics simulations. I have also carried out beam experiments in the Recycler using protons to demonstrate the technique. I was able to do momentum mining and capture the low momentum particles in nine barrier buckets. The high momentum particles were captured in a separate barrier bucket for future use. Further, I demonstrated the method of slicing each 6 eVs bunch into four 2.5MHz buckets. Very recently this method is successfully used in the Recycler on anti-proton stack for collider operation at the Tevatron.

The method proposed here can be easily generalized to different initial longitudinal emittance and needs. With modifications in the initial RF barrier pulses, we can populate different amount of emittances in different buckets and use them accordingly.

We plan to use momentum mining method at the Fermilab Recycler in future proton anti-proton collider operation.

I would like to thank John Marriner for many useful discussions and Pushpa Bhat for many valuable suggestions. Thanks are also due to Brian Chase for his help in LLRF issues and Jim MacLachlan for his help in issues related to multi-particle beam dynamics simulations.

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