Pbar Acceleration in the Main Injector
RR/AR → MI → Tevatron

Simulations and Tune up Studies Using Protons

Chandra Bhat,

Main Injector Department, Beams Division, Fermilab

(11/02/2000)

MI Note 268

ABSTRACT

I discuss here both simulation and experimental studies of a potentially beneficial acceleration scheme in the MI for pbars from the Accumulator Ring and Recycler Ring. The scheme involves accepting the pbars bunches with 2.5 MHz rf structure from either of these two storage rings, re-bunching using 53 MHz rf system and accelerating using 53 MHz rf system. Various stages of rf manipulation are discussed and some improvements are suggested.

1. Introduction

Presently the collider Run-II is scheduled to start in March 2001. The initial goal of this run is to achieve ppbar instantaneous luminosity of $5\times10^{31}cm^{-2}sec^{-1}$ and an integrated luminosity of $2fb^{-1}$ in the Tevatron[1]. During the collider run the pbars will be extracted from the Accumulator Ring (AR) and transferred to the newly built Main Injector (MI) [2] and accelerated from 8 GeV to 150 GeV. The advent of the Recycler Ring (RR)[3], a new pbar storage ring, will facilitate in the accumulation of about two and half times more pbars and boost the ability of the Tevatron to provide more luminosity to the collider detectors. The ultimate goal is to achieve $1\times10^{33}cm^{-2}sec^{-1}$ (Tev33) with electron cooling installed in the RR. In any case, reaching these goals primarily depend on how well intense bunches of antiprotons (and protons) are accelerated in the MI without beam loss and/or emittance growth.

Over the years, we have developed a few different schemes of pbar acceleration in the MI. Each one of them have been studied in some detail theoretically, some of them experimentally, as well. Longitudinal beam dynamics simulation code ESME[4] (which, recently has been improved significantly) enabled us to follow every stage of the acceleration process. The four methods of pbar acceleration schemes developed are listed below. In each scheme, the beam will be transferred to the Tevatron.

1. Transfer the pbars from AR to MI into the matched 53 MHz rf buckets, accelerate them to 150 GeV and coalesce [5].

2. Transfer the pbars from AR/RR to MI in 2.5 MHz rf buckets and bunch adiabatically in 53 MHz rf buckets in MI, accelerate them to 150 GeV and coalesce.
3. (a) Transfer four bunches of pbars from AR/RR to MI in 2.5 MHz rf buckets, (b) Accelerate to 25 GeV using 2.5 MHz rf system, (c) Rotate the bunches at 25 GeV, (d) Transfer to 53 MHz rf buckets and (e) Finally accelerate further using 53 MHz rf system [3,6].
4. (a) Transfer the pbars from AR/RR to MI in 2.5 MHz rf buckets, (b) Bunch adiabatically in 53 MHz rf buckets, (c) Accelerate them to ~35 GeV, (d) Debunch the 53 MHz bunches adiabatically in to 2.5 MHz rf buckets, (e) Rotate the bunch in 2.5 MHz bucket and capture in 53 MHz rf buckets, and (f) Accelerate to 150 GeV [7].

A method similar to the first scheme mentioned above was extensively used during the collider Run-I [5]. In that scheme, a bunch of pbars was extracted from the core of pbar stack in AR using ARF2, h = 2 rf system with one of the buckets suppressed. Such a bunch was further re-bunched using ARF1, h=84 rf system before extraction. The beam was then transferred to MR 53 MHz rf buckets. The beam was accelerated in the Main Ring from 8 GeV to 150 GeV and coalesced at 150 GeV into one bunch before injecting into the Tevatron. The coalesced pbar bunches are found to have an average longitudinal emittance of about 3 eV-sec [5]. Nevertheless, this method of pbar coalescing was adopted throughout Run-I.

For Run II, we have a significantly higher luminosity demand than was for Run-I. The method adopted for pbar bunch preparation in Run–I was too slow and is not adequate for Run-II. Here, we need to

(a) extract more number of pbar bunches from the pbar stack at a given time.
(b) the pbar longitudinal emittance requirement in Tevatron is <2eV-sec.
(c) inject 36 (or more) number of pbar bunches into the Tevatron per collider store.

Hence, modification were made in the AR to extract four bunches of pbars using ARF4, h=4 system (2.5 MHz rf system). Also, built a new pbar storage ring, RR in the MI enclosure. During the RR era, the cooled pbars from the AR will be transferred to RR very often. Besides, we plan to recycle the unused pbars in the Tevatron and add to the already built pbar stacks. Thus, RR will be used as the main storage ring for pbars. As and when the pbars are needed by the Tevatron for collider operation, the cooled pbar beam from the RR will be extracted to MI in four bunches (of 2.5 MHz type) and accelerated to 150 GeV before injection into the Tevatron. The extracted beam from RR will have 2.5 MHz rf structure. At present, the MI has the ability to capture pbar bunches with 2.5 MHz rf structure at 8 GeV, but, can not accelerate the bunches in 2.5 MHz rf system directly. Only the way to accelerate the beam in MI is by using 53 MHz rf system. Notice that the function of the MI is the same irrespective of the origin of the pbars, either from the RR or from the AR.

In this paper, we discuss in detail the results from theoretical as well as experimental studies carried out on the second scheme mentioned above. The emphasis will be given to the limitation of this method. The experimental studies are done with protons from the Booster. The theoretical studies were carried out using ESME. Note that in this scenario the 2.5 MHz rf system is not only used for bunch coalescing at 150 GeV but also used for 8 GeV beam capture. The 8 GeV front-porch is made 2-3 sec long to accommodate all rf manipulations.

2. ESME Calculations

The scheme for pbar acceleration that I wish to discuss has several stages of rf manipulations : (a) a group of four pbar bunchs of 2.5 MHz rf structure is transferred to MI to a matched rf buckets, (b) each bunch is re-bunched into 7-11 bunches with 53 MHz rf structure, (c) the beam is accelerated to 150 GeV, (d) the bunches are coalesced in to a group of four bunches and transferred to the Tevatron. The longitudinal emittance of the pbar beam in 2.5 MHz rf bucket at injection is in the range of 0.5 eV-sec to 1.5 eV-sec; the beam from the AR can be as small as 0.5 eV-sec while that from the RR is about 1.5 eV-sec[3]. I have performed full scale ESME calculations for both extreme scenarios. The results are presented below.

The MI parameters used in the calculations are displayed in Table I. The accelerator is designed to have a maximum dp/dt of ≈270 GeV/c/sec. At present, the accelerator uses dp/dt ≈220 GeV/c/sec near transition for 8-150 GeV pbar acceleration ramps. For purpose of calculation, we assume MI ring with an average radius of 528.309 meters.

Table I: MI parameters used in the ESME calculations

Parameters		**Units**
Mean Radius of the MI Ring (R)	528.3019	M
Transition γ	21.836	
dp/dt (Transition)	~220	GeV/c/sec
α	0.002091	
Accelerating RF System		
Frequency	53	MHz
Maximum Voltage	4	MV
Coalescing RF System -I		
Frequency	2.5	MHz
Voltage	60	kV
System -II		
Frequency	5	MHz
Voltage	15	kV
Beam pipe Radius (min)	5	cm
Broad Band Impedance	3	Ω

The matching RF voltages between AR and MI for 2.5 MHz pbar bunches are shown in Table II. If we assume the ratio of the bunch area to bucket area in AR at the time of extraction to be approximately 4, then the typical bucket area for the 0.6 eV-sec bunch is about 2.4 eV-sec . From Table II we find that the required rf voltage on ARF4 is about 200 V and the 2.5 MHz rf voltage in MI is about 1 kV.

In the case of pbar transfer from RR to MI we need about 2 kV on the 2.5 MHz rf systems in both accelerators.

Figures 1 and 2 show the distributions of beam particles in (θ,ΔE)-space in a 2.5 MHz rf bucket at injection corresponding to longitudinal emittance of 0.6-eV sec from ESME. The code ESME in its present version calculates the 1σ-emittance. The projection of the pbar distributions in a bunch on the θ–axis is also shown for each case. Figures 3 and 4 show similar simulations for the beam with 1.5 eV-sec bunches.

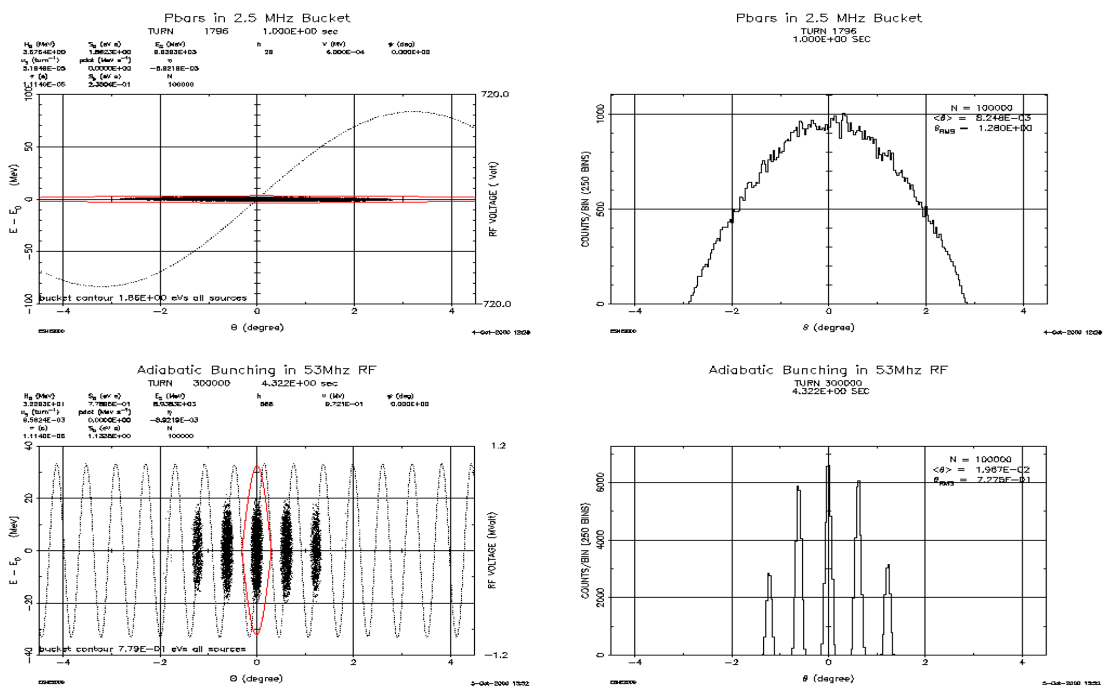
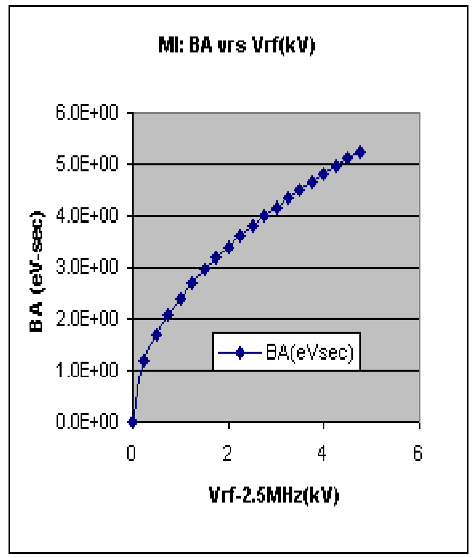


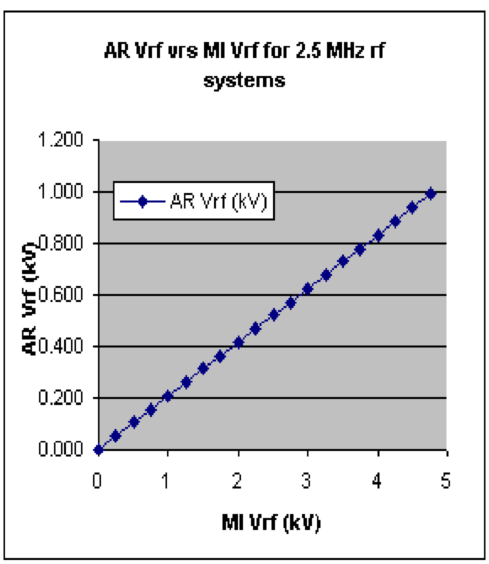
Fig.1 : ESME results for 0.6 eV sec pbars in the MI. First figure (top left) is the phase space distribution at injection. The bunch profile in a 2.5 MHz bucket is shown in top right picture. Bunches in 53 buckets before acceleration are shown in lower left and right pictures. The bucket contours are shown in red which embed the phase space distributions. The rms longitudinal emittance are also indicated. The emittance for the re-bunched distribution (lower left) has to be cautiously interpreted (contact the Author of ESME to clarify)

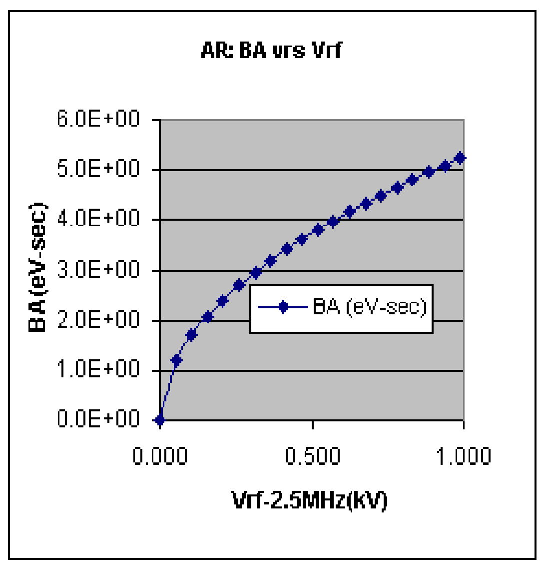
Table II. Matching rf voltage between the Accumulator Ring and the Main Injector during the pbar transfer, assuming 2.5 MHz bunch transfer.

MI to AR Matching with 2.5 MHz RF system

MI Vrf (kV)	BA(eVsec)	AR Vrf (kV)	BA (eV-sec)
0	0.00E+00	0.000	0.00E+00
0.25	1.20E+00	0.052	1.20E+00
0.5	1.70E+00	0.104	1.70E+00
0.75	2.08E+00	0.156	2.08E+00
1	2.40E+00	0.208	2.40E+00
1.25	2.69E+00	0.260	2.69E+00
1.5	2.94E+00	0.312	2.94E+00
1.75	3.18E+00	0.364	3.18E+00
2	3.40E+00	0.416	3.40E+00
2.25	3.60E+00	0.468	3.60E+00
2.5	3.80E+00	0.520	3.80E+00
2.75	3.98E+00	0.572	3.98E+00
3	4.16E+00	0.624	4.16E+00
3.25	4.33E+00	0.677	4.33E+00
3.5	4.50E+00	0.729	4.50E+00
3.75	4.65E+00	0.781	4.65E+00
4	4.81E+00	0.833	4.81E+00
4.25	4.95E+00	0.885	4.95E+00
4.5	5.10E+00	0.937	5.10E+00
4.75	5.24E+00	0.989	5.24E+00







The pbar bunches captured in 2.5 MHz rf buckets are adiabatically re-bunched in 53 MHz rf buckets in about 3.3 sec. The adiabatic re-capture is done in accordance with [10]

$$\frac{dS}{S} = a_c \frac{dT}{T_s} \qquad \cdots(1)$$

Where S and T_s are bucket area and synchrotron oscillation period, respectively. The quantity a_c is the adiabaticity constant. This quantity should be <<1 to keep the emittance growth during the adiabatic re-bunching to be minimal. The synchrotron oscillation period for the pbars in 2.5 MHz rf bucket with Vrf= 2kV is about 8.5Hz at 8 GeV in MI.

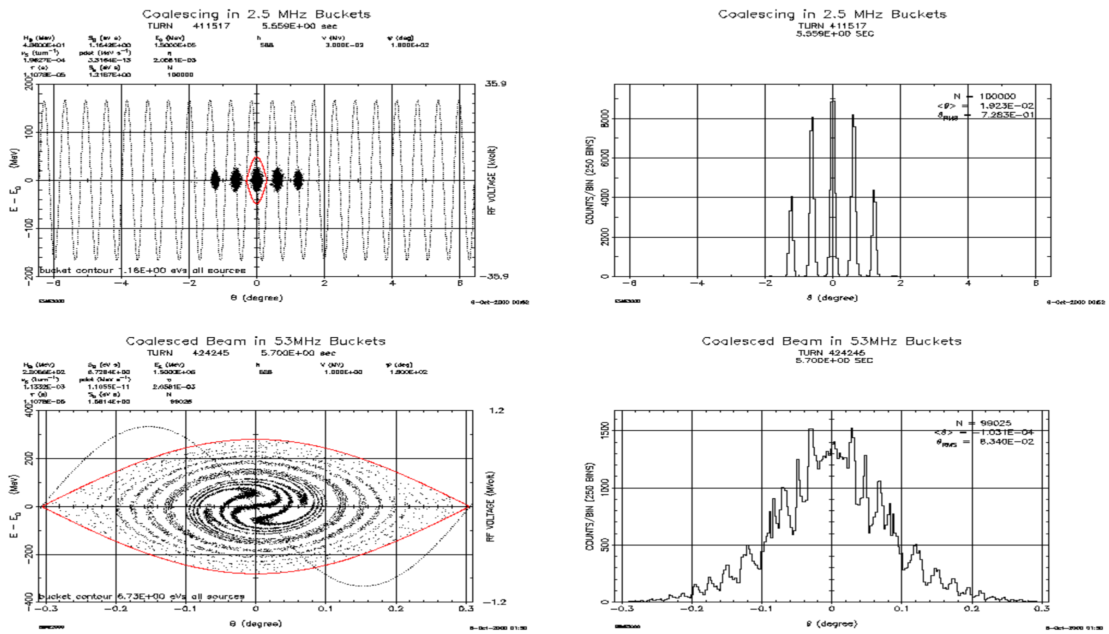


Fig.2 : ESME simulation results for 0.6 eV sec pbars in the MI at 150 GeV before and after coalescing. All of them show beam particles in 53 MHz rf buckets. The coalescing efficiency in this case was about 99% and the 53 MHz rf bucket was almost full. For other details see caption for Figure-1.

The bunches prepared by the method outlined above have to be coalesced at 150 GeV. The coalescing efficiency has a strong dependence on number of pbar bunches in 53 MHz rf buckets generated at 8 GeV as well as individual bunch emittance. Small number (>9 bunches) of low emittance bunches (emittance ~ 0.15 eV-sec) are preferred. To achieve optimum number of 53 MHz bunches with individual emittance <0.15 eV-sec the 2.5 MHz bunches are iso-adiabatically squeezed by raising the 2.5 MHz rf voltage by about a factor of four. This gives rise to a final rms bunch length ~ 40nsec. As a result of this rf manipulation the maximum number of bunches in 53 MHz buckets after re-bunching are 5 (see figure 1) for 0.6 eV-sec bunches and 7 for 1.5 eV-sec bunches (see Fig. 3). The final emittance predicted from ESME are listed in Table III. From the simulations, we expect emittance growth in both cases (up to about 40%). This emittance growth can be controlled by slowing down the re-bunching process.

After re-bunching the beam in 53 MHz rf buckets the bunches are accelerated from 8 GeV to 150 GeV in about 1 sec performing a transition phase jump at 20.49 GeV. At 150 GeV a group of five to seven bunches are coalesced into one bunch.

Figures 2 and 4 show the simulation results for snap coalescing at 150 GeV. The predicted rf voltage for the 53 MHz rf system is shown in Fig. 5. During snap coalescing the bunches in 53 MHz rf buckets are rotated in a quarter of synchrotron oscillation period in a matched bucket (with Vrf ~ 30kV) and put off instantly in a few revolution periods. At the same time the 2.5 MHz rf bucket is opened with about 60-70 kV

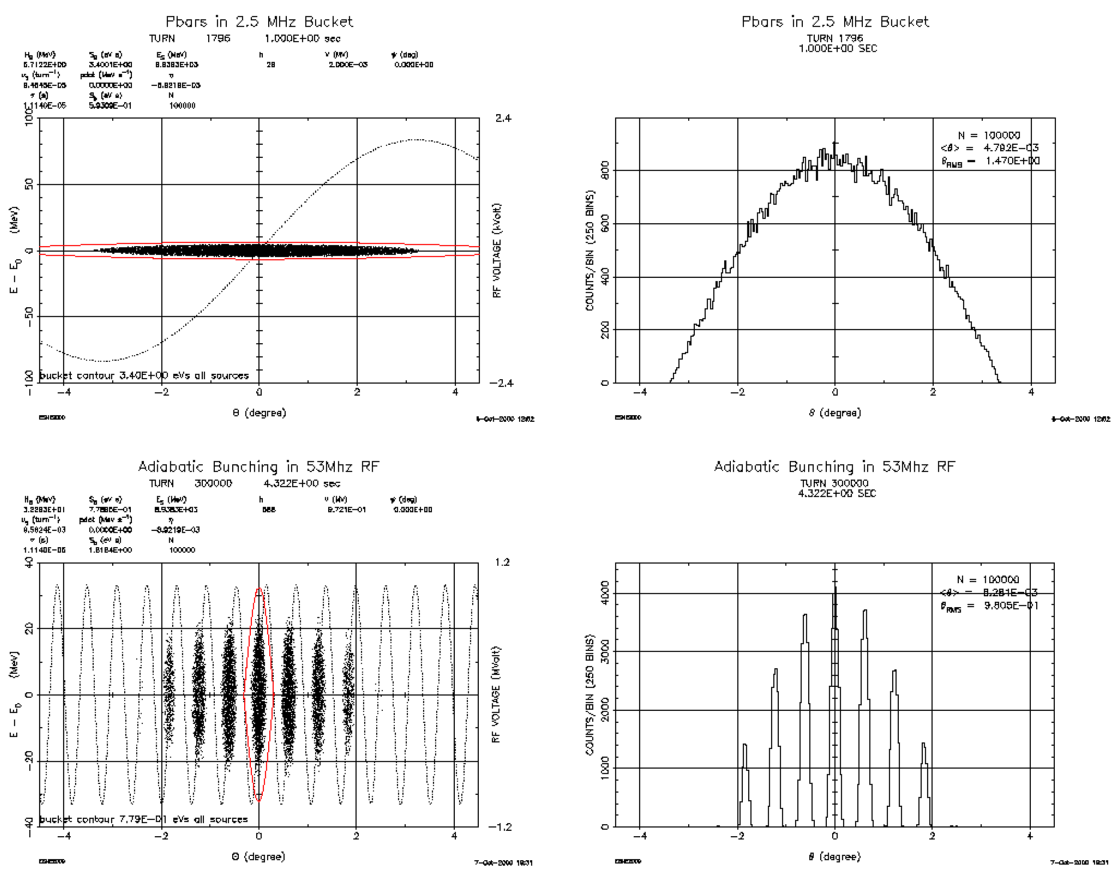


Fig.3 : ESME results for 1.5 eV sec pbars in the MI. The description of the figure is very similar to that of figure 1.

(along with about 14% of 5 MHz rf amplitude to linearize the rf wave around 180 deg phase). This voltage is held for about 50 msec. When the train of bunches are rotated by

90 deg in (θ,ΔE)-space, i.e., when the bunch length is at its minimum, the 2.5 MHz rf system (along with the 5 MHz rf system) is turned off and 53 MHz rf bucket is opened with about 1 MV amplitude. Table III shows the simulated final emittance after coalescing. The simulation suggests that the emittance growth during the acceleration process is of the order of 20% for "1.5 eV"-bunches, while that for "0.6 eV" bunches it is low. This difference arises because of an uneven distribution of longitudinal emittance among the re-bunched bunches. The simulation also shows that the emittance growth during acceleration is mainly arising during transition crossing.

The ESME calculation described here starts from the beam injection at 8 GeV to the extraction at 150 GeV, hence, is referred to as full-scale simulation. We have taken in to account of space charge effect and use a broad band impedance of about 3Ω, with a safety margin of a factor of two[2]. There is a lot of scope for improvement in the simulation: include higher ordered cavity resonances, beam loading and multi-bunch effects into the calculation. But, this simulation is good enough to represent low intensity pbar operation in the MI. The simulation clearly indicates uneven distributions of particles and emittance in 53 MHz rf buckets in a consistent manner with the beam measurements (see table IV). These naturally arise from re-bunching beam particles from 2.5 MHz bunches using 53 MHz rf system. We assume a parabolic distribution of particles in 2.5 MHz rf buckets at the beginning and end up with a distribution shape very close to very close to measurements. The previous simulations[2], however, assume uniform emittance in all 53 MHz buckets. Hence, the case presented here is inherently different from the previous ESME calculations and the results from the present calculations are more realistic.

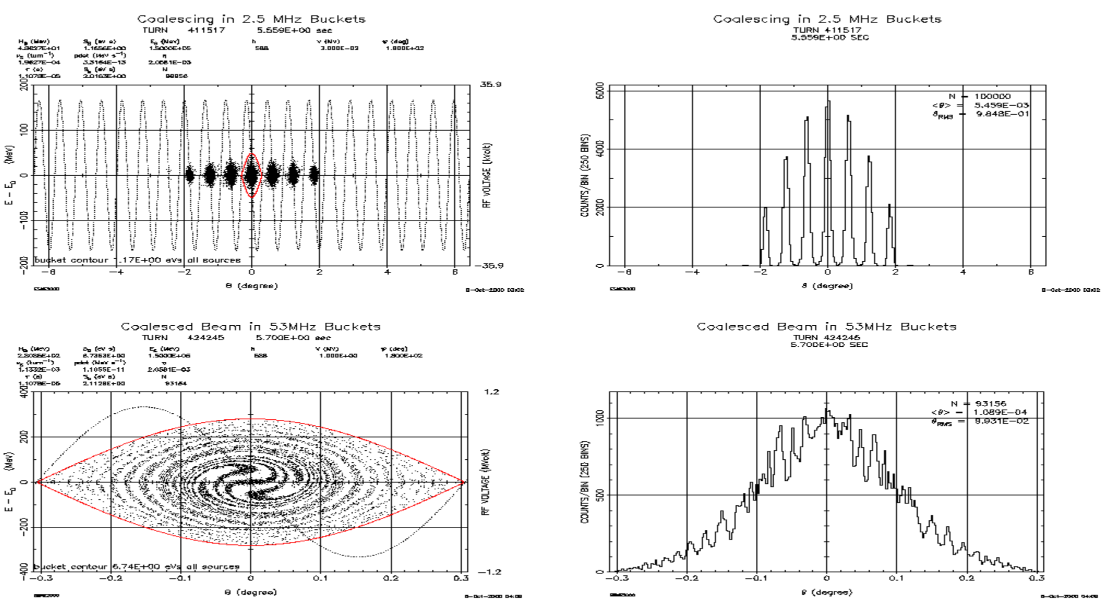


Fig.4 : ESME results for 1.50 eV-sec pbars in the MI at 150 GeV before coalescing and after coalescing. For detailed description, see caption of Fig. 1.

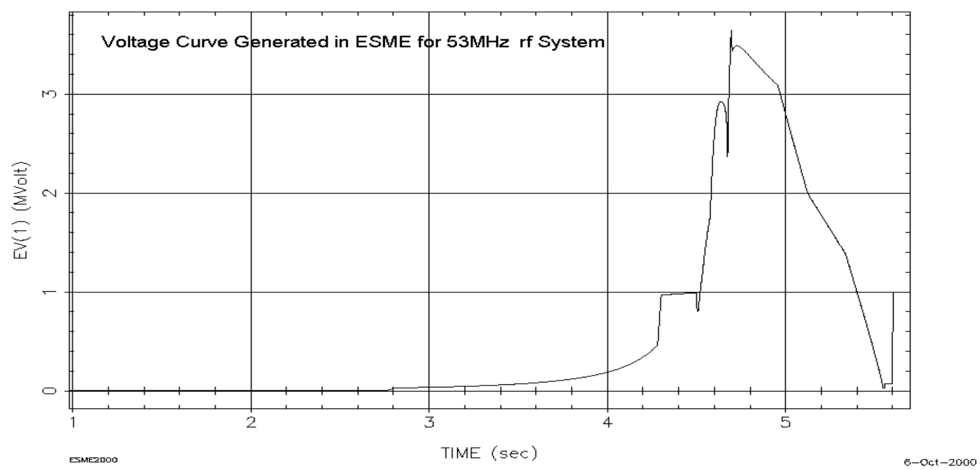


Fig. 5 : ESME predicted rf voltage, (which can be compared with Figure-6). At the end of the rf manipulation at 8 GeV the maximum rf voltage is about 1 MV.

Table III. Longitudinal emittance from ESME simulations for initial beam emittance of 0.6 eV-sec and 1.5 eV-sec.

Time of the cycle (sec) And other details	**0.6 eV-sec bunches Final ε (eV-sec)(95%)**	**1.5 eV-sec bunches Final ε (eV-sec)(95%)**
0.98 sec - at Injection energy - in 2.5 MHz rf bucket	0.6	1.5
	Re-bunched to 5 bunches	Re-bunched to 7 bunches
4.5 sec - at Injection energy - in 53 MHz rf bucket	1 (total emittance for 5 bunches)	1.9 (total emittance for 7 bunches)
5.6 sec - before coalescing at 150GeV - in 53 MHz rf bucket	1.1 (total emittance for 5 bunches)	2.3 (total emittance for 7 bunches)
5.8 sec - after coalescing at 150GeV - in 53 MHz rf bucket	2.9	3.5
Coalescing Efficiency	99%	93%

3. Experiments in the MI with Proton Beam

We have carried out experiments in the MI with Booster proton beam to test the proof of the principle of rf manipulation on the beam presented above. A group of four 2.5 MHz bunches are prepared in the Main Injector using the method outlined in Ref.[5]. These bunches are re-bunched using 53 MHz rf system and accelerated to 150 GeV. Before extracting the beam, four groups of 53 MHz bunches are coalesced into four high intensity bunches.

Figure 6 displays typical data obtained from an experiment with protons. The orange and blue traces show the beam performance and the rf peak voltages on 53 MHz rf cavity during the entire operation, respectively. The 2.5 MHz rf voltage is also shown here.

Figure 7-11 show bunch display of the beam at various stages of the beam rf manipulation from injection to end of coalescing. These are responses from a resistive wall pickup monitor[9] installed in MI60 location in the Main Injector ring captured using RDT720 digitizer. The mountain range picture for the bunch coalescing at 150 GeV shown in Fig.11 illustrates a case for one group of four. The coalescing efficiency was about 90%. A typical case of multi-batch coalescing for four Booster batches starting from the beam injection to the end of coalescing is shown in Fig. 12.

The longitudinal emittance of the beam at injection energy and the flat-top energy of 150 GeV are determined by measuring the bunch lengths and the rf voltages. The longitudinal emittance ε_l of a bunch in a stationary rf bucket with peak rf voltage Vrf is given by [10],

$$\varepsilon_l = 4\sqrt{\frac{2eV_{rf}R^2E_s}{2\pi h^3c^2\eta}}\int_0^Q \sqrt{\cos(x)-\cos Q}\,dx \qquad \cdots(2)$$

where, R, E_s, h, c, η, Δ and ϕ_s are, respectively, synchronous radius, synchronous energy of the particle, harmonic number, velocity of the light, slip factor (which is a function of the energy), bunch length (in radian) and rf phase of the bunch (for stationary bucket it is 0 deg for energy below transition energy and 180 deg for beam energy above transition). The quantity $Q=\Delta/2$. For $\Delta \leq 4$ radian (small angle formula) the longitudinal emittance is given by [11],

$$\varepsilon_l = 16\sqrt{\frac{eV_{rf}R^2E_s}{2\pi h^3c^2\eta}}\frac{\pi}{64}\Delta^2\left[1-\frac{5}{384}\Delta^2\right] \qquad \cdots(3)$$

If the particle distribution in a bunch is assumed to be Gaussian then the measured 99% bunch length is related to 95% bunch length by,

$$\Delta_{95\%} = \frac{2}{3}\Delta_{99\%} \qquad \cdots(4)$$

In the present case we have measured the 99% bunch lengths for proton bunches at injection, both after de-bunching in 2.5 MHz, after re-bunching in 53 MHz rf buckets (very close to the acceleration and at the end of the acceleration cycle.) The measured values are listed in Table IV. The bunch lengths are then used to calculate the 95% longitudinal emittance using Eq.(2).

Table IV. Measured longitudinal emittance in MI. We have used Eq.2 to evaluate the longitudinal emittance from the measured bunch length.

Time of the Cycle /Energy	**Bl (95%) (nsec)**	**# of Bunches**	**Vrf (kV)**	**emittance* (95%) (eV-sec) /bunch**	**Total Emittance* (95%) (eV-sec)**
At 8GeV near injection: Bunches in 53 MHz buckets	5.1	6	890	0.1	0.6
After De-bunching : in 2.5 MHz RF buckets	~140	1	2.5 kV	0.85	0.85
After Re-bunching:	4.2		0.89	0.07	
in 53 MHz RF buckets	5.3	Total of 8		0.11	
(Just before acceleration)	6.3	bunches		0.15	
	6.3			0.15	
	6.3			0.15	
	5.4			0.11	
	4.2			0.07	
	3.2			0.04	
					0.85
Before Coalescing at	3.2		1200	0.4	
150 GeV in 53 MHz rf buckets	3.7			0.53	
	4.2	Total of 8		0.68	
	4.7	bunches		0.85	
	4.7			0.85	
	3.7			0.53	
	3.1			0.38	
	2.6			0.27	
					4.49
After Coalescing	< 12.5	1	1200	<4.8	<4.8

** Error on the measured emittance is about 20%*

The source of error in the measured longitudinal emittance in the present case is mainly arising from

a) estimation of the 99% bunch length
b) the rf voltage
c) assumption that the bunches are gaussian (the bunches in Fermilab accelerators are very close to parabolic shape).

The final error indicated in the Table IV should be taken with caution. Rigorous analysis is necessary.

The studies with proton beam in the MI indicated that we expect about 40% emittance growth during de-bunching in the 2.5 MHz rf bucket at 8 GeV. This is in consistent with reference [8]. We saw no emittance growth, within errors, during re-bunching the 2.5 MHz bunches in 53 MHz rf buckets. However, this is in contrast to our simulation results shown in Table III.

As shown in Fig. 6, the beam transmission efficiency throughout the cycle was 100%. The life time of the beam at 8 GeV was <300 sec. In the experiment, however, we observed a significant amount of emittance growth during acceleration from 8 GeV to 150 GeV. Generally, one expects emittance growth in the vicinity of transition crossing. Many mechanisms are known to contribute to this phenomenon. MI design incorporates many precautionary steps to reduce the emittance growth associated with transition crossing[2]. For example, by crossing the transition energy as fast as 270 GeV/c/sec (in Main Ring it was 120 GeV/c/sec). Our simulation presented here suggests about 20-30% emittance dilution during the transition crossing and no emittance growth during any other part of the acceleration cycle.

To investigate the source of the emittance growth in the acceleration cycle, we have measured transverse emittance along with the longitudinal emittance in the MI injector on $2A (dedicated time-line for pbar acceleration) cycle. Typical flying-wire data at 8 and 150 GeV are shown in Fig. 13. Our study indicates emittance growth even in transverse planes by a factor < 2. We see more emittance growth in horizontal plane than in vertical plane. Careful control of this emittance is needed. This can be done both by understanding the orbit as well as tune and chromaticity of the MI at any given energy in the acceleration cycle.

During recent pbar acceleration studies, we have seen a spurious bunch length increase at about 60 GeV. The cause for these emittance growths during acceleration in MI is not fully understood at present.

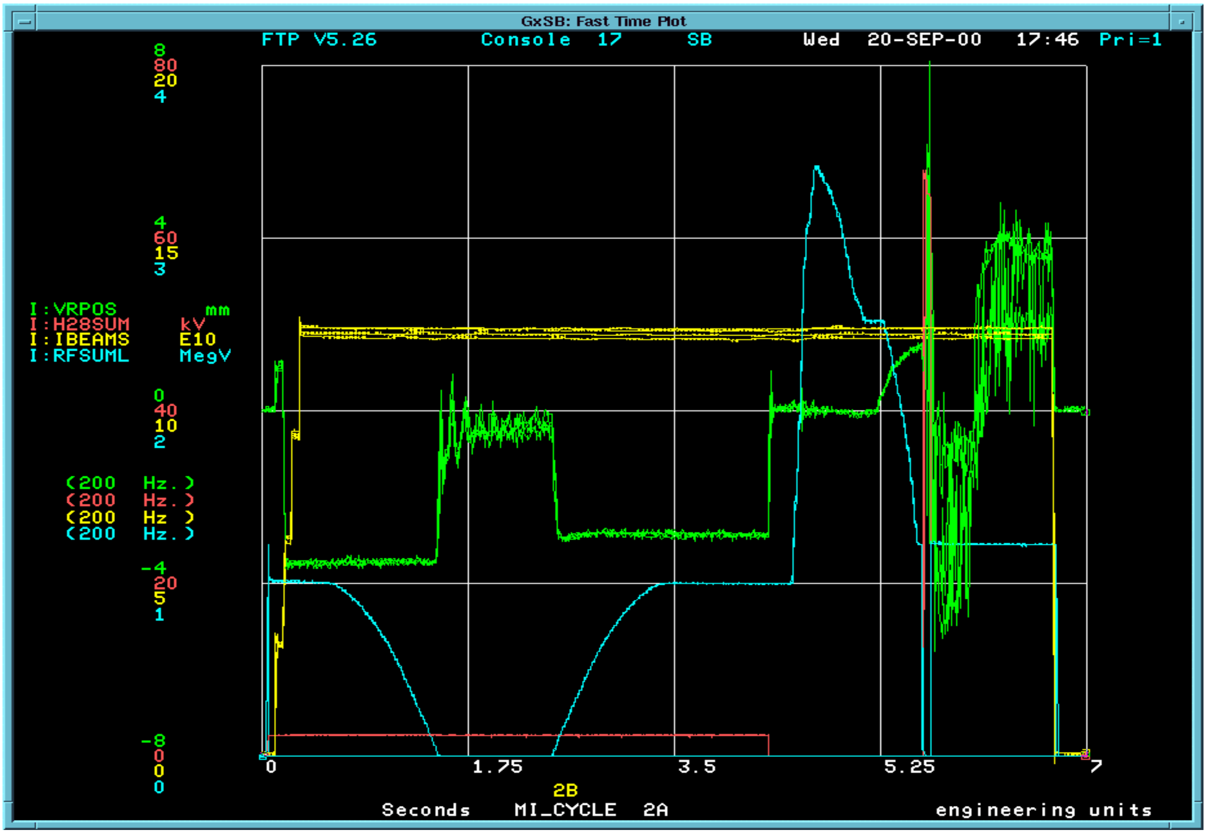


Figure 6. Beam intensity (I:IBEAMS), 53 MHz peak rf voltage (I:RFSUML), 2.5 MHz rf peak voltage (I:H28SUM), beam radial position detector output (I:VRPOS) vs cycle time. The data represents the beam transmission efficiency of 100% through the acceleration and various rf manipulations. On this cycle, the beam was at 8 GeV between 0 to 4.5 sec and was at 150 GeV between 5.6 sec and above. The steps on I:IBEAMS trace indicate the four Booster batches injected into MI. They were fully de-bunched in 2.5 MHz rf buckets between time intervals of 1.5 sec to 2.5 sec in the cycle at 8 GeV. By raising Vrf(53 MHz) they were re-bunched in to 53 MHz rf buckets. The bunch profiles at injection are shown in figure 7.

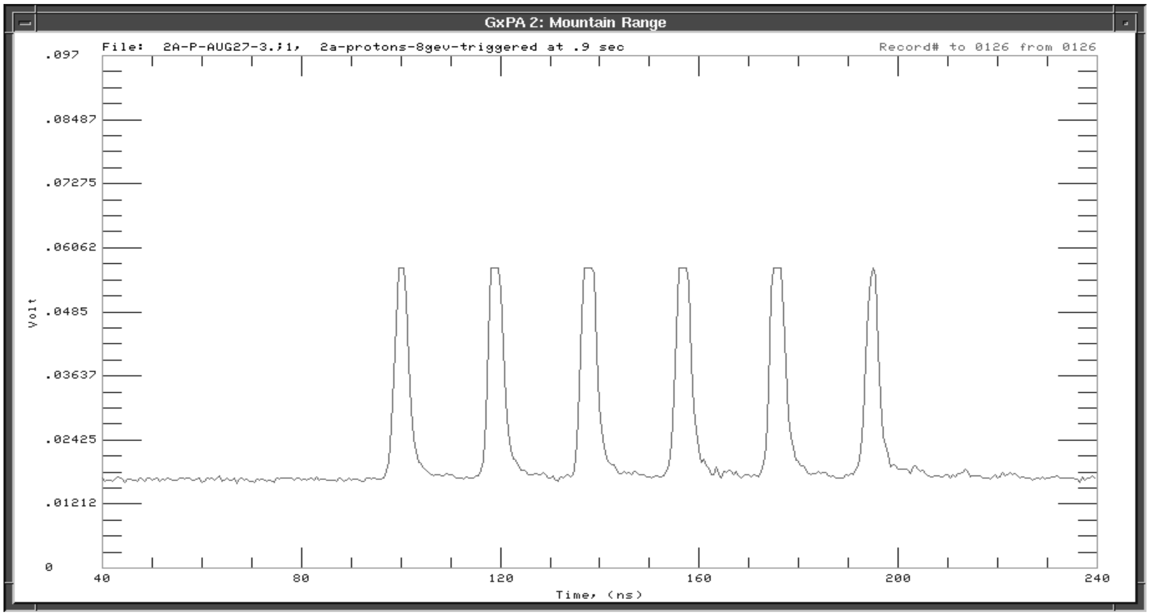


Figure 7. Bunch display of protons at injection obtained by using a wall current monitor at MI60 location. These are 53 MHz buckets.

Figure 8. Bunch display of protons at 8 GeV after de-bunching in 2.5 MHz rf bucket.

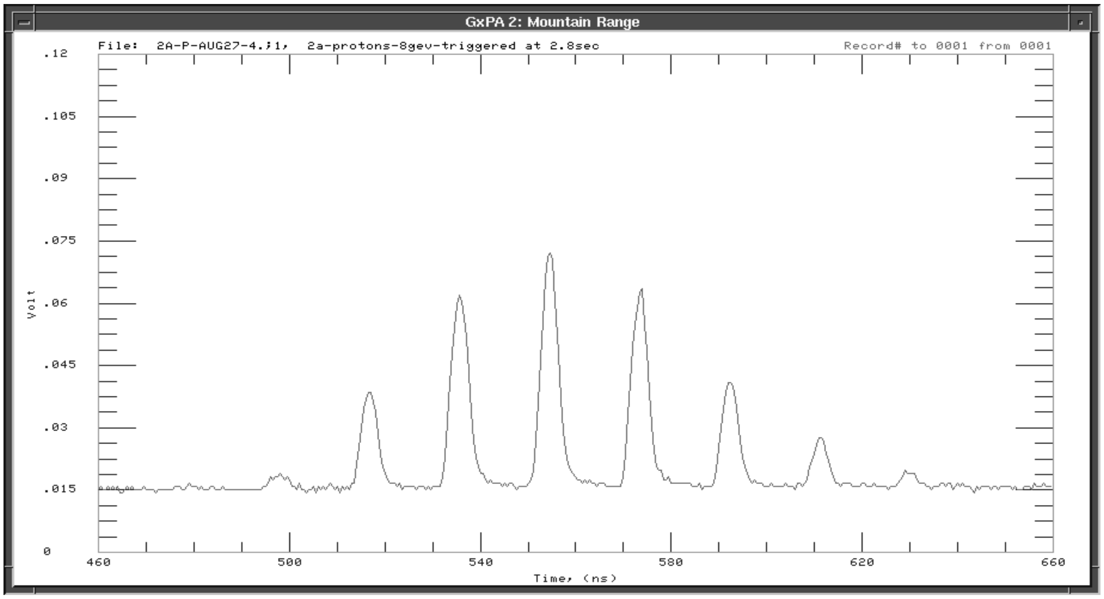


Figure 9. Bunch display of protons at 8 GeV after re-bunching in 53 MHz rf bucket, before acceleration.

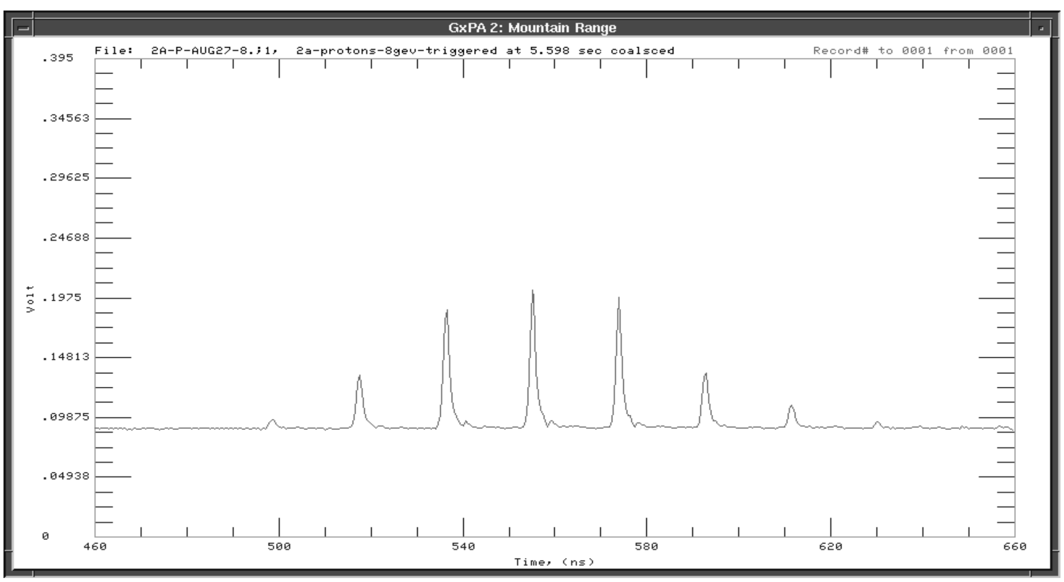


Figure 10. Bunch display of protons at 150 GeV just before coalescing.

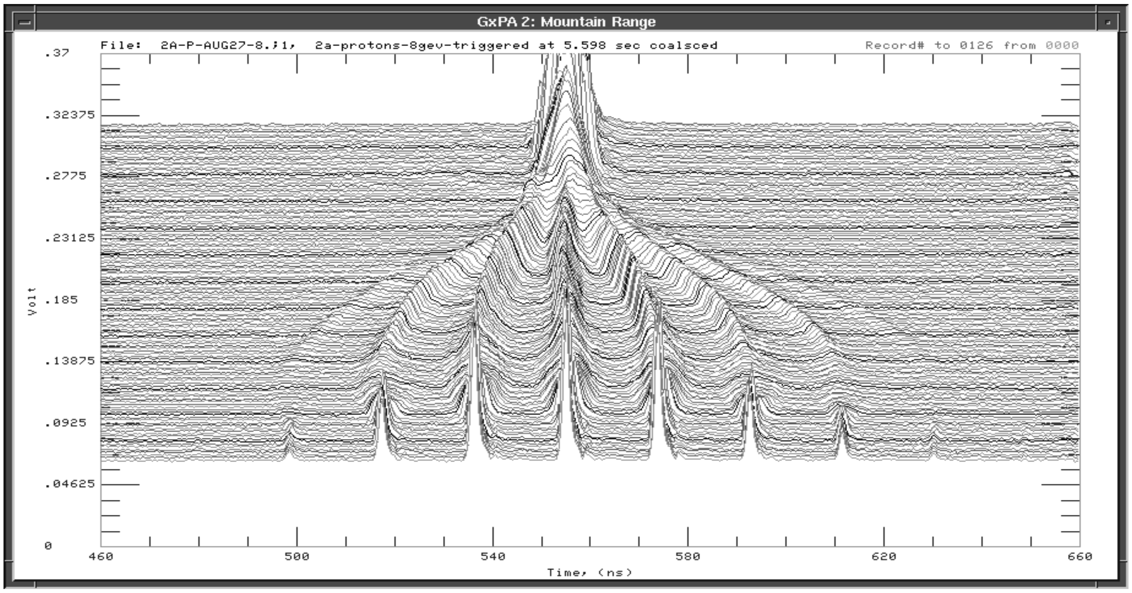


Figure 11. Mountain range data taken during the coalescing of protons at 150 GeV.

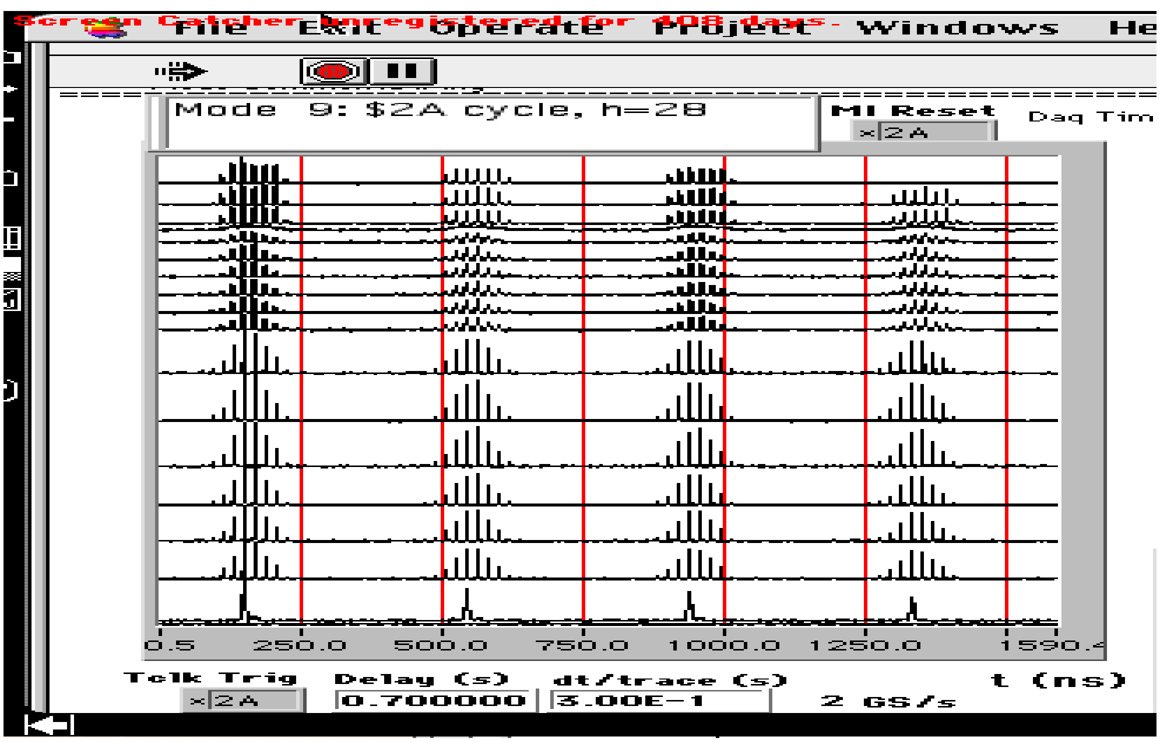


Figure 12. Typical multi-batch beam acceleration and coalescing in the MI. These data are obtained with protons.

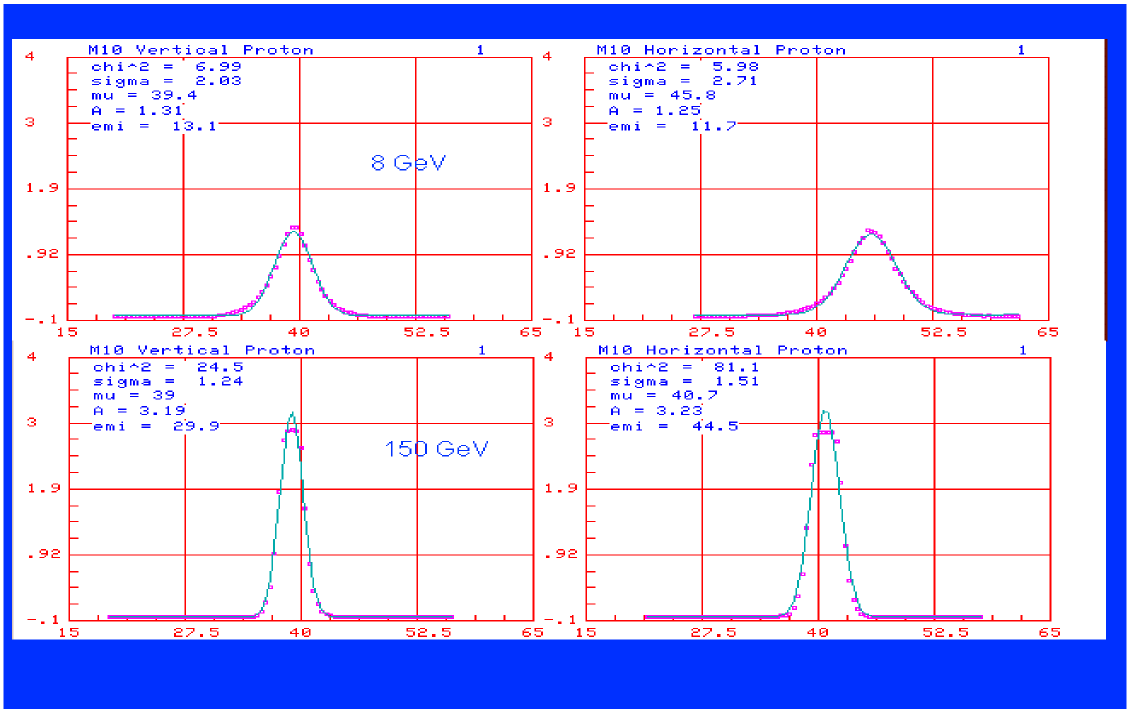


Figure 13. Flying-wire data at 8 GeV and 150 GeV on proton beam. These data were taken on two different beam pulses with similar conditions of MI. We see significant beam dilution in transverse planes during the acceleration.

4. Summary and Conclusions

We have studied a pbar acceleration scheme in the Main Injector which is suitable for the beam coming from Accumulator Ring or Recycler Ring with a 2.5 MHz rf bucket structure. By de-bunching them iso-adiabatically in 53 MHz rf buckets and accelerating to 150 GeV using 53 MHz rf system and further coalescing we end up with high emittance beam bunches. Both experimental and simulation studies indicate that by snap-coalescing according to a method outlined in this note we will have a final emittance of ~4 eV-sec. The coalescing efficiency will be in the range of 90% to 99% depending upon initial longitudinal emittance of the beam. In any case, it may be quite difficult to achieve the Run II requirements of 1.5-2 eV-sec bunches in the Tevatron by adopting this method.

There is scope for improvements in several areas both in simulations as well as in experiments with beam. We need to understand the longitudinal emittance growth through the transition in the Main Injector during acceleration. Simulation predicts that emittance growth is of the order of 20% depending on the beam emittance. But experimentally we found the emittance to grow by about a factor of four to five in the

MI. In principle, crossing the transition energy at a faster rate during acceleration should help a lot. We are planning to increase the dp/dt through the transition from 220 GeV/c/sec to ≈270 GeV/c/sec. This may improve transition crossing noticeably. However, this in turn may raise an issue of voltage curve control for the rf system through out the acceleration. Study of both of these issues are in progress.

5. Acknowledgement

I would like to thank Jim MacLachlan for useful discussions regarding the ESME inputs for full scale ESME calculations discussed above. I also would like to thank Keith Meisner, Brain Chase and Joe Dey for their help in RF set-up for the experiments with the proton beam.

References :

1. Fermilab Run II Hand Book, 1995 (unpublished).
2. Fermilab Main Injector Technical Design Hand Book, 1994 (unpublished).
3. G. Jackson, The Fermilab Recycler Ring Technical Design Report, FERMILAB-TM-1991, 1996 (unpublished).
4. J. MacLachlan, User's Guide to ESME 2000, March 2000, (unpublished).
5. V. Bharadwaj *et.al.*, "Fermilab Collider Run 1b Accelerator Performance" FERMILAB-TM-1970.
6. C. M. Bhat, " pbar acceleration in the MI using 2.5 MHz RF system and RF specifications, MI-Note 260 (2000).
7. C.A. Rodriguez and C.M. Bhat, "pbar acceleration in the Main Injector fir Run II: ESME simulations," MI-Note 265 (2000).
8. C. M. Bhat, Preparing the proton bunches in 2.5 MHz buckets in MI for RR tune-up, MI-Note 263 (June 1, 2000).
9. J. Crisp (Private communication)
10. P.S. Martin and S Ohnuma, AIP Proceedings NO. 184 (1989), 1942
11. S. Ohnuma, The beam and the bucket, FERMILAB-TM-1381 (1986).