# Preparing the Proton Bunches in 2.5 MHz Buckets in MI for RR Tuneup

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**MI Note 263**

During the Run II commissioning of the Tevatron Collider (June to August 2000) four pbar bunches in 2.5 MHz rf buckets in the Accumulator Ring will be transferred to matched 2.5 MHz rf buckets in the MI. The beam will rebunched in 53MHz rf buckets and accelerated to 150 GeV. Just before the injection into the Tevatron, they will be coalesced into four bunches separated by 21 rf buckets of 53MHz rf system. Also, the beam in 2.5 MHz rf buckets from the MI needs to be transferred to 2.5MHz /7.5 MHz rf buckets in the Recycler Ring. In both cases, it is essential to develop a scheme to prepare the beam in 2.5 MHz rf buckets of MI and understand the beam dynamics in details.

To tune the Main Injector for the acceleration of antiprotons and to tune the Recycler Ring [1] for antiproton storage, we will use proton beam instead of pbars. Once the the tune up is accomplished, the proton beam will be replaced by pbars with appropriate changes in both the machines. To mimic the handling the pbars from the Accumulator Ring in the MI, we have developed a method of preparation of proton bunches in MI using the the beam from the Booster. The proton beam in 53MHz rf buckets from the Booster is injected into the MI, it is rf manipulated, captured in 2.5 MHz rf bunches and further rf manipulated to prepare for acceleration or for transfer to the Recycler Ring.

We have carried out beam dynamics simulations using ESME[2] to understand various stages of the bunch manipulation and done beam measurements for different scenarios of the beam and the accelerator conditions to optimize the performance of the beam. The beam prepared by this method is adopted for MI pbar acceleration tune up studies and Recycler Ring tune up.

In Section 1 of this report, we discuss the results of measured of longitudinal beam emittance at injection energy and emittance dilution as a function of capture voltage of 53 MHz rf system. A method of debunching the injected bunches using 2.5 MHz rf system and a discussion on final emittance of the beam is outlined in Section 2. In this section we also discuss the results of ESME simulations of the debunching process. Section 3 deals with multi-batch operation. Finally, we discuss the beam transfer to Recycler Ring.

## 1. Beam in the MI 53 MHz RF Buckets at Injection:

At the time of extraction of the beam from the Booster, the rf voltage was about 375kV. The corresponding matching voltage in the MI is calculated using,

$$\left|\frac{V_1 Cos(\phi)}{h_1\eta_1}\right|_{MainInjector} = \left|\frac{V_2 Cos(\phi)}{h_2\eta_2}\right|_{Booster}$$

where V, $\phi$, $\eta$ and $h$ are rf voltage, rf phase angle, slip factor and harmonic number of the Main Injector and Booster, respectively. The rf phase angle for the beam bunches in stationary buckets in the Booster at flat-top energy of 8 GeV, is 180 degs and in the MI it is 0 deg. The harmonic numbers are 84 and 588 in Booster and MI, respectively. The slip factors are 0.0223 and 0.0089. Thus,

$$V_1 = \frac{588\times 0.0089\times 375}{84\times 0.0223} kV = 1.047\, MV$$

is the matching voltage in the MI. Before the injection of the beam into the MI we set rf voltage of 53MHz system very close to the matching voltage, i.e., 890 keV. Also, the 2.5 MHz rf system was turned on and brought up to about 3.75kV.

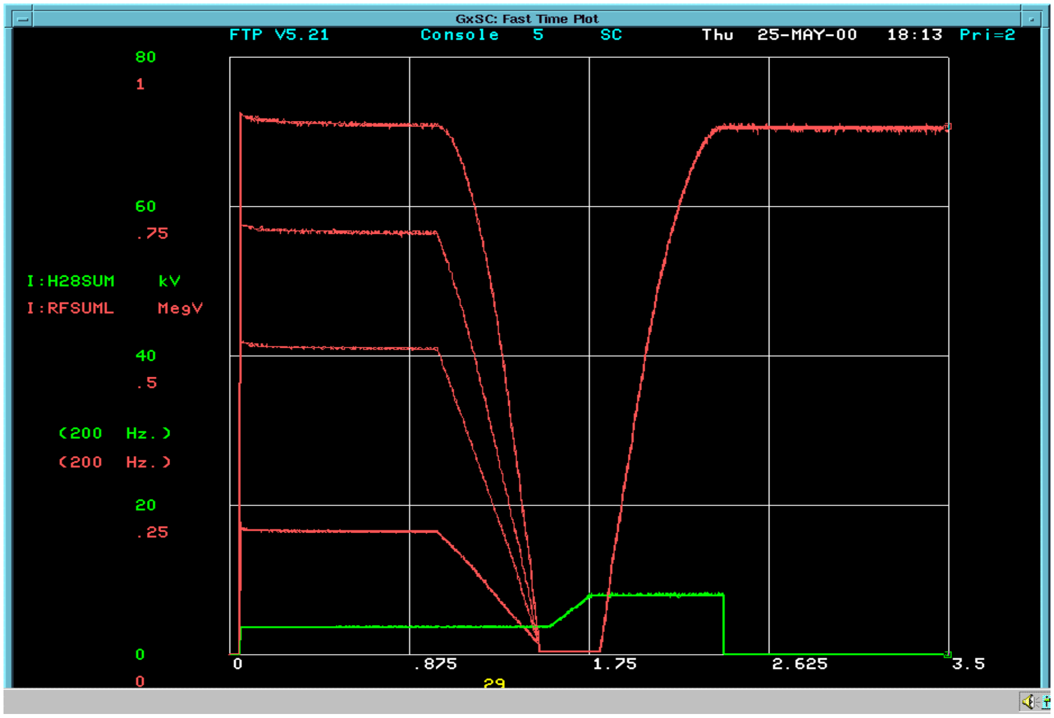



*Figure 1: The 53MHz rf voltage (I:RFSUML) and 2.5MHz rf voltage (I:H28SUM) for the rf manipulation of the proton bunches in MI as a function of time are shown. The data is taken on $2A MI reset. On this cycle the beam is injected at about .4 sec and extracted to RR either at 1.53 sec or 1.78 sec.*

During the beam measurements, a batch of 3 to 11 bunches (i.e., a "short batch") of proton beam in 53MHz rf buckets are transferred from Booster to MI 53MHz buckets. Typically, we have used one to two turns of Booster beam with a fewer bunches for pbar acceleration tune up in MI. For RR tune up, higher intensity beam with a larger number of bunches were used. The operating conditions of 53 MHz as well as 2.5 MHz rf systems during beam injection are shown in Figure 1. To investigate the effect on beam dilution after they are captured in 2.5MHz rf buckets, we also varied the voltage on 53 MHz rf system in the range of 200kV to 890kV The four traces for I:RFSUML in Figure 1 are respectively for 200kV, 513kV, 709kV and 890kV. The first trace on upper and lower bunch profiles on Figure 2 shows SBD[3] picture of the initial conditions of the bunches in MI at injection energy for two extreme 53MHz rf voltages, i.e., at 200kV and 890kV respectively.

*Table 1: Measured longitudinal emittance (95%) in the MI at injection for different I:RFSUML. The data for this case is shown in Figures 1 and 2. The bunch intensity was ≈8.3E9protns.*

I:RFSUML=200kV

| **Bunch Number** | **Bunch Length (Radian)** | Bunch Length (nsec) | **Emittance(95%) (eV-sec)** |
|---|---|---|---|
| 1 | 2.6 | 8 | .11 |
| 2 | 3.1 | 9 | .15 |
| 3 | 3.4 | 10 | .17 |
| 4 | 3.4 | 10 | .17 |
| 5 | 3.4 | 10 | .17 |
| 6 | 3.1 | 9 | .15 |
| Total | | | 0.92±0.20 |

I:RFSUML=890kV

| **Bunch Number** | **Bunch Length (Radian)** | Bunch Length (nsec) | **Emittance(95%) (eV-sec)** |
|---|---|---|---|
| 1 | 1.8 | 5 | .11 |
| 2 | 2.1 | 6 | .15 |
| 3 | 2.4 | 7 | .19 |
| 4 | 2.1 | 6 | .16 |
| 5 | 2.1 | 6 | .15 |
| 6 | 2.1 | 6 | .15 |
| Total | | | 0.91±0.20 |

The Table 1 displays the longitudinal emittance [4] of the beam at injection for the two scenarios mentioned above. The emittances for individual bunches are listed. The measured longitudinal emittance are known to an accuracy of about 20%. The major source of error comes from the bunch length and rf voltage measurements. We find that during these studies, the longitudinal emittances for two widely separated I:RFSUML values are the same within the errors.

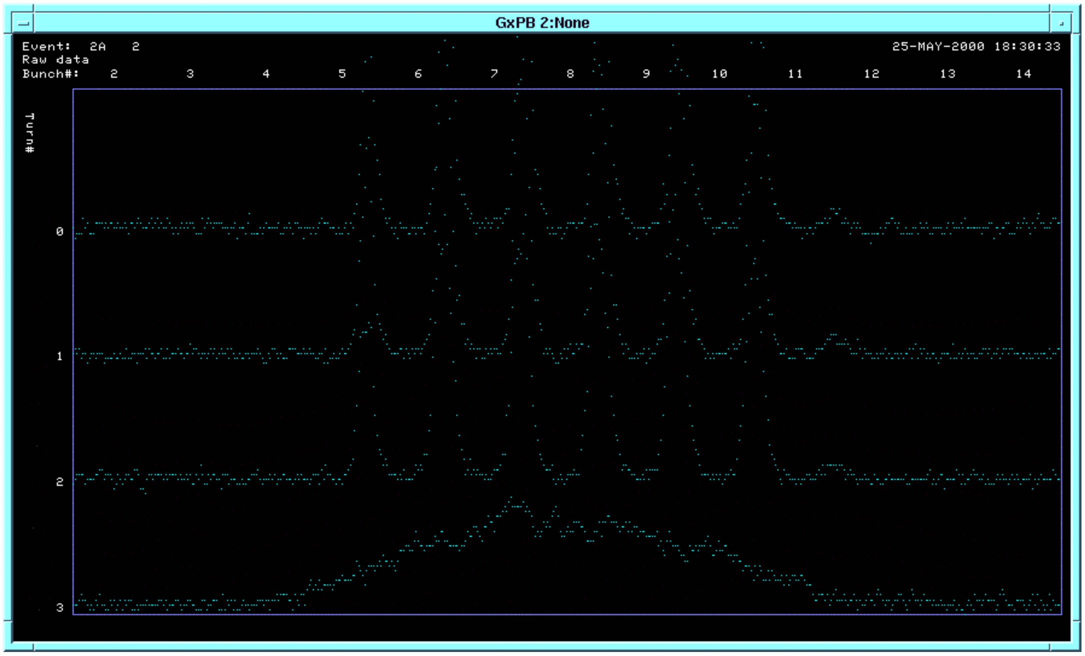
**2. Debunching the Beam in 2.5 MHz rf Buckets:**

Once the beam are captured in the 53MHz rf buckets in MI, they are adiabatically debunched in the 2.5 MHz rf buckets in about 0.5 sec. The debunching done by linearly decreasing the 53 MHz rf voltage from injection value to a minimum value in about 0.5 sec. In the present scheme, we paraphase two groups of rf cavities of nearly equal amplitudes to 180 deg in two steps. First, we bring down the rf voltage to about 20 kV. This uses 720 Hz LLRF internal clock. Further reduction in the rf voltage is achieved by using a faster LLRF internal clock of 16.6 kHz; which uses an internal array of time and paraphase angle. Thus a final rf voltage of <5kV achieved, which is minimum attained value during these studies. Ideally, we need to reach I:RFSUML nearly zero. However, beam loading on the cavities would set a lower limit on I:RFSUML. During 53MHz rf manipulation the 2.5 MHz rf wave is held at about 3.75 kV. After the 53 MHz brought to its minimum value, we increase the 2.5 MHz rf voltage from 3.75 kV to 8.1 kV to shrink the bunch in 2.5 MHz rf bucket. This is necessary to recapture the bunches in 53 MHz rf buckets for pbar tune up or to transfer to RR 2.5/7.5 MHz rf buckets.

The last traces from Figure 2 show the bunch profile after debunching in MI. The 53MHz component on these bunches are negligibly small. The measured longitudinal emittance in the MI after debunching the beam are 1.3±0.3 eV-sec and 1.1±0.2 eV-sec for initial I:RFSUML values of 200kV and 890kV, respectively. Comparing this results with the total emittances from Table-1 we find that there is an overall emittance growth of about 30%. From the data shown in Figure 2 it appears that capturing the beam with I:RFSUML= 890kV gives marginally better results than that with 200kV.

Figure 3. shows two sets of SBD LABVIEW data taken for different number of bunches from Booster per batch. As per our expectations, more number of bunches give rise to larger bunch length in 2.5 MHz rf bucket, indicating a larger emittance as compared with the less number of bunch scenario.

The results of ESME simulations for the operating conditions described above is shown in Figure 4. In this simulation, the beam is assumed to be injected with 53 MHz rf voltage at 200kV and the final rf voltage of 0kV. With five bunches of each with a longitudinal emittance of 0.1 eV-sec/bunch at injection, the final emittance of the beam in the 2.5 MHz rf bucket is found to be about 0.6 eV-sec. Since the bunch intensity during the experiment was about 8.3E9, which is much below the space charge limit, we did not include any space charge contributions in our simulations. The simulations showed about 20% emittance growth during the rf manipulation which is in agreement with our observations discussed previously. The simulation carried out with a final rf voltage of 5 kV indicates about 2-3% modulation from 53MHz component on the bunch in 2.5 MHz rf bucket.



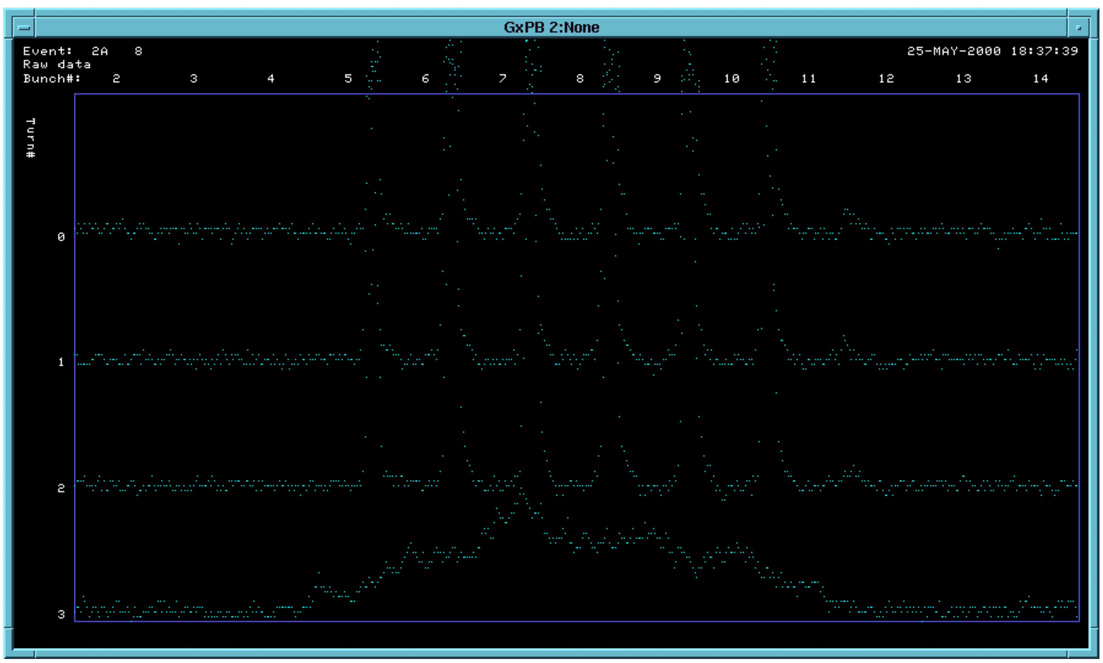




*Figure 2. The SBD bunch profiles in MI during capture in 53 MHz rf system and the bunch manipulation for a short batch of 6 bunches. The first trace on top and bottom displays are for initial I:RFSUML = 200kV and 890kV, respectively. The last trace on each of the figures is for fully debunched conditions in 2.5 MHz rf buckets. We had total beam of about 5E10 protons per 6 bunches in both the cases. No beam loss occurred during the rf manipulation. Bunch traces are separated by 0.3 sec with the first trace at 0.7 sec on both cases.*

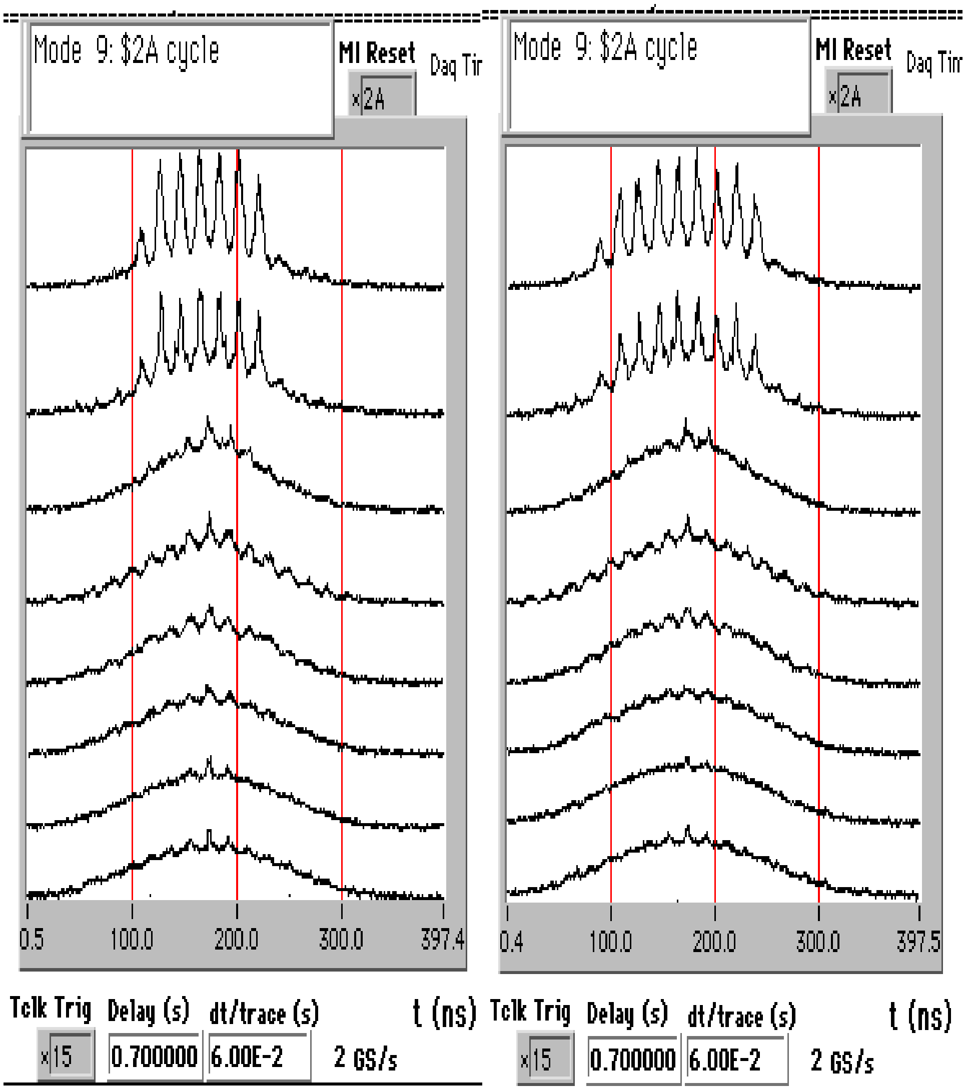



*Figure 3. SBD LABVIEW data on single Booster batch injection in MI with different numbers of bunches in 53 MHz buckets in MI. The bunches are captured in 53 MHz rf buckets with I:RFSUML=200 kV and all of them are debunched using the 2.5 MHz rf wave.*

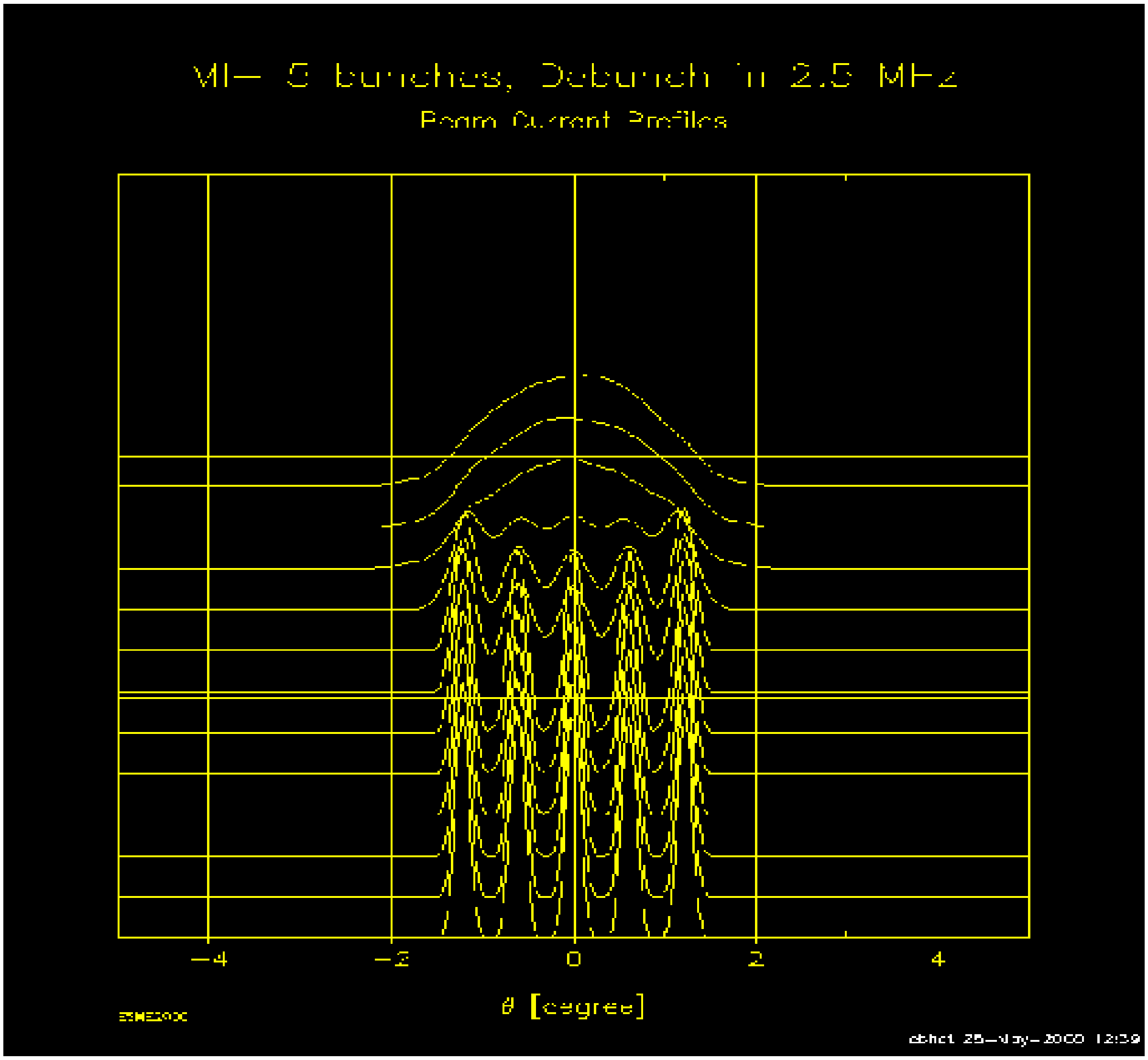



*Figure 4. Mountain Range simulation of the beam in the using ESMEfor five bunches. The capture voltage in the MI is assumed to be 200kV. The horizontal scale is in MI angle (i.e., 360 deg for entire MI). The vertical scale is the time. The simulation shown here is for the first 1.78 sec in the MI, before the acceleration in MI or injection into the RR.*

## 3. Multibatch Beam Injection in the MI:

Short batchs of 5-6 bunches each, which are separated by 21 rf buckets of 53 MHz wave are injected in to the MI. All of them are debunched in 2.5 MHz rf system. Figure 5 shows a typical data taken during such a study.

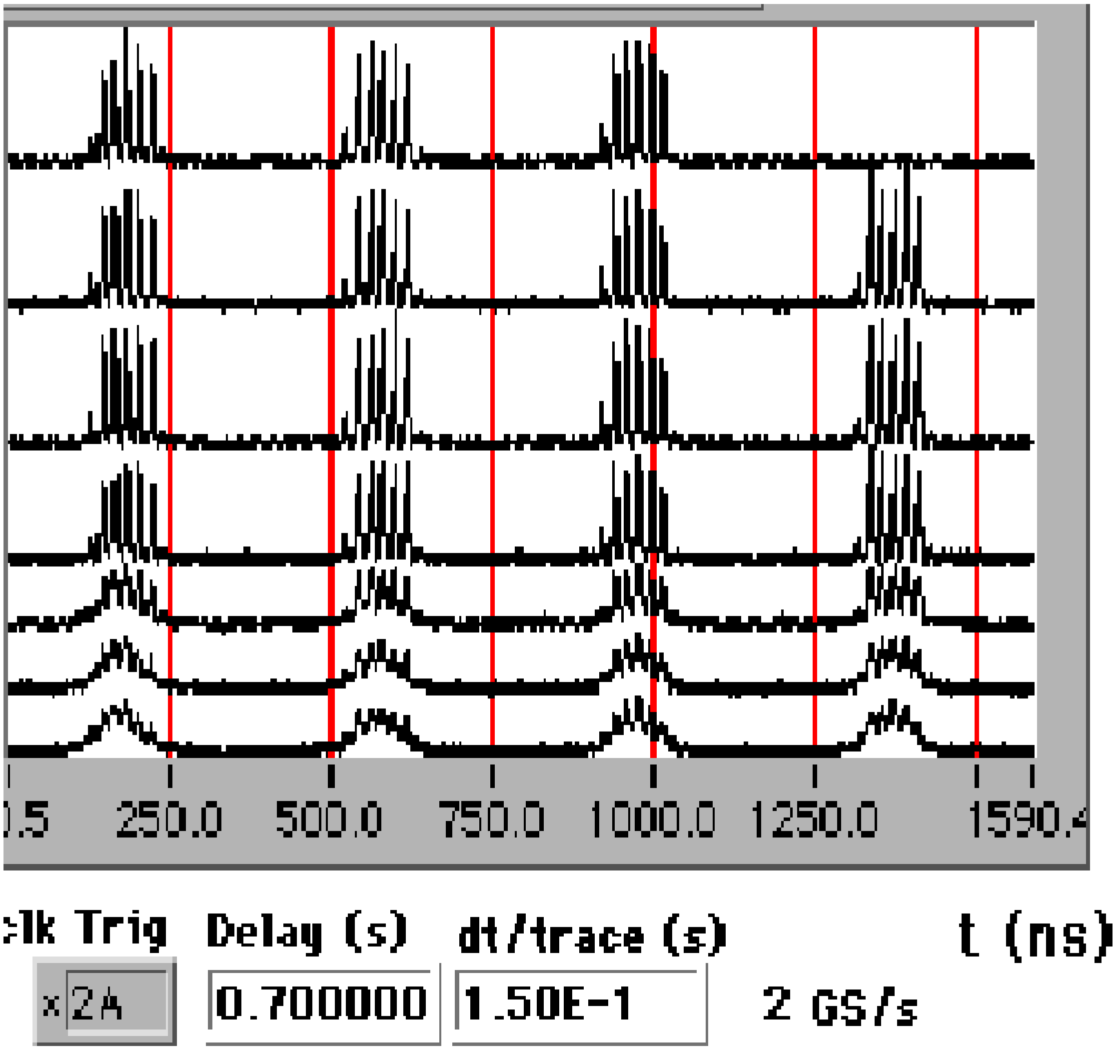



*Figure 5. Multibatch injection into the MI. The batches of 5 bunches are separated by 21 rf buckets of 53 MHz. The bunches are captured in 53 MHz rf buckets with I:RFSUML=200 kV and all of them are debunched using the 2.5 MHz rf wave. During this data taking we had about 15kV of 53 MHz rf voltage. Hence, we had observable amount of 53 component on the final trace.*

Figure 6 shows beam (I:IBEAMS), 2.5 MHz rf voltage (I:H28SUM), 53 MHz rf voltage (I:RFSUML) and 53 MHz rf phase with respect to the beam bunch (I:PHIS) through the rf manipulation on pbar acceleration tune up cycle. The data corresponding to the time <1.6 sec is not relevant to the present discussions.

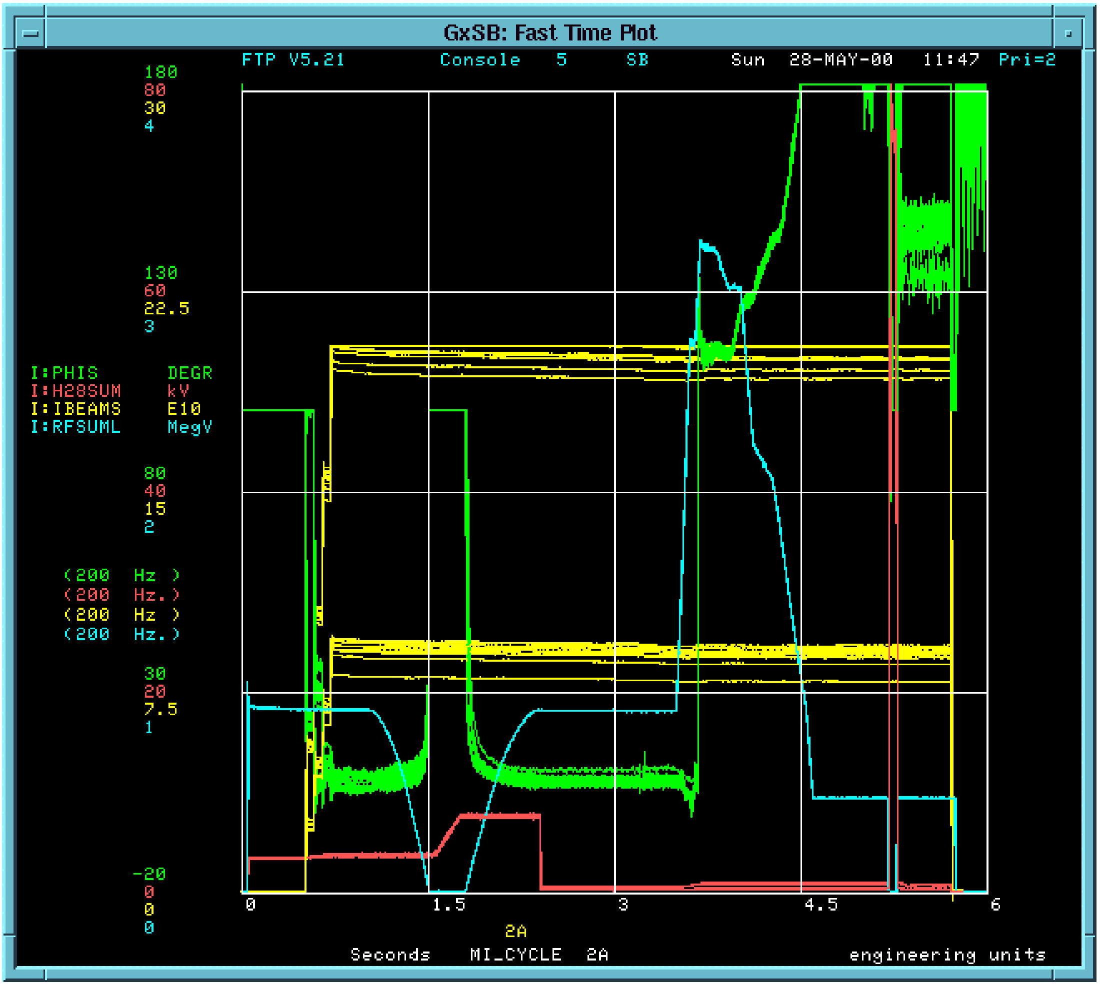



*Figure 6. Multibatch beam injection from Booster into the MI. The batches of 5 bunches are separated by 21 rf buckets of 53 MHz. The bunches are captured in 53 MHz rf buckets with I:RFSUML=890 kV and all of them are debunched using the 2.5 MHz rf wave by about 1.5 sec in the cycle. The lower set of yellow curves (I:IBEAMS) are corresponding to the 1 Booster turn beam, where as the upper set corresponds to the 2 Booster turn beam. During this data taking we had about 5kV of 53 MHz rf voltage. The beam response for time >1.6 sec are not relevant to the present discussion.*

## 4. Transfer of 2.5 MHz Bunches into the RR:

For the RR tune up studies, the 2.5MHz bunches are transferred from the MI to the RR 7.5 MHz rf buckets (see RR. LOG BOOK[5]). During these studies, bunches in the 2.5 MHz buckets are produced with an rf voltage of about 4kV. The ESME simulation of this situation shows that, when such a bunch is transferred to buckets of 7.5 MHz rf wave, about 20% of the beam will be captured in the neighboring buckets resulting in one satellite on each side. Calculations show that by increasing the 2.5MHz rf voltage amplitude from 3.75 kV to ~7kV in about 0.2 sec adiabatically after fully debunching in

2.5MHz buckets in MI  would reduce considerably the beam particles in the neighboring buckets. Results of such an ESME calculation is shown in Figure 7.     However, it may be

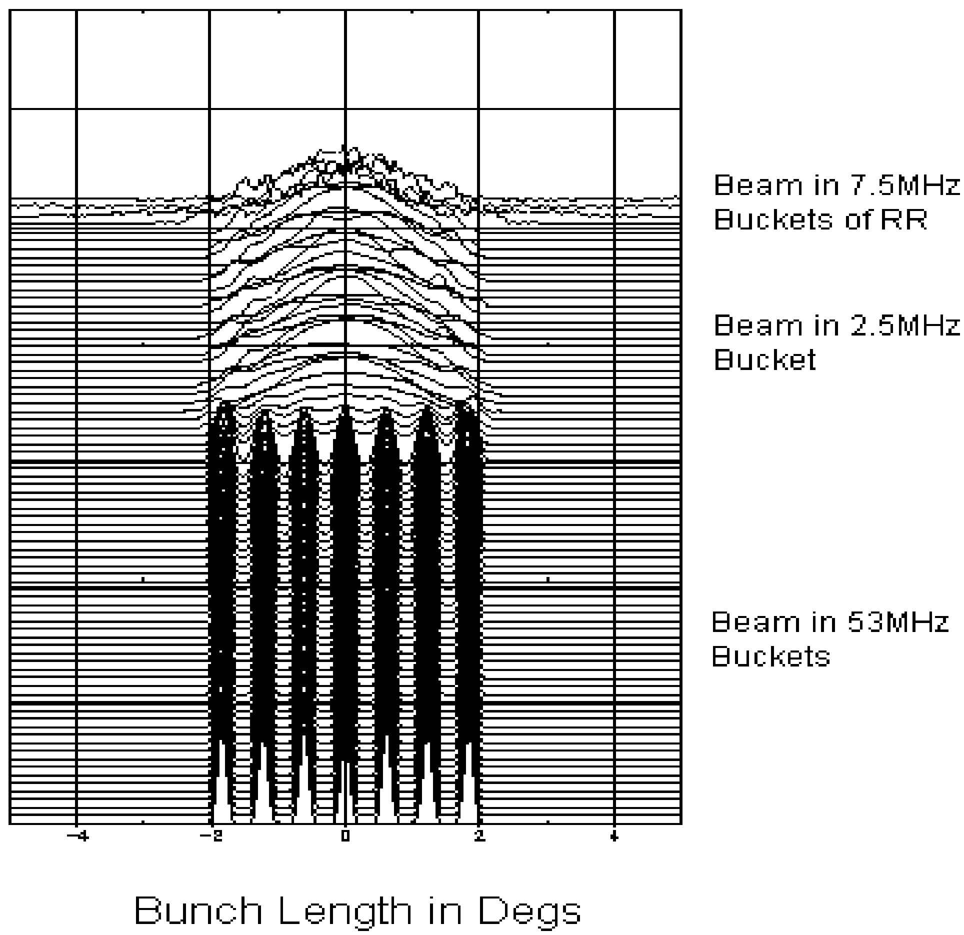



*Figure 7. Longitudinal beam dynamics simulation of the bunch transfer from MI2.5 MHz rf buckets to 7.5MHz rf buckets of Recycle Ring. We assume the amplitude of 7.5MHz rf wave in Recycle Ring is 2kV. Horizontal scale assumes 360 deg for  MI/RR ring. Vertical scale is time (900MI revolution /trace)*

very difficult to completely eliminate the satellite formation by the  this method of beam transfer in to the RR.

A typical waterfall SBD data in Recycler shown in  Figure 8. During this study four bunches prepared in 2.5 MHz  buckets with about 13kV rf wave amplitude and  are transferred to RR.  No effort is made to shrink the bunches before transfer to RR.

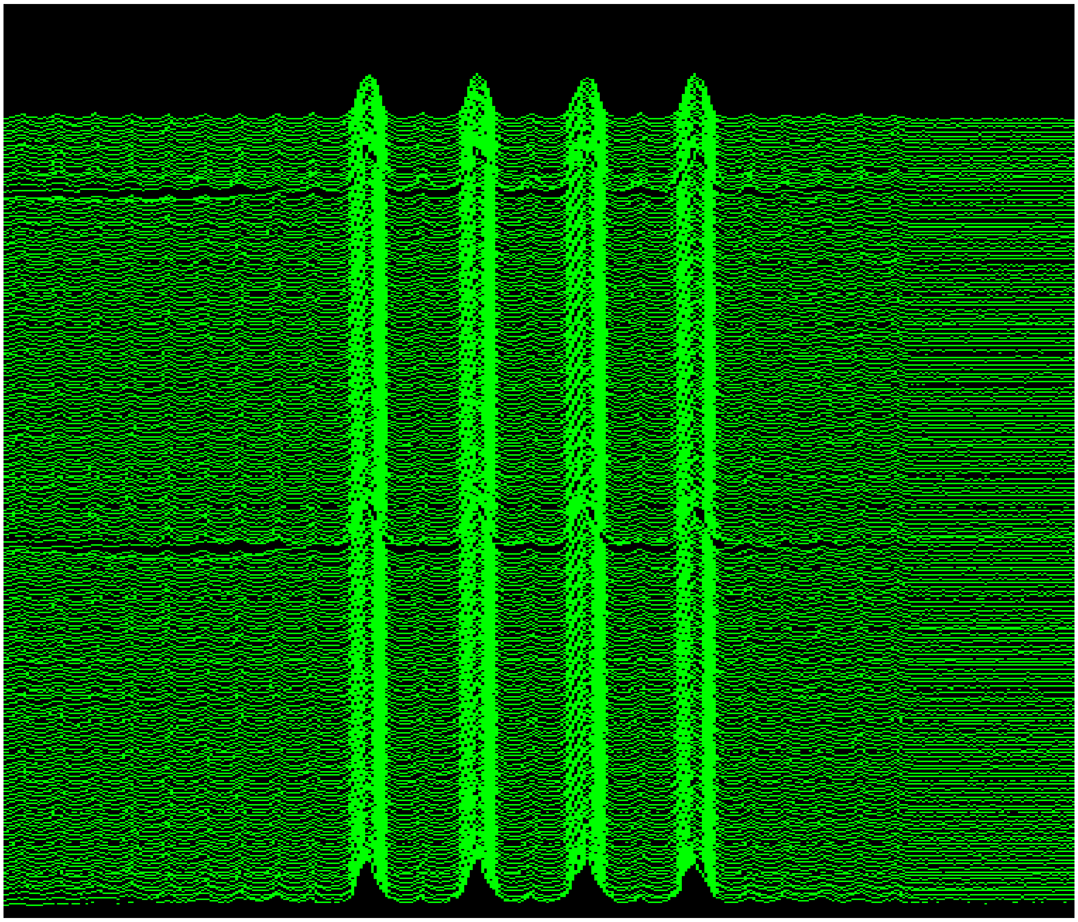


*Figure 8. The water fall data of four bunches in 7.5 MHz rf buckets in RR. [Ref. RR ELECTRONIC LOGBOOK, this data is taken by Gerry Jackson May 20, 2000]. We can see satellites around each bunch.*

**Acknowledgement:**

I would like to thank RF and MI personnel for their help during this work. My special thanks to MCR operation group.

**References:**

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