pbar Acceleration in the MI using 2.5 MHz RF system and RF Specifications

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During Run II we are using the Recycler Ring (RR)[1] for pbar storage and MI for pbar acceleration before injecting the pbars into the Tevatron. The pbar beam from the Accumulator Ring and unused pbars from the Tevatron will be transferred to the Recycler Ring via MI. Then the beam will be cooled. For details see the Recycler Ring design report. Whenever the pbar beam is needed for the collider operation the cooled pbars from the RR will be used.

There are numbers RF manipulations involved before the beam bunches are transferred to the Tevatron. This writeup will summarize the details of rf operation and also gives specifications. The entire acceleration cycle and rf manipulations have been simulated using longitudinal simulation code ESME [2]. The specifications have been estabilished using the simulation results.

The Recycler Ring RF and bunch parameters before injection of the bunches in to the MI are as follows (from Design Report, ref. 1):

Invariant 95% longitudinal emittance	= 1.5 eV-sec
Total Beam energy	= 8.938 GeV
RF Voltage for 2.5 MHz system	= 2 kV
Momentum Compaction factor	=-0.008683
RMS bunch length	= 38 nsec
RF bucket half height	= 6.9 MeV
RF bucket area	= 3.5 eV-sec
Ratio of bunch area to bucket area	= 0.43
Number of particles	= 6E10/bunch

Four pbar bunches with above property are transferred from RR to the MI with 2.5 MHz RF buckets open. This will be a bucket to bucket transfer. After a few thousand turns in MI, the RF voltage of 2.5 MHz system is raised from 2 kV to 60 kV to adiabatically shrink the bunch length. This will take about 1.25 sec. Then the bunches are accelerated to 25 GeV front porch in about 4.3 sec with Vrf_peak(2.5MHz) = 60 kV. After about 0.5 sec at 25 GeV, the Vrf_peak(2.5MHz) is brought down from 60kV to 6kV in about 1.0 msec. Bunch is rotated for quarter synchrotron period which is about 0.09 sec. Vrf_peak(2.5MHz) is increased to 60kV in 0.001 sec and 16% h=56 component is added to linearize the RF curve in the region of 180 deg phase angle. Further the bunch is rotated for quarter synchrotron period to match with 53MHz rf bucket with about 0.7 MV. Beam is accelerated from this point to 150 GeV using 53MHz system. Finally the bunches are transferred to the Tevatron. The RF and pbar bunch properties at 150 GeV are given below.

Invariant 95% longitudinal emittance	~2.2 eV-sec
Total Beam energy	= 150 GeV
RF Voltage for 53 MHz system	= 0.8 MV
Momentum Compaction factor	=-0.008683
RMS bunch length (RMS)	= 1.9 nsec
RF bucket half height	= 210 MeV
RF bucket area	= 5.7 eV-sec
Ratio of bunch area to bucket area	= 0.38
Number of particles	= 6E10/bunch

The Figure 1 show the acceleration scheme discussed above. Some ESME results are shown in Figure 2.

The emittance dilution in this method will be at the most 50% (for well tuned rf manipulations). ESME simulations indicated that about 5-10% dilution occurs during the transition phase jump. The remaining dilutions occurs during the rf manipulation at 25 GeV.

References :

[1] The Fermilab Recycler Ring Technical Design Report, Gerry Jackson, FERMILAB – TM- 1991 (1996).

[2] J. MacLachlan, User's Guide to ESME 2000, March 2, 2000

Table 1: RF Voltage and Phase Requirements for the pbar Acceleration in MI.

Approximate@ cycle time (sec)(dt)	p (GeV/c)	Description	h=28	h=56	h=588	h=1176
0.05 (0.05)	8.9	hold and beam transfer (Constant voltage)	V=2kV Ph=0	- -	- -	- -
1.3 (1.25)	8.9	shrink the bunch (Iso-adiabatic)	V=2-60kV Ph=0	- -	- -	- -
4.01 (2.71)	8.9- ~20.4	Accelerate (Constant voltage)	V=60kV 0<Ph<90	- -	- -	- -
4.012(0.002)	20.4	Tran. Xing (Constant voltage)	V=60kV Ph<90 to ph>90	- -	- -	- -
5.6 (1.588)	25	Accelerate (Constant voltage)	V=60kV 90<ph<180	- -	- -	- -
7.1 (1.5?)	25	hold voltage)	V=60kV Ph=180	- -	- -	- -
7.101(0.001)	25	Match (Linear decrease)	V=60-6kV Ph=180	- -	- -	- -
7.1876(.0866)	25	Rotate for 1/4 period (Constant voltage)	V=6kV Ph=180	- -	- -	- -
7.1886(0.001)	25	(Linear increase)	V=6-60kV Ph=180	- -	- -	- -
7.221(.0324)	25	Rotate for 1/4 period (Hold the voltage and phase)	V=60kV Ph=180	V=12kV Ph=0	- -	- -
7.223(.002)	25	Transfer to h=588 sysm.	0kV Ph=180	0kV Ph=0	0.7MV Ph=180	- -
7.423 (.2)	25		- -	- -	V=.7-3MV Ph=180	- -

Table 1. continued

Approximate@ cycle time (sec)	(dt)	p (GeV/c)	Description	h=28	h=56	h=588	h=1176
9.229	(1.8)	150	Beam Accel.	-	-	V=3.5	-
9.235	(.006)	150	(Linear	-	-	V=3.5	-
			decrease in			to 1.5MV	
			rf voltage)	-	-	Ph=180	-
9.4	(.171)	150	(Linear	-	-	V=1.5	-
			decrease in			to 0.8MV	
			rf voltage)	-	-	Ph=180	-

@ There may be a small difference in timings depending upon the details of the ramp structure.

Table 2. Frequency Requirements for the 2.5 MHz system

Acceleration time (sec)	cp(GeV)	beta	f0(Hz)	f(h=28)(MHz)
0.0	8.8886	0.9944	89871	2.516391
5.6	25.	0.9993	90313	2.528782
		df =		12.39 kHz

The Q value of the 2.5 MHz cavity is ~100 (Dave Wildman and Joe Dey). Hence, df = f0/Q = 25kHz and we need not have to tune the frequency of the cavity during the acceleration.

Table 3. RF Requirements for the pbar Acceleration
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A. 8 GeV Front porch:
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1. 1.5eV-sec pbar bunch transfer from RR to MI:
   - h = 28
   - Vrf = 2kV +/- 100V
   - Phase = 0.0
   - Hold the beam for .05 sec

2. Shrink the bunches adiabatically for 1.25 sec.
   The bunch length will be shrunk from 40ns to 18nsec
   during this time.
   - h = 28
   - Vrf = 2kV - 60 kV (+/- 5kV)
   - Phase = 0.0

3. Accelerate from 8.900-25 GeV, through
   transition in about 4.3 sec. The non-adiabatic time
   is of the order of 100 msec.
   - h = 28
   - Vrf = 60kV +/- 5kV

   At the transition energy the acceleration phase should
   be changed from
   phase angle < 90 deg to
   phase angle > 90 in about 50 msec (??)

B. 25 GeV Front Porch :
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1. Stay for about 0.5 sec with
   - h = 28
   - Vrf = 60kV +/- 5kV
   - Phase = 180.0

2. Bring down the Vrf for h=28
   - h = 28
   - Vrf = 60kV - 6 kV (+/- 100V)
   - Phase = 180.0
   - in dt = 1 msec

3. Bunch rotation for 1/4 synchrotron period with
   for h=28
   - h = 28
   - Vrf = 6 kV
   - Phase = 180.0
   - in dt = 86.6 msec

4. Raise the Vrf for h=28

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       h    =  28
      Vrf   =  6 kV - 60 kV (+/- 5kV)
      Phase   =  180.0
     in dt  =  1 msec
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5. Add 16% of h= 56 to linearize the wave form and rotate the bunch for 1/4 synchrotron period.

```
       h    =  28 +56
      Vrf   =  60 kV (h=28) + 12kV (h=56)
      Phase   =  180.0 (h=28) + 0 deg (h=56)
     in dt  =  28.4  msec
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6. Turn on the h=588 system and off the h=28+56 RF systems and hold h=588 system for 0.2 sec at 0.7 MV

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       h    =  588
      Vrf   =  0.7 MV
      Phase   =  180.0
     in dt  =  0.2 sec
```

C. 25-150 GeV Acceleration :
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1. Accelerate with h=588 system

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       h    =  588
      Vrf   =  2-4MV
    in  dt  =  1.8sec.
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2. Hold the Vrf   = 1.5 MV and reduce to 0.8 MV in ~.2 sec.

3. Tevatron transfer

```
       h    =  588
      Vrf   =  0.4MV
    in  dt  =  1.0 sec.
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Table 4. MI Acceleration Ramp for the above scenario:

(the exact form of real ramp may differ from this)

t (sec)	p (GeV/c)	pdot (GeV/c/sec)		
0.0	8.9	0.0	***	with h=28
1.3	8.9	0.0	***	with h=28
5.6	25.0	3.77	***	with h=28
6.351	25.0	0.0	***	with h=28
8.151	150.0	69.44	***	with h=588

Some Comments :

In the scenario discussed we assume that the beam is coming from the RR with 2.5 MHz bunch structure into the 2.5 MHz rf buckets. The buckets are fully matched. Acceleration of the bunches in the MI is carriedout mainly with 2.5 MHz rf system. ESME simulation showed that at any given time during rf mipulation (either at 8.9 GeV or 25 GeV) up to about 10% 53MHz modulations is acceptable if beam has to be seen by existing MI BPM system. I believe that this amount of modulation may not be reachable from the HLRF stand point. For example at 8.9 GeV during beam capture our Vrf(2.5MHz) specification is about 2kV. 10% of this on 53MHz system will be 200V. This is a very small voltage. Also beam loading may be an issue. However, if we want to modulate during acceleration with Vrf(2.5MHz)=60 kV, that may be o.k. Also we do not want to modulate during transition crossing. That is because the modulation due to 53 MHz would introduce micro-structure in the bunches (microwave type instability) and emittance dilution arising from this. For this purpose, during the transition crossing we may even put off modulation.

Recently we have noticed that because of the changes in the Accumulator lattice the beam from the Accumulator will not be frequency matched to RR. This has caused an additional responsibility on the MI before the beam is injected into the RR from Accumulator Ring and MI can not be used as a transferline. The beam bunches with 2.5MHz structure from AR have to be transferred to 2.5MHz buckets in MI and then match the frequency to RR, cog and transfer to RR. If the RR is not ready before the collider commissioning runs then we may as well accelerate the beam to 150 GeV as outlined in the above scheme.

We also need a tuneup procedure with proton beam from Booster which has not been included in the above scenario. We may take about 9 bunches of Booster protons capture it with 53 in MI and adiabatically debunch into 2.5 MHz bucket of ~2kV. This process will take about 3 sec. This capture can also be done with snap coalescing which is much faster but will be having larger emittance growth. Then we may accelerate the proton beam with 2.5 MHz rf system.

We call above scheme of beam acceleration in the MI as Scheme I. Other viable scheme (Scheme -II) will be bunching the beam in MI with 53 MHz rf system at 8.9 GeV/c, and accelerate using the 53 MHz system. At 150 GeV/c bunches will be coalesced before extraction from MI. We have done simulations on both schemes. The results are summarized in the below table.

Table 5 : Comparison Between Two Schemes of pbar Accelerations in MI. The longitudinal emittance are 95% emittances.

	Scheme I: Accl. with 2.5MHz and 53 MZ	Scheme II: Accl. with 53MHz
Longitudinal emittance (e_l) in MI at 8.9 GeV (95%)	1.5 eV-s	1.5 eV-s
e_l after Adiabatic bunching with 53 MHz RF system	N/A	1.6 eV-s (11 bunches with with emittance varying from 0.2 eV-s for the 3- central bunches to 0.05 eV-s for the last two bunches)
e_l at the beginning of the 25 GeV front porch (i.e.,after the transition crossing)	1.6 eV-s	~1.6 eV-s
e_l at the end of RF manipulations with 2.5 MHz system at 25 GeV	1.6 eV-s	N/A
e_l at the end of RF capture with 53 MHz system at 25 GeV	>2.2 eV-s	N/A
e_l at 150 GeV	>2.2 eV-s	1.6 eV-s
e_l after coalescing at 150 GeV	N/A	<3.5 eV-s
e_l at extraction	>2.2 eV-s	<3.5 eV-s
Cycle time	~14s(+/-3s)	~5 s

References :

1. The Fermilab Recycler Ring Technical Design Report, G. Jackson, Fermilab-TM-1991 (1996)

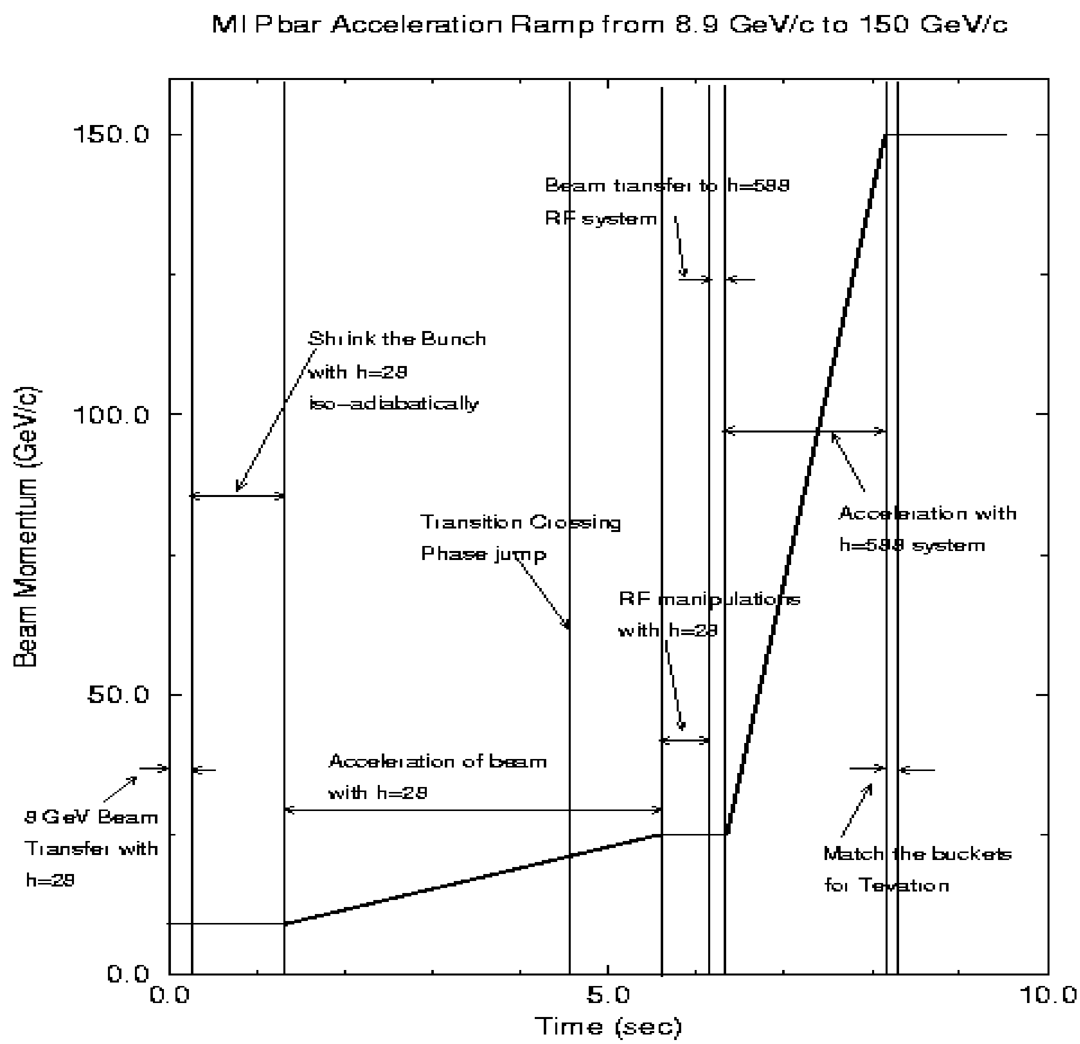

Figure 1: Pbar acceleration ramp in the MI for Scheme –I. Various stages of RF manipulations during the acceleration cycle is also indicated.

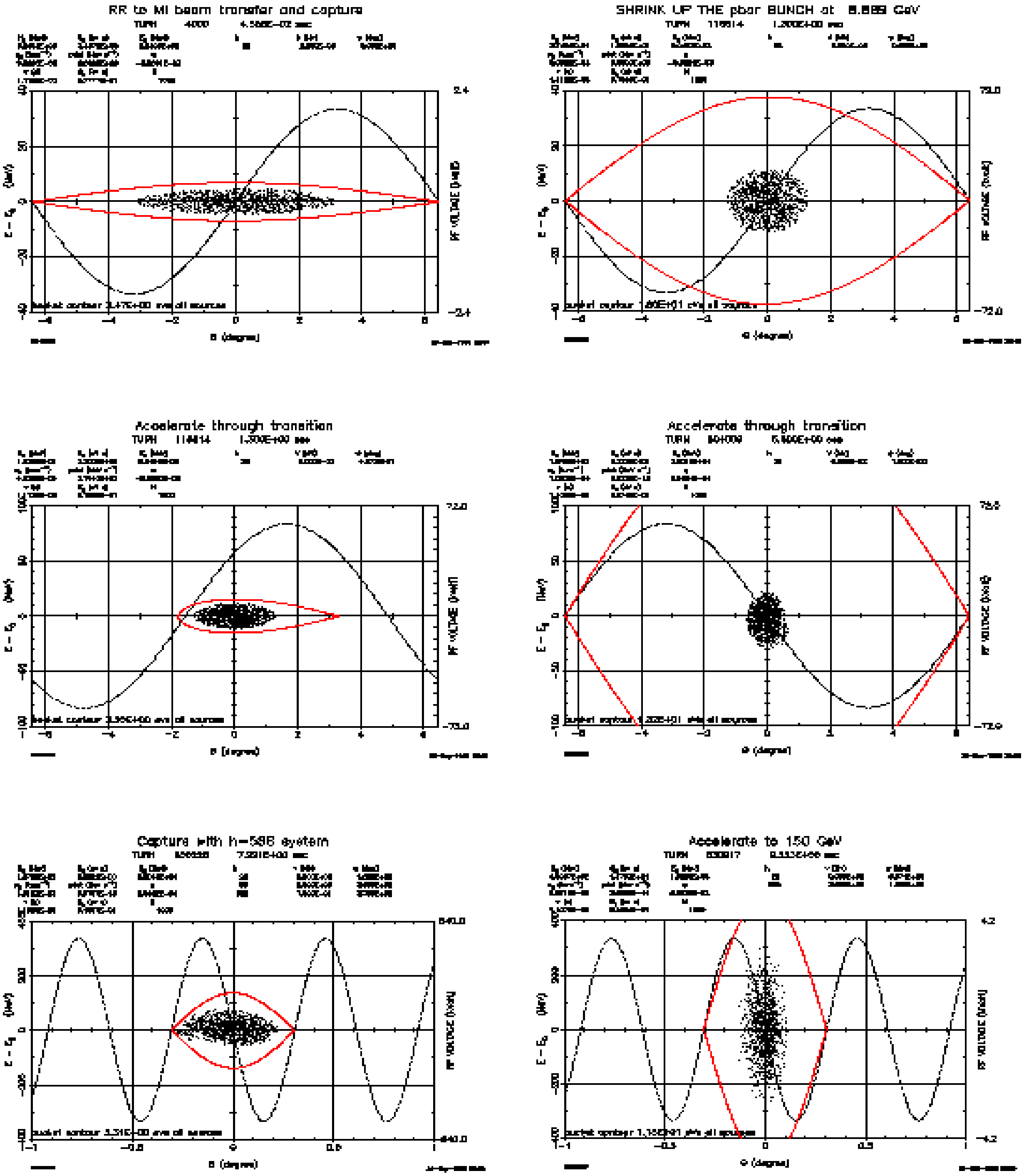

Figure 2: ESME simulations for the Scheme-I. Row 1: MI bunch at 8.9 GeV/c at injection with 2.5 MHz rf structure and after shrinking. Row 2: bunch in accelerating bucket at 8.9 GeV/c and in stationary bucket at 25 GeV/c with 2.5 MHz rf system. Row 3: bunch captured in 53 bucket at 25 GeV/c and at 150 GeV/c.