Pbar Acceleration in the Main Injector for Run II: ESME Simulations

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Abstract

The Fermilab Main Injector plays a crucial part in the success of collider RUN II [1]. The integrated luminosity delivered to the Fermilab collider detectors critically depends upon how well high intensity bunches of pbars are accelerated in MI from 8 GeV to 150 GeV with high efficiency and minimal or no emittance growth. In this paper a scheme to accelerate bunches of antiprotons coming from Accumulator Ring or Recycler Ring to Tevatron energy is presented. We have used a longitudinal beam dynamics simulation code ESME [2] to study this process. Preliminary results from an experiment to simulate above scenario using proton beam in the MI have also been presented.

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I. INTRODUCTION

The Fermilab Main Injector (MI) is a high-energy proton/antiproton synchrotron. One of the purposes of the MI is to inject protons and antiprotons to the Tevatron at 150GeV. It can properly match the needed energies of the Booster, the Accumulator (antiproton production source) and the Recycler Ring (RR) and, after accelerating protons and antiprotons match the injection beam parameters of the Tevatron. The Fermilab Main Injector plays prime part in the future high energy programs of Fermilab III [1], which include the studies of the properties of the top quark, Higgs physics and new neutrino oscillation experiments.

During the Run II of the Tevatron Collider [1] it will be necessary to transfer low emittance antiprotons (pbars) bunches from the Accumulator Ring / RR into the 2.5MHz buckets of MI. Significant RF manipulations are needed before and during the beam acceleration to 150 GeV. It is also desired to maintain the bunch intensity and emittance through out the acceleration process of the beam in the MI.

In this paper we investigate a scheme to accelerate pbars in MI to 150GeV, which include capturing the beam at 8GeV, bunch the beam in 53MHz rf buckets, accelerate it across transition energy to 35GeV, debunch in 2.5 MHz buckets, rotate, further capture in 53 MHz buckets and accelerate to 150GeV. Longitudinal beam dynamics involved in these RF manipulations is studied in detail using a Monte Carlo code ESME [2]. This study presented here should serve as a guideline to the understanding of other cases of similar nature in the MI, and further improvement of its luminosity.

ESME is one the oldest computer program that helps modeling RF manipulations needed in proton synchrotron. This code has been revised several times to incorporate many new features of longitudinal beam dynamics necessary to understand behavior of beam bunches. In the past, ESME has helped to study processes in RF manipulations included in transition crossing and coalescing which are otherwise very difficult to control. ESME is a macroparticle simulation code that permits the understanding of the evolution of proton or antiproton bunches in energy-azimuth coordinates by iterating on each particles equations of motion and has been used in the past to understand the beam dynamics in accelerators [3].

Section II of this document presents the general theory of proton synchrotrons, longitudinal motion and RF manipulations, giving emphasis on concepts such as transition energy and bunch coalescing. Details associated with the ESME computer program and how it has been used here to describe the MI are given in Section III. Results and their discussion are given in section IV. Conclusions and suggestions for further work are discussed in section V. We also present some results from the experiments carried out using the proton beam in the Main Injector, which emphasize the rf manipulations at 8 GeV.

II. THEORY

A. SYNCHROTRONS

Synchrotrons, such as the MI, are circular accelerators where particles follow a closed loop inside a vacuum beam pipe under a dipole magnetic field. They are kept focused by using quadrupole magnets, and other multipole magnets are used for higher ordered corrections. The momentum of a particle of electronic charge e is related to the dipole bend field B by,

$$P = \frac{eBR}{c}$$

where R is the radius of the orbit of the particle in the accelerator [4,5].

B. LONGITUDINAL MOTION

Acceleration is provided by radio frequency resonant cavities. The cavities operate at a resonant frequencies so that the voltage $V(t)$ changes as follows [4,5],

$$V(t) = \hat{V} \sin \phi(t)$$

$\hat{V}$ is the maximum voltage and $\phi(t)$ is the phase of the RF voltage. To be accelerated properly, the particle must arrive to the RF cavity at the right time and receive the designed energy. Such particles are called synchronous particles. This particle has a phase ϕ_s. The phase of a given particle can be expressed in terms of the azimuthal angle, θ, of the accelerator as follows:

$$\phi = -h\theta$$

where is h is the harmonic number of the voltage source.

These RF cavities operate at a frequency $\omega_{rf} / 2\pi$ and it is related to the angular velocity of the synchronous particle by

$$\omega_{rf} = h\omega_s = \frac{h\beta_s c}{R}$$

The synchronous particle then gains an energy dE whenever it goes through the acceleration gap, where:

$$dE = e\hat{V} \sin \phi.$$

Particles that do not arrive at right time are called non-synchronous particles and are offset from the parameters of the synchronous particle as follows:

$$r = r_s + \Delta r\ , \qquad \phi = \phi_s + \Delta\phi\ , \qquad \theta = \theta_s + \Delta\theta$$

$$P = P_s + \Delta P\ , \qquad E = E_s + \Delta E$$

The non-synchronous particles have a different position, energy and momentum from the synchronous particle, creating an energy and momentum spread. At low velocities (non relativistic) the more energetic particles, that is particles with more energy than the synchronous particle, reach the rf cavity gap earlier than the synchronous particles and reach the rf wave at its first $\pi/2$ part (meaning that $0 < \phi_s < \pi/2$), receiving less energy than the synchronous particle. In the same way, the less energetic particles receive more energy. This process of energy fluctuation centered in the synchronous particles is called synchrotron oscillation, and is the principle that keeps particles grouped in what are called bunches. The mechanism which keeps the particles in bunches is called phase focusing.

When the particles are relativistic (speed close to speed of light), the situation reverses. As the particle energy increases, an increase in energy is seen more in an increase in mass than in velocity. The more energetic particles go to the outer part of the orbit, and its velocity is the same as compared to the synchronous particle. Hence, they start lagging behind in time. As a result of this phenomena, the more energetic particles receive more energy and eventually they are got lost. The energy at which this effect is more important than the non-relativistic effects, previously discussed, is called transition energy, and has a relativistic parameter associated with it, called transition gamma. γ_t . The γ_t is characteristic of the lattice of the accelerator.

During the transition crossing the bunch becomes highly unstable and phase focusing will be lost. In order to prevent beam loss at this point, the phase of the RF cavities should be changed from $\phi_s < \pi/2$, to $\pi/2 < \phi_s$. By this, the more energetic particles receive less energy than the synchronous particle, and the less energetic particles receive more energy, recreating the balance. This maintains the phase stability of the particles.

Related to the transition, a parameter is used and is called the slip factor η given by:

$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma_s^2}$$

The synchrotron oscillation frequency is given by:

$$\Omega_{syn} = \sqrt{-\frac{e\hat{V}\eta\omega_s \cos\phi_s}{2P_s R}}$$

where ω_s and P_s are the angular velocity and momentum of the synchronous particle, respectively.

The general form of the equations of motion for the particles is given by [6]:

$$H(q, y) = \frac{1}{2}\omega_{rf}^2 \frac{\eta}{\beta^2 E_s} y^2 + \frac{eV}{2\pi h}\left[q\sin\phi_s + \cos(q + \phi_s)\right]$$

where

$$q = \phi - \phi_s, \qquad y = \frac{E - E_s}{\omega_{rf}}$$

From the above equations two areas in phase-space can be identified. The first area corresponds to stable synchronous oscillations around a synchronous particle and is called a bucket. The other is that of non-stable oscillations, and particles in this area will ultimately be lost. The separating line of these two areas is called separatrix and is defined by:

$$\frac{A}{2}y^2 + B[\phi \sin\phi_s + \cos\phi - (\pi - \phi)\sin\phi_s - \cos(\pi - \phi_s)] = 0$$

with [6,7]

$$A = \omega_{rf}{}^2 \frac{\eta}{\beta^2 E_s} = \left(\frac{hc}{R}\right)^2 \left(\frac{\eta}{E_s}\right), \qquad B = \frac{eV_{rf}}{2\pi h}$$

If the RF source has a phase of 0 or π, it is said to be a stationary bucket. Any other phase will be corresponding to an accelerating or decelerating bucket, also referred as a moving bucket. The bucket area, S, of a stationary bucket in terms of A and B is given by [6,7]:

$$S = 16\sqrt{\frac{B}{|A|}}$$

This quantity is usually expressed in units of eVs.

The particles in a bucket can perform synchrotron oscillations and if they occupy the entire bucket then the bucket is full. The total phase-space area occupied by the particles in a bucket is called longitudinal emittance of the bunch S_b, and is of extreme importance during acceleration as well as beam transfer from one machine to another machine. The bucket is referred to as matched to a given bunch if the ratio:

$$\Re = S/S_b \approx 2.4$$

The longitudinal emittance of a bunch in terms of bucket length Δ is [7]:

$$S_b = S\left[\frac{\pi}{64}\Delta^2\left(1 - \frac{5}{384}\Delta^2\right)\right]$$

where $\Delta < 4$ radians. For $\Delta > 4$ radians the evaluation of S_b is more complicated [7].

C. RF MANIPULATIONS

The RF manipulations are integrated parts of beam storage, beam acceleration and beam transfer from one accelerator to the another. The previous formulas are of extreme importance to understand RF manipulations. The final goal of these manipulations, in general, is to get intense, isolated bunches. Many RF manipulations have to be performed keeping the emittance constant. The RF manipulations must be sufficiently slow so that the particles do not leave the buckets until the bucket area is reduced below the bunch area. The rate of change of an RF bucket is related to the change in bucket area by,

$$\frac{dS}{S} = a_c \frac{dT}{T_{syn}}$$

where a_c is the adiabaticity parameter and, T_{syn} is synchrotron period of the synchronous particle. If a_c is less than unity, the process is said to be adiabatic. This is usually accomplished by slowly varying the parameter such as peak RF voltage and RF phase.

Bunching is a process where a bunch is divided into multiple bunches of higher harmonic. Decreasing the lower harmonic voltage while increasing the higher harmonic voltage can perform this manipulation. If done properly, the bunch is chopped in to matching buckets of higher frequency, and the sum of the emittance of these has to be the same as the total emittance at the beginning.

The reverse of this process is called debunching, and it is associated with bunch coalescing [8,9,10]. Bunch coalescing is the process where a group of bunches are debunched and combined into one bunch of lower harmonic. If needed, the bunch in lower harmonic is rotated and captured in a bucket of higher harmonic. The debunching process can be performed by applying a lower harmonic voltage, while decreasing the higher harmonic voltage. By doing this adiabatically one can preserve the longitudinal emittance.

A Bunch squeezing is one standard way of reducing the bunch length. In this process the voltage is slowly increased, as a result the momentum spread increases. This may be desired to change the phase-space shape of the bunch for the manipulations that follow.

One of the steps involved in bunch coalescing is bunch rotation, where the voltage is increased almost instantly within a time interval much less than the synchrotron oscillation period. This increase makes the bunch to rotate, so the initial bunch length and bunch height are interchanged without any emittance growth. If the momentum spread has not been properly adjusted, some particles may lag behind while the rotation, distorting the bunch in to an 'S' shape that results in beam loss and emittance growth in the bunch capture. The bunch rotation process ends one quarter of synchrotron oscillation after it started with capturing of the bunch.

III. SIMULATIONS

A. ESME

The macro-particle simulations program version esme2000 has been used here to optimize the parameters of the needed RF manipulations. This program uses as a main system of coordinates the energy difference from the synchronous particle, and the phase difference from the synchronous particle, giving an insight into the quantitative and qualitative aspects of how to perform the process in the real system. This program tracks the energy-azimuth distribution of a map corresponding to the single-particle equations of motion [2]:

$$\Theta_{i,n} = \frac{\tau_{s,n-1}}{\tau_{s,n}}\Theta_{i,n-1} + 2\pi\left(\frac{\tau_{i,n}}{\tau_{s,n}} - 1\right)$$

$$E_{i,n} = E_{i,n-1} + eV\left(\phi_{s,n} + h\Theta_{i,n}\right) - eV\left(\phi_{s,n}\right)$$

where this equations give the azimuth and energy for the particle i after n turns of the synchronous particle s and period τ. The program uses macro-particles to represent a group of protons or anti-protons, so a larger number of macro-particles describes more closely the real behavior of the particles.

The program receives as an input file with parameters related to the accelerator, such as the average radius for the central orbit, gamma transition, kinetic energy of the central orbit, RF waves (harmonic, maximum voltage, phase). The system can be populated with the desired longitudinal emittance and distribution. Different types of graphical outputs can be selected, of special interest are the phase-space graphics.

B. MAIN INJECTOR PARAMETERS

The Main Injector is capable of accelerating 8.889GeV/c protons and pbars coming from the Booster and the Accumulator Ring/Recycler, respectively, to 150 GeV/c. Finally the 150 GeV beam will be injected to the Tevatron. For the ESME simulations, the parameters like the gamma transition (21.8), reference radius for central orbit (528.57m), and radius of beam pipe (0.0508m) are used. Also, three RF systems were used: 2.5MHz (h=28), 5MHz (h=56). and 53MHz (h=588) [1]. Additional specifications related to the MI are given in Table I. The multi-particle effects like space charge forces, broadband impedance and beam loading were neglected for these simulations.

Final typical Dipole ramp used in these simulations is shown in Figure 1.

IV. RESULTS AND DISCUSSION

Using the parameters given above, the MI has been modeled to perform the desired simulations for pbar acceleration from 8 GeV to 150 GeV. The results of ESME calculations are shown in Table II and Figures 2-7. A bunch of pbars of emittance 1.0 eVs with an elliptical distribution is populated in a matched 2.5MHz rf bucket. This bunch will very closely mimic the bunches from Accumulator Ring (0.5 eV-sec) or Recycler Ring (1.5 eV-sec). The peak amplitude of the 2.5MHz voltage source is taken to be 2.5kV. To keep the time variation of the rf voltage more linear actoss zero phase angle about 16% h=56 wave form is added to h=28 wave form. The peak rf voltage for h=56 system was about 400V.

In the scheme presented here the pbar acceleration is performed in 53 MHz rf buckets. Therefore, prior to the beam acceleration it is necessary to rebunch the 2.5 MHz bunch into 53MHz buckets. At .0549 seconds, a 53MHz voltage source is added, starting with a low voltage of 5kV, increasing it adiabatically to 0.5MV while adiabatically reducing the 2.5MHz voltages from 2.5kV to zero along with its corresponding 5 MHz system. The process takes about one second. This produces about 9 smaller bunches. The emittance at this point went up to 1.1 eVs, or an about 10% growth.

During 1.68 sec to 1.99 sec the pbar bunches are accelerated from 8 GeV to 35 GeV with $dP/dt \approx 240$ GeV/c/sec at transition. It is desired to go to as far as 35GeV because of power supplies limitations of MI. During transition crossing we have used the standard rf phase jump to prevent the beam loss and maintain the phase stability. At 35GeV the longitudinal emittance was 1.2eVs, indicating about 20% emittance growth. This growth seems to be related to an instability observed just after gamma transition. The bunches were off-centered, and then assumed a distorted diagonal shape. The bunches are then captured using a 83 kV voltage at 2.0 seconds without any particle loss.

The voltage from the 53MHz system was reduced adiabatically starting at 2.0 sec. At 2.1 sec the 2.5MHz rf system is added with 1kV of peak voltage. The bunches are merged into one by reducing the peak voltage of both systems (2.5Hz and the 53MHz), adiabatically. The final peak rf voltage needed on 2.5 MHz system is found to be about 30V. This process takes about 8.0 seconds at 35 GeV. This left the bunches with a final emittance of 1.4 eVs.

At this stage an adiabatic bunch squeeze is performed. This process took 9 sec. During this period the bunch was squeezed by increasing the voltage adiabatically to 1.25kV using 2.5 MHz rf system. While performing this rf manipulation no beam loss or emittance growth is observed.

Abruptly increasing the voltages to 60kV in the 2.5 MHz rf system harmonic and to 1kV in the 5 MHz rf system, bunch rotation is accomplished in .028 sec, and the bunch was captured using a 53MHz RF voltage of 620kV. During capture emittance grew to 1.5eVs and 0.51% of the particles are lost.

From 17.3 sec to 19.23 sec the bunch is accelerated to 150GeV, resulting in a total loss of 0.6% particles and no emittance. The Table II summarizes the results from ESME simulations. For a more complete description of the RF manipulations, see appendix with its ESME input file.

We have also carried out more simulations with different initial conditions for the beam. The overall results are very similar to the previous case. For higher emittance more particle loss is observed.

Almost all of the rf manipulations described above can be tested on proton beam to understand the beam dynamics. We have conducted experiments with the Fermilab Booster proton beam and studied the beam dynamics at 8 GeV. The bunches in 2.5 MHz rf buckets are produced using 3-5 bunches from Booster. Typically, we had 0.5-1 mAmp of protons per 53 MHz bunches. The total number of protons in the 2.5 MHz rf buckets were in the range of 2.5-5 mAmp, which is comparable to the pbar bunch intensity during the Run II [1]. The Figure 8 shows the rf voltage curve (top picture) and the resistive wall pick monitor responses (bottom picture) during the rf manipulation at 8 GeV. The Table III displays the measured longitudinal emittance corresponding to the case shown in Figure 8. The Figure 8 and Table III are shown to represent the proof of principle not for quantitative comparison, because, the initial conditions of beam and rf voltages used in the experiment are not quite similar to the one used in simulation.

V. CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

Preserving longitudinal emittance during acceleration of pbars in the Main Injector is essential for a high luminoscity in Tevatron collider runs. A working scheme for capturing pbars at 8GeV, bunching them, accelerating to 35GeV, coalescing and finally accelerating to 150GeV has been presented. The transition crossing was one of the difficult part in the simulation. It is critical to choose right time parameters, particularly for bunching, debunching and squeezing. It was also shown that with another case the scheme still works under reasonable conditions, although some adjustments may be necessary.

For future work it would be desirable to reduce the coalescing time, and study the possibility of further longitudinal emittance growth reduction, and prevent particle loss.

Considering the space charge forces, beam loading and broadband impedances, are essential for a more accurate representation of the MI.

VI. ACKOWLEDGEMENTS

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REFERENCES

[1] "Run II Handbook" March 20, 1998. http://www-bd.fnal.gov/runII.index.html Accessed July20, 2000.

.[2] J. MacLachlan and J.-F. Ostiguy. "User's Guide to ESME 2000." March 2, 2000. http://www-ap.fnal.gov/ESME/esme-manual/esme-manual.html, accessed July 20, 2000; J. MacLachlan. "Difference Equations for Longitudinal Motion in a Synchrotron." Fermilab pre-print FN-529, December 15, 1989

[3] C.M. Bhat *et. al* ., "Transition crossing in proton syncrhrotrons using a flattened rf wave." Phys. Rev. E 55, 1 (1997), pp 1028-1034 ; S. Stahl and S.A. Bogacz. "Coupled-Bunch instability in a circular accelerator and possible cures: Longitudinal-phase-space simulations", Phys. Rev. D 37, 5 (03/1988), pp 1300-1036

[4] W.T. Weng. “Fundamental of Longitudinal Motion.” AIP Conference Proceedings 184, Vol. 1. Eds. Melvin Month and Margaret Dienes. New York: American Institute of Physics, 1989, pp. 243-287.

[5] J. Le Duff. “Longitudinal Beam Dynamics in Circular Accelerators.” CERN Accelerator School, Fifth General Accelerators Physics Course. Vol. 1. Ed. S. Turner. CERN 94-01, Jan/1994, pp 289-311.

[6] P.S. Martin and S. Ohnuma.“Longitudinal Phase Space in Circular Accelerators.” Aip Conference Proceedings 184, Vol 2. Eds Melvin Month and Margaret Dienes. New York: American Institute of Physics, 1989, pp. 1941-1968.

[7] S. Ohnuma. “The Beam and the Bucket.” Fermilab pre-print TM-1381, January 1986.

[8] J. MacLachlan. “Debunching into a Bucket of Lower Harmonic Number.” Fermilab pre-print TM-1504, December 9, 1987.

[9] J. MacLachlan. “Limits to Coalescing and Bunch Rotation for pbar Production Resulting from Microwave Instability”, In Proc. of the Fermilab III Instabilities Workshop, Fermilab internal note TM-1696 (June 1990) p70.

[10] J.Griffin. “Bunch Coalescing”, In Proc. of the Fermilab III Instabilities Workshop, Fermilab internal note TM-1696 (June 1990) p88.

TABLE I

Main Injector Parameter List [1]

Circumference	3319.419 m
Injection Momentum	8. 9 GeV/c
Peak Momentum	150 GeV/c
Max. Courant-Snyder Beta Function (ß max)	57m
Maximum Dispersion Function	1.9 m
Phase Advance per Cell	90 degrees
Nominal Horizontal Tune	26.425
Nominal Vertical Tune	25.415
Natural Chromaticity (H) -	-33.6
Natural Chromaticity (V)	-33.9
Transverse Admittance (@ 8.9 GeV)	> 40πmm-mr
Longitudinal Admittance	> 0.5 eVs
Transverse Emittance (Normalized)	12πmm-mr
Longitudinal Emittance 0. 2 eVs	0.2 eVs
Harmonic Number (@53 MHz)	588
RF Frequency (Injection)	52.8 MHz
RF Frequency (Extraction)	53.1 MHz
RF Voltage	4 MV
Transition Gamma	21.8
Superperiodicity	2
Number of Straight Sections	8
Length of Standard Cell	34.5772 m
Length of Dispersion-Suppressor Cell	25.9330 m
Number of Dipoles	216/128
Dipole Lengths	6.1/4.1 m
Dipole Field (@150 GeV)	17.2 kG
Dipole Field (@8.9 GeV)	1.0 kG
Number of Quadrupoles	128/32/48
Quadrupole Lengths	2.13/2.54/2.95 m
Quadrupole Gradient at 150 GeV	200 kG/m
Number of Quadrupole Busses	2

TABLE II

The emittance budget for pbar in MI at various stages of acceleration. These calculations have been carried out using ESME without including collective effects like space charge effects, impedance and beam loading.

Description	**Fraction of**	**Emittance**	**Total Emittacne**	**Emittance**
	Particles	**(eV-s)**	**(eV-s)**	**Growth**
8 GeV Front Porch				
Bunch in 2.5 MHz	100%	1	1	0%
Bucket				
Bunches in 53 MHz				
Buckets				
Central Bunch	20%	0.18		
	17%	0.17		
	13%	0.15		
	8%	0.11		
	2%	0.04	1.1	10%
35GeV Front Porch				
Bunches in 53MHz				
Buckets				
Central Bunch	20%	0.2		
	17%	0.19		
	13%	0.16		
	8%	0.11		
	2%	0.04	1.2	20%
Bunch in 2.5 MHz	100%		1.4	40%
Bucket				
Bunch in 53 MHz	100%		1.4	40%
Bucket				
150 GeV Flattop				
Bunch in 53 MHz	100%		1.5	50%
Bucket				

TABLE III :

The measured emittance of proton beam in MI in 2.5 MHz rf buckets and 53 MHz rf buckets. The measured emittances have an error of about 20% which mainly comes from the uncertainty in bunch length determination and rf voltage.

The stationary Bucket Area of 2.5MHz system:		Vrf (kV) =	7	kV
		A=	2.52E+02	
		B=	39.78873577	
		Bucket Area=	6.36E+00	eVsec
Bunch Number	**Full bunch width**	**Beam emittance**		
	in radian	**(eV-s)**		
1	2	**1.2E+00**	<- Bunch in 2.5 MHz bucket	

The stationary Bucket Area of 53MHz system:		Vrf (kV) =	890	kV
		A=	1.11E+05	
		B=	240.897788	
		Bucket Area=	7.45E-01	eV-sec
Bunch Number	**Full bunch width**	**Beam emittance**	**Full bunch width**	
	in radian	**(eV-s)**	**in nsec**	
1	1.3	5.7E-02	3.8E+00	
2	1.9	1.2E-01	5.7E+00	
3	2.2	1.7E-01	6.6E+00	
4	2.5	2.1E-01	7.6E+00	
5	2.5	2.1E-01	7.6E+00	
6	2.5	2.1E-01	7.6E+00	
7	2.5	2.1E-01	7.6E+00	
8	2.0	1.4E-01	6.2E+00	
9	1.7	1.0E-01	5.2E+00	
10	1.4	7.1E-02	4.3E+00	
		1.5E+00	<- The bunches in 53 MHz buckets	

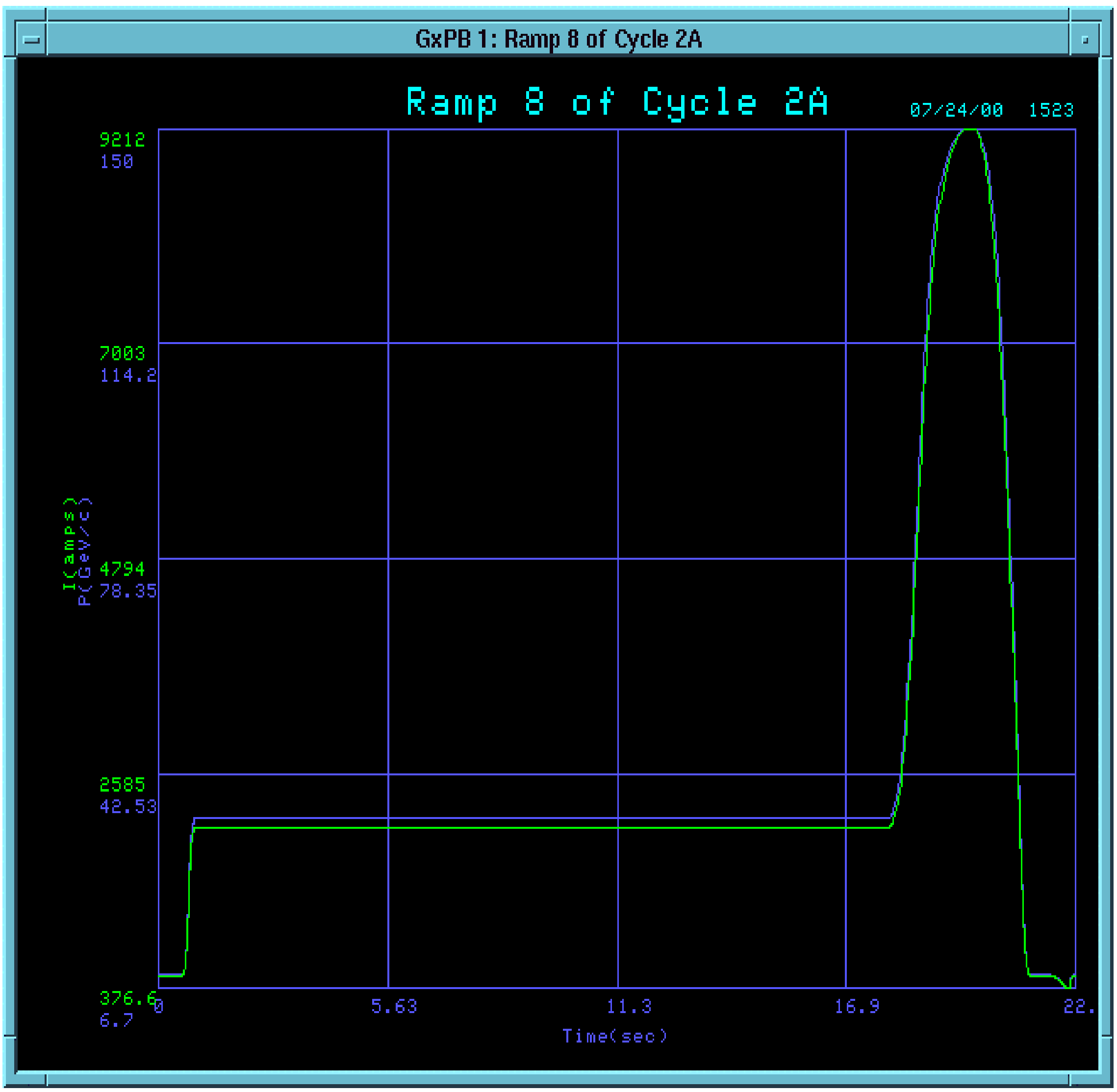

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FIG 1: The dipole ramp used in ESME simulations of pbar acceleration

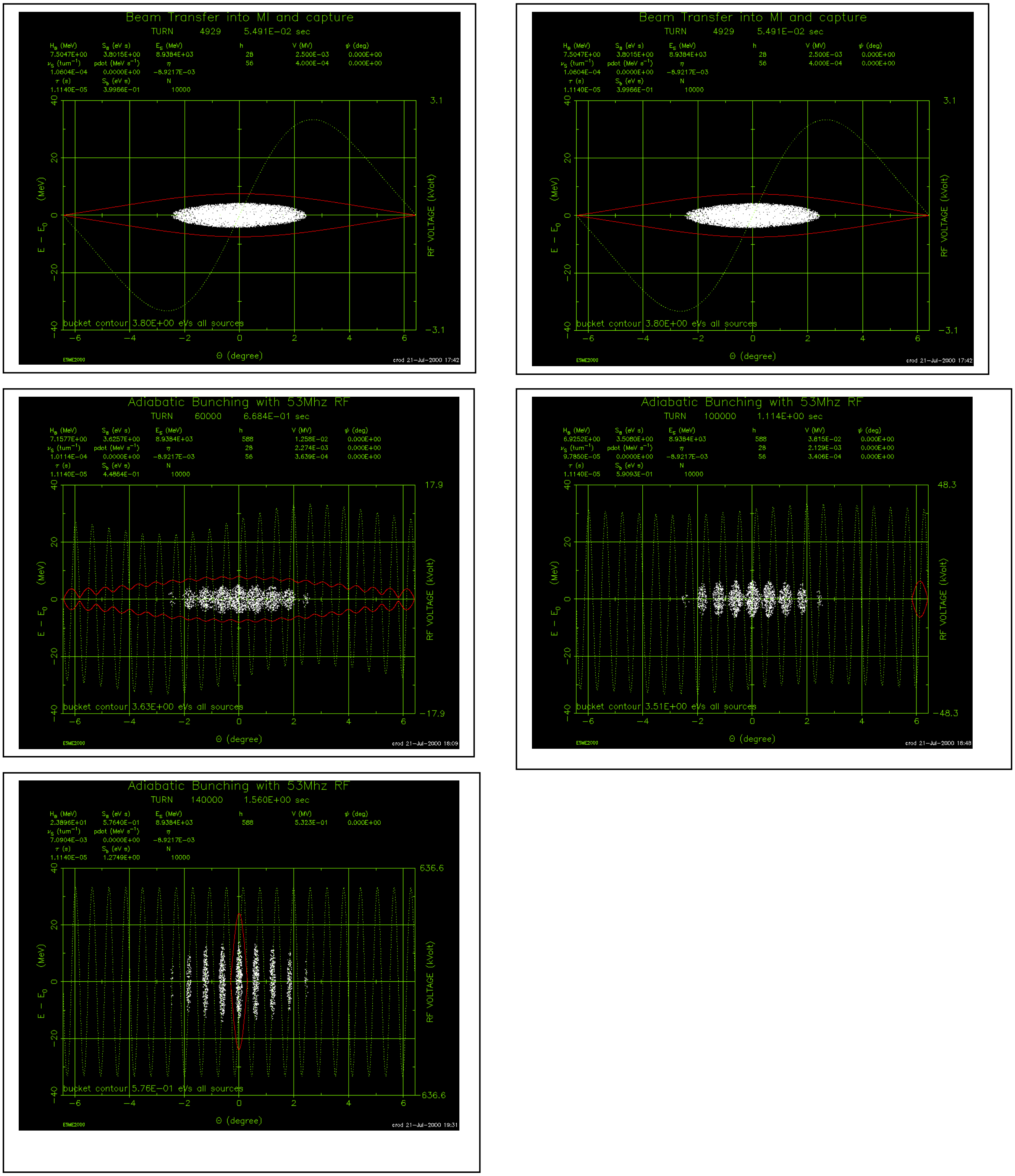


FIG 2. From Left to Right and Top to Bottom: Succesful bunching from 2.5MHz to 53MHz

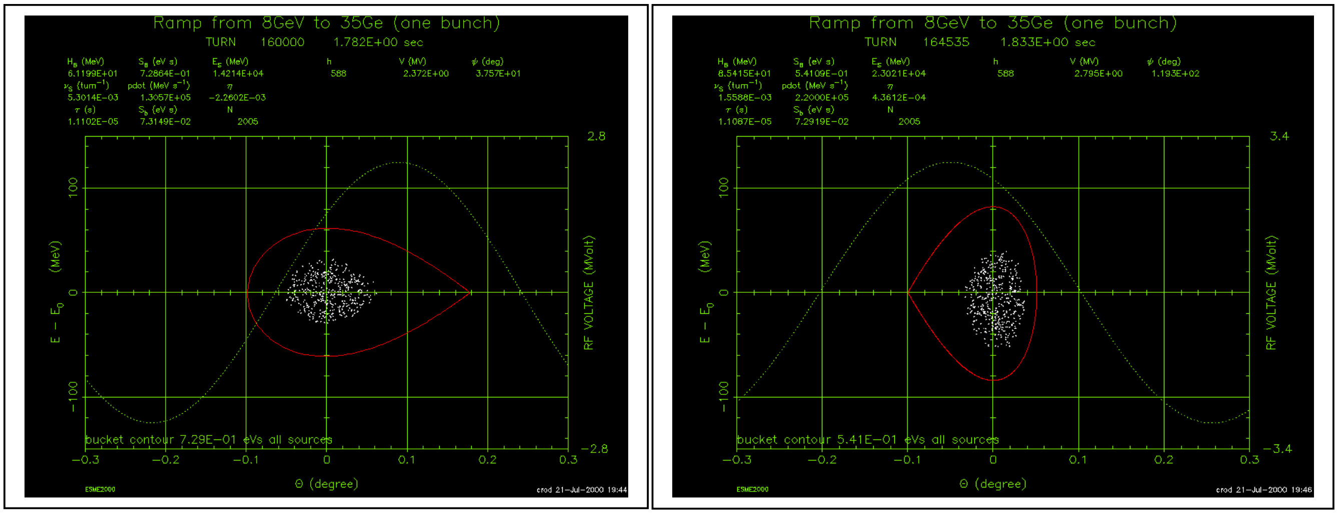


FIG 3. Accelerating central bunch before (left) and after (right) transition.

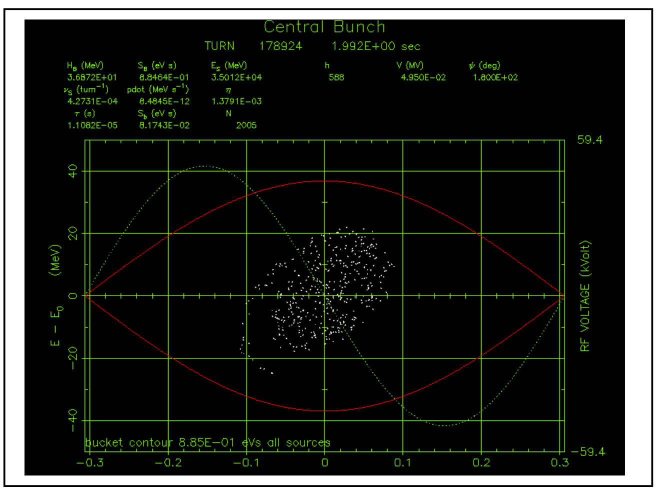


FIG 4. Central bunch. Notice the rotated shape. This creates emittance growth.

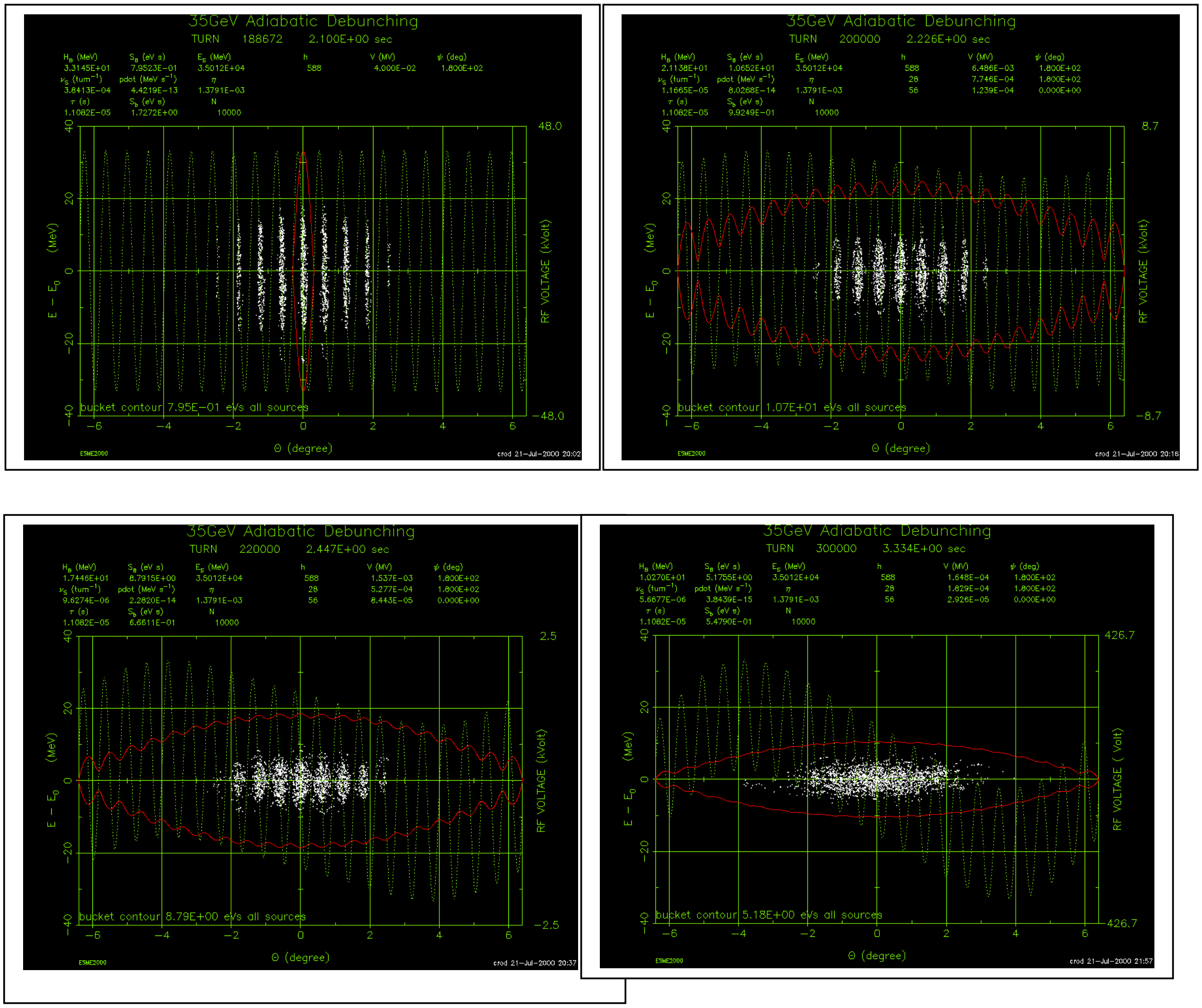


FIG 5. From Left to Right and Top to Bottom a secuence of adiabatic debunching can be observed.

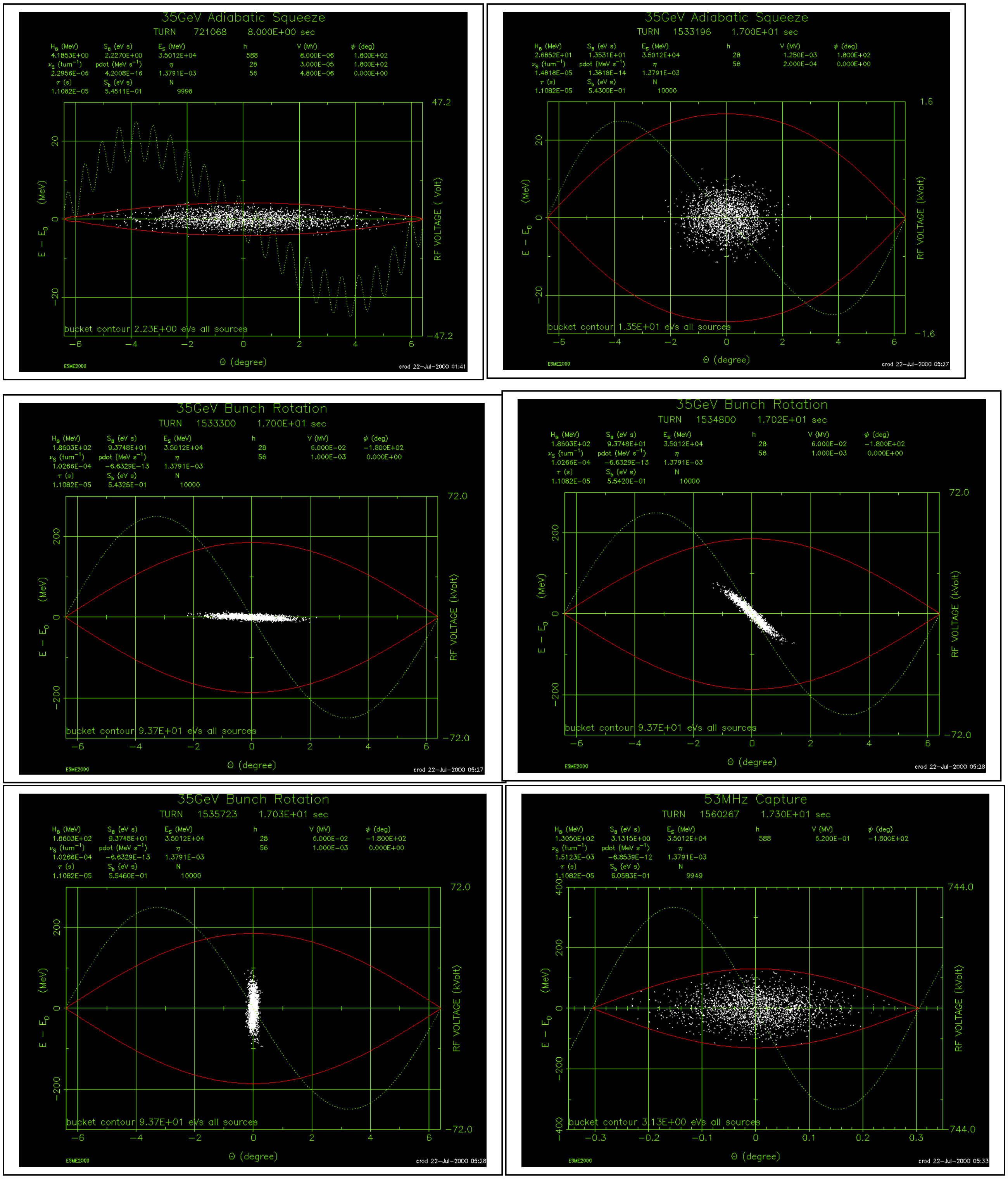


FIG 6. Bunch Squeezing, Rotation and Capture

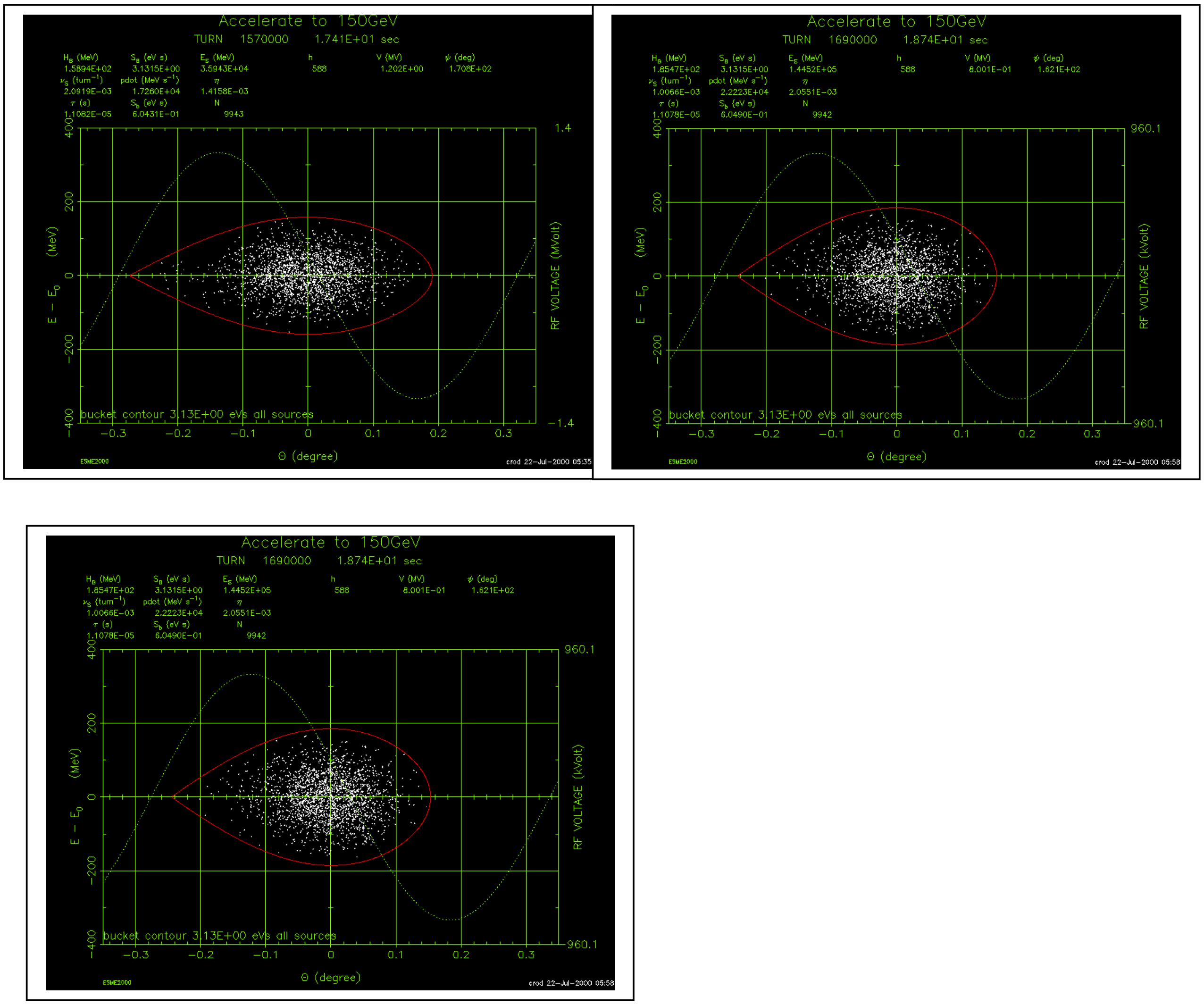
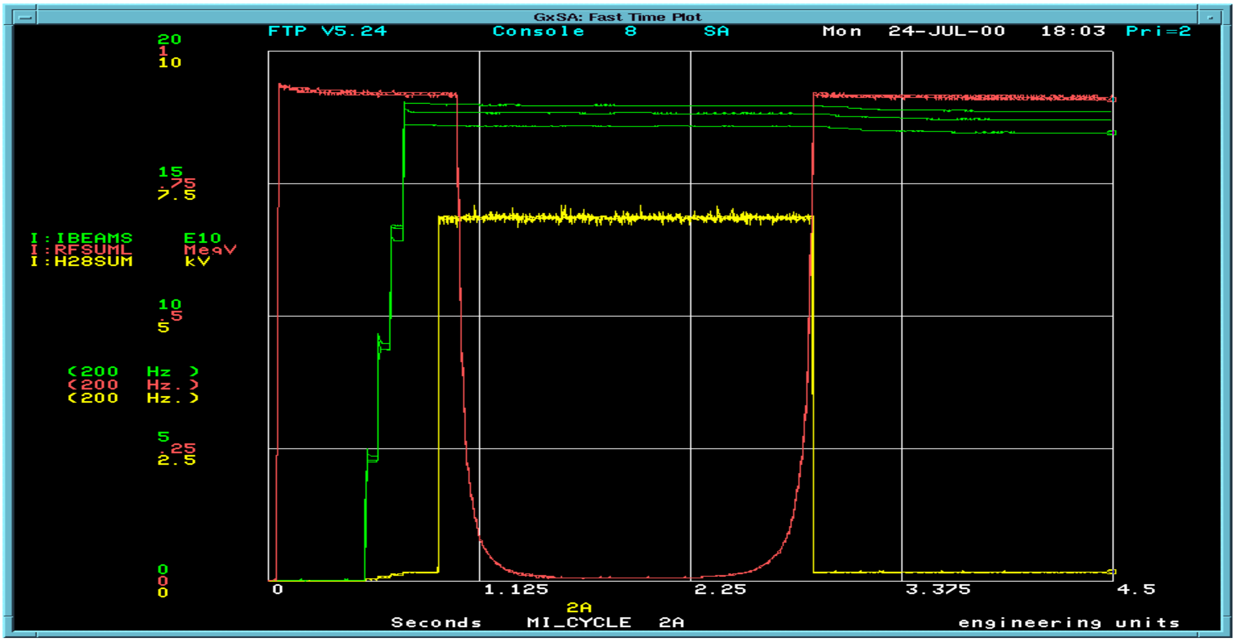


FIG 7. Acceleration to 150GeV



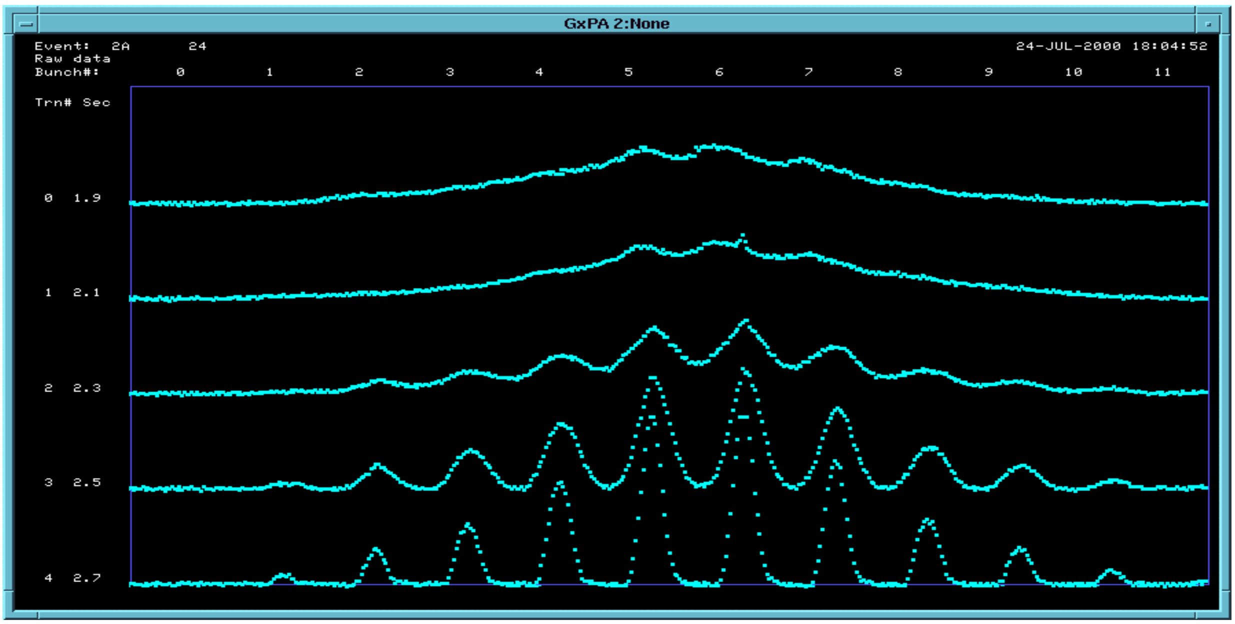


FIG. 8: The protom beam rf manipulations at 8 GeV. I:RFSUML and I:H28SUM represent the rf peak voltage during the rf manipulations, respectively for 53 MHz rf system and 2.5 MHz rf system. The rf manipulations from 0.0 sec to 1.5 sec is performed to prepare bunches in 2.5 MHz rf buckets. The rest of the manipulations aresimilar to that required for pbar acceleration in MI.. The resistive wall pickup monitor response is show in the figure below. The first trace represents the bunches in 2.5 MHz rf buckets and the last trace is for bunches in 53 MHz rf buckets.

```
W++++++++++++++++++++++++++++++++++++++++++++++++++
W PBar Acceleration from 8Gev to 35GeV to 150Gev
W++++++++++++++++++++++++++++++++++++++++++++++++++
Y         Dynamic Memory Allocation
$MEMORY    KNPHASE=10000         $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
R           FermiLab Main Injector
$RING    REQ=528.57
    P0I=8.889E3    P0IDOT=0.
    GAMMAT=21.836    ALPHA1=0.00156
       FRAC=28.    PIPRAD=0.0508      $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
A        Harmonic=28 (2.5MHz)
$RF NRF=2 H=28,56    VI=.0025,0.0004    VKON=.F.
    KURVE=0,0    VF=.0025,.0004
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-40.    DEPMAX=40.
    MPLOT=10000    IRF=0
    ICONTUR=1    NPJMP=1
    THPMIN=-6.4286    THPMAX=6.4286
    NBINTH=50    DELCON=0.005
    PLTSW(8)=.F.    PLTSW(10)=.F.
    PLTSW(12)=.F.,.F.,.F.,.F.
    PLTSW(5)=.T.
    titl='Beam Transfer into MI and capture'
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
P
$POPL8    KIND=14  SBNCH=1.0  NPOINT=10000
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
T
$CYCLE TSTOP=0.0549    HISTRY=.T.
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
A       Adiabatic from 2.5MHz to 53MHz
$RF    NRF=3    H=588,28,56    VKON=.T.
     VI=.005,.0025,.0004    VF=.5,.002,.00032
    PSII=0.,0.,0.    KURVE=2,2,2
    TVBEG=0.0549,0.0549,0.0549
    TVEND=1.5489,1.5489,1.5489
    ISYNC=0
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-40.    DEPMAX=40
    MPLOT=20000    IRF=0
    ICONTUR=1    NPJMP=5
    THPMIN=-6.4286    THPMAX=6.4286
    DELCON=0.005    NBINTH=50
```

```
    PLTSW(8)=.F.    PLTSW(10)=.F.
    PLTSW(12)=.F.,.F.,.F.,.F.
    PLTSW(5)=.T.
    TITL='Adiabatic Bunching with 53Mhz RF'
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++
T
$CYCLE    TSTOP=1.5489    HISTRY=.T.   $END
W++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++
A           Harmonic=588 (53MHz)
$RF    NRF=1    H=588
    ISYNC=0    VI=.5    VF=.9916
    PSII=0.0    KURVE=2
    TVBEG=1.5489    TVEND=1.649
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++
T
$CYCLE TSTOP=1.649    HISTRY=.T.
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=-.3062    THPMAX=.3062
    TITL='Central Bunch'    ICONTUR=1
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++
D
W emittance at the end of the 8 GeV RF manipulations
W++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=.3062    THPMAX=0.9183
    TITL='Bunch Number 1'    ICONTUR=1
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=0.9183    THPMAX=1.5306
    TITL='Bunch Number 2'    ICONTUR=1
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=1.5306    THPMAX=2.14287
    TITL='Bunch Number 3'    ICONTUR=1
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++
```

```
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=2.14287    THPMAX=2.7551
    TITL='Bunch Number 4'    ICONTUR=1
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=2.7551    THPMAX=3.3673
    TITL='Bunch Number 5'    ICONTUR=1
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=3.3673    THPMAX=3.9795
    TITL='Bunch Number 6'    ICONTUR=1
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=3.9795    THPMAX=4.5917
    TITL='Bunch Number 7'    ICONTUR=1
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
W++++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=4.5917    THPMAX=5.2039
    TITL='Bunch Number 8'    ICONTUR=1
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    MPLOT=90000    IRF=0
    ICONTUR=1
    THPMIN=-6.4286    THPMAX=6.4286
    DELCON=0.005    NBINTH=50
    PLTSW(8)=.F.    PLTSW(10)=.F.
    PLTSW(12)=.F.,.F.,.F.,.F.
    PLTSW(5)=.T.
    TITL='Adiabatically Bunched at 53MHz'
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
S
cesar8gev.dat
W++++++++++++++++++++++++++++++++++++++++++++++++++
```

```
O
$GRAPH DEPMIN=-40.    DEPMAX=40.
    MPLOT=90000    IRF=0
    ICONTUR=1
    THPMIN=-6.3    THPMAX=6.3
    DELCON=0.005    NBINTH=50
    PLTSW(8)=.F.    PLTSW(10)=.F.
    PLTSW(12)=.F.,.F.,.F.,.F.
    PLTSW(5)=.T.
    TITL='Bunched at 53MHz'
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
R       Main Injector Ramp 1
$RING    KURVEB=6
    TF=1.6845
    P0F=8.96E3    P0FDOT=6E3
    JNRAMP=.T.
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH TITL='Start of Ramp (before transition)'
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
A
$RF    NRF=1    H=588
    ISYNC=1       HOLDBA=.F.
    KURVE=4       KURVP=4
    VI= .9916       VF=0.0495
    PSII=0.0    PSIF=180.0
    TVBEG= 1.649    TPBEG= 1.649
    TVEND=1.99197    TPEND=1.99197
    FILCRV='vramp8to35.dat'
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
W    The VRamp was generated using .8EVs
W    of bucket area in the mirf program.
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-200    DEPMAX=200
    THPMIN=-6.3    THPMAX=6.3
    TITL='Ramp from 8GeV to 35GeV'
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
T
 $CYCLE TSTOP=1.6845    HISTRY=.T.
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-200    DEPMAX=200
```

```
    THPMIN=-6.3    THPMAX=6.3
    TITL='Ramp from 8GeV to 35GeV'
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
R        Main Injector Ramp 2
$RING    KURVEB=6
    TF=1.72
    P0F=9.5E3    P0FDOT=20E3
    JNRAMP=.T.
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
T
 $CYCLE TSTOP=1.72    HISTRY=.T.
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-150    DEPMAX=150
    THPMIN=-.3    THPMAX=.3
    MPLOT=10000
    TITL='Ramp from 8GeV to 35Ge (one bunch)'
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
R        Main Injector Ramp 3
$RING    KURVEB=6
    TF=1.8325
    P0F=23E3    P0FDOT=220E3
    JNRAMP=.T.
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
T
 $CYCLE TSTOP=1.8325    HISTRY=.T.
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-150    DEPMAX=150
    THPMIN=-.3    THPMAX=.3
    MPLOT=10000
    TITL='Ramp from 8GeV to 35Ge (one bunch)'
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
R        Main Injector Ramp 4
$RING    KURVEB=6
    TF=1.85
    P0F=26.5E3    P0FDOT=180E3
    JNRAMP=.T.
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
T
 $CYCLE TSTOP=1.85    HISTRY=.T.
                  $END
```

```
W+++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-200    DEPMAX=200
    THPMIN=-.3    THPMAX=.3
    TITL='Ramp from 8GeV to 35Ge (one bunch)'
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-200    DEPMAX=200
    THPMIN=-6.3    THPMAX=6.3
    TITL='Ramp from 8GeV to 35GeV'
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W
W
W+++++++++++++++++++++++++++++++++++++++++++++++++
R        Main Injector Ramp 5
$RING    KURVEB=6
    TF=1.90106
    P0F=32.5E3    P0FDOT=55E3
    JNRAMP=.T.
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
T
 $CYCLE TSTOP=1.90106    HISTRY=.T.
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-200    DEPMAX=200
    THPMIN=-6.3    THPMAX=6.3
    TITL='Ramp from 8GeV to 35GeV'
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
R        Main Injector Ramp 6
$RING    KURVEB=6
    TF=1.99197
    P0F=35E3    P0FDOT=0.0
    JNRAMP=.T.
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
T
 $CYCLE TSTOP=1.99197    HISTRY=.T.
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-200    DEPMAX=200
    THPMIN=-6.3    THPMAX=6.3
    TITL='Ramp from 8GeV to 35GeV'
```

```
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++
D
W
W     emiitance at 35 GeV before RF manipulations
W++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=-.3062    THPMAX=.3062
    TITL='Central Bunch'    ICONTUR=1
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=.3062    THPMAX=0.9183
    TITL='Bunch Number 1'    ICONTUR=1
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=0.9183    THPMAX=1.5306
    TITL='Bunch Number 2'    ICONTUR=1
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=1.5306    THPMAX=2.14287
    TITL='Bunch Number 3'    ICONTUR=1
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=2.14287    THPMAX=2.7551
    TITL='Bunch Number 4'    ICONTUR=1
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=2.7551    THPMAX=3.3673
    TITL='Bunch Number 5'    ICONTUR=1
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++
D
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=3.3673    THPMAX=3.9795
    TITL='Bunch Number 6'    ICONTUR=1
```

```
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=3.9795    THPMAX=4.5917
    TITL='Bunch Number 7'    ICONTUR=1
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
W+++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    THPMIN=4.5917    THPMAX=5.2039
    TITL='Bunch Number 8'    ICONTUR=1
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-50.    DEPMAX=50.
    IRF=0       ICONTUR=1
    THPMIN=-6.4286    THPMAX=6.4286
    DELCON=0.005    NBINTH=50
    PLTSW(8)=.F.    PLTSW(10)=.F.
    PLTSW(12)=.F.,.F.,.F.,.F.
    PLTSW(5)=.T.
    TITL='Bunches at 35GeV'
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
A    Capture at 35GeV in 53MHz bucket
$RF    NRF=2    KURVE=2    VKON=.T. ISYNC=1
    PSII=180
    VI= 0.0495    VF= 0.083
    TVEND=2.0
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH    DEPMIN=-40    DEPMAX=40
    THPMIN=-5    THPMAX=5
    TITL='Capture at 35GeV'
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
T
$CYCLE    TSTOP=2.0       HISTRY=.T.
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
S
cesar35gev1.dat
```

```
W+++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-40.    DEPMAX=40.
    MPLOT=20000    IRF=0
    ICONTUR=1
    THPMIN=-6.4    THPMAX=6.4
    DELCON=0.005    NBINTH=50
    PLTSW(8)=.F.    PLTSW(10)=.F.
    PLTSW(12)=.F.,.F.,.F.,.F.
    PLTSW(5)=.T.
    TITL='35GeV'
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
A
$RF    NRF=1    H=588    VKON=.T.
    PSII=180    PSIF=180
    KURVE=2    ISYNC=0
    TVBEG=2.0    TVEND=2.1
    VI=0.083
    VF=0.04
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
T
$CYCLE    TSTOP=2.1       HISTRY=.T.
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
W+++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-40.    DEPMAX=40.
    MPLOT=20000
    TITL='35GeV Adiabatic Debunching'
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
A    Debunch
$RF    NRF=3    H=588,28,56    VKON=.T.
    PSII=180,180,0    PSIF=180,180,0
    KURVE=2,2,2       ISYNC=0
    HOLDBA=.T.
    TVBEG=2.1,2.1,2.1    TVEND=8.,6.5,6.5
    VI=0.04,  0.001, .00016
    VF=0.000008, 0.00003, 0.0000048
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
T
$CYCLE    TSTOP=8.       HISTRY=.T.
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
S
cesar35gev2.dat
W+++++++++++++++++++++++++++++++++++++++++++++++++
W+++++++++++++++++++++++++++++++++++++++++++++++++
```

```
O
$GRAPH DEPMIN=-30.    DEPMAX=30.
    MPLOT=30000
    TITL='35GeV Adiabatic Squeeze'
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
A    Hold
$RF    NRF=2    H=28,56    VKON=.T.
    PSII=180,0    PSIF=180,0
    KURVE=2,2       ISYNC=0
    HOLDBA=.T.
    TVBEG=8., 8.    TVEND=17.0,17.0
    VI= 0.00003,  0.0000048
    VF= 0.00125,   0.0002
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
T
$CYCLE    TSTOP=17.0       HISTRY=.T.
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
S
35squezed.dat
W++++++++++++++++++++++++++++++++++++++++++++++++++
W++++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-300.    DEPMAX=300.
    MPLOT=300
    TITL='35GeV Bunch Rotation'
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
A    Rotate
$RF    NRF=2    H=28,56    PHKON=.T.
    PSII=180,0    PSIF=180,0
    KURVE=0,0    KURVP=0,0    ISYNC=0
    HOLDBA=.T.
    TVBEG=17.,17. TVEND=17.028,17.028
    TPBEG=17.,17.    TPEND=17.028,17.028
    VI= 0.06,0.001
    VF= 0.06,0.001
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
T
$CYCLE    TSTOP=17.028    HISTRY=.T.
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
O
$GRAPH DEPMIN=-400.    DEPMAX=400.
    THPMIN=-.35    THPMAX=.35
    MPLOT=20000
```

```
    TITL='53MHz Capture'
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
A    test
$RF    NRF=1    H=588    PHKON=.T.
    PSII=180    PSIF=180
    KURVE=0    ISYNC=0
    HOLDBA=.T.
    TVBEG=17.028  TVEND=17.3
    VI= .62
    VF= .62
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
T
$CYCLE    TSTOP=17.3    HISTRY=.T.
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
W++++++++++++++++++++++++++++++++++++++++++++++++++
S
    cesar150gev.dat
W++++++++++++++++++++++++++++++++++++++++++++++++++
W++++++++++++++++++++++++++++++++++++++++++++++++++
W++++++++++++++++++++++++++++++++++++++++++++++++++
W++++++++++++++++++++++++++++++++++++++++++++++++++
O
$GRAPH DEPMIN=-400.    DEPMAX=400.
    THPMIN=-.35    THPMAX=.35
    MPLOT=10000
    TITL='Accelerate to 150GeV'
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
W++++++++++++++++++++++++++++++++++++++++++++++++++
W++++++++++++++++++++++++++++++++++++++++++++++++++
W++++++++++++++++++++++++++++++++++++++++++++++++++
R        Main Injector Ramp 7
$RING    KURVEB=6
    TF=17.55
    P0F=40E3    P0FDOT=40E3
    JNRAMP=.T.
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
A
$RF    NRF=1    H=588 VKON=.F.
    ISYNC=1       HOLDBA=.T.
                  $ENDW
WVI=.62
W++++++++++++++++++++++++++++++++++++++++++++++++++
T
 $CYCLE TSTOP=17.55    HISTRY=.T.
                  $END
W++++++++++++++++++++++++++++++++++++++++++++++++++
D
```

```
W+++++++++++++++++++++++++++++++++++++++++++++++++
R        Main Injector Ramp 8
$RING    KURVEB=6
    TF=18.00455
    P0F=85E3    P0FDOT=158E3
    JNRAMP=.T.
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
T
 $CYCLE TSTOP=18.00455    HISTRY=.T.
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
R        Main Injector Ramp 9
$RING    KURVEB=6
    TF=18.3827
    P0F=130E3    P0FDOT=80E3
    JNRAMP=.T.
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
T
 $CYCLE TSTOP=18.3827    HISTRY=.T.
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
R        Main Injector Ramp 10
$RING    KURVEB=6
    TF=18.56452
    P0F=140E3    P0FDOT=30E3
    JNRAMP=.T.
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
T
 $CYCLE TSTOP=18.56452    HISTRY=.T.
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
R        Main Injector Ramp 11
$RING    KURVEB=6
    TF=19.23119
    P0F=150E3    P0FDOT=0
    JNRAMP=.T.
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
T
 $CYCLE TSTOP=19.23119    HISTRY=.T.
                  $END
W+++++++++++++++++++++++++++++++++++++++++++++++++
D
W+++++++++++++++++++++++++++++++++++++++++++++++++
W            +++++++++++++++++++++++++++
W            +++++ This is THE END +++++
W            +++++++++++++++++++++++++++
W+++++++++++++++++++++++++++++++++++++++++++++++++
```

```
Q
SOURCE 1
VOLTS
        19
   1.649      0.9916
   1.66899     1.2619
   1.68899     1.2579
   1.70899     1.3956
   1.72899     1.5792
   1.74899     2.0680
   1.76899     2.3028
   1.78899     2.3829
   1.80899     2.3994
   1.82899     2.7373
   1.84899     2.8379
   1.86899     2.2517
   1.88899     1.5943
   1.90899     0.9535
   1.92899     0.7752
   1.94899     0.5947
   1.96899     0.4033
   1.98899     0.1853
   1.99197     0.0495
PHAS
        19
   1.649      0.0000
   1.66899     3.4001
   1.68899     3.8001
   1.70899     6.5001
   1.72899    10.2001
   1.74899    19.0001
   1.76899    27.6002
   1.78899    37.8001
   1.80899    50.5999
   1.82899   124.7996
   1.84899   130.0997
   1.86899   133.1999
   1.88899   136.4001
   1.90899   141.3004
   1.92899   143.4005
   1.94899   146.5007
   1.96899   151.2010
   1.98899   161.0016
   1.99197   180.0000
```