Fermilab

Doc Number: Beams-doc-3857
Version: 1.0
Category: Notes

Main Injector Counterwave Properties and MI300 Collimator Motion Limits

Bruce C. Brown
Main Injector Department
Fermi National Accelerator Laboratory*
P.O. Box 500
Batavia, Illinois 60510

4/26/2011

***Operated by the Fermi Research Alliance under contract with the U.S. Department of Energy.**

Abstract

The counterwave orbit distortions used to optimize the aperture available for Main Injector beam transfers to and from the Recycler Ring displace the circulating beam in the region from LAM321 to K403 or from K304 to LAM222. The Main Injector Collimation System impacts apertures in this region. This note will review the motion limits for collimators which leave room for transfer of anti-protons from MI to RR and from RR to MI. At the same time, the counterwave implementation will be reviewed and enhanced in order to match the transfer orbit to an improved 8 GeV orbit which has lower losses near LAM321 for high intensity 8 GeV injected beam.

Introduction

For transferring beam from the Main Injector to/from the Recycler, a single kicker, K304, is used in combination with permanent magnet Lambertsons at LAM222 and LAM321. In order to take best advantage of the aperture in the multicell-long transport within the Main Injector, the central orbit is distorted by a 'counterwave' so that the circulating orbit is displaced across the center of the aperture (approximately symmetrically) from the the transfer orbit which passes through the Lambertson magnet transfer line aperture.The kicker moves the beam from (or to) the transfer orbit to (or from) the circulating counterwave orbit. The counterwave (a closed three bump) is implemented by using a time bump. For LAM321 transfers from the Recycler, as the time bump expires, the closed orbit returns to the 8 GeV orbit as set by smoothing to the 8 GeV desired positions. The details of these closed bumps will be provided below. The same counterwave concept is employed in portions of the Recycler but we will not document those in this note.

The counterwave creates offsets of the beam at the collimator locations, C301, C303, C307 and C308, so collimator positions must be constrained to provide adequate aperture for the antiproton transfers. The proton transfers to/from the Recycler would be of concern also except that losses for these transfers are of less concern. One may find the bumps to be slightly different but the only **in principle** differences are in the beam emittances and the small change in K304 kick due to electric field effects. The following issues are being addressed in this document:

1. The collimator motion limits need to be more carefully documented.

2. The orbit in the region of LAM321 was not optimal for beam loss on high intensity proton cycles[1]. We believe that the most reliable way to make this change is to modify the 8 GeV desired orbit to match the aperture as determined by a three bump and cancel the effect on the PBar transfers by adding the opposite three bump into the time bump.
3. In attempting to implement this solution, we find that the time bump implementation was more complex than we currently prefer. We will simplify the setup to make it more obvious and easier to implement further changes.

The high intensity operation for NuMI and PBar achieved in recent years has demanded attention to these issues. We find that the present counterwave setup was designed before the current Recycler or Main Injector BPM systems and Main Injector BLM systems were available to confirm various aspects of the orbits and losses. Improved simulation (with I90) and improved diagnostics makes these changes straightforward.

Counterwave Time Bump and Orbits for LAM321

For transfers at LAM321, a closed 3-bump consisting of H304, H318 and H320 creates a distortion of the closed orbit just prior to the transfer event. Fig. 1 shows the counterwave orbit and the transfer orbit used for LAM321 transfers. The counterwave distortion places the orbit with about 25 mm excursions at focusing quads, inward at Q306 and Q314 and outward at Q310 and Q318. When PBar beam arrives from LAM321, it passes through Q320 and H320 but at nearly the opposite angle from that of the closed orbit (as defined by the counterwave time bump). This 'transfer' orbit has maximum outward displacement at Q314 and Q306 and is displaced inward at Q318 and Q310. K304 then kicks the PBars onto the closed orbit where they remain centered (from 304 to 100 to 320) until they reach the distortion at H320 at which point they are on the counterwave orbit until the end of the time bump. For proton injection to the Recycler, this counterwave distortion is established, then K304 kicks beam to the transfer orbit to achieve extraction at LAM321.

In Appendix A, the details for creating these time bumps are documented. Ramps which execute on $E2 (protons MI to RR) and $E4 (PBars RR to MI) are required. On December 27, 2010, the ramp definitions and bump MULT's were modified to achieve 'unit' bumps (see below). I90 was used to confirm that the MULT produced a closed bump and the time bump current for H318 was slightly modified to produce an improved (design) closure. [The expected difference in the closure from that used for the last half-decade is small.]

A low loss orbit for high intensity operation on $23 or $29 slip stacking events requires a position at HP322 of -21 mm and at HP320 of -10 mm. The 8 Gev orbit which was being used since a half-decade ago when the counterwave was established, set the 8 GeV desired position at -17 mm for HP322. To maintain the transfer orbit positions and angles, ramp definitions for $E2 and $E4 events were added to H322 and H324 CAMAC 453 ramp definitions (on I14). The 8 GeV orbit was modified (initially with a H322:3 3-bump - then by changing the desired position for I50 8 GeV and 9-30 GeV smoothing files). Using a H322S:3 mult, the ramp current was set to cancel the change in the desired position so that the beam from/to the Recycler would see the traditional -17 mm position at transfer time. The loss improvement is primarily at LAM321. The simulation illustrated in Fig. 1 calculated the orbit change at H322 to be 4.66 mm but at LAM321, the difference is only 1.2 mm, small but sufficient for x4 lower losses. Efficient transfers of PBars from RR to MI were observed to confirm these changes.

Time Bumps Including HP322 Control

To implement the above time bump orbit definitions for the counterwave along with the bump for the change in orbit at H322:3, the changes to the ramp card definitions described above were implemented. The 'unit' bumps similar to (and including) those shown in Fig A3 (first image) establish the values in the CAMAC cards. The required MULTs for the scale factors (to match the unit ramps) were defined on a parameter page (temporarily on I133 DEVEL < 4>). Scale factors such as I:H304S[1] are used for $E2 (Protons from MI to RR) while one like I:H304S[4] are used for $E4 (PBars from RR to MI). Here are the MULT definitions used:

```
 !  December 2010 Counterwave Changes
 ! New Counterwave for $E2 PROTON Transfers
```

```
 MULT    :3
-I:H304S [1]*.1 04 Scale Factors          1.711 Amps
-I:H318S [1]*-.02414cale Factors          -.41  Amps
-I:H320S [1]*-.09608cale Factors         -1.969 Amps

 ! New Counterwave for $E4 PBAR Transfers
 MULT    :3
-I:H304S [4]*.1 04 Scale Factors          1.711 Amps
-I:H318S [4]*-.02414cale Factors          -.41  Amps
-I:H320S [4]*-.09628cale Factors         -1.965 Amps

 ! Mult for H322 3-Bump on $E2
 MULT    :3
-I:H320S [1]*.1 20 Scale Factors         -1.969 Amps
-I:H322S [1]*.00254Scale Factors          -.008 Amps
-I:H324S [1]*.13818Scale Factors          -.445 Amps
 ! Mult for H322 3-Bump on $E4
 MULT    :3
-I:H320S [4]*.1 20 Scale Factors         -1.965 Amps
-I:H322S [4]*.00254Scale Factors          -.008 Amps
-I:H324S [4]*.13818Scale Factors          -.437 Amps
```

While the $E2 and $E4 counterwaves should be identical, an error was made in entering the multiplier for H320S such that they differ in the third decimal place. This is not significant and will be ignored.

In Fig 1 we show these orbits. We note that the change due to the H322:3 bump is 4.66 mm at H322 but at LAM321, where we improved the loss, the change in the horizontal position is only 1.2 mm.

Fig. 1 Counterwave Orbits for LAM321

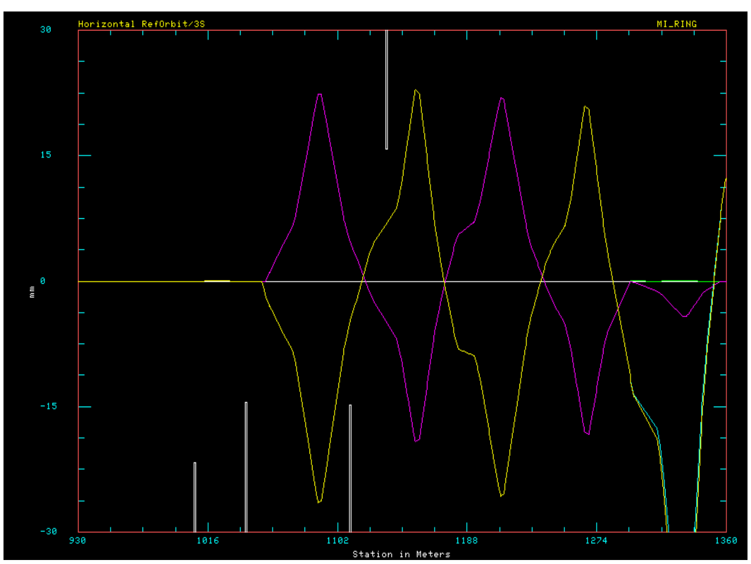
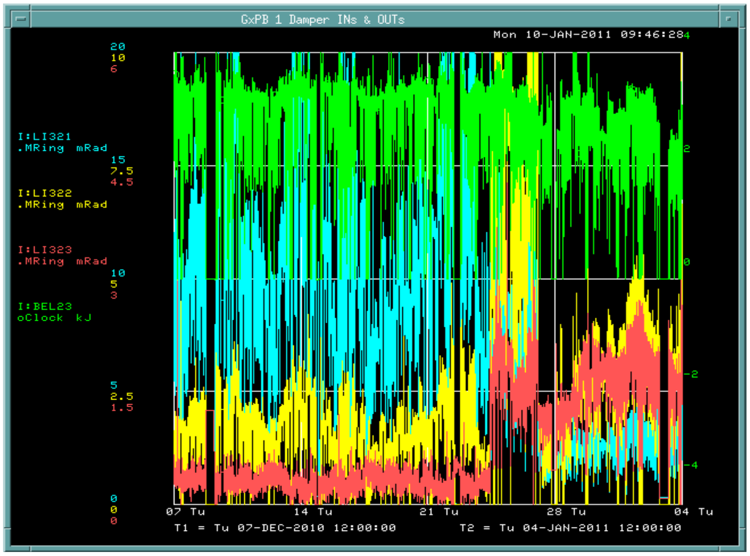
Image from Console Program I90	Description
	The central 8 GeV orbit through the region is in white. Purple indicates the orbit created by the $E2 and $E4 time bumps for LAM321 transfers. Green (on axis) indicates that the orbit was not displaced until the H322:3 time bump was added. Yellow indicates the transfer orbit. Cyan is the transfer orbit without the H322:3 time bump. The Yellow and Cyan orbits indicated beyond H322 are not real -- the beam is not in the MI Aperture but in the transfer line from or to Recycler. This simulation did not include the 2E-3 dp/p momentum offset of the beam which is needed to match to the Recycler, Note that I90 uses a coordinate system in which positive is radially inward.

Fig. 2 Loss History near LAM321

Image from Console Program D44	Description
	Losses from 7 Dec 2010 through 10 Jan 2011 are shown with integrated power loss. Note the different scales. Losses dropped significantly at LI321. While they rose at LI322 and LI323, the level to which they rose is still quite low.

The change in loss patterns near LAM321 is shown in Fig. 2. Looking at one week averages (9-16 Dec 2010 and 1-8 Jan 2011) we find

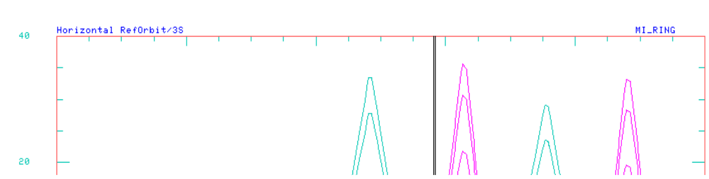
- LI321 dropped from 11.0 to 3.72;
- LI322 rose from 1.68 to 3.87;
- LI323 rose from .233 to 2.65;

So we seem to have accomplished a significant improvement but may not have yet completed the task.

Beam Edges for PBar Transfer at LAM321

The PBar beam from the Recycler has been cooled. Typical measured 95% emittance is about 3 pi mm-mr. One inputs a 1 sigma size into I90 of 0.5 pi mm-mr for the cooled PBar beam. I90 conveniently outputs the 3 sigma edges. However, these PBars are very precious so we will keep the collimators outside the edge for a substantially larger beam. We will assume an emittance of 10 pi mm-mr and keep outside of the 4 sigma beam size. [If one inputs 1 sigma of 2.222 then the '3-sigma' edge calculation will provide the 4 sigma edge for a 95% 10 pi mm-mr beam.] For a 95% emittance of 20 pi mm-mr, one uses sigma = 3.33 pi mm-mr. Figure 3 illustrates these beam sizes for the transfer and counterwave orbits at LAM321.

Fig. 3 Beam Edges for PBar transfer RR => MI => TeV

Image from Console Program I90	Description
	Antiprotons travel from right to left in this view. The undeflected orbit for beam with dp/p = 2E-3 is shown in black. The

	beam edges for the first turn beam is shown in violet where the smaller beam corresponds to 3 sigma of a beam with 95% emittance of 3 pi mm-mr and the larger beam corresponds to a 4 sigma edge of a beam with 95% emittance of 10 pi mm-mr. Shown in cyan are these edges for subsequent turns when the counterwave is being excited. The location of K304 is apparent where these beam edges join. The limiting edges of C301, C303, C307 and C308 collimators are indicated by the black apertures.

Counterwave Time Bump and Orbits for LAM222

The counterwave implementation for Accumulator to Recycler transfers includes a transfer from MI to RR at LAM222. Losses near this magnet are significant but still small. Examination of this region has not revealed adjustments which will improve the beam loss on high intensity Main Injector cycles.

The counterwave implementation has remained unchanged for many years. We will document it as found, simulate it with I90 to obtain the positions and beam edges for PBars during these transfers and calculate limits for collimator offsets to avoid losses during PBar transfers.

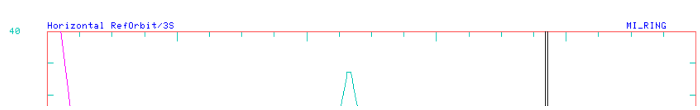
Parameters for LAM222 Counterwave and Kicker

The counterwave for LAM222 PBar and Proton transfers are defined with unit bumps. The mults for tuning are found on R66 CNTWAVE -< 3>+. We required these counterwaves for $E0 events (PBars from MI to RR) which employs scale factors such as I:H304S[3] and for $E3 events (Protons from RR to MI) which employs scale factors such as I:H304S[2].The MULT definitions are

```
 !MI COUNTER RAMP FOR $E0 PBAR INJECTION
 MULT    :3
-I:H224S [3]*1  24 Scale Factors          1.777   Amps
-I:H230S [3]*-.2964Scale Factors          -.48    Amps
-I:H304S [3]*.8819 Scale Factors          1.578   Amps
 MULT    :3   TERWAVE FOR $E3 PROTON
-I:H224S [2]*1  24 Scale Factors          1.523   Amps
-I:H230S [2]*-.2964Scale Factors          -.406   Amps
-I:H304S [2]*.8819 Scale Factors          1.355   Amps
```

The RR30 KICKER control is on R66 KICKER < 3> timing and control parameters with voltages controlled on R66 KICKER < 5>.

Fig. 4 Beam Edges for PBar transfer Acc => MI => RR

Image from Console Program I90	Description
	

	Antiprotons travel from right to left in this view. The undeflected orbit for beam with dp/p = 2E-3 is shown in black. The beam edges for the last turn beam is shown in violet where the edges corresponds to 3 sigma of a beam with 95% emittance of 20 pi mm-mr Shown in cyan are these edges for previous turns when only the counterwave is being excited. The location of K304 is apparent where these beam edges join. The limiting edges of C301, C303, C307 and C308 collimators are indicated by the black apertures.

Collimator Motion Limits

The Main Injector Collimators at C301, C303, C307 and C308 [2] are provided with motion control which would permit them to obscure up to half of the available aperture (i.e. the collimation edge can be at the centerline of the MI300 straight section). The orbits and beam edges illustrated above for the PBar transfers demand a substantial clear aperture with large motions in the radial (horizontal) direction. Since the collimators are far from horizontal Beam Position Monitors (BPM's), we employ the I90 beam simulation program to determine the orbits and beam edges which are implied by the PBar transfer orbits described above. By comparing these orbits with measured BPM positions during PBar transfers, we can confirm those orbits and establish the edges which must be kept clear for the transfers. The limits on these motions are reported below along with a description of the studies used to determine the limits. Details of these studies are preserved and annotated in CntrWave2011.xls, a spreadsheet which is part of this document. The spreadsheet was created using OpenOffice Calc and can be read with that product or Excel.

The Shot Data Analysis (SDA) system provides orbit information for transfers from the Accumulator to the Recycler and from the Recycler to the Tevatron. On the 'Tevatron shots', the intensity is sufficient to get an adequate measurement, but only the injection orbit is routinely stored for these transfers. We used a separate measurement to determine the counterwave orbit. It has been established previously that I90 is quite successful in using the ring geometry and trim magnet and power supply properties to simulate the orbits. This confirms that the calibration constants are correctly determined. For the kickers, this has not been achieved, In addition, there are corrections for electric field effects which make PBar and Proton transfers different. For LAM321, we find that the kicker voltage to be input in I90 is 9.5% higher than the reading in the parameter page. Using the SDA data for a number of shots, we find that the RMS error is less than 1 mm and even for the poorly measured devices, the RMS error is only about 2.5 mm.

The SDA data for Acc => RR shots is more complete, however, the intensity for normal operations is so low that the LAST turn data (one measurement) has huge errors -- up to 15 mm. The PROFILE data which averages 20 turns to determine the counterwave orbit provides RMS errors of about 2.5 mm. We have decided that despite this meager result, we can have reasonable assurance about the simulation. Average values from these SDA measurements are close enough to the simulation for the purpose we have -- identifying collimator limits. We employ the corrector currents as specified on the parameter pages and simulate a LAST turn which requires more aperture than the average of the measured orbits. The kicker value used on I90 is 96% of the parameter page setting.

As described above, the limits for PBar transfers to the Tevatron (at C307, C308) are determined from simulations using 95% emittances of 10 pi mm-mr with 4-sigma edges used as the limits. They are then compared to the 3-sigma edges for the measured beam size from the Recycler of 3 pi mm-mr (95%). For transfers from Accumulator to Recycler, we are more relaxed but the beam is larger. The edge used for setting the limit is a 3-sigma edge for a beam of 20 pi mm-mr (where the measured emittance is typically between 15 and 17 pi mm-mr).We have seen no evidence that any antiprotons are lost at the Main Injector Collimators.

The positions for the collimators is read back using LVDT sensors. However, this has been found to have a drift of up to a mm or more so 'current position software' which stores the requested net steps of change for the stepper motor controllers are now used to document collimator position. The collimation for uncaptured beam uses the horizontal offset at MI230 due to a positive dispersion and a negative momentum offset. The proper placement of collimation edges then follows from the horizontal phase advance from that locations. The resulting collimation edges are as follows: C301 (radially out), C303 (radially out), C307 (radially out), C308 (radially in). The relevant beam edges which limit PBar transmission are based on these edges. The readback is based on the displacement to place an edge at the prescribed location given a collimator horizontal aperture of ± 2 inches.

Table 1. MI Collimator Motion Limits for PBar Transfer Efficiency

Collimator	Transfer Orbit	Location	Prescription	Edge Limit (mm)	Beam Sigma (mm)	Displacement Limit (mils)	Readback Device	Current Setting (4/2011) (mils)	Available Aperture (mils)
C301H	LAST	LAM222	3 sigma 20 pi	17.235	2.16	-1321	C1HCP	-1237	84
C303H	LAST	LAM222	3 sigma 20 pi	10.658	2.06	-1580	C3HCP	-1410	170
C307H	FIRST	LAM321	4 sigma 10 pi	11.247	1.687	-1557	C7HCP	-1415	142
C308H	FIRST	LAM321	4 sigma 10 pi	-14.725	2.409	1420	C8HCP	1340	80

Summary

The collimation system at MI300 limits the Main Injector aperture. However, the beam transfers from the main Injector to the Recycler involve large orbit excursions in the region of the collimators. Since these transfers require transport through many cells of the MI lattice, a counterwave system is employed to allow the aperture needs to be more symmetrically used from both sides of the central orbit. This document has reviewed this counterwave implementation, modified it for simplicity, and extended the counterwave to match to an improved orbit for high intensity Main Injector operation. Using generous beam size assumptions for the antiproton transfers, we have documented beam edges which define collimator open aperture requirements. Table 1 documents these requirements and translates them to collimator offset limits which must be observed in routine operations.

The modifications which implement counterwaves as 'unit' time bumps have been put in place and the 'desired orbit' at LAM321 was modified to reduce losses on high intensity beam cycles. Appendix A provides details on time bump definitions. Appendix B documents a review of the time bumps for Horizontal Correctors which we use for the counterwaves and demonstrates that the required changes are in place. A few time ramps are in a 'less obvious' condition but not in any way which limits normal operation.

A spreadsheet which documents some of the measurements and calculations described above is included in this document as a separate file: CntrWave2011.xls.

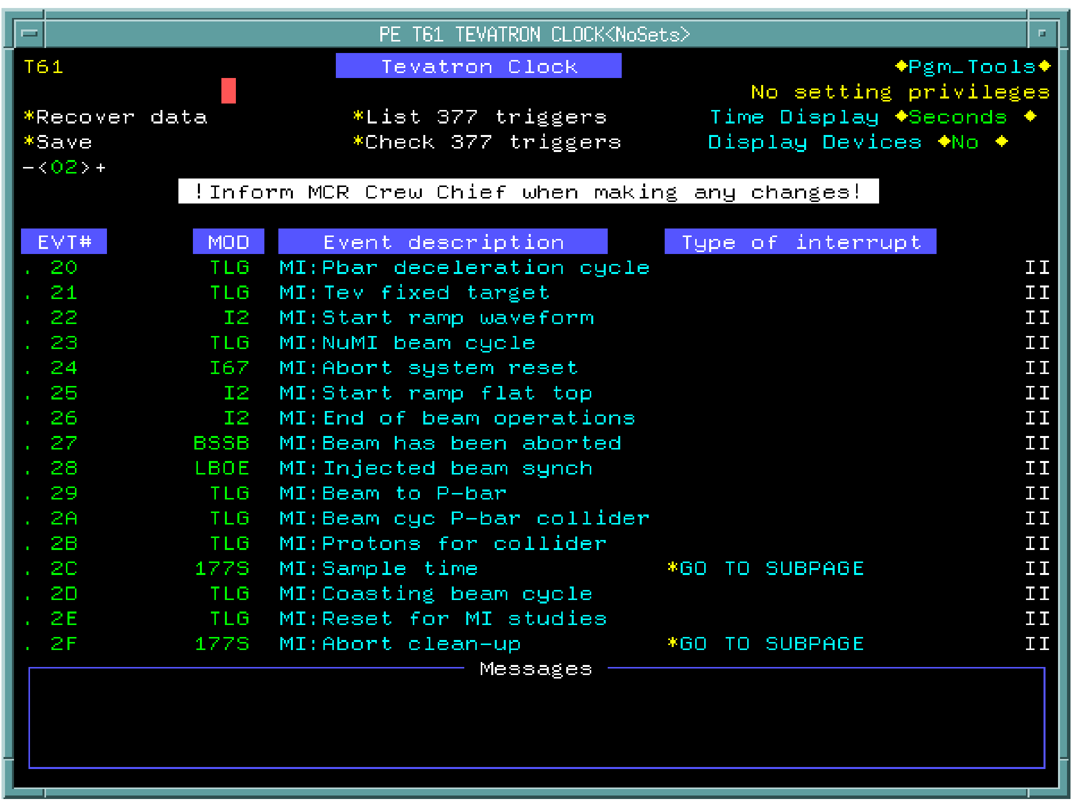
Appendix A: Counterwave and Collimator Clock Events and Time Bumps

Simple time bumps to provide orbit distortions are most straightforward when defined with unit amplitude with a flat time profile preceded and followed by a ramp. They are triggered by a Tevatron Clock Event which causes the 453 CAMAC card to play out the ramp. The values in the time ramp are then multiplied by a scale factor. By using the "unit" ramps (see below) and displaying the scale factors on parameter pages, we can do the required tuning with MULT: sets where the scale factor values set by the MULT: have an obvious meaning -- the values of the scale factors are the currents in amperes.

Clock Events

We find the description of the Tevatron Clock Events on page T61 as shown in Fig. A1. **[We note that some browser/screen combinations may have inadequate resolution to cleanly display these console screen capture views. The reader may find the image easier to view by using a right-click and choosing 'view image' for viewing these items.]** We define collimation orbit distortion bumps using unit time ramps with respect to the Main Injector ramp reset events $23 and $29 (with ramps for $21 to be considered if required). For RR proton transfers we employ bumps triggered by events $E2 for MI => RR using LAM321 and $E3 for RR => MI using LAM222 . For pbar transfers from Acc => MI we use event $E1 to trigger (no counterwave) whereas for MI => RR using MI:LAM222 we use $E0. Transfers from RR to MI using MI:LAM321 use $E4 for a trigger.

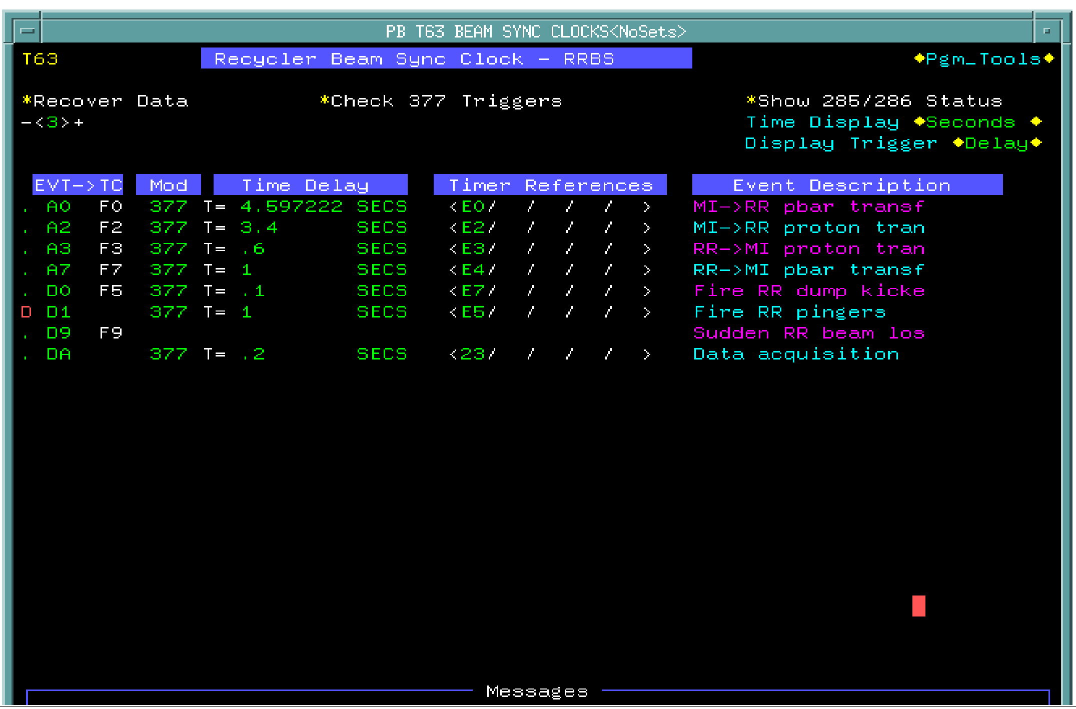
Fig. A1 Tevatron Clock Events from T61

<table>
<tr><th>Image from Console Program T61</th><th>Description</th></tr>
<tr><td>
</td><td>Tevatron Clock Events for Main Injector on T61 Subpage 02. These are the list of Main Injector acceleration cycles plus related events.</td></tr>
<tr><td>
</td><td></td></tr>
</table>

	Tevatron Clock Events for Main Injector on T61 Subpage 14. These Recycler events include the events which transfer beam between MI and RR.

In addition to timing using Tevatron Clock Events, some control functions require synchronization with the beam in the Main Injector. For these requirements, the Beam Sync Clock provides additional timing information. For RR <=> MI transfers, Beam Sync Clock Events are used in Kicker voltage and timing control. Fig. A2 shows Beam Sync Clock events which are used for controlling the kickers on transfers to/from the Recycler.

Fig. A2 Beam Sync Clock Events from T63

<table>
<tr><th>Image from Console Program T63</th><th>Description</th></tr>
<tr><td>


</td><td>Beam Sync Clock events which are used for controlling the kickers on transfers to/from the Recycler.</td></tr>
</table>

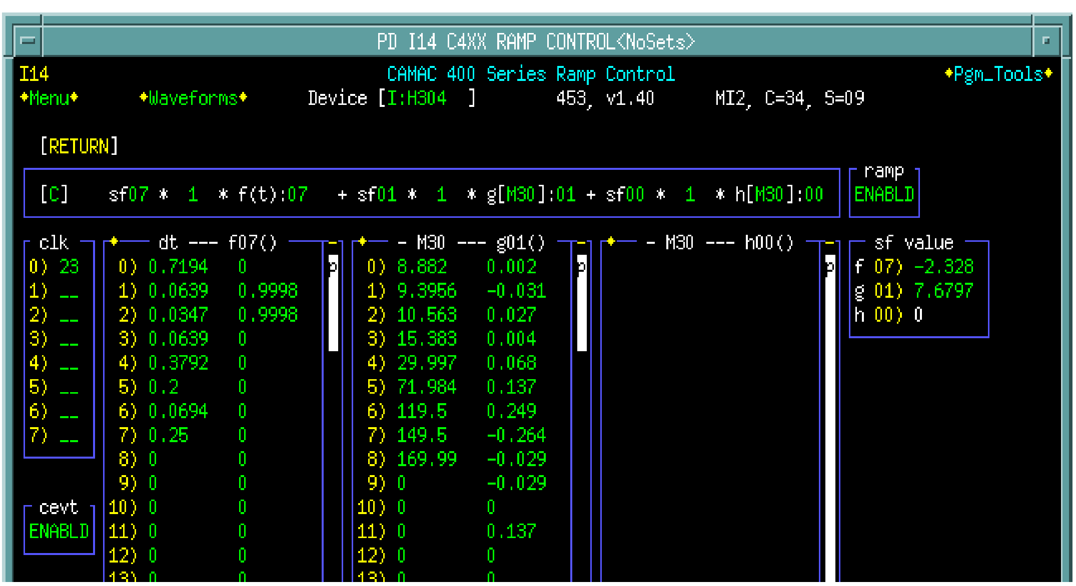
Collimation Time Bumps

In Fig. A3, we show the ramp definitions for I:H304 which is one of the correctors used to create the horizontal collimation orbit. We note that the time ramp has ramping segments of 0.0639 sec length and a flat top segment of 0.0333 sec length for $29 (0.347 sec for $23). The ramp starts at 0 and ramps to 1, holds flat and ramps back to 0. We call this a 'unit ramp.' It starts up at 0.2514 sec for $29 (0.7194 sec for $23) which get it to flattop while the momentum is changing by one or so percent, allowing the orbit to be defined for capturing the uncaptured beam from slip stacking. As shown in the line below [RETURN], the time ramp f(t) is multiplied by scale factor sf08 (sf07 for $23). These scale factors are then controlled on parameter pages such as I133 MICOLTUNE < 03> (or < 01> for $23 ramps). This setup is repeated for devices needed for for collimation orbit ramps. We then set scale factors on parameter pages as follows:

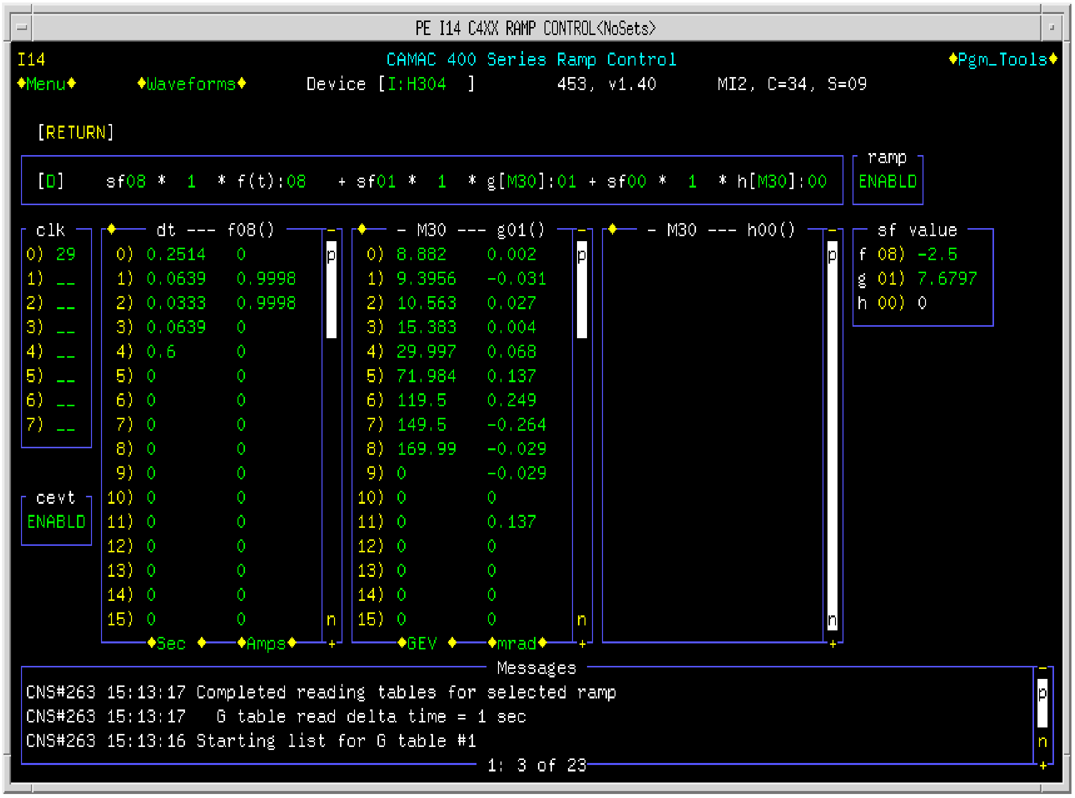
```
For $23 we have
-I:H226S [6]
-I:H228S [6]
-I:H230S [6]
-I:H232S [6]
-I:H302S [6]
-I:H304S [6]
-I:H306S [6]
-I:H308S [6]
-I:H310S [6]
-I:H312S [6]

-I:V231S [6]
-I:V301S [6]
-I:V303S [6]
-I:V305S [6]
-I:V309S [6]
-I:V311S [6]
```

With similar devices with [7] for $29 ramps. The time bumps are defined but not currently needed for I:V307.

Fig. A3 Typical Ramp Definitions for Collimation

<table>
<tr><th>Image from Console Program I14</th><th>Description</th></tr>
<tr><td>


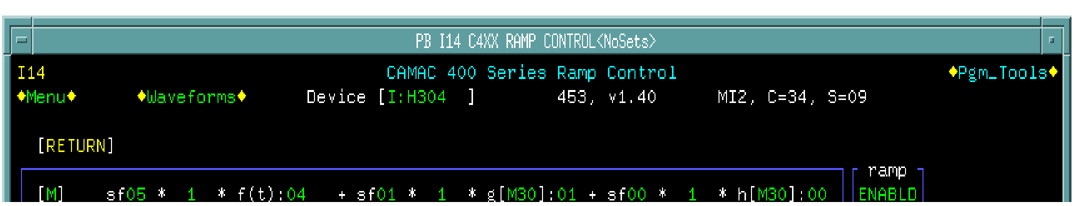
</td><td>$23 Ramp Definitions (Mixed Mode and NuMI Only) for H304 which are typical for collimation orbits, both horizontal and</td></tr>
</table>

<table>
<tr><td></td><td>vertical</td></tr>
<tr><td>
</td><td>$29 Ramp Definitions (PBar Only Cycles) for H304 which are typical for collimation orbits, both horizontal and vertical.</td></tr>
</table>

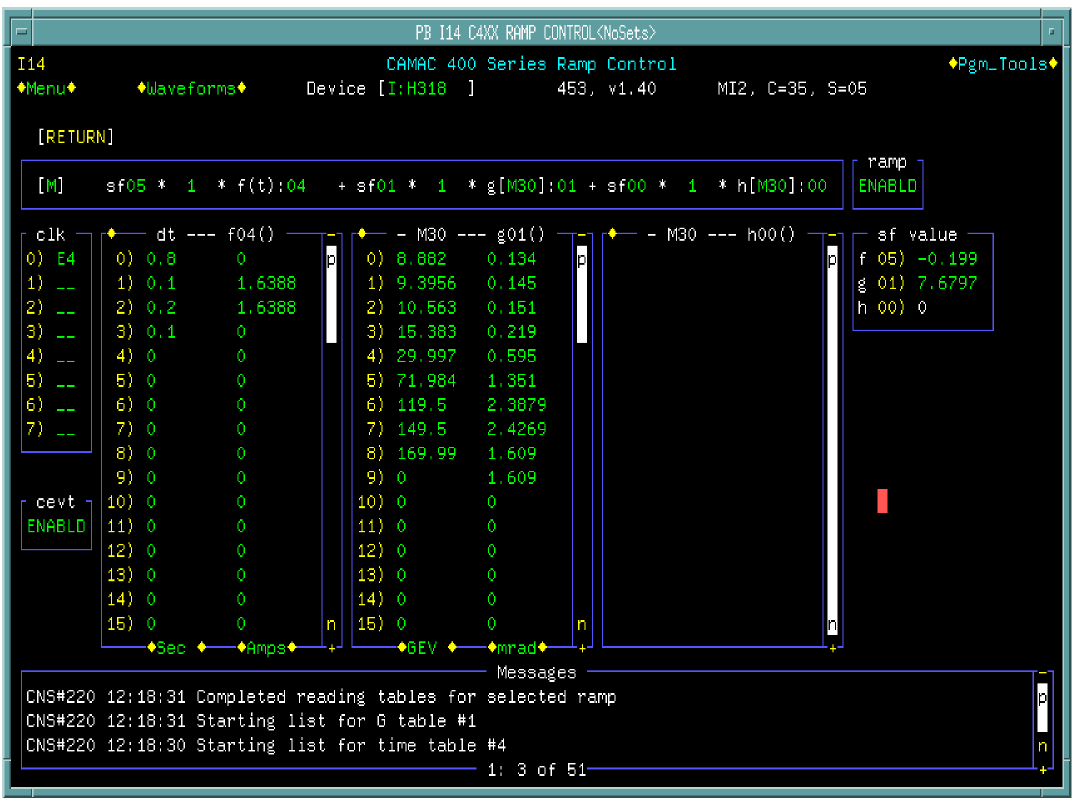
Counterwave Time Bumps and MULT's

The LAM321 counterwaves which use H304, H318 and H320 were not defined using unit time bumps. [We have documented that these were used at least from 2005 through 2010 but perhaps were created earlier]. We wish to document them and make changes to achieve the more obvious implementation using unit time bumps. In Fig. A3, we show the time bumps definition for H304,H318 and H320 on $E4 cycles (PBar RR => MI => Tev).

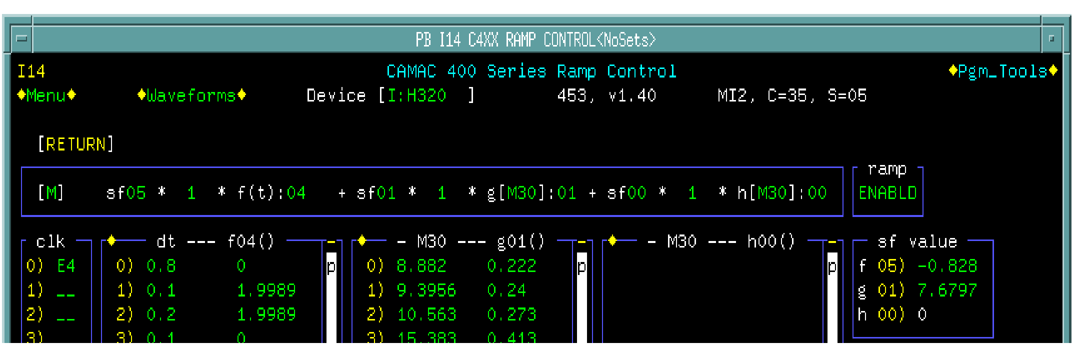
Fig. A4 Old Ramp Definitions for Counterwaves

<table>
<tr><th>Image from Console Program I114</th><th>Description</th></tr>
<tr><td>
</td><td></td></tr>
</table>

$E4 Ramp Definitions for H304. This is a 'unit' ramp definition which will be used for all transfers to/from RR.



Old $E4 Ramp definition for H318. Note that the amplitude is 1.6388 (not 1). Revisions will make this 1 with corresponding change of sf05 to create the same ramp current.



Old $E4 Ramp definition for H320. Note

	that the amplitude is 2 (not 1). Revisions will make this 1 with corresponding change of sf05 to create the same ramp current.

Appendix B: Status of Counterwave Time Ramps - April 2011

Results of a review of the I14 ramp definitions.

```
Reminder:
E0       PBars from MI (LAM222)   Acc => MI => RR
E2       Protons from MI (LAM321) Boo => MI => RR
E3       Protons to MI (LAM222)   RR  => MI
E4       PBars to MI (LAM321)     RR  => MI => TeV

Time to carefully check the time bump definitions....

Location  E0            E2            E3            E4

H224              Note b)       Note g) sf=0  Note i)       Note f) sf=1.9
H230              Note b)       Note f) sf=0  Note i)       Note f) sf=-0.53
H304              Note c)       Note h)       Note i)       Note j)
H318              Note d) sf=0  Note h)fixed  Note k) sf=0  Note j)
H320              Note e) sf=0  Note h)       Note l) sf=0  Note j)
H322              Note f) sf=1  Note h)       Note m) sf=0  Note j)
H324              Note f) sf=1  Note h)fixed  Note m) sf=0  Note j)

Notes:
a) Looked at H222 since it came up.  Find E3 ramp with 1.6388 amplitude
   and times of 0.3, 0.2, 0.2, 0.2 but sf = 0 so it is OK.
b) E0 Time Ramp Times: 3.2, 1.2972, 0.05, 0.1, 0.05
                Amplt:   0,     0,     1,   1, 0    (well actually 0.9998)
c) E0 for H304 same as Note b) except time 2 is 1.2986
d) Funky ramp:  Times: 3.2,    0.1,    0.2, 0.1
                Amplt:   0, 1.6388, 1.6388, 0
e) Funky ramp:  Times: 3.2,    0.1,    0.2, 0.1
                Amplt:   0, 1.9989, 1.9989, 0
f) NULL ramp
g) Funky ramp:  Times: 3.2,    0.1,   0.05,    1.1, 0.05
                Amplt:   0,      0, 0.9998, 0.9998,    0
h) E2 Time Ramp Times: 2.2,    0.1,   0.05,    0.1, 0.05
                Amplt:   0,      0, 0.9998, 0.9998,    0
i) E3 Time Ramp Times: 0.4,    0.1,   0.05,    0.1, 0.05
                Amplt:   0,      0, 0.9998, 0.9998,    0
j) E4 Time Ramp Times: 0.8,    0.1,    0.2, 0.1
                Amplt:   0, 0.9998, 0.9998, 0
k) Funky ramp:  Times: 0.2,    0.1,    0.2, 0.1
                Amplt:   0, 1.6388, 1.6388, 0
l) Funky ramp:  Times: 0.2,    0.1,    0.2, 0.1
```

```
                Amplt:   0, 1.9989, 1.9989, 0
m) Funky ramp:  Times: 0.2,    0.2,    0.2, 0.2
                Amplt:   0, 0.9998, 1.9998, 0

Fixed E2 for H318 on 26 April 2011.
Fixed E2 for H324 on 22 April 2011.
```

References

[1]Phil Adamson, Private Communication, November 2009.
[2] Bruce C. Brown, Main Injector Collimation System Hardware Beams-doc-2881-v2