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S. Saritepe and G. Annala

*Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510*

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S. Saritepe* and **G. Annala**
Fermi National Accelerator Laboratory[†]
Batavia, Illinois, USA

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1 Introduction

Bunched beam transfer from one accelerator to another requires coordination and synchronization of many ramped devices. During collider operation timing issues are more complicated since one has to switch from proton injection devices to antiproton injection devices. Proton and antiproton transfers are clearly distinct sequences since protons and antiprotons circulate in opposite directions in the Main Ring (MR) and in the Tevatron. The time bumps are different, the kicker firing delays are different, the kickers and lambertson magnets are different, etc.

Antiprotons are too precious to be used for tuning purposes, therefore protons are transferred from the Tevatron back into the Main Ring, tracing the path of antiprotons backwards. This tuning operation is called “reverse injection”. Previously, the reverse injection was handled in one supercycle. One batch of uncoalesced bunches was injected into the Tevatron and ejected after 40 seconds. Then the orbit closure was performed in the MR. In the new scheme the lambertson magnets have to be moved and separator polarities have to be switched, activities that cannot be completed in one supercycle. Therefore, the reverse injection sequence was changed. This involved the redefinition of TVBS clock event \$D8 as MRBS \$D8 thus making it possible to inject 6 proton batches (or coalesced bunches) and eject them one at a time on command, performing orbit closure each time in the MR.

Injection devices are clock event driven. The TCLK is used as the reference clock. Certain TCLK events are triggered by the MR beam synchronized clock (MRBS) events. Some delays are measured in terms of MRBS ticks and MR revolutions. See Appendix A for a brief description of the beam synchronized clocks.

2 Proton Injection in the Collider Mode

Table 1 shows the clock events and the delays involved in the proton transfer during collider operations. Protons are injected into the MR at A0 and accelerated to 150 GeV on a \$2B cycle. Proton injection into the Tevatron at 150 GeV involves time bumps in the MR and in the Tevatron. FERMILAB TM-1790 [1] contains more details about the time-bumps involved in the beam transfer. In this note timing issues are stressed.

*current address: SSCL, MS 1040, 2550 Beckleymeade Ave. Dallas, TX 75237

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PROTON INJECTION (COLLIDER)		
TCLK Event	Delay	Description
00		Supercycle reset
61	<00> 0.1 sec	DFG:Start
2B	TLG	Reset: MR cycle for collider (proton).
4D	TLG	Reset: Proton injection.
22	<2B> 0.6 sec	MR:Start ramp to 150 GeV.
25	<2B> 2.5048 sec	MR:Start of flattop at 150 GeV.
	<2B> 5.5 sec	Start proton coalescing.
	<4D> 7.0 sec	Start the MR time bump (M:MRD46, M:MRE17). (these are now 465 cards)
	<4D> 7.5 sec	Start the Tev time bump (handled by E0 465 cards, see Operations Bulletin 1233)
	<4D> 7.6 sec	Start the MR time bump (T:IBMP1, T:IBMP2, T:IBMP3)(160 cards).
Sequencer complex command: "inject protons Pn" (n=1-6)		
C1		Align MRBS A-Marker with the TVBS A-Marker. Occurs only once after "setting at 150 GeV".
		Enable MRBS \$7C.
7C → 5C (MRBS)	<4D> 13.80 sec	Initiate MR → Tev transfer.
		Disable MRBS \$7C.
end "inject protons Pn"		
	MRBS <7C> 2.044 mrev	Fire MR C48 kicker. Rise time is 360 nsec. Flattop length $\approx 21\mu\text{sec}$.
	MRBS <7C> 1.975 mrev	Fire Tev E17 kicker. Rise time is 550 nsec. Flattop length 2-21 μsec (adjustable).
		These delays take into account the transit time for the clock pulse to travel around the ring and the position of the beam relative to the clock pulse.
26	<2B> 13.9748 sec	End of MR \$2B flattop (150 GeV).

Table 1: Proton injection timing in the collider mode. The transfer cogging offsets are 0,186,371,557,742,928 RFCYC, for P1 through P6, respectively. Note that kickers are referenced to MRBS \$7C not TCLK \$5C.

3 Antiproton Injection

Antiprotons are injected into the MR at F17 and accelerated to 150 GeV on \$2A cycles. Since the antiproton kicker in the MR (at E17) is a short distance away from E0, the time bump (T:IBMP1, T:IBMP2, T:IBMP3) is not necessary. Due to differences in the MR-C48 and MR-E17 kickers and due to the proximity of the MR-E17 Kicker to E0, the kicker timings are very different than the ones in \$2B cycle. The cogging offsets are also different.

In the transfer cogging there is no energy or path length manipulation in the Tevatron. The MR energy is manipulated, however, for this correction. The A-Marker of the MRBS is delayed with respect to the TVBS A-Marker. The TVBS A-Marker remains fixed with respect to Tev RF while the MR RF is phase shifted. Using transfer cogging offsets one can inject a proton or an antiproton bunch into a particular Tevatron bucket. The antiproton injection sequence is summarized in Table 2.

4 Reverse Injection

The antiproton injection line is tuned with protons by reverse injecting them from the Tevatron into MR. This simulates the forward antiproton injection. The reverse injection timing system has been changed. In the previous scenario, a single proton bunch was injected into the Tevatron on a \$2B cycle. The cogging offset for this bunch was 0 RFCYC. Forty seconds later in the supercycle, the same bunch was reverse injected into MR on a \$20 cycle. In the new timing scheme, six proton bunches can be injected into the Tevatron on six \$2B cycles, and then reverse injected into MR on six \$20 cycles on demand. The reverse injection request is issued by the sequencer.

Transfer cogging can only be done in the MR RF system. Therefore, a MRBS clock event has to fire the kickers for reverse transfer of protons. In the previous scenario, a TVBS clock event, \$D8, was used. Since \$D8 always came out in the same position relative to the TVBS A-Marker (revolution marker), only the first proton bunch, P1, could be ejected. The solution [2] was to make the \$D8 a MRBS clock event. So in the new scheme, one can change the time difference between the TVBS A-Marker and the \$D8 by changing the transfer cogging offset. The cogging offset can be set by the sequencer, providing reverse injection on demand. Any proton bunch can be selected. The reverse injection sequence is shown in Table 3.

5 Proton Injection in the Fixed Target Mode

In the fixed target mode, protons are accelerated to 150 GeV on \$21 cycles. There is no coalescing and transfer cogging. The markers in the two machines are locked after MR and then a Tevatron bucket is labeled as bucket 1. Then the MRBS event \$78 initiates the beam transfer. This sequence is shown in Table 4.

6 Appendix A

MRBS and TVBS: Beam synchronized clocks MRBS and TVBS are not really “beam synchronized”. They are synchronized to RF frequencies. MRBS and TVBS generate a clock event AA (A-marker) at every 1113 RF cycles which corresponds to 159 clock ticks (7 RF cycles = 1 clock tick). The A-Marker is sometimes referred to as the “revolution marker”.

ANTIPROTON INJECTION (COLLIDER)		
TCLK Event	Delay	Description
00		Supercycle reset
61	<00> 0.1 sec	DFG:Start
2A	TLG	Reset: MR cycle for collider (antiproton).
40	TLG	Reset: Antiproton injection.
22	<40> 0.6 sec	MR:Start ramp to 150 GeV.
25	<40> 2.5048 sec	MR:Start of flattop at 150 GeV.
	<40> 5.4 sec	Start antiproton coalescing.
	<40> 7.5 sec	Start the Tev time bump (handled by E0 465 cards, see Operations Bulletin 1233)
Sequencer complex command: "inject pbars An" (n=1-6)		
C1		Align MRBS A-Marker with the TVBS A-Marker. Occurs only once after "setting at 150 GeV".
	CSBREQ request	Start transfer cogging.
	984 RFCYC 242 RFCYC 427 RFCYC 613 RFCYC 798 RFCYC 56 RFCYC	Cogging offset for AP1. Cogging offset for AP2. Cogging offset for AP3. Cogging offset for AP4. Cogging offset for AP5. Cogging offset for AP6.
		Enable MRBS \$7B.
7B → 5B (MRBS)	<40> 13.80 sec	Initiate MR → Tev transfer.
		Disable MRBS \$7B.
end "inject pbars An"		
	MRBS <7B> 0 mrev	Fire MR E17 kicker. Rise time is 6 μ sec. It has a half-sine wave form.
	MRBS <7B> 2.396 mrev	Fire Tev D48 kicker. Rise time is 3 μ sec.
26	<2A> 13.9748 sec	End of flattop (150 GeV).

Table 2: Antiproton injection timing. Note that there is no IBMP for this cycle. The TCLK event \$5B disables \$40 and also triggers the Bull's Eye Plot. Kickers are referenced to MRBS \$7B not TCLK \$5B.

CP Cogging: The Collision Point (CP) cogging is accomplished by changing the antiproton path length. The cogging DF controller (CDFC) operates both CP cogging and transfer cogging therefore one cannot do CP cogging in the Tevatron while transfer cogging takes place in the MR RF system. The CP cogging rate cannot be varied, it is fixed at 2 buckets per second. Once initiated CP cogging always goes to completion [3]. The relevant parameters are:

T:ACPS specifies the magnitude and direction of CP cogging. The “+” retards the antiproton beam relative to the proton beam. The antiproton pathlength becomes longer than the proton pathlength. This is accomplished by decreasing the frequency of the antiproton RF. The “-” advances the antiproton beam relative to the proton beam by increasing the Frequency of the antiproton RF. The antiproton pathlength becomes shorter.

T:MCPS does fractional (RF bucket) CP cogging. The cogging is measured in mm units.

T:MCPCOG starts the fractional bucket CP cogging.

References

- [1] S.Saritepe and G.Annala, “Beam Transfer at E0: An Overview”, FERMILAB-TM-1790 (1993).
- [2] R.J.Ducar, “Why TVBS \$D8 Became MRBS \$D8”, Unpublished Note (July 1991).
- [3] K.Meisner, “Console page M19, help subpage.”

REVERSE PROTON INJECTION		
TCLK Event	Delay	Description
	Sequencer command	Disable \$4D. Wait 8 sec.
4B	Sequencer trigger	Tev:Abort clean-up
	Sequencer command	Disable \$4B.
Load sequencer files 10,13		
Inject 6 coalesced proton bunches into the Tevatron on 6 \$2B cycles		
	Sequencer command	Tev:Move the proton lambertsons out.
	Sequencer command	Tev:Set the separator polarities to "-". (C:C1SVP, C:B1SHP, C:B0SHP)
C3	Sequencer trigger	Open the helix. (Camac-465 tables are preloaded by C49)
	Sequencer command	Insert \$20 cycles in the timeline.
20	TLG	Reset: MR cycle for reverse injection.
22	<20> 0.6 sec	MR:Start ramp to 150 GeV.
25	<20> 2.5048 sec	MR:Start flattop at 150 GeV.
	<20> 7.5 sec	Start the Tevatron time bump (handled by E0 456 cards, see Operations Bull. 1233
Sequencer complex command: "eject protons Pn" (n=1-6)		
		Execute Sequencer file 35. This file sets up MR BPM events to take data on \$20 cycle only.
C1		Align MRBS A-Marker with the TVBS A-Marker. Occurs only once after "setting at 150 GeV".
D8 → 55 (MRBS)	<20> 13.8 sec	Initiate Tev → MR transfer.
	<D8> 2.038 mrev	Fire the Tev D48 kicker. Rise time is 3 μ sec.
	<D8> 1.409 mrev	Fire the MR E17 kicker. Rise time is 35 μ sec. Half-sine wave form.
		Disable \$D8.
end complex command "eject protons Pn"		
26	<20> 13.9748 sec	MR:End of \$20 cycle flattop (150 GeV).
eject all 6 bunches, tune the antiproton injection line		
C0	Sequencer trigger	Close the helix.
	Sequencer command	Set C:C1SVP, C:B1SHP, C:B0SHP polarities to "+".
	Sequencer command	Move the proton lambertsons in.
	Sequencer command	Remove the \$20 cycle from TLG.

Table 3: The new reverse injection timing. The transfer cogging offsets are 0,186,371,557,742,928 RFCYC, for P1 through P6 respectively. TCLK event \$55 triggers the Bull's Eye plot.

PROTON INJECTION (FIXED TARGET)		
TCLK Event	Delay	Description
00		Supercycle reset
61	<00> 0.1 sec	DFG:Start
21	TLG	Reset: MR cycle for fixed target.
4D	TLG	Reset: Proton injection.
22	<21> 0.6 sec	MR:Start ramp to 150 GeV.
25	<21> 2.5048 sec	MR:Start flattop at 150 GeV.
	<4D> 7.0 sec	Start the MR time bump (M:MRD46, M:MRE17). (these are now 465 cards)
	<4D> 7.5 sec <4D> 7.8 sec	Start the T:IHTU,T:IHTD,T:IQUAD ramp Start the MR time bump (T:IBMP1, T:IBMP2, T:IBMP3)(160 cards)
	<4D> 7.8 sec	Start the Tevatron time bump.
78 → 58 (MRBS)	<4D> 13.8 sec	Initiate MR → Tev transfer.
	MRBS <78> 2.044 mrev	Fire MR C48 kicker. Rise time is 360 nsec. Flattop length $\approx 21\mu\text{sec}$.
	MRBS <78> 1.975 mrev	Fire Tev E17 kicker. Rise time is 550 nsec. Flattop length $\approx 21\mu\text{sec}$.
		These delays take into account the transit time for the clock pulse to travel around the ring and the position of the beam relative to the clock pulse.

Table 4: Proton injection timing in the Fixed Target operation.