7. Operating Scenarios*

7.1 36 x 36 Collider Operations

7.1.1 Shot Setup

Much of this scheme has been described elsewhere,[1] but it will be repeated here in more generality. This scenario is easily generalized to 109×144 operating scenarios (132 nsec bunch spacing). Table 7.1 shows the sequence of operations for each machine during future "shot setups". Shot setup starts at the end of a collider store (TCLK event $CE) with proton removal from the Tevatron and proceeds through antiproton deceleration, transfer to the Recycler Ring (RR), reverse proton tune-up, proton loading, antiproton loading, acceleration, low beta squeeze and beam halo scraping. It ends with the commencement of the next store (TCLK event $CB). During Run I, the average shot setup time was 202 minutes (including downtime). For Run II the goal is to reduce the optimum shot setup time to less than 40 minutes.

Protons are removed from the Tevatron by collimators in a dogleg insertion at E0. The collimators are first placed close to the beam, and then a local 3 bump is exercised, with feedback control, to move the beam into the collimators. The dogleg prevents beam losses from quenching superconducting magnets. Calculations suggest that this process can be done in 100 seconds. After the protons are removed the low beta regions are "unsqueezed", and the helix closed, in order to maximize the Tevatron aperture. Then all 36 antiproton bunches are decelerated to 150 GeV. At this point, the total RR antiproton stack will occupy approximately 1/4th of the RR azimuth between two rf barrier buckets.

A group of 4 antiproton bunches are transferred to the MI, after appropriate cogging, on MI $20 cycles and decelerated to just above transition. The bunches, which are captured by the 53 MHz rf system, are adiabatically transferred to 2.5 MHz buckets and decelerated to 8 GeV (as described in section 5.x.x). The MI is appropriately cogged, and the 4 antiproton bunches are transferred to the RR into 2.5 MHz RF buckets. In the RR the 2.5 MHz is adiabatically decreased and the beam is captured between a pair of barrier buckets. The barrier buckets are then used to move the injected beam out of the way in preparation for the next injection. This process is repeated 9 times, with each new injected bunch being azimuthally merged with the previous injected bunches by combinations of rf barrier buckets. At the end of this process in the RR there is a "cold" bunch of antiprotons, occupying about 1/4 of the ring, and a "warm" bunch of freshly injected antiprotons occupying another portion of the ring.

At this stage beam lines for antiproton transfers can be tuned up with reverse protons on $20 cycles (150 GeV) or $2D cycles (8 GeV). This includes reverse proton transfers from the Tevatron to the MI via the A150 line and reverse proton transfers from the RR to the MI via the MI-22 line.

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* Last revised on March 10, 1998.

Table 7.1. Shot setup timeline

Tevatron Sequence	MI Operations	RR Operations	time (min)
remove protons	$29's for $\bar{p}$ production; $2B's for proton tune-up	cooling; possible transfers from antiproton source	5
unsqueeze, close helix, decelerate antiprotons to 150 GeV	$29's for $\bar{p}$ production; $2B's for proton tune-up	prepare RR stack for $\bar{p}$ injections	3
transfer 4 antiproton bunches to MI for deceleration to 8 GeV; repeat 9 times	inject, decelerate, extract 9 groups of 4 $\bar{p}$ bunches; $29's for $\bar{p}$ production interleaved	Inject and stack 9 groups of 4 $\bar{p}$ bunches	5
stop at 150 GeV			0
reverse proton tune-up	$20's and $2D's for 150 and 8 GeV reverse proton tune-up; $29's for $\bar{p}$ production interleaved	$2D's for 8 GeV reverse proton tune-up	3
setup for injection	$29's for $\bar{p}$ production; $2D's for 8 GeV reverse proton tune-up	$2D's for 8 GeV reverse proton tune-up	2
inject protons (9 groups of 4 bunches)	inject, accelerate, and extract 9 groups of 4 proton bunches; $29's for $\bar{p}$ production interleaved	prepare stack for $\bar{p}$ extraction	2
inject antiprotons (9 groups of 4 bunches)	inject, accelerate, and extract 9 groups of 4 proton bunches; possible $29's for $\bar{p}$ production interleaved	extract 9 groups of 4 $\bar{p}$ bunches	5
accelerate, squeeze	$29's for $\bar{p}$ production	resume cooling; possible transfers from antiproton source	4
adjust tunes, correct orbit, scrape beam halo	$29's for $\bar{p}$ production	cooling; possible transfers from antiproton source	6

Protons are accelerated, coalesced, and injected into the Tevatron similar to current procedures, except that instead of single batch coalescing, 1 to 4 batches will be injected, accelerated, and coalesced simultaneously. Proton injection will thus require from 9 to 36 Main Injector cycles. Extraction of antiprotons from the RR and acceleration in the MI is essentially the reverse of injection. A group of antiprotons is separated from the "cold" antiprotons in the RR with barrier buckets. These are then bunched at 2.5 MHz, transferred to the MI, and accelerated to 25 GeV. These are then bunch rotated, captured by the 53 MHz RF, accelerated to 150 GeV, and transferred to the Tevatron. This process is repeated 9 times.

Once all the bunches are injected into the Tevatron, they are accelerated to 1 TeV, and collisions are initiated at CDF and D0 by squeezing and collision cogging. The acceleration ramp will be decreased from the current 80 seconds to perhaps 50 seconds. At this point the orbit and the tunes will be routinely corrected and the beam halo scraped by an automated collimation system using feedback from local loss monitors.

There is no provision for experimental "quiet time" in this scenario, and if the colliding beam experiments require it, the shot setup time will need to be increased by that much, since there is almost no time in which there is no beam in the Tevatron. In addition, there is no provision for ramping the Tevatron 6 times, as has been done in the past, so provision will have to be made to correct for persistent currents.

7.1.2 Accumulator to RR Antiproton Transfers

Antiprotons are stacked into the Accumulator in much the same way as in the past, except at a 1.5 second/pulse repetition rate. Depending on the cooling rate in the RR, after 1 to 4 hours the antiprotons are transferred to the RR via the AP3/AP1/MR remnant/MI partial turn/MI-22 line. The proposed AP-5 beam line will allow for direct transfer between the Accumulator and RR later in Run II. The mechanics of the transfer will be similar in both cases, however, the major disadvantage of the later transfer is that the AP1 line needs to be set up for 8 GeV before each transfer, which takes considerable time.

When the RR stack is cool enough, RF barrier buckets are used to form an azimuthal gap in the stack with enough space for injection of a 1.4 μsec antiproton batch from the Accumulator. Stacking into the Accumulator is halted, and the core briefly cooled. An H=4 RF system accelerates the core to the extraction orbit. At the extraction orbit the Accumulator rf is phase-locked to the RR rf, kickers are fired synchronously with the RR aa marker, and a bucket-to-bucket transfer into the RR is obtained.

This scenario assumes that electron cooling in the RR has not yet been commissioned. In the present case, the RR will use stochastic cooling exclusively and Accumulator to RR transfers will take place every 1-4 hours. At a stacking rate of 20×10^{10}/hour, this corresponds to about 20-80×10^{10} antiprotons/transfer. When electron cooling has been commissioned, the transfer rate between the Accumulator and RR may be significantly increased.

7.2 Beam Transfers and Synchronization

The coming reality of the Main Injector (MI), including a Recycler Ring in the same enclosure, presents new and unique demands for beam transfers and synchronization of those transfers. The Tevatron 10 MHz Time Clock (TCLK) and various beam synchronous clocks are envisioned to play continuing important roles for these transfers in conjunction with extant or new demands on the low level RF systems of the accelerators and storage rings.

The Tevatron Clock structure is sufficient to meet the new requirements. However, the Time Line Generator (TLG) hardware which is currently implemented in CAMAC, is being upgraded to a VME-based system. Existing TCLK events for the Main Ring are being reassigned to the Main Injector, with present definitions of events being adhered to in almost all cases in order to assure operational continuity. Current existing event assignments number 175 out of a potential 256, and this is being updated to 188 to encompass new scenarios: deceleration, RR operation, NUMI, and 120 GeV fixed target operation. Some events associated with obsolete scenarios are being deassigned, and this number is included in the above accounting.

There presently exist three beam synchronous clocks, each approximately 7.5 MHz (one seventh of the normal rf frequency), derived from the Tevatron proton, Tevatron antiproton, and Main Ring rf systems. These are called TVBS, APTVBS, and MRBS, respectively. MRBS will be reassigned to the Main Injector and will be referenced as MIBS. Events synchronous to the revolution frequency are coded onto each of these clocks and are always denoted by the hexadecimal code \$AA. A beam synchronous clock is being developed for the RR employing existing techniques and will be referred to as RRBS. Beam Transfers between machines are approximately driven by delays from particular TCLK events, or a combination of them. The actual transfers are initiated by uniquely coded beam synchronous events on particular beam synchronous clocks. These transfer events, which are encoded immediately subsequent to the revolution event, are detected and generally result in the generation of a TCLK event. This reflecting of beam synchronous transfer events in the Tevatron Clock has proven extremely useful for diagnostic purposes and this practice will be continued.

Some of the details of new (or modified) beam transfers and synchronization are described below for individual types of transfers. TCLK events are designated as \$nn (with a TLG subscript if they are sourced from the Time Line Generator), and beam synchronous events are denoted as \$nn subscripted with the relevant clock descriptor. Of particular note are the following additions and modifications to event usage: 1) addition of a new Booster reset event $\$0E_{TLG}$ dedicated to RR studies cycles; 2) reassignment of Booster reset event $\$19_{TLG}$ for NUMI beam; 3) addition of a new MI reset event $\$23_{TLG}$ dedicated to NUMI operation; 4) reassignment of MI reset event $\$20_{TLG}$ for MI deceleration cycles.

7.2.1 Proton transfers from Tevatron to MI

This transfer is used to tune up the MI to Tevatron antiproton transfer line prior to antiproton transfers to the Tevatron, and it is accomplished in two steps. First, protons are injected into the Tevatron on a normal $2B cycle ($\$15_{TLG}$, $\$2B_{TLG}$, $\$4D_{TLG}$). Second, protons are extracted from the Tevatron on either of the two cycles: $\$2A_{TLG}$, $\$5D_{TLG} \rightarrow \$D8_{MIBS}$ --> $55; or $\$20_{TLG}$, $\$5D_{TLG} \rightarrow \$D8_{MIBS} \rightarrow \$55$.

7.2.2 Antiproton deceleration

The following sequence of events is used to decelerate antiprotons from 1 TeV in the Tevatron to 8 GeV in the RR:

- Sequencer → $ED (prepare RR stack for antiproton injection)
- Sequencer→ $6D or $6E (start of ramp down in Tevatron)
- Sequencer→ $44 (start of ramp "back porch" in Tevatron)
- TLG → $\$20_{TLG}$, $\$54_{TLG} \rightarrow \$D6_{MIBS} \rightarrow \$5F$
- → $D0 (prepare for deceleration in MI)
- → $D1 (start deceleration in MI)
- → $D2 (end deceleration in MI)
- → $\$E0 \rightarrow \$A0_{MIBS}$ (inject into RR).

7.2.3 NUMI operation

Six Booster batches are loaded into the MI, accelerated, and extracted to the NUMI beam line with the sequence $\$19_{TLG}$, $\$19_{TLG}$, $\$19_{TLG}$, $\$19_{TLG}$, $\$19_{TLG}$, $\$19_{TLG}$, $\$23_{TLG}$, $\$A8_{TLG}$. The MI can simultaneously serve NUMI and antiproton production by interleaving NUMI cycles with antiproton production cycles, or, slightly more efficiently, by replacing the first $\$19_{TLG}$ in the above sequence with $\$14_{TLG}$ and extracting the first Booster batch to the antiproton production target by careful placement of an $80 in the timeline.

7.2.4 120 GeV Fixed Target operation

Similar to NUMI operation, this sequence is $\$13_{TLG}$, $\$13_{TLG}$, $\$13_{TLG}$, $\$13_{TLG}$, $\$13_{TLG}$, $\$13_{TLG}$, $\$21_{TLG}$, $\$30_{TLG}$, and it may also be combined with antiproton production cycles.

7.2.5 Inject decelerated antiprotons from the MI via the MI-22 transfer line

This sequence is $\$20_{TLG}$, $\$54_{TLG}$, $\$E0 \rightarrow \$A0_{MIBS}$. MI cogging, RR rf manipulations, and the RR Lambertson bump are initiated by $E0 or $\$20_{TLG}$. Extra time is required after the transfer to perform RR rf manipulations, which will be enforced by the TLG.

7.2.6 Inject antiprotons from Accumulator via AP5 line

This sequence is $\$2D_{TLG}$, $\$E1_{TLG}$, $\$91_{TLG} \rightarrow \$A1_{MIBS} \rightarrow \$98$. $\$E1_{TLG}$ initiates Accumulator and RR rf manipulations, which take up to 20 seconds to complete. The reflected TCLK event $98 is concurrent with the $\$A1_{MIBS}$. The $91 is set to occur 0.5 sec before the transfer in keeping with all other Antiproton Source transfer scenarios. This same sequence can be used for transfers via AP3/AP1/MR remnant/MI/MI-22. The Accumulator extraction kicker is fired by $\$A1_{MIBS}$.

7.2.7 Inject protons from MI via MI-32 line

This transfer is used to inject protons into the RR for studies. The sequence is $\$0E_{TLG}$, $\$2D_{TLG}$, $\$E2_{TLG} \rightarrow \$A2_{MIBS}$. MI cogging, RR rf manipulations, and the RR Lambertson bump are initiated by $\$E2_{TLG}$. The MI-32 kickers are fired by $\$A2_{MIBS}$. If there is already an antiproton stack in the RR, $ED will need to be issued by the Sequencer prior to proton injections to prepare the antiproton stack.

7.2.8 Extract protons to MI via MI-22 line

This transfer is used to tune up the MI-22 line before injecting antiprotons into the RR. The sequence is $\$0E_{TLG}$, $\$2D_{TLG}$, $\$E2_{TLG} \rightarrow \$E3 \rightarrow \$A3_{MIBS}$. This cycle is generally concurrent with a proton injection cycle, and the timing delay for the generation of $E3 is set so the proton beam circulates in the RR for approximately 100 turns. The MI-32 kickers are fired by $\$A3_{MIBS}$.

7.2.9 Extract antiprotons to MI via MI-32 line

This sequence is $\$2A_{TLG}$, $\$40_{TLG}$, $\$E4_{TLG} \rightarrow \$7A_{MIBS}$. MI cogging, RR rf manipulations, and the RR Lambertson bump are initiated by $\$E4_{TLG}$. MI-32 kickers are fired by $\$7A_{MIBS}$. If required, $EE will be issued by the Sequencer just prior to this cycle to prepare the RR stack for antiproton extractions.

7.2.10 Extract protons to the Accumulator via the AP5 line

This transfer is used to tune up the AP5 line prior to antiproton transfers. The sequence is $\$0E_{TLG}$,$\$2D_{TLG}$,$\$E2_{TLG} \rightarrow \$96 \rightarrow \$A6_{MIBS} \rightarrow \$97$. The $96 is referenced to the $E2 with a delay such that beam circulates in the RR for about 100 turns before extraction to the Accumulator. The $96 occurs 0.5 sec before beam transfer in keeping with all other Antiproton Source transfer scenarios. AP5 kickers are fired by $\$A6_{MIBS}$, and $97 is concurrent with $\$A6_{MIBS}$. This same sequence can be used for transfers via AP3/AP1/MR remnant/MI/MI-22.

7.2.11 Extract protons via MI-40 (dump)

This sequence is $\$A5_{RRBS} \rightarrow \$F5$. The $\$A5_{RRBS}$ is sourced to a 377 timer module which can be fired by the Sequencer or by any suitable TCLK event. The $F5 is concurrent with the transfer and is used for data collection.

7.2.12 Transfer Synchronization

Transfers between the MI and Tevatron are somewhat complicated by the different harmonic numbers of the Main Injector and Tevatron, being 588 and 1113 respectively. The following scheme will allow the full range of transfer possibilities. The 53 MHz RF is divided by 21 for each machine. This yields 53 rf/21 pulses (396 nsec spacing) for each Tevatron turn, and 28 rf/21 pulses for each MI turn. Before initiating transfer, the Tevatron is frequency matched to the MI, the phase difference is measured, and the Tevatron frequency is then phase shifted by less than one 53 MHz bucket to be phase locked to the MI. The Tevatron is then transfer cogged no more than ±10 53 MHz buckets to align the RF/21 pulses to the MI. On each turn, the $\$AA_{MIBS}$ marker will then align with a different RF/21 pulse from the Tevatron, with the sequence repeating itself every .587 msec (53 MI turns). An MIBS event is issued with appropriate delay which takes into account the location of the beam (bucket number) in the first machine and the desired location of the beam in the second machine. All beam line kickers are referenced to this MIBS event. This scheme is easily extended to 132 nsec spacing.

In many cases, transfers into the RR from the MI will require placement of the beam at a specific longitudinal azimuthal in relation to beam already present in the RR. This will require "fast cogging" of the MI to align the RR beam gap and $\$AA_{MIBS}$ markers. This "fast cogging" can be done in the time between the start of the beam injection cycle and actual beam injection into the Booster—*i.e.*, when there is no beam in the MI. Since the MI and RR have the same revolution frequency, this is anticipated to be straightforward. Beam line kicker timing will be referenced to MIBS events.

Transfer synchronization from the Accumulator into the RR is described above in section 7.1.2. For transfers from the RR to the Accumulator, no cogging is required. The beam line kickers will be referenced to RRBS events.

7.3 Transverse and Longitudinal Emittance Budget

7.3.1 Antiprotons - Transverse

All transverse emittances in this section are stated as 95% normalized values, and are based on the assumption of beams which are both round and gaussian. Almost all of the emittances cited here are best measured in the vertical plane, and are assumed to be the same in the horizontal plane. Measurement of horizontal emittances requires correction for the effects of dispersion through use of lattice functions. However the uncertainties in the lattice functions and momentum spread tend to make this measurement less accurate.

In Table 7.2 below are listed typical values of the proton and antiproton emittances, as measured during Run Ib and as projected for Run II, at points taken throughout the acceleration chain. The antiproton value assumes essentially no change. With the upgrade of the stochastic cooling systems in the Debuncher from 2-4 GHz to 4-8 GHz and liquid helium temperatures, the cooling rate in the Debuncher is expected to dramatically increase. Even with an increase of the transverse aperture with modifications to the antiproton injection line (AP2), and a decrease in antiproton production cycle time from 2.4 seconds to 1.5 seconds, the transverse antiproton emittance coming out of the Debuncher is expected to decrease below Run Ib. During Run Ib the antiprotons were cooled in the Accumulator for a long period of time during each shot setup before extraction to the MR, resulting in a large decrease in emittance in the Accumulator. For Run II, only a few minutes will be allotted to cooling the beam after stacking is stopped and before the beam is transferred to the RR, and therefore the Accumulator will not contribute as much to cooling the beam transversally as in Run Ib. During stacking most of the transverse cooling power goes toward counteracting the transverse heating of the stack tail momentum cooling system.

Table 7.2. Transverse emittances through the accelerator chain

	Protons		**Antiprotons**	
location	Run Ib	Run II	Run Ib	Run II
Linac (400 MeV)	6	6	—	—
Booster (8 GeV)	12	15	—	—
Debuncher (inj–ext)	—	—	200–40	320–30
Accumulator (inj–ext)	—	—	40–8	33–10
RR	—	—	—	10
MR / MI (150 GeV)	14	18	12	12
Tevatron (1 TeV)	23	20	15	15

For stochastic cooling, the cooling rate is dependent on the number of particles -- more particles means slower cooling. Therefore the antiproton emittances are dependent on stack size in both the Accumulator and in the RR. However, the use of the RR to keep stacks from ever getting large in the Accumulator eliminates this effect in that machine, and the eventual use of electron cooling in the RR will eliminate the effect.

There has been an ongoing problem with emittance growth for the antiprotons in the AP3/AP1 beam line. During Run Ib much effort went into trying to solve this problem, with only limited success. The beam line model is not accurate enough to obtain a good beam line match, and, in addition, there are shot-to-shot variations which are not understood. This problem will be alleviated with the scenario of Run II, in which any emittance growth which has occurred during the transfer will be reversed by cooling in the RR. The eventual construction of an AP5 beam line will eliminate many of the transfer problems experienced in the past.

The transfer to the MI is through a very short beam line, so that emittance growth is expected to be small. Emittance growth during the MI acceleration, MI to Tevatron transfer, and Tevatron acceleration are expected to be similar to Run Ib, as indicated in Table 7.2

Emittance growth from RR to Tevatron during acceleration is expected to be 5π mm-mrad, and it is reasonable to expect the same emittance growth during the deceleration of antiprotons from 1 TeV to 8 GeV in the RR. At the end of a store, the antiproton emittance is expected to be about 20π mm-mrad. Therefore, we expect emittances of 25π mm mm-mrad for freshly injected decelerated antiprotons in the RR.

7.3.2 Protons - Transverse

The parameter list for Run II, Table 1.1, indicates a proton transverse emittance goal at collisions of 20π mm-mrad which is 3π mm -mrad (13%) lower than the Run Ib value. In terms of 2D phase space density, the proton value is increased by 34% from Run Ib. A major source of emittance growth for protons occurs in the Booster. This dilution is a topic deserving of study, and indeed the Booster Group has plans for such investigations. An ion profile monitor has led to the collection of a considerable amount of data, with growth seen throughout the acceleration cycle. There appear to be several separate mechanisms at work (large tune shifts at low energy, synchro-betatron coupling just above transition, and rf power supply noise have all been mentioned), but in truth neither those mechanisms nor the detailed calibration of the monitor is sufficiently well understood. The Run II operating scenario extrapolates from current Booster performance (see Table 2.2). This reasonable assumption may or may not be confirmed as that machine is operated at somewhat higher intensity.

This leaves stringent requirements on proton emittance growth in the MI and Tevatron. Whereas in Run Ib the overall proton emittance growth from Booster extraction to Tevatron flattop was 11π mm-mrad (92%), in Run II we are assuming we can keep the overall emittance growth to 5π mm-mrad (33%). This is an ambitious goal and will require well matched beam line optics, accurate beam line steering control, and careful control of beam dynamics during the acceleration cycles in the MI and Tevatron to prevent undue emittance growth. In addition to the MI itself, both transfer lines are new (Booster to MI, and MI to Tevatron), and one might optimistically assume that this will give an improvement in beam transfers. However, the multi-bunch injection schemes for protons and antiprotons place more severe requirements on the Tevatron injection kickers. In the Tevatron at 1 TeV it is planned to do both an orbit smooth and a tune correction at the beginning of every store. This was not routinely done during Run Ib. In addition, a generic injection tuning application program is being written which will archive all beam line changes during tune-up. This will in principle make it easier to track and diagnose beam transfer problems.

7.3.3 Antiprotons - Longitudinal

The operational mode of the accelerator complex for preparing antiproton beams for collision will be distinctly different in Run II than it was in Run Ib, therefore a direct comparison is difficult. The goal for the antiproton emittance is 2 eV-sec, which yields an rms bunch length at the beginning of a store of about 37 cm. In Run Ib the typical longitudinal emittance in the Tevatron at the start of a store was 3.5 eV-sec as measured by the SBD (Single Bunch Detector). This corresponds to a bunch length of 50 cm (at 900 GeV). In this section all longitudinal emittances are quoted as 95%.

The history of the antiproton longitudinal emittance during accelerator operations is the following. After bunch rotation in the Debuncher, the longitudinal emittance is 42.2 eV-sec ($\Delta p/p_{95\%}$=.3%). After momentum cooling, just before transfer to the Accumulator, this becomes 23.9 eV-sec ($\Delta p/p_{95\%}$=.17%). This was the case in Run Ib, and it will remain approximately the same for Run II (see section 3.3). The Accumulator stack tail and core cooling systems will be required to decrease this to less than 10 eV-sec before transfer to the RR. The RR momentum cooling system will cool a stack of 3.1×10^{10} recycled antiprotons to 54 eV-sec (>90%) after 8 hours of cooling. Divided by 36 this is 1.5 eV-sec per bunch, which allows for a 33% longitudinal emittance blowup on acceleration and transfer to the Tevatron.

During the antiproton deceleration cycle, the antiproton beam remaining at the end of an 8 hour store is expected to have a longitudinal emittance of about 3.5 eV-sec. The RR momentum cooling aperture of ±20 MeV/c and the requirements of storing the "cold" antiproton beam and injecting new beam limit the tolerable longitudinal emittance at the RR to about 4 eV-sec.

7.3.4 Protons - Longitudinal

The goal for the proton bunch length at the beginning of a store is also (Table 1.1) 2.0 eV-sec. During Run Ib the proton longitudinal emittance at collisions was typically 3.8 eV-sec -- 10% larger than the antiproton longitudinal emittance. In Run Ib most of the proton emittance blowup came from trying to coalesce 11 53 MHz bunches at once in the MR. In Run II 5 proton bunches will be injected into the MI from the Booster, each with intensity 6×10^{10} and longitudinal emittance 0.1 eV-sec. We anticipate that acceleration and transition crossing will blow these up to 0.15 eV-sec before coalescing. ESME calculations show that coalescing will increase the longitudinal emittance from 0.75 eV-sec to 1.5 eV-sec, which allows for only a modest increase in emittance in the Tevatron. This scheme clearly requires coalescing to work well in the MI, and for the Booster beam emittance to be as small as possible, consistent with avoiding instabilities in the MI during transition crossing. It is quite possible that we will not be able to meet the transverse and longitudinal emittance goals simultaneously, and it may be possible to achieve low transverse emittance at the expense of longitudinal emittance by coalescing more low intensity bunches.

7.4 Instrumentation and Controls Requirements

7.4.1 Software

Numerous application programs are being modified or rewritten for Run II, either to accommodate new hardware (MI, RR,...) or to improve current operating procedures. Table 7.3 lists application programs currently planned to be modified or written for Run II. The tasks listed in this table range from a few hours of work to make minor changes in existing programs, to many months of work to rewrite large programs. A few of the more important items—SDA, TLG, Sequencer, TOP, and the injection closure program—are discussed in more detail below.

7.4.1.1 SDA

The Shot Data Acquisition program supporting collider operations, will undergo substantial changes before the next collider run. SDA collects megabytes of scalar and snapshot data during defined stages of shot setup for postmortem and shot improvement analysis. SDA's file structures and operations will migrate from the record management services of the VMS operating system to relational database tables with Standard Query Language, SQL, access. The database tables will be designed to remove the restrictions on the number of cases defining the collection of data. SQL access with join capability across shots will be exploited by the data logger plot package, and tools will be provided to export shot data to commercial applications. SDA's architecture will also change to support shortened shot setup times. SDA will have a new user input interface, likely run continuously, support a threaded database write facility, and employ new methods of coupling to the collider Sequencer. Open Access front end clients, specialized data loggers, snapshot logging facilities, and other applications may also contribute to the population of these Shot Data tables, to complement or relieve traditional SDA collection responsibilities.

7.4.1.2 TLG

The old Time Line Generator (TLG) hardware will be rebuilt within a VME platform utilizing a finite state machine architecture. Many of the "kludges" added on to the system over the years will be eliminated and their function engineered into the basic hardware design. TCLK functionality will remain the same. However, the finite state machine architecture will allow for a more versatile user interface to the TLG hardware and more facile manipulation of timelines. The visible interface to the new timeline generator will be an application program that has some similarities to the current interface (D69). The new program will provide more automation in constructing timelines. Relevant information, such as ramp cycle lengths, will be supplied to the program via ACNET. The user will be able to specify new options in building timelines such as "packing" cycles or "spacing" cycles. The finite state machine will do the calculations for the actual time placement of the events, with the user specifying rules for *how* the events are triggered. The application program will be able to display timeline sequences in terms of the requested rules, or the actual event placement that will occur given the current machine parameters.

Table 7.3. Application programs for Run II

Category	Description
general	rewrite SDA -- Shot Data Acquisition
	rewrite SDA display (C1,C2)
	rewrite TLG -- Time Line Generator
	modify Sequencer
	miscellaneous modifications to D1,D6,D18,D20,D42,D59,D61,D68,D100,T61
	Sequencer aggregate development
	modify channel 13 display
Main Injector	ramp & tune (M2)
	PS control/status (M11,M12,M13,M17)
	LLRF display/control (M3,M5,M6,M73)
	MI orbit (M24,M25,M26,M55,M56,M128,M135))
	harmonic correctors (M27,M28,M33)
	transfer line steering (M57)
	BPM/BLM display/control/test (M37,M38,M39,M40,M46)
	BPM TBT (M126)
	Multiwire display (M53)
	Flying wire display (M47,M48,M49)
	HLRF status/control (M74,M77)
	LCW display and control (M105)
	Vacuum display and control (M106)
	lattice display (M131,M133)
	beam permit (M67)
	beam dampers

Tevatron	TOP -- Tevatron Orbit Program (C10)
	C49 -- TEV ramp modules
	tune measurement (GFSDA, ...)
	damper control
	modify T57 to accommodate Camac 160 upgrade
	36x36 beam parameters display
	modify flying wire program
	modify C23 -- ADC compare
	rewrite T106 -- lifetime plotting
	IP feedback
	TEV collimator control
Antiproton Source	modify P35 -- switch tree program
	rewrite P133 -- network analyzer display/control
	modify P134 -- delta kicker fitting
	modify P34 -- TWT status and control
	write new closed orbit program to accommodate Accumulator BPM upgrade
	modify P53 to accommodate new Accumulator lattice
	upgrade SEM grid display and control
	upgrade graphics programs for RF, stochastic cooling and diagnostics
Recycler	BPM control/display
	LLRF control/display
	Vacuum control/display
	stochastic cooling phase and gain measurement (like P133)
	TWT status and control (like P34)
	beam synch clock page (like T63)
	switch tree program (like P35)
	spectrum analyzer control/display (like P41,P42,P45,P112)
	tune and chromaticity measurement (like P43)
	beam lifetime/emittance monitor
	longitudinal emittance viewer (like P9)
	graphics programs for stochastic cooling, dampers, wide band pickups
	clearing electrode current monitoring (like P111)

Other features will be included to facilitate manipulation of timeline sequences. Booster study cycles will be handled outside the constraints of the saved timeline "files". They will be enabled, disabled, and adjusted in frequency via an ACNET parameter. The Sequencer will be able to trigger timeline sequences, with an option of loading a timeline sequence for repeat or for one shot play, for example.

7.4.1.3 Sequencer

The Sequencer will operate within the standard framework of console applications. It is envisioned that a single Sequencer instance will control the entire shot setup procedure, with the capability of multitasking to speed up the setup. It will make use of CLIB functionality and push for extensions to the current system where it appears necessary. The basic concepts used in the existing program will remain, with the design to extend and enhance features where needed. Old Sequencer modes and commands will not be ported, therefore new modes, aggregates, and commands will have to be constructed. This will allow for the enhancement of the command grammar—*i.e.*, which commands will be changed, consolidated, dropped, added, *etc.* Some features to be provided include the following: use of CLIB lock routines for more flexible aggregate and command edit and execution locks, a uniform and extended communications package (ACNET, tcp, udp/multicast) for programs used by the Sequencer; support for scheduling (*viz.*, triggering aggregates on time-of-day or TCLK events), allowing for the Sequencer to be run in the background, support for copying and archiving Sequencer modes and aggregates, and more extensive edit protection. There will be streamlining of commands, specialized activity will be pushed to client applications and devices, a set of more general commands will be provided, commands will be stored in Sybase tables, user constructed "complex commands" will be supported, and conditional execution of commands will be supported.

7.4.1.4 *TOP*

The Tevatron Orbit smoothing Program (TOP) will be rewritten to support the new 460 function generator cards and to support the more complex operating scenarios of Run II. Both the three bump and least squares algorithms will be supported. The ability to make a three bump at a single location will also be supported. An attempt will be made to make this program much more user friendly than previous generations of this program so that it may be used routinely during shot setup.

7.4.1.5 *Injection Closure*

A single general purpose injection closure program is being written to service the Tevatron, MI, RR, and Antiproton Source Rings. Currently there are at least 5 application programs being used for injection closure (M56, M58, T120, T121, and P58). The new program will support both TBT mode and "first turn minus desired position" mode. It will have a manual mode, semi-automatic mode, and fully automatic mode. It will control BPM timers, set beam line devices, maintain a history of settings for trending studies, take input from either BPM's or a file, be callable from the Sequencer, have a built in learning capability (so it is model independent), have digital control, and have a variety of plotting options. This program is intended to greatly reduce the time required for reverse proton tune-up during shot setups.

7.4.2 Controls Upgrades

In addition to the topics mentioned above, there are other upgrades in progress which are worth noting.

1. The 160 ramp cards which drive the Tevatron correctors are being upgraded to 460 ramp modules in order to handle the increased complexity of operations.
2. The current GPIB/CAMAC interface (488/89 modules) in the Antiproton Source are being replaced by GPIB/Ethernet interfaces. The old CAMAC interfaces had some bugs which were never ironed out and which caused reliability problems. In addition, the new interfaces are faster, which is critical in some applications where megabytes of data are being read out. These interfaces are used for spectrum analyzers, network analyzers, oscilloscopes, DVM's, and miscellaneous other diagnostic equipment using the GPIB protocol.
3. A new generic MADC is being designed with the following features: 16 bits digitization, 100 kHz digitization rate, more channels available to the user, more general triggering capability, and more memory. These new MADC's will be installed first in areas requiring high throughput, such as F0.
4. A VME-based front end and new interface boards to the old vacuum controller (CIA) crates have been designed and are being installed in the MI. These systems solve the memory limitation problems of the existing CAMAC 170 modules. All vacuum crates in the Antiproton Source, Tevatron, and transfer lines will eventually be upgraded to this system.
5. A new Alarms system will be in place for Run II. The architecture utilizes daemon processes on local machines receiving alarms from a central processor through multicasting. This reduces the network bandwidth and central cpu cycles required to process alarms. An unlimited number of processes are able to connect with the local

daemon utilizing the tcp/ip network protocol. Alarm block information is being expanded to promote addition alarm display applications.

7.5 Main Injector Fixed-Target Operations

A major positive impact of the Fermilab Main Injector is that it will make available year-round 120 GeV fixed target beams. The fixed target program is beyond the scope of this handbook, but an outline of the strategy is given here because of its general interest and because it has some effect on Collider operation. The details are provided elsewhere.[2,3] Design studies have demonstrated the feasibility of slow and fast spill resonant extraction at 120 GeV from the MI during collider operation. These beams will be directed at both the existing fixed target switchyard, as is detailed below, and at a new neutrino area located in the western part of the laboratory. A beam energy of 120 GeV is appropriate for two types of fixed target experiments of current interest: neutrino oscillations and kaon decays. The high cycle rate and beam intensity of the MI will allow detailed studies in both of these areas. Additionally, test beams will be available on a year-round basis. Beams of the MI energy are appropriate for testing and calibrating a variety of HEP equipment—wide angle parts of collider detectors, fixed target detectors and targets, and some segments of muon colliders. During the Tevatron Collider era test beams have only been available at Fermilab during fixed target runs, which have been years apart. Their essentially continuous availability will be a major improvement and will allow much more efficient utilization of that beam which is delivered to running experiments.

The Main Injector has been designed to execute a variety of cycle types in support of both collider and fixed target operation. Extraction may be single turn, as is appropriate for antiproton production, fast resonant (1 ms) for neutrino experiments, and slow resonant (1-sec) for other fixed target experiments and the test beams. In the original configuration the single turn and slow resonant extraction will take place at the MI-52 short straight section and the fast resonant extraction at MI-60. The fast beam is in support of the NuMI (Neutrinos at the Main Injector) program will deliver beam to the COSMOS and MINOS experiments. MINOS is a long baseline neutrino oscillation experiment with two detectors under design, one to reside in the Soudan mine in northern Minnesota and the other on site to provide a short baseline comparison.

A redesign has been made of the upstream portion of the fixed target Switchyard so that it can receive beam either from the Tevatron at 800 GeV or from the MI at 120 GeV; this design is shown schematically in Figure 7.4. A major design concern for 120 GeV SY operation is the apertures of electrostatic septa in light of the larger MI beam size compared to that of the Tevatron. Septa gaps must be small to provide sufficient electric fields at reasonable voltages for efficient operation at high energy, while at lower energy a larger gap is more appropriate. The feasibility of transporting MI beams with modifications to the SY optics has been demonstrated in computer simulations. One such change which is significant is the relocation of the FSEPs, the septa that split the Meson beam into separate lines.

Operationally it appears possible to run either NuMI or the Switchyard simultaneously with antiproton production for the collider program. In one scenario production cycles of 1.9 second length are alternated with those for SY, 2.9 seconds, or NuMI, also 1.9 seconds. A more aggressive scenario involves filling the MI with six Booster batches, of which one is destined for antiproton and the others to a fixed target region, thus combining both programs on the same cycles.

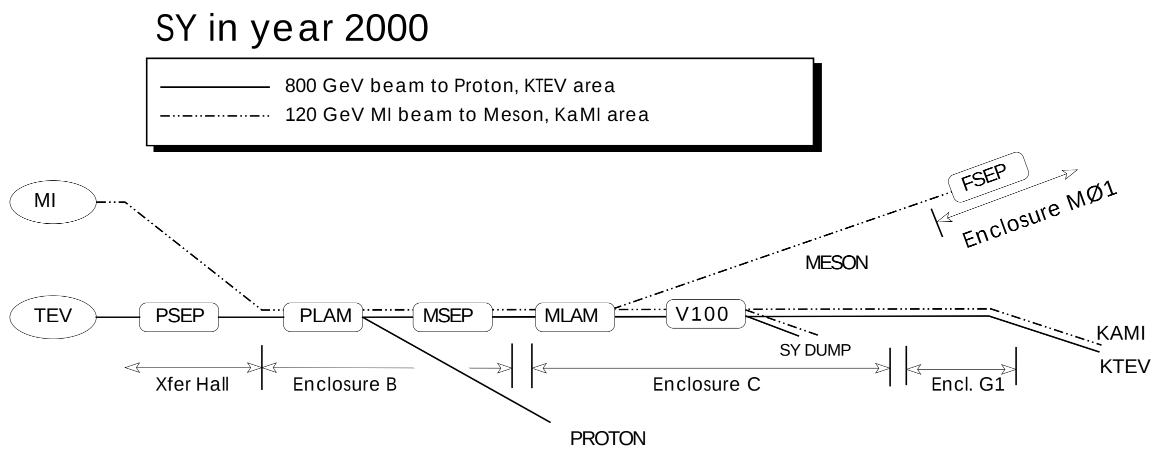

Figure 7.1. Schematic of the switch yard configuration allowing 120 GeV MI beams to be delivered to the meson area.

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[1]GP Jackson, "The Fermilab Recycler Ring Technical Design Report", Fermilab-TM-1991, 1996
[2]C. Brown, *et al.*, "Switchyard in the Main Injector Era Conceptual Design Report", Fermilab-TM-2014, 1997.
[3]D.A. Crane, *et al.*, "Status Report: Technical Design of Neutrino Beams for the Main Injector (NuMI)", Fermilab-TM-1946, 1995.