MI NOTE: #0192

Timing Requirements for the 8 GeV Proton Injection Kicker

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June 2, 1997

Introduction

The MI-10 8 GeV proton kicker will be used to fill the Main Injector with protons for all cycles. Therefore, this kicker must accommodate the required bunch loading schemes for the basic Main Injector cycles.

The kicker is located just upstream of Q103 in the MI and uses three 1.09 meter modules as described by MI Note #0163. The required kick, for the nominal injection trajectory, is 1.02 mr. The vertical lattice functions at the downstream end of the kickers are: β_y= 53 m, α_y= -2 m which implies that the beam envelope for a 20 π-mm-mr beam is $\approx$ 21 mm as compared to the MI beam pipe physical aperture of $\approx$ 45 mm.

The rise time, flattop length , and fall time of the proton injection kicker were specified in the MI Title I to be $\leq$50 ns., 1.6 us., and $\leq$150 ns., respectively. This note re-examines these requirements.

Filling Scenarios

There are two basic methods of filling the Main Injector. The first, currently used in Main Ring, is a boxcar loading scheme where each successive batch is injected behind the circulating beam in the ring. The second involves interleaving the injected and circulating bunches which may be attractive for high intensity operation. Although, the boxcar loading is intended to be the primary loading scheme, the interleaving scheme will be examined for timing considerations.

The cycles used for proton acceleration and the beam filling requirements are:

Table 1: Operation Scenarios

Scene Rio	Beam Requirement
FIXED TARGET:	Full ring (6 batches) with normal abort gap
RESONANT EXTRACTION:	Full ring with normal abort gap
MIXED MODE:	Full ring with reduced abort gap
PBAR PRODUCTION:	Single Booster batch
PROTONS FOR COLLIDER:	Single or multiple short batches for coalescing

Full Ring

Kicker Rise Time

The first three cycles above require a full ring of six batches. The nominal injection scheme will use boxcar loading. To inject a full ring, Booster cycles 6 times each time injecting a batch of 84 bunches. Currently, the first two and last two bunches (1,2,83, and 84) do not get the full kick from the Booster extraction kickers [1], hence these buckets are not fully populated. For the purposes of determining timing specification, all buckets are assumed populated evenly. Any departure from this will reduce the rise/fall time requirements. Figure 1 shows a cartoon of the kicker waveform (with a 50 ns. rise time of the magnetic field) superimposed over the leading and trailing edges of the bunch trains for two successive batches in the MI with two batch delays. Here batch N is already circulating in the MI when the injection kicker fires. If the batch delay between successive batches is N*85 RFC (upper figure) where N=0-5. The distance in ns. between bunch 84 of batch N and bunch 1 of batch N+1 is given by

$$dt[ns] = \frac{n+1}{f_{rf}} - L \tag{1}$$

where n in the number of empty buckets, f_{rf} is the rf frequency, and L is the bunch length in ns (assumed to be 8 ns). The first bunch in the injected batch

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[1] Jim Lackey, private communication.

will see only part of the correct kick amplitude which could lead to emittance dilution or beam loss. This, however, only corresponds to 1% of the total beam in the machine for a full ring. The second bunch will be affected, but to a much lesser extent. (It is assumed that the kicker timing is adjusted such that it will not kick beam already in the machine.) A batch delay of n*86 RFC (lower figure) leaves two empty buckets between each batch. This gives approximately 49 ns between bunches in adjacent batches. Only minor perturbations are expected to the first bunch of the injected batch depending on kicker waveform details. For each increase of 20 ns. in the rise time above the 49 ns. will result in an additional bunch getting tickled. The amplitude of the kick will determine if the beam is lost or the emittance is increased. Assuming this error effects the first bunch in five out of the six batches, this would correspond to 1%of the total beam intensity.

Kicker Fall Time

Since each successive bunch is loaded into the MI following the circulating beam, the fall time of the injection kicker is dictated by the remaining space between the end of the batch just injected and the closest batch circulating in the ring. Figure 2 shows four batch loading schemes for a full ring (of six batches). A standard batch delay of 86 RFC for the rise time is shown. Figure 2A shows the normal full ring **box car** loading with the 1.4 μs. abort gap. For the **mixed mode** , shown in Figure 2B, batch 6 is delayed by about 700 ns. and injected in the middle of the normal 1.4 μs abort gap. This constrains the fall time to be less than 38 buckets or $\approx$730 ns. Figure 2C shows the loading sequence for an full ring **interleaved injection** for Tevatron Fixed Target or MI resonant extraction. Note that 2 batches are potentially affected, batch two (upon injection of batch five) and batch one (upon injection of batch six). The amount these batches (number of bunches and size of kick) are affected depends on the details of the kicker fall time. The bottom picture, Figure 2D, shows a interleaving scenario for the mixed mode operation, **interleaved mixed mode** . This is basically the mixed mode scenario with the gap between batches two and five reduced to 8 buckets. With a fall time of 150 ns (99%-5%) the first bunches of batch two get a kick of ≤ 50 μr, increasing the emittance of these bunches. With batch two shifted this leaves about 2.9 μs to inject batch six, for pbar production. The location of batch six is determined by the rise time of the mixed mode kicker at MI-52, currently specified as $\leq$ 750 ns. As shown in Figure 2D the space between batch six and one is about 578 ns which means some of the bunches in batch one will also experience a kick. The number of bunches and amplitude will depend on the details of the injection kicker fall time.

Therefore, for the boxcar loading with the normal abort gap, the fall time has to be less than 1.4 us (for an 86 RFC delay) or 1.5 us (for an 85 RFC delay). For boxcar loading with a reduced abort gap, as used in the mixed mode or interleaved injection, the fall time should be less than 730 ns for an 86 RFC delay or 767 ns for an 85 RFC delay (as shown in the bottom two pictures). For the "interleaved mixed mode" the fall time of the kicker (99%-5%) should be $\leq$150 ns.

Single Batch

The injection of single batches for **pbar production** cycles presents no timing constraints other than the fall time has to be less than 9 μs.

Short Batch

The current filling scheme for filling the MI with protons for 36 on 36 Collider operation will utilize **boxcar** loading. This is schematically pictured in Figure 3. Under this scenario, the Booster will cycle 12 times to fill the MI, each time transferring a short batch (of less than or equal to 11 bunches). Each successive batch (of 11 bunches) will be loaded behind the beam circulating in the MI. Each successive bunch will be delayed by 21 buckets (i.e n*21 RFC where n = 0 to 11). This implies 10 empty buckets (or 208 ns.) between each batch of 11 bunches. This defines the required rise time of the injection kicker for this mode. After injection, the 12 short batches span 242 buckets or 4.6 μs. leaving a 6.5 μs. abort gap. This scenario only places the constraint that the fall time be less than 6.5 μs, which is significantly less stringent than the requirements for mixed mode operation. Upon coalescing, the 12 coalesced bunches will span 231 buckets.

Summary of Rise/Fall Time Requirements

The following table, Table 2, summarized the requirements for various MI cycles and injection schemes. It is clearly

Table 2: Summary of Rise and Fall Time Requirements

cycle/loading scheme	rise time 1%-99%	flattop ±1%	fall time 99%-1%
Fixed target boxcar (normal abort)	≤50 ns	1.6 us	≤1.4 us
Fixed target interleaved	≤50 ns	1.6 us	≤750 ns
Mixed mode boxcar (reduced abort)	≤50 ns	1.6 us	≤750 ns
Mixed mode interleaved	≤ 50 ns	1.6 us	≤150 ns (99%-5%)
36x36 Collider boxcar	≤200 ns	≥208 us	≤6.5 us

Emittance Growth

To estimate the effect of an error in the kicker field either as a reflection at the end of the pulse or a flattop error the emittance growth and orbit distortion are calculated for a nominal 20π beam.

Emittance preservation is most critical during the cycles which fill the Collider. The fractional emittance dilution due only to a kicker field error, assuming no damping or steering errors, is given by:

$$\frac{\Delta\epsilon}{\epsilon} = 3(\gamma\beta)\frac{\beta_y \Delta y'^2}{\epsilon_N}. \tag{2}$$

At 8 GeV and a β_y of 53 meters, we have the following for a 20 π beam

$$\frac{\Delta\epsilon}{\epsilon} = 75\Delta y'^2 \tag{3}$$

where Δy is the kick, in mr, due to a field error. The absolute increase in emittance is given by

$$\frac{\Delta\epsilon_S}{\pi} = 3(\gamma\beta)\beta(\Delta y')^2. \tag{4}$$

Note that the increase in emittance is proportional to the kick squared.

The amplitude of the oscillations, in mm, introduced by the kicker error is given by

$$\Delta y = \pm \beta_y \Delta y' \tag{5}$$

Table 3 shows the absolute emittance growth, the fractional growth for a 20π beam, and the orbit distortion caused by five values of kicker field error.

Table 3: Summary

field error [%]	kick [mr]	$\frac{\Delta\epsilon_S}{\pi}$ [π-mm-mr]	$\frac{\Delta\epsilon}{\epsilon}$ [%]	Δy [mm]
1	.01	.15	.75	.53
2	.02	.6	3.0	1.05
4	.04	2.41	12.0	2.12
5	.05	3.74	18.7	2.64
10	.10	15.0	75	5.27

Summary

To keep the emittance growth under 1% for a 20π beam due to kicker field errors the specification for flattop field flatness and pulse to pulse variation should be ±1%. The effect of larger errors is shown in Table 3. Any increase in emittance has to be weighted by the cycle type and the number of effected bunches as determined by rise and fall times.

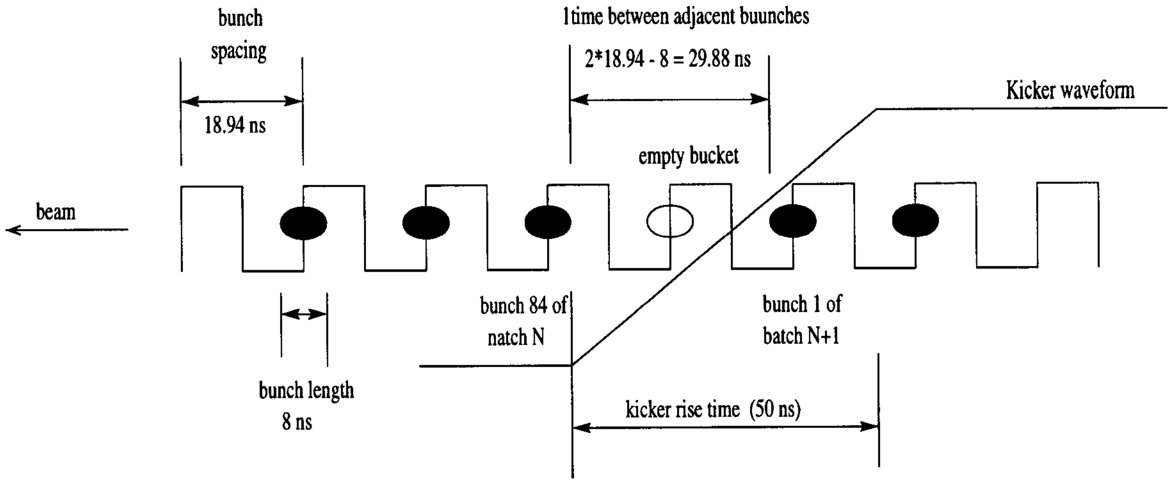
Assuming all 84 buckets are evenly populated, the kicker rise time of 50 ns from 1% to 99% is satisfactory for all injections with two (or more) empty buckets between batches. The fall time requirement is dependent upon cycle as listed in Table 2.

If the 99% to 1% fall time can be kept within the 720 ns in the mixed mode cycle, the issue of kicking individual bunches with the tail would not arise.

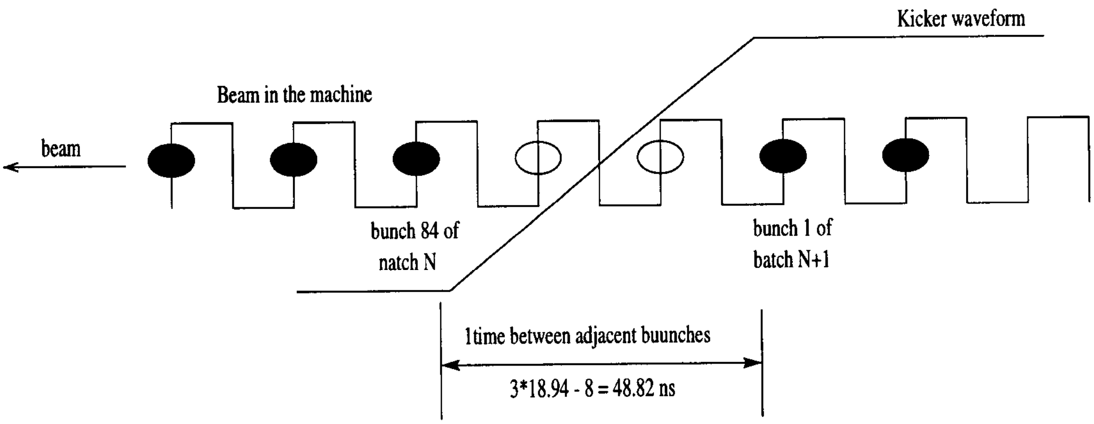
Therefore, the timing specifications are listed below.

Table 4: Proton Injection Kicker Specifications

flattop field error ($\Delta B/B$)	±1%
rise time (0% - 99%)	$\leq$50 ns
flattop length	1.6 us
fall time (99% - 5%)	150 ns
(99% - 1%)	$\leq$750 ns
(99% - 0%)	1.4 us

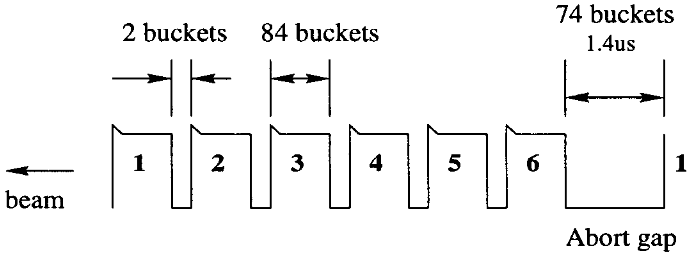


85 bucket injection bunch spacing

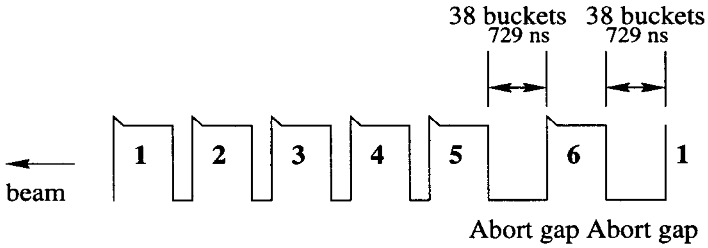


86 bucket injection bunch spacing

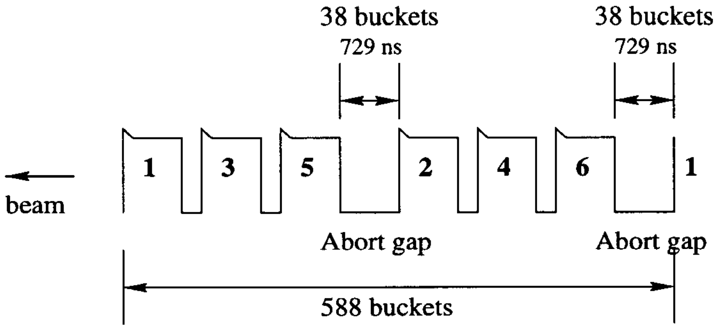
Figure 1: The proton injection kicker rise time as compared to two different batch spacing at injection.



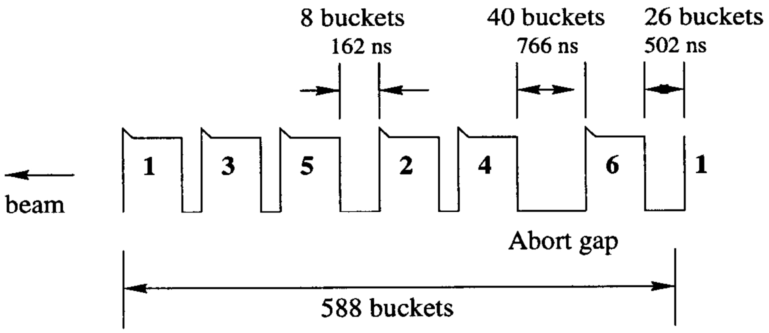
Bunch spacing for normal full ring using box car injection



Bunch spacing for mixed mode using box car injection



Bunch spacing and ordering in an interleaved mode of injection with full batches



Bunch spacing and ordering in a "mixed" interleaved mode of injection with full batches

Figure 2: Bunch spacings for full ring proton injection scenarios.

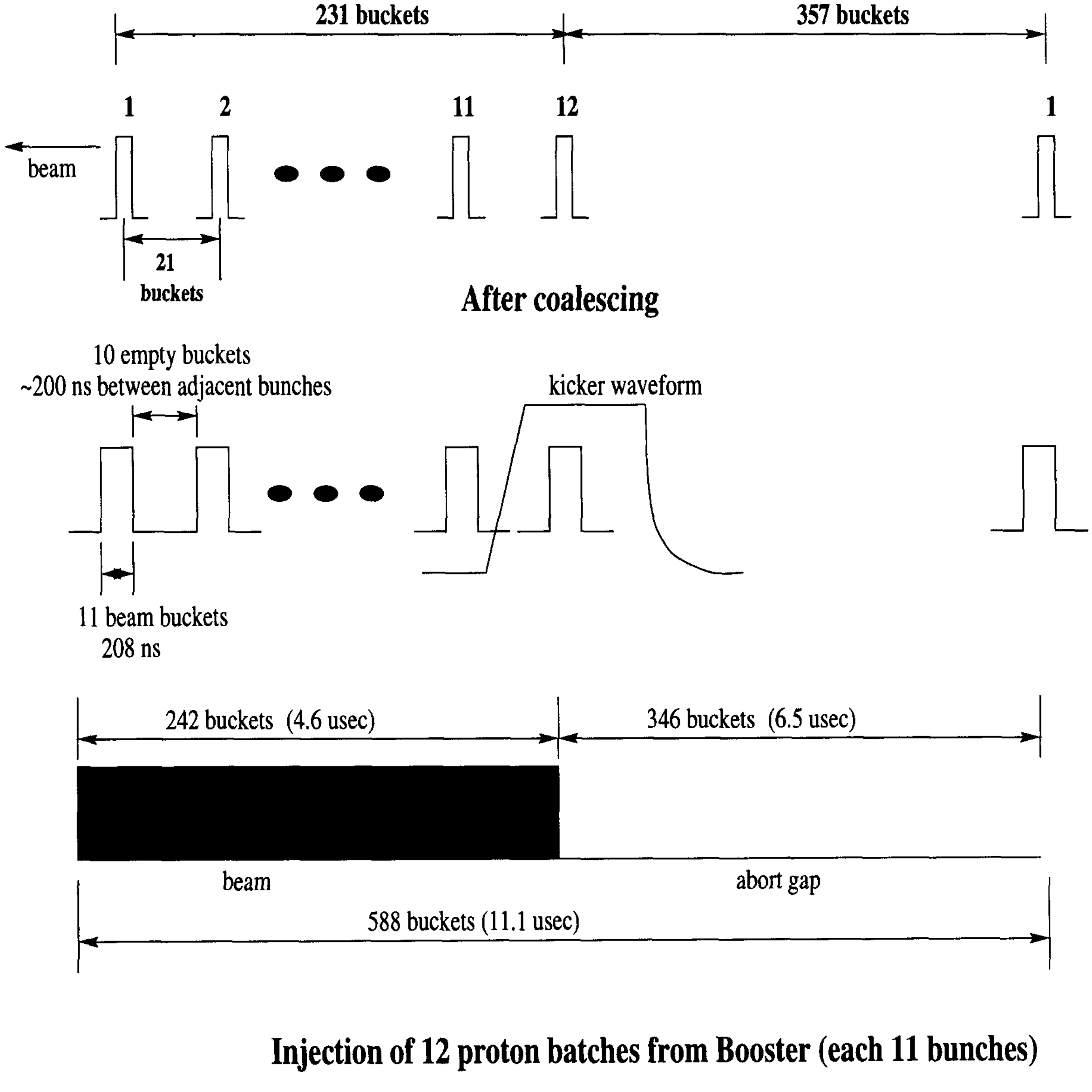


Figure 3: Bunch spacing for proton injection and coalescing in 36 on 36 bunch Collider operation.