Fermilab

MI Note 0027
"Standard" Ramps

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I have designed ramp and rf waveforms (120 GeV only) which satisfy the constraints under which the Main Injector will likely operate, namely:

(i) power supply voltage, regulation and parabola lengths,

(ii) rf dynamics, i.e. matching at transfer, bucket area, adiabaticity, transition crossing and synchrotron frequency considerations,

(iii) compatibility with 15 Hz Booster timing,

(iv) rf voltage limitations, both instantaneous (as a function of energy) and averaged over the cycle time (heating).

There are files on Page M3, File 1 under $29 resets, and also on D126, Files 4-5. Copies of these waveforms are attached. Please inform me if you discover problems with any of these waveforms, so that I can correct them and issue an update. The reason for the duplication is that M3 has twice the number of energy slots, and calculates bucket heights in MeV and power supply voltage, which D126 does not. M3 does not calculate $\delta p/p$ correctly, however. I have used D126, which uses momentum, instead of T126, which uses energy as the variable, to facilitate the parallel files on the two pages.

<u>Ramp description</u>

The ramp is shown in Figure 1, and the M3 specification is given in Table 1. The input to the calculations of power supply voltage are: 9400 A = 150 GeV/c; L = .6 H; R = .4 Ω; During convert, approximately 12000 V is the maximum available; during invert this drops slightly. The resistance assumed is comprised of approximately .24 Ω from the magnets, with the remainder coming from bus work, filters, etc. There is naturally some uncertainty in this number.

The ramp begins with a .108 sec injection level, followed by a single parabola with d^2p/dt^2 = 1200 GeV/c/sec^2, reaching a maximum ramp rate of 240 GeV/c/sec. Steve Hays has said that the maximum d^2p/dt^2 due to power supply limitations is about 2100 GeV/c/sec^2. The ramp rate falls off above 85 GeV due to power supply voltage limitations; similarly, invert has been adjusted to minimize the time required and utilize the power supplies to their fullest. Flattop is 40 msec long. The undershoot appears to me to be overly long; perhaps it can be shortened by changing the depth of the undershoot or the ramp rate returning to the 8 GeV level. For now, I am using the numbers Steve Hays gave me. A 40 msec dwell time follows the undershoot. The total time is 1.4666 sec, or 22 15-Hz cycles. Reducing the 120-GeV cycle time by one 15-Hz cycle to 1.4 sec, while theoretically possible, looks hard unless the undershoot can be shortened considerably; the flat portions of the ramp simply cannot be realistically decreased very much.

Rf description

The rf waveform is given in Figure 2 and Table 2; associated rf and bunch parameters are shown in Figures 3 - 5. The rf voltage required to keep a bucket area of .5 eV-sec results in a synchrotron frequency which rises above 720 Hz during the early part of the parabola. It is ASSUMED that this is NOT a problem.

The maximum rf voltage as a function of energy (less voltage is available at lower frequency) is less than required for the present $29 cycle. See Figure 6. This seems curious at first, since we are trying to ramp at twice the ramp rate, with a d^2p/dt^2 three times that of the present $29 ramp. I believe the reason is that less rf is required in the Main Injector to maintain the bucket area, and more can be used for acceleration.

The other concern is rf cavity heating. The rf curve shown results in less average heating than the present $29 cycle, assuming a 1.4667 (2.6) seconds cycle time for the Main Injector (Main Ring). See Figure 7. Note that the present $29 cycle has lowered the rf to just over 3 MV between about 52 GeV and 119 GeV, precisely because of excessive heating when the rf was maintained at a higher level throughout the high field part of the cycle. What is not included in this calculation is any rf voltage manipulations for bunch rotation. If the rf voltage is raised to 3.8 MV for the last 30 msec, this increases the heating to the point it is nearly equal to the present $29 cycle. (Keeping the voltage at 3.8 MV from 85 GeV on raises it substantially above the $29 cycle heating.)

The rf curve has been tuned, but not fully optimized, to give a reasonable rf voltage while crossing transition. The rf has been lowered near transmission, but limiting the synchronous phase to about 45 degrees. Some further voltage reduction may in fact be desirable to reduce the bunch momentum spread.

If it is later found that the synchrotron frequency must be kept below 720 Hz, then a second, slower parabola must be added at the start of acceleration, with $d^2p/dt^2 = 300$ GeV/c/sec^2. The cycle would have to be longer by one 15-Hz interval, and an additional 4 msec would have to be removed from some other part of the ramp. I tried other waveforms, e.g. a cubic at the beginning, but that didn't work as well as two separate parabolas.

Injection

The injection period looks very short and requires modifications to accelerator timing, namely, the ability to adjust Main Injector resets with respect to Booster resets in steps finer than 15 Hz increments. With present timing control, injections can take place only at .0508 sec, .1175 sec, .1841 sec, .2508 sec, etc. If a minimum of greater than .050 sec is required for the power supplies to stabilize after reset, the next injection is at .1175 sec, which is after the start of acceleration. It would be desirable to vary this time to place it a convenient distance before the start of acceleration, perhaps in 60 Hz intervals.

Other cyles

The 150 GeV ramps would presumably be very similar, with injection and flattop periods adjusted to account for injecting up to six batches, and for rf manipulations at flattop. Similarly, no allowance has been made for slow spill on the 120 GeV cycles, which requires additional time at both injection and flattop. The rf voltage levels at injection and flattop would also be cycle-dependent.

Momentum spreads and offsets

Some of the considerations involving momentum spread/offset are the requirements for bunch rotation at 120 GeV for antiproton production, bunch coalescing at 150 GeV, and transfer cogging to position the bunches properly for transfer to the Tevatron at 150 GeV. Each of these is addressed below.

(i) Bunch rotation. An rf voltage of 3.8 MV leads to a $\delta p/p$ of .09% for $\epsilon = .5$ eV-sec. The bunch is rotated to a long, low-momentum spread bunch, then rotated up to a momentum spread of .18%; the rotation takes just over 1 msec, so the bunches must circulate with a large momentum spread only for a time of less than 100 turns. (Question: how long does it take to get from the bunch rotation stage to a profile suitable for slow extraction? Probably several hundred msec. This has probably not been taken into account.) Also, the effectiveness of the bunch rotation decreases as the initial bunch length approaches 6 nsec; if there is longitudinal emittance growth during acceleration and transition crossing, the final bunch lengths attainable may be much longer than are presently achieved in the Main Ring. This is mainly an effect of the larger emittances anticipated in the Main Injector with the much more intense bunches.

(ii) Bunch coalescing. Assuming no changes to the Tevatron rf, the matching bucket has a height of 157 MeV, or $\delta p/p = .105\%$; S = 3.76 eV-sec. The bunches will be circulating at 150 GeV for tens of thousands of turns.

(iii) Transfer cogging. Assuming we are clever about the transfer, and have the different revolution times take care of the bulk of the alignment process, the maximum amount of transfer cogging is 10 buckets. Let us allow 100 msec for the operation; then $\Delta f = 100$ Hz, $\Delta r = 1$ mm, and $\Delta p/p = .08\%$, i.e. comparable to the $\delta p/p$ due to coalescing. Thus, either the cogging should be done first, or it must be done more slowly, e.g. over 1 second.

Table 1. Ramp Specification

------------------------values at end of sequence------------------

SEQ	TYPE	Dt	TIME	MOMENTUM	Pdot	Pddot	
01	INITI >	.108	.108 >	8.889	0	0	V-trans = 0
02	VPARAB	0	.108	8.889	0	0	T-trans = .23857
03	PARAB	.2	.308 >	32.889>	240	1200	P-trans = 19.118
04	PARAB	.21713	.52513>	85 >	240	0	
05	PARAB	.09892	.62405>	108 >	225	-151.63	
06	PARAB	.10667	.73072>	120 >	0	-2109.4	
07	CAPDEP>	.04	.77072	120	0	0	
08	PARAB	.05714	.82786>	110 >	-350	-6125	
09	PARAB	.30937	1.1372>	11 >	-290	193.94	
10	PARAB	.06966	1.2069>	.9 >	0	4163.4	T22 = .108
11	CAPDEP>	.02	1.2269	.9	0	0	T25 = .73072
12	PARAB	.1	1.3269>	4.9 >	80	800	T26 = .77072
13	PARAB	.00061	1.3275>	4.949 >	80	0	
14	PARAB	.0985	1.426 >	8.889 >	0	-812.18	
15	CAPDEP>	.04	1.466	8.889	0	0	

Table 2. Rf Curve Specification

------------------------values at end of sequence------------------

SEQ	TYPE	Dt	TIME	P	Pdot	%dP/P	PHI	HV18	AREA	%HITE
01	Initi>	.001	.001	8.889	0	0	0	>.393	.504	.236
02	Tramp>	.107	.108	8.889	0	0	0	>.393	.504	.236
03	Pramp	.02	.128	>9.129	24	0	13	>1.2	.584	.347
04	Pramp	.02	.148	>9.849	48	0	21	>1.5	.567	.357
05	Pramp	.02	.168	>11.049	72	0	28	>1.7	.568	.363
06	Pramp	.02	.188	>12.729	96	0	34	>1.9	.626	.39
07	Pramp	.02	.208	>14.889	120	0	39	>2.1	.774	.46
08	Pramp	.02	.228	>17.529	144	0	44	>2.3	1.28	.714
09	Pramp	.02	.248	>20.649	168	0	45	>2.65	1.65	.795
10	Pramp	.02	.268	>24.249	192	0	44	>3.04	1.19	.486
11	Pramp	.02	.288	>28.329	216	0	44	>3.42	1.14	.397
12	Pramp	.02	.308	>32.889	240	0	44	>3.8	1.17	.352
13	Pramp	.21713	.52513	>85	240	0	44	>3.8	1.57	.183
14	Pramp	.09892	.62405	>108	225	0	45	>3.55	1.67	.154
15	Pramp	.10667	.73072	>120	0	0	0	>1	5.65	.196
16	Tramp>	.04	.77072	120	0	0	0	>1	5.65	.196

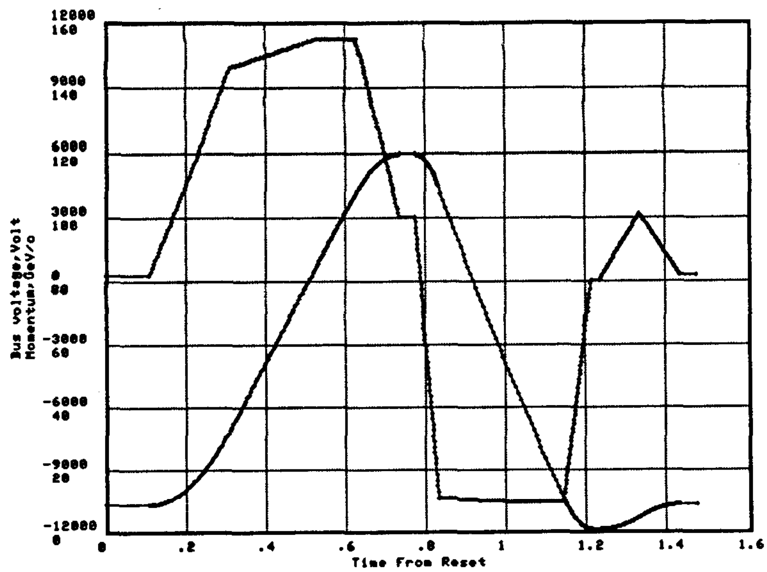

Figure 1. Ramp and Power Supply Waveform

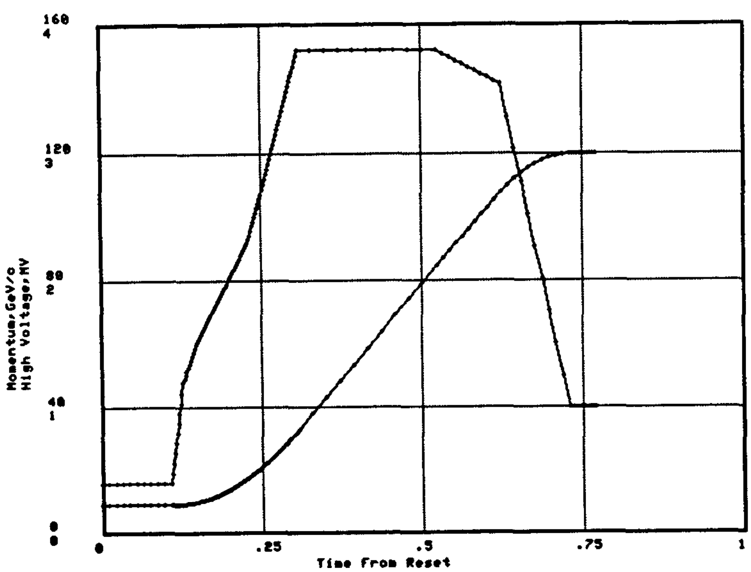

Figure 2. Rf Waveform

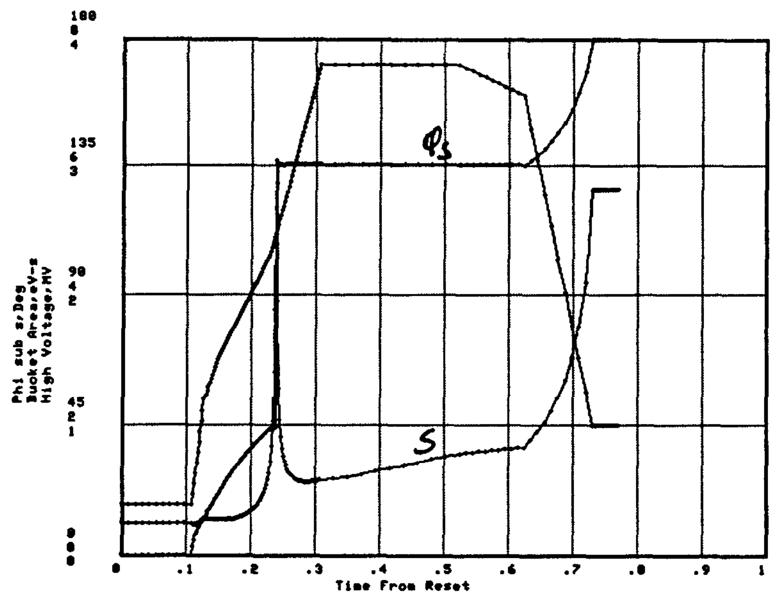

Figure 3. Rf, Bucket Area and ϕ_s

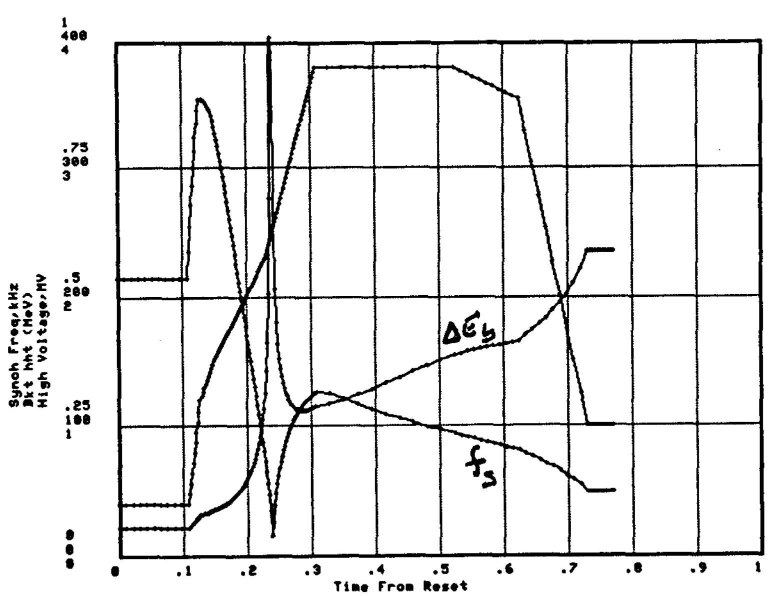

Figure 4. Rf, Bucket Height and Synchrotron Frequency

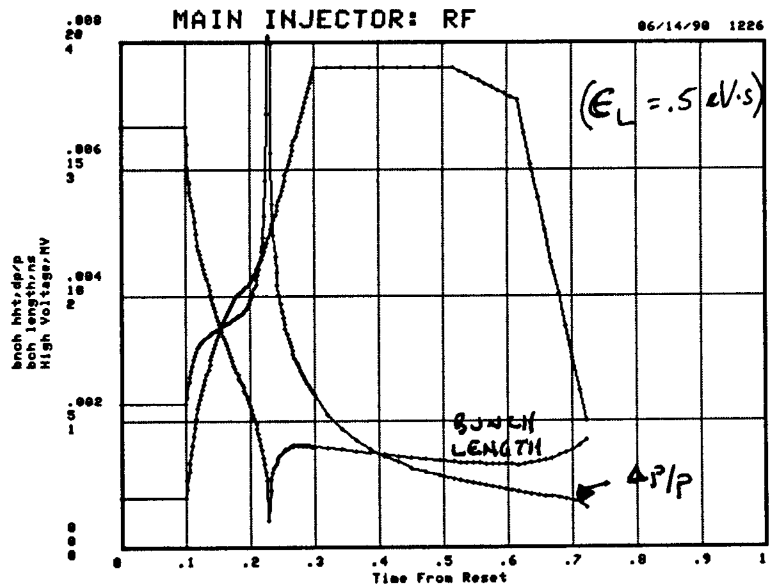

Figure 5. Rf, Bunch Length and Bunch Momentum Spread

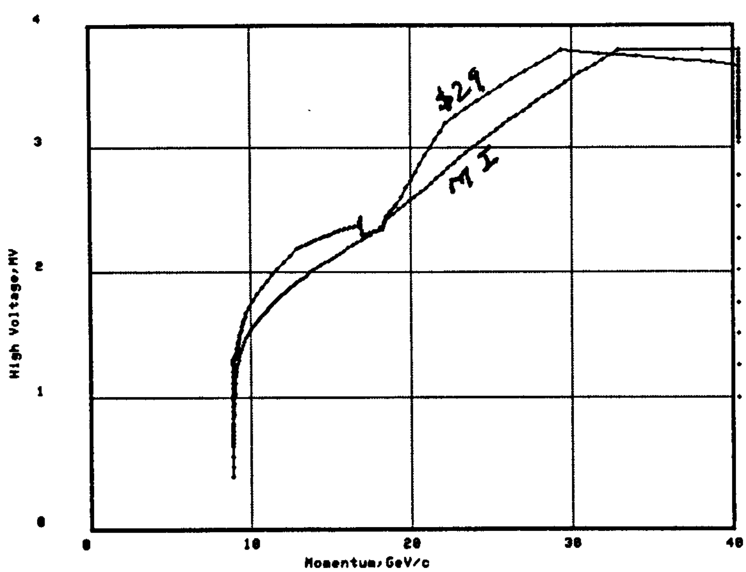

Figure 6. Rf Curve vs. Energy
for Main Injector and Main Ring $29 Cycle

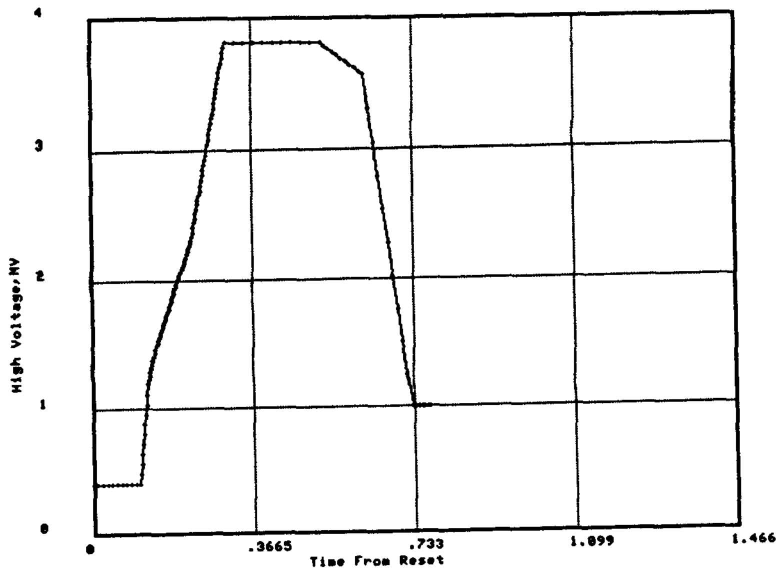

Figure 7a. Rf Curves for Main Injector

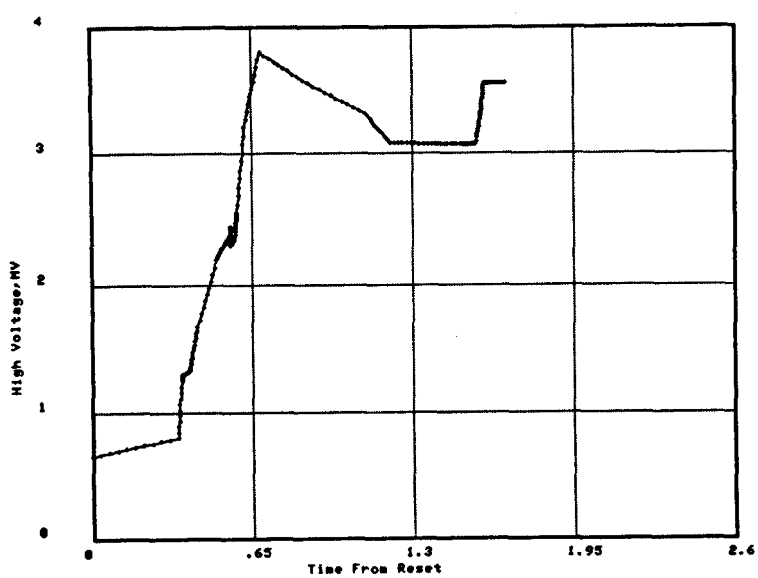

Figure 7b. Rf Curve for Main Ring $29 Cycle