RF CONSIDERATIONS IN THE MAIN INJECTOR

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Introduction. This paper discusses some of the rf-related aspects of the Main Injector design. If the Main Ring rf systems are moved to the Main Injector and operated at the same voltages, then the rf parameters in the Main Injector are related to those in the Main Ring by relations which involve h and η. The bucket height and area are proportional to the square root of $1/h\eta$ and the zero-amplitude synchrotron frequency is proportional to the square root of η/h. The present Main Injector design calls for h=588 and γ_t=20.4. Table I shows the changes at injection and at 150 GeV (120 GeV is essentially the same) in these quantities.

Table I
Rf related parameters for the Main Ring and Main Injector

	Main Ring	Main Injector	Ratio--MI/MR
h	1113	588	1.89
h(Coalescing)	53	28	1.89
8 GeV:			
η	0.00817	0.00862	1.06
$h\eta$	9.093	5.066	0.56
$\sqrt{(1/h\eta)}$	0.332	0.444	1.34
$\sqrt{(\eta/h)}$	0.00271	0.00383	1.41
150 GeV:			
η	0.00280	0.00236	0.84
$h\eta$	3.116	1.388	0.44
$\sqrt{(1/h\eta)}$	0.566	0.849	1.50
$\sqrt{(\eta/h)}$	0.00159	0.00200	1.26

The ratios apply to the coalescing rf as well as to the 53 MHz accelerating rf. Thus, for coalescing at 150 GeV, if the same coalescing rf voltage is used, then the bucket height in the Main Injector (and hence the energy spread of the rotated bunch) will be increased by a factor of 1.5, and the rotation will take 1/1.26 times as long.

Injection and acceleration. The Main Injector design provides a momentum acceptance of ±1%, but the rf has been said to limit this at injection to about one-fourth of this value (corresponding to a bucket area of .5 eV-sec.) This limitation is imposed solely to keep the synchrotron frequency below 720 Hz. This is a timed-honored procedure for the Main Ring, but may not be necessary for the Main Injector. Figure 1 shows a possible rf program and the resulting bucket area and zero-amplitude synchrotron frequency during the ramp, with the synchrotron frequency remaining above 720 Hz for the first 60 msec. The calculations assume a 150 msec parabola ending at a 240 GeV/c/sec ramp rate. The transition through 720 Hz is made very quickly. The assumption has been made that the rf voltage at 8 GeV can be raised to the level of 1.5 MV, which may require modifications to the rf tuners. If this is possible, then bucket areas of 1 eV-sec are not to be ruled out. This places the real limitation on intensity back in the Booster, where the beam intensity may well be determined by the bucket area available for however many rf cavities are operational. In addition to the zero-amplitude synchrotron frequencies listed above, there is an amplitude-dependent lowering of the synchrotron frequency. For example, if the zero-amplitude frequency is 1 kHz, the particles (for a stationary bucket) that go through about ±120 degrees at their phase extremum will have a frequency of 720 Hz. If power supply noise excites these particles, one might expect some emittance growth or even beam loss. If 720 Hz has to be avoided at all costs, an rf voltage at injection of 700 kV is the upper limit, which reduces the bucket area to .67 eV-sec. The beam emittance will then be somewhat less than this, by whatever tolerance is required to allow for phase errors during injection, and the inherent problems at the start of acceleration during which time the bucket width shrinks. (Particles too close to the unstable fixed point will be lost.) If the rf voltage is lowered so that the synchrotron frequency remains below 720 Hz for the entire cycle, the bucket area has a minimum of around .3 eV-sec at about 30 msec into the ramp. A slower parabola could increase this minimum bucket area, at the expense of a longer cycle time. Figure 2 shows a reasonable rf program; the parabola has been slowed by almost 100 msec.

Matching between the Main Injector and other machines. To match rf buckets between machines, the quantity $V/h\eta$ should be the same for the two machines. Table II lists the parameters for the various machines.

Table II
Matching parameters for the Main Injector, Booster, Accumulator and Tevatron

	Main Injector	Booster or Accumulator	Tevatron	Ratio—MI/Other
h	588	84	1113	
8 GeV:				
η	0.00817	0.0227		
$h\eta$	5.066	1.907		2.66
150 GeV:				
η	0.00236		0.00280	
$h\eta$	1.388		3.116	.445

For injection from the Booster, this means the rf voltage in the Main Injector should be 2.66 times the Booster rf voltage. If the Main Injector rf voltage is 1.5 MV at injection, then the Booster matching voltage is 564 kV (1 eV-sec bucket area). While 12 Booster cavities can provided this voltage at extraction, what is the maximum bunch area that can be accelerated in the Booster as a function of the number of rf cavities? This is a complicated problem that depends critically upon the details of the longitudinal emittance growth after transition. As one lowers the Main Injector rf voltage, there are all the considerations about avoiding 720 Hz synchrotron frequencies discussed above.

For matching to the Accumulator, the situation is somewhat different, since the 53 MHz system in the Accumulator is limited to 100 kV; the matching requirement is the same as for the Booster. This limits the rf voltage in the Main Injector to 266 kV, and the bucket area to .41 eV-sec. Since the synchrotron frequency is already below 720 Hz, then one presumably would like to remain below 720 Hz throughout the cycle. In order to keep the bucket area from shrinking considerably during acceleration, while keeping the synchroton frequency low, the parabola must be slowed down at the beginning. The time involved is small, but it does imply slightly different operating conditions for antiprotons than for the fast-cycling high intensity proton operation. Presumably, the proton cycle for collider injection would operate on an identical cycle to that for the antiprotons, to allow tuning rf parameters to optimize transmission.

The other transfer to be considered is the transfer to the Tevatron. In fixed target mode, assuming a voltage in the Tevatron of 1.2 MV, the voltage at extraction from the Main Injector should be 534 kV. This corresonds to a bucket area of 4.59 eV-sec. In Collider mode, using 800 kV for the voltage in the Tevatron, a Main Injector voltage of 356 kV (bucket area 3.75 eV-sec, bucket height 157 MeV) is required. The Main Injector cavities would have to be paraphased to achieve this low voltage at the time of transfer.

Coalescing. As mentioned earlier, the change in h and η result in a 50% increase in the coalescing bucket height for the same voltage as used in the Main Ring. This leads to improved efficiency, but a larger bucket must be used for capturing. Alternatively, one could reduce the coalescing rf voltage to keep the bucket height the same as is presently used. The rotation period then becomes 1.50/1.26 = 1.19, or 19% longer than at present. At the reduced power level, this should not be a problem. Achieving the high intensity bunches (2 to 5 10^{11}) desired for the upgrade looks feasible, provided that (1) the presently observed intensity-dependent coalescing efficiency decrease is cured, either through the fast cavity shorts or through some other mechanism, e.g. use of the 2.5 MHz cavities during the debunching process, and (2) the Booster is able to deliver bunches of the desired density. The ability to produce intense bunches with the present longitudinal emittance would be easier to guarantee if the bunches before coalescing were to have smaller longitudinal emittances than presently assumed. The present Main Injector design has sufficient margin to produce intense bunches, but to do so may require a larger longitudinal emittance than presently foreseen. This may even require additional rf in the Tevatron to capture all the beam.

To go through the numbers, if 7 bunches of intensity .6 10^{11} and longitudinal emittance .5 eV-sec can be debunched perfectly, and rotated so that the width after rotation is just the 53 MHz bucket width, then the rotating voltage should be 23 kV (bucket height 186 MeV). The bunch height is 93 MeV. Capturing this bunch in a 53 MHz bucket and then adiabatically increasing the bucket up to the level required for transfer will give a bunch which almost fills the bucket, as was the case during the 1988-89 collider run. The 7 bunches had an assumed intensity of 4.2 10^{11}; allowing for a reasonable coalescing inefficiency, the desired coalesced bunch intensity of 3.3 10^{11} should be achievable. If the desired bunch density (before coalescing) cannot be achieved, then more than 7 bunches will need to be coalesced, and the bunch height will grow. This increased emittance coalesced bunch will completely fill the limited rf bucket in the Tevatron.

Table III lists the 2.5 MHz voltage, bucket height and rotation time, and the 53 MHz capture voltage, capture bucket height, transfer (to the Tevatron) voltage and transfer bucket height for the present Main Ring conditions, and for two cases for the Main Injector. In the first case, the bucket heights are kept the same as those used in the Main Ring. In the second case, the capture voltage is the same as the transfer voltage for matching the present Tevatron rf voltage. In the third case, the rotation and cature voltages are the same the present Main

Ring. The Main Injector could operate anywhere in this range. The 5 MHz system is ignored in the calculation of the bucket heights and rotation periods.

Table III
Coalescing voltages and bucket heights

	2.5 MHz system			53 MHz system			
	V	ΔE_b	T_{rot}	V_{cap}	ΔE_b	V_{tran}	ΔE_b
Main Ring	26 kV	129 MeV	110 msec	500 kV	124 MeV	800 kV	157 MeV
Main Injector--1	12 kV	129 MeV	130 msec	223 kV	124 MeV	356 kV	157 MeV
Main Injector--2	19 kV	163 MeV	103 msec	356 kV	157 MeV	356 kV	157 MeV
Main Injector--3	26 kV	194 MeV	87 msec	500 kV	185 MeV	(?)	(?)

One problem with coalescing high intensity, large longitudinal emittance bunches will be the amount of charge outside the central bucket. A superdamper in the Main Injector should be provided to allow eliminating this charge before transfer to the Tevatron. How much time will be required for that operation?

The Main Injector with $\gamma_t = 8.1$. If transition-crossing can be avoided by modifying the lattice to shift transition below the injection value of γ, what are the implications for the rf behavior of the machine? The major impact is on the coalescing process at 150 GeV. There will be a reduction of the bucket height for the coalescing cavities by roughly a factor of 8.1/20.4 = .40. If one tries to overcome this by coalescing at a lower energy, e.g. injection, then the 53 MHz system becomes the limiting factor. The minimum bucket area (for Γ=0 and fixed voltage) occurs at $\surd 2\ \gamma_t$. For 4 MV, the limiting bucket area is 2.65 eV-sec, i.e. smaller than the coalesced bunch emittance. Accelerating at 80 GeV/c/sec reduces this to about 1 eV-sec. Thus one is forced to coalesce at or near flattop, and the coalescing cavity system must be increased substantially (by a factor of 2.87 to equal the present Main Ring bucket height.)

Main Injector rf voltage requirements. Note that the synchronous phase for acceleration in the Main Injector is quite small. The number of rf cavities could be reduced to 14 and still keep the synchronous phase below 54 degrees. This does reduce the bucket area, though, by more than a factor of two. However, voltage is not the only issue. The power that can be delivered to the beam must also be considered, especially in the context of determining the ultimate intensity limitations of the Main Injector. This is discussed in more detail by J. Griffin elsewhere in these proceedings.

Debunched beam for slow extraction. The slow extraction experimenters desire beam with as good a duty factor as possible. Ideally, the beam should be totally debunched. However, a gap must be established for the abort, and therefore either the beam must remain within buckets or a barrier bucket must be established. Using a second harmonic rf (106 MHz) would allow the beam to remain in buckets while improving the duty factor over what would be attainable with only the 53 MHz; the second harmonic might also improve the debunching for coalescing. Figure 3 shows a bunch in a bucket formed by the combination of 53 and 106 MHz.

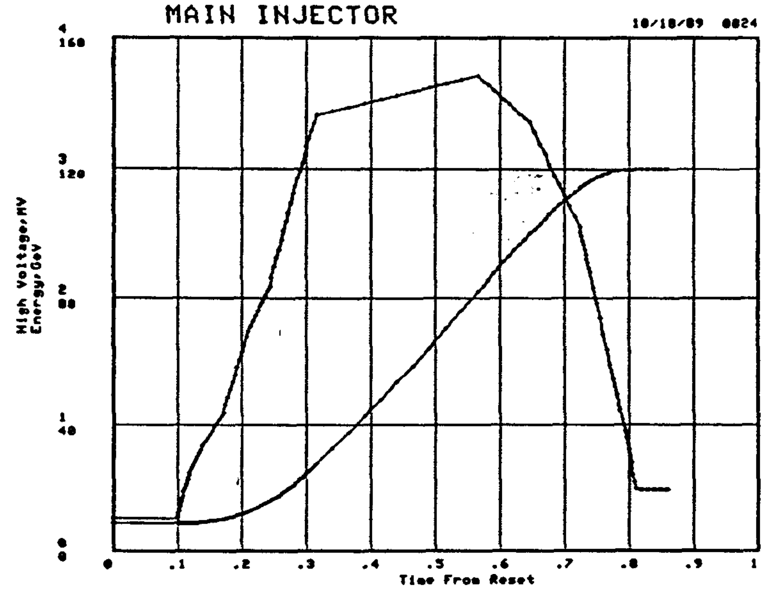

Figure 2a.
Energy and rf voltage for slow cycle with
synchrotron frequency less than 720 Hz.

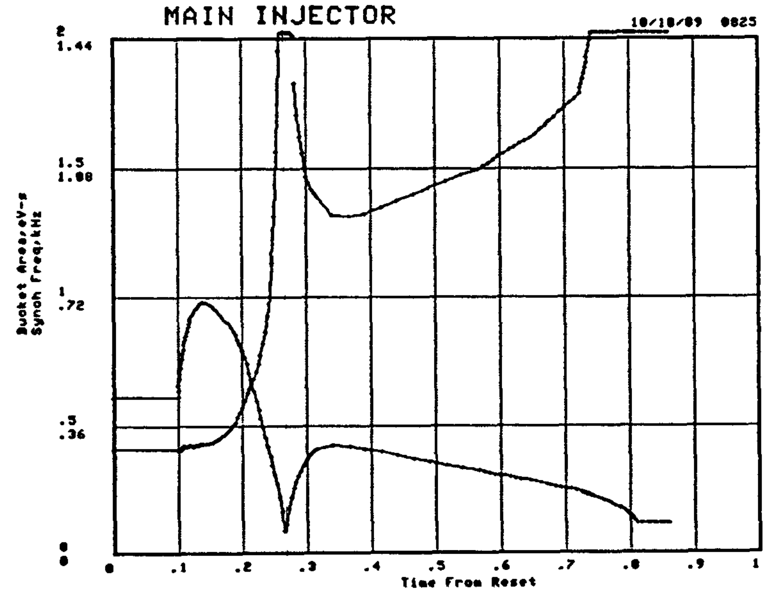

Figure 2b.
Bucket area and synchroton frequency for slow cycle with
synchrotron frequency less than 720 Hz.

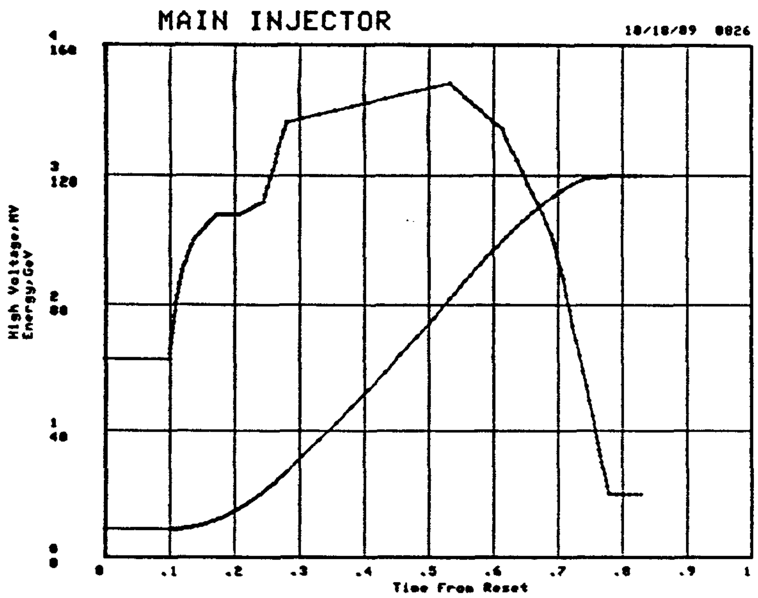

Figure 1a.
Energy and rf voltage for maximum ramp rate and bucket area.

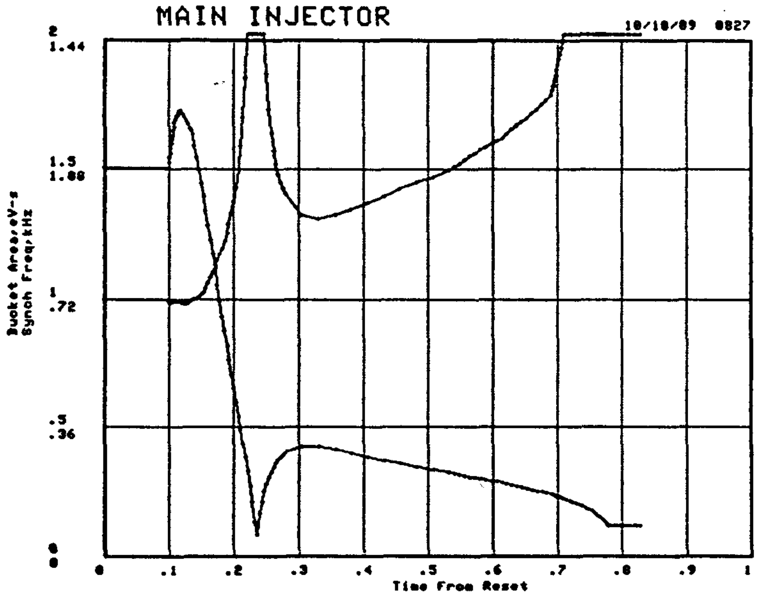

Figure 1b.
Bucket area and synchrotron frequency for maximum ramp rate and bucket area

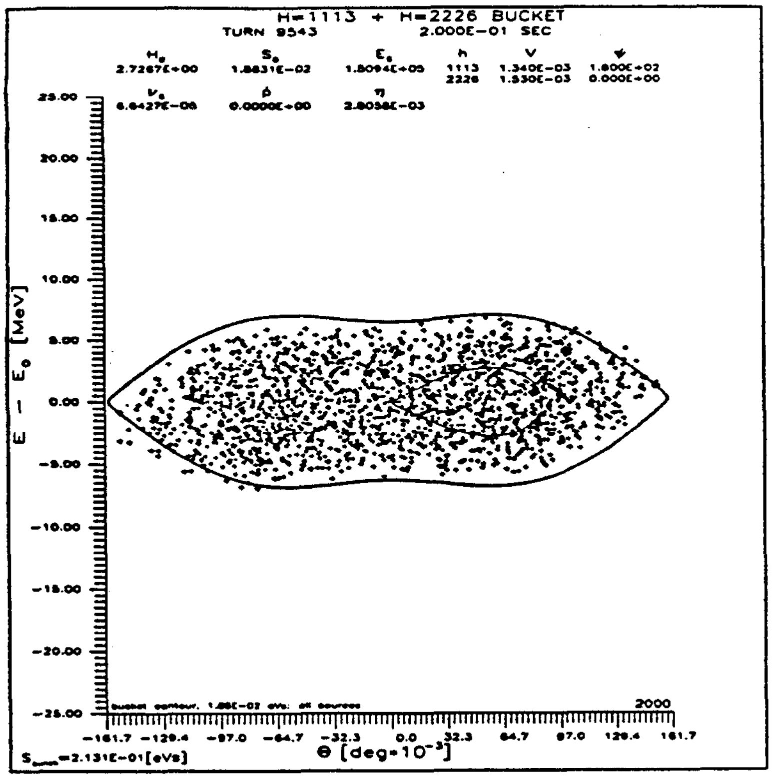

Figure 3a.
Bucket formed by 53 MHz plus 106 MHz.

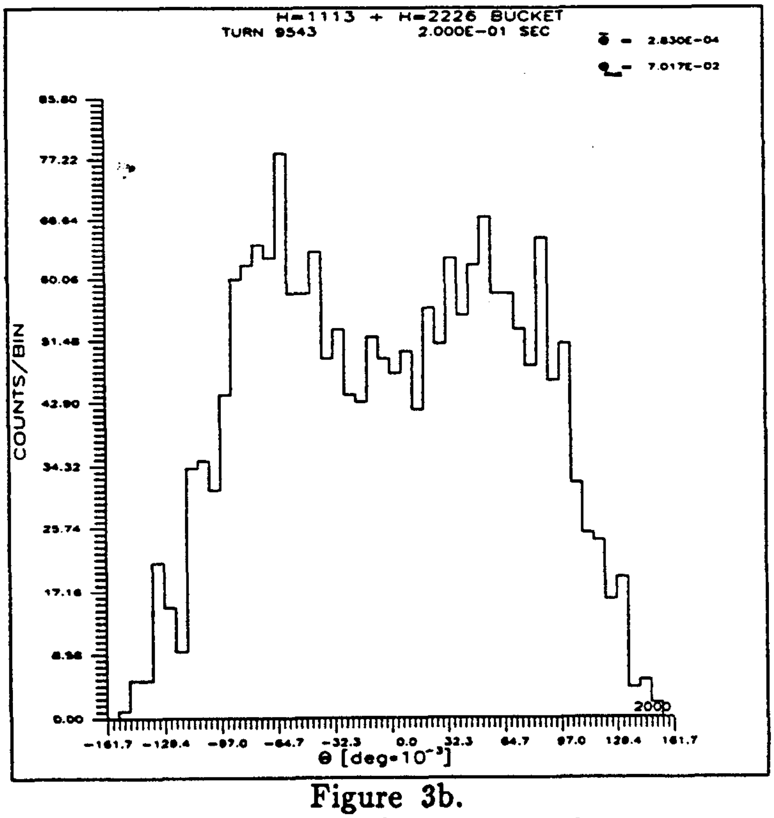

Figure 3b.
Particle density as a function of phase for a bucket formed by 53 MHz plus 106 MHz.