Analysis of the Beam Loss Observed During the October 12, 2000 Main Injector Deceleration Studies

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Abstract

On October 12, 2000 the first systematic attempt to decelerate protons in the Main Injector down to a momentum of 2.0 GeV/c occurred. Beam was observed down to a momentum of 3.0 GeV/c, with some peculiar structure in the beam loss pattern. The RF system used for deceleration was the 2.5 MHz coalescing system. In this paper much of the beam loss is explained in terms of loss of longitudinal bucket area.

1. Observed Beam Loss

At the very end of the study period the beam survival during the ramp was observed with four different 2.5 MHz RF amplitude curves. The purpose of this effort was to ascertain if the observed rate of beam loss was due to loss of bucket area during deceleration or due to transverse problems such as incorrect closed orbits, tunes, and chromaticity. The beam survival observation was in the form of a control system fast time plot, shown in figure 1.1.

The green curves are of the control system parameter I:IBEAMS, which is the beam intensity in units of 10^{10} protons. The plot ranges from 0 to 16. The fact that one trace, which happened to correspond to the requested 2.5 MHz RF amplitude of 25 kV, has a lower initial intensity has nothing to do with the measurement conditions. It just happened to be a low pulse out of the Booster.

The red curves are the 2.5 MHz RF system voltage in units of kilovolts. The name of the parameter is I:H28SUM, and it ranges from 0 to 40. Note that on two traces one of the cavities in the tunnel lost its voltage for approximately 1 second before resetting and coming back on.

The blue curve is the measured deceleration ramp in units of GeV/c. The parameter is called I:MMPRQ, and represents the central momentum of the Main Injector as calculated by the MECAR power supply feedback system. The momentum range on the plot is 1 to 9 GeV/c.

Finally, the black curve is I:VDSPFO, which is the RF frequency of the 53 MHz RF system minus 50 MHz. The injection frequency is 52,811,400 Hz, and the expected frequency at 2 GeV/c is approximately 48 MHz. Therefore, the range of this parameter on the plot is -4,000,000 to +4,000,000 Hz. Note that the frequency was limited to values above that corresponding to 2.8 GeV/c. This limitation was introduced due to the fact that the beam synchronization system was not tracking the RF frequency below 50 MHz, causing errant pulses to be emitted into various subsystems such as the Tevatron injection kickers. For the time being, since beam was not making it below 3 GeV/c anyway, it was prudent to introduce this limit. It can easily be removed in later studies when we are ready to decelerate protons further down the ramp.

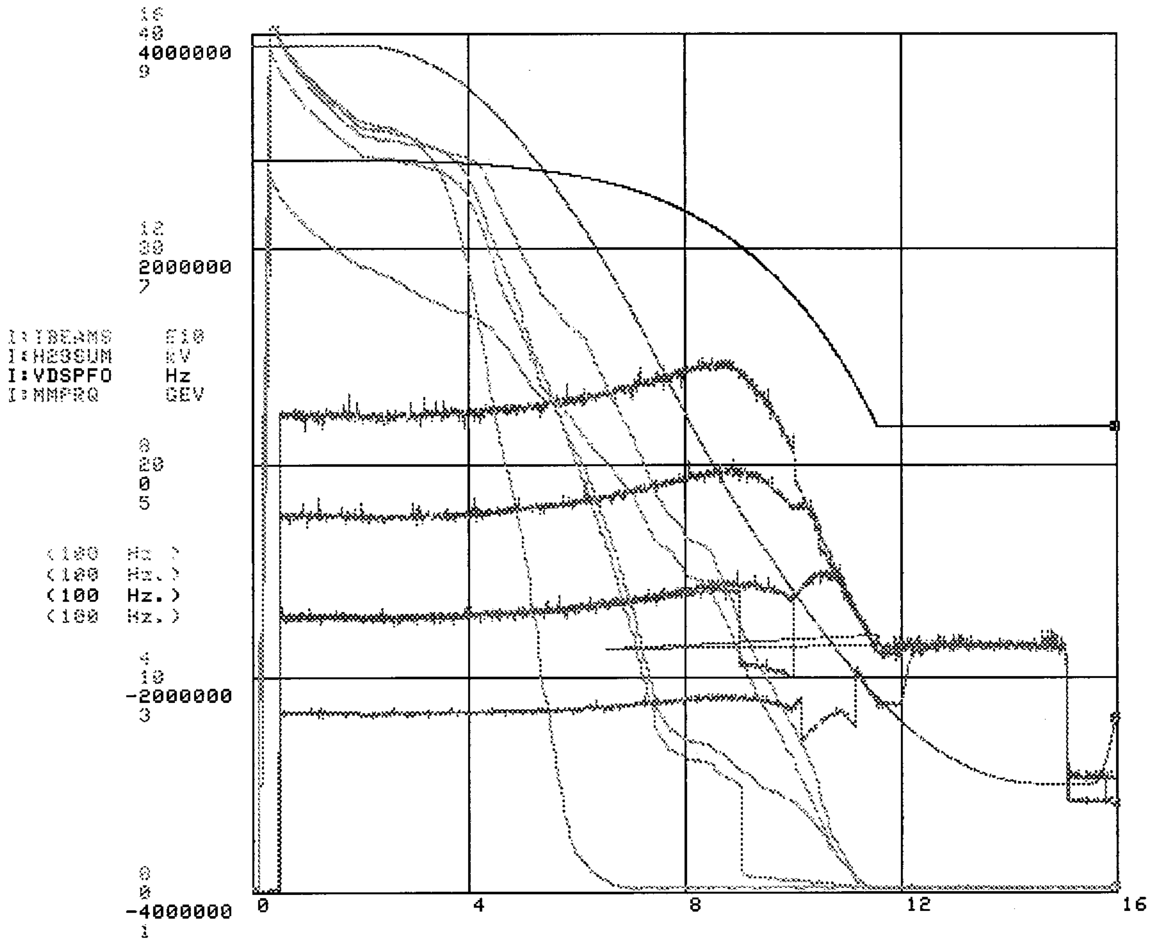

Figure 1.1: Proton intensity (green) as a function of time for four different RF amplitude curves (red). The RF voltage settings used were 25, 20, 15, and 10 kV. Note that the beam falls out completely by 7 seconds with an RF voltage request of 10 kV. There are two sets of traces for the 15 kV RF amplitude request, in which one is normal and the other had an RF station drop out during the ramp. The fact that most of the remaining beam fell out of the Main Injector after the voltage drop is a clear indication that loss of bucket area is dominating the beam loss during deceleration.

2. Spreadsheet Model

A Microsoft EXCEL spreadsheet was written to simulate the data recorded in figure 1.1. The model uses the precise Main Injector ramp definition as output by MECAR. Broken down into 0.1 second intervals, the momentum, ramp rate, RF frequency, RF amplitudes, and longitudinal parameters such as momentum compaction factor, bucket height, bucket area, and beam fraction inside the RF bucket are calculated in each slot. The bucket parameters are calculated using the moving bucket correction factors.

In calculating beam survival, the fraction of a Gaussian distribution with the specified 95% invariant bucket area is calculated in each time slot. What is actually reported in that slot is the minimum of this calculation and the value of the previous slot. Therefore, as the bucket area starts to again increase, the simulation does not end up "creating" protons. All of these calculations assume that the ramp and RF manipulations are adiabatic and that no source of longitudinal emittance growth is at work.

3. Spreadsheet Results

The first spreadsheet result to be presented is the simulation of the 10 kV observation. Given that the longitudinal emittance of the proton bunch was not quantitatively measured but only observed on an oscilloscope, a range of longitudinal emittances are always presented. Figure 3.1 shows the initial simulation prediction of beam survival down the ramp only assuming bucket area limitations. The three traces correspond to 95% invariant bunch areas of 1, 3, and 5 eV-sec matched to the 2.5 MHz RF bucket. Note the incredible quantitative agreement between this simulation result and the observed beam loss.

The only major difference between the simulation result and the measured data is the fact that the final loss of beam is more gradual in reality. The reason for this difference is that the simulation assumes that once a proton falls outside of the RF bucket, it is immediately lost. In reality, the lost protons persist for a few hundred milliseconds until the proton radial position moves toward the wall of the vacuum chamber.

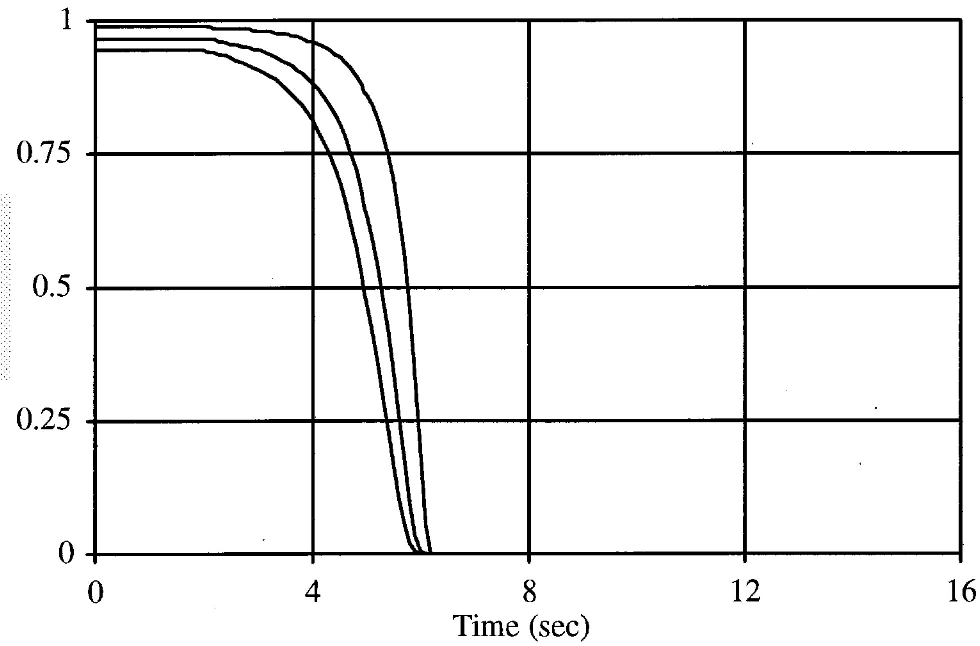

Figure 3.1: Beam survival during deceleration when the 2.5 MHz RF system is set to a peak voltage of 9 kV. This corresponds the the trace in figure 1.1 in which an amplitude of 10 kV was requested. In this simulation the longitudinal emittance of the coalesced beam was set to 3.0 eV-sec for the middle curve, and the lower and upper curves are for 5 and 1 eV-sec respectively. Note the incredible quantitative agreement between this simulation result and the observed beam loss.

The next simulation result corresponds to the 15 kV RF amplitude request. As shown in figure 3.2, an effort was made to create an RF amplitude curve which is a reasonable approximation of the measured cavity gap voltage.

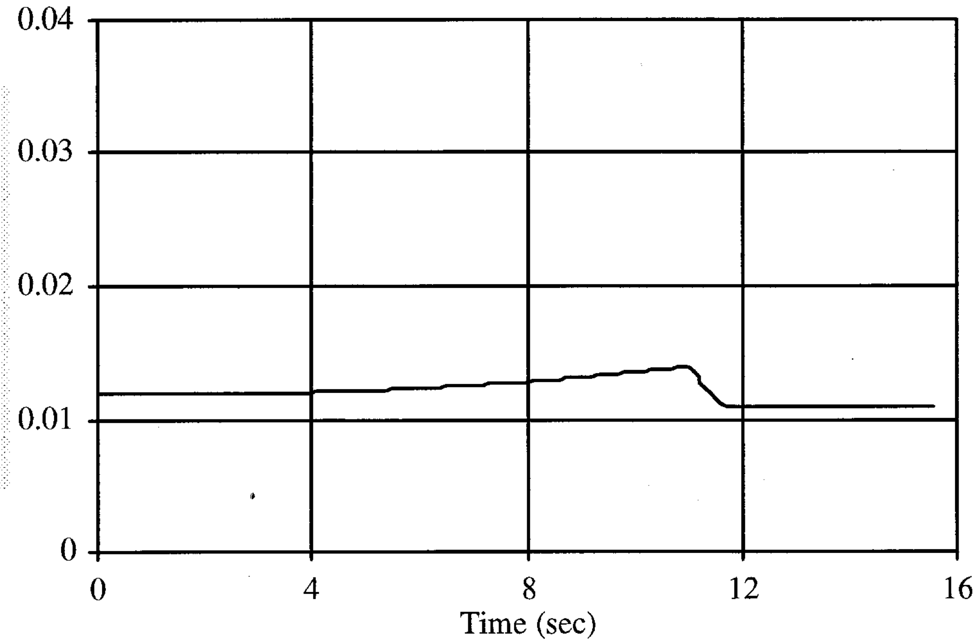

Figure 3.2: RF voltage curve used in the simulation for the condition in which 15 kV was requested. This has been tuned so that it approximates the observed cavity voltage.

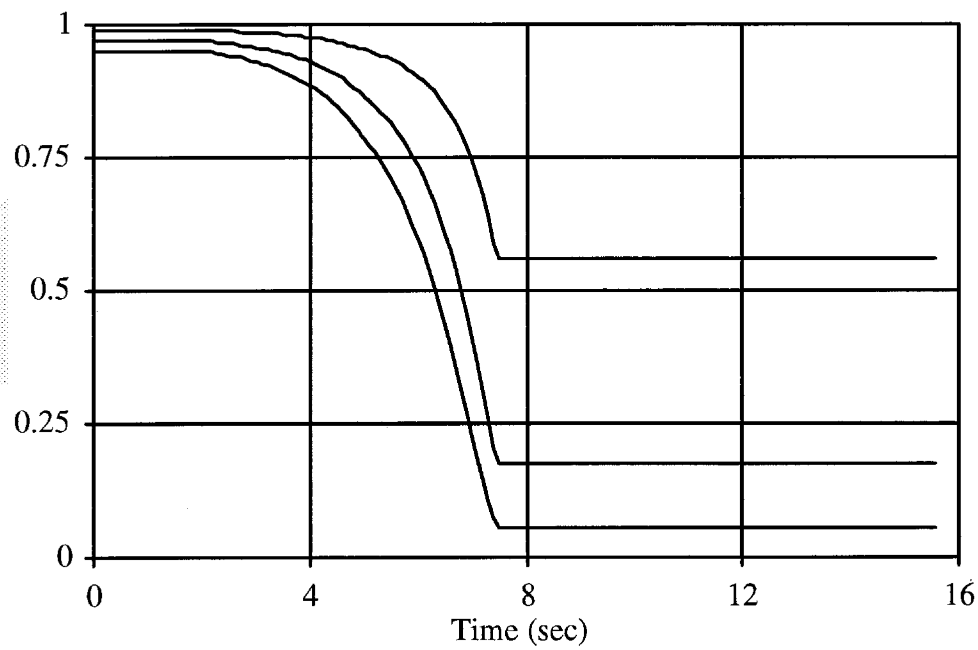

Figure 3.3: Beam survival during deceleration when the 2.5 MHz RF system is matched to the observed RF amplitude in the Main Injector when 15 kV is requested. In this simulation the longitudinal emittance of the coalesced beam was set to 3.0 eV-sec for the middle curve, and the lower and upper curves are for 5 and 1 eV-sec respectively.

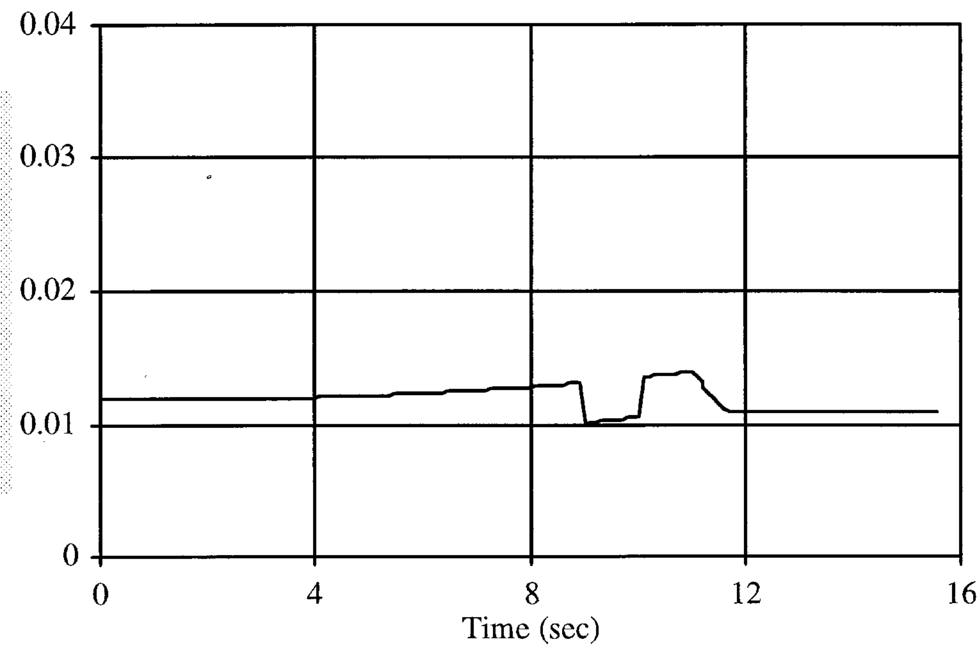

Figure 3.4: RF voltage curve used in the simulation for the condition in which 15 kV was requested. This has been tuned so that it approximates the observed cavity voltage, including the cavity trip event that is evident in figure 1.1.

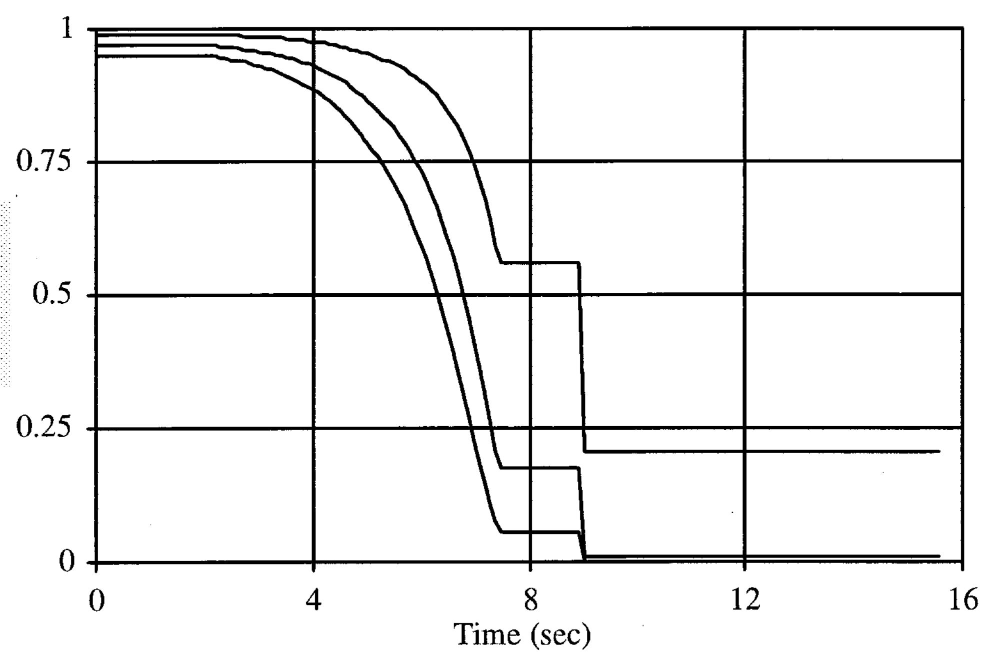

Figure 3.5: Beam survival during deceleration when 15 kV is requested, but when a cavity trip also occurs during deceleration. Note that the immediate drop in beam survival precisely mimics the observation.

Figure 3.3 contains the beam survival prediction for the 15 kV RF amplitude request. Accounting for the lifetime of the background lifetime of the beam (which is not simulated because of its transverse origin), it is clear that the emittance of the proton bunch is at or below 3 eV-sec.

It turned out that there are two traces at this voltage level. While taking the data the first trace contained one of the previously mentioned RF cavity trips. The second trace was therefore recorded in order to get a nominal deceleration history. But let us now take advantage of this trip event to further study the relationship between the simulation predictions and the measured beam survival down the ramp.

Figure 3.4 contains the simulated RF amplitude curve containing an RF trip of the correct depth and timing. The resultant beam survival prediction is shown in figure 3.5. The remarkable agreement between this prediction and the data in figure 1.1 gives one confidence that this simulation is very accurate, and is a useful tool for predicting future deceleration efficiency performance.

The next of simulation results are for the conditions that most of the studies were executed under, in which 20 kV was requested from the coalescing system. The RF amplitude curve was tuned to look like the measured data, in which the frequency change is so great that the cavity feedback loops saturate the output power of the amplifiers and the RF voltage drops to 12 kV. Figure 3.6 shows the simulated RF amplitude curve.

The result of this simulation is shown in figure 3.7, again for the longitudinal emittances of 1, 3, and 5 eV-sec. Note that the simulation does not limit the RF frequency swing to 2.8 GeV/c. Therefore, the important conclusion which can be drawn from this data is that if the background beam lifetime can be corrected there will be no further bucket area limitations. From the point of view of the RF system, it should be possible to decelerate approximately half of the present proton beam to 2.0 GeV/c.

In support of the above claim that no futher bucket area limitations should occur during the deceleration ramp to 2.0 GeV/c, figures 3.8 and 3.9 contain the momentum vs. time and bucket area vs. time, respectively. Note that though the bucket area is quite small, it will be sufficient to decelerate more than half the antiproton beam. In the future a modification to the coalescing cavities, or new cavities all together, will be needed if 100% transmission to 2.0 GeV/c is required.

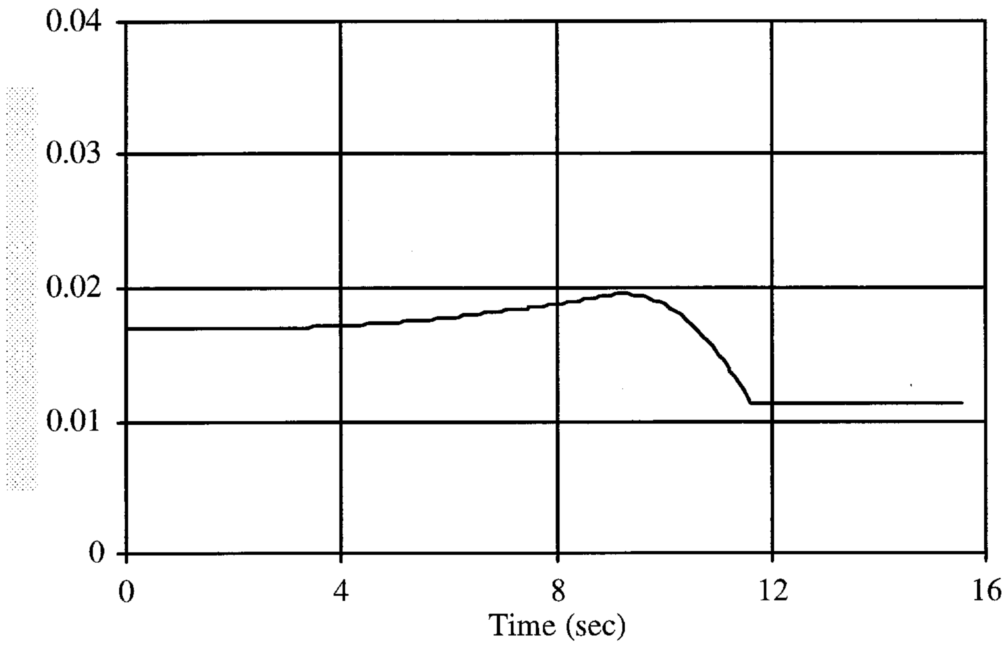

Figure 3.6: RF voltage curve used in the simulation for the condition in which 20 kV was requested. This has been tuned so that it approximates the observed cavity voltage.

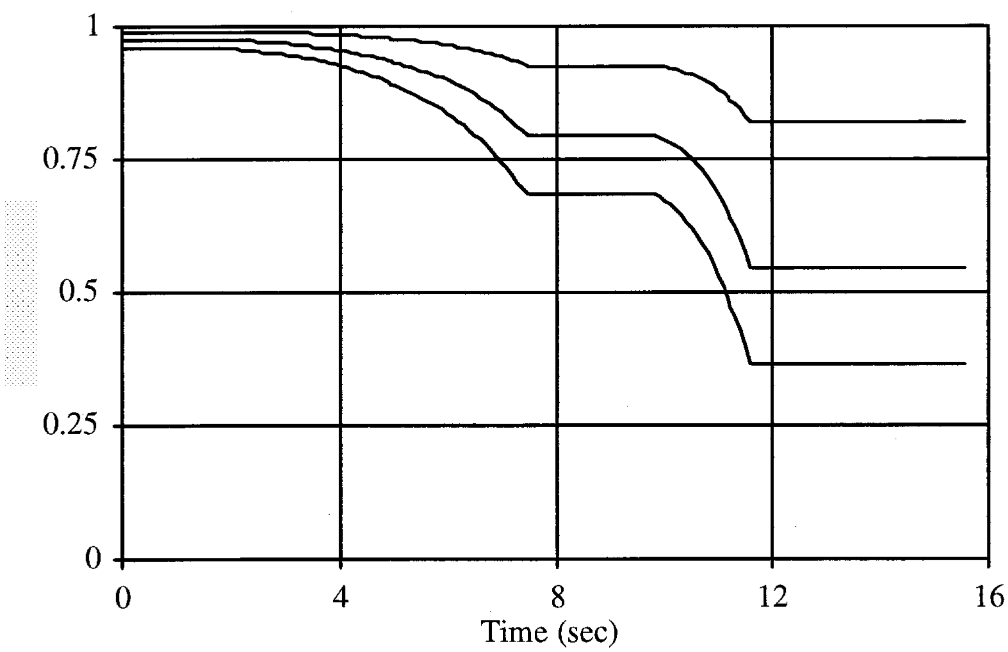

Figure 3.7: Beam survival during deceleration when 20 kV is requested, but when a cavity trip also occurs during deceleration. This is the first time that comparisons with measured figure 1.1 data in the Main Injector are not so precise. At this point the background beam lifetime is clearly the dominant source of beam loss.

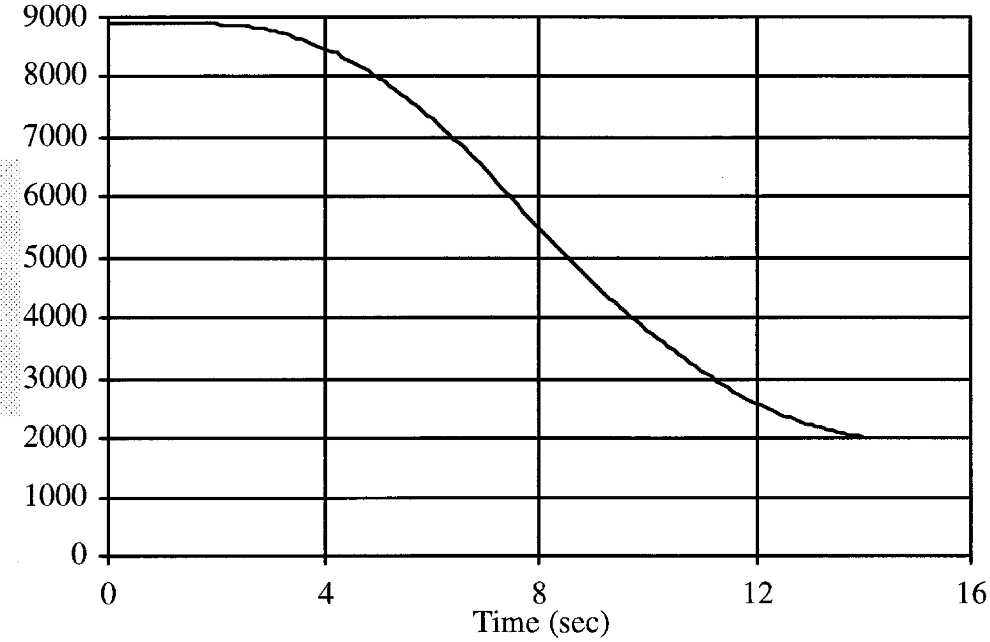

Figure 3.8: Momentum ramp of the Main Injector during the deceleration cycles.

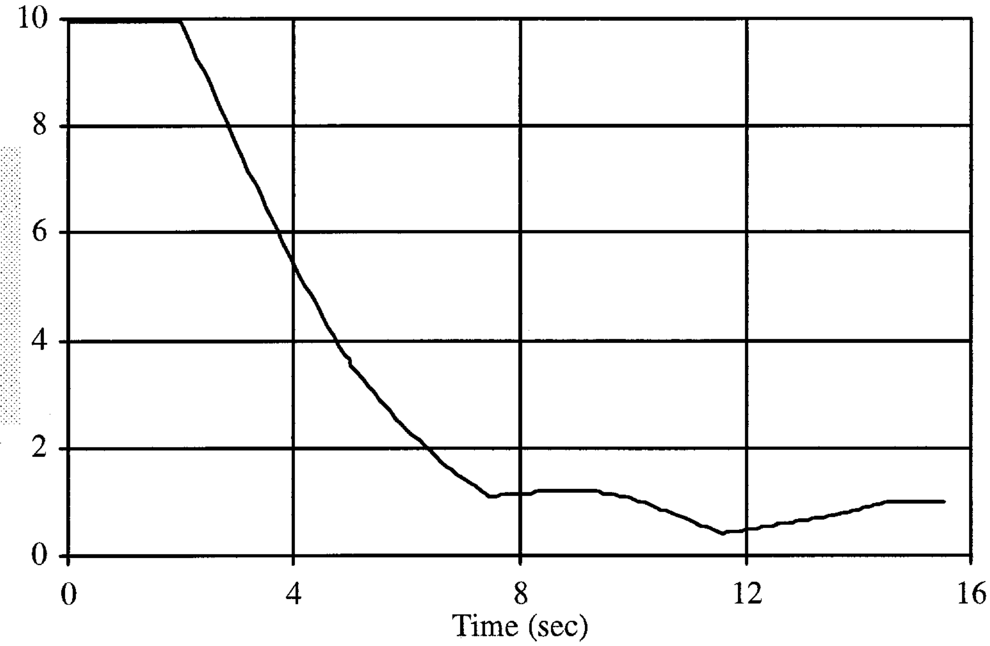

Figure 3.9: Bucket area vs. time for the RF amplitude curve corresponding to the 20 kV request that was used for most of the study period.