TRANSIENT BEAM LOADING REDUCTION DURING MULTI-BATCH COALESCING IN THE FERMILAB MAIN RING

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Abstract

Increasing the number of proton bunches in the Tevatron Collider from 6 to 36 places new demands on the bunch coalescing process in the Main Ring. As many as 132 proton bunches may have to be simultaneously coalesced into 12 high intensity bunches before being injected into the Tevatron. In order to efficiently produce these high intensity bunches, the total Main Ring rf cavity fundamental voltage at h=1113 must first be adiabatically reduced to below a few kV. Under these conditions, with many proton bunches filling a fraction of the Main Ring, the transient beam loading voltage generated in the cavities can exceed this value by an order of magnitude. A method of reducing this transient loading by temporarily shorting 16 of the 18 rf cavities is described along with data illustrating the transient voltage reduction.

1. INTRODUCTION

Two ways to increase the luminosity of the Tevatron Collider are to increase the number of colliding proton and antiproton bunches from 6 to 36, and to increase the intensity of the individual proton bunches from 6×10^{10} protons to 3 x 10". Both of these improvements place stringent demands on the coalescing process in the Main Ring. The coalescing process was initially designed to coalesce 11 individual proton bunches into a single high intensity bunch of 6×10^{10} during one Main Ring cycle.[1] To improve the Tevatron Collider luminosity, 12 Booster batches of 11 bunches each will be sequentially loaded into the Main Ring during a single Main Ring cycle.[2] The 12 batches will be spaced by 21 rf buckets at h=1113 so that the beam will occupy less than 1/4 of the circumference of the ring. The 12 batches will then be simultaneously coalesced into 12 high intensity bunches before being injected into the Tevatron. This process will then be repeated twice to achieve a total of 36 high intensity bunches circulating in the Tevatron. Higher individual bunch intensities will be possible after the completion of the Fermilab Linac Upgrade and the Main Injector. During the last Collider run coalesced bunches of 1.2 x 10" could be produced, so the upgrade plans call for the circulating beam current in the Main Ring to be increased by a factor of approximately 30. This means that under the present conditions, the transient beam loading effects in the 18 Main Ring rf cavities will dominate the coalescing process. For example, the 12 batches of 11 narrow bunches with a total intensity of 3.6×10^{12} protons transversing the rf cavities will generate an rf sum voltage difference of over 300 kv at the fundamental rf frequency, fo, between the first and the last bunches.[3] During the adiabatic voltage reduction in the coalescing process, the voltage difference will decrease by about a factor of 5 as the beam spreads out to fill the entire h=1113 bucket. This will leave a transient voltage difference of approximately 60 kV between the first and the last bunches. For efficient coalescing, the h=1113 rf voltage must be adiabatically reduced to below 5kV. Without modifications to the Main Ring rf system, the transient loading will be an order of magnitude larger than the rf sum voltage required and beam will be lost from the last bunches as the rf bucket area shrinks to zero while the first bunch is still only partially filling its rf bucket. This effect has already been observed experimentally with a single Booster batch intensity of 2.4 x 10".

*Operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy.

II. REDUCTION OF TRANSIENT BEAM LOADING EFFECTS

Two different methods were considered to reduce the transient beam loading in the rf cavities. First, a fast feedback beam loading compensation system that measured the h=1113 component of each bunch and produced a different rf sum voltage for each bunch was considered. The drawback of this approach is that the voltage corrections that must be applied are an order of magnitude larger than the desired final rf sum voltage (2-5kV). The alternative method that was chosen was to lower the impedance of the rf cavities at the fundamental frequency during the adiabatic voltage reduction phase of the coalescing process. This method was chosen since it is independent of the bunch intensity and the charge distribution within the individual bunches. Before describing the impedance reduction method, it is useful to summarize the present coalescing procedure. Beam is accelerated from 8 GeV to 150 GeV in the Main Ring using 18 rf cavities which produce a peak rf sum voltage of 4 MV. At 150 GeV the rf voltage is reduced to 800 kV. While two rf cavities stay in phase with a combined voltage of 80kV, the remaining 16 cavities are paraphrased to a net voltage of a few kV. The rf drive to the 16 paraphrased cavities is, then, removed (while the cavities are kept tuned to the fundamental frequency, fo.) The 2 cavities with a net voltage of 80 kV are then adiabatically paraphrased to 2kV in 500 ms. After the 2kV level is reached, h=53 and h=106 rf systems are turned on for a

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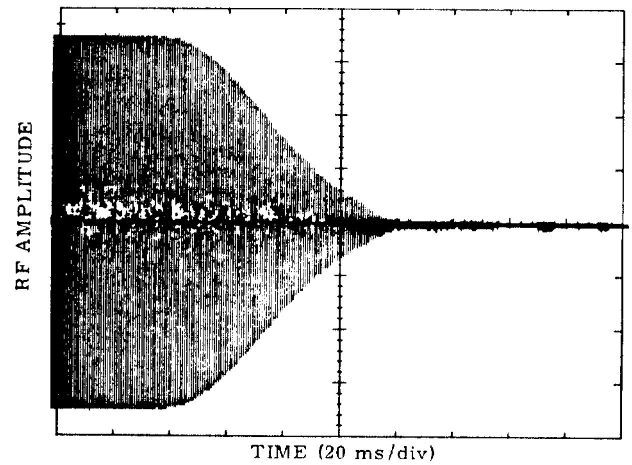

Figure 1 rf signal amplitude during insertion of the cavity short

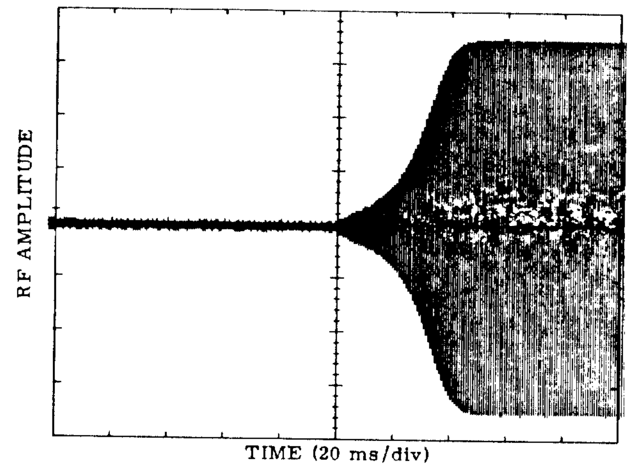

Figure 2 rf signal amplitude during extraction of the cavity short.

quarter of a synchrotron period (100ms) to rotate the debunched beam into a narrow time interval. The rf drive to the 16 cavities is then restored and beam is captured in a single h=1113 bucket with an rf sum voltage of 500 kV . The rf sum voltage is then increased to 800 kV for injection into the Tevatron. At high beam intensities, the above method breaks down since at the time of the lowest rf sum voltages (2-5 kV) there are 16 rf cavities tuned to the fundamental frequency, fo, with a total shunt impedance of 8 MΩ. The obvious solution is to change the resonant frequency and Q of these 16 cavities while they are powered off, but restore them to their normal fo and Q for recapturing the beam. Although the ferrite-loaded cavity tuners have sufficient speed to change the cavity personant frequency, they can only shift the resonant frequency by 300 kHz which still allows a large transient voltage to be induced in the cavity. To achieve a larger frequency shift and lower the cavity Q quickly, a fast acting, low inductance rf cavity short was installed on the Main Ring rf cavities. The new short is located approximately 50cm from the cavity gap between the intermediate cylinder and the outer cavity shell.[4] This position is as close to the gap as possible without breaking into the high vacuum region. With the short inserted, the cavity resonant frequency increases by 4 MHz and the cavity Q is reduced by a factor of 5. The short consists of a 2.5 cm diameter, 20 cm long stainless steel rod connected to a pneumatic cylinder with a 15 cm stroke. One end of the stainless rod has a beryllium copper loop which contacts the intermediate cylinder of the cavity when the short is inserted. The other end of the stainless rod is tapered and seats against a ring of beryllium copper fingers which complete the shorted current path.

Figures 1 and 2 show a low level rf signal at the normal cavity resonant frequency, fo, which is transmitted through the cavity and measured at the cavity gap voltage monitor as the shorts are inserted and removed. As shown in figures 1 and 2, the short can be inserted in less than 100 ms and removed inless than 50 ms. If the shorts are removed at the beginning of the 100 ms rotation time in the h=53 and h=106 rf bucket, an additional 50 ms is available for all interlocks to be re-established before the cavities need to be turned back on for recapture. The increased speed with which the short can be removed from the cavity is obtained by using two separate air switches to actuate the air cylinder. Normally, using a single air switch, one side of the air cylinder is pressurized while the other side is being exhausted. Two air switches allow both sides to be exhausted before applying the air pressure to remove the short from the cavity. This creates a greater pressure differential across the piston and reduces the piston travel time. The air cylinder is equipped with adjustable air cushions to gently slow the piston to a halt before coming to the end of its stroke. The cylinder is also uncoupled from the body of the cavity by 8, 5 cm diameter x 4 cm rubber vibration isolation mounts to absorb the shock generated by the piston motion. The entire air system is operated at 65 PSI. The position of the short is sensed by four magnetic position sensors that are activated by a magnetic ring attached to the cylinder piston. In the event of an interlock failure, the short is rugged enough to survive the cavity trying to re-energize with the short in place.

III. EXPERIMENTAL RESULTS

Figures 3 and 4 show the effect of the cavity shorts on the transient beam loading induced by 12 batches of 11 bunches spaced by 21 h=1113 buckets. The data was taken after 16 rf cavities had been shut off and the two remaining cavities were producing a net voltage of 85 kV. This time corresponds to the start of the adiabatic paraphrasing of the two rf cavities. The total number of protons in the Main Ring was

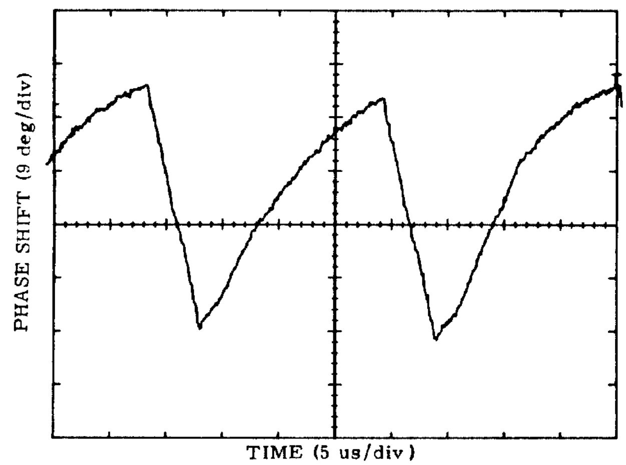

Figure 3 rf sum signal phase shift without cavities shorted.

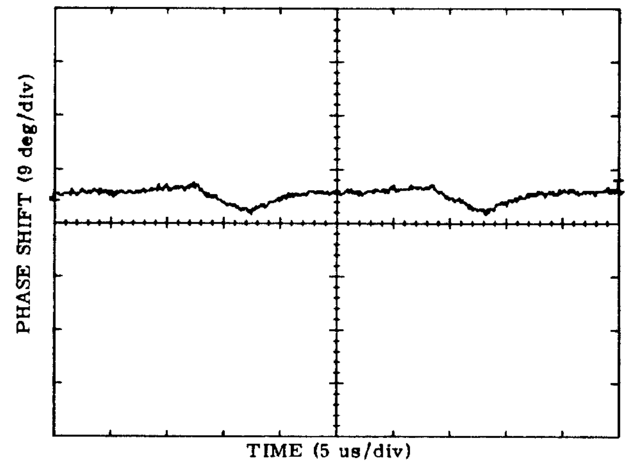

Figure 4 rf sum signal phase shift with 16 cavities shorted.

6.5 x 10" . Both figures 3 and 4 show the phase shift (9°/div) of the rf sum voltage (summing all 18 cavities) with respect to the phase of the constant rf drive to the cavities. The phase detector signal is seen to repeat at the 47.7 kHz Main Ring revolution frequency. In figure 3 the shorts were removed and a phase shift of 40° was observed. This corresponds to a beam induced differential voltage of 71 kV between the first and last bunches. Figure 4, with the fast shorts inserted, shows a reduction in the phase shift to only 4.5° or 6.7 kV of transient beam loading. This remaining phase shift can be attributed to the impedance of the two active rf cavities.

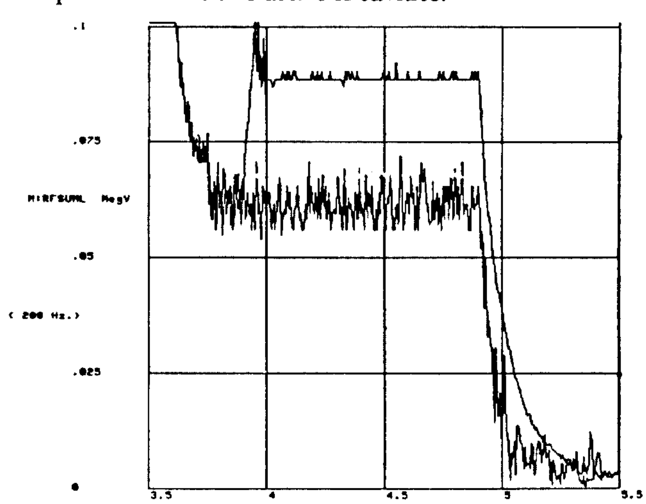

Figure 5 rf sum signal with (top trace) and without (lower trace) the 16 cavities shorted.

Figure 5 shows the difference in the steady state rf sum as a function of time with and without the 16 cavities shorted at a beam intensity of 6.1 x 10" protons. The top trace shows the effect of the shorts being inserted at 3.9 seconds, causing the rf sum voltage to increase from 60 kV to 85 kV. At 4.9 seconds, the two active cavities are paraphrased to approximately 5kV. Below 50 kV the beam induced voltage without the shorts in place dominates the rf sum signal and produces a non-adiabatic voltage reduction.

Without the fast cavity shorts acting on the 16 rf cavities, it was impossible to coalesce 12 batches simultaneously. The first bunch showed the highest coalescing efficiency while the last batch was totally lost during the final adiabatic voltage reduction. With the shorts active and the transient beam loading reduced by a factor of 9, the last batches had coalescing efficiencies close to those of the earlier batches. In some cases the last coalesced bunch had a greater intensity than the first bunch due to the shorter dwell time at the 8 GeV injection energy.

IV. References

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