BEAM LOADING EFFECTS DURING MULTI-BATCH SNAP COALESCING

D. Wildman
Fermilab

ABSTRACT

The snap coalescing proceedure has been shown to become inefficient at total beam intensities greater than 2E12 protons distributed in 12 Booster batches. Here the controled momentum reduction during the first rotation, necessary for high coalescing efficiency, is absent due to the large transient beam loading voltages. A method to circumvent this problem is presented and the basic compensation technique has been demonstrated with beam in the Main Ring.

INTRODUCTION

During the last Tevatron collider run a modified method of coalescing, known as "snap" coalescing, was introduced.[1] Instead of achieving a low momentum spread beam by an adiabatic rf voltage reduction, the rf voltage is "snapped" down from $\approx$ 500 kV to 50 kV. This allows the mismatched bunch to rotate to a lower $\Delta P/P$ during a quarter of a synchrotron period. This rotation is relatively fast, requiring only 16 ms, and has the advantage of thwarting instabilities by requiring a very fast instability growth rate. However; it has the disadvantage that the rf cavity mechanical shorting rods are not fast enough to be inserted during the 16 ms rotation time[2]. At high beam intensities and a large number of bunches this leaves a large beam induced voltage in the rf cavitieswhich can destroy the controled $\Delta P/P$ reduction.

Present plans for 36 X 36 operation in the Tevatron call for injecting 12 coalesced bunches from the Main Injector in a single 2B cycle. The Main Injector will initially be filled with 12 Booster batches, each batch containing 11 bunches of protons. The batches will be spaced by 21 rf buckets at h=588 so that they can be simultaneously coalesced by the h=28 2.5 MHz coalescing rf cavities. At Main Injector proton intensities of 6E10/bunch, a single narrow proton bunch passing through one h=588 rf cavity will generate a voltage, Δv, in the cavity given by[3]

$$\Delta v = \omega R \Delta q / Q$$

where $\omega = 2\pi$ X rf frequency = 2π X 53.104 MHz, R= rf cavity shunt impedance, Q = the unloaded rf cavity Q , R/Q = 100, and Δq = charge in the bunch. For Δq = 6E10, substituting into the above equation gives ΔV = 320 volts/cavity - bunch. For a train of proton bunches, the incremental voltages, Δv, from each bunch must be summed over all bunches to obtain the final voltage V in the cavity.

$$V = \sum_i \Delta v_i \, e^{-\omega_0 t/2Q} \qquad \text{Eq.1}$$

where ω_0 is the rf cavity resonant frequency which for most cases is very close to ω. At the 150 GeV flattop the cavity Q $\approx$ 4500 - 5000 so when the last of the 132 proton bunches passes through a tuned cavity, the voltage generated by the first bunch will have decayed to

$$\Delta v_1 \, e^{-2\pi\,(221\text{ buckets})/\,2 \times 4500} = 0.86\,\Delta v_1$$

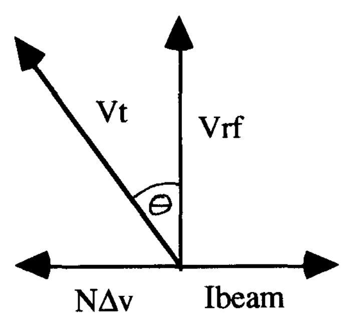
In all of the calculations that follow we will make the simplification that the cavity voltages do not decay during a single passage of the 12 batches so that all of the exponential terms can be set equal to 1 and

$$V = \sum_i \Delta v_i$$

We also assume that all bunches have approximately the same intensity so $\Delta v_i = \Delta v$.

With these simplifications, the last of N bunches through the cavity will see a voltage difference from the first bunch equal to $V = N\Delta v$. For our previous case, N = 132 bunches and Δq = 6E10 protons / bunch, the transient beam loading voltage V = 42.2 kV/ cavity. Since there are a total of 18 h=588 rf cavities, the total volage difference seen by the first and last bunches is 18 X 42.2 kV = 760 kV.

In order to proceed with the analysis it is convenient to introduce some vector diagrams to help represent what is happening in the rf cavity. We begin by defining a vector I_{beam} which represents the magnitude of the beam bunch current. Next introduce a vector V_{rf} which represents the magnitude and phase of the rf voltage in the cavity with respect to the beam current. V_{rf} is always independent of the beam current and is generated solely by the external power source driving the cavity. For low beam intensities, the projection of V_{rf} along the Ibeam axis gives the net acceleration given to the beam. At flattop, ϕ_s = 0 , so we can place the V_{rf} vector at 90 degrees to the beam current. Suppose now that we have a cavity tuned to resonance and increase the beam current. The beam bunch will then generate a voltage Δv in the cavity 180 degrees out of phase with the beam current, I_{beam}. After the passage of N bunches, the total cavity voltage V_t will be the vector sum $V_{rf} + N\Delta v = V_t$.



From the above diagram we can see that the magnitude of V_t will be larger than V_{rf} and will be displaced from V_{rf} by the angle θ . After all of the bunches have passed through the cavity , the voltage generated by the beam $N\Delta v$ will decay exponentially at the cavity's resonant frequency until the bunches re-appear at the cavity on the next turn around the ring.

MULTI-BATCH COALESCING IN THE MAIN RING

To begin to interpret the multi-batch coalescing data in the Main Ring, we start with a single Booster batch of 11 proton bunches with a total intensity of 2E11 rotating in a an rf bucket generated by a peak rf gap voltage of 50 kV. We can calculate the beam induced volage from eq. 1 to find $N\Delta v$ = 19.2 kV, a 21 degree phase shift, and a 7% increase in the total cavity voltage V_t.

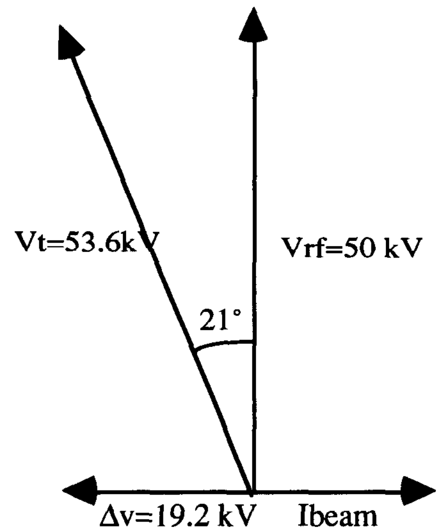
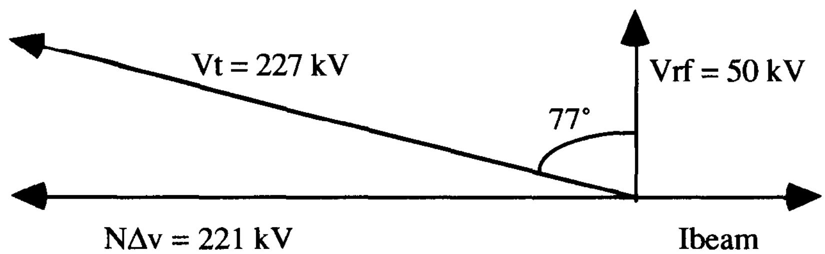


Figure 1 shows the fanout /fanback phase detector output with 2E11 protons in 11 bunches and an initial V_{rf} of 50 kV. The fanout / fanback phase detector measures the angle θ between the rf drive signal to the cavities (along the same direction as V_{rf}) and the total voltage V_t summed over all of the Main Ring rf cavities. The data in figure 1 was taken 1ms after the start of the rotation in the h=1113 bucket. The abrupt phase shift during the passage of the 207 ns batch of 11 bunches is seen followed by the exponential decay of the cavity voltage before the next turn. The measured initial phase shift is 24 degrees. The amplitude of the total voltage, V_t, is also seen to increase in figure 2. Here the vector sum V_t of all of the MRRF cavities is shown in the lower trace as the 11 beam bunches (top trace inverted) pass through the cavities. The apparent delay between the resistive wall beam current monitor signal (top trace) and the fanback signal (lower trace) is due to the shorter cable delay to the wall current monitor. The measured phase and amplitude data shown in figures 1 and 2 are in relatively good agreement with the calculated values.

Now let us increase the total intensity to 2.3E12 in 12 Booster batches of 11 bunches separated by 21 buckets. Figure 3 shows the fanout / fanback phase detector output under these conditions making an 80 degree jump as the rf voltage is switched from 500 kV to 50 kV at the start of the h=1113 rotation. Calculating the beam induced voltage we find $N\Delta v$ = 221 kV and a 77 degree phase shift in V_t.



This 221 kV beam loading voltage is more than four times the 50 kV necessary for the proper rotation and momentum reduction. With this large decelerating voltage the beam can only shear and be decelerated. Figure 4 shows this effect occuring. It is a mountain range plot of a 2 GHz bandwidth resistive wall monitor signal starting (lowest trace) at the time the rf sum voltage V_{rf} is reduced to 50 kV. Each successive trace is separated by 94 machine turns (1.97 μs) and shows the beam shearing and being decelerated (moving earlier in time above transition.) The 53 MHz component of the beam current during this shearing is shown in figure 5 . Although the beam bunches are longer at the end of the rotation time, their $\Delta P/P$ are not reduced as far as in the low intensity single batch case. This is obvious in figure 6 which shows the 12 "coalesced" bunches after recapture in the h=1113 buckets. Figure 6 shows multiple large central bunches with many large satellite bunches. This indicates a large $\Delta P/P$ existed at the start of the second rotation in the h = 53, 2.5 MHz bucket.

BEAM LOADING COMPENSATION

A straightforward solution to compensate for beam loading in the RF cavities during snap coalescing can be achieved by slightly modifying the existing coalescing proceedure. Instead of shutting off the 16 RF cavities during the first rotation, let them remain on and shift the phase of eight of the drive signals to the cavities by 180 degrees. Let these two sets of eight cavities be named "A" and "B". Another component,C, proportional to the 53 MHz component of the beam current and opposite in phase to the beam induced voltage can then be added to the rf drive signal to the 16 paraphased cavities. This compensation signal would be timed to arrive at the cavities only during the passage of the proton bunches to cancel the effects of the beam induced voltages.

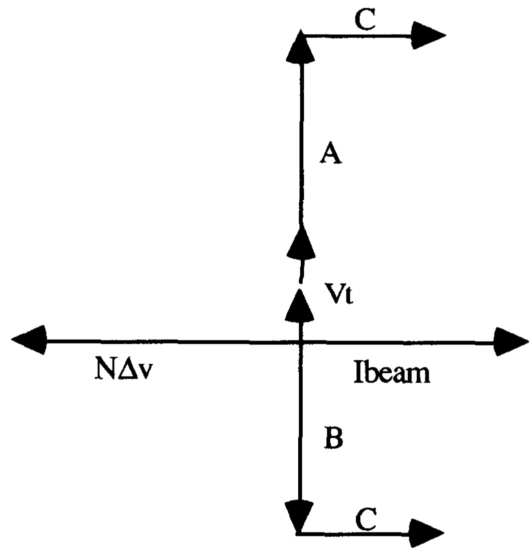


Figure 7 shows the fanout / fanback phase shift that results when this compensation signal was applied to the two MRRF cavities now operating during coalescing. With no compensation the two cavities have an rf sum voltage V_t of 50 kV. Notice that the phase shift is opposite to the beam induced phase shift during the 4.6 μs that the 132 proton bunches will be traversing the two cavities. During this time the phase of the total voltage V_t is shifted by 34 degrees. Substuting this value of 34 degrees and the expected Main Injector intensity of 6E10 / bunch , we can calculate the minimum voltage that must be generated by the 16 paraphased rf cavities in order to compensate for the maximum amount of beam loading. As we have already calculated, 132 bunches of 6E10 protons produces a transient beam loading voltage of 760 kV. The V_{rf} that must be produced by the 16 paraphased cavities must then be given by $\tan 34° = 760\ \text{kV}/V_{rf}$ or $V_{rf} = 1.13$ MV. Therefore; if we run each cavity at 760 kV/16 = 70.4 kV and apply a 34 degree phase shift the beam loading effects can be canceled. Figure 8 is an example of applying the 12 batch compensation to two stations with a single high intensity batch. In this case the compensation signal was deliberately reduced to illustrate the phase shift due to the beam and the phase shift due to the added compensation signal.

ACKNOWLEDGMENT

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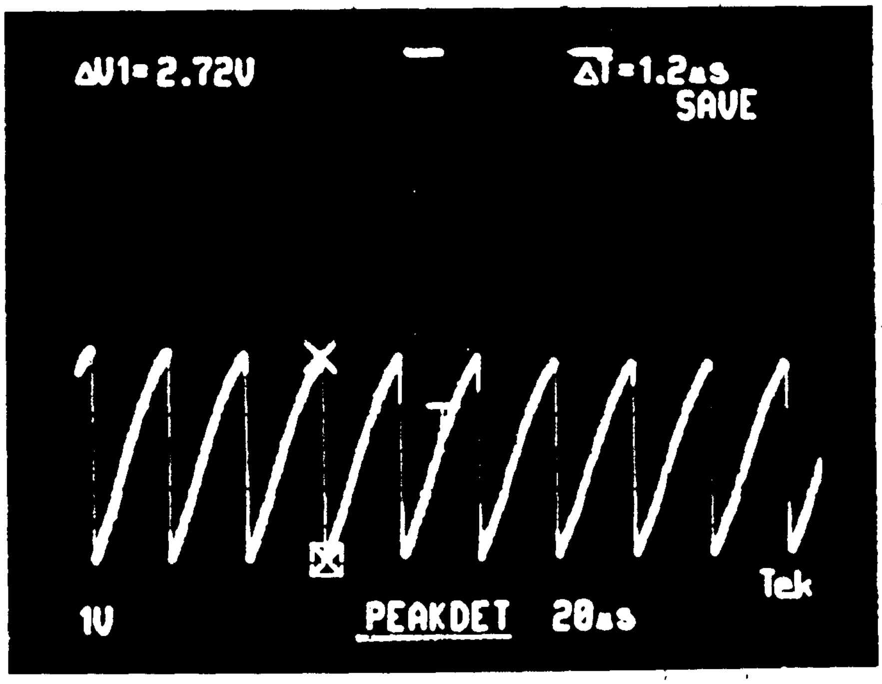

Figure 1. Fanout/Fanback phase detector output (9 degrees/volt) for a single Booster batch of 2E11 protons in 11 bunches with V_{rf} = 50 kV.

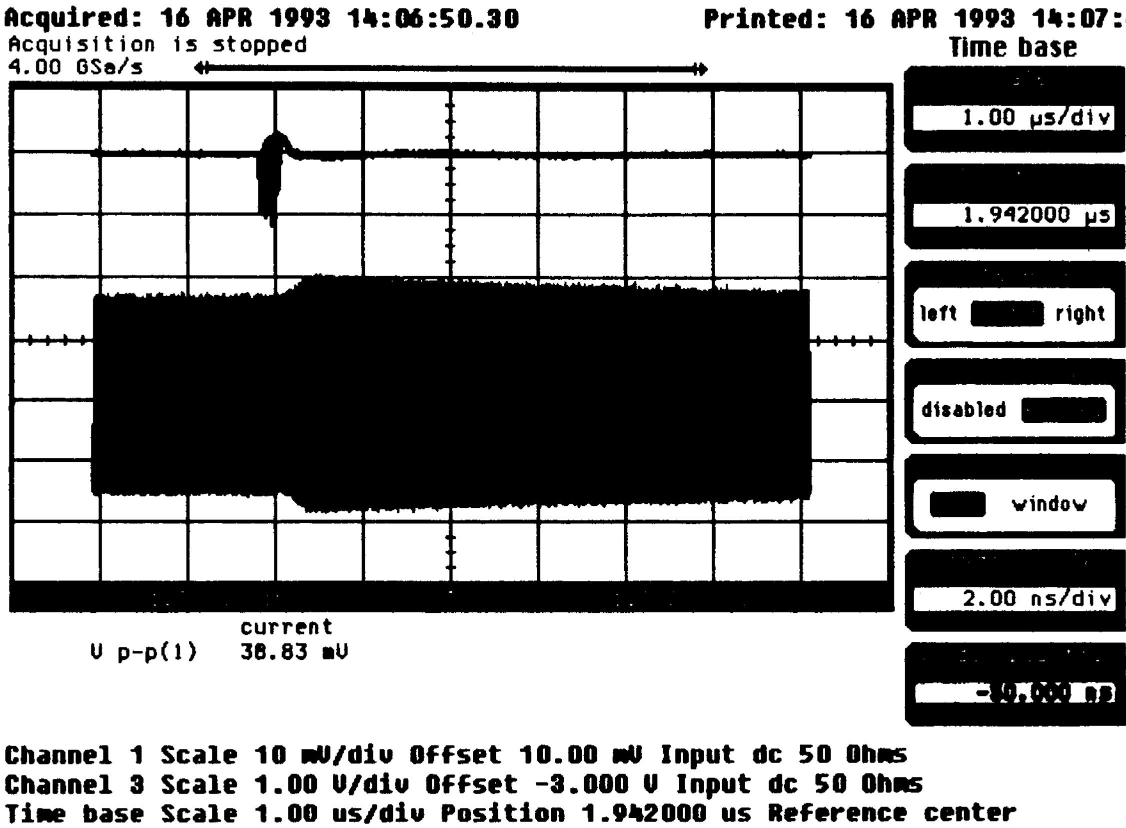

Figure 2. Top trace: 2 GHz resistive wall monitor signal of 11 proton bunches with a total intensity of 2E11. Lower trace: 53 MHz fanback signal (vector sum of 17 rf cavity gap monitors) showing beam excitation and exponential decay of the cavity rf fields.

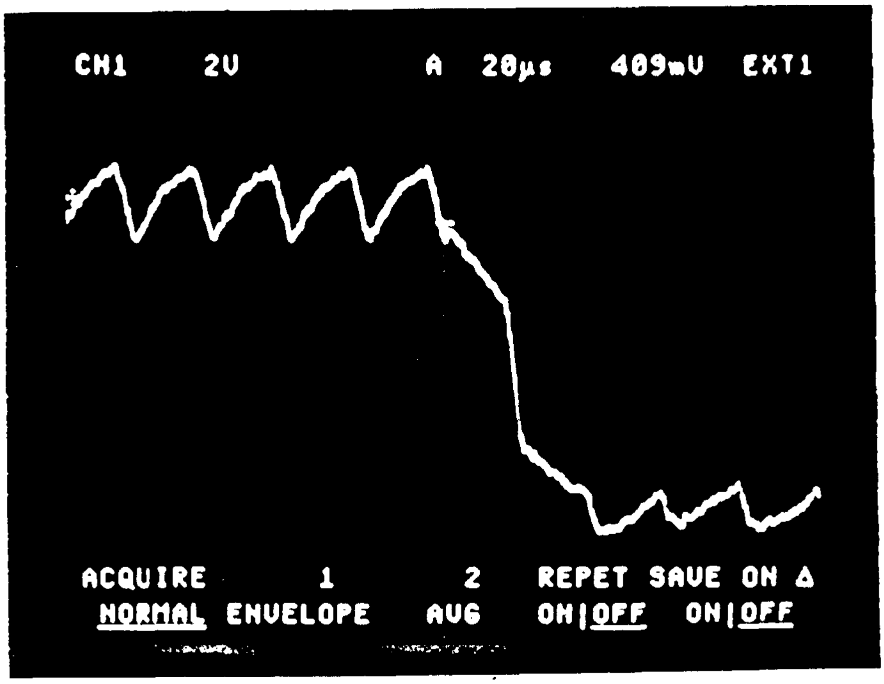

Figure 3. Fanout/Fanback phase detector output (9 degrees/volt) showing the phase shift occuring as the rf voltage is reduced from 500 kV to 50 kV.

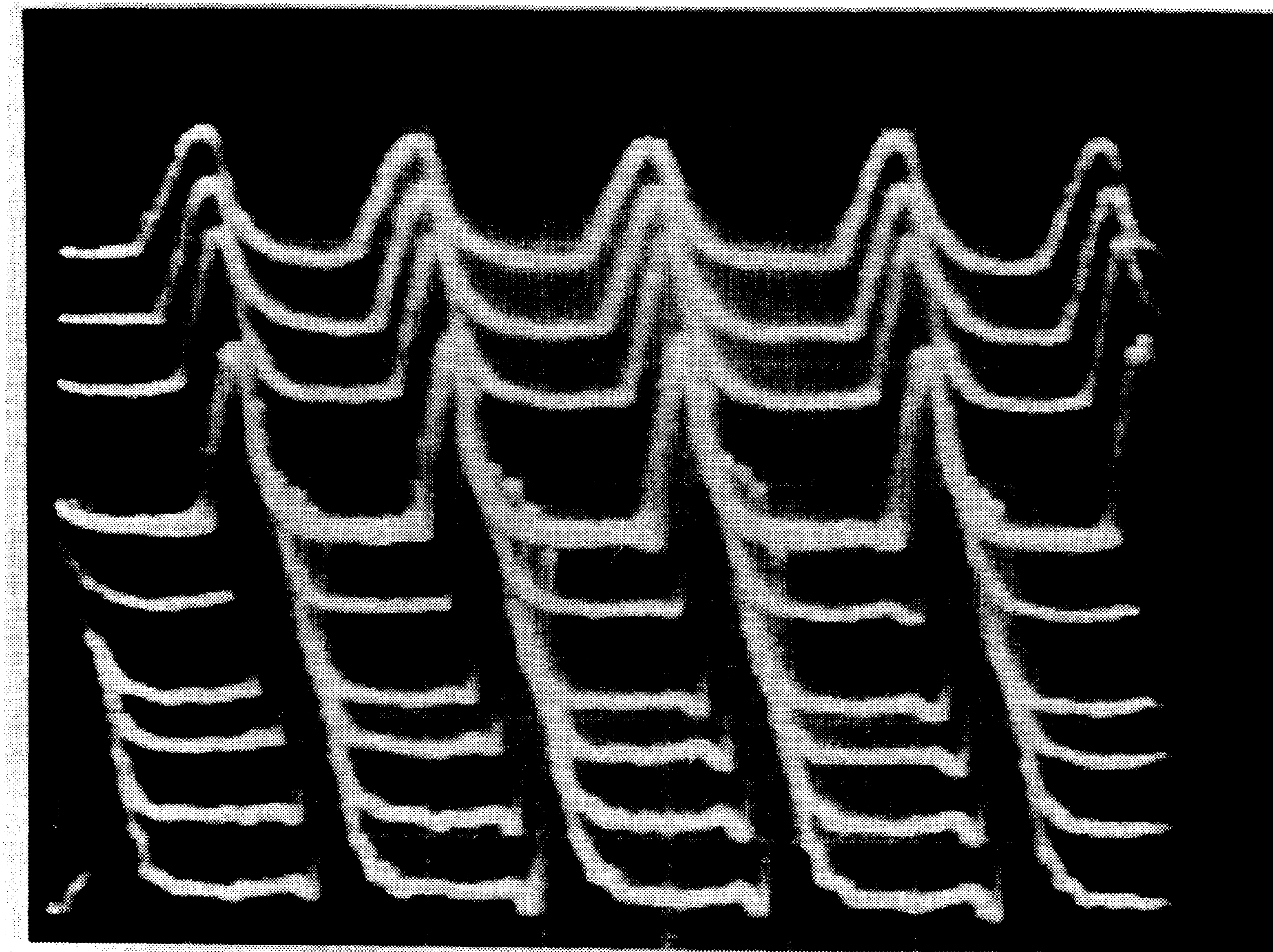

Figure 4. Mountain range plot (94 turns/trace = 1.97μs/trace) of a 2 GHz bandwidth resistive wall current monitor signal showing proton bunches being decelerated during rotation. The bunches shown are the 124th to 128th bunches of a 132 bunch train. The bunches were distributed in 12 Booster batches of 11 bunches each with a total intensity ≈ 2E12.

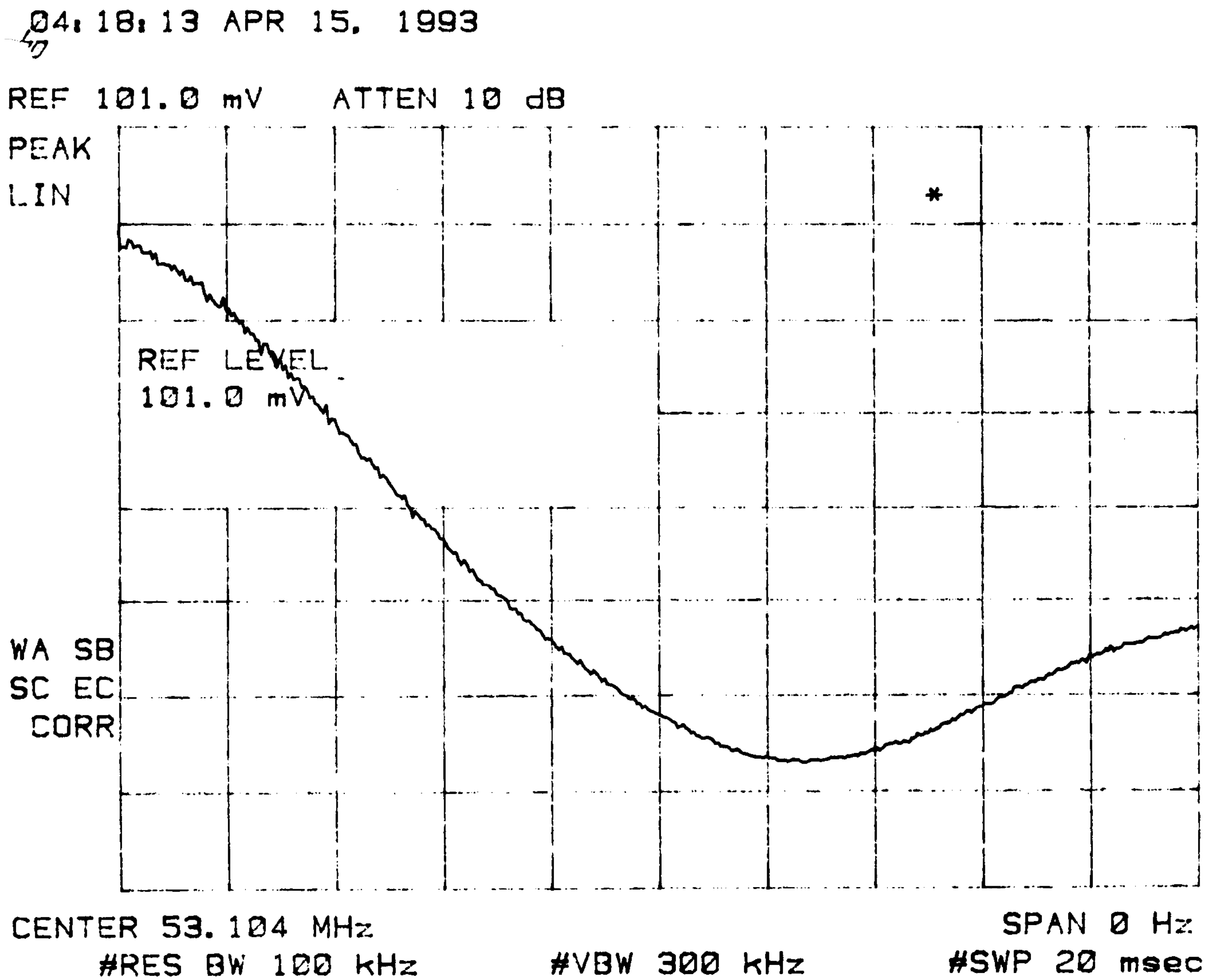

Figure 5. Spectrum analyzer output showing the 53 MHz component of the resistive wall current monitor during the ≈ 16 ms bunch rotation in the h = 1113 rf buckets. The trace starts at the beginning of the rotation when the rf voltage is reduced to 50 kV.

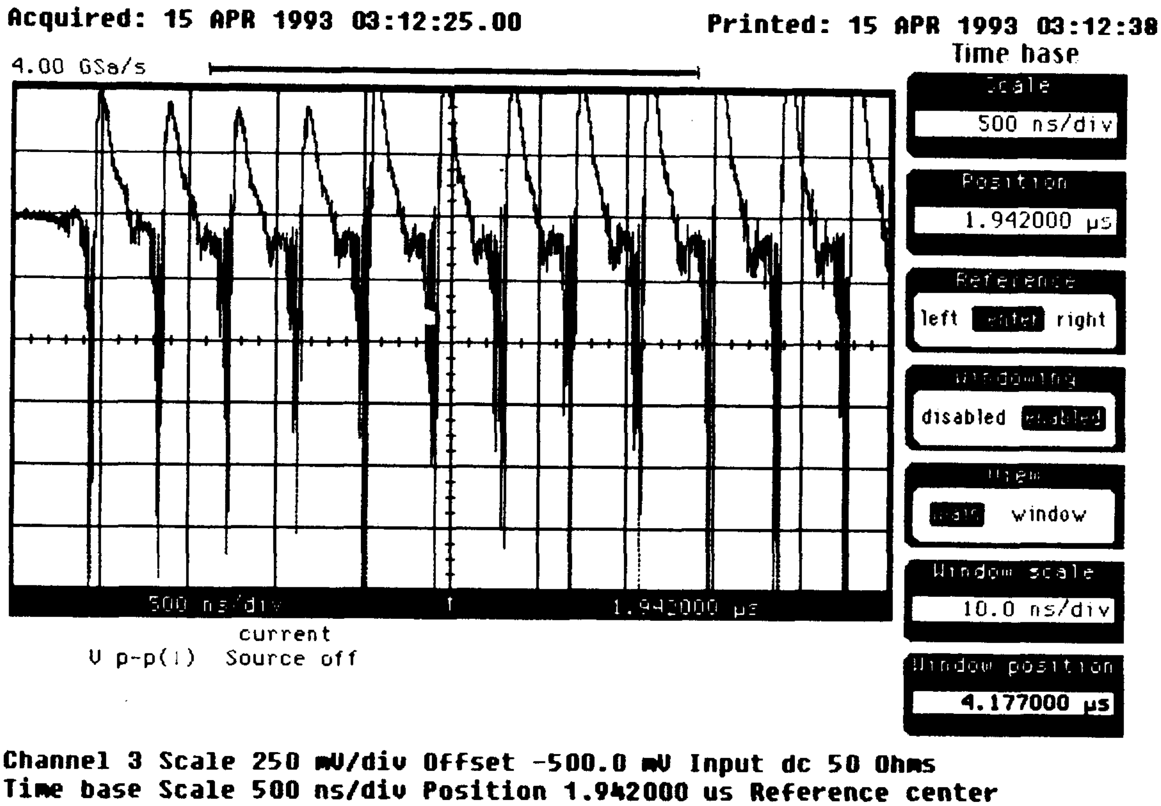

Figure 6. Digital oscilloscope (4GSa/s) trace showing the wall current monitor signal at an intensity of ≈ 2E12 showing the 12 "coalesced" bunches and satellite bunches after recapture in the Main Ring h = 1113 buckets.