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Bunch Coalescing in the Main Ring to Form Intense Proton and Antiproton Bunches Without RF Counterphasing

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Introduction

Both the proton and antiproton bunches which will collide in the Tevatron have longitudinal emittance greater than can be accelerated by the main ring from 8 GeV without large loss and emittance growth.[1] We have previously described the technique of combining several smaller bunches at the Tevatron injection energy with little increase in the total emittance and negligible loss.[2,3] This technique requires adiabatic debunching of several adjacent 53 MHz bunches by smooth reduction of the RF voltage from ~1 MV to ~100 V. The very low voltage is extermely difficult to attain with a high-Q system designed for megavolt accelerating potential. The counterphasing technique of voltage reduction which we have used in main ring experiments[4,5] and proposed for the TeV I project[3] is to divide the accelerating cavities into two closely matched groups and to smoothly shift the relative phase of the drive to the two groups by 180 degrees. When the net voltage has been reduced by this means to the lowest practical level, about 10 kV, the final voltage reduction may be performed by turning off the high-Q system and using a low-Q cavity. The voltage induced on the undriven gaps of the high-Q system is low enough not to be a major problem because the total intensity is low. However, the effects are not neglegible, and dynamic beam loading compensation is required.

This memo proposes that the process described above be simplified somewhat by replacing the counterphasing voltage reduction with a zero-voltage spreading of the bunches for several milliseconds followed by a few hundred microseconds of rotation to minimum energy spread in buckets produced at high voltage. This is the same idea recently suggested for narrowing proton bunches for antiproton production.[6] A test of this technique made during main ring studies on July 7 of this year was very succesful for bunch narrowing.[7] The application to bunch coalescing is somewhat more complicated because the 53 MHz RF has to be turned on for a precise, short interval to rotate the sheared distribution ~20 degrees and again much later, after debunching and coalescing have taken place. The shearing method can not achieve full debunching by itself; therefore, to complete the job it requires the same kind of low voltage 53 MHz system mentioned for the counterphasing approach. It is the significantly simpler requirements on the high voltage system that make the shearing alternative interesting. In principle this approach should be slightly inferior to the use of adiabatic voltage reduction, but given the technical difficulty in reaching the low voltage required, it may offer better performance in routine operation.

The full coalescing procedure incorporating bunch drifting consists of the following steps:

1. From 9 to 13 adjacent bunches containing a total of ~10^{11} particles

are accelerated to a main ring flattop at Tevatron injection energy. The emittance of the individual bunches may range from less than 0.1 eVs to 0.3 eVs at the most.

2. The usual 1 MV of 53 MHz (h = 1113) RF at flattop is turned off completely for a drift time ranging from 8.4 ms for 0.09 eVs to 4.2 ms for 0.3 eVs bunches.

3. The RF is turned back on at 1 MV for 461 μs (S_b = 0.09 eVs) to 775 μs (S_b = 0.3 eVs)

4. The rotated bunches are further debunched by slowly reducing the the RF voltage to 100 V in the presence of a very small matching h = 53 bucket. The precise h = 53 voltage depends on both the individual bunch emittance and the number of bunches and may range from 40 V to 400 V. This debunching requires ~1.5 s.

5. The h = 53 bunch is rotated to its minimum azimuthal projection by suddenly raising the voltage to 22 kV minimum. Additionally, a second harmonic voltage (h = 106) at the 17% level is produced by the same cavities to equalize the rotation time for all parts of the distribution.

The sequence just described is similar to that given in the Tevatron I Design Report except in the second and third steps. These steps replace about 100 ms of smooth voltage reduction from 1 MV to 10 kV with less than 10 ms of off/on/off sequence at 1 MV.

<u>Main Ring Study of Coalescing Without Benefit of Low-Voltage Cavity</u>

An opportunity arose to test some of this scheme in main ring studies 11 July 84,[8] before the calculations summarized later in this note were complete. So, following the chronology, we describe first this effort to establish empirically the best coalescing which could be obtained without the low voltage 53 MHz cavity for final debunching. The per bunch emittance measured by RF-off debunching of bunches matched to buckets of known size was ~0.1 eVs. Unfortunately, this small value reflects the low intensity of 4×10^9/bunch rather than an especially good operating mode. Working from the measurements of bunch narrowing made on 7 July[7] we estimated that an RF-off drift time of 12 ms would make a good starting value. We hoped that for proton bunch coalescing conditions, this technique might be marginally adequate even without the low voltage 53 MHz cavity. In this case the process is additionally simplified because the low voltage level of the h = 53 system is not required either.

A representive example of some of the better results is shown as Fig. 1. This is a photo of a "hill & valley" oscilliscope display in which the 20 ns/div traces are separated in time by 7.4 ms, the time increasing from bottom to top of the display. At the bottom one sees nine bunches at the time the 53 MHz voltage is turned on for 200 μs at 1 MV to rotate the bunches; thus, this picture starts after the 12 ms of bunch drift with the RF off. Besides the nine desired bunches which start at the lefthand side of the picture there are smaller tenth and eleventh bunches on the righthand side arising from incorrect adjustment of the vertical super damper which was being used to form the nine bunch sequence by transverse knockout from an 80-bunch booster batch. The 27 sweeps shown span 200 ms; for the first

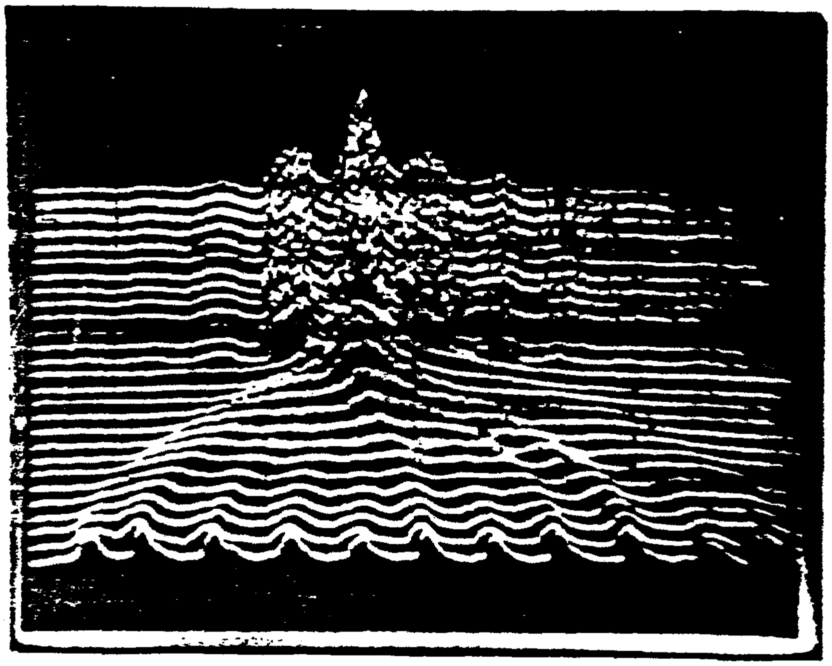

Fig. 1. Hill and valley display of the coalescing of nine bunches in the Main Ring. The time base is 20 ms/div and 7.4 ms between traces. The lowest trace is the earliest; it starts at the beginning of the 53 MHz rotation. The coalescing takes place for 98 ms; the 53 MHz recapture is shown in the final 100 ms.

98 ms the 2.5 MHz coalescing cavities are on to produce ~22kV. The second half shows the narrowing of the coalesced bunch as the 53 MHz voltage is turned on at 600 kV and raised to 2 MV. Much of the charge that appears in the buckets adjacent to the central coalesced bunch seems to come from unwanted bunches not adequately depopulated by the transverse knockout. This interpretation is supported by the observation that the area under the central peak is equal to the area of the nine intended bunches to ~10%, about as accurate an assesment as one can make by measuring from an enlargement of the photo in Fig. 1.

The result depicted in Fig. 1 falls considerably short of what is needed in for the TeV I program, particularly because the intensity and emittance of the initial bunches are much less than will prevail in making bunches of 10^{11}. For managing ~0.2 eVs initial bunches the full scheme including low voltage adiabatic debunching will be required for a clean coalesced bunch.

Calculations for Clarifying the Experimental Results

Although the studies proceeded by trial and error without a calculated optimum case for starting values, they came rather close to the desired results and were very useful in learning how to understand the required adjustment of parameters from the observed beam behavior. Calculations[9] done after the studies show that in fact we did not arrive at optimum conditions, in part because we did not establish the correct compensation for the unexpectedly small bunches. Fig. 2 shows a plot of the minimum rms energy spread of the 53 MHz bunches as a function of the RF-off drift time for 0.09 eVs and 0.15 eVs initial bunches. It should be noted that this optimum applies specifically to the conditions of the studies in that the bunches were allowed to drift to more than $\pm$ 90 degrees in phase spread to compensate as much as possible for the absence of further adiabatic debunching. The rotation after this drift produces substantial distortion of the bunch which does not occur in the complete scheme. The optimum calculated is precisely that between the reduction in energy spread from from the stretching of the bunch and the growth due to the straggling of the bunch ends during rotation. From this plot one finds that instead of 12 ms of drift time we should apparently have used 8.5 ms. In the calculations leading to the curves of Fig. 2 the matching optimum rotation times were also calculated. The correct time to match 8.5 ms is 440 μs instead of the 200 μs used.

Presumably, if there had been time during the studies and all of the equipment had performed faithfully we would have arrived at this optimum by trial and error. If one takes the values that we did use and the conditions we measured as the input for a calculation one finds the results illustrated Figs. 3 - 6. Fig. 3 is a "hill & valley" plot with the same time parameters as the photo, Fig. 1, except that the 53 MHz voltage is turned up faster (35 ms) and the calculation stops after 133 ms. Although Fig. 3 appears qualitatively satisfactory, when one looks at details there are problems. Fig. 4 shows the phase space distribution of the coalesced bunch just at the time of turning the 53 MHz RF on again. Clearly the 53 MHz recapture is not good. The "hill & valley" display is too crowded to see such detail easily. The histogram in Fig. 5 shows the azimuthal charge distributiion after the 53 MHz voltage has been raised to its final 2 MV. The well developed fellow travelers are plainly evident in this view but almost completely hidden in the multi-trace display. In Fig. 6 showing a single 53 MHz bunch after its

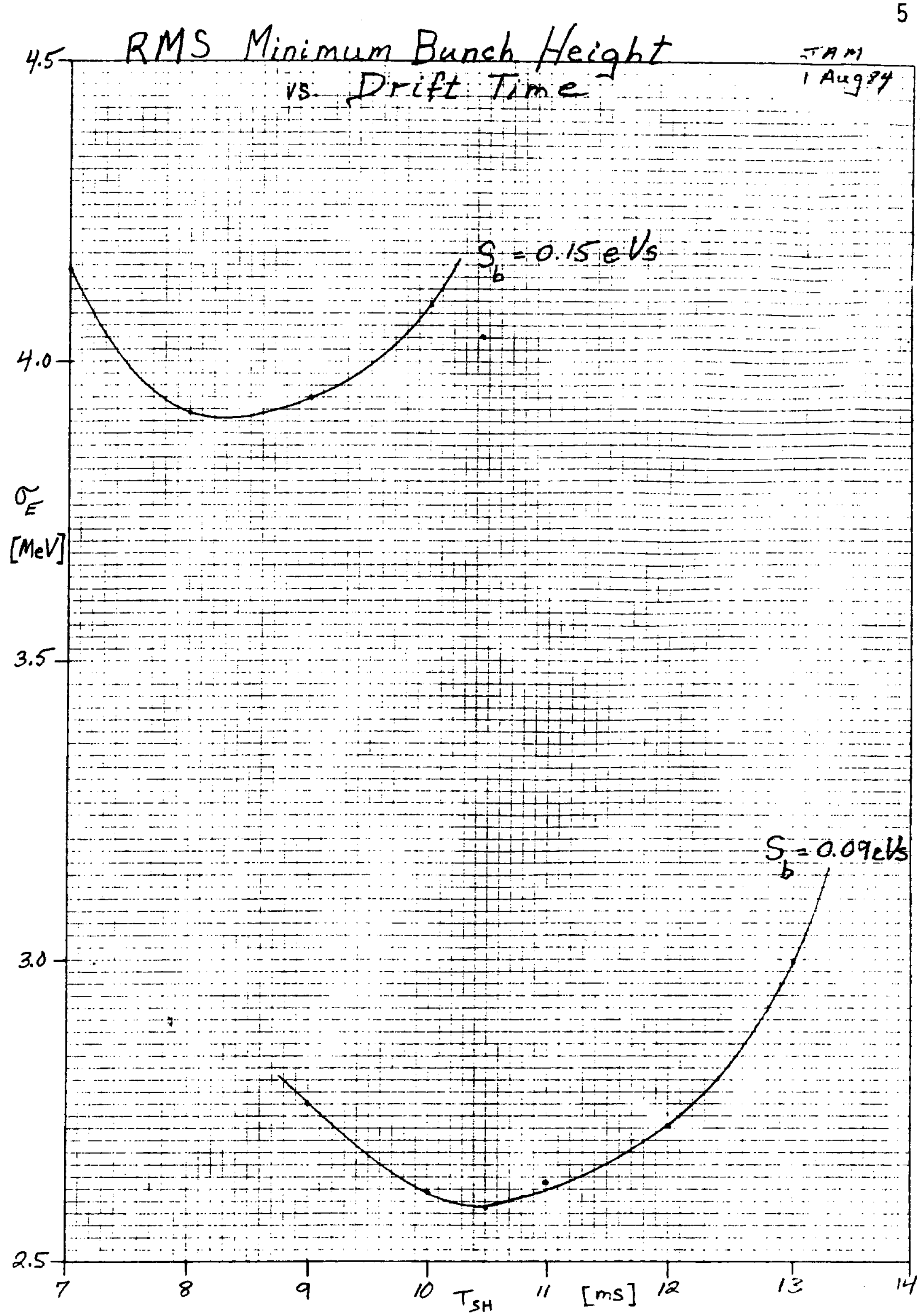

Fig. 2. Final rms energy spread of 53 MHz bunches as a function of the shearing time, where each shearing time has been followed by the corresponding optimum 53 MHz rotation time.

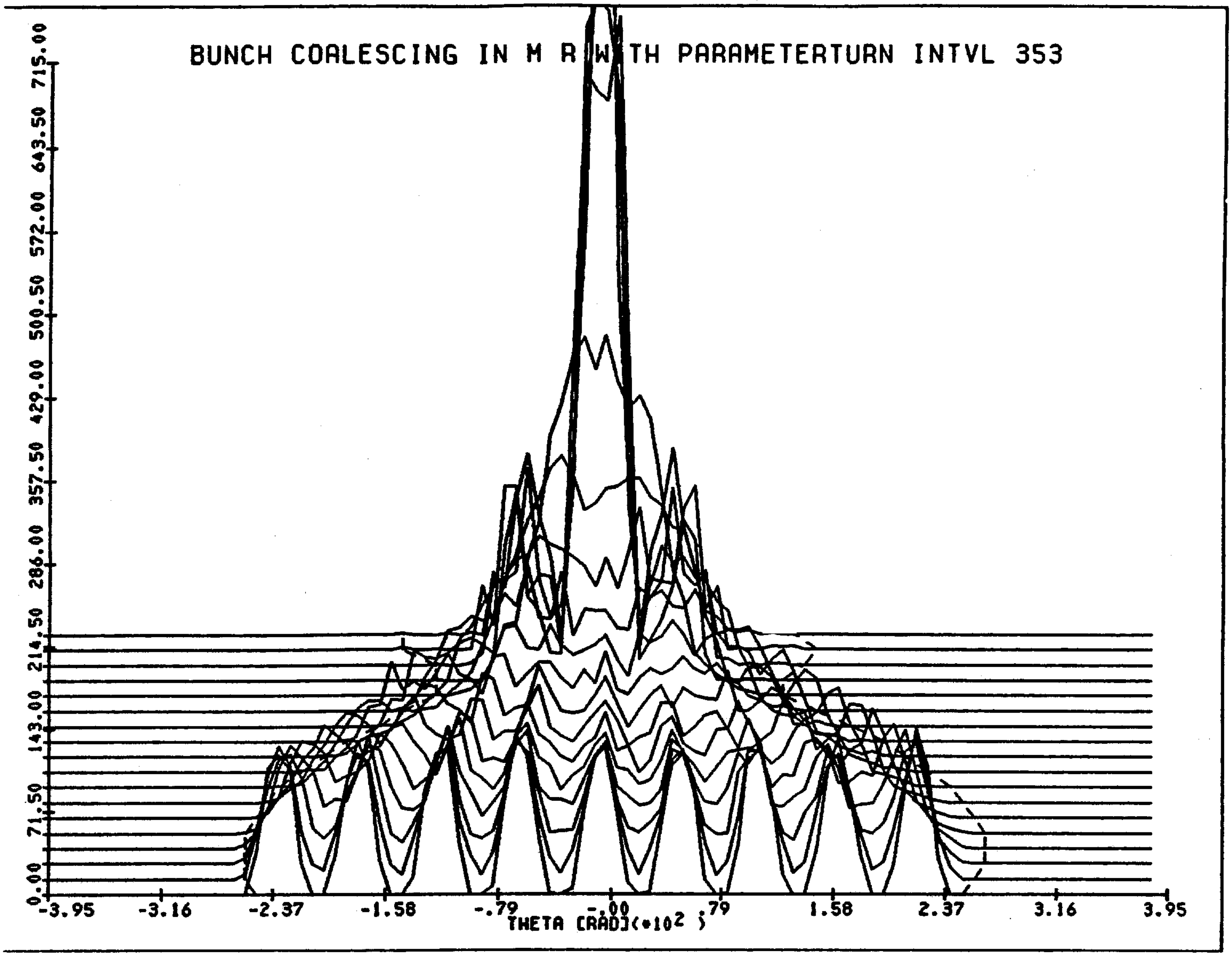

Fig. 3. Hill and valley simulation corresponding to the conditions of the Main Ring studies, c.f. Fig. 1. The time between traces is again 7.4 ms; the recapture phase which starts after 98 ms has been shortened to 33 ms.

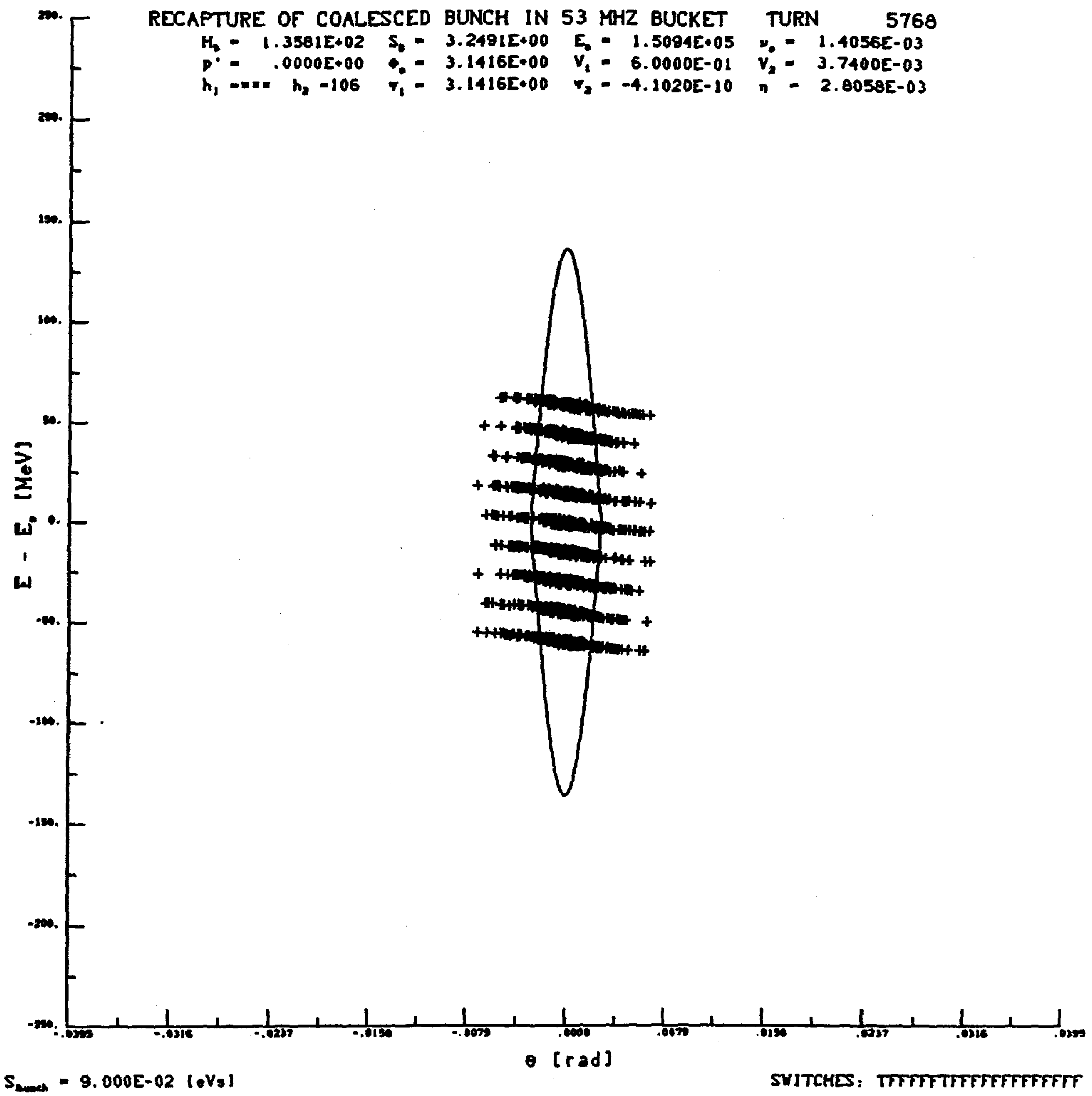

Fig. 4. Phase space distribution corresponding to the beginning of the recapture phase in Fig. 3.

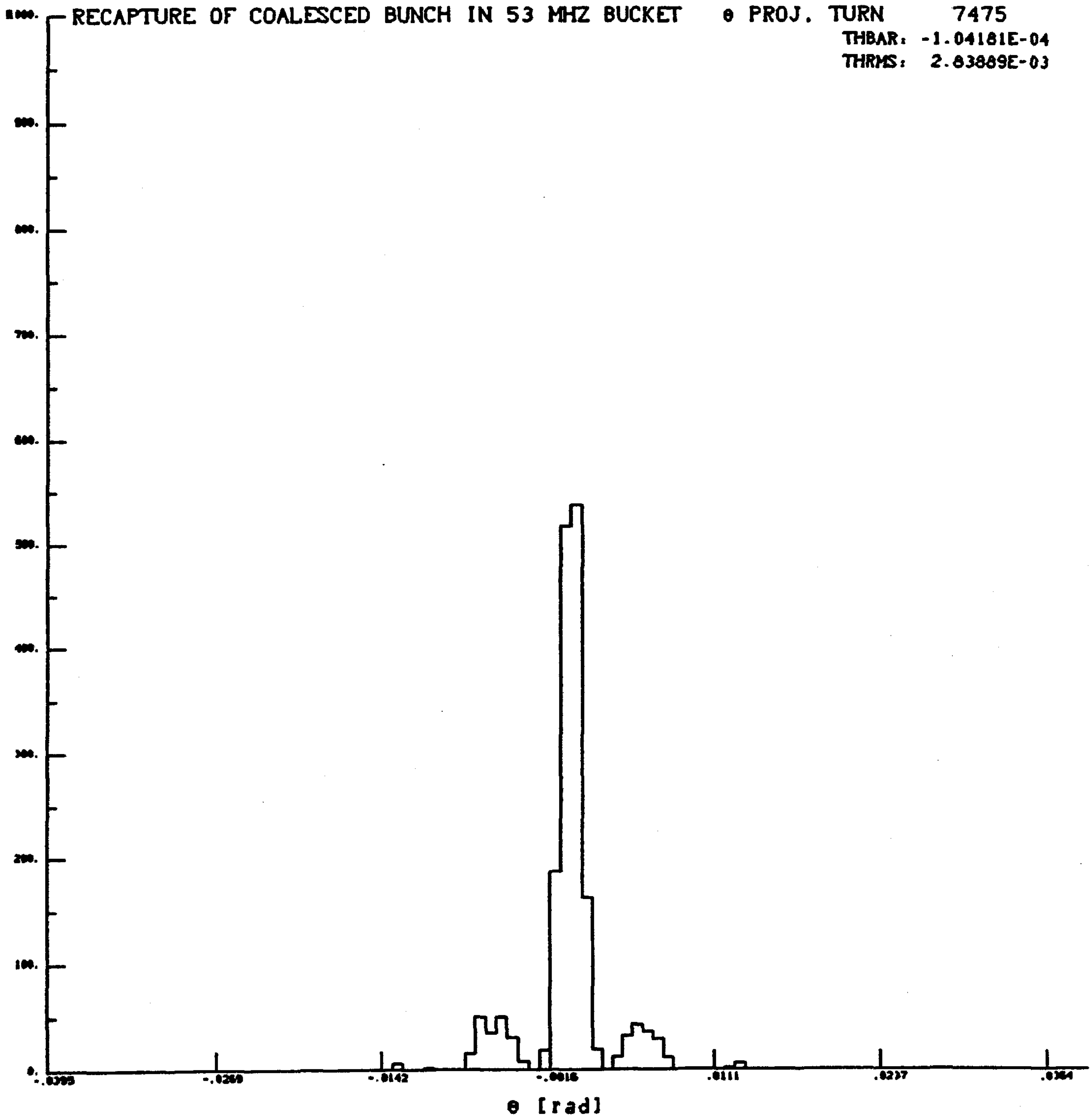

Fig. 5. Azimuthal charge distribution corresponding to the end of the recapture process in Fig. 3.

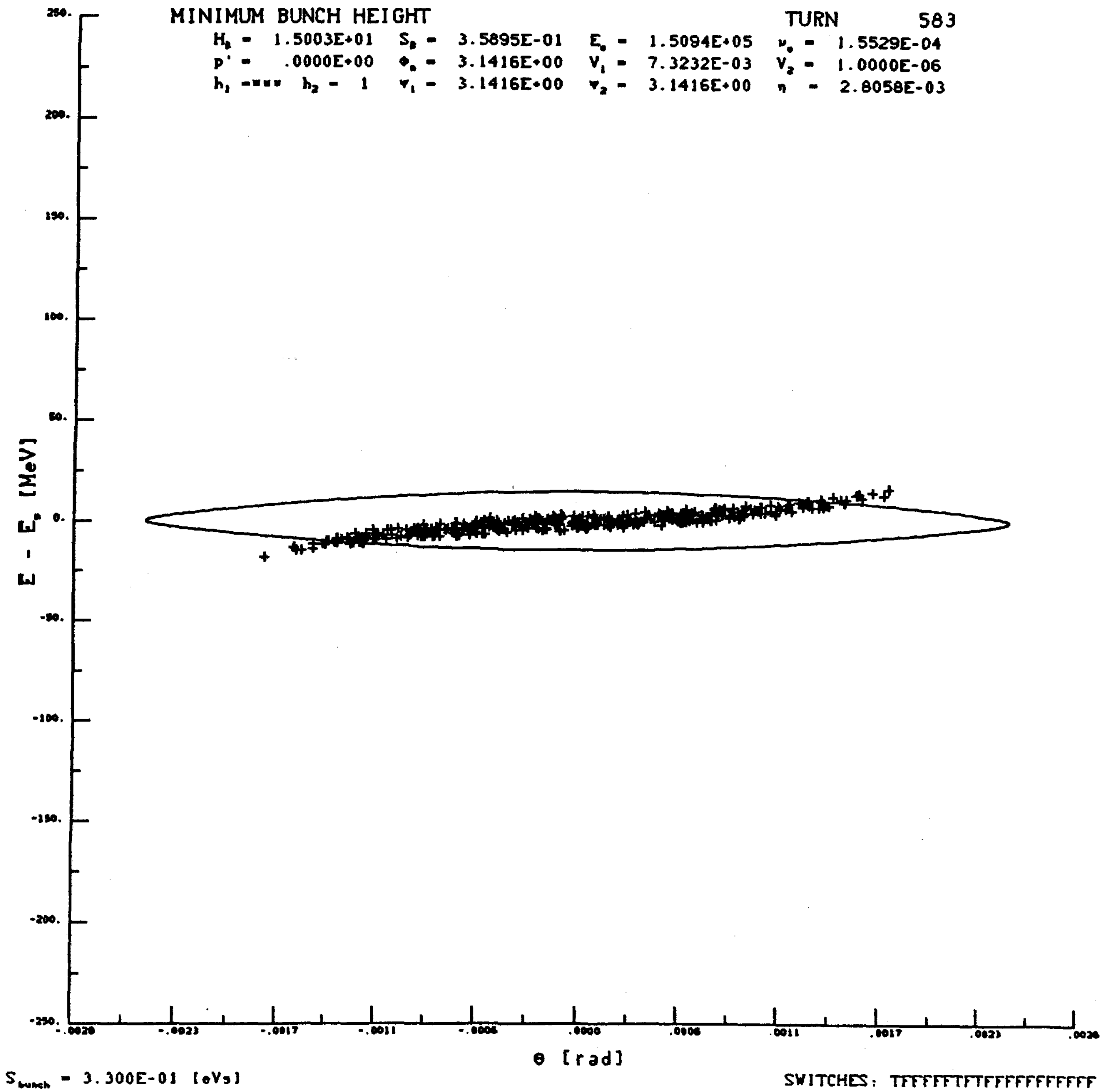

Fig. 6. Phase space distribution of a single 53 MHz bunch at the end of the rotation using the conditions of the Main Ring studies. This imperfect rotation corresponds to results shown in Fig. 1. The contour of 0.33 eVs encloses 95% of the effective area of the mismatched bunch.

200 μs rotation we see the biggest reason for failing to put all the charge in one bucket. The bunch has not rotated down to its minimum energy spread; 200 μs is not long enough.

Calculations Extending the Experimental Results

Having shown that what we calculate, Fig. 3, is a reasonable facsimile of what we observe, Fig. 1, it becomes interesting to find how well we would have done with optimum parameters. Fig. 7 shows the phase space distribution of the coalesced bunches when the timing is taken from Fig. 2. This result is to be compared with Fig. 4 calculated with timing from the studies. With 24/1800 = 1.3% of the particles falling outside the central bucket it is probably an acceptable result; recall, however, that the initial individual bunches were only 0.09 eVs. Thus, if the main ring bunch area for the necessary intensity can not be improved beyond current levels, some adiabatic debunching will be needed even for protons. There is substantial empty space within the effective area occupied by the distribution in Fig. 7; if that space can be filled efficiently the final distribution can be reduced in area by a factor of 2 to 3.

Even though somewhat better coalescing is needed for meeting TeV I design goals, one can show that the optimum shear and rotation timing produce as good debunching as could be obtained by lowering the 53 MHz voltage smoothly to 2.3 kV. The bunches are spread to about 194 degrees full width and have an energy half height of ΔE_b = 6.4 MeV. The relation between bunch height and the height of a matching bucket is

$$\Delta E_b = H_{bckt} \sin(\phi/2)$$

where ϕ is the phase half width of the bunch. From this one finds that the height of the bucket matching the bunch we obtained is 8.5 MeV; the voltage to produce a bucket of this height at 150 GeV in the main ring is 2.3 kV.

Application of the Shearing Technique to the Full Tev I Debunching Scheme

Consider now the application of this bunch shearing strategy to a fully developed coalescing system in which low levels of 53 MHz and 2.5 MHz voltage are available. What advantage is there in using the zero-voltage debunching and what penalty for using a manifestly non-adiabatic voltage program? The advantage has already been suggested: the technique replaces the smooth voltage reduction over the two decades from 1 MV to 10 kV with an off period and a short on period at high voltage. If that smooth voltage reduction were easily accomplished, then there would be little advantage in the drifting technique. However, our experience during machine studies is that it is not in fact simple to lower the net voltage to 10 kV.[4] The penalty side of the question can be answered by comparing the emittance of the h = 1113 bunch which has drifted and rotated to minimum energy spread with its initial value. For the sake of this comparison we make the reasonable assumption that the adiabatic debunching could be done without significant dilution. The shearing technique is used to produce a bunch phase spread of $< \pm$ 90 degrees so that the subsequent rotation will be reasonably linear. Fortunately this is sufficient spread to match up with a low-Q system at $\lesssim$ 10kV. Fig. 8 shows the evolution of the rms emittance of a 0.15 eVs parabolic bunch initially matched to an h = 1113 bucket produced by 1 MV as it undergoes drift and rotation to $\pm$ 90 degree phase spread. The

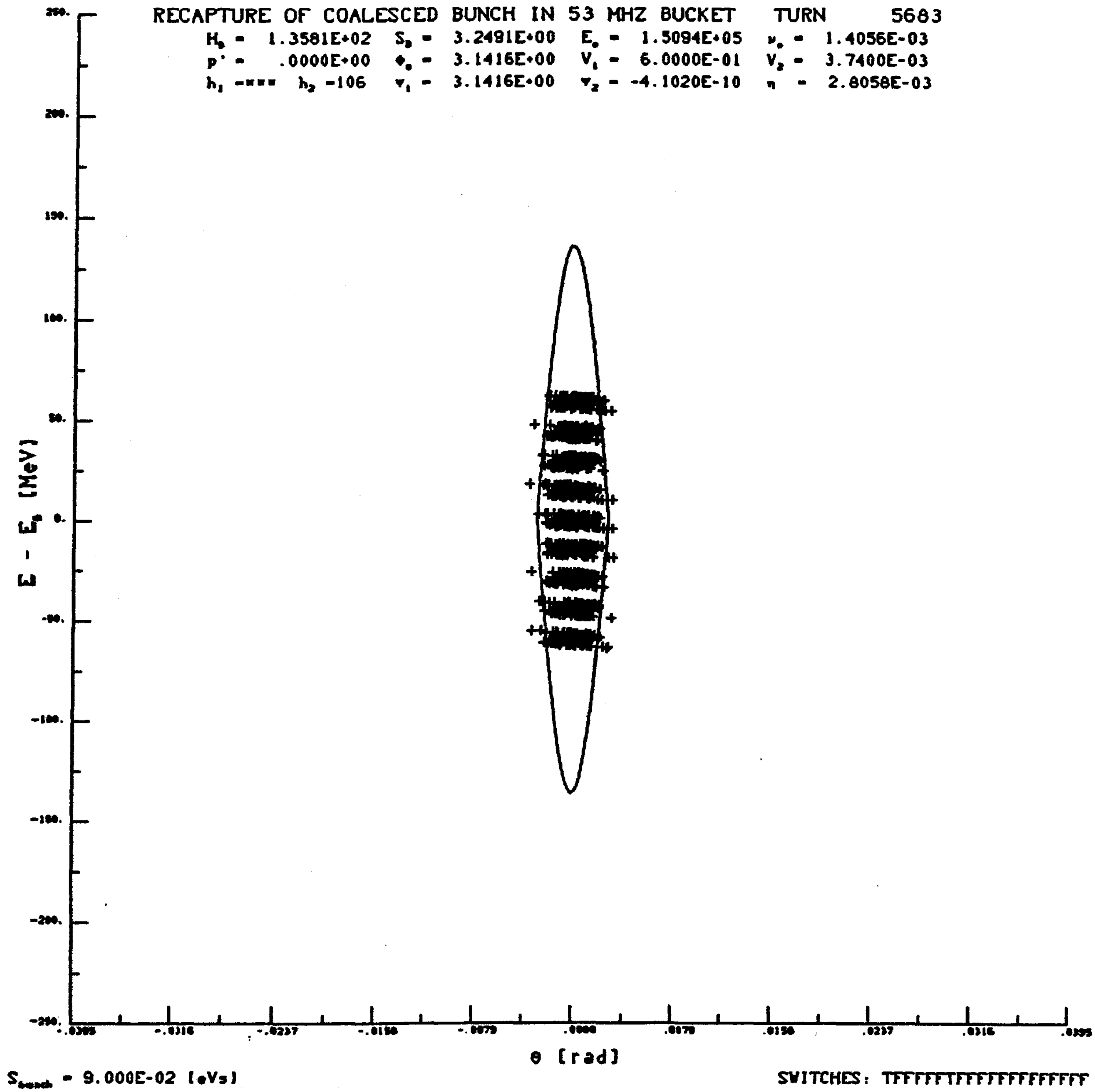

Fig. 7. Phase space distribution at the beginning of the 53 MHz recapture using calculated optimum timing. This result is to be compared to Fig. 4 for the timing used in Main Ring studies.

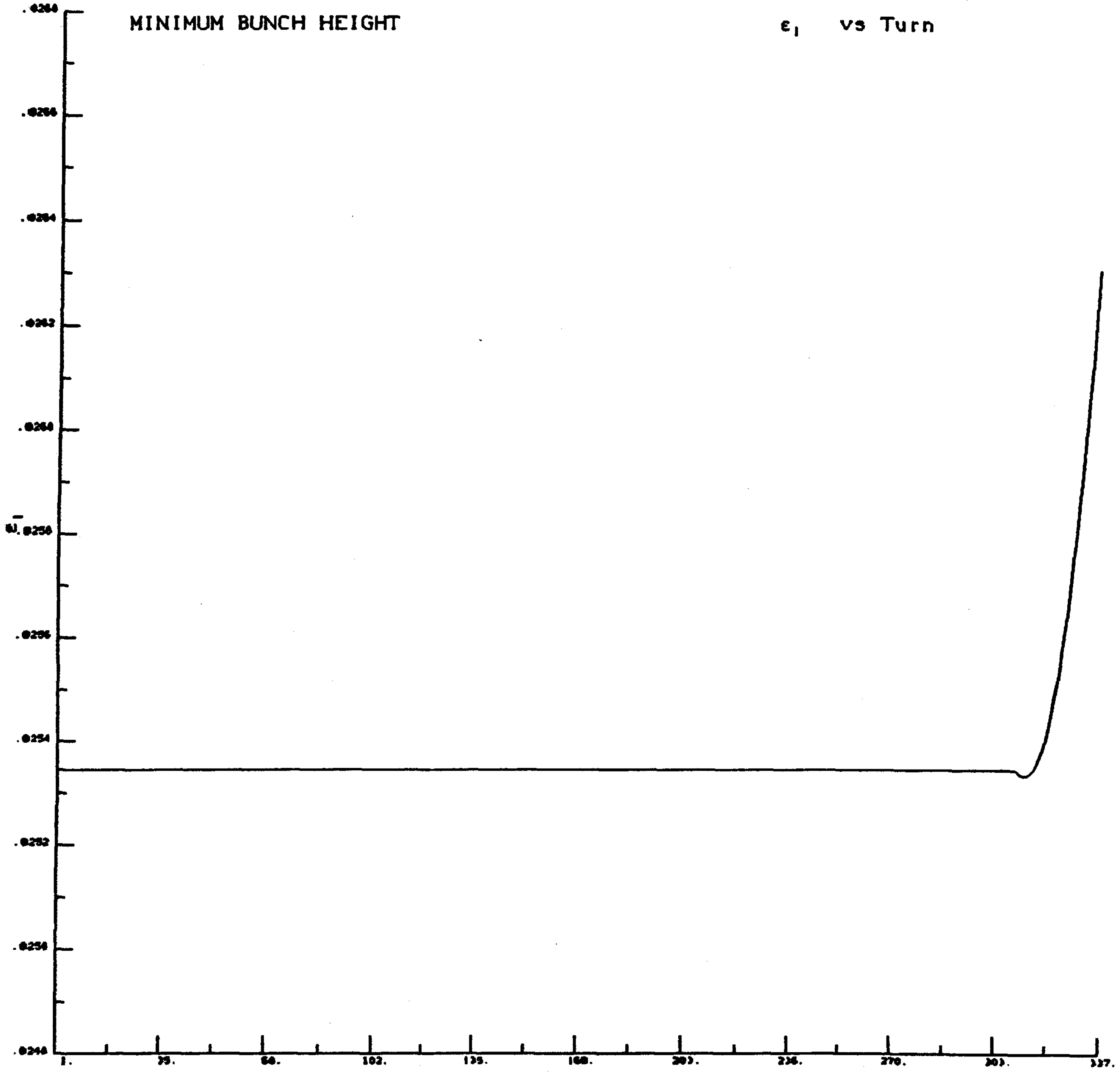

Fig. 8. Evolution of the rms emittance of a 0.15 eVs, 53 MHz bunch during shearing and rotation.

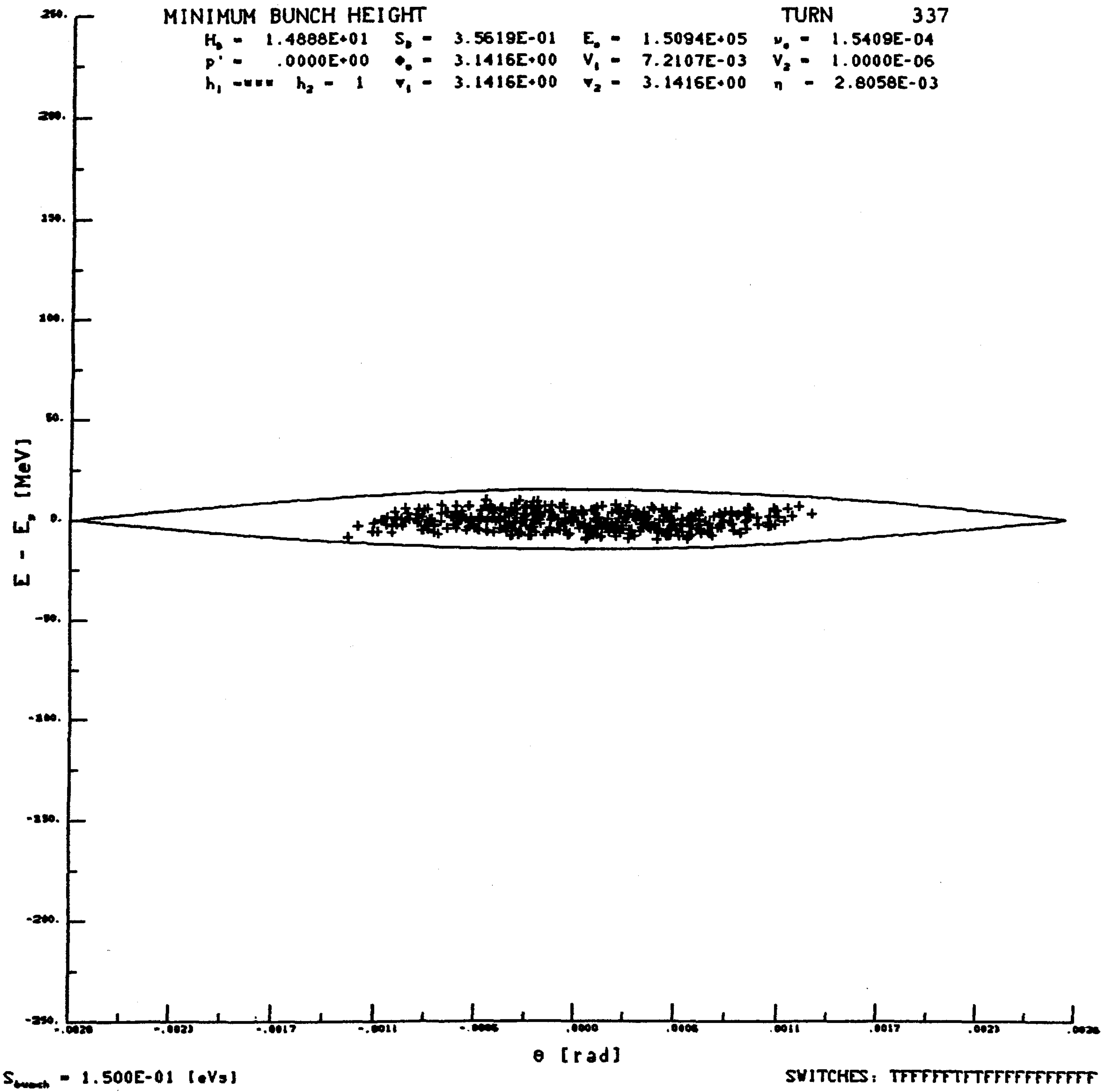

Fig. 9. Phase space distribution of a 0.15 eVs bunch after shearing and rotation to a phase spread of ±90 degrees. The matching bucket shown is produced by 7.2 kV of 53 MHz RF.

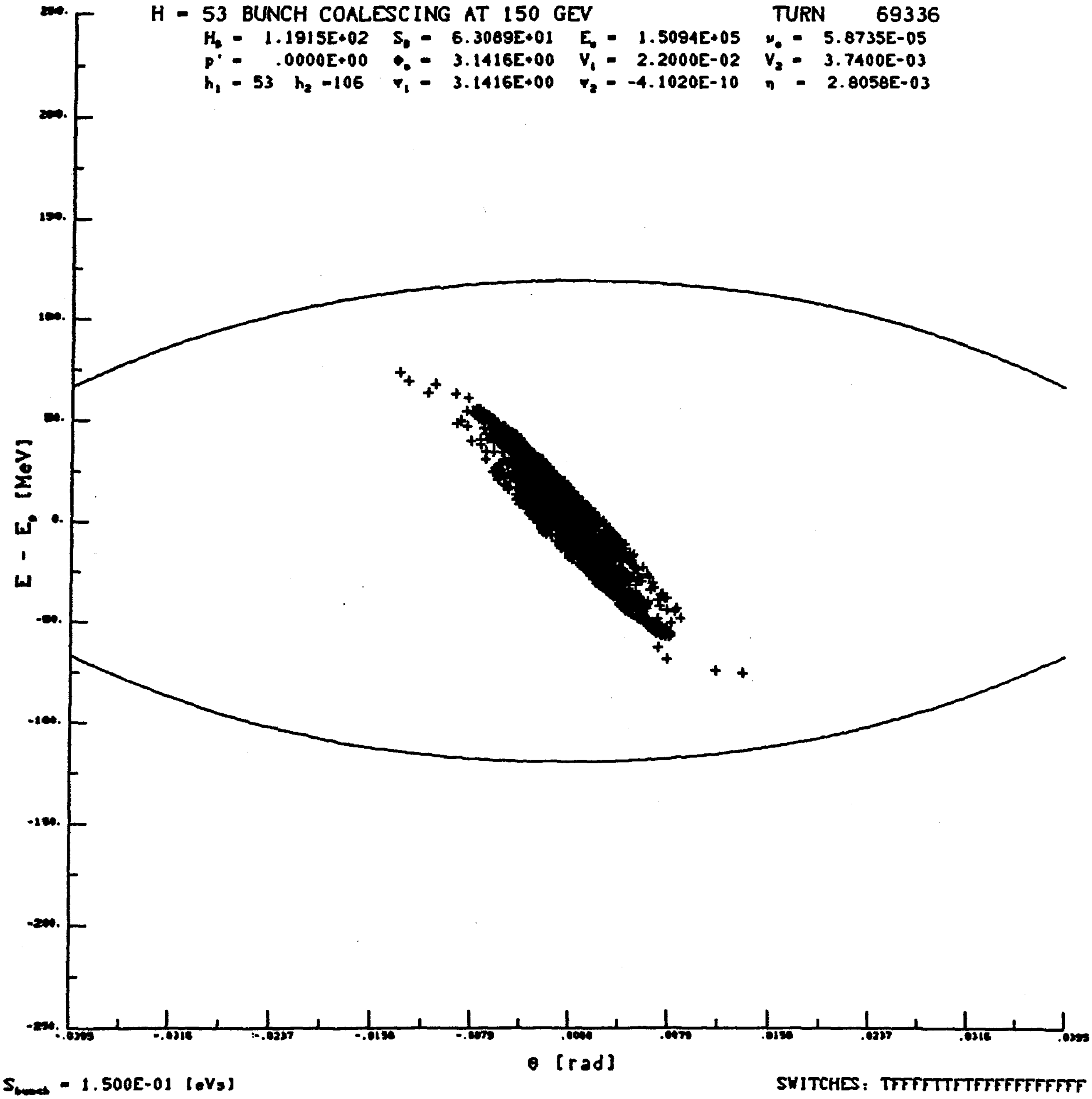

Fig. 10. Distribution resulting from the debunching of nine 53 MHz bunches, each of area 0.15 eVs. The distribution is shown about halfway through the coalescing rotation in a 2.5 MHz bucket.

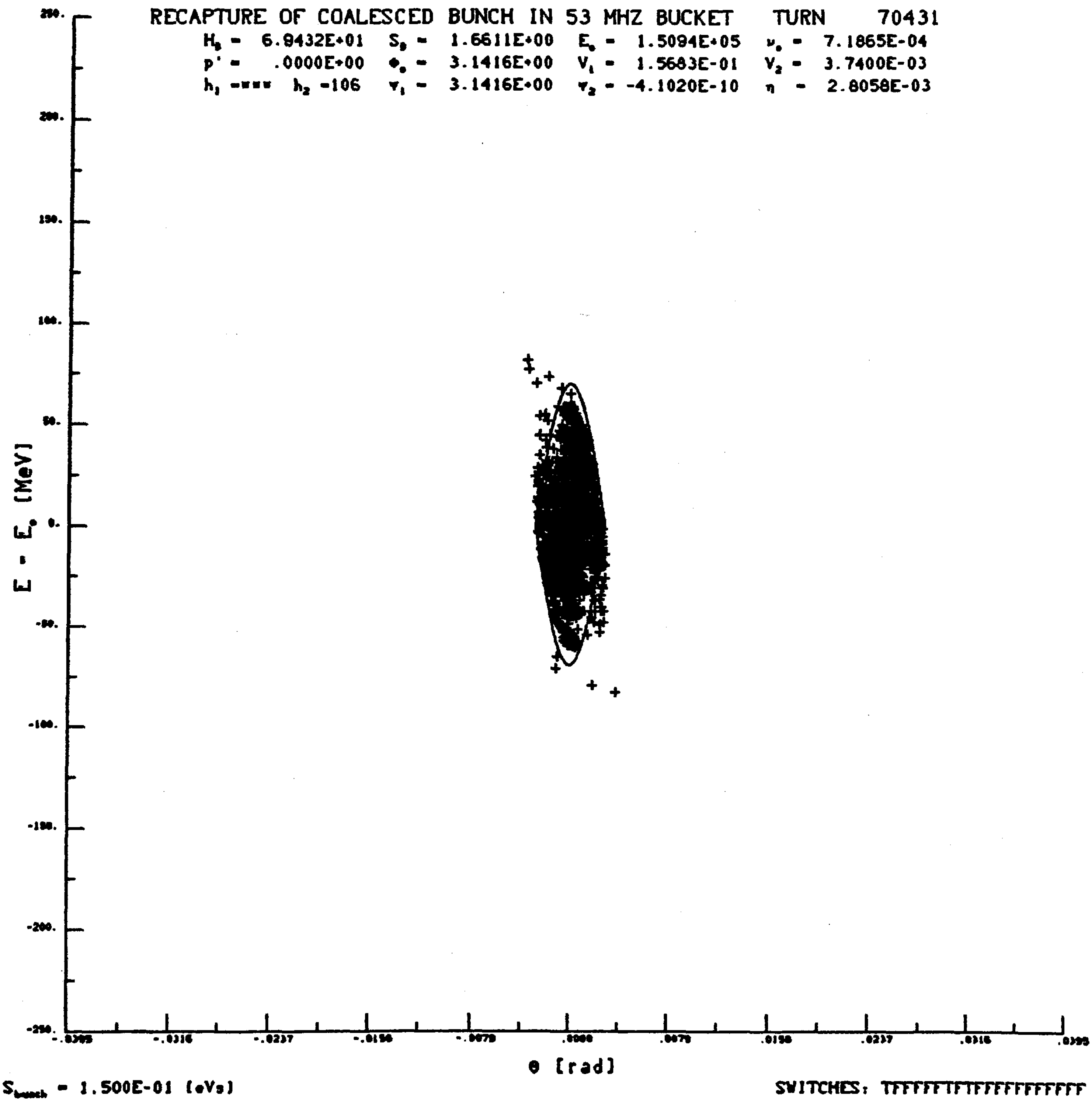

Fig. 11. Final coalesced distribution, the same distribution shown in Fig. 10 after recapture by a 53 MHz bucket produced by 155 kV.

dilution occurs all at the end, during the rotation, when the bunch, which is no longer exactly elliptical, starts to move on the elliptical trajectories in the new bucket. The resulting dilution is 3.8%, a value which seems tolerable if not completely negligible.

The remainder of the bunch coalescing proceeds as previously described(3) with no significant differences. The full cycle has been simulated with the modified debunching. The conditions applying to proton bunch coalescing were used, i. e., nine equal bunches of 0.15 eVs. The design report calculations had concentrated on the antiproton case because, having more bunches and higher total emittance, it appears more difficult. An interesting result of the recent calculations, having nothing to do with the RF-off debunching technique, is that the proton case is really almost equally difficult. Because the antiproton bunches are captured from a matched bunch at 8 GeV, their height distribution properly matches the low frequency bucket into which they are recombined at 150 GeV, whereas all the proton bunches are of the same height. Fig. 9 shows one of the h = 1113 bunches in the matching low voltage bucket at the start of the final debunching; 7.2 kV are required. Fig. 10 shows the debunched distribution halfway through the h = 53 rotation. Both the failure to remove all vestiges of the h = 1113 structure and the diffuse tails introduced by the the mismatch of the end bunches to the debunching trajectories are evident. Note that the tails are not simply the result of reducing the h = 1113 voltage too fast. Although the adiabaticity parameter $\alpha = (\tau/S_b)(dS_b/dt) = 0.75$ is not very conservative, experimentation with the debunching time shows that this is not the difficulty. Because the debunching time is already 1.4 s it does not seem very attractive to insist on lower α. Fig. 11 shows the recaptured bunch at the turn-on of the h = 1113 voltage. In this figure one sees a resulting bunch of 1.7 eVs. Although the area has grown by 24% it is still somewhat smaller than the antiproton bunch. The particles outside of the intended bucket do not constitute a practical problem; as the voltage is raised to 2 MV only about 1% evade capture. Their number might be reduced by turning on a bigger 53 MHz recapture bucket but only at the expense of diluting the dense distribution in the target bucket. The optimum values of the various voltages and times are collected in the following table where they are compared to the values for antiproton coalescing given in the Design Report for the original debunching scheme. This comparison is meaningful because the differences between the proton and antiproton cases are small.

Table: Proton[a] Bunch Coalescing Parameters

(Design Report Values for $\bar{p}$[b] in Parenthesis)

Step	Δt [ms]	53 MHz V_i [kV]	53 MHz V_f [kV]	2.5 MHz V_i [kV]	2.5 MHz V_f [kV]	5 MHz V_i [kV]	5 MHz V_f [kV]
start of flattop	--	1000	0.0 (500)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
drift	6.5	0.0	0.0	0.0	0.0	0.0	0.0
h=1113 rotation	0.566	1000	1000	0.0	0.0	0.0	0.0
adiabatic debunching	1.4 (1.6)[c]	7.21 (1000)	0.10 (0.06)	0.12 (0.04)	0.12 (0.04)	$\sim$0.0 ($\sim$0.0)	$\sim$0.0 ($\sim$0.0)
h=53 rotation	107 (111)	0.0 (0.0)	0.0 (0.0)	22.0 (22.5)	22.0 (22.5)	3.7 (4.9)	3.7 (4.9)
h=1113 recapture	0.0 (0.0)	155 (350)	155 (350)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
h=1113 bunch narrowing	$\sim$50 ($\sim$50)	155 (350)	1000 (1000)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)

(a) Protons: 9 bunches of 0.15 eVs each

(b) Antiprotons: 13 bunches of 1.5 eVs total emittance, largest 0.15 eVs.

(c) This debunching time changed from Design Report value of 1 s to this more conservative value.

Conclusion

The conclusion we wish to draw is that debunching by rf-off drifting and a high voltage rotation is an adequate substitute for adiabatic debunching from the 1 MV to the 10 kV level in the main ring bunch coalescing scheme for TeV I. Within a single study period we were able to achieve a credible demonstration of the principle and its implementation. As far as the performance of the Tevatron collider is concerned, the choice between this technique and adiabatic debunching by cavity counterphasing is a purely technical one involving operational simplicity and reliability. The scheme proposed here is attractive in this technical comparison because the hardware and controls are straightforward.

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