CERN/PS/RF/Note 98-14 (MD)

Study of single harmonic bunch flattening by high-harmonic phase space displacement on un-bunched beam in PS Booster

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Abstract

The purpose of this MD was to investigate the idea of creating hollow bunches by sweeping high-harmonic empty buckets into the particle beam prior to bunching, as proposed by F. Pedersen. Essentially, this is an example of phase space displacement and, if performed adiabatically, it should produce a beam that has a double humped distribution in the relative momentum spread dp/p. The effect of introducing these voids is that after capture the beam density distribution is anticipated to be hollow in phase and its projection, the bunch shape, should be lengthened and flattened. If successful, this should thereby reduce the transverse betatron tune spread in both the Booster and the PS.

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1 Introduction

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The advantage of this scheme over a more conventional beam blow-up[1] using phase modulation of a high harmonic cavity is two-fold. (i) The conventional scheme does not produce hollow bunches, only broader ones; (ii) the amelioration against space-charge effects takes place immediately, and one does not have to wait for bunching before applying the technique. This second advantage is the most useful.

2 Set up for MD

On 22nd May we set up a Booster cycle with a 50 millisecond flat bottom, normal acceleration to 100 MeV, and then a long flat top. The injection start is at C290 (i.e. 290 ms after the beginning of the synchronisation C train), beam arrives at C315, acceleration starts at C365 ms, and the flat top is reached at C490 ms. The cycle is stored under user MDAD shane-052298. Because the quadrupole field does not follow the dipole field, the Q-cycle was modified to account for flat bottom and top and saved as shane-980522. Incidentally, a longitudinal instability was observed with both RF systems off (C02 and C04). This was probably related to impedance of the C02 cavity which is not short-circuited when "off".

2.1 Frequency offset

On 26th May we began to set up the C16 system for sweeping high-harmonic empty buckets into the un-bunched beam. A number of choices of harmonic number had been considered (16,17,18) but the final choice was dictated by hardware limitations. The maximum frequency offset possible with the function generator is 19.6 kHz. Assuming a kinetic energy spread of ±160 keV leads to a frequency spread of 14.2 kHz at harmonic 16. But one must remember that the buckets must start completely outside the beam, which necessitates an additional frequency offset of at least 4.1 kHz for buckets of half-height 50 keV (C16=2keV) at harmonic 16. Though harmonic 17 were possible, to allow for the fact that the beam might be wider in dP/P than the nominal value we chose h=16 and a frequency offset starting 19.6 kHz below the RF (9.581 MHz) and diminishing to zero in 20 milliseconds. The fairly long ramp was chosen to give a fairly strong adiabaticity condition of 10% changes of parameters each synchrotron period of the h=16 buckets.

[1] An alternative scheme which might produce hollow bunches is phase modulation of the fundamental; but this is very sensitive to parameters.

2.2 Single harmonic

For the purpose of simplicity, we considered single harmonic acceleration (i.e. C04 off and shorted) and low intensity (3.1 injected turns) of 3E12 ppp. C02 comes on at 20 ms (after injection start) and ramps to 7 kV at 22 ms. Hence bunching starts prior to acceleration.

On 26th May there were a number of problems that delayed experimentation (Q-strips inadvertently left on which led to large transverse losses, MD on the linac leading to significant pulse-to-pulse variability, etc.) but finally a few simple things were done.
RF parameters are shown in Figure 1.

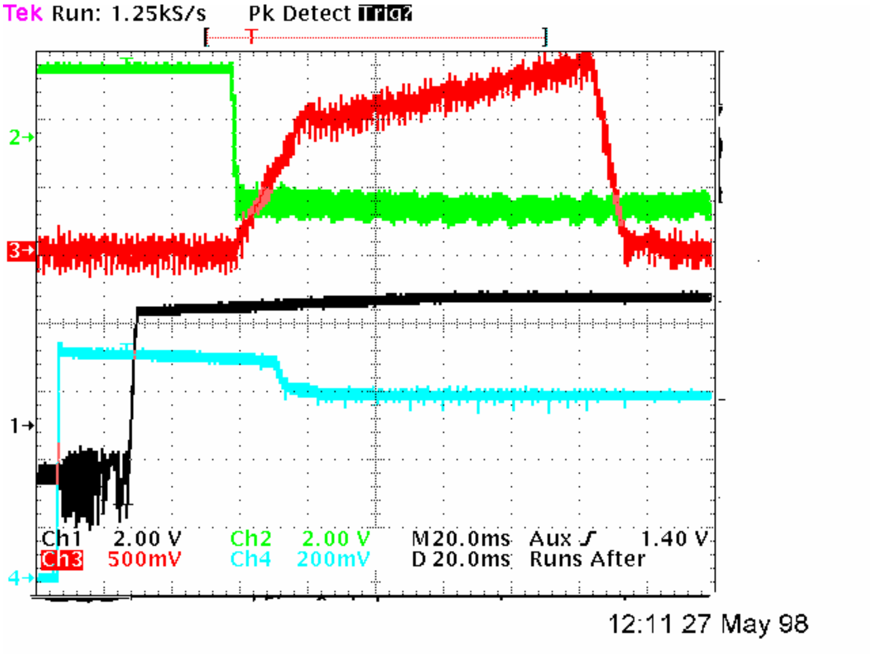

Figure 1: trace 1 = C02 voltage, 10db/V; trace 2 = C16 voltage, 10db/V; trace 3 = B-dot, 1V/T/s; trace 4 = d.c. beam current, 4E12p/V.

2.3 High harmonic voltage setting

The desirable C16 cavity voltage had been estimated at 0.6 kV. Bunch shapes were observed at 100 ms after beam arrival, as a function of C16 voltage and 1 kV found to be optimal.

2.4 High harmonic duration

Initially, it had been assumed to turn C16 voltage to zero immediately after the frequency sweeping and allow the empty buckets to debunch. However, from observation of the bunch shapes at 100 ms it was found to be advantageous to maintain the C16 voltage until the start of the B-field ramp (i.e. 50 ms after beam arrival). A possible explanation is that the empty phase space is maintained for longer in this case, and less prone to being filled in during the C02 bunching.

2.5 Tomography

During 26th --27th May Mats Lindroos and Steven Hancock made a number of beam tomography measurements starting at 175 ms (on flat top) and have compared cases with C16 on/off. The tomographic reconstructions indicate beautiful hollow bunches when C16 is on. During this time, the captured and accelerated beam intensity was some 2-->2.4E12 ppp. Figure 2, Figure 3 and Figure 4 show the case with C16 off; the bunches have the semi-parabolic shape and density distribution typical of beam captured into single harmonic RF. Figure 5, Figure 6 and Figure 7 show flat bunches with a phase space distribution that is *clearly hollow* with C16 on.

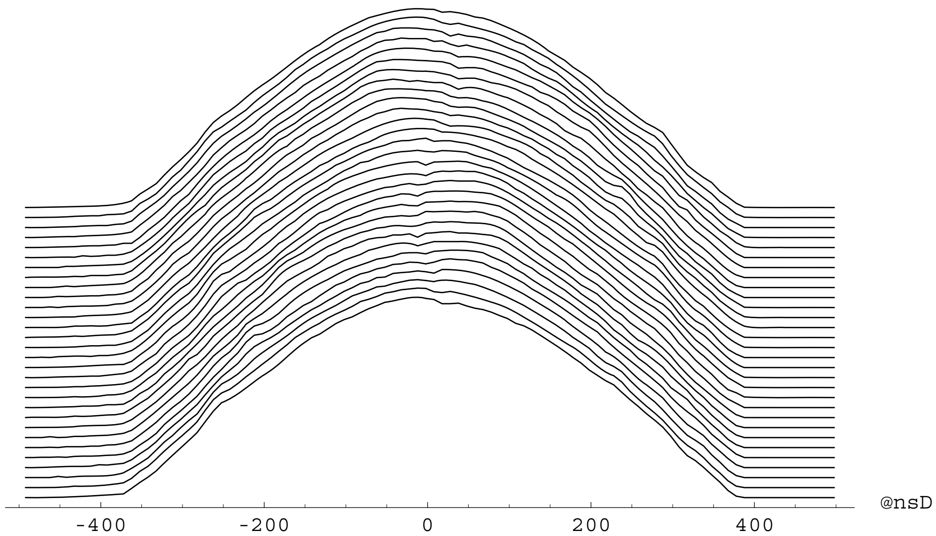

Figure 2: Bunch profiles; C16 off; low intensity; C02 7kV.

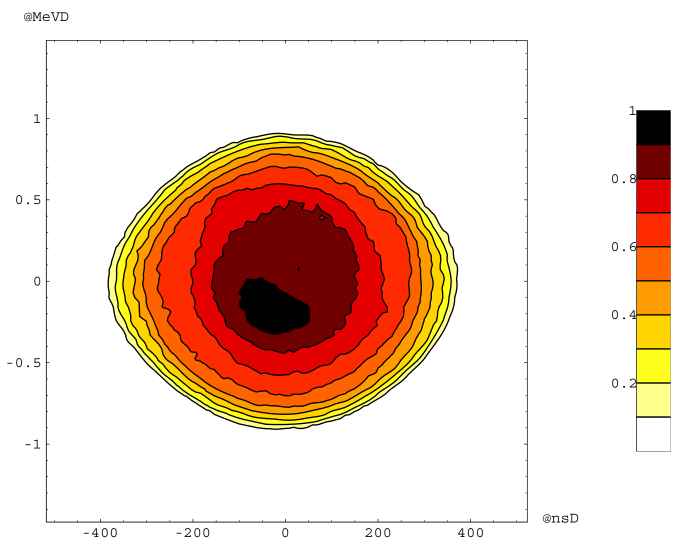

Figure 3: Phase space contour plot; C16 off, low intensity; C02 7kV.

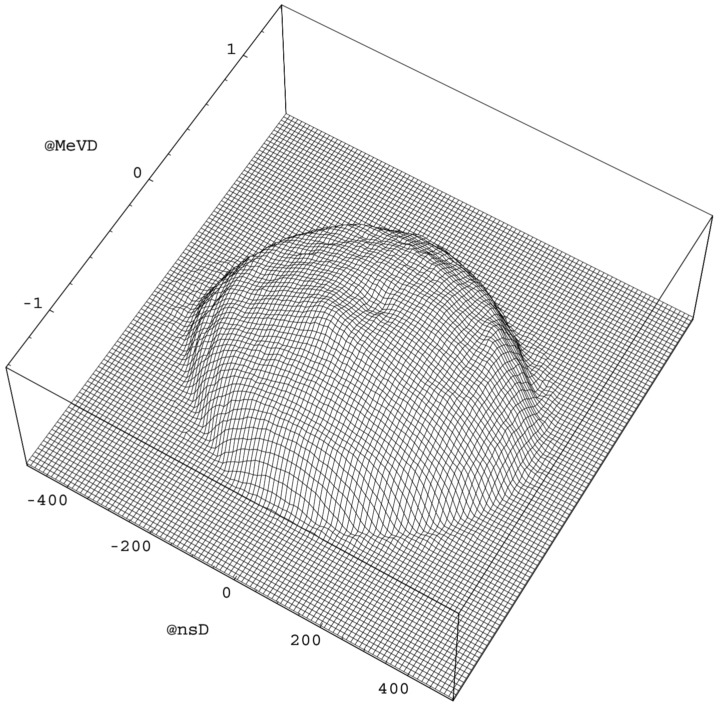

Figure 4: Surface plot of particle distribution; C16 off; low intensity; C02 7kV.

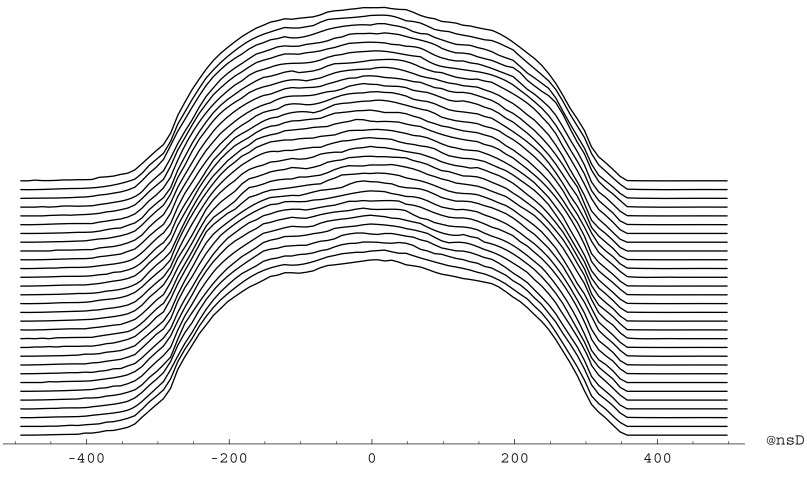

Figure 5: Bunch profiles; C16 1kV; low intensity; C02 7kV; Δf in 20 ms.

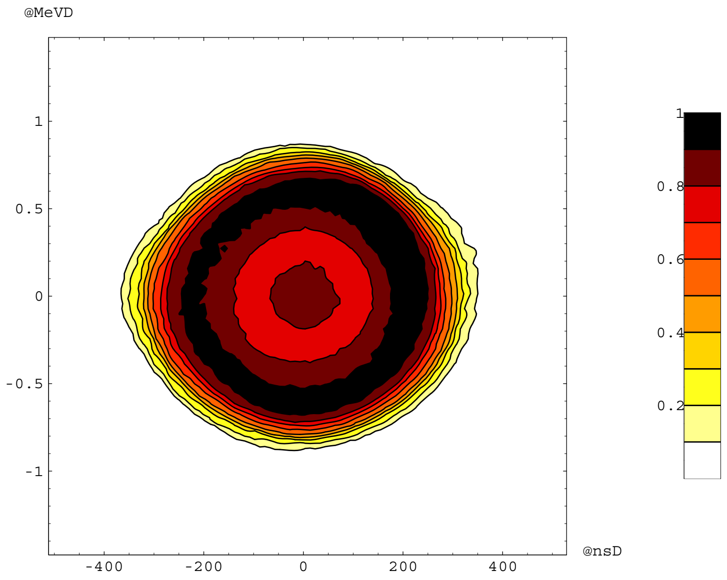

Figure 6: Phase space contour plot; C16 1kV; low intensity; C02 7kV; Δf in 20 ms.

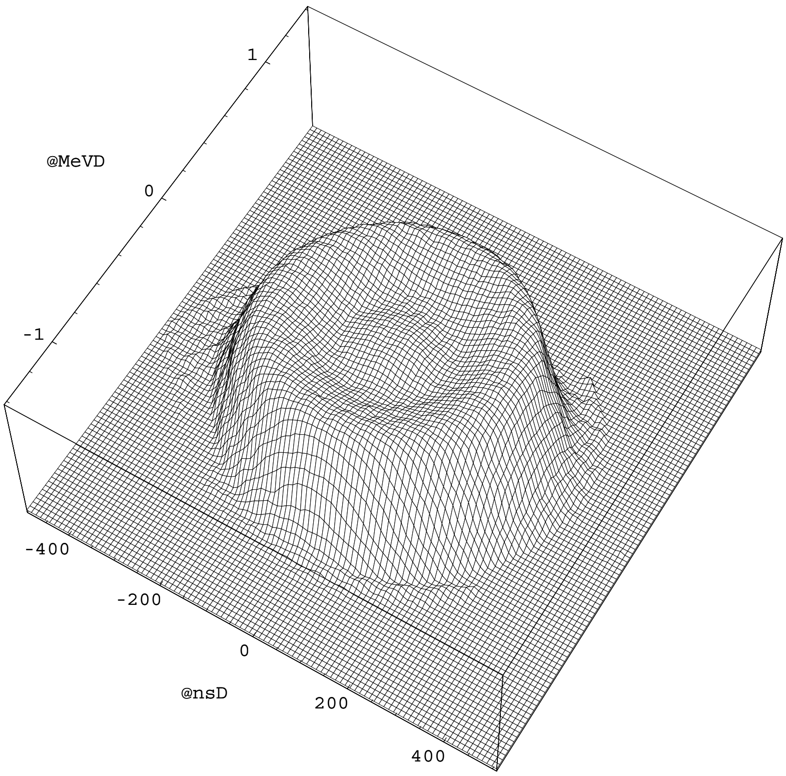

Figure 7: Surface plot of particle distribution; C16 1kV; low intensity; C02 7kV.

3 28th May MD

We began the afternoon using the low intensity settings of the previous day. RF parameters are shown in Figure 8 and Figure 9. The C16 frequency is swept upward 19.6 kHz in 20 ms. Small changes were made to the Q-strips to reduce transverse losses during the 50 ms flat bottom. The captured intensity was some 2.7→3E12 ppp.

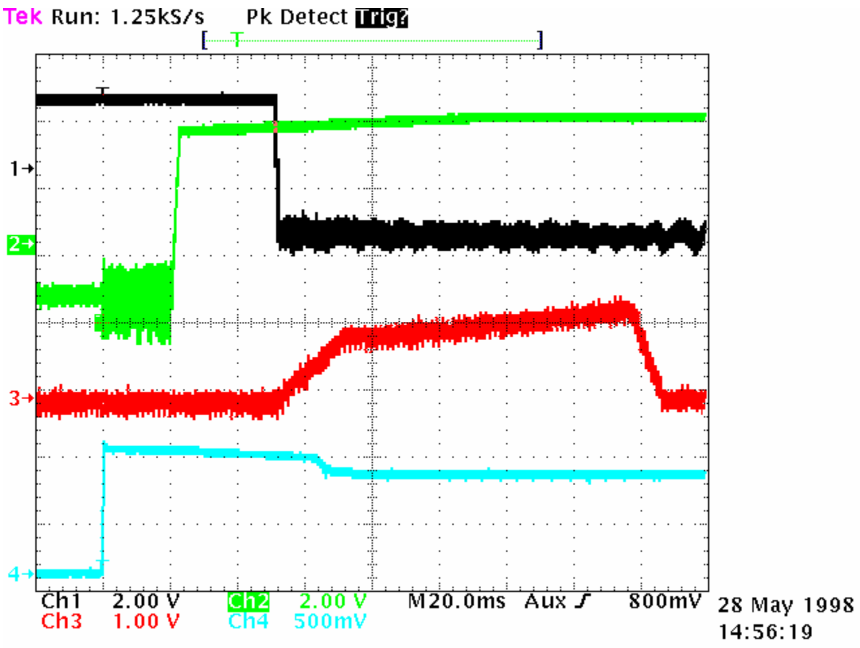

Figure 8: trace 1 = C02 voltage, 10db/V; trace 2 = C16 voltage, 10db/V; trace 3 = B-dot, 1V/T/s; trace 4 = d.c. beam current, 4E12p/V.

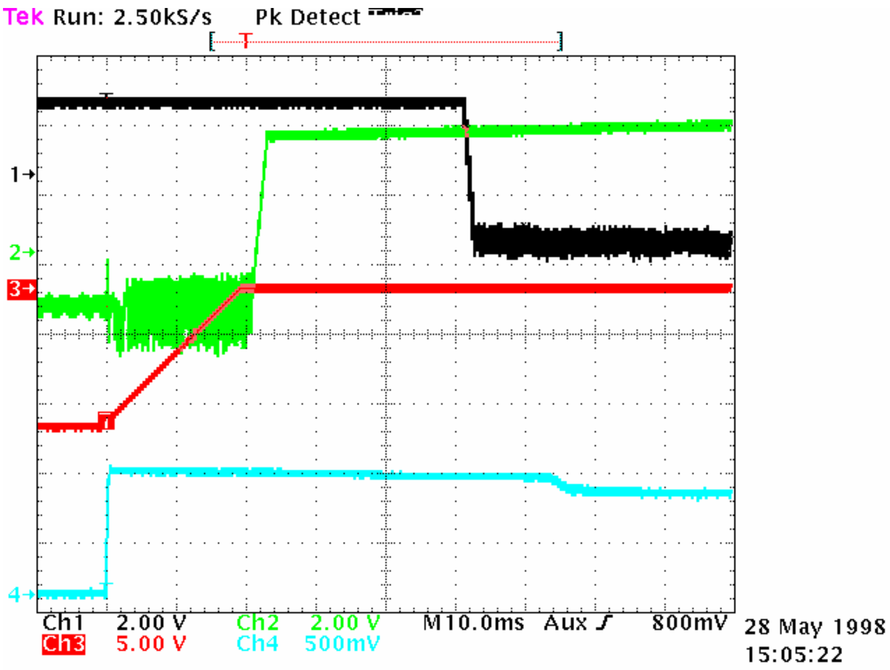

Figure 9: trace 1 = C16 voltage, 10dB/V; trace 2 = C02 voltage, 10dB/V; trace 3 = frequency offset ramping, 2kHz/V; trace 4 = d.c. beam current, 4E12p/V.

Pulse-to-pulse variability in the bunch shapes observed previously can be attributed, partially, to two possible causes:

- Energy variability of either the injected beam or of the final h=16 RF buckets
- Phase variability of the h=16 buckets compared with the h=1 RF used for capture.

The error contributed by difference of the C16 central frequency and that of the beam was reduced by two measures. (I) Not allowing the B-train pulses to reach the equipment during the flat bottom; and (II) empirically by adding a very small offset to the C02 frequency, which also forms the basis of C04 and C16. This led both to better bunch shapes and to more repeatable ones.

3.1 Beam evolution before acceleration

The beam modulation was observed on a Tektronix digital scope with triggering in synchronisation with C16/16. The modulation grows from 18 mV at 5 ms to 24 mV at 10 ms (**Figure 10**) to 32 mV at 19 milli-seconds after beam start.

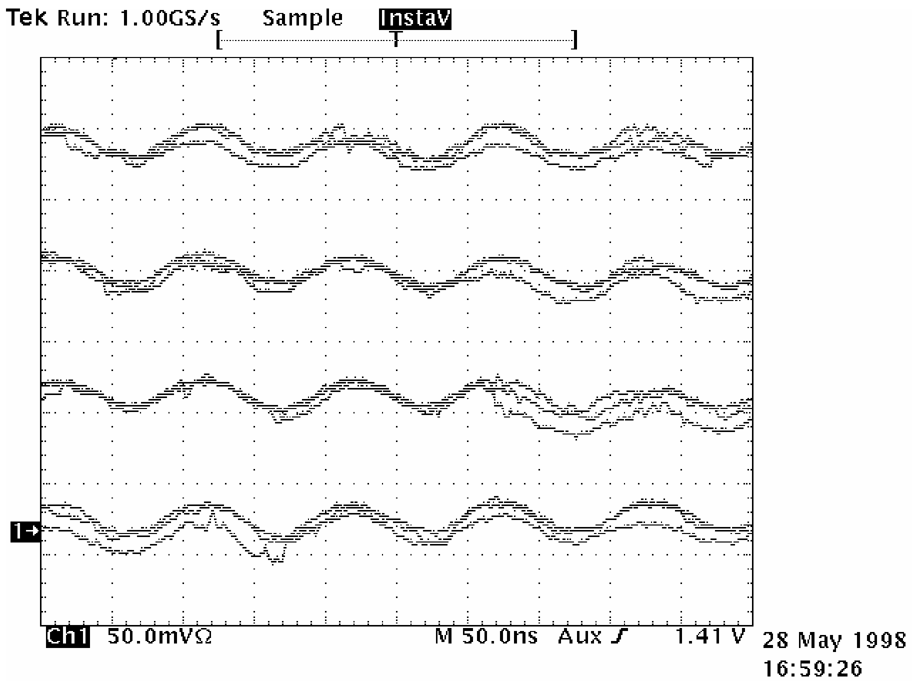

Figure 10: Beam current modulation at 10 ms.

3.2 C16 On

At 20 ms the C02 voltage rises semi-adiabatically and capture into the C02 buckets of the C16 modulated beam begins; this transition is shown in Figure 11 which spans a range of about 16 ms starting 19 ms after beam arrival. After capture and acceleration to 100 MeV (at 175 ms after beam arrival), the bunches typically look as in Figure 12 when phase space displacement is used. However, in a minority of pulses, a bad bunch shape occurs as in Figure 13 where the bunch is parabolic rather than square.

3.3 C16 Off

For comparison sake, we show bunch shapes at 175 ms when the modulation due to C16 is turned off. Again there is pulse-to-pulse variability. **Figure 14** shows a “good bunch”; the small notch appearing is due to the injection process, and arises from a small area of empty phase space being “trapped” at the stable fixed point of the RF bucket. **Figure 15** shows a “bad bunch” with C16 off. Despite this bunch’s’ ragged appearance, the mechanism is probably the same but with a larger and less-well-centred phase space void.

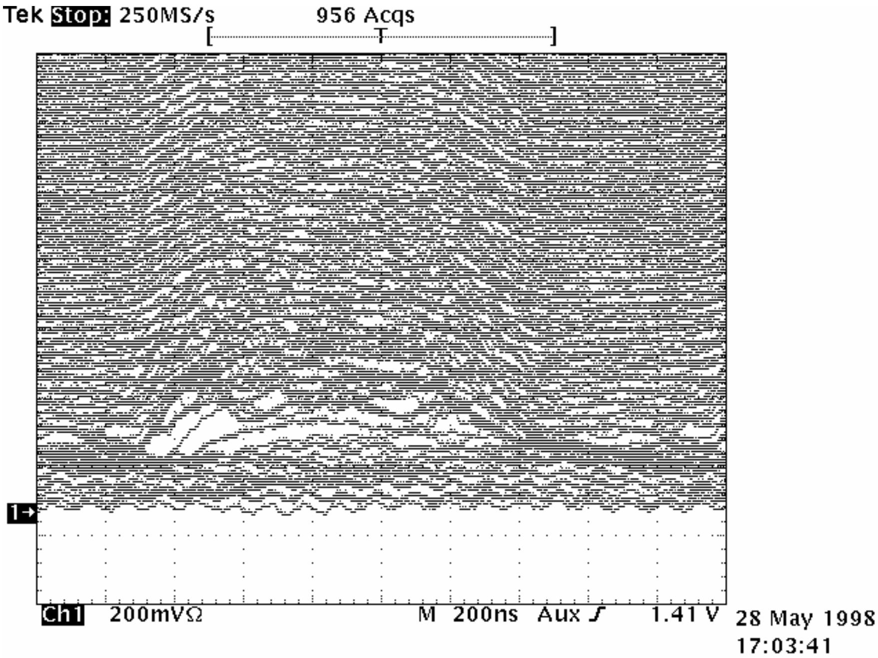

Figure 11: Capture of C16 modulation into C02 buckets at 19 ms; offset 200 revs/trace.

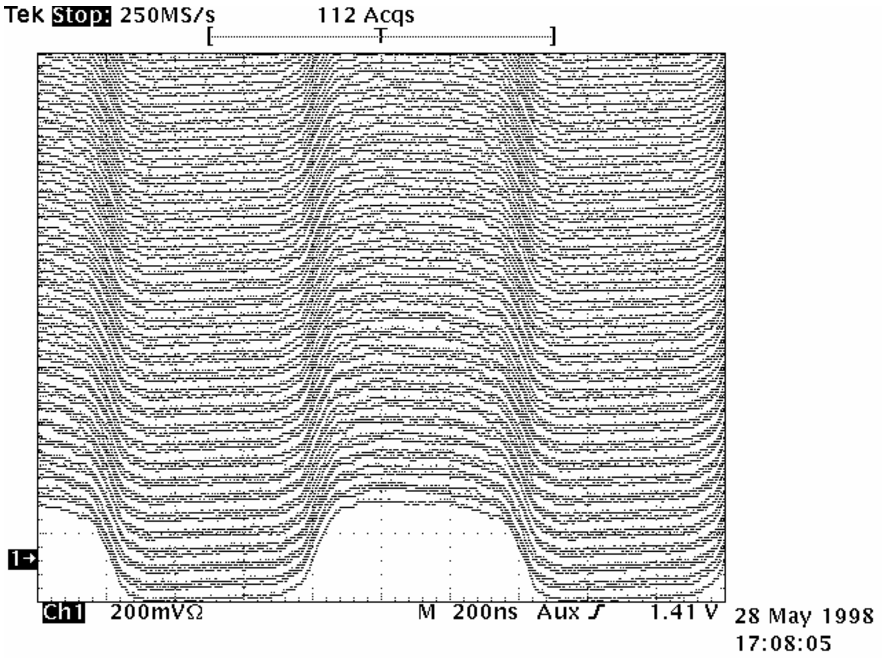

Figure 12: Typical bunch shape with C16 on; start at 175 ms; offset 400 revs/trace.

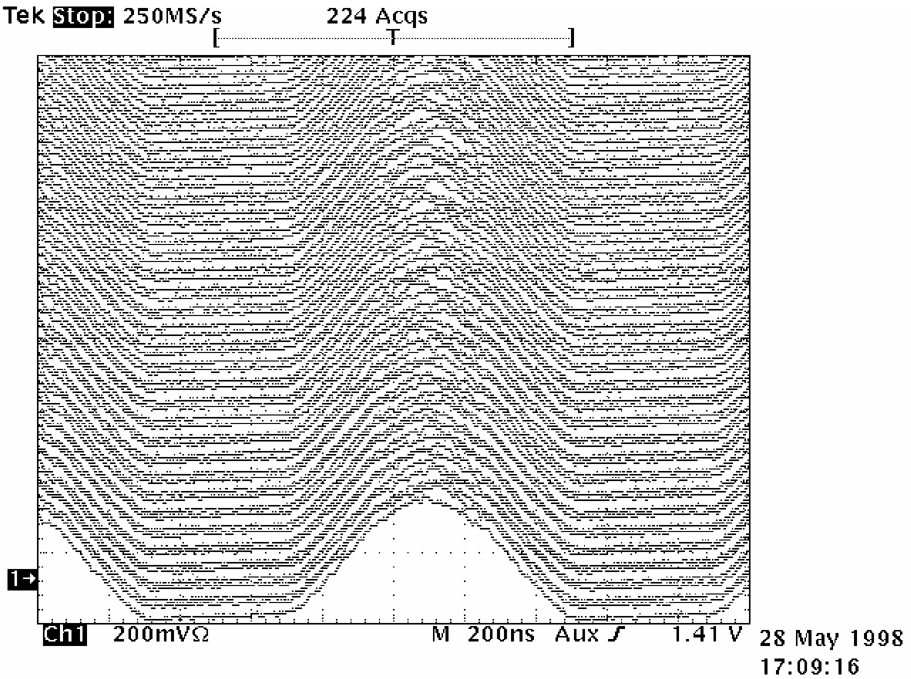

Figure 13: Rogue bunch shape with C16 on; start at 175 ms; offset 400 revs/trace.

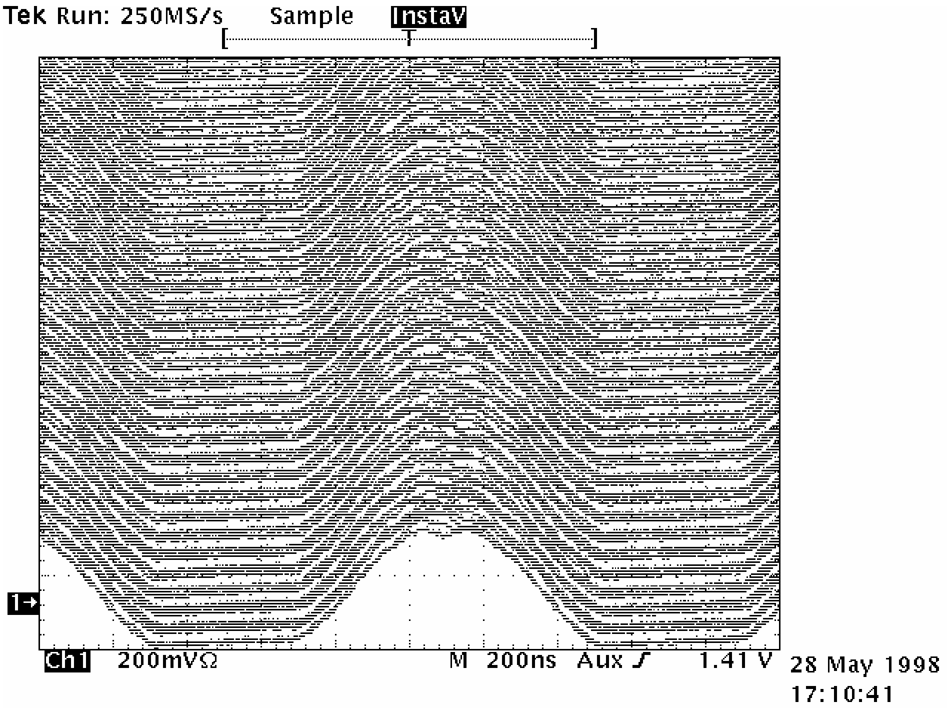

Figure 14: Typical bunch shape with C16 off; start @ 175ms; offset 400 revs/trace.

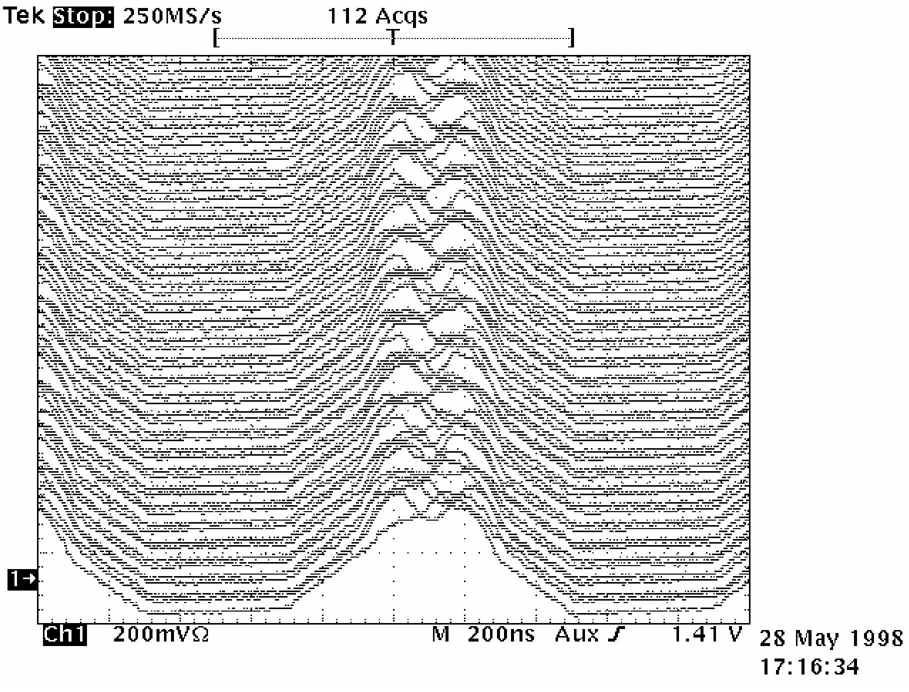

Figure 15 Rogue bunch shape with C16 off; start @ 175ms; offset 400 revs/trace.

3.4 Tomography/C16on

We present tomographic reconstruction of the phase space density distribution for the case C16 on. After the careful adjustment of central frequency during the flat bottom, there is a definite improvement. Figure 16 shows the bunches to be very flat; and Figure 17, Figure 18 show the particle distribution to be very hollow.

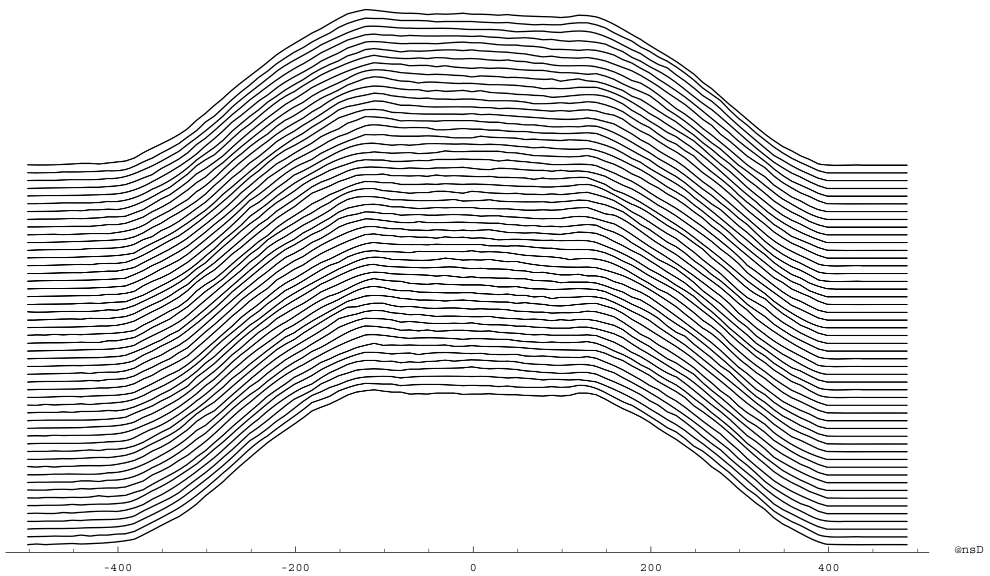

Figure 16: Bunch profiles; C16 on; low intensity.

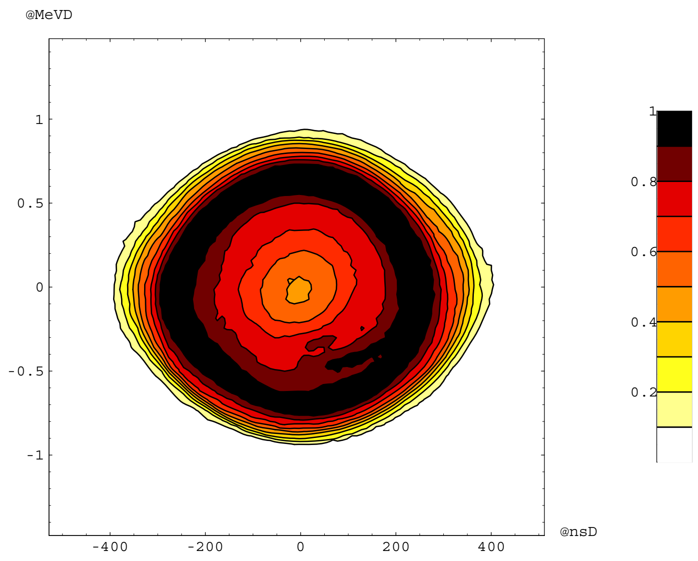

Figure 17: Phase space contour plot; C16 on; low intensity.

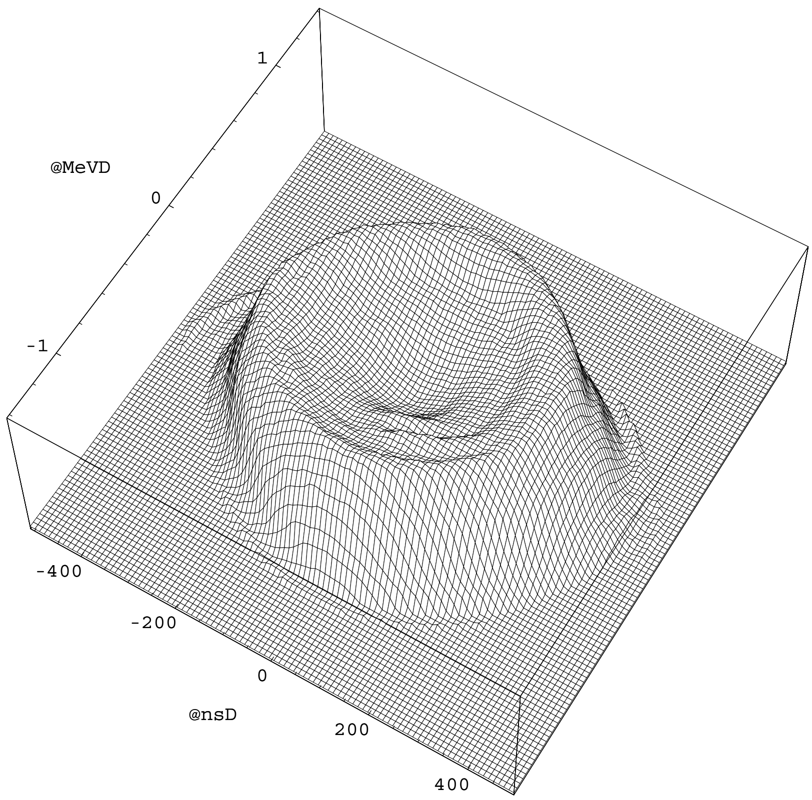

Figure 18: Surface plot of particle distribution; C16 on; low intensity.

4 High Intensity

Later in the afternoon we made an attempt to perform this capture and acceleration at high intensity, but still with first harmonic acceleration only. The number of injected turns was increased to 8 and the intensity to 7E12 ppp. The peak C02 voltage was raised to 8 kV. We considered both ramping of the C16 voltage from 1-to-2 kV and flat at 2 kV; the latter case produced flatter bunch shapes but slightly greater losses, and was chosen as the best compromise. At high intensity, there is substantial pulse-to-pulse variation in the bunch shapes; a typical example with C16 on is given in Figure 19.

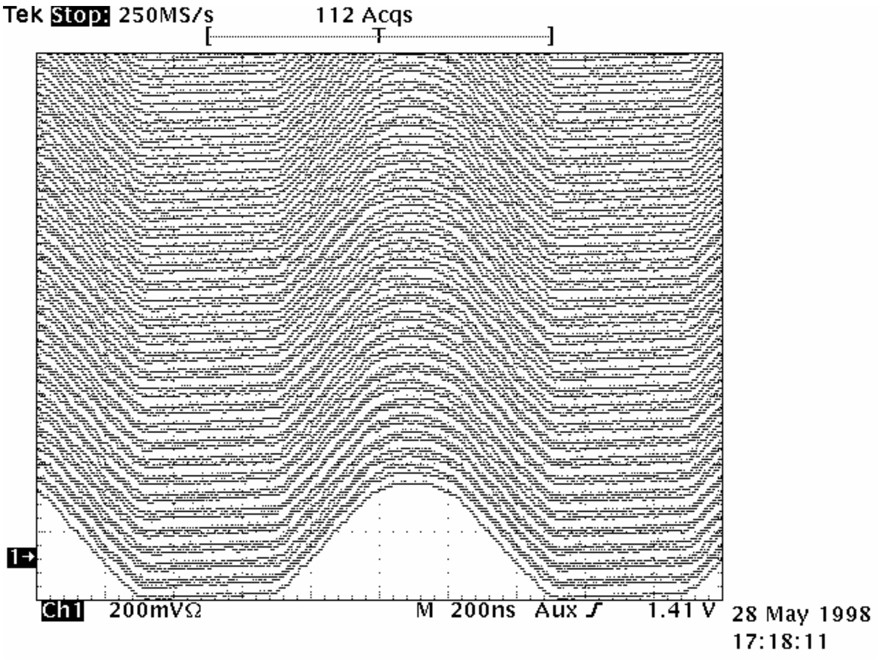

Figure 19: Typical bunch shape @ 175 ms & C16 on; of fset 400 revs/trace.

4.1 C16 = 8 kV

Lindroos adjusted the Q-strips to reduce transverse losses and the intensity was raised to 1E13 ppp (12 injected turns). With C16 on, bunches typically appear as in Figure 20 but occasionally there is still a square bunch shape as in Figure 21; there are also occasionally "bad bunches". The capture efficiency is typically in the range 60% to 70%, with the lower figure being associated with square bunches.

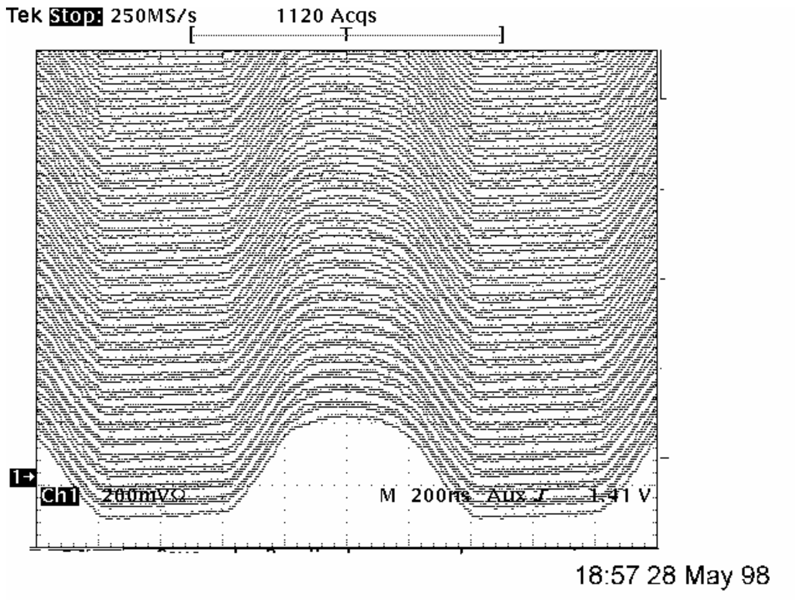

Figure 20: Bunch shape @ 175 ms with C16=2 kV; inject 12 turns; offset 400 revs/trace.

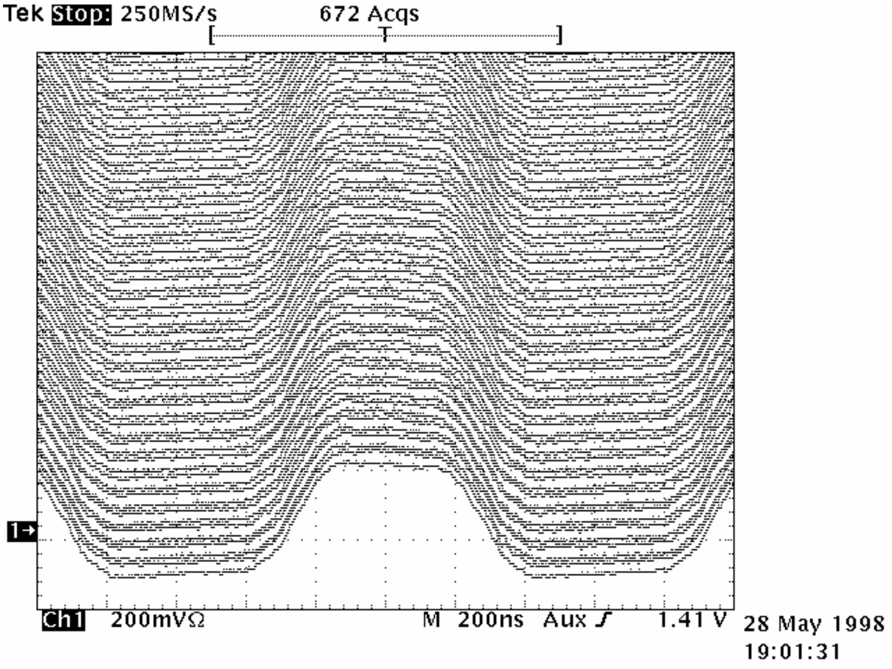

Figure 21: Bunch shape @ 175 ms with C16=2kV; inject 12 turns; offset 400 revs/trace.

4.2 C16 Off

With the C16 off, the capture efficiencies are 5-10% higher, usually being in the range 65% to 75%. However, the bunch shapes are narrower, as anticipated, and with the notching and dipole moment persisting to various amounts. Examples are shown in Figure 22 and Figure 23.

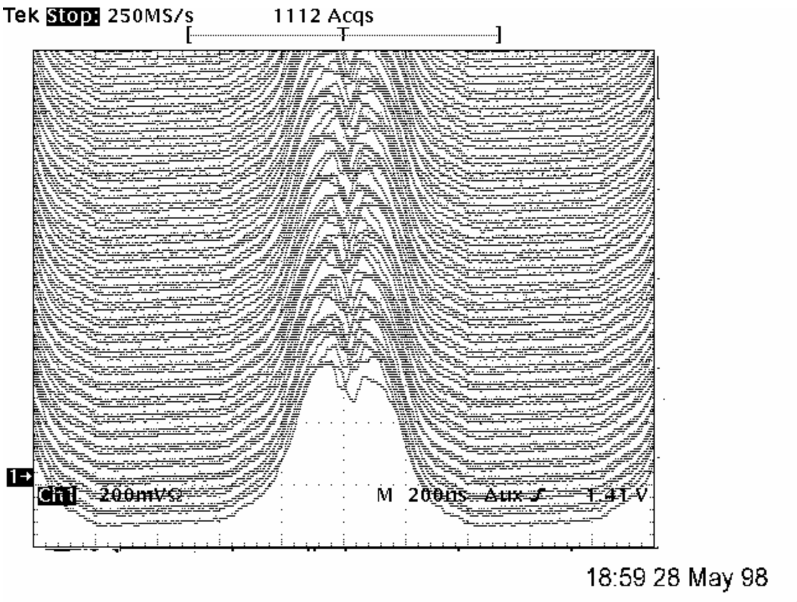

Figure 22 Bunch shape @ 175 ms with C16 off; inject 12 turns; offset 400 revs/trace.

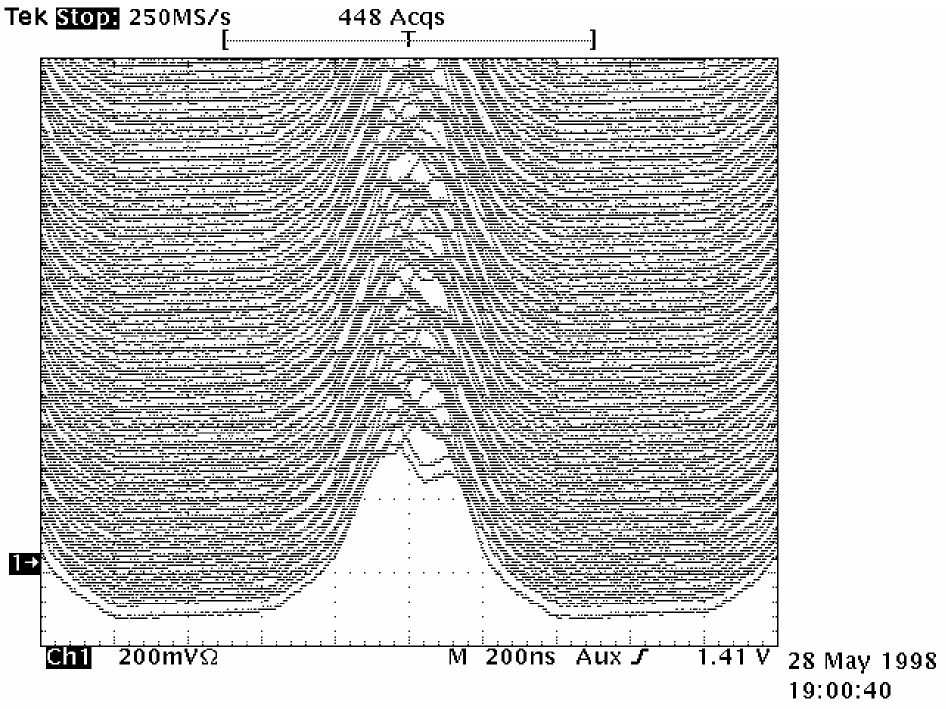

Figure 23: Bunch shape @ 175 ms with C16 off; inject 12 turns; offset 400 revs/trace

Finally just before the end of the MD, Michel Channel adjusted the Q-strips once again so as to increase the number of protons surviving to the beginning of the acceleration. To give us hope for the future, Figure 24 shows an example of a somewhat rare/unusual occurrence of a good bunch with some 75% of 1E13 transported to 100 MeV.

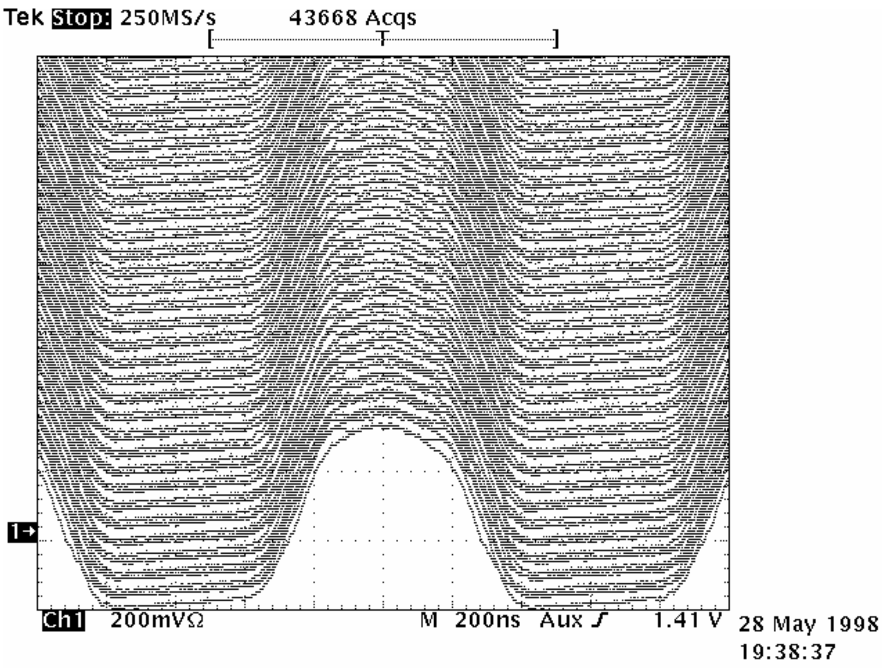

Figure 24: Bunch shape @175 ms with C16=2kV; inject 12 turns; offset 400 revs/trace.

4.3 Variability

At this high intensity and with a large betatron tune spread, the losses are dominated by transverse resonances. However, there is a minor longitudinal effect. Whenever there was a large transient at closure of the C02 phase loop, so there were slightly increased losses. This shows up in Figure 25 as discontinuity in the derivative of the d.c. beam current versus time.

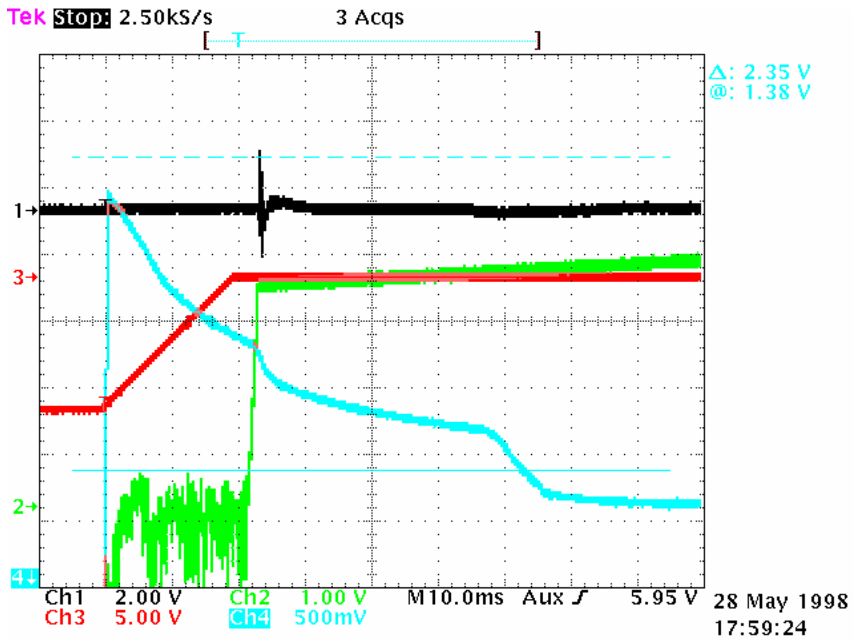

Figure 25: Loss at phse-loop closure; trace 1 phase error; trace 2 = C02 voltage; trace 3 = C16 frequency ramp, 10kHz/V; trace 4 = d.c. beam current 4E12p/V; 1.2E13 injected.

4.4 Tomography

We present tomographic reconstruction of the phase space. Despite the high intensity, the bunch shapes are still quite flat, as in Figure 26; but the particle distribution shown in Figure 27 and Figure 28 is less hollow than previously.

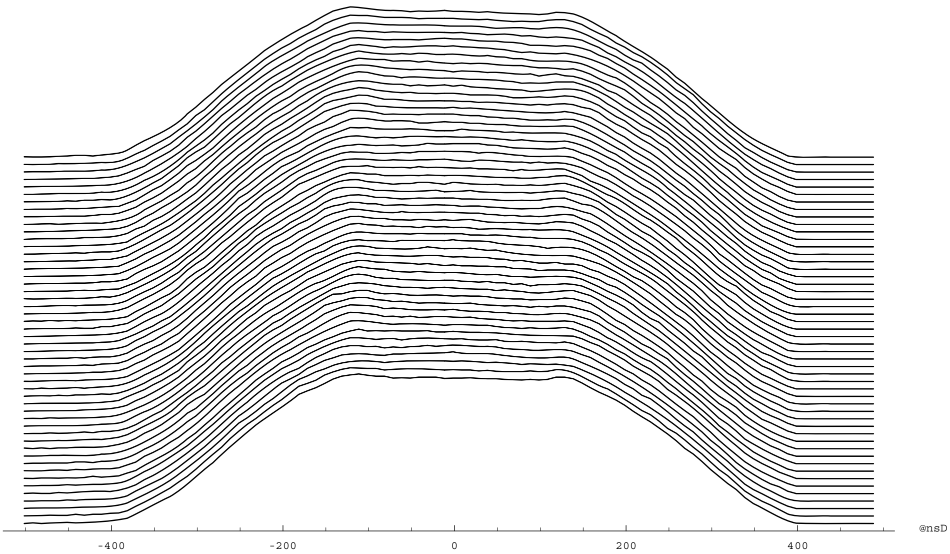

Figure 26: Bunch profiles; C16 = 2kV; high intensity; C02 = 8kV; Δf in 20 ms.

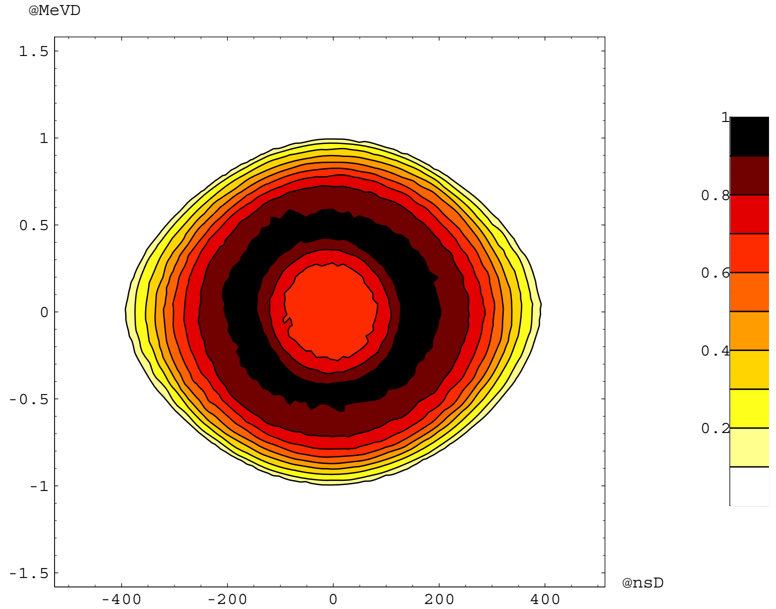

Figure 27: Phase space contour plot; C16 = 2kV; high intensity; C02 = 8kV; Δf in 20 ms.

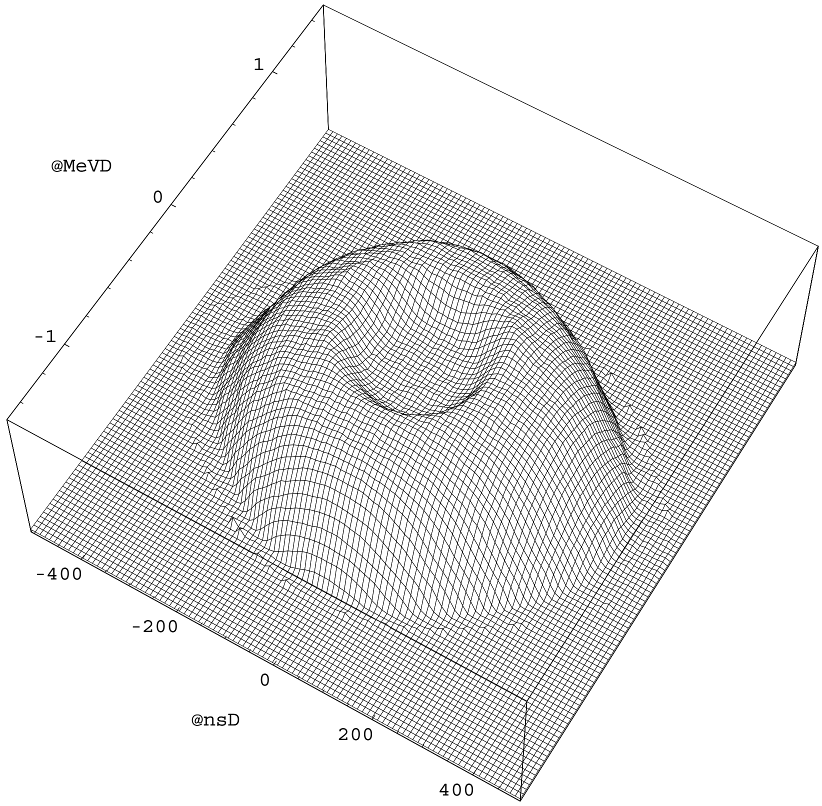

Figure 28: Surface plot of particle density; C16 = 2kV; high intensity; C02 = 8kV; Δf in 20 ms.

5 Conclusion

With really little effort this new technique of bunch flattening by high-harmonic phase space displacement has been shown to work (with a 20 kHz frequency ramp of 20 ms duration) at both low and moderately high intensity. Moreover, we have demonstrated that these beams can be accelerated (at least to 100 MeV) while maintaining their hollow characteristic. Consequently, it is a technique of some promise and should, we believe, be pursued further. The next intended steps should include shortening of the flat bottom, acceleration to 1 GeV and studies with dual harmonic. However, to prepare the way for high intensity, much needs to be done to get the transverse betatron losses firmly under control; and this will require long and patient work.