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PRELIMINARY INVESTIGATION OF INJECTION BUBBLES AND HIGH-HARMONIC HOLES IN CERN PS BOOSTER

A. Blas, S. Hancock, S. Koscielniak, M. Lindroos

The purpose of the 18th November 1999 MDs was a preliminary investigation of "linac bubbles" and high-harmonic holes in anticipation of the careful and lengthy study of 24th November. The "injection bubbles" derive from structure in the linac beam, but we do not here claim they are from the 200 MHz RF structure. A very rough estimate is made of the bubble energy width, and the holes are qualitatively studied as a function of injected intensity. The higher particle density between adjacent holes persists for several milliseconds, which suggests that the holes take longer to debunch/shear than expected from momentum width.

Geneva, Switzerland
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1 Introduction

During the 18th November 1999 MD, we made some preliminary investigation of the effect of particle beam intensity on voids in the longitudinal phase space. This was followed by the more careful and lengthy study of 24th November, which is documented separately. We began with a quick look for "linac bubles", followed by observing high harmonic holes as a function of intensity.

Observations were made with the "tomoscope": this waterfall displays show a "bird's eye view" of beam density versus time: selected longitudinal beam profiles are stacked in ascending order, and the relative intensity along a profile denoted by a greyscale with black the most dense and white the most rarified. The same information may, of course, also be displayed in the more conventional mountain-range plot where higher altitudes denote greater instantaneous current; both formats are used in this document. The abscissa running over 2000 ns spans 1.2 turns at the injection revolution period of 1.667 μs; the ordinate is the sample number.

2 C16 OFF

We began with the C16 cavity off and looked for "linac bubbles" in the coasting beam. Because any beam structure will "wrap around" in the waterfall plot if the beam frequency and data-acquisition reference frequency are not equal, we adjusted GSRPOS GFA (the radial position frequency offset) with the results as shown below.

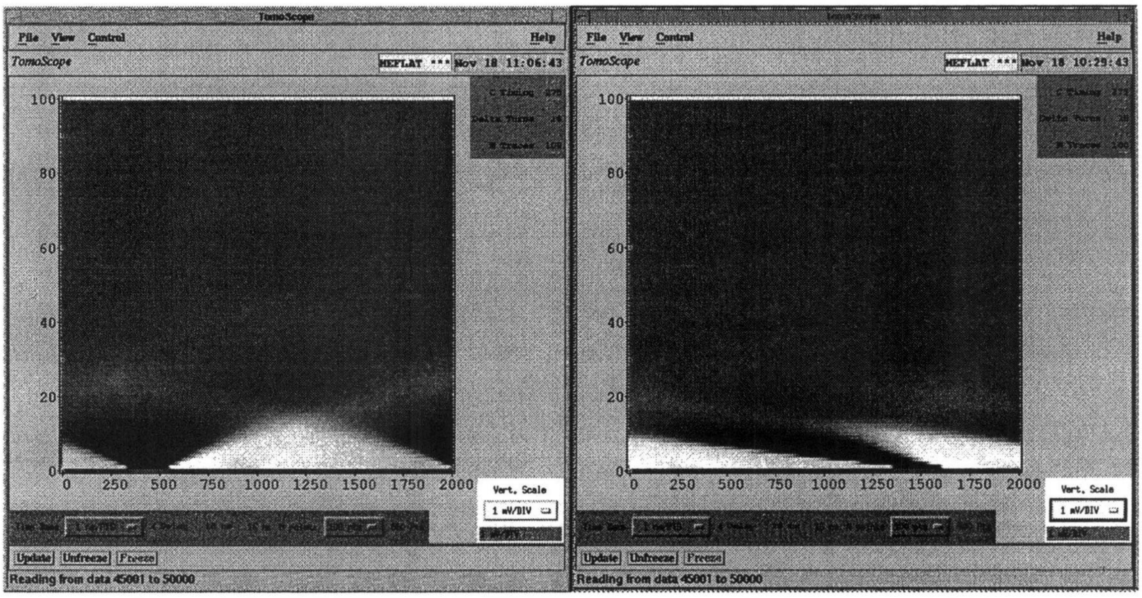

Figure 1: C16 Off, 0.1 turns injected, start @ 275 ms; left => span 2.67 ms & right => span 3.33 ms .

In the left of Figure 1, the reference RF and beam revolution frequencies have been made equal, whereas in the right figure no careful adjustment was made and so the beam slips w.r.t. the triggering of acquisition. The left figure displays "classic" debunching. This method of adjusting the reference RF by introducing partial turns was adopted, and then later an integer number of turns was introduced so as to allow the maximum possible dynamic range for the observation of "linac bubbles" and other features.

2.1 Linac "bubbles"

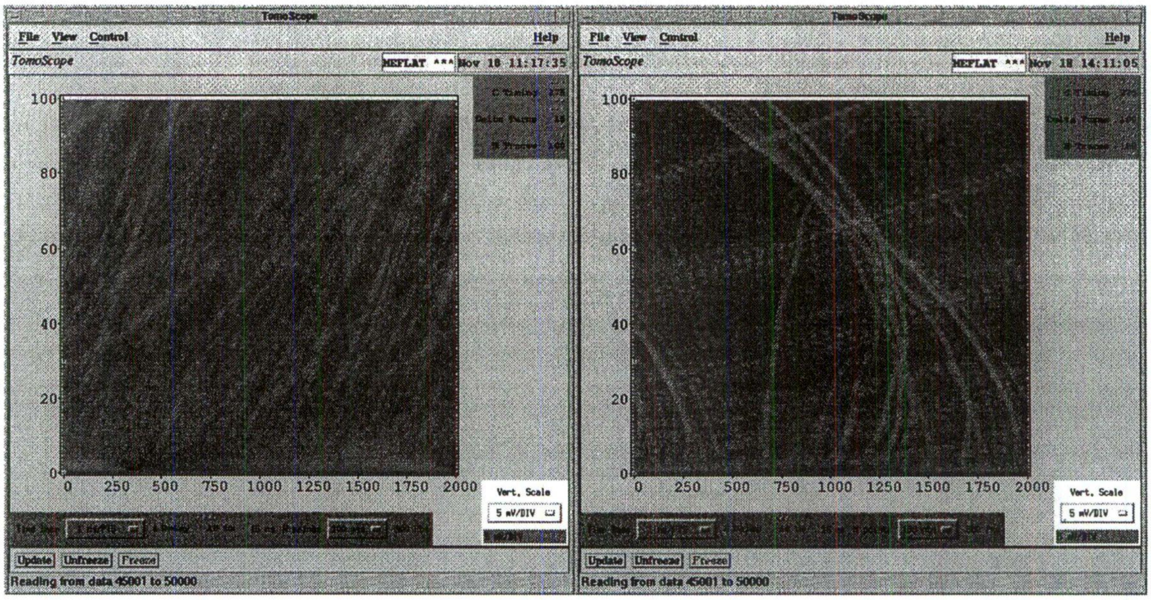

Figure 2: C16 Off, 3.0 turns injected, start @ 275 ms; left => span 2.67 ms & right => span 16.7 ms .

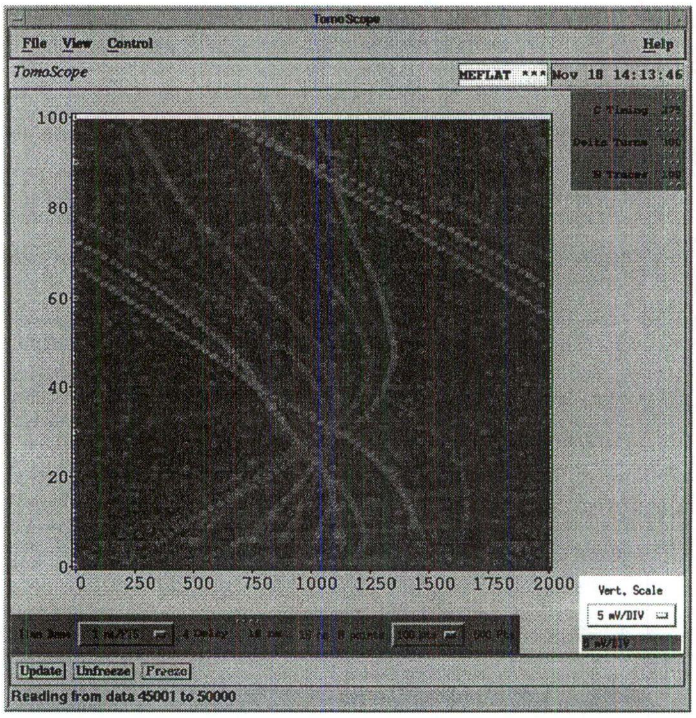

Figure 3: C16 Off, 3.0 turns injected, start @ 275 ms, span 50 ms .

Because the C16 cavity is turned off, the structure present (in the figures above) derives entirely from the linac beam and the injection process. Remarkably, these structures clearly survive for more than 50 ms. In figure 3, there is combination of several "linac bubbles". Adjusting the reference frequency for data acquisition based on the first 3 ms (Figure 1) is clearly not adequate for a 50 ms span and small frequency differences or ramps could easily generate the quasi-parabolic tracks appearing in Figure 3.

Though it is a hazardous calculation, we may by inverting the phase advance formula [$d\varphi/dt=2\pi\times\nu_{rf}\times\eta\times\gamma/(\gamma+1)\Delta T/T$] make a very rough estimate/bound for the momentum width of the linac bubbles. Because the graphical primitive is itself a circle, a problem arises in that we do not know the true RF-phase width of a bubble; but an upper bound is $\approx \pi/40$ at the fundamental. There is no detectable lengthening of the bubble in 50 ms, and so an upper bound on $d\varphi/dt \approx ½(\pi/40/50E\text{-}5) = 0.25\pi$ rad/sec. This implies $\Delta T < 5$eV, which is suspiciously small – it is 5×10^{-5} of the beam energy width!

3 C16 ON

Later, the C16 high harmonic cavity was turned on and periodic voids were deliberately introduced into the coasting beam by sweeping high-harmonic empty buckets into the beam. The relative momentum spread of these deliberately introduced holes is most probably far greater than that of the accidental "linac bubbles". These deliberately introduced holes have the advantage of having known and controllable characteristics.

The following C16 cavity program was adopted. We take harmonic number h=24, and cavity voltage 3 kV maintained for 2 ms. During this time, the fundamental frequency is swept by 2.8 kHz from outside into the beam centre giving an empty bucket deposit (GRSPOS GFA ramped through 4 volts). This procedure yields empty buckets with synchronous phase 9°, bucket length 277° @ h=24, and bucket width 0.17 MeV – assuming there are no space-charge effects. For comparison sake, the beam energy width prior to the deposit is some 0.55 MeV.

The effect upon the beam, as a function of injected intensity, is shown in Figure 4 through Figure 8. Excepting Figure 7, the figures, each composed of two panes, are arranged so that the left panes all correspond to the same short time span of 5 ms, whereas the right elements correspond to a similar long time span of ≈ 16 ms.

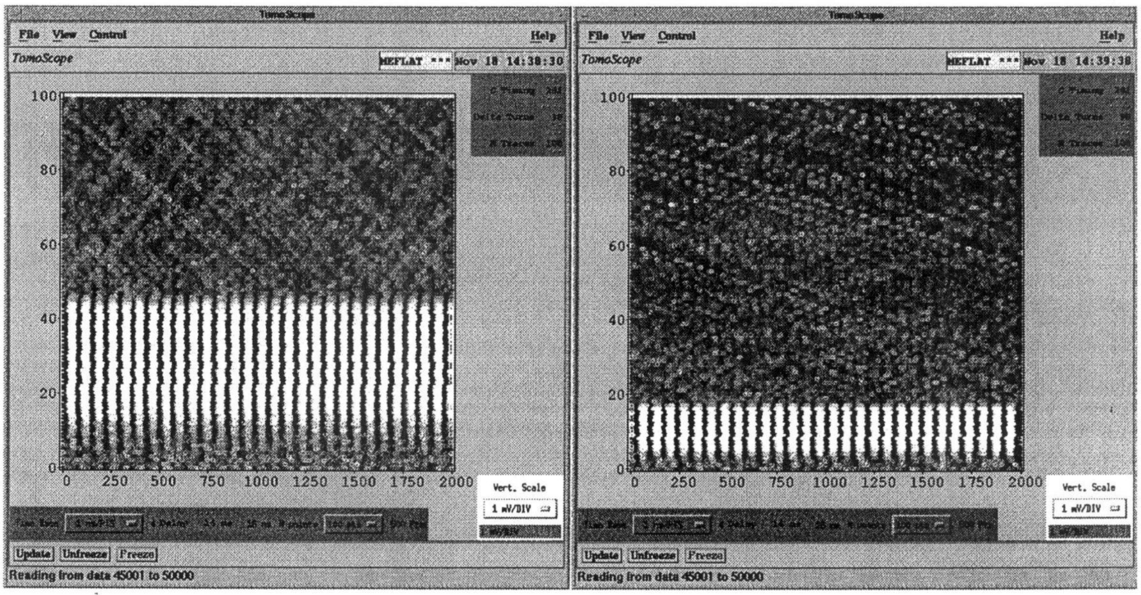

Figure 4: C16 On, 2.0 turns injected, start @ 281 ms; left => span 5 ms, right => span 15 ms .

The rate of phase advance (radian/sec) is given by $d\varphi/dt=2\pi\times\nu_{rf}\times\eta\times\gamma/(\gamma+1)\Delta T/T$ where ν_{rf} is the RF in Hz, $\eta=0.8433$ is the slip factor, $\gamma=E/(m_0c^2)$, ΔT is the kinetic energy difference and

T = 50MeV. Substituting ν_{rf} = 0.6 MHz and ΔT, the kinetic energy difference, equal to 169 keV, we find the holes should shear at a rate of $0.85\times2\pi$ radian per milli-second at h=1. Certainly in Figure 4, the h=24 periodic structure disappears very quickly – but this might also be due to lack of dynamic range because the grey scale is earlier saturated by the bucket sweep.

In Figures 5,6 and 8, the beam current is raised. The thin, vertical black lines between the white bands are regions of high particle density. When a black line does not widen, it implies that the two holes to either side of it are failing to shear – despite their momentum spread. The longevity of the black lines is noticeable in the left-hand panes of the figures below which should be compared against the low intensity case, Figure 4.

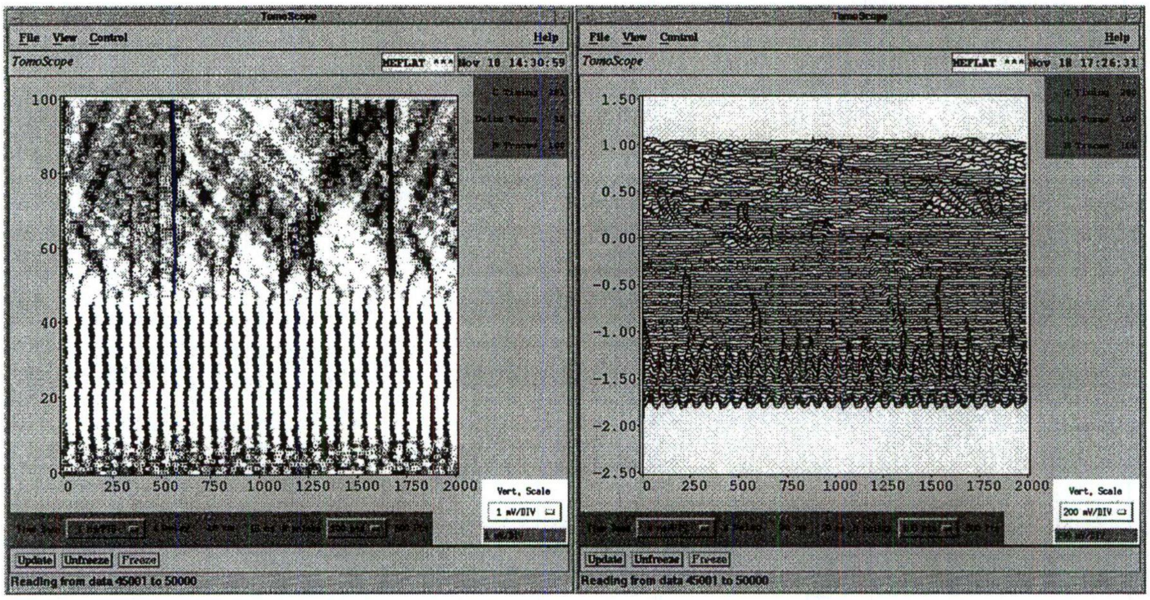

Figure 5: C16 On, 5.0 turns injected, start @ 281 ms; left => span 5 ms, right => span 16.7 ms .

In Figure 5 onward, the beam current was raised without changing the input range of the digital oscilloscope. This has the effect of saturating the scope, and this is particularly evident in the right-hand panels of Figure 6 through Figure 8 where mesa-like structures appear. It must be remembered, that these "mesas" are in fact the truncated remains of features like that sketched in Figure 9. The right hand pane of Figure 6 has compelling evidence for two phenomena: first, at early times, high harmonic holes merge to form swaths; second, at later times, the swaths flow over one another in a manner that suggests intimate coalescing of holes does not occur.

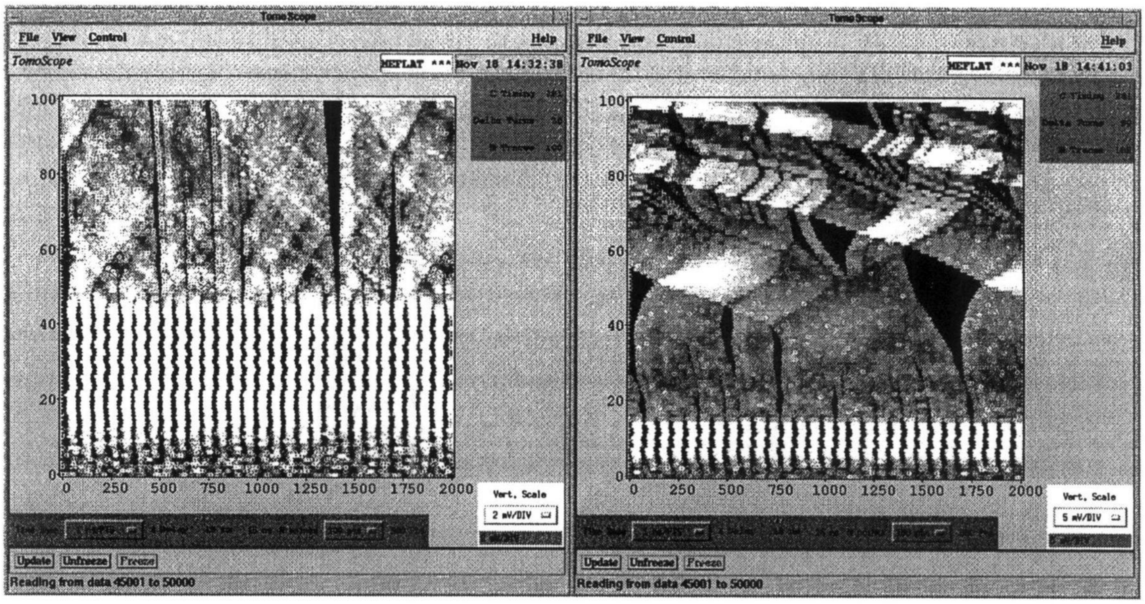

Figure 6: C16 On, 6.0 turns injected, start @ 281 ms; left=> span 5 ms, right=> span 15 ms .

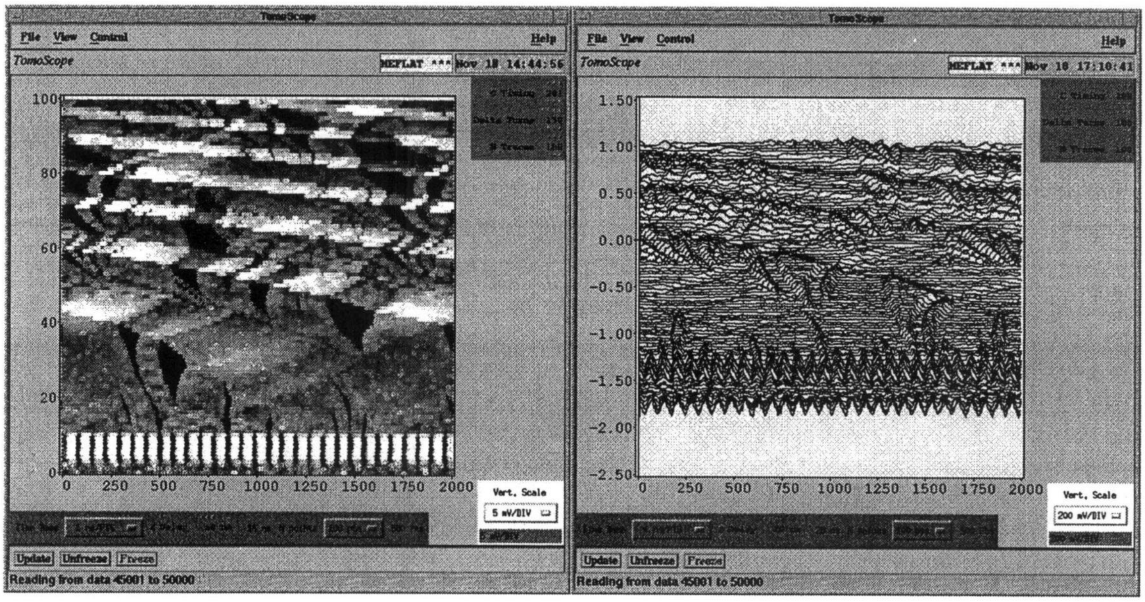

Figure 7: C16 On, 6.0 turns injected, start @ 281 ms; left => span 21.7 ms, right => span 16.7 ms.

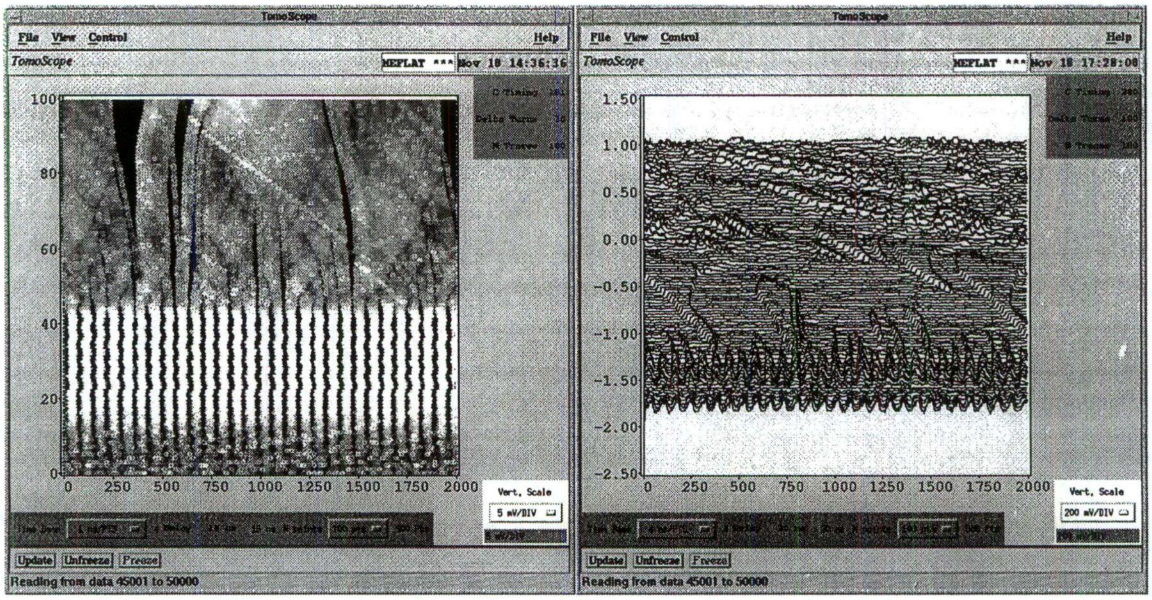

Figure 8: C16 On, 7.0 turns injected, start @ 281 ms, left => span 5 ms, right => span 16.7 ms .

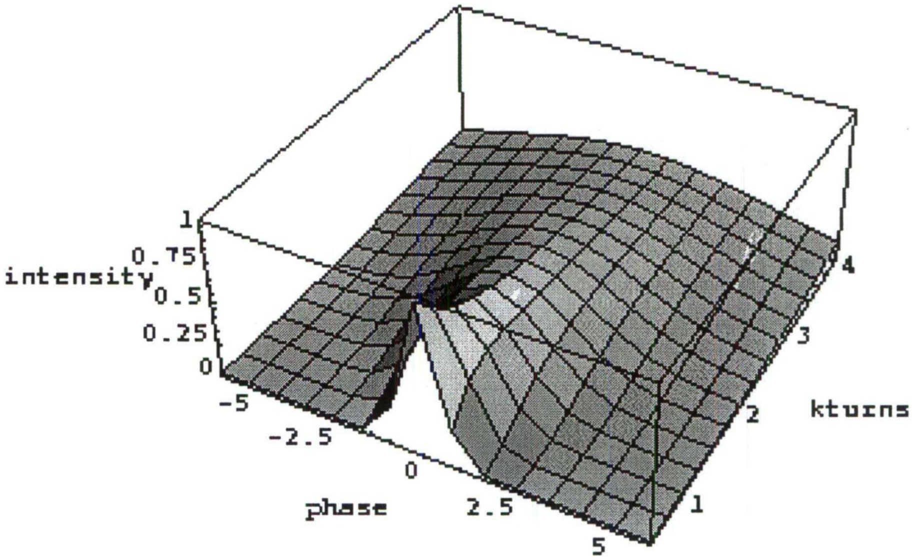

Figure 9: debunching of local peak density. .

Over the longer time span, there are complicated effects. For example, there is evidence in Figure 8 that several holes combine into swaths of low particle density, but there is also evidence in Figure 6 of individual holes surviving out to 15 ms and beyond. In Figure 8, a "linac bubble" crosses the screen diagonally, which implies that its momentum is rather different from that of the holes; and this offers an explanation of why it does not collide with the swath of holes.

Toward the end of the time span, there are bizarre "echo effects" which though most probably the result of space charge, filamentation, and the saturation of the scope, could (it must be admitted) be due to a coasting beam instability.

4 Conclusion

Injection bubbles can survive for at least 50 ms in the injected coasting beam. In part, this can be ascribed to their having a very small momentum width; but this cannot be the complete explanation. At some point the momentum width becomes so small that the bubbles would have no appreciable effect on the line density. It is tempting to assign "space charge" as the cause of linac bubble longevity.

Injected beam intensity has a marked effect on the evolution of high harmonic holes, but the phenomena are hard to interpret without a strong theoretical model as guide; and saturation of the display makes this even more difficult. Nevertheless, debunching of density modulations does appear to be delayed somewhat by increased beam current.

Realizing the possible deficiencies of the "tomoscope" (bad choice of graphic primitive, and need for careful adjustment of acquisition RF), these were made good in the measurements performed in the 24th November MD.