Short Bunch Production Near Transition

Microwave Instability near Transition

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June 30, 1999

For the muon collider proton driver, bunching to $\sigma \lesssim 2$ns is desirable.

Reasons.

1. Only piece of information transmitted to the π's and μ's. Thus less cooling will be required if the proton bunch hitting the target is as narrow as possible.

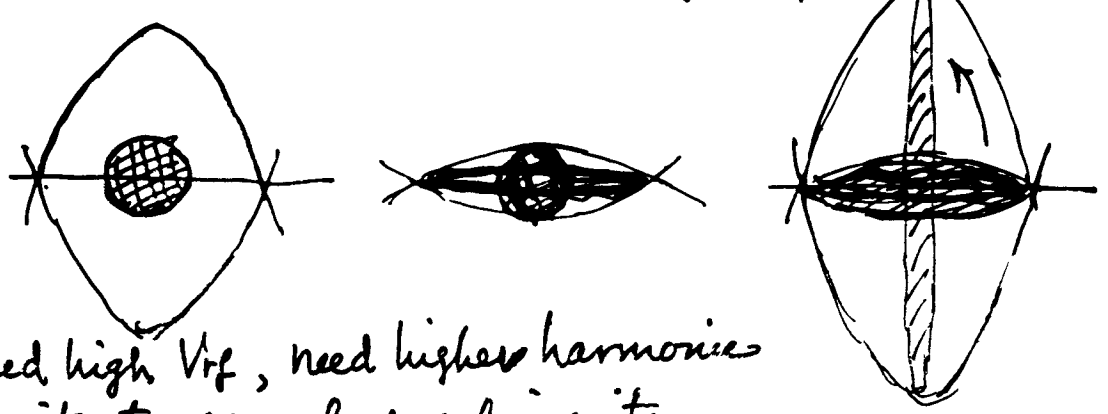
2. polarized μ states are easier to separate.

How to make short & intense bunches at low energy?

1. Adiabatic spreading of bunch followed by raising V_{rf} & bunch rotation.

   There may be microwave instability during the slow spreading

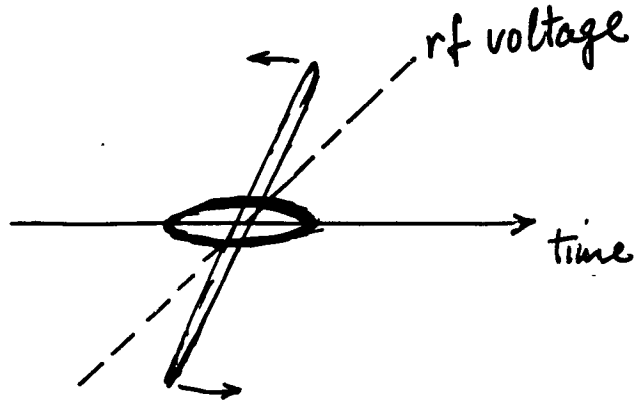
   Can do this fast by snapping V_{rf}



need high V_{rf}, need higher harmonics cavity to cancel nonlinearity.

2. Rebunching at higher rf frequency
need high frequency & high voltage cavities

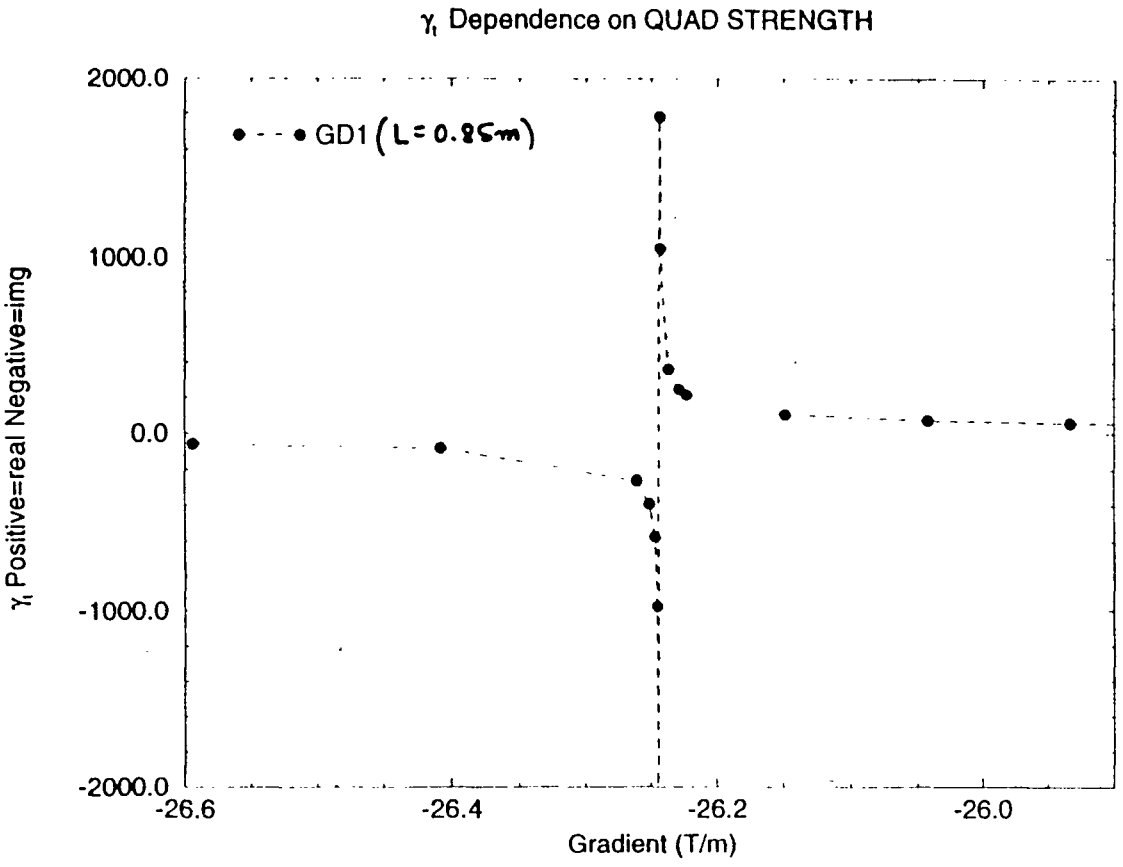
3. Energy accumulation near transition, followed by a partial rf rotation. (idea of Jim Norem)



However, we do not need to operate the ring near transition all the time. With FMC lattice, we can move close to transition only near extraction when the production of short bunches is required.

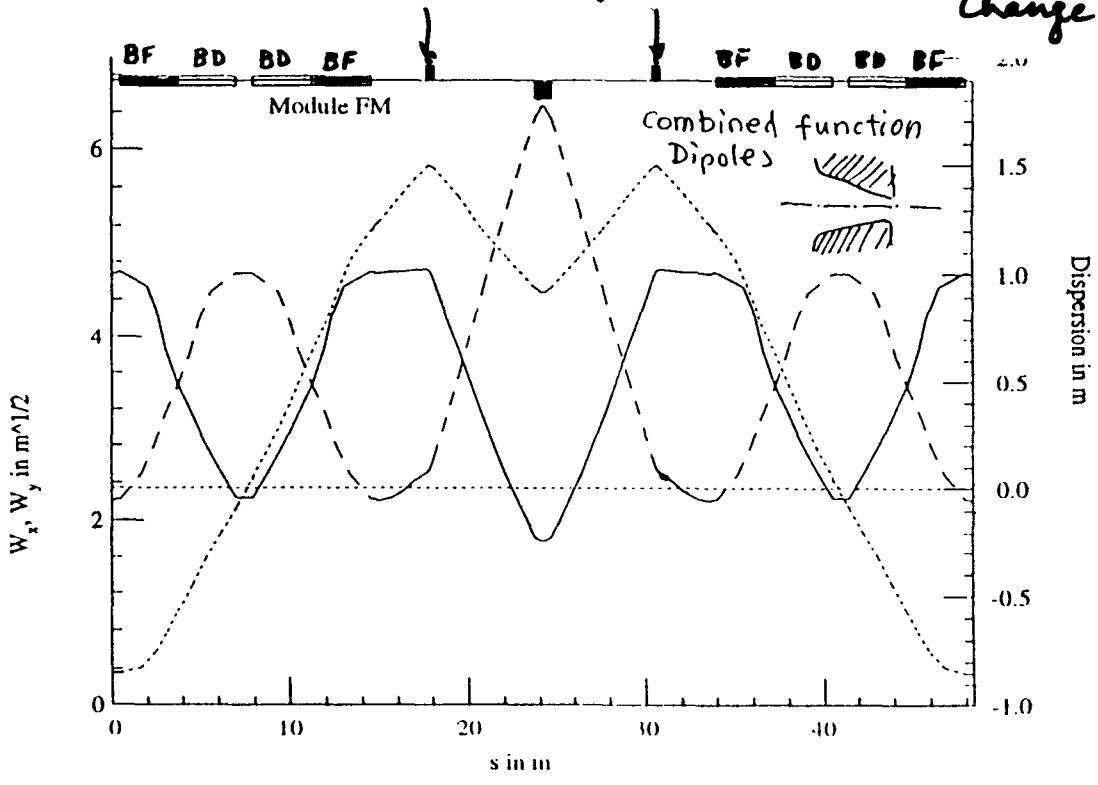
The merit of this method is that no additional hardwares, such as harmonic cavities, are required.

Trbojevic & Ng PAC 9



FMC Lattices can move γ_t easily and, presumably, quickly.

vary the gradient of these 2 quads will change γ_t



Dispersion max/min: 1.49327/-0.85000m,

β_x max/min: 22.22/ 3.12487m, ν_x: 19.90411, ξ_x: -24.32,

β_y max/min: 41.86/ 4.88857m, ν_y: 19.07570, ξ_y: -28.04,

γ_t: (60.23, 0.00)

Module length: 1163.8806m

Total bend angle: 6.28318548 rad

Trbojevic '90

The experiment was performed at BNL AGS in 1997.
Expt. E 932

Bunching Near Transition in the AGS

C. Ankenbrandt, K-Y. Ng, J. Norem,
M. Popovic, Z. Qian
FNAL

L. A. Ahrens, M. Brennan, V. Mane,
T. Roser, D. Trbojevic, W. van Asselt
BNL

Phys. Rev. ST Accel Beams
030101 (1998)

BNL, 6/99

Operating Mode of the AGS

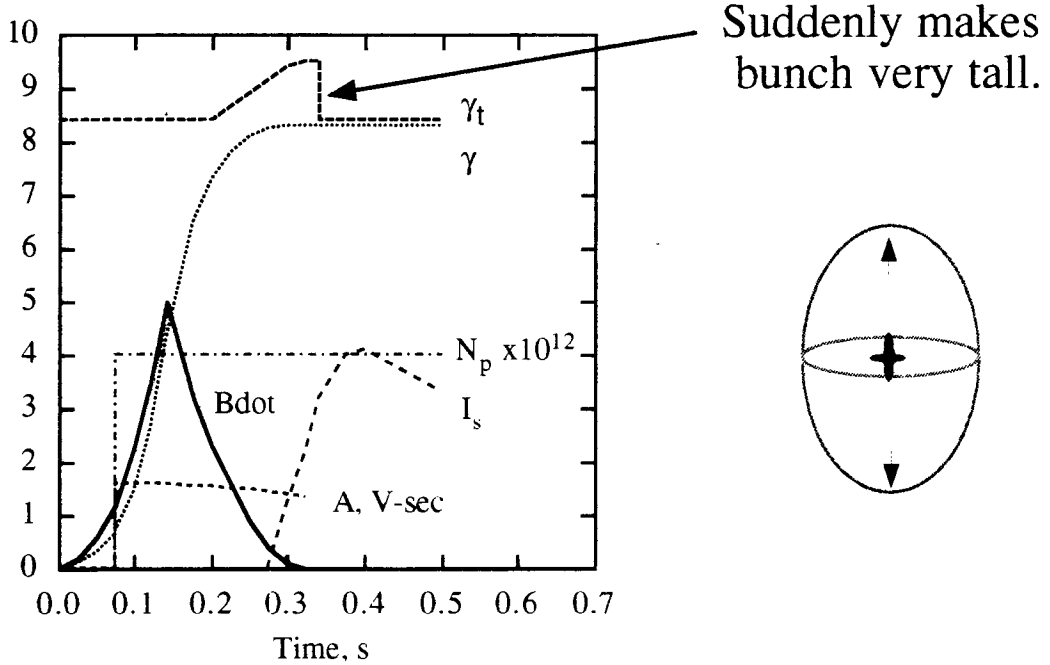
$n_p \sim 4 \times 10^{12}$ /bunch

$-0.05 < \gamma_t - \gamma < 0.05$

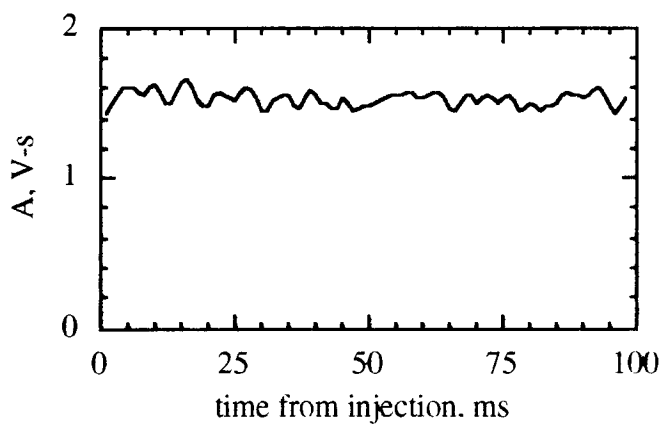
$E \sim 7$ GeV

$A \sim 1.5$ eV/s

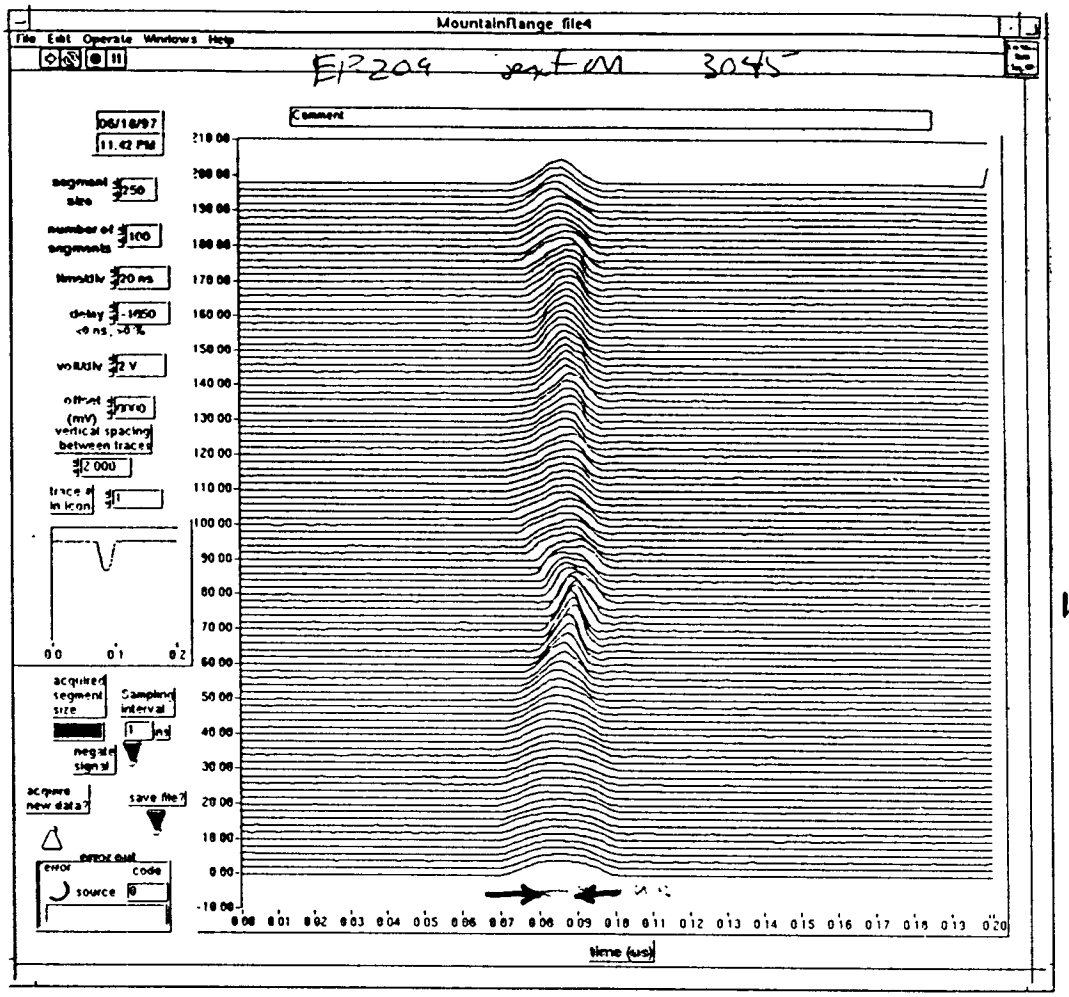
Machine parameters:



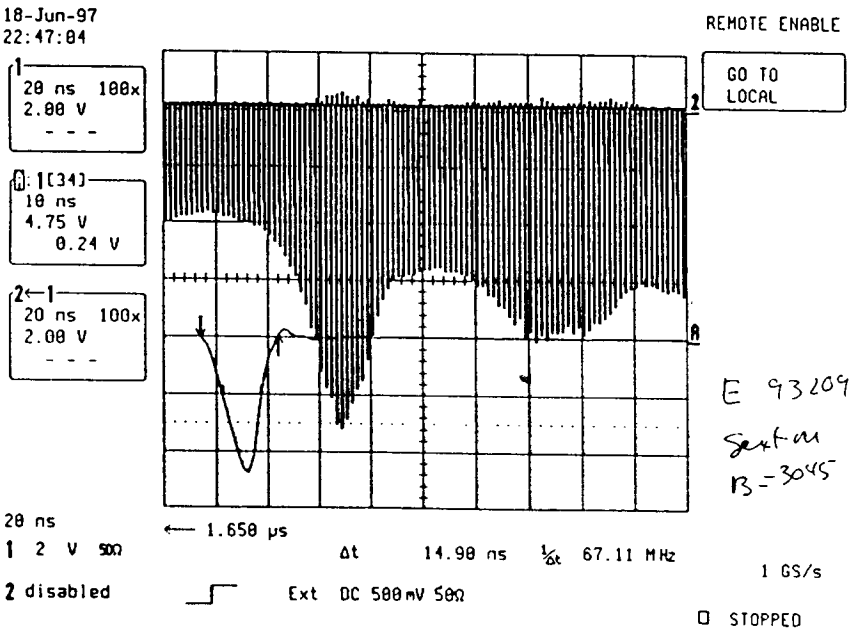
Bunch area measurements:

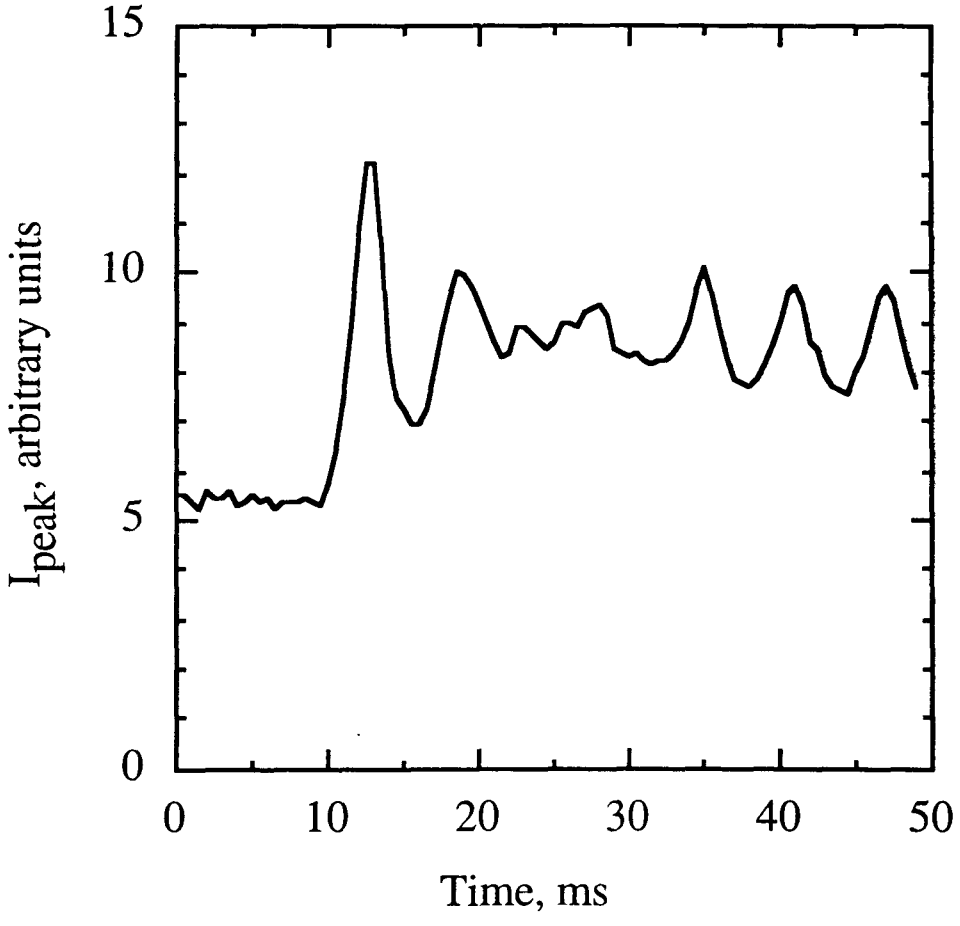


1. Beam cannot be too close to γ_t, otherwise the final rotation will take very long.
2. Beam cannot be too far from γ_t, otherwise the bucket will not be tall enough to produce a tall but narrow bunch.


MountainRange file4
File Edit Operate Windows Help
EP209 sext M 3045
Comment
06/18/97
11:42 PM
segment size 250
number of segments 100
time/div 20 ns
delay -1650
volt/div 2 V
offset (mV)
vertical spacing between traces
2.000
trace # in icon
acquired segment size
Sampling interval
negate signal
acquire new data?
save file?
error out
error
code
source
time (us)
10m

10ns


18-Jun-97
22:47:04
REMOTE ENABLE
GO TO LOCAL
20 ns 100x
2.00 V
10 ns
4.75 V
0.24 V
20 ns 100x
2.00 V
20 ns
1 2 V 50Ω
2 disabled
← 1.650 μs
Δt 14.90 ns 1/Δt 67.11 MHz
Ext DC 500mV 50Ω
1 GS/s
STOPPED
E 93209
Sext M
B-3045


15
10
5
0
0
10
20
30
40
50
Time, ms
I_{peak}, arbitrary units

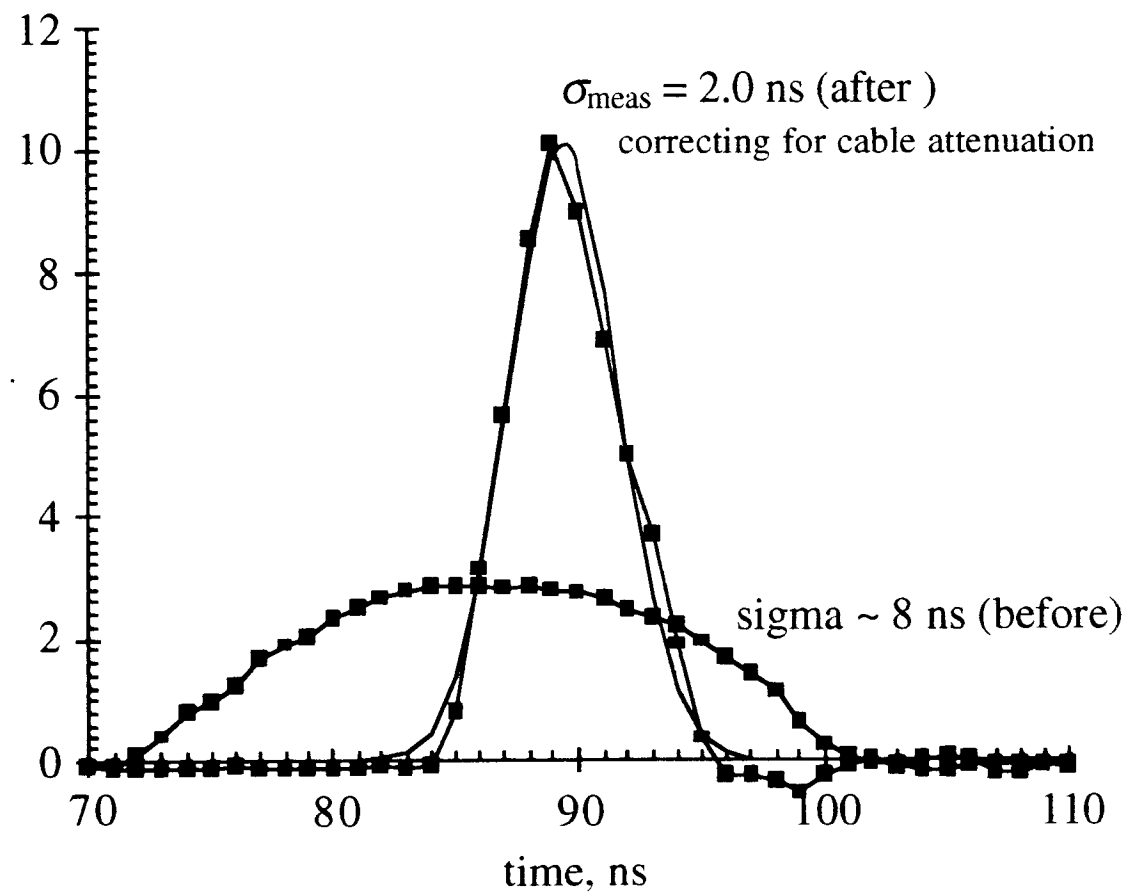
Bunching has been Demonstrated at the AGS

Bunching of the proton beam to $\sigma \sim 2$ ns is desirable because:

- Less cooling is required if the initial proton / pion / muon bunch is as small as possible.
- Polarization states are easier to separate by bunch rotation if the bunch is short.

The bunch rotation was done by dropping γ_t to the beam γ.

- $\varepsilon_{L,\ AGS} \sim \varepsilon_{\mu\ \text{collider driver}}$, charge ~ 1/10 required
- 2 ns at 3 MHz $\Rightarrow$ ~1 ns at 7 MHz
- Other options and better tuning are possible
- short bunches were stable



Comments

1. Nonlinear dispersion

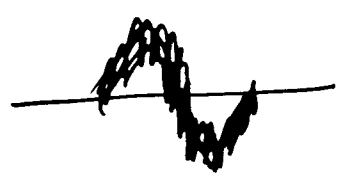
$$\eta(\delta) = \eta_0 + \frac{1}{\gamma^2}\left(\alpha_1 + \frac{3\beta}{2}\right)\delta + O(\delta^2)$$

$$\eta_0 \rightarrow \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$

So the bunch will shear nonlinearly

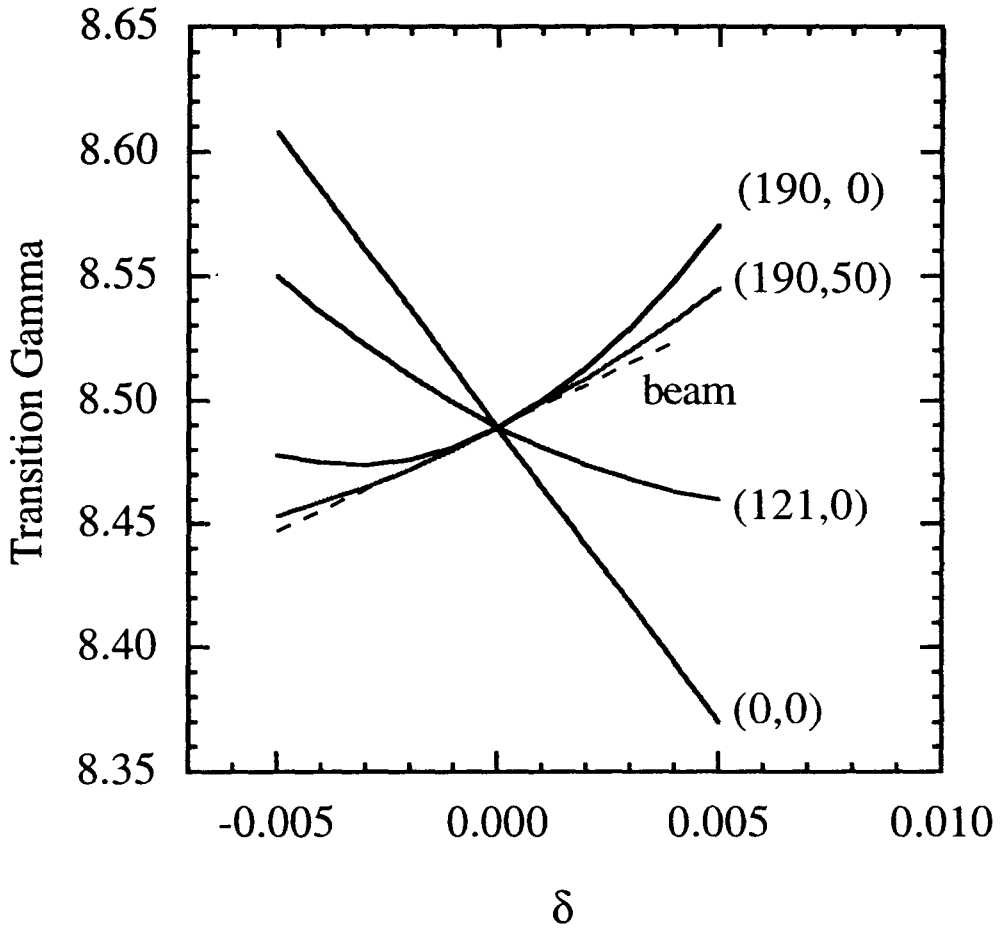
thus the bunch will become wider (can correct α_1 to $-\frac{3}{2}$ by sextupoles)

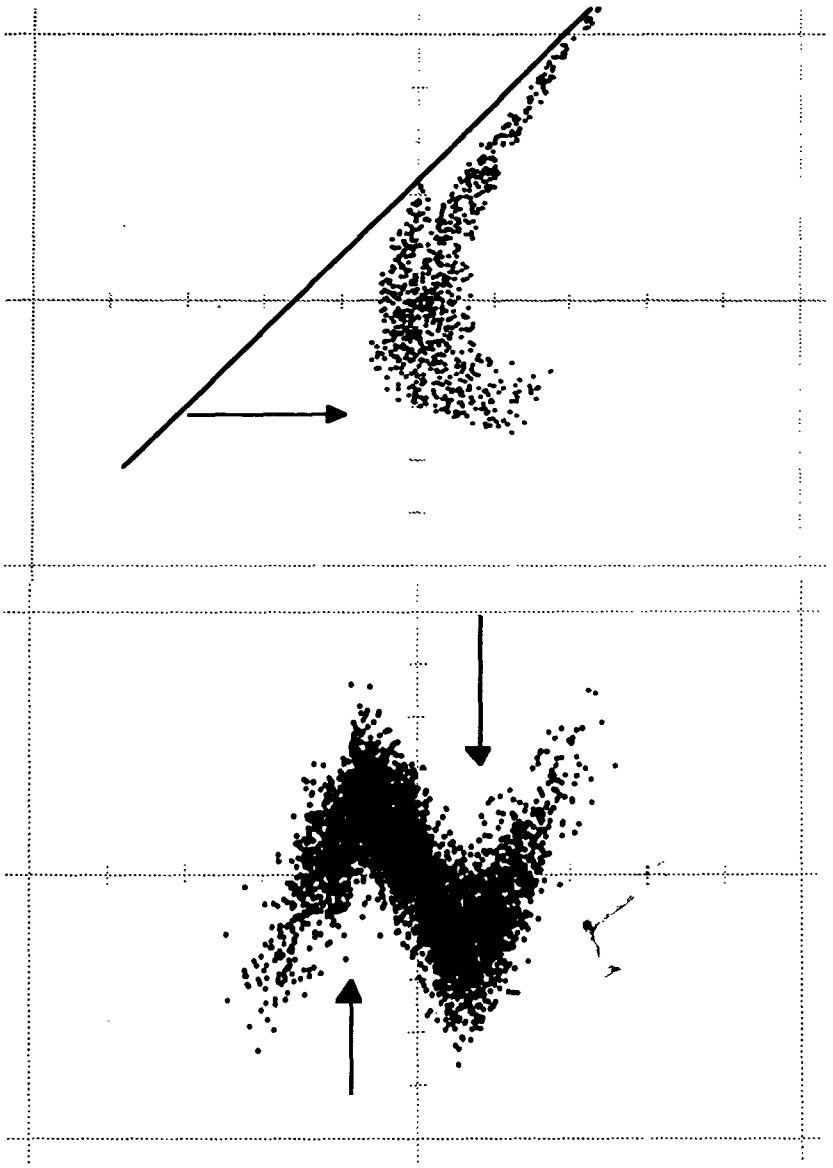
2. Space charge effect $\Longrightarrow$ bunch shape becomes



- if too close to γ_t
- can compensate by rf.

3. No beam instability observed


8.65
8.60
8.55
8.50
8.45
8.40
8.35
Transition Gamma
(190, 0)
(190,50)
beam
(121,0)
(0,0)
-0.005
0.000
0.005
0.010
δ



The plots span a phase space area of ± 100 MeV and ± 40 ns.

Microwave Instability near transition

Since $\eta(\delta) = \eta_0 + \underbrace{\frac{1}{\gamma^2}\left(\alpha_1 + \frac{3\beta}{2}\right)}_{\eta_1}\delta + O(\delta^2)$

the η_1 term must be included for meaningful discussion.

Alex Bogacz did that in PAC'91, but with $\eta_0 = 0$

result for Gaussian distribution in energy (coasting beam)

growth rate: $\frac{1}{\tau_n} = -2\alpha_1 n\omega_0\left(\frac{\sigma_E}{E}\right)^2 \tan^{-1}\frac{\mathrm{Im}\,Z_n}{\mathrm{Re}\,Z_n}$

$\mathrm{Im}\,Z_n > 0 \Rightarrow$ capacitive

$\therefore$ assuming $\alpha_1 > 0$ $\quad \frac{\mathrm{Im}\,Z_n}{\mathrm{Re}\,Z_n} > 0 \Longrightarrow$ stable

$\eta_0 = 0 \quad \alpha_1 > 0 \Rightarrow$ above transition

But stable above transition & capacitive impedance is something strange.

Jim Holt & Pat Colestock studied the same problem with $\eta_0 \neq 0$ but including η_1 PAC'95

Also with coasting beam & Gaussian energy distribution, they get dispersion relation in terms of complex error fcn. Their conclusion:

below transition: no unstable region in Re Z - Im Z plan

above transition: there are both stable & unstable region

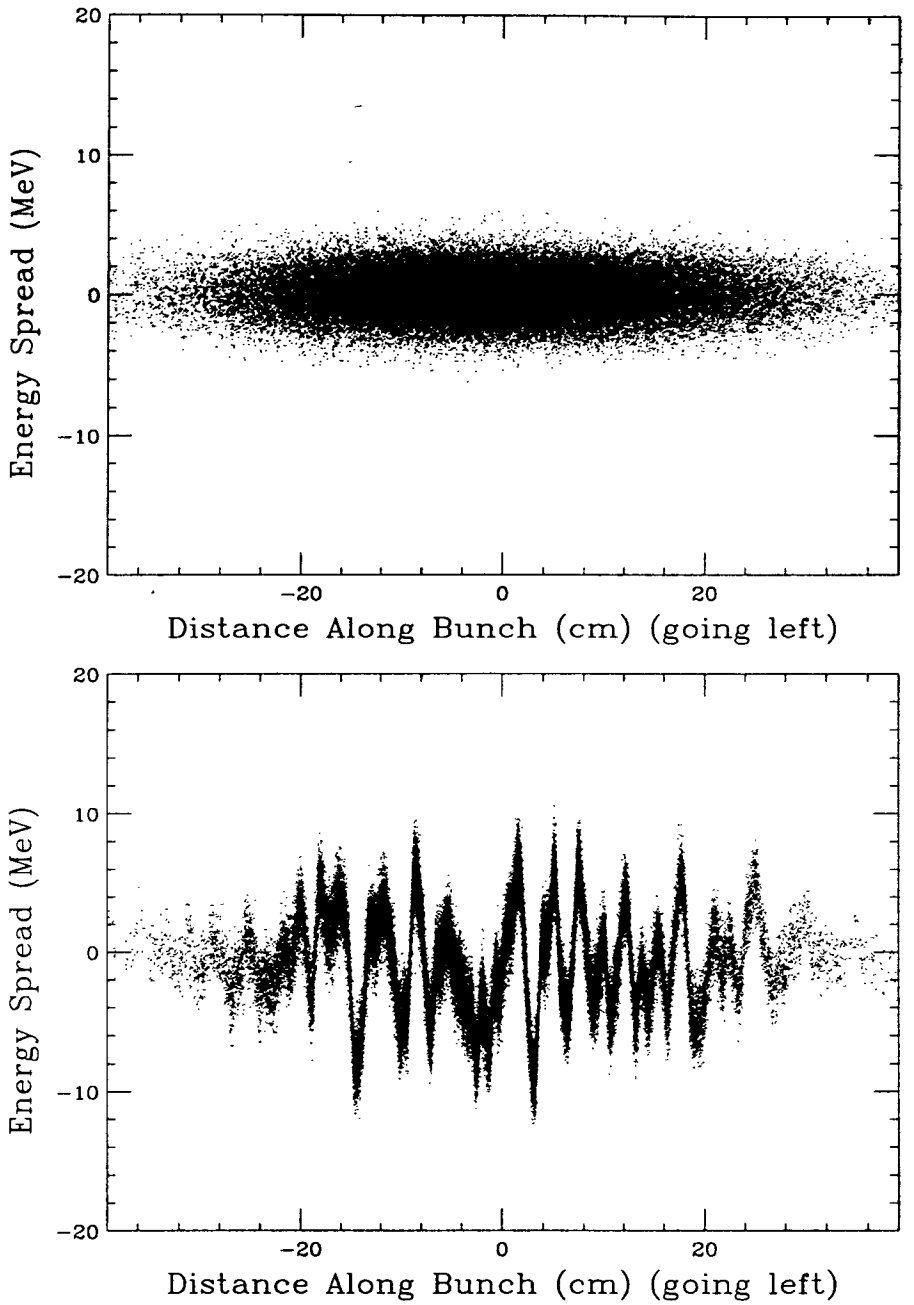
They had simulations to support their claim

However, they did not specify the values of η_0 & η_1 and others in their plots & simulations

It is hard for me to understand the situation below transition. According to their claim, there is no microwave instability at all below transition.

Notice that if $|\eta_0|$ is not too small, η_1 is irrelevant.

At least my own simulations show different results.



μ bunch at 50 GeV

$\sigma_\ell = 13$ cm

$\sigma_E = 1.5$ MeV

$(\sigma_\delta = 3\times10^{-5})$

Intensity $4\times10^{+12}$

$\eta = -1\times10^{-6}$

FIG. 5. Simulation of the 13-cm bunch of 4×10^{12} muons subject to a broad-band impedance with quality factor $Q = 1$ and $Z_{\|}/n = 0.5\ \Omega$ at the resonant angular frequency $\omega_r = 50$ GHz. The half-triangular bin width is 15 ps (0.45 cm) and 2×10^6 macro-particles are used. Top plot shows initial distribution with $\sigma_E = 1.5$ MeV and $\sigma_\ell = 13$ cm. Lower plot shows distribution after 1000 turns with compensating rf's initially at $\omega_1/(2\pi) = 0.3854$ GHz and $\omega_2/(2\pi) = 0.7966$ GHz, voltages $V_1 = 65.40$ kV and $V_2 = 24.74$ kV, and phases $\varphi_1 = 177.20°$ and $\varphi_2 = 174.28°$. The rf voltages decrease according to the decay of the muons.

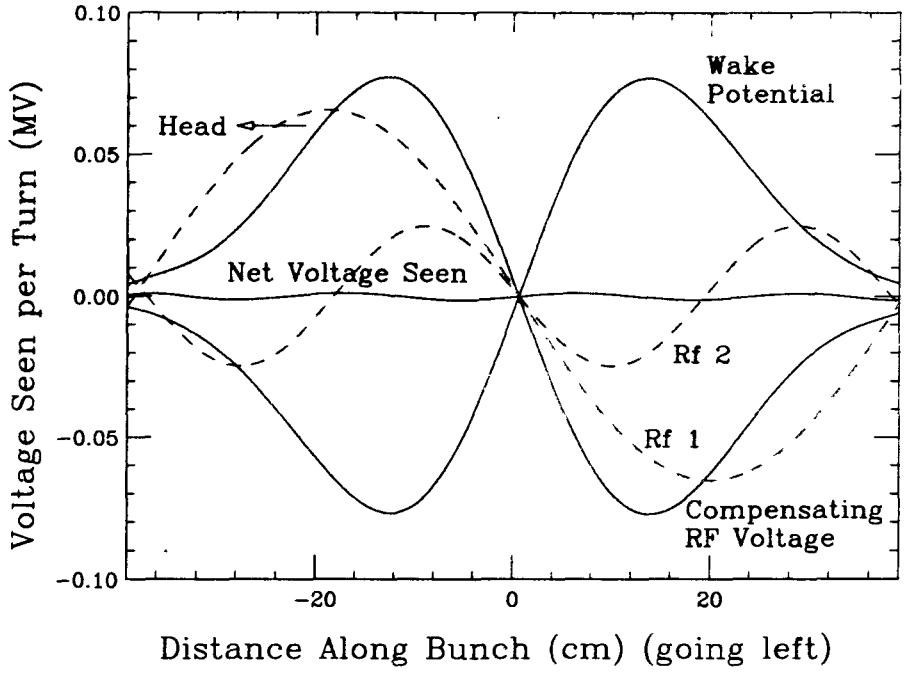


FIG. 4. Wake potential, compensating rf voltages, and net voltage seen by particles in the 13-cm bunch at injection. The compensating rf is the sum of two rf's represented by red and magenta dashes.

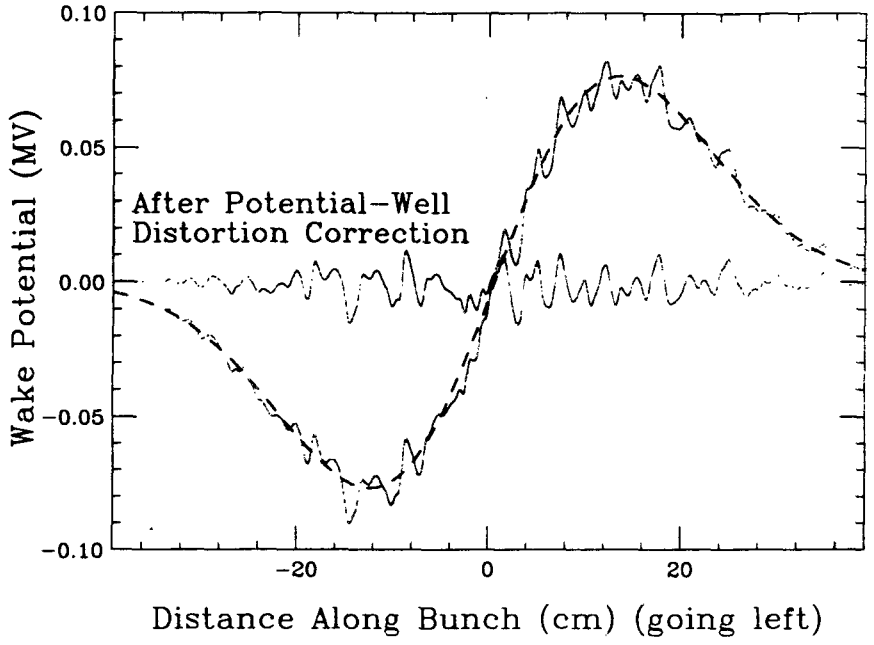
μ bunch at 50 GeV, $\sigma_\ell = 13$ cm. $\sigma_E = 1.5$ MeV $(\sigma_\delta = 3\times10^{-5})$

Broad band impedance $Q = 1$ $\frac{Z}{n} = 0.5\,\Omega$

$f_r \sim \frac{50}{2\pi} = 7.96$ GHz

$\eta = 10^{-6}$

Keil Schnell limit: $\frac{Z}{n} \sim 10^{-7}\,\Omega$



in 4000 turns including decay of muons, about 880 times

∴ Max-Min ~ 24 MV

FIG. 6. Wake potential seen by the simulated bunch is shown by the red curve, which differs slightly from the wake potential of an ideal smooth Gaussian bunch shown in blue dashes. The difference shown by the magenta solid curve represents the random fluctuation of the finite number of macro-particles.

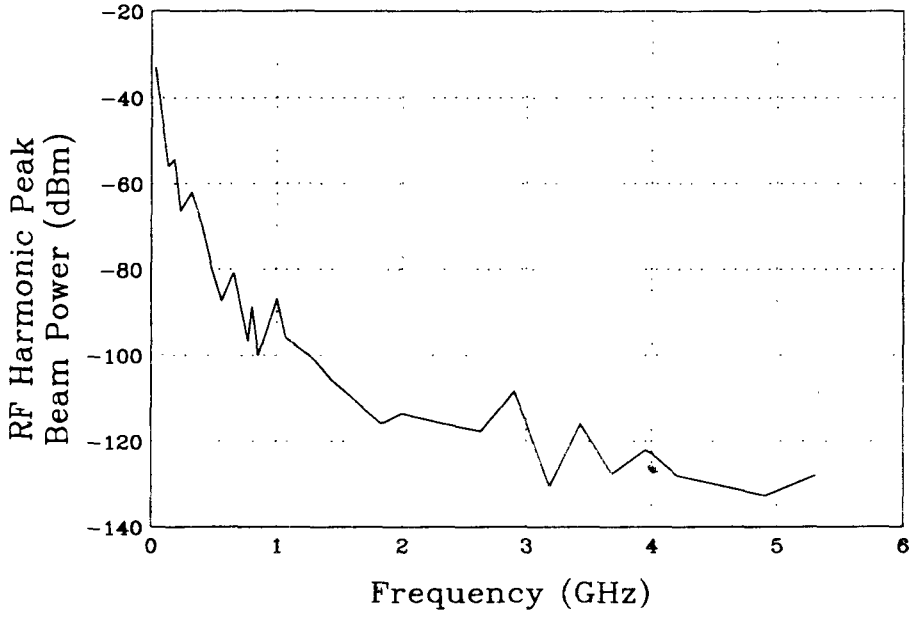
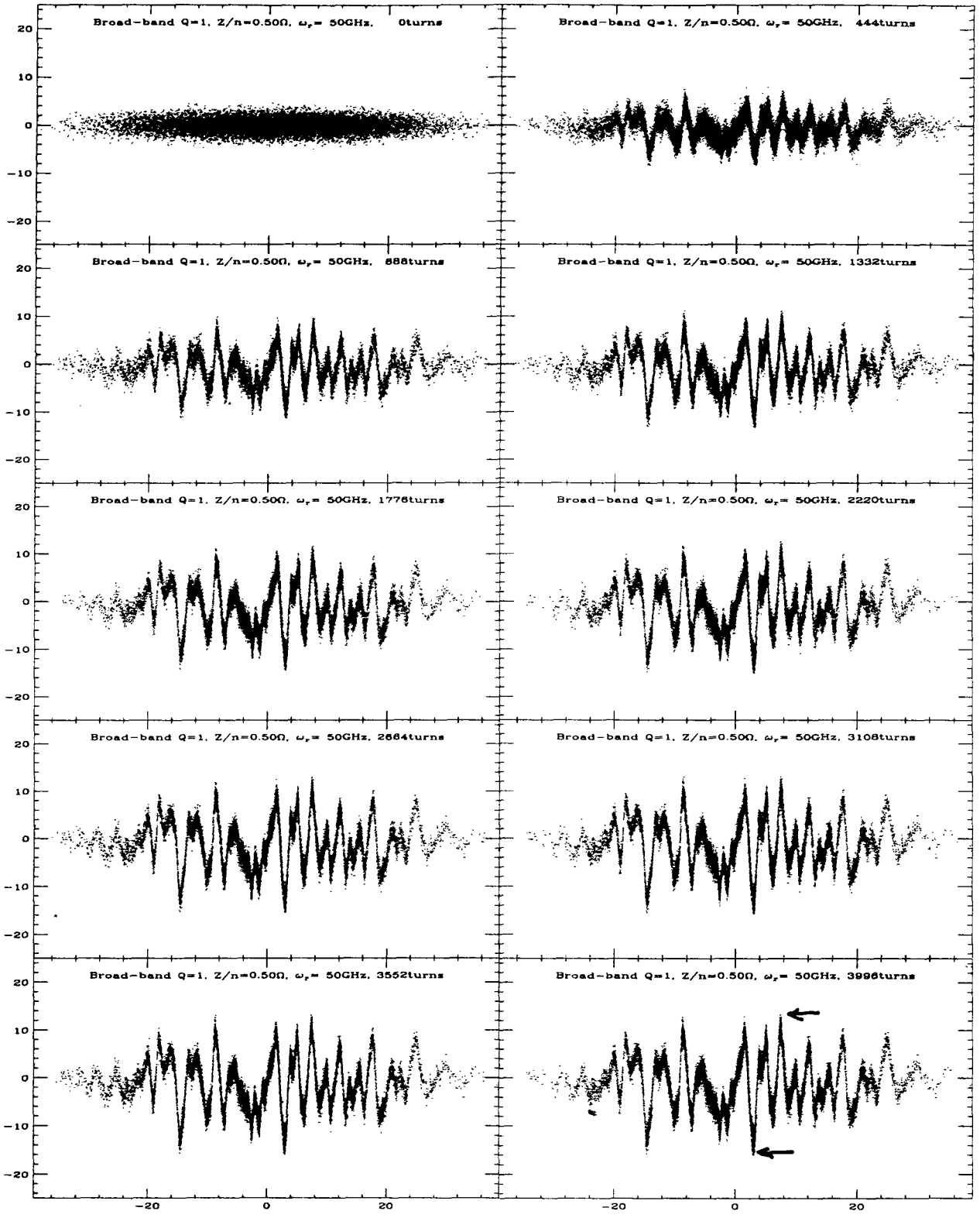
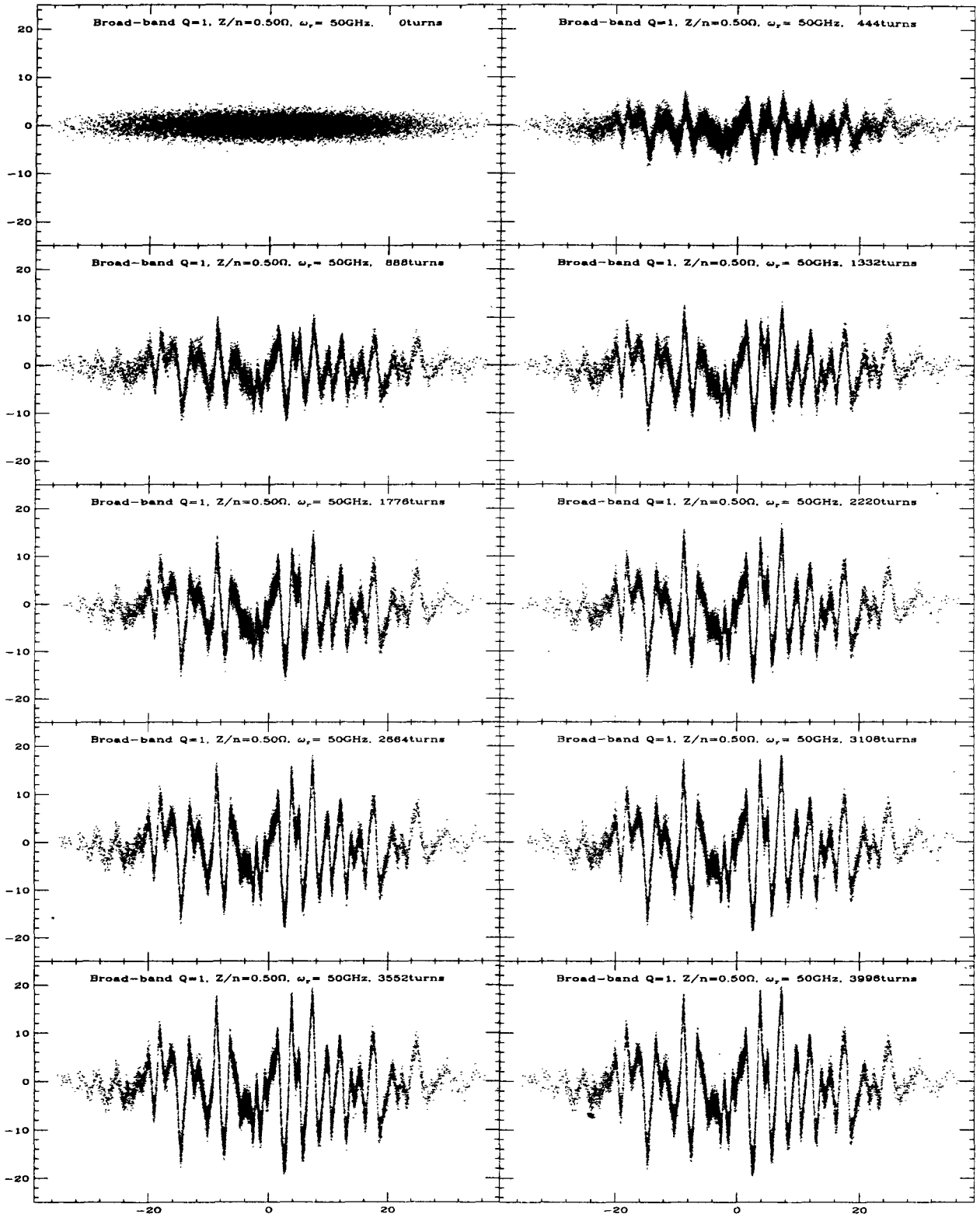


FIG. 7. Beam current power spectrum of the Tevatron, measured at each harmonic of the RF frequency.



Energy offset in MeV vs distance in cm, $E = 50$ GeV with $\sigma_E = 1.5$ MeV, $\sigma_\ell = 13$ cm. $\eta = -1 \times 10^{-10}$, 4×10^{12} particles (2×10^6 macro), half-triangle width 15 ps. Compensating rf's: 65.341, 24.645 kV, $\omega = 2421.83773$, 5005.13131 MHz, $\phi = 178.60214°, 177.15095°$. Decay of muons has been included, 4000 turns, File: 50ghz-5-13-decay-eta-10-4000turns-2e6.

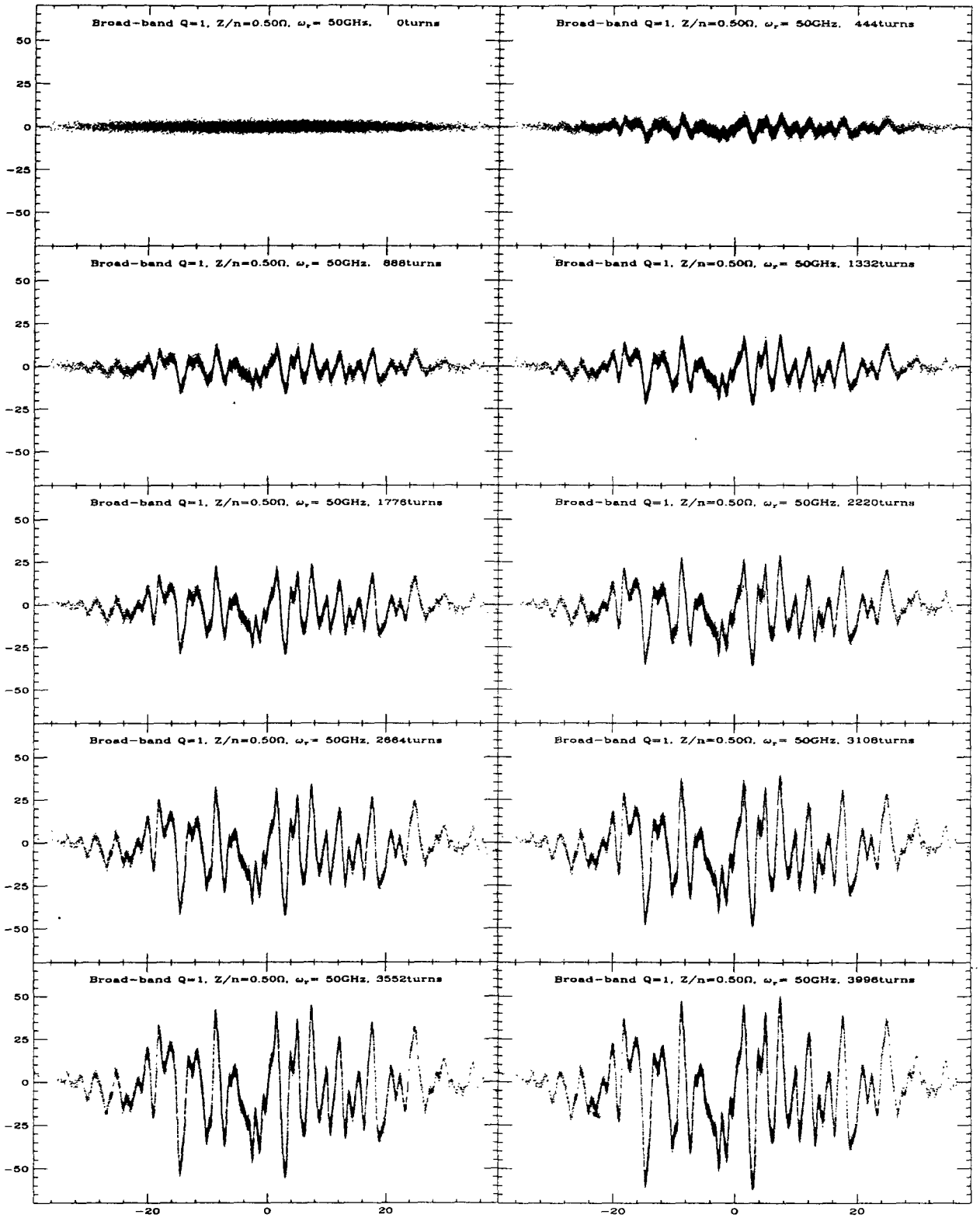
$\eta = -1 \times 10^{-6}$



Energy offset in MeV vs distance in cm, $E = 50$ GeV with $\sigma_E = 1.5$ MeV, $\sigma_\ell = 13$ cm. $\eta = +1 \times 10^{-6}$, 4×10^{12} particles (2×10^6 macro), half-triangle width 15 ps. Compensating rf's: 65.341, 24.645 kV, $\omega = 2421.83773$, 5005.13131 MHz, $\phi = 178.60214°$,177.15095°. Decay of muons has been included, 4000 turns, File: 50ghz-5-13-decay+eta-6-4000turns-2e6.

Shows μwave growth

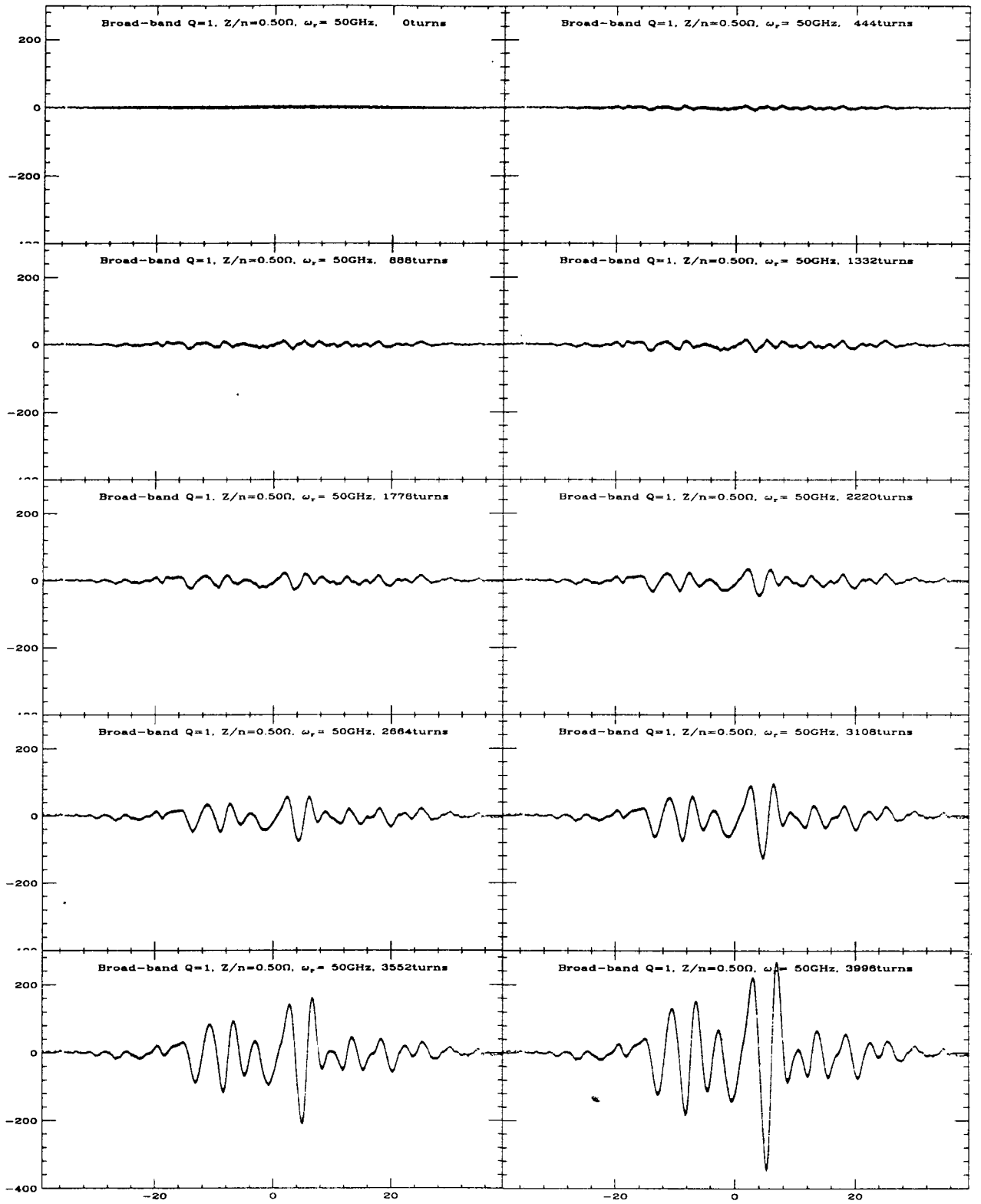
$\eta = +1 \times 10^{-6}$



Energy offset in MeV vs distance in cm, $E = 50$ GeV with $\sigma_E = 1.5$ MeV, $\sigma_\ell = 13$ cm. $\eta = -1 \times 10^{-14}$, 4×10^{12} particles (2×10^6 macro), half-triangle width 15 ps. Compensating rf's: 65.341, 24.645 kV, $\omega = 2421.83773$, 5005.13131 MHz, $\phi = 178.60214°$,177.15095°. Decay of muons has NOT been included, 4000 turns, File: 50ghz-5-13-nodecay-eta-14-4000turns-2e6.

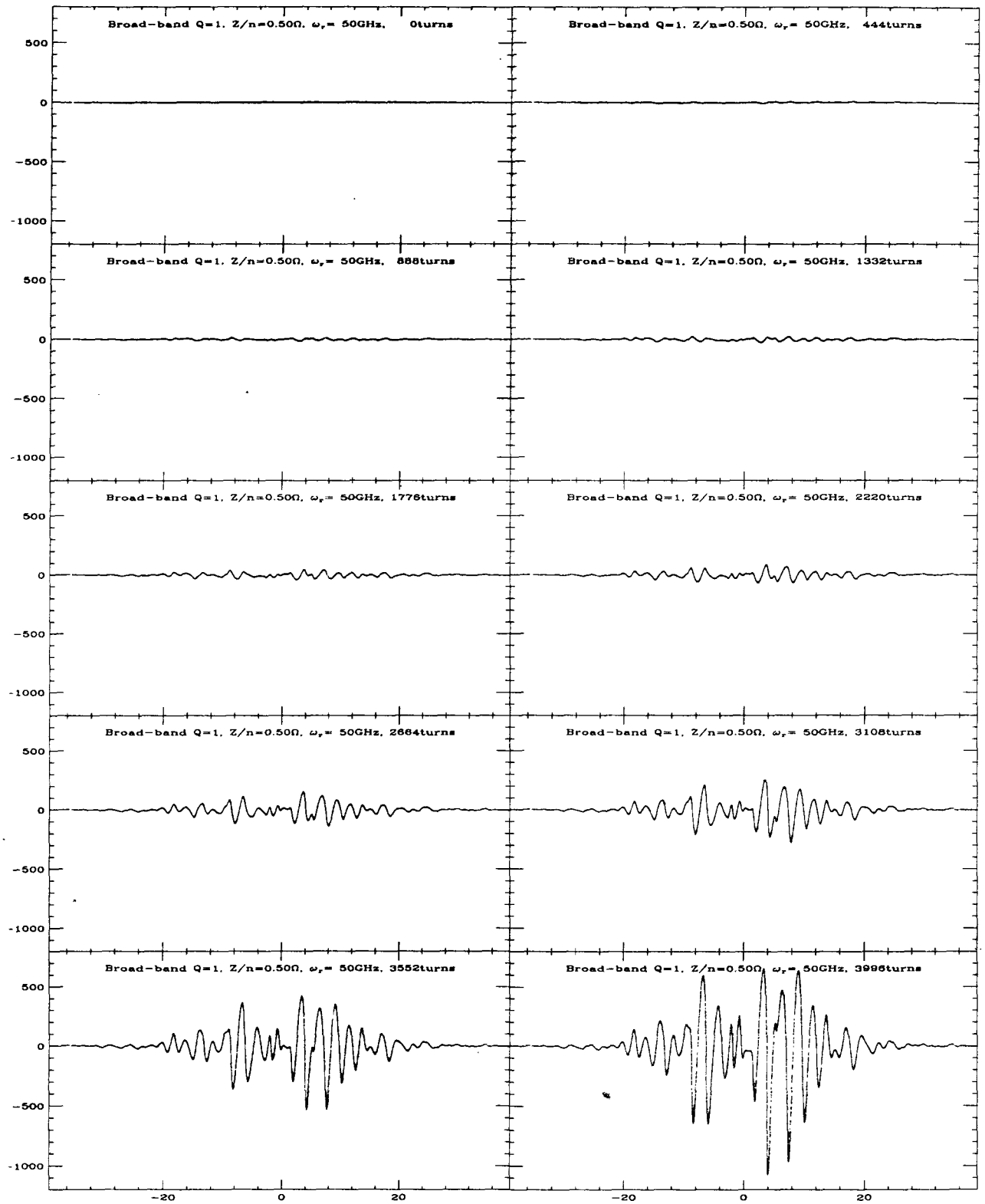
$\eta \sim 1 \times 10^{-14}$ almost zero

$\therefore$ no μwave effect



Energy offset in MeV vs distance in cm, $E = 50$ GeV with $\sigma_E = 1.5$ MeV, $\sigma_\ell = 13$ cm. $\eta = -1 \times 10^{-6}$, 4×10^{12} particles (2×10^6 macro), half-triangle width 15 ps. Compensating rf's: 65.341, 24.645 kV, $\omega = 2421.83773$, 5005.13131 MHz, $\phi = 178.60214°$,177.15095°. Decay of muons has NOT been included, 4000 turns, File: 50ghz-5-13-nodecay-eta-6-4000turns-2e6.

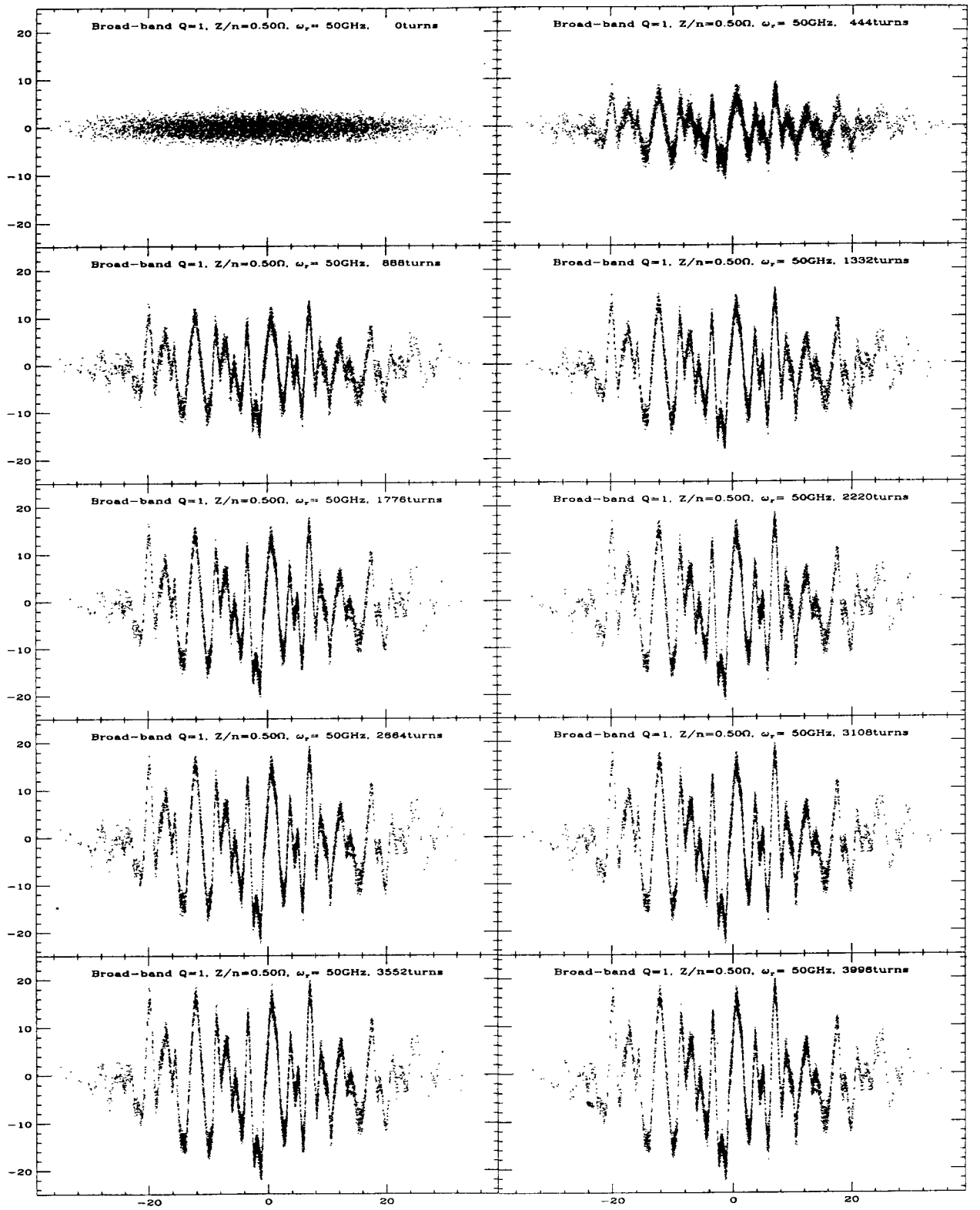
below transition no decay of μ



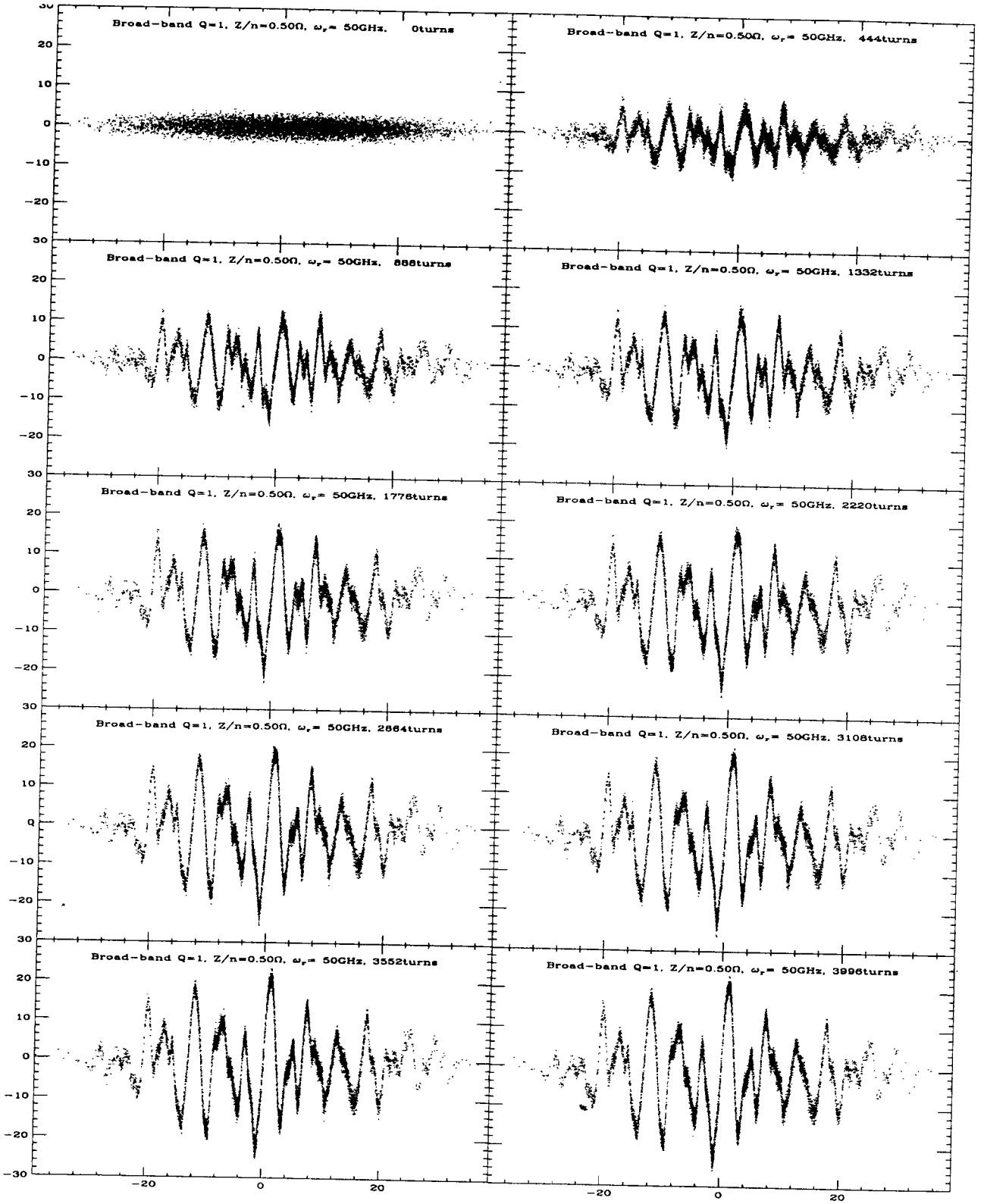
Energy offset in MeV vs distance in cm, $E = 50$ GeV with $\sigma_E = 1.5$ MeV, $\sigma_\ell = 13$ cm. $\eta = +1 \times 10^{-6}$, 4×10^{12} particles (2×10^6 macro), half-triangle width 15 ps. Compensating rf's: 65.341, 24.645 kV, $\omega = 2421.83773$, 5005.13131 MHz, $\phi = 178.60214°$,177.15095°. Decay of muons has NOT been included, 4000 turns, File: 50ghz-5-13-nodecay+eta-6-4000turns-2e6.

above transition

no decay of muons



Energy offset in MeV vs distance in cm, $E = 50$ GeV with $\sigma_E = 1.5$ MeV, $\sigma_\ell = 13$ cm. $\eta = -1 \times 10^{-14}$, 4×10^{12} particles (1×10^6 macro), half-triangle width 15 ps. Compensating rf's: 65.341, 24.645 kV, $\omega = 2421.83773$, 5005.13131 MHz, $\phi = 178.60214°$,177.15095°. Decay of muons has been included, 4000 turns, File: 50ghz-5-13-decay-eta-14-4000turns-1e6.



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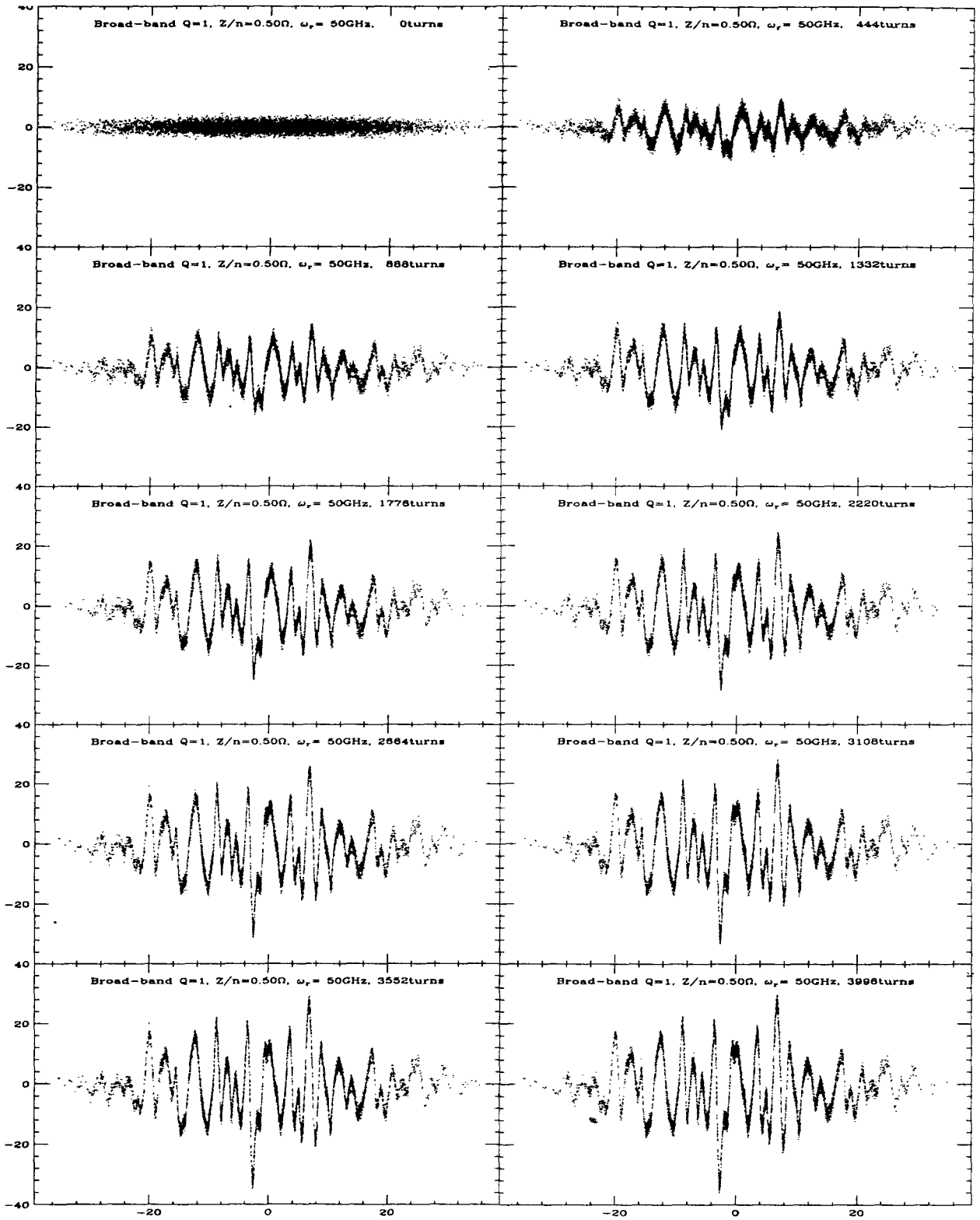
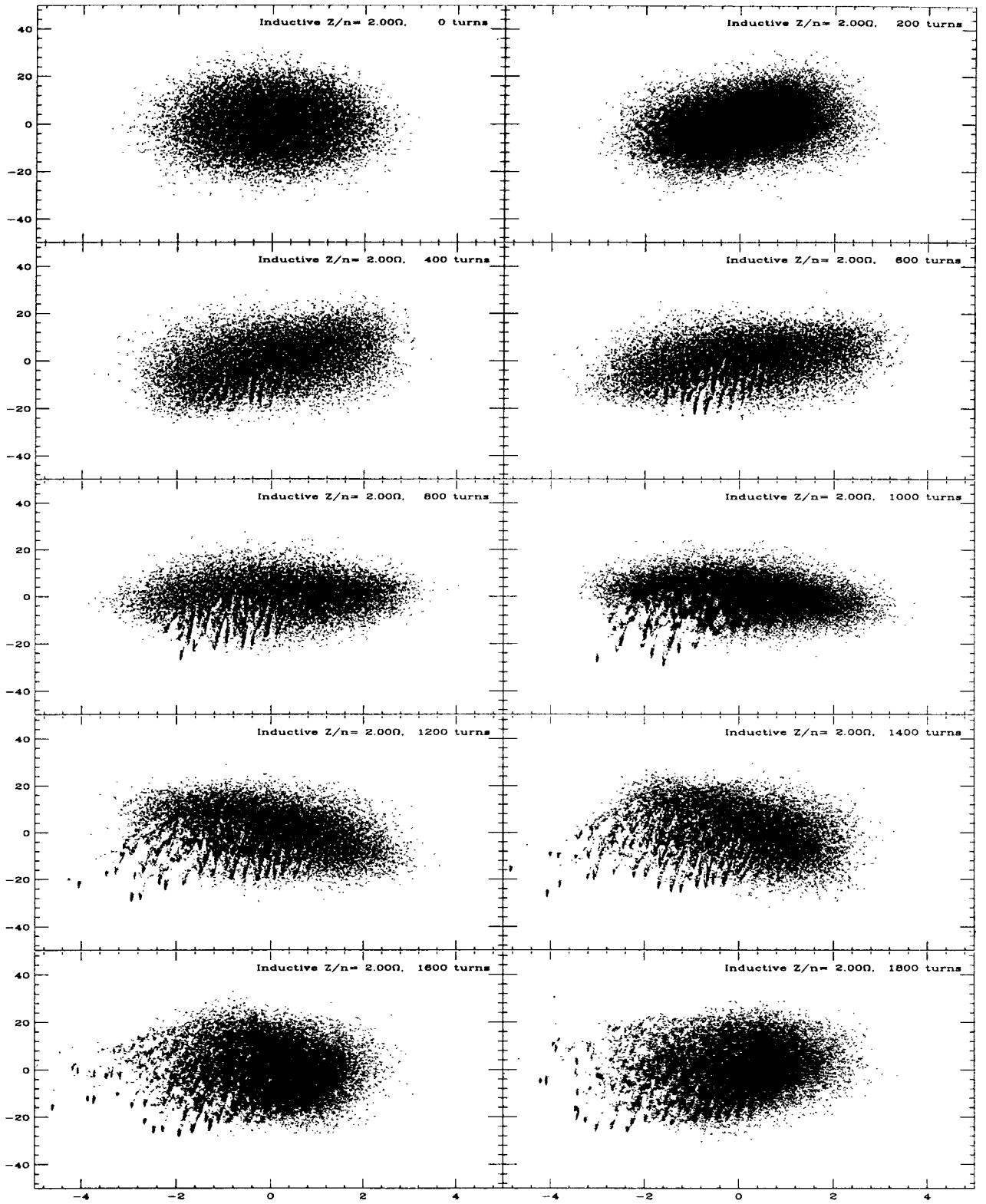


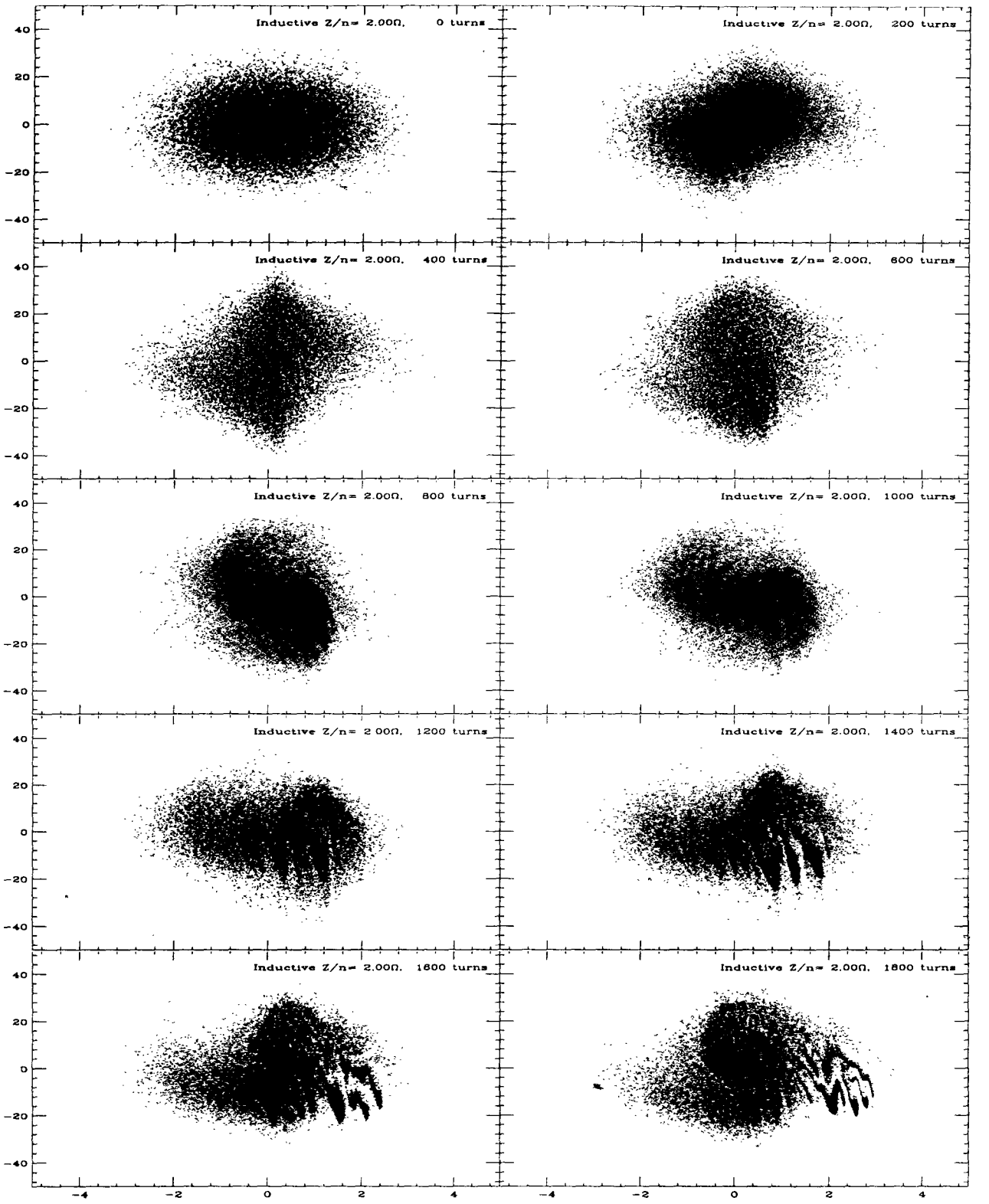
Energy offset in MeV vs distance in cm, $E = 50$ GeV with $\sigma_E = 1.5$ MeV, $\sigma_\ell = 13$ cm. $\eta = +1 \times 10^{-6}$, 4×10^{12} particles (1×10^6 macro), half-triangle width 15 ps. Compensating rf's: 65.341, 24.645 kV, $\omega = 2421.83773$, 5005.13131 MHz, $\phi = 178.60214°$,177.15095°. Decay of muons has been included, File: 50ghz-5-13-decay+eta-6-4000turns-1e6.



Energy offset in MeV vs time in ns, $E = 100$ GeV with rms Gaussian spread 0.0001, $\eta = +0.001$, 9.83013×10^{10} particles (400000 macro), half-triangle width 0.05 ns, frequency-independent pure reactive wake with inductive $Z/n = 2.00\ \Omega$.

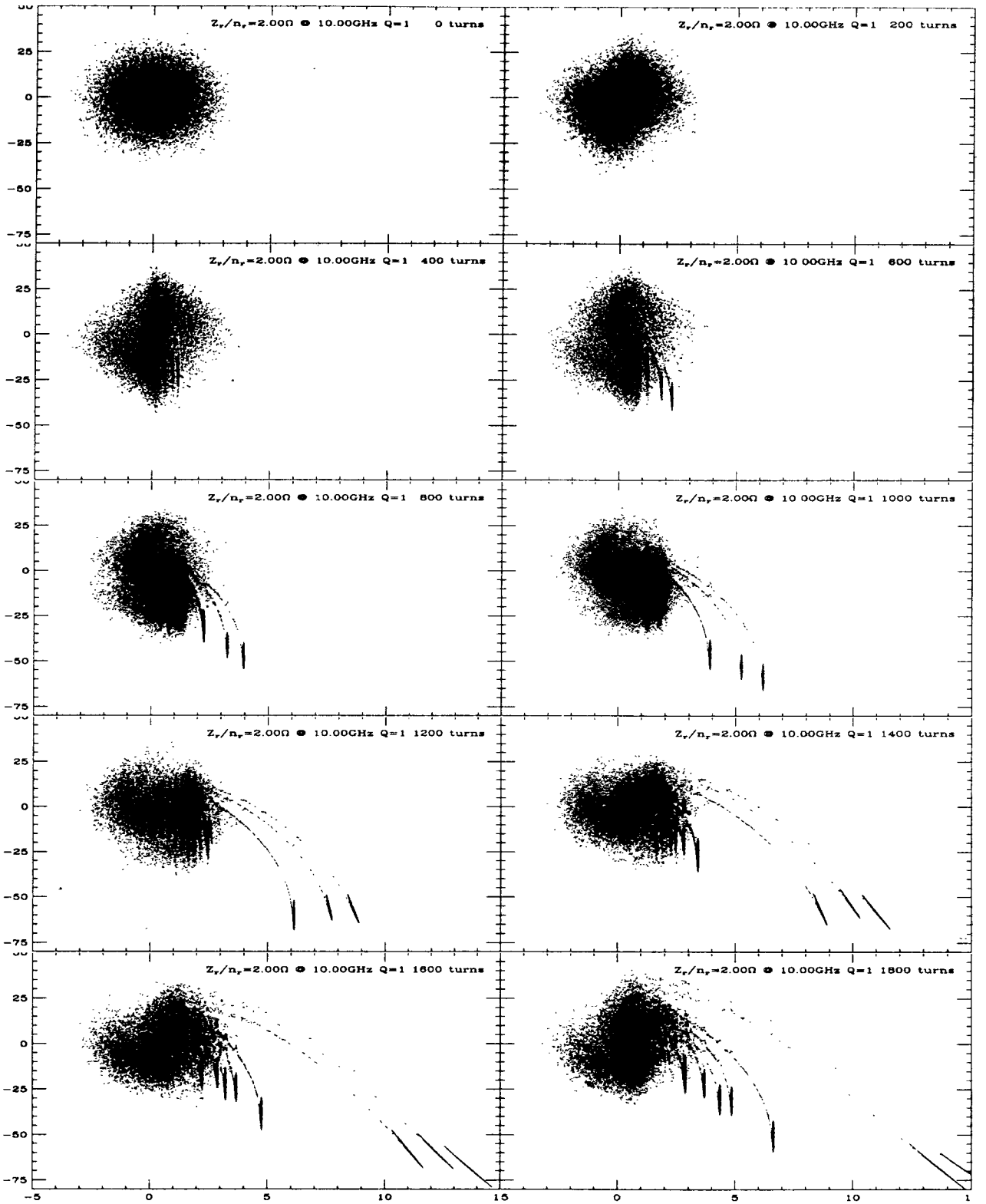
above transition

pure inductive, 2 times above threshold



Energy offset in MeV vs time in ns, $E = 100$ GeV with rms Gaussian spread 0.0001, $\eta = -0.001$, 9.83013×10^{10} particles (400000 macro), half-triangle width 0.05 ns, frequency-independent pure reactive wake with inductive $Z/n = 2.00\ \Omega$.

below transition
pure inductive, 2 x times above threshold

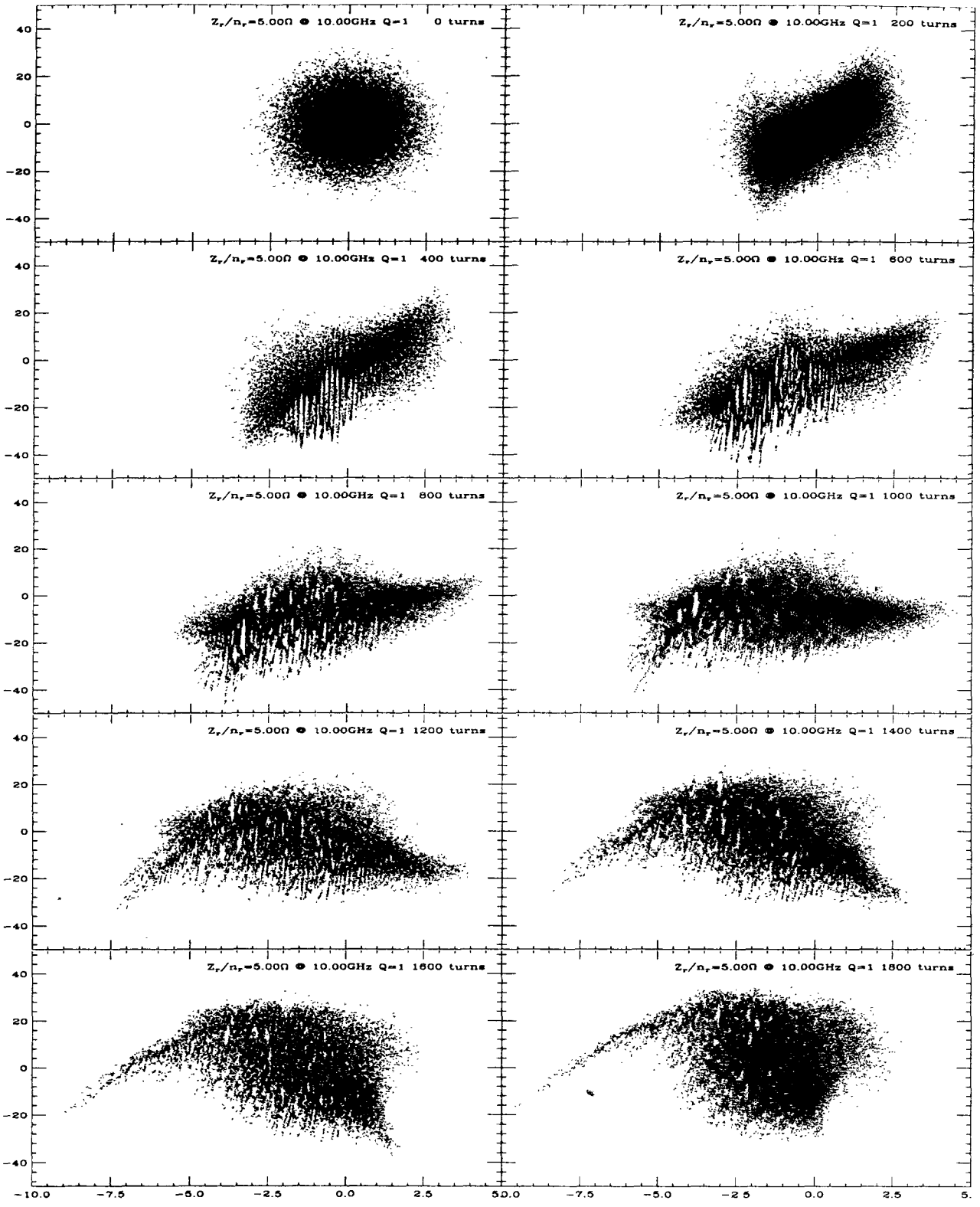


Energy offset in MeV vs time in ns, $E = 100$ GeV with rms Gaussian spread 0.0001, $\eta = -0.001$, 9.83013×10^{10} particles (400000 macro), half-triangle width 0.05 ns, broad-band impedance with $Z_r/n_r = 2.00\ \Omega$ at 10.0 GHz.

below transition

broad band $Q=1$ $\frac{Z}{n}$ 2 times above threshold

micro-bt-2.00-5-10

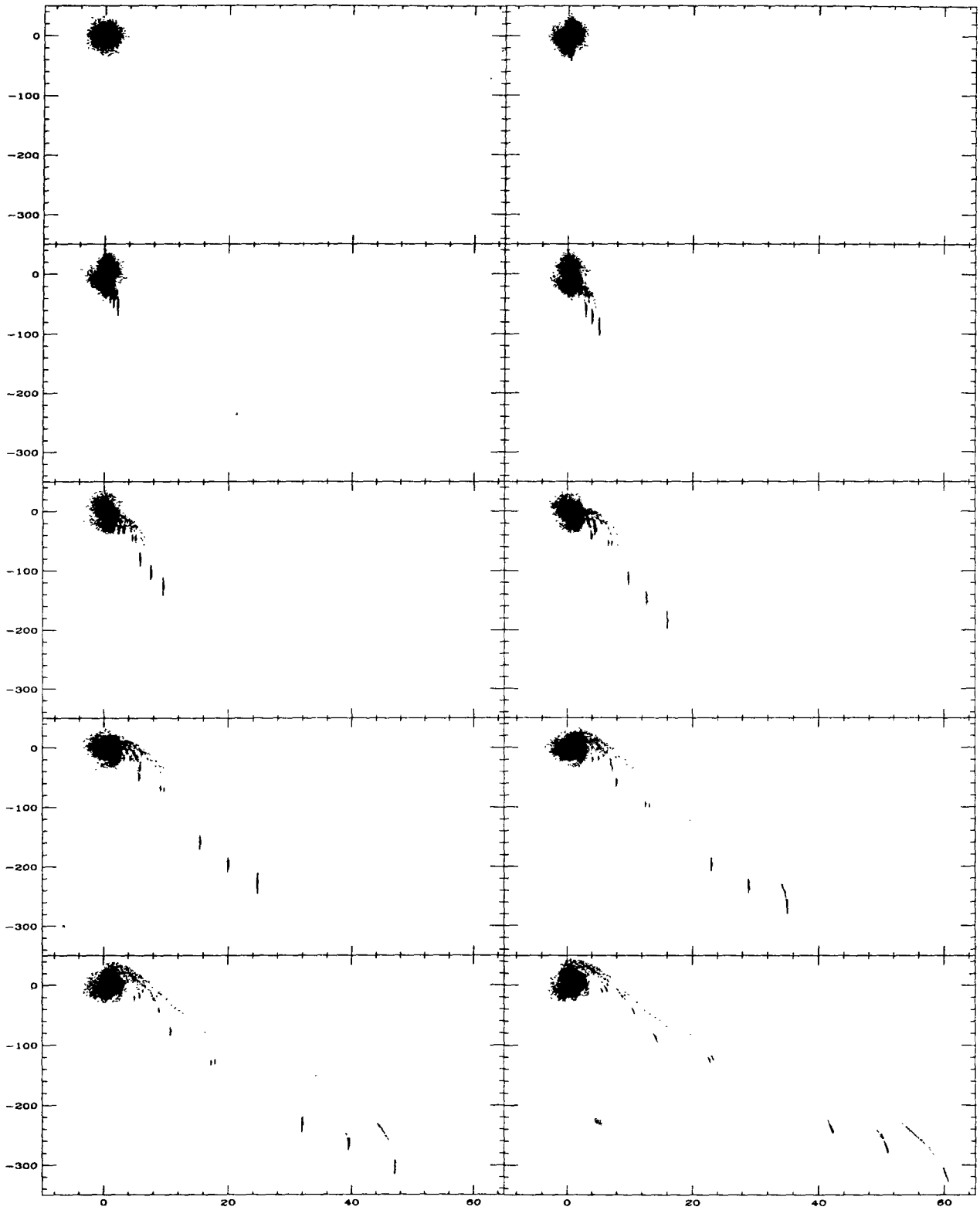


Energy offset in MeV vs time in ns, $E = 100$ GeV with rms Gaussian spread 0.0001, $\eta = +0.001$, 9.83013×10^{10} particles (400000 macro), half-triangle width 0.05 ns, broad-band impedance with $Z_r/n_r = 5.00\ \Omega$ at 10.0 GHz.

Above transition

broad band imp $Q=1$ $\frac{Z}{n}$ 5 times above threshold

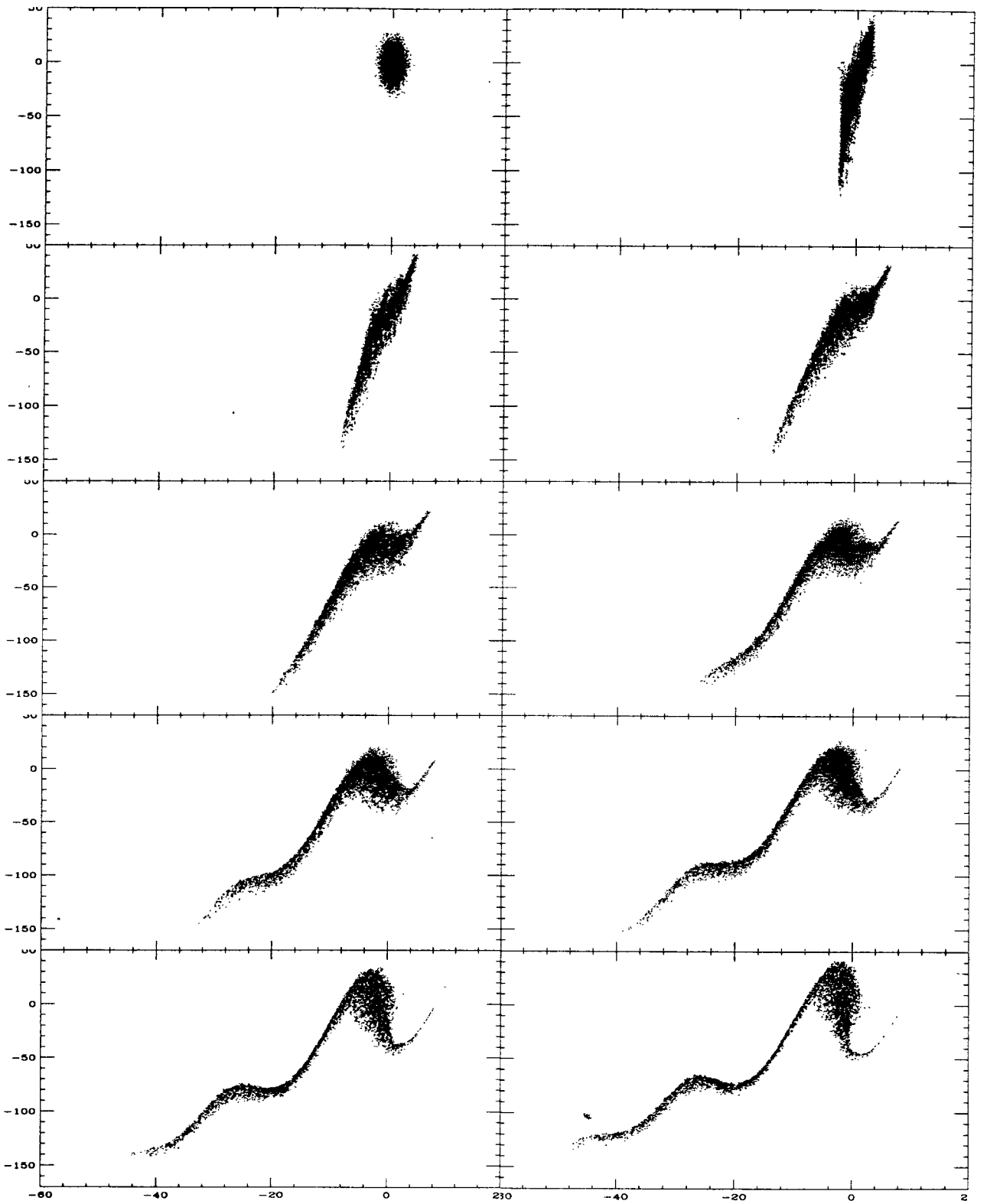
+bb-5.00-.5-10



Energy offset in MeV vs time in ns, $E = 100$ GeV with rms Gaussian spread 0.0001, $\eta = -0.001$, 9.83013×10^{10} particles (400000 macro), half-triangle width 0.05 ns, broad band of $Z/n = 8.0\ \Omega$, $Q = 3$ at 10 GHz. File: micro-bb-8,00-,5-10-q3,0-new

Below transition

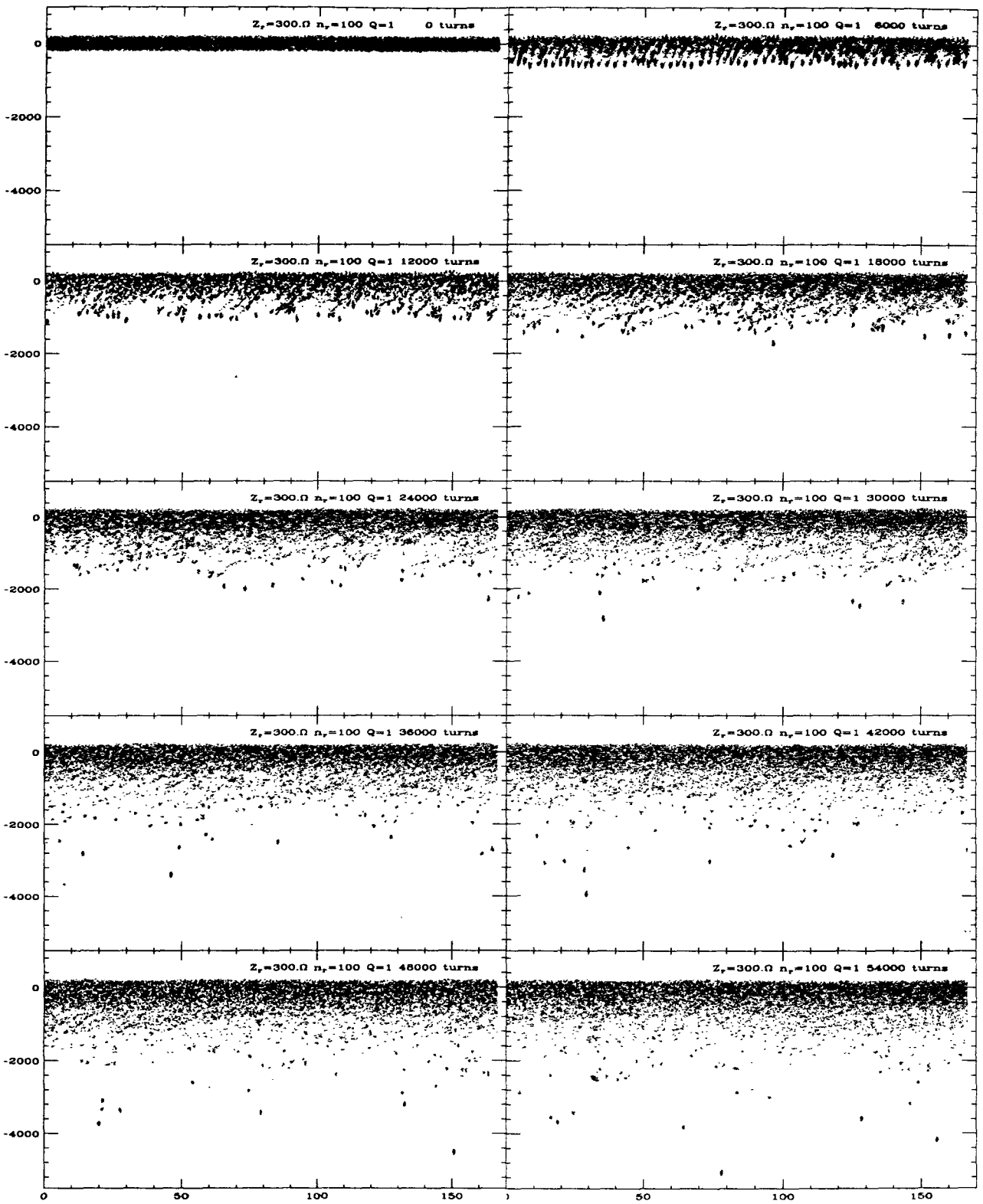
Broad band imp. $Q=3$ $\frac{Z}{n}$ 8 times above threshold



Energy offset in MeV vs time in ns, $E = 100$ GeV with rms Gaussian spread 0.0001, $\eta = +0.001$, 9.83013×10^{10} particles (400000 macro), half-triangle width 0.05 ns, broad band of $Z/n = 16.0\ \Omega$, $Q = 1$ at 10 GHz. File: micro+bb-16,00-,5-10-q1,0-new

Above Transition

broad-band imp. $Q=1$ $\frac{Z}{n}$ 16 times above threshold

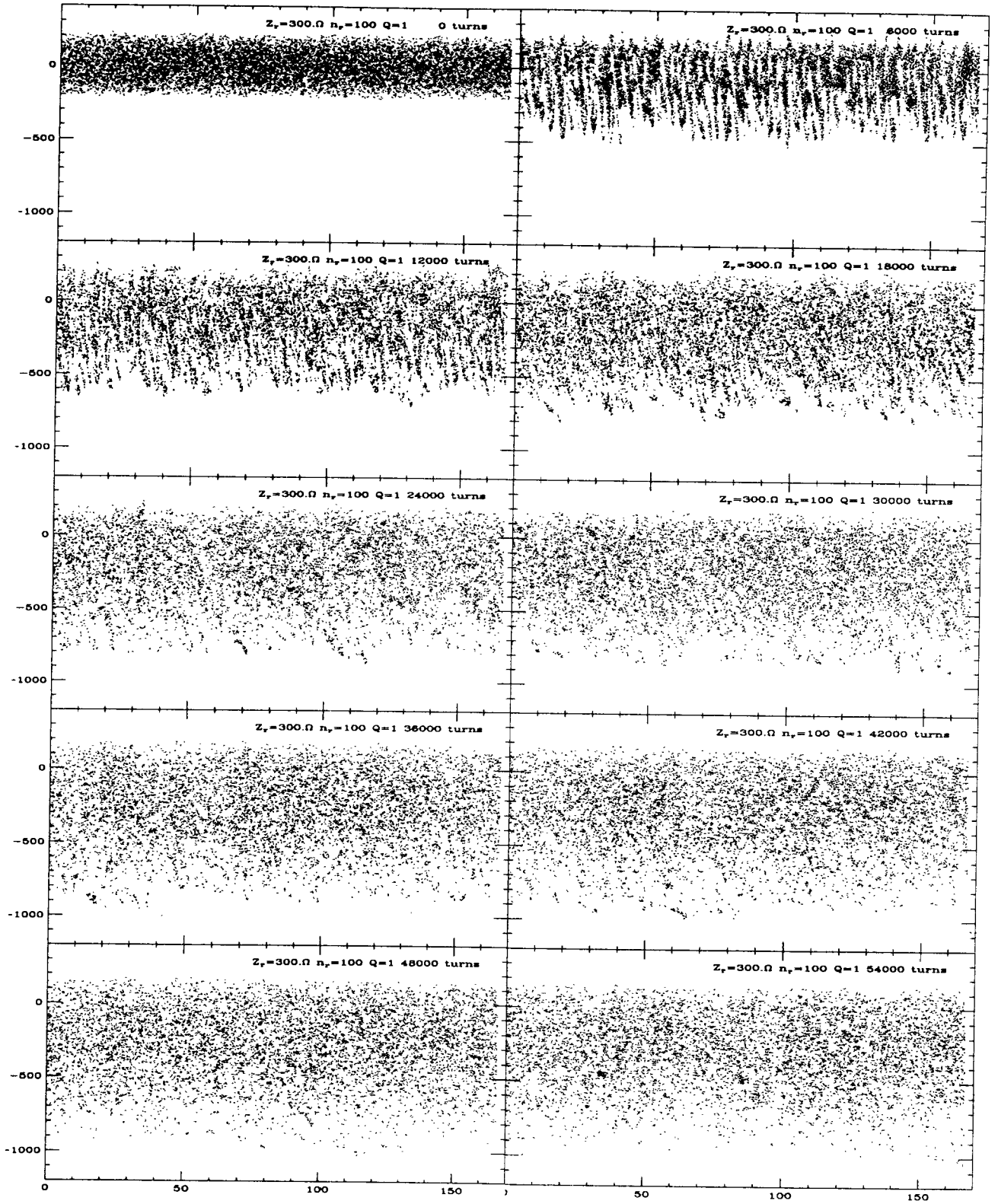


Energy offset in MeV vs time in ns. Ring circum. 50 m, $E = 100$ GeV with rms parabolic spread 0.001, $\eta = +0.005$, 3.27×10^{15} particles (800000 macro), 400 bins, resonant impedance $Z/n = 3.0\ \Omega$ (limit is 1.0 Ω).
File: coast-para-300-100+400

initial $\sigma_E = 100$ MeV

above transition

broad-band imp. $Q=1$ $\frac{Z}{n} =$ 3 times threshold

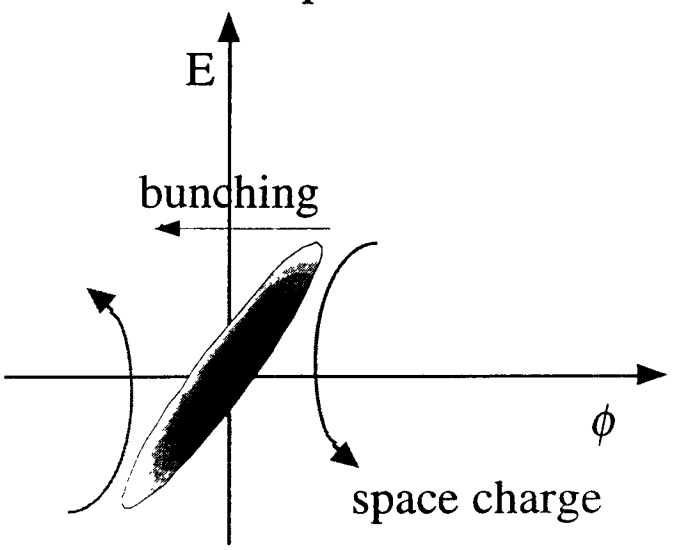


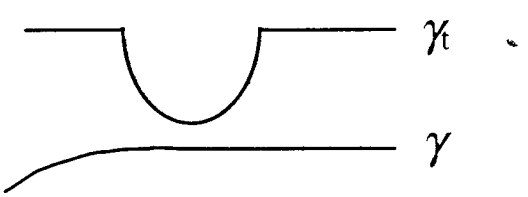
Energy offset in MeV vs time in ns. Ring circum. 50 m, $E = 100$ GeV with rms parabolic spread 0.001, $\eta = -0.005$, 3.27×10^{15} particles (800000 macro), 400 bins, resonant impedance $Z/n = 3.0\ \Omega$ (limit is 1.0 Ω).
File: coast-para-300-100-400

initial σ_E = 100 MeV
below transition
broad band imp. Q=1 $\frac{Z}{n}$ = 3 times threshold

A possible experiment at KEK . . .

- We have demonstrated that bunching is possible in the absence of space charge. Space charge can, however, prevent bunching due to self fields which rotate the bunch before it can be compressed.



- A possible solution to this problem is to move the transition energy far from the beam energy to make the final bunch rotation fast enough so that the space charge effects do not contribute. This requires $|\gamma - \gamma_t| \sim 2$.

- This can be tested at KEK where the γ_t jump waveform is a half sine wave. (The bunch charge will be low.)