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Experimental Study of the Momentum Effects at AGS Transition Energy

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U.S. Department of Energy

USDOE Office of Science (SC)

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Experimental Study of the Momentum Effects at AGS Transition Energy

Jie Wei, BNL, March 24, 1995

I. Introduction

II. Results of the Experimental Study

* measurement of the nonlinear momentum-compaction factor α_1
* enhancement of the nonlinearity (α_1) due to the γ_T jump
* effects of the sextupole excitations

III. Comparison with MAD and TIBETAN Simulations

* evaluation of α_1 and the dispersion using MAD
* preliminary longitudinal simulations using TIBETAN

IV. Conclusions and Discussion

Personnel:

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C. Saltmarsh, M. Syphers, S. Tepikian, ...
AGS operation crew

I. Introduction

$$\frac{\Delta t}{t} = \frac{\Delta L}{L_0} - \frac{\Delta v}{v_0}$$

$$= \underbrace{\left(\alpha - \frac{1}{\gamma^2}\right)}_{\eta} \frac{\Delta p}{p}$$

* No longitudinal focusing

* Non-adiabatic synchrotron motion

Characteristic time T_c

$$T_c = \left(\frac{\pi \beta^2 \gamma_T^3}{\xi e \hat{V} \, |\cos\phi_s| \, \dot{\gamma} \, h \omega_s^2} \right)^{1/3}$$

$$\sim \begin{cases} \pm 5 \text{ ms} & \text{w/o } \gamma_T \text{ jump} \\ \pm 1 \text{ ms} & \text{w/ } \gamma_T \text{ jump} \end{cases}$$

Single-particle effects

* Chromatic non-linearty (Jøhnsøn effect)

* timing mismatch, non-linear bucket

  ⇒ longitudinal dipole-mode oscillation, beam loss

Multi-particle effects

* bunch-bucket mismatch due to self fields

  longitudinal quadrupole mode, beam loss

* combination of self fields and non-linearity

  high current, slow ramp. e.g. RHIC

* micro wave instability

  beam microwave signal, break up.

  secondary bunches

⇒ Use γ_T jump

Use γ_T jump at transition

advantage :

* for given α_1, reduce the chromatic non linear effect

* reduce self field mismatch

  (e.g. space charge force ~ $1/\sigma_l^3$)

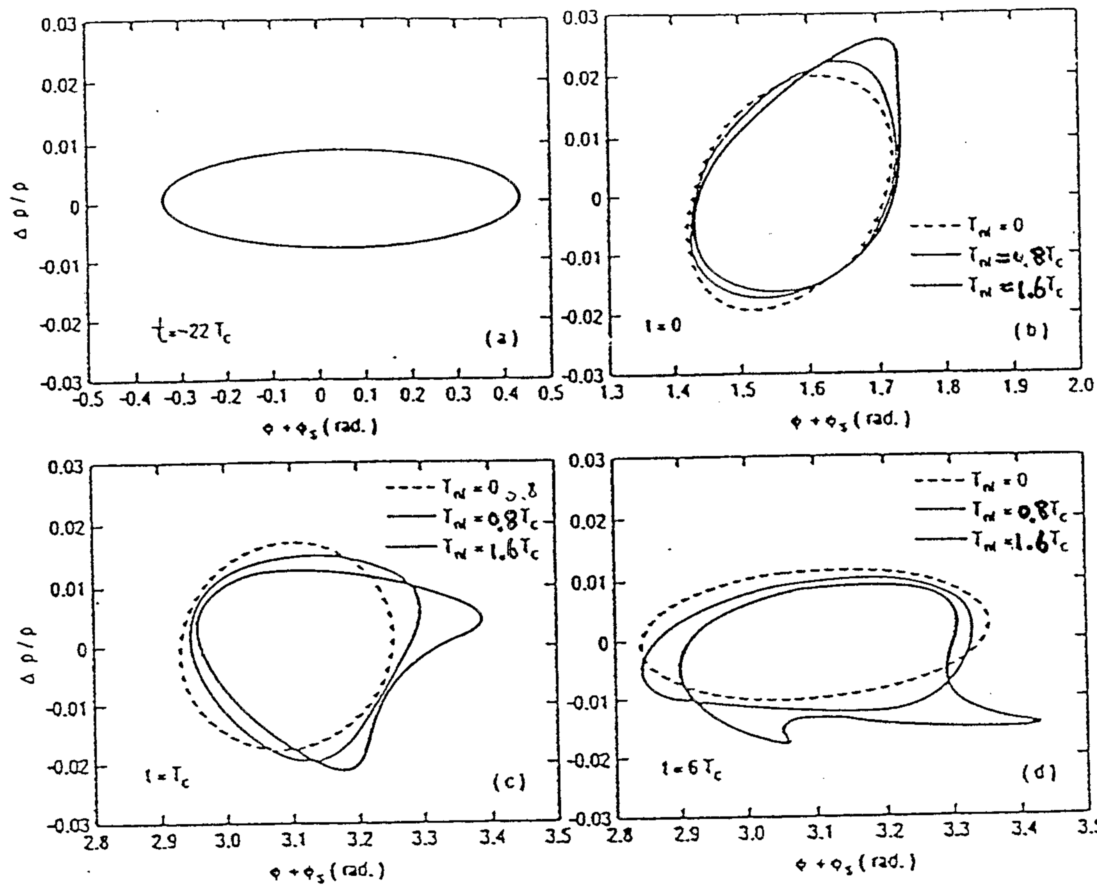
* reduce beam momentum spread at γ_T

disadvantage :

* distort the lattice, enhance α_1

* increase the dispersion, reduce the momentum aperture

Jøhnsen effect



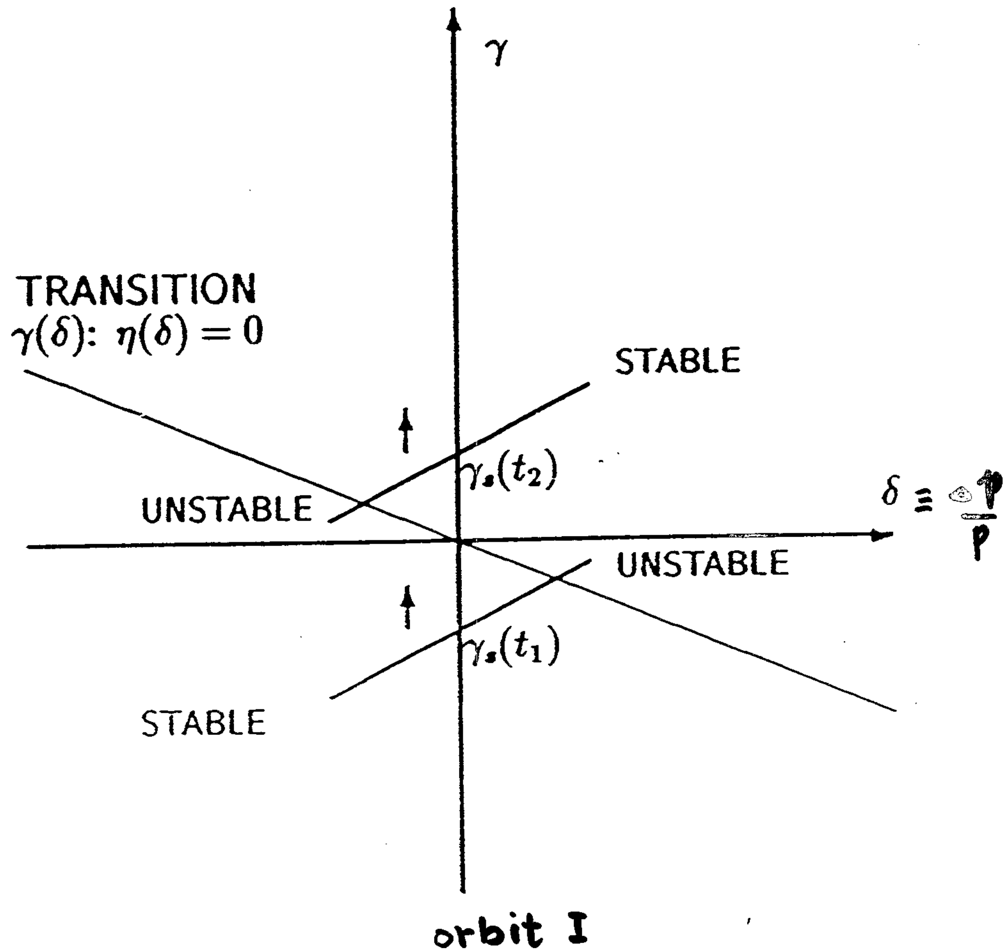
non-adiabatic time:

$$T_C = \left(\frac{\pi E \beta_s^2 \gamma_T^3}{qeV|\cos\phi_s|\dot{\gamma}_s h \omega_s^2} \right)^{\frac{1}{3}}$$

nonlinear time:

$$T_{nl} = \frac{\left|(\alpha_1 + \frac{3}{2}\beta_s^2)\right| \hat{\delta}(0)\ \gamma_{t0}}{\dot{\gamma}_s}$$

$$\frac{\Delta S}{S} \approx \begin{cases} 0.38\,\dfrac{T_{nl}}{T_c}, & \text{for } T_{nl} \ll T_c \\ e^{\frac{2^{1/2}}{3}\left(\frac{T_{nl}}{T_c}\right)^{3/2}} - 1, & \text{for } T_{nl} \geq T_c \end{cases}$$



particles of different momenta cross transition at different time

History:

* discovery of the transition energy

  N. M. Blackman and E. D. Courant

  Rev. Sci. Instr. 20 596 (1949)

* discussion on the chromatic nonlinear effect

  K. Jøhnsen, Proc. CERN Symp. High-Energy Accel. and Pion Phys. (Geneva, 1956)

  ...

* experimental study of the chromatic effect at AGS since 1993

  ⋮

* to cross transition in RHIC

European Particle Accelerator Conference
London, England
June 27-July 1, 1994

BNL-49856

Experimental Study of Slow-Rate Transition Crossing in AGS *

J. Wei, A. Warner, L. Ahrens, J.M. Brennan, W.W. MacKay, S. Peggs, A. Ratti, K. Reece, T. Roser, W.A. Ryan, C. Saltmarsh, T. Satogata, D. Trbojevic, W. Van Asselt
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Abstract

The nonlinear momentum-compaction factor α_1 has been obtained in the AGS by measuring transition energies at different radial orbits using a low-intensity slow-ramped Au^{77+} beam. The beam loss during the transition crossing is found to increase with increasing rf voltage, and to decrease with increasing ramping rate, which indicates that the effect of chromatic nonlinearity (Jøhnsen effect) dominates the transition crossing. The experimental measurement of beam loss agrees very well with TIBETAN computer simulation.

1 INTRODUCTION

During the past several decades, the crossing of transition

2 EFFECTS OF CHROMATIC NONLINEARITIES

In the low-intensity limit when the multiparticle effects are negligible, the longitudinal motion of the particle can be described in terms of its rf phase ϕ and energy deviation $W \equiv \Delta E/h\omega_s$ by the equations

$$\begin{cases} W_{n+1} = W_n + \frac{qeV}{h\omega_s}(\sin\phi_n - \sin\phi_{s,n}) \\ \phi_{n+1} = \phi_n + \frac{2\pi h^2\omega_s\eta(W_{n+1})}{E_s\beta_s}W_{n+1} + \phi_{s,n+1} - \phi_{s,n} \end{cases} \quad (1)$$

where ϕ_s, ω_s, $\beta_s c$, E_s are the synchronous phase, revolution frequency, velocity, and energy, respectively, and h and V are the rf harmonic and voltage. Here the slip factor

* use low intensity Au^{79+}, slow ramp
* γ_T jump off. sextupoles on/off
* developed GT-ANALY mountain range analysis
* calibrated system bandwidth, rf voltage, radial loop. etc.

and $\delta(0)$ is the maximum momentum spread at transition. Beam loss occurs when the particle escapes the rf bucket and when the momentum exceeds the aperture.

3 EXPERIMENTAL SETUP AND DATA REDUCTION

We perform the experiment in the AGS with Au^{77+} beams at an intensity of about 1×10^8 ions per bunch. The beam was made to cross transition ($\gamma_{t0} \approx 8.3$) at various rates $\dot{B}$=0.05, 0.1, and 0.5 T/s. The longitudinal bunch profiles measured through the wall current monitor were recorded at 5 ms time intervals on a LeCroy 7200 digital oscilloscope with 1 ns sampling resolution triggered by the gauss-clock event which corresponds to a specified B field. The recorded data (Fig. 1) was then transferred into SDS (Self-

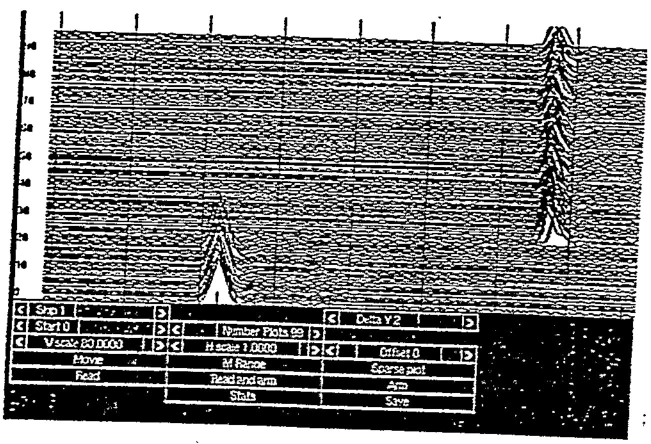


Figure 1: Typical digitized beam-profile data.

Describing Structure) format along with various beam and machine parameters, including beam intensity, V, B, $\dot{B}$, γ_t, and the trigger delay time.

Signal deterioration due to system bandwidth limitation and cable attenuation was determined by analyzing the signals on the LeCroy scope generated by a series of pulses of various time duration, inserted at the wall-current monitor terminal. For pulses of FWHM width (W_s) from 2 to 15ns, the measured width W_m is broadened by about 1.9 ns,

$$W_m = 1.03\ W_s + 1.9\ \ (\text{ns}). \qquad (5)$$

The corresponding correction is made to the measured data during the analysis.

A computer program GT_ANALY has been developed to analyse the SDS format beam-profile data generated either from the LeCroy scope or TIBETAN computer simulation.[3] GT_ANALY first evaluates the average background level using χ^2 fitting. After the background is subtracted, the beam intensity, rms bunch length, skewness, and kurtosis are subsequently evaluated by numerical integrations. The longitudinal beam emittance is calculated from the obtained bunch length using the calibrated rf voltage, magnetic field, and other machine parameters. The beam loss is determined by evaluating the difference in beam intensity at times (typically 100 ms) before and after the transition phase jump, which are long compared with T_c (typically 10 ms).

The accuracy of the beam emittance calculation depends on the calibration of the average magnetic field, the rf voltage, and the pulse broadening. The magnetic field is obtained from the gauss-clock reading which has been calibrated by the frequency measurement. The rf voltage is calibrated at various ramping rates ($\dot{B}$=0.05, 0.1, and 0.5 T/s) by evaluating, at various voltage settings from 20 to 270 kV, the actual rf voltage applied on the beam, which is deduced from the amount of synchronous phase jump at transition.

4 MEASUREMENT OF α_1 FACTOR

Measurement of the nonlinear momentum-compaction factor α_1 is performed under three sextupole current (I_H,I_V) settings at (190 A,0), (0,200 A), and (0,0), respectively. At each sextupole setting, the beam is made to cross transition at two different radial orbits. As shown in Fig. 2, the time of synchronous-phase switch-over near transi-

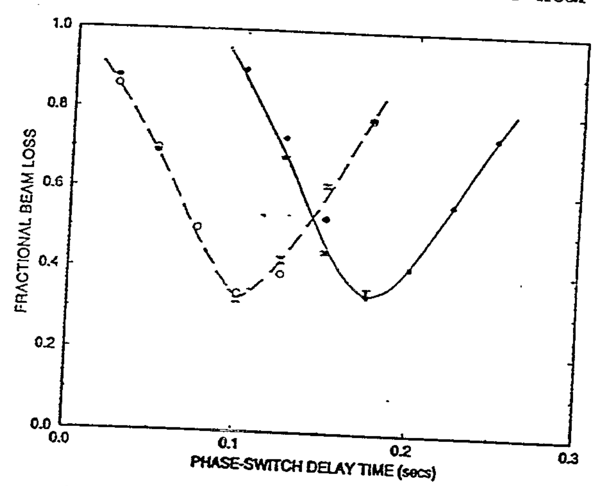


Figure 2: Beam loss versus the phase-switch delay time at radial positions V_R =3.0 V (left) and 2.5 V (right), respectively, at $\dot{B}$ =0.1 T/s with (I_H,I_V)=(190 A,0).

tion is varied at two radial-loop settings. The times for the beam center to cross the transition energy correspond to the times of the minimum beam loss. The difference $\Delta t \approx (-72\pm7)$ ms in the minimum-loss delay time between these two orbits corresponds to the difference in transition energy at these two momentum offsets.

In order to determine the factor α_1 using Eq. 3, the momentum offset δ is calibrated against the radial-loop setting V_R using the frequency measurement. The measurement is performed at energy γ = 12.0 far above the transition energy. The relation obtained is

$$\delta/\Delta V_R = (4.8 \pm 0.2) \times 10^{-3}\ \text{V}^{-1}. \qquad (6)$$

This result is consistent with the Ionization Position Monitor (IPM) measurement of the beam radial centroid position at different radial-loop settings using a dispersion of 3.2 meters at the IPM location.

Using Eq. 6, the factor α_1 has been obtained along with the transition energy γ_{t0} at the various sextupole settings. The results are summarized in Table 1.

5 COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS

With γ_{t0} and α_1 given in Table 1, and with the initial longitudinal emittance evaluated by GT_ANALY, computer simulation is performed to verify the experimental measurement on beam loss as functions of the phase-switch time, rf voltage V, and ramping rate $\dot{B}$. The simulation is performed with 2000 test particles using the computer program TIBETAN based on Eq. 1. The solid line in Fig. 3 shows the simulated beam loss versus switch-over time,

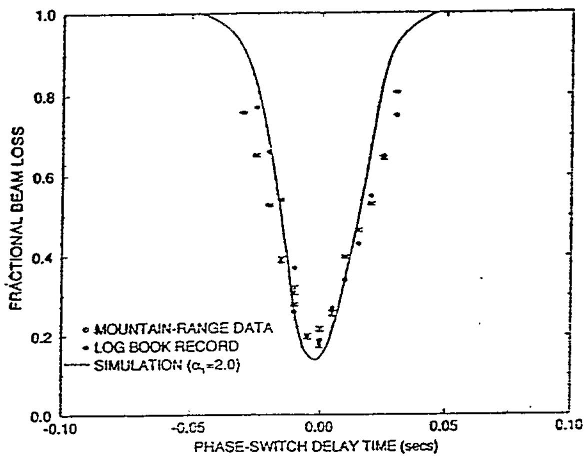


Figure 3: Beam loss versus the synchronous-phase switch-over time at $\dot{B}$ =0.5 T/s.

which agrees well with the experimental results of both the GT_ANALY beam-profile analysis and the beam current transformer readings (log book record).

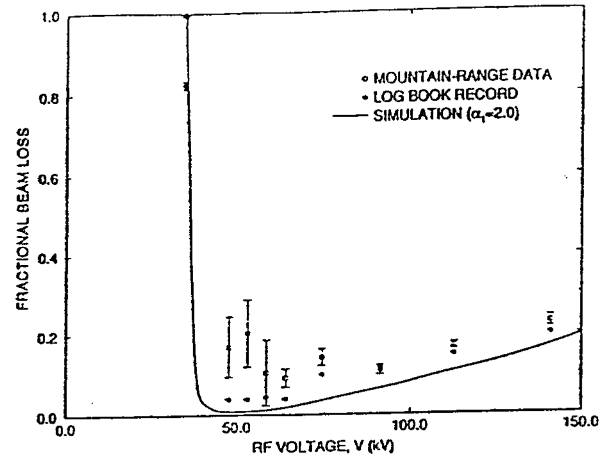


Figure 4: Beam loss versus rf voltage at $\dot{B}$ =0.5 T/s.

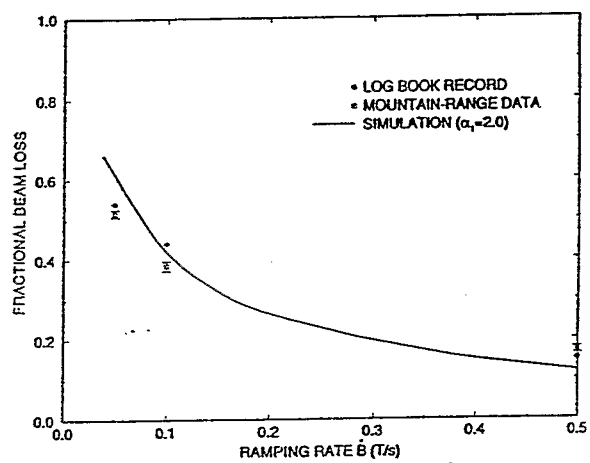


Figure 5: Beam loss versus crossing rate $\dot{B}$ at V =114 kV.

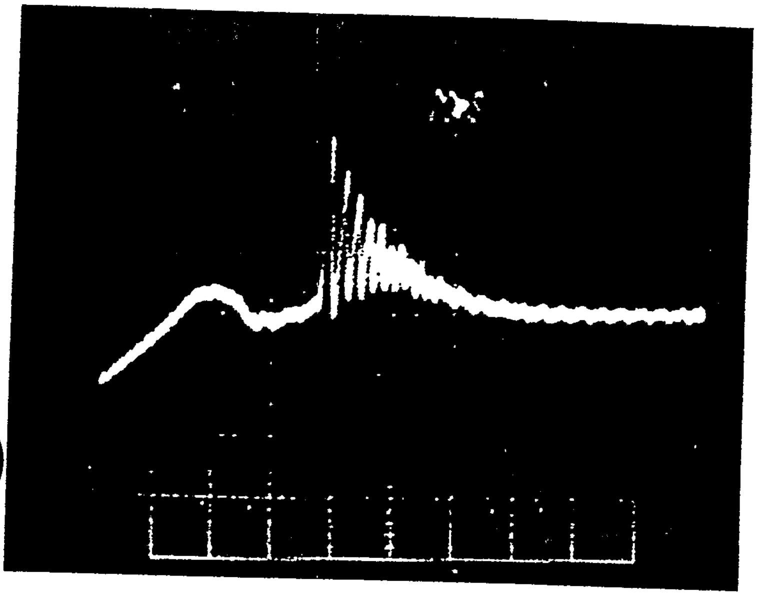
Table 1: AGS Transition energy and α_1 at $V_R = 3.0$ V.

(I_H, I_V) (A)	(190, 0)	(0, 200)	(0, 0)
γ_{t0}	8.28	8.34	8.31
α_1	2.1±0.5	4.5±0.9	5.4±1.0

AGS proton run, 1995

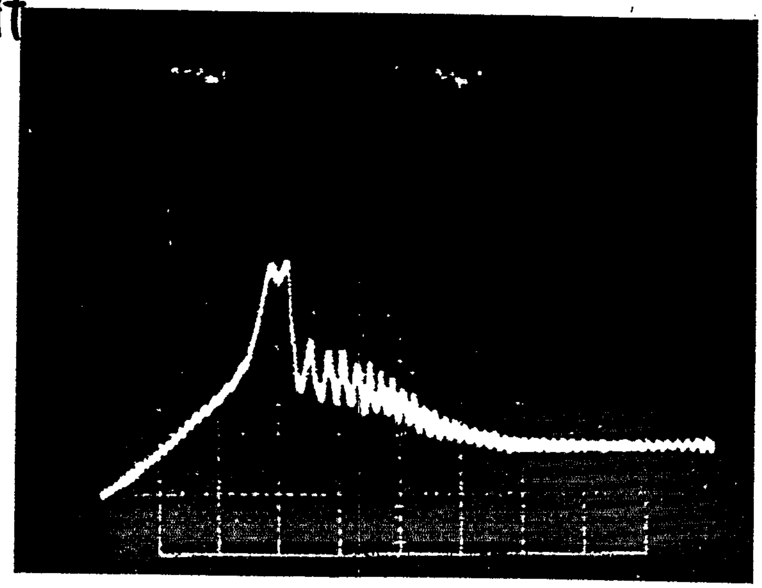
with γ_T jump on, even with low intensity beam, beam loss & quadrupole oscil. occur.

($\dot{B} = 2.2\,T/s$ fast ramp)



@ Transition 1/26/95

with γ_T jump off



1.3 Tp no γ jump

Peak detected signal in MCR

II. Resuts of the Experimental Study

Plan:

* measure α_1 when γ_T jump is off.

* measure α_1 in the γ_T-jump lattice

  study the ehhancement of the nonlinearity

* repeat step 2 with sextupoles excited

  observe the improvement in nonlinearity

* study the change in momentum aperture

$$\boxed{\beta^2 \frac{\dot{B}}{B} \cdot \Delta t = -\left(\alpha_1 + \frac{1}{2}\right) \cdot \frac{\Delta p}{p}}$$

* Vary $\frac{\Delta p}{p}$ by displace the radial orbit

  measure the change in average orbit

* measure beam loss at transition versus

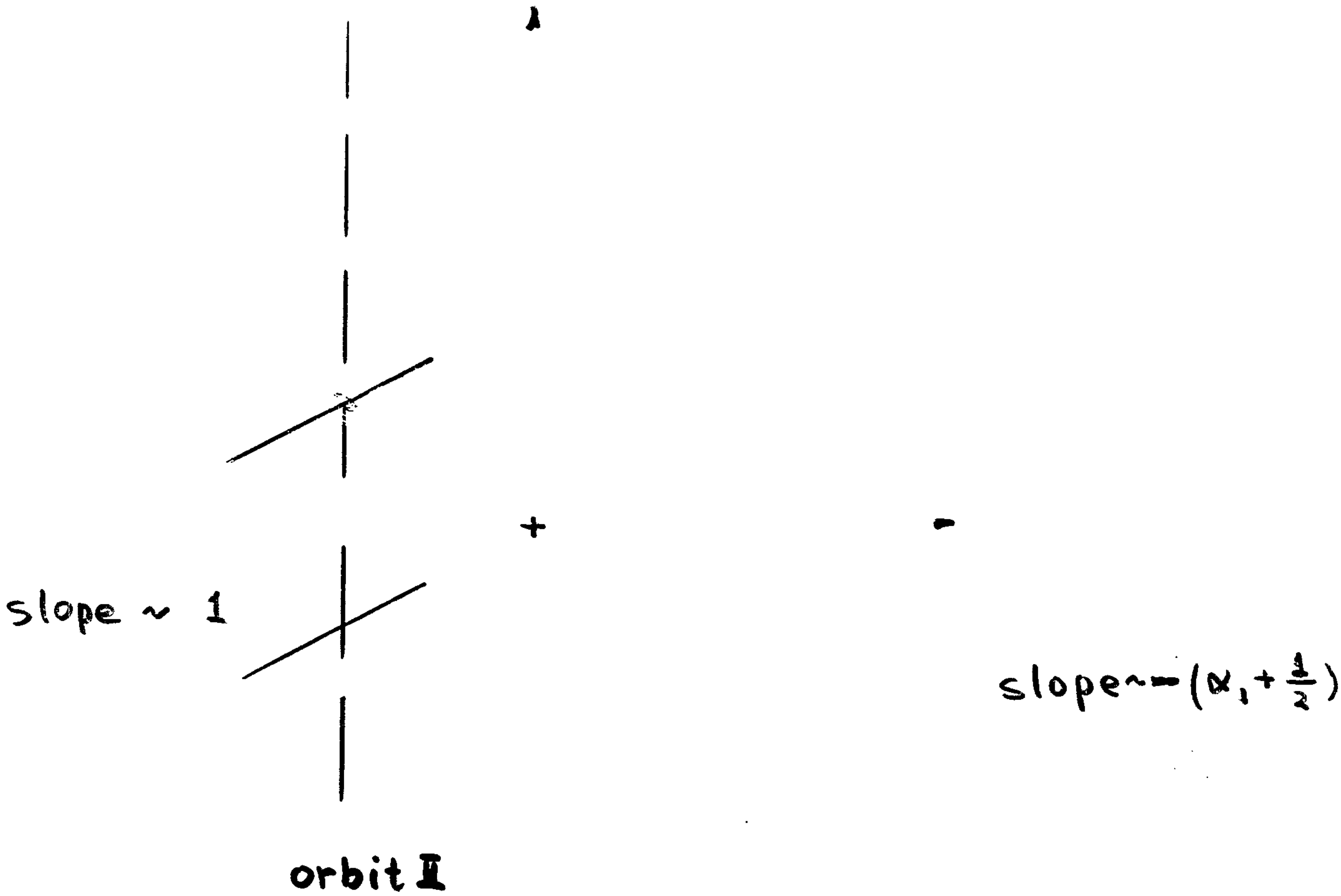
  the delay time for phase switch-over

  determine the transition energy timing (Δt)

  from the minimum loss

* extract α_1

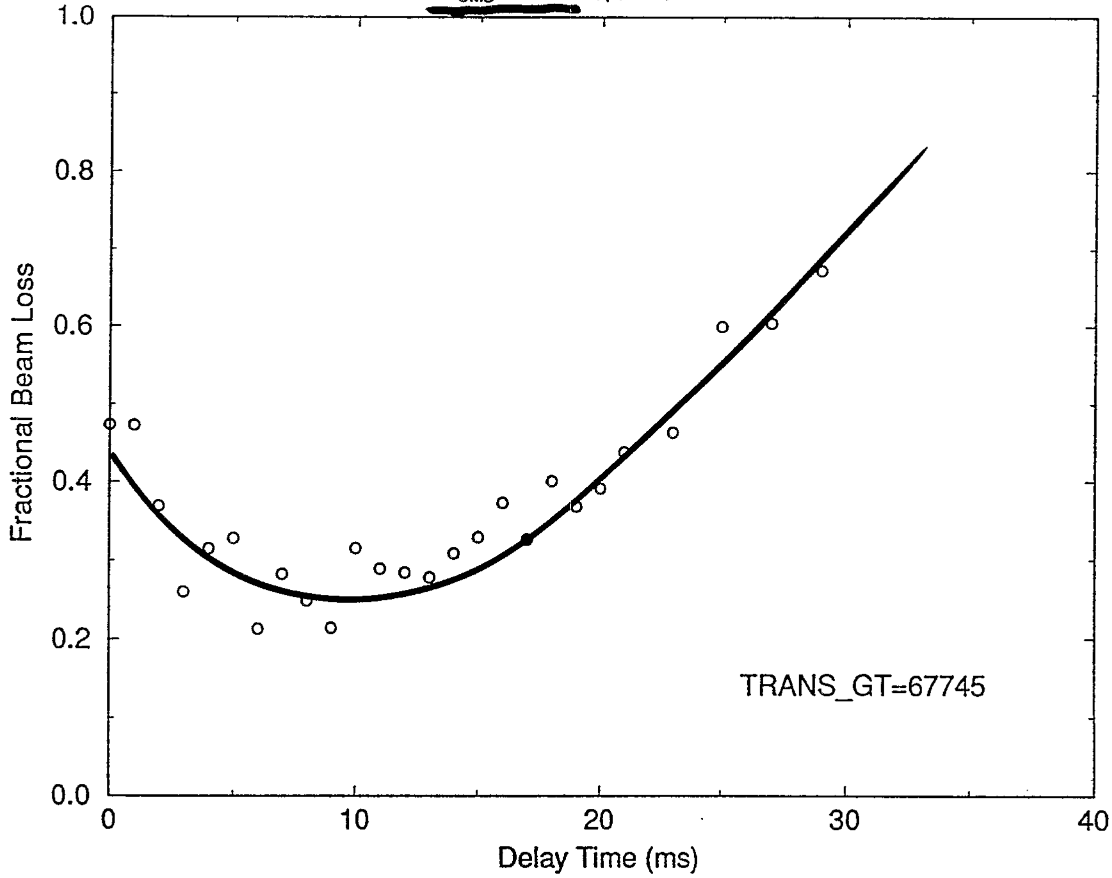
  ideal $\alpha_1 = -3/2$



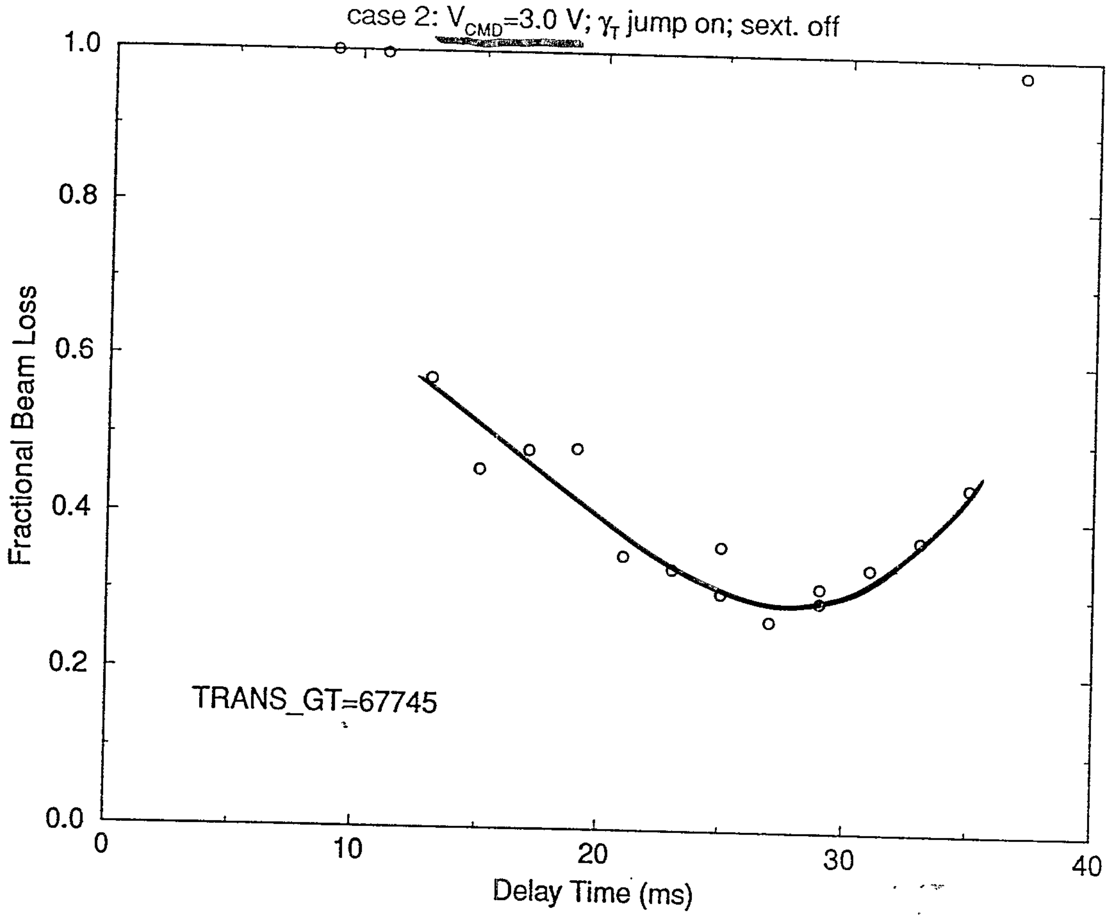
$$\frac{\Delta \gamma_T}{\gamma_{T0}} = \beta^2 \frac{\dot{B}}{B} \cdot \Delta t = -\left(\alpha_1 + \frac{1}{2}\right) \cdot \delta$$

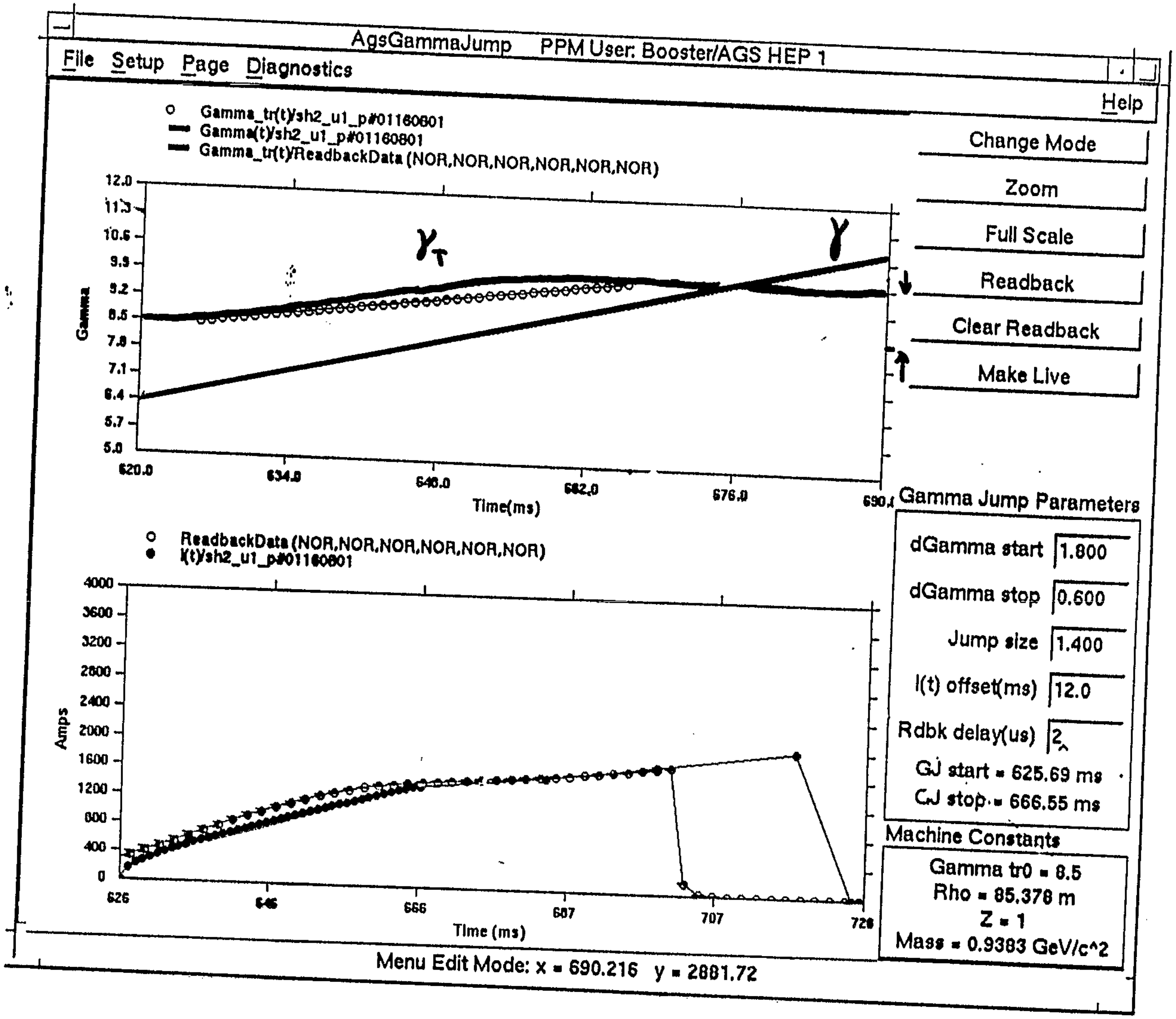
AGS Transition Study (Feb. 2, 1995)

case 1: V_{CMD}=3.3 V; γ_T jump on; sext. off

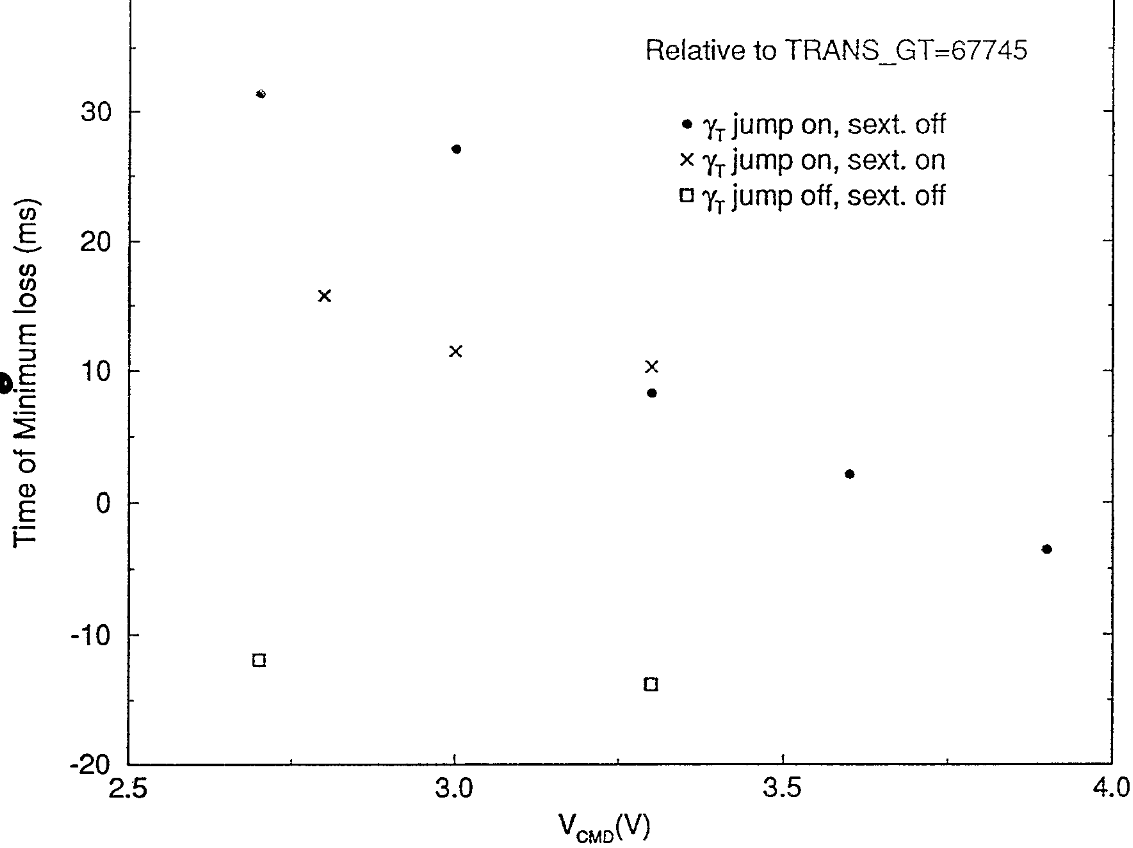


AGS Transition Study (Feb. 2, 1995)

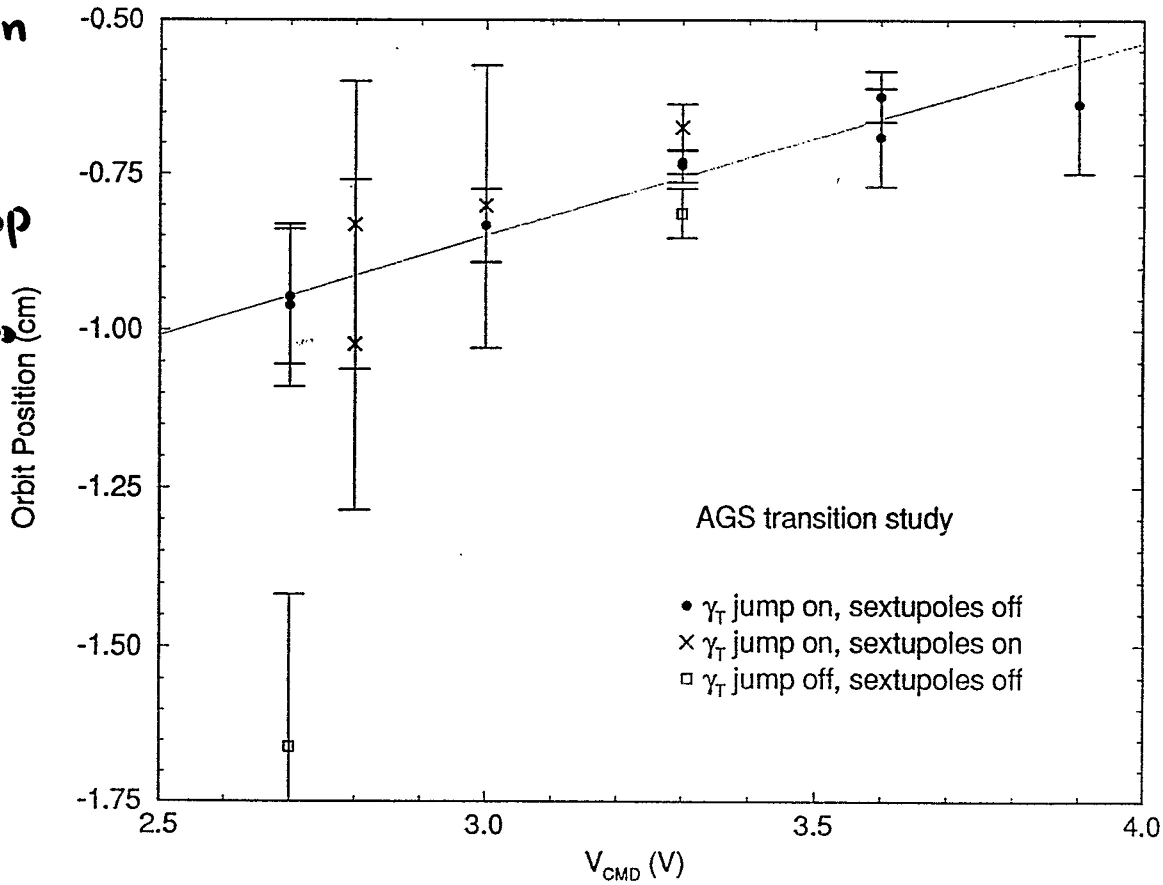


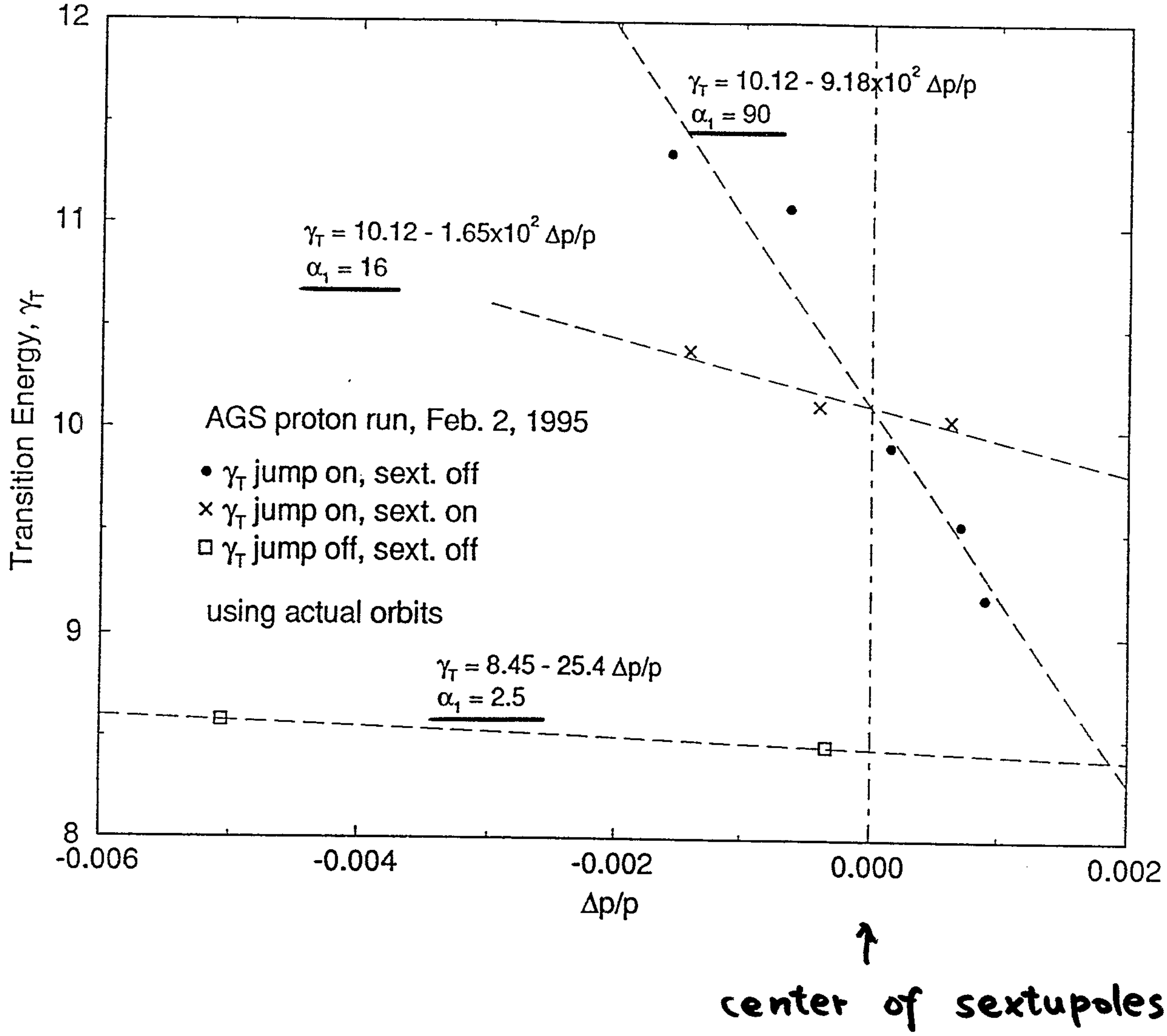

AgsGammaJump PPM User: Booster/AGS HEP 1
File Setup Page Diagnostics
Help
Gamma_tr(t)/sh2_u1_p#01160601
Gamma(t)/sh2_u1_p#01160601
Gamma_tr(t)/ReadbackData (NOR,NOR,NOR,NOR,NOR,NOR)
Gamma
Time(ms)
γ_T
γ
ReadbackData (NOR,NOR,NOR,NOR,NOR,NOR)
I(t)/sh2_u1_p#01160601
Amps
Time (ms)
Change Mode
Zoom
Full Scale
Readback
Clear Readback
Make Live
Gamma Jump Parameters
dGamma start 1.800
dGamma stop 0.600
Jump size 1.400
I(t) offset(ms) 12.0
Rdbk delay(us) 2
GJ start = 625.69 ms
GJ stop = 666.55 ms
Machine Constants
Gamma tr0 = 8.5
Rho = 85.378 m
Z = 1
Mass = 0.9383 GeV/c^2
Menu Edit Mode: x = 690.216 y = 2881.72

transition time vs. radial loop function V_{CMD}



Orbit mean vs. radial loop function V_{CMD}





"normal" AGS operation with high intensity protons :

$$\frac{\Delta p}{p} \sim \pm 0.005$$

⇒ partial beam not "jumped" across γ_T

reduction in momentum aperture due to γ_T jum

* γ_T jump off
  sext. off

$$\frac{\Delta p}{p}\Big|_{ap} \sim \pm 7.9 \times 10^{-3}$$

* γ_T jump on
  sext. off

$$\frac{\Delta p}{p}\Big|_{ap} \sim \pm 4.7 \times 10^{-3}$$

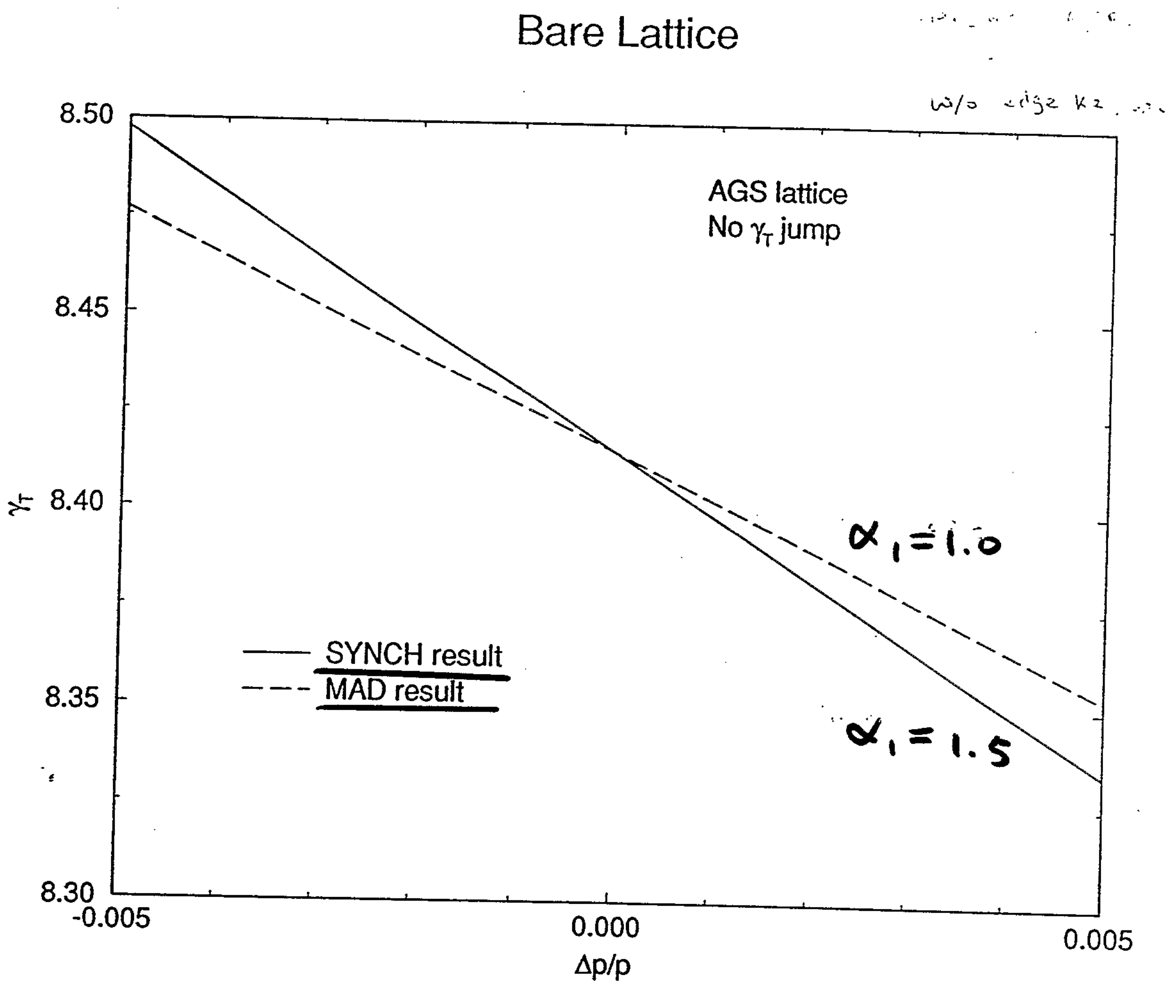
* γ_T jump on
  sext. on
  $I_H = 100\,A$

$$\frac{\Delta p}{p}\Big|_{ap} \sim \pm 4.3 \times 10^{-3}$$

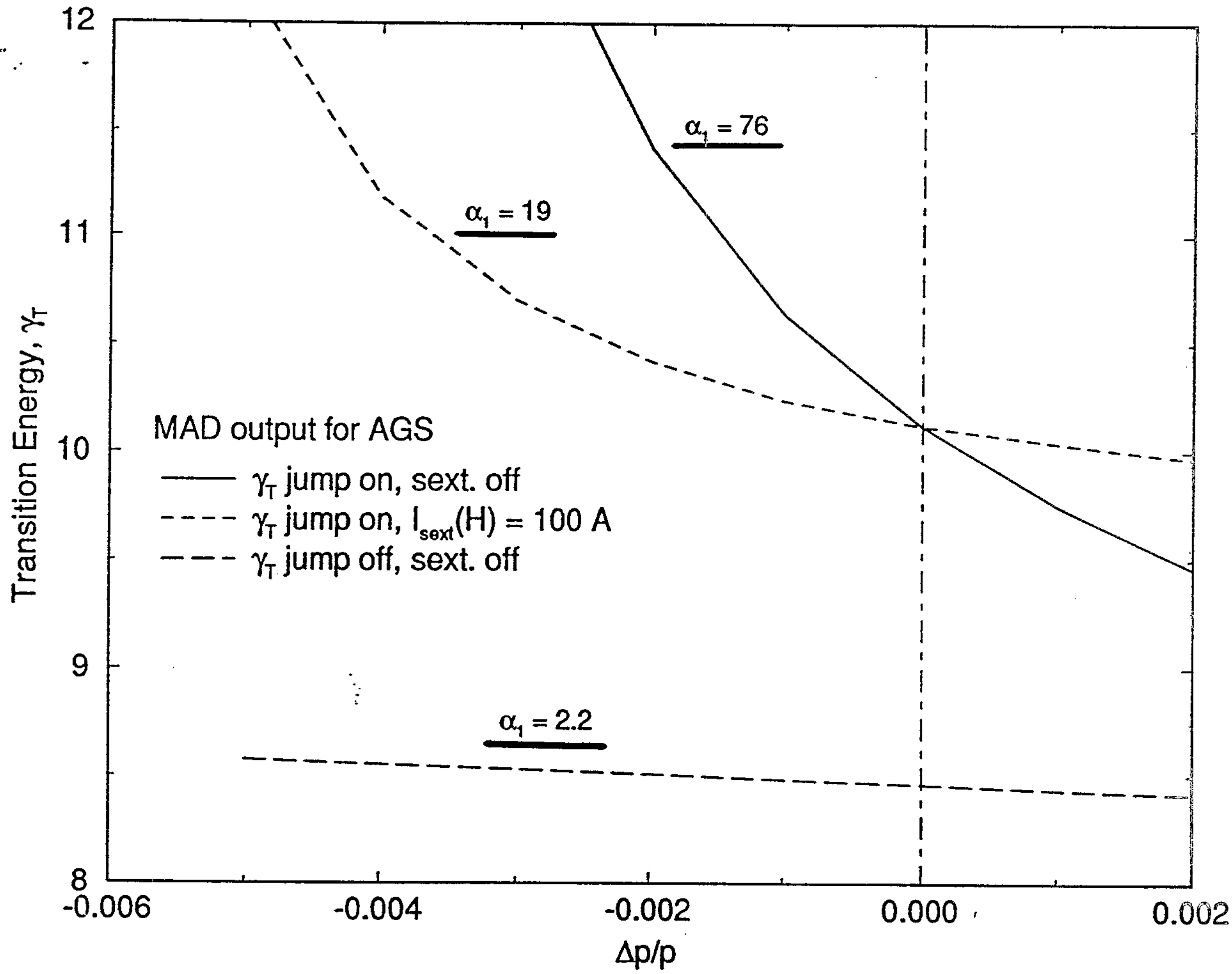
Note:

* size of the "pencil" beam : $S \cong 0.3$ eV·s
  $\frac{\Delta p}{p} \approx \pm 2.8 \times 10^{-3}$ at γ_T, without the
  jump across (both jump on / off)
* measured only in negative $\Delta p/p$ side

III. Comparison with MAD. TIBETAN Simulation



every program (MAD, SYNCH, ...) does not give identical result, especially when off momentum

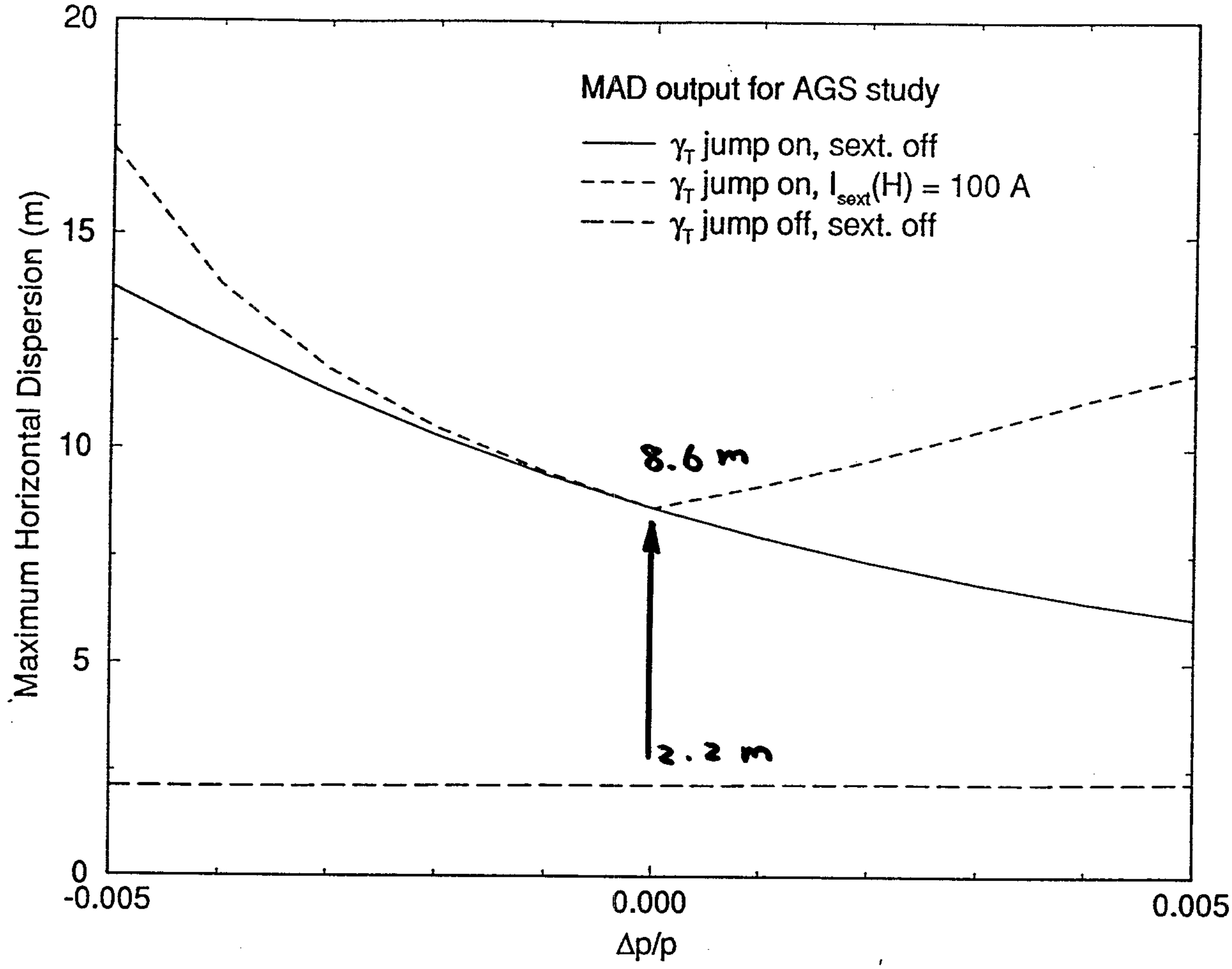


γ_T jump on: γ_T quads. at 1700 Amps.

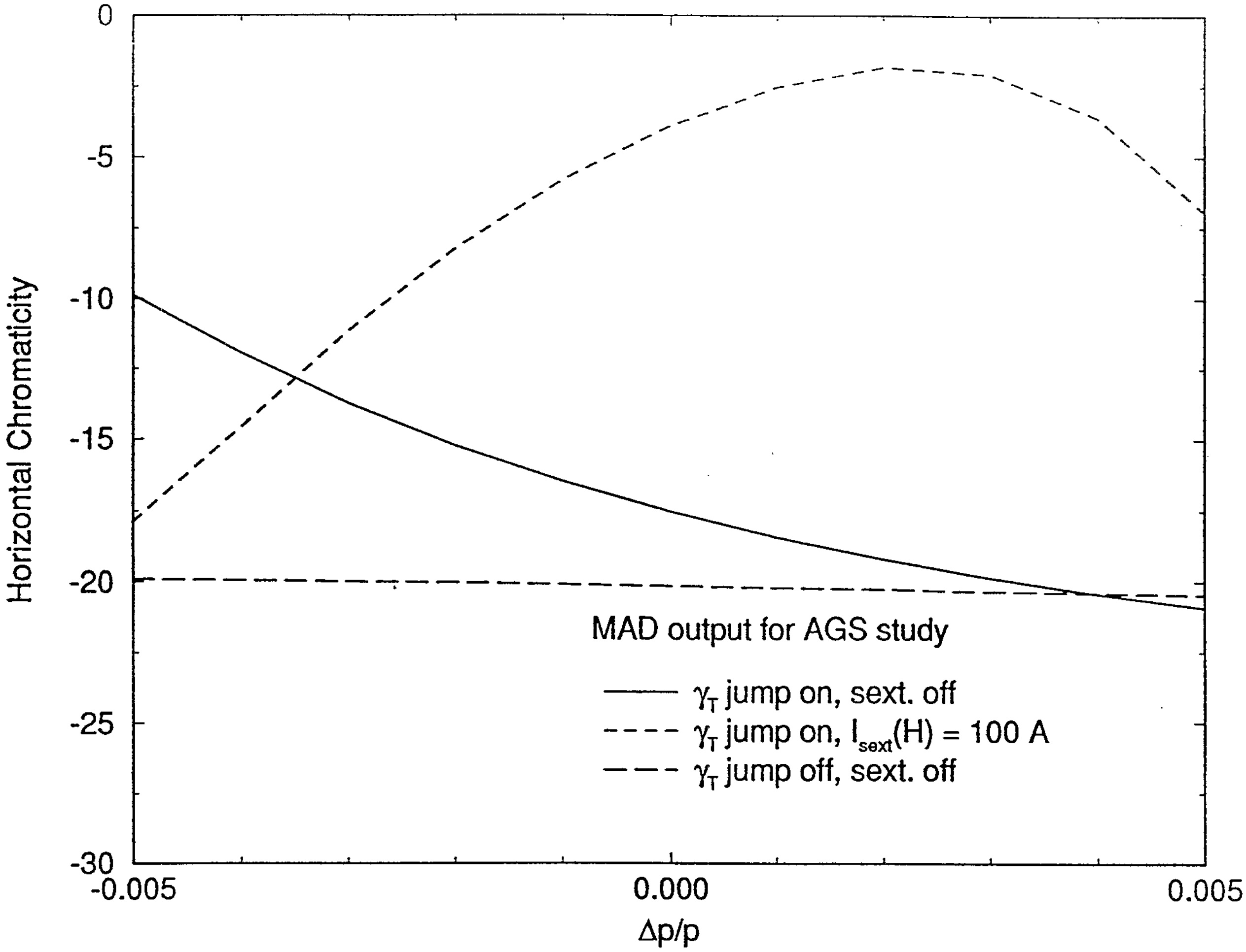
$\Rightarrow \Delta\gamma_T = 1.6$ for $\frac{\Delta p}{p} = 0$

sextupole on: $I_{sext}(H) = 100$ A,

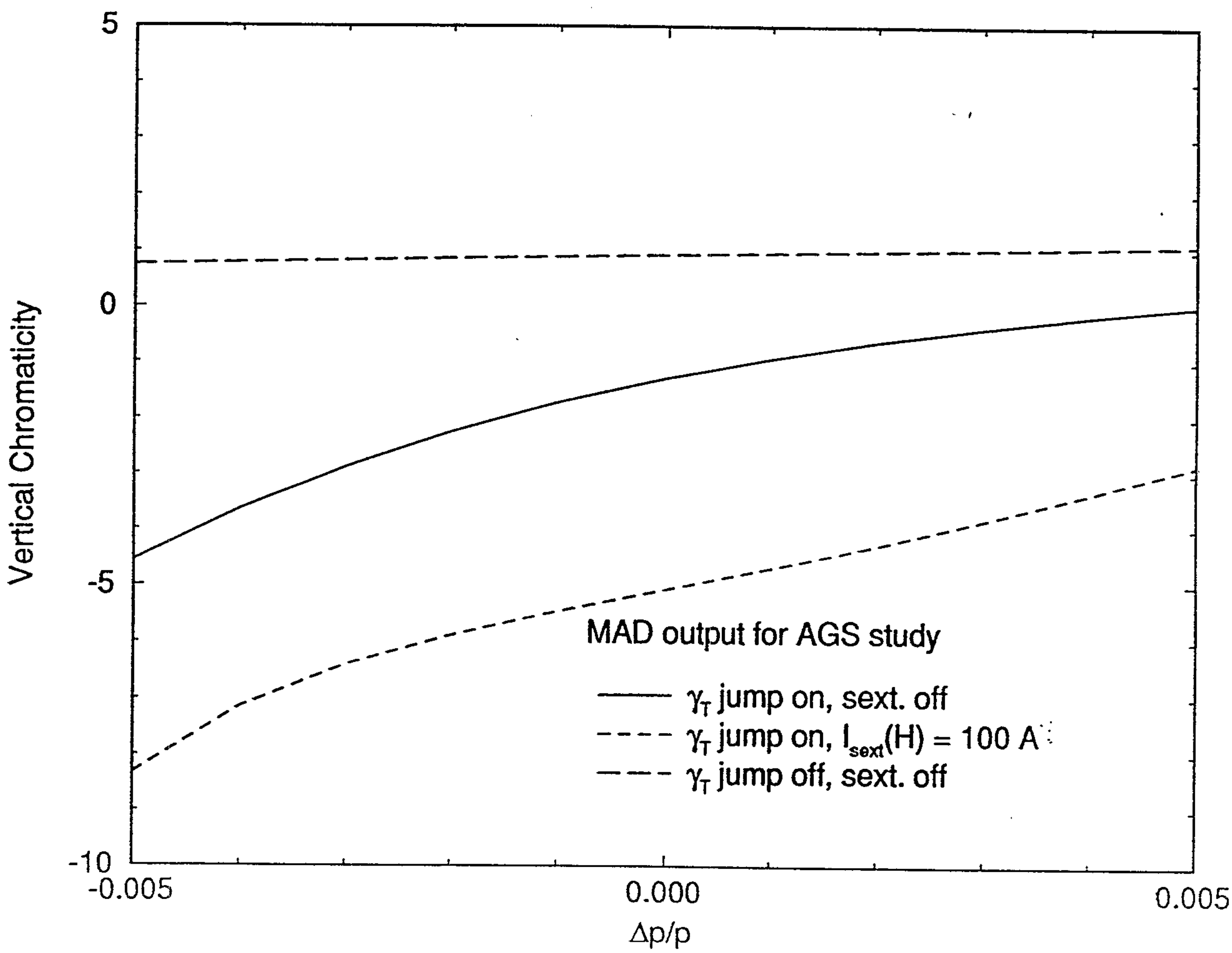
$I_{sext}(V) = 0$



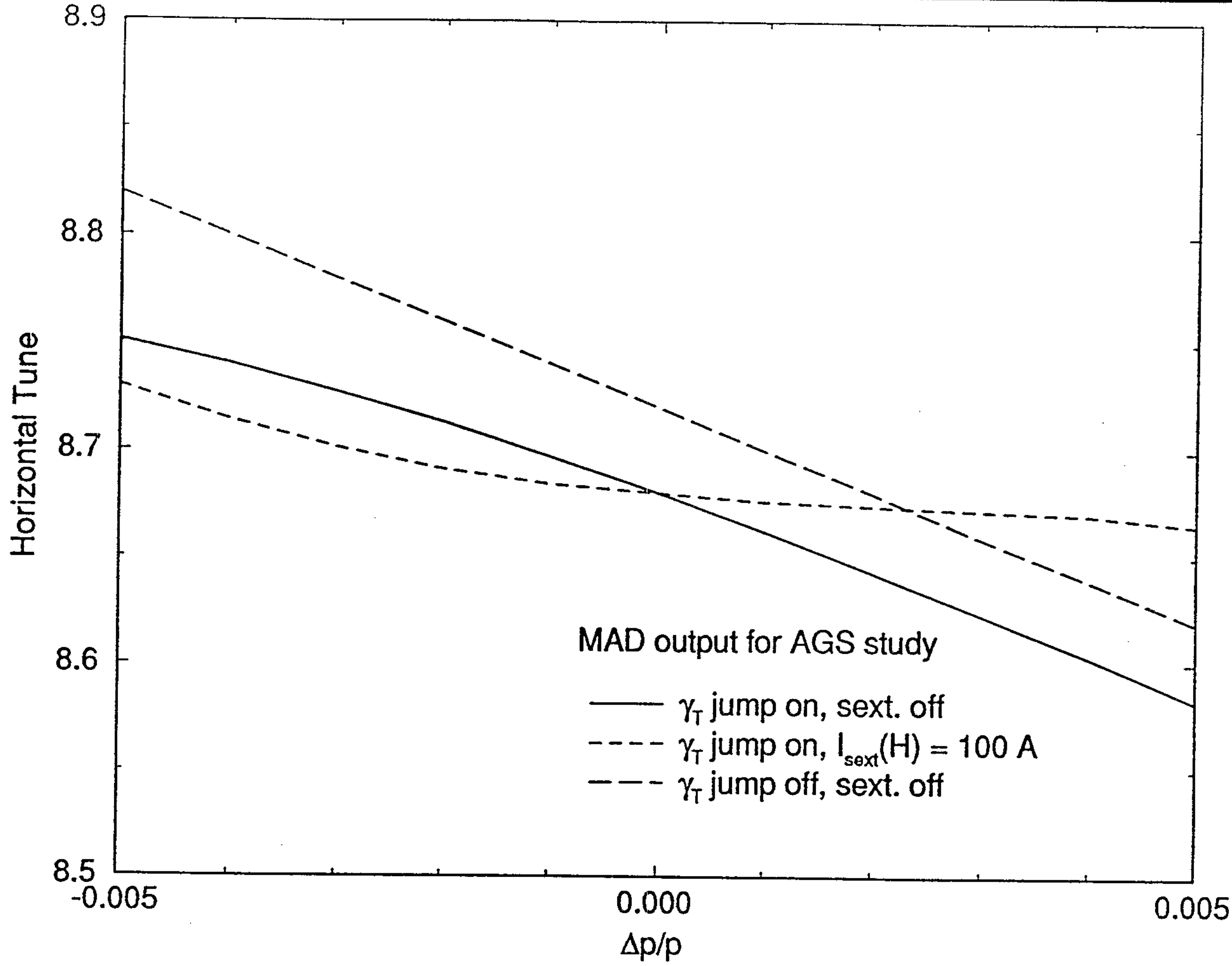
MAD output for AGS study
γ_T jump on, sext. off
γ_T jump on, $I_{sext}(H)$ = 100 A
γ_T jump off, sext. off
Maximum Horizontal Dispersion (m)
Δp/p
20
15
10
5
0
-0.005
0.000
0.005
8.6 m
2.2 m



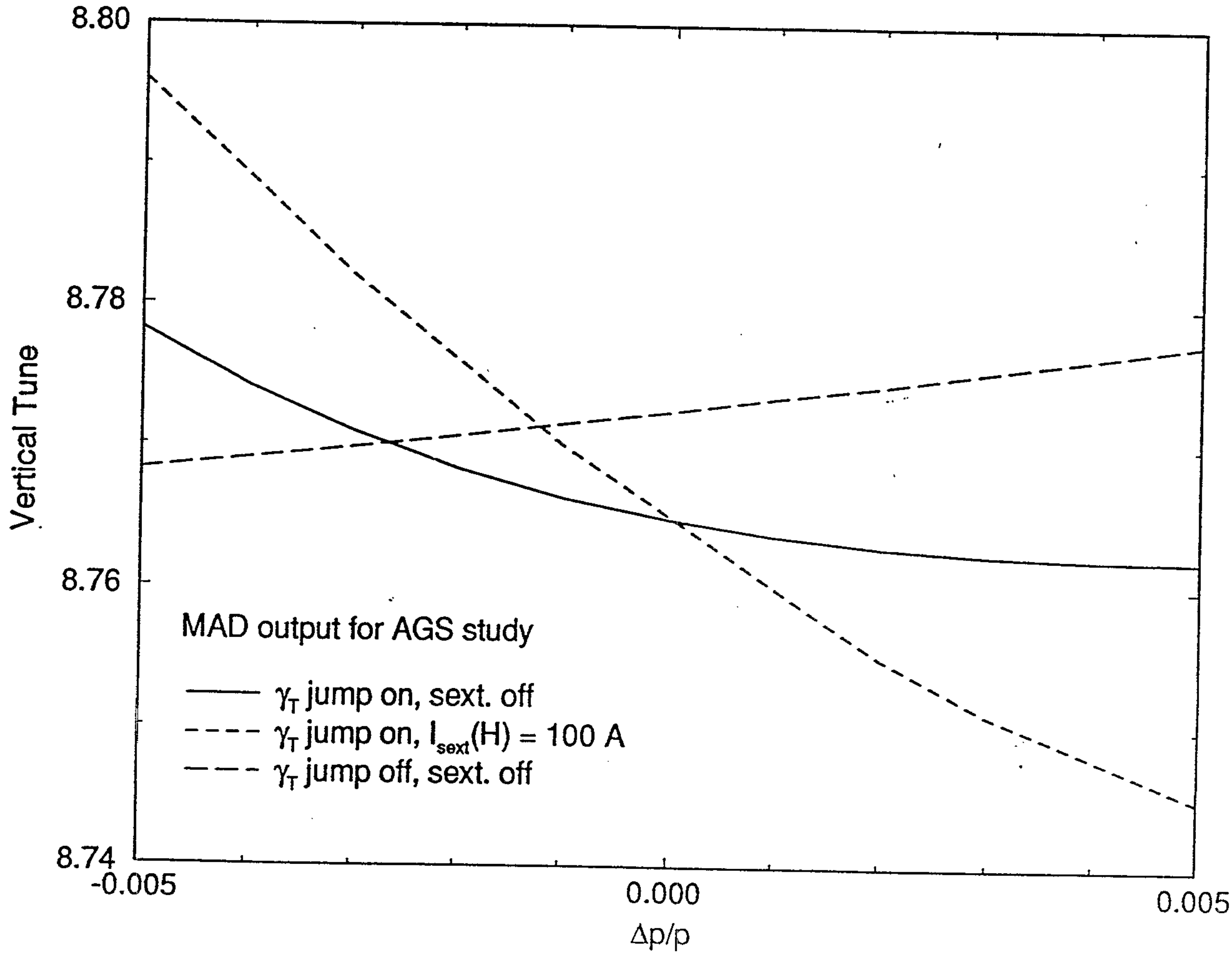
Horizontal Chromaticity
0
-5
-10
-15
-20
-25
-30
-0.005
0.000
0.005
Δp/p
MAD output for AGS study
γ_T jump on, sext. off
γ_T jump on, I_{sext}(H) = 100 A
γ_T jump off, sext. off



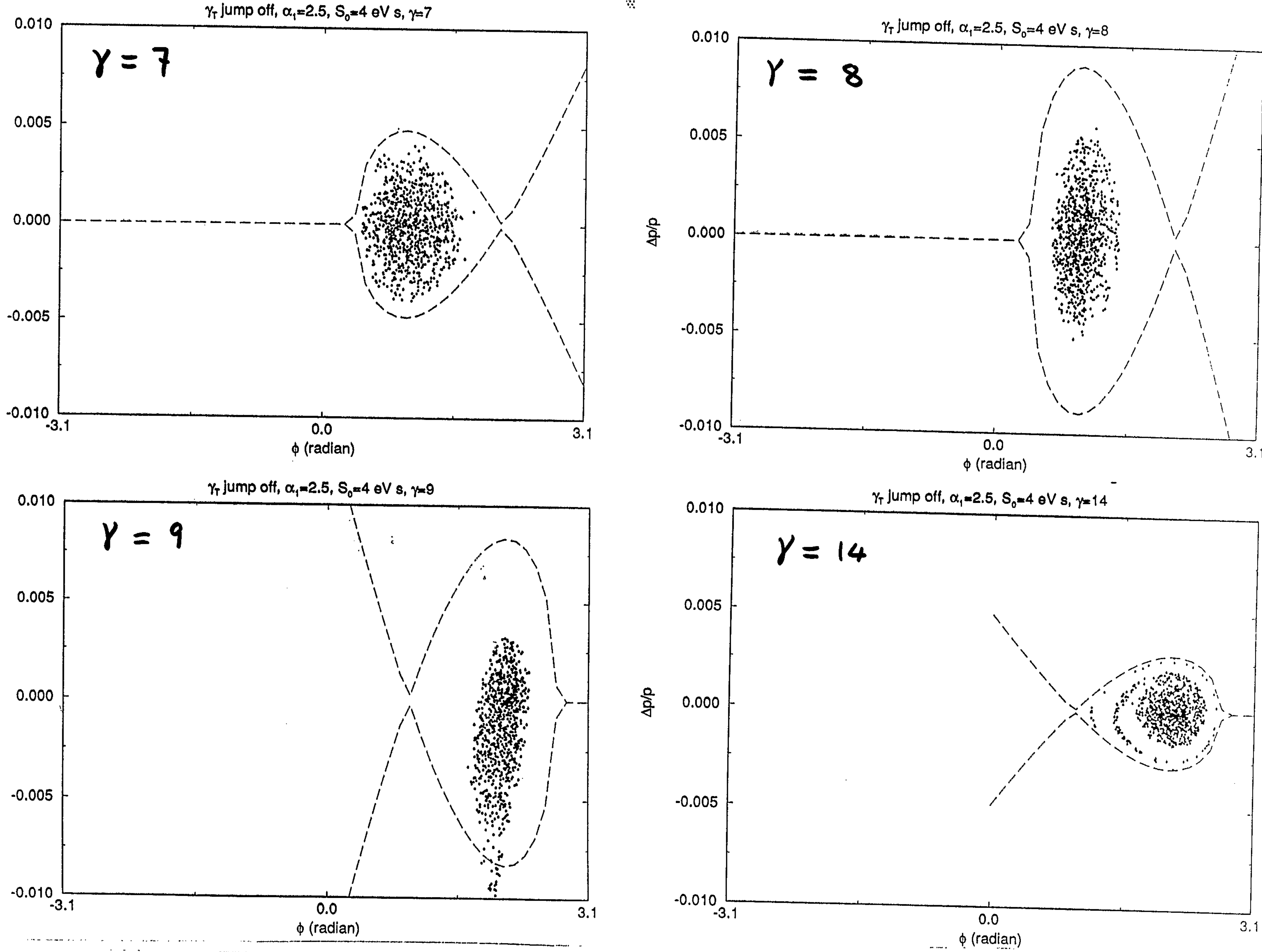
Vertical Chromaticity
5
0
-5
-10
-0.005
0.000
0.005
Δp/p
MAD output for AGS study
γ_T jump on, sext. off
γ_T jump on, I_{sext}(H) = 100 A
γ_T jump off, sext. off



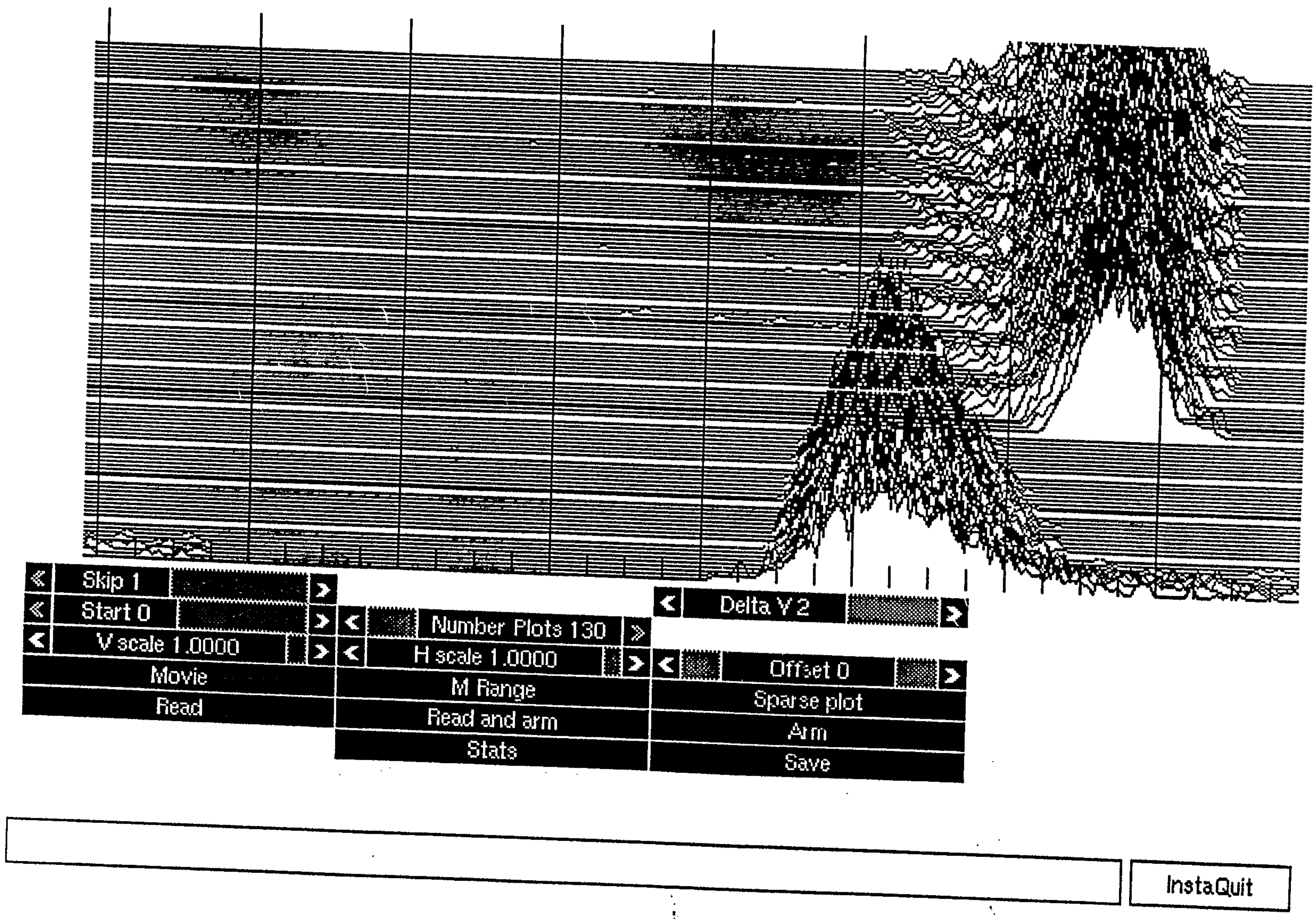
8.9
8.8
8.7
8.6
8.5
Horizontal Tune
-0.005
0.000
0.005
Δp/p
MAD output for AGS study
γT jump on, sext. off
γT jump on, Isext(H) = 100 A
γT jump off, sext. off



8.80
8.78
8.76
8.74
Vertical Tune
-0.005
0.000
0.005
Δp/p
MAD output for AGS study
γT jump on, sext. off
γT jump on, Isext(H) = 100 A
γT jump off, sext. off

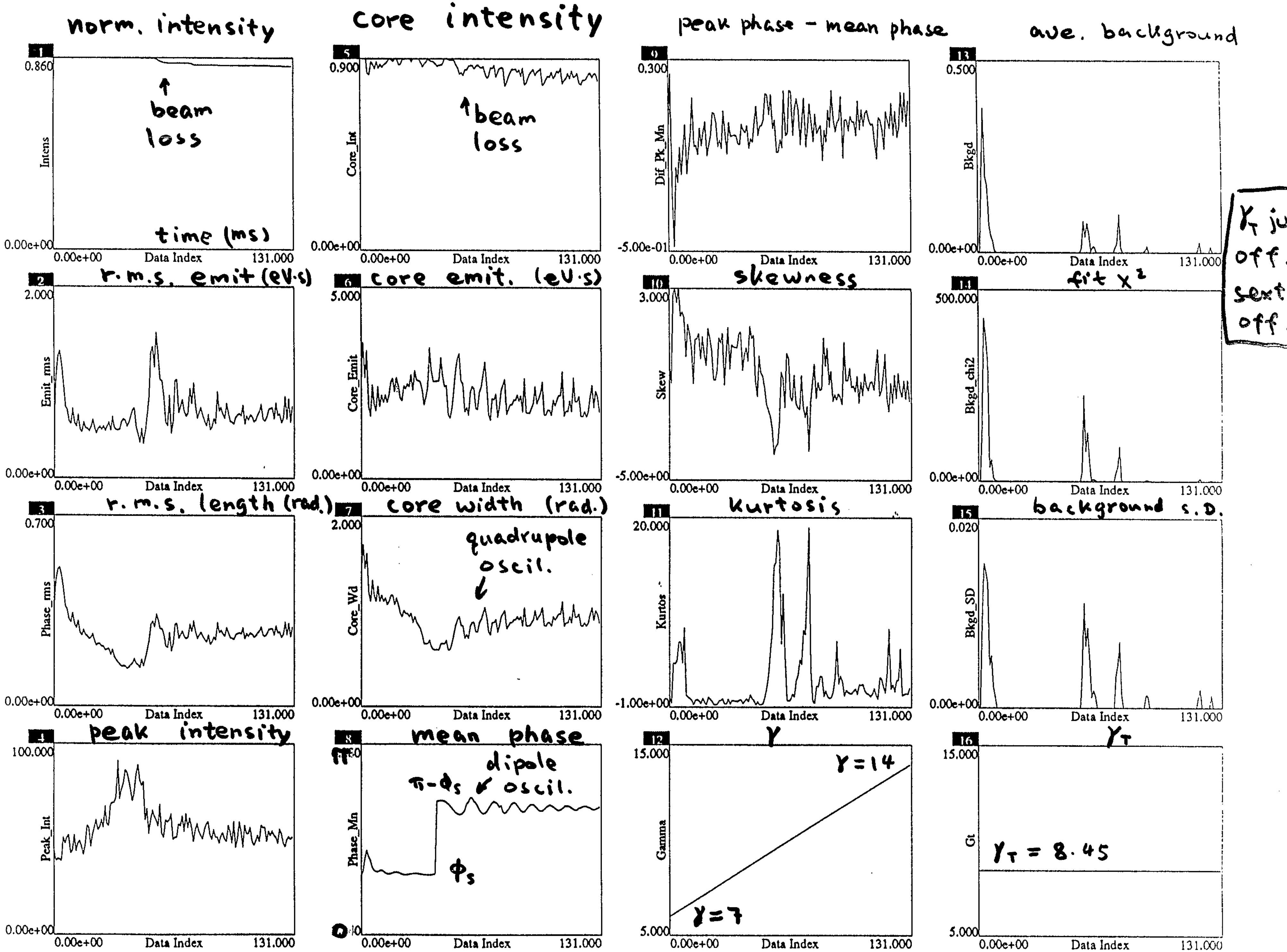


γT jump off, α1=2.5, S0=4 eV s, γ=7
γ = 7
0.010
0.005
0.000
-0.005
-0.010
-3.1
0.0
3.1
φ (radian)
γT jump off, α1=2.5, S0=4 eV s, γ=8
γ = 8
Δp/p
φ (radian)
γT jump off, α1=2.5, S0=4 eV s, γ=9
γ = 9
φ (radian)
γT jump off, α1=2.5, S0=4 eV s, γ=14
γ = 14
Δp/p
φ (radian)

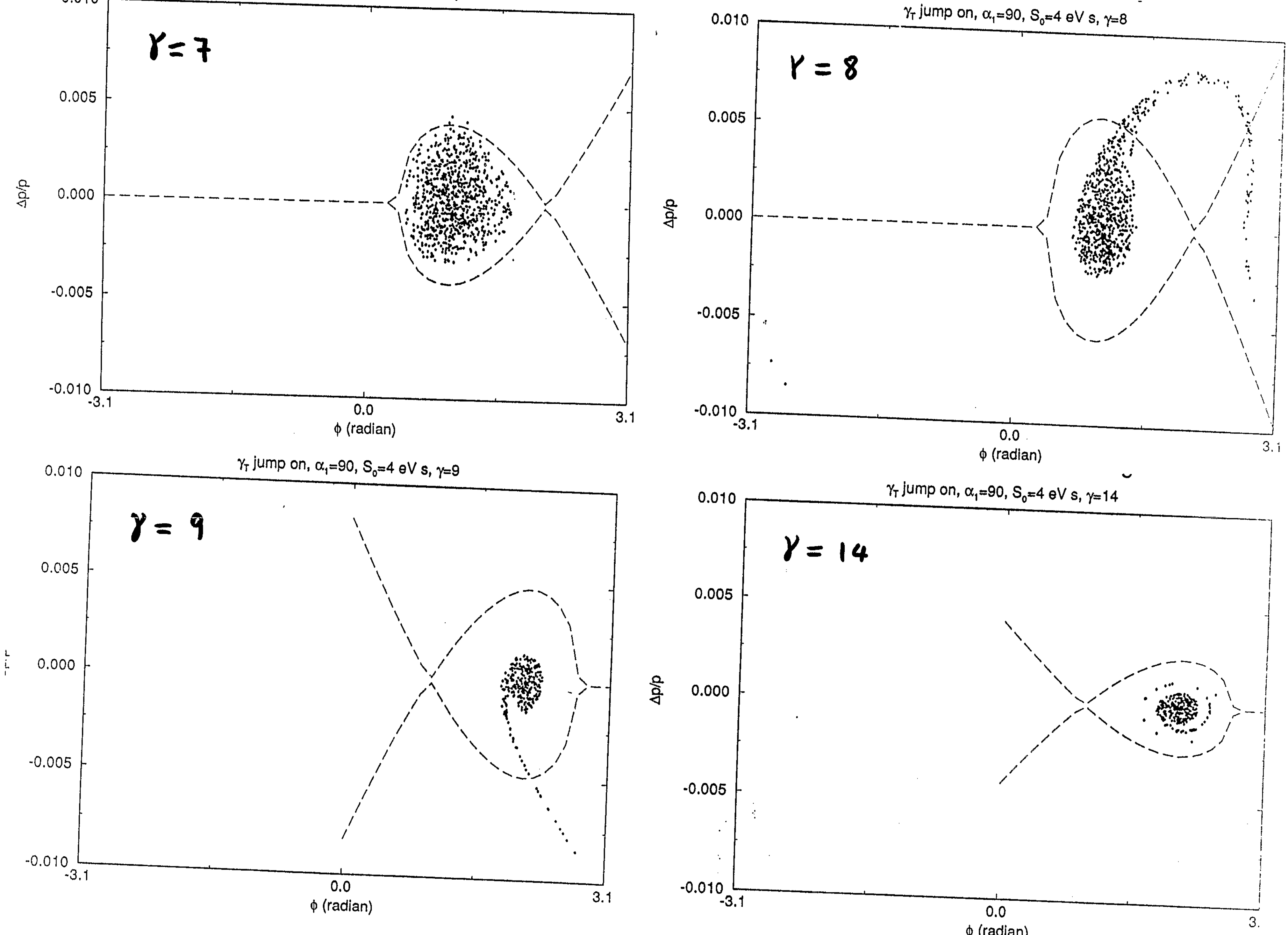


γ_T jump off

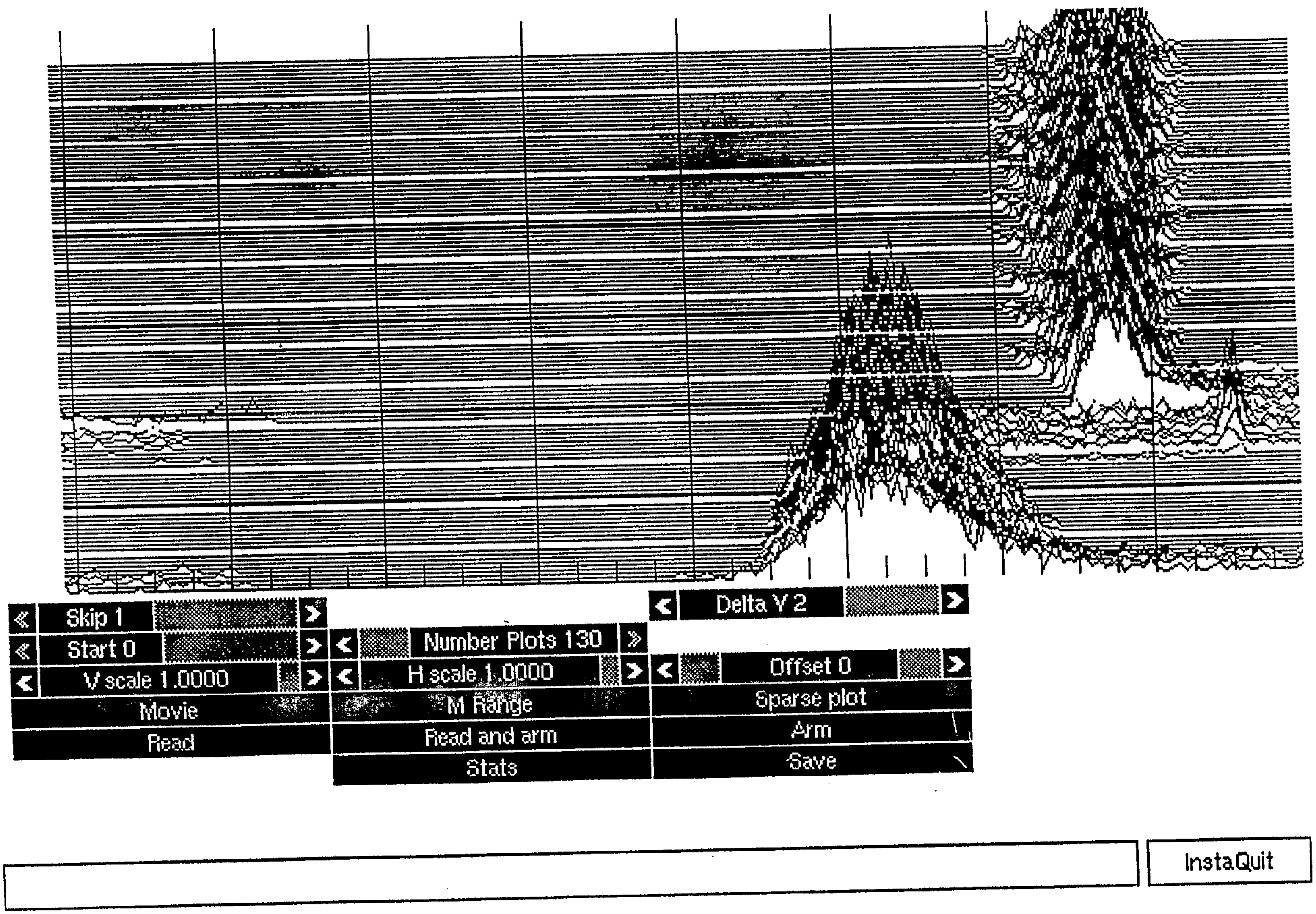
sext. off.



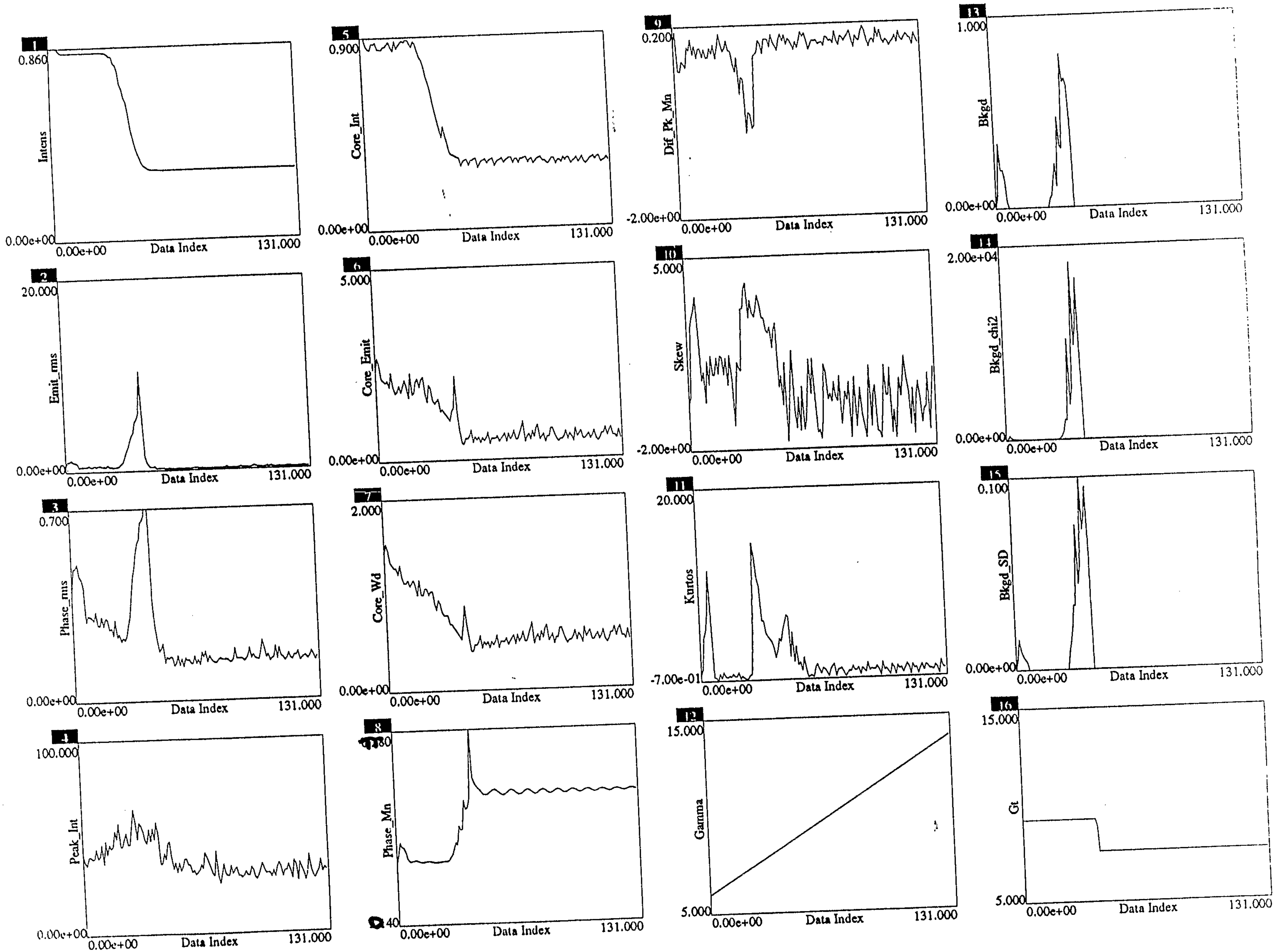
norm. intensity
core intensity
peak phase - mean phase
ave. background
beam loss
beam loss
time (ms)
r.m.s. emit (eV·s)
core emit. (eV·s)
skewness
fit χ²
r.m.s. length (rad.)
core width (rad.)
quadrupole oscil.
kurtosis
background s.D.
peak intensity
mean phase
dipole oscil.
π-φs
φs
γ
γ=14
γ=7
γT
γT = 8.45
Intens
Core_Int
Dif_Pk_Mn
Bkgd
Emit_rms
Core_Emit
Skew
Bkgd_chi2
Phase_rms
Core_Wd
Kurtos
Bkgd_SD
Peak_Int
Phase_Mn
Gamma
Gt
Data Index
0.00e+00
131.000



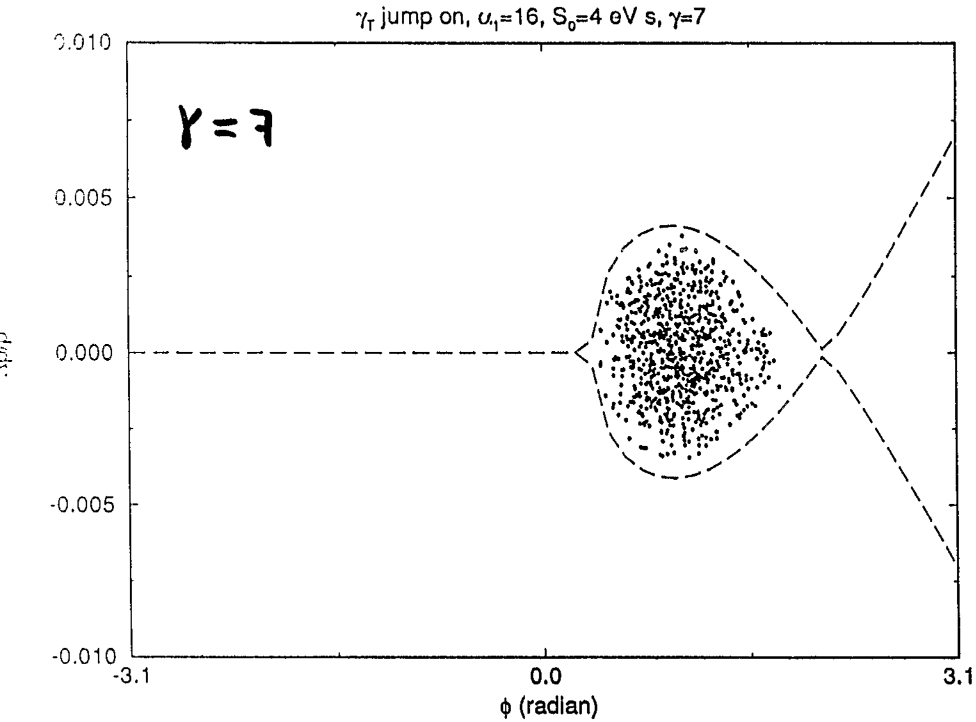
extreme case: $\alpha_1 = 90$ constant (actual: $\alpha_1 = 2.5 \rightarrow 90 \rightarrow 2.5$)

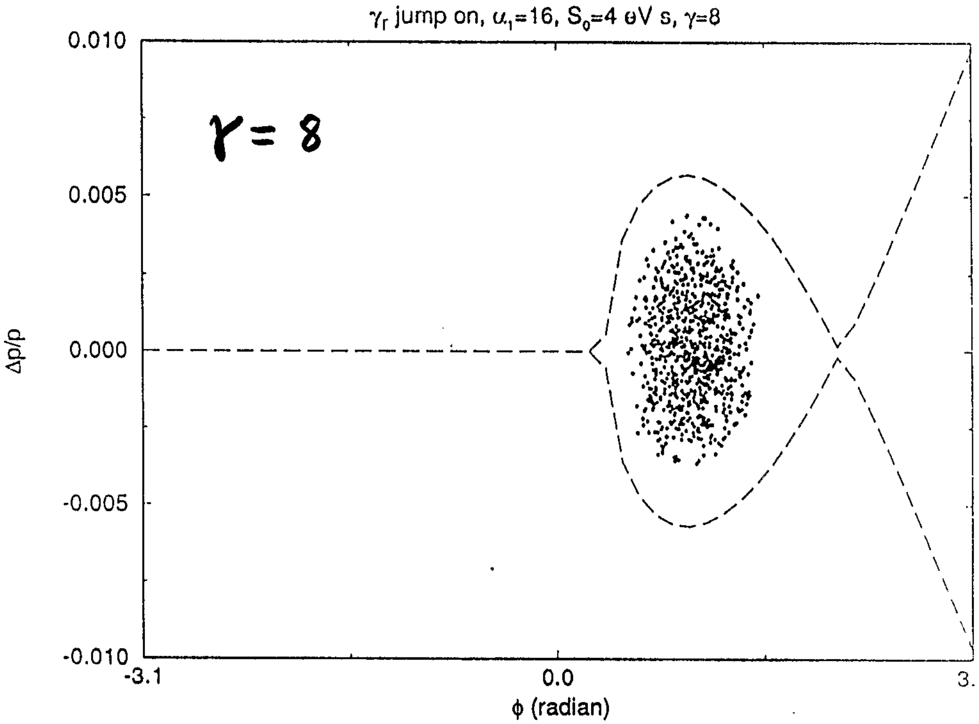


extreme case



extreme case





γ_T ju
on.
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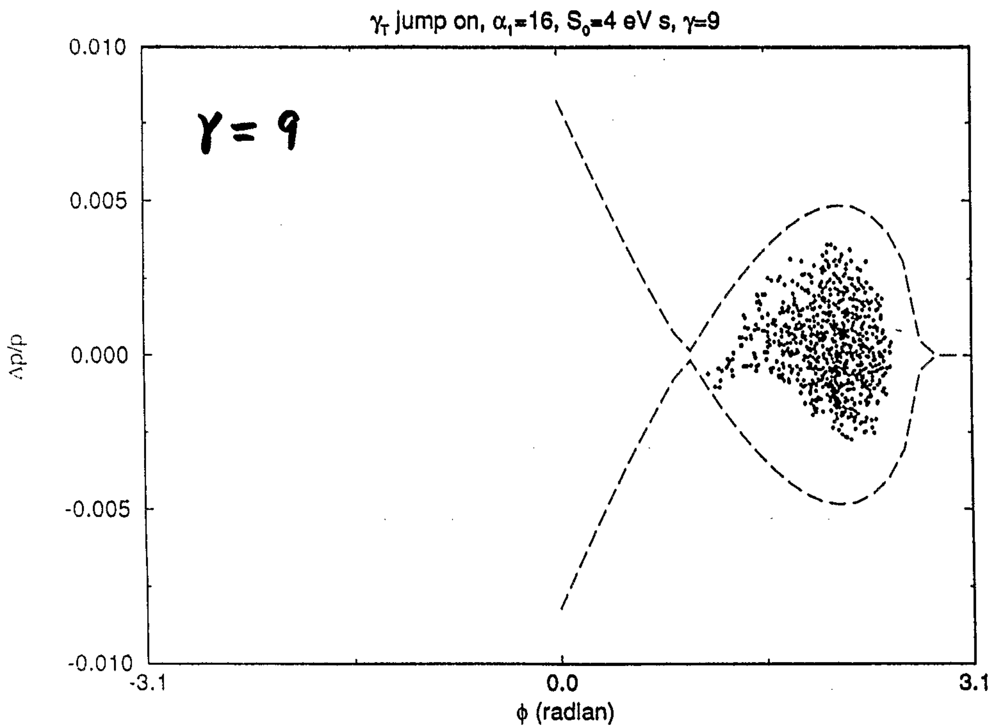
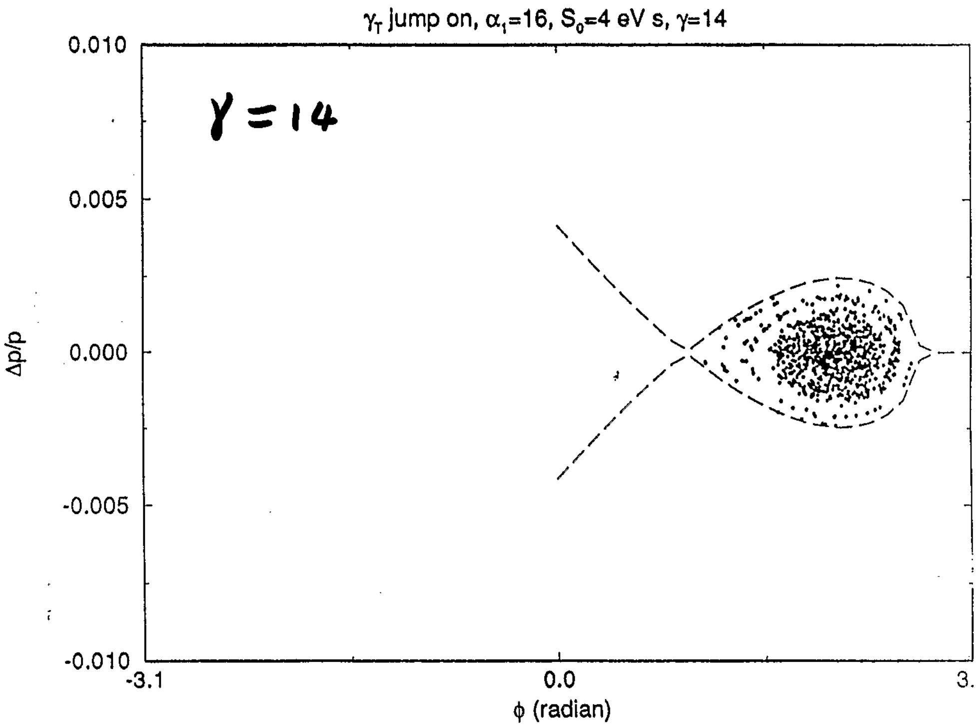
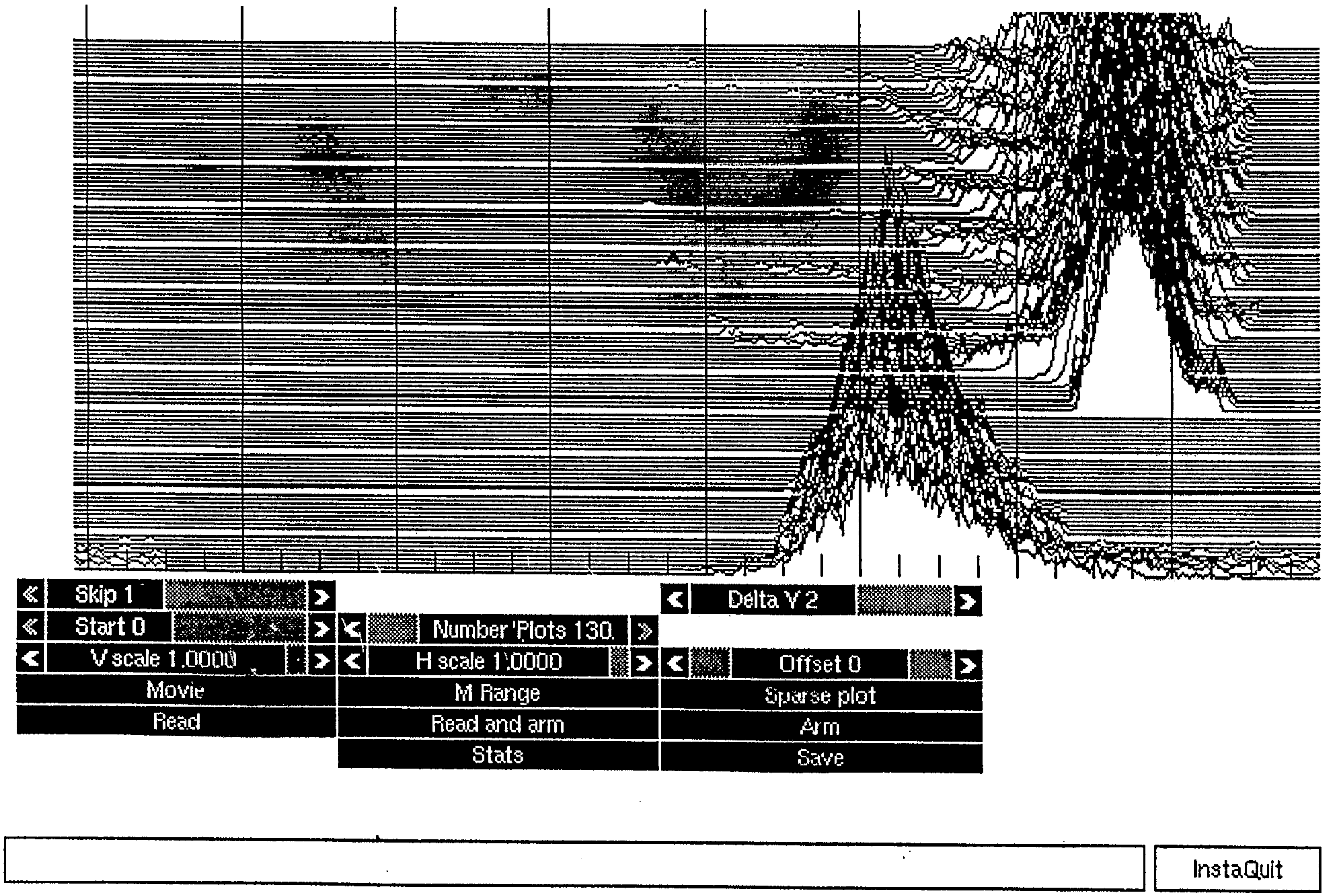
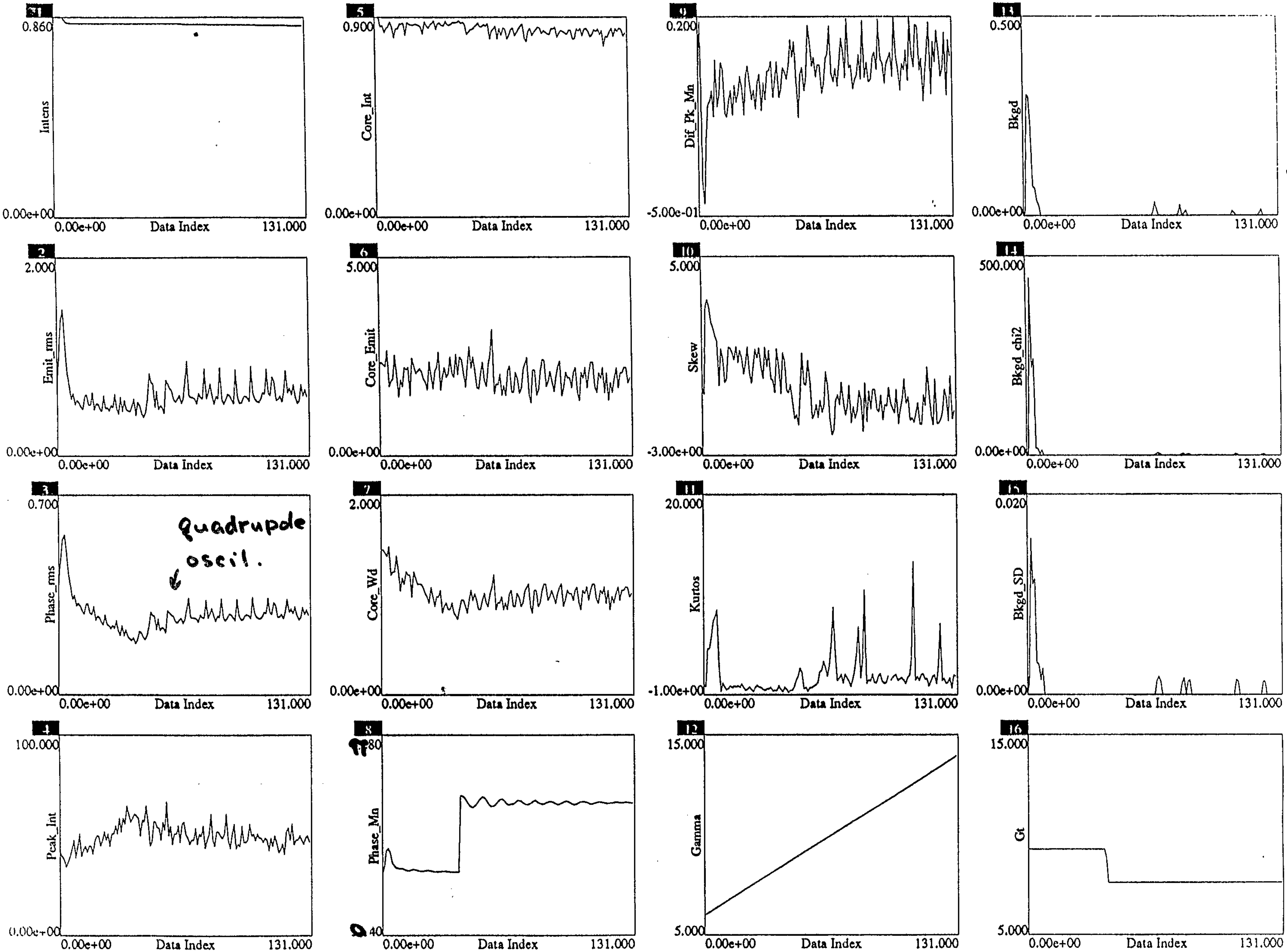
on.







γ_t jump on
sext. on



Y_t jum
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sext.
on.

Future improvements on simulation:

* α_1 ramp along with the jump
* program V_{rf}
* add radial loop tracking
* momentum aperture
* α_2 effect as per MAD

IV. Conclusions and Discussion

* The current γ_T jump scheme strongly distort the lattice and enhances nonlinearity α_1

  α_1 : 2.5 → 90 momentarily

  x_p : 2.2 → 8.6 m, on momentum

  14 m. at $\frac{\Delta p}{p} = -0.005$

* The current sextupole setup can greatly improve the longitudinal behaviour

  α_1 : 90 → 16

  but further limits the momentum aperture

* Improvements on γ_T jump / sextupole setup can improve the AGS operation