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TITLE *INEX MODELING OF THE BOEING RING OPTICAL RESONATOR FREE ELECTRON LASER*

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INEX Modeling of the Boeing Ring Optical Resonator Free-Electron Laser*

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We present new results from the integrated numerical model of the accelerator/beam transport system and ring optical resonator of the Boeing free-electron laser experiment. Modifications of the electron-beam transport have been included in a previously developed PARMELA model and are shown to reduce dramatically emittance growth in the 180° bend. The new numerically generated electron beam is used in the 3-D FEL simulation code FELEX to calculate expected laser characteristics with the ring optical resonator and the 5-m untapered THUNDER wiggler. Gain, extraction efficiency, and optical power are compared with experimental data. Performance sensitivity to optical cavity misalignments is studied.

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I. Introduction

The optical resonator of the Boeing rf-linac-driven free-electron laser (FEL) oscillator has been reconfigured during the past one year from a two mirror conventional optical cavity to a multiple-mirror unidirectional ring resonator. Characteristics of the performance of the FEL with the conventional resonator have reported in [1] and compared with theoretical simulations in [2]. The present work extends the modeling in [2] by incorporating changes in the beam transport system into the PARMELA model of the accelerator system. The resulting electron beam micropulse has been used to study some characteristics of the FEL with the ring optical resonator.

Modeling in [2] of the transport of the electron beam around the 180° bend of the Boeing accelerator system showed that emittance growth would be reduced as the transverse size of the electron beam at the entrance to the bend was reduced. Transport of the electrons between the end of the accelerator and the beginning of the 180° bend was accomplished by a FODO array of 10 quadrupoles. This system had a limited ability to focus the beam to a small size at the entrance of the bend. During the time that the optical elements of the ring resonator were being installed, the FODO array was replaced with two quadrupole triplets. The triplets could produce a smaller spot at the bend. This modification has been included in the accelerator model of [2], and we discuss the consequences for the numerically generated electron micropulse.

Operation of the ring resonator FEL has this far been hampered by startup problems. We study the sensitivity of the small-signal gain to variations of electron-beam properties. Startup is also hindered by improper alignment of the ring resonator which can cause large round-trip optical losses. We study some aspects of misalignments of the resonator. Finally, we obtain steady-state laser performance with the 5-m untapered THUNDER wiggler [3].

II. Accelerator/Electron Beam Transport Modeling

A complete description of the Boeing rf-linac can be found in [4]. A major problem with the operation of the beam transport system [2] has been large emittance growth during transport around the 180° bend. It was shown in [2] that this emittance growth is very sensitive to the transverse dimensions of the electron beam as it enters the bend. Reduction of emittance growth in the bend was achieved by using the FODO array of ten quadrupole magnets, located between the end of the accelerator and the entrance of the 180° bend, to focus the beam [2].

However, the FODO array had a limited focusing capability. Therefore, it was removed and replaced by two quadrupole triplet magnets. We have made the equivalent change in the PARMELA model of the accelerator/beam transport system. We found that the best performance was achieved by turning off the first triplet and only using the second one (the one closest to the bend's entrance). Figures [1] - [4] show, respectively, electron beam phase space properties from the numerical simulation at the end of the accelerator, at the entrance to the 180° bend, at the exit of the180° bend, and at the entrance to the wiggler. The "86%" normalized transverse emittance was reduced by the new focusing system from about 140π mm-mr to about 85π mm-mr. Experimentally, the measured emittance at the entrance to the wiggler was seen to drop from about 160 π mm-mr to about 100 π mm-mr (± 15%). Figure [5] shows further properties of the electron micropulse at the entrance to the wiggler: Fig. [5a] shows the current profile in a pulse of about 12 ps width; Fig. [5b] shows that the total energy spread is about 0.25%; Figs. [5e] and [5d] show, respectively, the variation of the x-emittance and y-emittance as a function of position within the micropulse (the plane of the 180° bend is the xz plane).

III. FEL Simulations

The optical resonator of the Boeing FEL was changed from a conventional two mirror resonator [1], [2] to a unidirectional ring resonator [5], [6] which consists of two telescopes. Each telescope has a grazing angle-of-incidence hyperboloidal mirror and a paraboloidal mirror. Eventually, sideband suppression and output coupling will be done via a grating rhomb, but at present the gratings have been replaced by two flat mirrors one of which is used as an output coupler.

Proper alignment of the ring resonator has been difficult to achieve. A primary consequence of this has been the measurement of anomalously large empty cavity roundtrip optical losses. For example, for perfect alignment, the known mirror reflectivities yield a round-trip cavity loss of about 23.75%. Tilting the downstream paraboloid by 4μR increases the loss to about 25.5%, and increasing the tilt to 10μR causes the losses to rise to 63.7%. A preliminary alignment resulted in measured round-trip losses of 70-80% per pass. For comparison, the previous two mirror cavity typically had losses of 7.5% per pass [2].

Under these circumstances, startup of the laser has been difficult and erratic. We have, therefore, studied the dependence of the expected small-signal gain upon various characteristics of the electron beam and wiggler. We expect that there will be fluctuations from micropulse to micropulse about the characteristics given by the PARMELA simulations. Figure 6 shows contour plots of the small-signal gain (defined to be the output power divided by the input power) for various values of peak current and energy spread (for a fixed emittance of 105π mm-mr). Figure 7 shows contour plots of gain as a function of energy spread and emittance for a fixed peak current of 250A. Figure 8 shows contour plots of the gain as a function of peak current and emittance at a fixed energy spread of 0.5%. All of these results are from single-pass single-wavefront 3-D FEL-

EX simulations. Some additional results: mismatch of the electron beam to the wiggler by ± 50% (which results in betatron oscillations) reduces the small-signal gain by about a factor of two; offset of the optical axis from the electron beam (assumed to be coaxial with the wiggler) by one-half of the empty cavity focal spot radius reduces the gain by 30%, while an offset equal to the focal spot radius reduces the gain by 60%; 0.5% rms wiggler field errors reduce the gain by about 30% from the perfect wiggler case.

All of the above calculations were single-pass, assuming that the initial optical mode was Gaussian with a 2.4-m Rayleigh range. We have also performed several different kinds of multiple pass simulations. In Fig. (9a) we show the calculated oscillation ("walking mode", [7], [8]) of the optical beam centroid due to a 4 μR tilt of the downstream paraboloid for the unloaded cavity. In Fig. (9b) we show the same plot except in the presence of gain. Note that the steady-state displacement of the centroid of the optical mode is about two thirds of the radius of the focal spot for the aligned cavity. The small-signal gain is reduced by about a factor of four from that in the aligned case. Elimination of walking mode effects appears to be a sensitive way to align the ring resonator [9].

Resonator alignment determines round-trip losses and can be critical in determining if the FEL is above threshold. Figure 10 shows startup simulations from spontaneous emission noise for two cases, 80% round-trip loss and 70% round trip loss. The assumed electron beam conditions were 240A peak current, 160π mm-mr emittance, and 1% energy spread. The 80% loss case achieves only 10% net gain after 100 passes, while the 70% loss case reaches saturation. Losses during startup exceed the empty cavity losses because the spontaneous emission is not limited to the lowest order empty cavity eigenmodes.

Finally, we have studied the effects of jitter of the mean energy of successive micropulses upon the performance of the FEL. Figure (11a) shows the buildup to steady state for the extraction efficiency for a 250 A, 105 π mm-mr emittance, 0.5% energy spread electron beam in an aligned resonator. Figure (11b) shows the effects of 0.3% rms random jitter in the mean micropulse energy: one sees that the steady state extraction efficiency is reduced from the no jitter case by about 30%.

IV. Summary and Conclusions

We have studied some aspects of the Boeing ring optical resonator FEL oscillator experiment with the INEX simulation method. We modified the previous transport line between the end of the rf-linac and the entrance of the 180° bend and found that emittance growth in the bend was substantially (by about 40%) reduced, in qualitative agreement with experiments. We have studied the dependence of the small-signal gain upon various electron-beam parameters such as peak current, emittance, and energy spread. We have also studied gain degradation due to an offset between the wiggler and optical axes, and wiggler field errors. Multiple pass simulations were used to study walking mode effects in a misaligned resonator, startup from spontaneous emission noise, and performance with jitter in the micropulse mean energy.

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9. S. C. Bender, private communication.

Figure 1: Calculated electron beam phase space characteristics at the end of the linac.

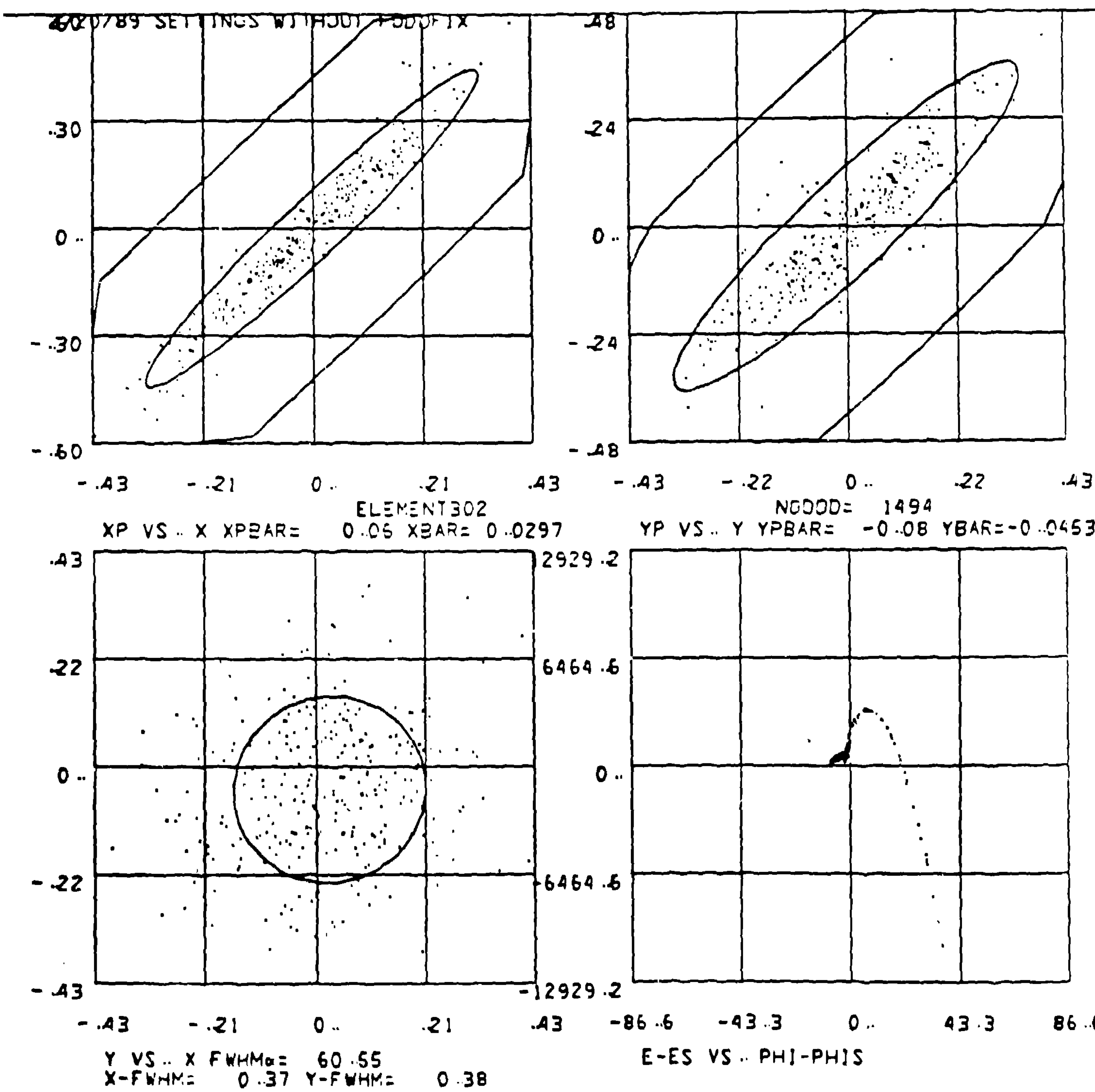


Figure 2: Calculated electron beam phase space characteristics at the entrance to the 180° bend.

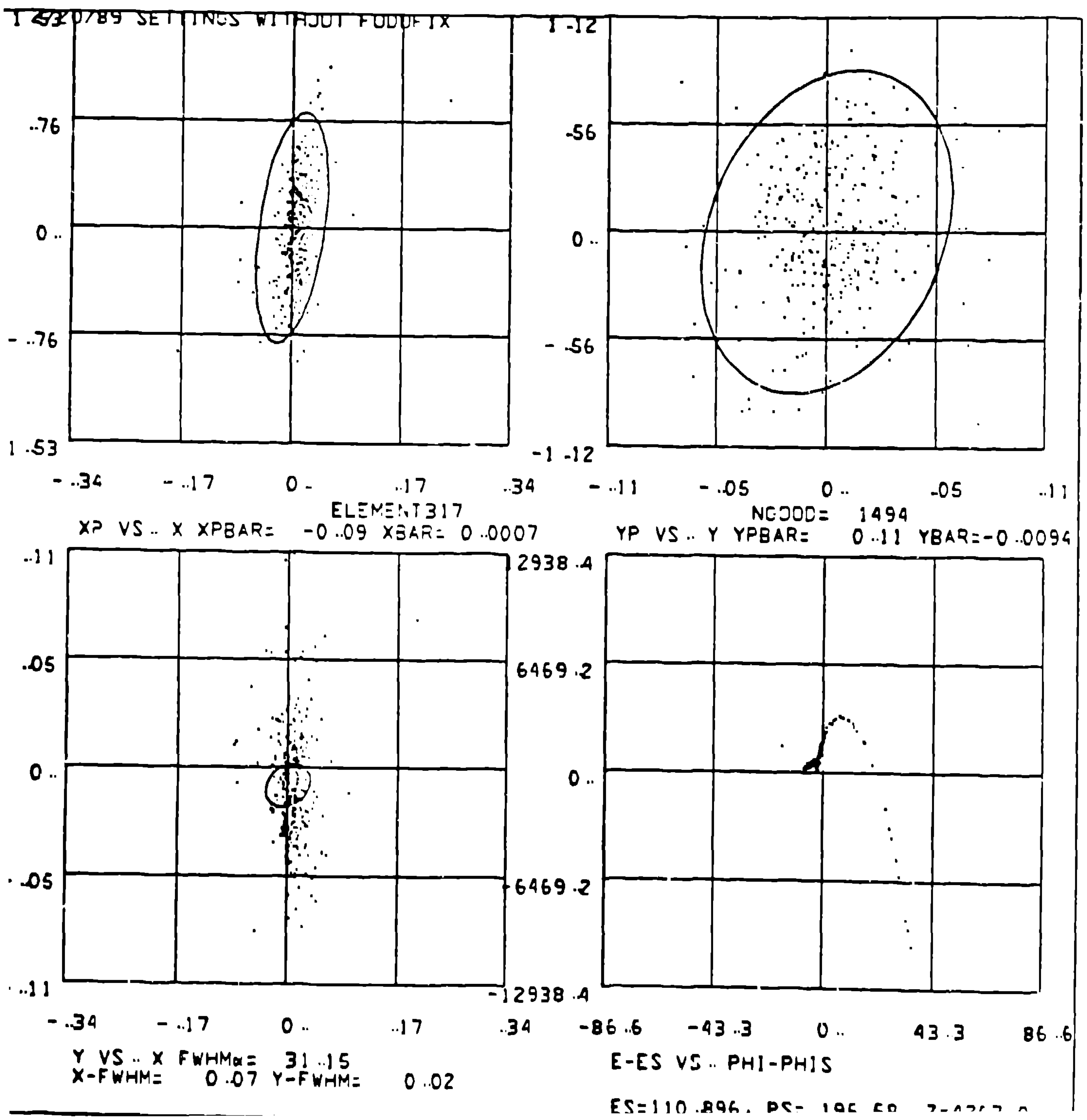


Figure 3: Calculated electron beam phase space characteristics at the exit of the 180° bend.

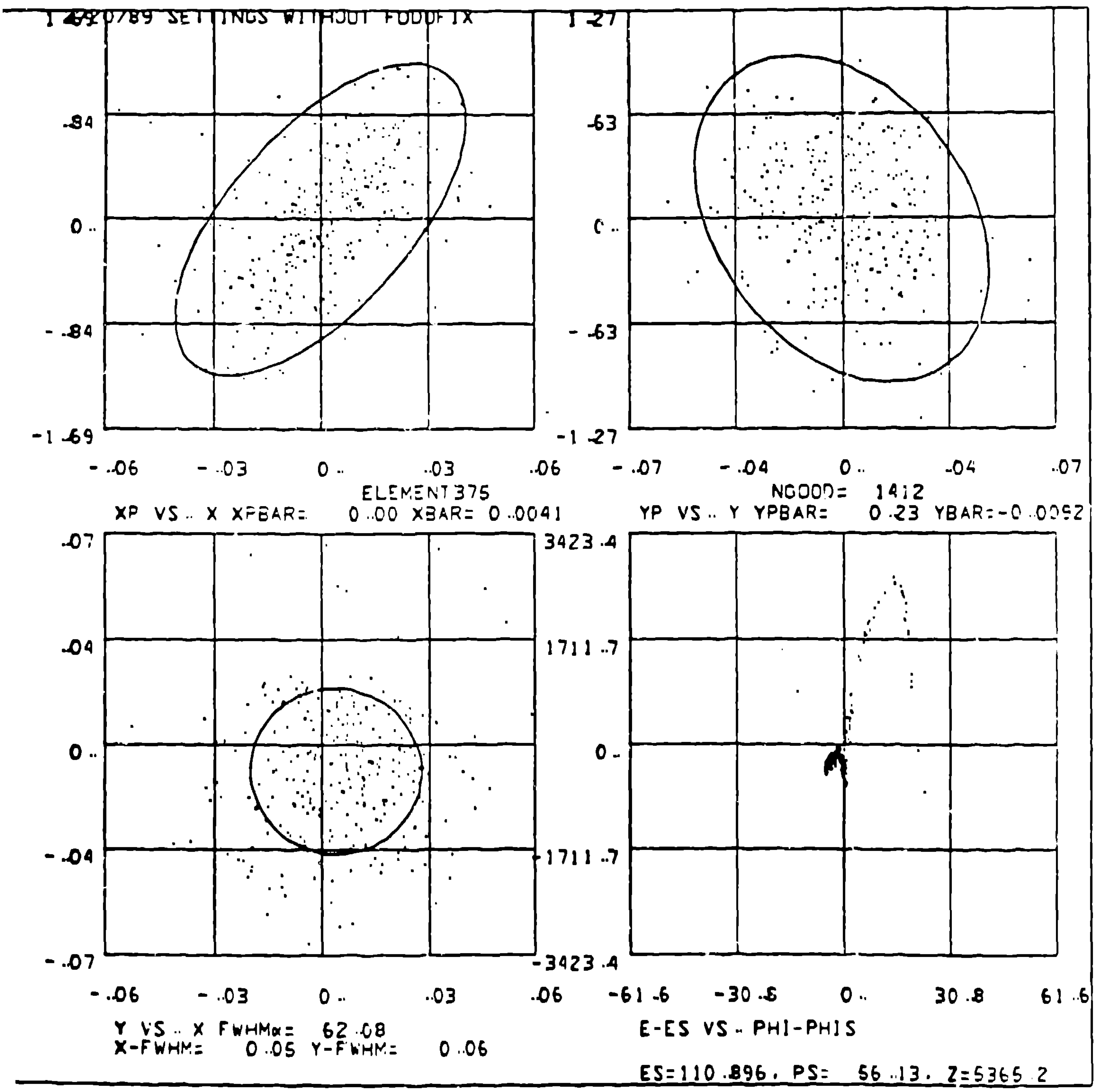


Figure 4: Calculated electron beam phase-space characteristics at the entrance to the wiggler magnet.

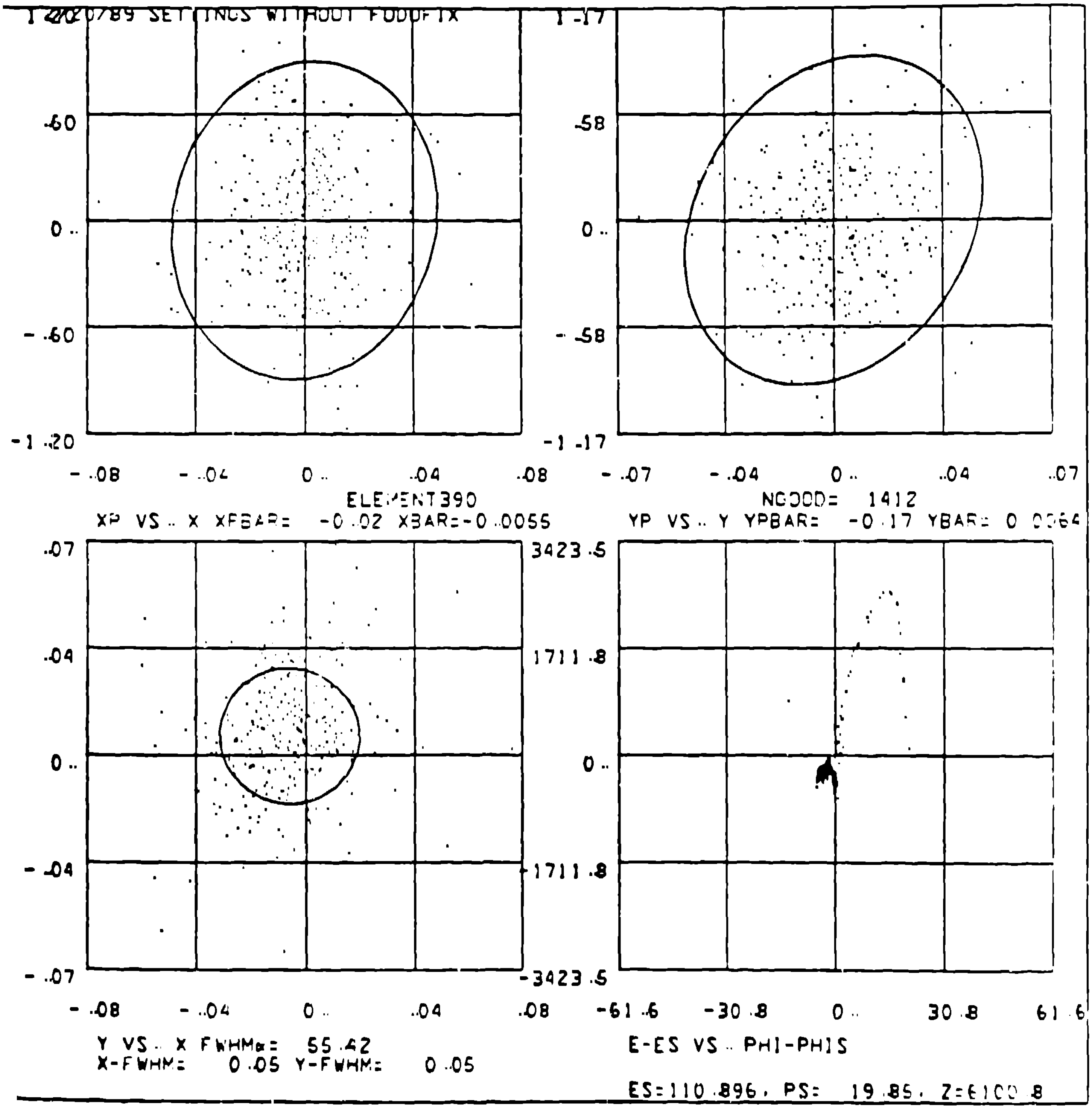


Figure 5a: Calculated micropulse current profile.

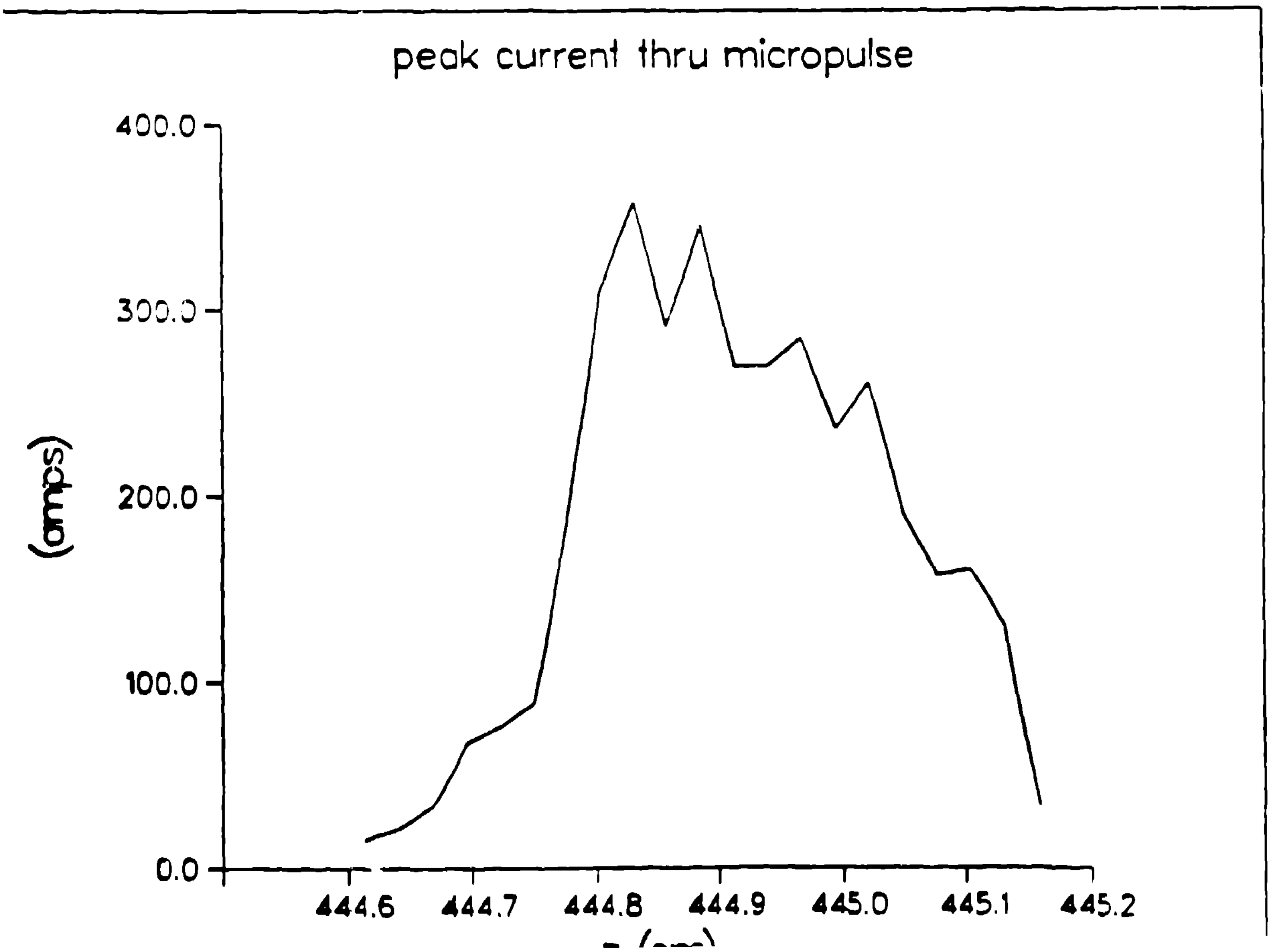


Figure 5b: Calculated micropulse energy distribution.

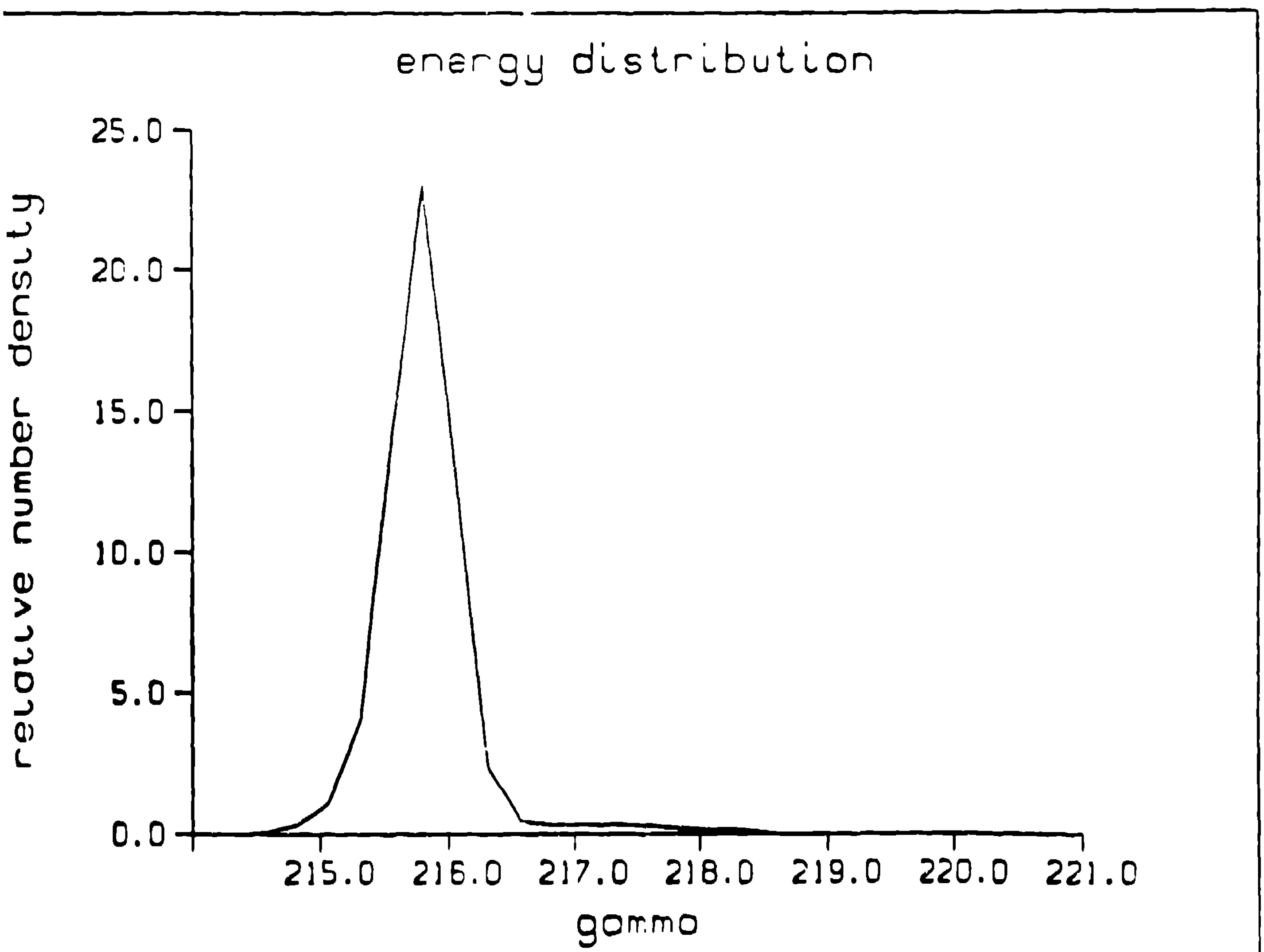


Figure 5c: Calculated x-emittance vs. position in micropulse.

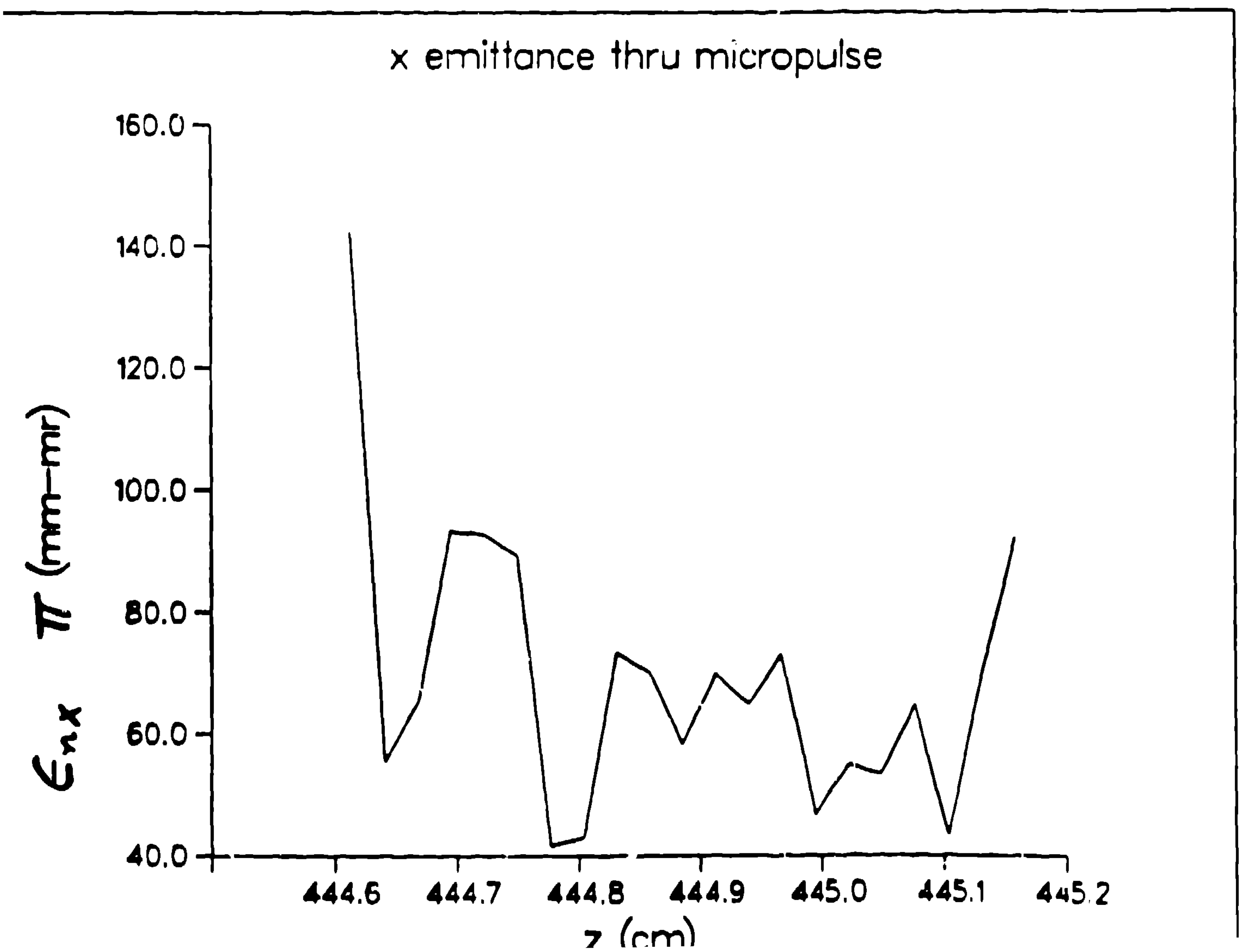


Figure 5d: Calculated y-emittance vs. position in micropulse.

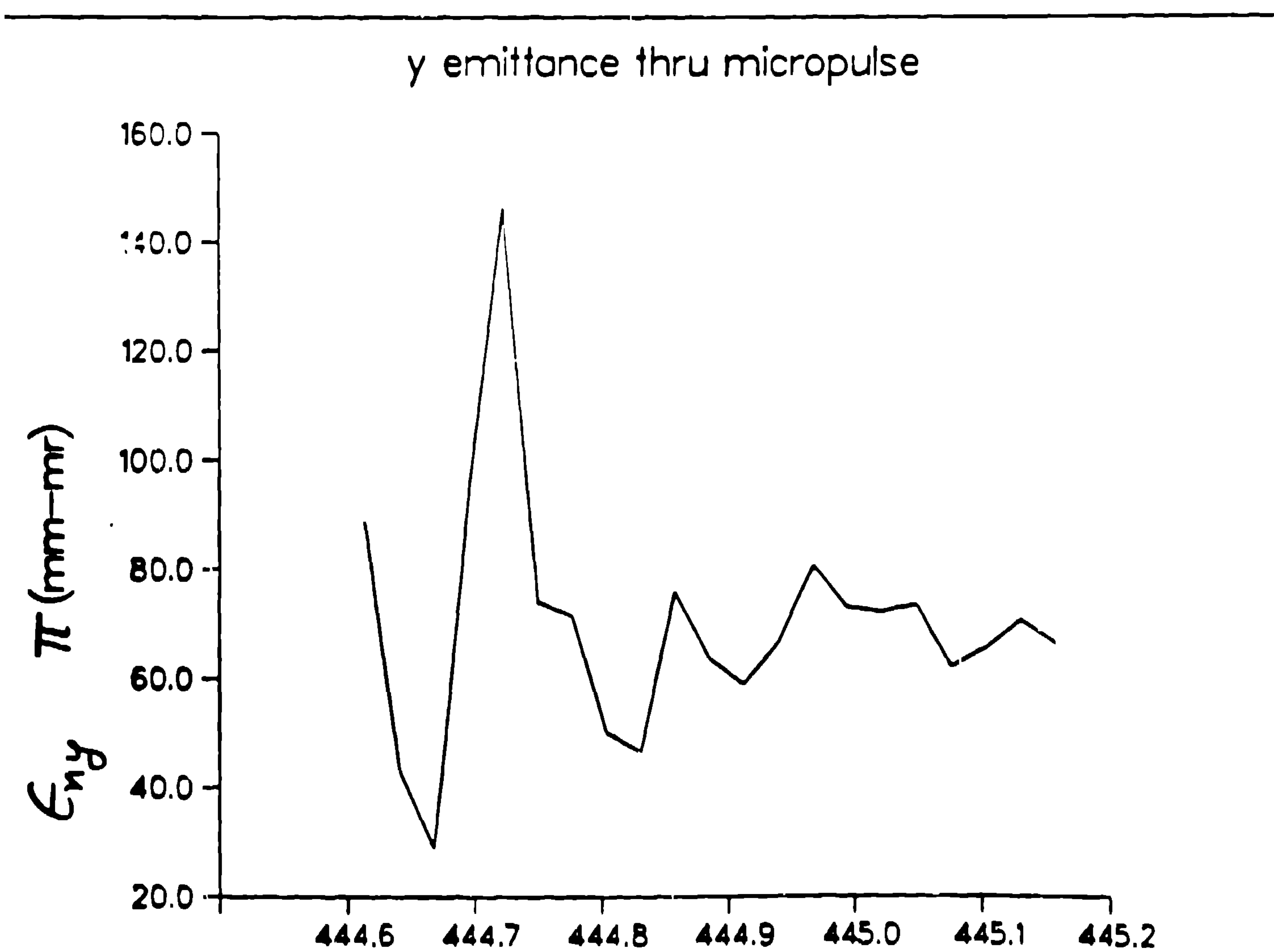


Figure 6: Small-signal gain as a function of peak current and energy spread at a fixed emittance of 105π mm-mr.

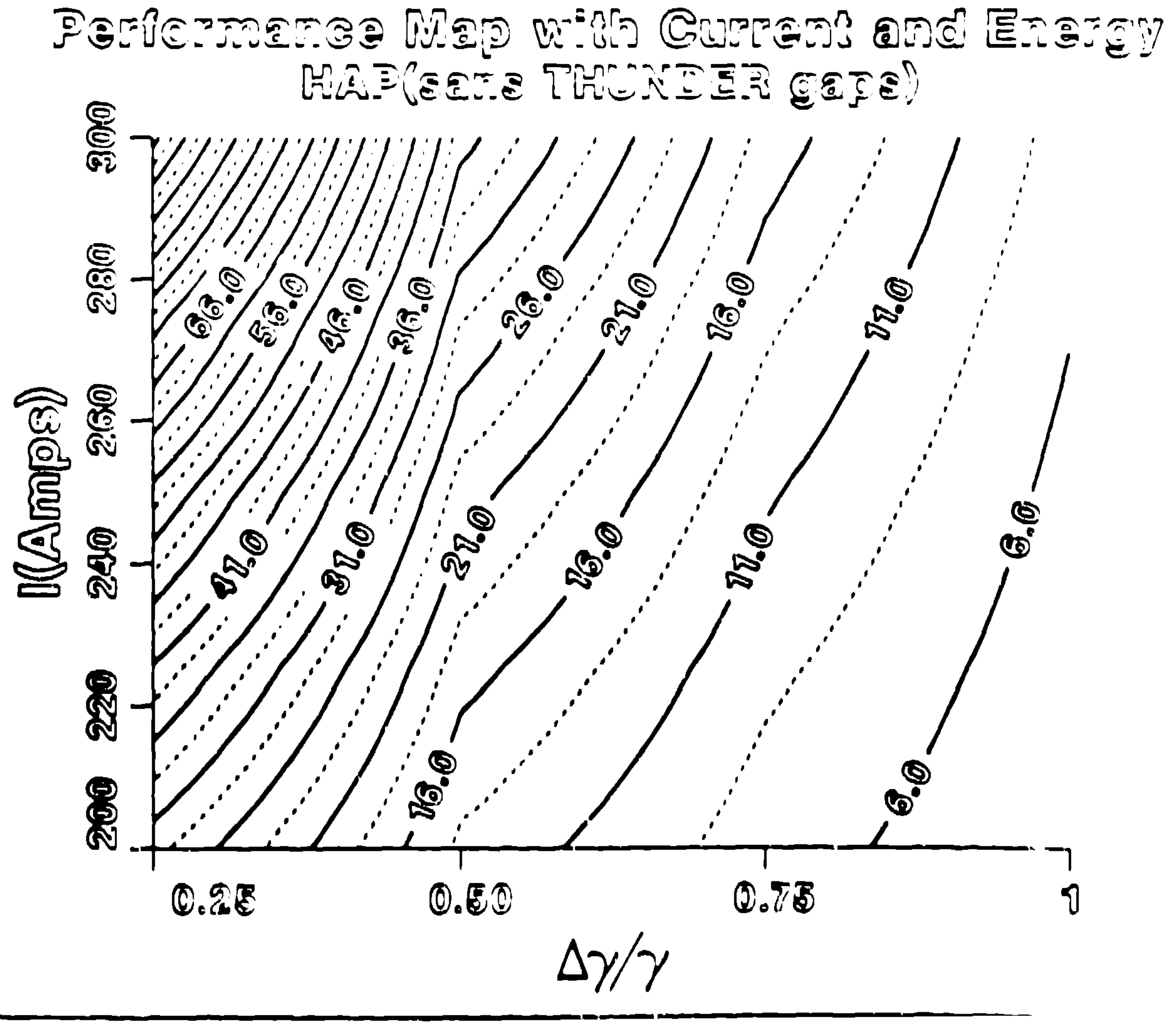


Figure 7: Small-signal gain as a function of energy spread and emittance at a fixed peak current of 250A.

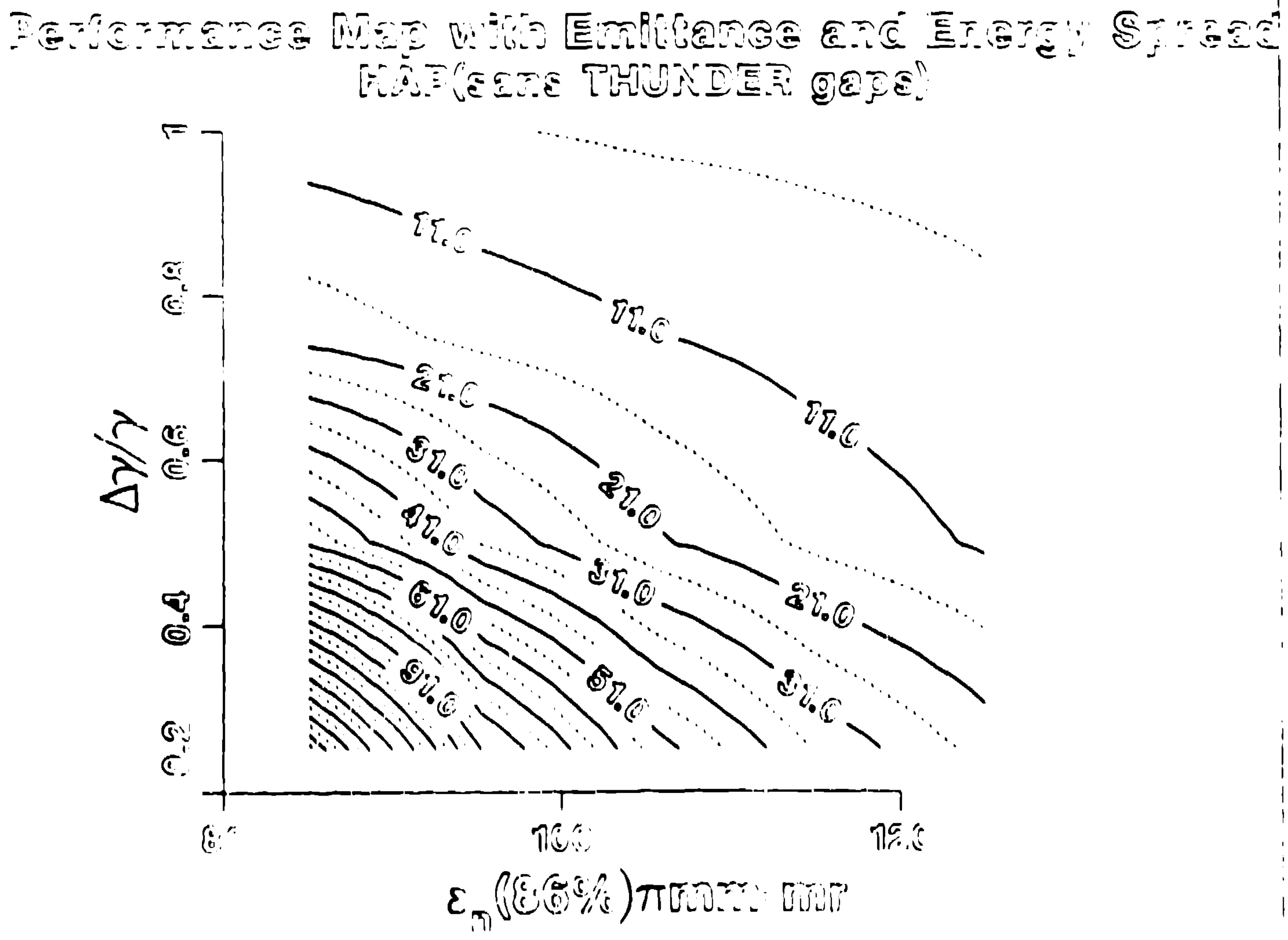


Figure 8: Small-signal gain as a function of peak current and emittance at a fixed energy spread of 0.5%.

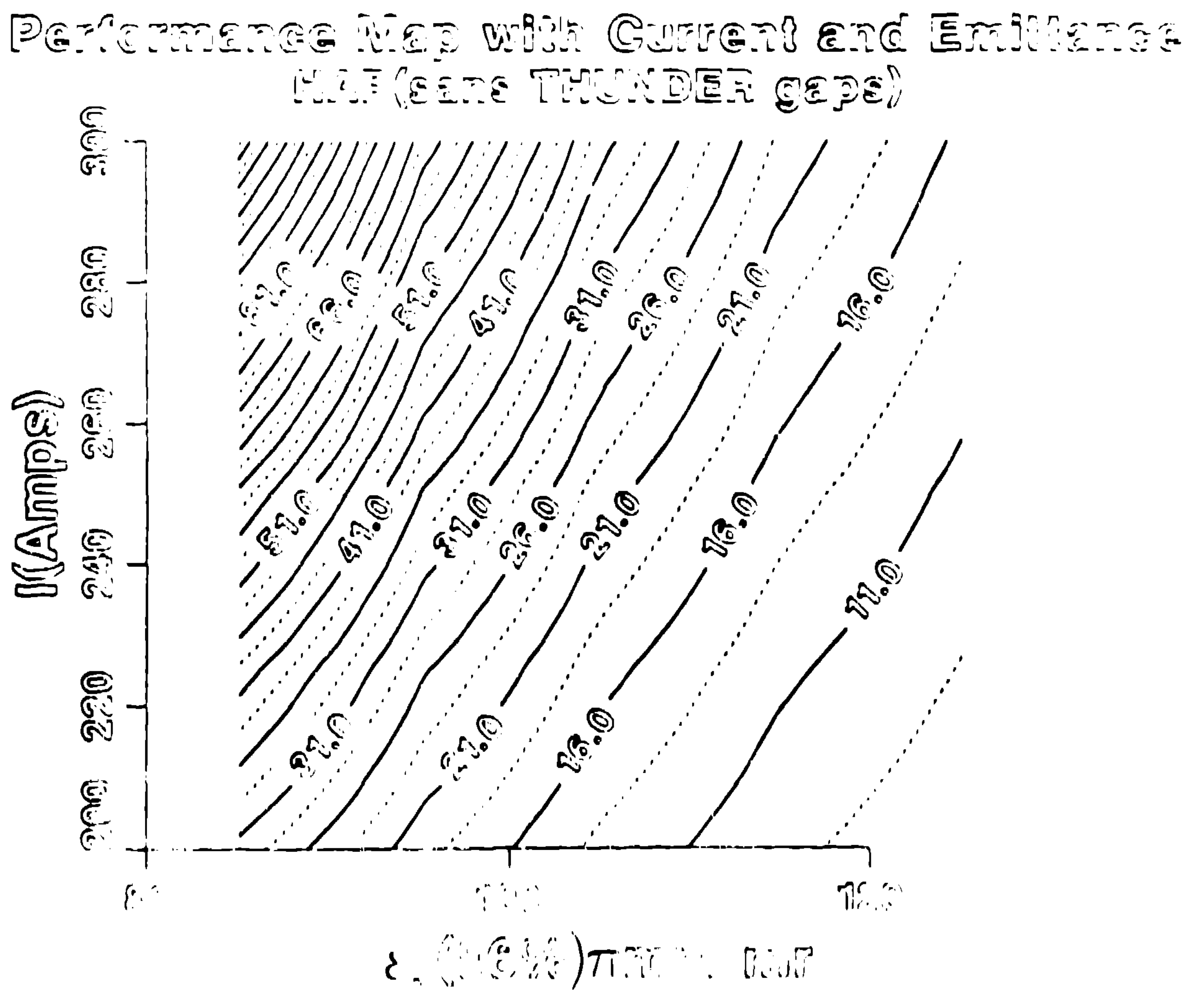


Figure 9a: Empty cavity walking mode for 4μR tilt of the downstream paraboloid.

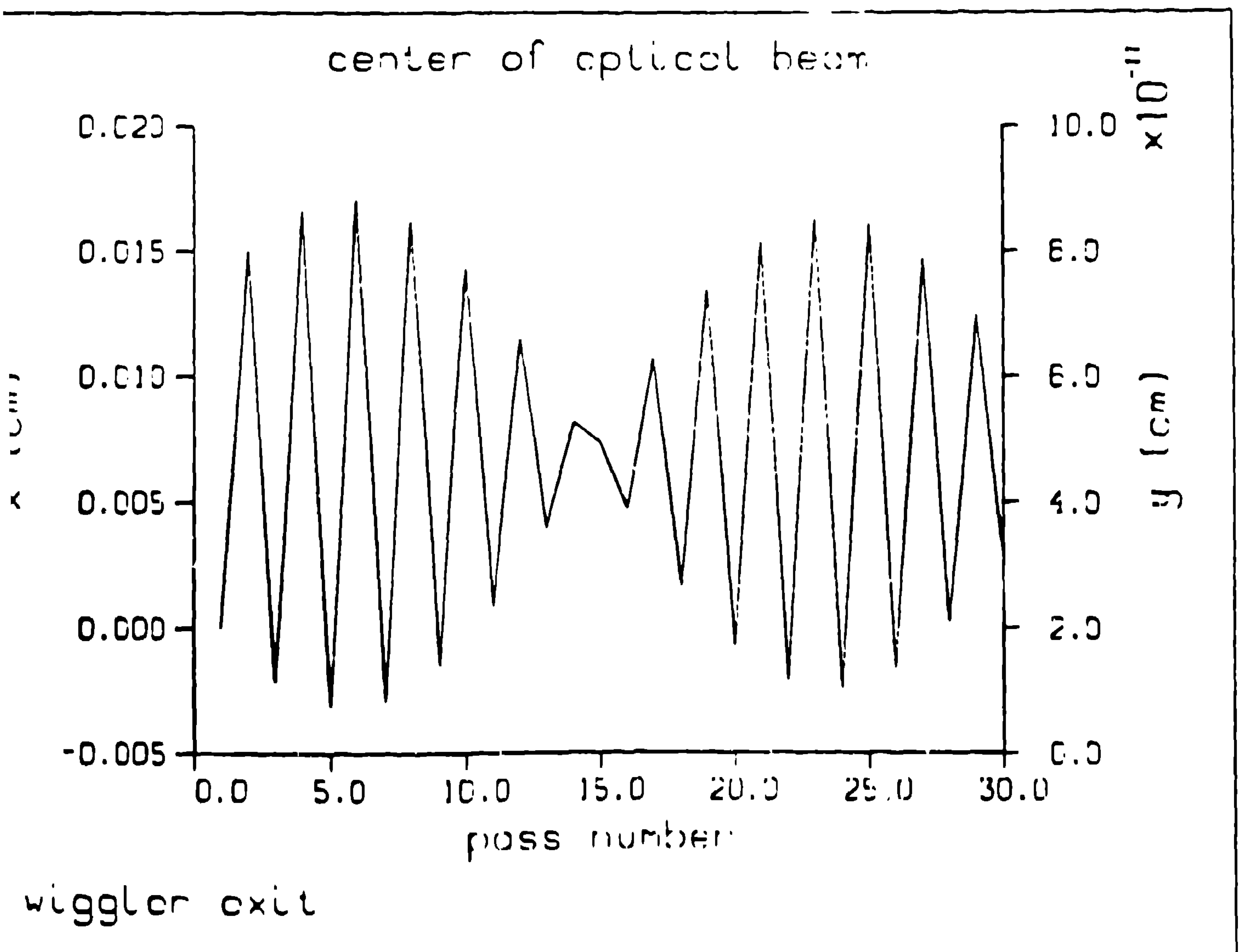
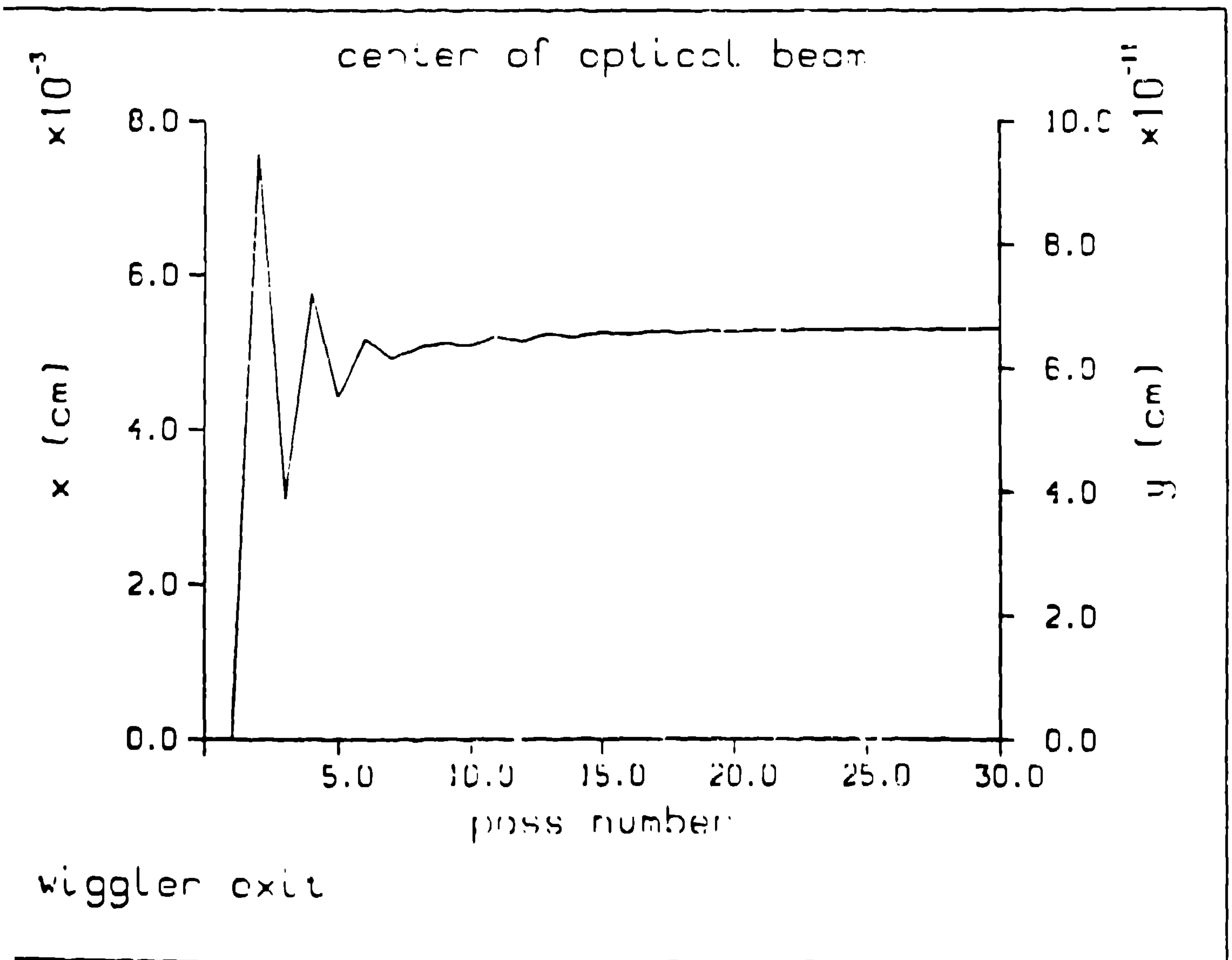


Figure 9b: Loaded cavity walking mode for 4μR tilt of the downstream paraboloid.



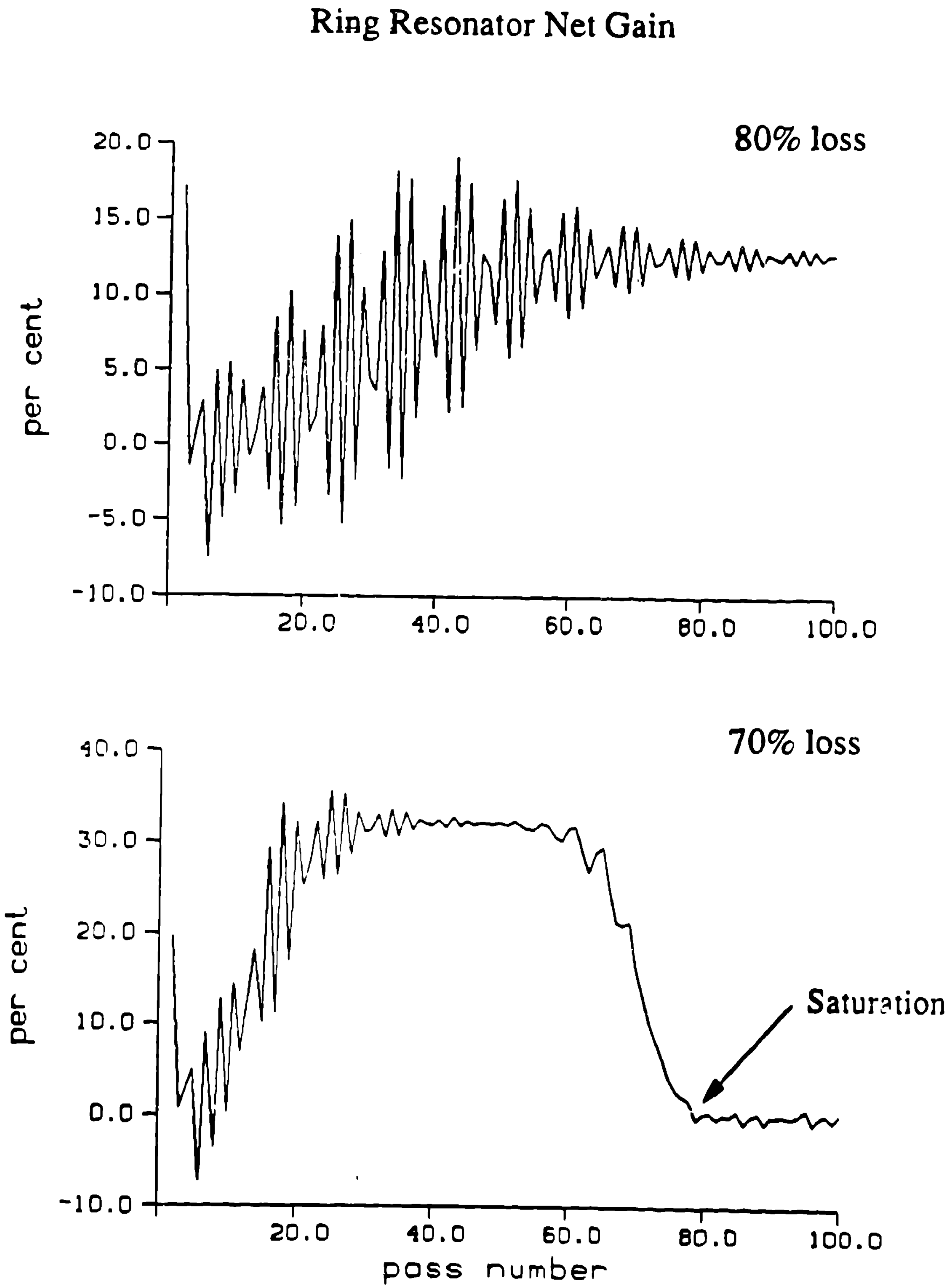


Figure 10: Startup from noise for roundtrip cavity loss of 80% and 70% per pass.

Figure 11a. Extraction efficiency vs. pass number for no energy jitter.

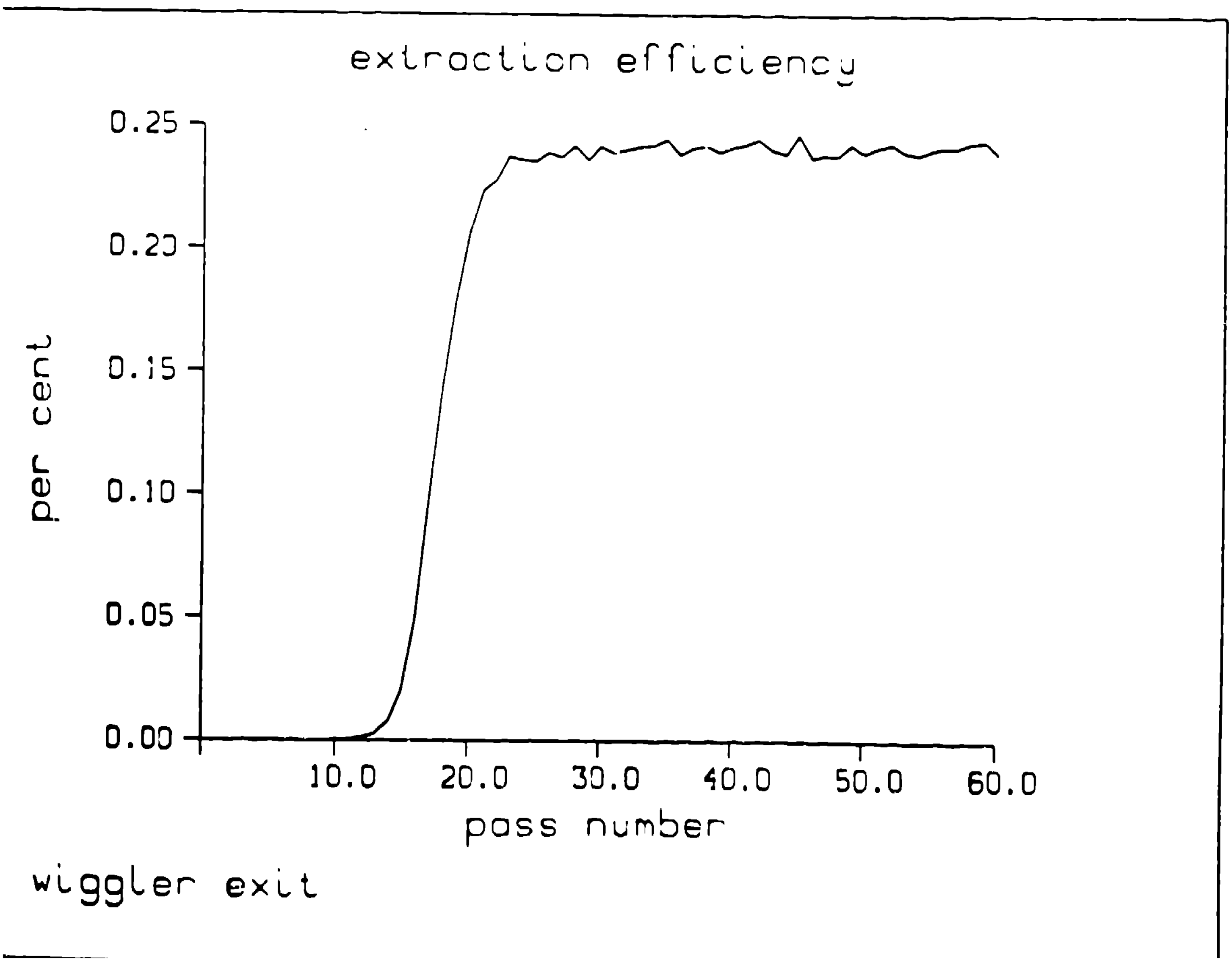


Figure 11b: Extraction efficiency vs. pass number for 0.3% rms energy jitter.