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Study of the High γ_t Lattice for a 5-MW Proton Synchrotron: FODO-I

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August 11, 1995

Abstract

We studied the lattice suitable for a 5-MW proton source. In this study, we assumed that the 2-GeV, 1-MW proton source whose feasibility study was recently completed will be used as the injector. As a consequence, the design energy of the 5-MW source is 10 GeV. One of the primary requirements in the design of the lattice is to achieve a transition energy, γ_t , as high as possible in order to avoid crossing the transition and to reduce the effect of microwave instability. Even though various methods for achieving a high γ_t lattice exist, we chose the lattice made of FODO cells because of its simplicity and its well-known properties. Another important requirement of the lattice is the large dynamic aperture, for the emittance of beam is necessarily large in order to reduce the space-charge effects. In the FODO lattice these two requirements conflict, for the former can be achieved through the small dispersion and the large phase advance but the latter favor the opposite.

We found a lattice with transition energy $\gamma_t = 14.7$ and dynamic aperture larger than 200π mm-mrad.

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1 Introduction

In this lattice study of a 5-MW proton synchrotron we assume that the 1-MW synchrotron [1] will be used as the injector. The injector is a 30-Hz synchrotron accelerating the 10^{14} protons from 400 MeV to 2 GeV during each accelerating cycle. In order to achieve the beam power of 5-MW, we need to increase the beam energy to 10 GeV. Thus, we consider the lattice with the design energy of 10 GeV.

2 Lattice Requirements

The highlights of the lattice requirements are:

- The transition energy, γ_t , will be as high as possible not only to avoid transition-crossing but also to reduce the effect of microwave instability. We temporarily set the requirement as $\gamma_t \geq 14$.
- The lattice will provide ample acceptance in order to accommodate the injecting beam an emittance of 130π mm-mrad in the transverse planes. Thus the dynamic aperture should be $\geq 260 \pi$ mm-mrad, preferably at the highest sextupole settings, i.e., at the zero chromaticity.
- The rf and injection/extraction equipment requires magnet-free straight sections longer than 200 m.
- The circumference of the synchrotron will be the integral multiple of the injector circumference. We choose the circumference to be 761.6 m.
- The bending magnetic field will be less than 1.4 T at the extraction energy of 10 GeV.
- The lattice needs to be easily tunable within the tune range ± 1 in both transverse planes without degrading overall performance.
- Since a synchrotron is an AC (alternating current) machine, the lattice needs to be as simple as possible, i.e., avoid insertion-matching as much as practicable.

3 Lattice

In obtaining a high γ_t we can use either the regular FODO lattice in the arc or a variant of Teng's π -insertion method [2]. Even if the lattice based on the π -insertion method has many attractive features, such a machine has never been built. Thus we choose the lattice made of the regular FODO cells. The overall lattice consists of the arc and the dispersion-free straight sections forming a super-period.

The transition energy of the FODO lattice can be written as

$$\alpha \equiv \frac{1}{\gamma_t^2} = \frac{1}{(1 + S/A)} \left(\frac{1}{\sin^2 \mu} - \frac{1}{4} \right) \theta^2, \quad (1)$$

where

- α = the momentum compaction factor,
- A = the arc length, where the dispersion is non-zero,
- S = the length of dispersion-free straight sections,
- μ = the half-cell phase-advance,
- θ = the half-cell bend-angle.

From the equation we can see that, if $S = 0$, γ_t is completely determined by the two parameters, namely the phase advance per cell and the bending angle per cell. The large phase advance and the small bending angle will decrease the α by making the dispersions small at the bending magnets, thus increasing γ_t . Since the required straight sections occupy about 30% of the circumference, it will further increase γ_t .

The resultant lattice will have a very simple structure, but there is the price to pay. Since the dispersions in the arc are small and the tunes (arc+straight) are high, we may need strong chromaticity-correcting sextupoles.

We found a lattice which satisfies the design requirements. The lattice consists of a superperiod of three, and each superperiod has reflection-symmetries at the middle and ends. Lattice functions for one-half of a superperiod are shown Figure 1.

The arc is made of FODO normal cells with the two families of the chromaticity-correcting sextupoles included. The phase advance of the normal cell is close to 90° in order to achieve a high γ_t of 11.5.

The dispersion can be suppressed at the end of an arc as long as the arc phase is an integral multiple of 2π , as shown in Appendix A. However, in order to have less peak-to-peak variation of dispersion, we use the missing-magnet cell at the end of the arc.

The dispersion-free straight sections consist of repeated empty cells with the same quadrupole families used in the normal cells. These empty cells further increase γ_t to 14.7.

The detail parameters of the magnetic lattice are shown in Table 1. Other interesting features of the lattice are:

- Beam-Stay-Clear (BSC) for one-half of a superperiod are shown in Figure 2, where $BSC_{x,y} = \sqrt{2\epsilon_{x,y}\beta_{x,y} + D_{x,y}\delta}$. We assumed that $\epsilon_{x,y} = 130 \pi$ mm-mrad and $\delta \equiv \Delta p/p_0 = 0.01$. The maximum values at the elements are shown in Table 2.
- Lattice functions of the normal cell are shown in Figure 3.
- Normal cell parameters are shown in Table 3.

4 Working Point and Dynamic Aperture

Since the phase advance per cell is close to 90° in both transverse planes, the natural tunes of the lattice are $\nu_x \simeq \nu_y \simeq 18.75$. In order to minimize the effect of the difference resonance $n\nu_x - n\nu_y = 0$, which may be excited by the zeroth harmonic component of the skew-quadrupoles and the nonlinear elements around ring, we have the integral parts of tunes differ by one unit.

A working point is chosen which will provide a sufficient dynamic aperture to contain the beam. After the extensive tracking studies (see Appendix B), we chose $\nu_x = 19.11$ and $\nu_y = 18.10$. The dynamic aperture at the zero chromaticity is shown in Figure 4.

5 Discussion and Conclusion

The lattice considered in this study has a very simple structure, namely an array of FODO cells. In general, the FODO lattice has a large dynamic aperture. However, in a high γ_t lattice made of FODO cells, since the dispersions in the bending magnets are small and the tunes are high (large phase advance per cell plus long straight sections), the chromaticity-correcting sextupoles become strong, which results in the marginal dynamic aperture with respect to the BSC. Even though we may not need the full chromaticity correction because the beam energy is below transition energy, it is reassuring to have a larger dynamic aperture. Increasing the dynamic aperture is the subject of the next study.

References

- [1] "IPNS Upgrade - A Feasibility Study," ANL Report ANL-95/13 (April, 1995).
- [2] L. C. Teng, "Infinite Transition-Energy Synchrotron Lattice Using π -Straight Sections," Part. Accel., Vol. 4, pp. 81-85 (1972).

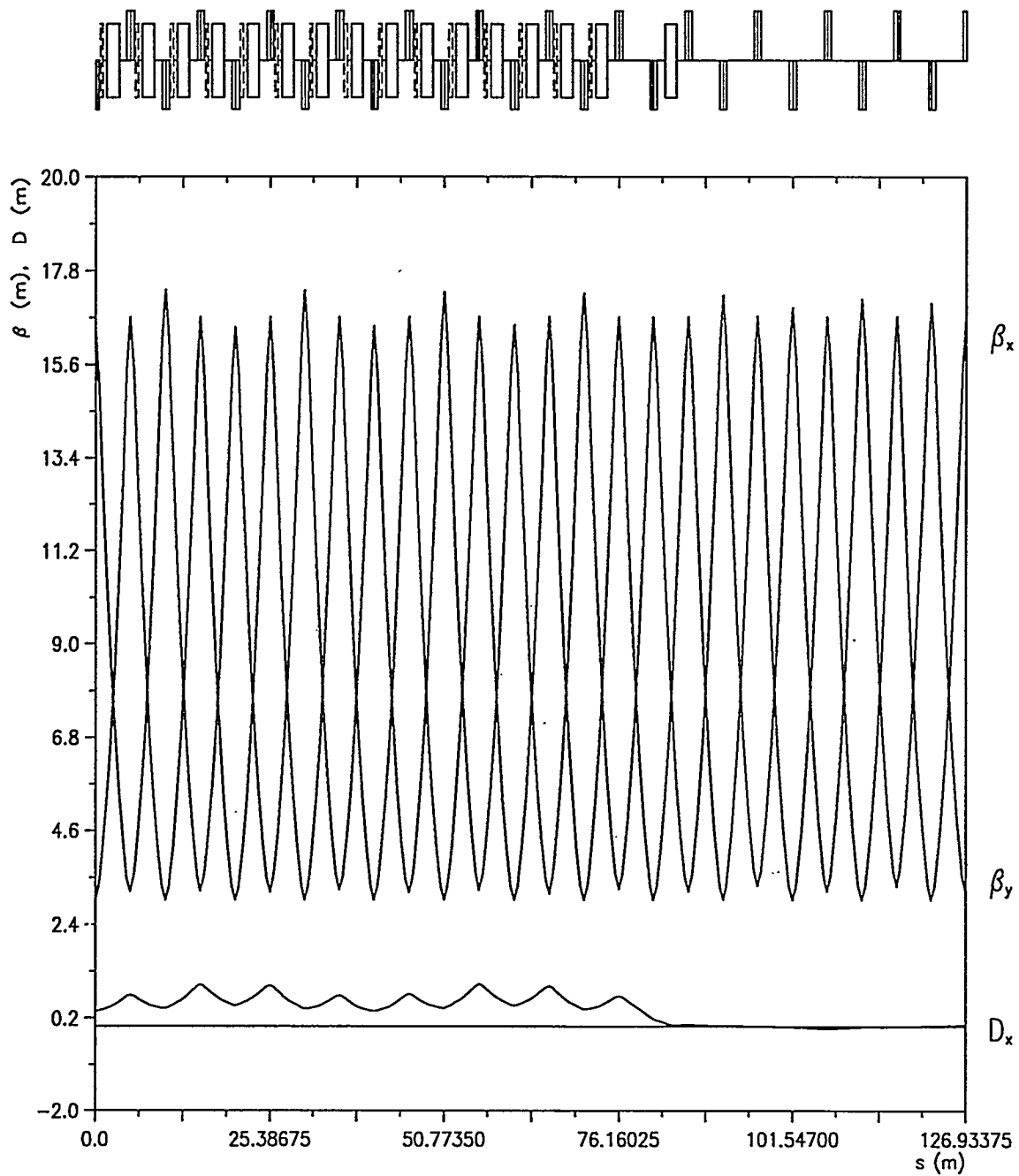


Figure 1: Lattice Functions for One-Half of a Superperiod.

Table 1: Lattice Parameters (10 GeV, $B\rho = 36.352$ T-m)

Parameters	Values	Units
Circumference	761.6	m
Superperiodicity	3	-
Total number of cells	75	-
Number of normal cells	45	-
Number of dispersion suppressor cells	6	-
Number of straight section cells	24	-
Nominal length of cell	10.1547	m
Nominal length of straight section	4.07735	m
Bending radius	26.39196	m
Number of Dipole	96	-
Dipole length	1.72735	m
Dipole field at 10 GeV	1.377	T
Number of Quadrupole	150	-
Quadrupole length	1.0	m
Maximum quadrupole gradient (B')	10.95	T/m
Number of Sextupoles (F)	42	-
Number of Sextupoles (D)	48	-
Sextupole length	0.4	m
Maximum sextupole strength (B'')	120.4	T/m ²
Transition energy, γ_t	14.74	-
Horizontal tune, ν_x	19.11	-
Vertical tune, ν_y	18.10	-
Natural chromaticity, $\xi_x = (\Delta\nu/\nu)_x/(\Delta p/p)$	-1.241	-
Natural chromaticity, $\xi_y = (\Delta\nu/\nu)_y/(\Delta p/p)$	-1.265	-
Maximum β function, β_x	16.73	m
Maximum β function, β_y	17.36	m
Maximum dispersion	1.0	m

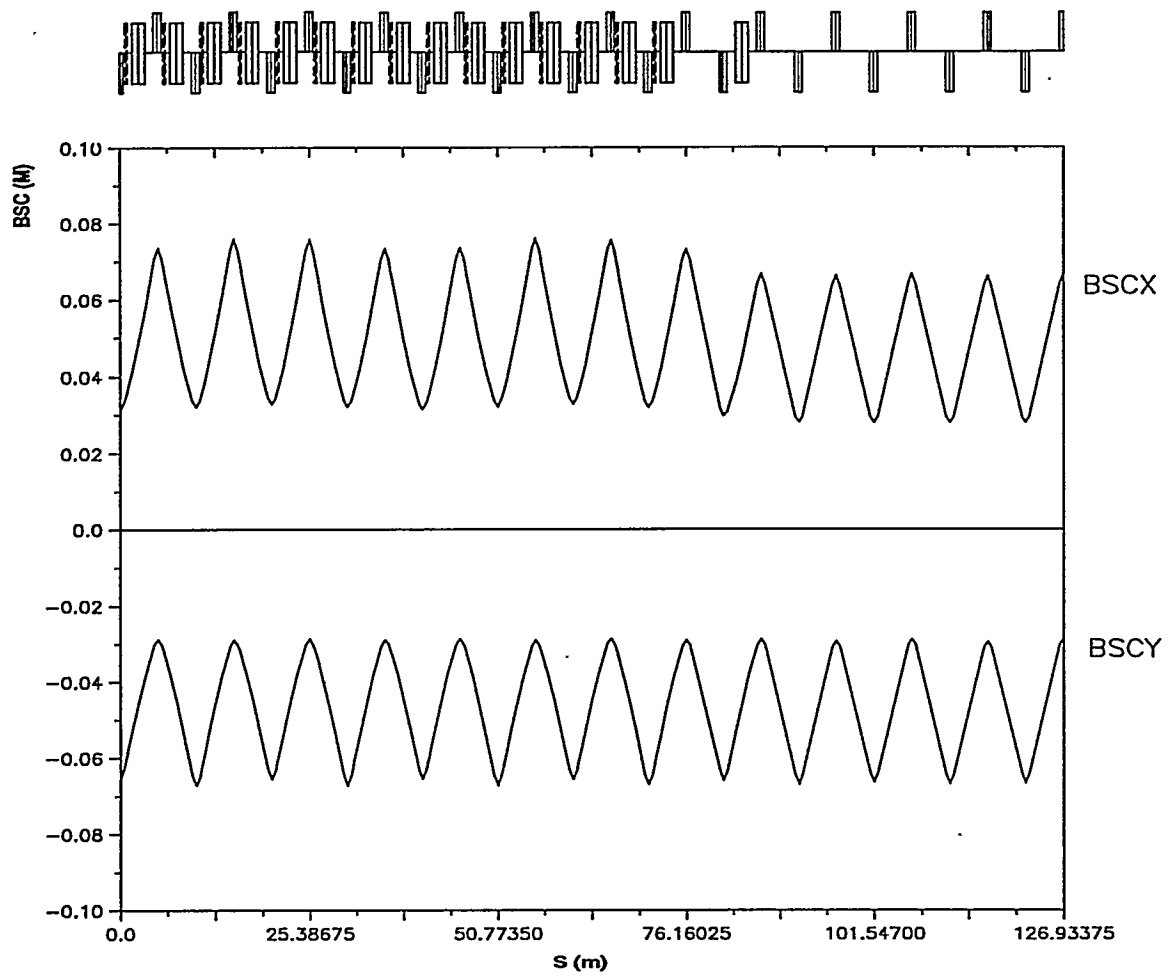


Figure 2: BSC (Beam Stay Clear) for One-Half of a Superperiod.

Table 2: Beam Stay Clear

Elements	BSC-X (cm)	BSC-Y (cm)
QF	7.59	3.08
QD	3.44	6.72
BEND	6.03	5.38
SF	6.87	3.43
SD	3.86	6.10

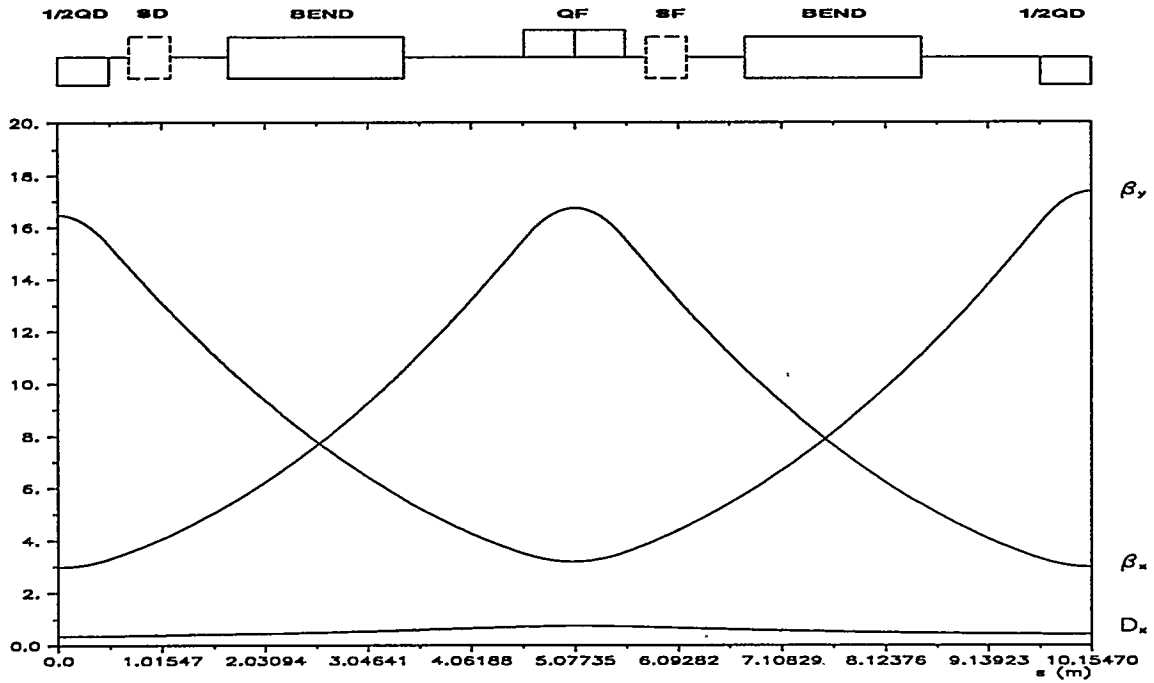


Figure 3: Lattice Functions of the Normal Cell.

Table 3: Normal Cell Parameters (10 GeV, $B\rho = 36.352$ T-m).

Elements	Length	Strength	Units
QD	0.75	-10.588	T/m
DQS	0.2		m
SD	0.4	-1.325	m^{-2}
DSB	0.575		m
BEND	1.72735	1.377	T
DBQ	1.175		m
QF	1.0	10.950	T/m
DQS	0.345		m
SF	0.4	0.905	m^{-2}
DSB	0.575		m
BEND	1.72735	1.377	T
DBQ	1.175		m
QD	0.5	-10.588	T/m

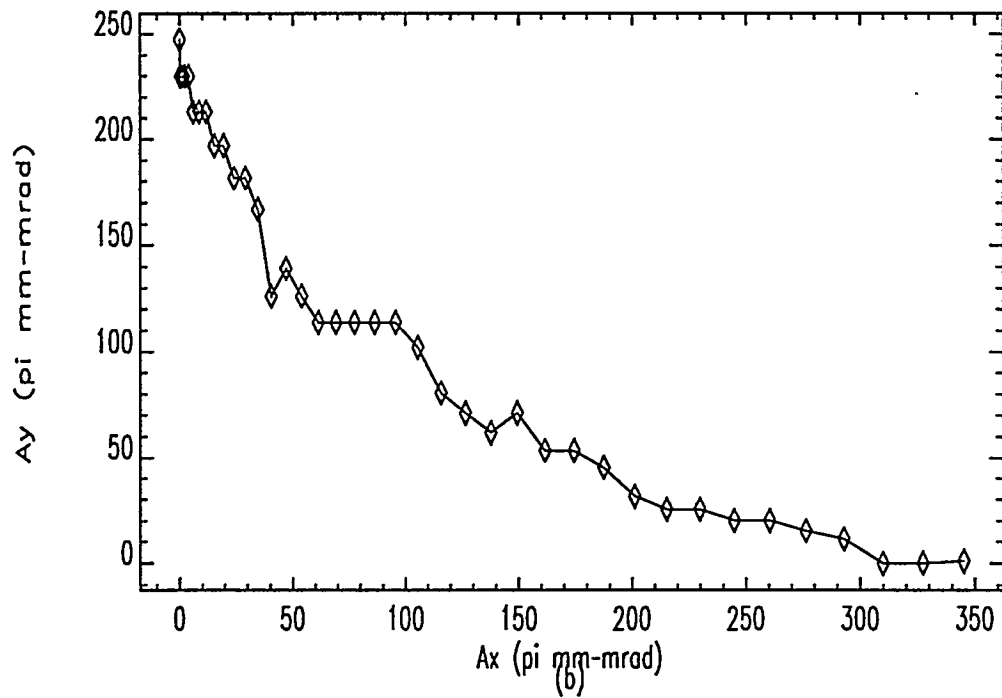
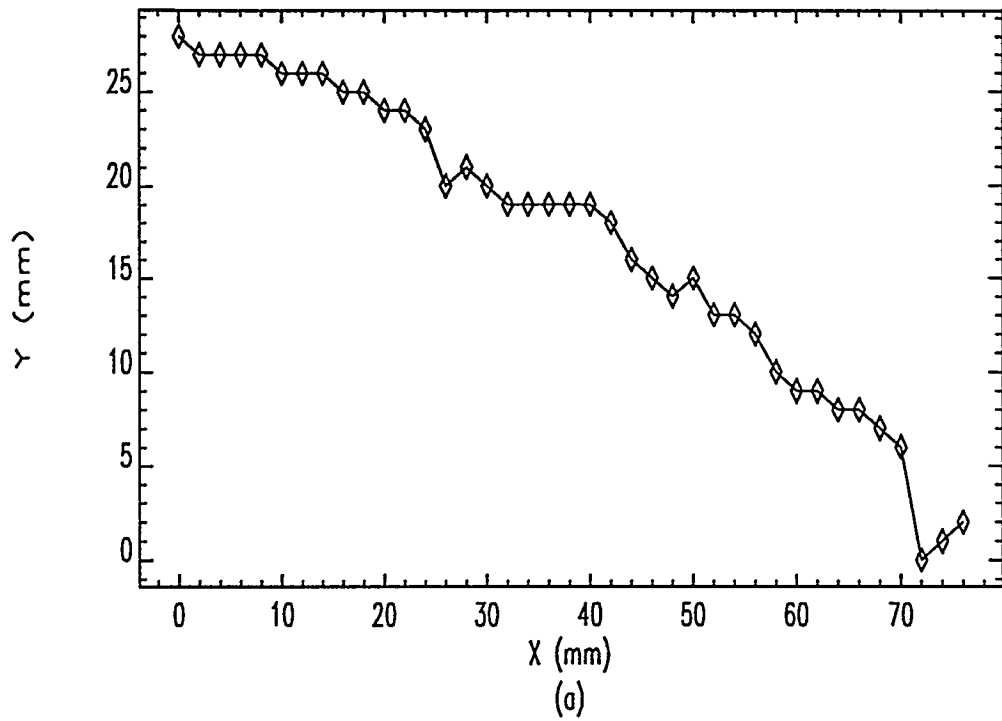


Figure 4: Dynamic aperture of the lattice in mm units (a) and π mm-mrad units (b). (Particle motions are observed at the middle of the straight section, where $\beta_x = 16.730$ m and $\beta_y = 3.171$ m.)

Appendix A: Construction of Arc

The arc is made of normal cells (FBDB or DBFB). Since the arc should be matched to empty cells (FODO, or DOFO) in the dispersion-free straight sections, the dispersion should be suppressed at the end of the arc. The first-order achromat can be achieved without using the dispersion-suppressor cells if the horizontal phase advance of the arc is $2n\pi$. Thus the number of normal cells in the arc is $N_{cell} = 2n\pi/\mu_x$, where μ_x is the horizontal phase advance per cell.

When the dispersion-suppressor cells are used, the simplest way is using one missing magnet cell. In this case, the first-order achromat is achieved by arranging $N_{cell} - 1$ FBDB cells in the arc together with a FODB dispersion-suppressor cell at each end of the arc.

Examples are shown in Figures 5, 6, and 7 for the FBDB cells with the phase advances 90° , 72° , and 60° , respectively.

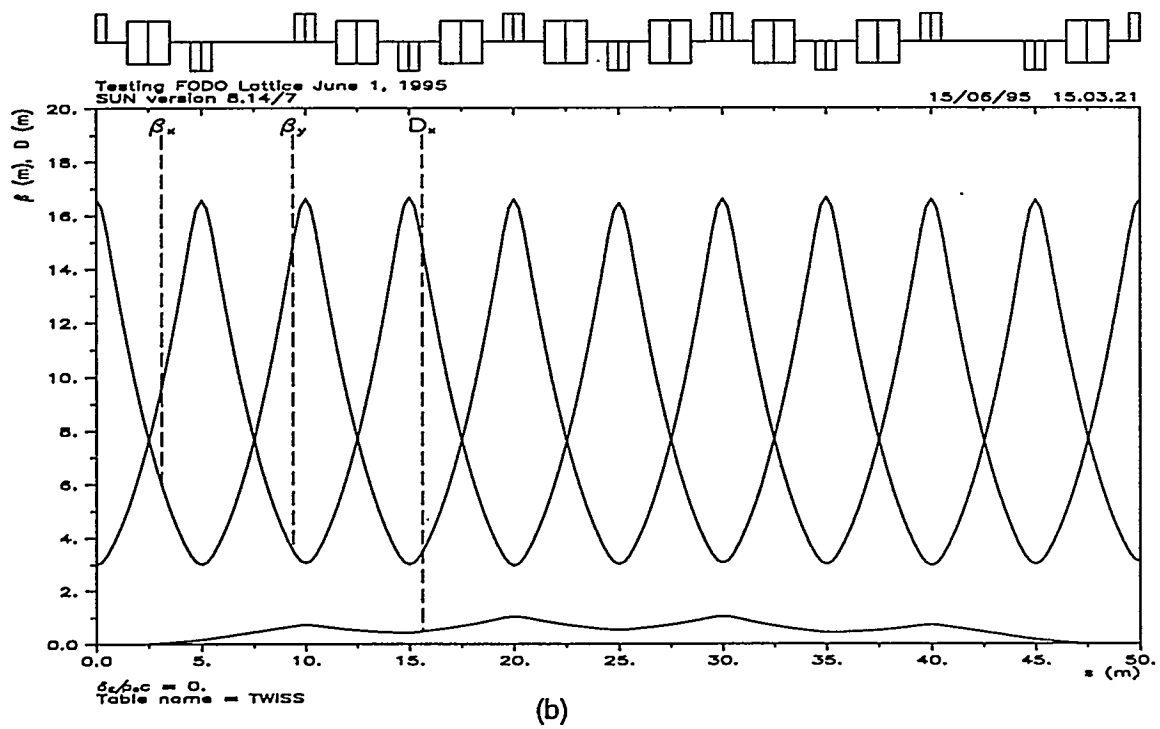
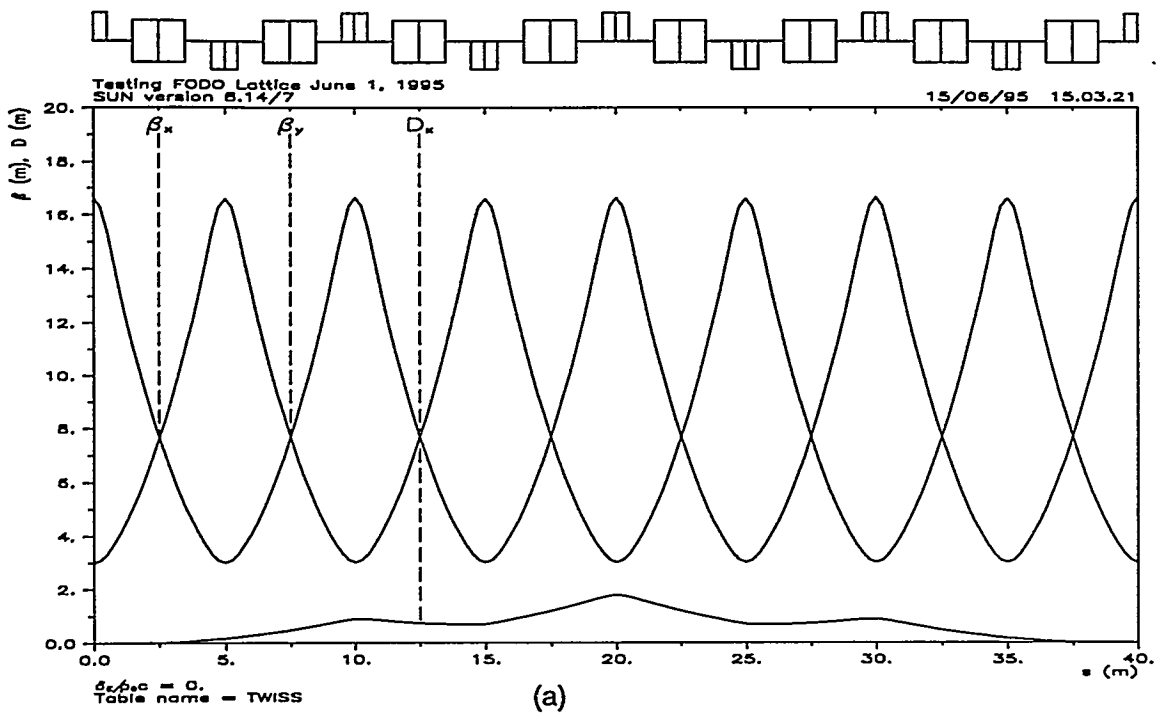


Figure 5: Formation of the arc using 90° FBDB cells without missing magnets (a), and with missing magnets (b).

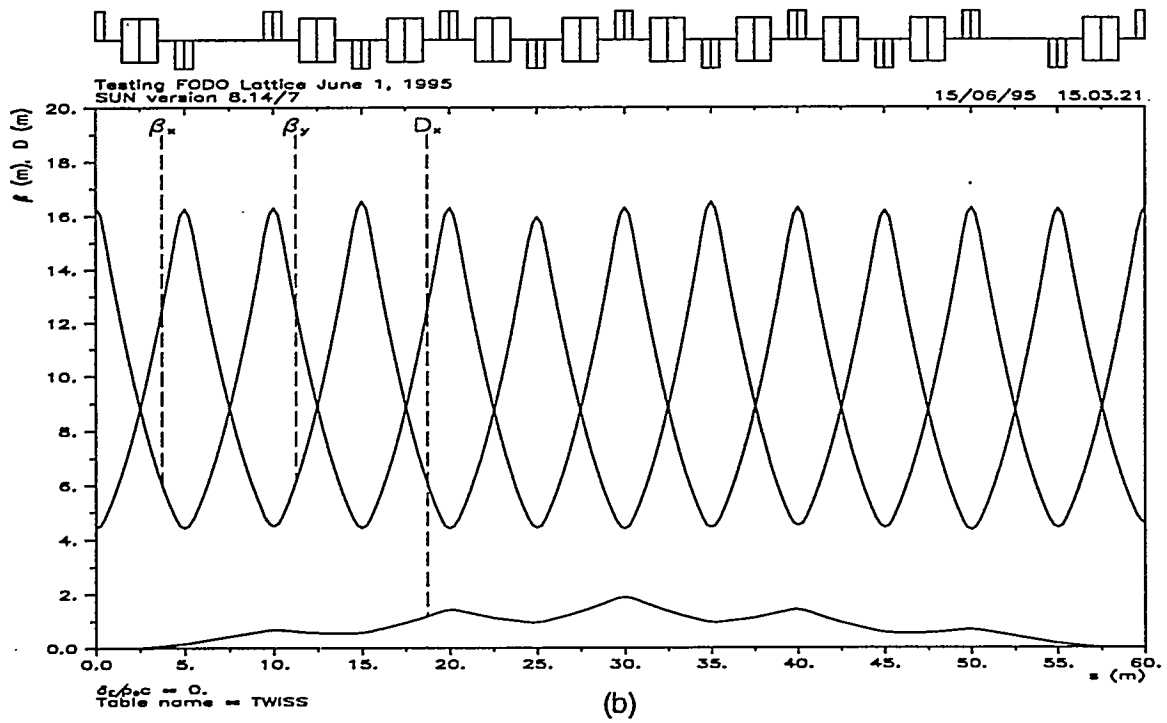
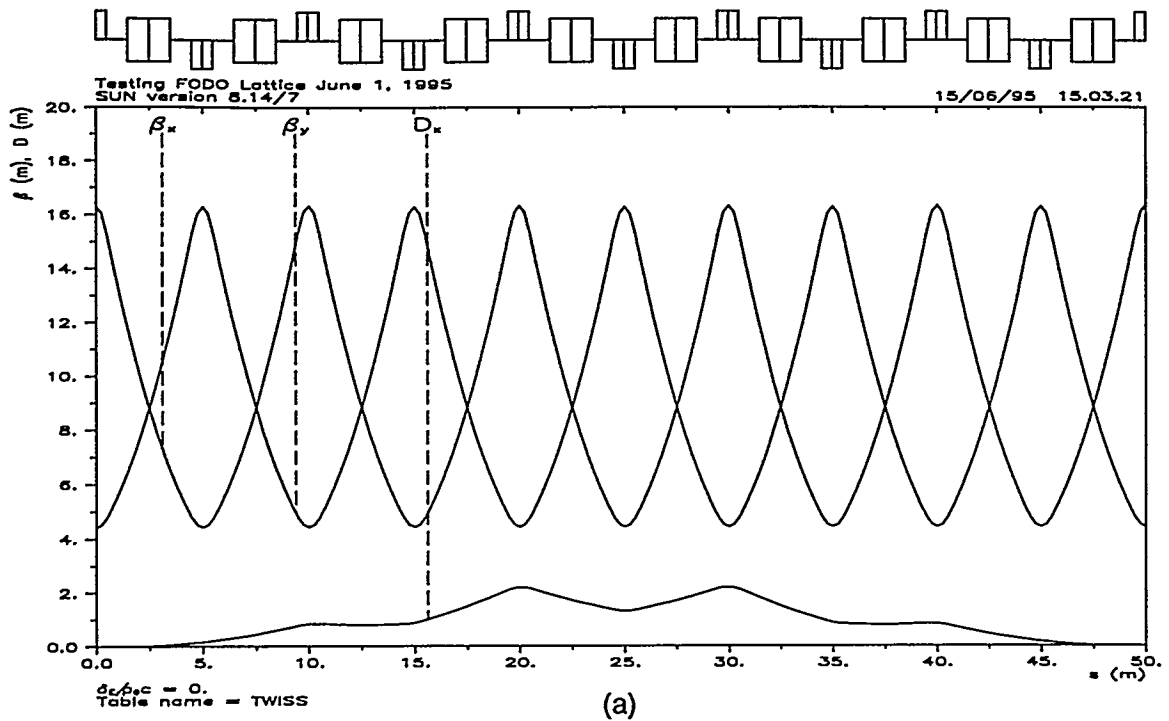


Figure 6: Formation of the arc using 72° FBDB cells without missing magnets (a), and with missing magnets (b).

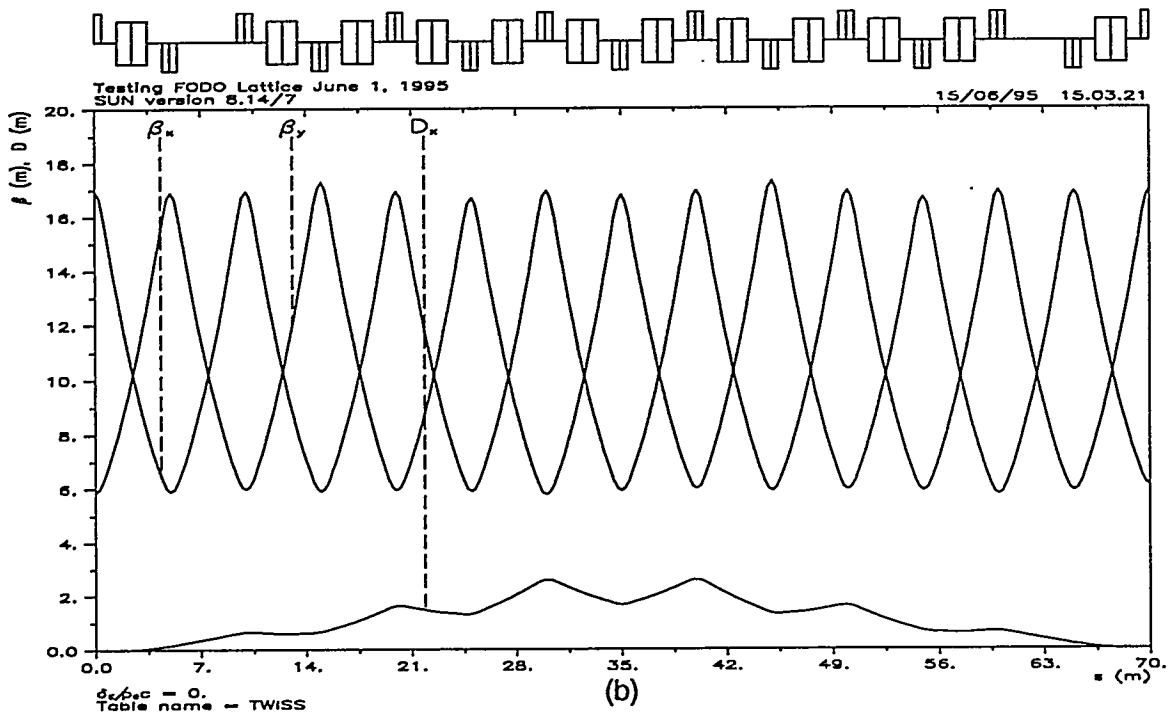
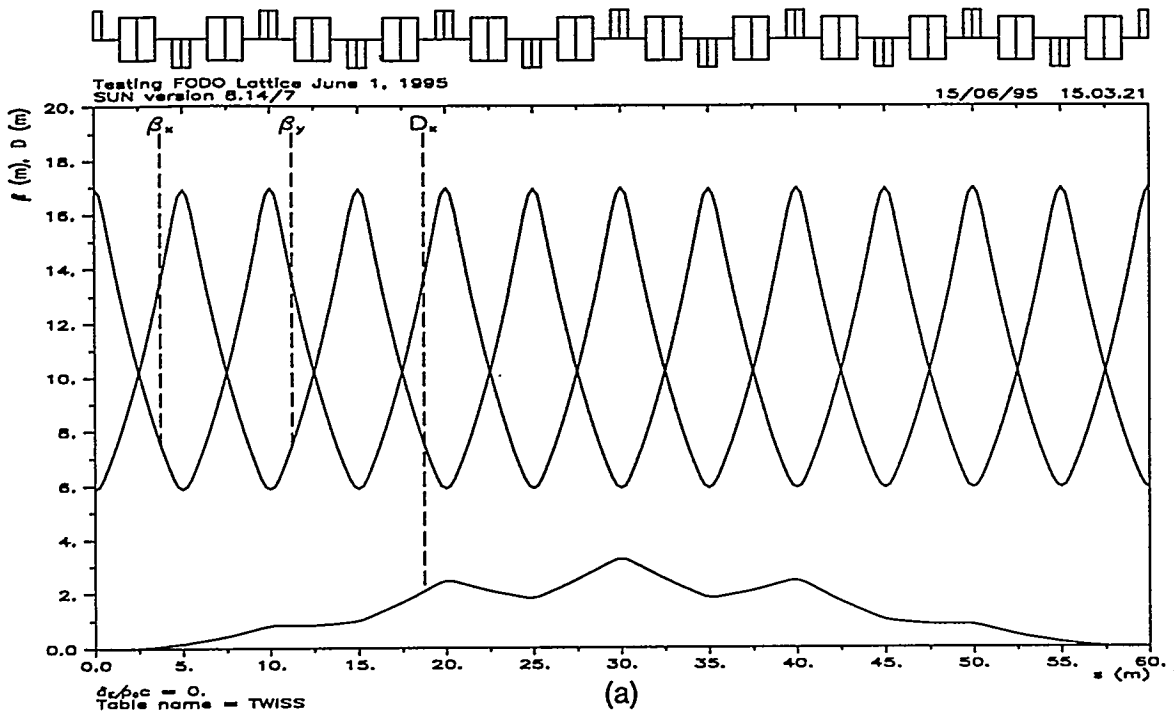


Figure 7: Formation of the arc using 60° FBDB cells without missing magnets (a), and with missing magnets (b).

Appendix B: Tune Search

B.1 Tune Search #1

We searched the tune plane to find the optimum tune where the dynamic aperture was largest.

- The horizontal and vertical tunes are listed in Table B.1 and shown in Figure 8.

Table B.1: Tune Number Table for Tune Search #1

Tune Number	Horizontal Tune, ν_x	vertical Tune, ν_y	β_x/β_y (m) at Observation Point
1	18.56	17.57	16.577/3.453
2	18.63	17.64	16.595/3.432
3	18.82	17.83	16.648/3.393
4	18.87	17.88	16.662/3.397
5	19.11	18.12	16.736/3.179
6	19.19	18.20	16.761/3.181
7	18.56	17.55	16.571/3.458
8	18.63	17.62	16.590/3.437
9	18.82	17.81	16.643/3.394
10	18.87	17.86	16.657/3.393
11	19.11	18.10	16.730/3.171
12	19.19	18.18	16.756/3.182

- The tunes, γ_t , quadrupole strengths, and sextupole strengths for the various tune numbers are shown in Figure 9.
- The dynamic apertures for the various tune numbers are shown in Figures 10 and 11 in units of mm and π mm-mrad, respectively.

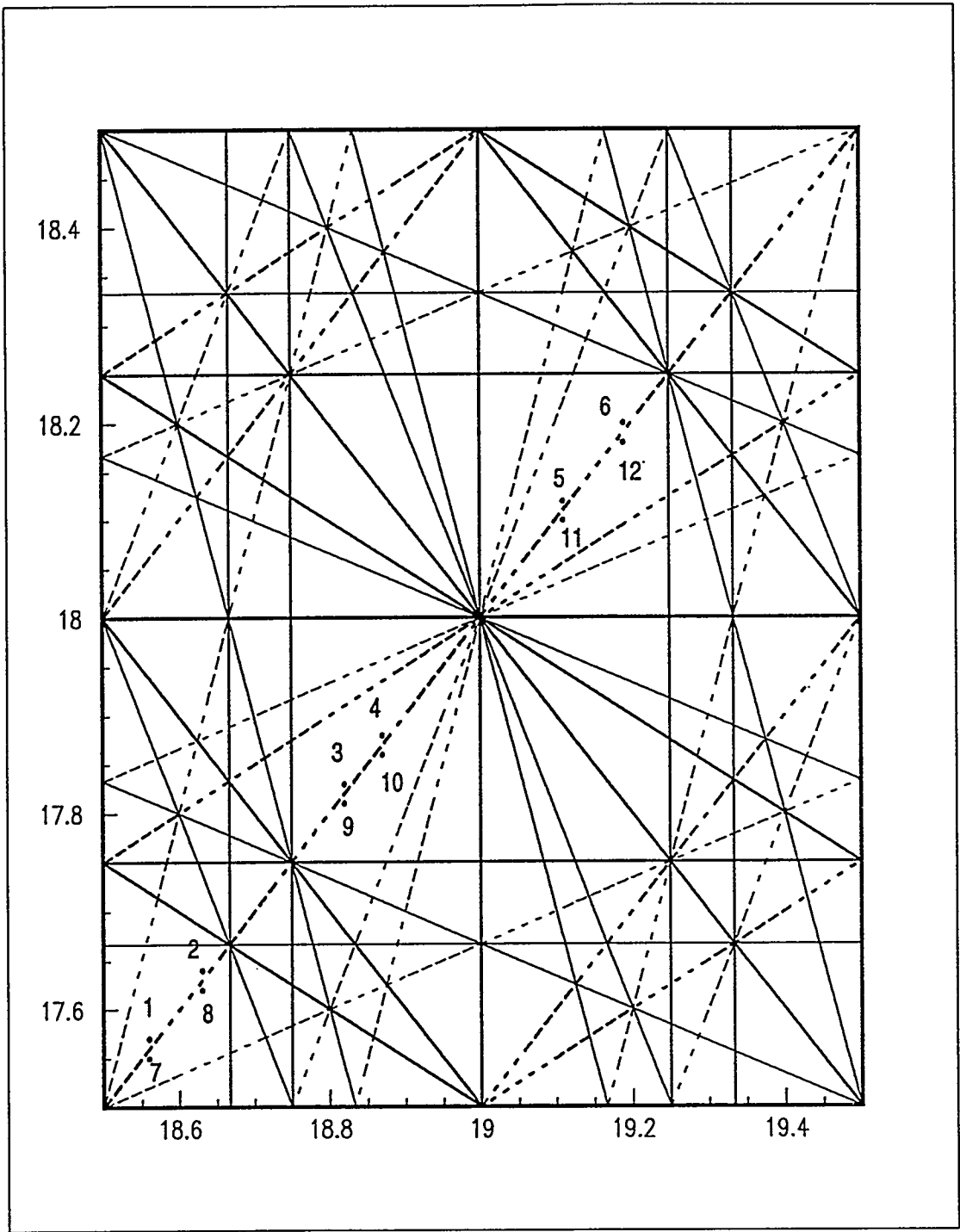


Figure 8: Tunes used in Tune Search #1.

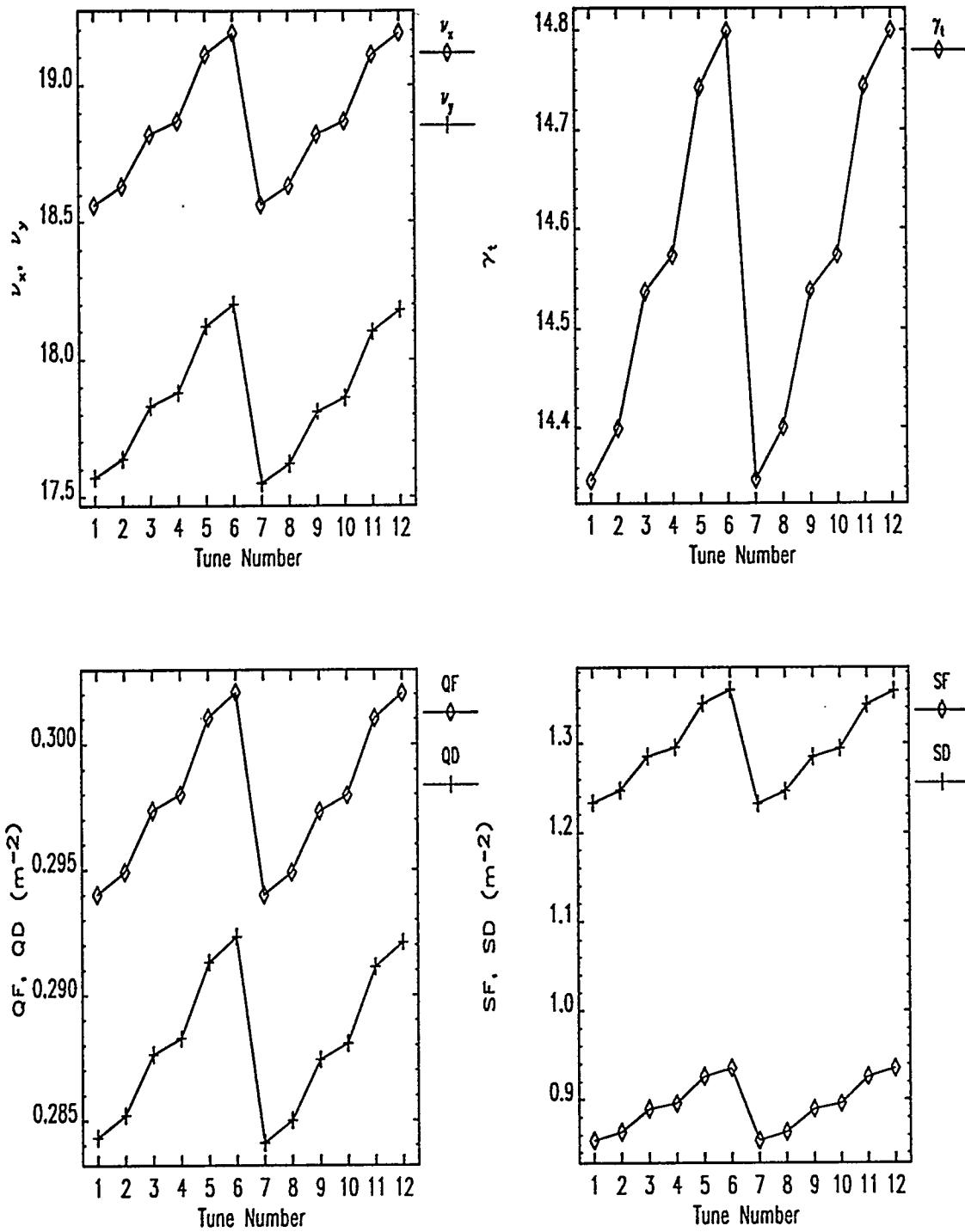


Figure 9: Various Quantities vs. Tune Number.

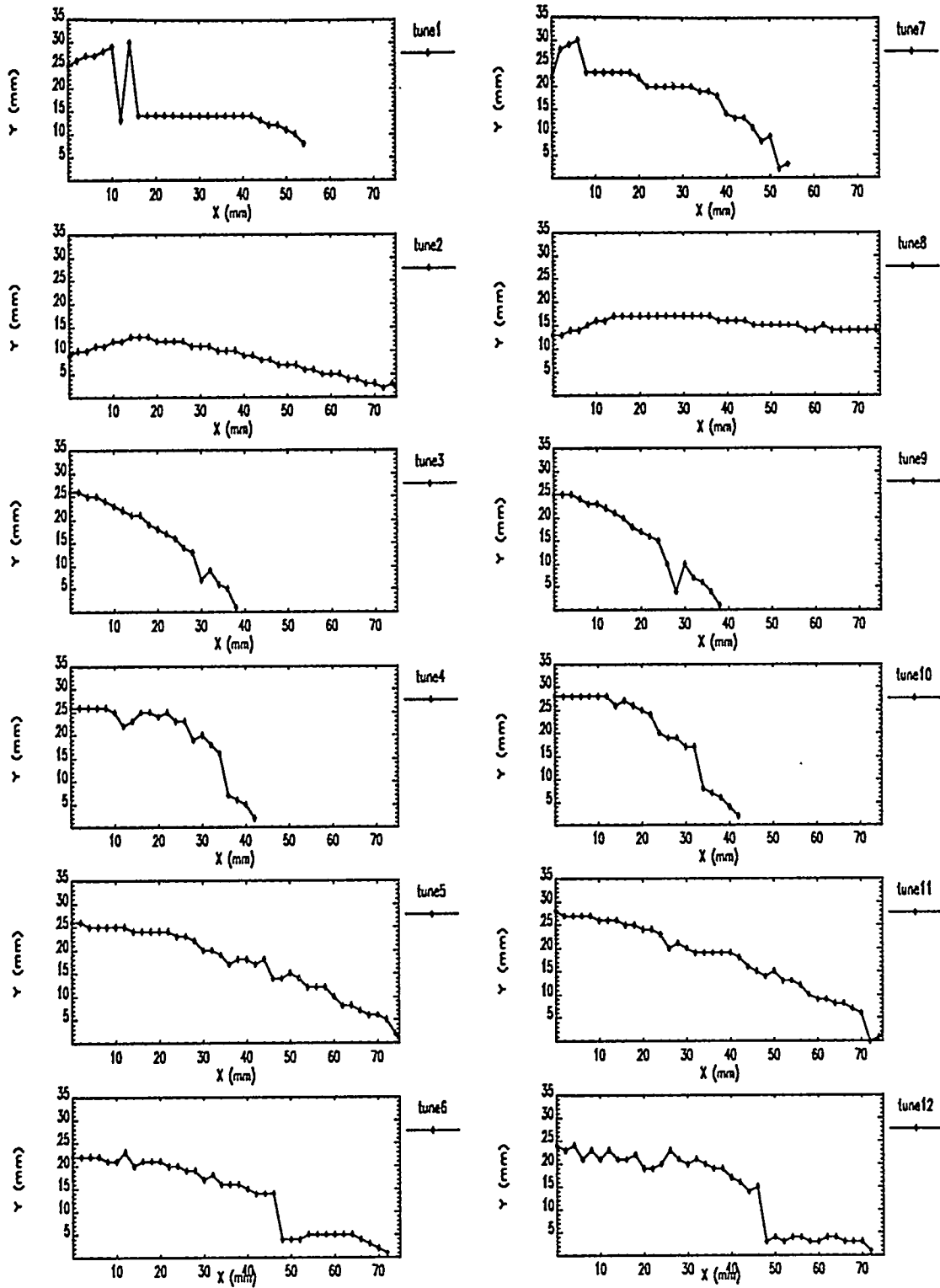


Figure 10: Dynamic aperture of the lattice for the various tunes in mm. (Particle motions are observed at the middle of the straight section, where β_x/β_y are given in Table B.1.)

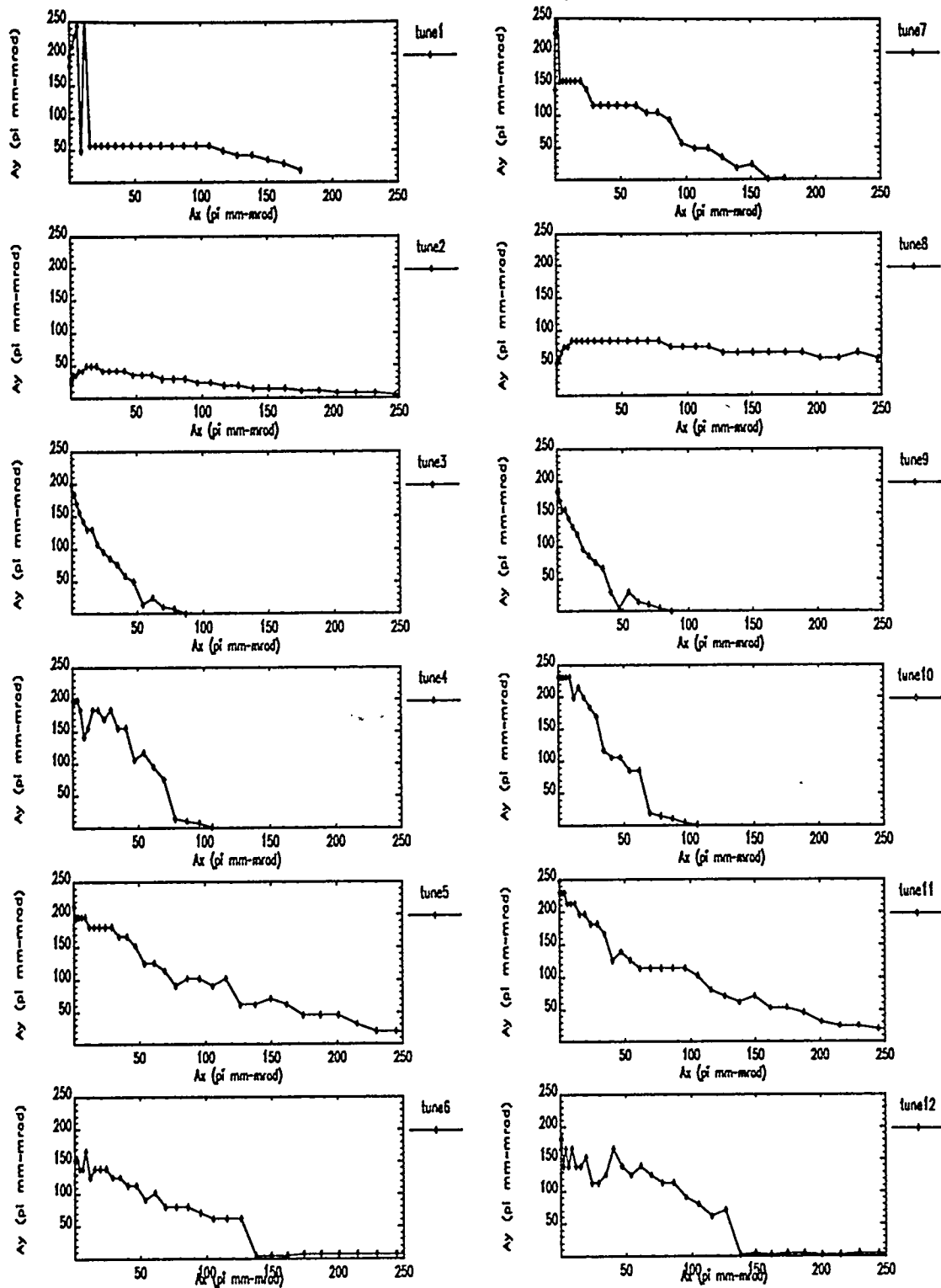


Figure 11: Dynamic aperture of the lattice for the various tunes in π mm-mrad. (Particle motions are observed at the middle of the straight section, where β_x/β_y are given in Table B.1.)

B.2 Tune Search #2

We searched the tune plane to find the optimum tune where the dynamic aperture was largest.

- The horizontal and vertical tunes are listed in Table B.2.

Table B.2: Tune Number Table for Tune Search #2

Tune Number	Horizontal Tune, ν_x	Vertical Tune, ν_y	β_x/β_y (m) at Observation Point
1	19.11	18.10	16.729/3.172
2	19.13	18.13	16.731/3.171
3	19.15	18.10	16.733/3.170
4	19.17	18.10	16.734/3.169
5	19.19	18.10	16.735/3.168
6	19.13	18.13	16.739/3.181
7	19.15	18.13	16.740/3.180
8	19.17	18.13	16.742/3.179
9	19.19	18.13	16.743/3.178
10	19.15	18.16	16.748/3.184
11	19.17	18.16	16.750/3.183
12	19.19	18.16	16.751/3.182

- The dynamic apertures for the various tune numbers are shown in Figures 12 and 13 in units of mm and π mm-mrad, respectively.

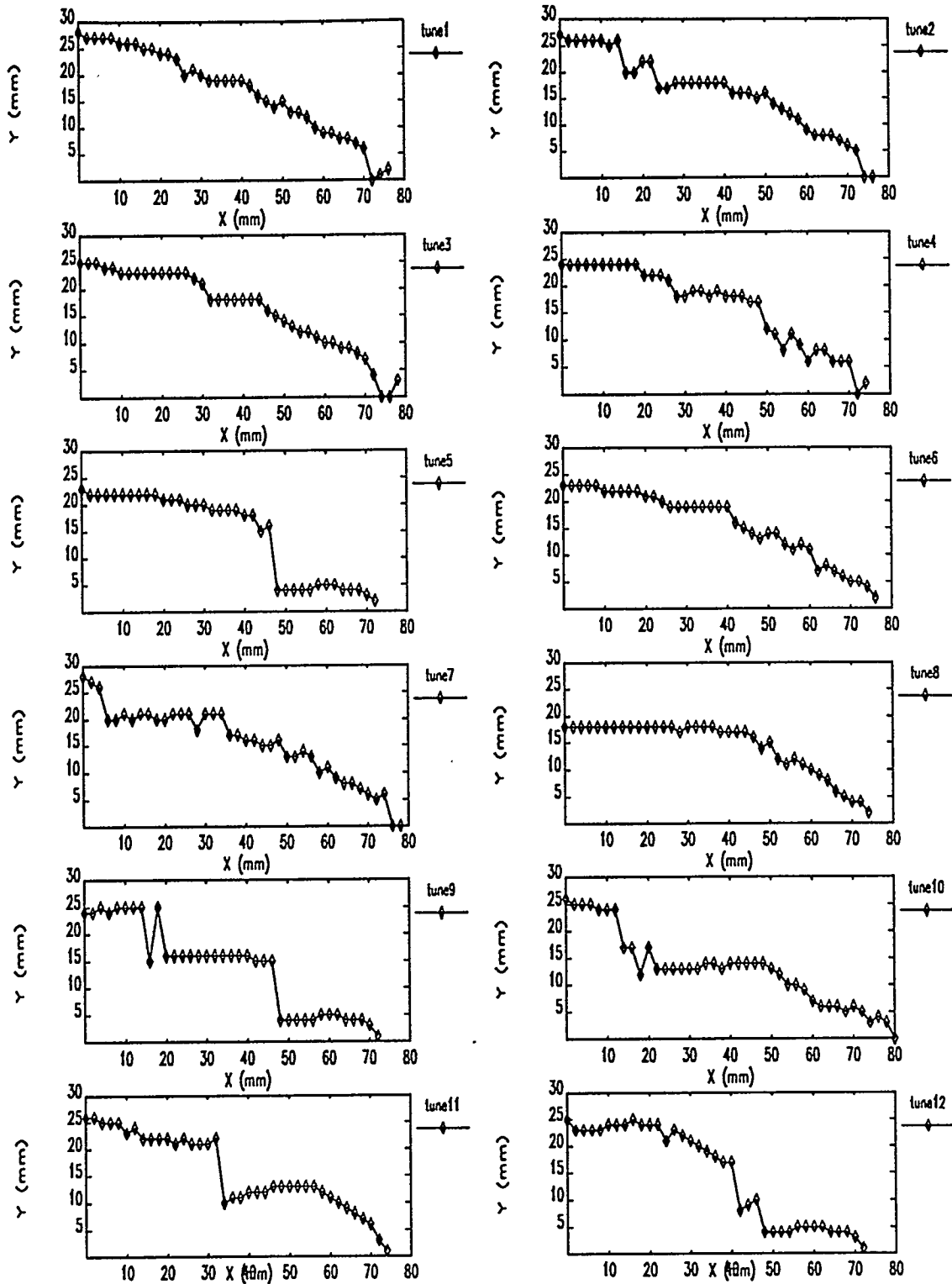


Figure 12: Dynamic aperture of the lattice for the various tunes in mm. (Particle motions are observed at the middle of the straight section, where β_x/β_y are given in Table B.2.)

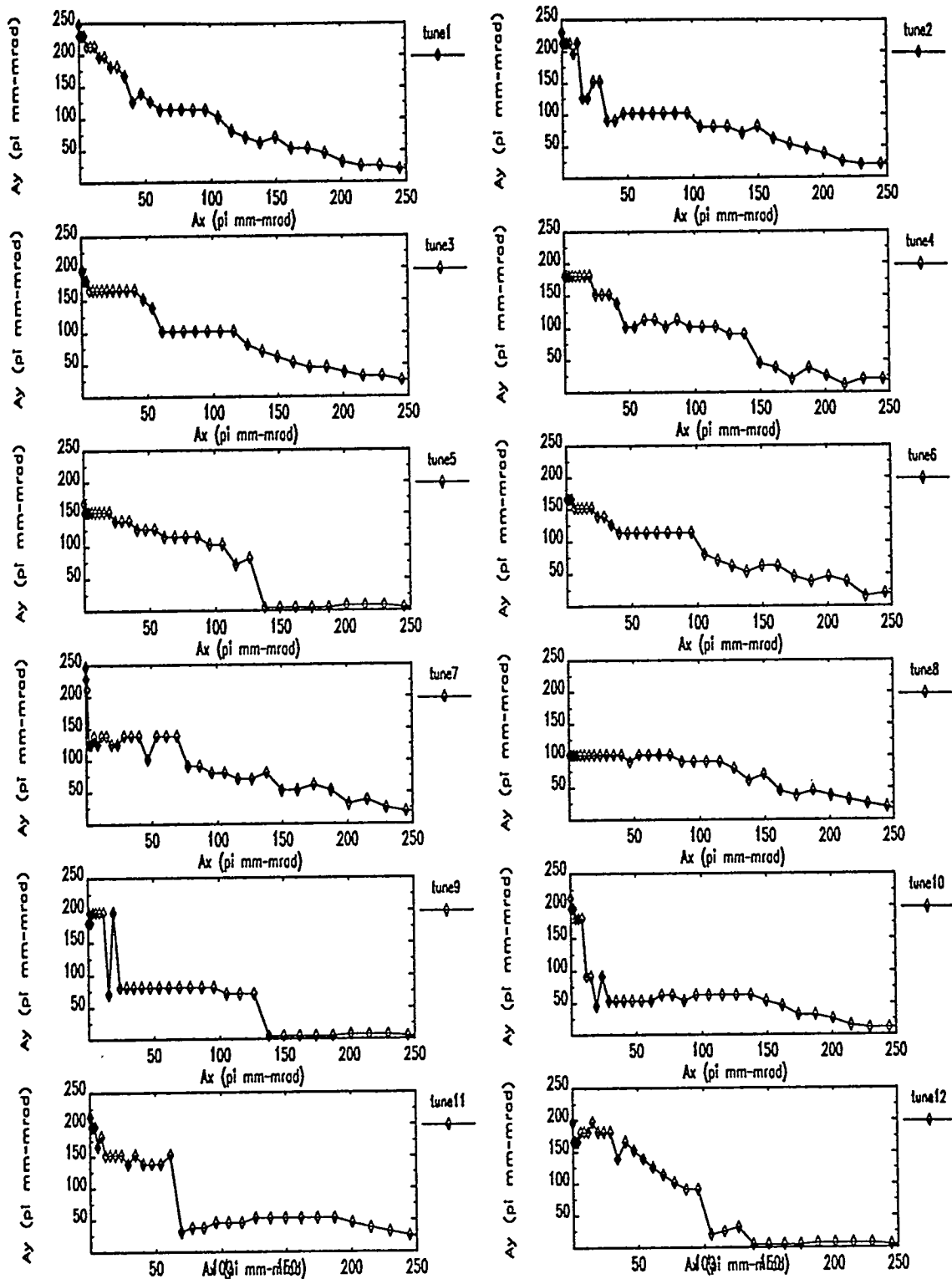


Figure 13: Dynamic aperture of the lattice for the various tunes in π mm-mrad. (Particle motions are observed at the middle of the straight section, where β_x/β_y are given in Table B.2.)