AHF SYNCHROTRON LATTICES

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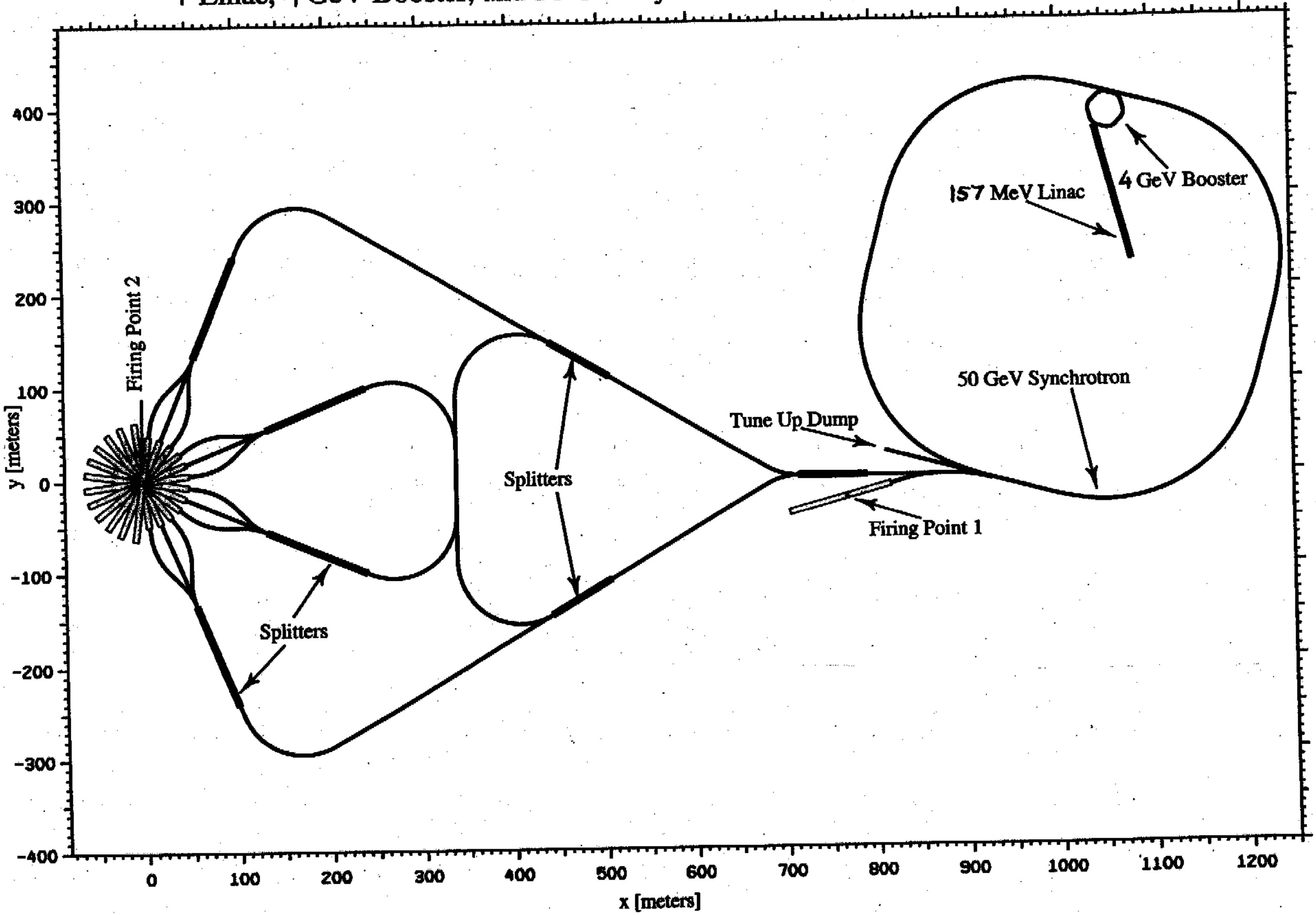
Machines

I. 50 GeV Main Ring

II. 4 GeV Booster Ring

Stand Alone AHF Layout: 12 View Isochronous SC Crossover + Linac, 4 GeV Booster, and 50 GeV Synchrotron



Main Ring Lattice Options

A. Reference FODO Lattice

B. Transitionless Lattice

Transition-Crossing Choices for Main Ring Lattices

1. **Reference FODO Lattice**: passage through transition with only requisite rf phase jump, as in Fermilab MI. But note: accel. rate $d\gamma/dt$ for AHF factor 15 lower than for FMI – may set intensity limit. **Fallback option:** γ_t–jump.

2. **Transitionless Lattice**: tuned to imaginary γ_t to avoid transition crossing, as in Fermilab Proton Driver.

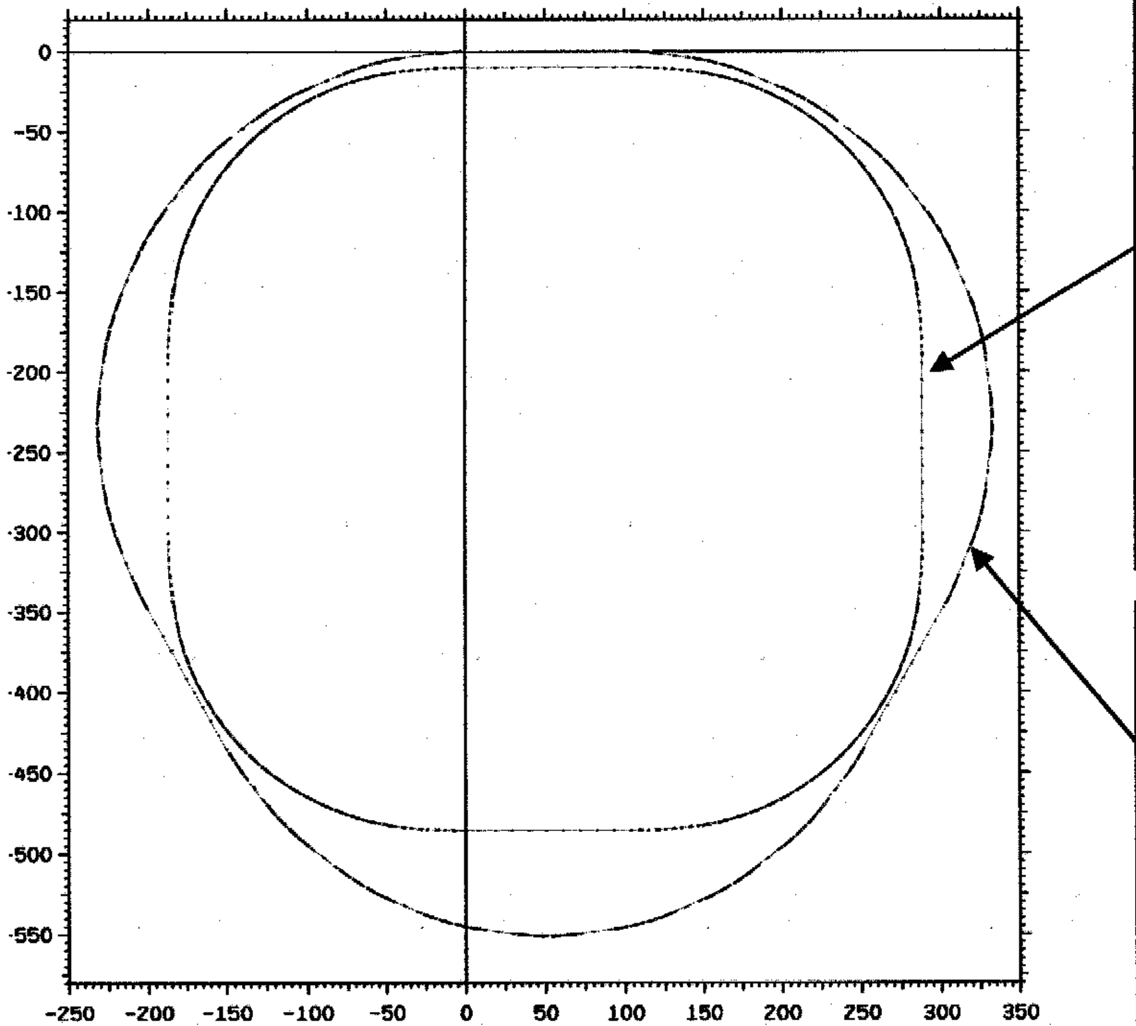
Main Ring Lattice Design Criteria

- conventional, conservative design (high operating reliability)
- simple, low-cost lattice (identical cells & magnets)
- operational simplicity (few "knobs")
- transition-crossing options (imaginary γ_t or γ_t–jumping capability, if needed)
- moderate momentum acceptance (at least $\pm 0.4\%$)
- moderately large dynamic aperture (at least 60π)

Lattice Design Criteria (cont'd)

- at least 3 long, dispersionless straights (for injection, RF, and single-bunch extraction)
- circumference to accomodate 25 200-ns beam buckets with up to 1.5×10^{12} protons per bunch
- 0.8 GeV injection energy, upgradable to 4 GeV
- uses Fermilab Main Injector dipoles

Two 50 GeV Main Ring Designs under Study
Conventional 4-sided and Transitionless 3-sided



Conventional 4-sided ring:

Circumference 1613.42 m

80 dipoles (6.78 m long)

32 dipoles (3.39 m long)

152 quads (1.295 m long)

$\nu_x = 19.42$, $\nu_y = 19.38$

$\gamma_T = 14.99$

Transitionless 3-sided ring:

Circumference 1757.4 m

96 dipoles (6.78 m long)

172 quads (1.55 m long)

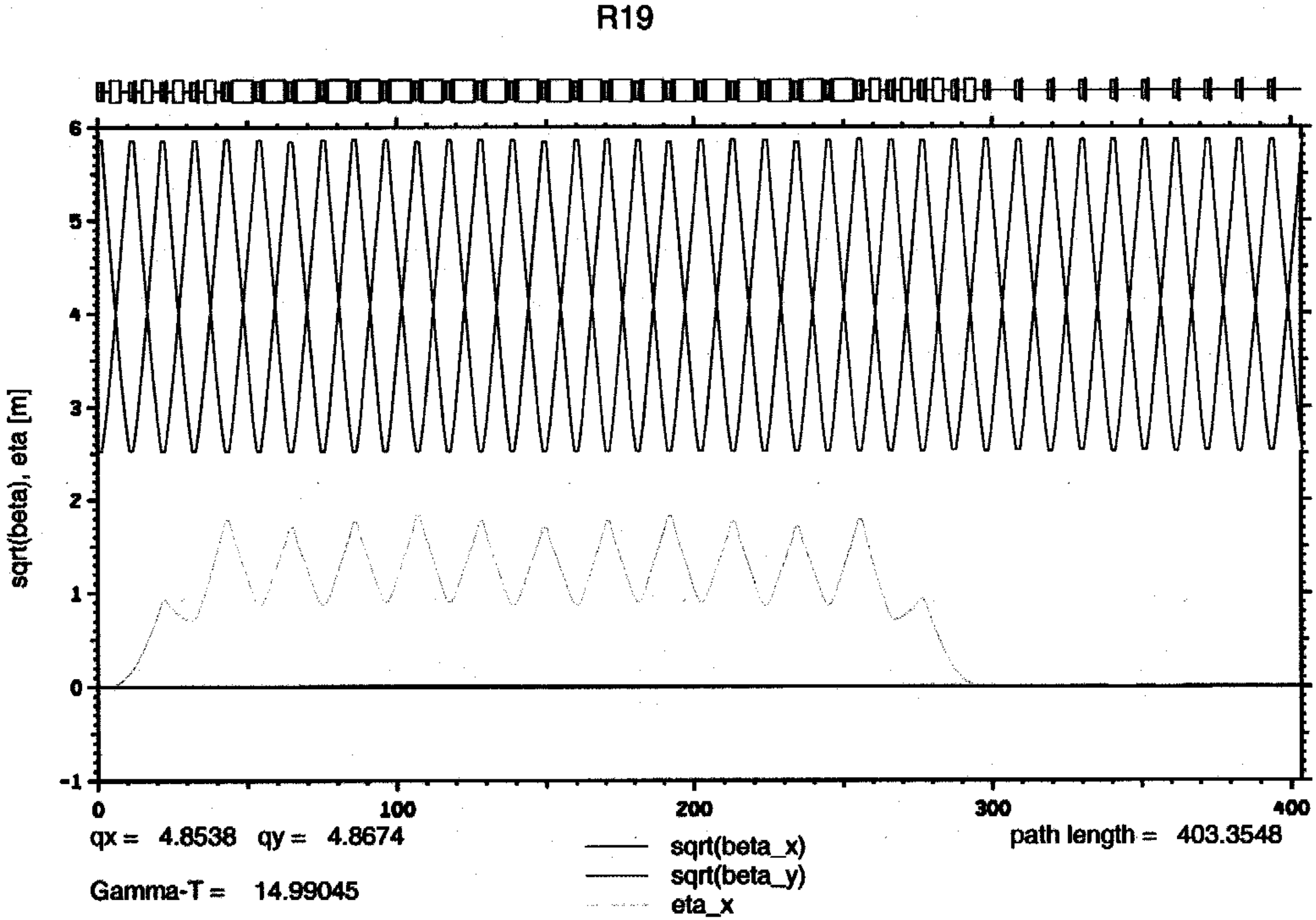
$\nu_x = 25.42$, $\nu_y = 22.38$

$\gamma_T = i26.02$

Lattice Option A.: Reference FODO Lattice

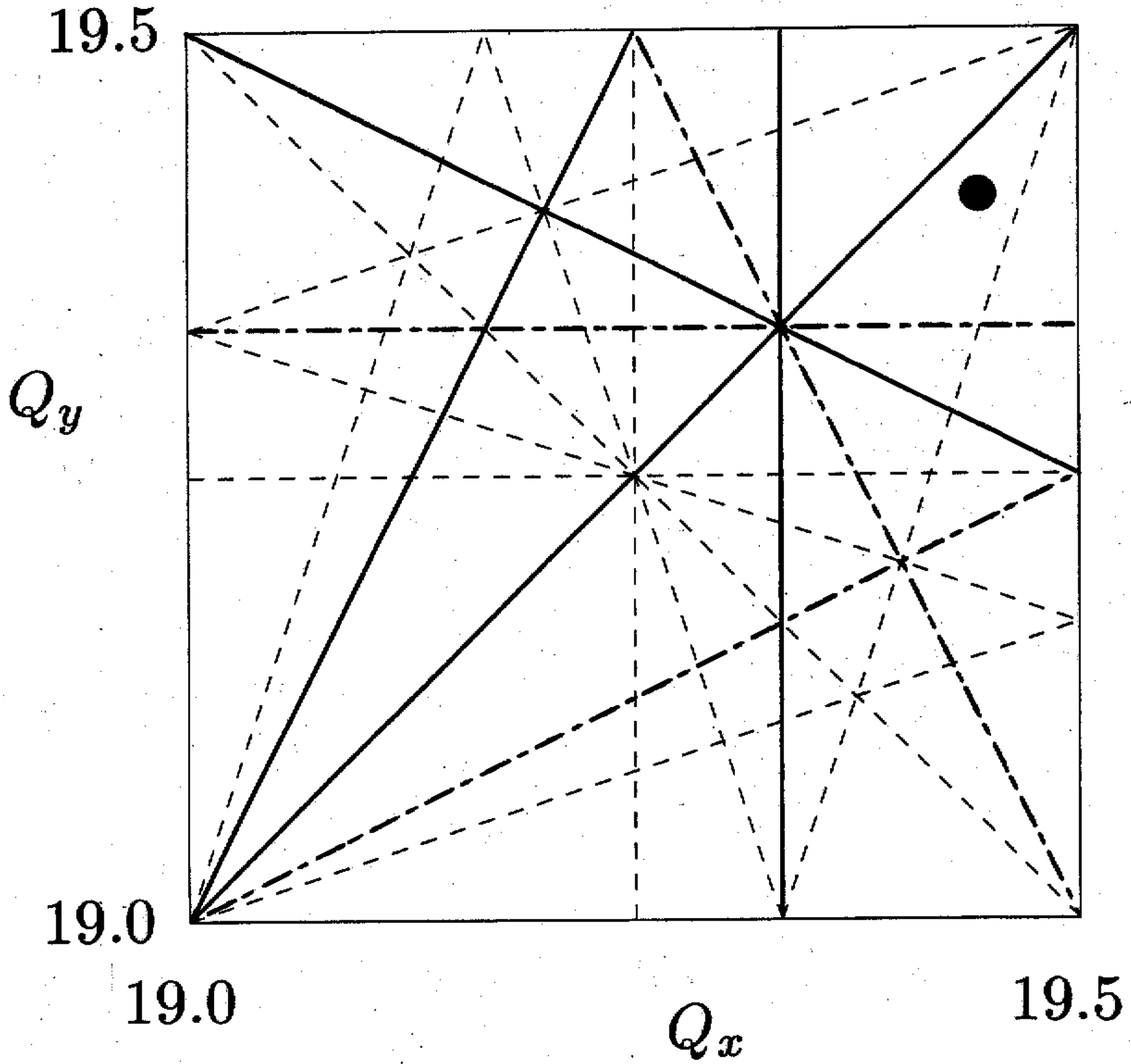
- modelled after 150 GeV Fermilab Main Injector
- symmetric 4-sided ring geometry
- regular FODO cell structure throughout (results in a "smooth" lattice, w/o. beta-modulation, but places γ_t within operating range: $\gamma_t < \gamma_{max}$)
- dispersion-suppressing sections at end of arcs
- requires both full- and half-length dipoles
- allows for later addition of pulsed γ_t–jump quadrupole insertions (but cell phase advance not optimum for this mode)

Conventional 4-sided Ring Lattice Functions for 1/4 of the Ring



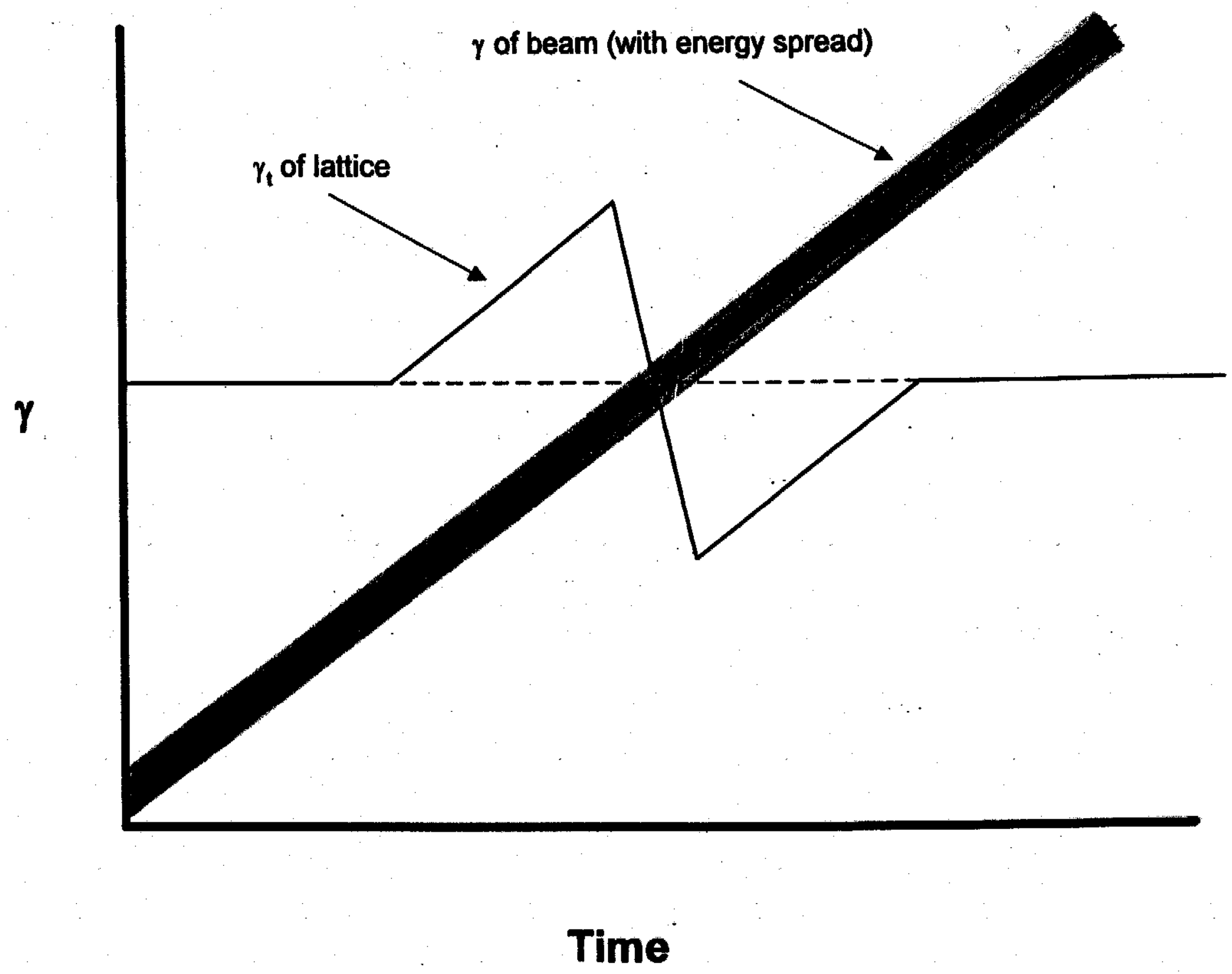
Betatron Tune Space

(4 orders, periodicity 1)

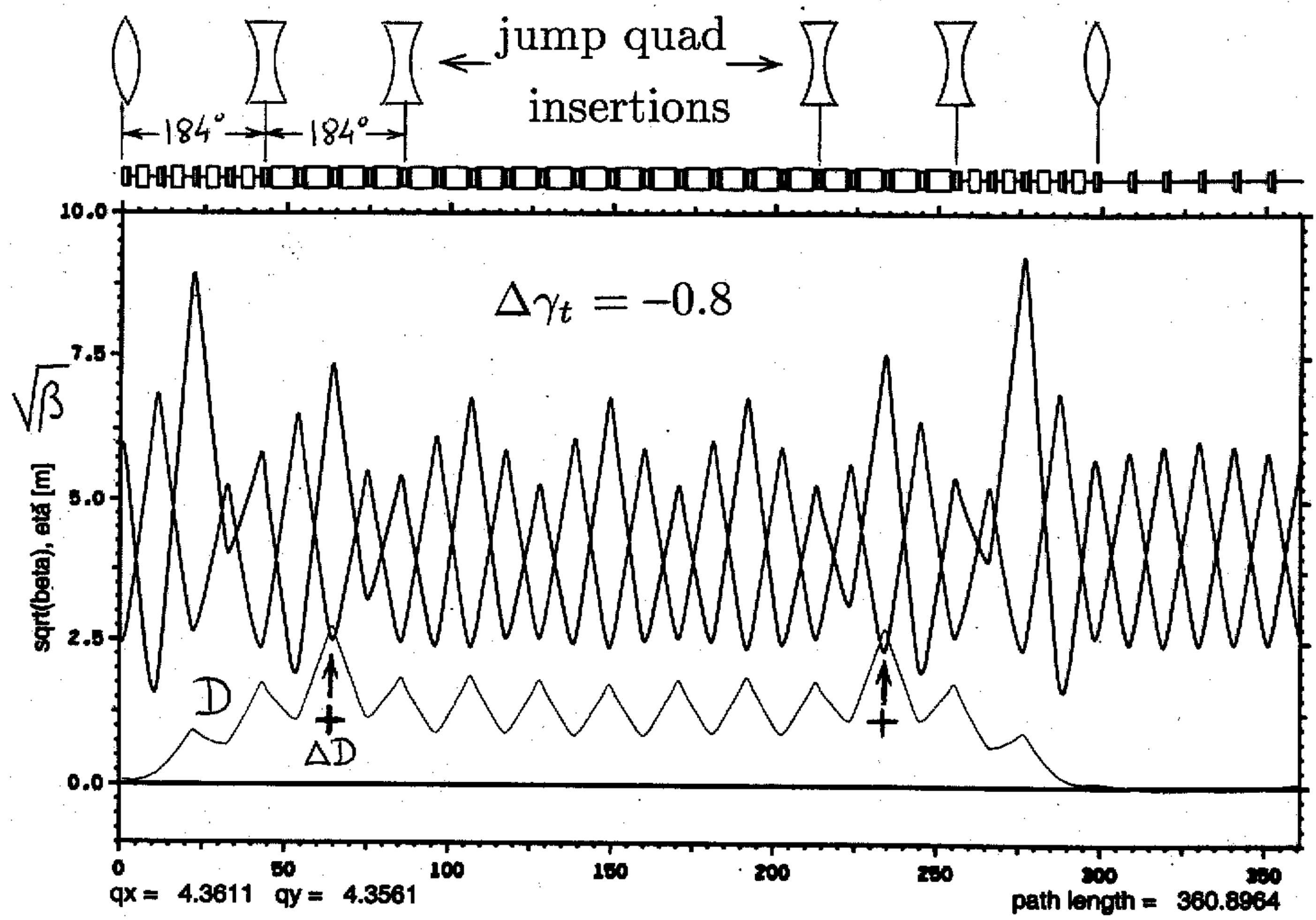


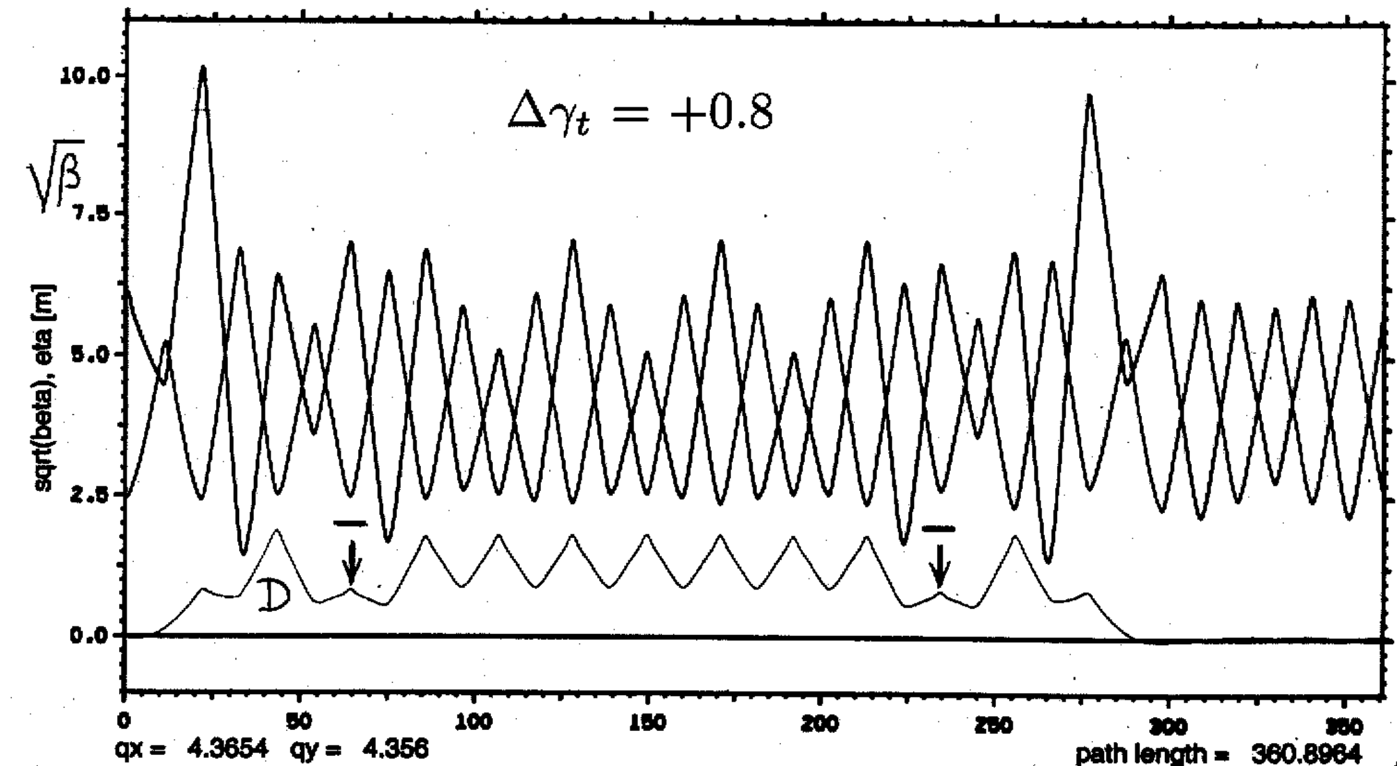
Reference FODO Lattice ($\gamma_t = 15$)

Transition-Crossing by γ_t–Jump



Reference Lattice With γ_t–Jump





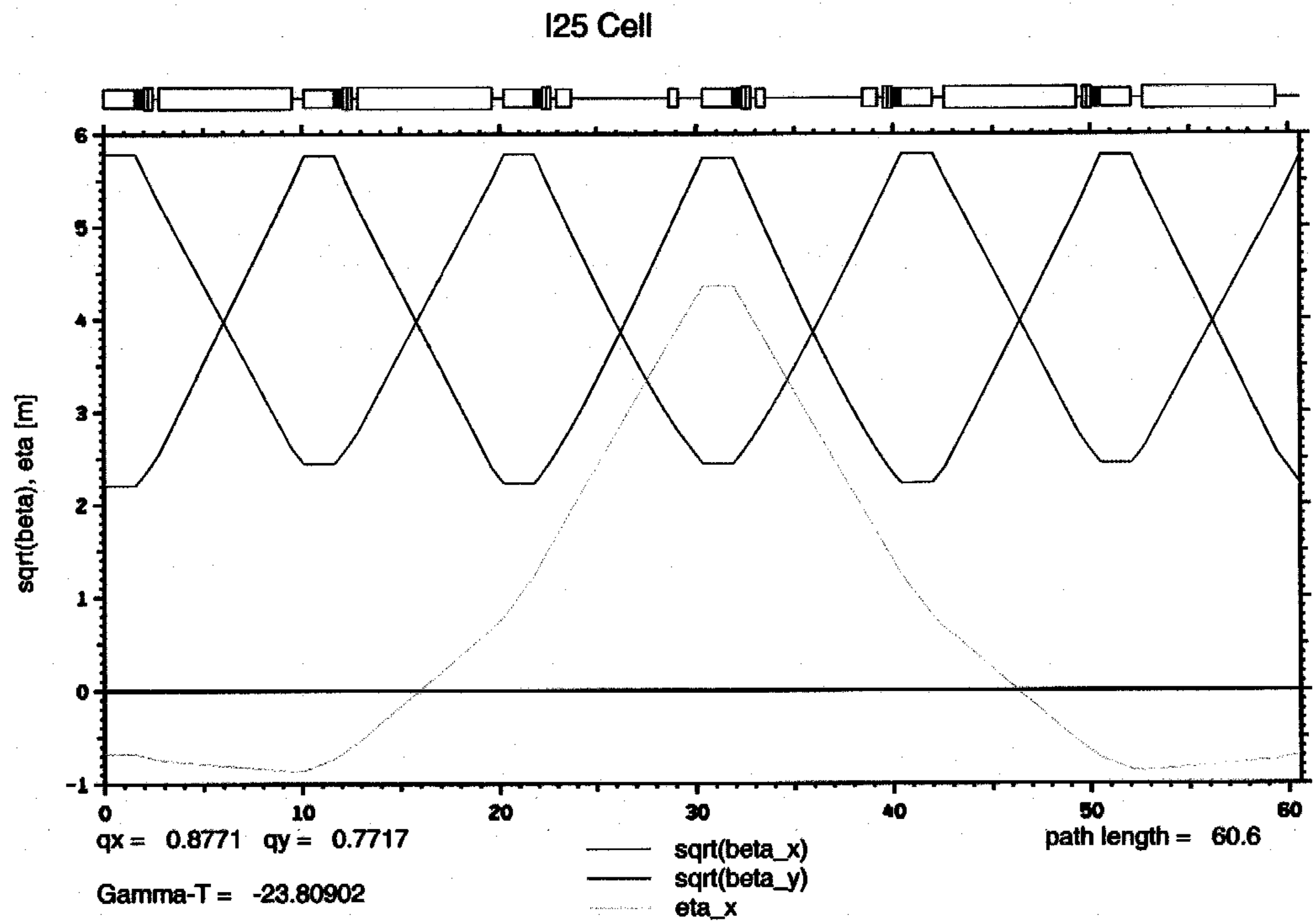
Lattice Option B.: Transitionless Lattice

- modelled after proposed FNAL Proton Driver, proposed JHF(JKJ) Main Ring
- symmetric 3-sided ring geometry
- arc cell structure (DOFO) incorporates missing-dipole cells to reduce (or change sign of) momentum-compaction factor $\alpha = \gamma_t^{-2}$ [known as a "FMC" lattice]
- achromatic arcs provide zero horizontal dispersion in the long straights

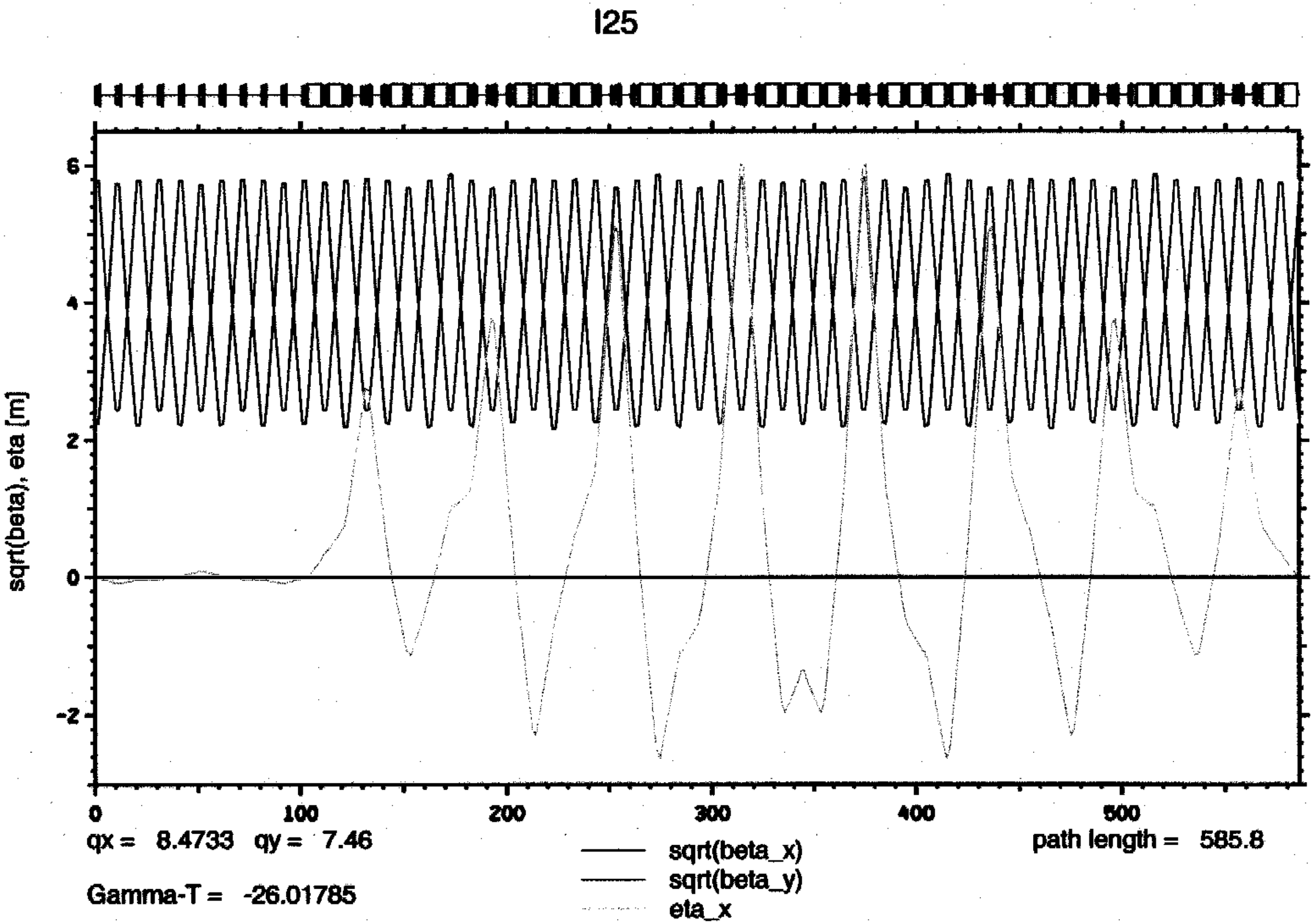
Transitionless Lattice, cont'd

- single, fixed ring lattice for operation at imaginary γ_t, but can also be tuned to real $\gamma_t < \gamma_{max}$ [the latter optimized for addition of an effective γ_t–jump system]
- 9% greater ring circumference than Reference lattice to accomodate missing-magnet arc cells

Transition-Less 3-sided Lattice Functions (Arc Cell)

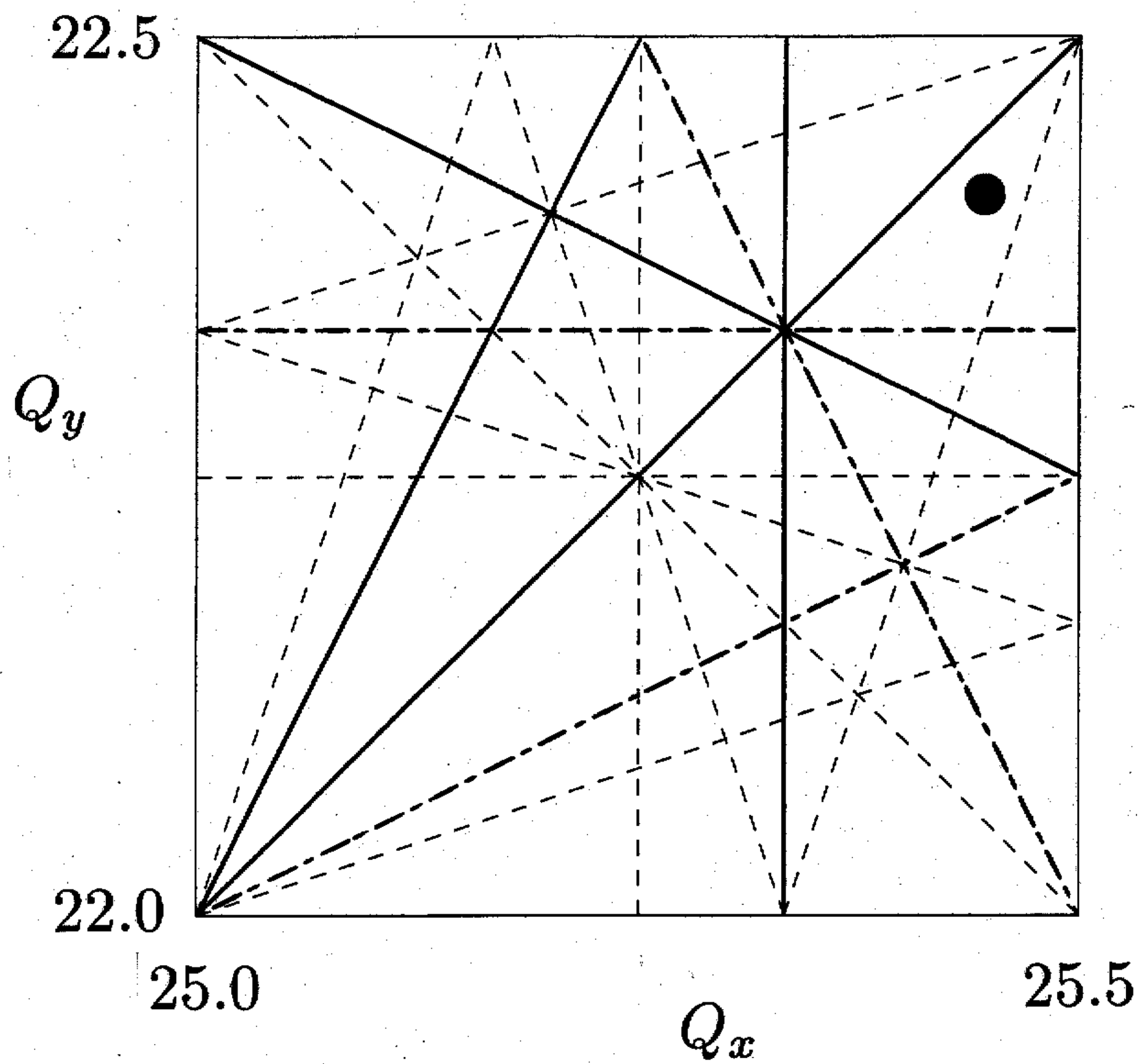


Transition-Less 3-sided Lattice Functions (1/3 of the Ring)



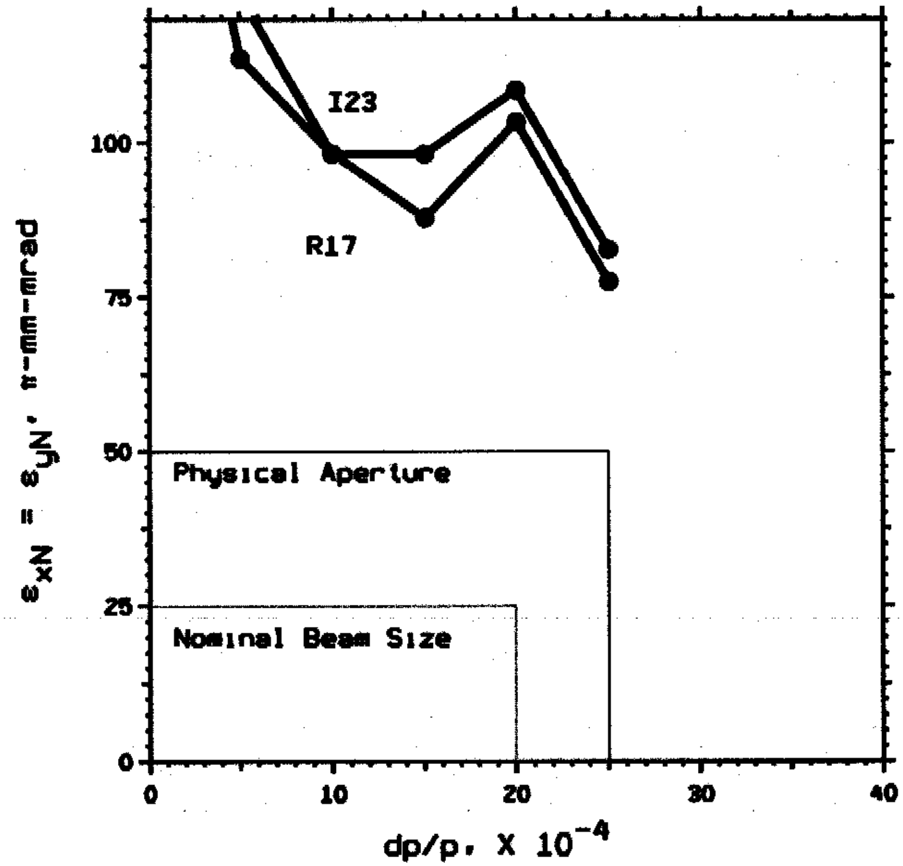
Betatron Tune Space

(4 orders, periodicity 1)



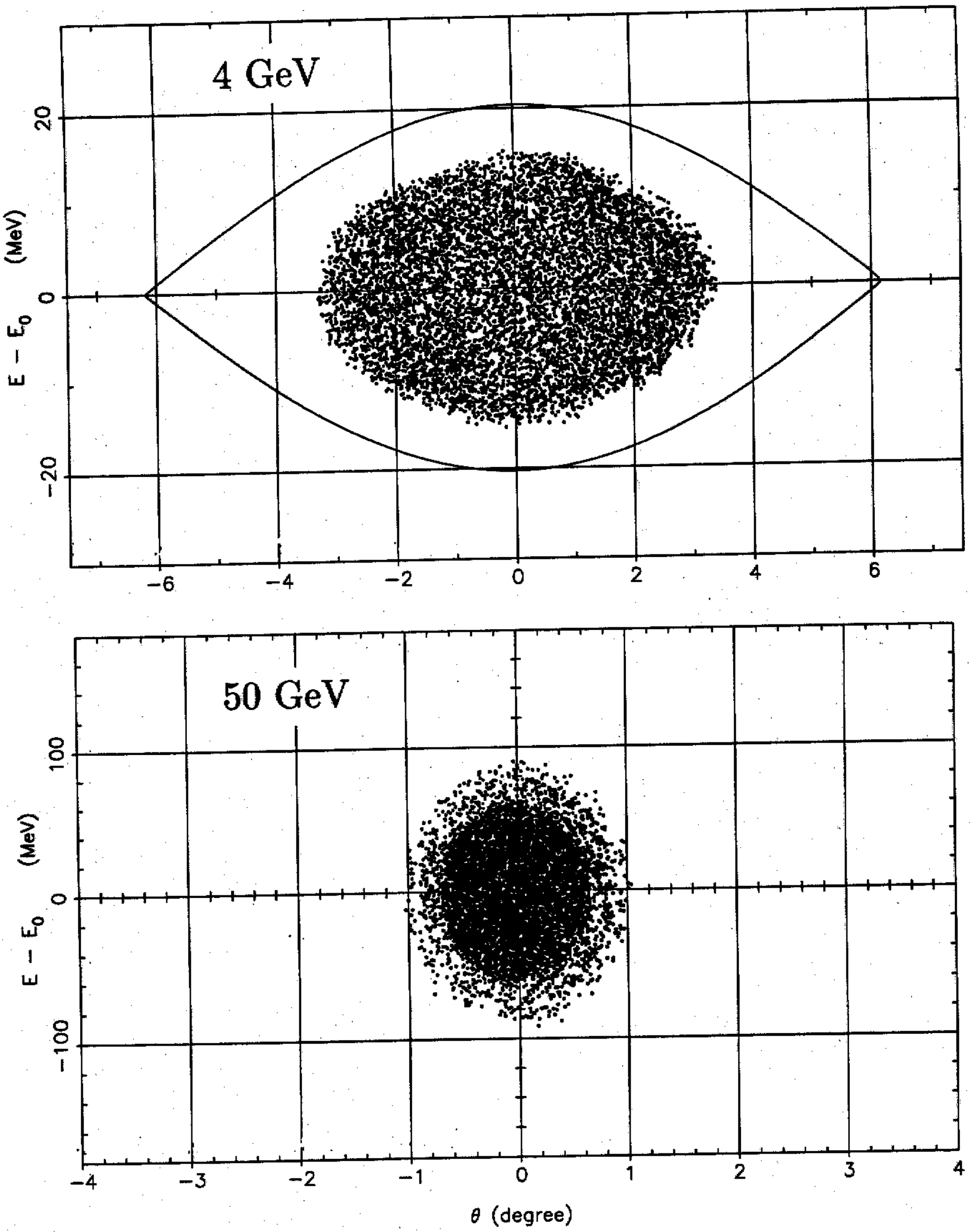
Transitionless Lattice (γ_t = i26)

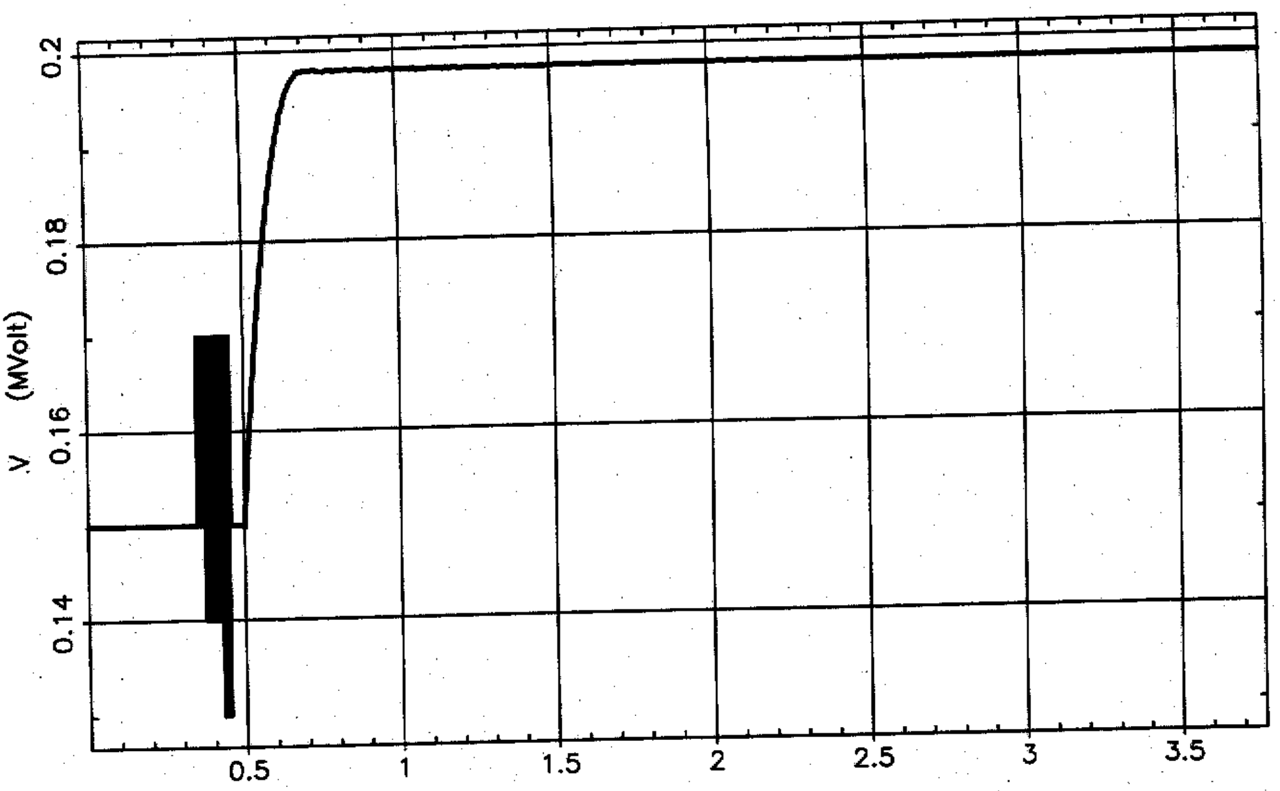
Both Main Ring Dynamic Apertures at 4 GeV with New Errors
Conventional 4-sided in blue - Transitionless 3-sided in red

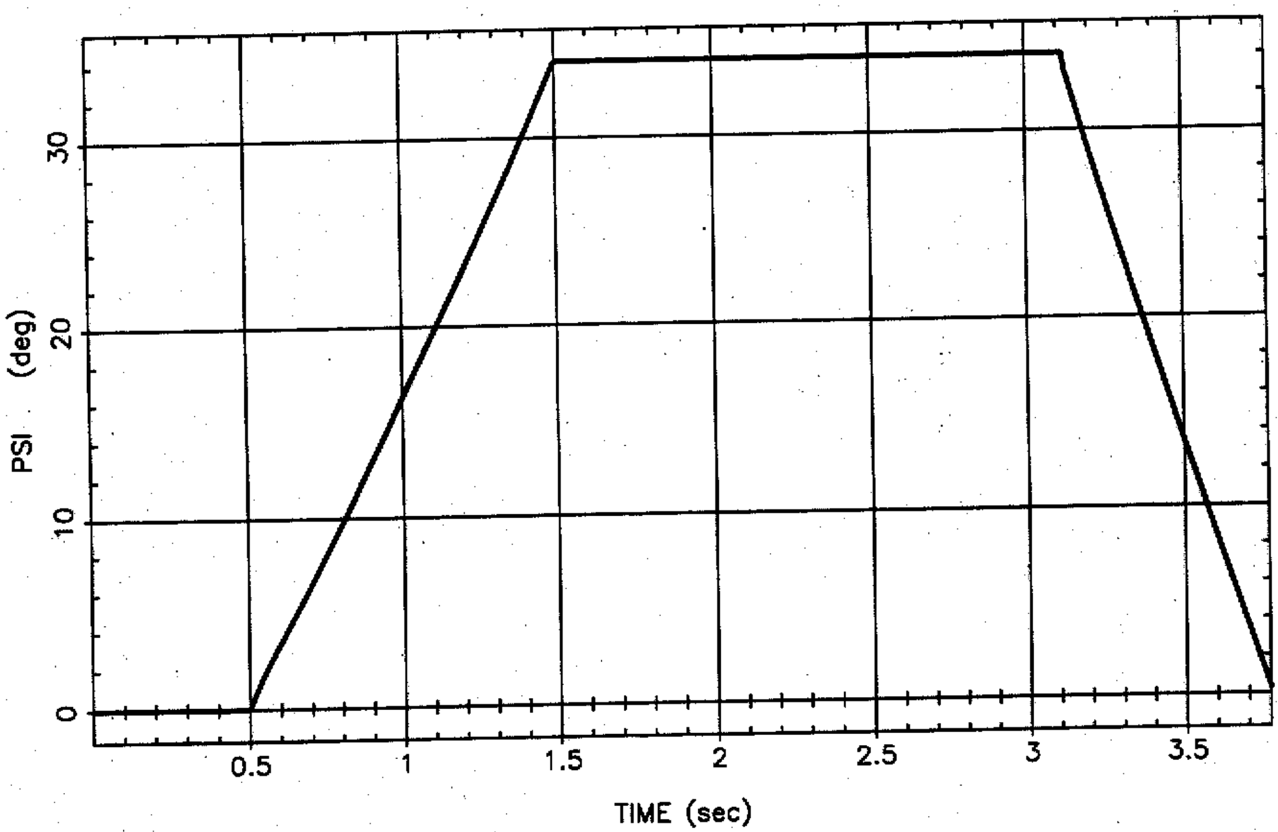


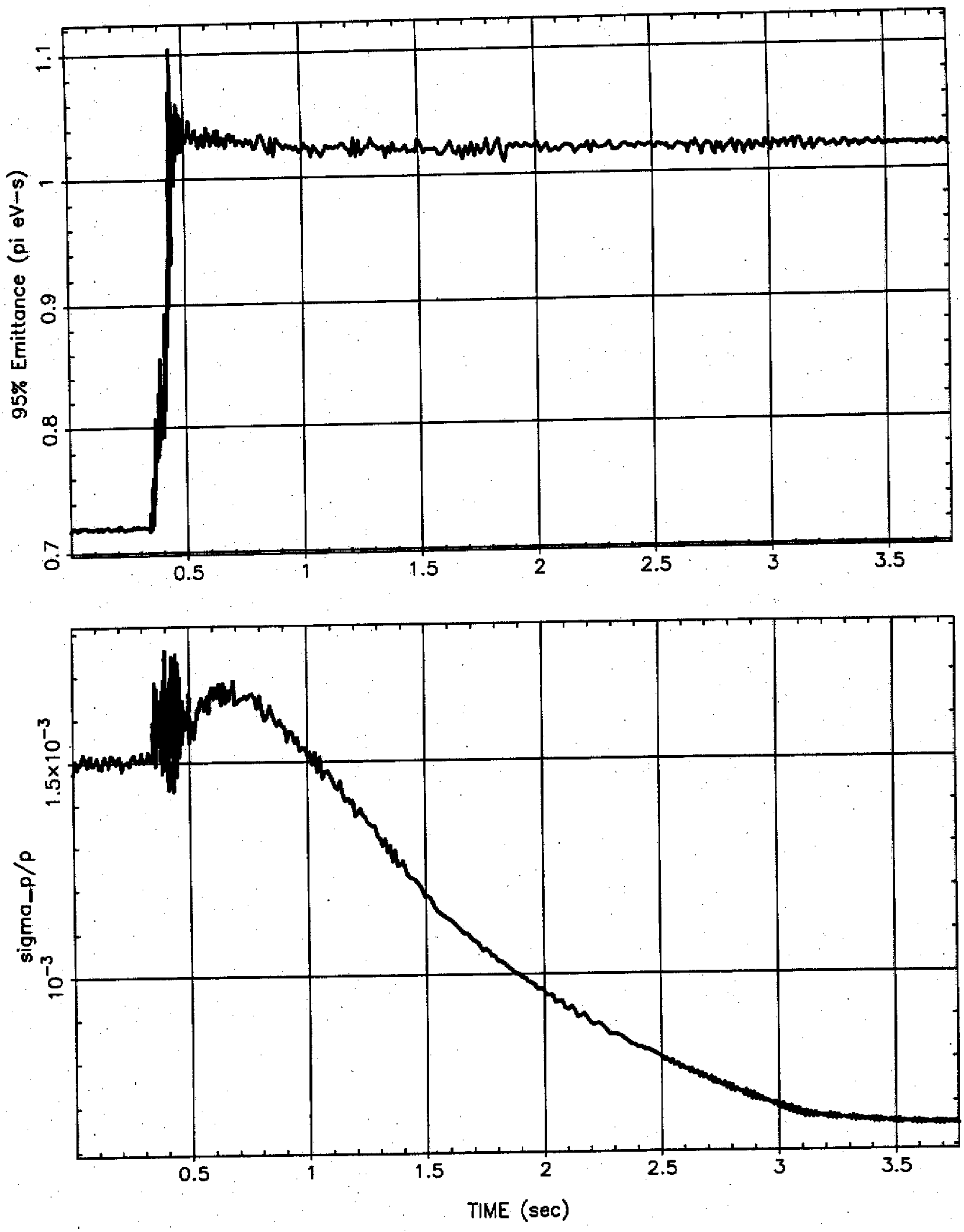
The dynamic aperture is comfortably larger than the physical aperture

Chromaticity corrected to -6 for both rings


4 GeV
E − E0 (MeV)
20
0
−20
−6
−4
−2
0
2
4
6
50 GeV
E − E0 (MeV)
100
0
−100
−4
−3
−2
−1
0
1
2
3
4
θ (degree)


V (MVolt)
0.2
0.18
0.16
0.14
0.5
1
1.5
2
2.5
3
3.5


PSI (deg)
30
20
10
0
0.5
1
1.5
2
2.5
3
3.5
TIME (sec)


95% Emittance (pi eV-s)
0.7
0.8
0.9
1
1.1
0.5
1
1.5
2
2.5
3
3.5
sigma_p/p
10^{-3}
1.5×10^{-3}
0.5
1
1.5
2
2.5
3
3.5
TIME (sec)

Summary and Conclusions

- Two promising lattice designs:
  - both conservative & reasonably conventional
  - smooth, well-behaved lattice functions
  - capable of meeting desired criteria (dynamic aperture, momentum acceptance, beam intensity & time structure)
  - capable of providing simple & reliable operation
  - employing existing & low-cost technology, very few types of many identical magnetic elements
- Reference FODO lattice:
  - standard dispersion suppression more robust than achromatic arcs in providing zero dispersion in straights
  - compact lattice, but transition energy within operating range, unsplit tunes and undesirable phase-slip factor

Main Ring Synchrotron Lattices

- Transitionless FMC lattice:
  - imaginary transition energy avoids transition crossing
  - imag. γ_t adopted in several recent high-energy, hi-intensity lattice designs, but no operating experience
  - FMC lattice has great flexibility of operating modes: imag. γ_t, high real γ_t, or efficient γ_t–jump capability with only minor, localized lattice perturbation.
  - widely-split tunes and more desirable phase-slip factor.

4 GEV BOOSTER LATTICE

1. Criteria:

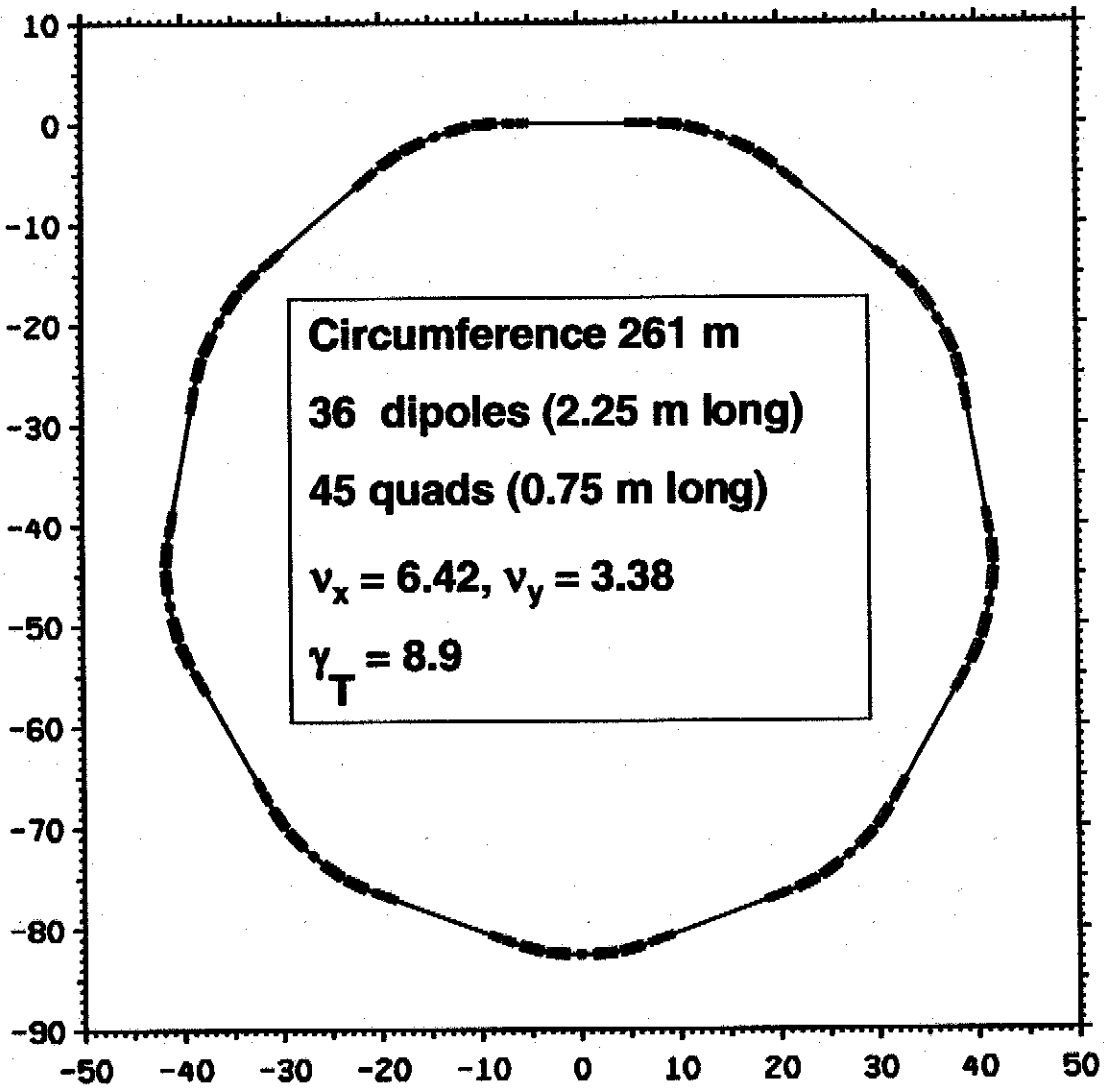
- transitionless ($\gamma_t > \gamma_{max}$)
- conventional/conservative design
- operational simplicity (few "knobs")
- low cost (small, compact ring, identical magnets)
- 5 Hz ramp rate (moderate RF power)
- 157 & 800 MeV H^- strip injection
- $3 - 4 \times 10^{12}$ protons @ h = 1

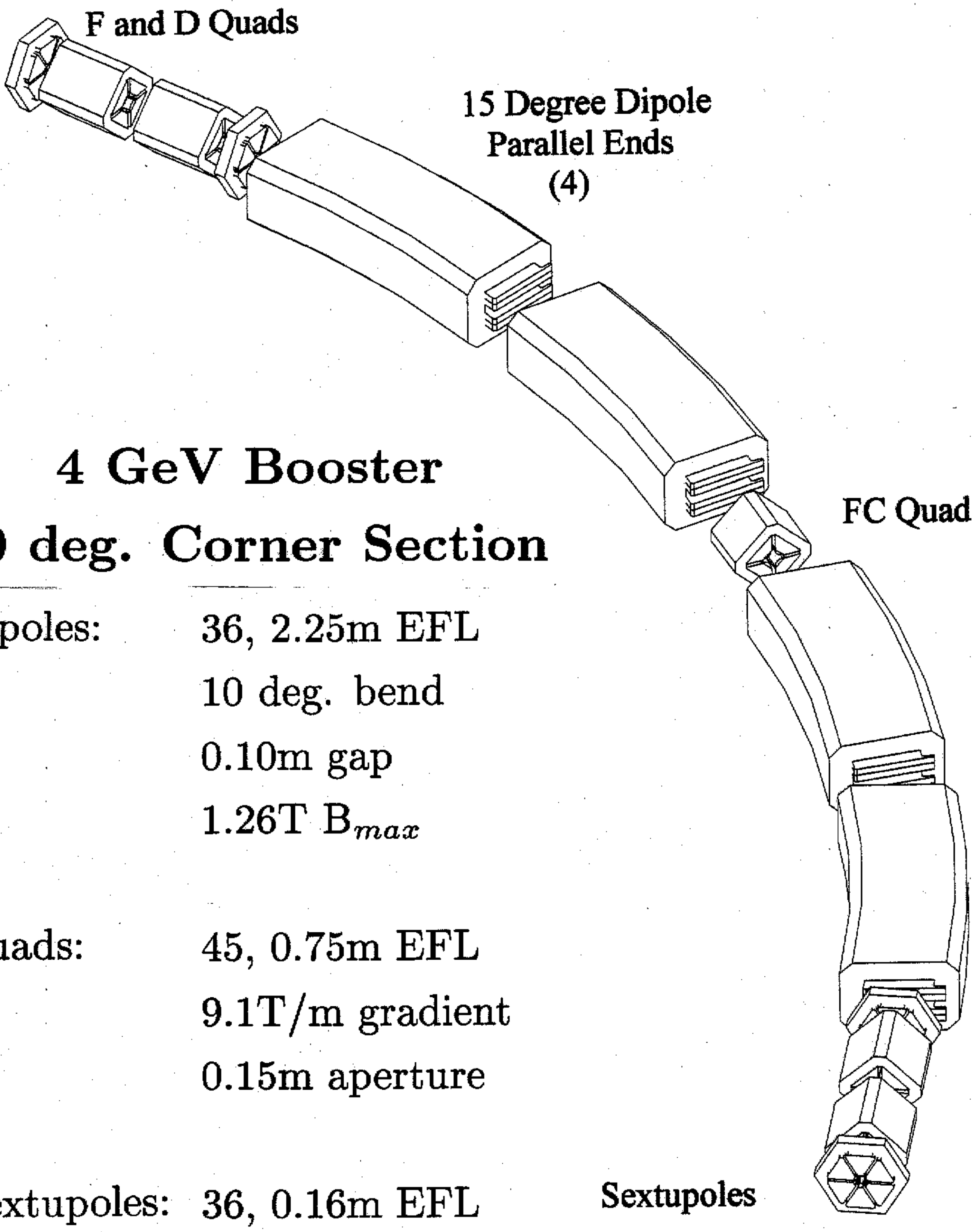
4 GEV BOOSTER LATTICE

2. Lattice: we will discuss

- ring geometry
- superperiod lattice structure
- transition energy
- operating point in tune space
- lattice functions, dynamic aperture
- chromatic properties
- longitudinal dynamics (RF program)
- injection, extraction systems

4 GeV Booster Layout (see talk by P. Schwandt)



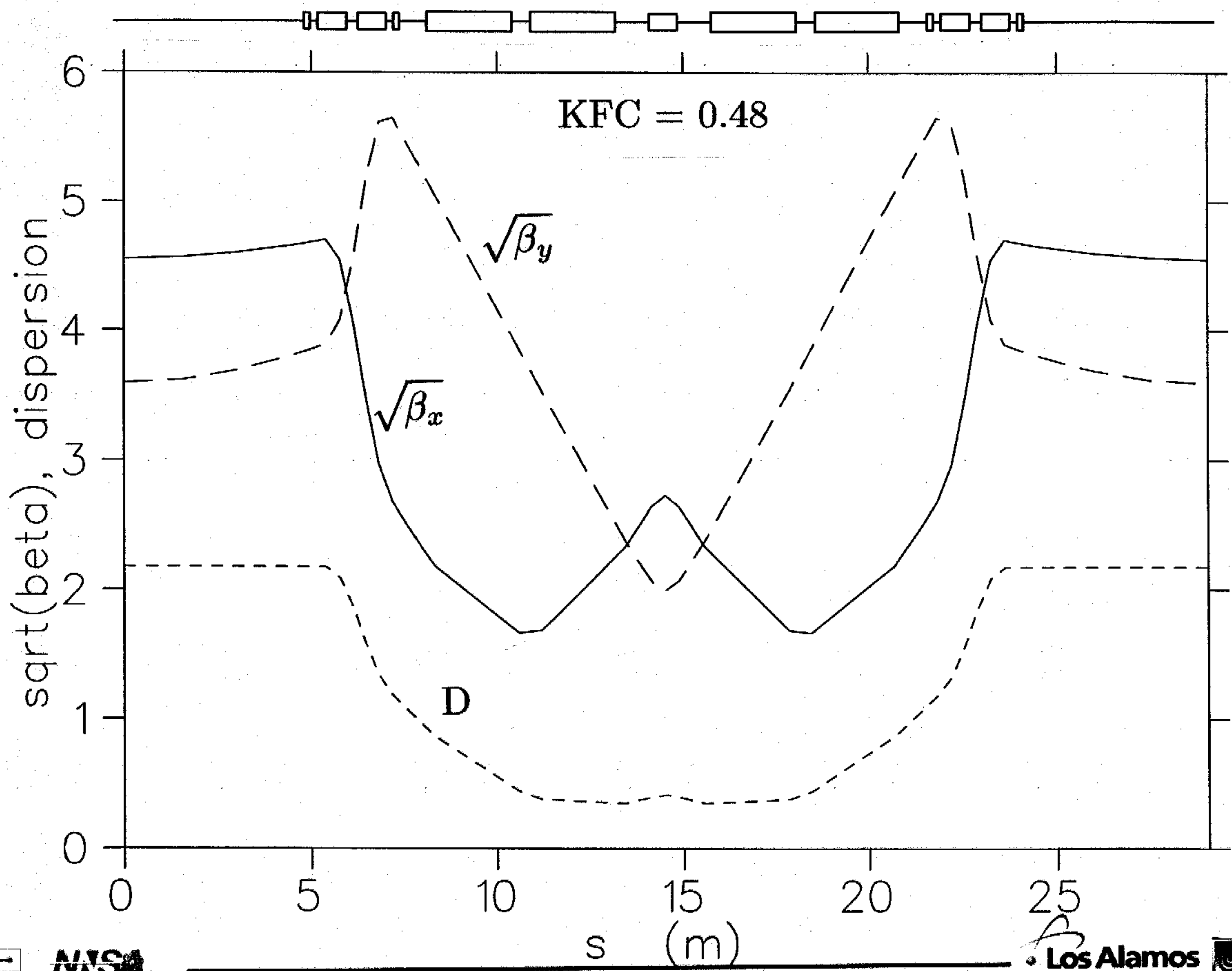


4 GeV Booster

40 deg. Corner Section

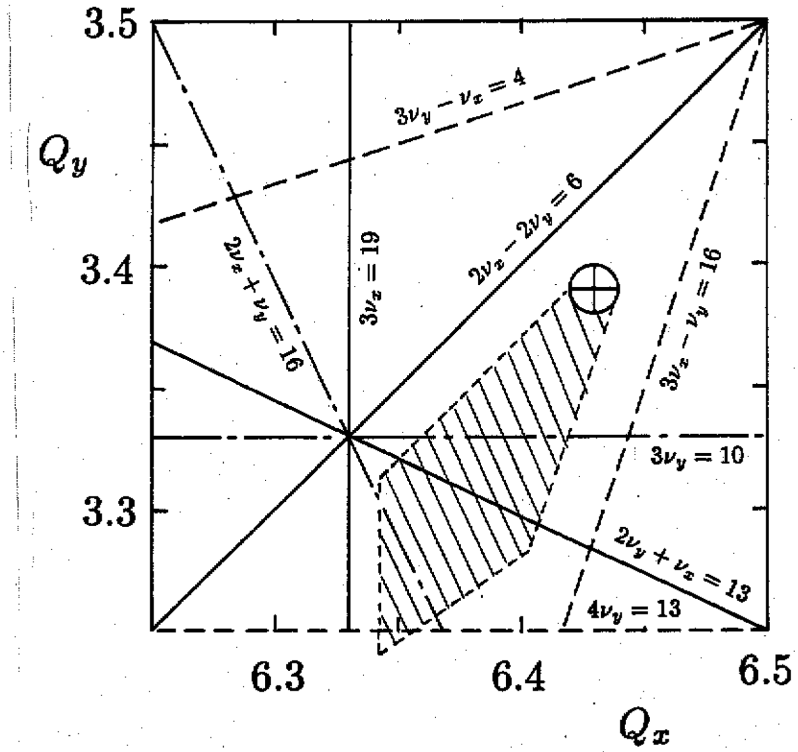
Dipoles:	36, 2.25m EFL
	10 deg. bend
	0.10m gap
	1.26T B_{max}
Quads:	45, 0.75m EFL
	9.1T/m gradient
	0.15m aperture
Sextupoles:	36, 0.16m EFL
	0.12T B_{pole}
	0.15m aperture

Booster-9L



KFC = 0.48
$\sqrt{\beta_y}$
$\sqrt{\beta_x}$
D
sqrt(beta), dispersion
0
1
2
3
4
5
6
0
5
10
15
20
25
s (m)

Booster Tune Diagram
(with resonances up to 4^{th} order)



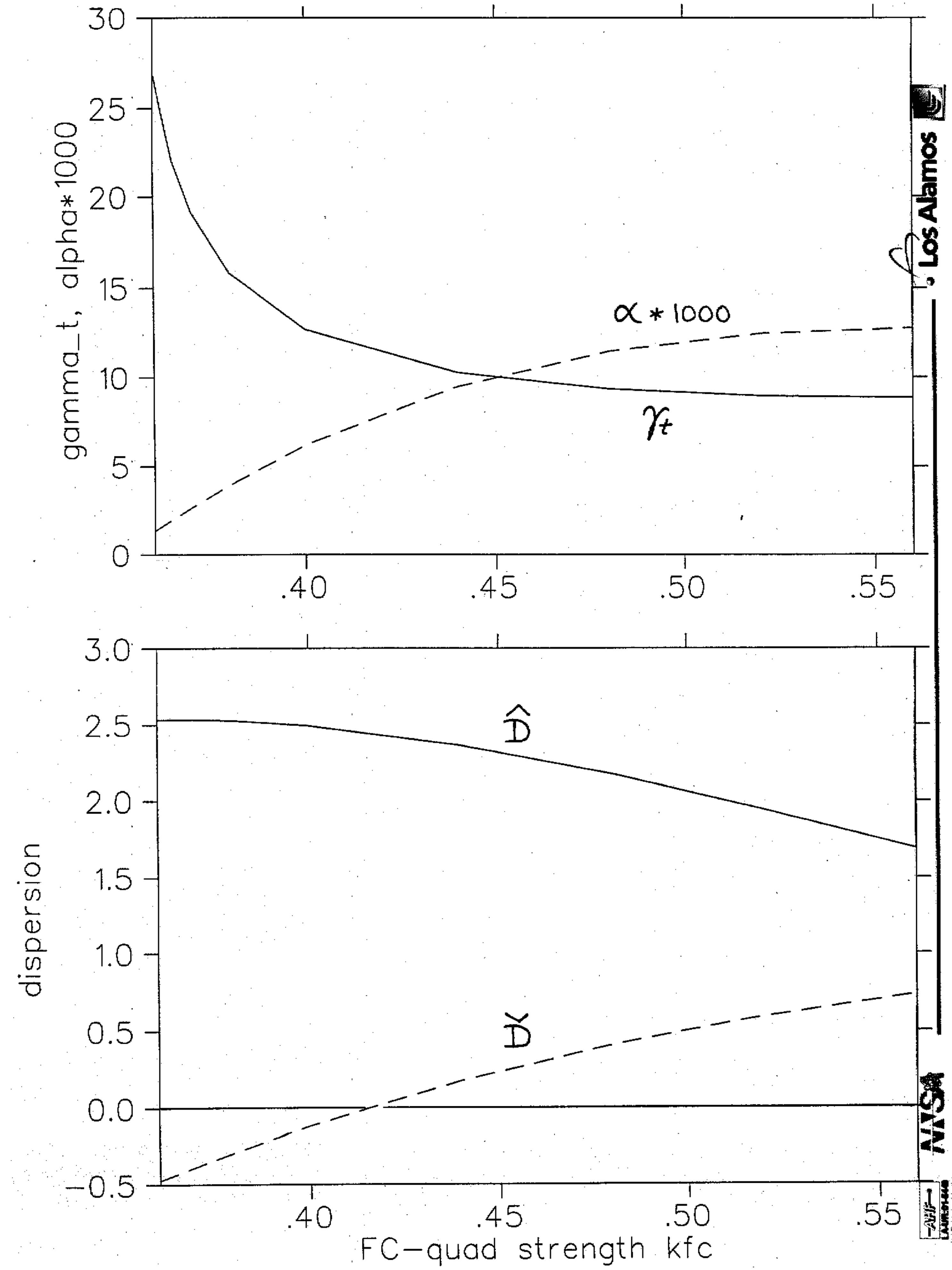
Systematic resonances for P = 9:

$$n\nu_x \pm m\nu_y = kP = 9, 18, ...$$

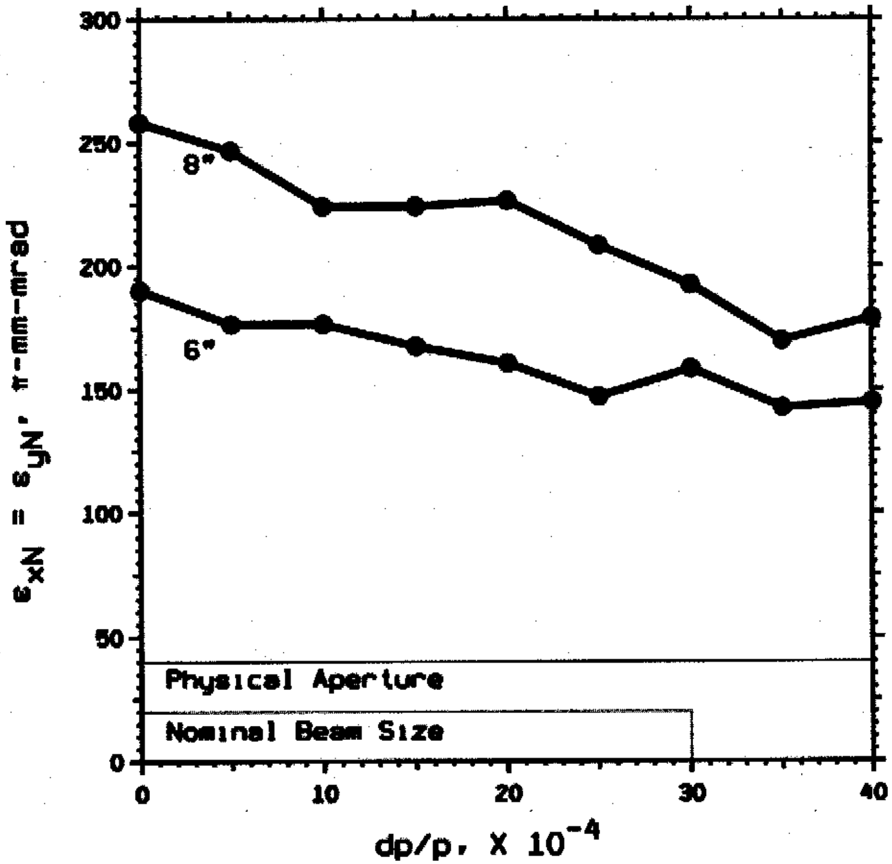
No systematic/structural resonances in operating region!

Important **sum** resonances:

$2\nu_y + \nu_x = 13$	(normal sextupole)	———
$3\nu_y = 10, \quad 2\nu_x + \nu_y = 16$	(skew sextupole)	— - —
$4\nu_y = 13$	(octupole)	- - - - -


gamma_t, alpha*1000
30
25
20
15
10
5
0
α * 1000
γ_t
.40
.45
.50
.55
dispersion
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
$\hat{D}$
$\check{D}$
.40
.45
.50
.55
FC−quad strength kfc

4 GeV Booster Dynamic Aperture at 140 MeV with New Errors 6 in Quads shown in blue - 8 in Quads shown in red

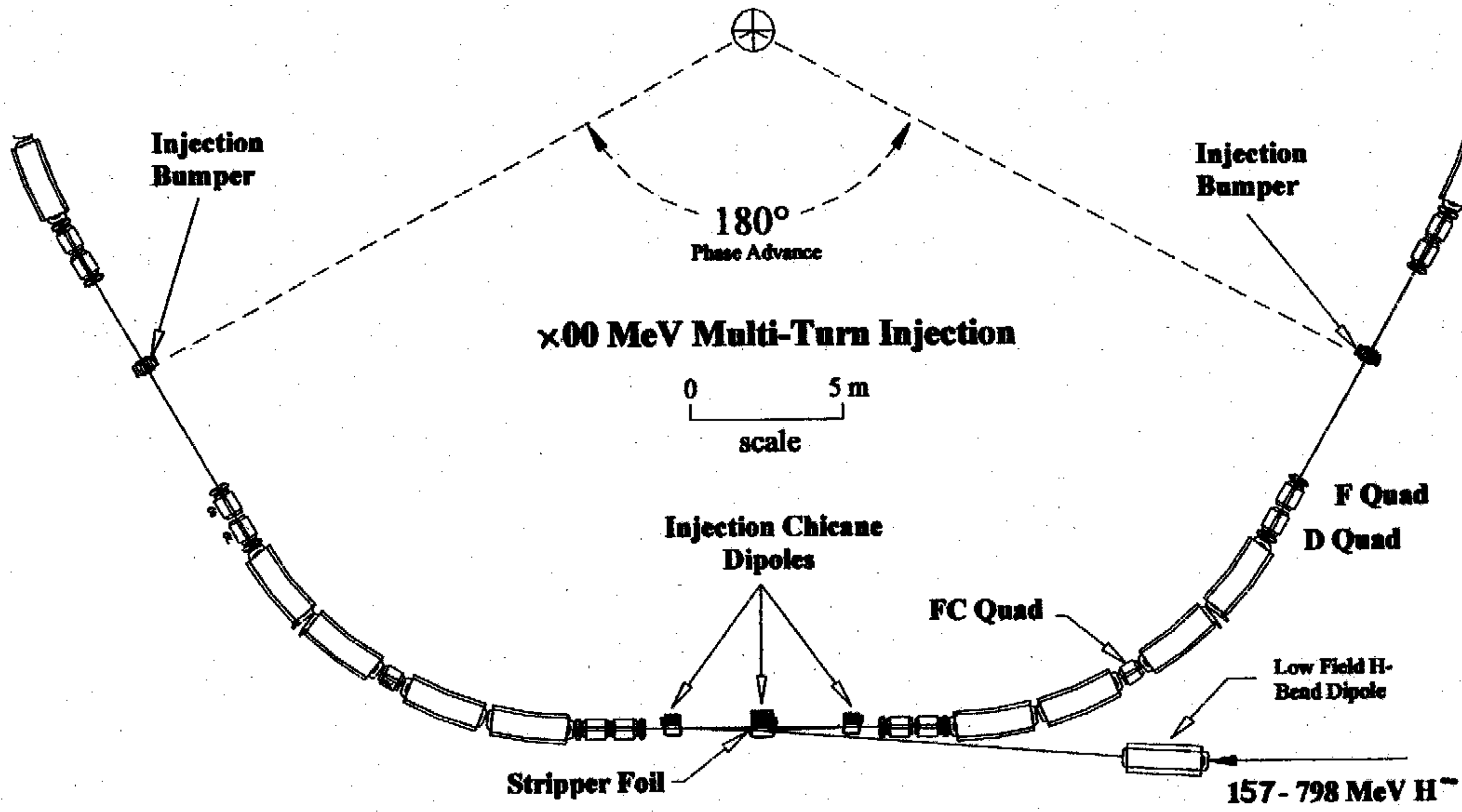


Quadrupoles error multipoles scaled from AHF main ring quadrupole error requirements

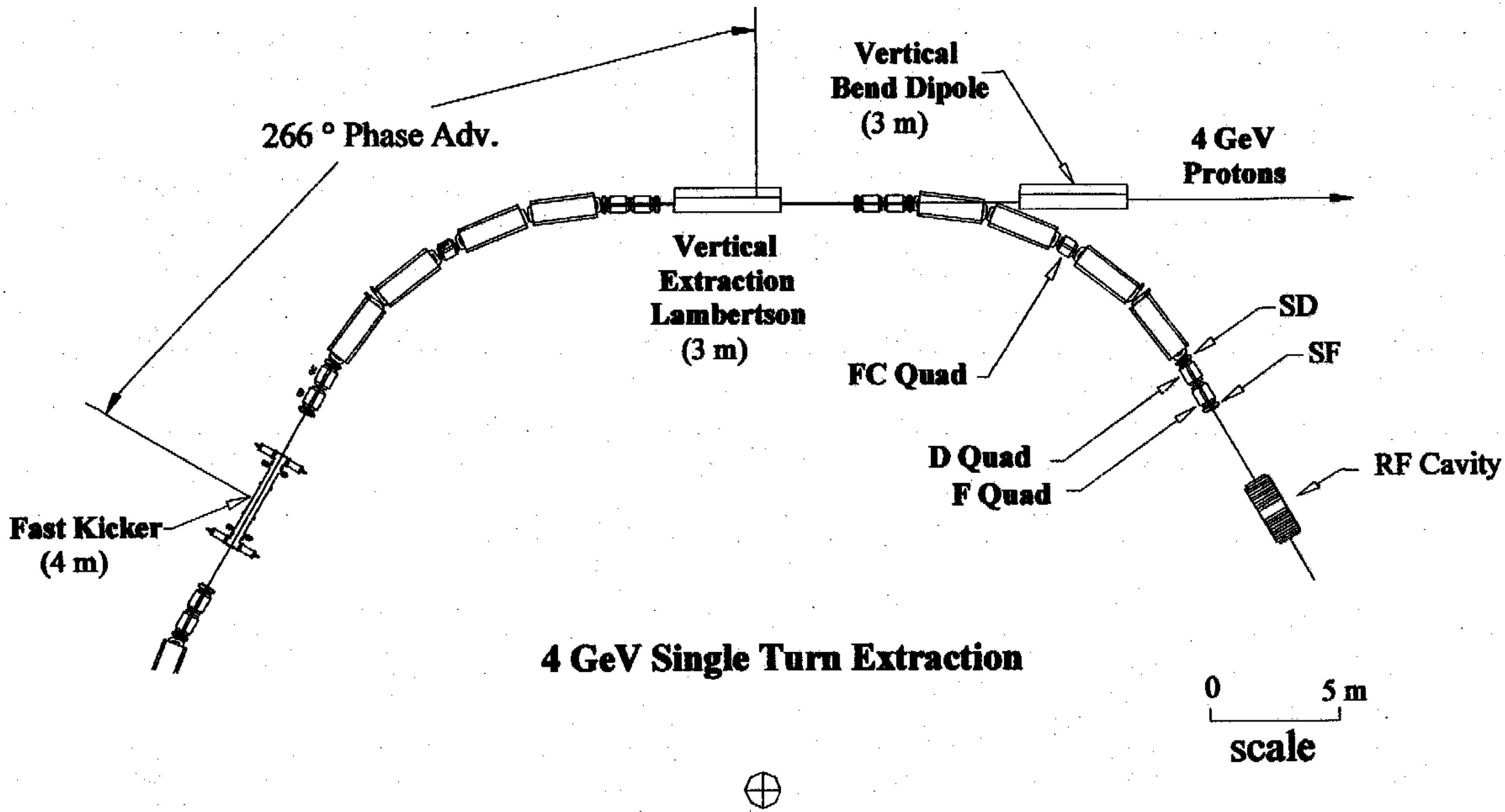
Shown are the results for two different quadrupoles diameters

Dynamic apertures seems dominated by dipoles (not much different for larger quadrupoles)

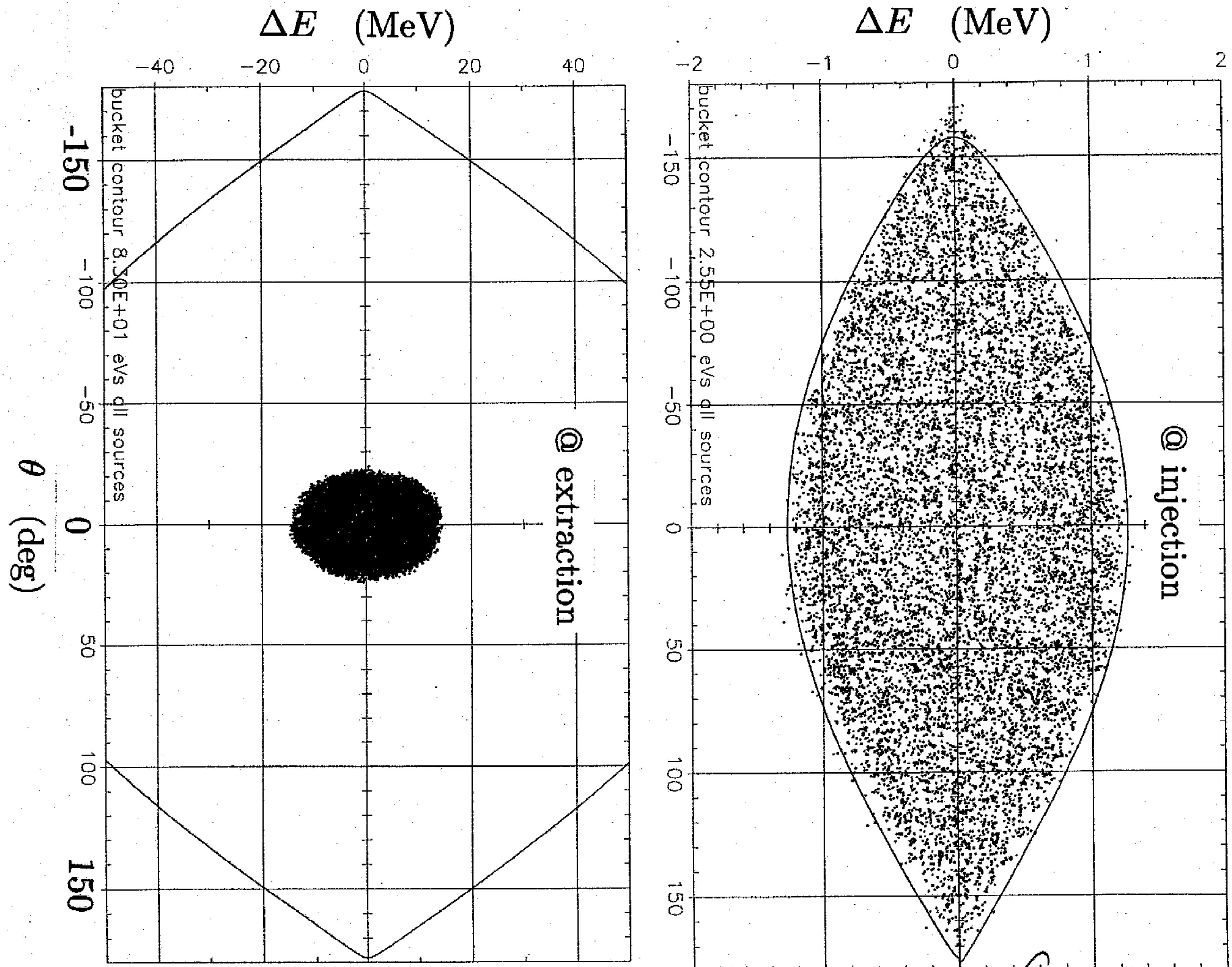
The dynamic apertures is much larger than the physical aperture

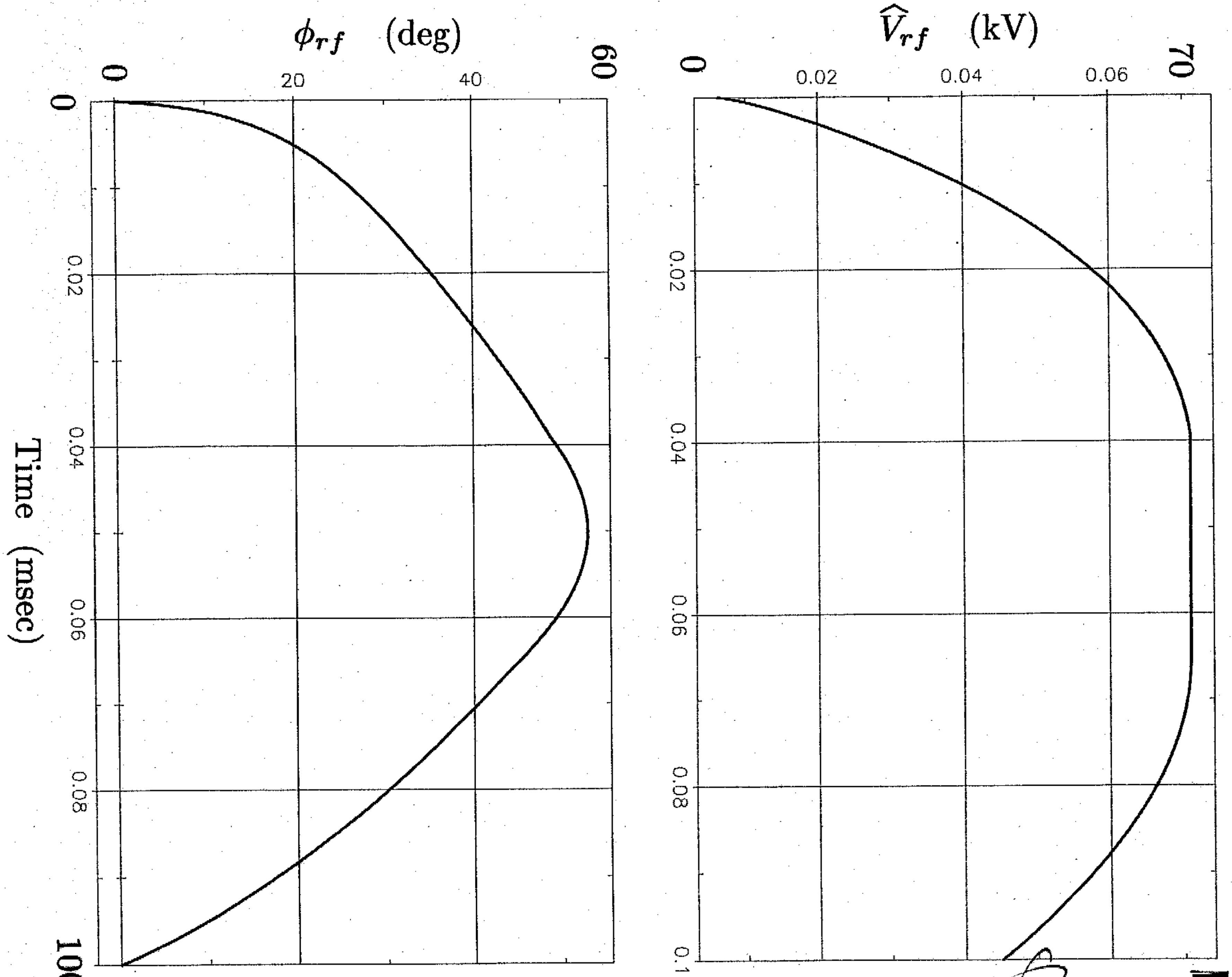


Layout of the H⁻ strip injection straight showing the locations of the injection bumpers, dc chicane dipoles and carbon stripper foil.

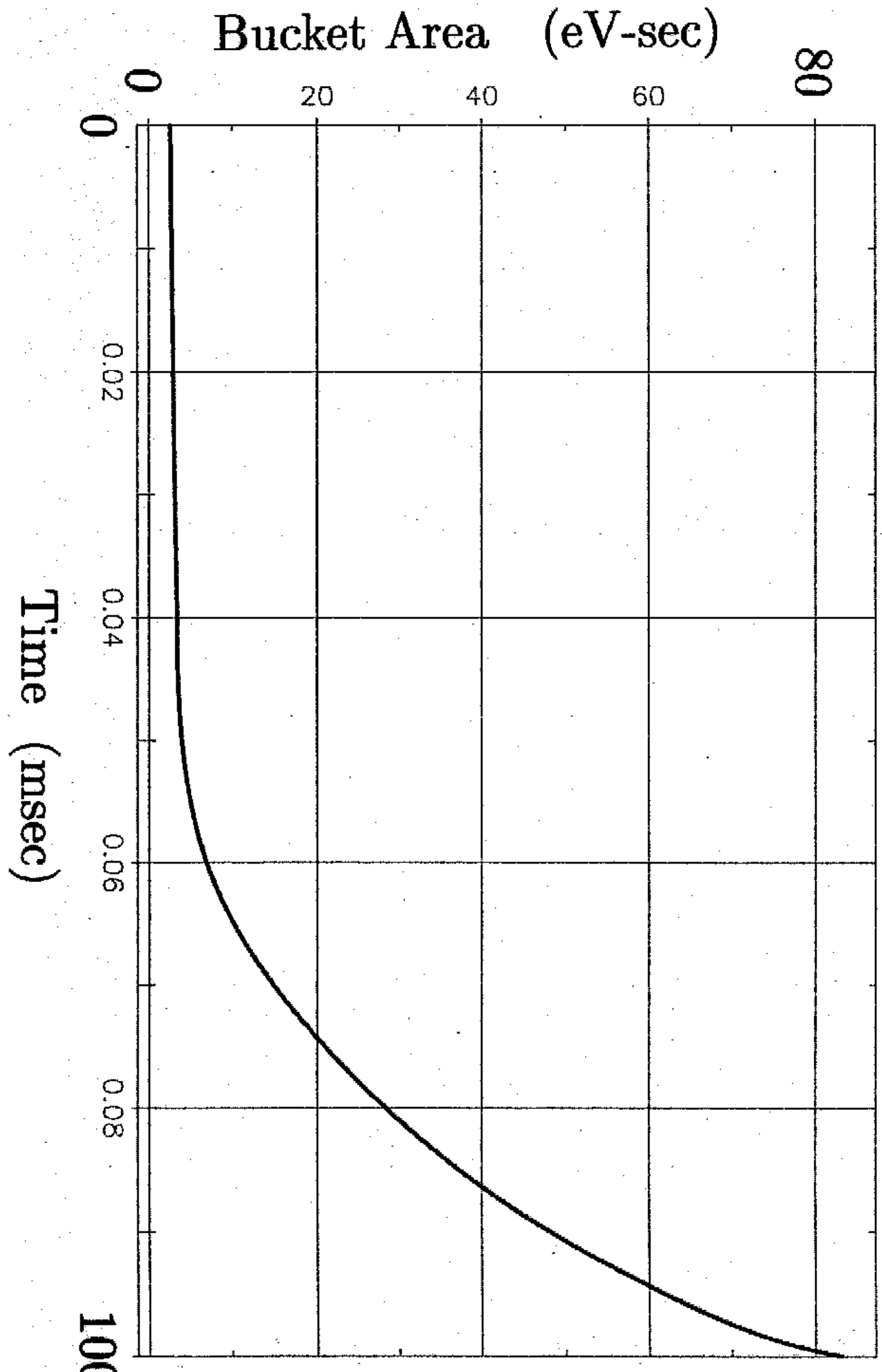


Layout of the booster single-turn fast extraction system.

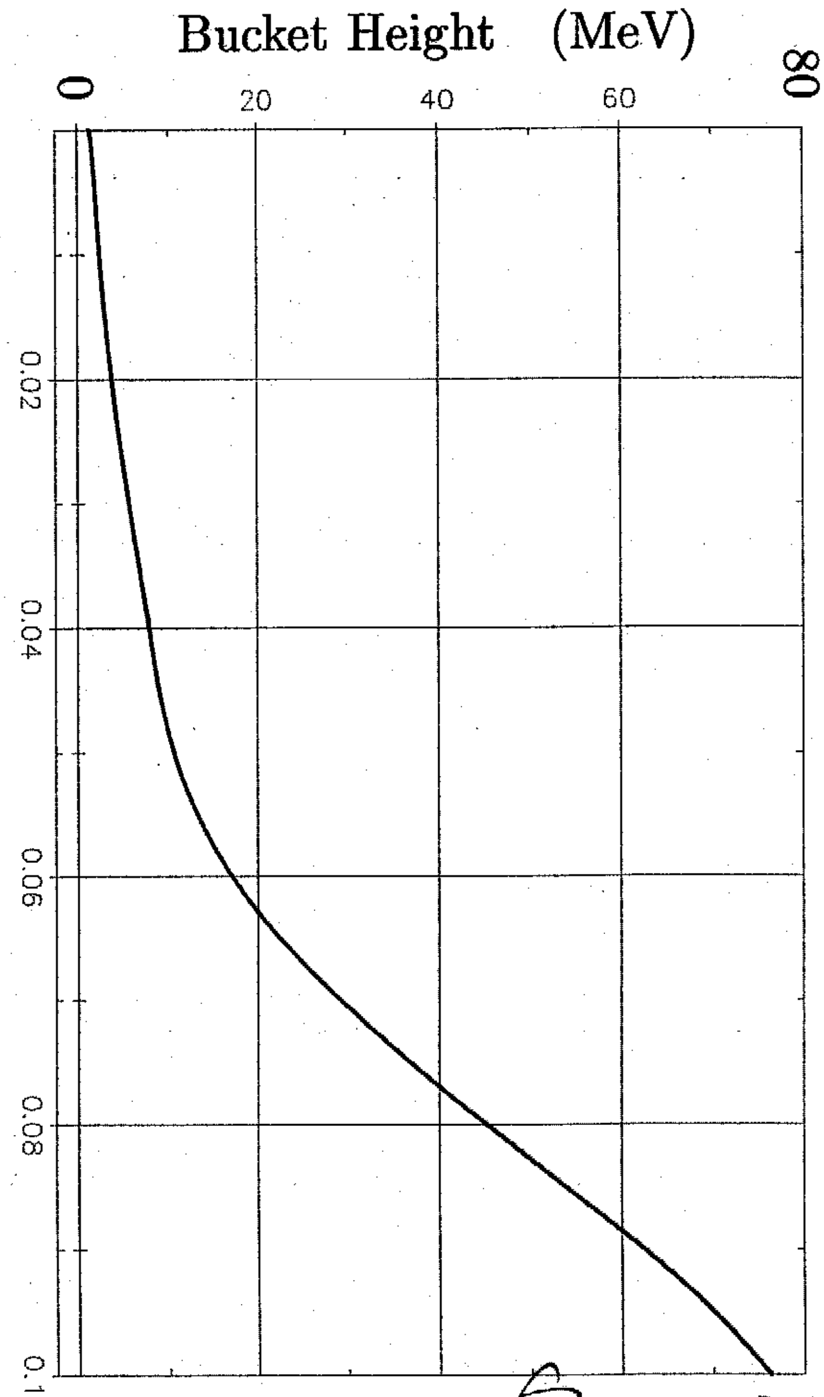

ΔE (MeV)
@ extraction
bucket contour 8.30E+01 eVs all sources
θ (deg)
ΔE (MeV)
@ injection
bucket contour 2.55E+00 eVs all sources



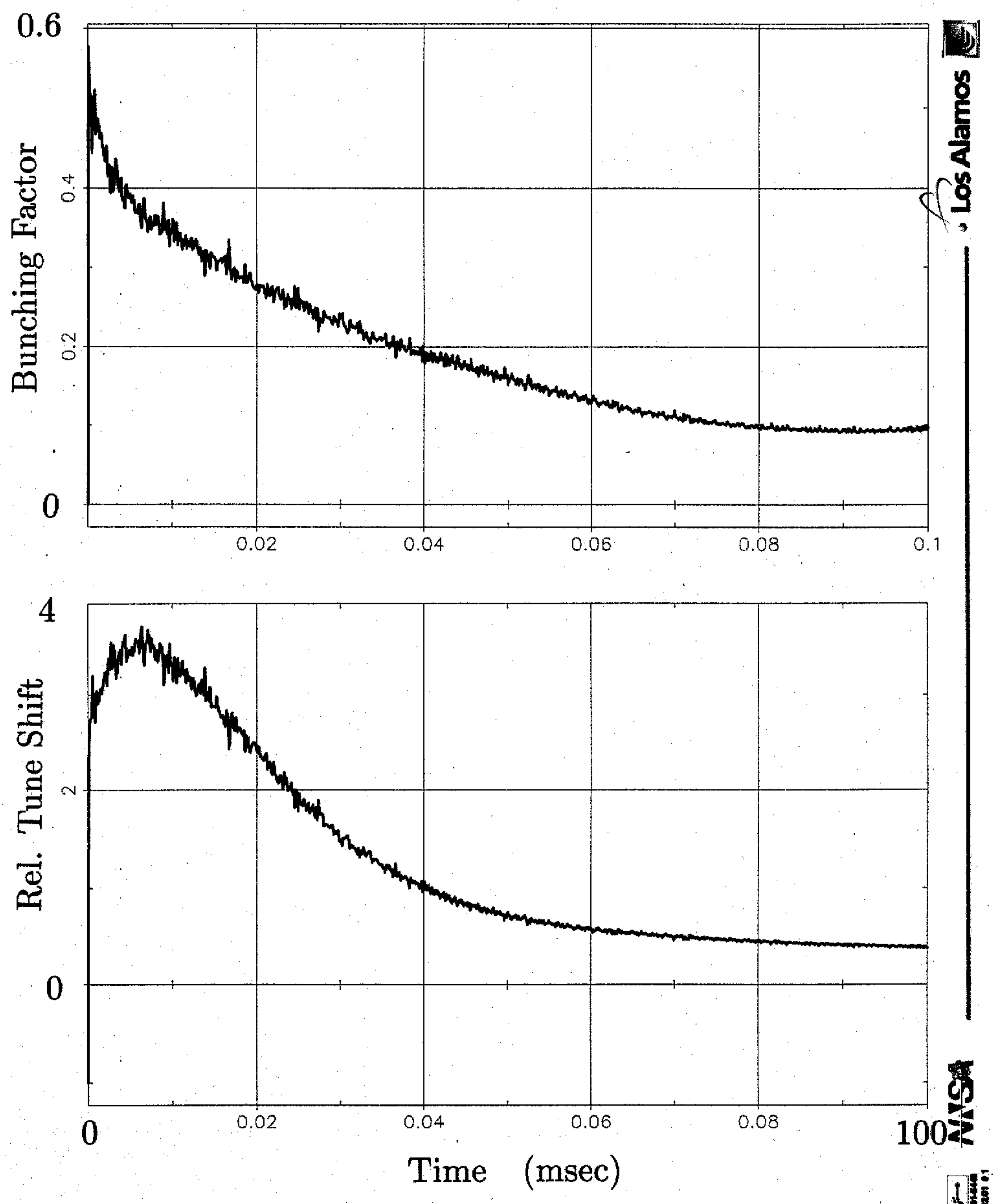
ϕ_{rf} (deg)
0
20
40
60
$\widehat{V}_{rf}$ (kV)
0
0.02
0.04
0.06
70
Time (msec)
0
0.02
0.04
0.06
0.08
100
0.1



Bucket Area (eV-sec)
0
20
40
60
80
0
0.02
0.04
0.06
0.08
100
Time (msec)



Bucket Height (MeV)
0
20
40
60
80
0.02
0.04
0.06
0.08
0.1


0.6
0.4
0.2
0
Bunching Factor
0.02
0.04
0.06
0.08
0.1
4
2
0
Rel. Tune Shift
0
0.02
0.04
0.06
0.08
100
Time (msec)
Los Alamos
NASA