LANL AHF LATTICES

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I. 50 GeV AHF Synchrotron

A. Reference FODO lattice with γ_t–jump capability

B. Transitionless lattice (imaginary or high real γ_t operation)

II. 3-4 GeV Booster Synchrotron

COMMENTS ON TRANSPARENCIES

1 --- Arch Thiessen in his M6 talk on Wednesday morning described the purpose and conceptual design of the AHF project, so I will confine myself strictly to the discussion of the accelerator lattices.

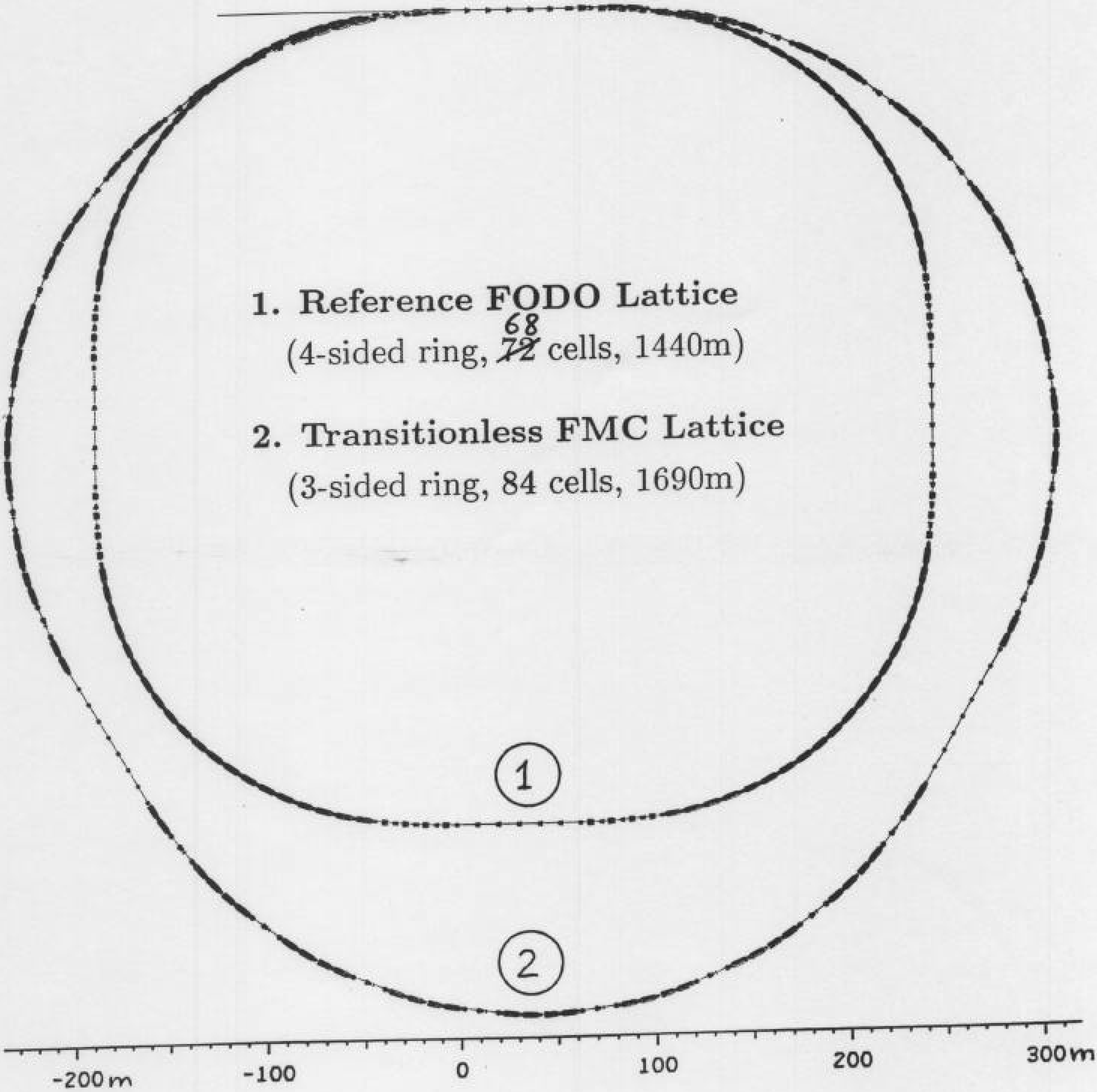
--- STATUS:
The conceptual lattice designs are essentially complete (this report, on 1st-order ion optics).
Longitudinal dynamics and the RF acceleration program are being looked at right now.
Multi-turn particle tracking has been done for the Reference lattice and is about to get underway for the transitionless lattice.
Calculations of impedances, collective effects and instabilities will begin in early Fall.

2 --- We want a conventional & conservative design because operational reliability is of utmost importance for the intended use of this accelerator complex.

50 GEV AHF LATTICE

1. Criteria:

- conventional/conservative design
- simple, low-cost lattice
  (identical cells & magnets)
- operational simplicity (2 knobs)
- transition-crossing options
  (imaginary γ_t, high real γ_t, or
  γ_t – jumping capability in same lattice)
- moderate momentum acceptance ($\pm 0.4\%$)
- moderately large dynamic aperture (40π)
- at least 3 long, dispersionless straights
  (injection, single-bunch extraction, RF)
- circumference accomodates 24 200-ns
  beam buckets (2×10^{12} ppb)
- 800 MeV injection energy, upgradable to
  3-4 GeV
- uses Fermilab Main Injector dipoles



1. Reference FODO Lattice
(4-sided ring, ~~72~~ 68 cells, 1440m)
2. Transitionless FMC Lattice
(3-sided ring, 84 cells, 1690m)
1
2
-200m
-100
0
100
200
300m

50 GEV AHF LATTICE

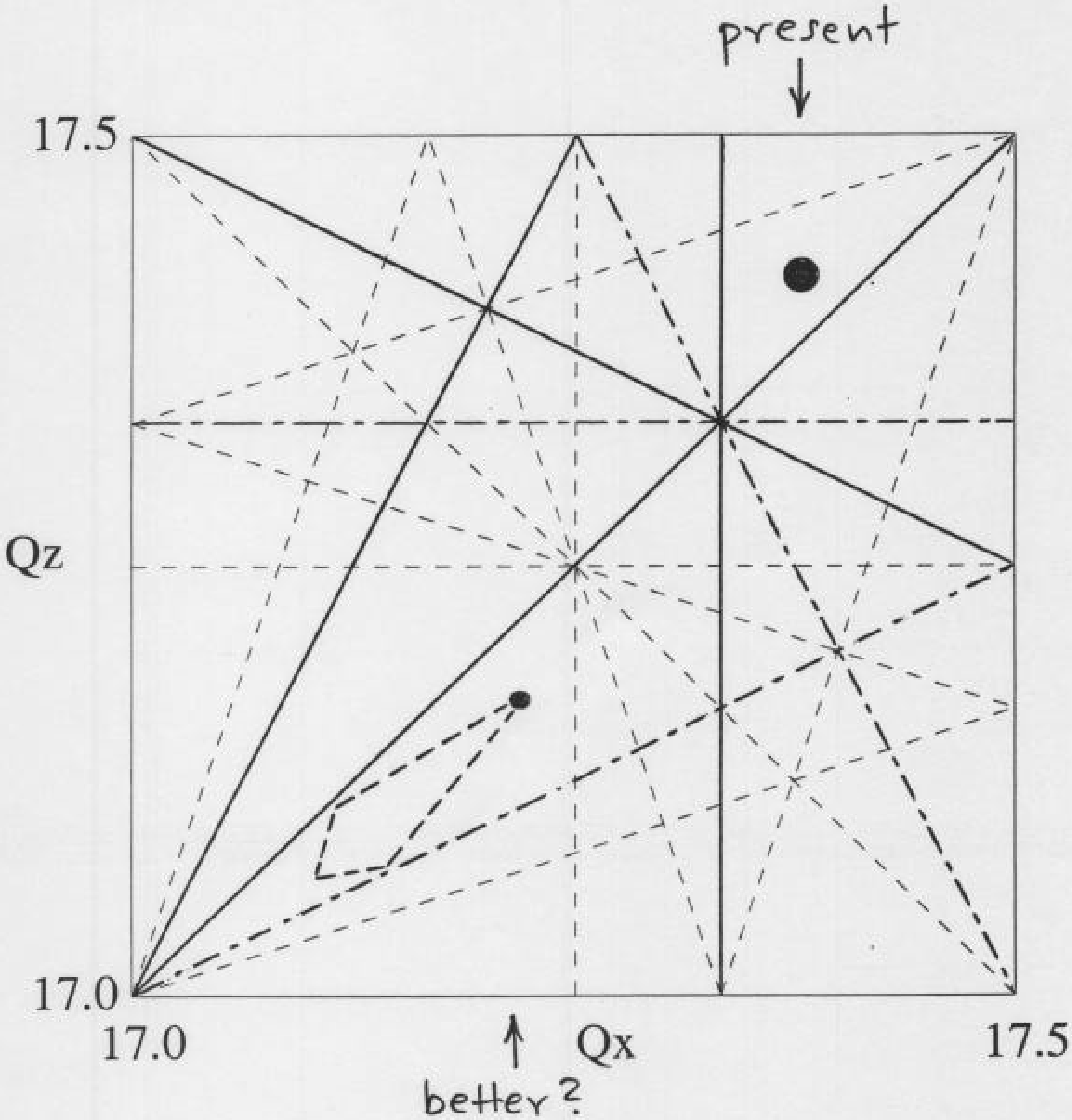
2. Lattices:

Option A. Reference FODO Lattice:

- symmetric 4-sided geometry
- regular FODO cell arc structure (resulting in $\gamma_t < \gamma_{max}$)
- dispersion suppressors at ends of arcs
- provides for later addition of a system of pulsed γ_t – jump quads

Resonances

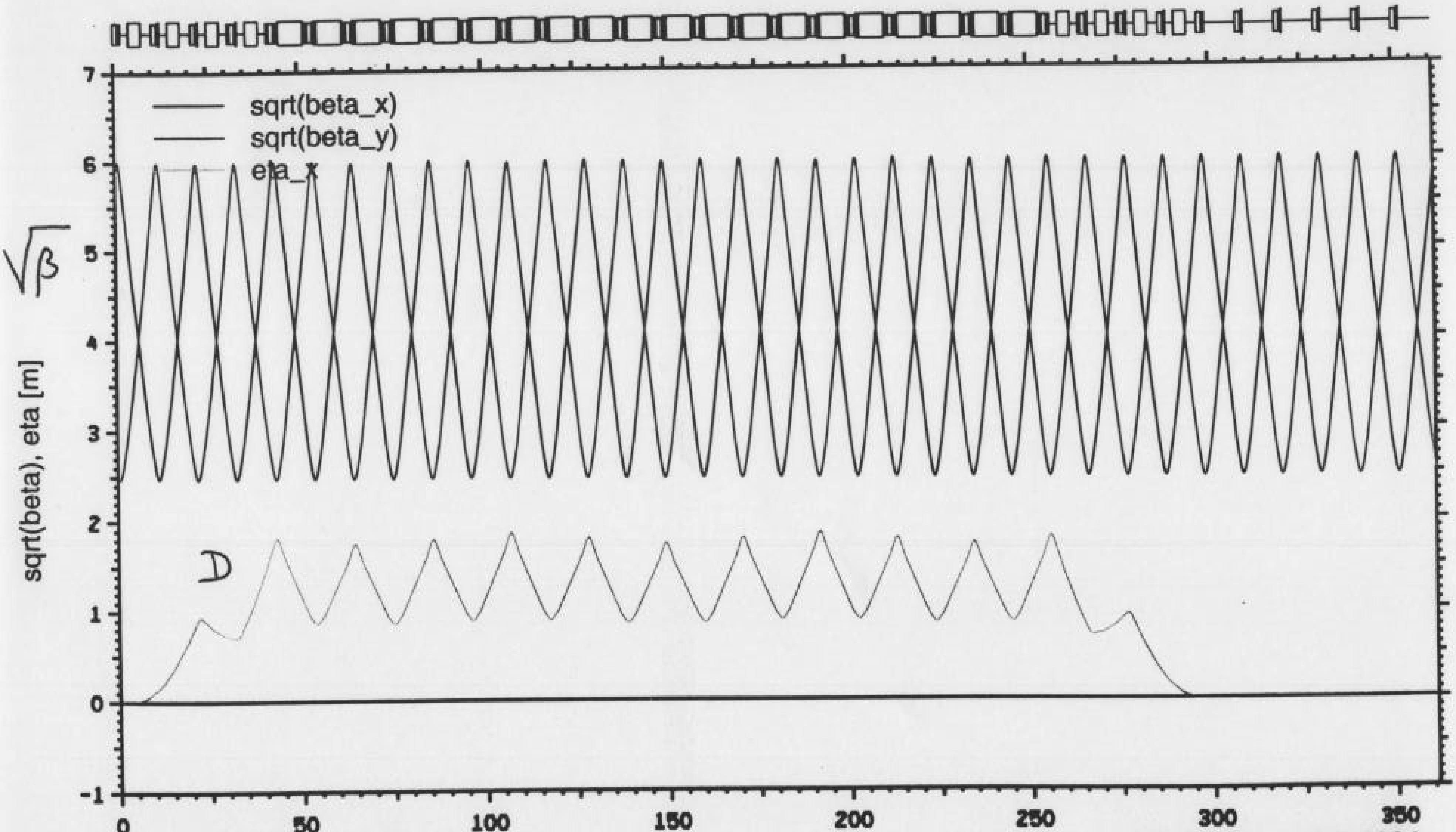
4 orders



Reference FODO Lattice

$\gamma_t = 14.2$

Four Sided Ring - Nominal GT = 14.2



qx = 4.345 qy = 4.355

path length = 360.8964

Gamma-T = 14.17954

1/4 ring

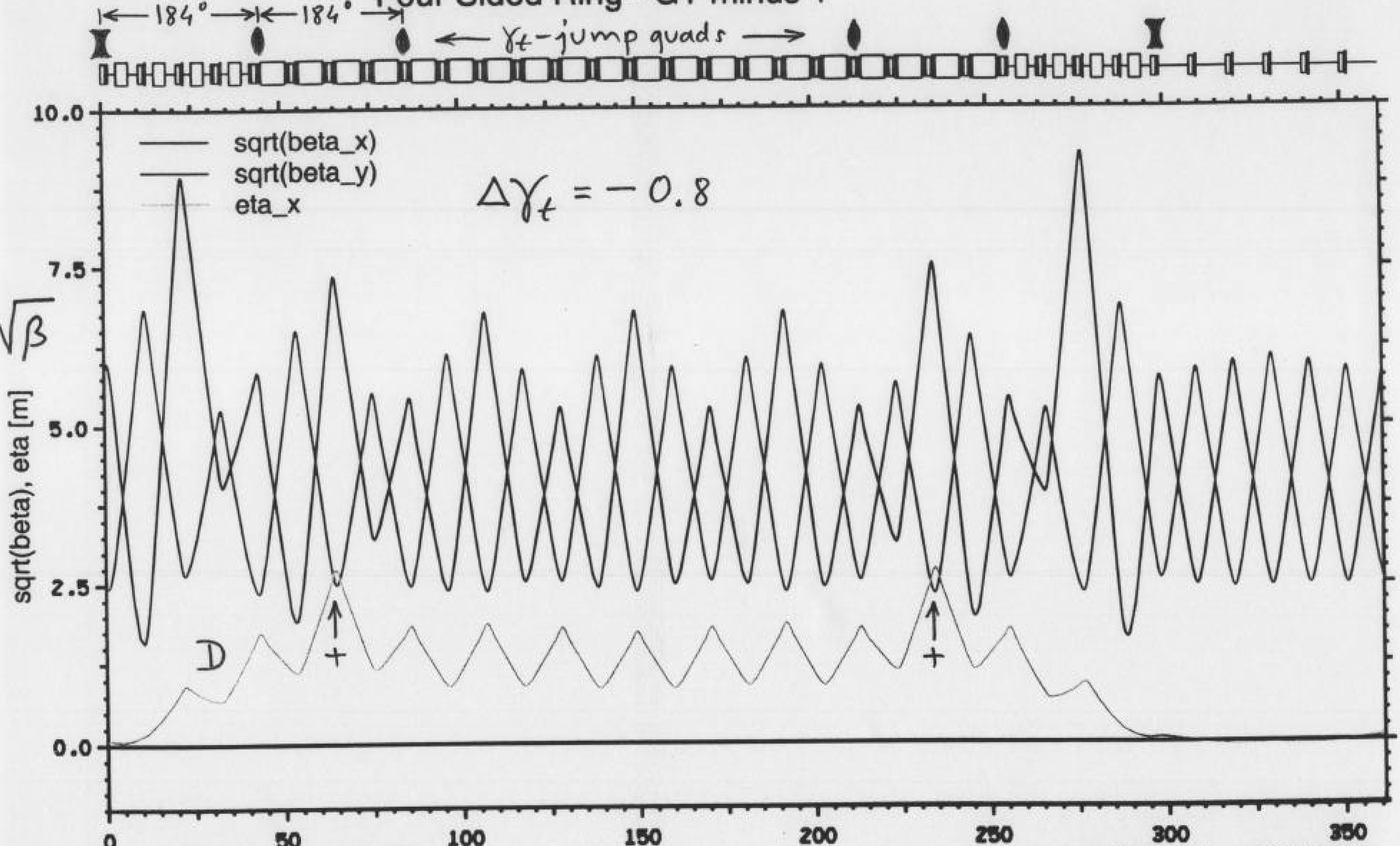
(17 identical FODO cells, $\mu_x = 92°$/cell)

(6) --- The Reference FODO lattice is a very simple, straight-forward and very "smooth" lattice that needs no further elaboration.

--- This lattice, in which the beam has to cross transition, is not ideal for addition of a γ_t - jump system of fast, pulsed quads which locally changes the dispersion D (hence changes γ_t) without global perturbation of the other lattice functions. The FODO cell phase advance is not exactly 90°, so the γ_t - jump quads are 184° apart (instead of the desired 180°); the consequences are illustrated in transparencies 7 & 8 for a γ_t - jump of +-0.8

(7,8) -- the jump quads produce the desired D-change but also induce considerable (factor 2) modulation of the beta-functions [note that $\sqrt{\beta}$ is plotted here!]. This is undesirable but probably not fatal.

Four Sided Ring - GT minus 1



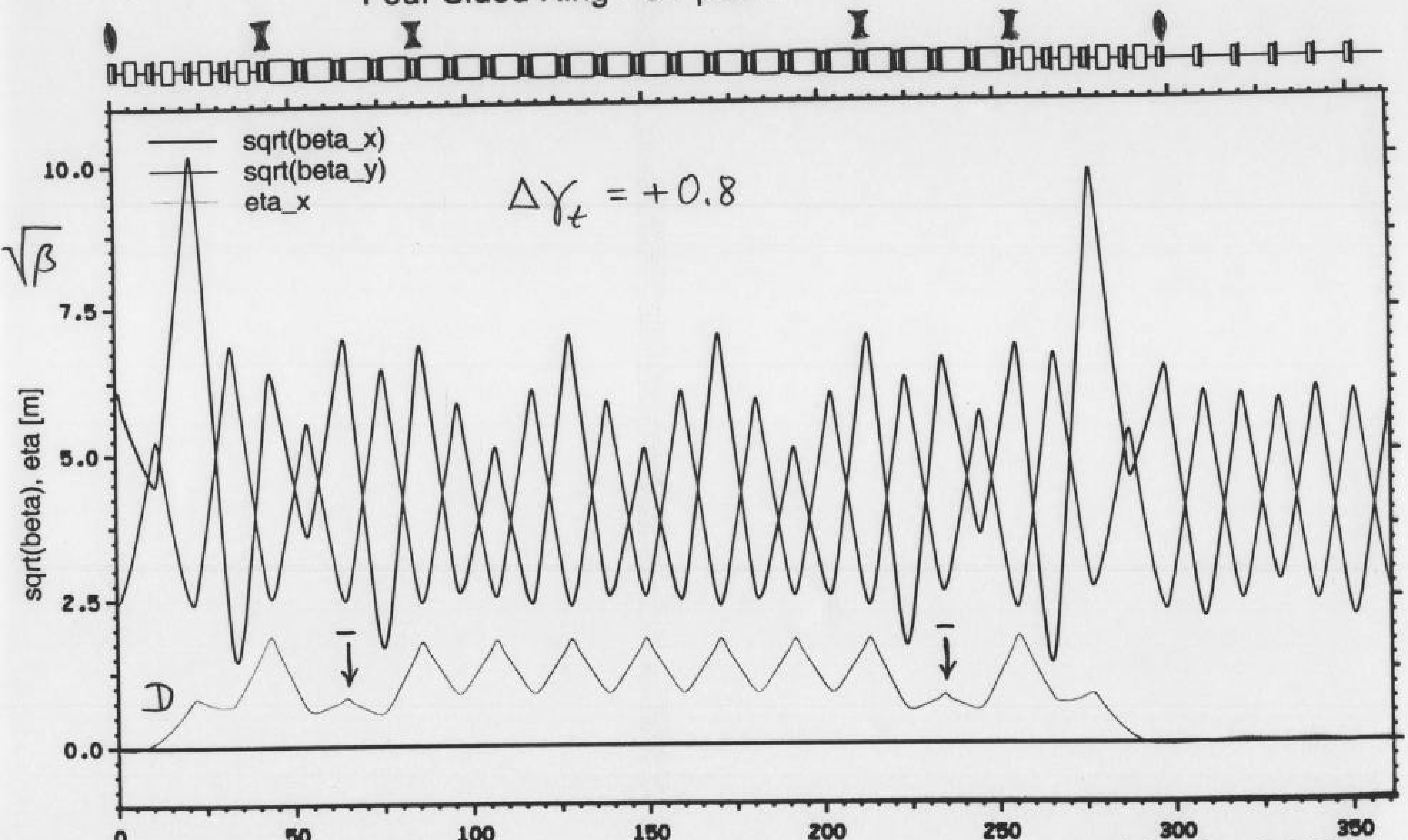
qx = 4.3611 qy = 4.3561

path length = 360.8964

Gamma-T = 13.45675

$\boxed{\gamma_t\text{-jump}}$

Four Sided Ring - GT plus 1



qx = 4.3654 qy = 4.356

path length = 360.8964

Gamma-T = 15.06989

8

50 GEV AHF LATTICE

Option B. Transitionless FMC Lattice:

- conceptually similar to Fermilab Proton Driver & SSC LEB designs & JHF
- symmetric 3-sided geometry
- regular FODO cell arc structure with missing-magnet cells to reduce (or change sign of) momentum compaction factor $\alpha = \gamma_t^{-2}$
- achromatic arcs provide zero dispersion in long straights
- single, fixed ring lattice for operation at 3 γ_t-options: real $\gamma_t > \gamma_{max}$, imag. γ_t, or real $\gamma_t < \gamma_{max}$ with addition of γ_t – jump system, if needed

9 --- Recently we looked at an alternative to the simple, smooth FODO lattice which would avoid transition crossing: the "Flexible Momentum Compaction" (FMC) lattice.

--- 1st bullet: in contrast to these machines, the AHF ring is a very-slow-cycling machine for lower-intensity (1/10) beams of smaller emittance and smaller momentum spread than a proton driver.

12 --- We retained a structure of identical DOFO quad cells throughout the FMC lattice (as in the Reference FODO lattice) to give us a "smooth" lattice (no significant beta-modulation), i.e., the empty (no dipole) and full (with dipoles) arc cells are the same length.

--- The dispersion wave in the arcs exhibits both positive and negative D, with dipoles preferentially located in -D regions, providing negative momentum compaction and hence imaginary γ_t for the DOFO cell structure.

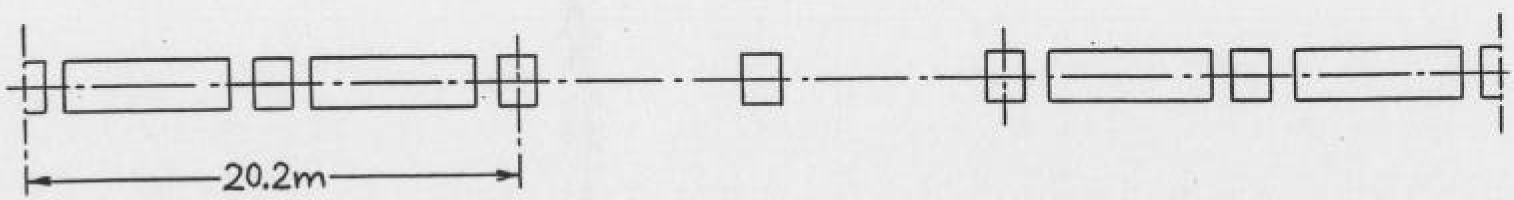
--- The arc lattice also incorporates 2 families of sextupoles capable of fully correcting the ring's natural chromaticity of about 30, if desired.

3-SIDED RING LATTICE

γ_t	cell	arc module μ_x	arc module μ_y	ring tunes Q_x	ring tunes Q_y	arc $\hat{D}_x$ (m)
i23	DOFO	315°	276°	24.43	21.38	6.42
80	FODO	315°	276°	24.43	21.38	3.80
23	FODO	270°	283°	20.92	21.88	1.86

Q_x (arc) = 7 or 6

3-CELL ARC MODULE

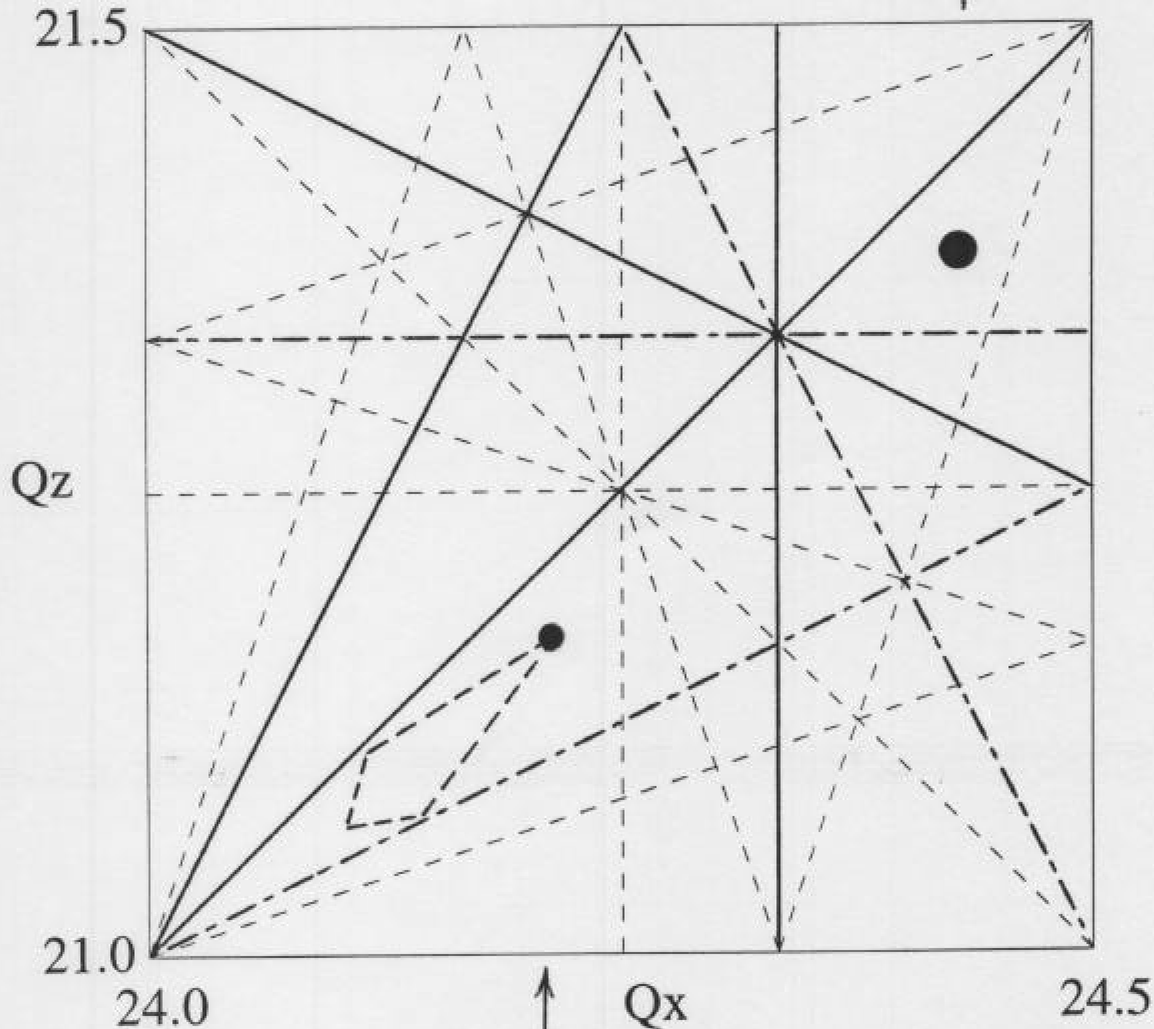


(3 identical focussing cells)

Resonances

4 orders

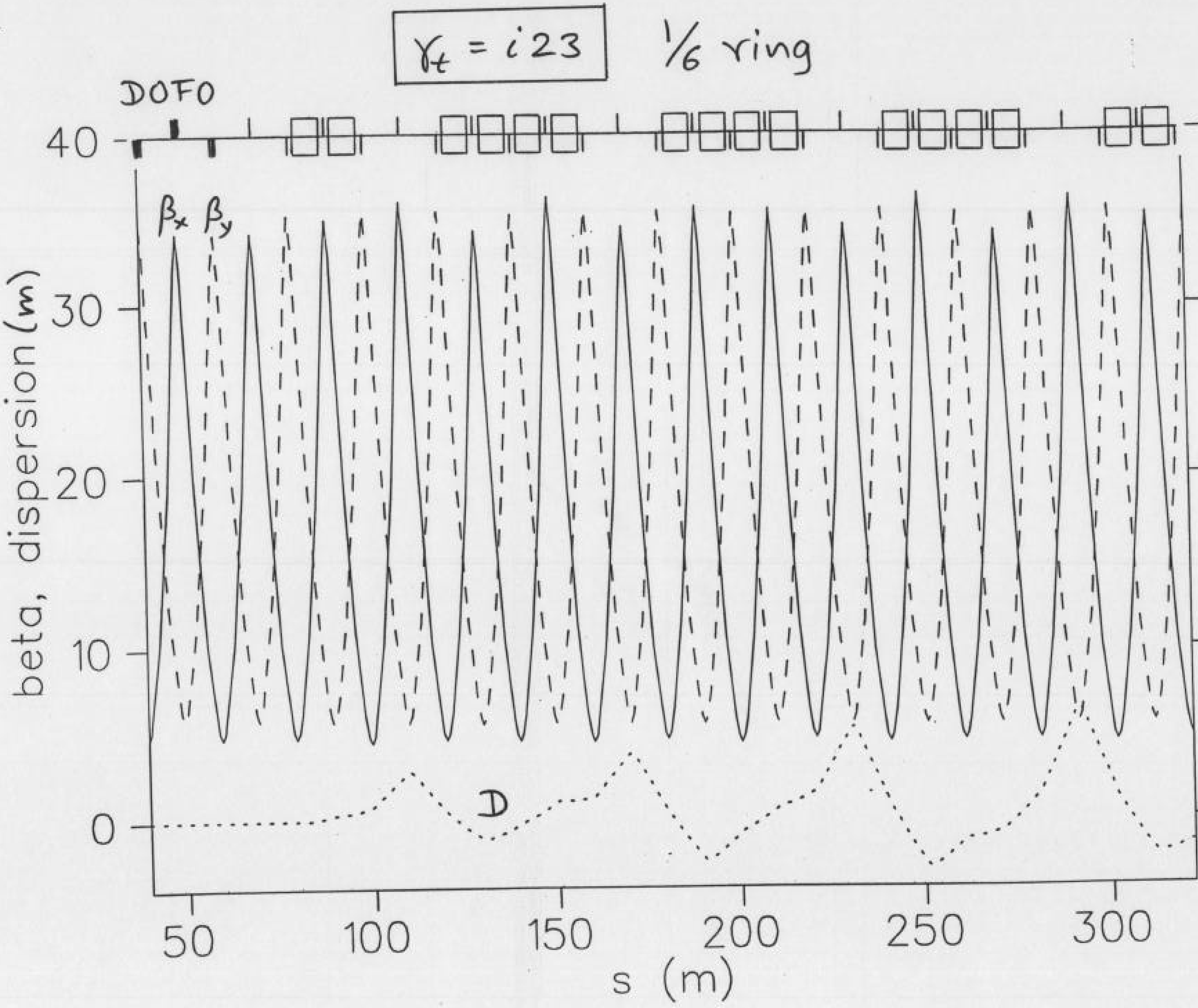
present



better?

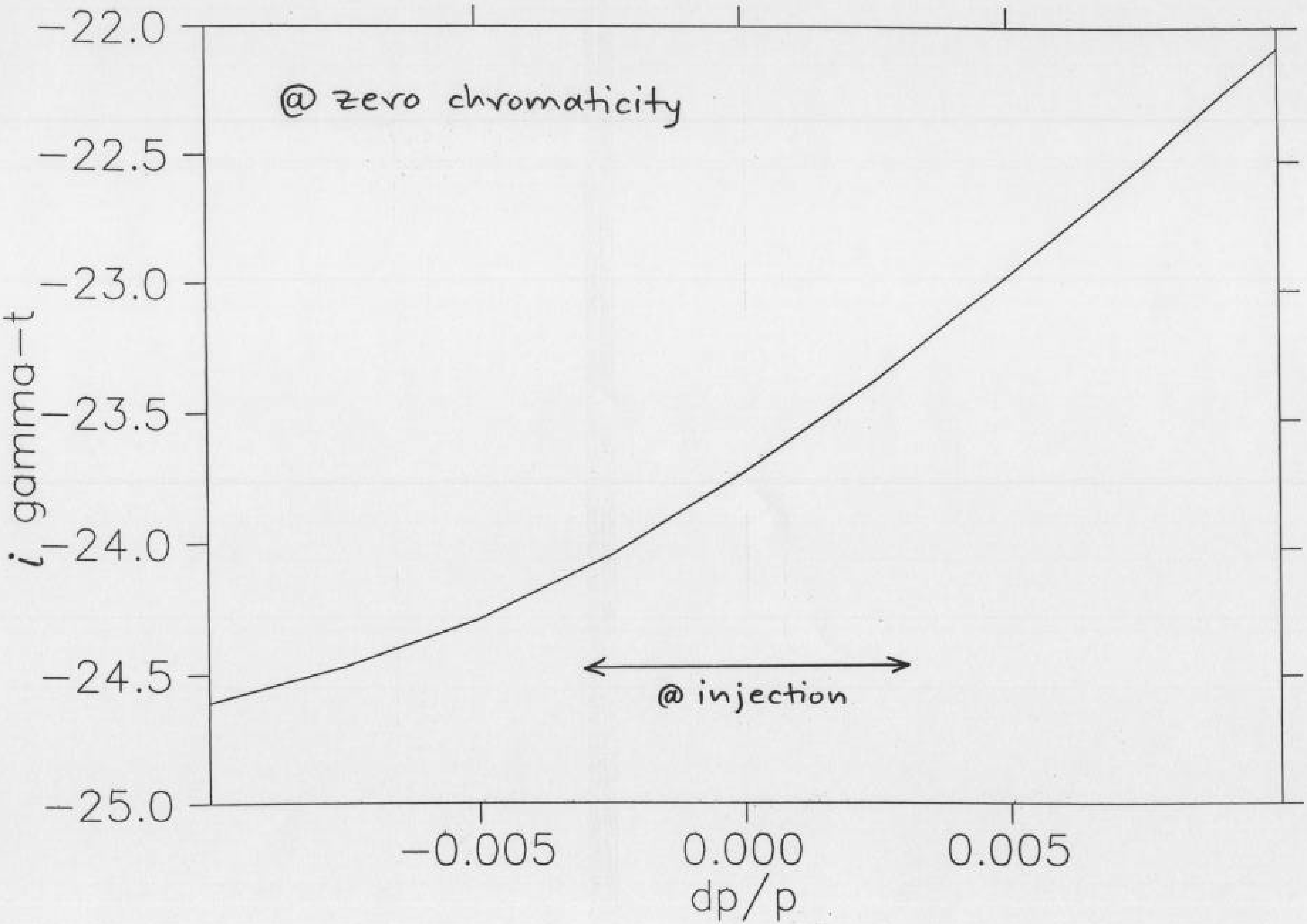
FMC Lattice

$\gamma_t = i23$ or 80



$\gamma_t = i23$
1/6 ring
DOFO
β_x β_y
D
beta, dispersion (m)
s (m)
40
30
20
10
0
50
100
150
200
250
300

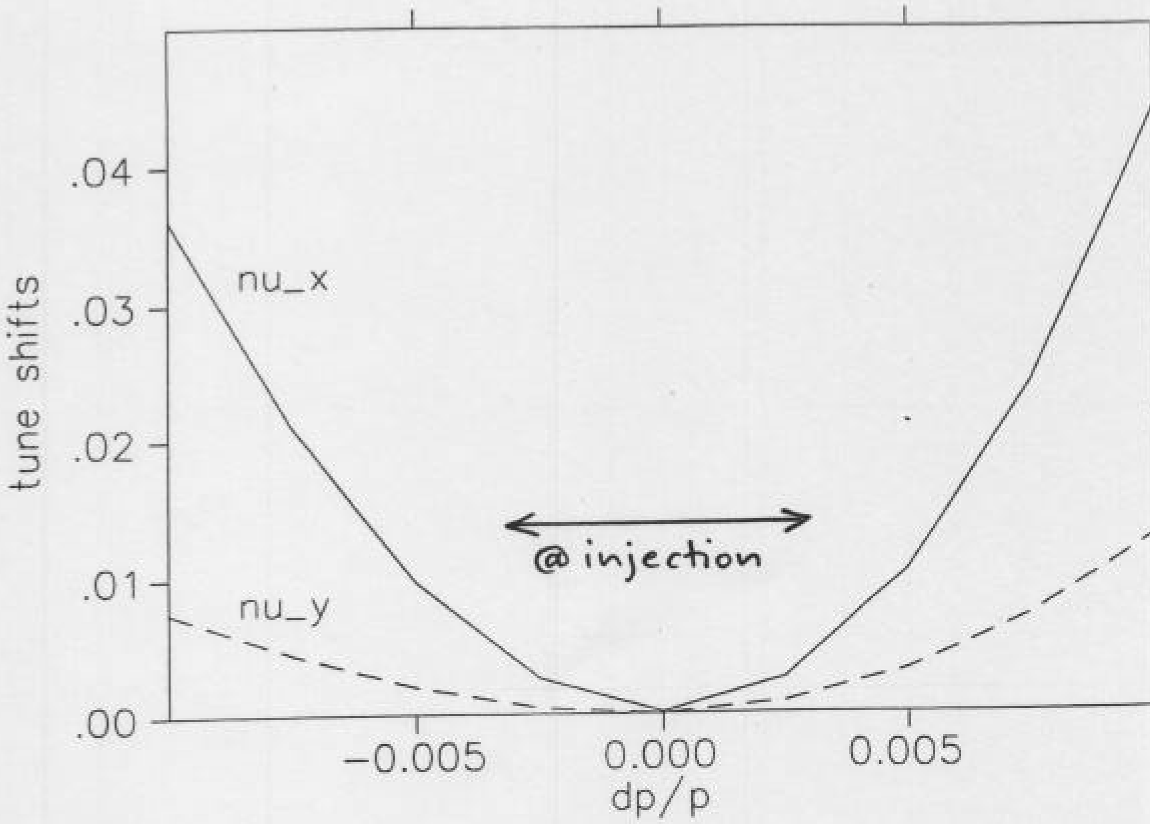
12

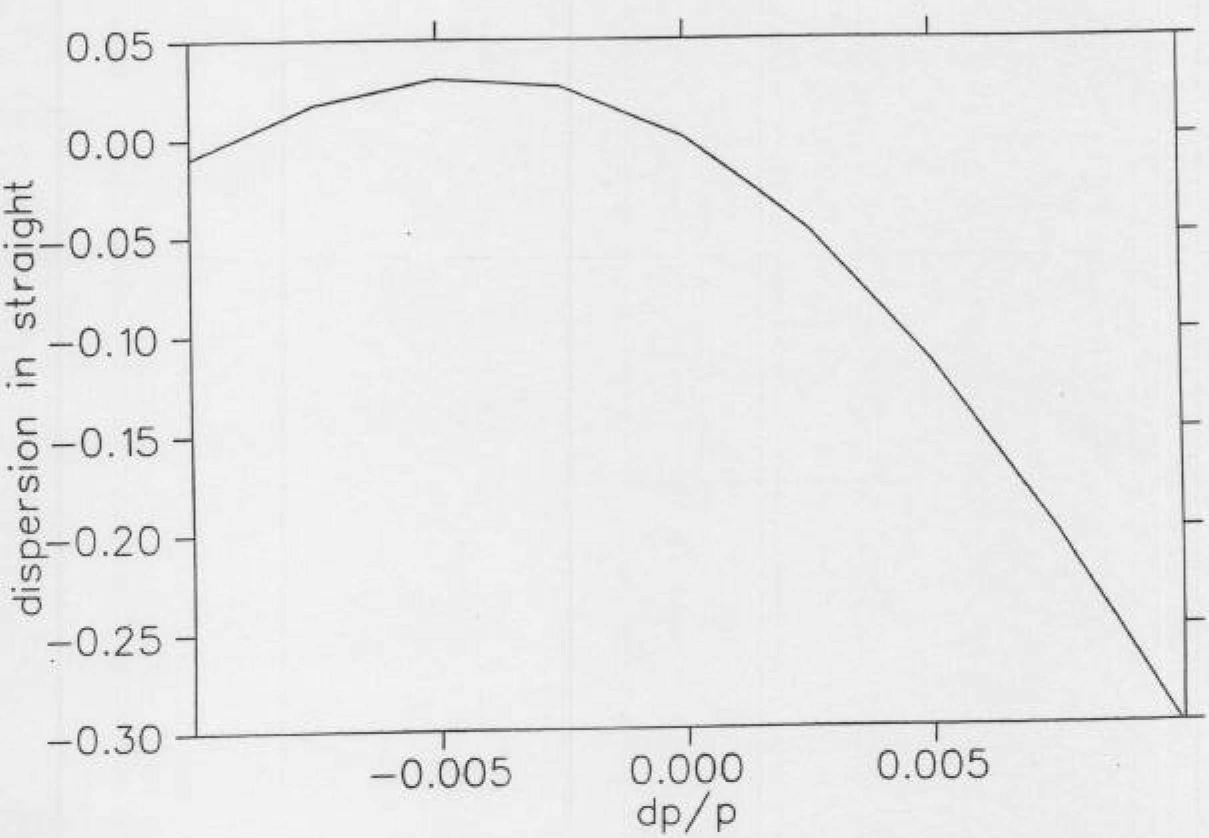


@ zero chromaticity
@ injection
-22.0
-22.5
-23.0
-23.5
-24.0
-24.5
-25.0
i gamma-t
-0.005
0.000
0.005
dp/p

13

@ zero chromaticity



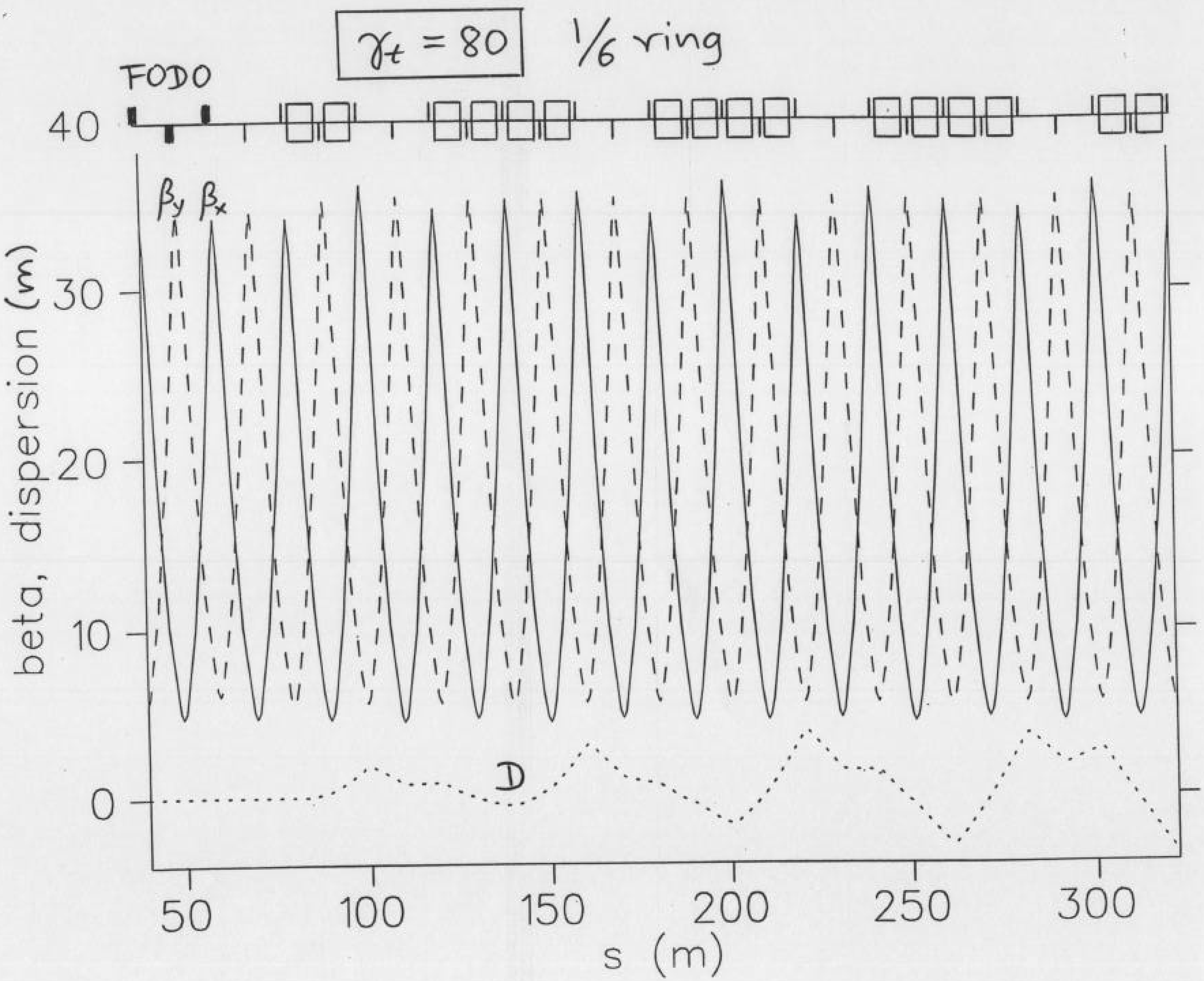


13, 14--- Residual chromatic effects in a ring of zero chromaticity:

(1) iγ_t is seen to be fairly "robust" in this lattice, varying by about 1 unit for particles within a +-0.003 relative momentum spread at injection;

(2) max. spread of ring tune is less than 0.005 at injection;

(3) the achromatic arcs provide D=0 in straights only for central-momentum particles; for off-momentum particles, D instraights is non-zero but acceptably small in this case: at most +-5cm.



$\gamma_t = 80$
1/6 ring
FODO
β_y β_x
D
beta, dispersion (m)
s (m)
0
10
20
30
40
50
100
150
200
250
300

15

15 --- the ONLY change here from the γ_t =i23 scenario is a change in quadrupole polarities: DOFO $\longrightarrow$ FODO. This results in a lattice with large, real γ_t = 80. [now the dipoles sample both +D and -D regions, with strong cancellations of contributions to the momentum compaction α, resulting in a very small α and hence a large γ_t]. Note also the smaller peak values of D compared to those for the imaginary-γ_t case.

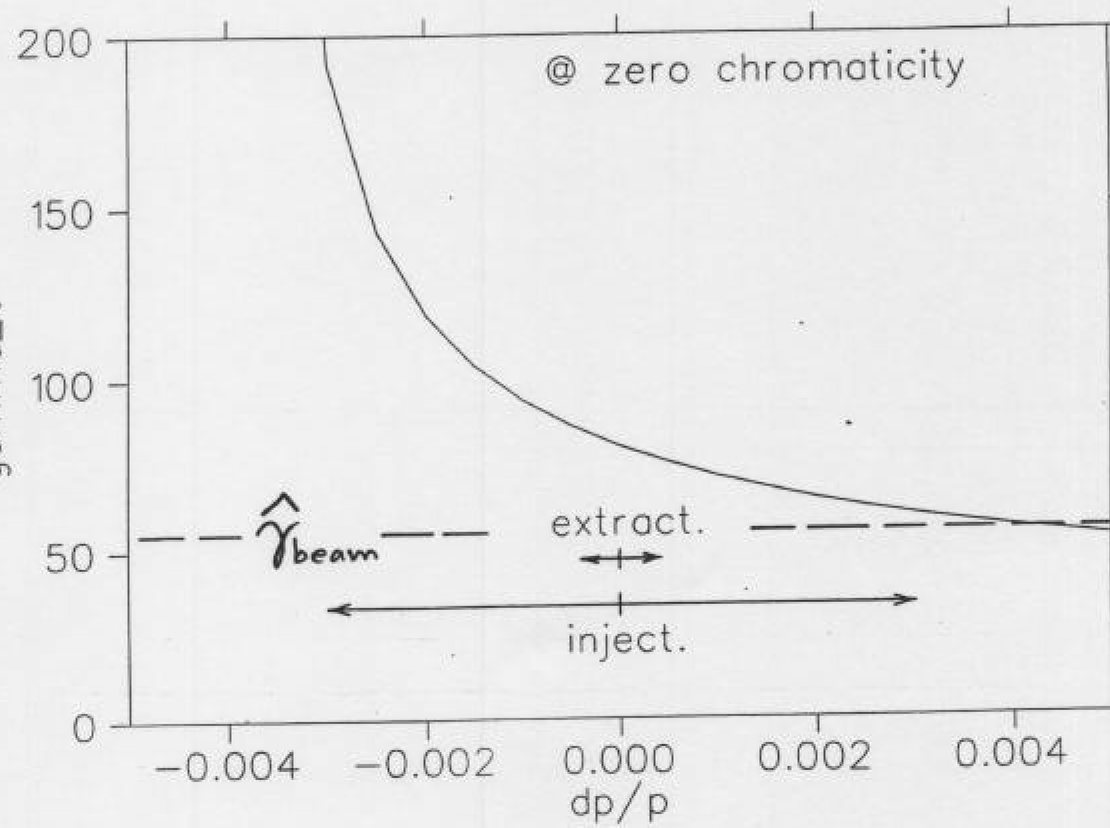
16 --- The large γ_t value is NOT "robust" but varies strongly with momentum within the beam, especially at injection.

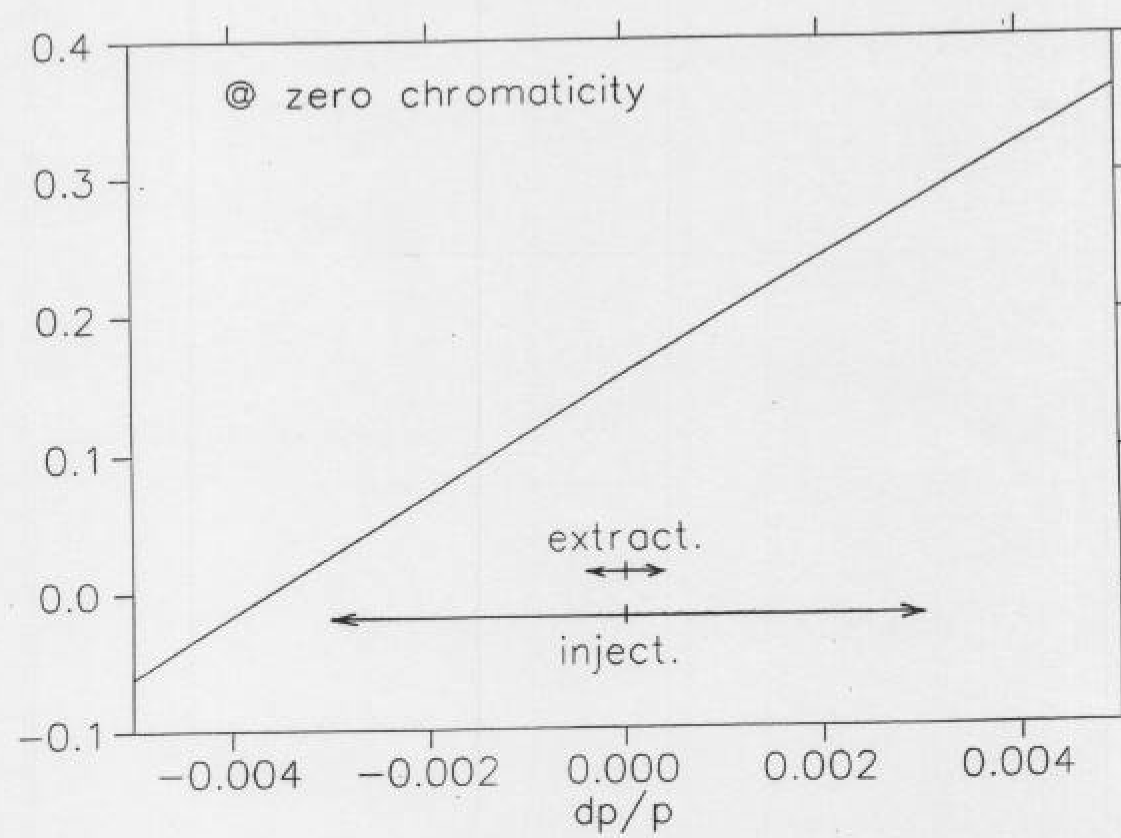
--- In this case, it is more meaningful to look at the momentum compaction α vs. momentum spread: α at p_o is an order of magnitude smaller than for the imag. γ_t case, its slope with p is greater, and α approaches 0 for low-momentum particles.

--- The implication for longitudinal dynamics of a beam with this kind of momentum spread is not as drastic as the enormous γ_t -variation would seem to indicate. Let's look at the slip factor η:

17 --- at injection, η is dominated by the small beam-γ, hence is large and $\Delta\alpha$ is negligible relative to η;

--- near full energy, the beam-γ and γ_t are comparable, so η becomes very small such that now even a small $\Delta\alpha$ due to a small Δp is more significant but still provides an acceptably (?) small spread in η .


@ zero chromaticity
gamma_t
200
150
100
50
0
$\hat{\gamma}_{beam}$
extract.
inject.
−0.004
−0.002
0.000
0.002
0.004
dp/p


@ zero chromaticity
alpha (x10**−3)
0.4
0.3
0.2
0.1
0.0
−0.1
extract.
inject.
−0.004
−0.002
0.000
0.002
0.004
dp/p

Slip Factor $\eta = \gamma^{-2} - \alpha$

$$\alpha_\circ = 1.6 \times 10^{-4}$$

$$\Delta p/p \Rightarrow \Delta\alpha \Rightarrow \Delta\eta$$

@ injection (1 GeV):

$\Delta p/p = \pm 3 \times 10^{-3} \Rightarrow \Delta\alpha = \pm 1.25 \times 10^{-4}$

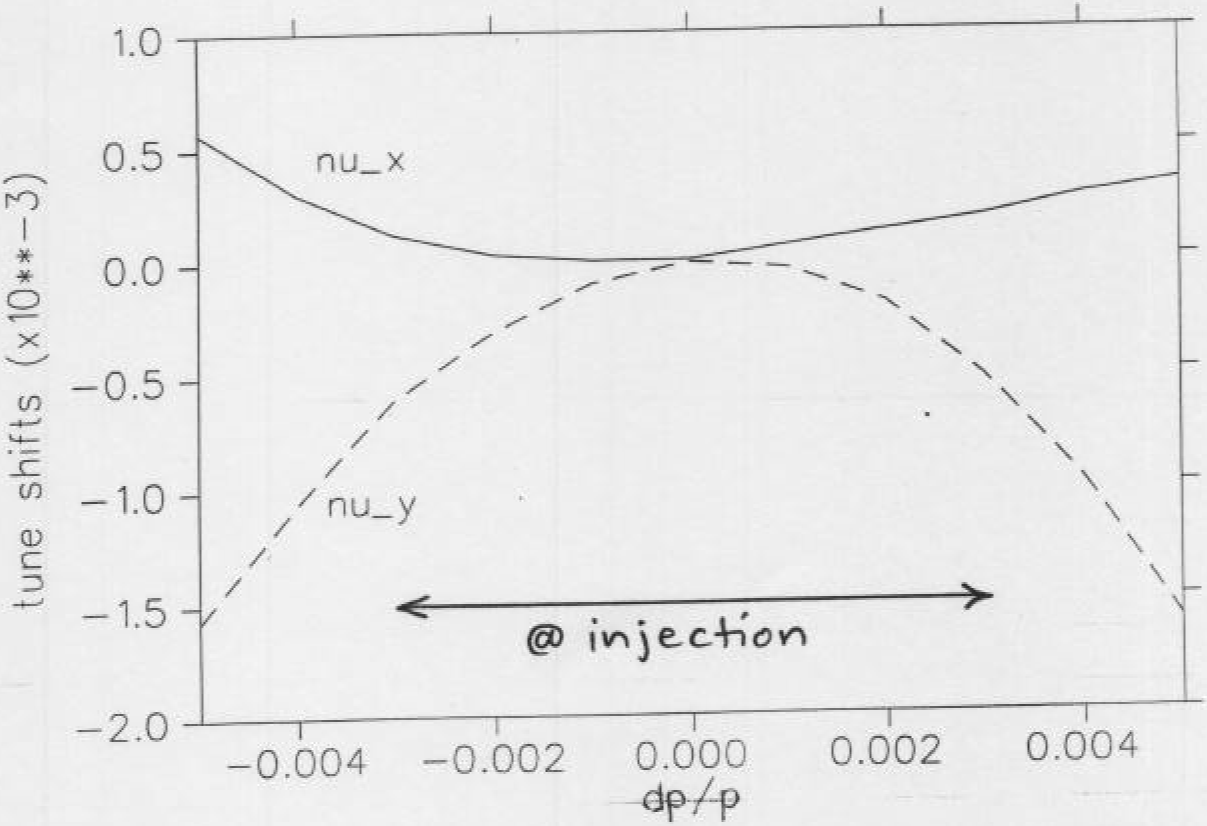
$\eta = 0.233 \Rightarrow \underline{\underline{\Delta\eta/\eta = \pm 0.05\%}}$

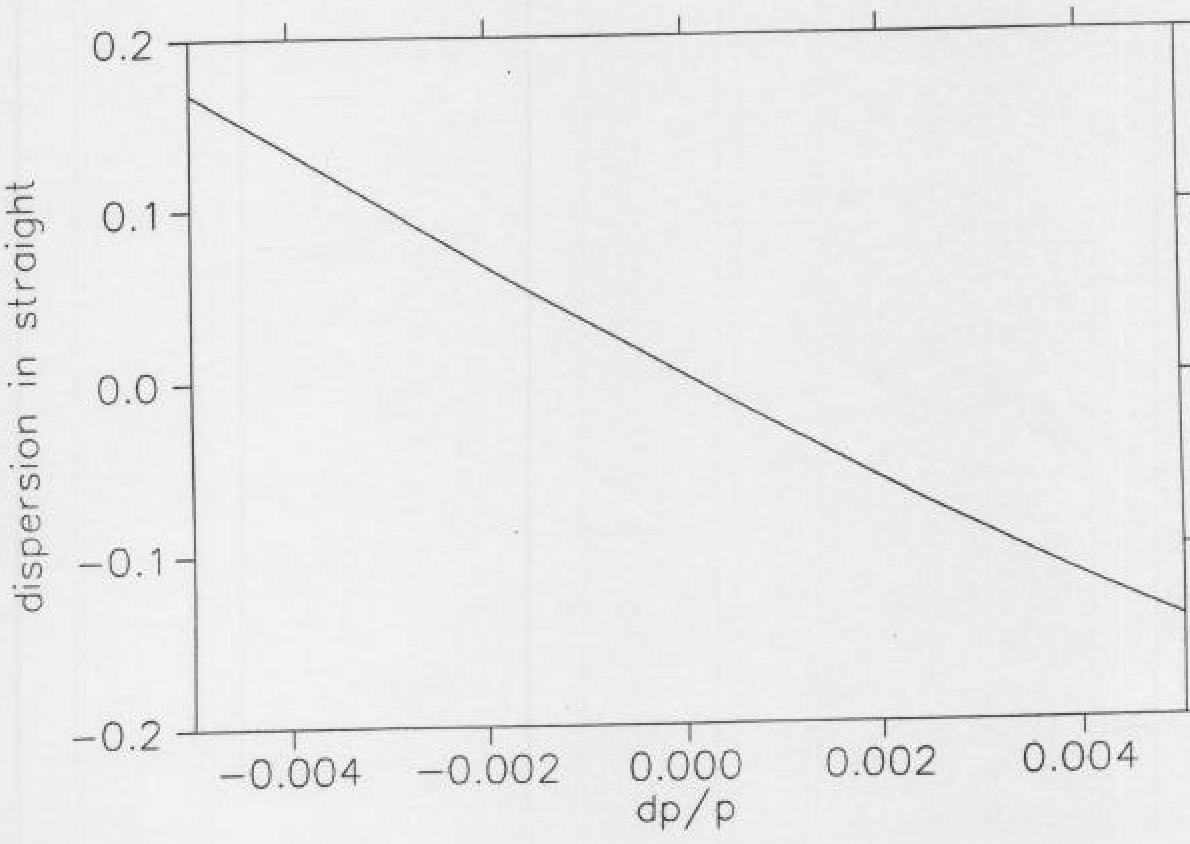
@ extraction (50 GeV):

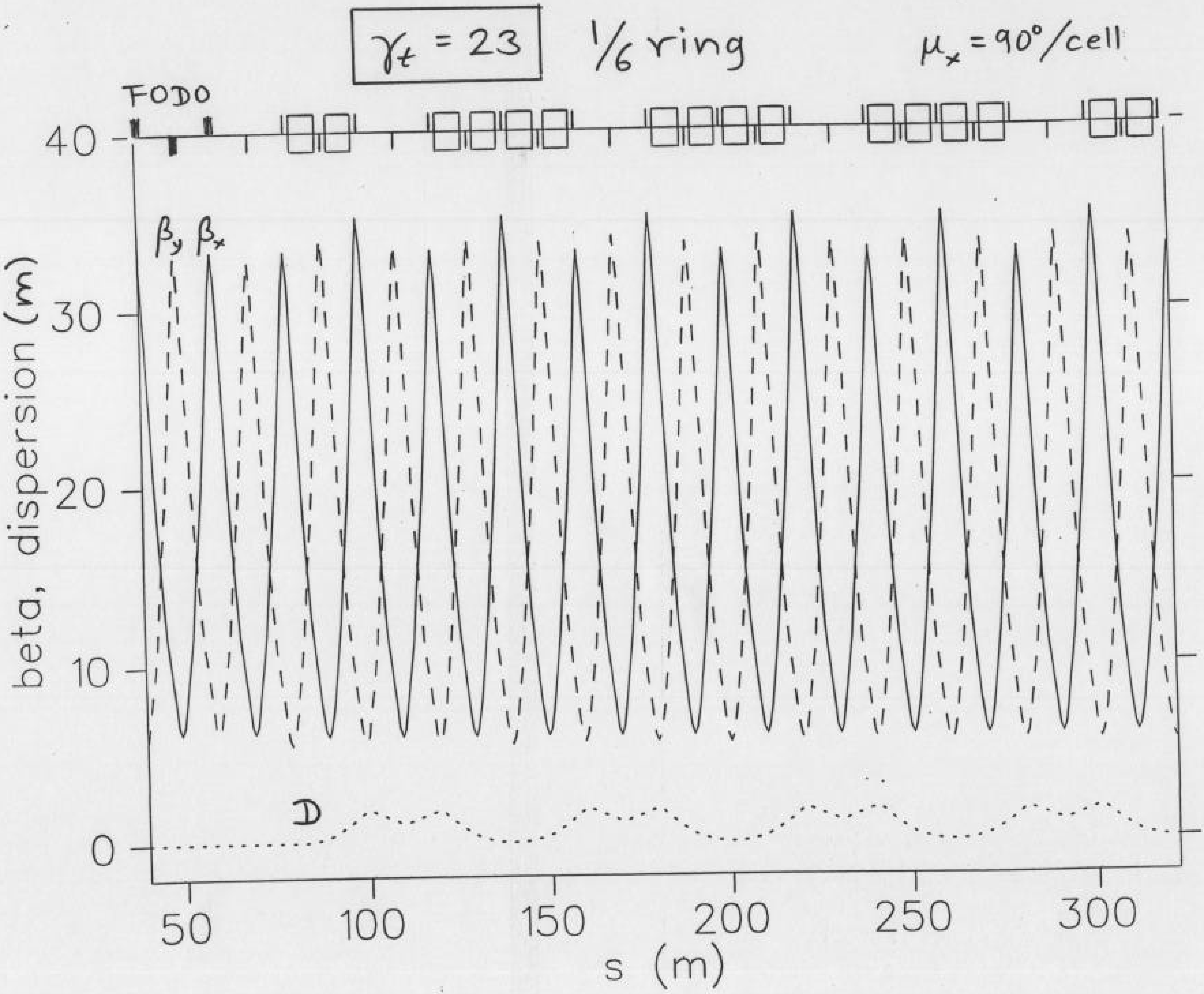
$\Delta p/p = \pm 4 \times 10^{-4} \Rightarrow \Delta\alpha = \pm 0.17 \times 10^{-4}$

$\eta = 0.18 \times 10^{-3} \Rightarrow \underline{\underline{\Delta\eta/\eta = \pm 9.3\%}}$

@ zero chromaticity






$\gamma_t = 23$
1/6 ring
$\mu_x = 90°/\text{cell}$
FODO
β_y β_x
D
beta, dispersion (m)
40
30
20
10
0
50
100
150
200
250
300
s (m)

19 --- Why even consider a γ_t=23 mode (implying transition crossing) when we can accelerate beam in this lattice to full energy "below" transition?

We would like to make comparison with the transition jump in the Reference FODO lattice!

--- This FMC lattice in fact turns out to be superior to the Reference lattice for implementing an effective and efficient γ_t - jump system for 2 reasons (see later transparencies 23 - 26).

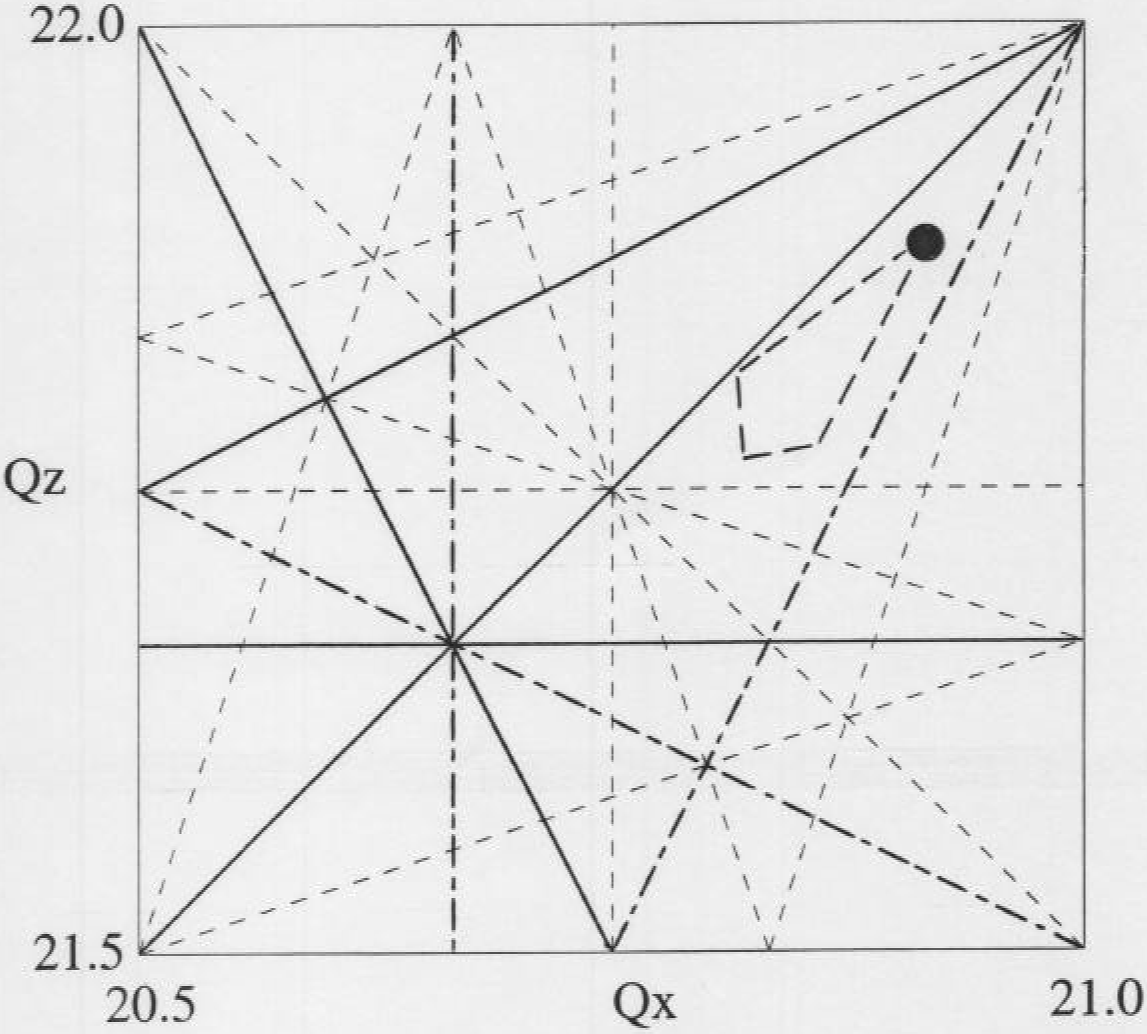
--- Note that now D > 0 everywhere and D is very small, resulting in a γ_t that is real and moderately large (but less than the max. beam-γ).

21 --- We note that the low γ_t - value is again "robust" against momentum variation.

22 --- The non-zero dispersion in the straights for off-momentum particles is now somewhat larger, +-15cm, but still acceptably small.

Resonances

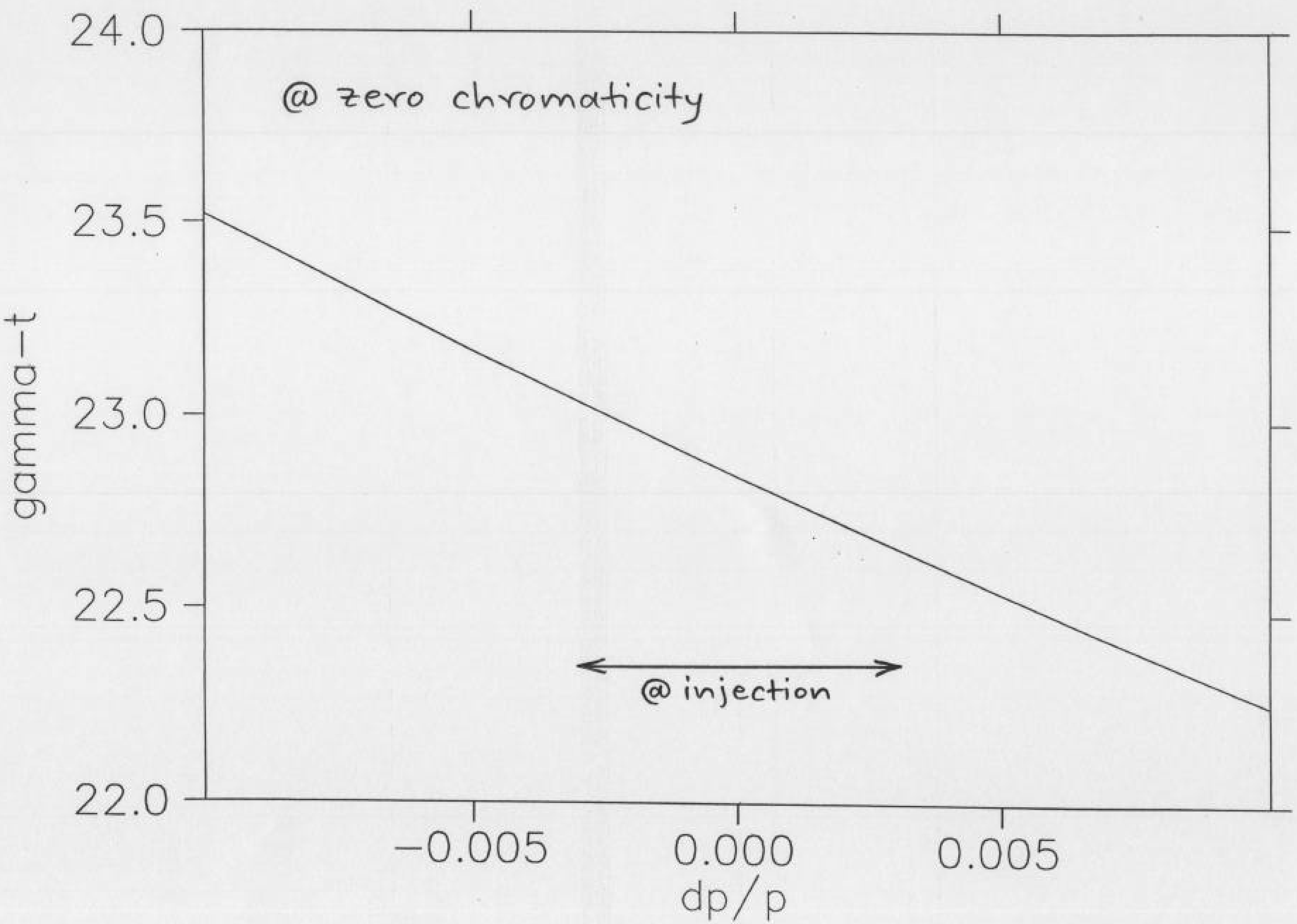
4 orders



FMC Lattice

$\gamma_t = 23$

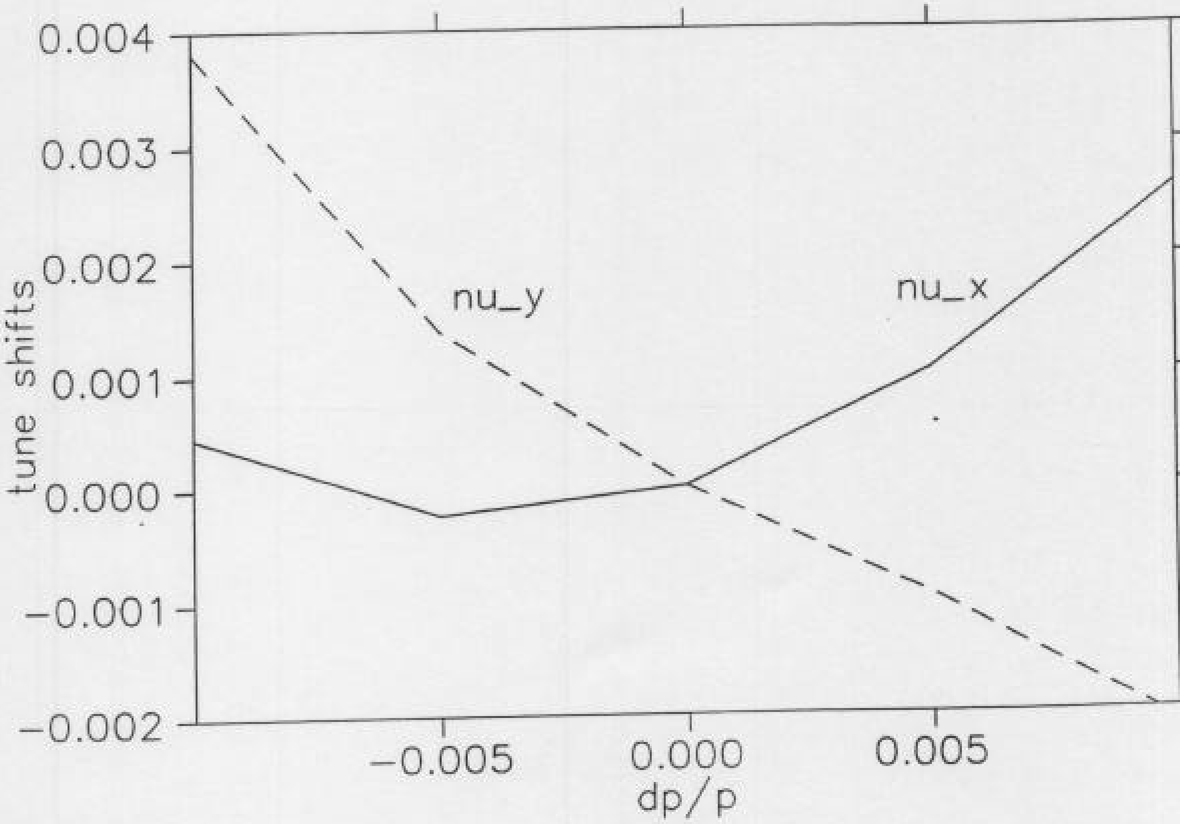
$\mu_{x,cell} = 90.0°$



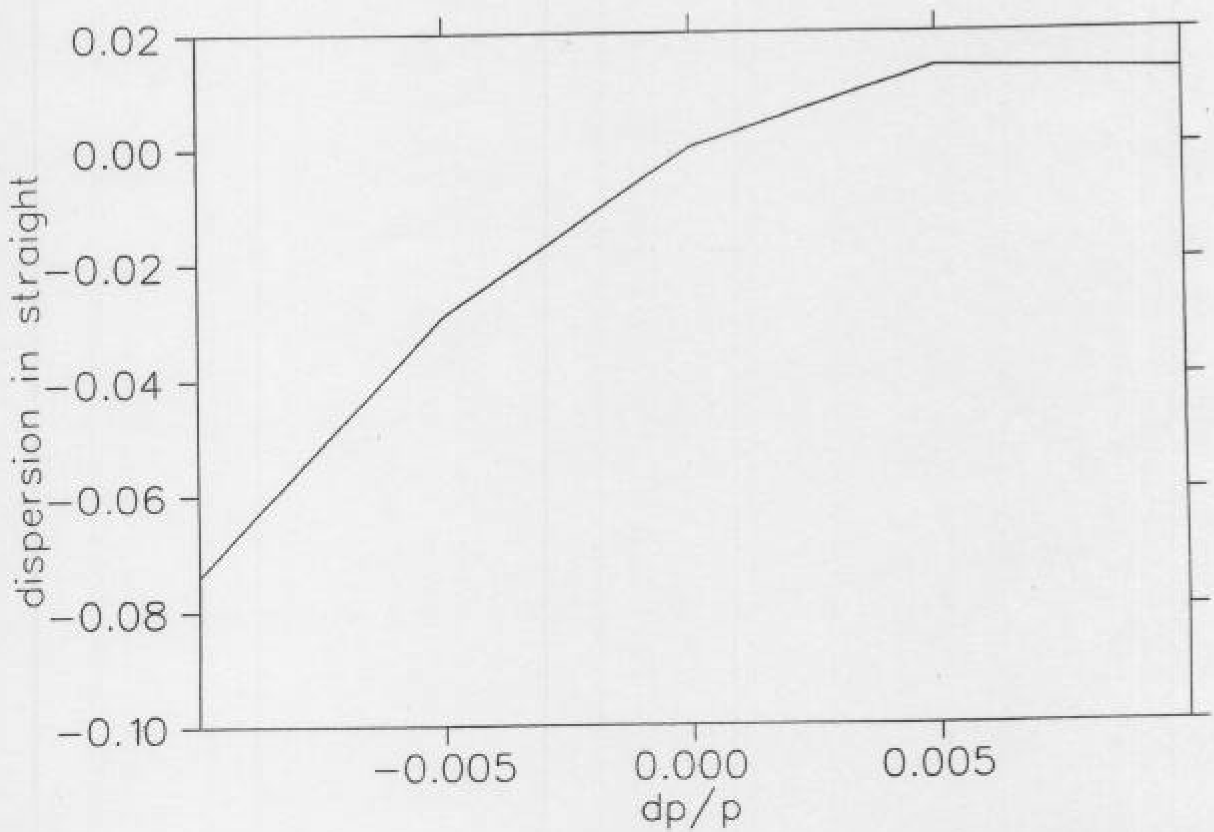
24.0
23.5
23.0
22.5
22.0
gamma-t
@ zero chromaticity
@ injection
-0.005
0.000
0.005
dp/p

21

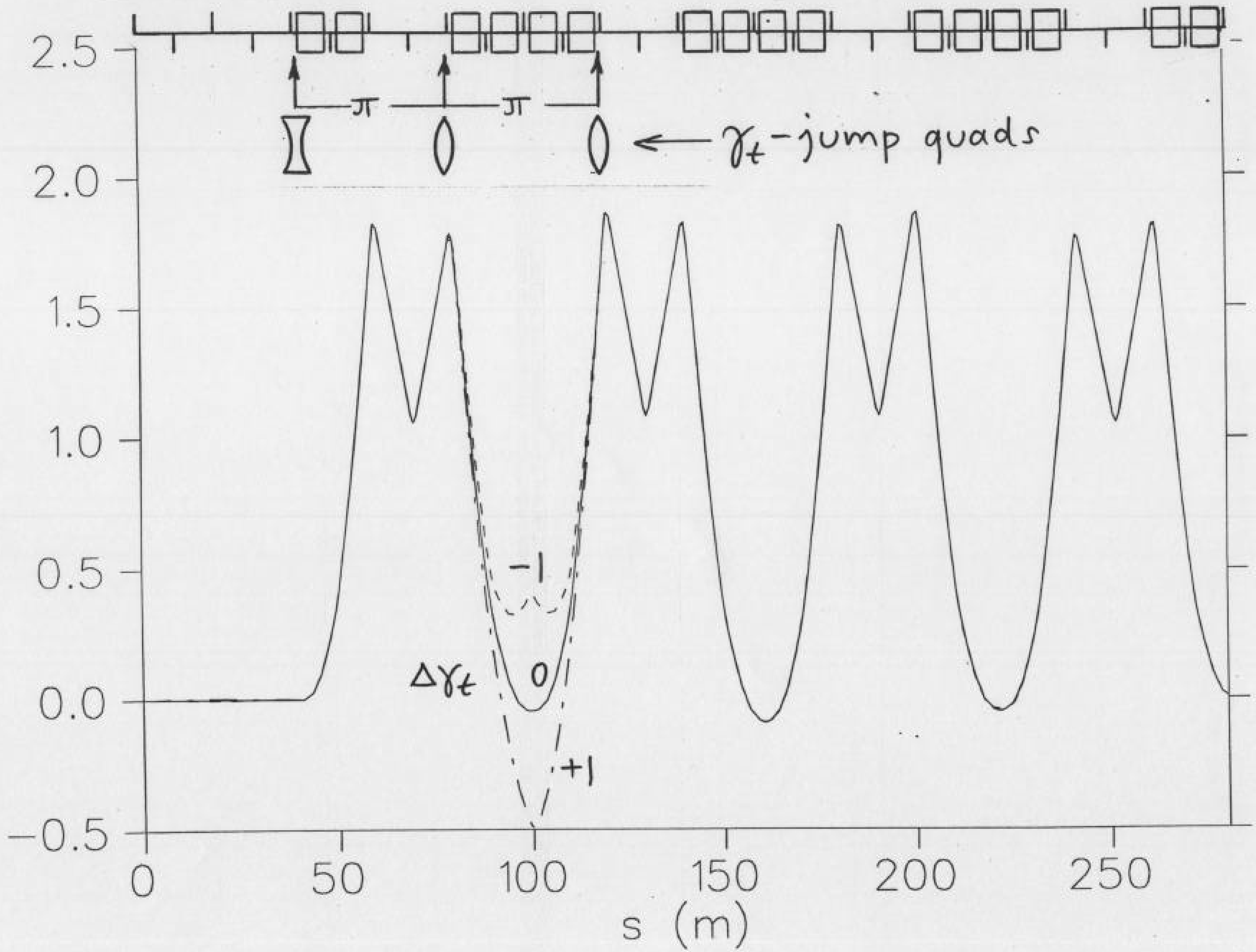
@ zero chromaticity



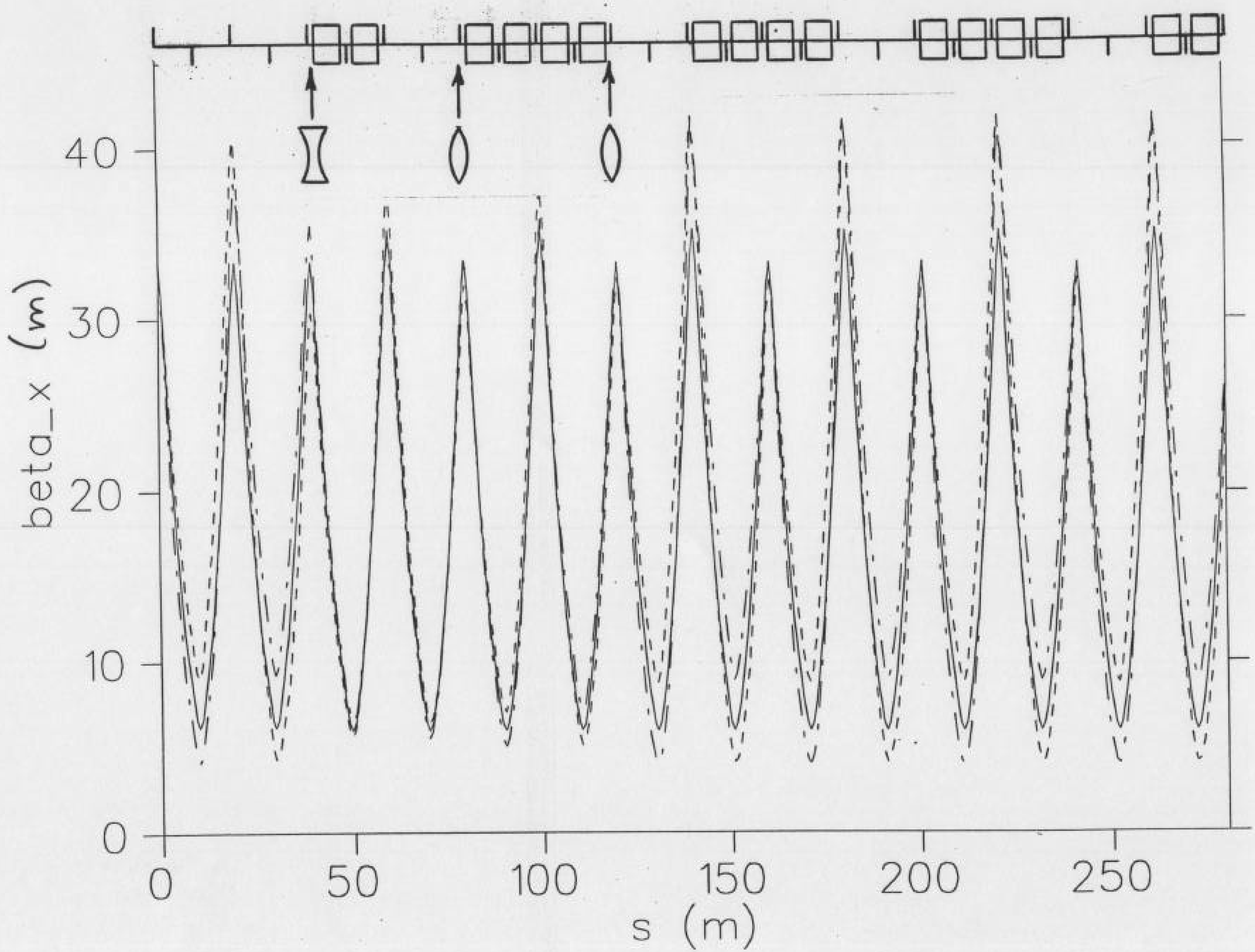
@injection



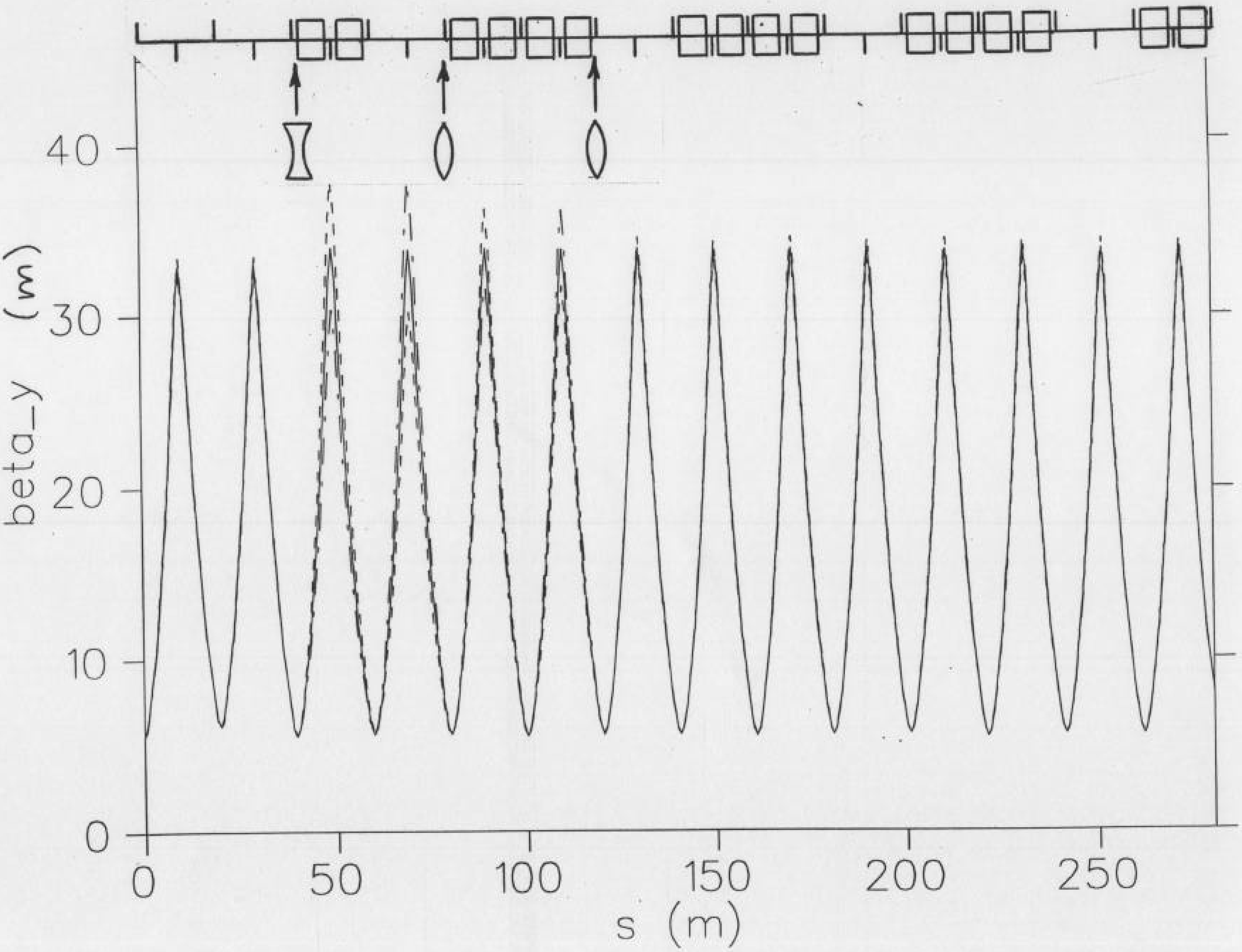
γ_t-jump



π
π
γ_t-jump quads
dispersion (m)
s (m)
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
0
50
100
150
200
250
−1
$\Delta\gamma_t$
0
+1



24


beta_y (m)
s (m)
0
10
20
30
40
0
50
100
150
200
250

23 — 25 --- Gamma_t jump insertion: localized D-perturbation; the 3 beta_x curves for $\Delta\gamma_t$ = -1,0,+1 show SMALL differences, in contrast to factor-2 effects seen in Reference FODO lattice (6,7); even smaller effects of γ_t - jump on beta_y.

--- Insignificant global perturbations of lattice functions by jump insertions in this case because phase advance μ_x per cell now exactly 90° $\Longrightarrow$ phase advance between jump quads now exactly the required 180°.

26 --- Other advantage of FMC lattice over Refer. lattice is the larger value of γ_t which results in a smaller change of the average ring dispersion, $\langle \Delta D \rangle$, needed to provide a given $\Delta\gamma_t$, hence requiring weaker jump quads (factor 3 KL).

COMPARISON OF γ_t– JUMP LATTICES

	4-SIDED (REF. [redacted])	3-SIDED (NEW)
transition γ_t	14.2	22.9
γ_t– jump $\Delta\gamma_t$	± 0.8	± 1.0
no. of jump quads	24	18
quad length (m)	<u>0.35</u>	<u>0.20</u>(F), 0.40(D)
gradient (T/m)	± 5.1	± 2.85
tune jump $\Delta\nu_x$	$\begin{cases} +.015 \\ -.020 \end{cases}$	$\begin{cases} +.002 \\ -.005 \end{cases}$
tune jump $\Delta\nu_y$	.001	.001
max. $\hat{\beta}_x$– change	+128%	+18%

factor of 3 in KL

$$\langle \Delta D \rangle \propto \Delta\gamma_t / \gamma_t^3$$

ACHROMATIC ARCS

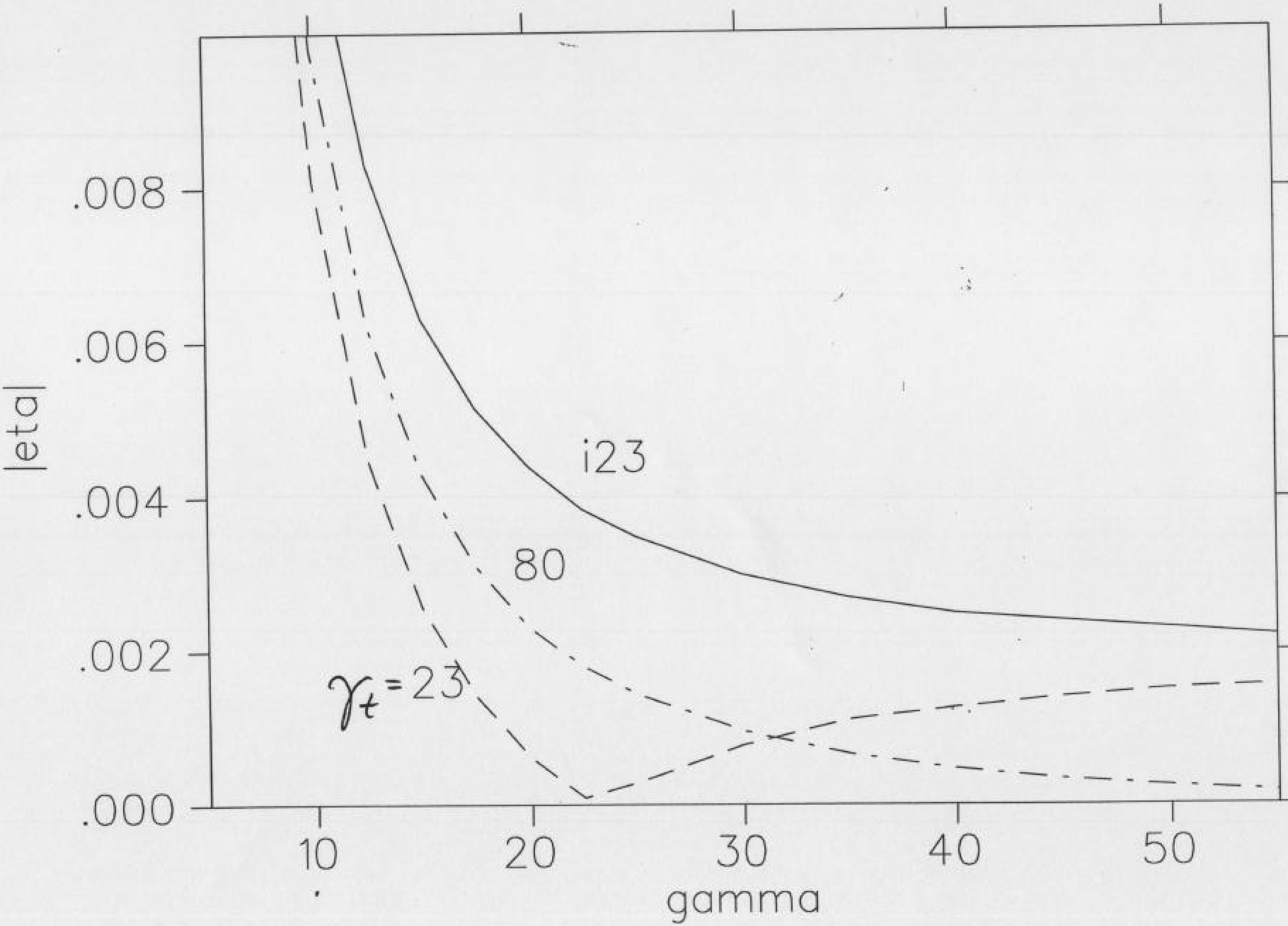
SENSITIVITY OF DISPERSION IN STRAIGHTS AND γ_t TO CHANGE IN PHASE ADVANCE $\Delta\mu_x = \pm.001$ (arc module) $= \pm.008$ (arc)

	LATTICE		
	high real γ_t	imaginary γ_t	low real γ_t
D_0 (m)	$0\,{}^{-.078}_{+.088}$	$0\,{}^{-.036}_{+.041}$	$0\,{}^{+.009}_{-.005}$
γ_t	80 ± 7.3	$(23 \pm 0.3)i$	23 ± 0.3

27A --- What are the effects of having the arcs not EXACTLY tuned to integer horizontal tune? Negligible for low-γ_t modes (real or imag.), but for high-γ_t mode deviation of dispersion in straights from zero amounts to +-10cm for every 0.01 deviation in arc tune, and γ_t changes by 10%.

27B --- This summarizes the slip factor $|\eta|$ (absolute magnitude) during the acceleration ramp for the 3 FMC lattice modes [the discontinuity in the curve for $\gamma_t = 23 = \gamma$ represents a change in sign from + to - for η].

--- For beam acceleration, a clear preference for the imag. γ_t mode emerges: η remains large and nearly constant over the upper 2/3 of the acceleration ramp!



B 27

3-4 GEV BOOSTER LATTICE

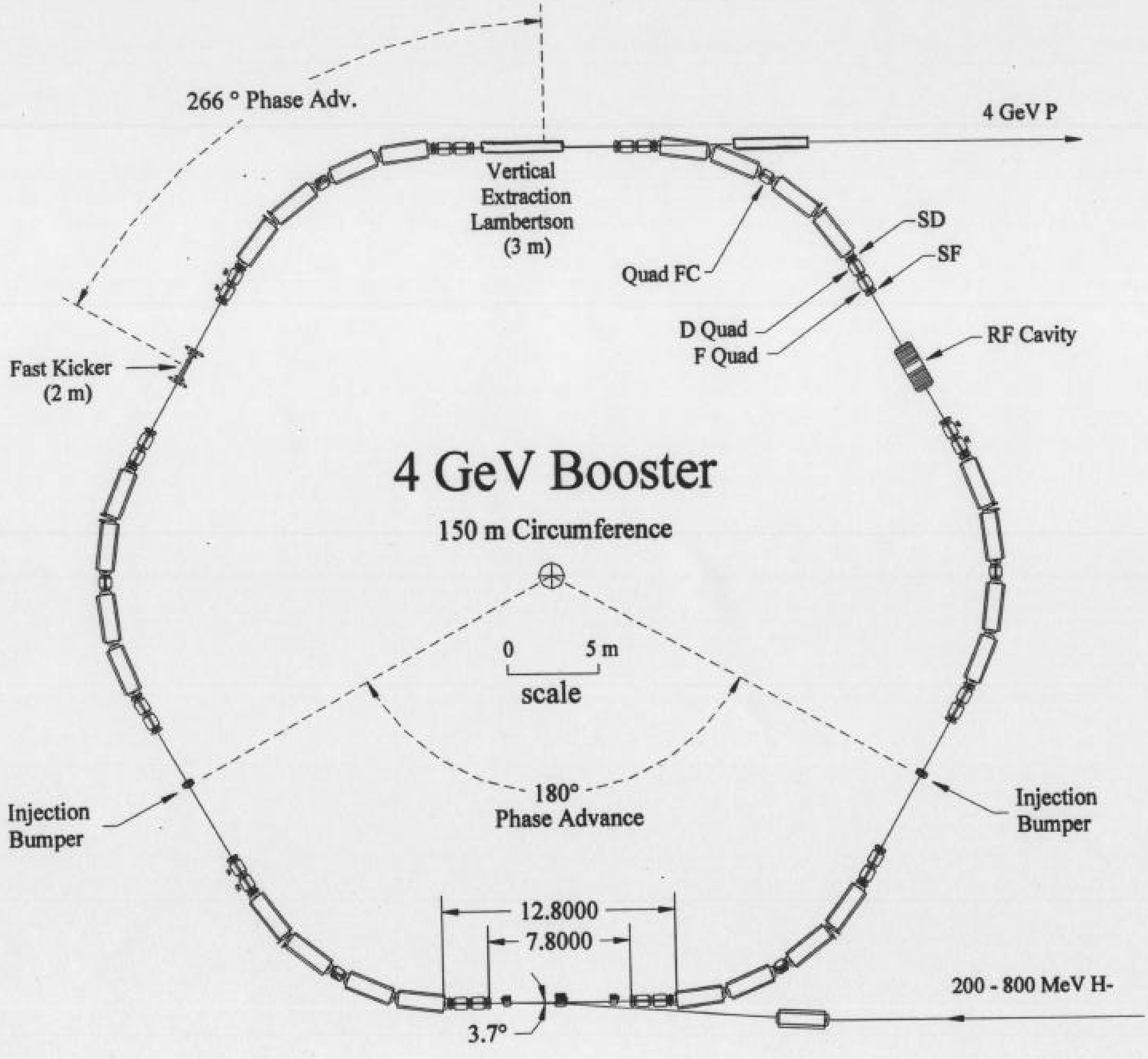
1. Criteria:

- transitionless ($\gamma_t > \gamma_{max}$)
- conventional/conservative design
- operational simplicity
  (2 tune knobs, 1 γ_t knob)
- low cost (small ring, identical magnets, low RF power)
- 140 – 800 MeV H^- strip injection
- 2.5×10^{12} p , h = 1

3-4 GEV BOOSTER LATTICE

2. Lattice:

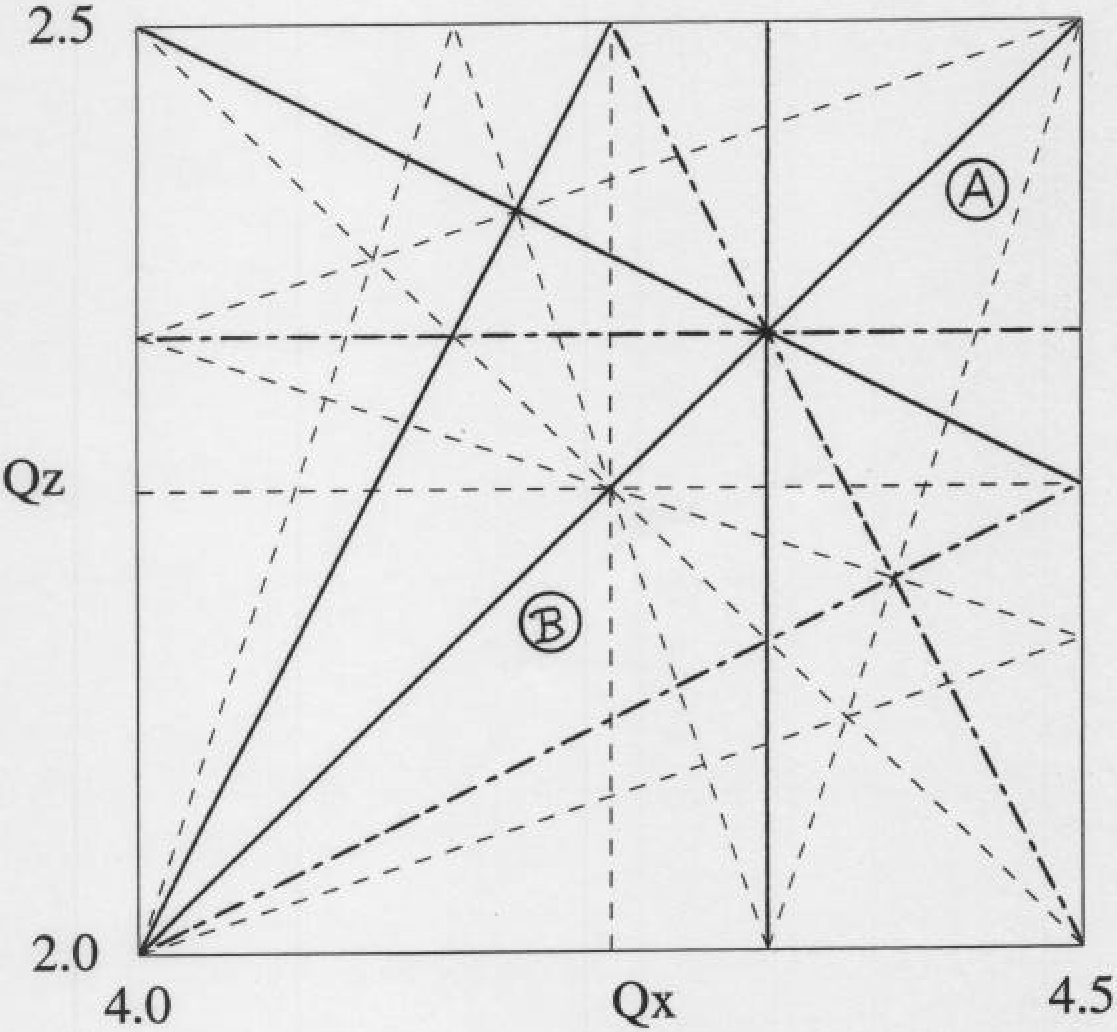
- ring geometry: regular hexagon ($P=6$)
- superperiod lattice structure
- operating points in tune space
- γ_t, lattice functions
- chromatic properties


266 ° Phase Adv.
4 GeV P
Vertical
Extraction
Lambertson
(3 m)
Quad FC
SD
SF
D Quad
F Quad
RF Cavity
Fast Kicker
(2 m)
4 GeV Booster
150 m Circumference
0
5 m
scale
Injection
Bumper
180°
Phase Advance
Injection
Bumper
12.8000
7.8000
200 - 800 MeV H-
3.7°

31

Resonances

4 orders



Booster Lattice

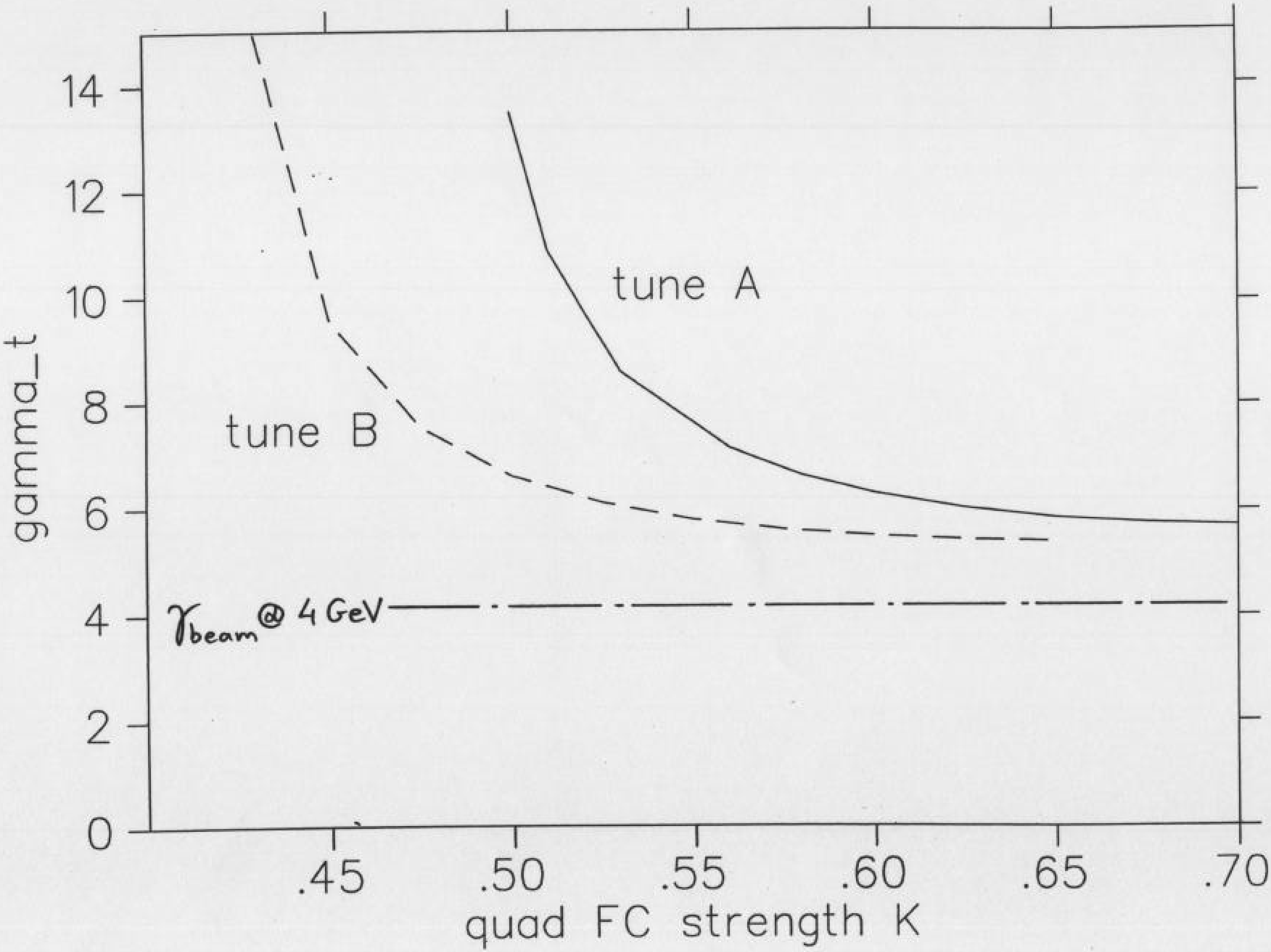
$\gamma_t \gtrsim 6$

29 --- Tune A is preferred because horiz. phase advance of superperiod is closer to 270° (-90°), ideal for locating extraction kicker & extraction septum magnets in adjacent straight sections.

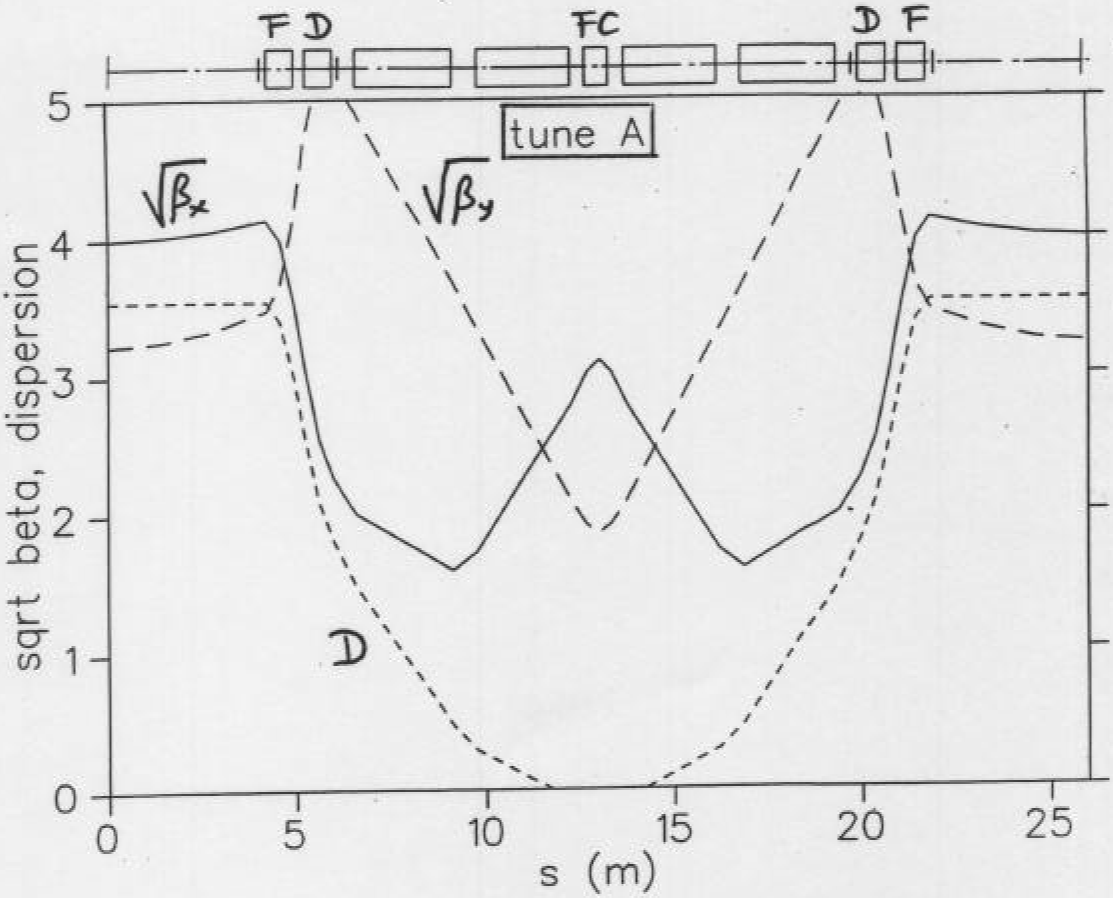
32 --- The "FC" quad, located in the center of every bend (see superperiod lattice, Fig.33), provides a convenient "γ_t-knob" to select any desired $\gamma_t > \gamma_{max}$ between 6 & 12.

33 --- The FC quad also keeps beta_x large in the straights, desirable for efficient kick-extraction of beam: small kick gives large beam displacement at septum,

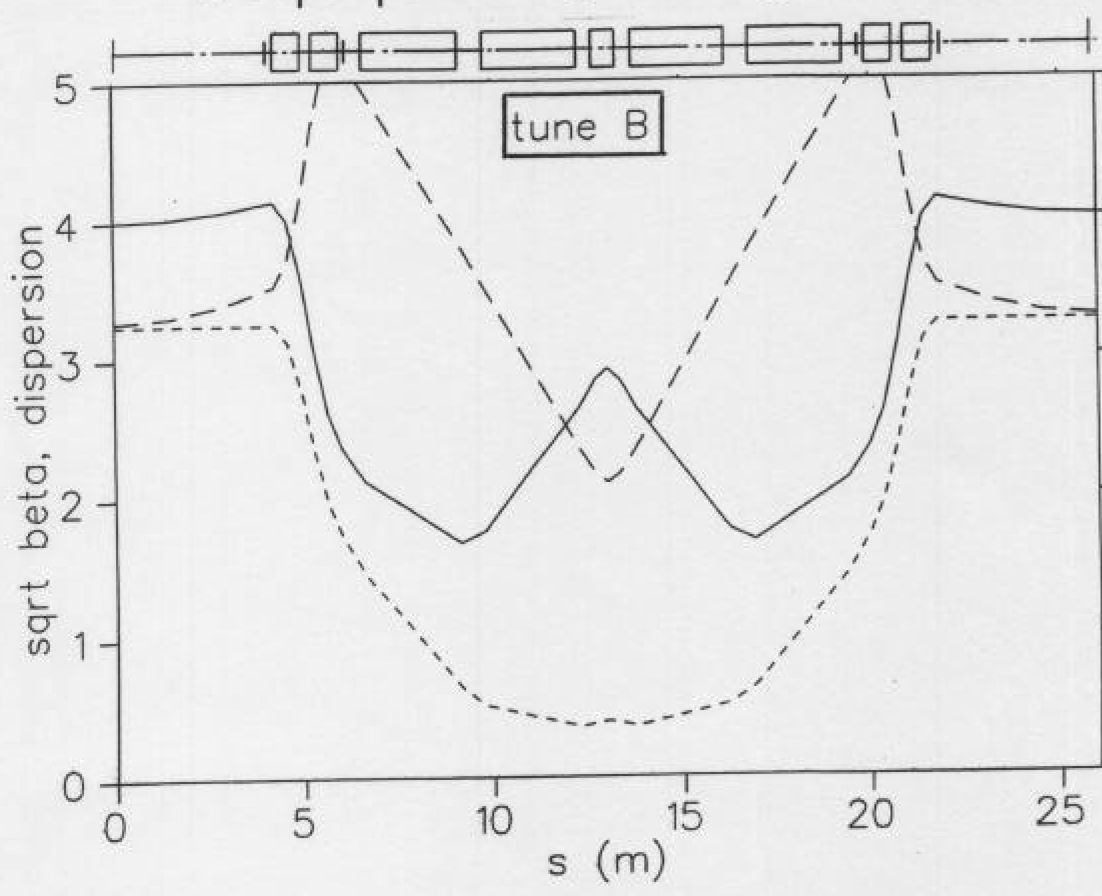
34 as illustrated in Fig. 34.

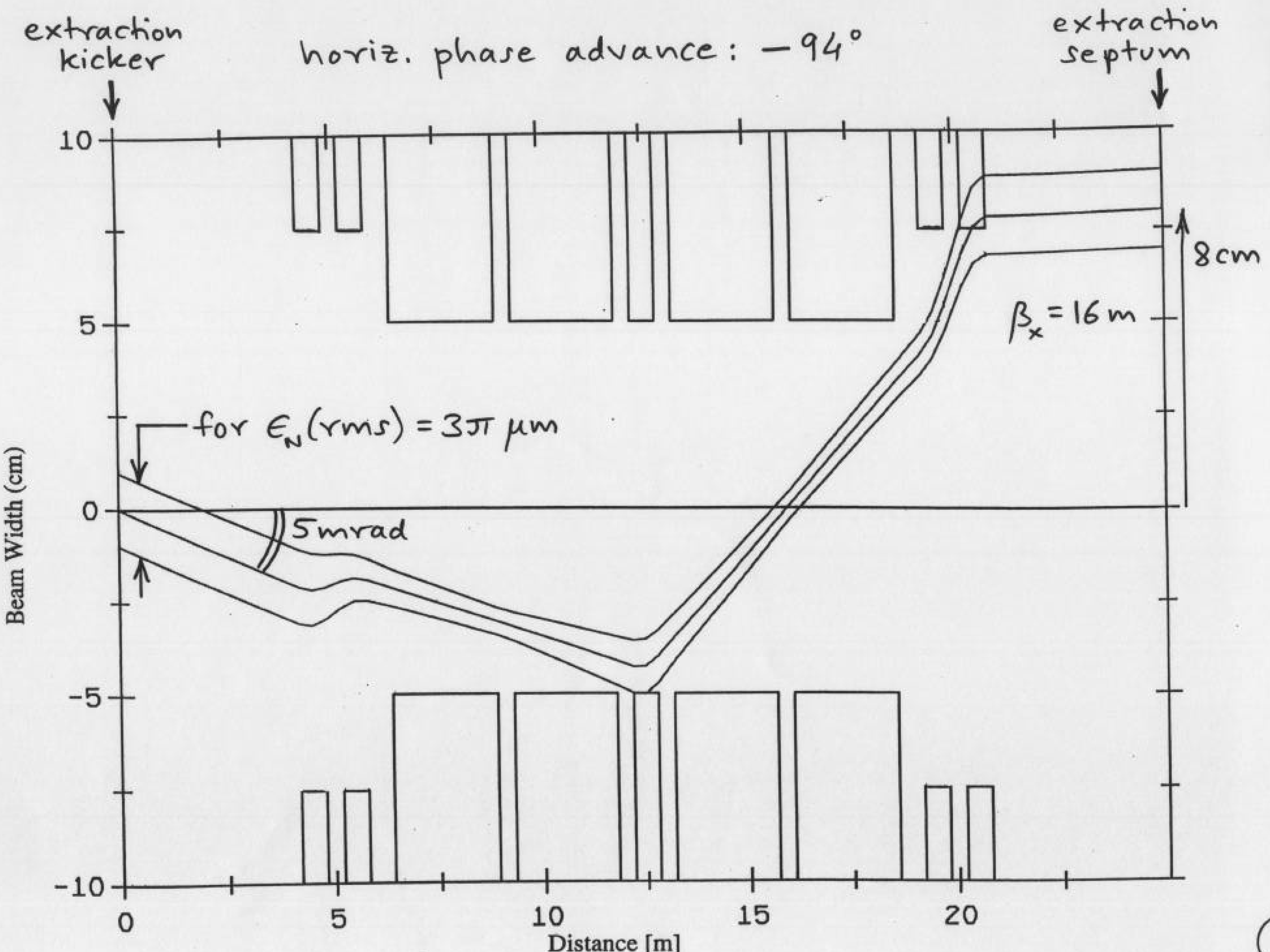


14
12
10
8
6
4
2
0
gamma_t
tune A
tune B
γ_{beam} @ 4 GeV
.45
.50
.55
.60
.65
.70
quad FC strength K



1 superperiod (1/6 ring)





extraction kicker
horiz. phase advance: −94°
extraction septum
10
5
0
-5
-10
for ϵ_N(rms) = 3π μm
5 mrad
8 cm
β_x = 16 m
Beam Width (cm)
0
5
10
15
20
Distance [m]