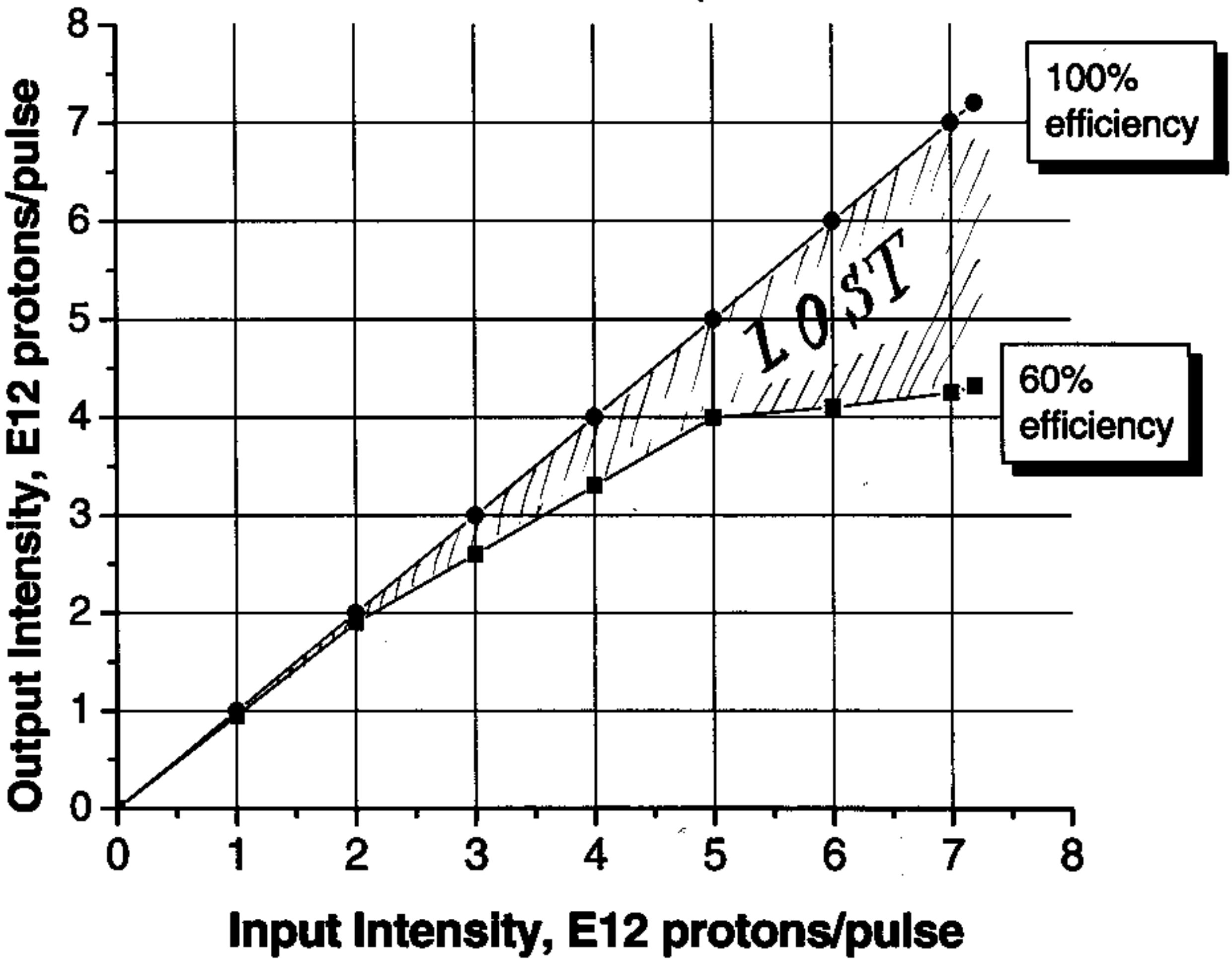
Vladimir Shiltsev

Space Charge Compensation in the Booster

1. Scope: what's up with the Booster?
2. Space-charge effects & theory
3. Proposal to use electron beams
4. Degree of compensation
5. E-beam shape/modulation/direction
6. E-gun and magnetic field
7. Set of parameters vs TEL
8. Suggested R&D plan
9. Resources: $$, people

Booster Efficiency and Losses



Space-charge-like phenomena in the Booster:

1. Most of the losses take place some few thousands turns (5ms) after injection while the beam energy is minimum

2. Since pre-upgrade era it's known that beam brightness stays constant for high intensities

   Np/emittance ≈ const

3. strong dependence on the working point

there are many suggestions to reduce the losses with cosmetic measures, like

- increase aperture
- split the tunes by one unit
- improve γ_t jump system
- 2nd harmonic RF to reduce bunching
- increase RF gap volts and improve beam loading compensation

...but only one thing can kill the beast –

get rid of the Space-Charge

$\nu_x \approx 6.7$ $\nu_y \approx 6.8$

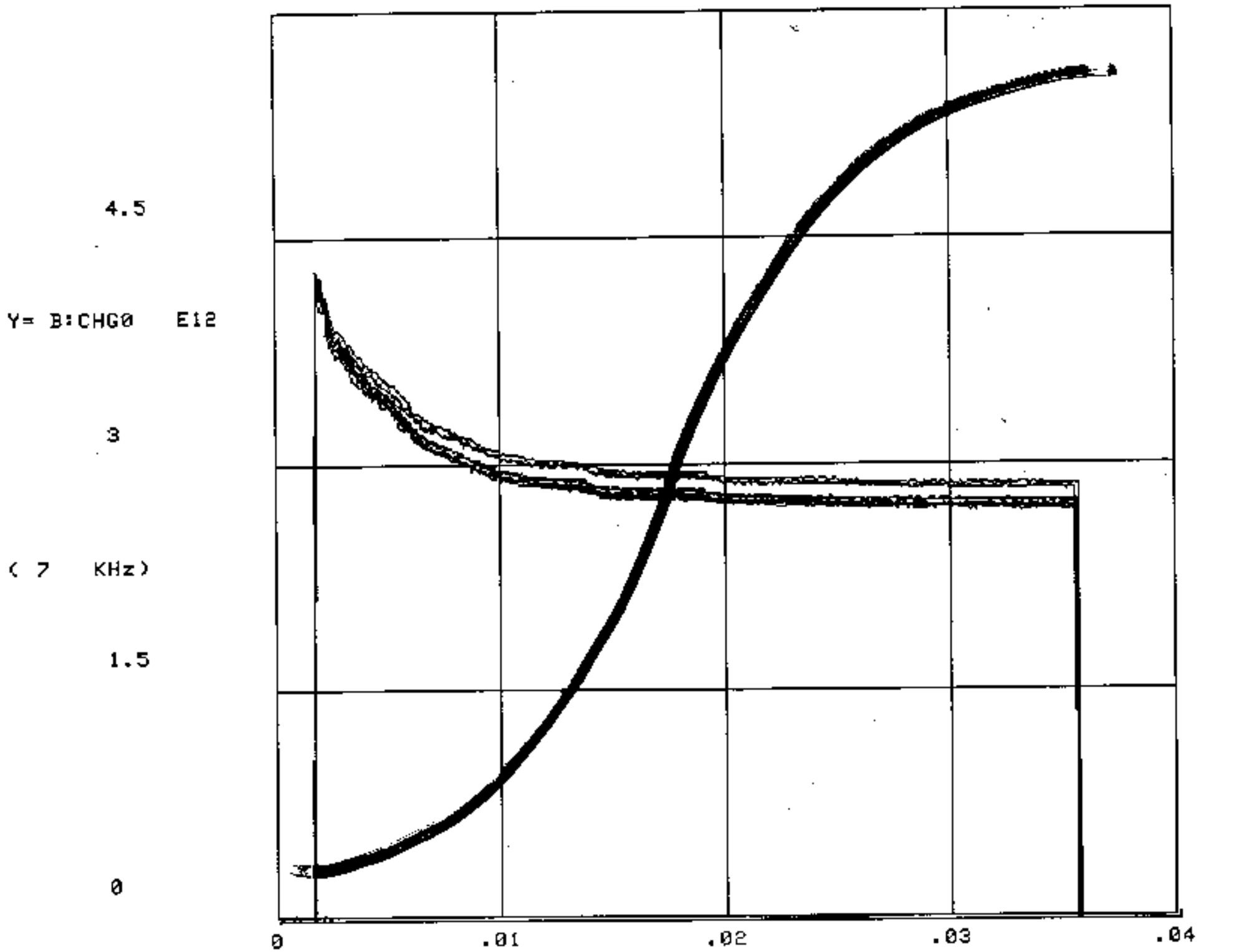
Q/L0
0.06

normal $Q_{x,y}$

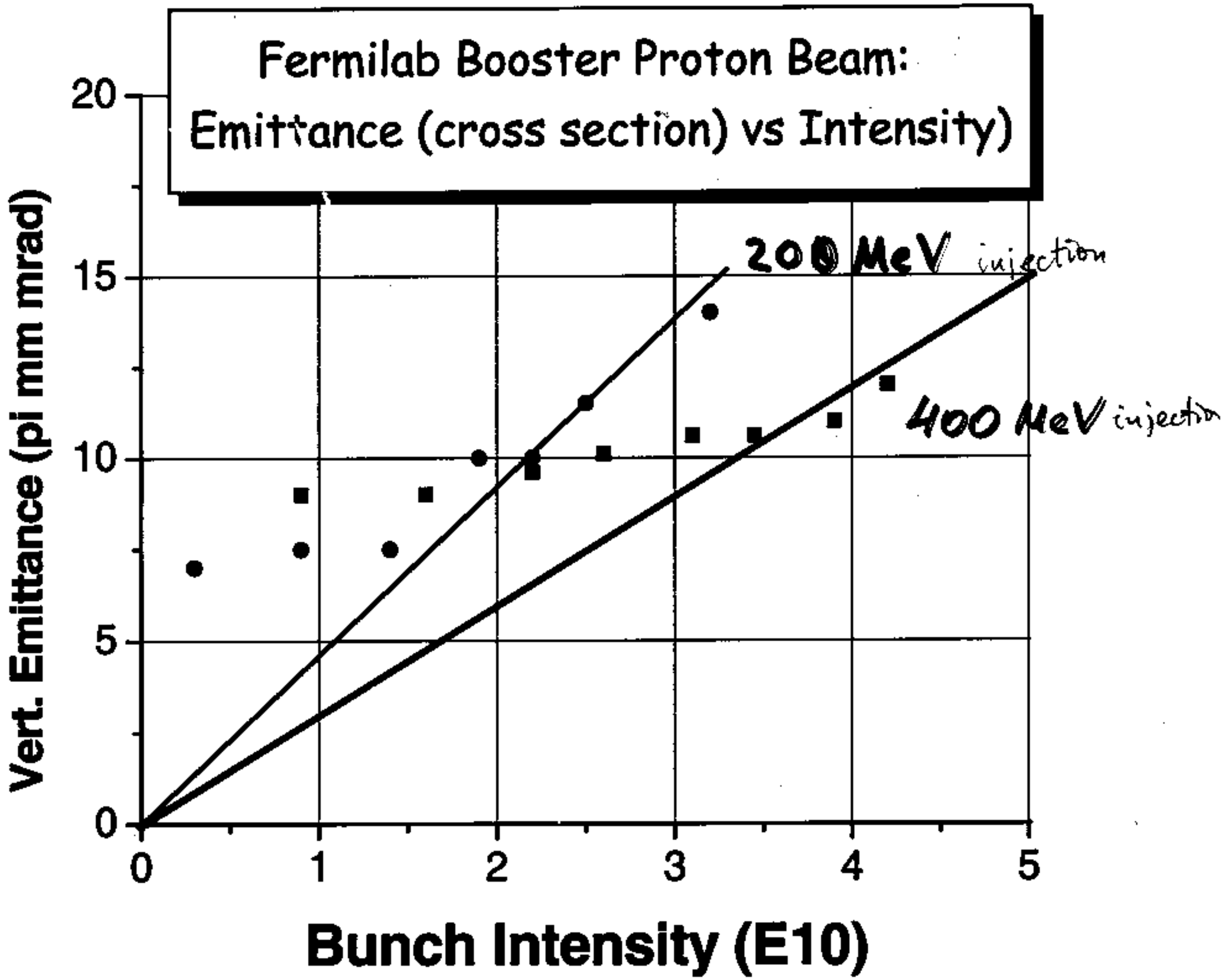
T4coMM 1 -49 SNP V1.41 Console 2 Tue 16-JAN-01 14:08 Pri=2

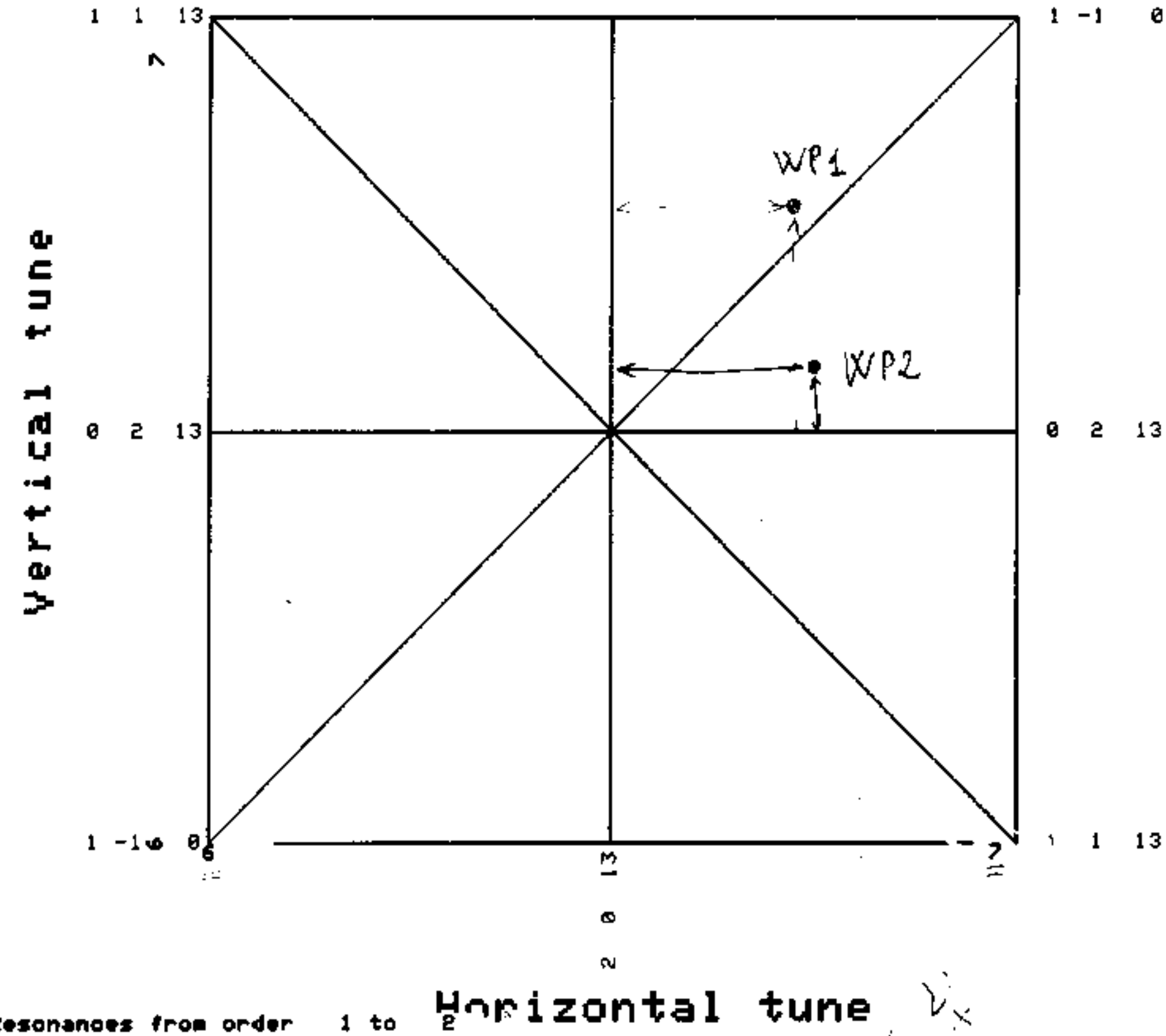
Console Location 2,
Snapshot Plot

16-JAN-2001 14:10



PLOTTING Seconds Trig = EVENT 17 engineering units


Fermilab Booster Proton Beam:
Emittance (cross section) vs Intensity)
200 MeV injection
400 MeV injection
Vert. Emittance (pi mm mrad)
Bunch Intensity (E10)
0
5
10
15
20
0
1
2
3
4
5

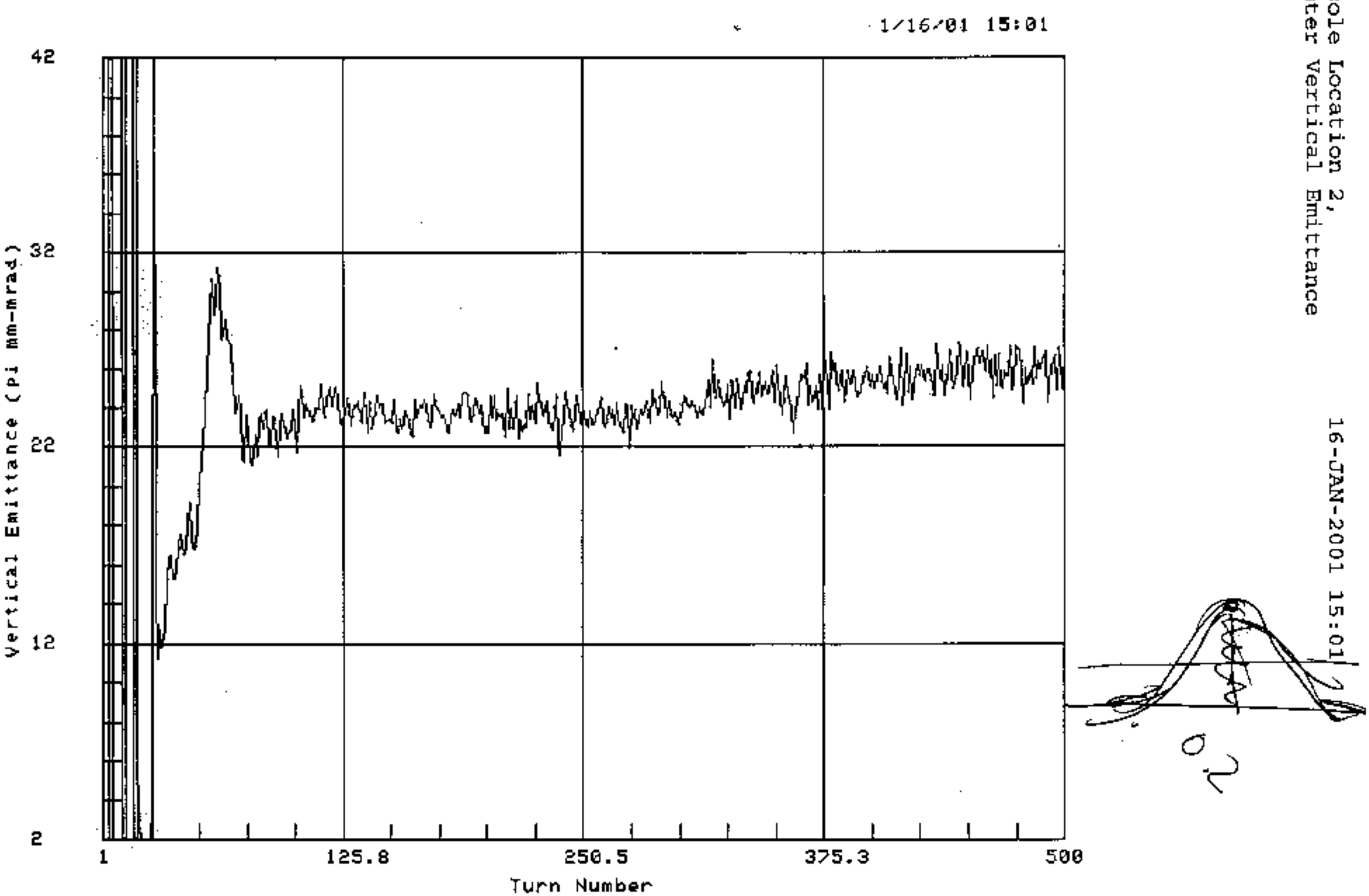


Resonances from order 1 to 2

WP 1

Q_L −0.25 A
Q_S +0.25 A

$2Q_Y$ = [illegible]



Console Location 2,
Booster Vertical Emittance

16-JAN-2001 15:01

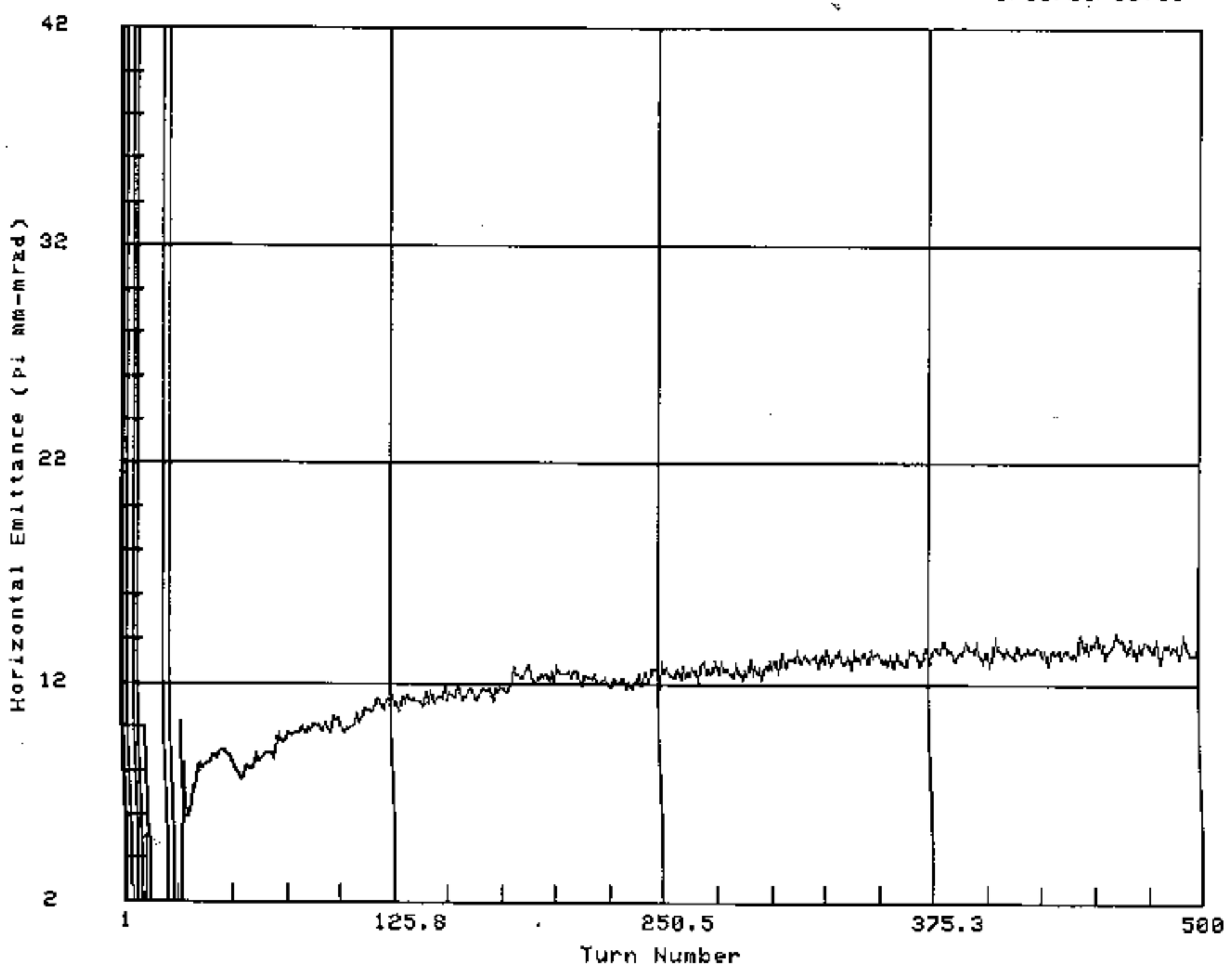
0.2

$\nu_x = 4.3$ $\nu_y = 4.77$

Q_L -0.25 Amps

Q_S $+0.25$ Amps

1/16/01 15:01



Console Location 2,
Booster Horizontal Emittance

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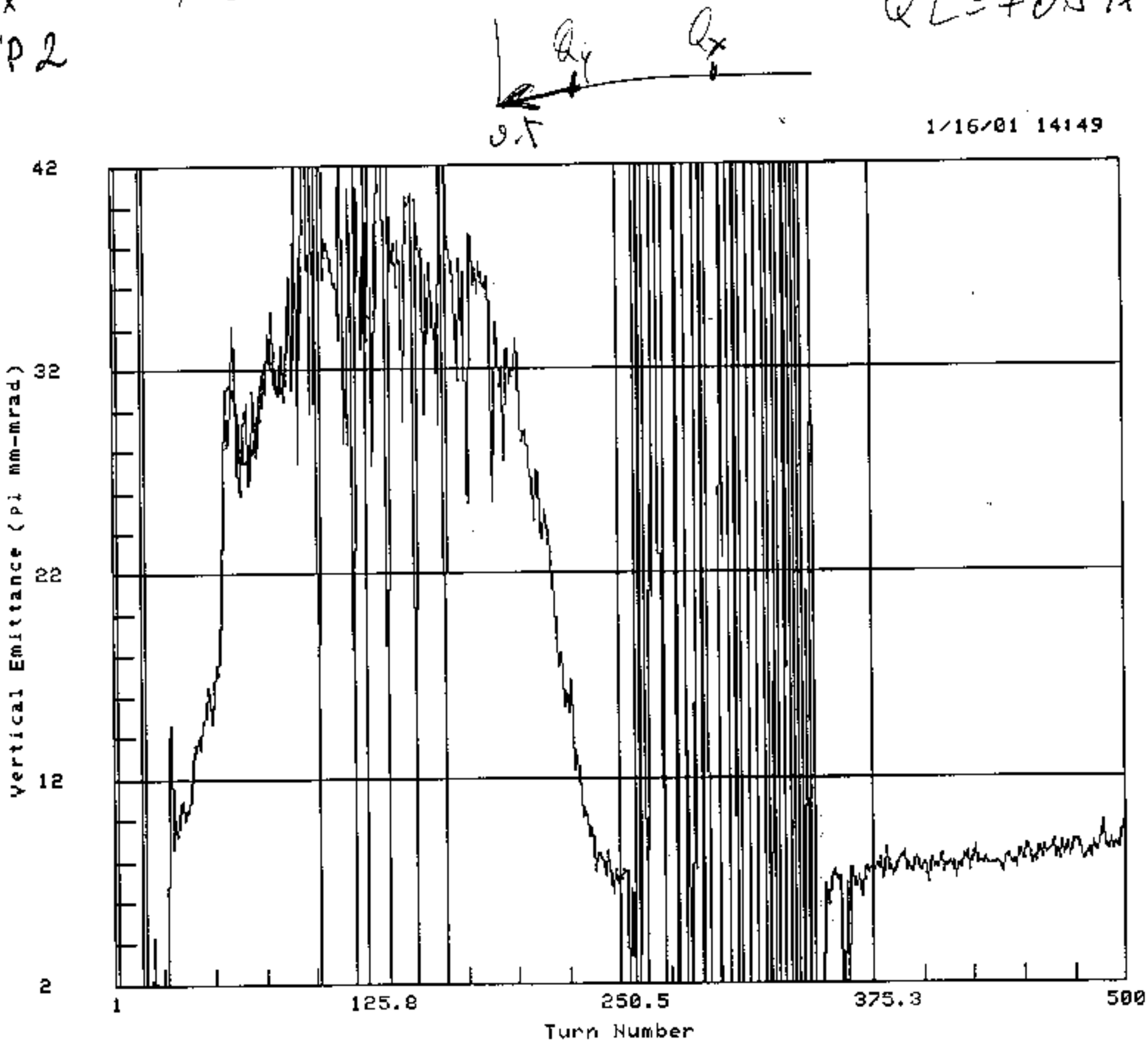
$\nu_x = 6.85$ $\nu_y = 6.5$

WP 2

QL = +0.5 A



Console Location 2,
Booster Vertical Emittance

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$\nu_x = 0.75$ $\nu_y = 0.57$

WORKING point 2

QL= +0.5 A

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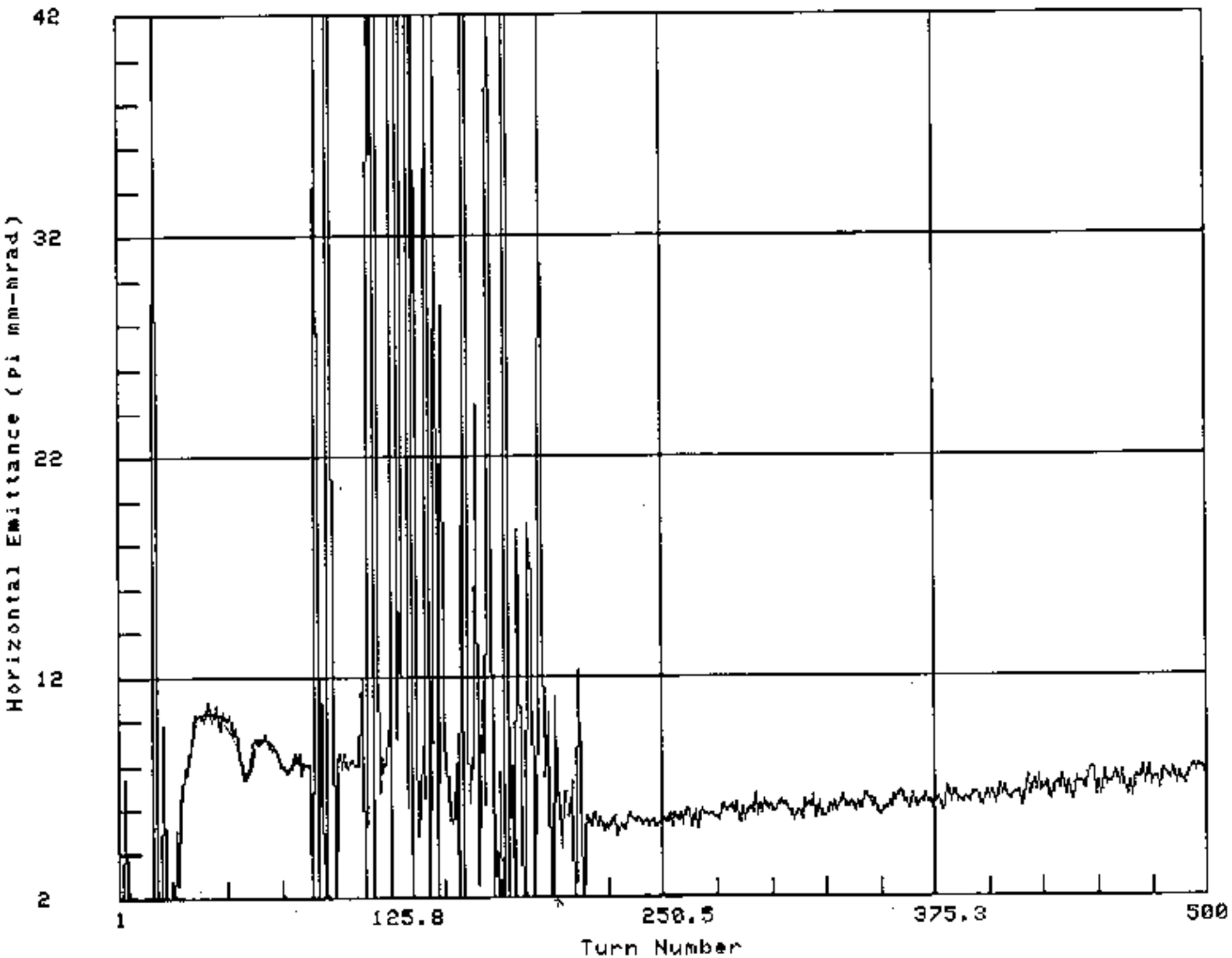

Console Location 2,
Booster Horizontal Emittance

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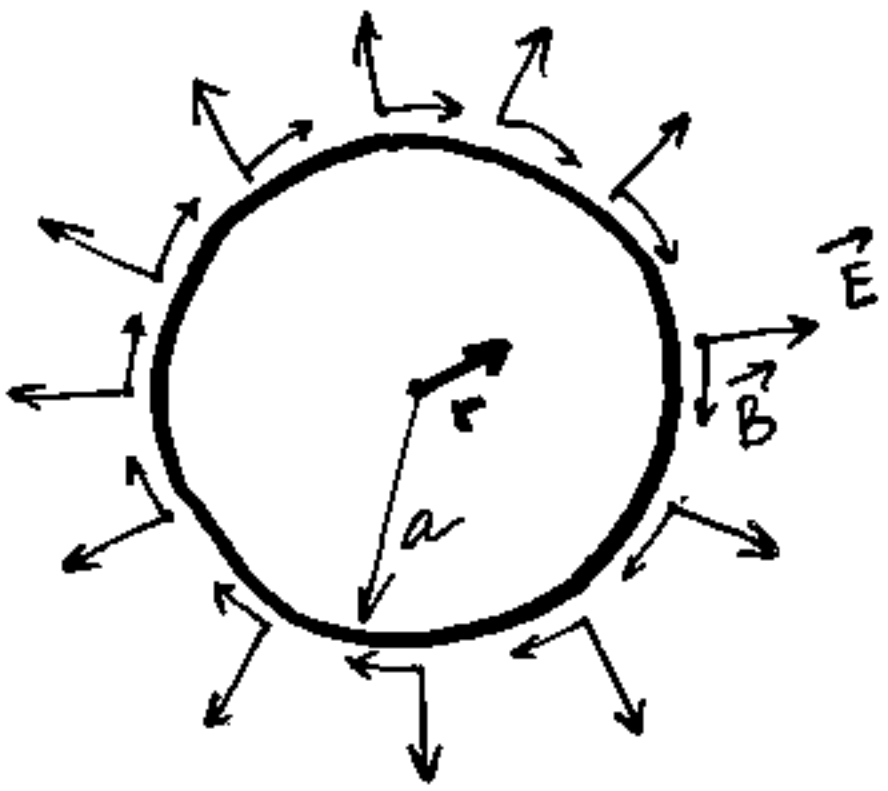
Space-Charge Forces



if total number of particles in the ring is N

then line density is

$$\lambda = \frac{N}{2\pi R}$$

and

$$E_r = \frac{2\lambda e}{a^2} \cdot r$$

similarly, magnetic field is

$$B_\theta = \beta E_r \quad , \beta = \frac{v}{c}$$

The Lorentz force is repulsive:

$$F_r = e(E_r - \beta B_\theta) = \frac{2\lambda e^2}{a^2 \gamma^2} \cdot r$$

it vanishes at higher energies

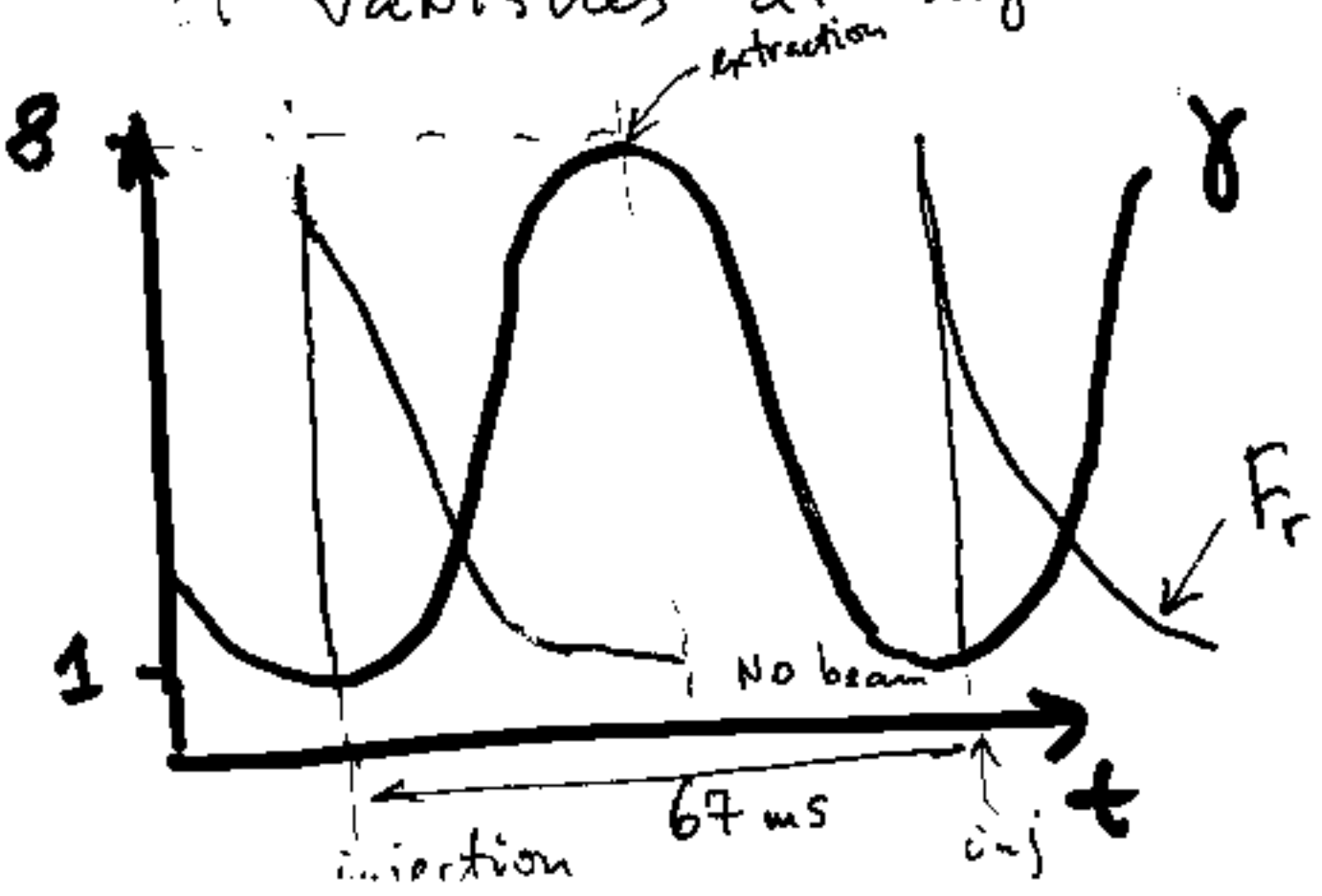


Figure of merit for SC-effects is tuneshift

equation of (incoherent) motion:

$$y'' + \left(\frac{\nu_0}{R}\right)^2 y = \frac{F_y}{m\gamma\beta^2c^2} \rightarrow$$

$$\Delta\nu_{sc} = -\frac{N_{tot}\cdot r_p\cdot B_f}{4\pi\,\epsilon_n\cdot\beta_p\cdot\gamma_p^2}$$

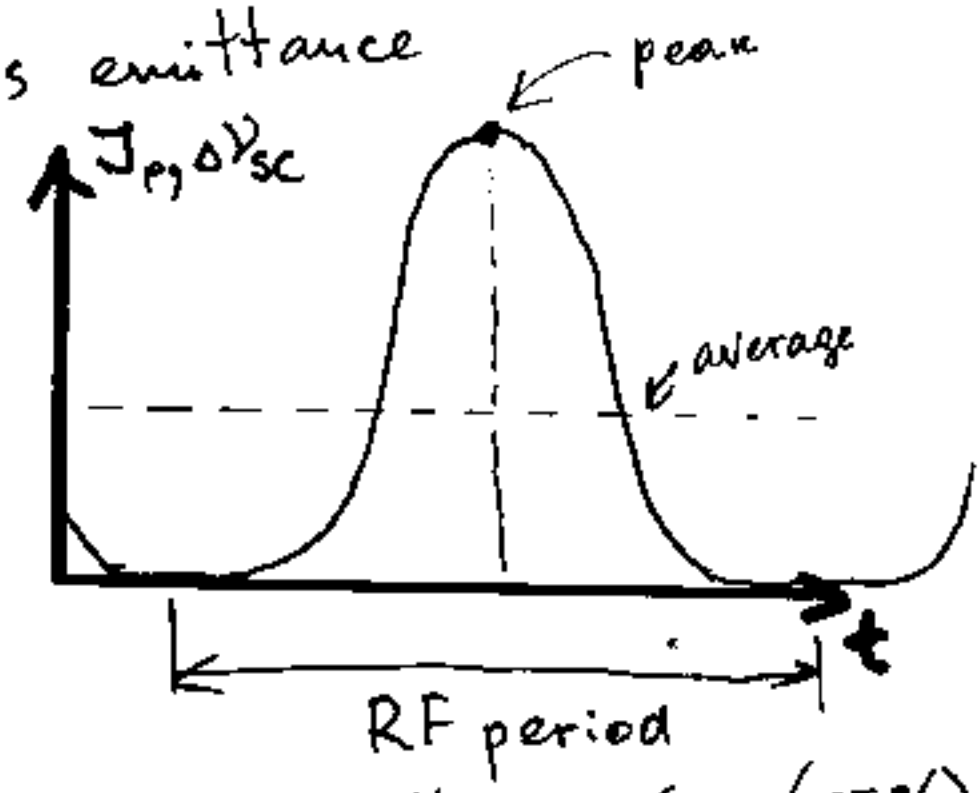
$r_p = 1.53\cdot10^{-18}$ m

$\beta_p = \delta_p/c$

$\gamma_p = (1-\beta_p^2)^{-1/2}$

$$\epsilon_n = \frac{\sigma_{rms}^2}{\beta_{x,y}}\cdot\gamma_p\cdot\beta_p \leftarrow \text{rms emittance}$$

$$B_f = \frac{\hat{J}_p}{\langle J\rangle_p} = \frac{\text{peak}}{\text{average}}$$



Booster: @ injection

protons $\epsilon_n = 2$ mm-mrad

$\beta_p = 0.7$

$\gamma_p = 1.4$

$N_{tot} = 5\cdot10^{12}$

in FNAL units $\rightarrow \times 6\pi$ (95%)

$\sim 12\pi$ mm.mrad IPM data

$\sim 18\pi$ mm.mrad Wire scan dat

$$\Delta\nu_{sc} = -0.22\cdot B_f(t)\cdot\frac{N_{tot}}{5E+12}\cdot\left[\frac{\epsilon_n\cdot\beta_p\cdot\gamma_p^2(t=0)}{\epsilon_n\cdot\beta_p\cdot\gamma_p^2(t=t)}\right]$$

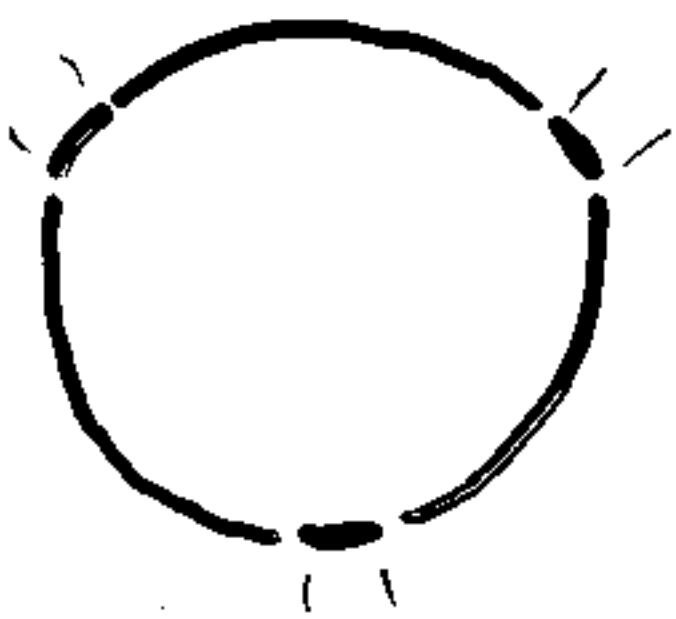
$\uparrow$

-0.15 if $\epsilon = 18\pi$

We proposed to compensate space-charge repulsion in (+) proton beam by adding (−) electrons into accelerator

Burov, Foster, Shiltsev (200

FOR COMPENSATION, charge of ELECTRONS has to be equal (and opposite) TO THE proton beam charge



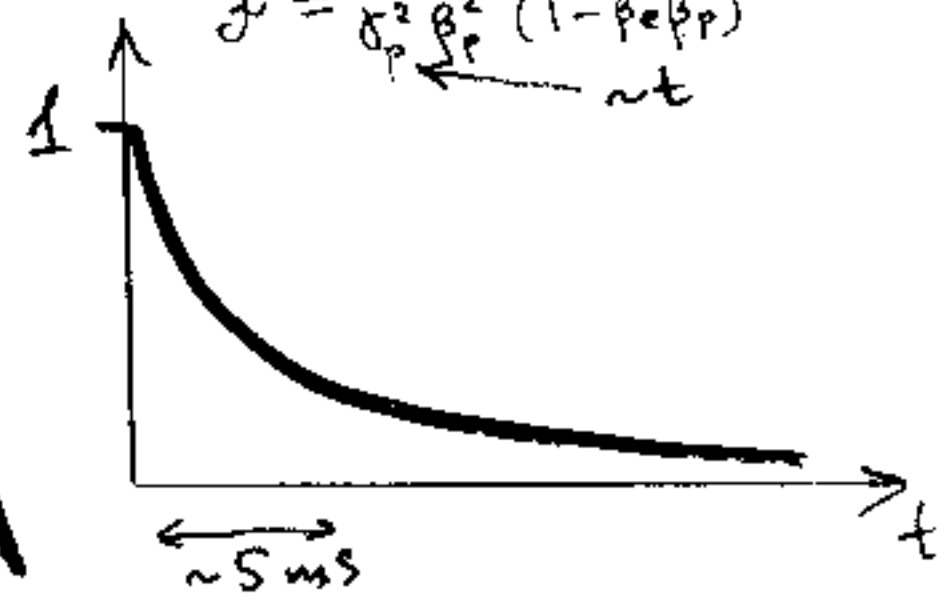
or, if $\beta_e \approx \beta_p$ THEN

$$J_e^{max} = J_p^{max} \cdot \left(\frac{C}{L_e}\right) \cdot \mathcal{F}^{\approx 1}$$

TOTAL e-LENGTH

$$\mathcal{F} = \frac{\beta_e}{\gamma_p^2 \beta_p^2 (1-\beta_e\beta_p)}$$

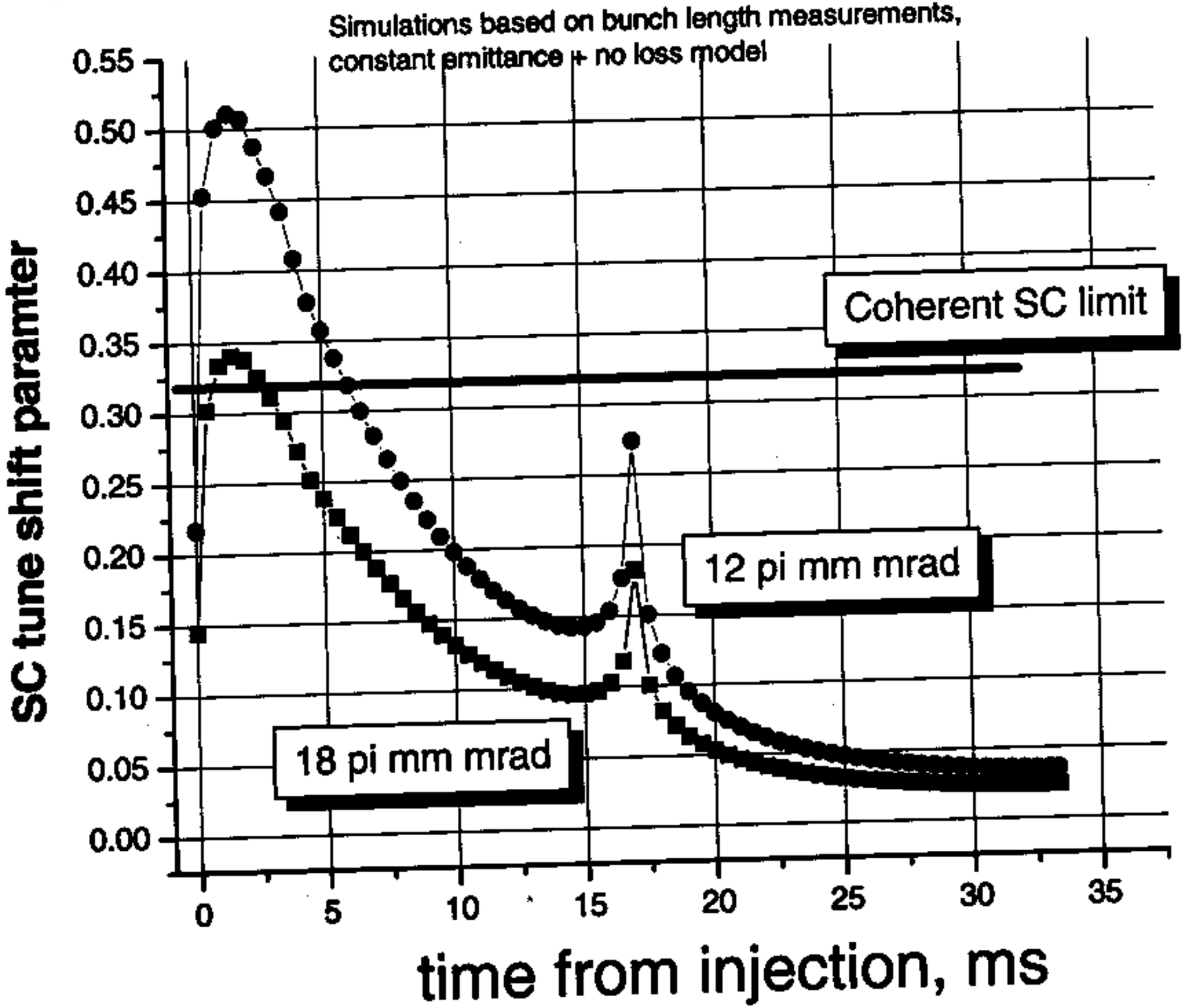
$\sim t$



E.g. for BOOSTER

$J_p^{max} \sim 0.5\,A$
$C = 480\,m$
$L = 3 \times 4\,m = 12\,m$
$\Big\} \rightarrow J_e \simeq 20\,A$

Booster dQ_SC vs time in cycle, 5e12 ppp



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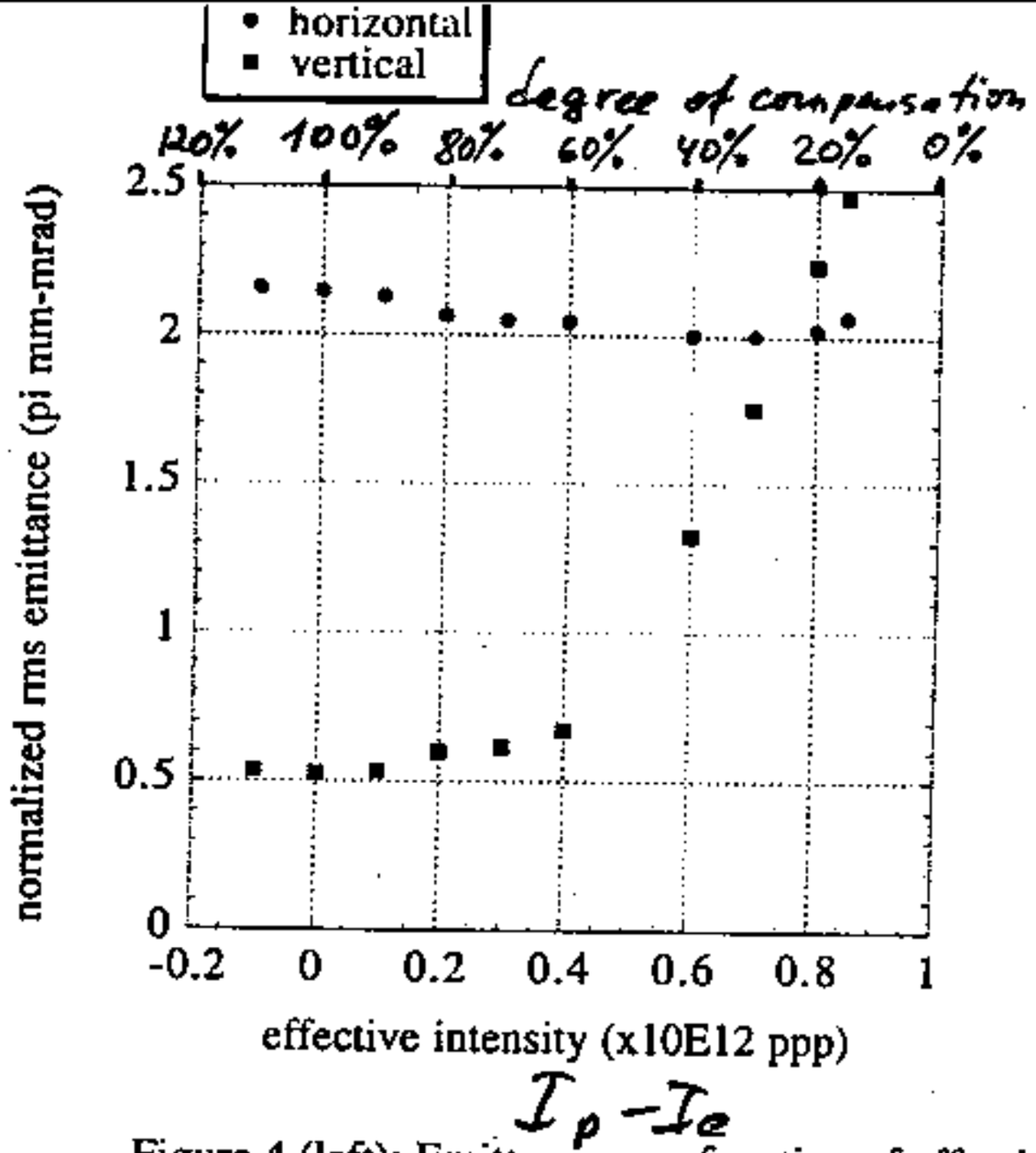


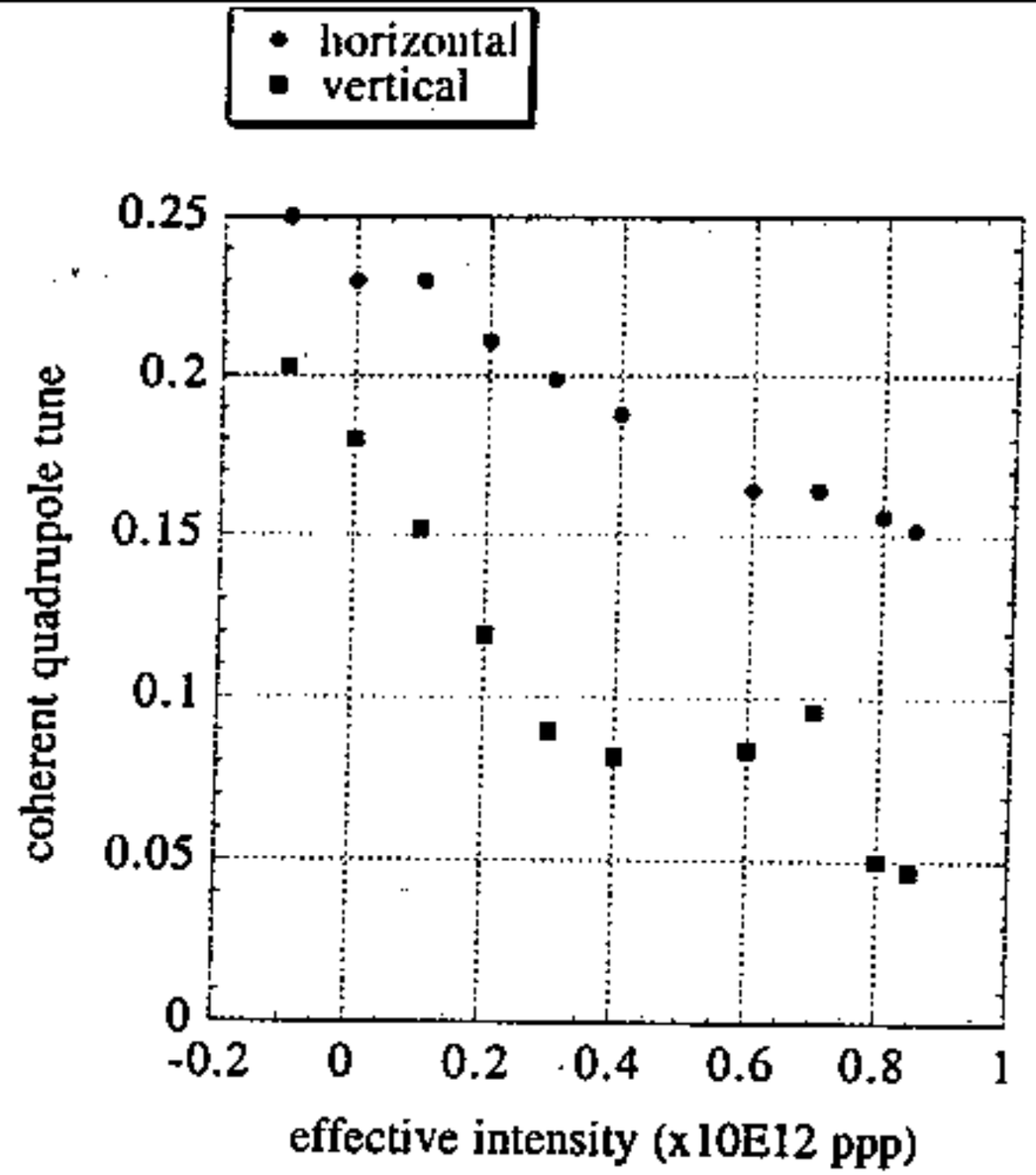
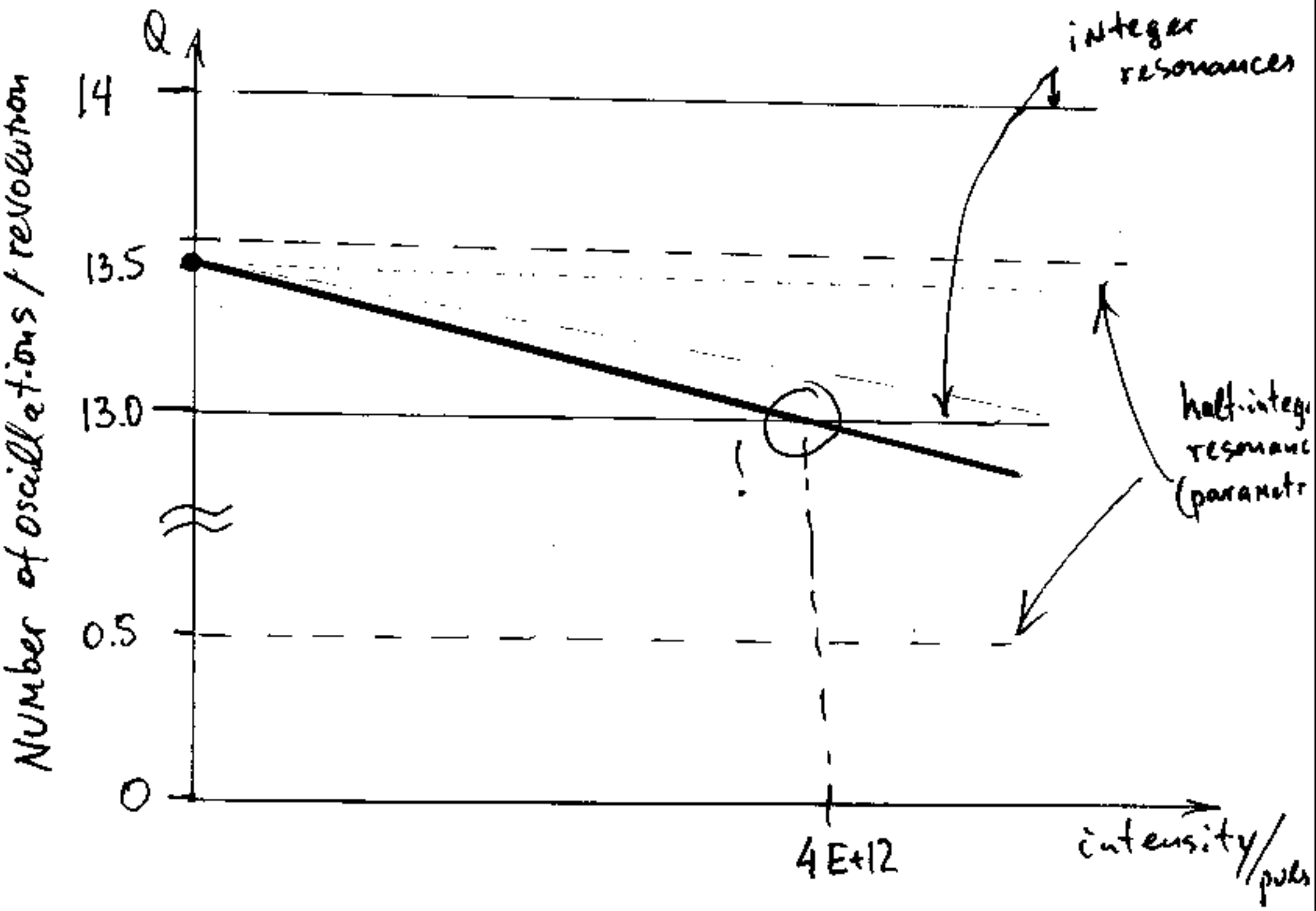


Figure 4 (left): Emittance as a function of effective beam intensity

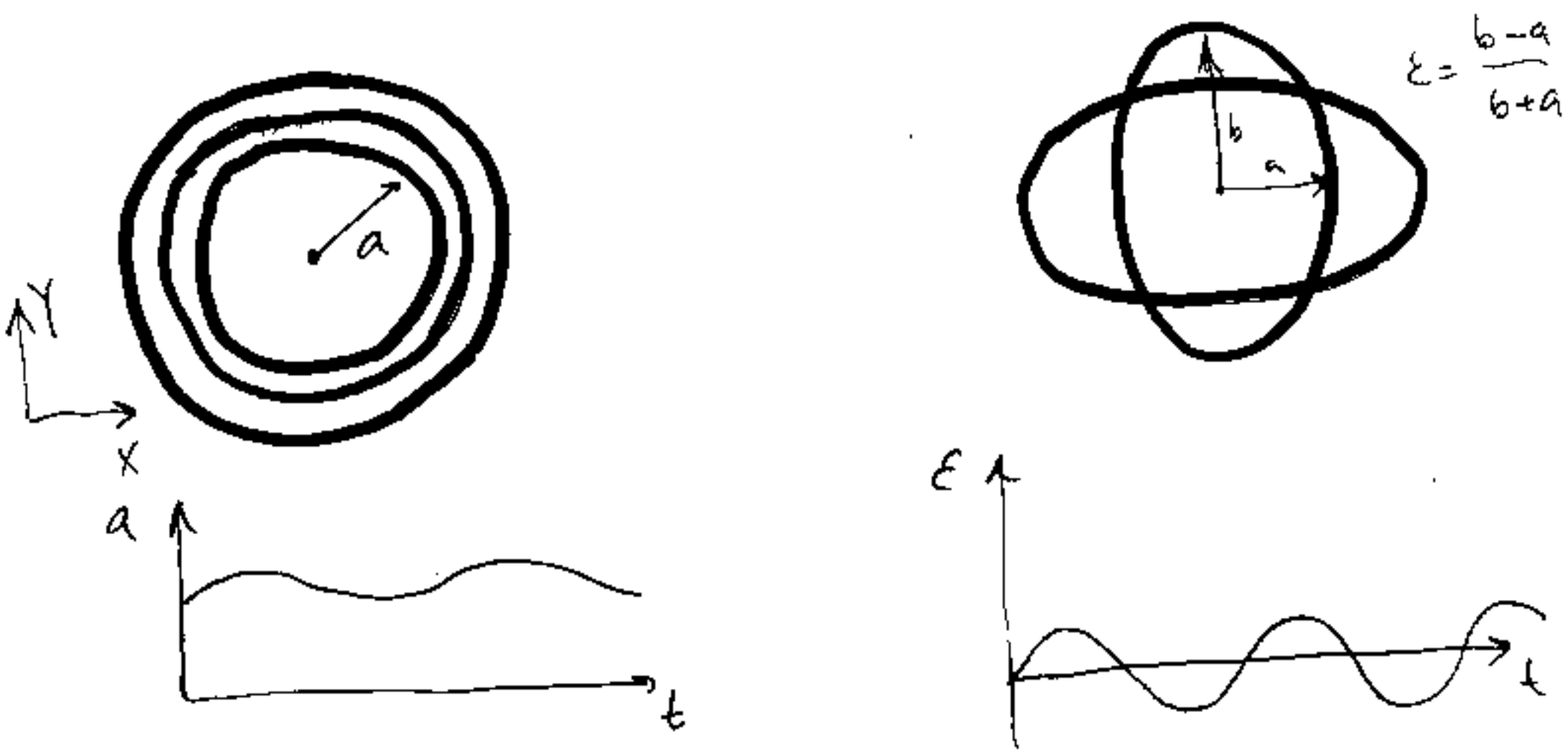
Figure 5 (right): Coherent quadrupole tune as a function of effective beam intensity.

electron intensity is more than necessary to cancel the overall space charge effects, the effective intensity becomes negative, meaning that the overall field is attractive.

As shown in Fig. 4, when the electron intensity is high enough and the effective intensity is low, emittance growth is suppressed. Above the effective intensity of 0.4×10^{12} ppp, the vertical emittance start blowing up. The coherent quadrupole tune is decreased as the effective intensity is increased as shown in Fig. 5. The interesting results we can see from Figs. 2-5 are that 1) the space charge compensation with electron beams works as predicted, and 2) effective intensity solely accounts for space charge effects on a proton beam.



in fact there are 2 modes:



Proton tuneshift due to local electron beam space-charge

$$\Delta\nu_e = + \frac{\beta_{x,y}}{4\pi} \cdot \frac{J_e(t) \cdot L \cdot r_p}{e \beta_e c \sigma_e^2 \cdot \gamma_p \beta_p^2} \cdot \left(1 - \vec{\beta}_e \cdot \vec{\beta}_p\right)$$

$\beta_{x,y}$ – beta function @ location of e-lens

L – length of the e-lens

σ_e – rms ebeam size (assuming Gaussian distribution)

$J_e(t)$ – electron current

$\beta_e = \delta_e / c$

Major Questions:

Q1: what is optimum degree of compensation α

$$\Delta\nu_e = -\alpha \, \Delta\nu_{sc} \ ?$$

Q2: should e-beam have the same transverse profile as p-beam?

Q3: — match longitudinal pbunch profile?
- direction of e-beam

Q4: How many e-lenses are needed?

Q5: parameters?

Beam Modes in Presence of Space Charge

(Baartman model → TM-2125)

1. Plot below illustrate behavior of the 4 relevant modes with the Laslett tune shift

All the tune shifts are taken as small in comparison with the tunes themselves. Behavior of these mode fractional tunes without any compensation ($\alpha=0$) is illustrated in Fig. 1 for approximately Booster's fractional tune $\{\nu_0\} = 0.75$.

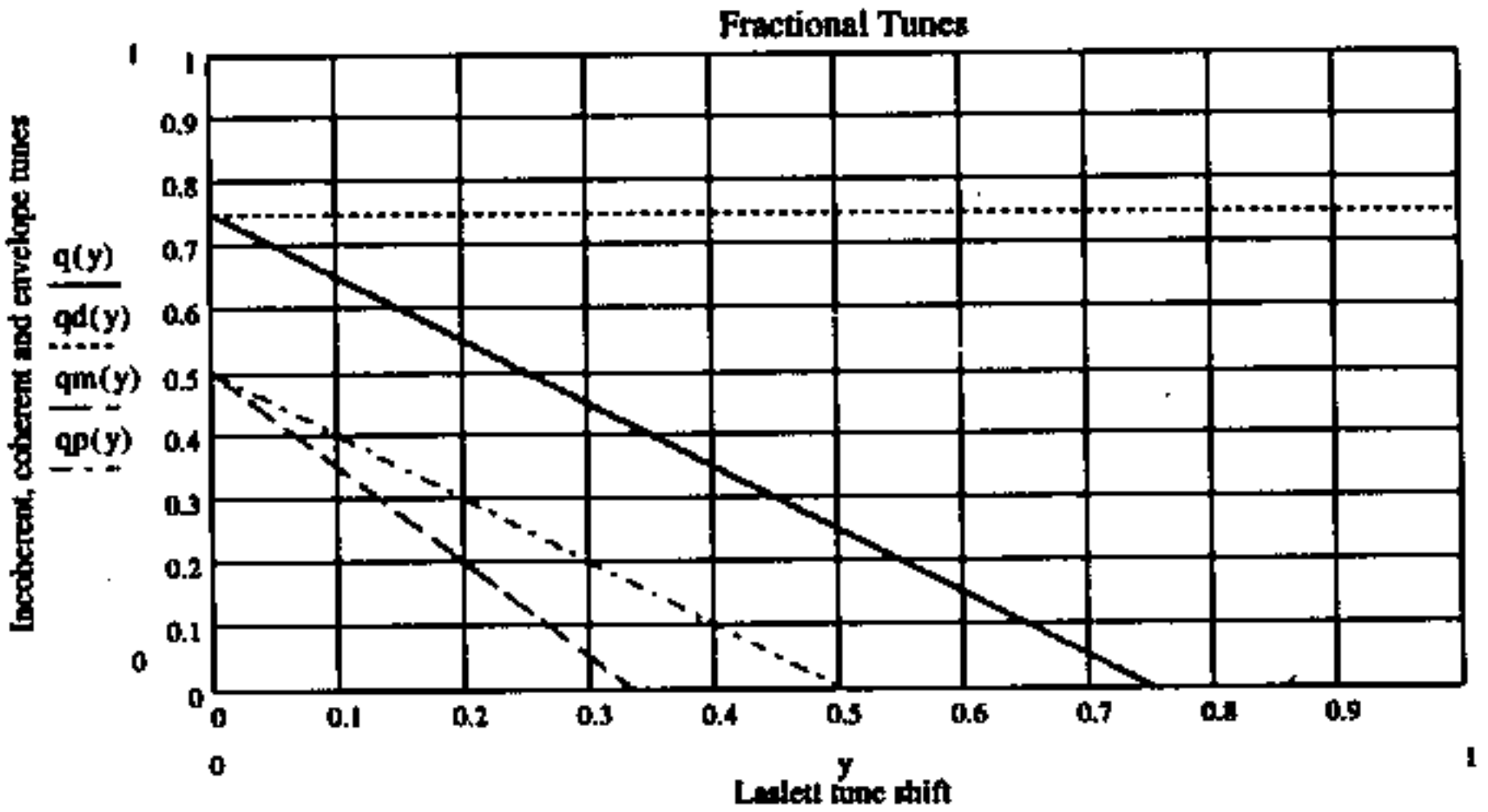


Fig. 1. The red line corresponds to the single-particle mode, the blue line – to the dipole mode, magenta – envelope in-phase mode, brown – envelope out-of phase mode. Empirical results of several low-energy booster-synchrotrons lead to a conclusion that the incoherent tune is able to cross any resonance without significant beam deterioration. Indeed, for the Fermilab Booster the half-integer resonance is crossed at $\Delta\nu_L = 0.2$, while the experimental limit $\Delta\nu_L = 0.4$. The same conclusion follows for the AGS and CERN PS machines. In the figure above, this empirical limit is close to the resonance crossing by the out-of-phase envelope mode. From the other side, it is known theoretically and from simulations that integer and half-integer resonances of the envelope modes are very strong and normally cannot be overcome. Nothing to say that linear integer and half-integer resonances of the dipole mode must be avoided; the beam must stay at a safe distance from them, not smaller than 0.05 – 0.1. Taking these considerations into account, the compensation parameter α can be optimized to have maximal Laslett tune shift when a first half-integer resonance crossing by one of the coherent modes (dipole or envelope) takes place.

Q1

Plots below illustrate behavior of the 4 relevant modes with the Laslett tune shift $\Delta\nu_L$, when an applied electron lens tune shift $\Delta\nu_e$ is proportional to it $\Delta\nu_e = \alpha\Delta\nu_L$ with an optimized coefficient α. Assuming both the lattice tunes identical and equal to ν_0, these modes are:

2. Incoherent (single-particle) mode, with the tune $\nu_i = \nu_0 + (\alpha - 1)\Delta\nu_L$
3. Coherent dipole mode, $\nu_d = \nu_0 + \alpha\Delta\nu_L$
4. Envelope in-phase mode, $\nu_+ = 2\nu_0 + (2\alpha - 1)\Delta\nu_L$
5. Envelope out-of-phase mode, $\nu_- = 2\nu_0 + (2\alpha - 3/2)\Delta\nu_L$

For same working point and the compensation $\alpha = 1/3$, the modes are shown in Fig. 2

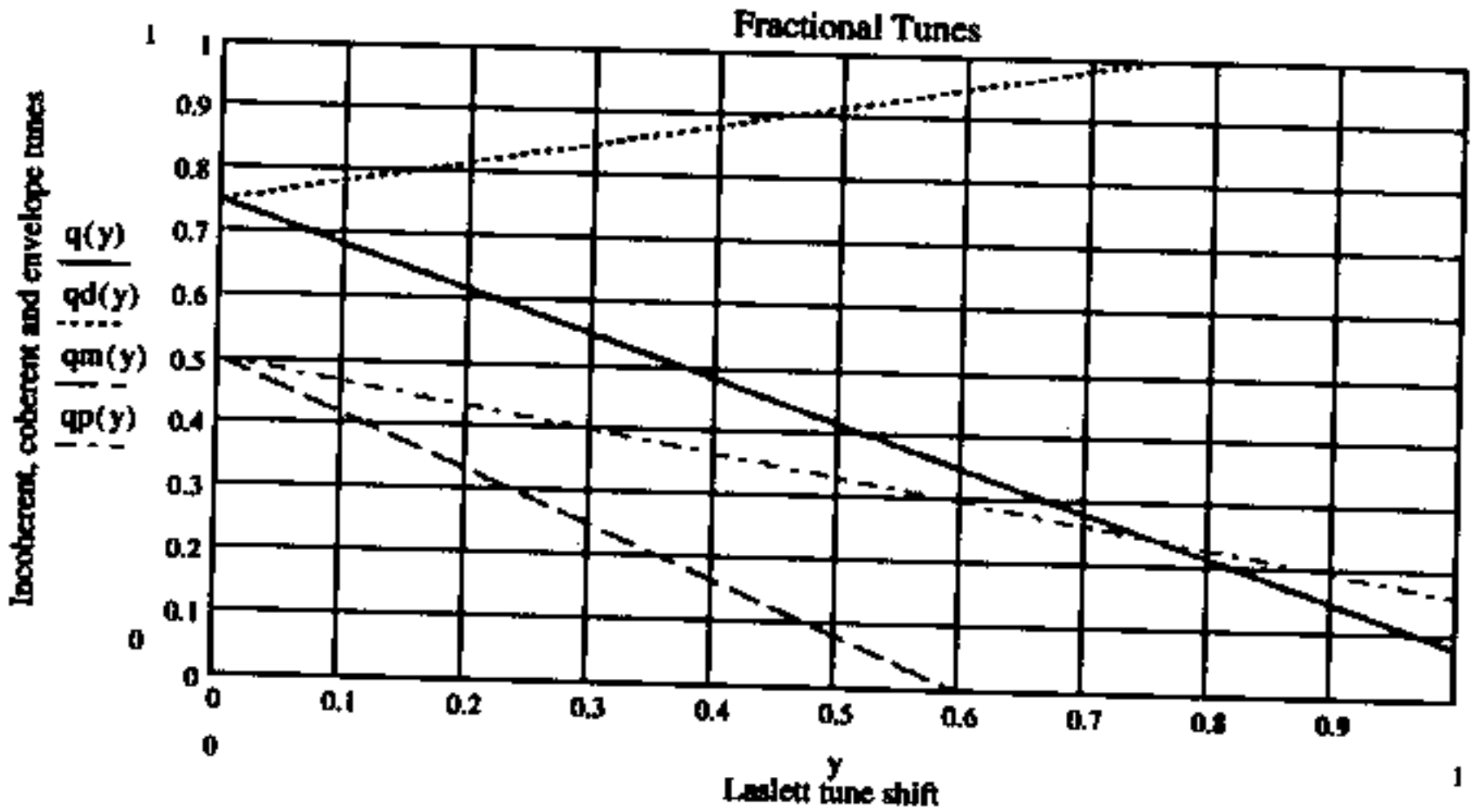


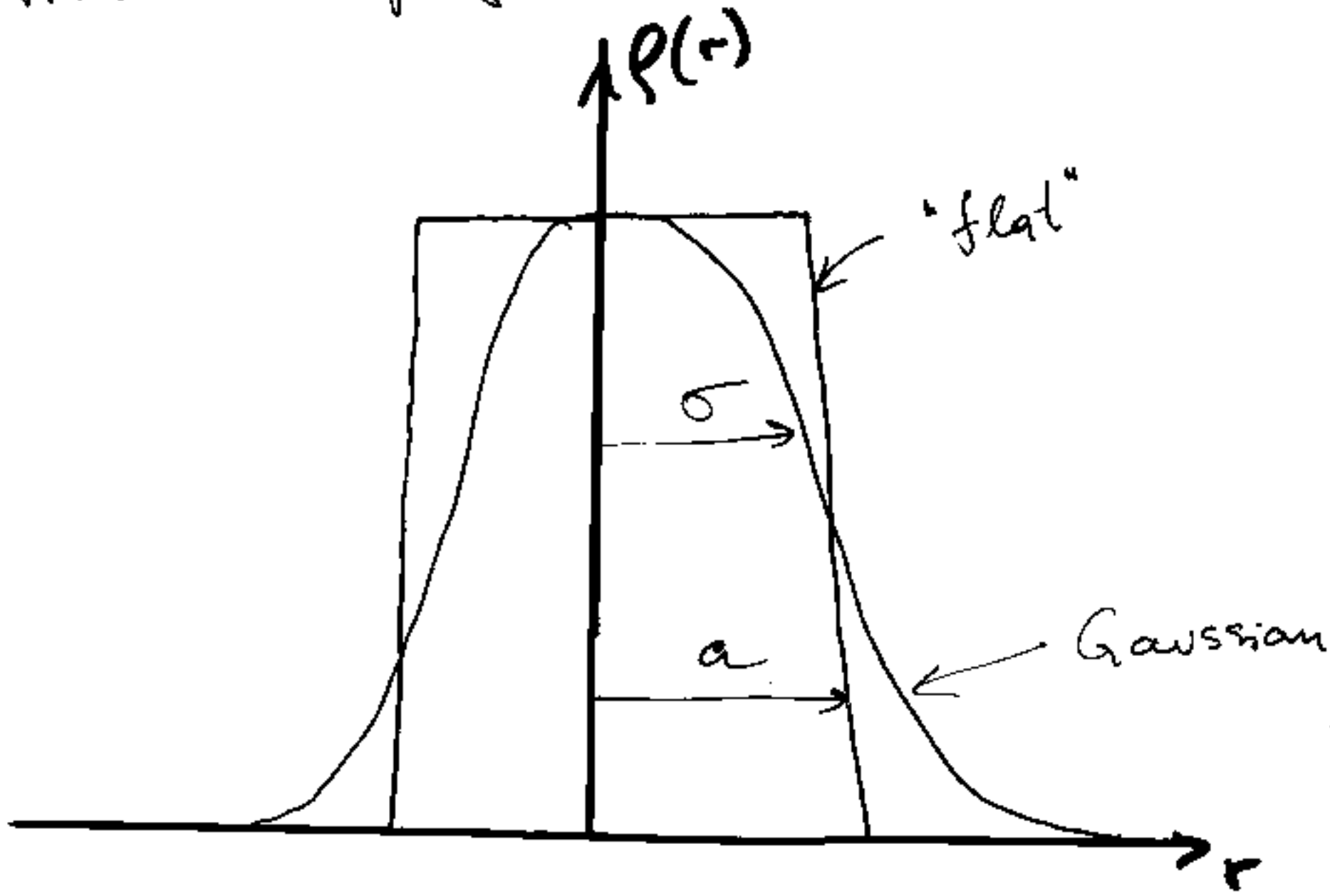
Fig. 2. The same as Fig. 1, but with the compensation $\alpha = 1/3$.
For this choice of the compensation, the dipole and the out-of-phase envelope mode cross their resonances simultaneously, which shows that for this working point the compensation is optimal. These crossings occur at $\Delta\nu_L = 0.6$, which number is 1.5 – 1.7 times higher than the threshold without any compensation, presented in Fig. 1. For other working points, this threshold is either pretty close to 0.6, or worse.

Conclusion:

At best, the space charge compensation could allow to increase the current threshold 1.5 - 1.7 times, not more (→ see, tune jumps idea in talk of A.Burov)

- an idea of dipole mode suppression by feedback
  → additional possibility ~2 times increase of threshold

(Q2) TRANSVERSE profile:



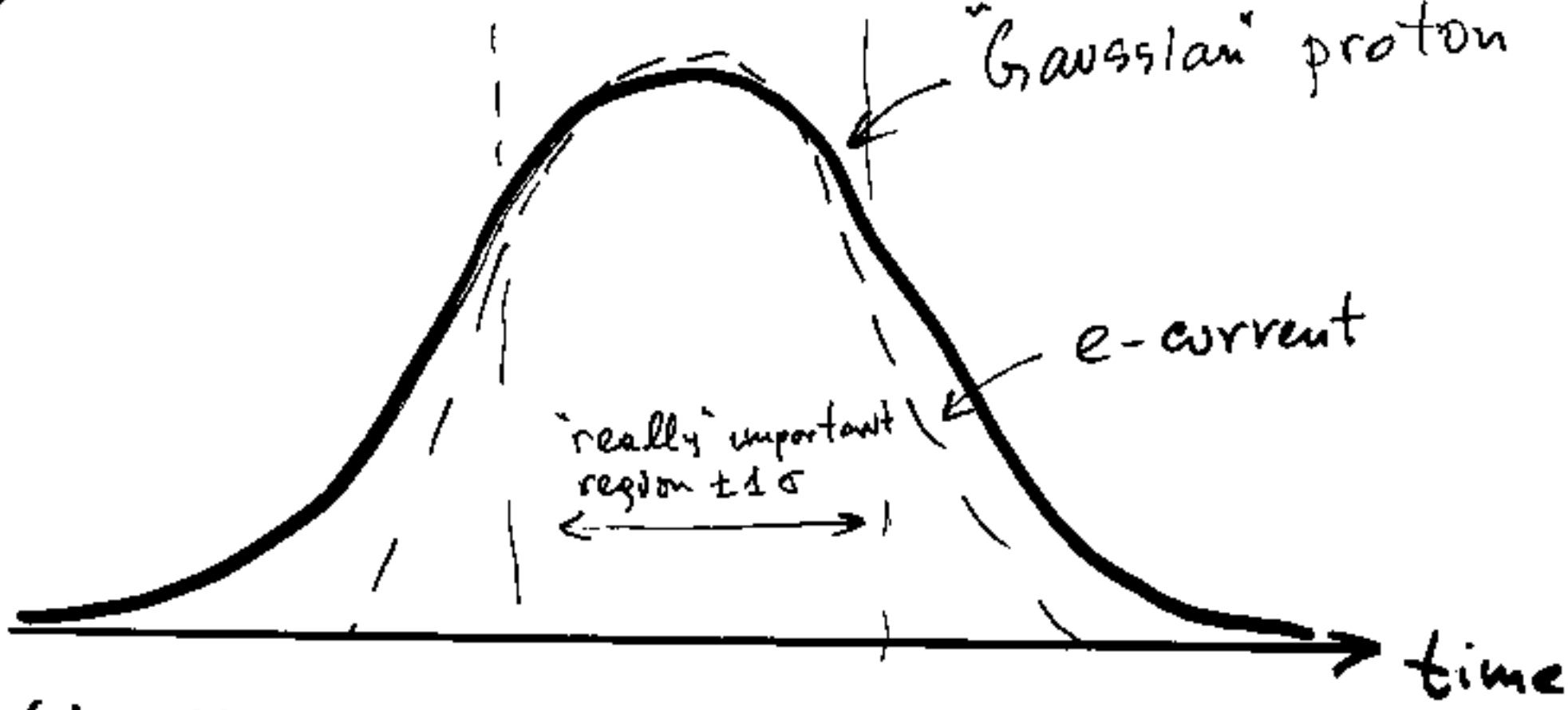
- $\rho(r)$ affects incoherent dynamics
- coherent modes: "+", "−", and dipole are NOT sensitive to the distribution details as far as rms values are THE SAME:

  e.g. $a^2 = 2\sigma^2$

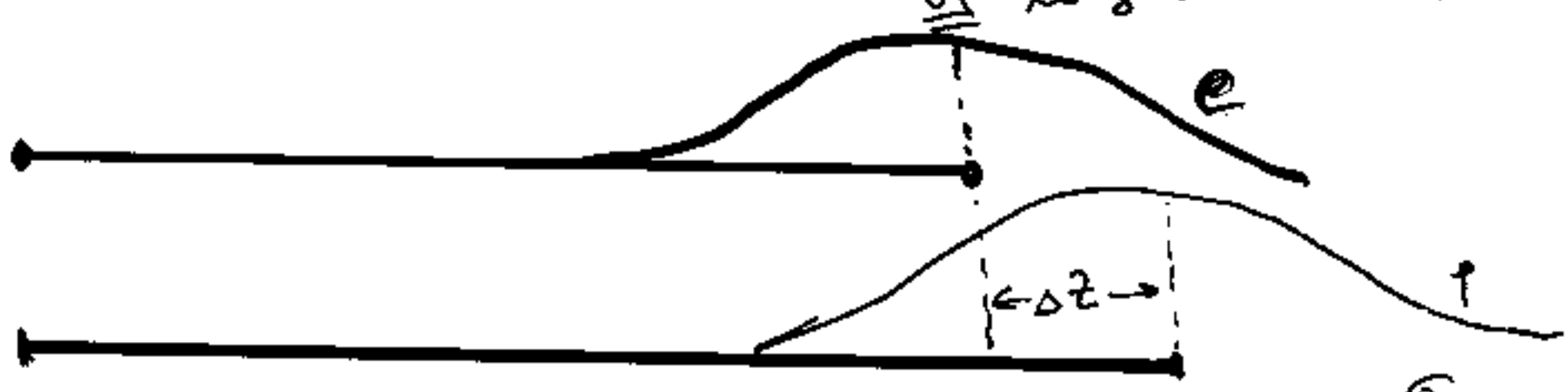
- from all WE KNOW NOW, THERE IS NO NEED to STICK WITH Gaussian ELECTRON beam profile
- simulations can answer THE QUESTION in MORE decisive MANNER

(... we "believe", THAT if we can easily obtain "SMOOTH" distribution, THAT it'll NOT MAKE THINGS WORSE)

Q3: Longitudinal profile of e-beam current



- $J(t)$ affects all modes
- seems to be beneficial to match electron and p-current profiles
- only simulations can answer in detail "how big mismatch allowed"
- from general considerations: matching is more important for center portion of p-bunch (as the portion stays closer to resonance), than for "tails"
- **direction of e-beam** → same as p-beam if long. matching is needed



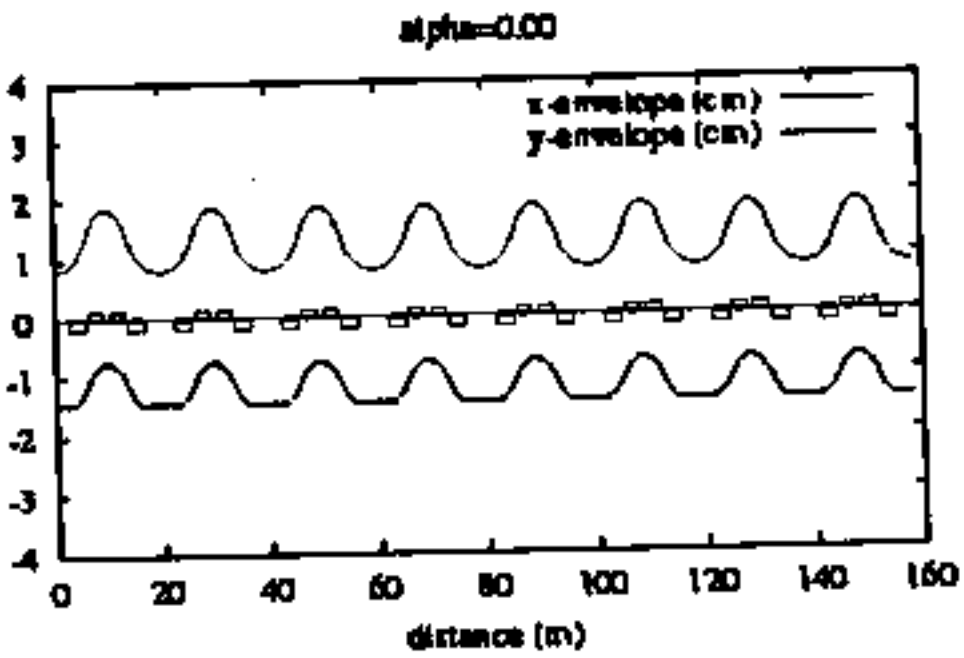
if we require $\Delta z < \sigma \rightarrow \frac{L}{\beta_p}(\beta_p - \beta_e) < \sigma \rightarrow |\beta_p - \beta_e| < \frac{\sigma}{L}\beta_p$

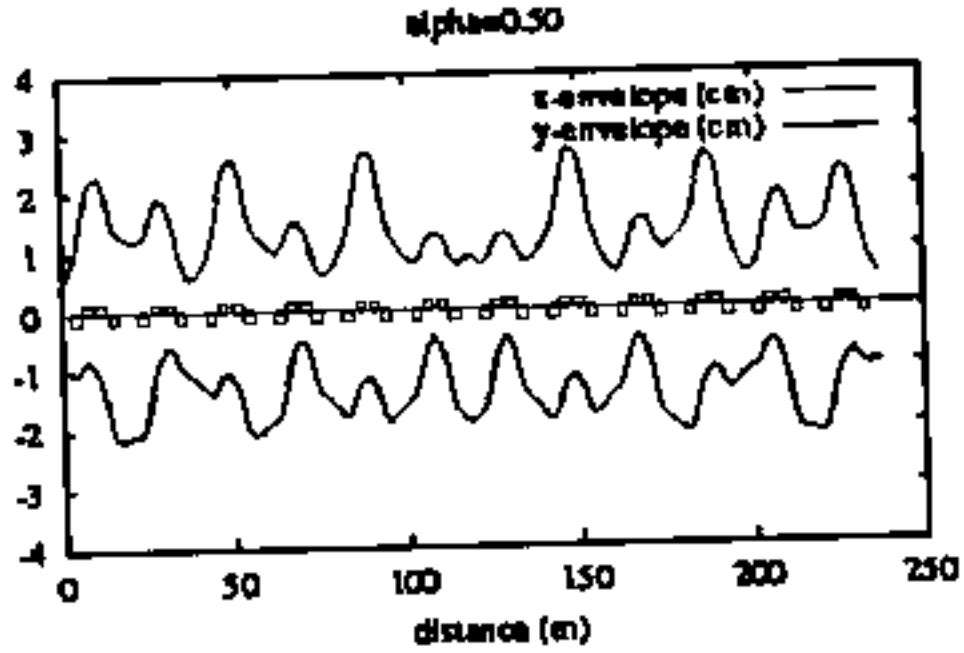
e.g. in Booster $\sigma \sim 1\,m$, $L \sim 4\,m$, $\beta_p = 0.7 \rightarrow \beta_e \approx 0.7\left(1 - \frac{1}{4}\right) = 0.52$ (69 kV)

R. Baartman

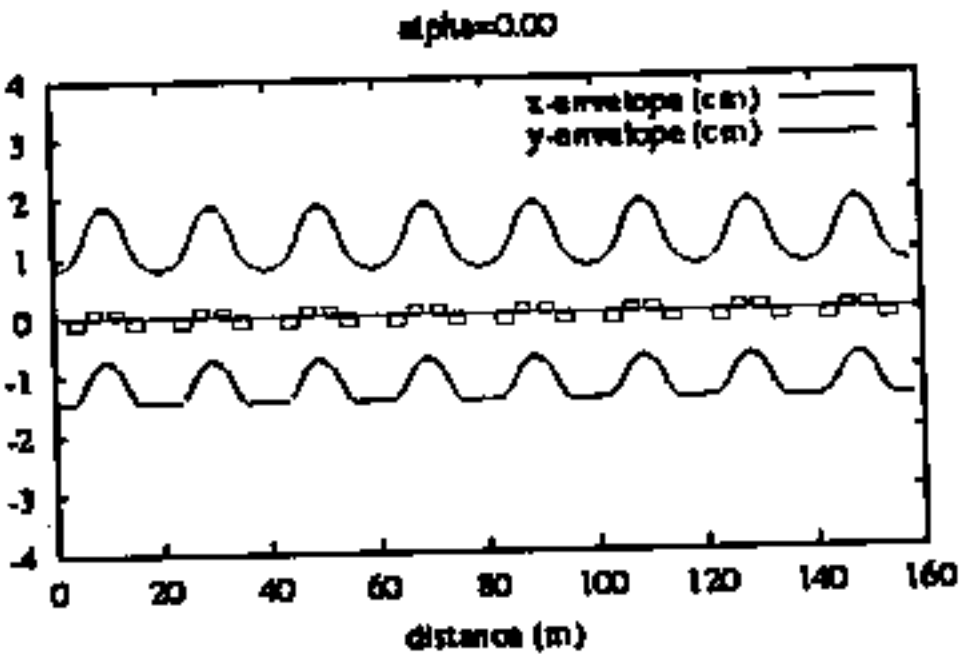
TWO Booster Electron Lenses

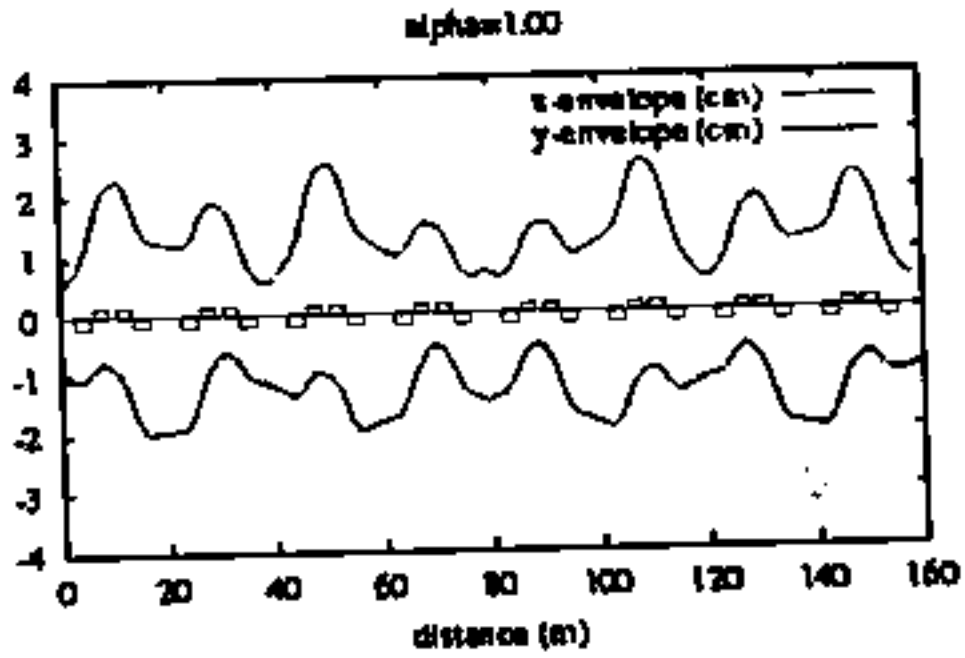
Booster Q_x,y=(6.70,6.80), Current=1.7Amps, x- and y-emittances are 10pimm-mrad (these are 4 times the raw emittance). Tune shifts (-0.386,-0.376).



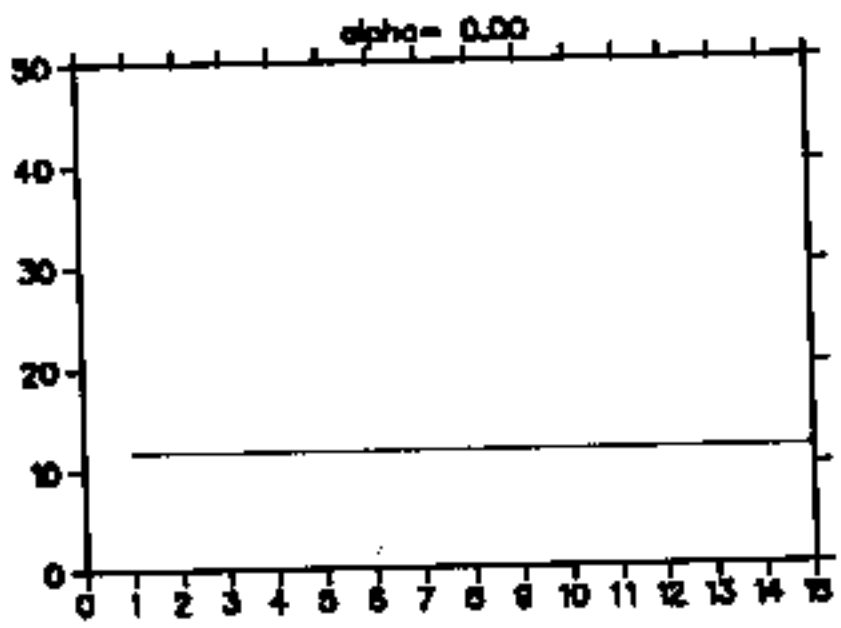


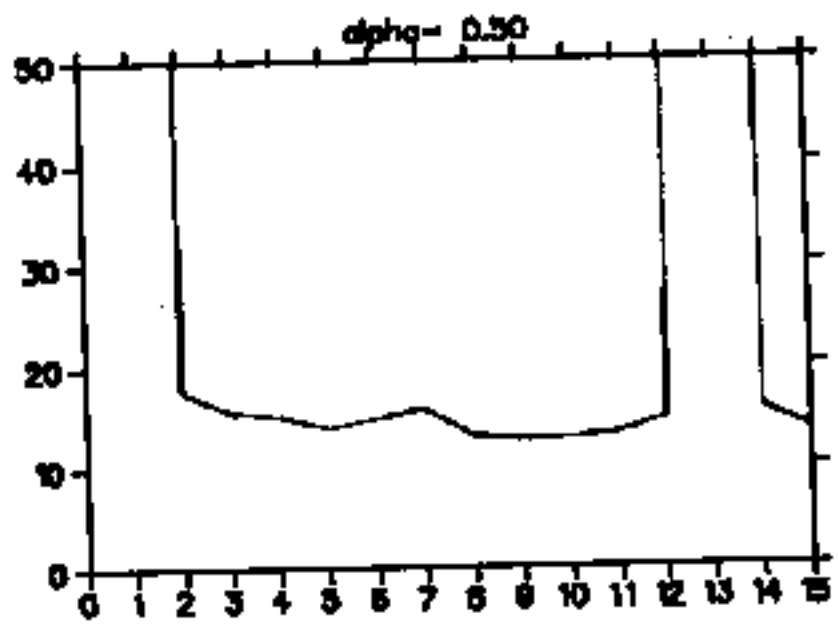
THREE Booster Electron Lenses





n- Booster Electron Lenses : max beta-functions with/without BELS





NUMBER OF e-LENSES N_L = ?

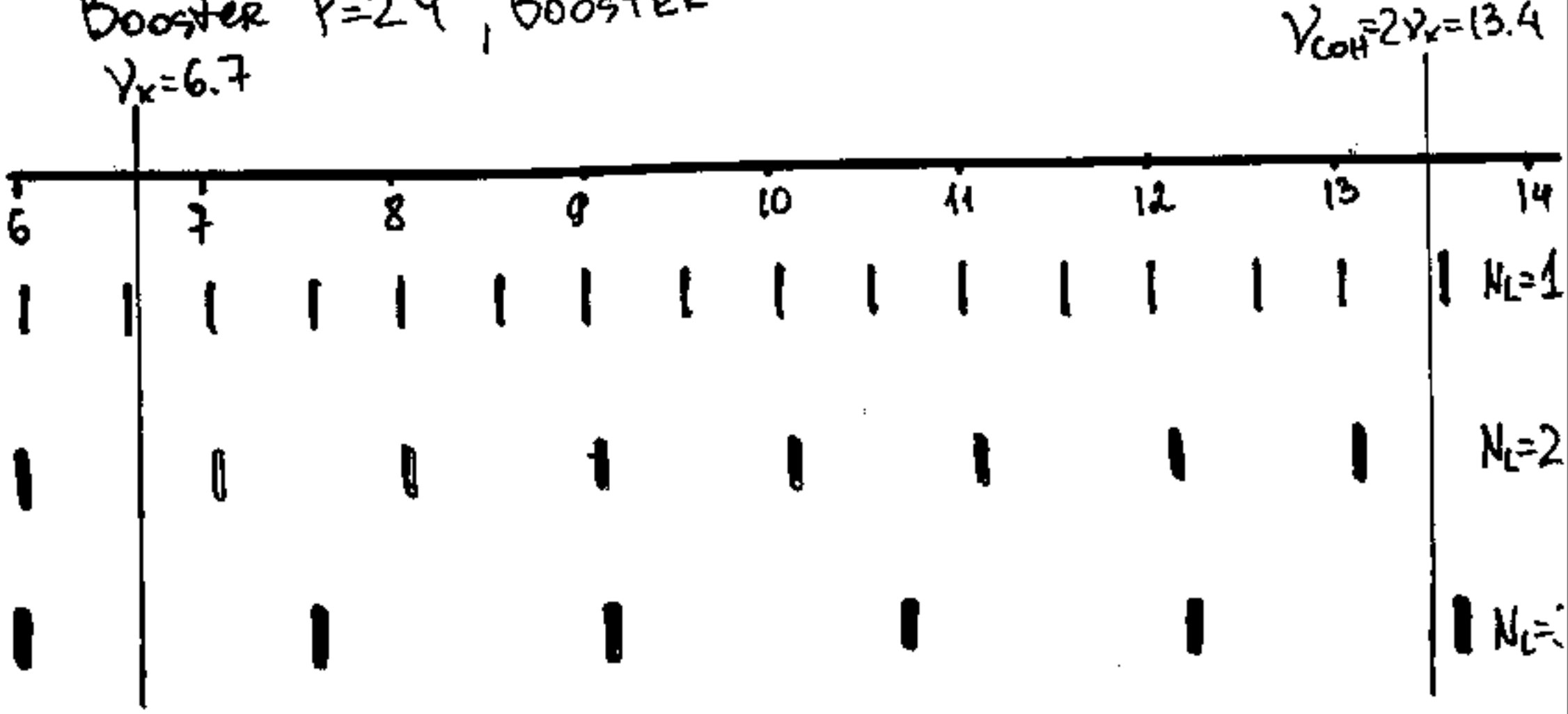
- from point of view of convinience + cost $\longrightarrow N_L = 1$
- from point of beam dynamics $\longrightarrow N_L$ = large (say 24 for Booster)
- optimum N_L choice depends on what resonances one wants to avoid

if focusing lattice consists of **P** identical periods

then the strogest linear resonances (int + half int)

occur at $$\nu_{coh,inc} = \frac{P \cdot m}{2}, \quad m\text{-integer}$$

Booster $P=24$, Booster with N_L lenses $P = N_L$



So, $N_L = 3$ — "minimal model"

(Q5): PARAMETERS

- Parameters depend on what we'd like to achieve
  1. reduce losses in Booster with existing intensity & emittance
  2. double the intensity/pulse — twice the e-current
  3. reduce ϵ_N blow up $\times 0.5$ — $\sim 2\times B_{main\ solenoid}$
  4. both (2) & (3) — $2\times J_e$, $2\times B_{main\ solenoid}$

We are asked to consider <u>only</u> GOAL #1 (R. Webber, Oct. 06)

Now, assuming we need modulated e-beam with Gaussian transverse profile, we get

$$\Delta\nu_e = -\alpha\cdot\Delta\nu_{sc} \rightarrow \frac{\beta_x}{4\pi}\,\frac{J_e\cdot L_e\cdot r_p(1-\beta_e\beta_p)}{e\beta_e c\,\sigma_e^2\gamma_p\beta_p^2}\cdot N_L = -\alpha\cdot\frac{N_{tot}\cdot r_c\cdot B_f}{4\pi\,\epsilon_n\beta_p\gamma_p^2}$$

- TRANSverse profile matching $\sigma_e=\sigma_p=\sqrt{\epsilon_n\beta_x/\gamma_p\beta_p}$ (e.g. 6.3 mm @ inj, $\epsilon_n = 2\,\mu m$)

$$J_e^{max} = (\alpha B_f)\cdot\frac{eN_{tot}}{N_L\cdot(L/c)}\cdot\frac{\beta_e}{\gamma_p^2(1-\beta_e\beta_p)}$$

- FOR Booster @ inj $\alpha = 1/3$ $B_f^{max}\simeq 3$ $\beta_p = 0.7$ $\gamma_p = 1.4$ $N_{tot} = 5e12$
  $N_L = 3$ $L = 4m$ $\beta_e = 0.52$

$$J_e^{MAX} = 8.3\,[A]\times\underbrace{(\alpha B_f)}_{=1}\times\underbrace{\left(\frac{N_{tot}}{5e12}\right)}_{=1}$$

in each of 3 RFLL = Booster Fillers

MAGNETIC FIELD

E-beam is born in magnetic field and transported in (adiabatically changing) magnetic field → adiabatic invariant = const

$$B_{cathode} \cdot \sigma^2_{cath} = B_{main\ sol} \cdot \sigma_e^2$$

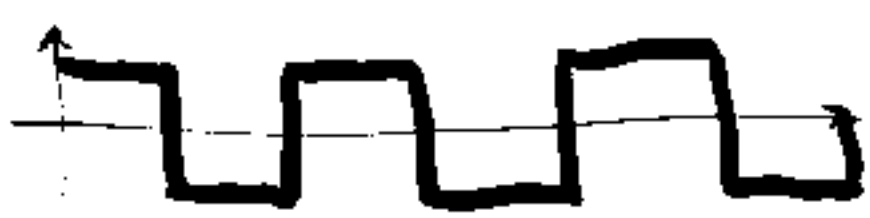
$$\sigma_e^2 = \beta_x \cdot \epsilon_n / \gamma_p \beta_p \approx 20\,m \cdot 2 = 40\,mm^2$$

$$B_{MS} = B_{cath} \cdot \frac{\sigma^2_{cath}}{\sigma_e^2} = \frac{1.9\,kG}{[\beta_x / 20\,m]}$$ ← See Carol how to get $\beta_x = \beta_r$

introducing "safety factor" of 2, we look into magnetic system design with $B_{MS}^{max} = 4\,kG$

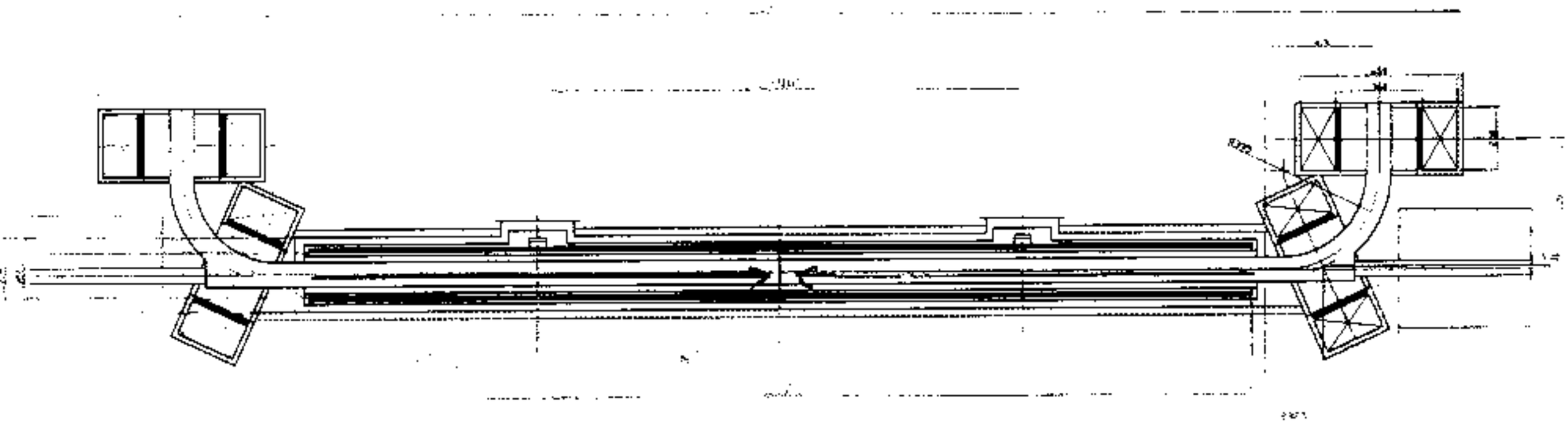
- To avoid x-y coupling → $\int B_z dz = 0$ $\quad B_{MS}^{max} \cdot L = 4 \cdot 4 = 16\,kG \cdot m$
  → two compensating solenoids $L_{cs} = 0.5\,m$
  with $\underline{B_{cs} = 16\,kG}$

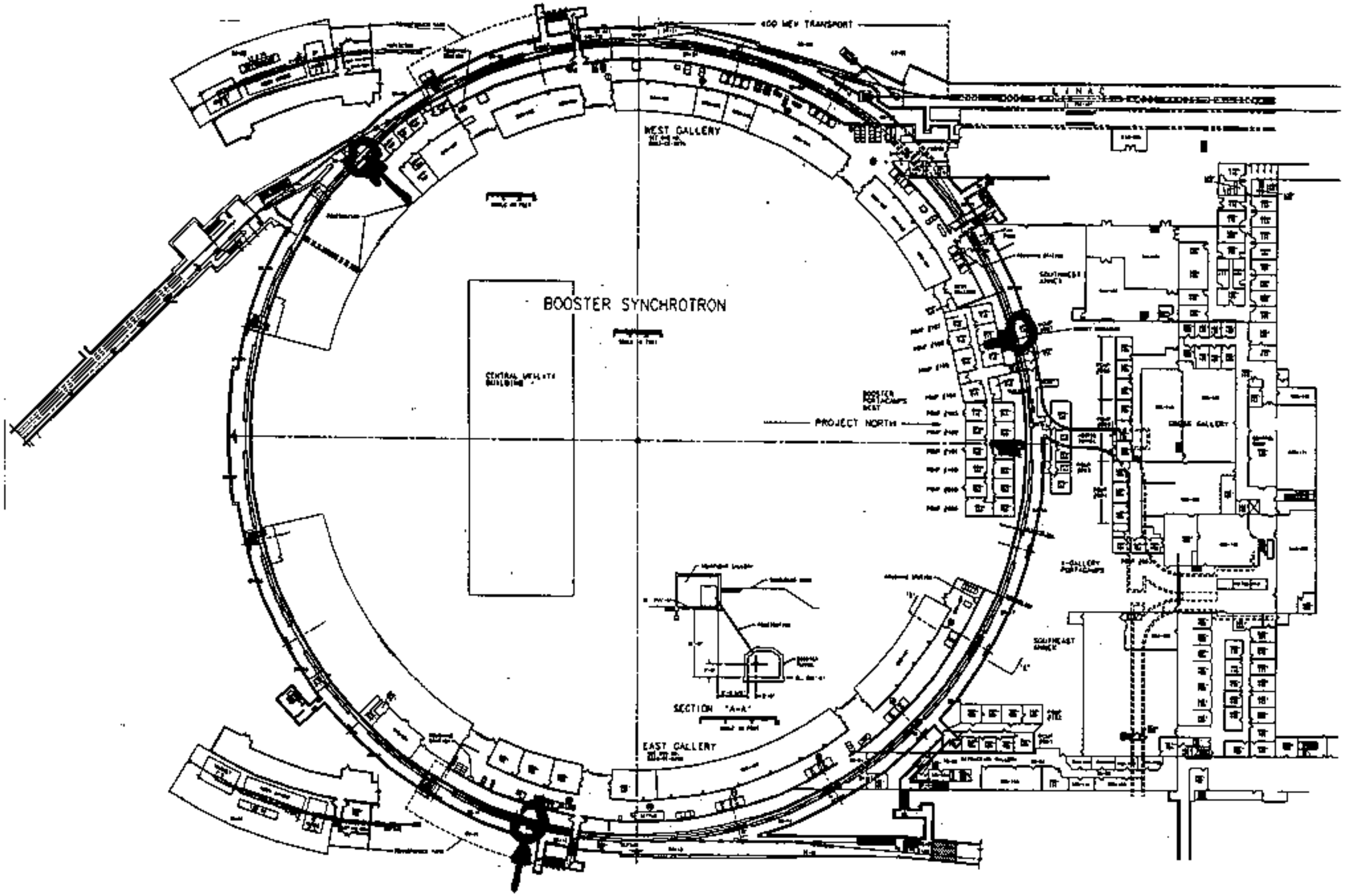
→ [illegible] alternative solenoids



BELL = booster Electron Lens:

- ELECTRON current ~20 A @ 50 kV
- LENGTH 4.0 m
- MAIN SOLENOID FIELD 4 - 16 kG
- SIDE SOLENOIDS 2 - 4 kG
- ELECTRON current duration 5 ms
  rep. rate 15 Hz (max)



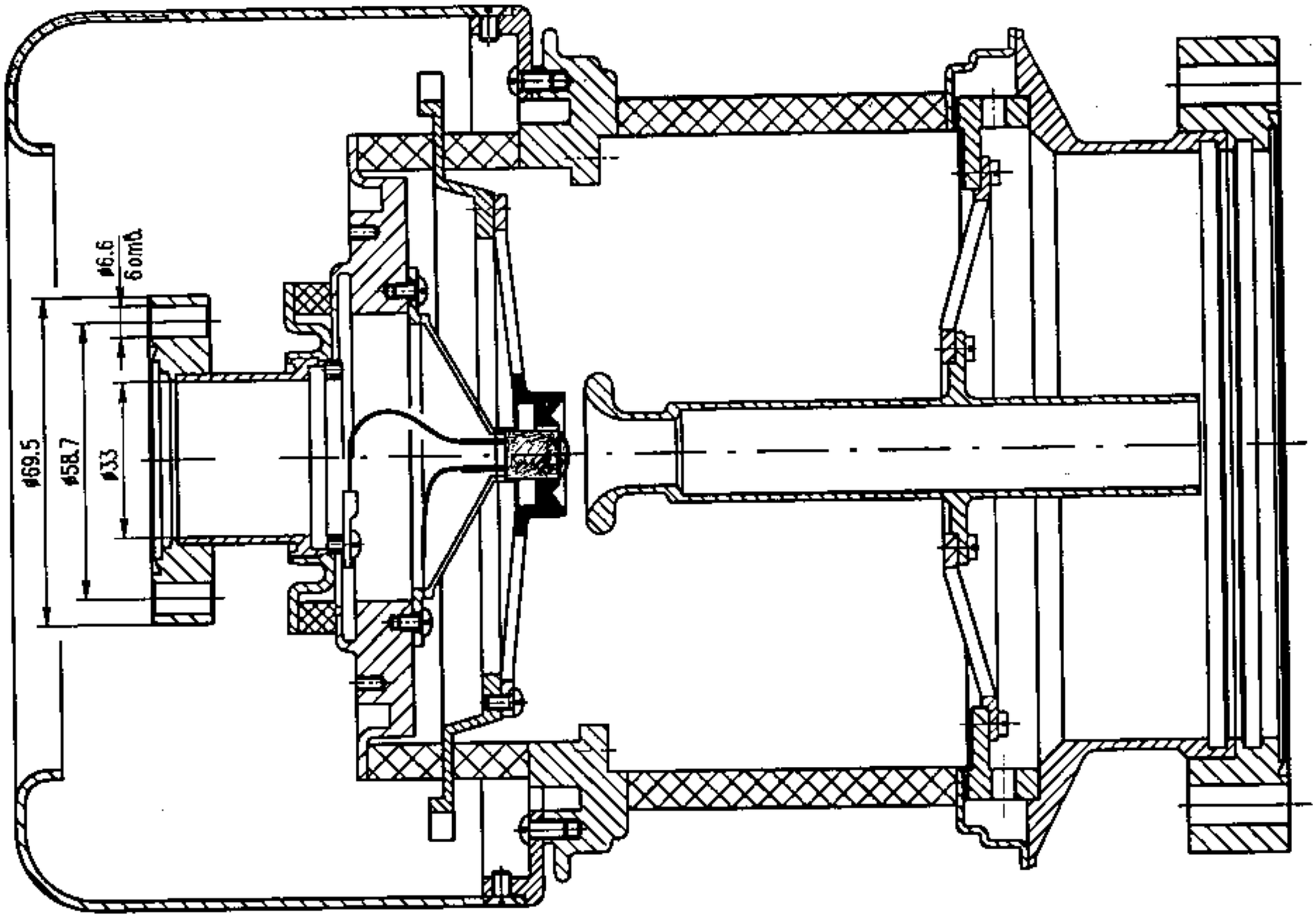

400 MEV TRANSPORT
LINAC
WEST GALLERY
BOOSTER SYNCHROTRON
CENTRAL UTILITY BUILDING
PROJECT NORTH
SECTION "A-A"
EAST GALLERY
SOUTHEAST ANNEX

MAGNETS FOR BOOSTER ELECTRON LENS

	Main(each)	Side1	Side2
Length, cm	200	25	25
Inner radius, cm	9	18	18
Outer radius, cm	9.3	32.5	32.5
Central field, kG	4	4	4
Current, kA*turns	2700	135	135
Curr.dens, A/mm^2	440	3.7	4.3
Angle, grad	0	22.4	90
Stored energy, kJ	25	3.1	4.1
Power, kW	0	42	55

Conventional "warm" magnets

Length, cm	320		
Inner radius, cm	6		
Outer radius, cm	12		
Central field, kG	4		
Current, kA*turns	1024		
Curr.dens, A/mm^2	5		
Angle, grad	0		
Power, kW	≈80		
Oper.current, A	800		
#Water contours	≈12		
Weight, kG	≈1500	≈200	≈200



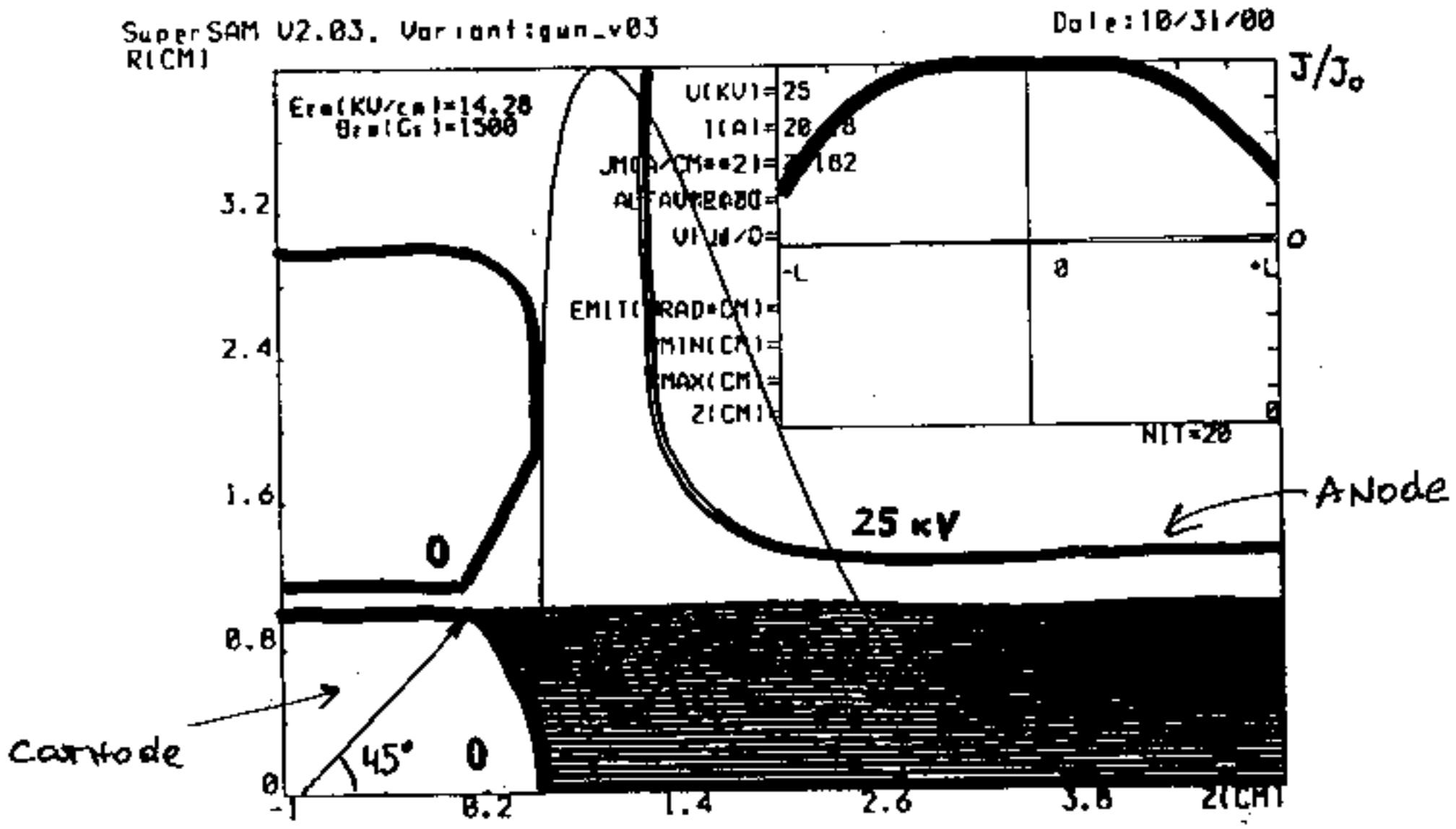
3: Electron gun with convex cathode and perveance of $\mathcal{P} = 5.6\mu A/V^{3/2}$ [5].

! HOW TO GET THE current

See Talk of N. Solyak

Gun with Convex Cathode

Child's law $J_e = P \cdot U_{a-c}^{3/2}$



"Safety factor" $\Phi > 2$

$$\begin{cases} a = 10 \text{ mm} \\ U_{cath} = -25 \text{ kV} \\ \text{Current} = 20 \text{ A} \\ B_{min} = 1.5 \text{ kG} \end{cases}$$

$\mu P = 5.06$

$J = 8.3$ A @ $U = 14$ kV

- THIS technique is proven in TEVATRON e-lens gun $\mu P = 6$, $J^{max}_{pulsed} \sim 13$ A
- A. Shemyakin will present another approach for $\mu P \sim 20$ (reduction in U_{cath} → voltage and power at modulator)

Booster Electron Lens

	Booster e-Lens	Tevatron 1st e-lens
main solenoid length	3.87 m	2.50 m
total length	5.63m	3.67 m (v-v)
No.lenses/ring	3	2
configuration	2 bends	2 bends
e-energy	70 kV	17 kV
max e-current	8.3A (20max)	2-8 A
anode voltage	14 kV(25)	10-13 kV
current stability	< 1%	<0.1%
current modulation	26 ns	396 (132) ns
cathode radius	10 mm	5 mm
e-beam radius	rms 6.3 mm	1.5 mm
area compression	<2	16-25
B field solenoid/gun	1.9/1.5 kG	65/4 kG
B straightness, rms *	0.5 mm	0.05 mm
beam shape control	yes?	yes
vacuum	≈10^-8 Torr	<10^-9 Torr

Space Charge Compensation in Booster-still unanswered "simple" issues:

1) suppress coherent dipole mode by feedback

2) accuracy of transv and long matching

3) $\beta x \neq \beta y$ issues

4) effects of longitudinal forces

5) computer simulations

6) wobbling of p-bunch (transv,long)

7) Booster beam studies: coupling, lattice non-symmetry, dQ(t), fast BLM

8) need of the e-current jumps

Essential features required of BELL magnetic system:

1) provides 2kG (operational) to 4kG (max) longitudinal field in the region of the e-gun cathode

2) brings the e-beam to interaction region adiabatically

3) 2kG to 4kG longitudinal magnetic field in the 4m (as long as possible) interaction region
   - field line straightness < 0.25σ=1 mm
   - two (or more) compensating solenoids $\int B_z dz=0$
   - 6 correctors: injection coordinates X,Y ±2cm
     extraction X,Y ≈ ±2cm
     angles at IR X',Y' ≈ ±5mrad
   - (optional) beam shape variation if $B_z(z)$

4) brings e-beam to the collector

5) fits Booster long straight section v-v≈5.1m

Cost Projection for Booster SC Compensation with 3 BELs (k$) for 50-100% increase in output N_p

	SC Magnets	Warm Magnets
Magnetic system:	1095	935
Design	60	40
Fabrication	600	450
Cryocoolers	210	-
QPS	60	-
Tests/magn.meas	15	15
Power supplies	120	340
Installation	30	90
Vacuum system:	145	
Electron beam system:	570	
e-guns	60	
e-collectors	60	
diagnostics	45	
HV modulators	300	
HV PSs	105	
TOTAL	1800	1650

Proposed Schedule/Plans:

1. Most time consuming: Magnets design - 6 mos
   Fabrication - 12 mos

2. Seems possible (having $$ and people) to have 1 BELL installed/operational in Jan, 2004; then 2 more BELLS on Aug, 2005

For that:

Year'02: Computer simulations are done - May
Major parameters fixed - May
Booster SC studies completed - May
80k$ e-beam test in Linac lab done - May
Review in June 2002
60k$ Design of solenoids June - Dec

Year'03: Fabrication of 2 Solenoids - Dec
500k$ Fabrication of the rest - Dec

Year'04: Test of the 1st BELL Jan - May
Review in June 2004
600k$ Start fabrication of 2 TELs - Aug

Year'05: fabrication of "the rest" - June
500k$ installation/operation - Aug.