Summary

1. Three or more e-beam section (5m each) with half compensation can suppress emittance growth.
2. Precise alignment of e-beam (<1mm) is a must.
3. Effects of e-beam distribution (different from proton) should be investigated.

Theme

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Simulation results of space charge compensation with electron beams

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Abstract A space charge compensation scheme with a localized electron beam travelling with protons is studied with a numerical tracking code SIMPSONS [1]. The results show that a electron beam matched to the proton distribution can suppress emittance growth due to space charge effects. We have looked at the emittance growth and coherent quadrupole tune as a function of electron beam current and an offset of electron orbit.

1. Model lattice

As a test lattice, KEK Proton Synchrotron (PS) is chosen. The superperiodicity is 4 and the designed bare tune is (7.11, 7.24) so that there should be no lower order structure resonances around the bare tune except 2vx-2vy=0. However, in order to see the space charge effects due to lattice errors, 4 localized quadrupole errors are introduced, which excite the half-integer resonance at vx,y=7 with the resonance width of 0.02. Furthermore, the vertical bare tune is moved down to 7.08 such that the depressed tune hits the resonance of vy=7 with relatively lower intensity than usual.

The beam intensity is set to be 1×10^{12} ppp. In fact, the calculation is done here taking a coasting beam approximation. That is we look at the slice of bunch center only with bunching factor of 0.25. The initial normalized rms emittance of both transverse plane is 2.32 pi mm-mrad in horizontal and 0.58 pi mm-mrad in vertical, respectively. Since the injection energy of KEK PS is 500 MeV, the incoherent space charge tune shift becomes

$$\Delta\nu_x = -\frac{n_t r_p}{\pi\beta\gamma^2\varepsilon_x\left(1+\sqrt{\varepsilon_y/\varepsilon_x}\right)B_f} = -0.079$$

$$\Delta\nu_y = -\frac{n_t r_p}{\pi\beta\gamma^2\varepsilon_y\left(1+\sqrt{\varepsilon_y/\varepsilon_x}\right)B_f} = -0.158$$

which is large enough to see the space charge effects due to 2vy=14. The initial distribution is Gaussian.

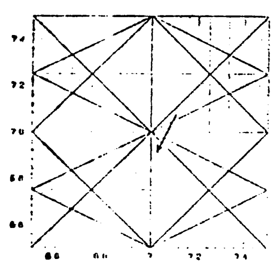
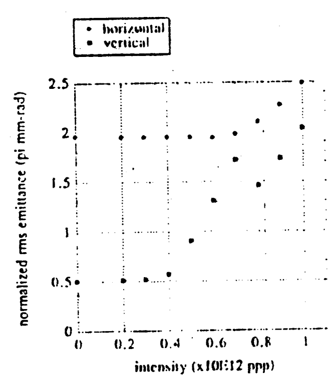


Figure 1: Tune diagram of KEK PS and its bare tune assumed in the simulation. The allow indicates the incoherent tune shift when the beam intensity is 1×10^{12} ppp.

2. Emittance growth due to space charge effects

Before studying the compensation scheme by electron beams, we have looked at the emittance growth due to space charge effects as a function of beam intensity. Throughout this paper, we define emittance as the value after 256 turns tracking without a momentum ramping. In most cases, emittance is not saturated in 256 turns but it is enough to see the effects.

Figure 2 shows the emittance as a function of beam intensity. Above 0.4×10^{12} ppp, the vertical emittance starts blowing up while the horizontal one stays constant. The horizontal emittance becomes larger also above 0.8×10^{12} ppp. The cause of emittance growth, at least of vertical plane, is explained by the resonance of a coherent quadrupole mode [2]. When the beam intensity is increased, coherent quadrupole tune is decreased as shown in Fig. 3. The resonance occurs for a whole beam when the coherent tune becomes integer. According Sacherer's calculation [2], the coherent quadrupole tune shift is 2x5/8 of the incoherent tune shift and that is shown in Fig. 3 (Δvy_coh=-0.20/1×10^{12}).



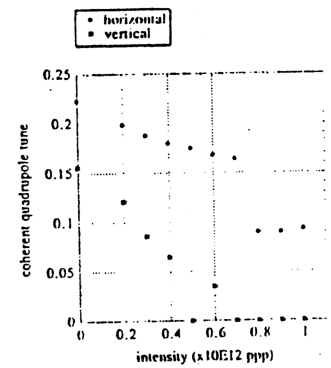


Figure 2 (left): Emittance as a function of beam intensity.
Figure 3 (right): Coherent quadrupole tune as a function of beam intensity.
The slope is about Δvy_coh=-0.2/1×10^{12} and it agrees with Sacherer's calculation,
that is 2x5/8x(incoherent tune shift=-0.158).

3. Compensation with electron beams

In order to study a space charge compensation scheme with electron beams, we take the following model. In a section of the KEK PS ring whose length is 34 m, that is one tenth of the circumference of 340 m, we assume an electron beam are traveling with protons. The electron distribution is the same as the proton so that, in principle, a space charge field of electrons can cancel that of protons exactly. In order not to cancel space charge field of proton only in that section, but to cancel in a whole ring, electron intensity is further increased. When a space charge field of electrons is nine times stronger than that of protons in that section, the overall space charge effects of protons should be cancelled. That is an underlying idea. In a code, that is simply realized by applying a nine times attractive force instead of a calculated repulsive space charge force in that section.

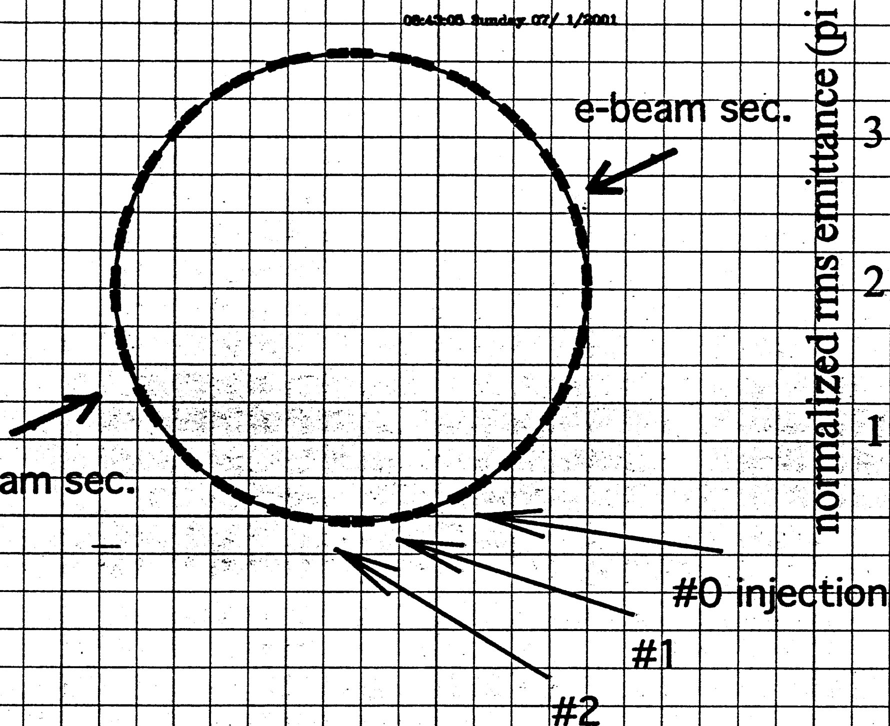
Figures 4 and 5 show the simulation results. We defined "effective intensity" that is,

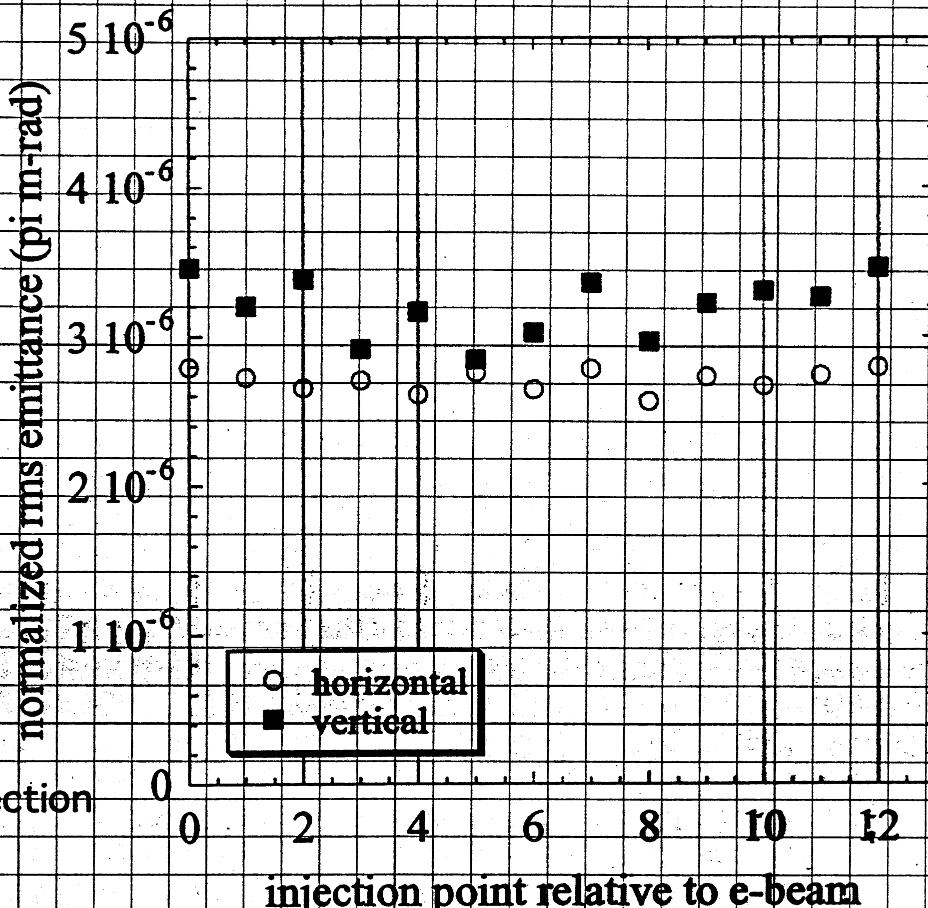
$$I_{eff} = |(1-f) - kf|\,I$$

where f is the fraction of ring where a electron beam is merged (one tenth), k is the ratio of a space charge field of electrons and protons, and I is proton intensity. We make k always positive value and put minus sign in front. When

Initial Mismatch

e-beam sections	2
compensation f.	0.3
proton current	1.2 A





Beta function is distorted, but initial mismatch is not the primary cause of the growth.

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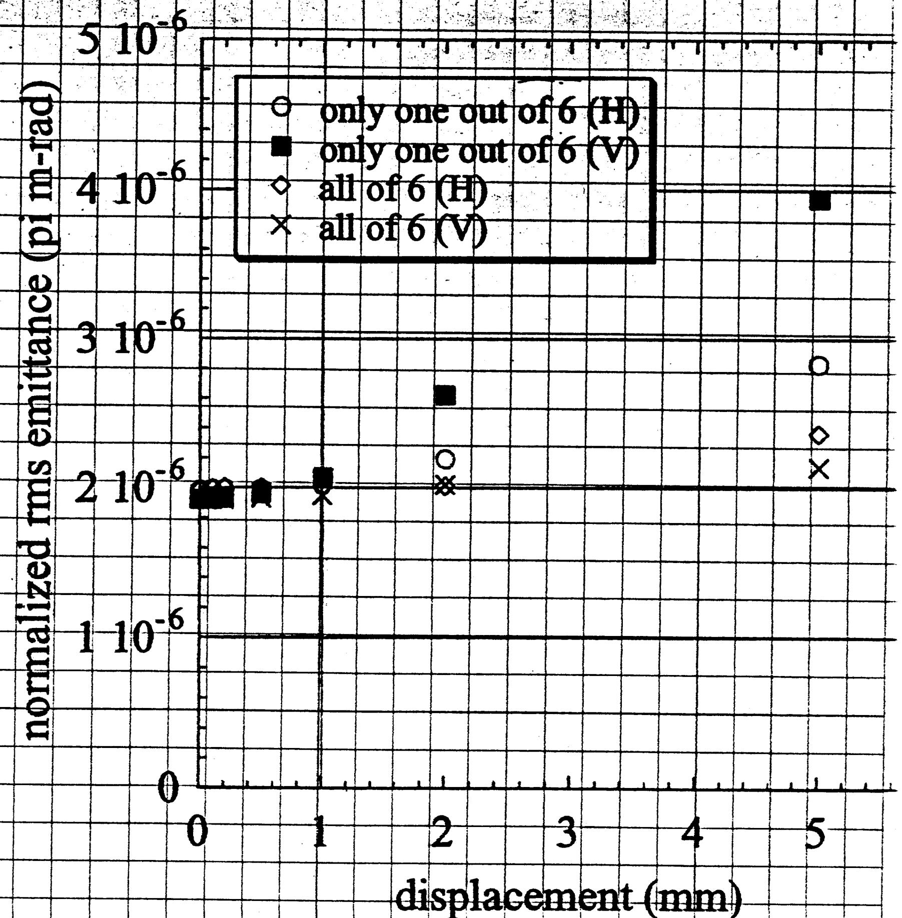
Effects of e-beam Misalignment in vertical

e-beam sections	6
compensation f.	0.5
proton current	1.2 A
rms beam size at e-beam	
horizontal	3.2 mm
vertical	5.9 mm



If the displacement of all e-beams is the same, which is not realistic, the effects is small. In reality, there should be random misalignments, that may distroy the compensation.

--> precise alignment is a must.

Beam Parameters

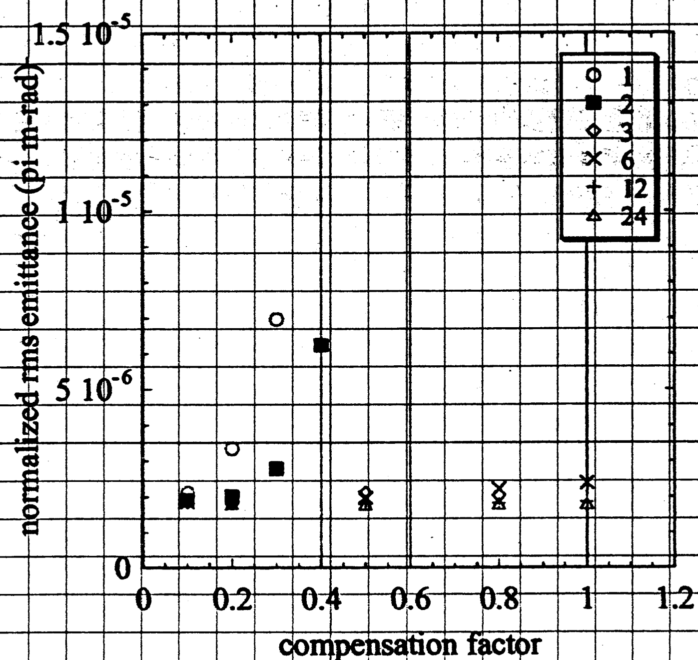
normalized rms emittance	1.75e-6 pi m-rad
transverse distribution	waterbag
momentum spread (rms)	+-0.2%
momentum distribution	parabolic
kinetic energy	400 MeV

2D model with Simpsons

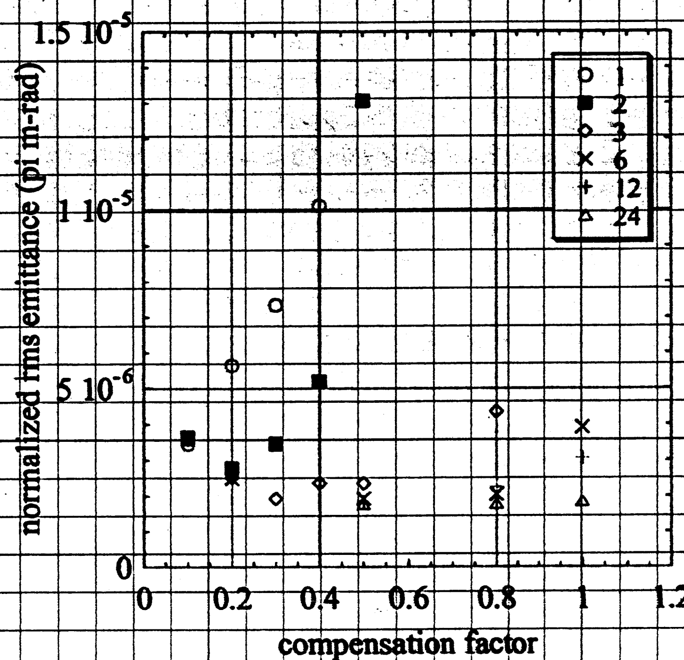
130 turns after injection

Necessary Number of e-beams and its Strength

horizontal



vertical



One section of e-beam compensation (5m out of 474 m) makes more grow

Two with small compensation (comp. fac. 0.2) works a little, but larger compensation makes worse.

Three and more with a half compensation are necessary.

Intensity Dependence

proton intensity

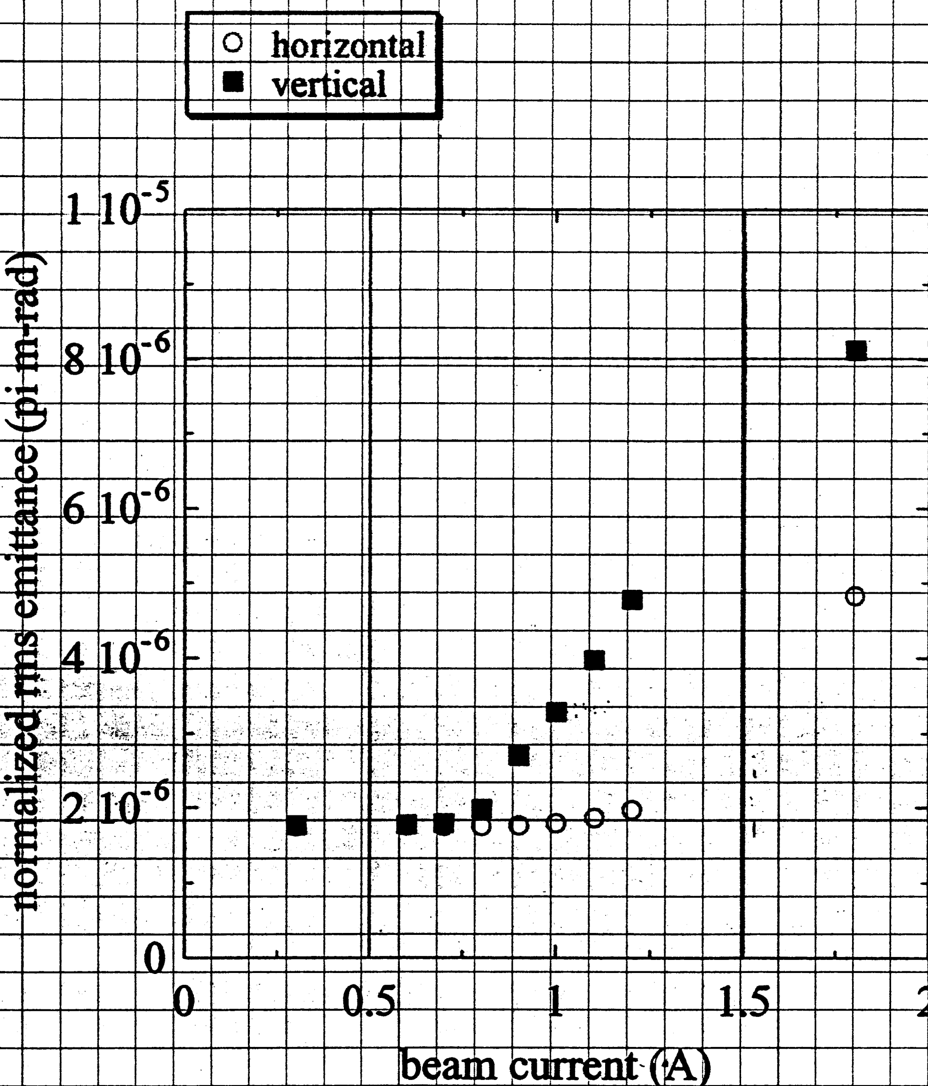
1 A = 4.2E12 ppp

bunching factor

0.3

inc. tune shift

$\Delta\nu = -0.33$



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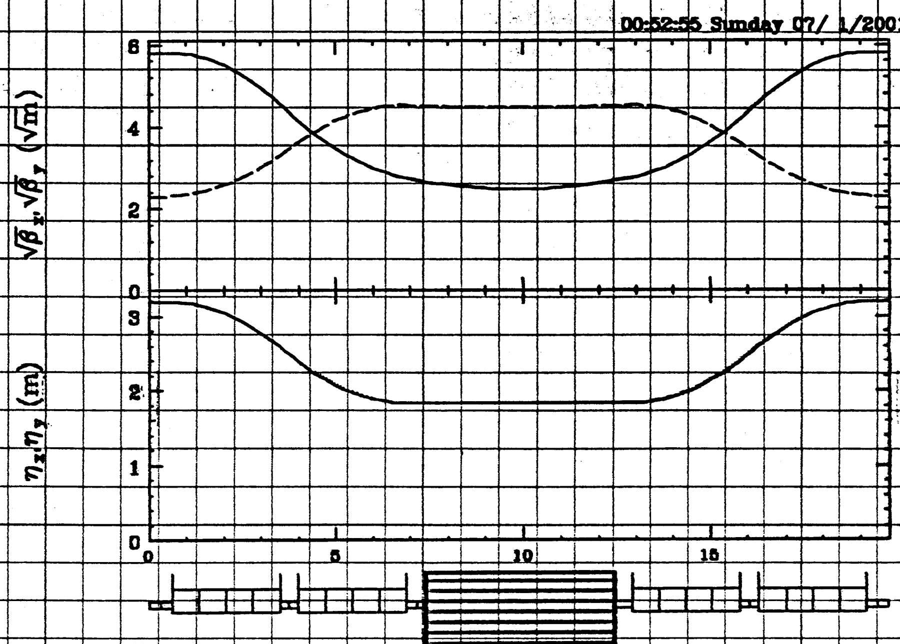
Space Charge Compensation with e-beam

idea by Vladimir Shiltsev et. al.

Let us assume there are several 5 m e-beam sections in 24 long straights.

24 straights
12
6
3
2
1

Also assume the e-beam has the same distribution as proton.
Effects of misalighment will be discussed later.



e-beam sec.

Simulation Study of Space Charge Compensation with e-beams

idea by Vladimir Shiltsev et. al.

Shinji Machida

July, 2001 @ snowmass

Theme

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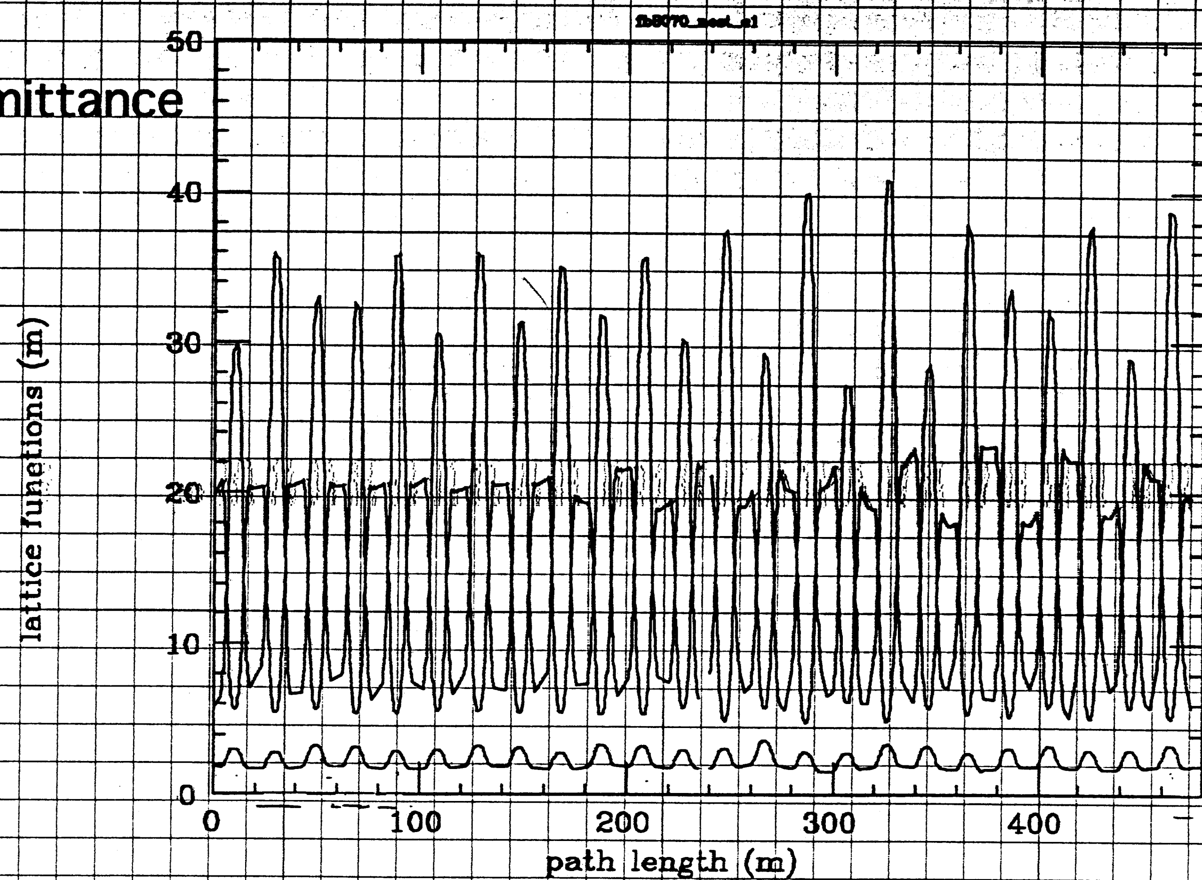
A Model of Fermilab Booster

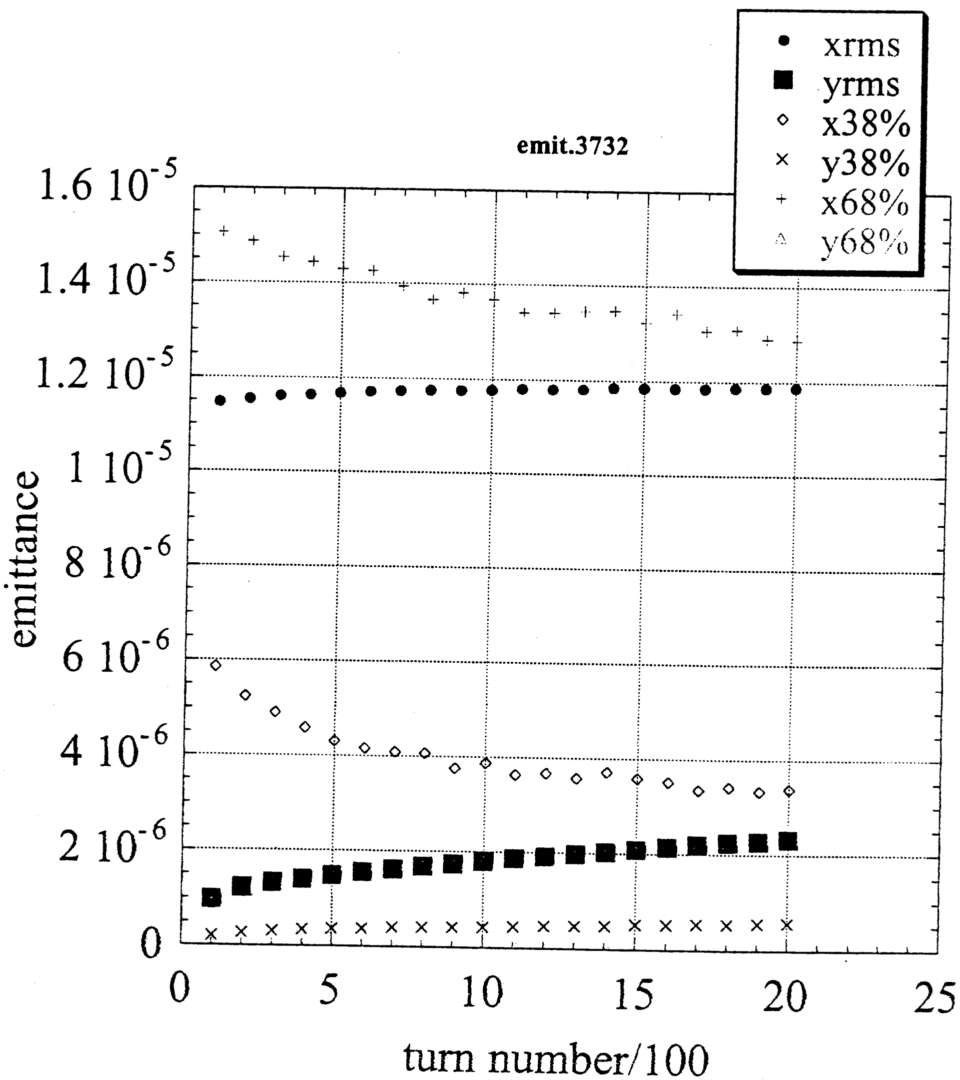
24 cells

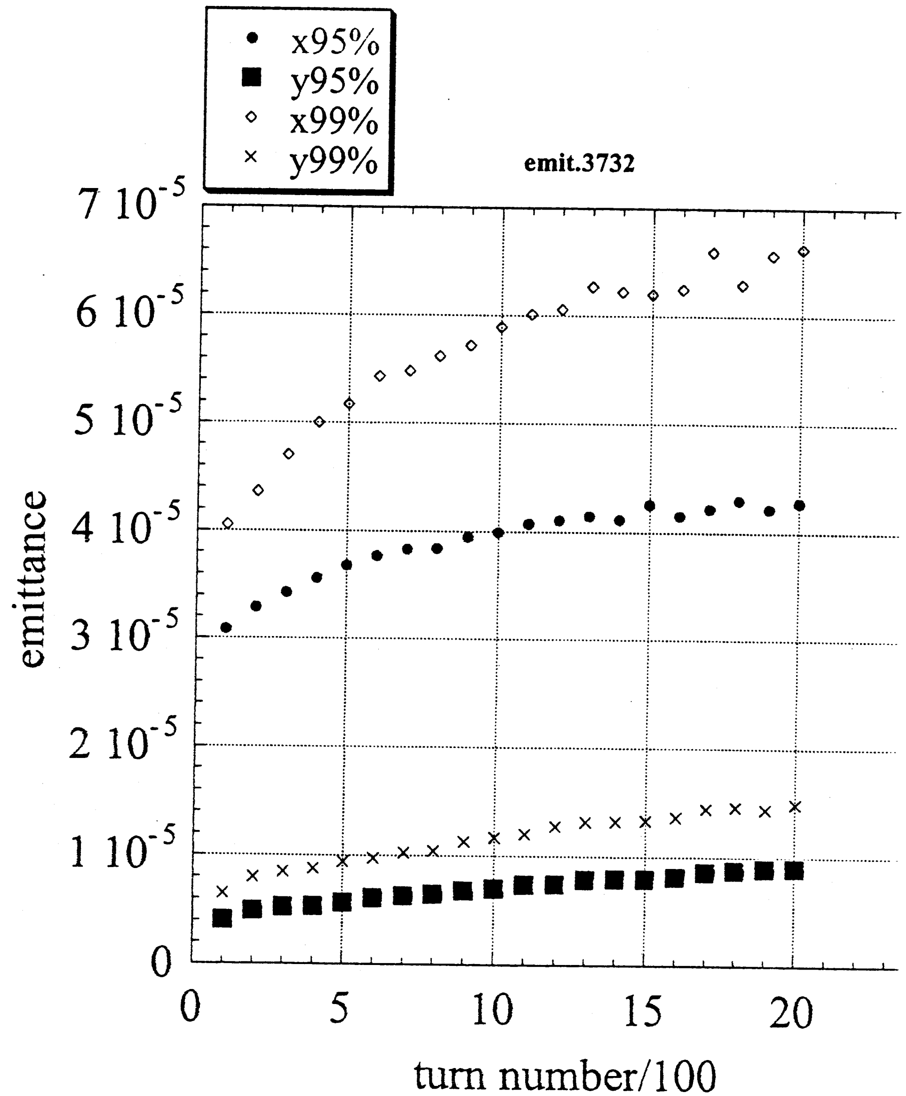
bare tune (6.80, 6.70)

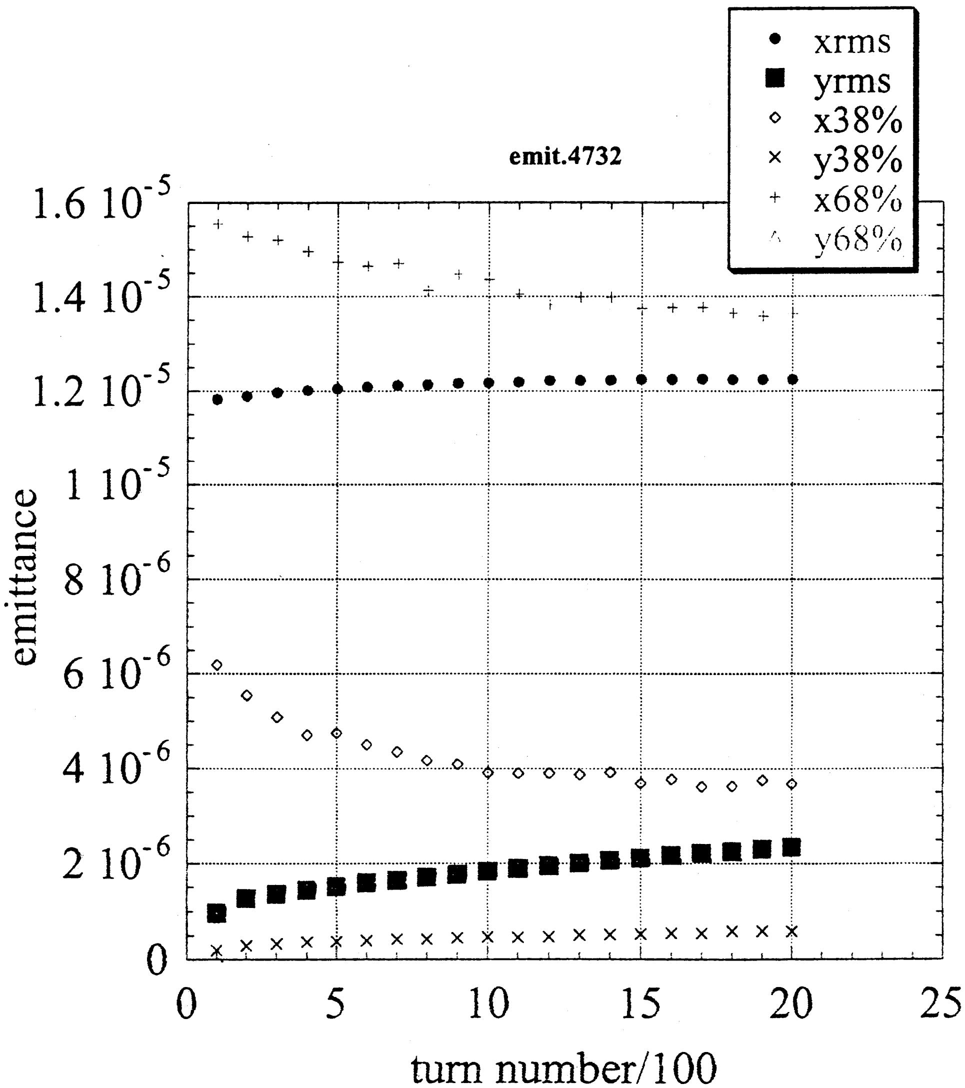
quadrupole errors makes (-0.02, +0.01)

major source of the emittance growth is $2\nu x,y=13$




emit.3732
xrms
yrms
x38%
y38%
x68%
y68%
emittance
turn number/100


emit.3732
x95%
y95%
x99%
y99%
emittance
turn number/100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xrms
yrms
x38%
y38%
x68%
y68%
emittance
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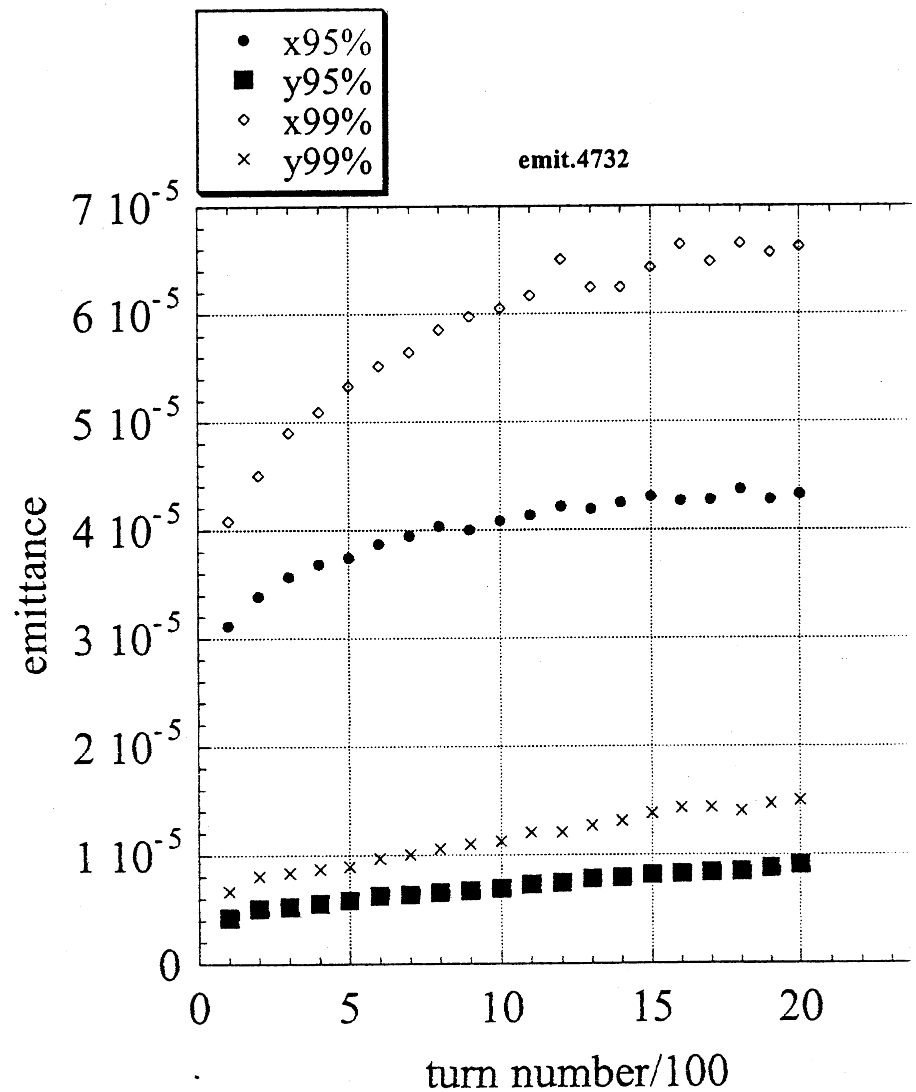
1.4 10^-5
1.2 10^-5
1 10^-5
8 10^-6
6 10^-6
4 10^-6
2 10^-6
0
0
5
10
15
20
25
turn number/100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x99%
y99%
emittance
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6 10^-5
5 10^-5
4 10^-5
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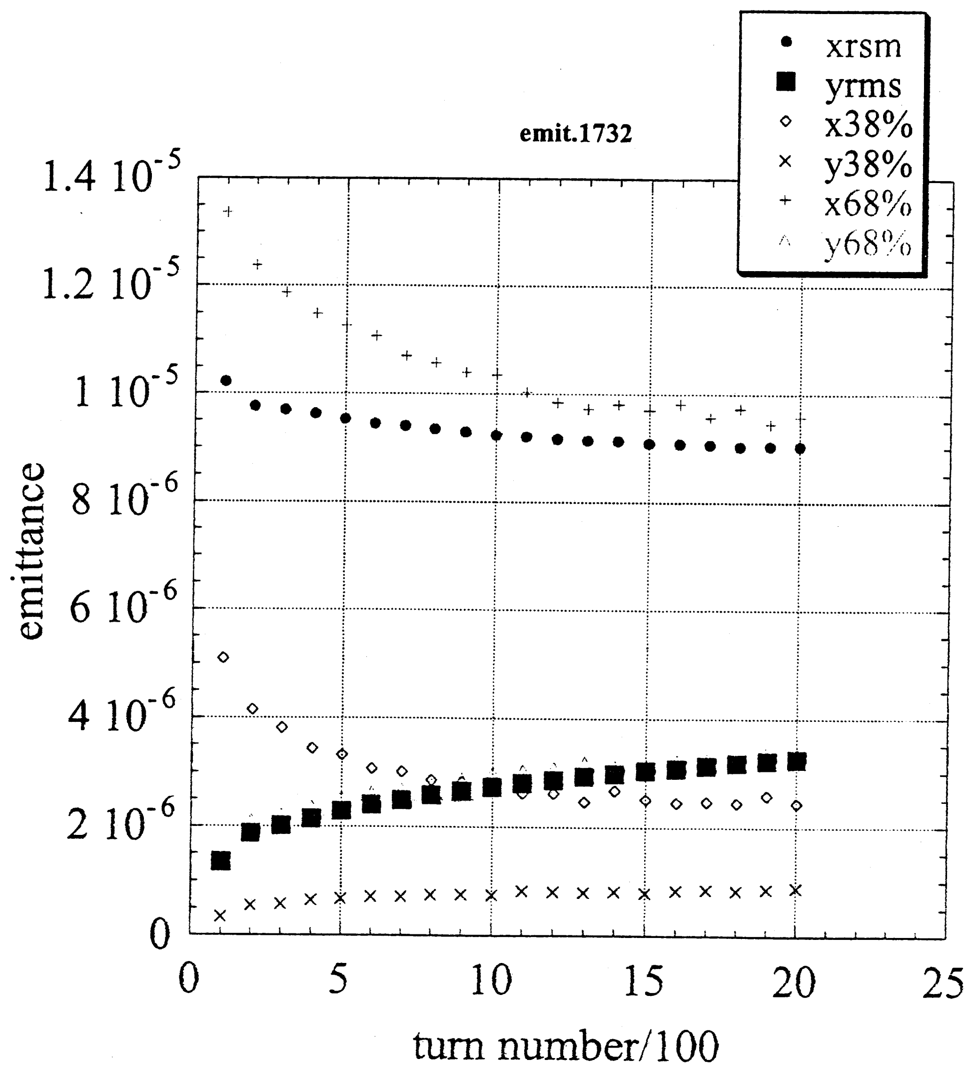
turn number/100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xrsm
yrms
x38%
y38%
x68%
y68%
emittance
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1.2 10-5
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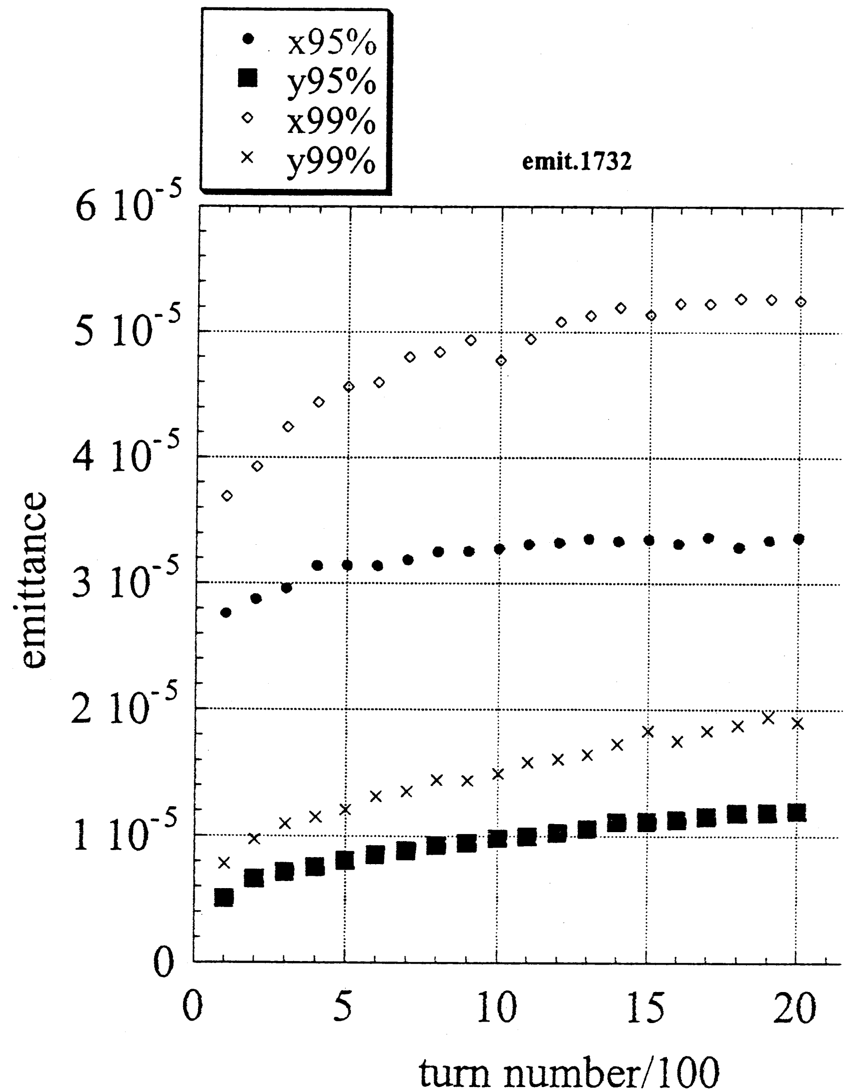
2 10-6
0
5
10
15
20
25
turn number/100


emit.1732
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emittance
6 10-5
5 10-5
4 10-5
3 10-5
2 10-5
1 10-5
0
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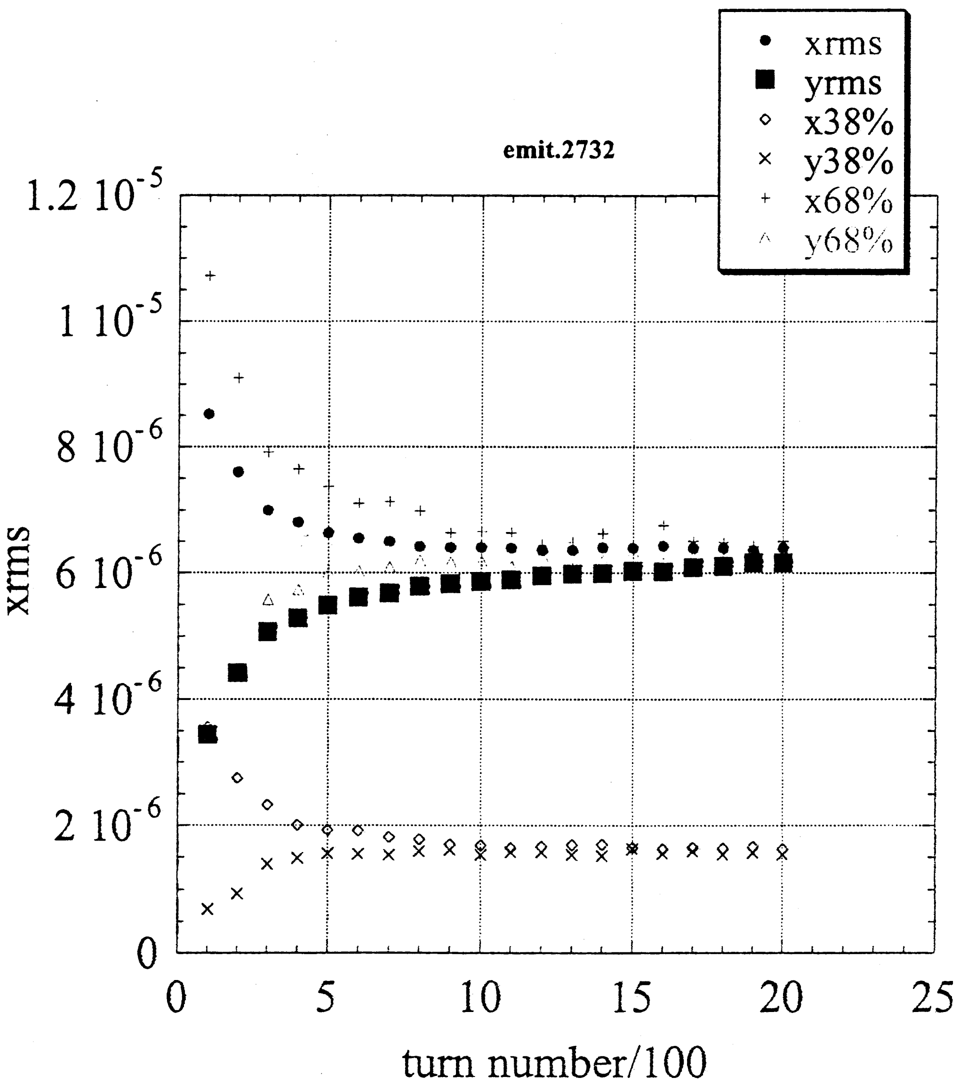
10
15
20
turn number/100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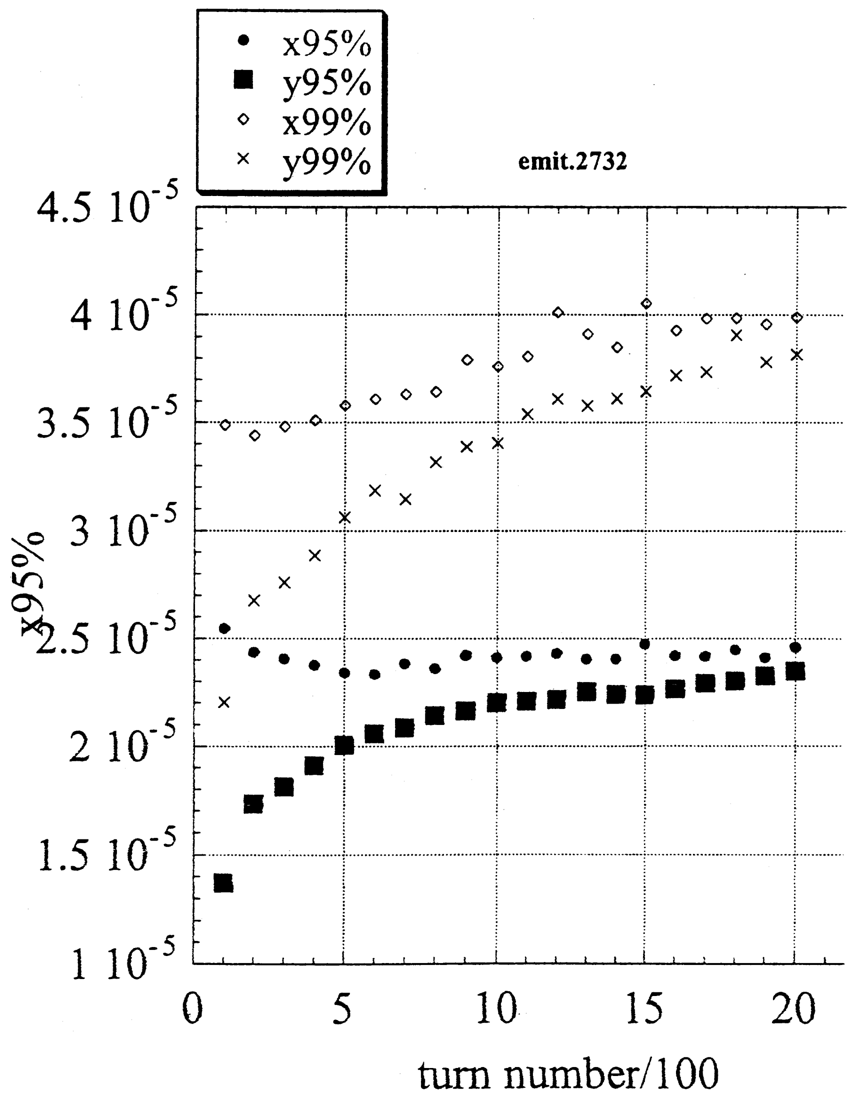
turn number/100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3.5 10^-5
3 10^-5
2.5 10^-5
2 10^-5
1.5 10^-5
1 10^-5
x95%
0
5
10
15
20
turn number/100

Next steps

With this simulation tool, we will explore

- If the coupling resonance with nonzero harmonic ($2\nu_x - 2\nu_y = p$: p is integer) may cause the problem.

  In fast, the answer is yes in the 3 GeV PS.

  How far we should be away from?

- Its impact on injection process, especially during anti-correlated injection, where the transient emittance is asymmetric.

- Whether this is incoherent or coherent effect.

  It is a very interesting question to me.

Summary (2)

- 3D space charge simulation results agrees with the experiment, at least qualitatively.

  In simulation, we take rms emittance.

  In experiment, we measure 95% emittance.

- To make more quantitative comparison, we need to know

  - $\Delta p/p$ of an incoming beam.

  - Beam loss and its effects on 95% emittance.

Summary (1)

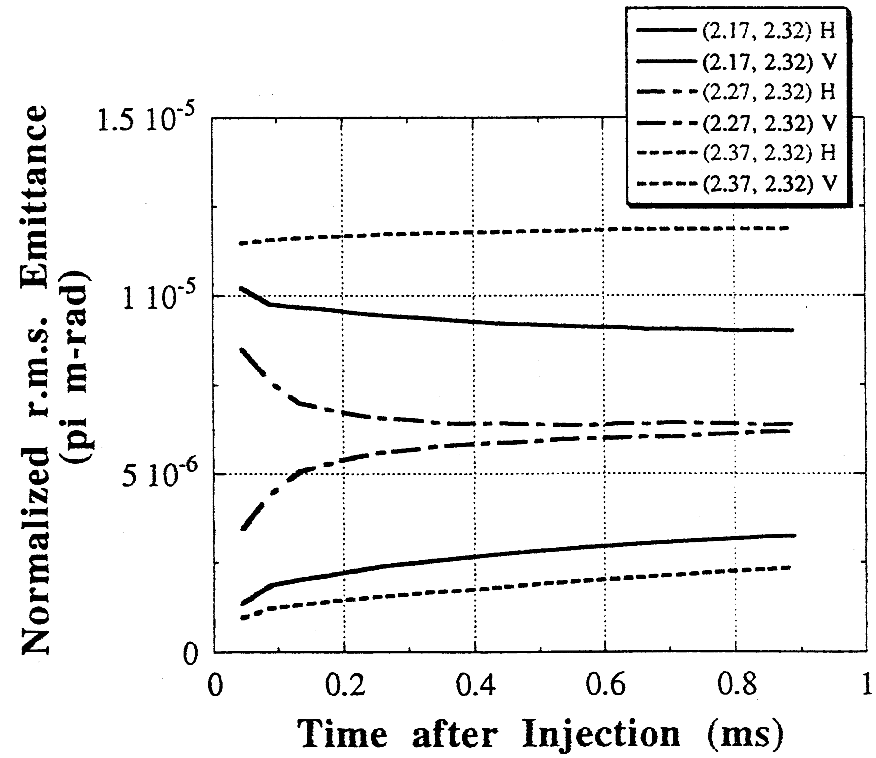
- The coupling of horizontal and vertical emittance due to space charge potential is the source of emittance exchange.

- This may happen during the anti-correlated painting injection if the tune choice is not careful.

Emittance Exchange with Three Different Bare tunes

(3D tracking simulation with space charge)

If the emittance exchange is caused by the coupling resonance, it should be enhanced or suppressed depending on the bare tune. Figure 6 shows that with three different bare tunes. There are larger exchange at (2.27, 2.32) and no exchange at (2.37, 2.32) where no particles cross the coupling resonance.



Emittance Exchange with Three Different Bare tunes

Horizontal and Vertical Emittance at 0.9 ms after Injection with Various Beam Intensity

(3D tracking simulation with space charge)

Figure shows horizontal and vertical emittance at 0.9 ms after injection with various beam intensity. The total beam intensity is adjusted by reducing linac peak current with a fixed injection turn number. Although quantitative comparison with the experimental data is still premature at the moment, the emittance exchange between two transverse planes agrees qualitatively.

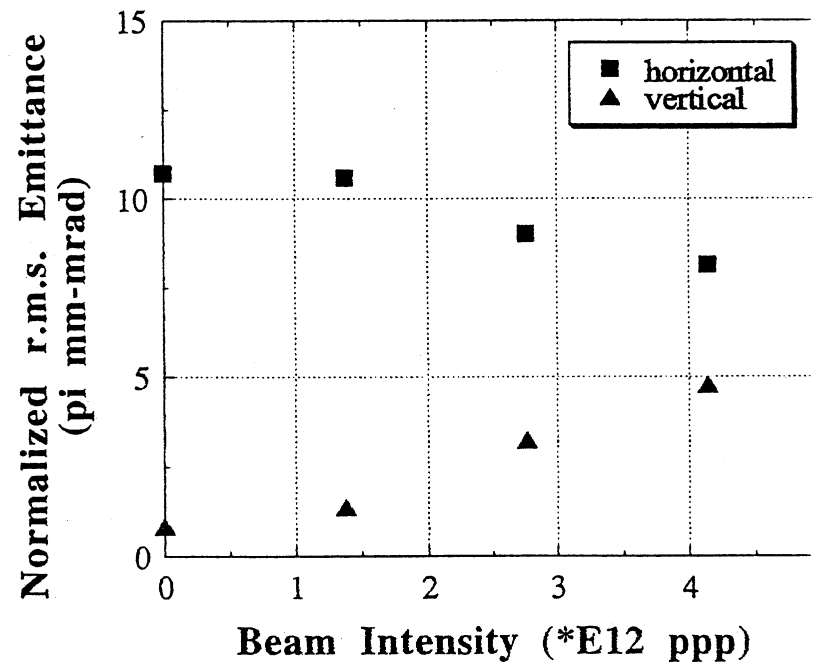


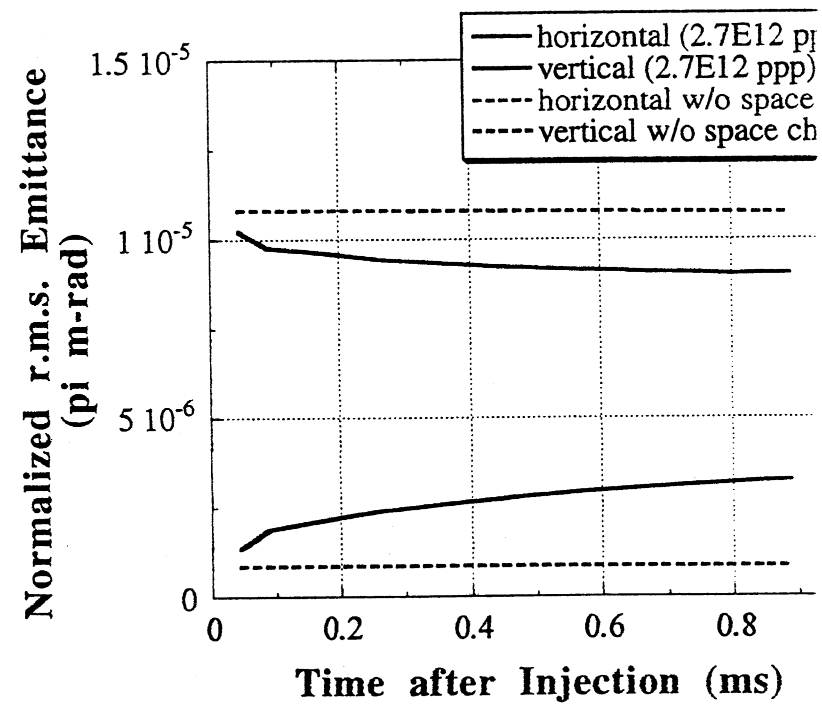
Figure 4: Horizontal and Vertical Emittance at after Injection with Various Beam Intensi

The Time Scale of Emittance Exchange

(3D tracking simulation with space charge)

Figure shows a emittance exchange through accelerating process. The space-charge dominant phenomenon and the without space-charge phenomenon are compared.

The time scale of emittance exchange shows good agreement with experiment as depicted in Fig. 5.

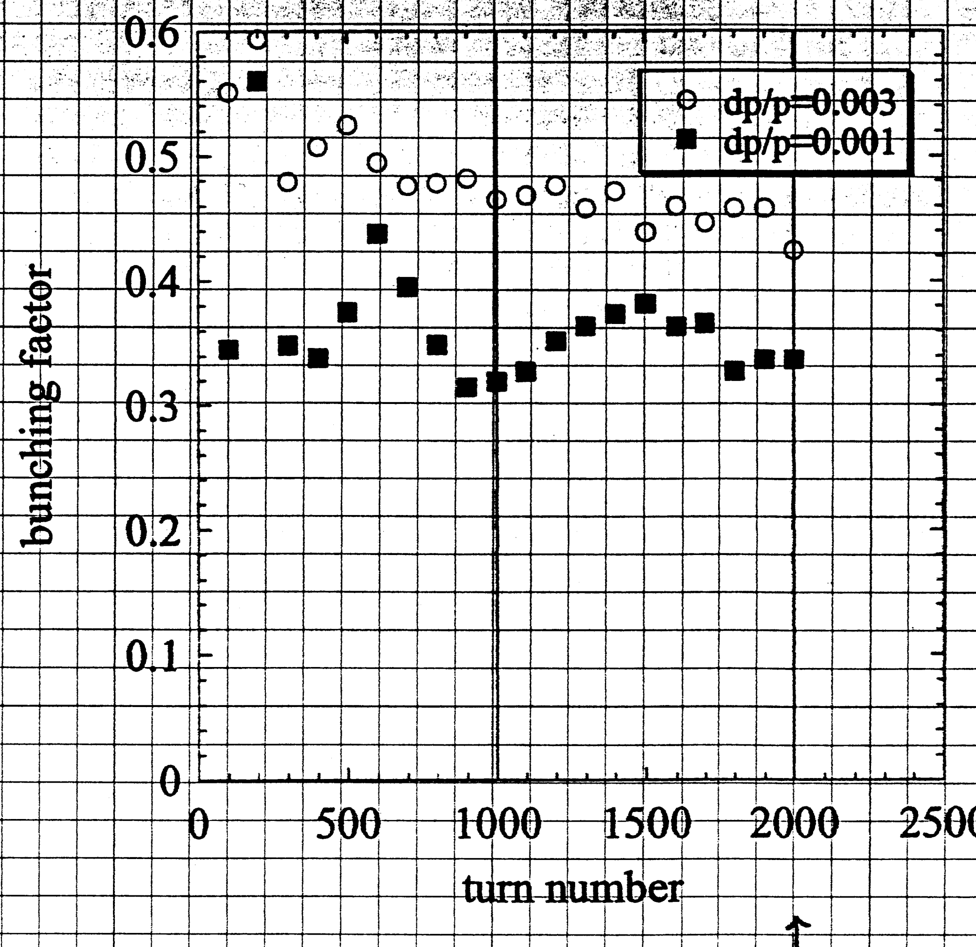


Simulation results

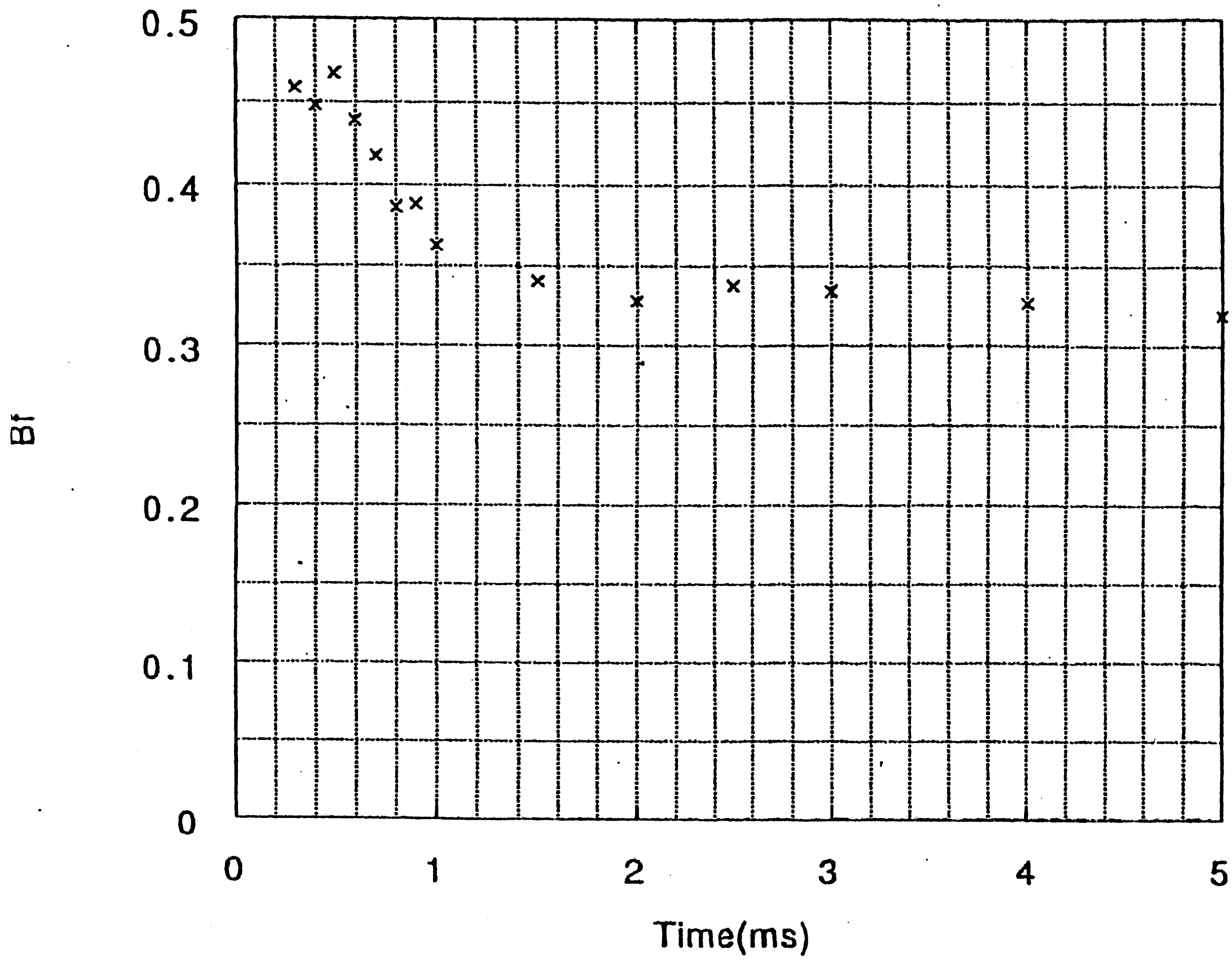
- rms emittance vs. beam intensity at 0.9ms after injection.
- rms emittance evolution during the first 0.9ms after injection.
- rms emittance evolution with different bare tune.

  This cannot be checked in the experiment.

Bunching Factor by 3 D Simulation



Bunching Factor

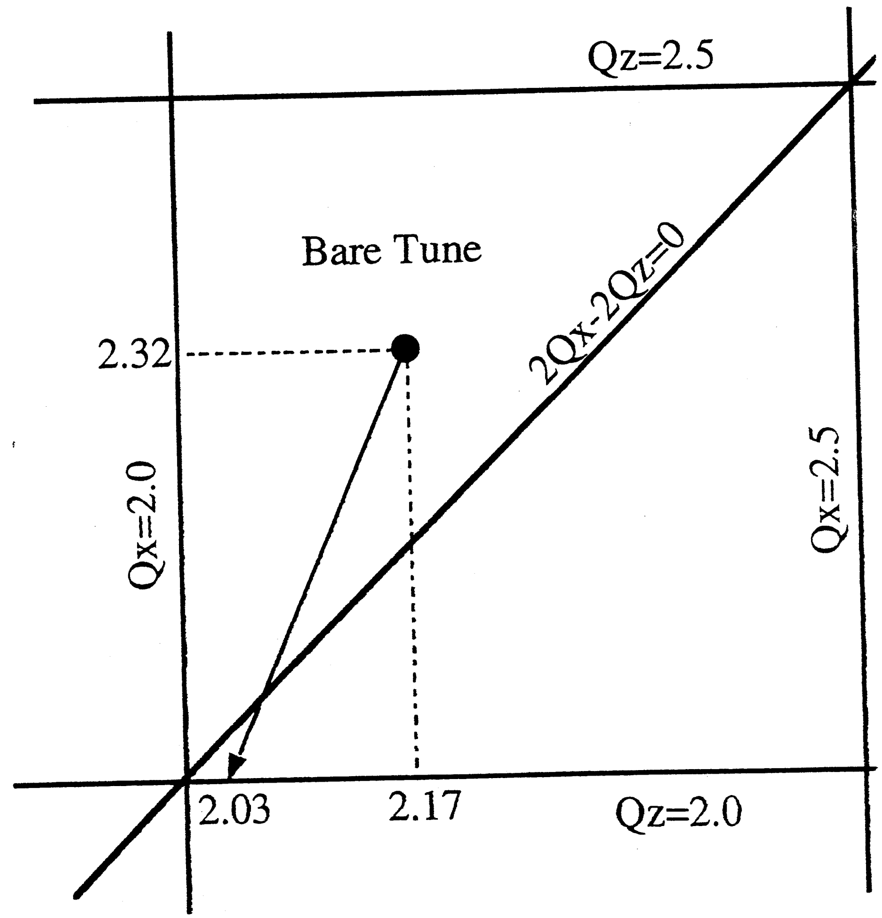


Simulation of the process

- The process involves,
  - bunching in longitudinal direction.
  - "painting" in transverse direction.
- 3D modeling is a must.
- No field errors in the lattice are included.

Tune Diagram

The experimental and simulation results imply that the space-charge potential of a beam induces coupling between the horizontal and vertical planes. Although a linear coupling term in the Hamiltonian, namely x z, is not excited by space charge because of the axial symmetry of a beam, the octupole term ,x^2 z^2, exists. In addition, the present bare tune is (2.17, 2.32), slightly above the coupling resonance line of $2Q_x$-$2Q_z$=0, and the depressed tune approaches as the beam intensity is increased.



Operating point of KEK Booster

- The bare tune of KEK Booster is (2.32, 2.17) and it is just above the coupling resonance $2\nu_x - 2\nu_y = 0$.

- Unfortunately, the machine consists of 8 combined function magnets with no trim quad, meaning no knob to change the tune.

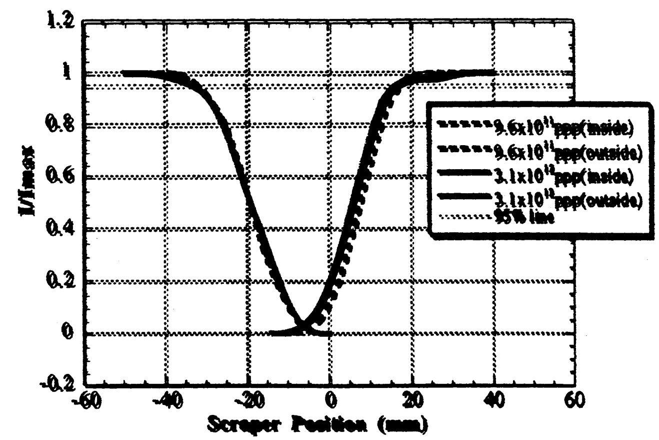
CIRCULATING BEAM EMITTANCE

Scraper Profile

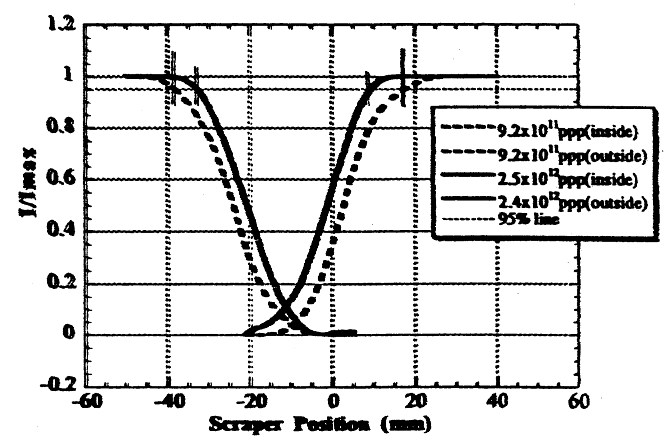
The beam size is measured in the accelerating process using a scraper and bump magnets system.

The horizontal beam sizes, which are expanded to full acceptance by off-center injection, were measured in a period of 0.06ms to 1.5 ms after injection, where the injected coasting beams were captured in a RF bucket. In this bunching process, the momentum spread and the line charge density increases in a RF bucket. The bunching factor decreases from 1.0 to 0.4 in this period (from 0.06ms to 1.5 ms after injection).

The typical values of the beam size measured by the scraper method are shown, where the data are 0.06ms and 1.5ms after injection, respectively. In Fig.4, at the 1.5ms after injection, the whole beam size of the high-intensity mode is clearly decreased compared with the low-intensity mode.



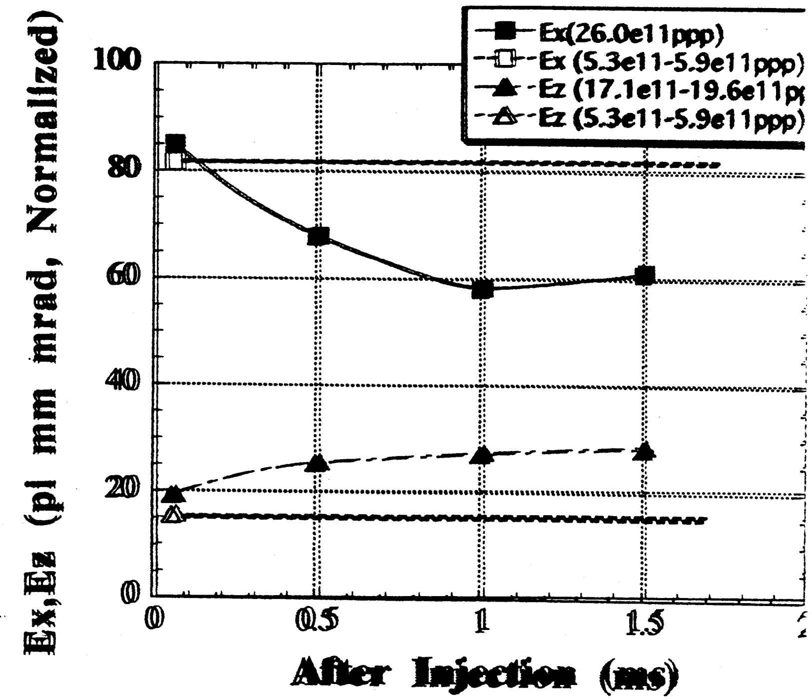
0.06ms after injection



1.5 ms after injection

EMITTANCE-EXGHANGE THROUGH ACCERELATING PROCESs

In high-intensity mode operation, a decrease in the horizontal emittance and the increase in the vertical emittance take place simultaneously during the period from 0.06ms (or faster) to 1.5ms after injection has been completed. The emittance changes saturate until 2.0ms and the values of the circulating beam emittance are close to the extracted beam emittance in Fig. 2. The vertical emittance growth reaches to the acceptance limit of the vertical plane. The experimental results suggest the existence of an X-Y coupling resonance by space-charge effects.



Normalized Ex, Ez Through Accelerating Proc After Injection as a Parameter of High & Lo Intensity under the Horizontal Off Center Injectio

Emittance right after injection

- Using scraper and bump magnets, we measured 95% beam size right after injection (~ 2ms).

  we also measured a distribution, but it may not be accurate.

- Detailed measurements show the emittance exchanges occures during 1ms after injection, which corresponds to a bunching time.

Theme

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INTESITY DEPENDENCE OF THE EXTRACTED BEAM EMITTANCE

The intensity dependence of the extracted beam ittance in the case of 15mm off-center injection is own in Fig.2. The extracted beam emittance is asured by multi-wire profile monitors at the persion-free points on the extracted beam line. The -center painting injection is tried only in the izontal plane. In the vertical plane, the injection point l angle are adjusted to the center of the phase space to ain the minimum emittance in the vertical plane.

he horizontal emittance decreases with the beam ensity nevertheless the injected beam is expanded to full acceptance by the 15mm off-center injection. On other hand, vertical emittance increases with the am intensity.

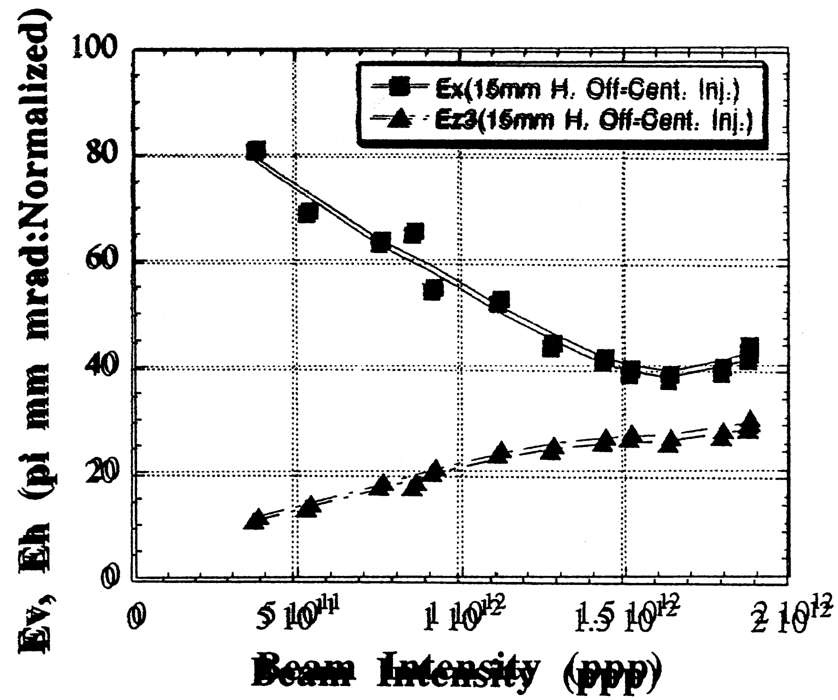


Figure 2: Intensity dependence of the extracted beam emittance as the parameter of the off-center injection.

Decrease of Expanded Beam Emittance with Beam Intensity

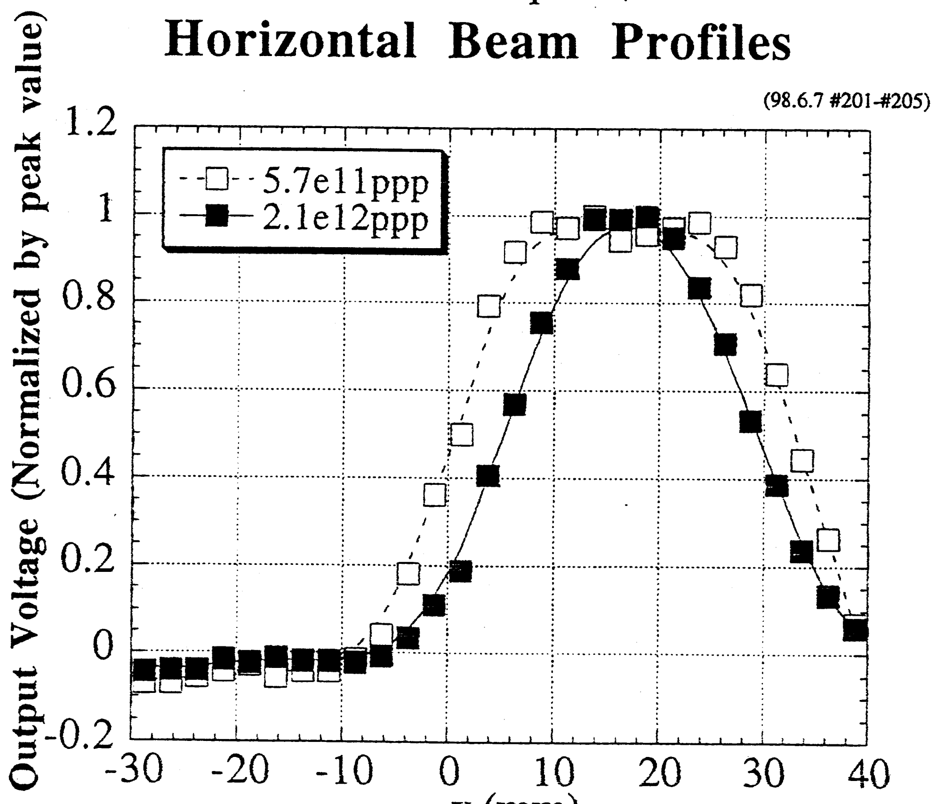
Horizontal and vertical beam profiles under the 15mm off-center injection in the horizontal plane as param the beam intensity are shown in Fig.1.

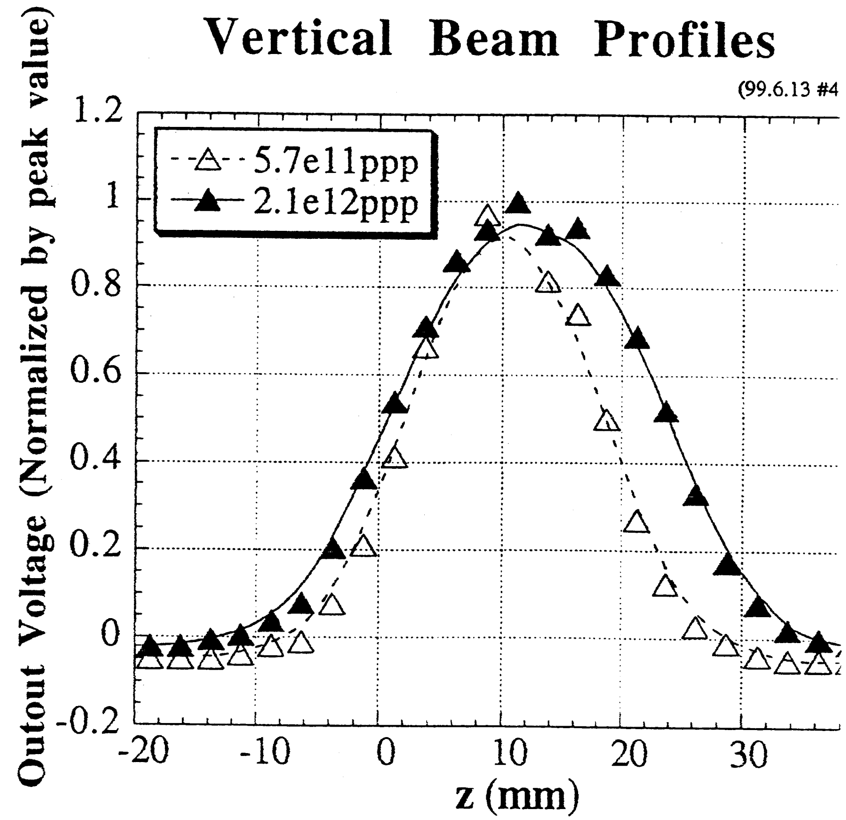
In the low-intensity mode, the extracted beam profiles coincided with the calculated values at injecti simulation in which the space charge effects were not included.

In the high-intensity mode operation, 2.0×10^{12} ppp, extracted beam profiles are not directly reflected by the s of the painting injection. The distributions of injected beams are no longer conserved.

In horizontal plane, the width of the extracted beam profile shrinks compared with low-intensity mode operati

On the other hand, in vertical plane, the extracted beam profiles blow-up in the vertical plane.





Emittance of extracted beam

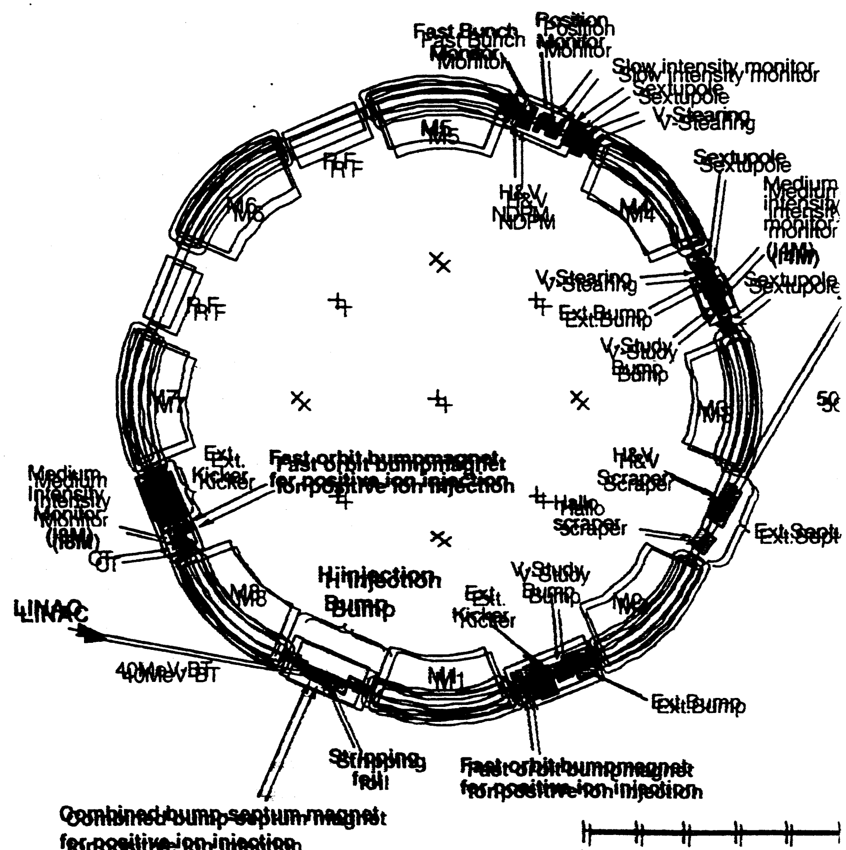
- With low intensity, $\sim 6\times10^{11}$ ppp, both horizont[al] and vertical emittance are as expected, namely $\varepsilon_H \sim 4\,\varepsilon_V$.

- With the intensity is increased, 2×10^{12} ppp, horizontal emittance shrinks and vertical emittance grows, $\varepsilon_H < 4\,\varepsilon_V$.

- The amount of emittance exchange depends on beam intensity.

Structure of the KEK Booster

The features of the 500-MeV KEK booster are rapid cycling (20Hz), very compact and comprising combined function magnets. It supplies proton beams to the 12-GeV main ring (MR) and the neutron and meson science laboratory (NML). The MR demands to control the extracted beam emittance from the booster for optimum injection and the NML demands the high intensity beams as high as possible.



Beam injection with transverse offset

- Not exactly painting, but off-center H^- injection (+15mm) simulates transverse painting.

- Offset only in horizontal direction, so that the asymmetric emittance of horizontal and vertical is formed. ($\varepsilon_H \sim 4\varepsilon_V$)

3 GeV PS lattice and space charge

50 GeV PS lattice and correction

Experiment and simulation in KEK Booster

Simulation of e-beam compensation in FNAL Booster

Background

- Recently, detailed measurements of emittance (beam size) in the KEK booster were performe taking beam intensity as a parameter.
- The results imply a strong coupling resonance ($2\nu_x - 2\nu_y = 0$) induced with space charge poten.
- From the simulation point of view, this is the great opportunity to validate a 3D space charge code.