Analizing combined space charge and lattice nonlinearities based on an experiment at the CERN PS

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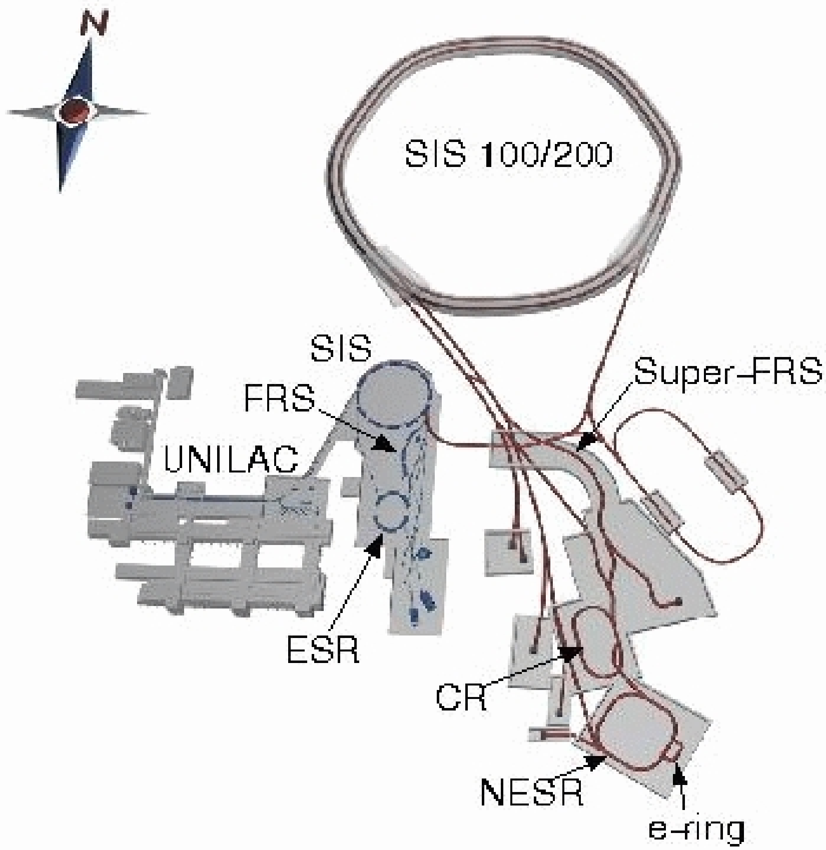
Orsay, April 1st–2nd 2004
Lure, Building 209, room 110

Proposed GSI Upgrade

'An International Accelerator Facility for Research with Ions and Antiprotons'



Predicted Gain Factors:

- primary beam intensities: 100 (10^{12} uranium/s)
- RIB intensities: up to 10^4
- beam energy: 15

Special Properties:

- fast cooled beams of exotic nuclei
- internal targets (p,e) for in-ring experiments

Technology Challenges:

- Fast cycling SC magnets for SIS 100/200
- Fast bunch compression in SIS 100
- High-power fragmentation target
- Fast stochastic cooling in the CR
- Medium energy electron cooling in the NESR

<u>Accelerator Physics Challenges for SIS 100/200</u>:

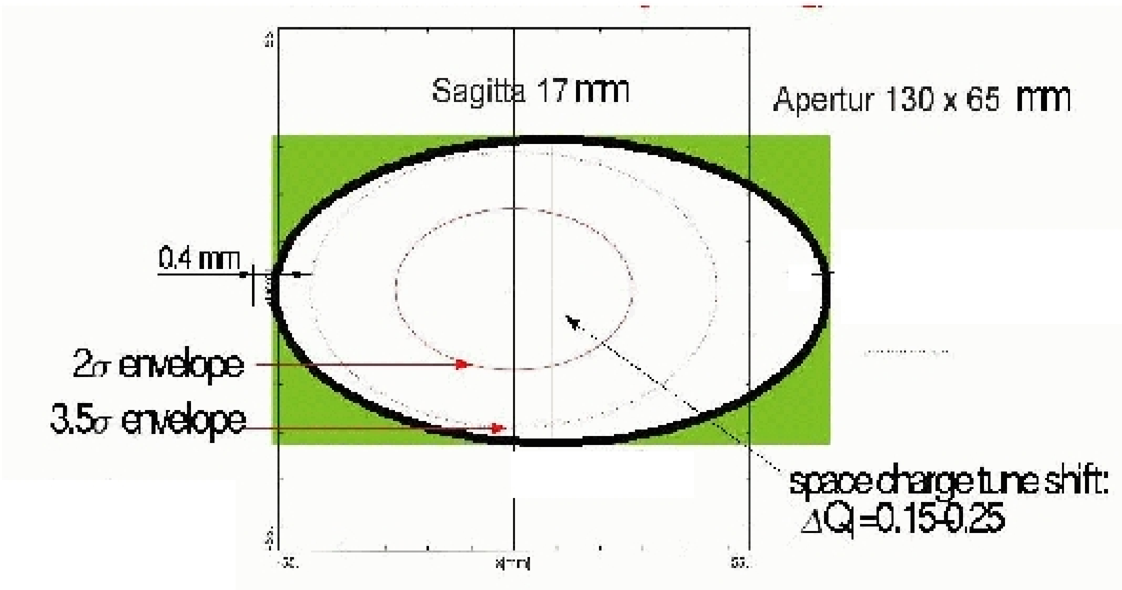
- Low tolerable relative beam loss
- Control of space charge effects
- Control of dynamic pressure effects

Of Particular Interest for GSI Project

- Accumulation of four SIS18 batches of U +28 at 96 MeV/u in the SIS100 in about 1 second.
- This takes hundreds thousand turns
- Maximum tuneshift of a bunched beam is 0.2

Challenges

- The beam fills a good fraction of the beam pipe
- Beam loss at the percent level



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A New Area of Studies

Single Particle Nonlinear Dynamics

- no self consistent effect
- nonlinearities intrinsic to the machine lattice
- hundred thousand turns

Space Charge Dominated beams

- self consistent effect
- nonlinearities from lattice+beam
- thousand turns

For SIS100 this distinction is no more justified.

1 s storage in presence of lattice nonlinearities + space charge

Work done:

- G.Franchetti et al. PRSTAB 6, 124201 (2003)
- G. Franchetti, I Hofmann, M. Giovannozzi, M. Martini, E. Metral
  29th ICFA Workshop HALO03 693, 73
- G. Franchetti, I. Hofmann
  20th ICFA Workshop 642, 248

International effort on

Code Benchmarking on Space Charge and Nonlinear Dynamics

http://www–w2k.gsi.de/ihofmann/Benchmarking/Bench–marking.htm

In this talk

- Present our understanding of the dynamics of long term storage of space charge dominated bunched beams.
- We show that up to a certain extent this can be modeled in a single particle framework
- We present the comparison between experimental results and simulation

Our interests in this workshop

- Open a discussion for understanding better interplay of lattice nonlinearities and "collective nonlinearities".
- Role of FMA in disentangling in the theory or in experiments the dynamics of these complex system.

A 2D example

equation of motion

$$x'' + \left(\frac{q_0}{R}\right)^2 x = K\frac{x}{r^2}\left(1 - e^{-\frac{x^2}{2\sigma^2}}\right)$$

lattice
focusing strength

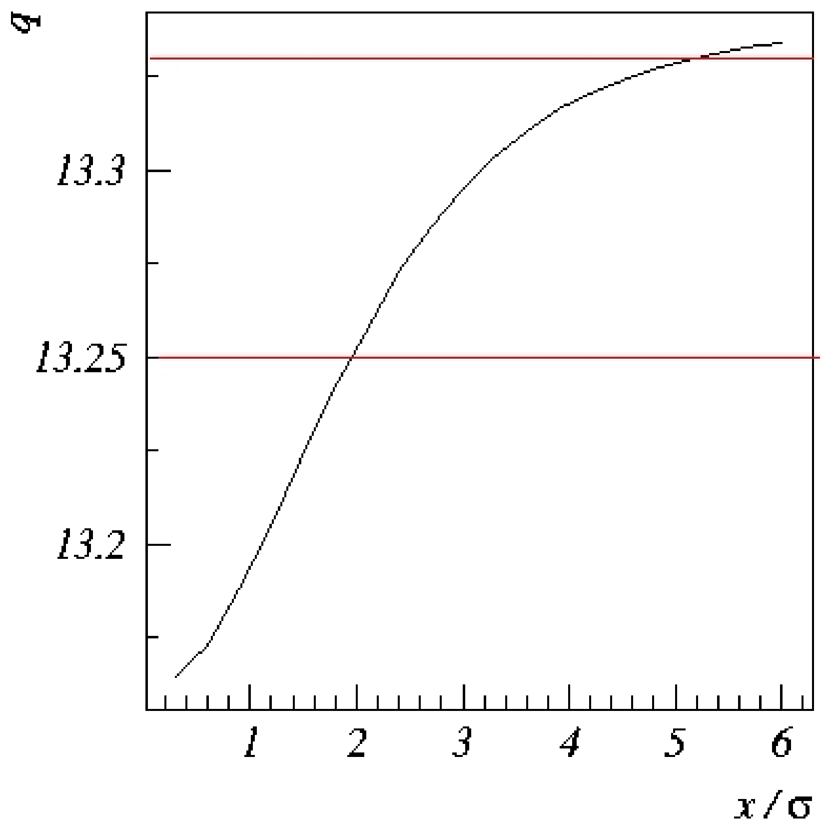
space charge nonlinear
defocusing term

Symplectic integration: space charge is included through kicks

Space charge induced nonlinear tune

$q_0 = 13.36$

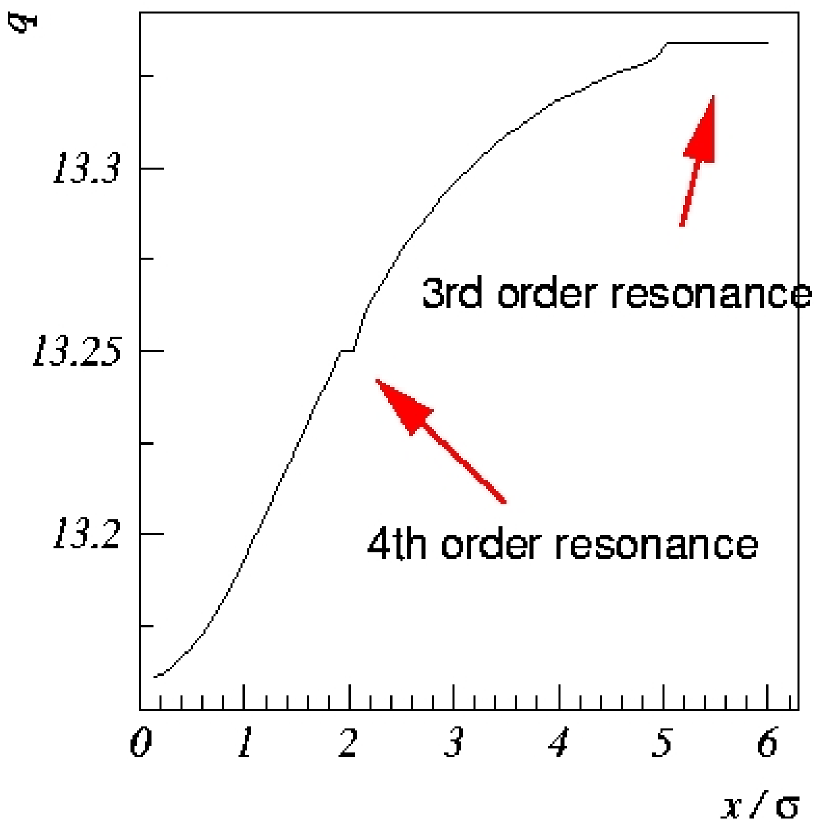
$\Delta q = 0.2$

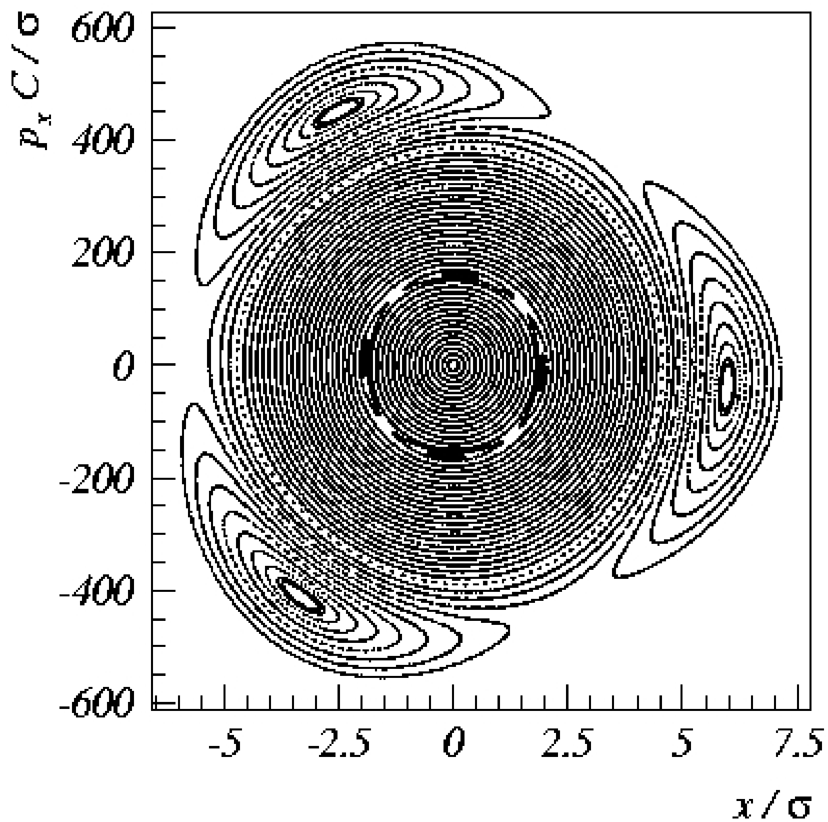


$3\,q = 40$

$4\,q = 53$

When the lattice has nonlinearities





20 sext. error   a2 = 0.01   53 oct. errors   a3 = 0.005

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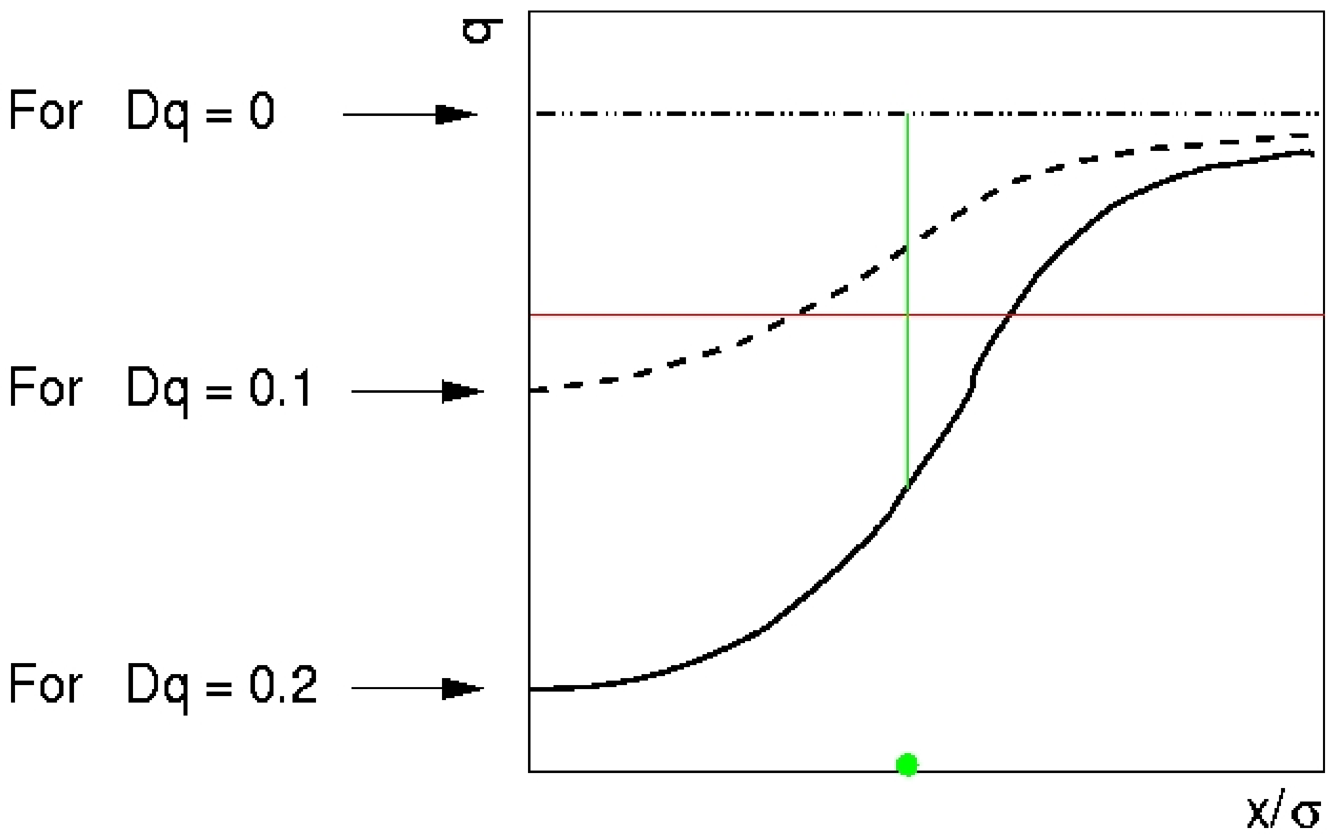
What happen when the perveance is dynamically changed when in the lattice nonlinearities are present ?



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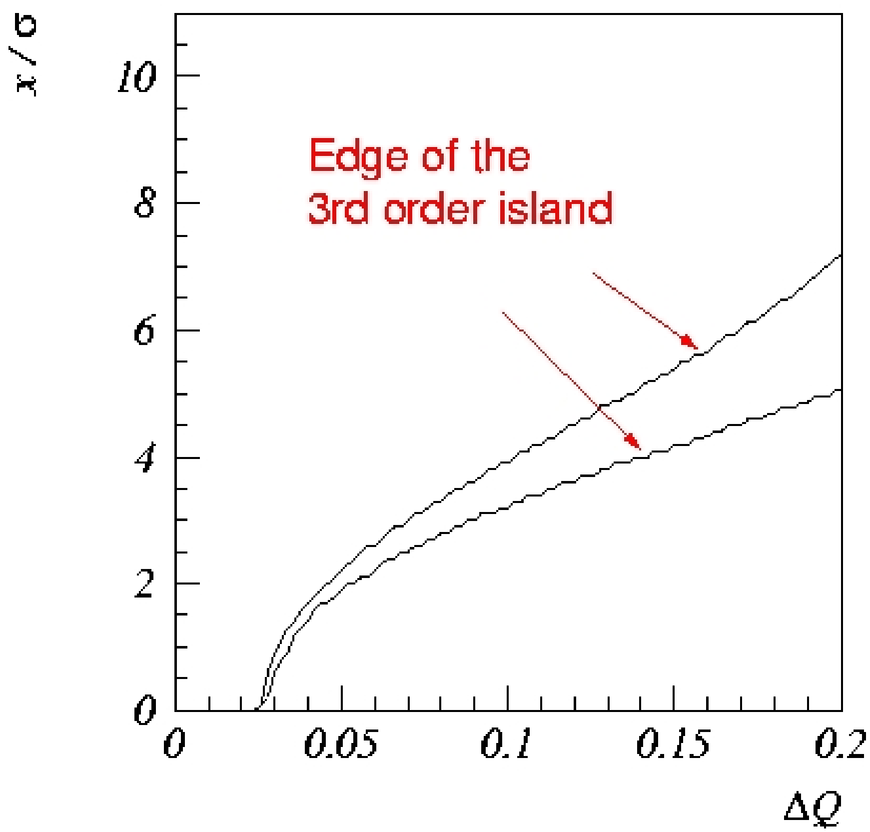
When the perveance K is changed

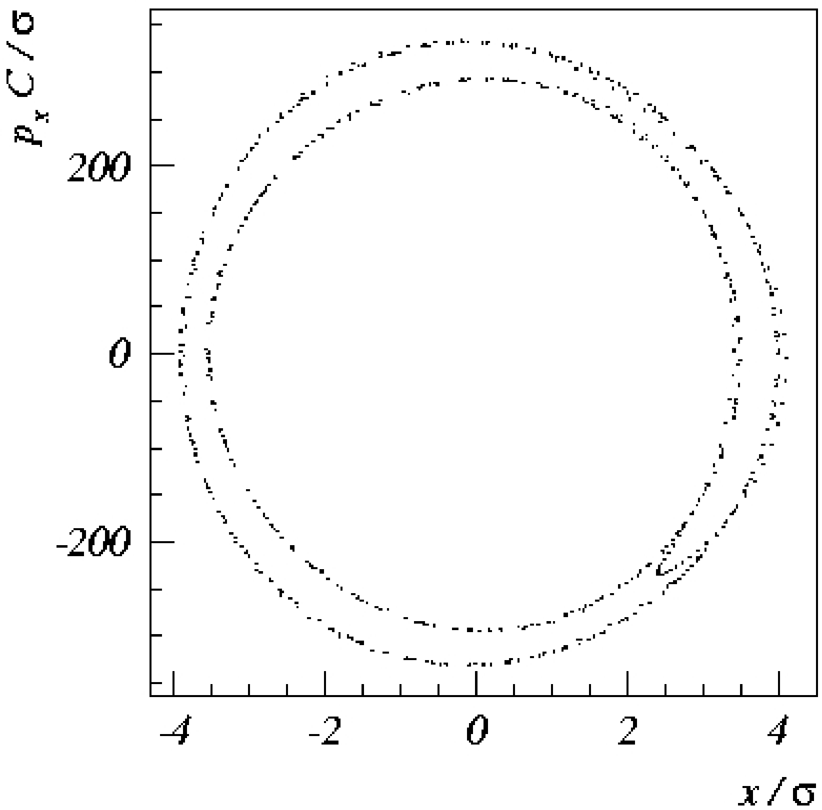


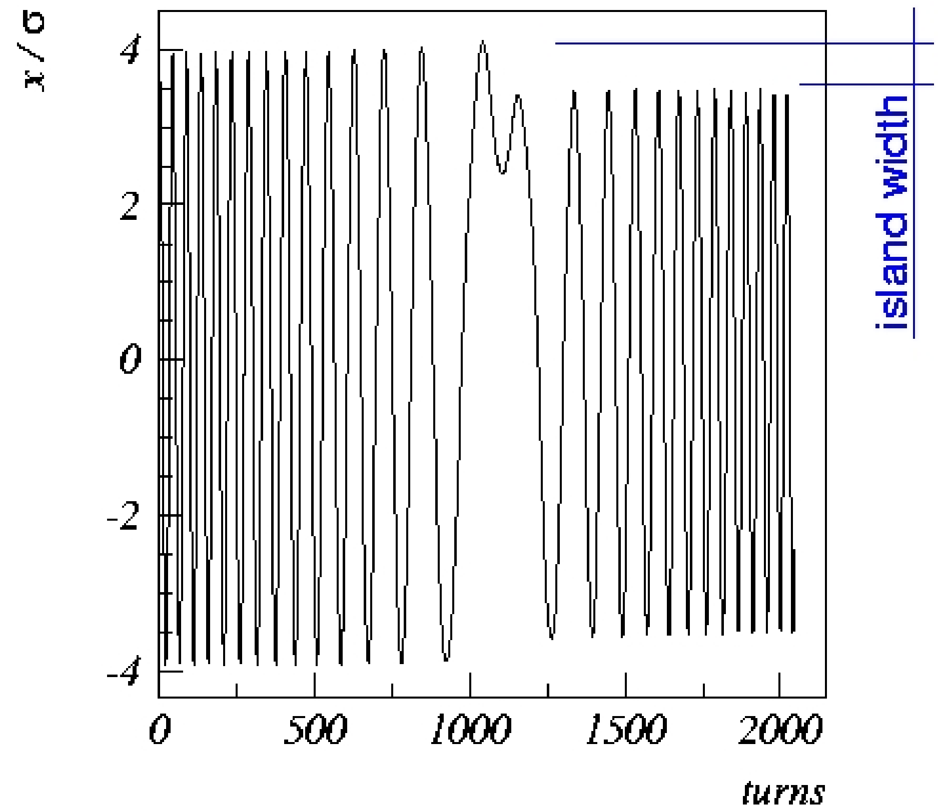
island coming from inside particle orbit

x = 4
px = 0

q = 13.36

current ramp 0.2 / 2048 [Δq/turns]



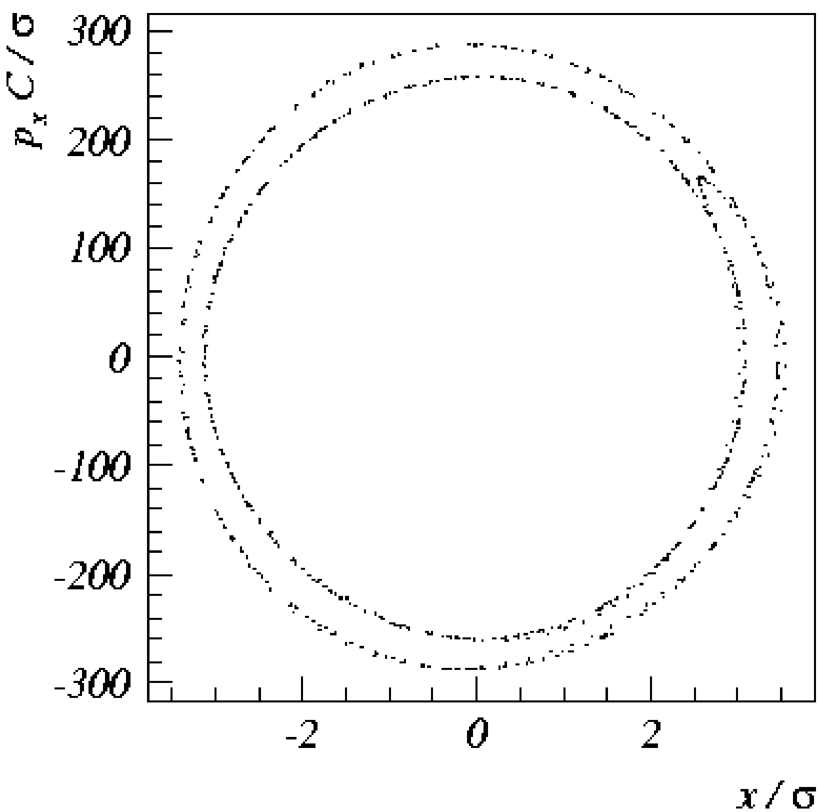


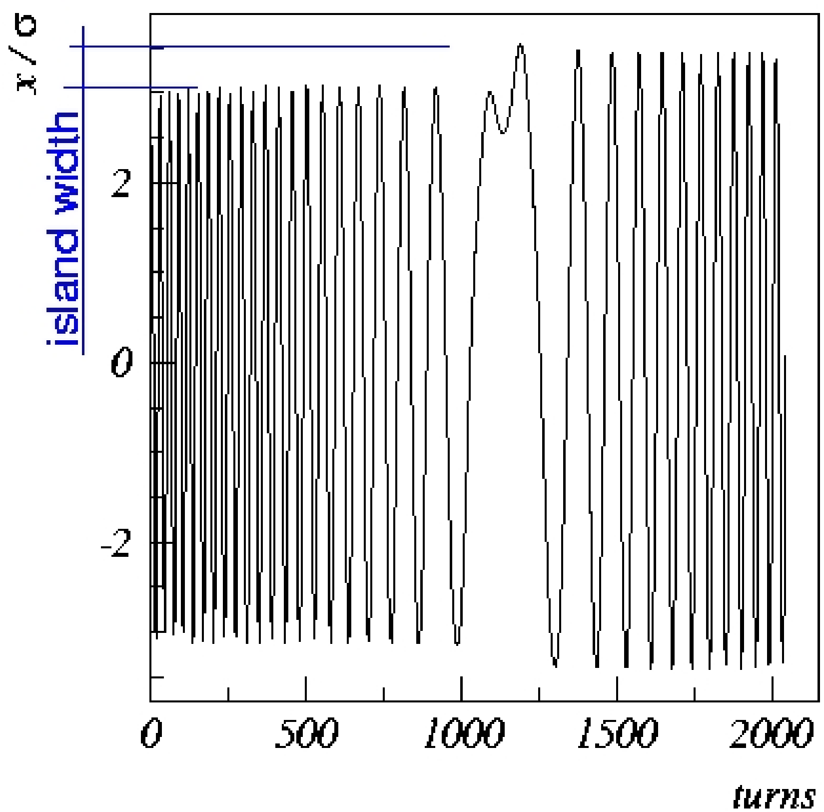
Island coming from outside the particle orbit

x = 3
px = 0

q = 13.36

current ramp –0.2 / 2048 [Δ q/turns]





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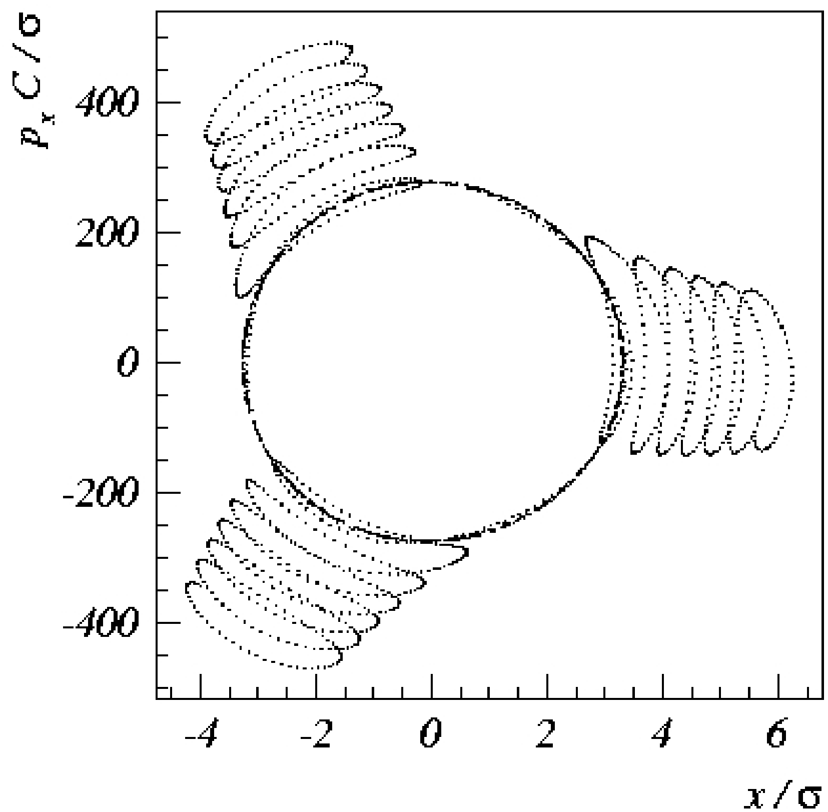
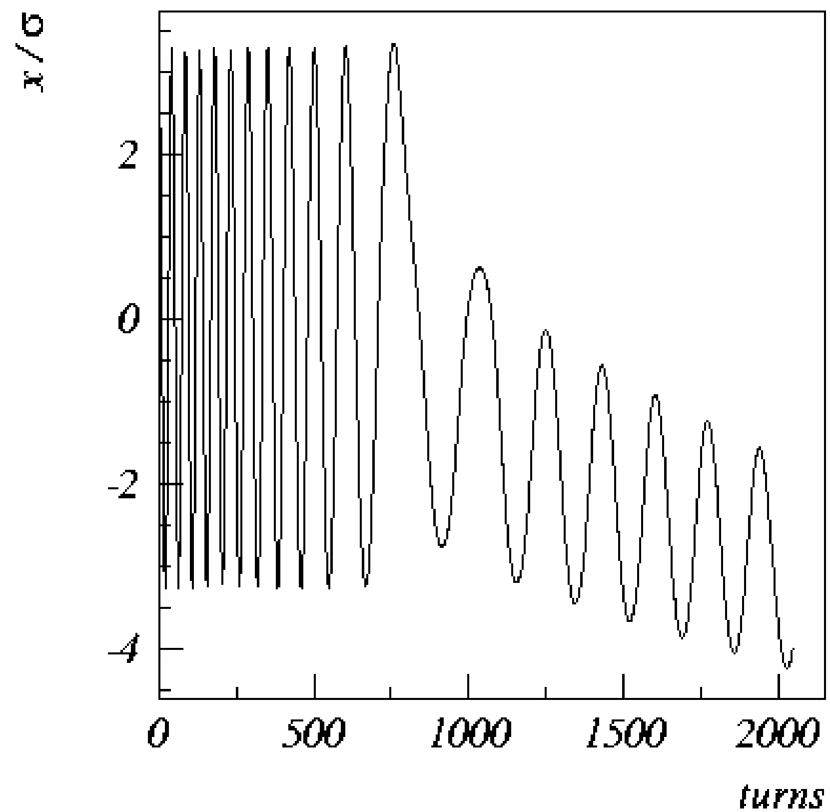
Trapping of particle into the island

x = 3.3
px = 0

q = 13.36

current ramp 0.2 / 2048 [Δq/turns]





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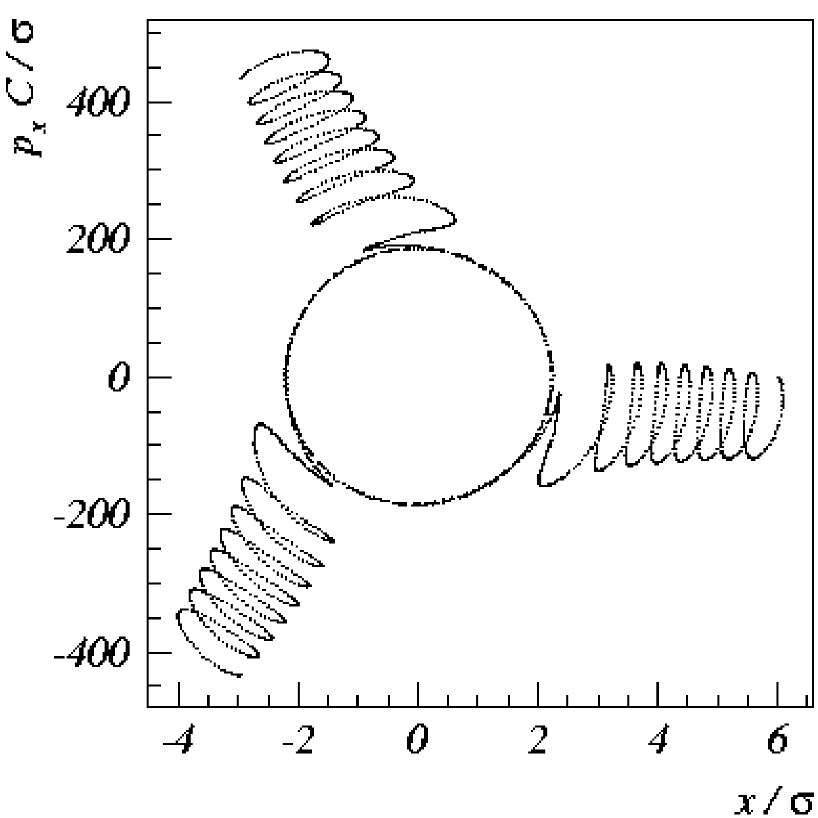
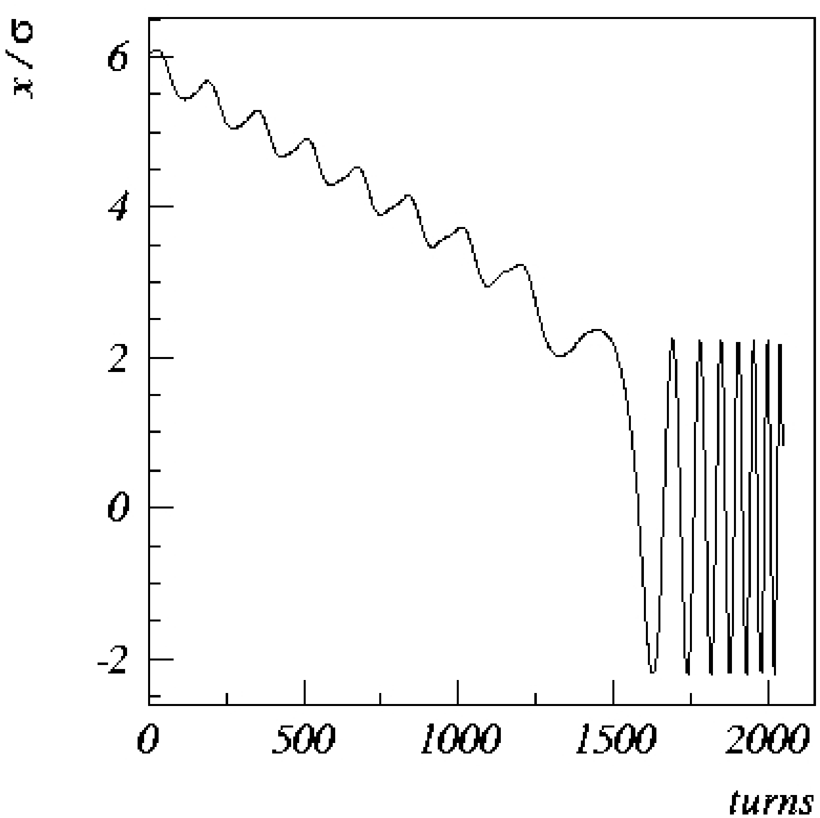
For a negative rate the capture process inverts the effect

initial coordintes x=6, px = 0

from Dq = 0.02   to Dq = 0





Change of space charge intensity causes resonance trapping

Resonance trapping is not new in accelerators:

Studies of trapping induced by chromaticity

- A.W. Chao et al. Nucl. Instrum. Methods 133, 405 (1976)
- T. Satogata et al. PRL 68, 1838 (1992)

BUT

Space charge induces a nonlinear tune, whereas the previous studies considered a detuning induced by chromaticity which is amplitude independent

Consequencies

- Particles may be transported out of a beam: HALO formation in rings
- Maximum distance of the particles depends on bare tunes and resonance position

Open questions

- What is the probability of trapping/detrapping with space charge ?
- What is the fraction of particles in a bunch which will be brought up to a certain amplitude ?
- What is the role of dynamic aperture ?

Measurements at the CERN–PS

(October, 15–18, 2002)

R. Cappi, G.Franchetti, M. Giovannozzi, I.Hofmann, M. Martini, E. Metral

excite the resonance 4 Qx = 25 by using a single octupole

working point range: qx = 6.23 – 6.28, qy = 6.08 – 6.4

octupole strength: $K_3 = 1.215\ I\ \ (m^{-3})\quad I = 0 \sim 400$ A

momentum spread $dp/p_0 = 2.6\ 10^{-3}$

beam emittances (2σ unnormalized): ex = 9 mm mrad
ey = 4.5 mm mrad

bunch length: 200 ns

beam energy: 1.4 GeV

flat–top: of 1.2 seconds

Emittance measurements: flying wire (< 1ms) momentum spread $dp/p_0 = 10^{-3}$

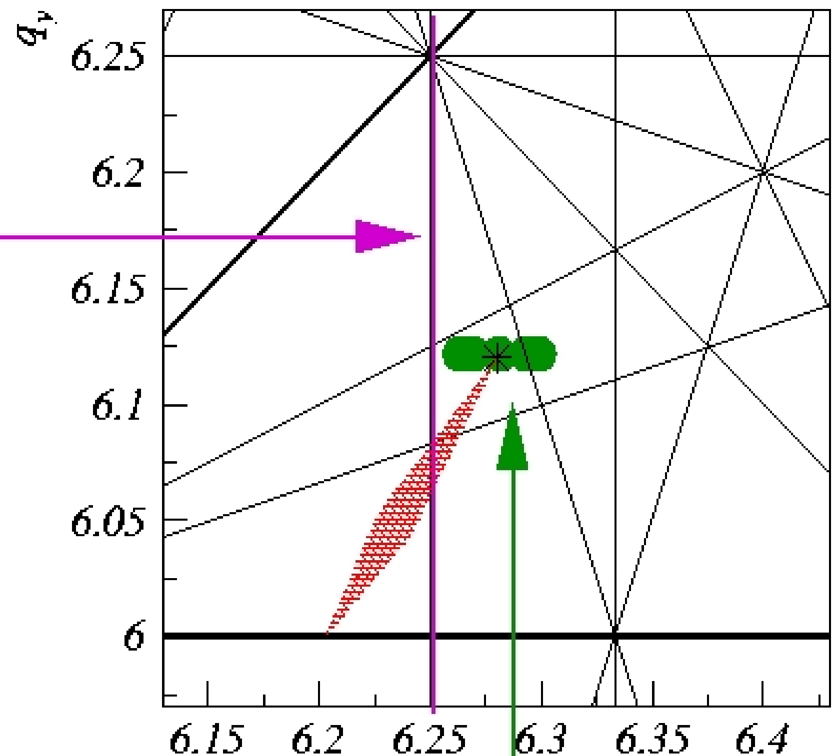
beam emittances (2σ unnormalized): ex = 9 mm mrad

ey = 4.5 mm mrad

bunch length: 200 ns

The PS experiment

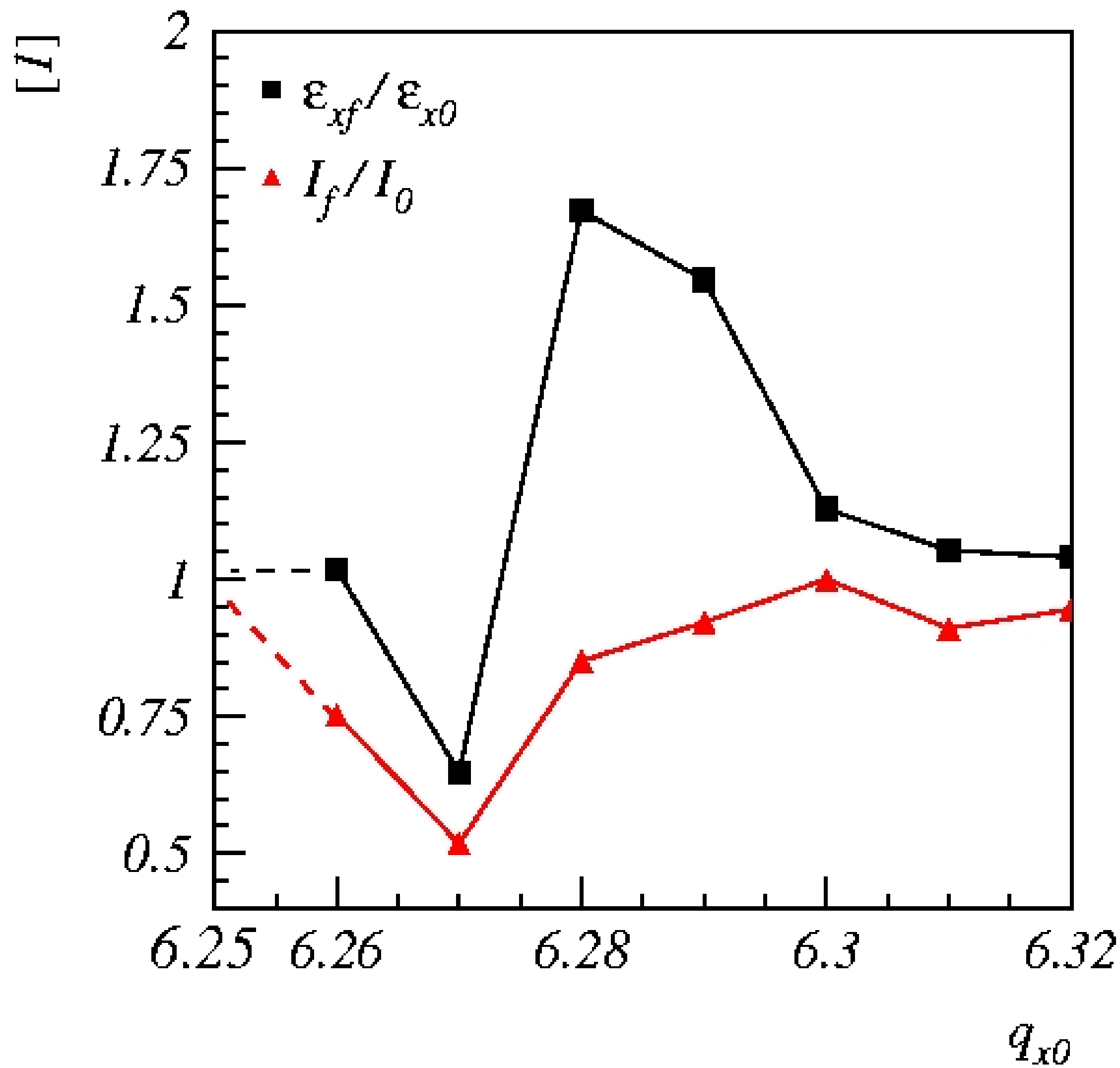
excitation of
4th order resonance
by using 1 octupole



scan of qx0
from 6.32 to 6.25
qy0 = 6.12

PS experiment on Resonance Crossing: Summary

qy0 = 6.12
K_3 = 49 m^{-3}
Dqx = 0.077
Dqy = 0.12
flat–top 1.2 sec
turns 5*10^5



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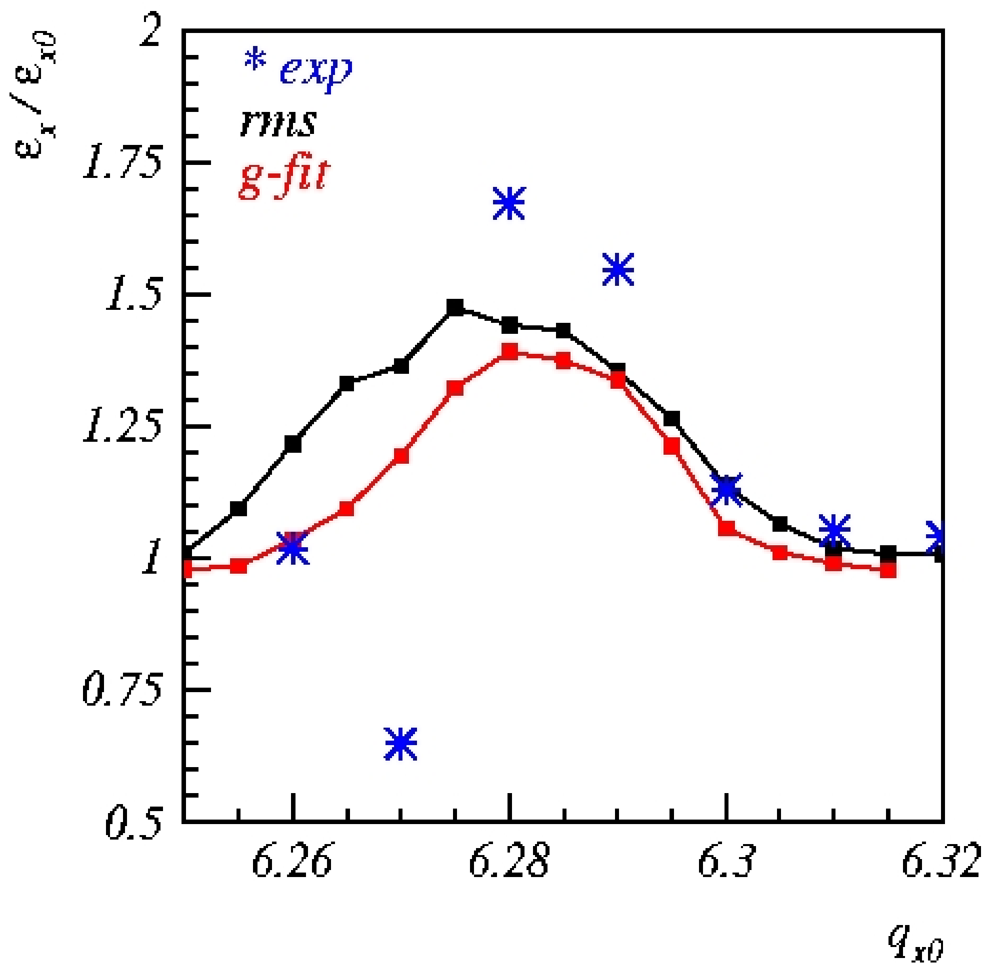
Benchmarking: experiment vs simulation



3D long term simulation

$$n(x,y,z) = \hat{n}(T)/(4\pi abc), \qquad \int_0^1 \hat{n}(t^2)t^2 dt = 1,$$

with

$$T = \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2}.$$

The charge distribution is given by $\rho(x,y,z) = Q\,n(x,y,z)$, with Q the total charge in the bunch. The electric field is given by

$$E_x = \frac{Q}{2} x \int_0^\infty \frac{\hat{n}(\hat{T})}{(a^2+t)^{3/2}(b^2+t)^{1/2}(c^2+t)^{1/2}}\,dt,$$

with

$$\hat{T} = \frac{x^2}{(a^2+t)} + \frac{y^2}{(b^2+t)} + \frac{z^2}{(c^2+t)}.$$

if $a = b$ then:

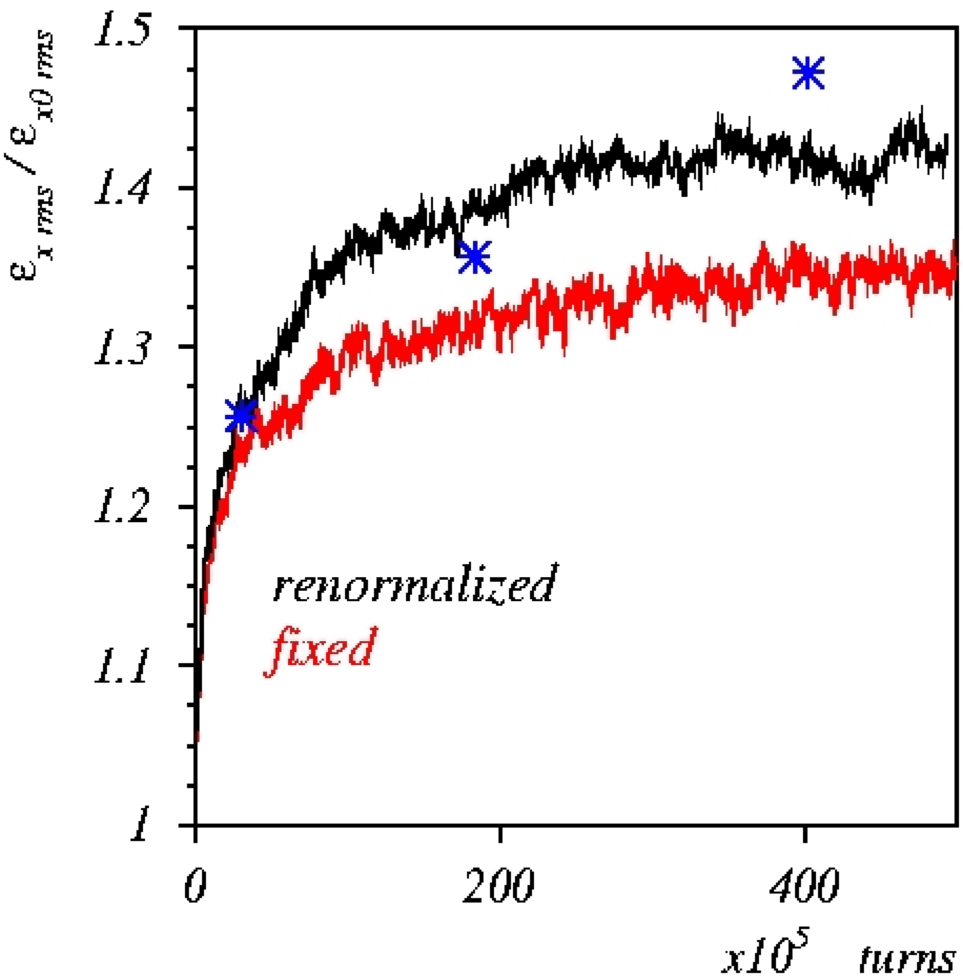
$$\hat{n}(t) = \sum_{l=0}^{\infty} c_l t^l$$

$$E_x = \frac{Q}{2} x \sum_{l=0}^{\infty} c_l \sum_{i+j=l} \binom{l}{i} r^{2i} z^{2j} I_{i+1,j}(0) \qquad I_{n,m}(t_1) = \int_{t_1}^{\infty} \frac{1}{(a^2+t)^{1+n}(c^2+t)^{1/2+m}}\,dt$$

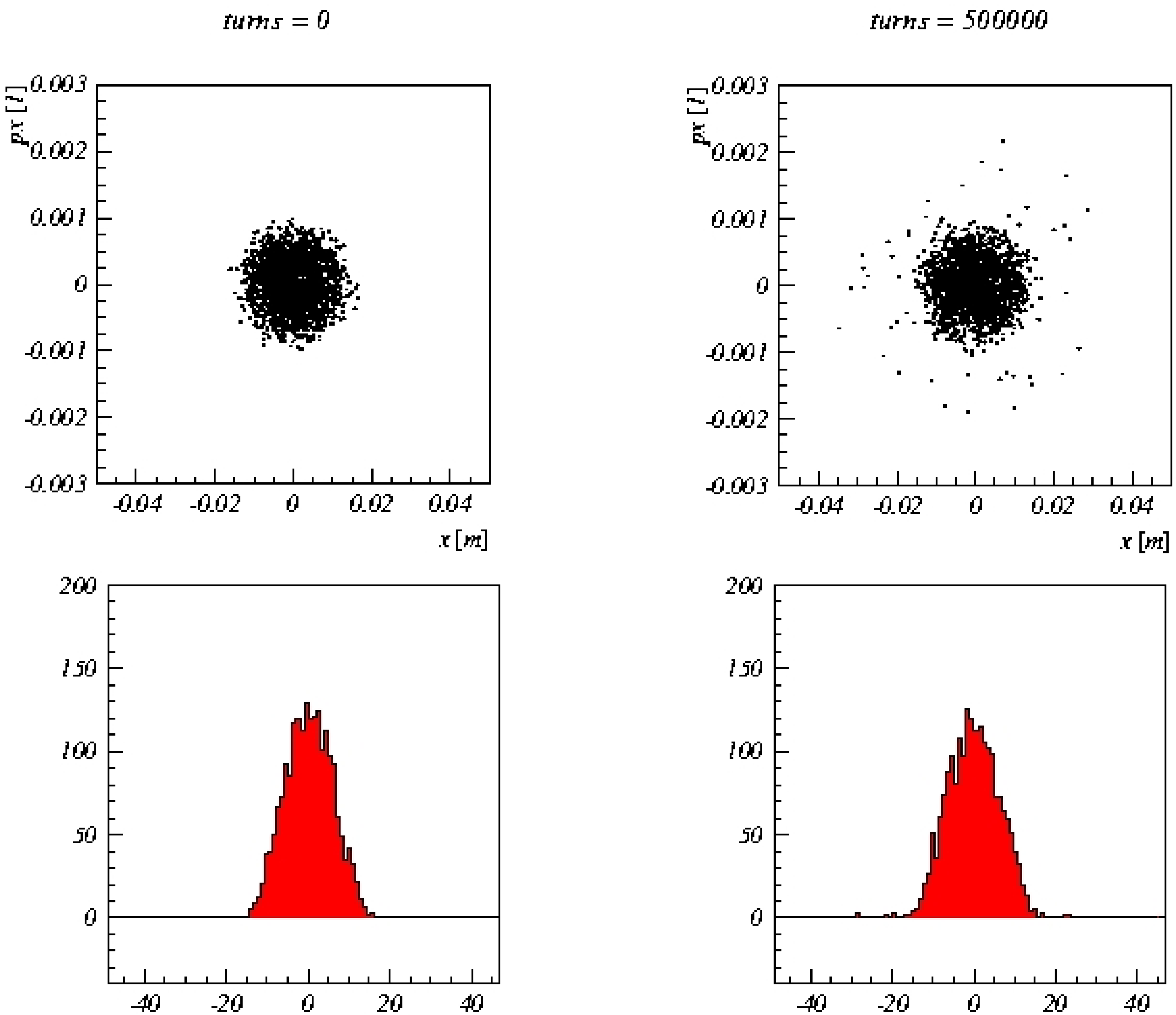
For the simulation

$$\hat{n}(t) = \begin{cases} \frac{105}{8}(1-t)^2 & if \quad t \le 1 \\ 0 & if \quad t > 1 \end{cases} \qquad n(x) = \frac{35}{32a}[1-(x/a)^2]^3$$

renormalizing beam size by computing the rms emittances every 500 turns



qx0 = 6.26



turns = 0
turns = 500000
px [1]
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.04
-0.02
0.02
0.04
x [m]
200
150
100
50
-40
-20
20
40

Conclusion

- We have described a mechanism for halo formation in rings
- Simulation prediction are in good agreement in the region of emittance growth
- We predict a halo radius which increases as Qx0 approaches the resonance
- Beam loss may occur when halo radius exceed dynamic aperture