Long Term Simulations of the Space Charge and Beam Loss in the SIS18 Experiment

G. Franchetti

30/9/2010

GSI, Darmstadt

Introduction

Nonlinear modeling of the SIS18

Experimental results and simulations

The truth in theory and the truth in the experiment

Trapping or Scattering ?

Conclusion/Outlook

Introduction

Space charge effects

Coherent

Coulomb forces
feed back on the
beam as whole changing
beam properties

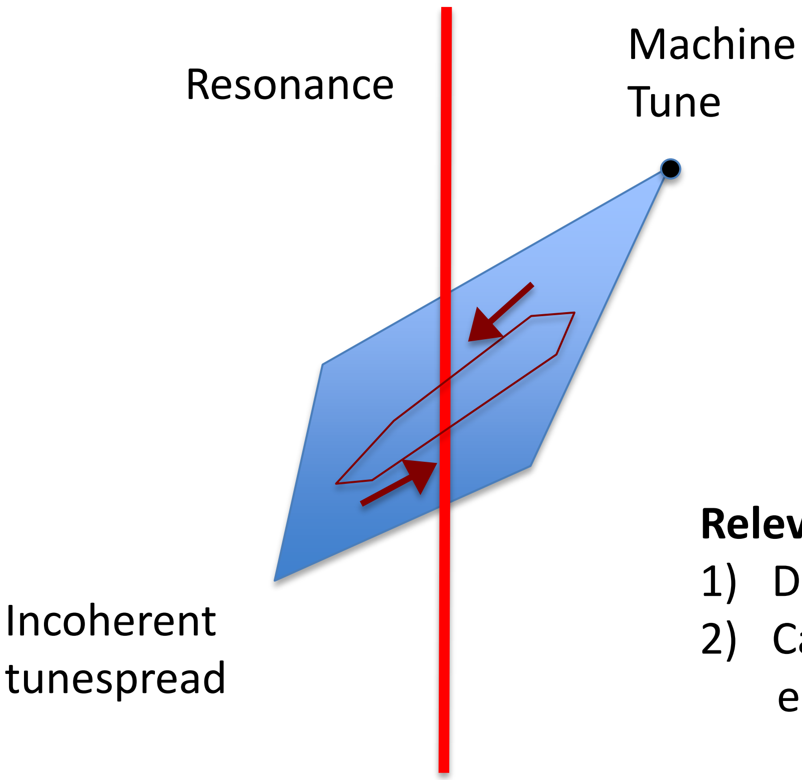
Incoherent

The Coulomb forces from
the beam are created by
a beam distribution which
does not change

The incoherent force acts
like a lattice force
(approximation)

Relevant for long term storage
(= hundreds of synchrotron oscillations)

Schematic of the study



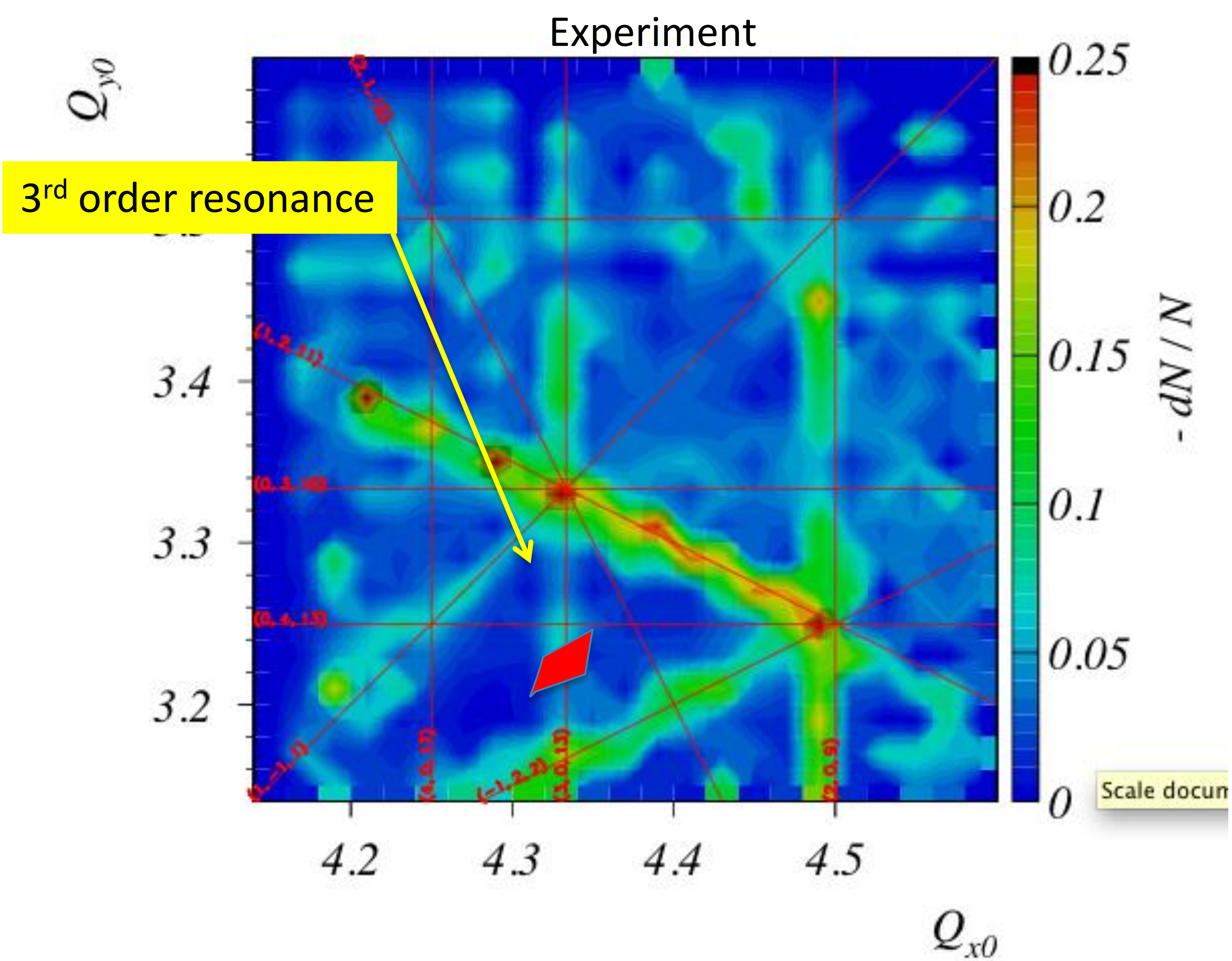
Aim

Study the beam dynamics
of a high intensity bunched beams
stored for several 10^5 turns

Relevant Issues

1) Do we understand what is going on ?
2) Can we predict beam loss & emittance increase?

Choice of the resonance



Systematic studies on the effect of the synchrotron motion on the bunched beam dynamics

Experiment parameters

Typical parameter of the measurements

Parameter			Value	Units
Energy per nucleon			11.28	MeV/u
Ion mass number			40	
Ion charge state			18	
RF Harmonics			4	
RF Voltage			4	kV
Total particles per bunch	10^8	$\times$	3.125	
Gamma transition			5.01	
Rigidity			1.077	Tm
SIS18 circumference			216.1	m
Average β_x			~ 8	m
Average β_y			~ 10	m
Revolution time			4.673	μs
Eta transition			0.9362	
Synchrotron tune	10^{-3}	$\times$	6.915	
Bunching factor			0.3357	
Rms momentum spread	10^{-3}	$\times$	1.3	
Bunch length 4σ			560	ns
Max $\delta p/p$ in the bucket	10^{-3}	$\times$	7.4	
Horizontal emittance at 2σ			19	mm mrad
Vertical emittance at 2σ			14	mm mrad
Horizontal peak tune shift	10^{-2}	$\times$	-4	
Vertical peak tune shift	10^{-2}	$\times$	-4.5	

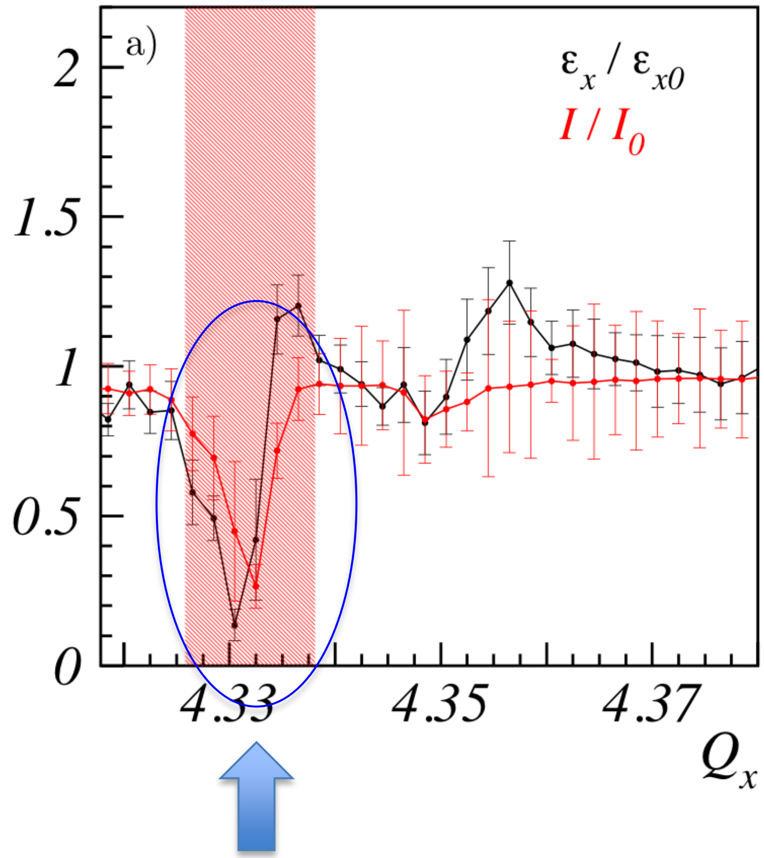
We have created 4 types of bunches:

1) low intensity coasting beams
2) high intensity coasting beams
3) low intensity bunched beams
4) high intensity bunched beams

Ideal situation: the incoherent tunespread should be the same for high intensity coasting beams and bunched beams

Scan at low intensity

Experiment



$\Delta Q_x = -0.008/ - 0.011$

1) Chromatic correction sextupoles
2) Possible 4th order nonlinearities (octupoles)

Model:

1 Sextupole driving the 3rd order resonance
1 Octupole to match the slope in beam loss

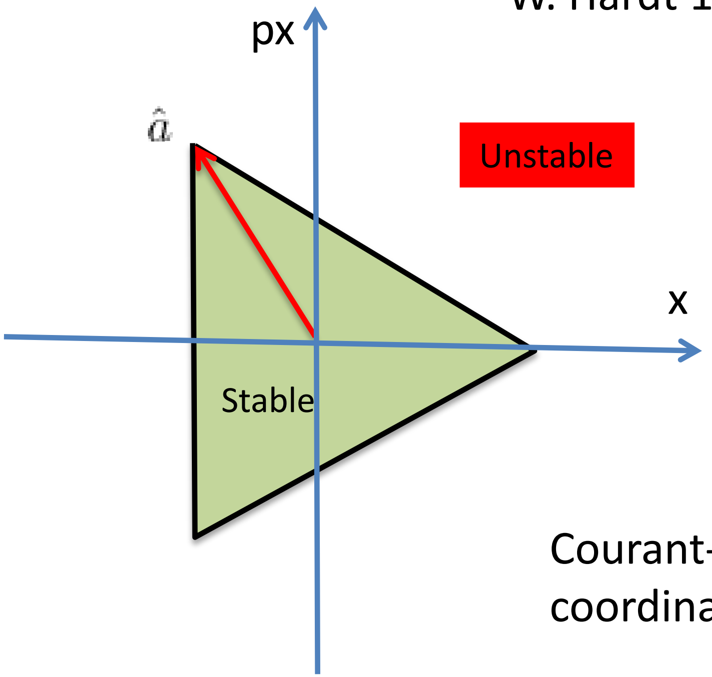
Beam loss appears titled → indication of detuning effects

The effect of resonance 3 Q_x = 13

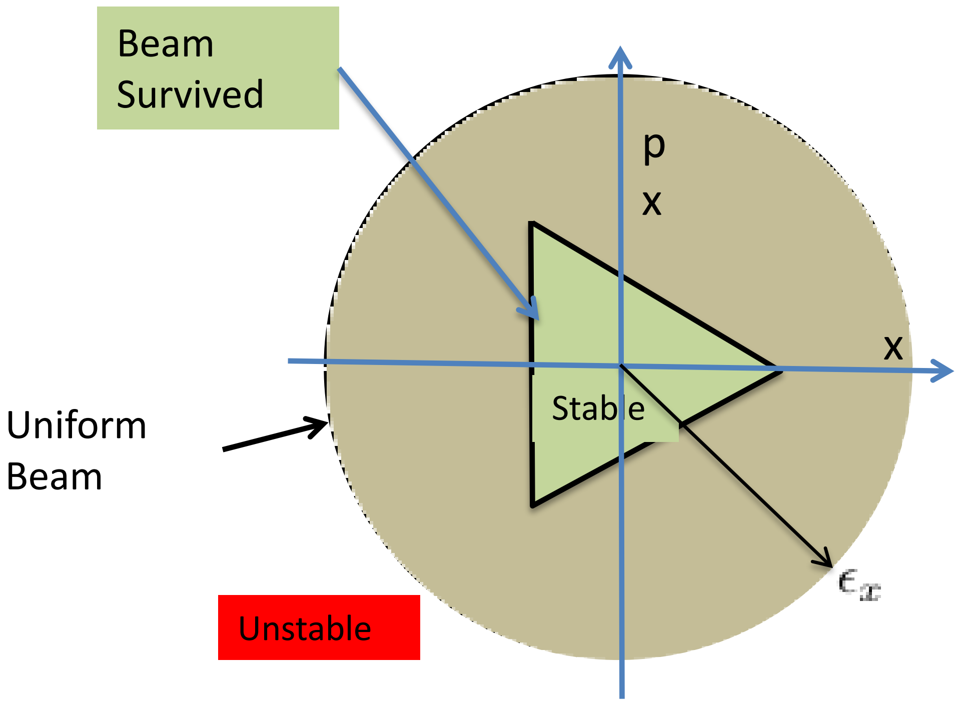
Classical theory of
3rd order resonance

$$\hat{a} = \frac{16\pi}{\beta_x^{3/2} K_2} \Delta Q_x$$

W. Hardt 1981



Courant-Snyder
coordinates



$$\frac{N}{N_0} = \frac{1}{\epsilon_x} 3\sqrt{3} \frac{64\pi}{\beta_x^3 K_2^2} \Delta Q_x^2$$

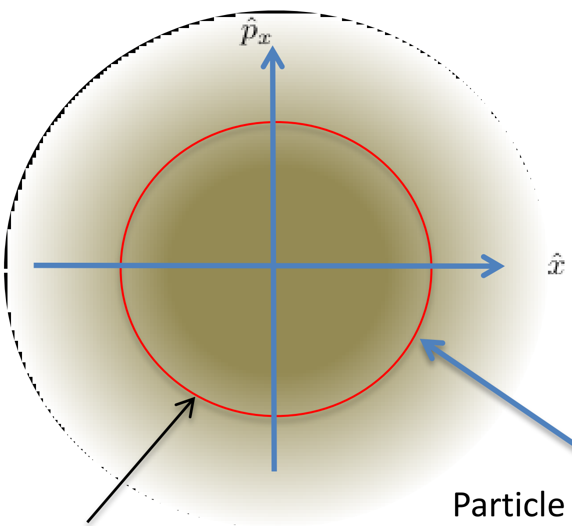
Beam loss in a Gaussian distribution

Example of a Gaussian cut in energy

matched distribution

$$\rho \propto \exp\left(-\frac{1}{2}\frac{\hat{x}^2+\hat{p}_x^2}{\tilde{\epsilon}_x}\right)$$

$\tilde{\epsilon}_x$ rms emittance



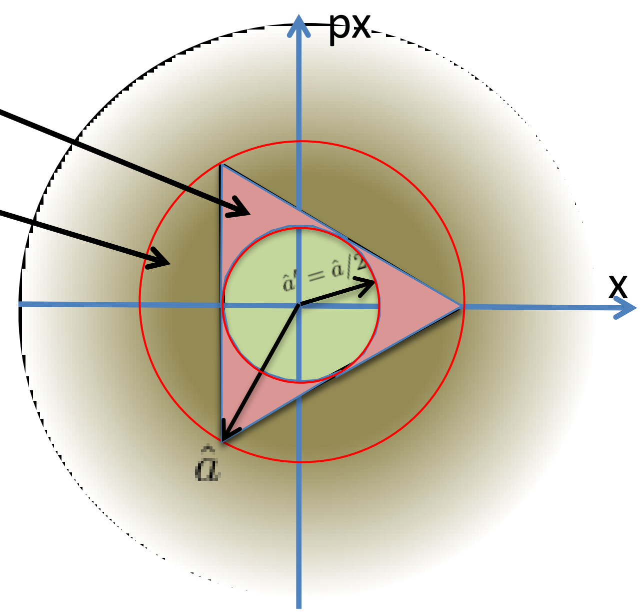
Cut of particles with r > r_c

Particle survival for cut in Energy

$$N/N_0 = 1 - e^{-\hat{r}_c^2/(2\tilde{\epsilon}_x)}$$

Beam survived

Beam lost



Beam loss is bounded by

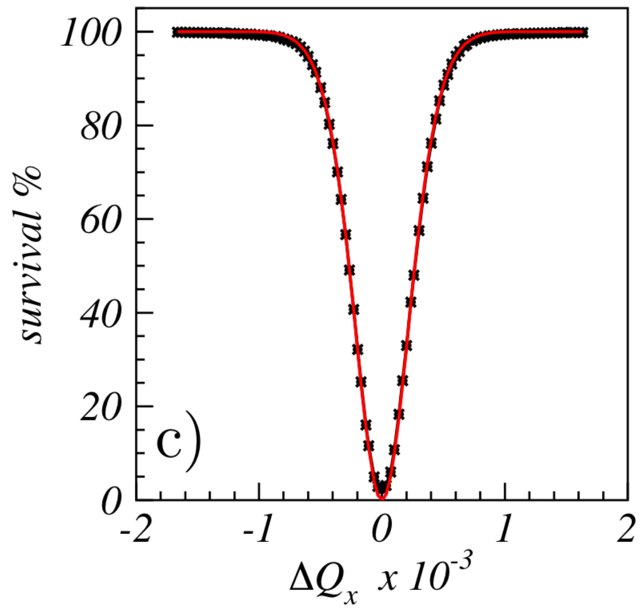
$$1 - e^{-\hat{a}'^2/(2\tilde{\epsilon}_x)} < \frac{N}{N_0} < 1 - e^{-\hat{a}^2/(2\tilde{\epsilon}_x)}$$

Beam loss stop band by 1 sextupole

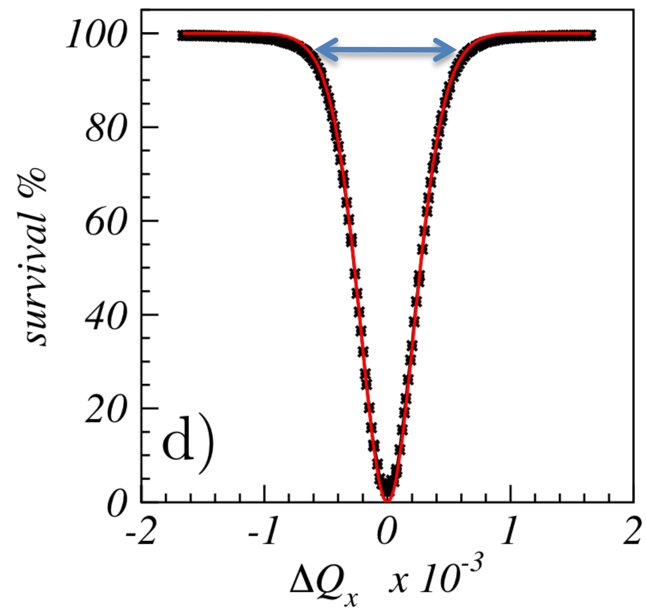
Search for a solution of type $\frac{N}{N_0} = 1 - e^{-\sum_{n=1}^{\infty} \alpha_n (\hat{a}^2/\tilde{\epsilon}_x)^n}.$

When ΔQ_x is close the resonance only α_1 is important → $\alpha_1 = \frac{3\sqrt{3}}{8\pi}$

1D example



2D example



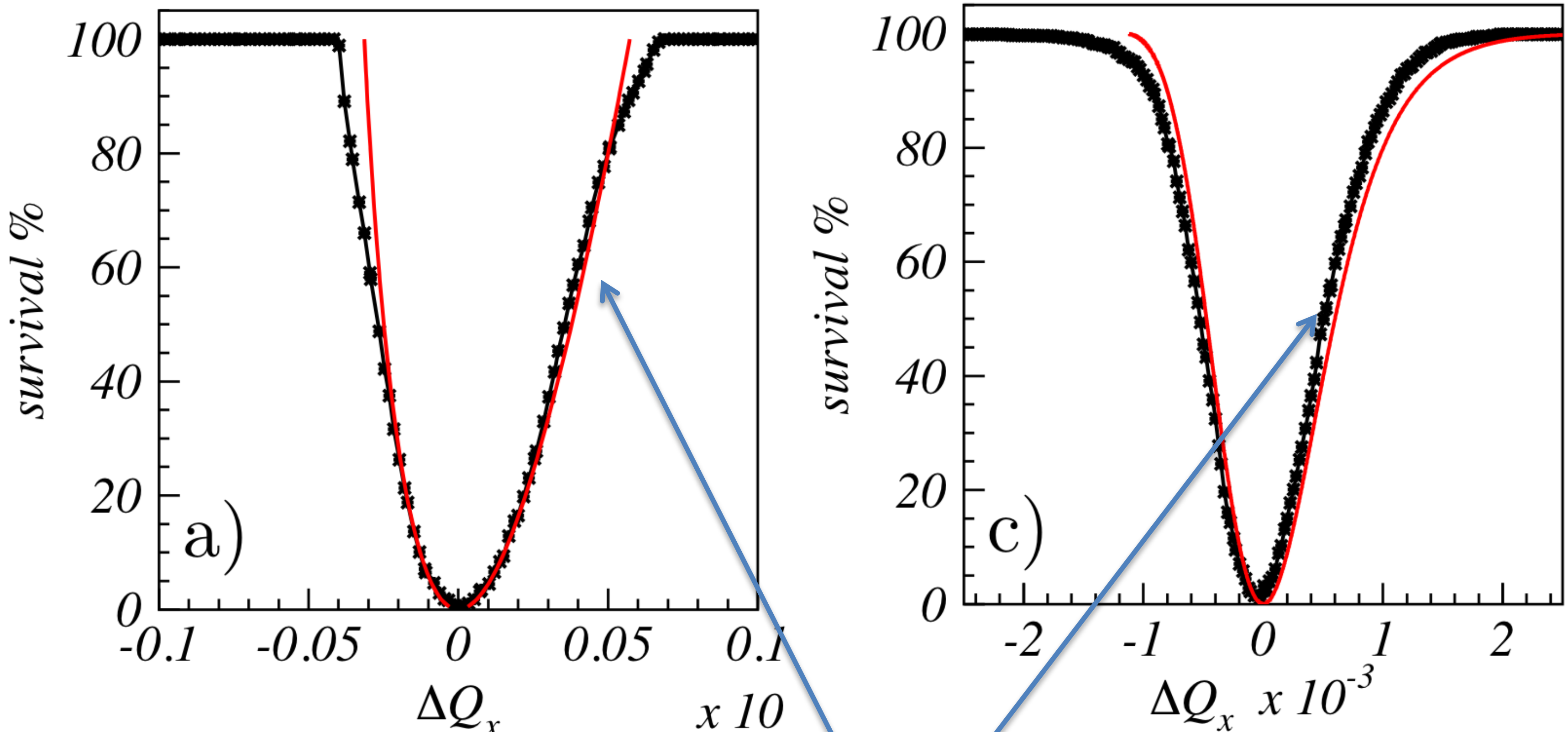
Beam loss stop-band $\boxed{\Delta Q_{x,sb} = 0.217\, \sqrt{\tilde{\epsilon}_x}\beta_x^{3/2} K_2}$

Effect of an octupole on beam loss

The octupole acts as a source of detuning

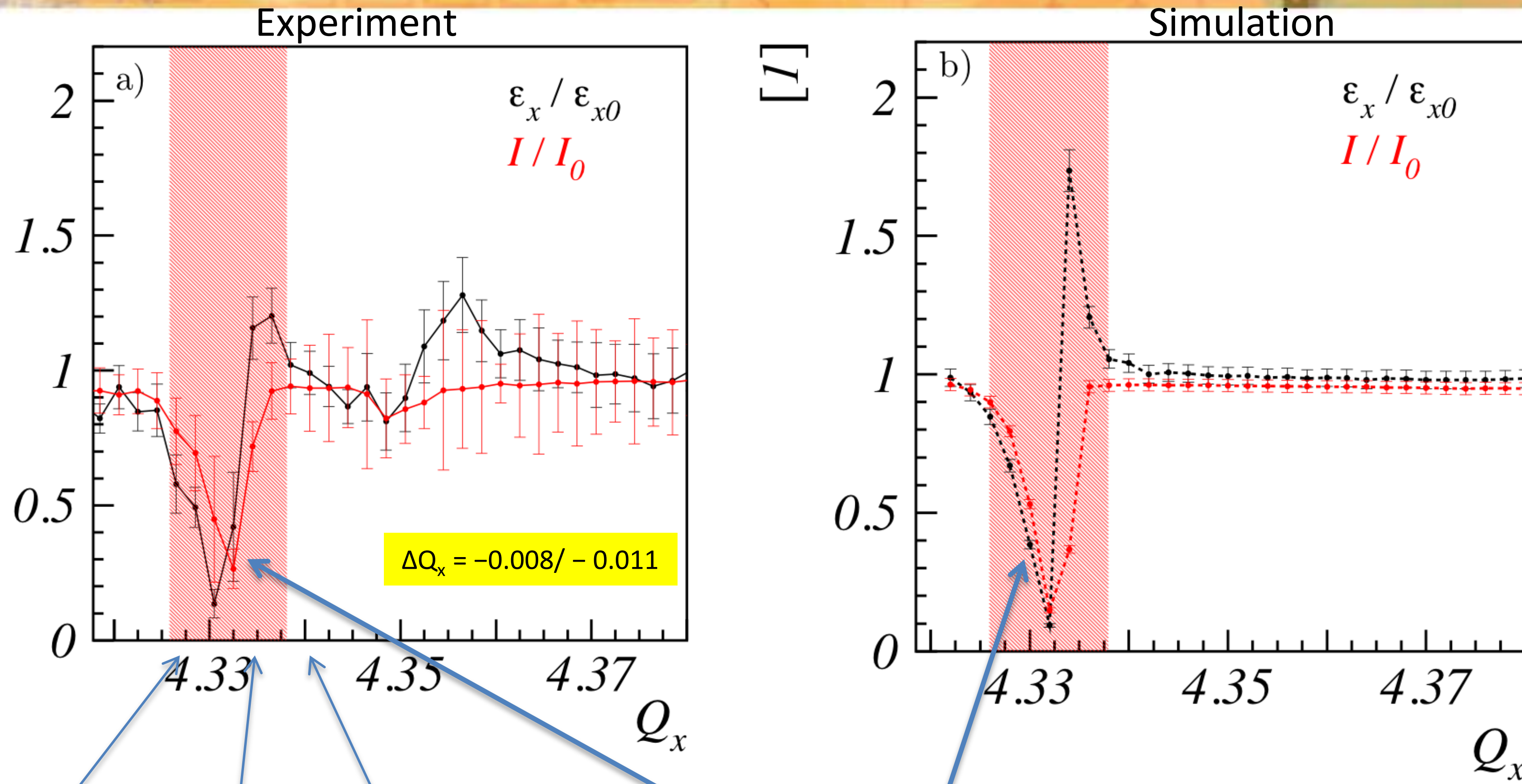
For a KV distribution

for 2D Gaussian beam



Asymmetry in the beam loss because of a detuning effect

Modeling of the nonlinear SIS18



Below resonance

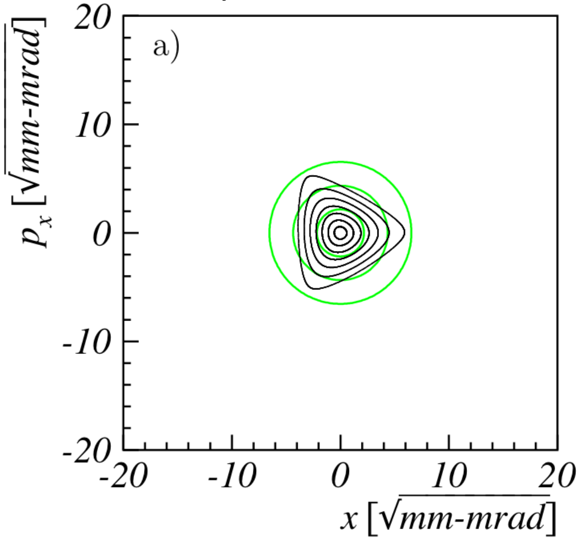
On the resonance

Above the resonance

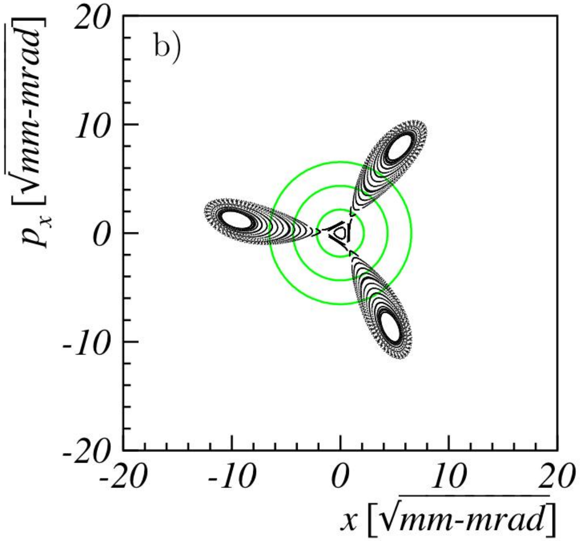
The pattern of beam loss is "similar"

Stability in phase space

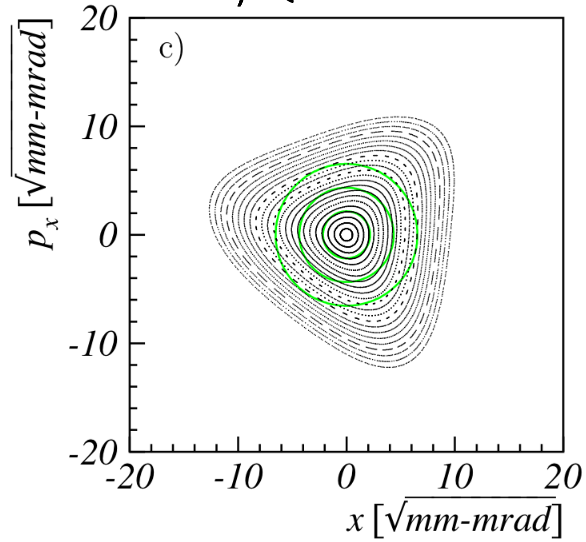
a) Qx = 4.328



b) Qx = 4.334



c) Qx = 4.34



Below the resonance

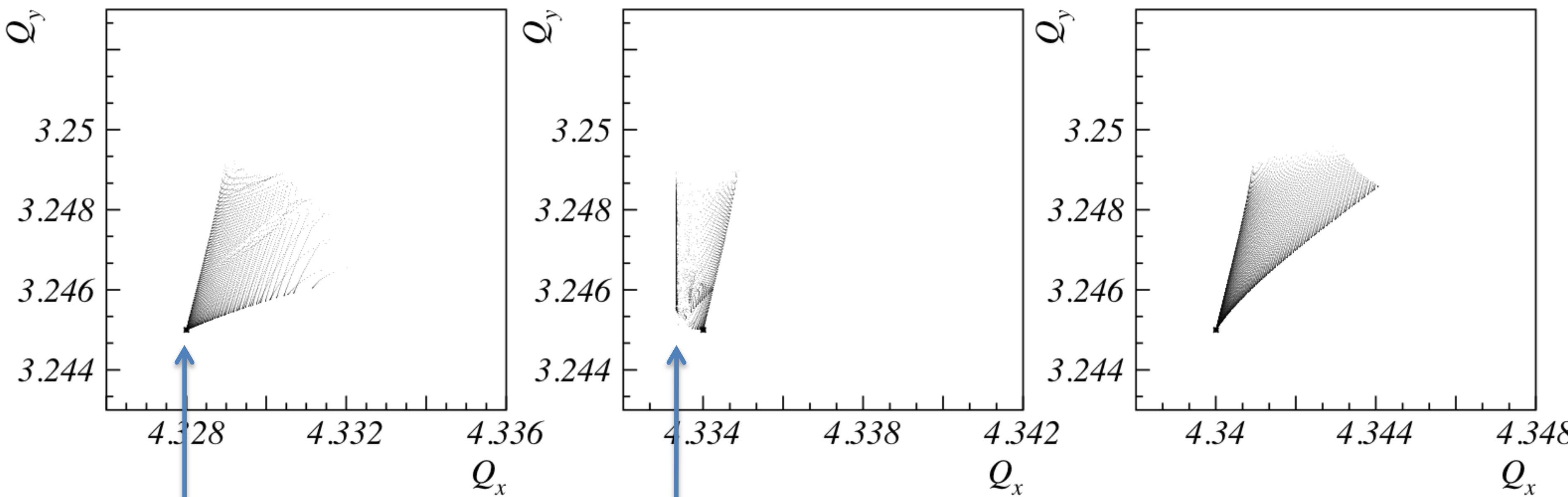
On the resonance
The detuning of the octupole creates a new stable islands

Above the resonance

Frequency map analysis

Only synchrotron nonlinearities = small effect

a) Qx = 4.328 b) Qx = 4.334 c) Qx = 4.34



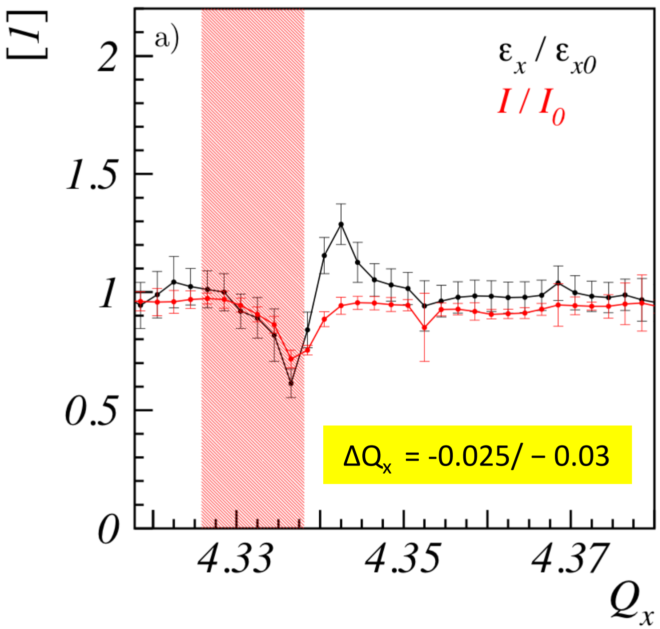
Bare tune

Particles locked on the 3rd order islands

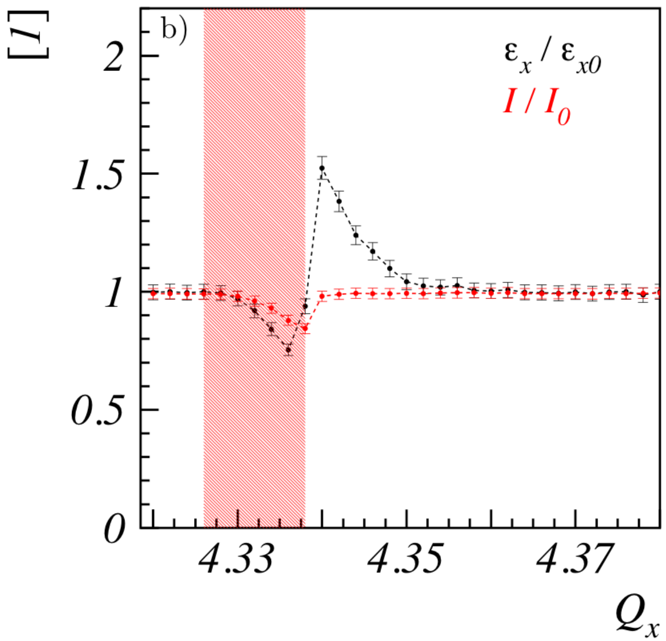
The effect of the space charge

Effect of the space charge on a coasting beam

Experiment

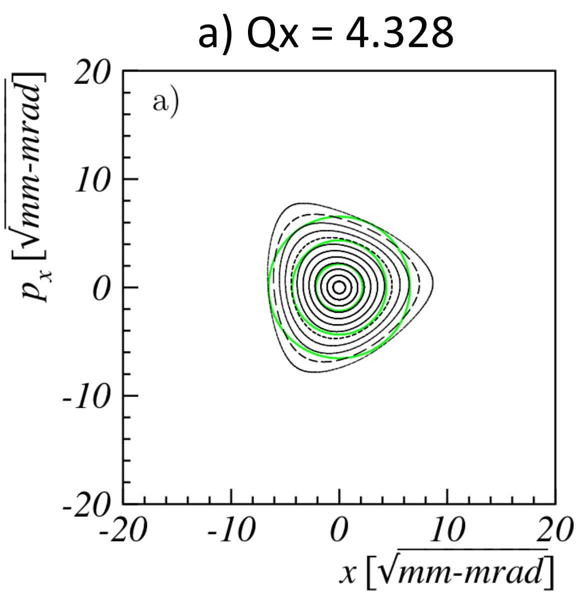


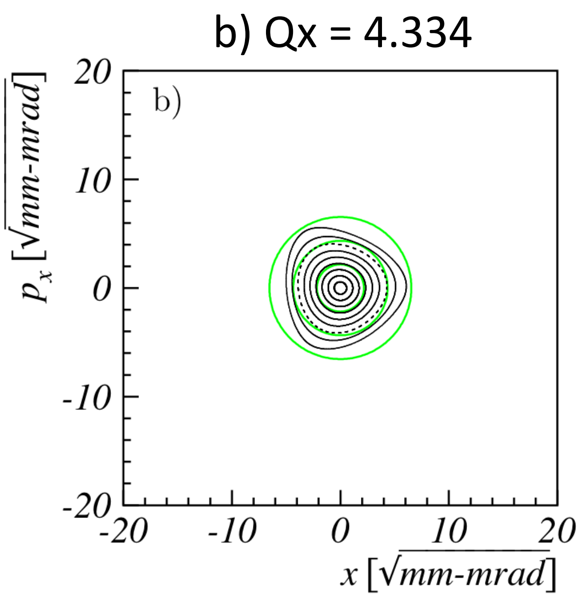
Simulation

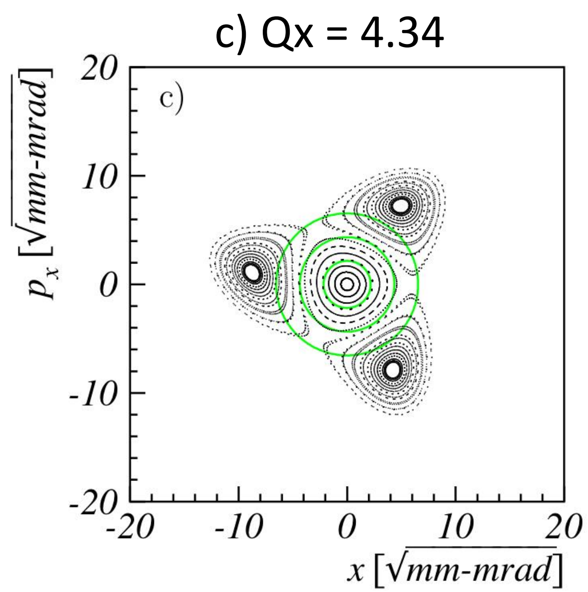


The peak of the emittance shifts on the right because of the space charge detuning

The effect of space charge: a phase space view







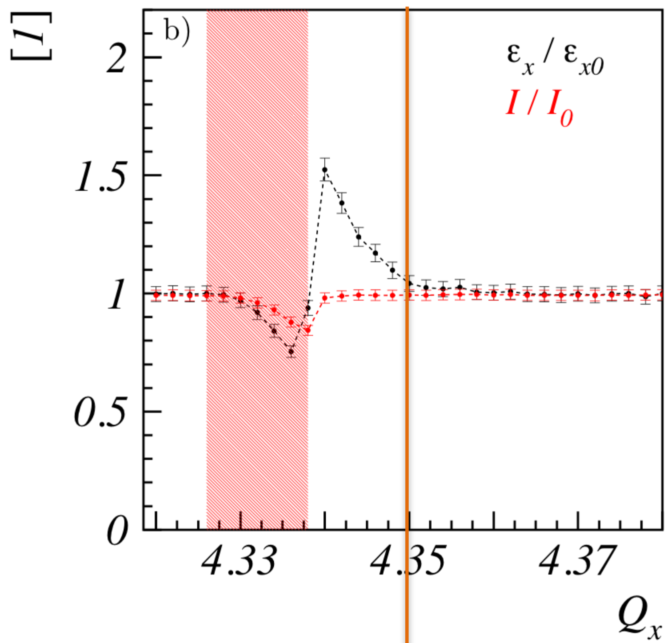
Below the resonance:
space charge stabilizes
a larger phase space area

On the resonance
The detuning of the
space charge
enlarge the separatrix

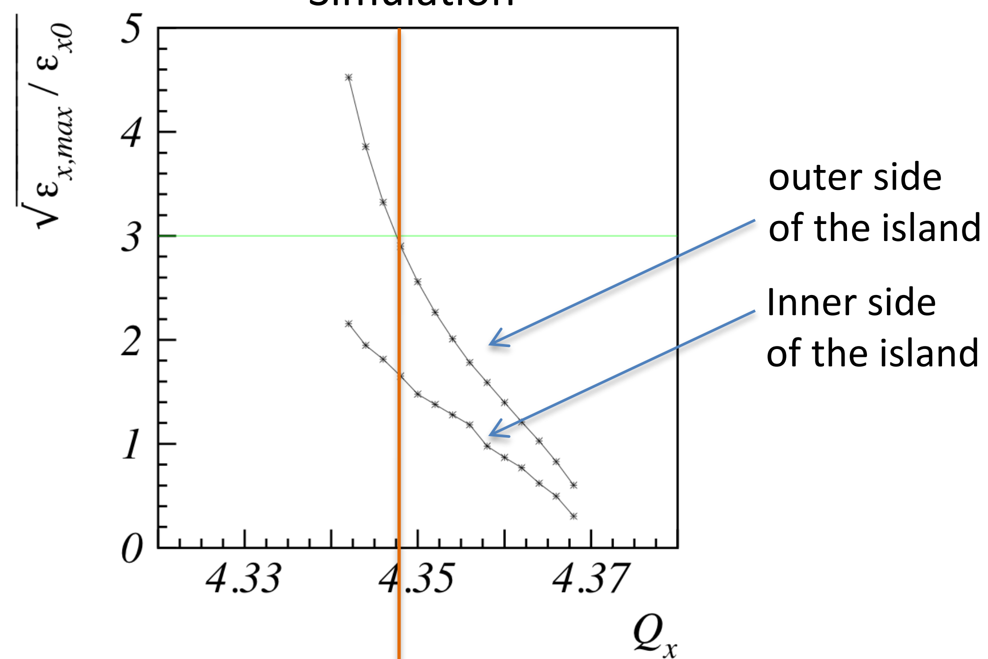
Above the resonance:
Large stable 3rd order islands
are created

Origin of the emittance growth (incoherent)

Simulation



Simulation



Emittance growth region

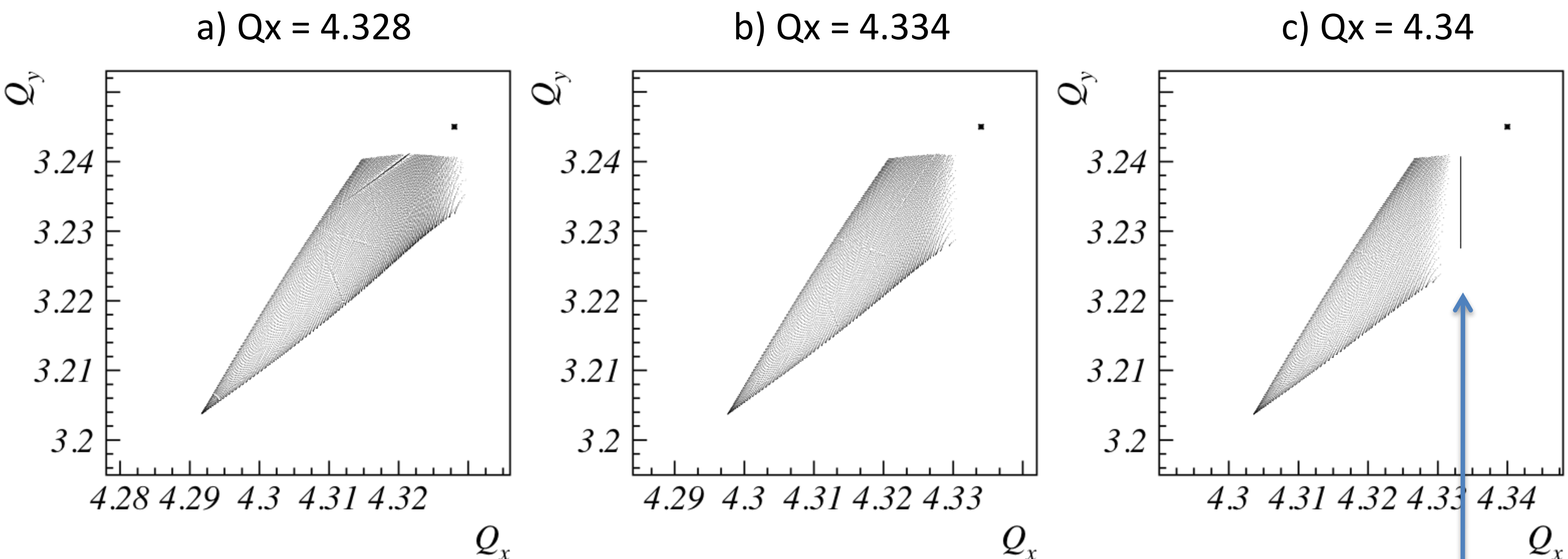
No Emittance growth region

Here the islands are inside the beam

Here the islands are inside the beam

The effect of space charge

Synchrotron Nonlinearities + Space Charge



The detuning created by space charge overcome those created by the lattice nonlinearities

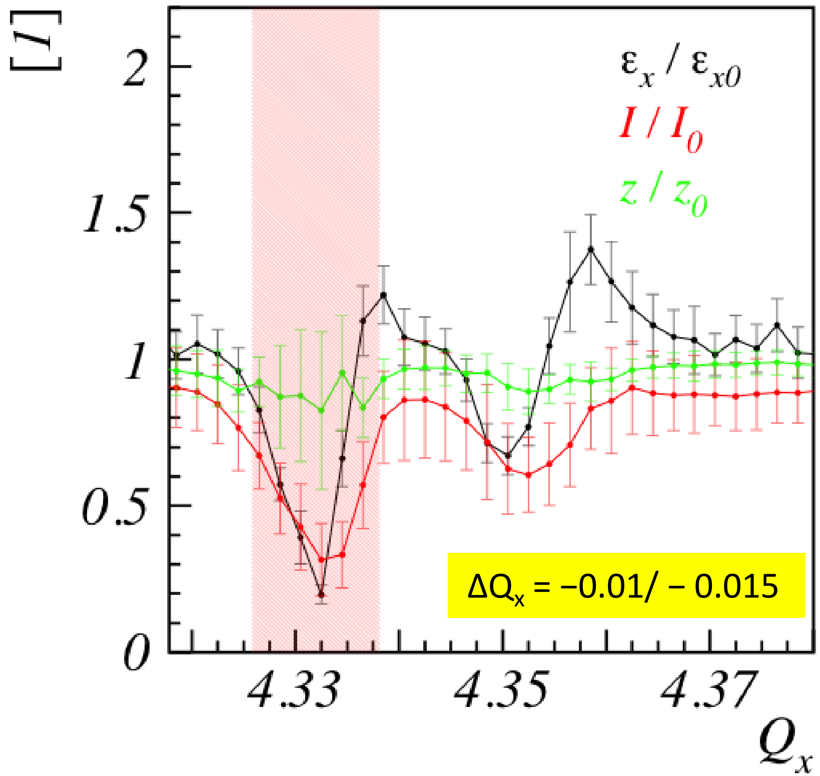
Particles locked on the large islands

What happen with a Bunched beam ?

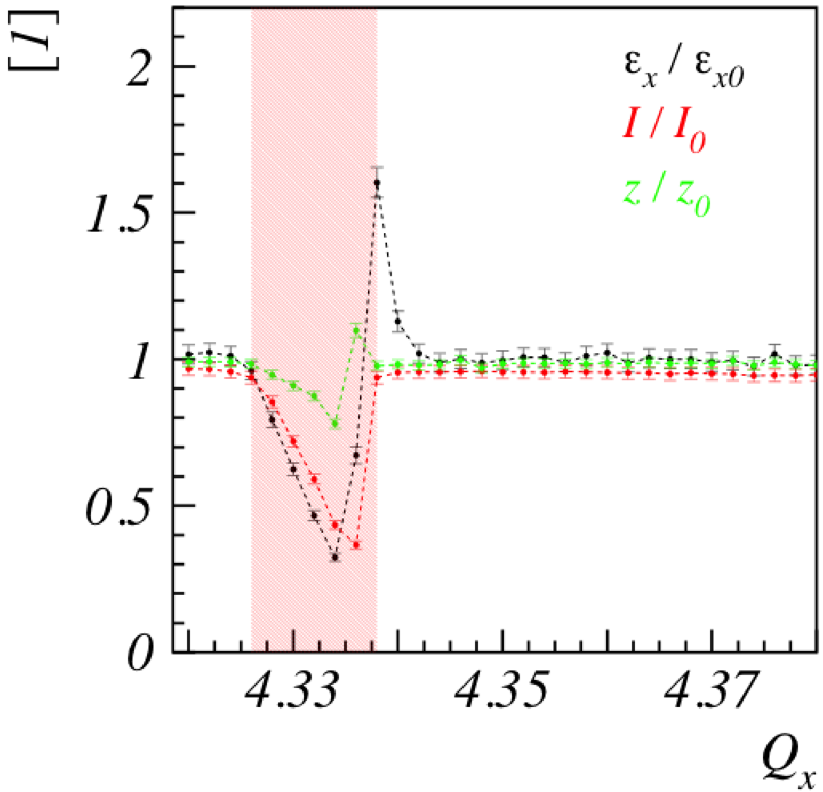
Low intensity

Chromaticity compensated with built-in control setting: not checked after set

Experiment



Simulation



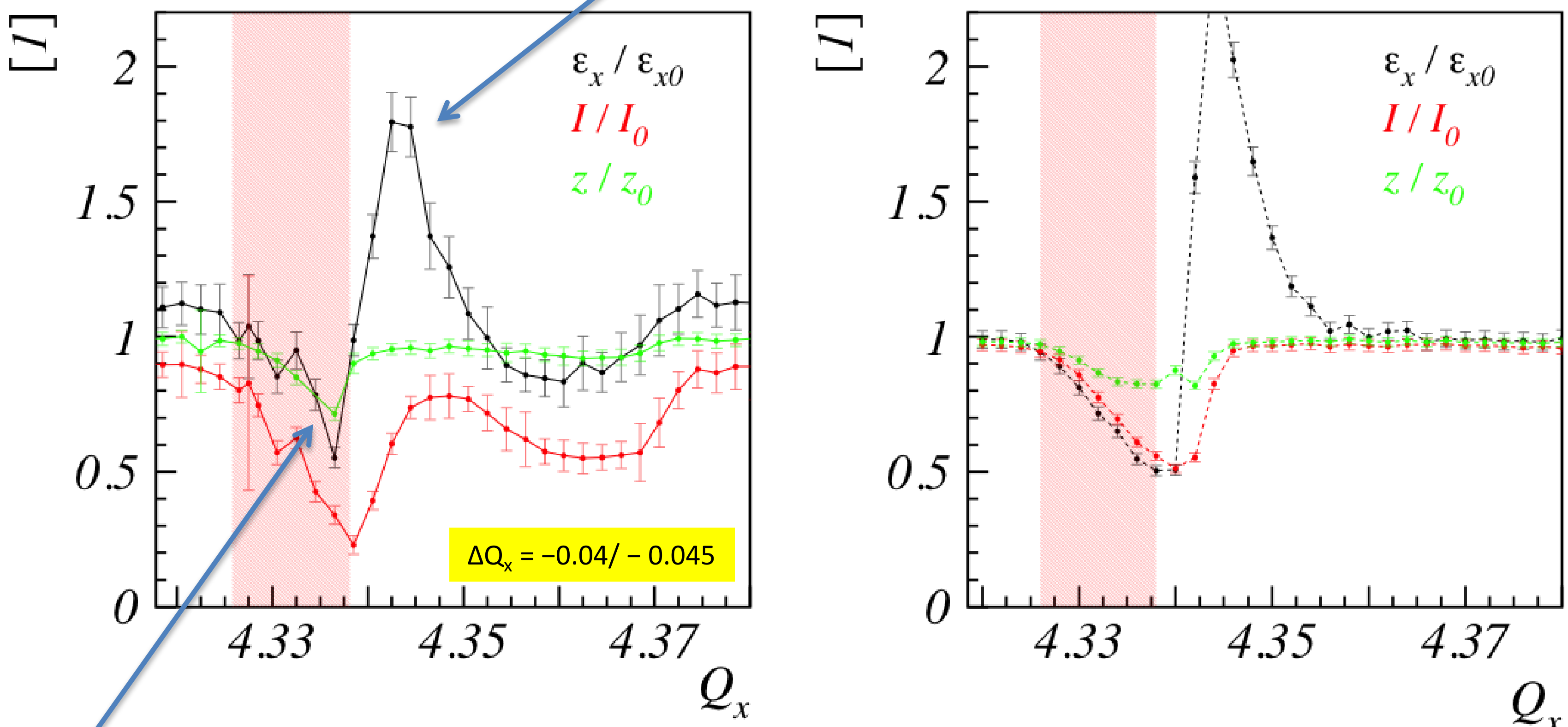
The beam loss stop-band is enlarged

Bunched beam at high intensity

Large emittance growth

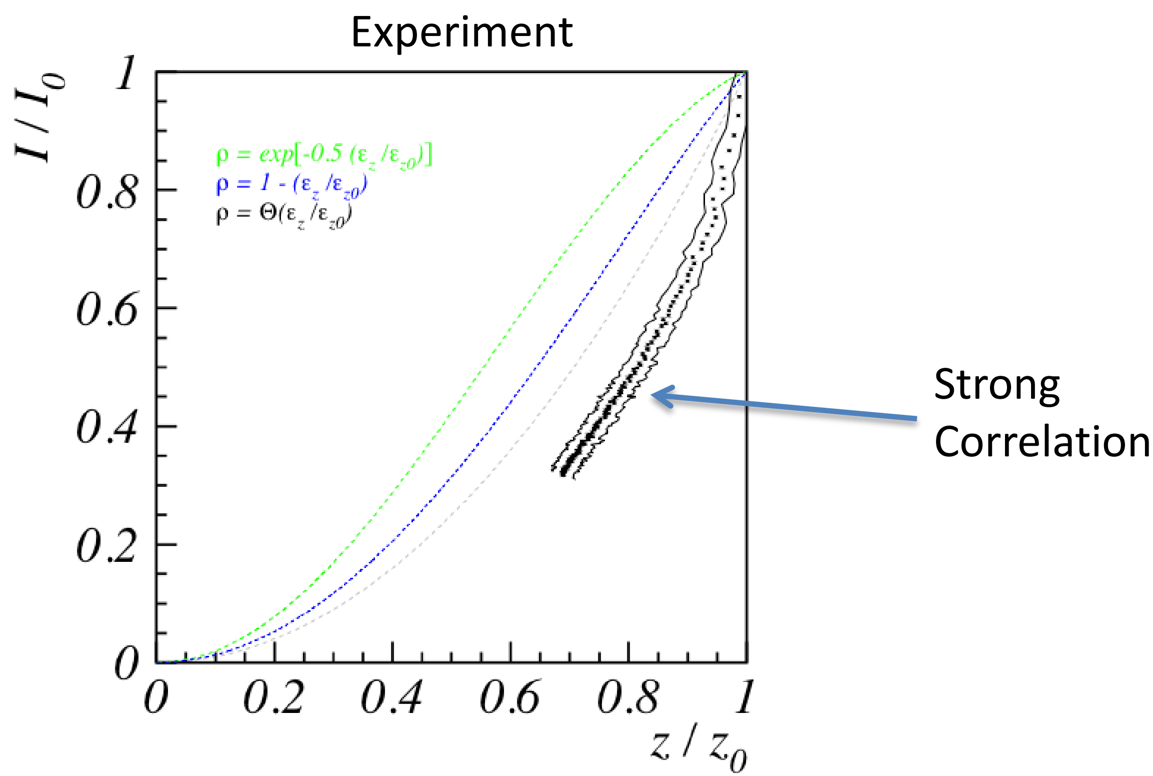
Experiment

Simulation



The bunch is shorter !

Bunch length vs. beam survival

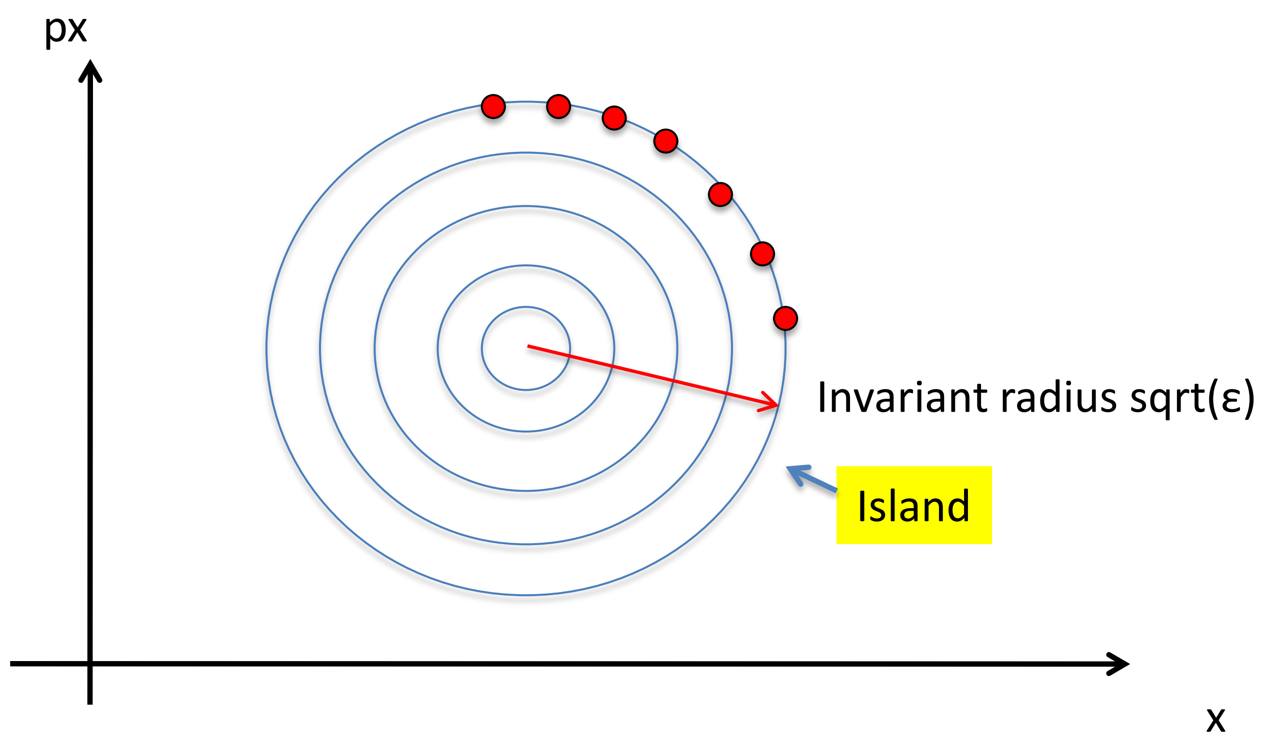


This effect happens only when the resonance takes place

Trapping or Scattering ?

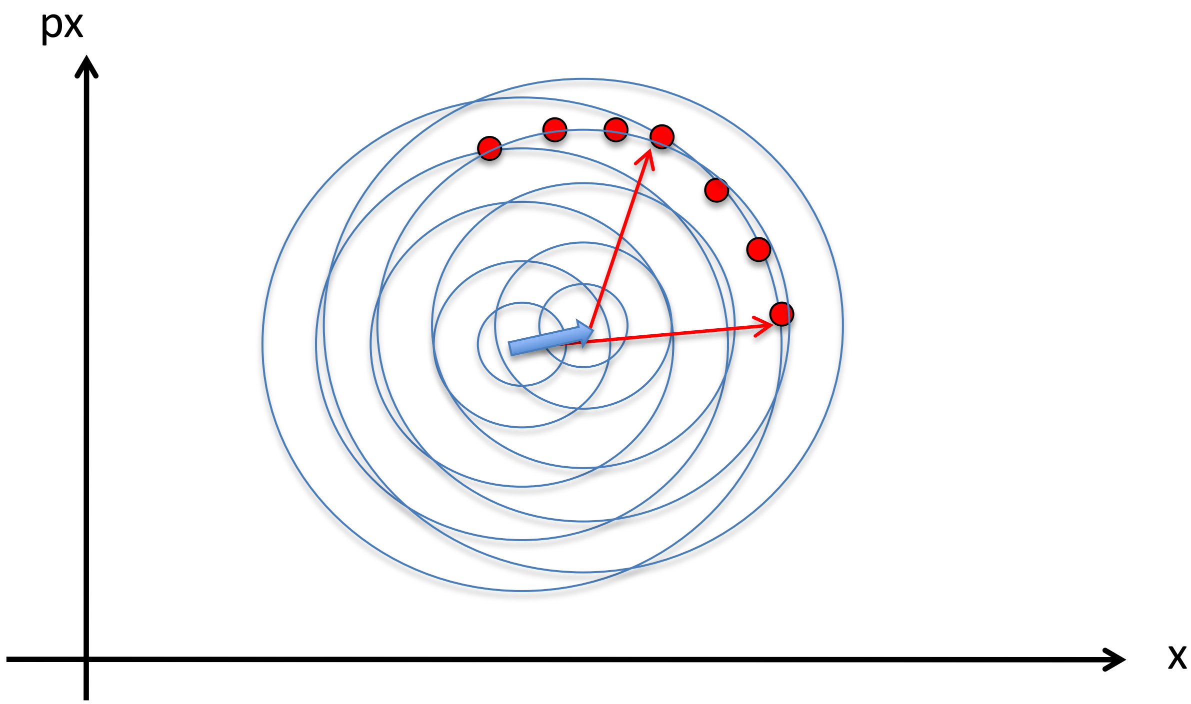
Trapping happens when particles can follow the ``frozen fixed point''

In a static system



Trapping or Scattering ?

Dynamics in a slow varying system

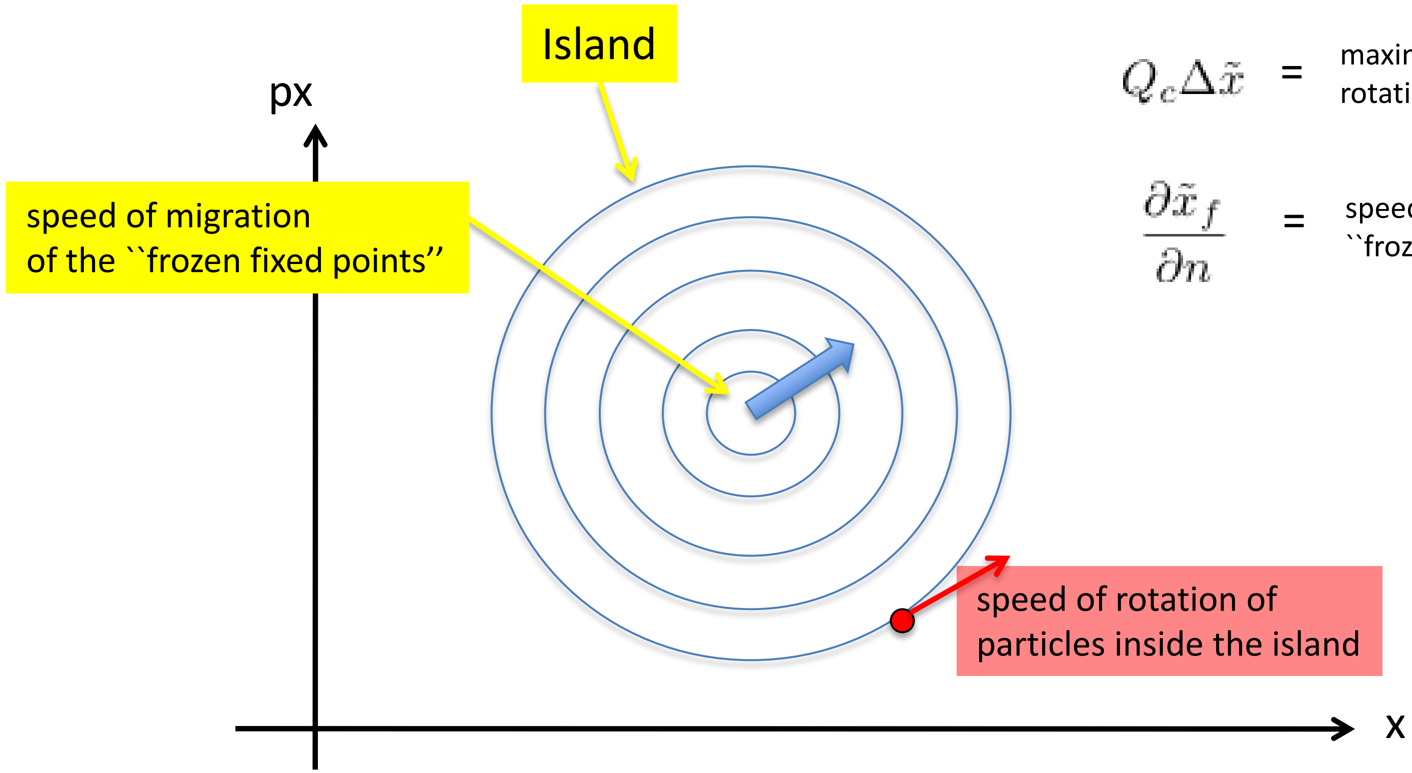


Trapping is related to an adiabaticity condition

$$T = \frac{\partial \tilde{x}_f(n)/\partial n}{Q_c \Delta \tilde{x}}$$

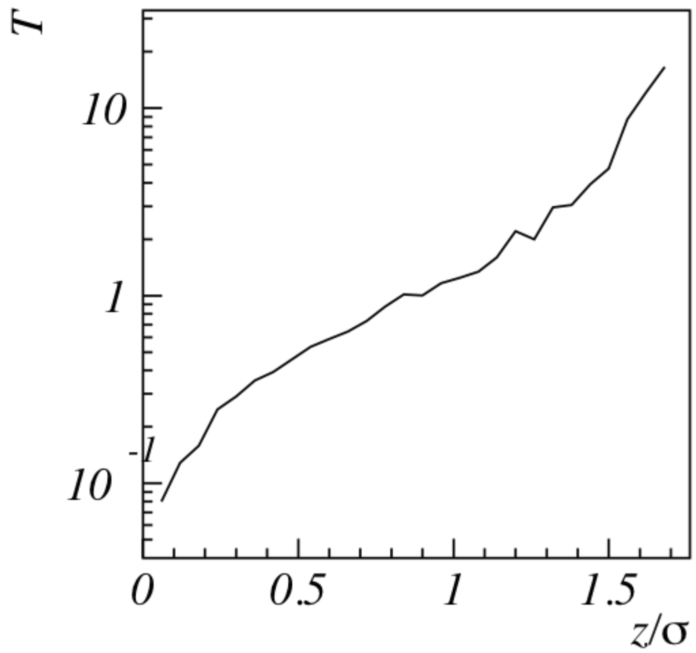
$Q_c \Delta \tilde{x}$ = maximum speed of rotation inside the island

$\dfrac{\partial \tilde{x}_f}{\partial n}$ = speed of migration of the ``frozen fixed points''



The picture is complicated…

T depends on the longitudinal location at which the frozen island cross particles



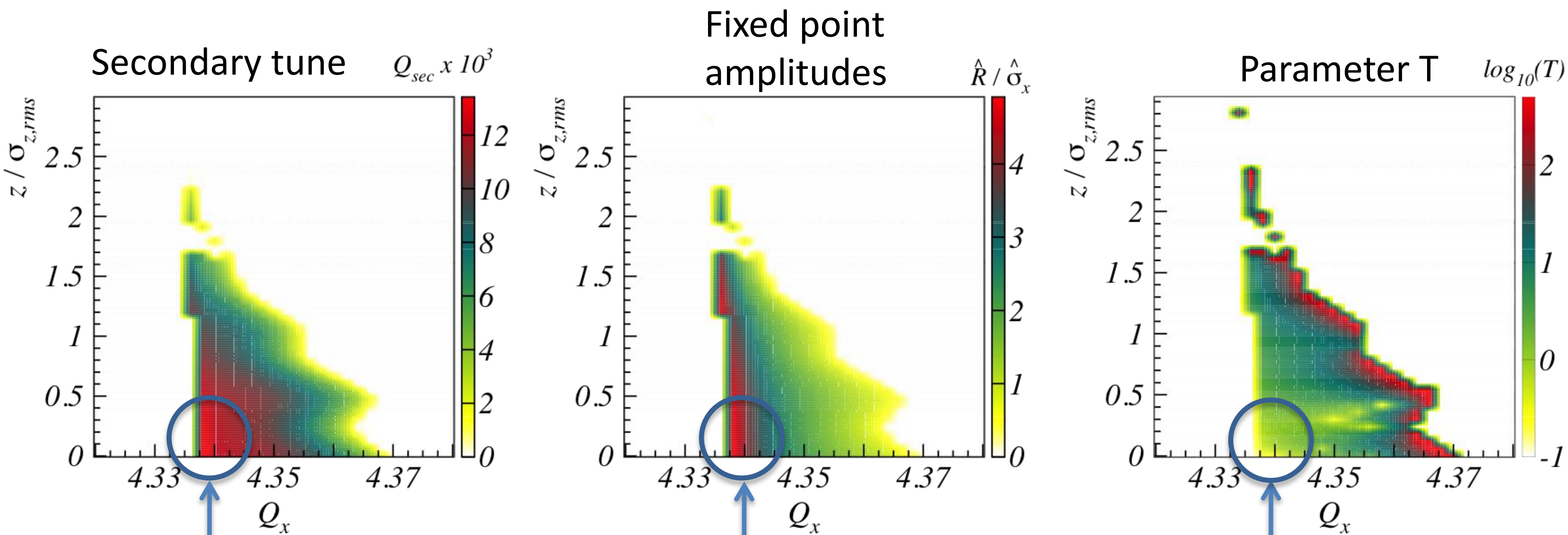
Trapping or Scattering ?

$$T = \frac{\partial \tilde{x}_f(n)/\partial n}{Q_c \Delta \tilde{x}}$$

is applied for a longitudinal dynamics of

$$z = z_{max} \cos(2\pi Q_z n)$$

where we take $z_{max} = 3\sigma_z$



Only these particles could get trapped

Conclusion

Experimental evidence:

Transverse emittance have a large growth only if high intensity and synchrotron motion are simultaneously present for a tune near the 3rd order resonance

Beam loss are accompanied by bunch shortening: effect happens always close the 3rd order resonance

Simulation benchmarking:

All 4 types of measurements have been reproduced with discrepancies probably due to the incomplete modeling of the SIS18 nonlinear lattice and to the self-consistence of the space charge calculations.

Maximum beam loss are predicted with factor 2 accuracy

Mechanism:

Numerical analysis of the experiment suggests that the dominant regime is of scattering. However the prove of this effect does not come out univocally clear as the experiment shows always observable quantities. A model of the induced diffusion regime induced by scattering is necessary.

Outlook

Studies of semi-analitic models for space charge calculation should be developed and tested with dedicated measurements.

Tests on the scattering-induced diffusion should be devised:
the effect of island scattering creates a nonlinear diffusion.
Experiments with beam of different size might reveal a distinct time pattern in beam loss or emittance growth which demonstrate the scattering mechanisms.

Studies of longitudinal bunch shaping (2RF) to be compared with the present findings (1RF).

Thanks to

I. Hofmann, W. Bayer, F. Becker, U. Blell,
O. Boine-Frankenheim, O. Chorniy, P. Forck,
T. Giacomini, M. Kirk, V. Kornilov, T. Mohite,
C. Omet, A. Parfenova, S. Paret, P. Schuett,
S. Sorge, P. Spiller