Multiple Resonance Crossings with Space Charge and Electron Cloud

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Overview

Resonance crossing phenomena

Space charge multiple resonance crossing

Electron cloud multiple resonance crossing

Conclusions

The dynamics issue

$$x'' + [k(s) + K(\epsilon)\cos(\omega s)]\,x = k_n(s)x^n$$

fast frequency → Machine Tune

slow frequency → slow tune modulation

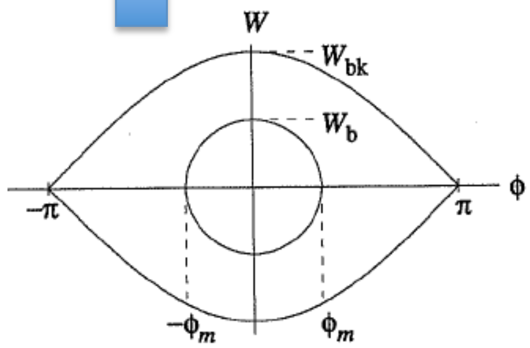
resonant term → excited by machine nonlinearities

The slow tune modulation creates a regime of resonance crossing

Incoherent Force

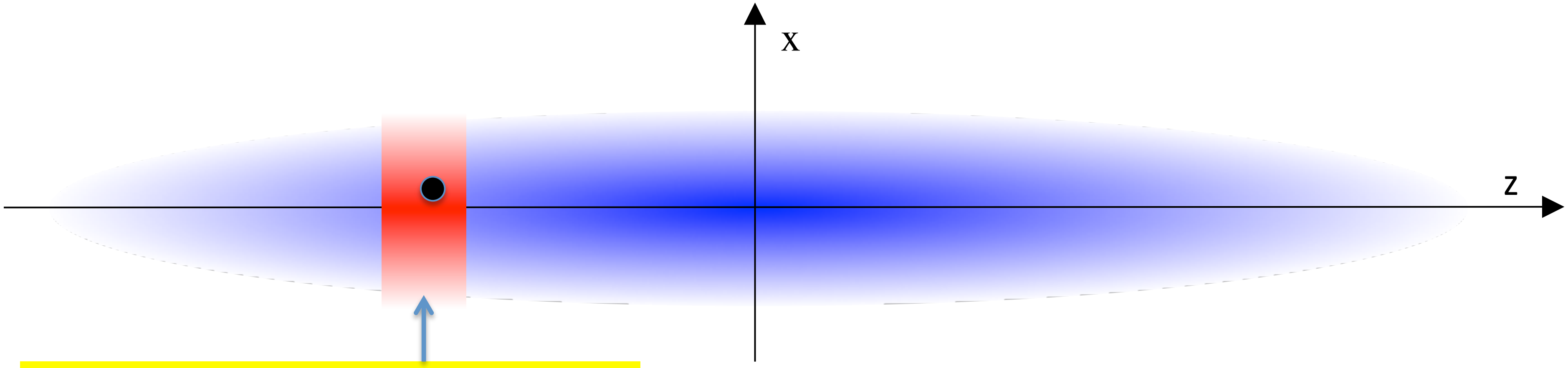
$$\propto K(\epsilon)\cos(\omega s)x$$

This force is driven by the "weak" coupling with the longitudinal plane (here a cosine function)



If the tune modulation frequency is small with respect to the fast frequency the dynamics can be of a "tune migration"

Transverse-Longitudinal coupling via space charge



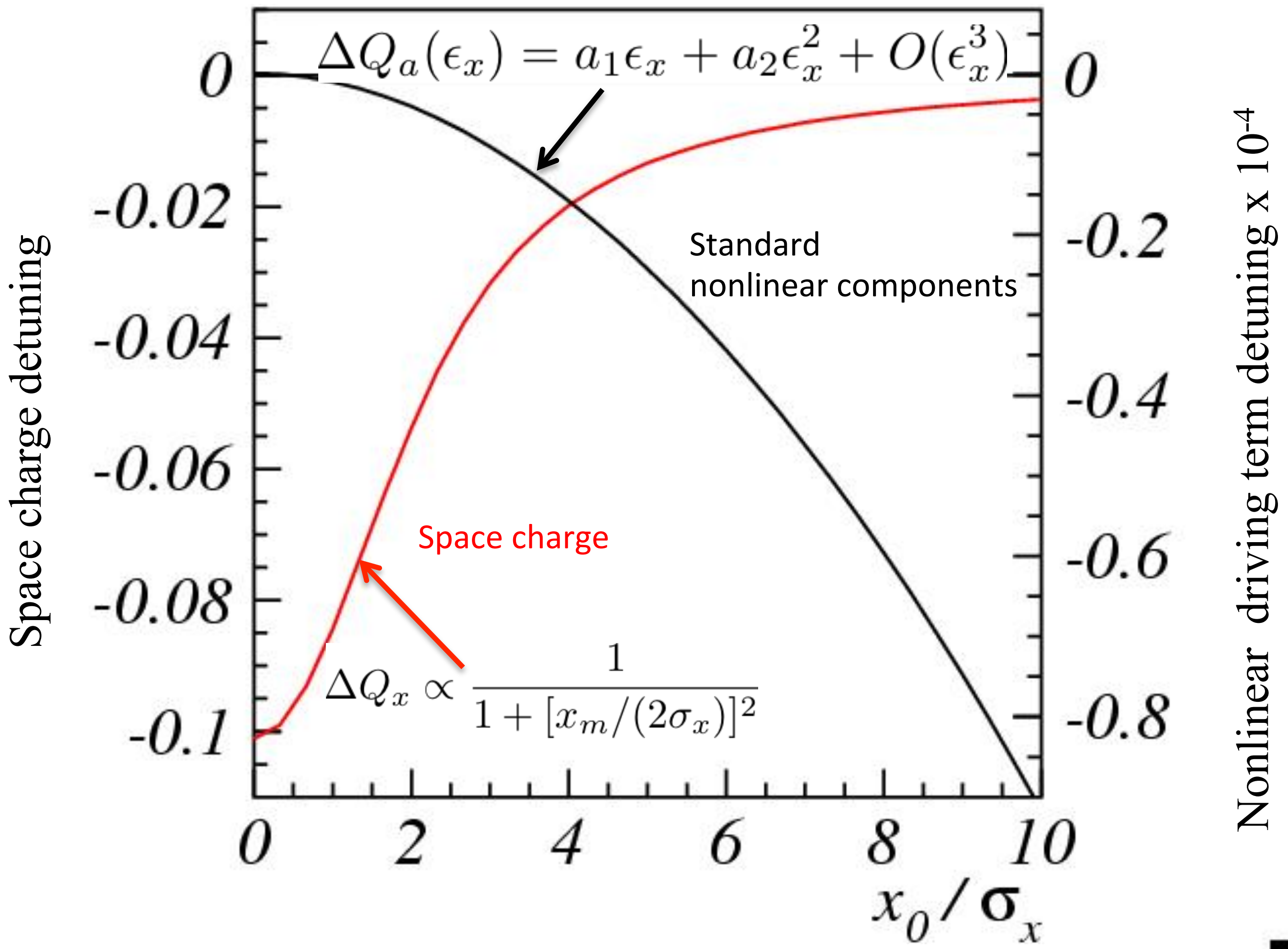
A particle experiences a space charge strength from the local bunch density, which is proportional to the longitudinal position

Transverse space charge force

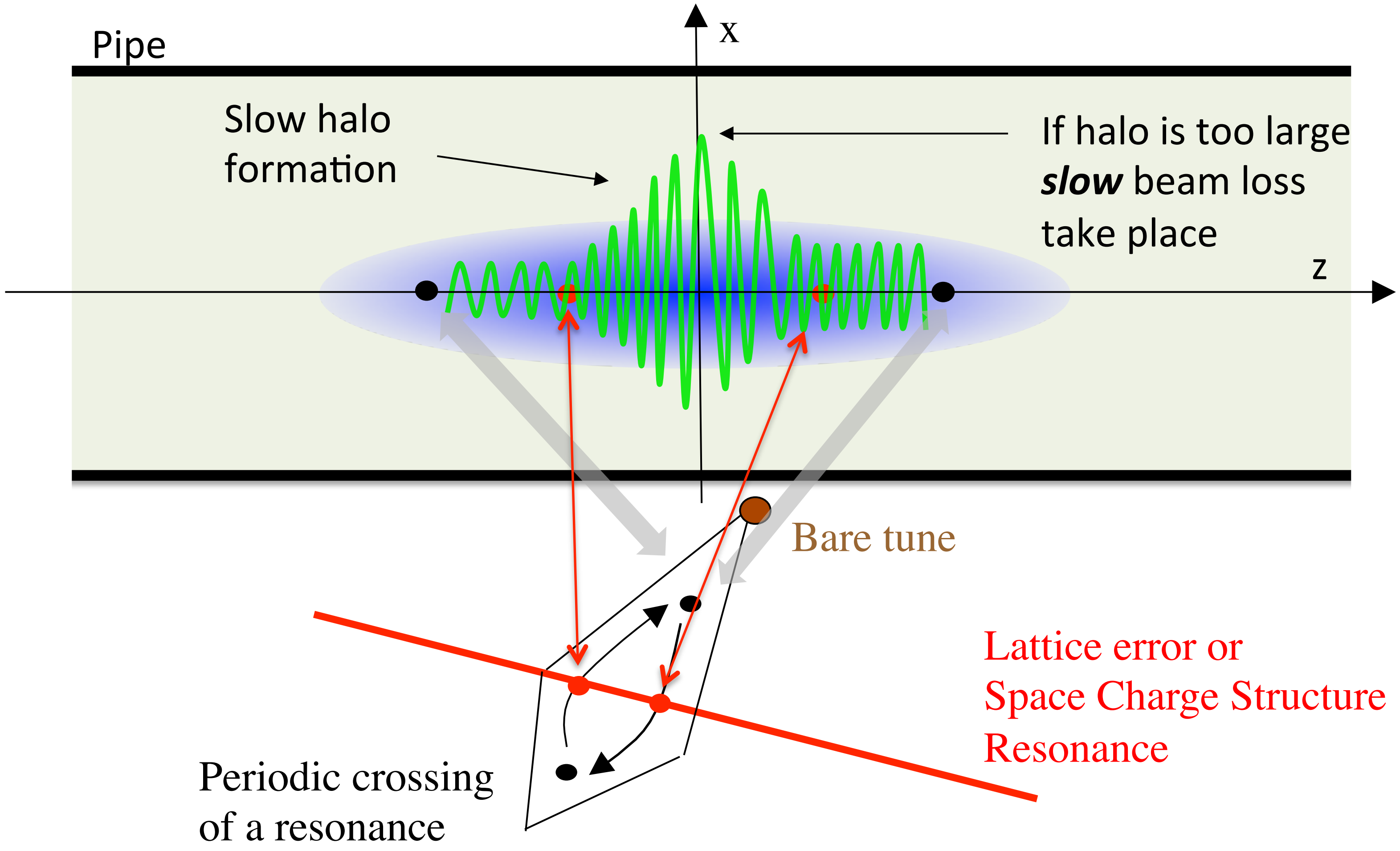
$$F \propto \underbrace{\exp\left[-\frac{1}{2}\left(\frac{z}{\sigma_z}\right)^2\right]}_{\text{longitudinal modulation}} \times \underbrace{\frac{1}{r}\left\{1 - \exp\left[-\frac{1}{2}\left(\frac{r}{\sigma_r}\right)^2\right]\right\}}_{\text{transverse}}$$

Amplitude dependent detuning from space charge

The space charge detuning has different nature from the lattice nonlinear errors induced detuning



Multiple resonance crossing in bunched beams induced by space charge



Classification of resonance crossing

Trapping into resonance

although the tune is modulated particles remain locked on the resonance

Large excursion of particles locked to compensate the modulation of the detuning

Basic phenomena

Separatrix crossing

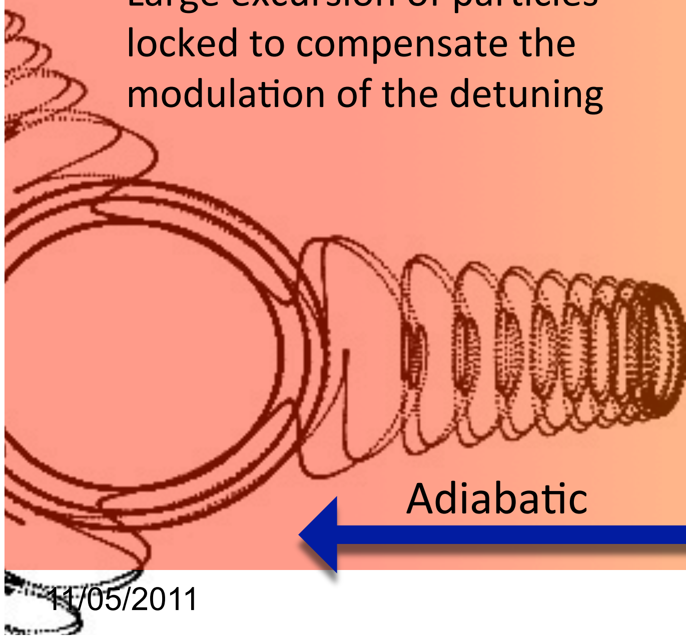
Scattering by resonance

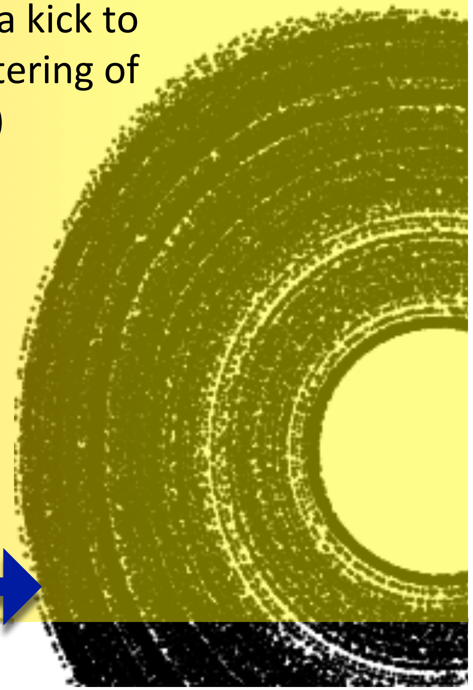
particles cross the separatrix but do not remain inside the island

Islands gives a kick to particle (scattering of the invariant)

All possible intermediate dynamical regimes are possible

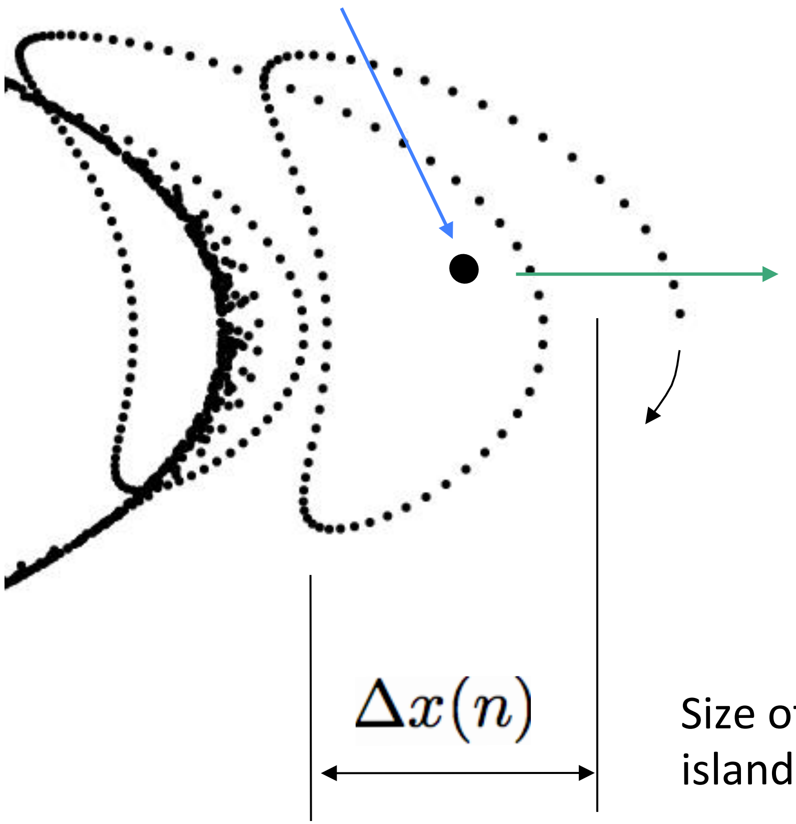
Adiabatic ⟷ Non-Adiabatic





Adiabatic / Non adiabatic Regimes

Tune on the Fixed point $Q_{xf}(n)$



Speed of the fixed point $\frac{\partial x_f(n)}{\partial n}$

$\Delta x(n)$

Size of the island

If during 1 revolution around the fixed point the island moves less than its size than the particle can remain trapped

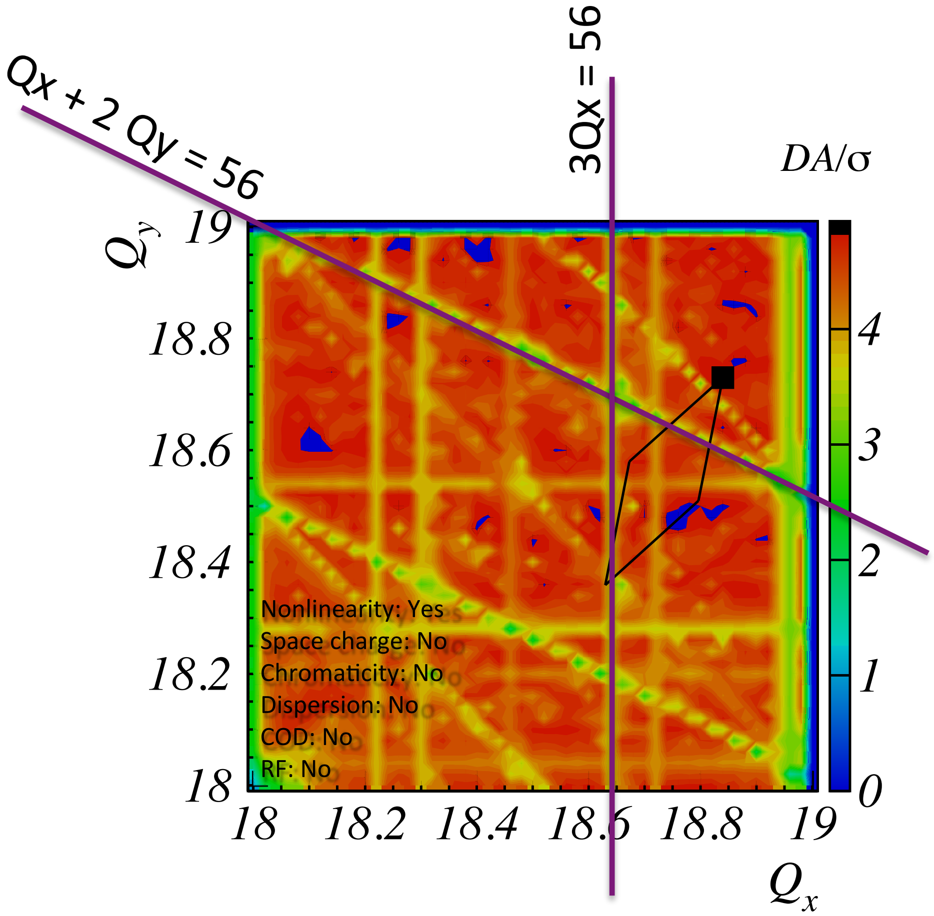
$$T \equiv \frac{\partial x_f(n)}{\partial n} \frac{1}{Q_{xf}(n)\Delta x(n)}$$

T << 1 characterize the adiabatic regime

A.W. Chao and Month NIM 121, 129 (1974).
A. Schoch, CERN Report, CERN 57-23, (1958)
A.I. Neishtadt, Sov. J. Plasma Phys. 12, 568 (1986)

Machine operations typically are in a non adiabatic regime

Multiple resonance crossing in SIS100



SIS100 resonances for the

Standard seed

Mitigation of long term effects

Compensate the resonance
Qx + 2 Qy = 56
without exciting the resonance
3 Qx = 56

Compensation strategy

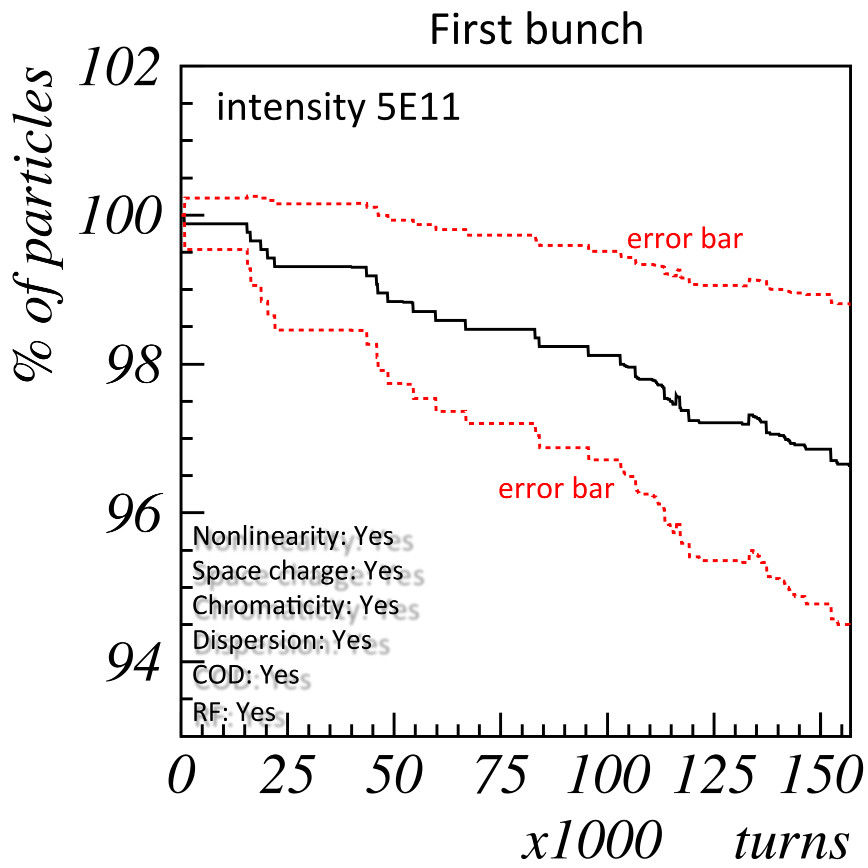
Cancellation of the driving terms of
Qx + 2 Qy = 56 and 3 Qx = 56
at the crossing of the two resonances

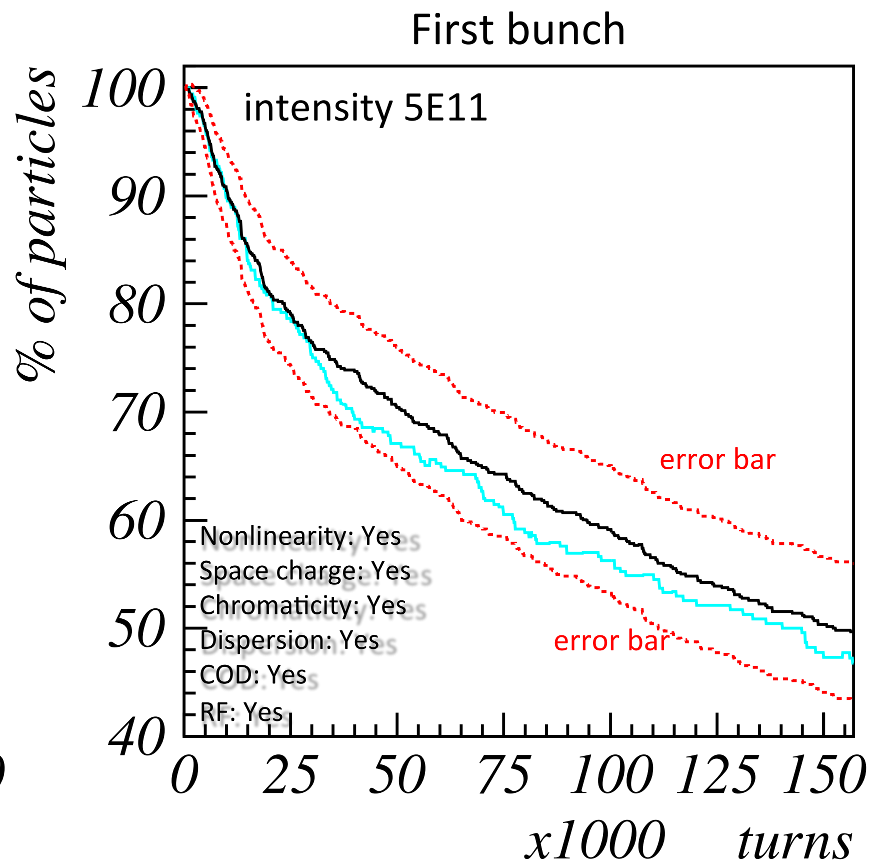
Beam loss prediction for SIS100

main resonance compensated

Standard seed

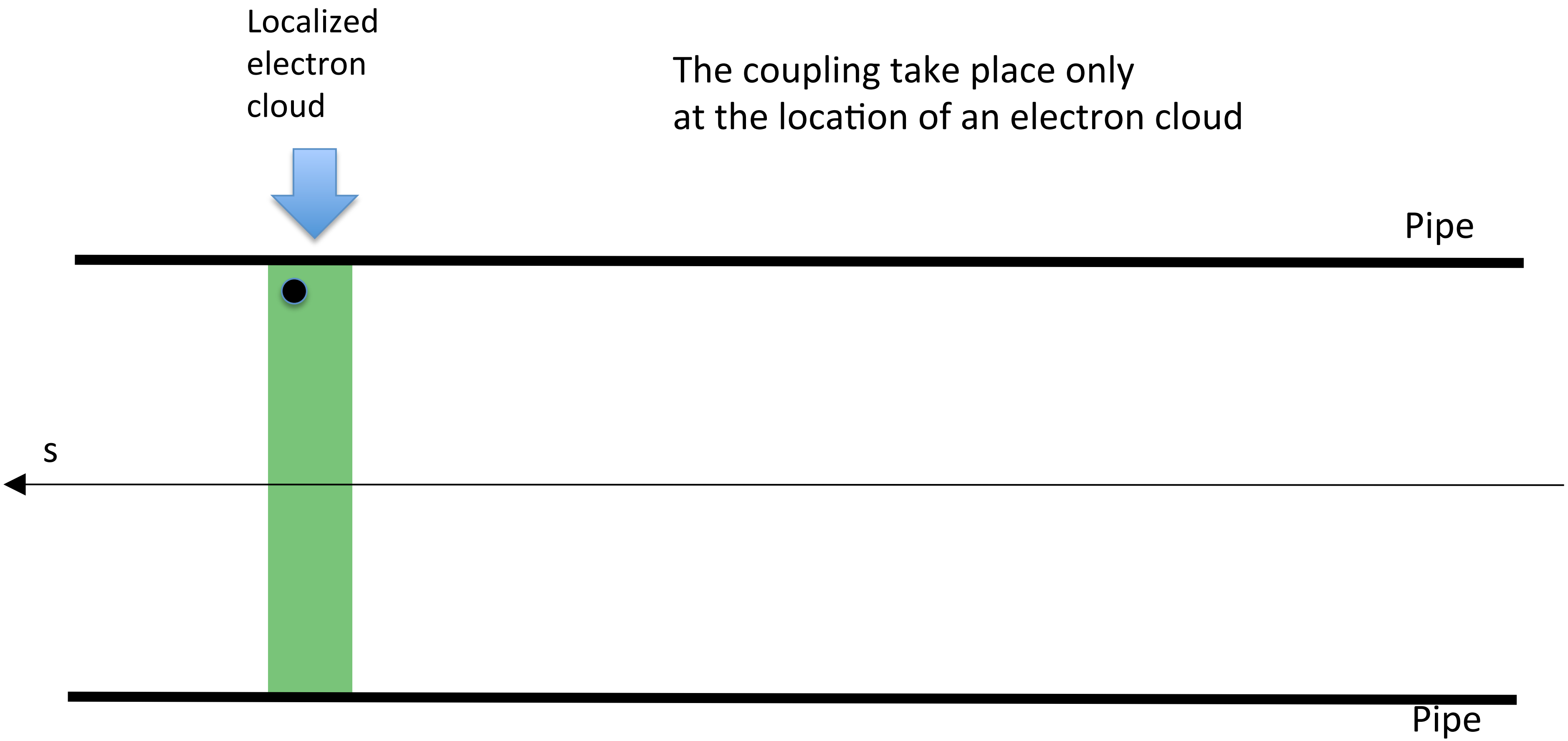
Main resonance un-compensated



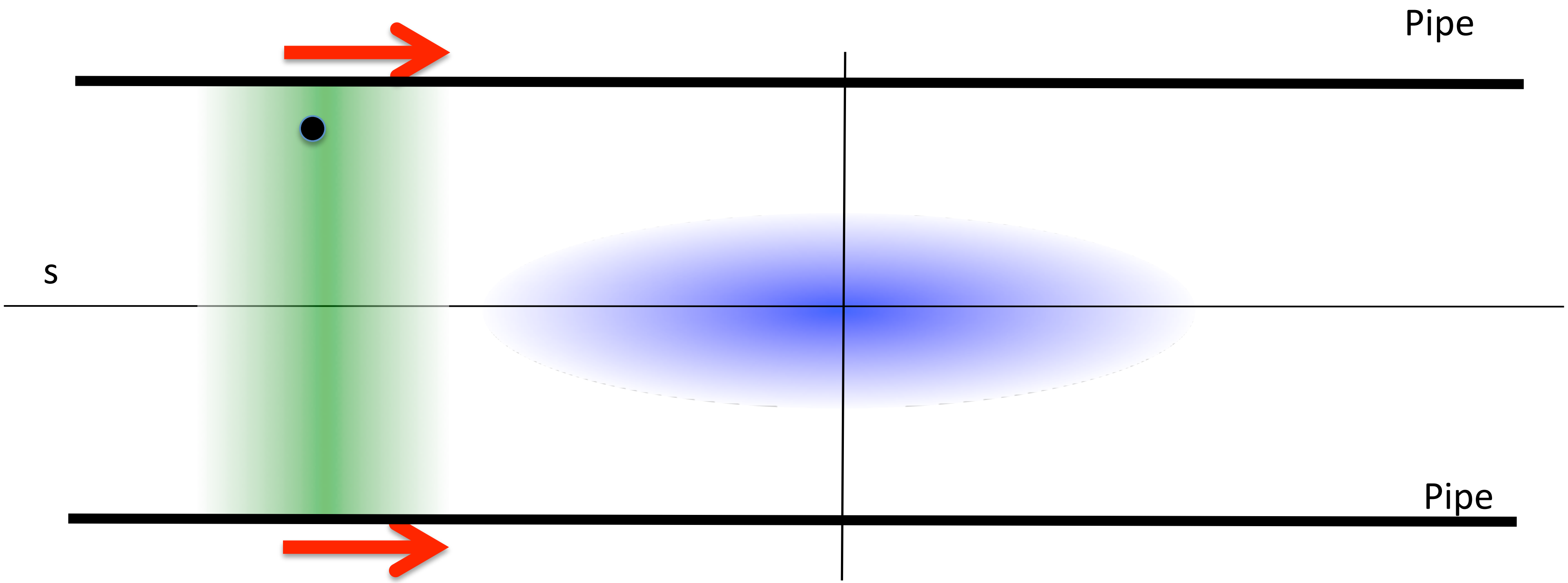


Transverse-Longitudinal coupling via electron-colud

The coupling take place only
at the location of an electron cloud



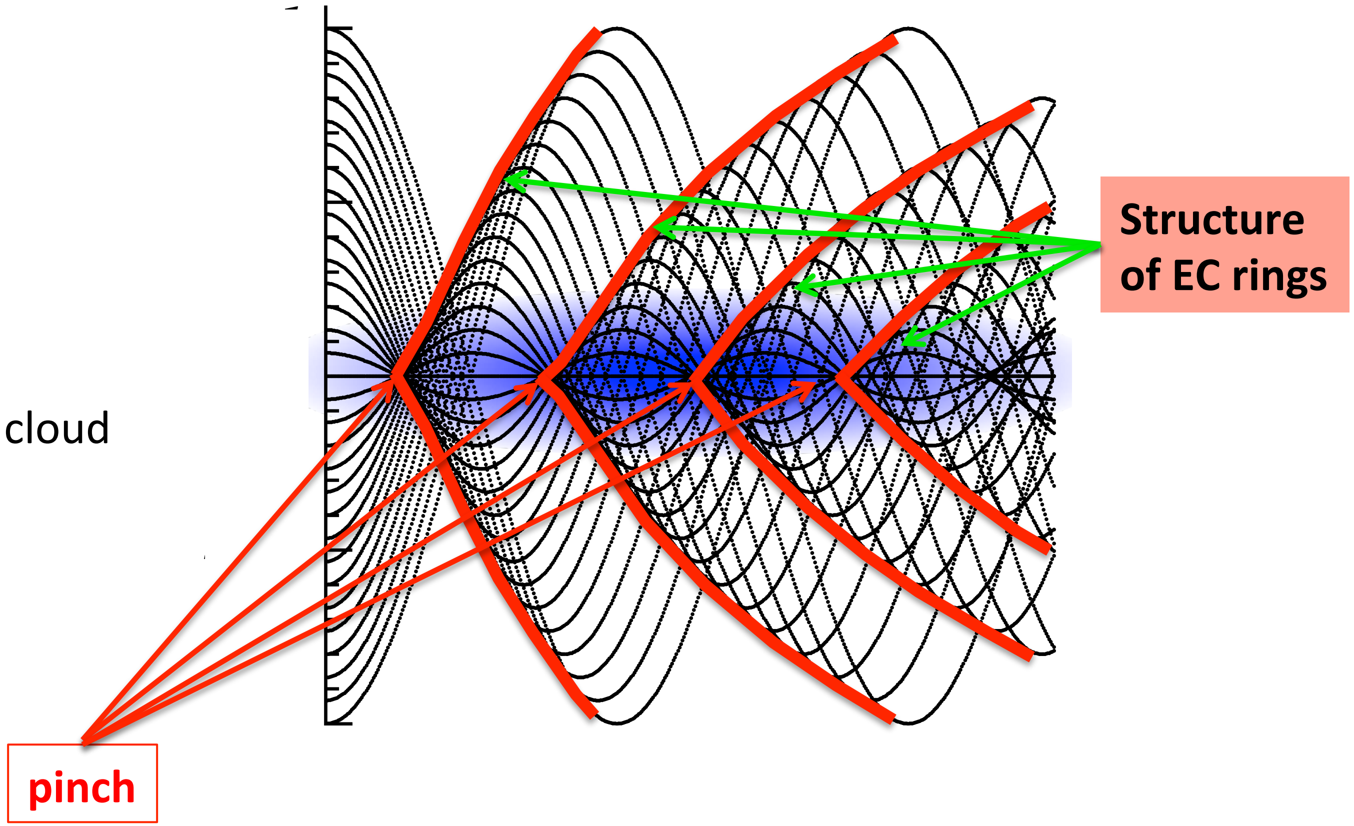
In the reference frame of the bunch



But electrons have different wavelength according to their amplitude

$$\omega = \frac{\omega_0}{1 + r^2}$$

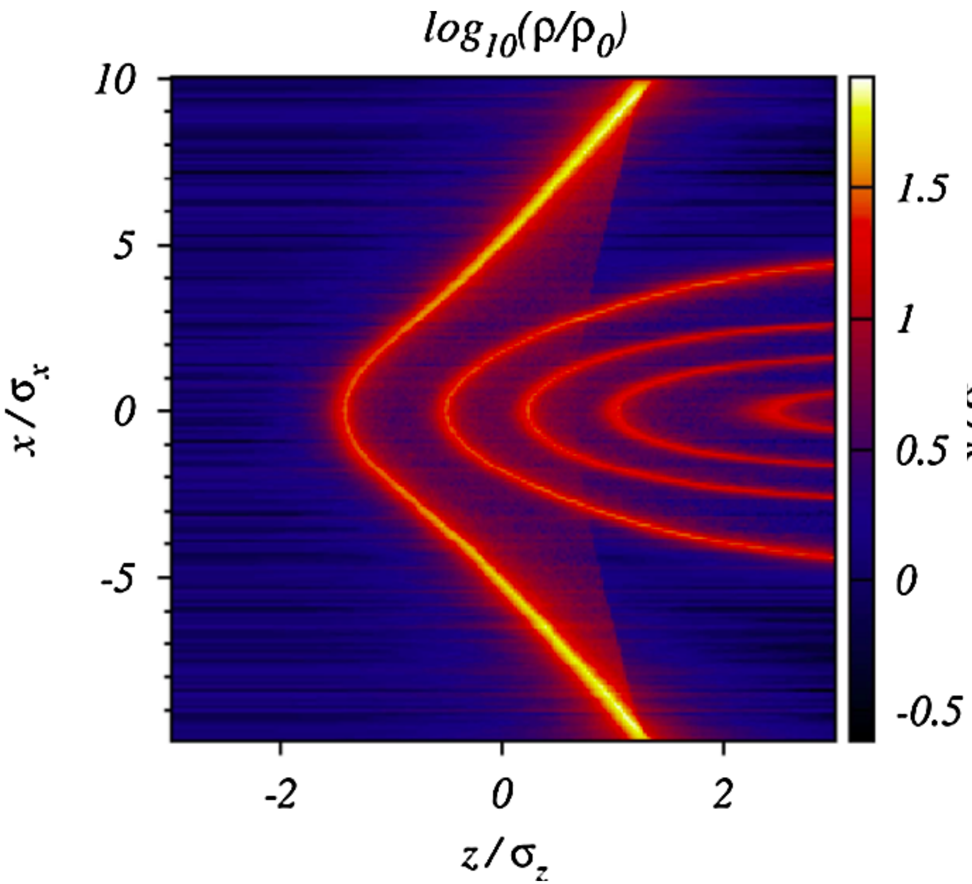
The slight difference
of frequency construct
a structure of electron cloud
along the bunch



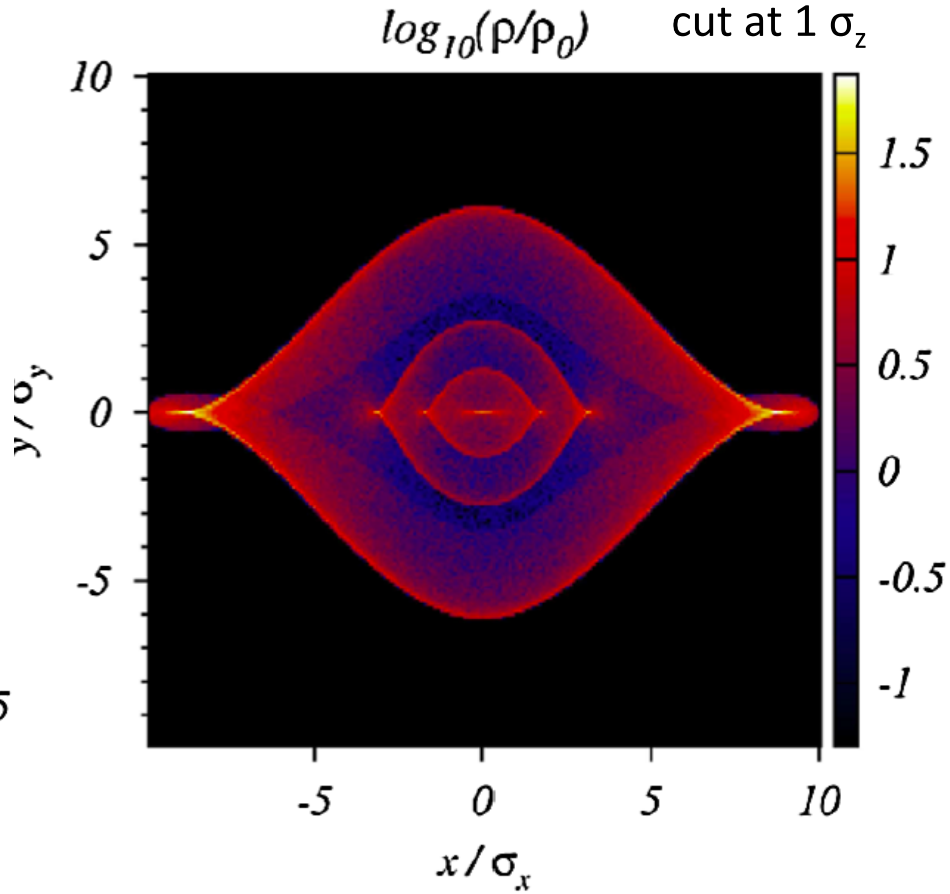
EC-pinch in dipoles

For nominal LHC bunch

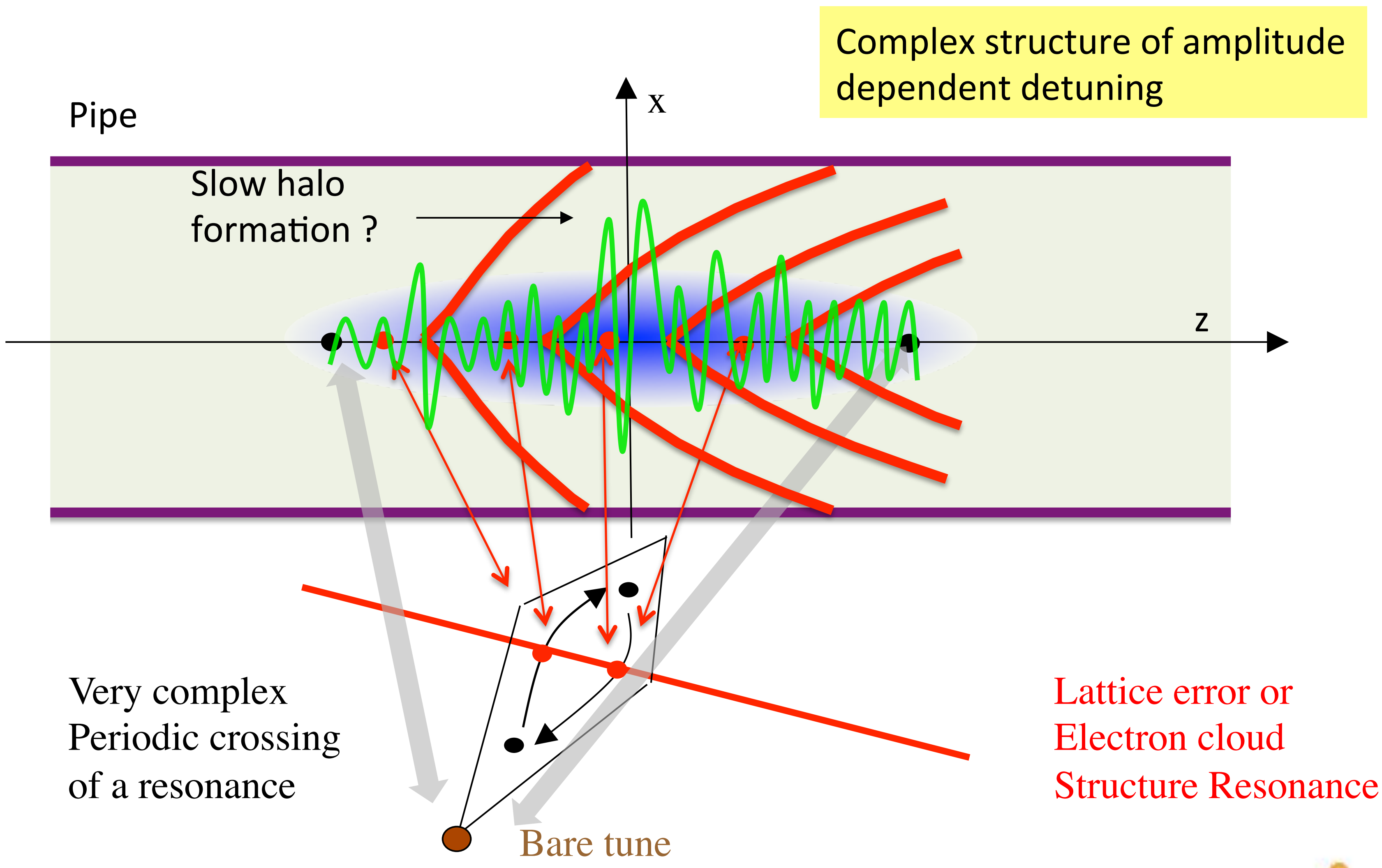
Based on the ``strong field approximation''



cut at 1 σ_z



Multiple resonance crossing in bunched beams induced by electron cloud



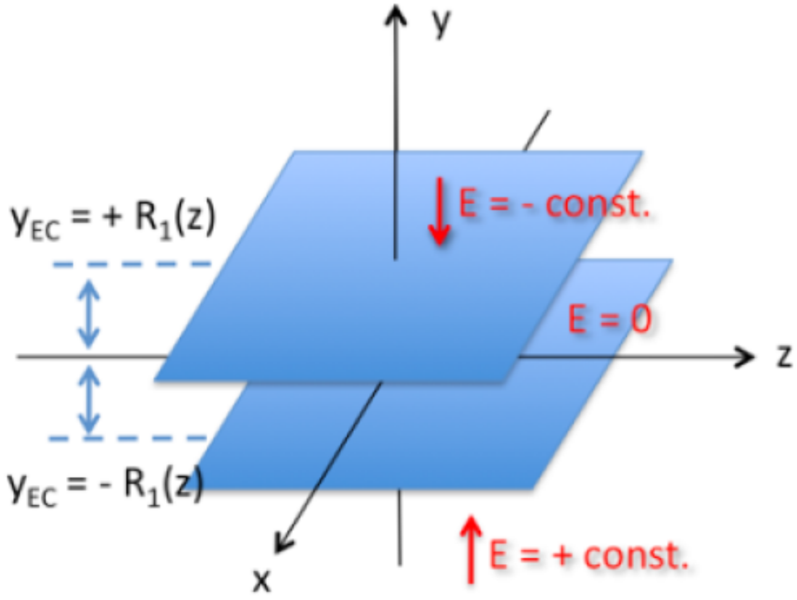
1D Modeling of EC incoherent effects

BEAM07

1D model of EC pinch

Electrons are in two planes moving apart according to the longitudinal position of a particle in a bunch

1 localized EC kick excite all structure resonances



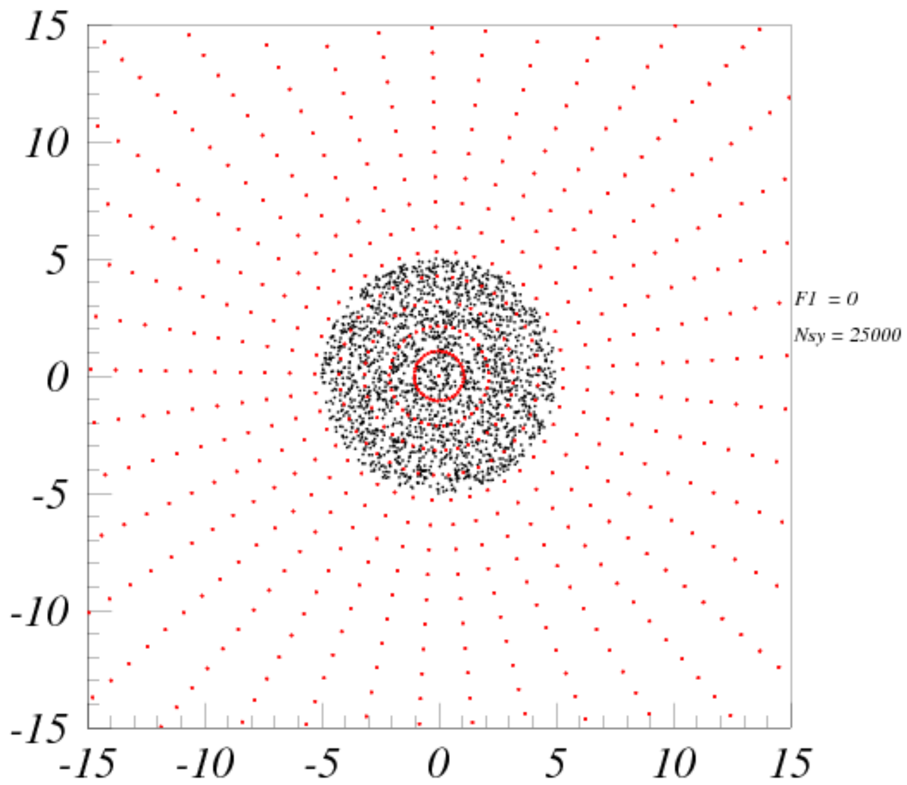
$$\begin{pmatrix} \hat{y}_1 \\ \hat{y}'_1 \end{pmatrix} = \begin{pmatrix} \cos\omega & \sin\omega \\ -\sin\omega & \cos\omega \end{pmatrix} \begin{pmatrix} \hat{y}_0 \\ \hat{y}'_0 + \mathcal{F}(y_0) \end{pmatrix}$$

Crossing of the 4th order structure resonance

Trapping process for the 1D electron-cloud map

In red are show the orbit of the "frozen system"

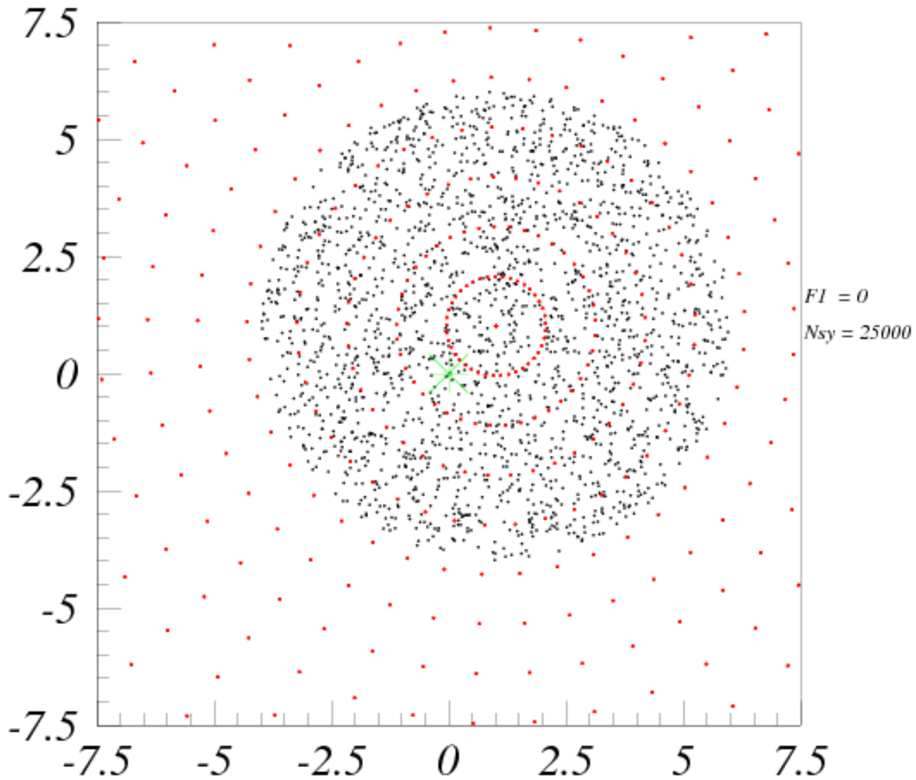
This resonance crossing in NOT ADIABATIC



Sinusoidal Periodic Crossing: Period 25000 turns

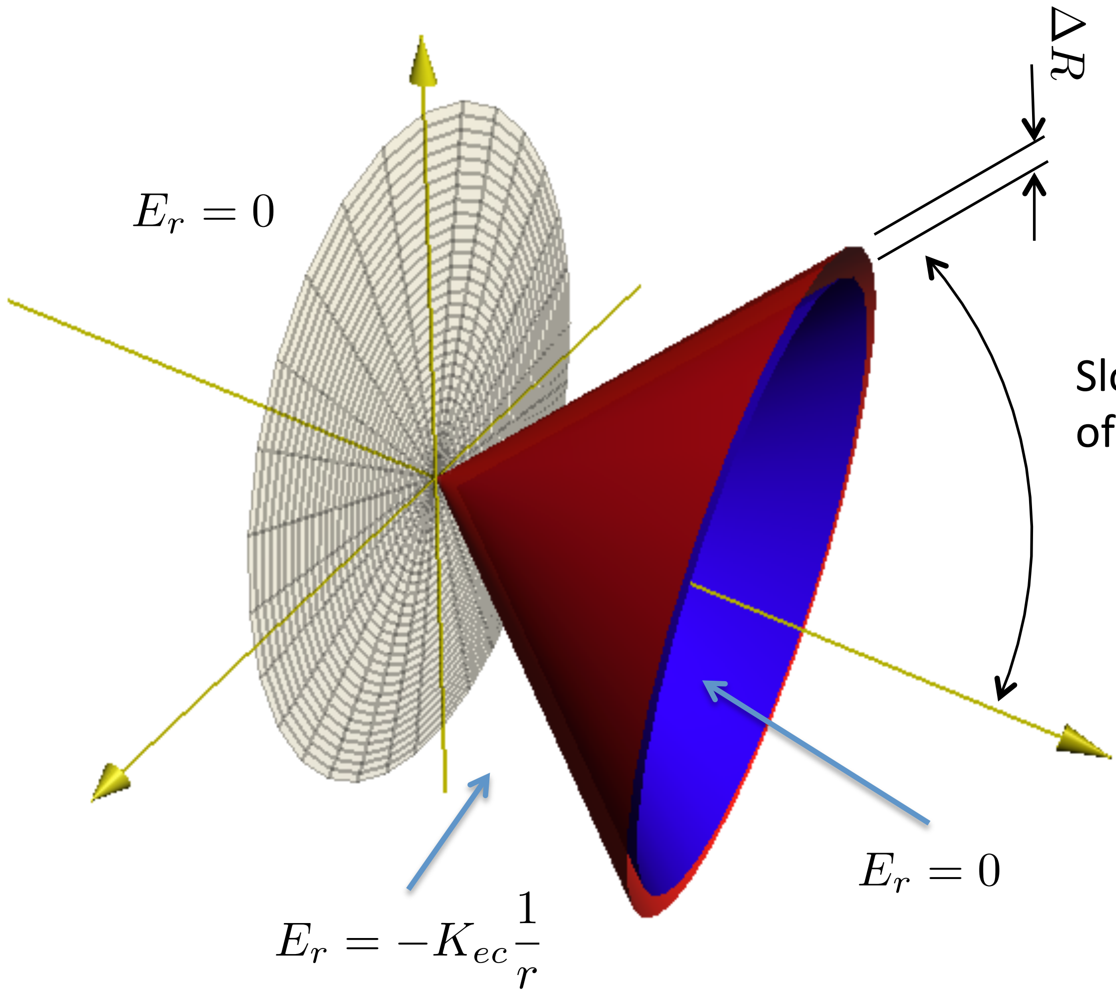
We find the existence of an "attraction point", which characterize the trapping of particles

The same beam dynamics in the reference frame of the "attraction point"



Sinusoidal Periodic Crossing: Period 25000 turns

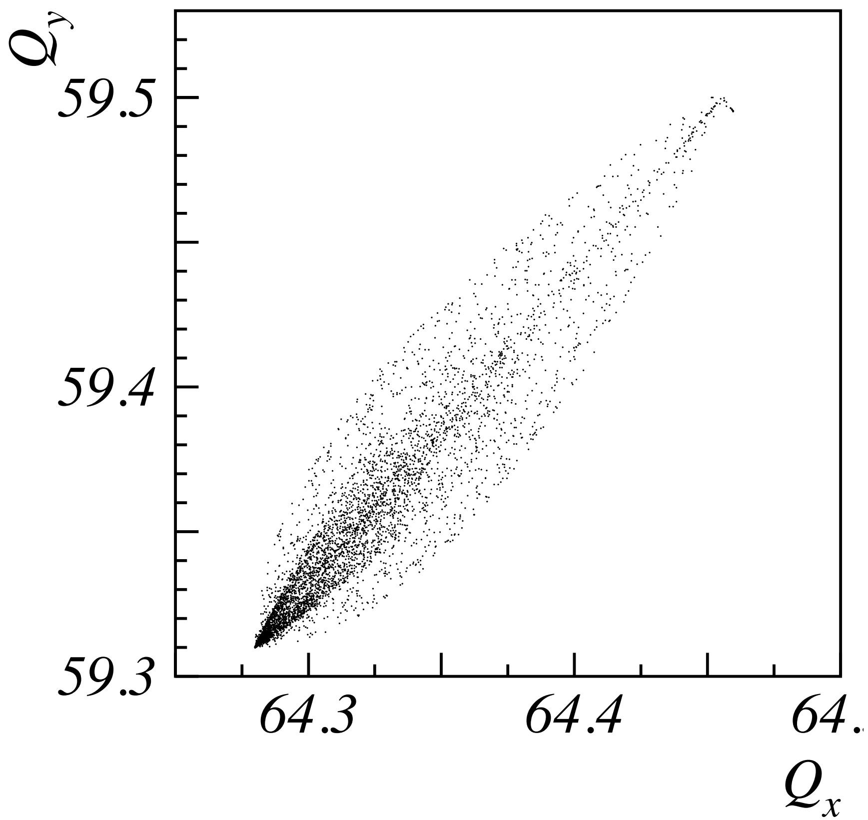
Modeling of the EC rings in field free regions



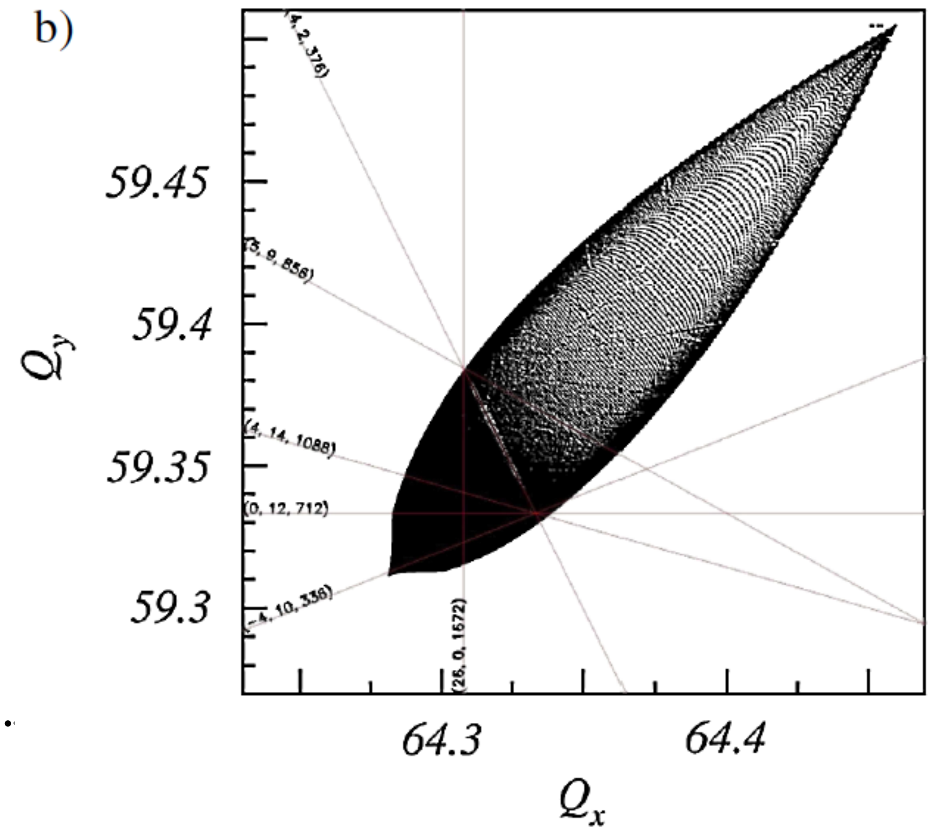
Tune footprint

Example for DQ = 0.2

Tune-footprint
of the full bunch



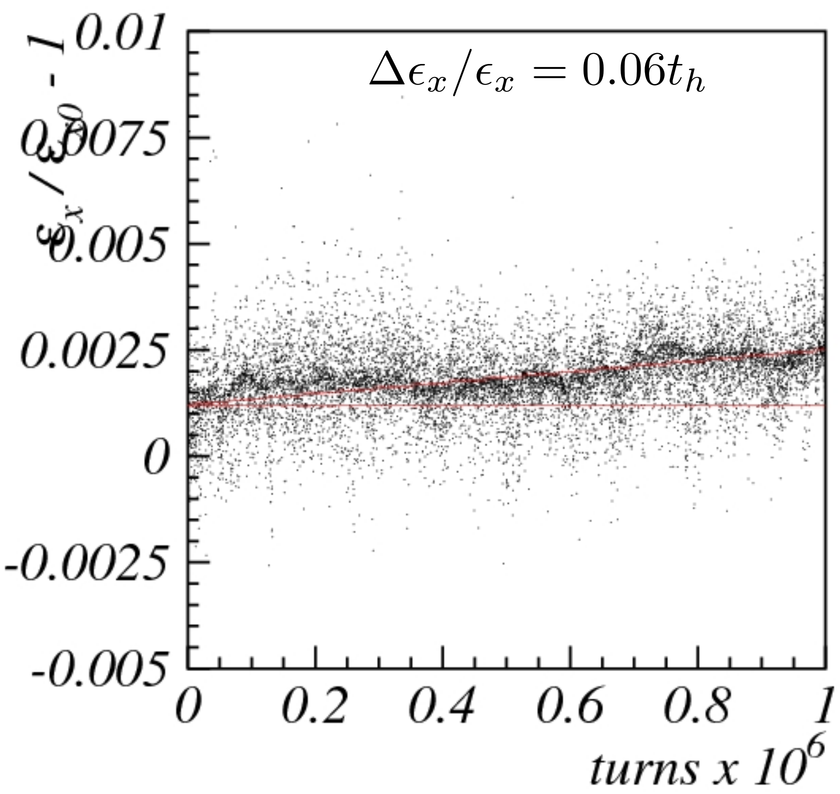
EC kicks create a web of high order structure resonances

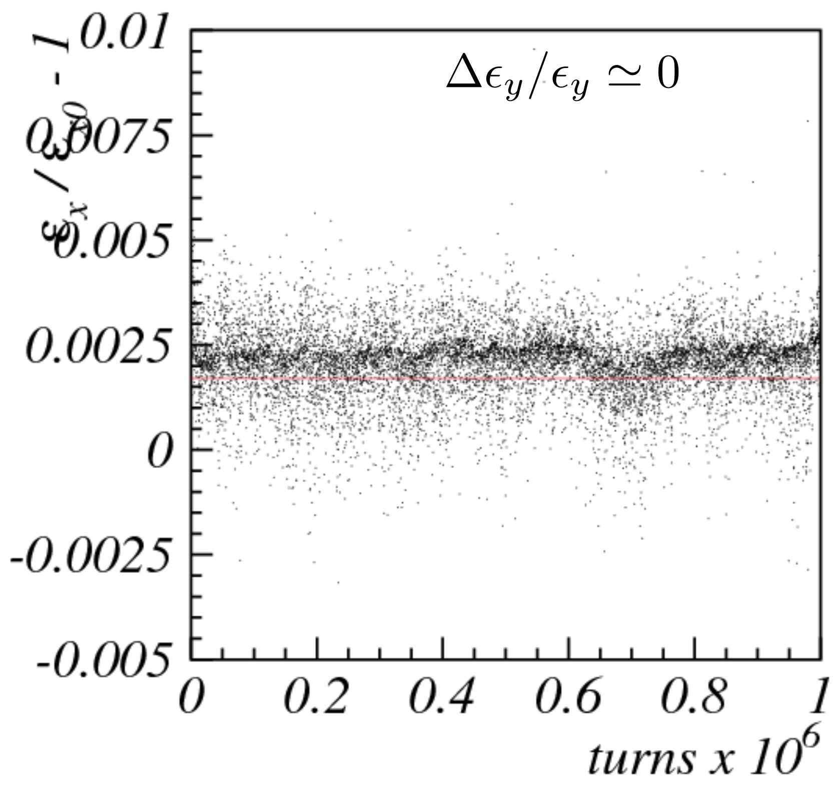


Example of an estimate for LHC

EC Kicks all dipoles all quad,
but EC structure of free pinch

Simulation DQe = 0.1





Conclusion

- Incoherent effect are caused by the multiple crossing of the same resonance by a beam particle
- The single particle tune modulation is caused by transverse-longitudinal coupling created by: chromaticity, space charge, pinched electron cloud
- The difference between the source of the coupling arises from the type of amplitude dependent detuning created
- These effect are of relevance for long term storage in high intensity machines and in presence of electron cloud (LHC, SIS100)

Source/Feature	**Detuning**	**Amplitude dependence**	**Driving resonances**	**Experiment verification**
Chromaticity	weak	weak	no (?)	yes
Space Charge	strong	strong/decrease	yes/no	yes/ongoing
Electron Cloud	strong/weak	strong/decrease	yes	?
Nonlinearities	strong/weak	strong/increase	yes	yes

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