# Incoherent effects and long term beam behavior below the e-cloud instability threshold

7-8.03.2011, CERN

G. Franchetti

Thanks to:

G. Arduini, V. Baglin, E. Benedetto, O.E. Berrig, K. Li, K.Ohmi, E. Metral, G. Rumolo, E. Schaposhnikova, F. Zimmermann

# Overview

Incoherent effect: Trapping or not Trapping
that is the problem !

The power of the (a) pinch

Modeling and estimates for LHC

Towards a systematic approach

# Incoherent effects

it is caused by the repeated crossing of a 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 they create

| **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 |

# Resonance crossing

**Basic phenomena → Separatrix 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

All possible intermediate dynamical regimes are possible

Trapping or not Trapping ?

**Scattering by resonance**

particle cross the separatrix but does not remain inside the island

Islands gives a kick to particle

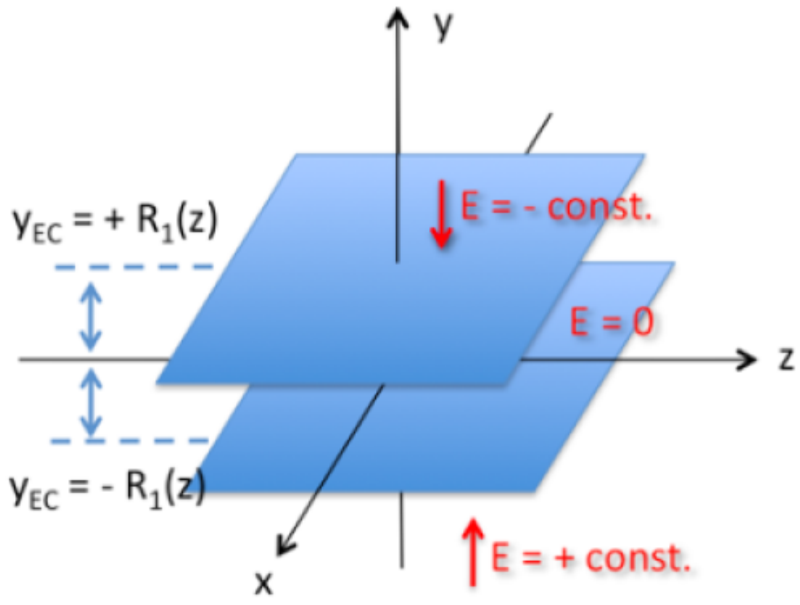
# Modeling incoherent effect of EC

**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

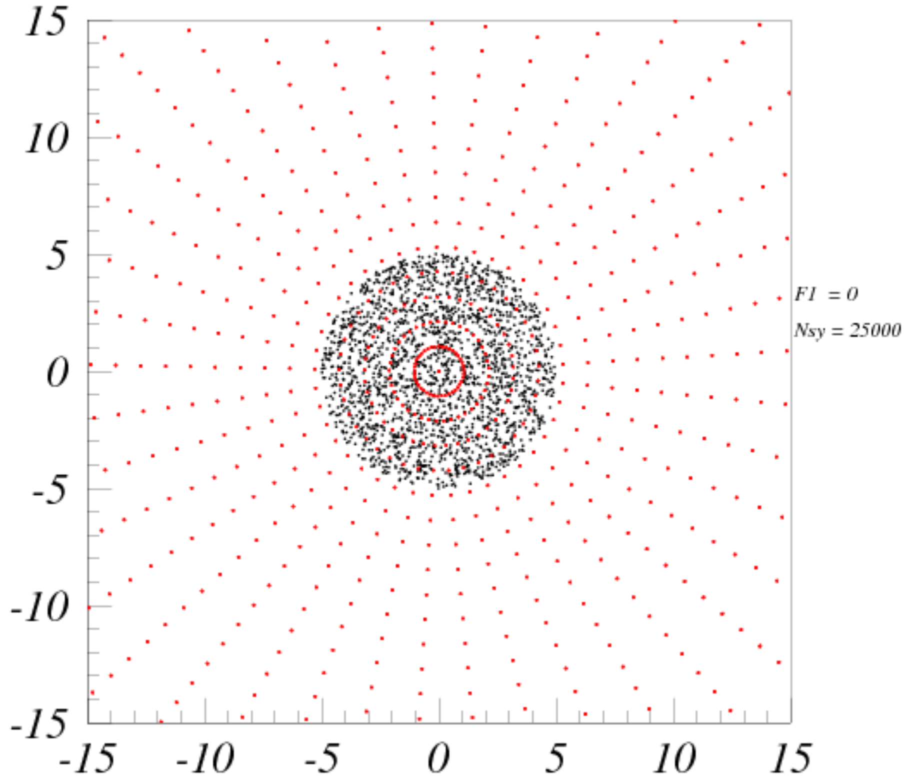


**Crossing of the 4th order structure resonance**

Trapping process for the 1D electron-cloud map

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

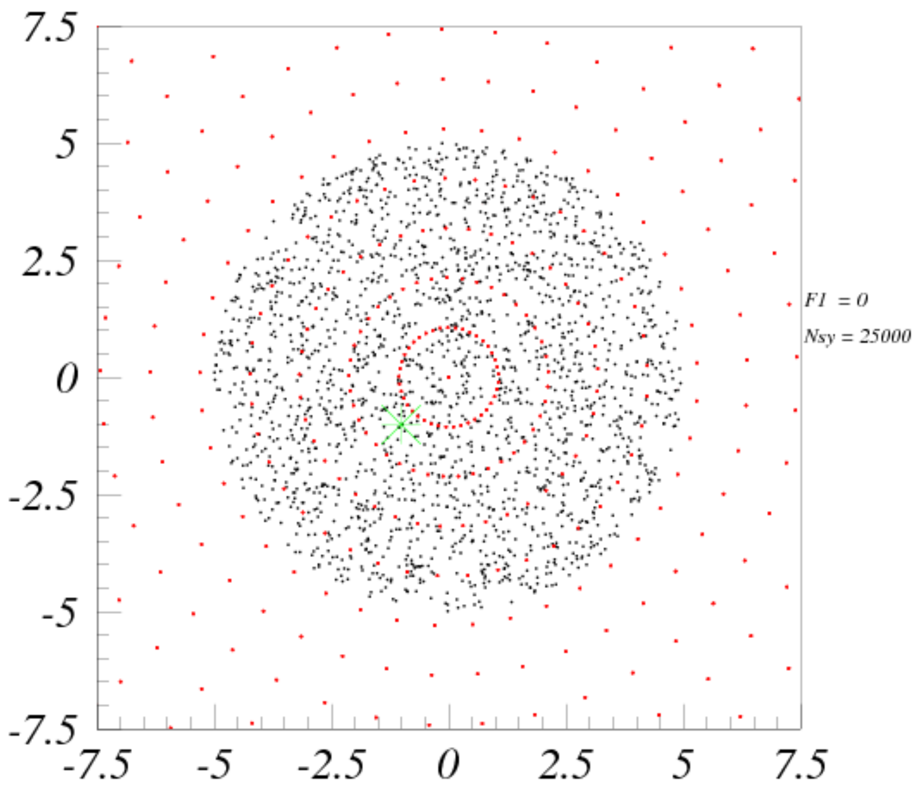
This resonance crossing in NOT ADIABATIC




Sinusoidal Periodic Crossing: Period 25000 turns

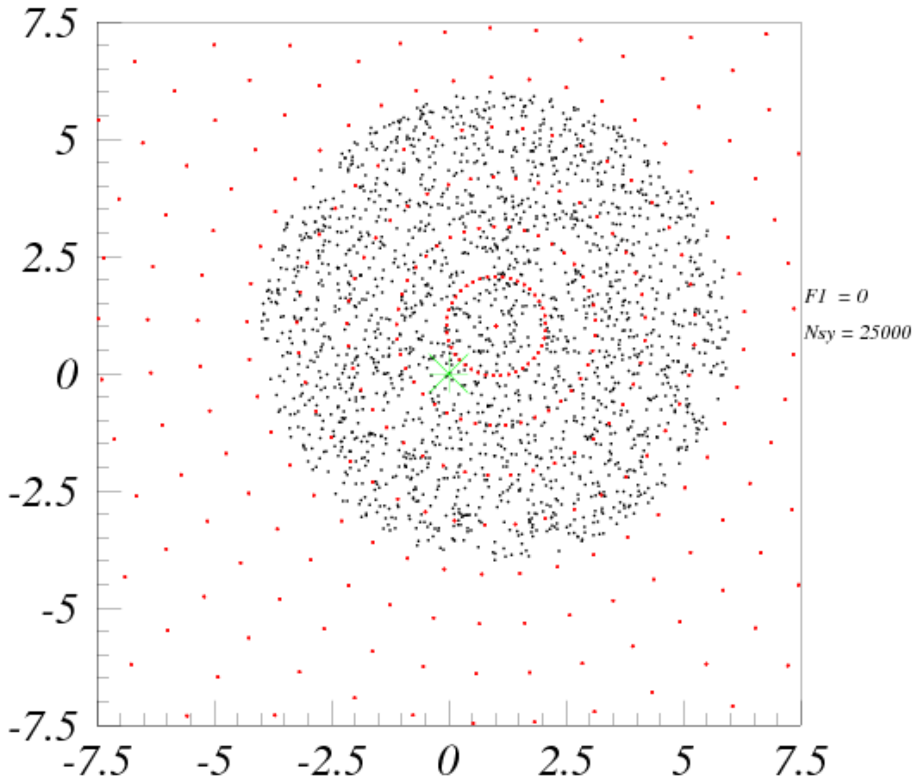
The same periodic crossing
seen from the “frozen fixed point”

In green is shown where is the
real attraction point which exert
the trapping function




Sinusoidal Periodic Crossing: Period 25000 turns

The same beam dynamics seen from the reference frame of the “attraction point”




Sinusoidal Periodic Crossing: Period 25000 turns

# Structure of EC-pinch

Scattering diffusive effect depends on the correct modeling of the induced EC pinch structure

However

diffusive effect acts on time scale of $10^6$ turns

**An analytic modeling allow avoiding artificial emittance in long term tracking**

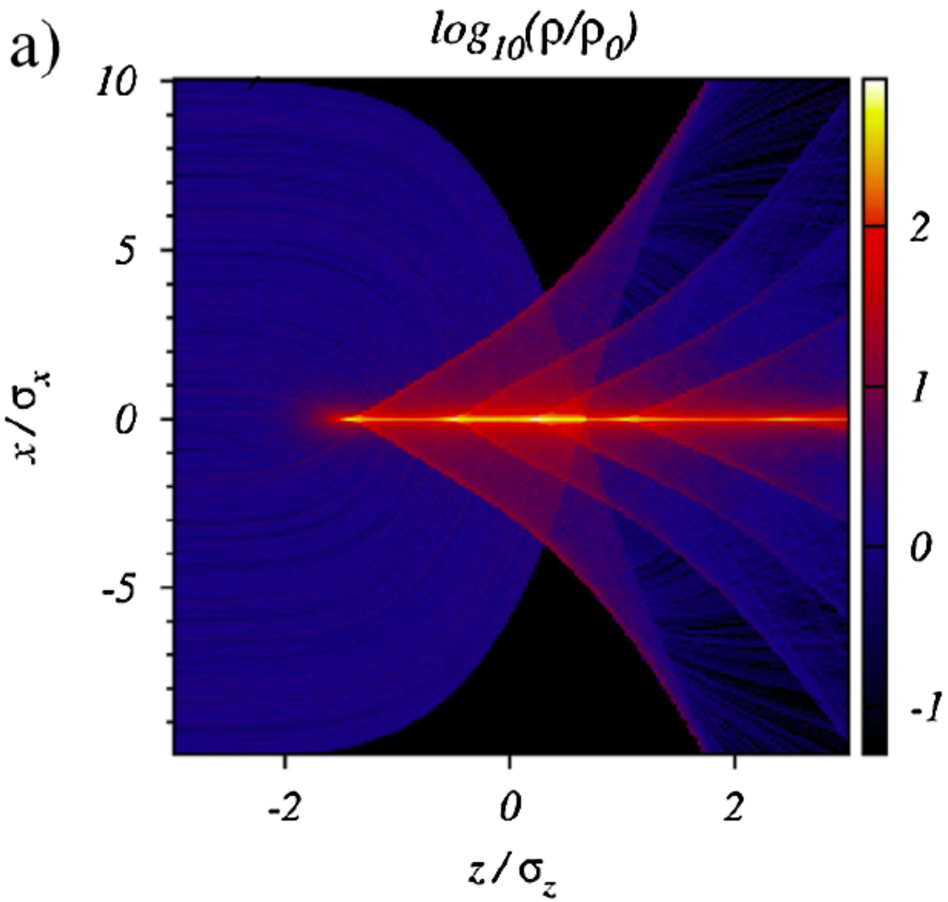
**Closer look at the EC-pinch induced structure**

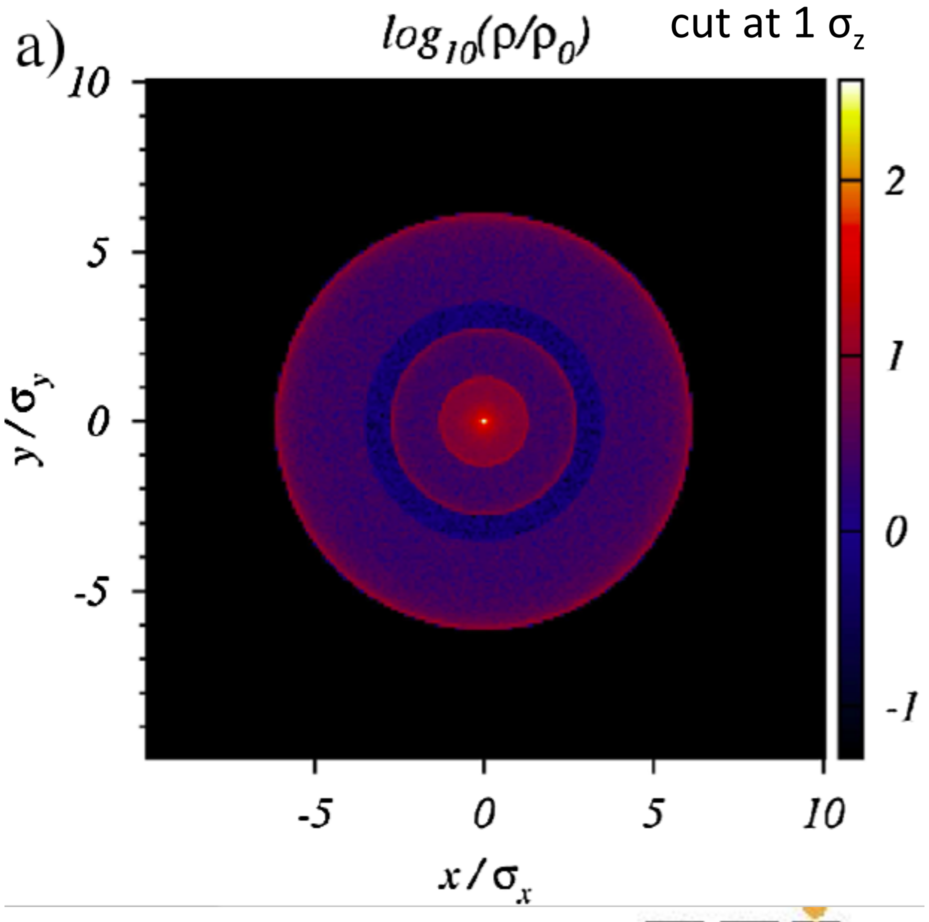
# EC-pinch in field free region

For nominal LHC bunch

$N_b = 1.15 \times 10^{11}$, $\sigma_{x,y} = 0.88$ mm
$\sigma_z = 11.4$ m. Initial electrons in a circle $10\sigma$

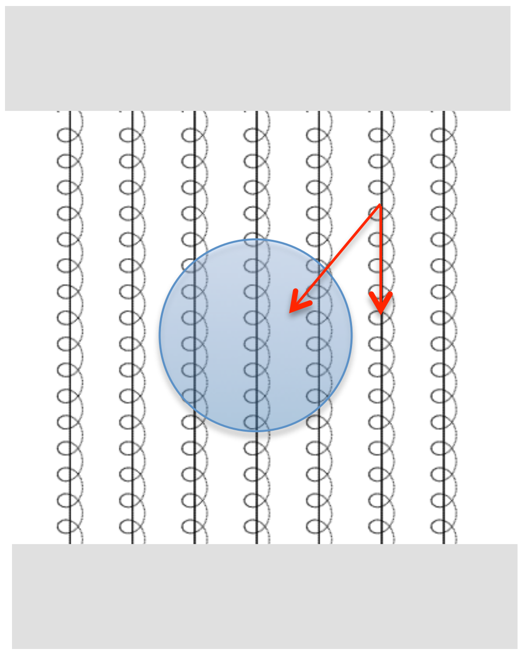
No EC-self force



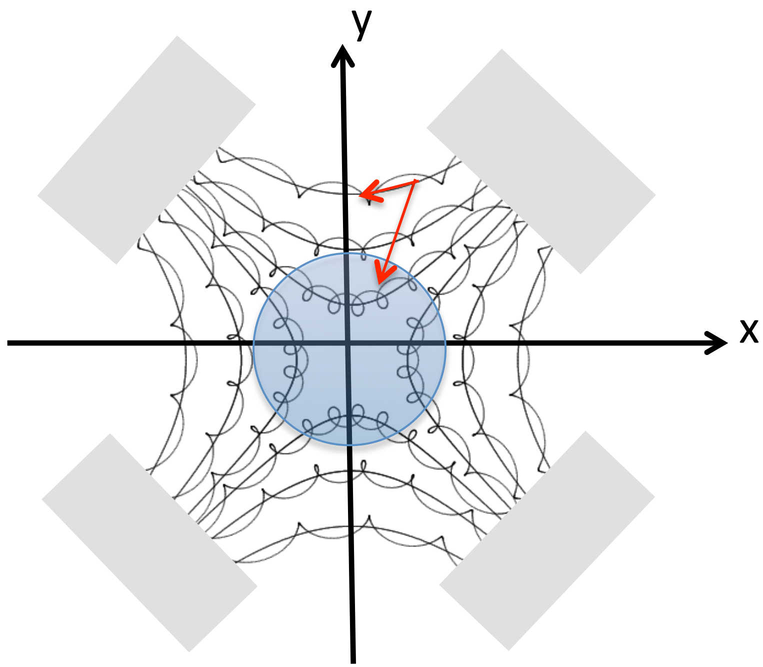



# Strong field approximation

Dipole



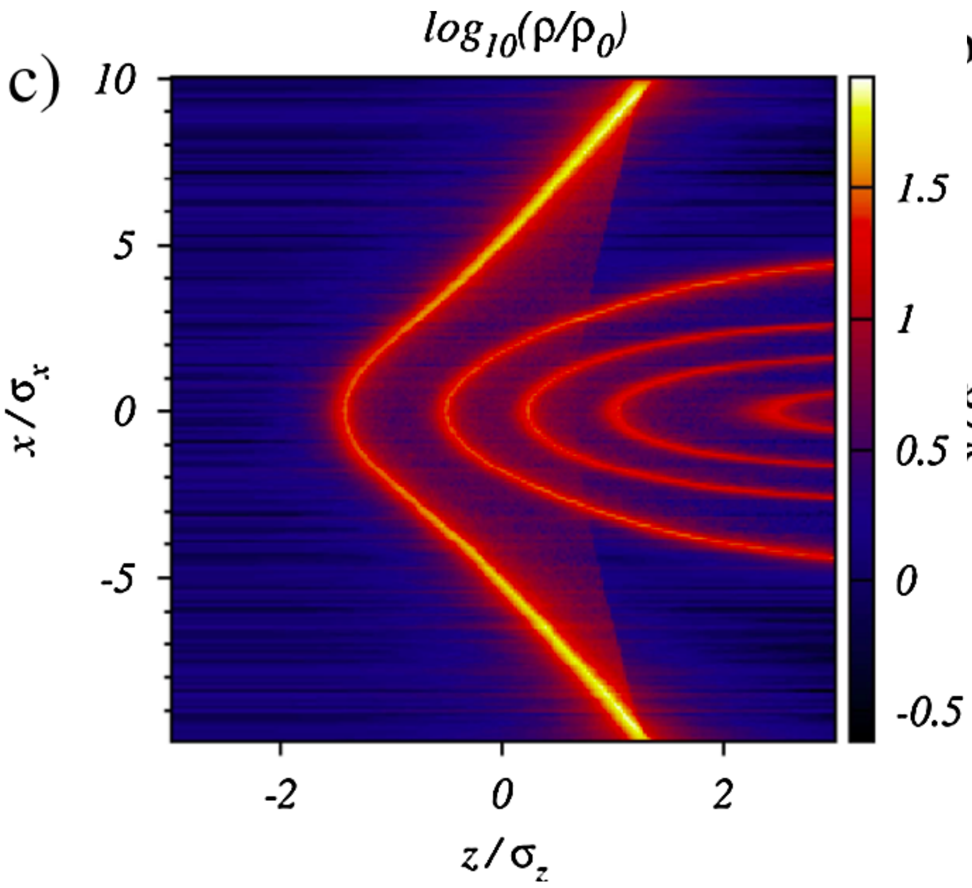
Quadrupoles

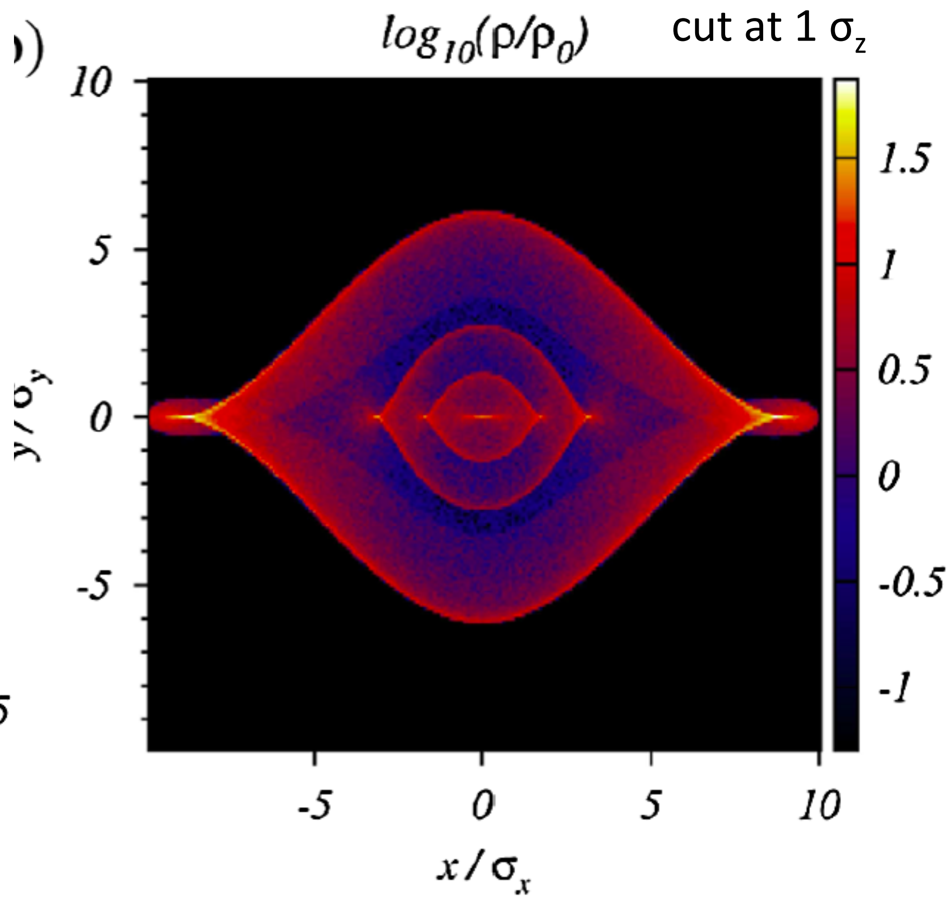



Force on the electrons is the projection of the force from the beam on the direction of the vector line field

# EC-pinch in dipoles

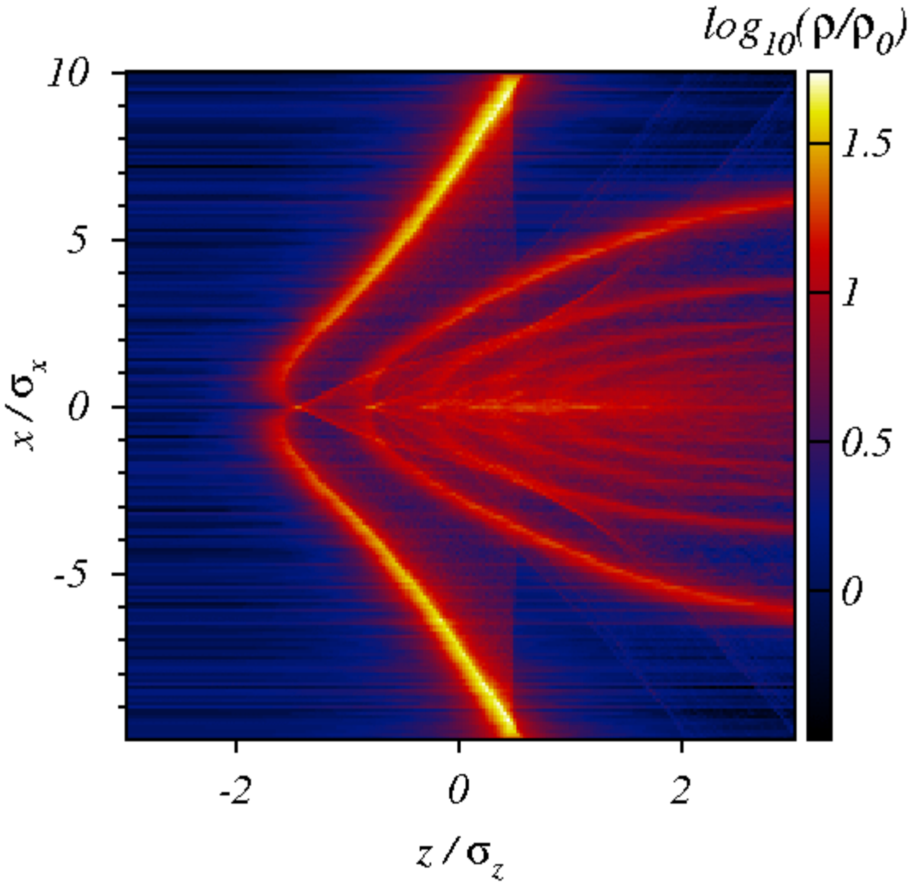
For nominal LHC bunch        Based on the ``strong field approximation''

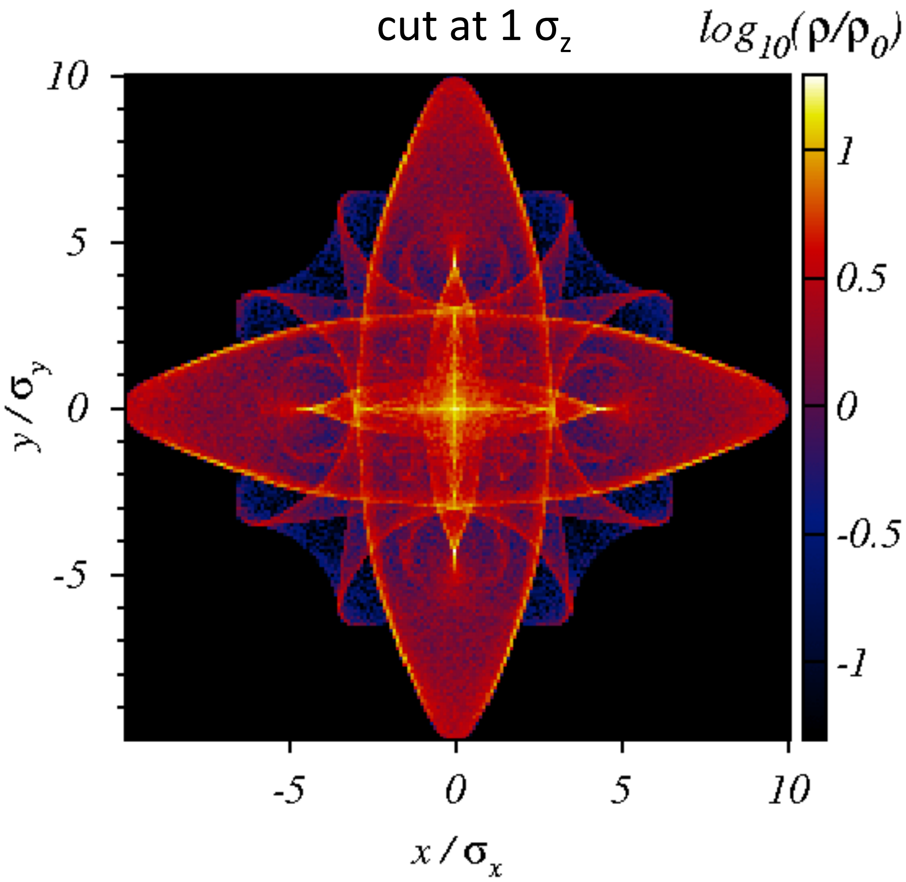


# EC-pinch in Quadrupoles

For nominal LHC bunch Strong B-field approximation



# Approximations

Comments of K. Ohmi and G. Rumolo

Electrons follow the magnetic field

This approximation is not valid at small radii

Comparison of quadrupoles with dipoles

$$k_x = \frac{1}{B\rho} g$$

$$B_y = gx$$

$$\Rightarrow \quad \frac{B_y}{B_0} = k_x \rho x$$

For $\rho \simeq 2.8Km$

$$\frac{B_{quad}}{B_0} = 0.023 \quad \text{at} \quad r = \sigma = 0.88mm$$

Strong B approximation not applicable → **Analysis of complete dynamics is necessary**

# EC-pinch in Quadrupole analysis

Complete equations

$$\frac{d}{dt}\left(m_e\gamma_e\frac{d\vec{R}}{dt}\right) = e\vec{E} + e\frac{d\vec{R}}{dt}\times\vec{B}$$

| Assumptions of 2D bunch and 2D quadrupole | |
|---|---|
| | • $\vec{E} = (E_x, E_y, 0)$<br>• $\vec{B} = (B_x, B_y, 0) = (gy, gx, 0)$, quadrupole field. |

Equation of motion of one electron

$$\frac{d^2x}{ds^2} = \frac{e}{c^2 m_e\gamma_e}E_x - k\frac{\gamma_p m_p}{\gamma_e m_e}\frac{dz}{ds}x$$

$$\frac{d^2y}{ds^2} = \frac{e}{c^2 m_e\gamma_e}E_y + k\frac{\gamma_p m_p}{\gamma_e m_e}\frac{dz}{ds}y$$

$$\frac{d^2z}{ds^2} = k\frac{\gamma_p m_p}{\gamma_e m_e}\left(\frac{dx}{ds}x - \frac{dy}{ds}y\right)$$

$$x = \sigma_r\tilde{x},\ y = \sigma_r\tilde{y},\ z = \sigma_r\tilde{z}.$$

Including the force exerted by the protons the equations become

$$\frac{d^2\tilde{x}}{ds^2} + k\sigma_r \frac{\gamma_p m_p}{\gamma_e m_e} \frac{d\tilde{z}}{ds}\tilde{x} + \omega_e^2(s)\tilde{x} = -\tilde{x}\frac{\omega_e^2(s)}{\tilde{r}^2}\left[2\left(1 - e^{-\frac{\tilde{r}^2}{2}}\right) - \tilde{r}^2\right]$$

$$\frac{d^2\tilde{y}}{ds^2} - k\sigma_r \frac{\gamma_p m_p}{\gamma_e m_e} \frac{d\tilde{z}}{ds}\tilde{y} + \omega_e^2(s)\tilde{y} = -\tilde{y}\frac{\omega_e^2(s)}{\tilde{r}^2}\left[2\left(1 - e^{-\frac{\tilde{r}^2}{2}}\right) - \tilde{r}^2\right]$$

$$\frac{d^2\tilde{z}}{ds^2} = k\sigma_r \frac{\gamma_p m_p}{\gamma_e m_e}\left(\frac{d\tilde{x}}{ds}\tilde{x} - \frac{d\tilde{y}}{ds}\tilde{y}\right)$$

Note: the effect of the quadrupole depends on $\frac{d\tilde{z}}{ds}$

But the change of kinetic energy is

$$\tilde{E}_k(\tilde{r},\tilde{r}_0) = \int_{\tilde{r}}^{\tilde{r}_0} \frac{\omega_e^2(s)}{\tilde{r}}\left[2\left(1 - e^{-\frac{\tilde{r}^2}{2}}\right)\right] d\tilde{r} = \omega_e^2(s) F(\tilde{r},\tilde{r}_0)$$

Therefore certainly $$\frac{1}{2}\left(\frac{d\tilde{z}}{ds}\right)^2 \le \tilde{E}_k(0,\tilde{r}_0)$$

which allows to estimate that for the electrons that start at rest

$$\beta_e \le \sqrt{2}\,\sigma_r\,\omega_e(s)\sqrt{1.32 + 2\ln(\tilde{r}_{pipe}/2)}$$

For LHC bunch → $\omega_e(0) = 38.26\ \mathrm{m}^{-1}$, $r_{pipe} = 0.025$ m, and $\sigma_r = 0.88$ mm

→ $\beta_e \sim 0.1$ → $\gamma_e \simeq 1$

# Strong/Weak B threshold

The field B produced by the quadrupole is weak with respect to the field created by the protons if

$$\left(k\sigma_r \frac{\gamma_p m_p}{\gamma_e m_e}\right)^2 \left(\frac{d\tilde{z}}{dt}\right)^2 \quad =< \quad \frac{\omega_e^4(s)}{\tilde{r}^4} 4 \left(1 - e^{-\frac{\tilde{r}^2}{2}}\right)^2$$

But we can estimate the maximum $\frac{d\tilde{z}}{ds}$ from $\tilde{E}_k(\tilde{r}, \tilde{r}_0)$

These two equations allow the definition of a threshold radius $r_t$

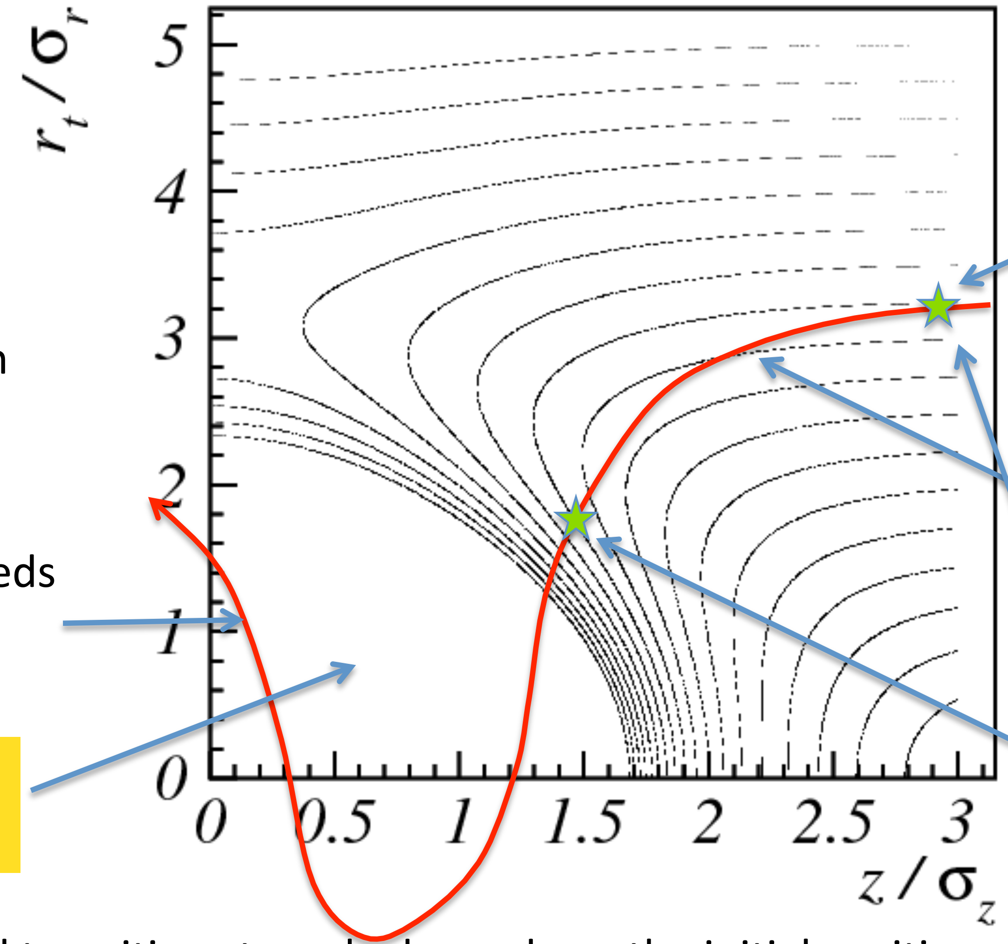
such that all the electron $\tilde{r}_0 < \tilde{r}_t$ are dominated by a Weak B dynamics

**There are region in which the pinch evolves very similar to a field free region and others in which is dominated by the quadrupole field**

# Example for the LHC injection energy

The transition of dominance of forces depends on the initial position of the electrons

curves of $r_t$ for several initial position $r/\sigma_r$ as function of $z/\sigma_z$




At the beginning the force of the protons dominates

Quadrupole force dominate

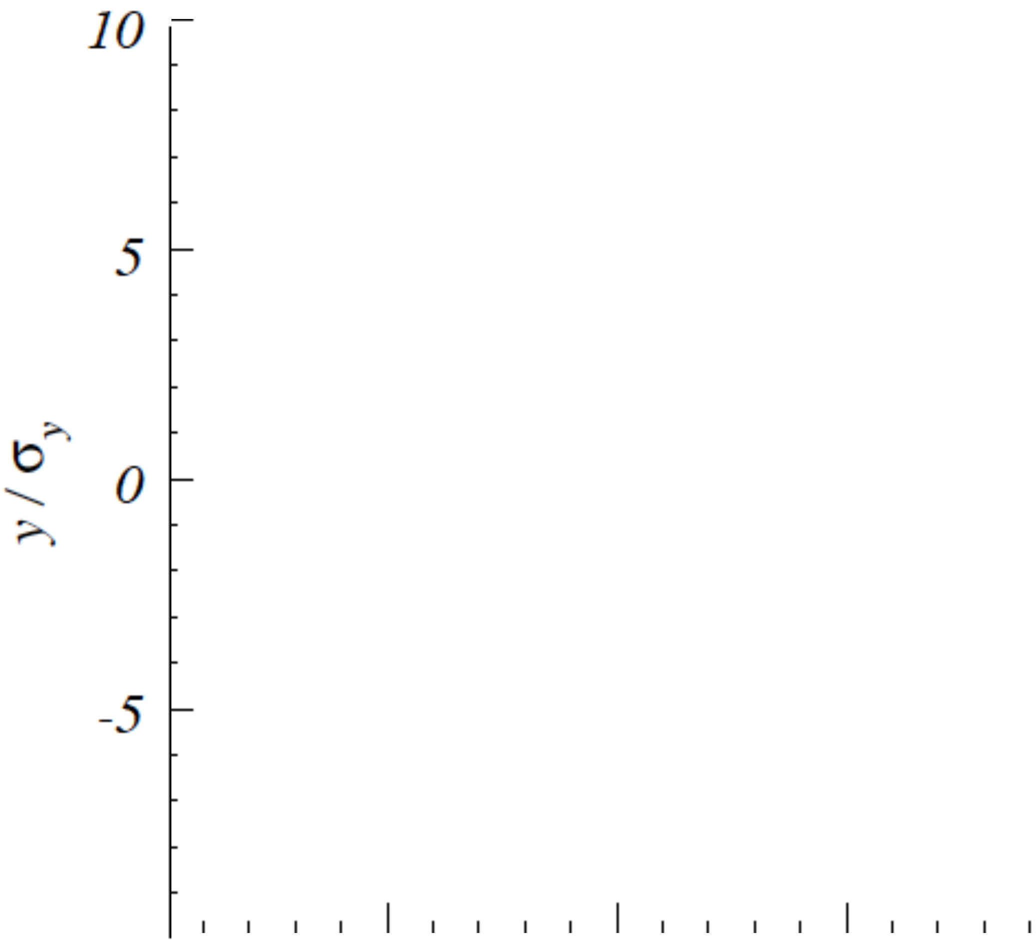
The dynamics needs to be computed

Proton force dominate

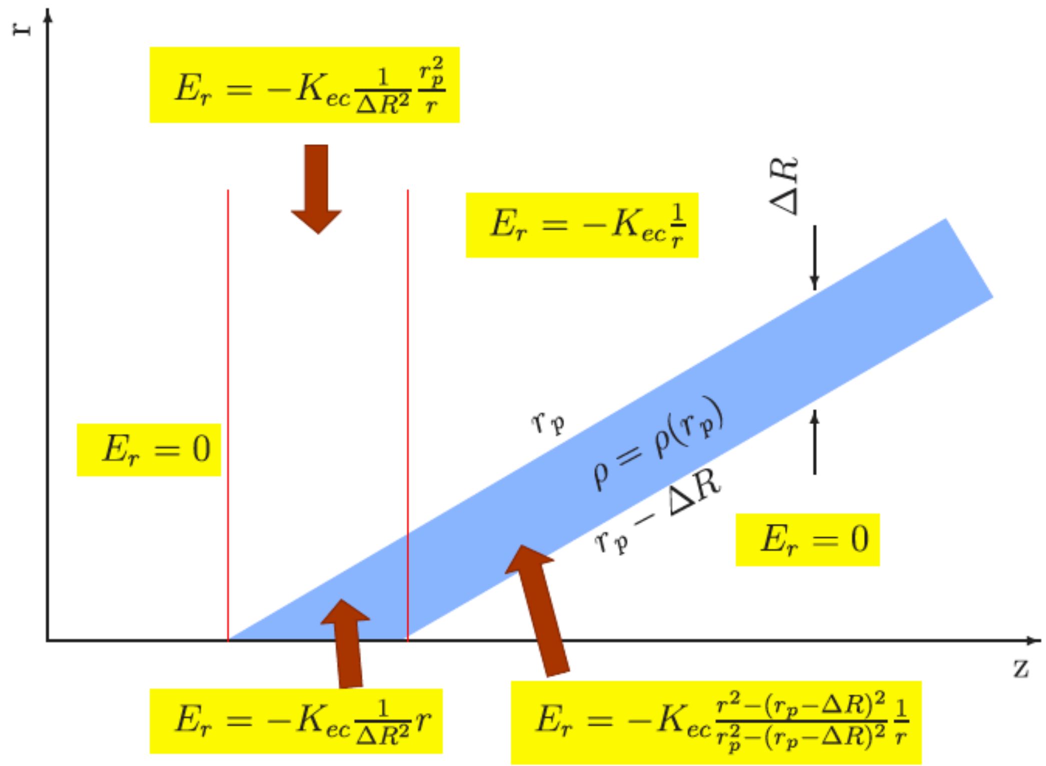
Transition

The full dynamics and transition strongly depends on the initial position of each particle

# Pinch in Quadrupoles: strong B limit



# Present modeling for long term tracking



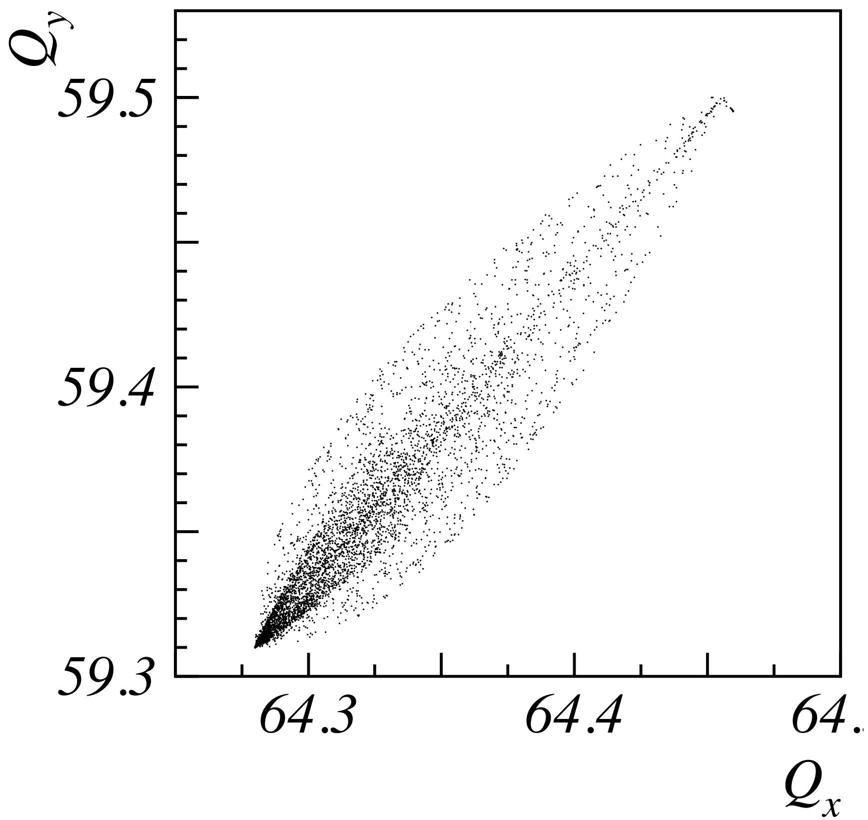

Input parameters

1) Maximum detuning
2) Ring slope
3) Number of rings

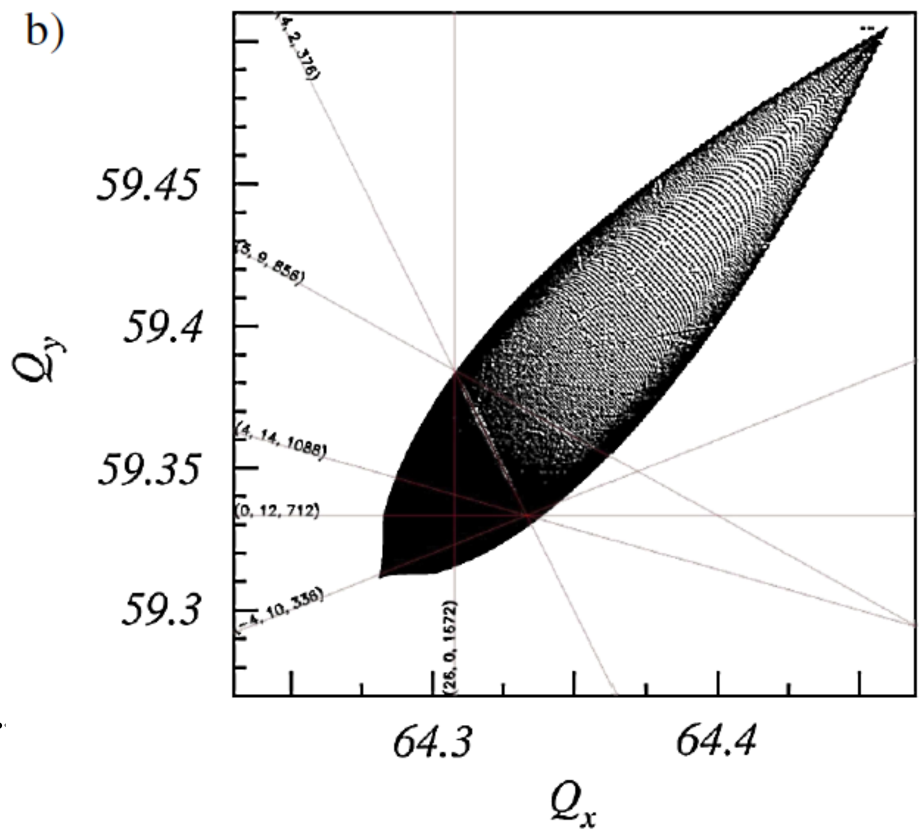
# Tune footprint

Example for DQ = 0.2

Tune-footprint
of the full bunch




EC kicks create a web of high order structure resonances



# Estimates for LHC

Input parameter: the maximum incoherent tune spread created by EC

Related to electron density

DQe = 0.1 DQe = 0.02 → K. Li

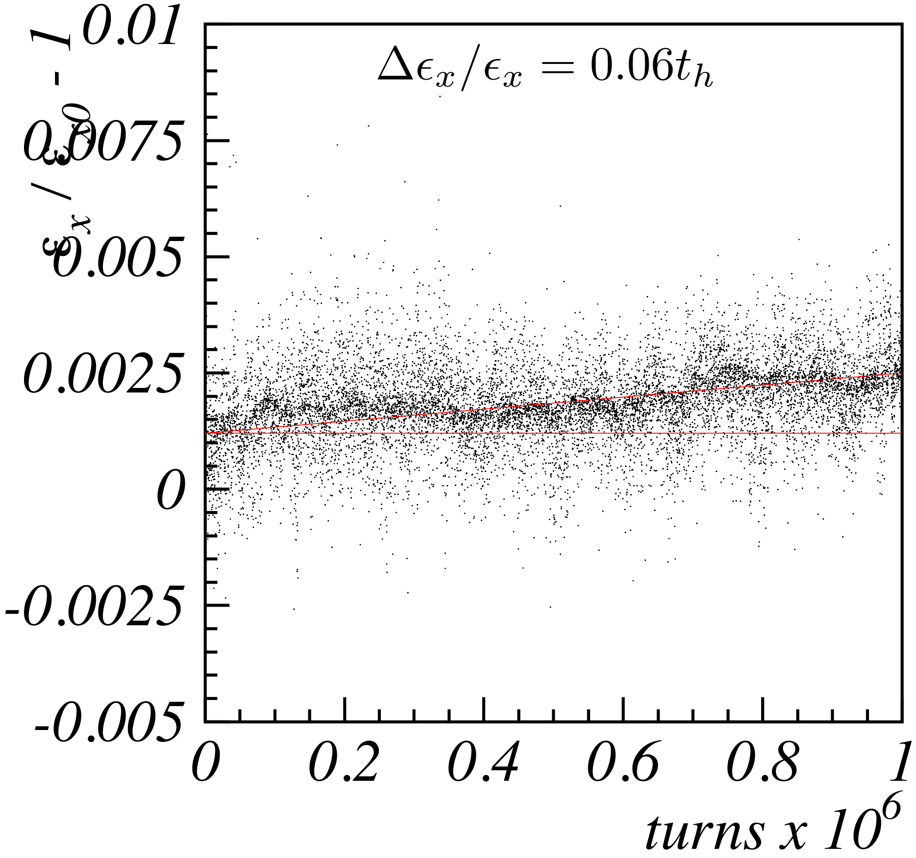
Qx = 64.28 Qy = 59.31 (injection)

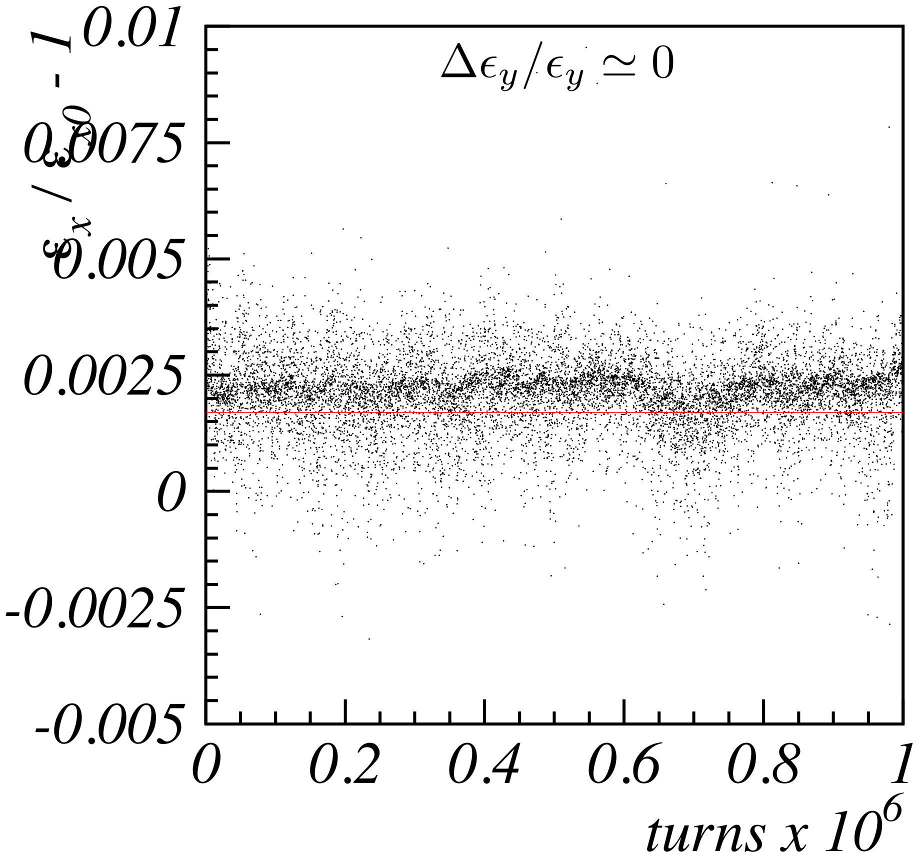
Pinch modeling: as field free → conservative estimates

# Estimates for LHC

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

Simulation DQe = 0.1

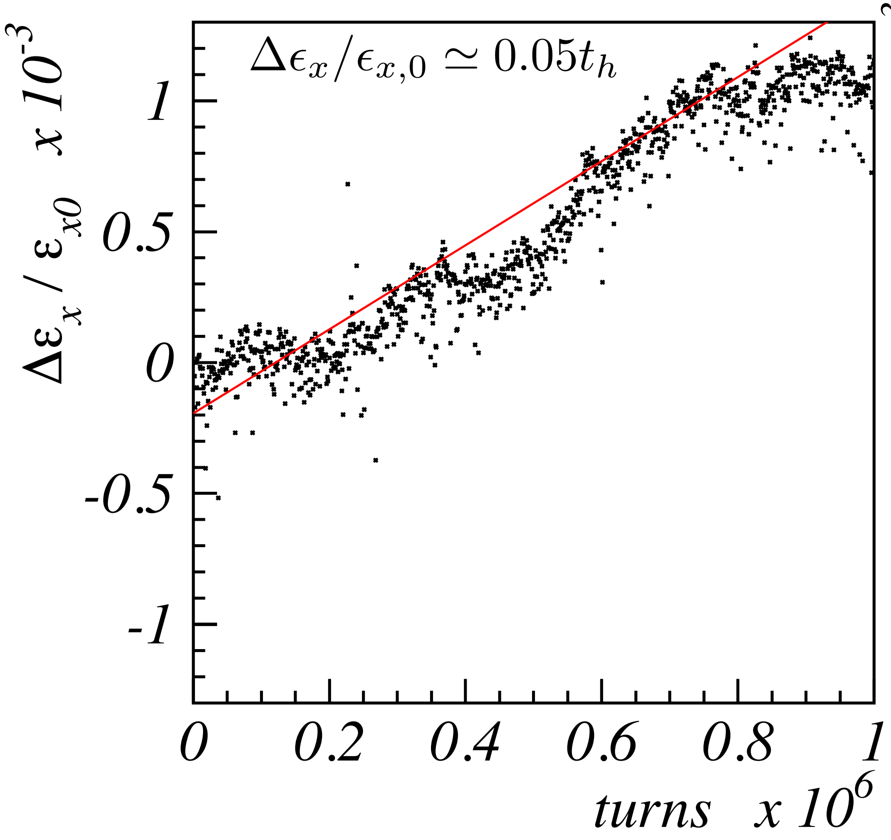


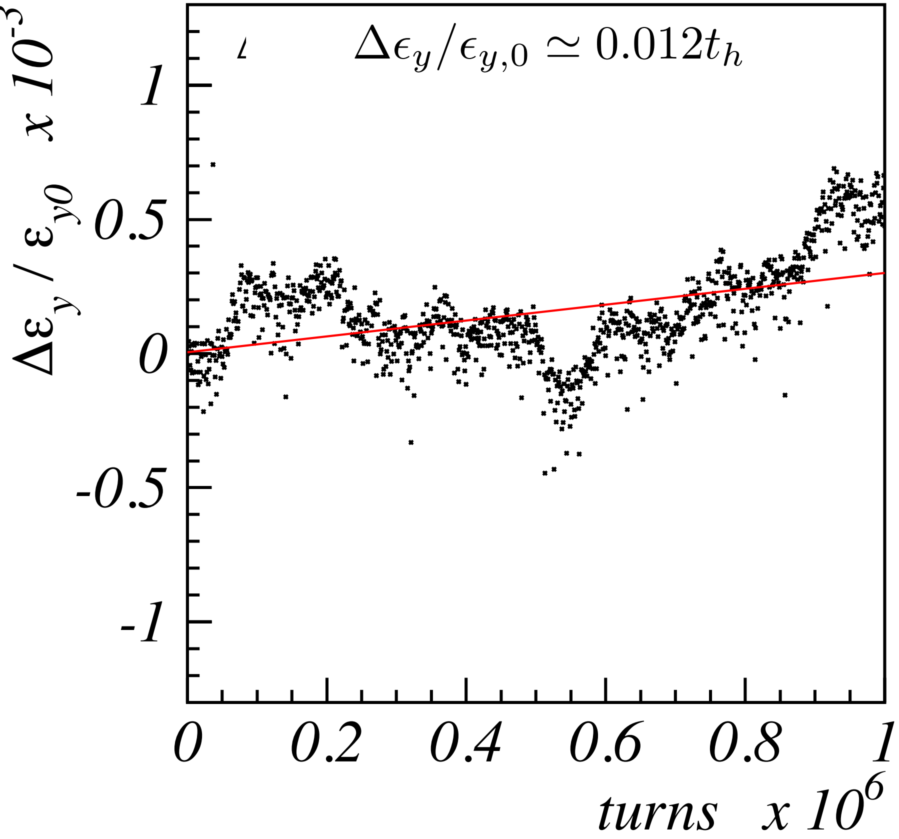



# Sensitivity to number of macro-particles

EC Kicks only in Dipoles,
but EC structure of free pinch

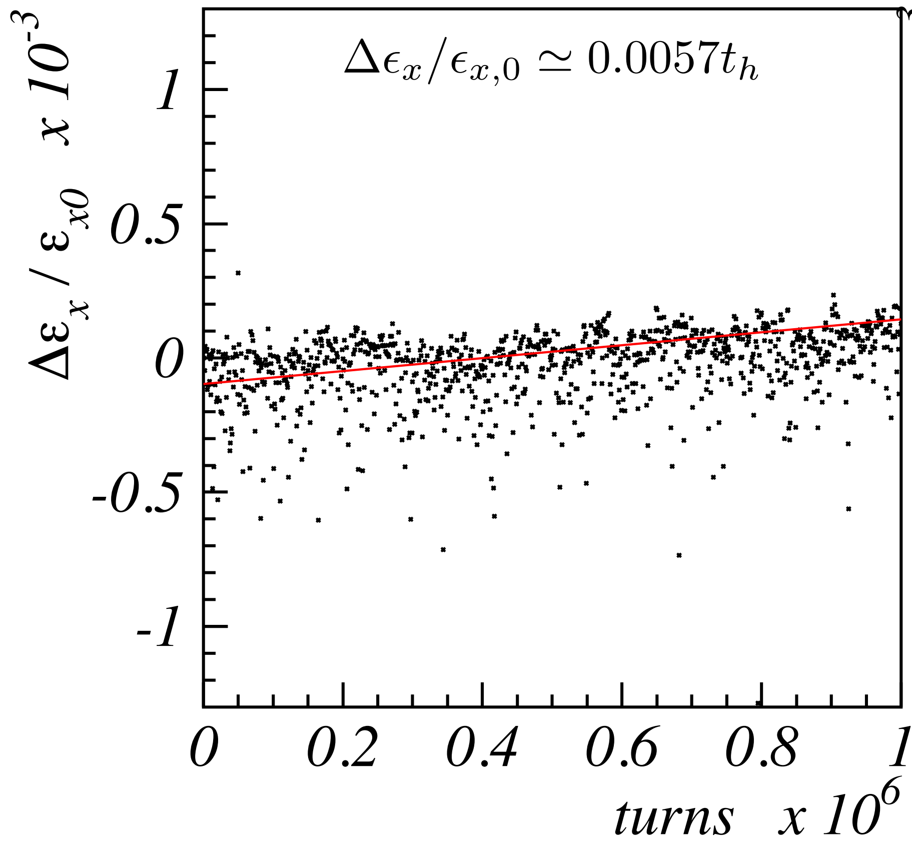
1152 dipoles DQe = 0.1

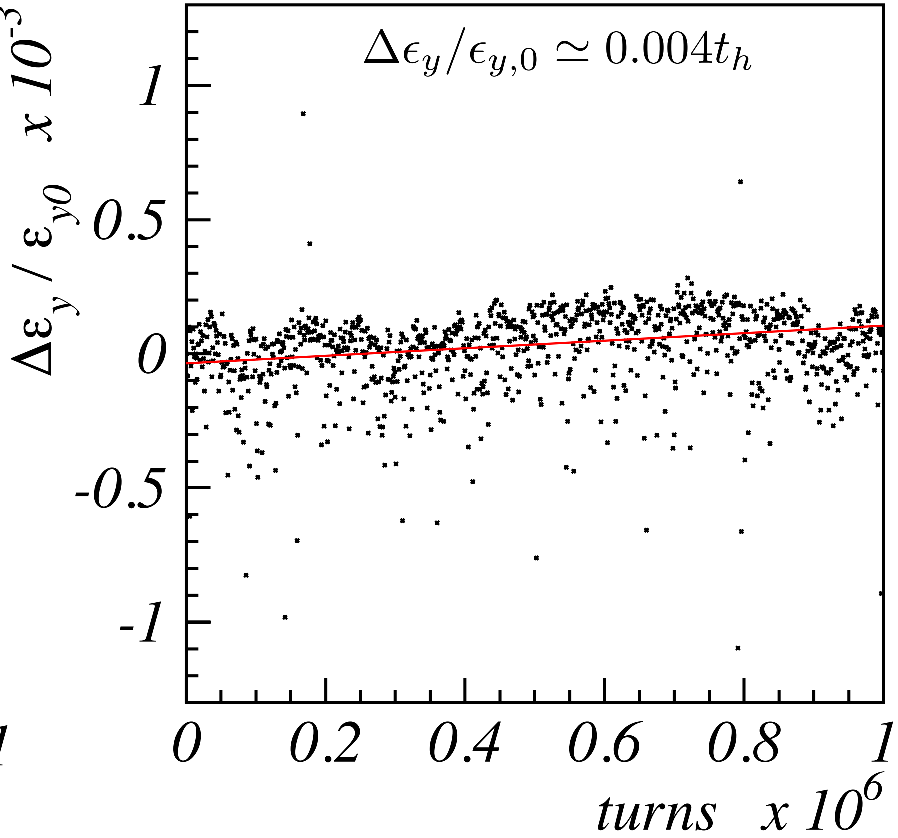


EC Kicks in all dipoles + Quadrupoles ,
but EC structure free field

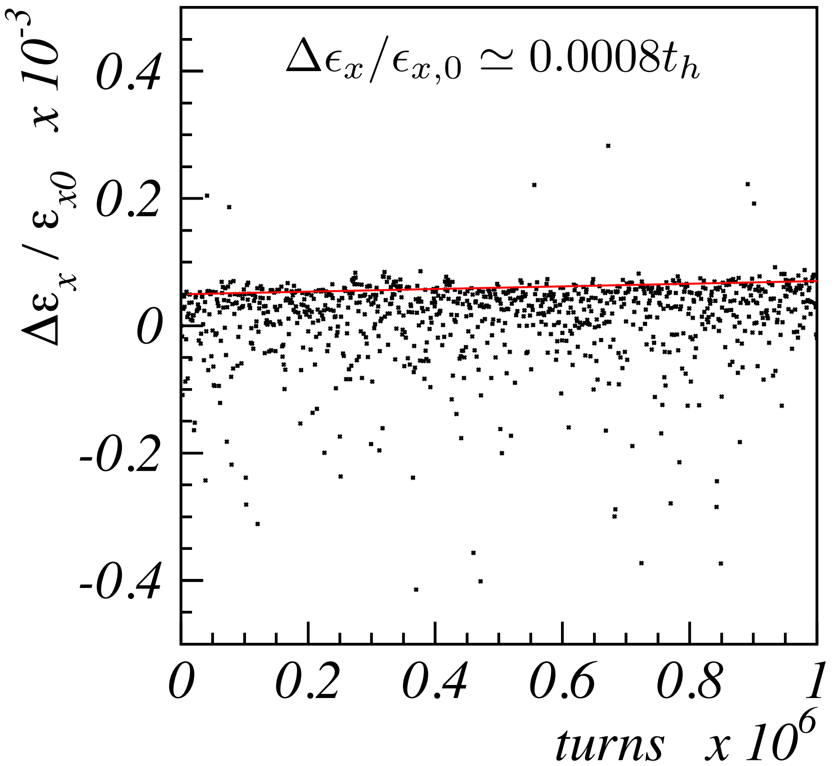
DQ = 0.02 Npar = 8000

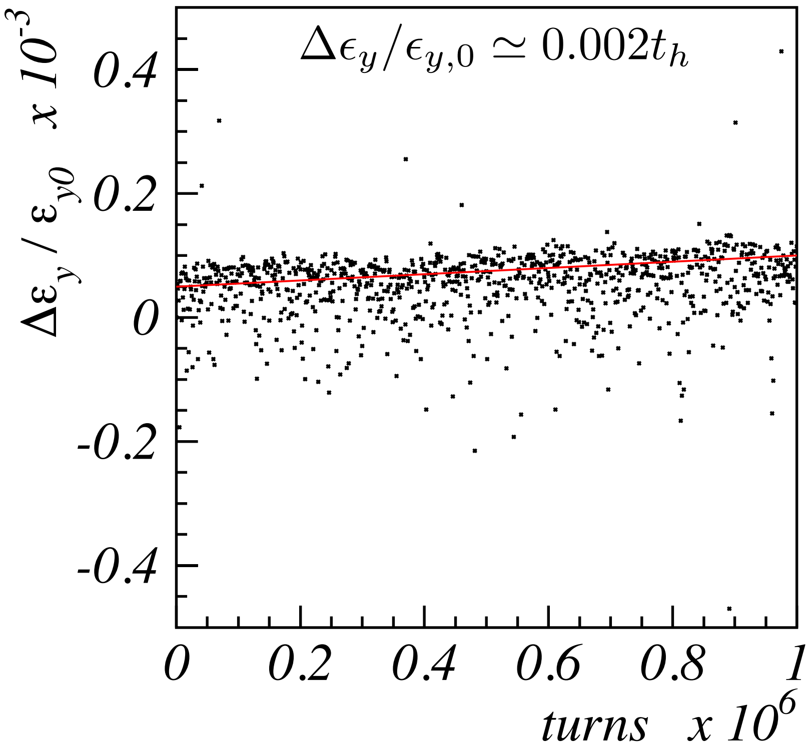


EC Kicks all Dipoles,
EC structure of free pinch

DQ = 0.02    Npar = 19000



# Present estimates

Issues affecting the results:

sensitivity to number of particles
sensitivity to EC-structure
sensitivity to EC kick random error
sensitivity to actual density of electrons
that is to maximum tune spread

**Results sensitive to parameters: but emittance growth very slow**

| DQe | Dex/ex hour | Dey/ey hour | N macro-particles | Turns in simulation | Dipole arc 1152 | Dipole | Quad |
|---|---|---|---|---|---|---|---|
| 0.1 | 6% | ~0% | 8000 | $10^6$ | yes | yes | yes |
| 0.1 | 5% | 1.2% | $1.6 \times 10^4$ | $10^6$ | yes | no | no |
| 0.02 | 0.57% | 0.4% | 8000 | $10^6$ | yes | yes | yes |
| 0.02 | 0.08% | 0.2% | $1.9 \times 10^4$ | $10^6$ | yes | yes | no |

# Approaching a Systematics

Difficult to have all information

EC kicks should take into account of

1) actual sizes of the beam (betax/betay)
2) pinch with actual electron extension (pipe vs. beam size)
3) realistic optics → correct phase advance among EC kicks → correct excitation of high order resonances
4) analytic modeling (acceptable approximation) of Coulomb field

**Creating an element ``EC Kick'' which can be included into the accelerator structure for reaching the best modeling.**
**Help of O.E. Berrig, V. Baglin → location of solenoids, coated-uncoated sections**

↓

modeling the effect of random error on EC kicks → excitation of random resonances

Large overlap of topics between space charge and electron cloud incoherent effects. Development of models for analytic-diffusion based prediction is desirable to tracking simulations

Development of smart strategies for long term simulations (beam dynamics scaling)

**LHC issue: what will be the flexibility of LHC working point ???**
**over which range of Qx,Qy is it possible to move ???**