Incoherent effect of space charge and electron cloud

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Overview

Space charge incoherent effects

Electron cloud incoherent effects

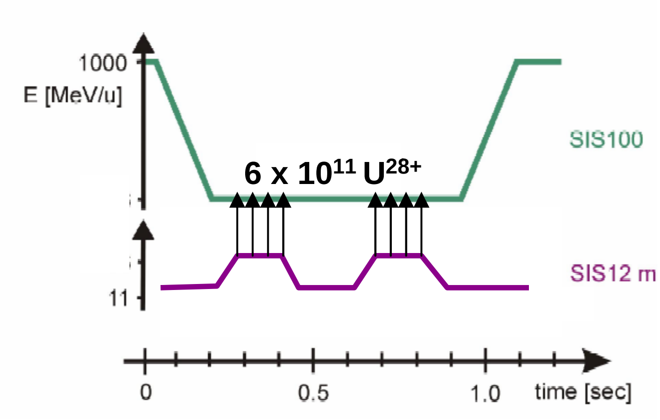
Comparison of SC & EC incoherent effects

Examples of Incoherent effects

Conclusion / Outlook

The beginning

SIS100 beam dynamics requirements brought to the attention the mixed area of high intensity effects in presence of lattice nonlinearities

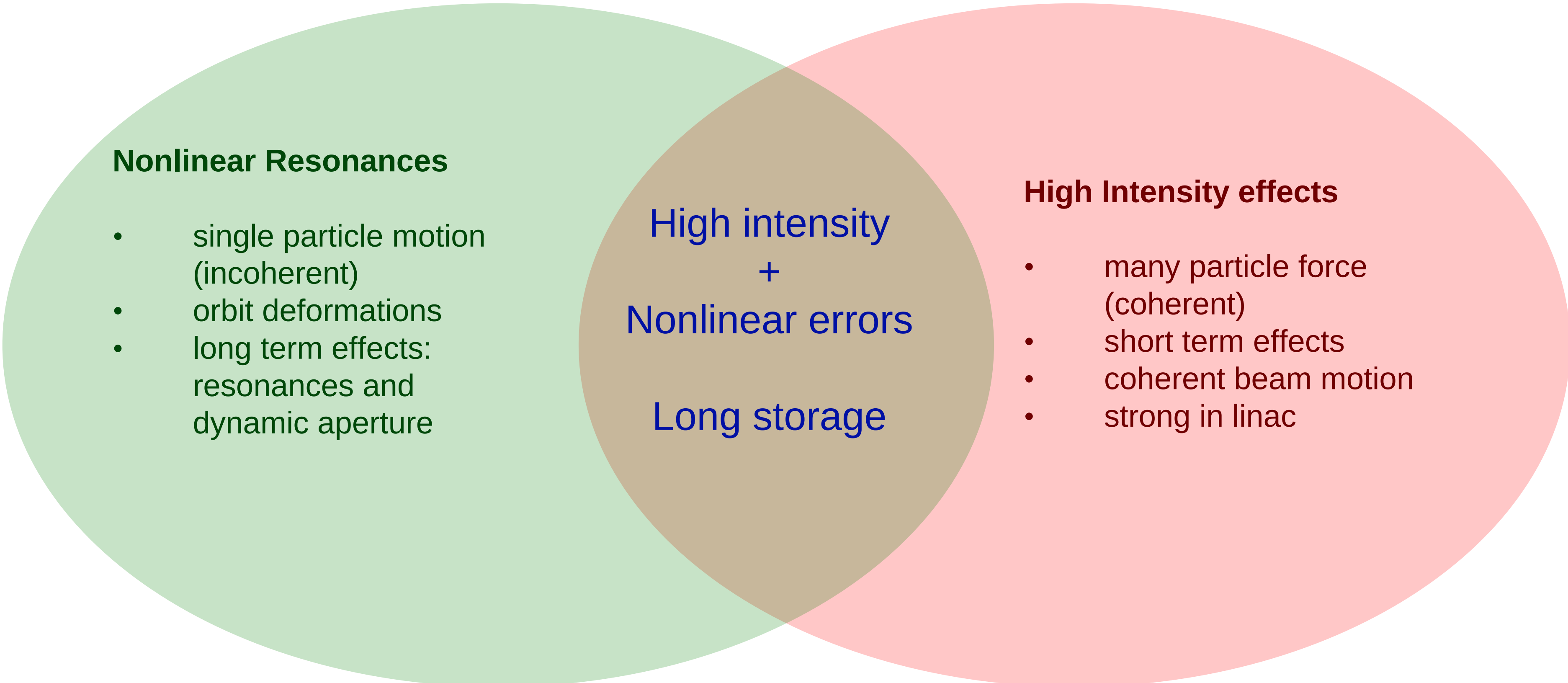


Space charge tunespread

$\Delta Q \sim 0.3$

•P. Spiller *et al*., MOPC100, these proceedings;
•J. Stadlmann *et al*., MOPC124, these proceedings

The long term high intensity-driven incoherent effects



Example of space charge incoherent effects

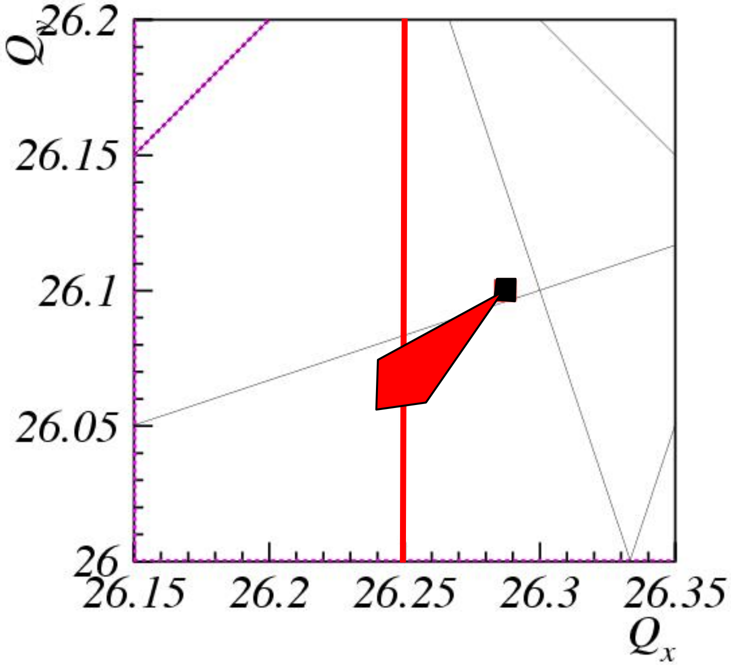
Liner lattice + 1 octupole

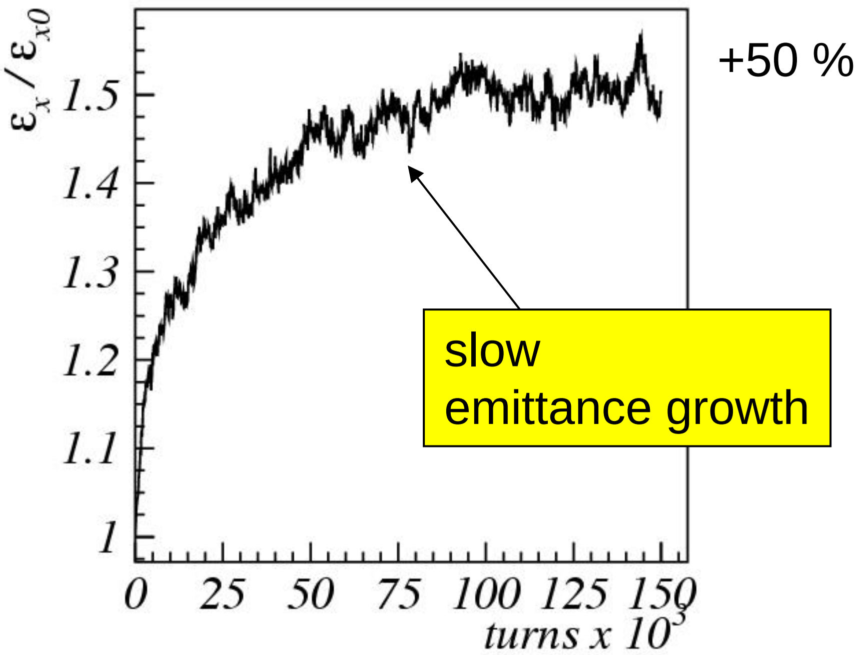
Q_{x0} = 26.28 Q_s = 1/300

Q_{y0} = 26.1

High intensity bunched beam:

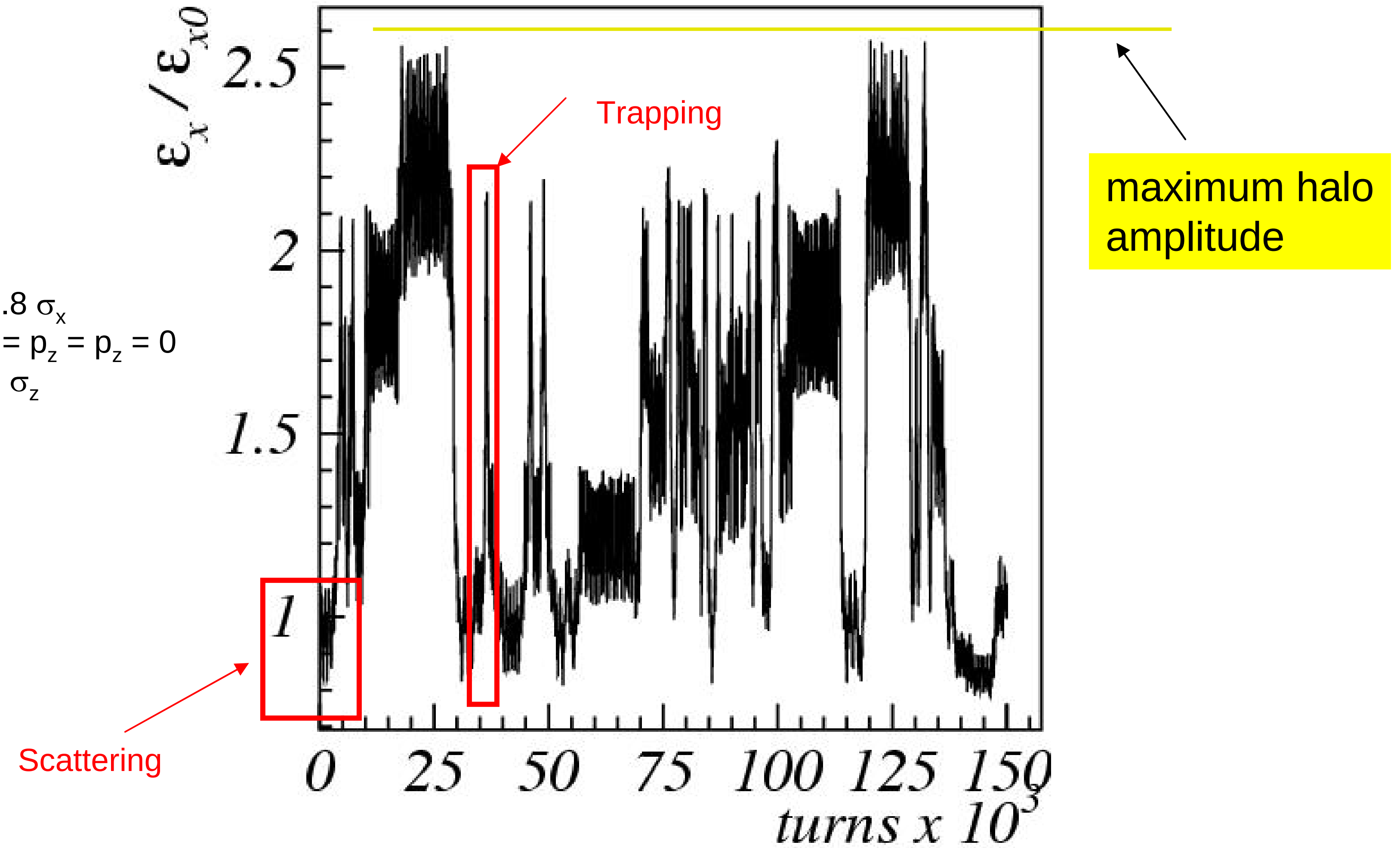
ΔQ_x = -0.075



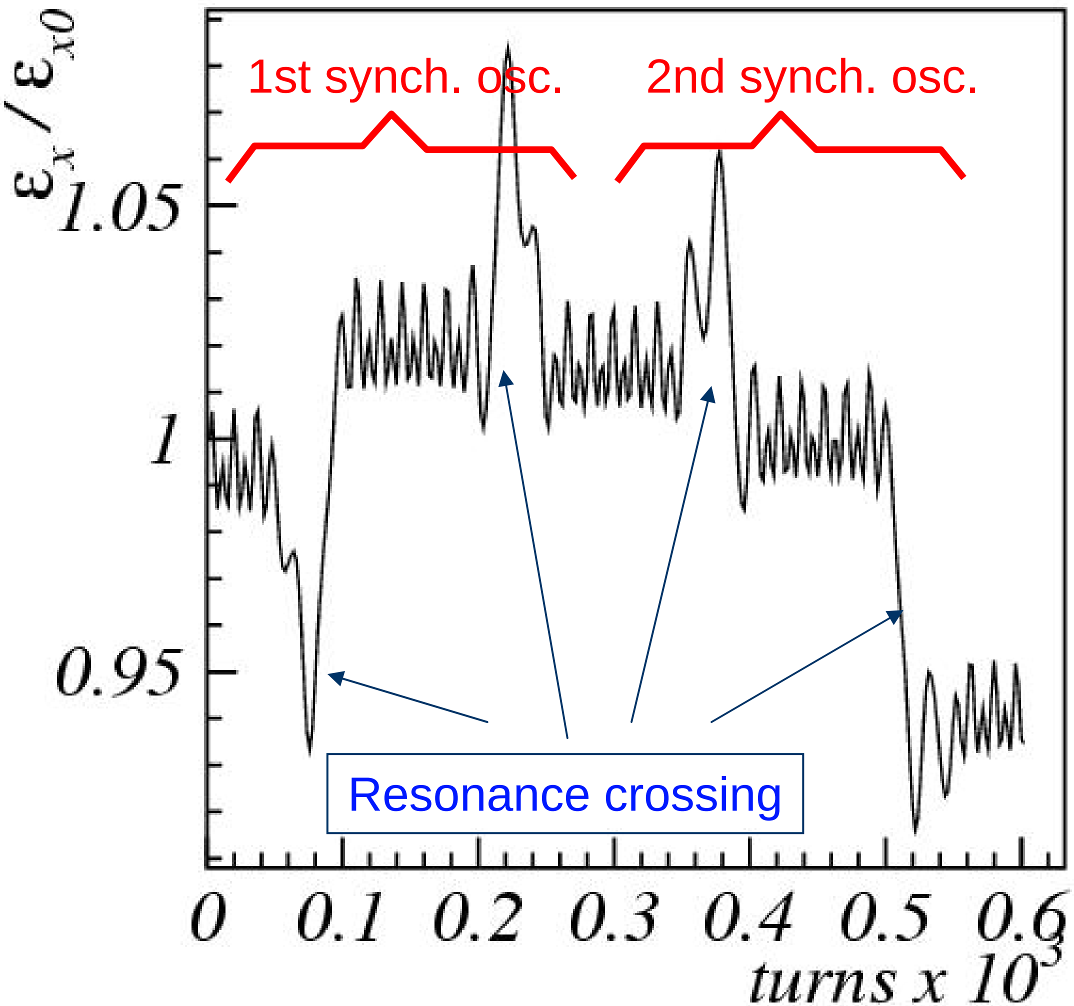


One beam particle motion

x = 1.8 σ_x
$p_x = y = p_z = p_z = 0$
z = 3 σ_z

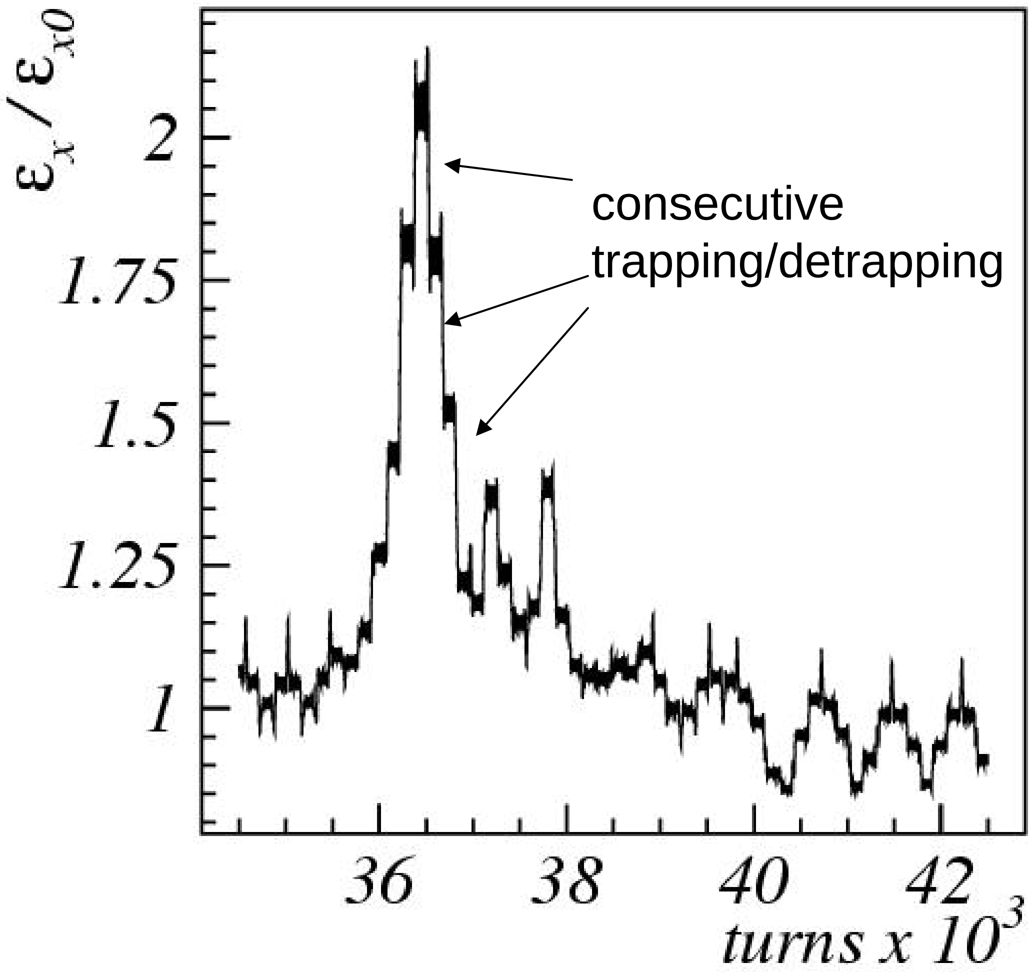


Scattering



- *A.I. Neishtadt, Sov. J. Plasma Phys. 12, 568 (1986)*
- *A.I. Neishtadt, A.A. Vasiliev NIM A **561**, (2006) 158*

Trapping



- 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)

Electron Cloud

Electron cloud effects

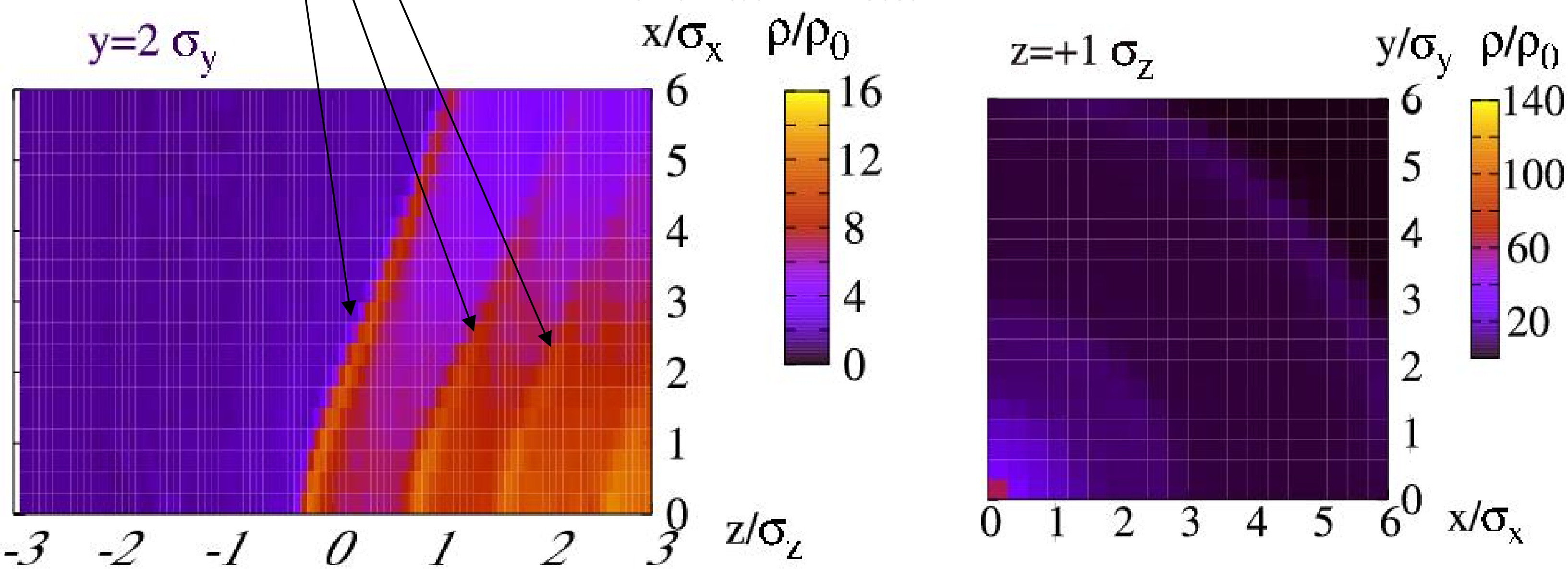
EC build up
EC heat load
EC induced single
bunch instability
Pressure rise
EC pinches during
bunch passage

The pinch of the electron cloud

During the bunch passage through an uniform EC,
electrons oscillates in the bunch potential creating a pinch

Electron cloud rings created by a Gaussian bunch in free field region

F. Zimmermann et al. THPC089

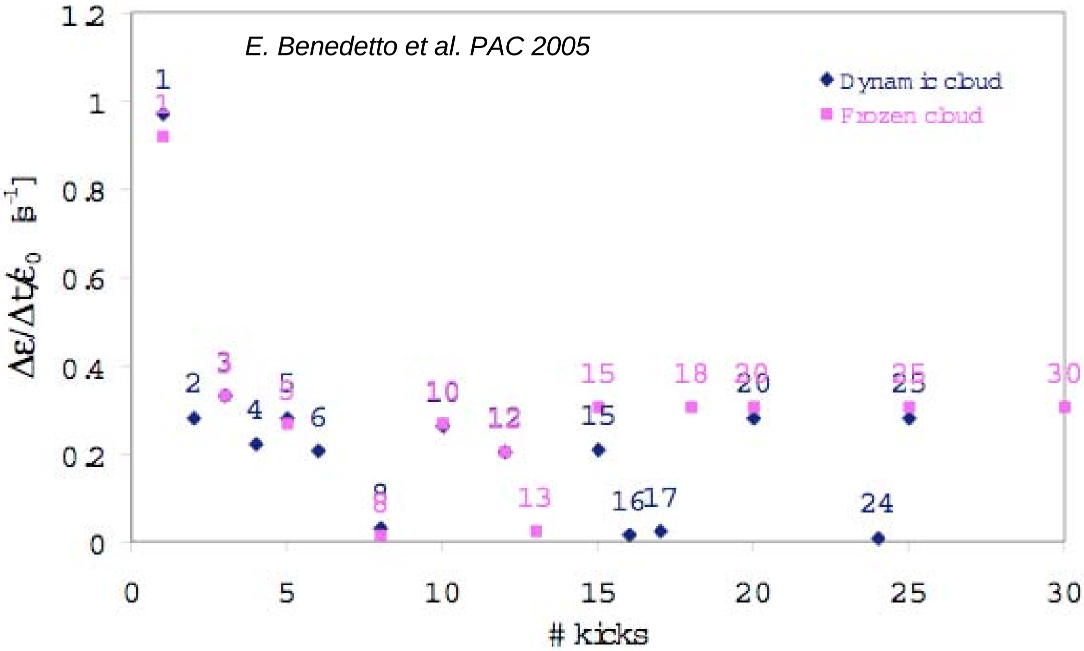


Pinched EC creates nearly circular rings which feed back on the main beams

Electron cloud incoherent effects

Discussions on EC incoherent effects started in the ICFA-HB2004 workshop in relation to the SPS beam lifetime observations
(F. Zimmermann, E. Metral,E. Shaposhnikova, G.Arduini, L. Trevor)

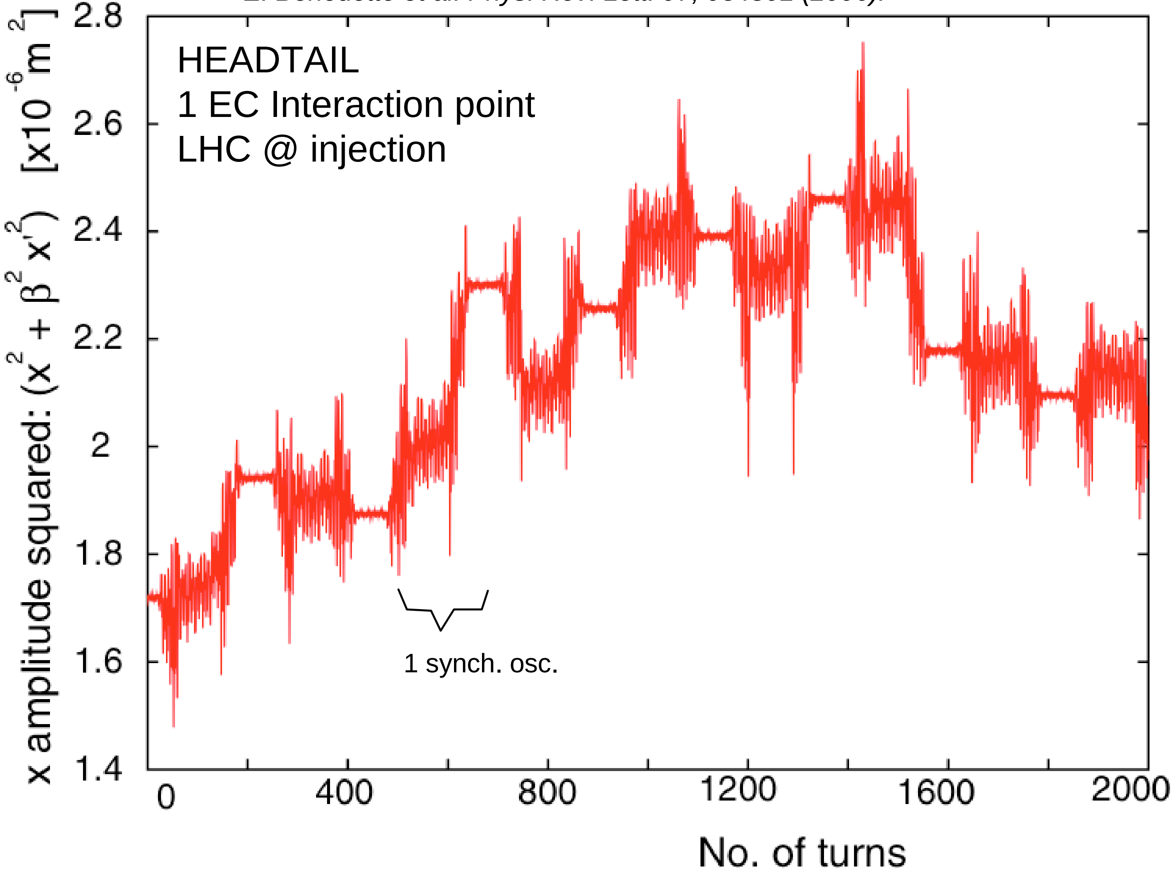
In simulations: unexplained slow emittance growth (noise?)



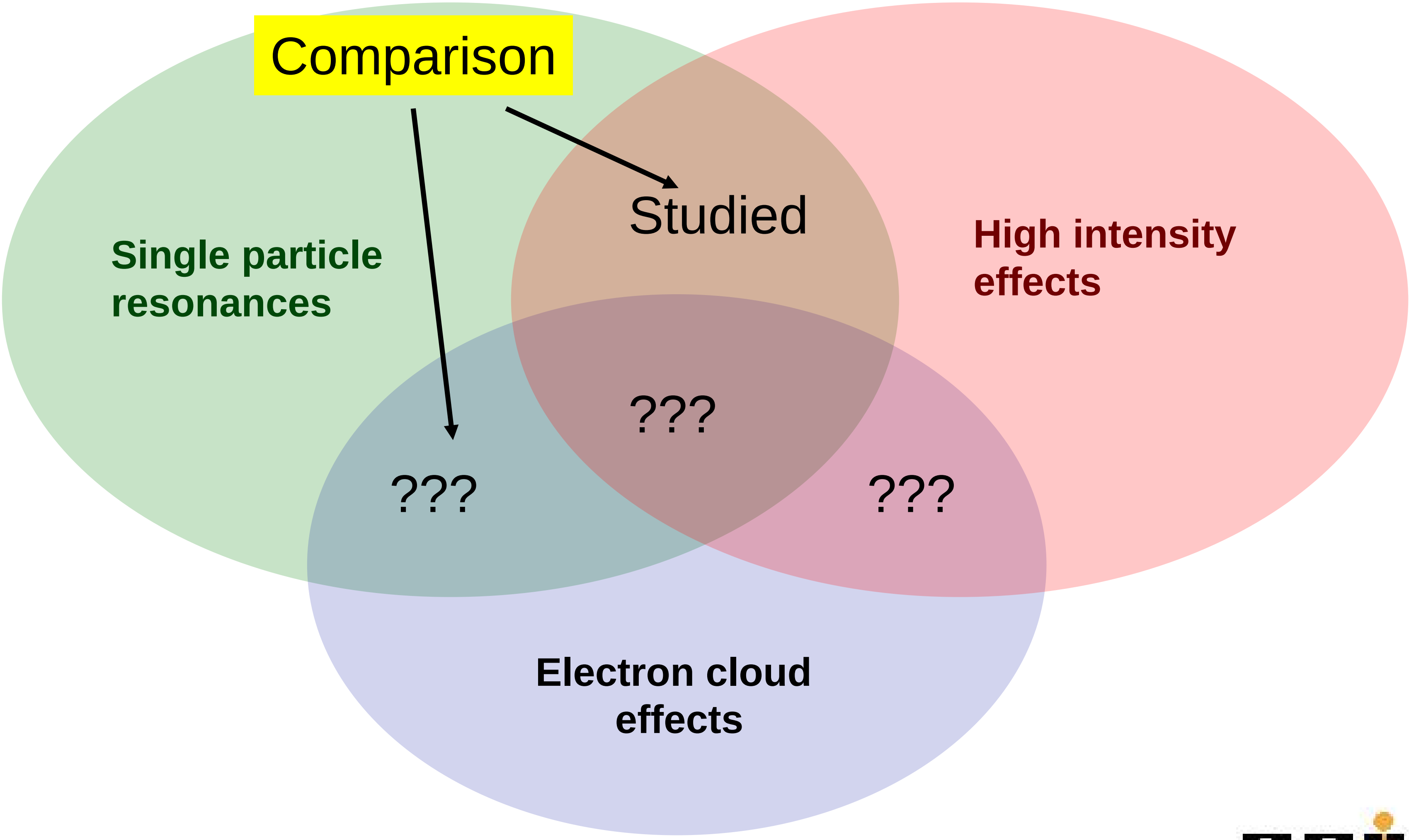
Average growth rate $\Delta\varepsilon/(\varepsilon\,\Delta t) \sim 0.4$

Evidence of EC induced scattering

E. Benedetto et al. Phys. Rev. Lett. 97, 034801 (2006).



EC and SC and error resonances



The problem of long term tracking

Fully self-consistent simulations with the present computer capabilities:
for bunches of 10^6 macro-particles limits of ~10^6 SC kicks.
For SIS100 10^8 SC kicks. For RHIC/LHC much more!
R. Ryne THYM03, these proceedings

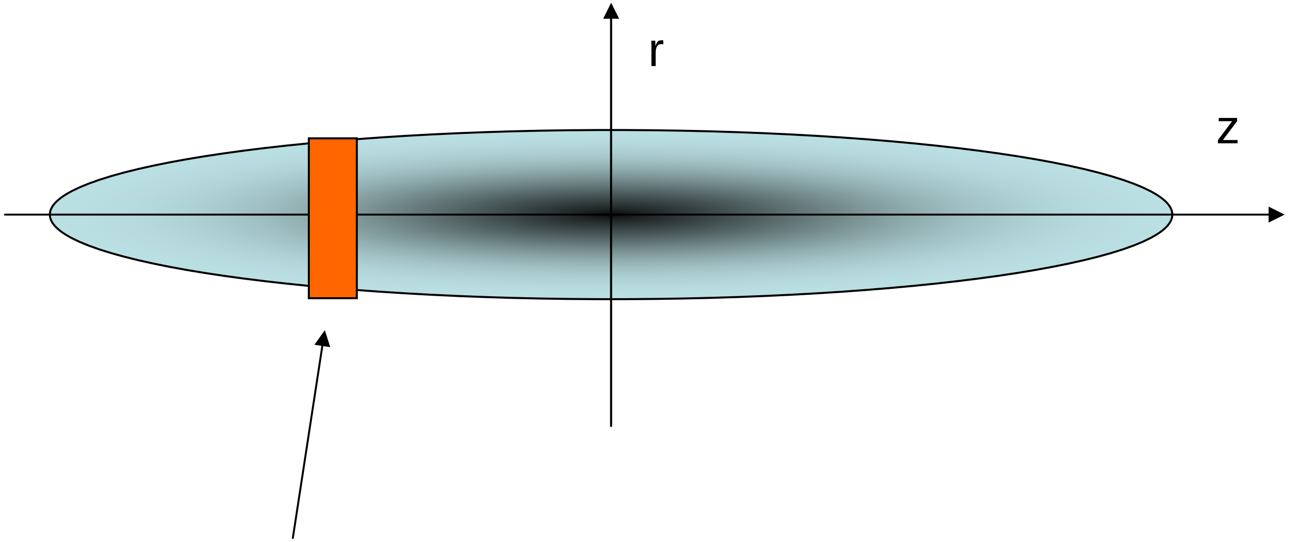
Numerical noise may affects the long term beam predictions:
Noise is reduced by increasing the number of macro-particles

It is essential to develop simplified models which incorporate the basic physical mechanisms responsible for the long term effects

Medium term verification via large scale self consistent simulations

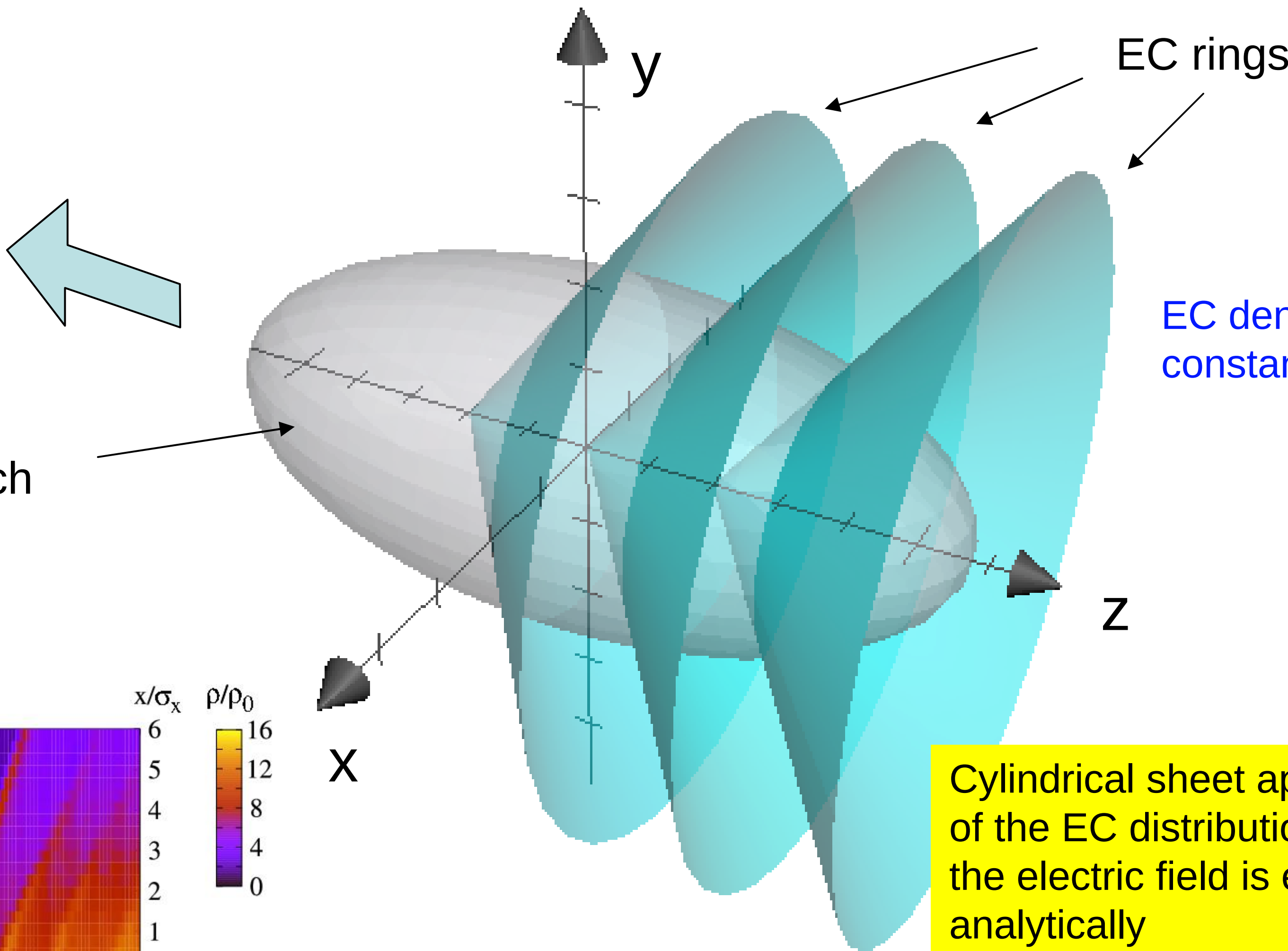
SC model

3D Gaussian bunch

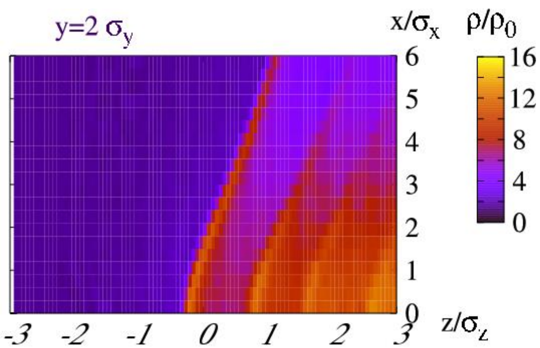


This looks like a piece of a coasting beam ⇨ Electric field can be analytically computed

EC model



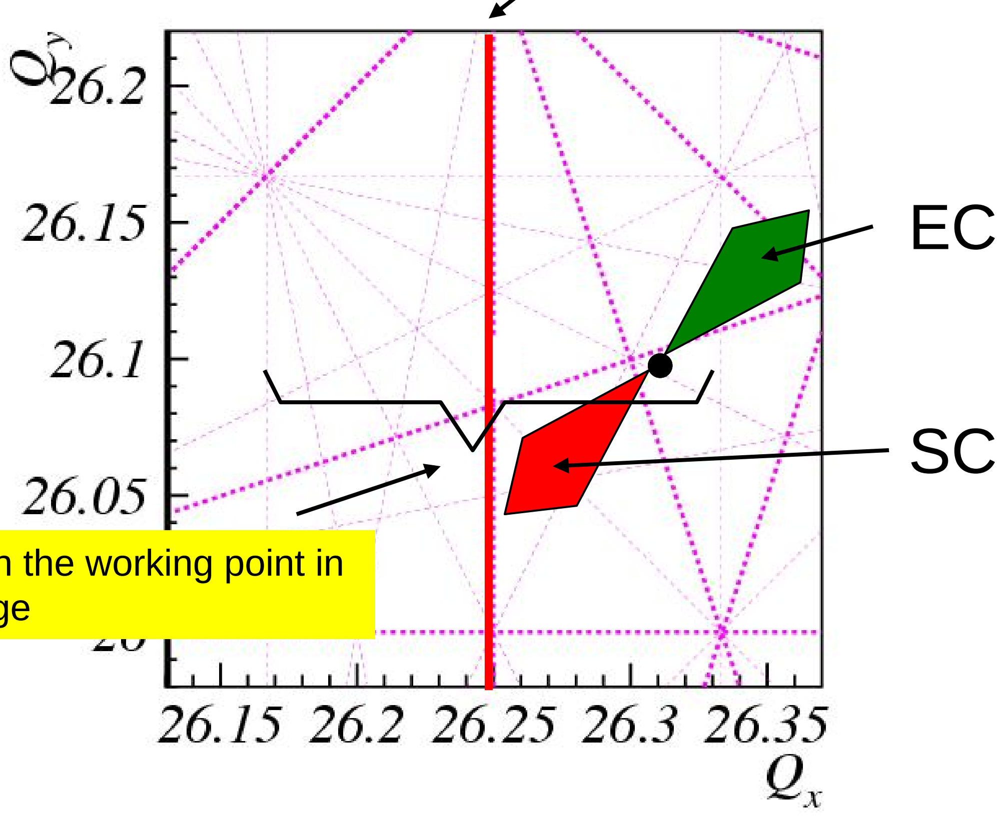
EC density
constant in the rings



Cylindrical sheet approximation of the EC distribution: the electric field is expressed analytically

Comparison of EC and SC incoherent effects

We excite one lattice resonance



We scan the working point in this range

Equal SC and EC detuning

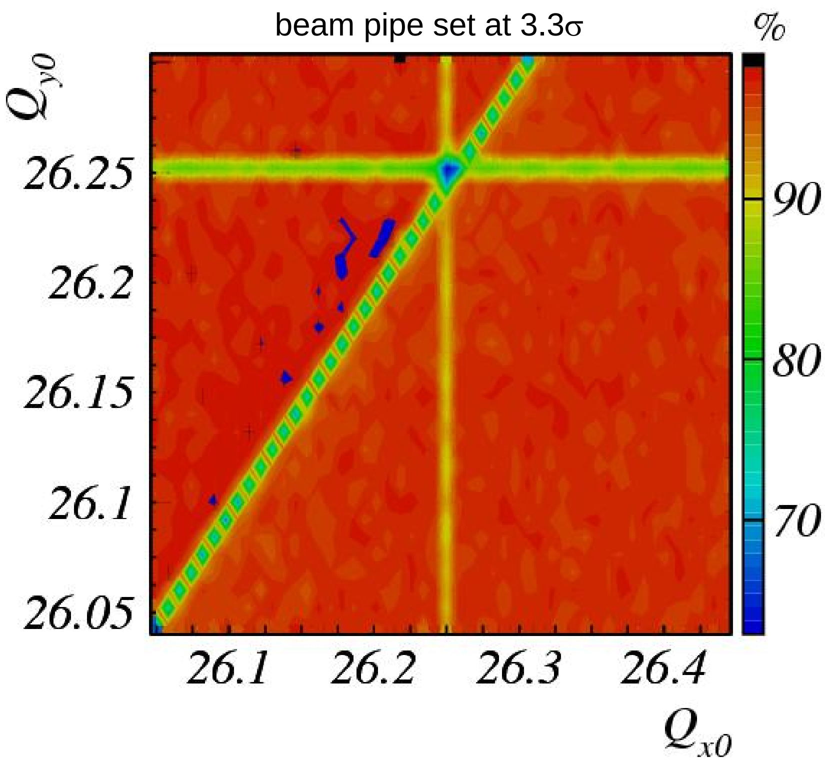
$\Delta Q_{sc} = - \Delta Q_{ec} = -0.075$

Resonance excitation (no space charge)

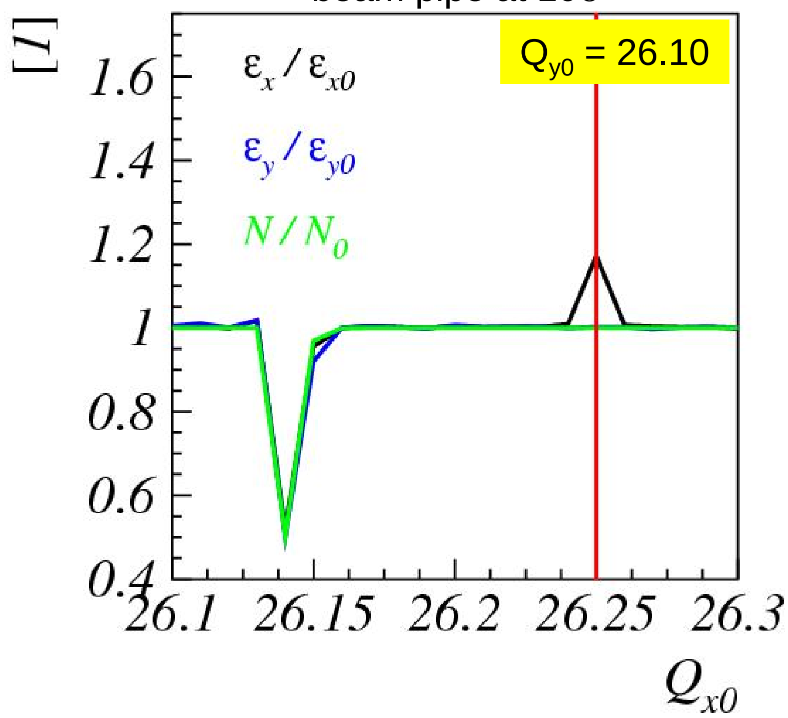
Error resonance

One octupole excites 4th order resonance

beam pipe set at 3.3σ



beam pipe at 10σ



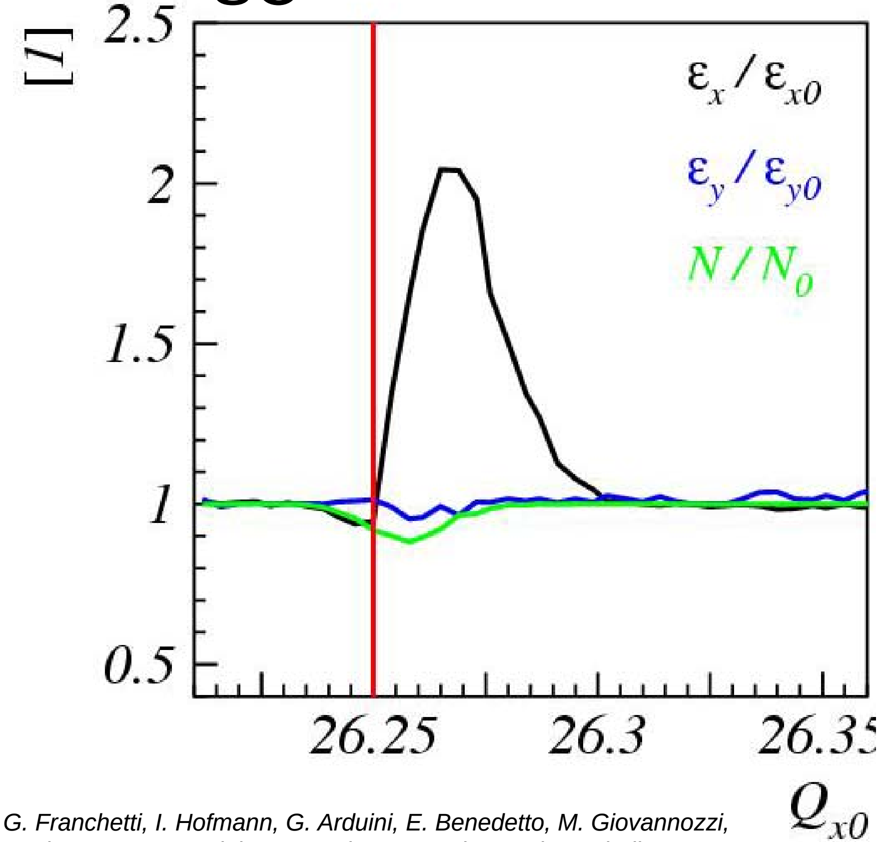
Comparison of SC and EC incoherent effects

Error resonance

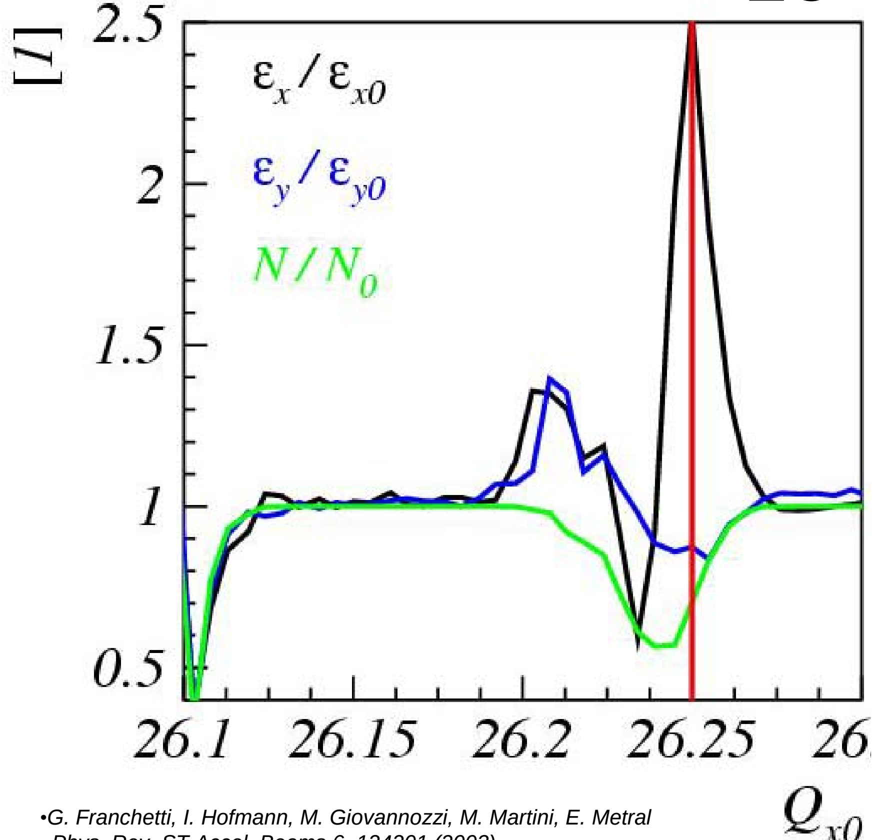
Emittance growth and beam loss regimes

Results are affected by the strength of K_3

SC



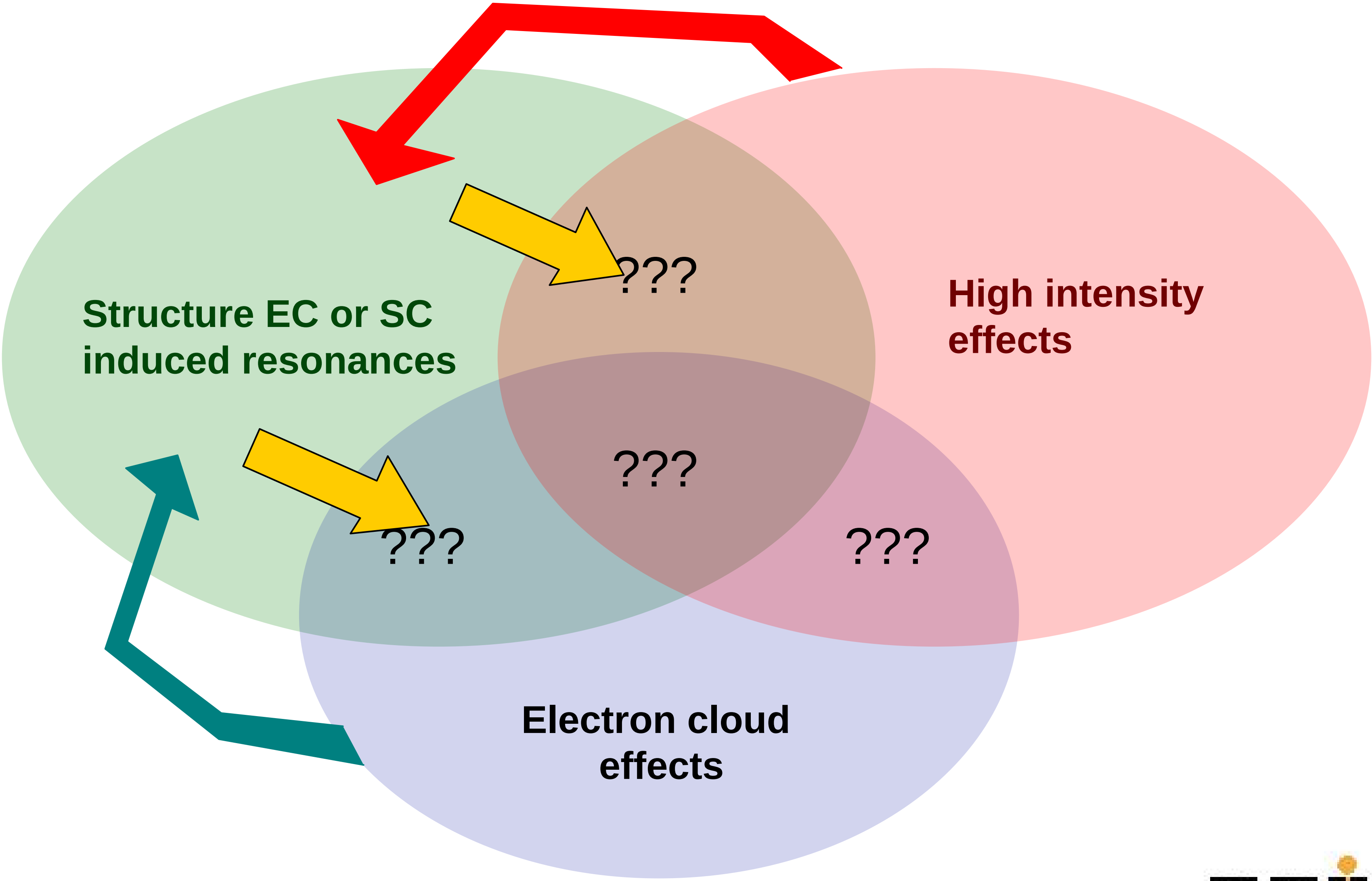
EC



G. Franchetti, I. Hofmann, G. Arduini, E. Benedetto, M. Giovannozzi, T. Linnecar, M. Martini, E. Metral, G. Rumolo, E. Shaposhnikova, F. Zimmermann, LHC Lumi 2006, October 16-20 2006, Valencia, Spain

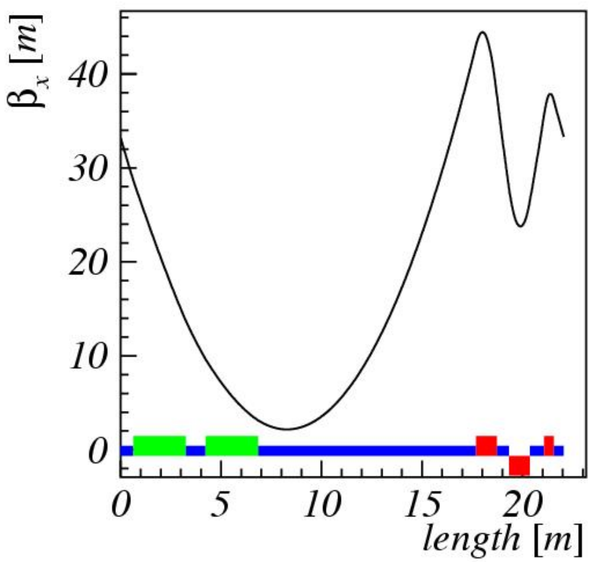
- *G. Franchetti, I. Hofmann, M. Giovannozzi, M. Martini, E. Metral Phys. Rev. ST Accel. Beams 6, 124201 (2003).*
- *E. Metral, G. Franchetti, M. Giovannozzi, I. Hofmann, M. Martini, R. Steerenberg Nucl. Instr. and Meth. A 561, (2006), 257-265.*

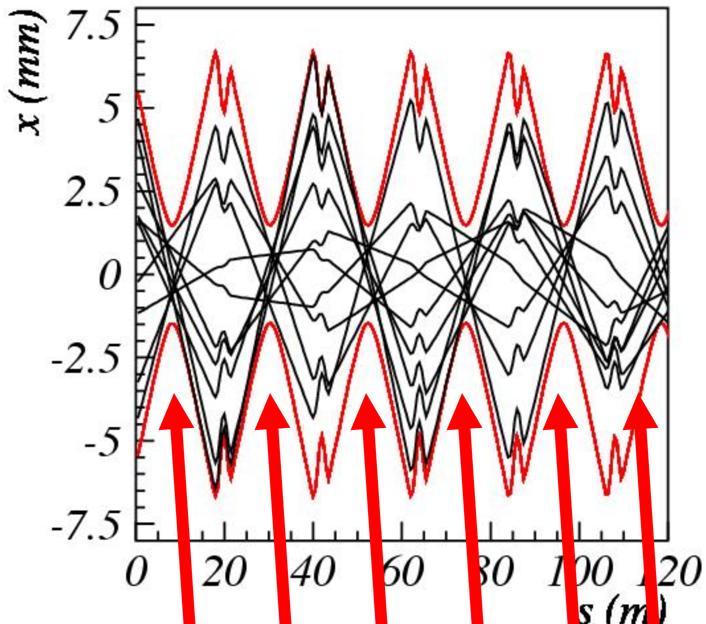
SC and EC + structure resonances



Space charge induced structure resonances

Lattice with fodo cell

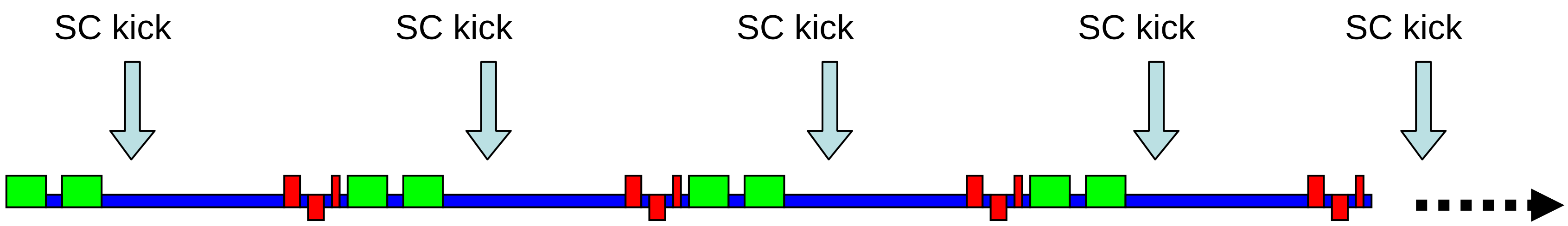




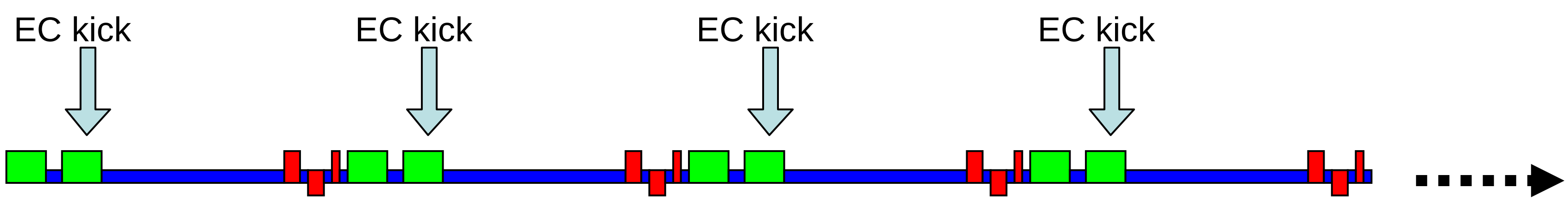
At these positions of minimum transverse size space charge creates strong nonlinear forces which acts like nonlinear errors

Space charge and electron cloud structure resonances

The lattice optics induces a structure of space charge kicks, which excites a resonance



The electron cloud creates also structure resonances as it is strongly localized



Due to the property of Coulomb forces

$$E_x(x) = -E_x(-x)$$

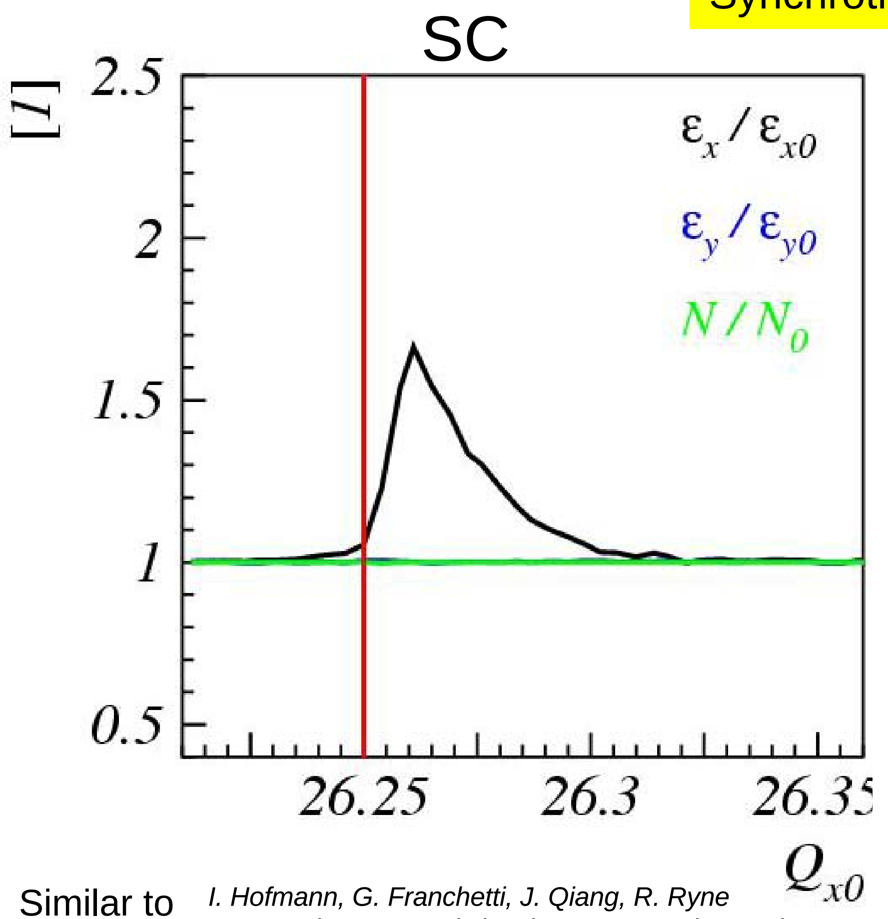
resonances of order 2,4,6,8,.. are excited

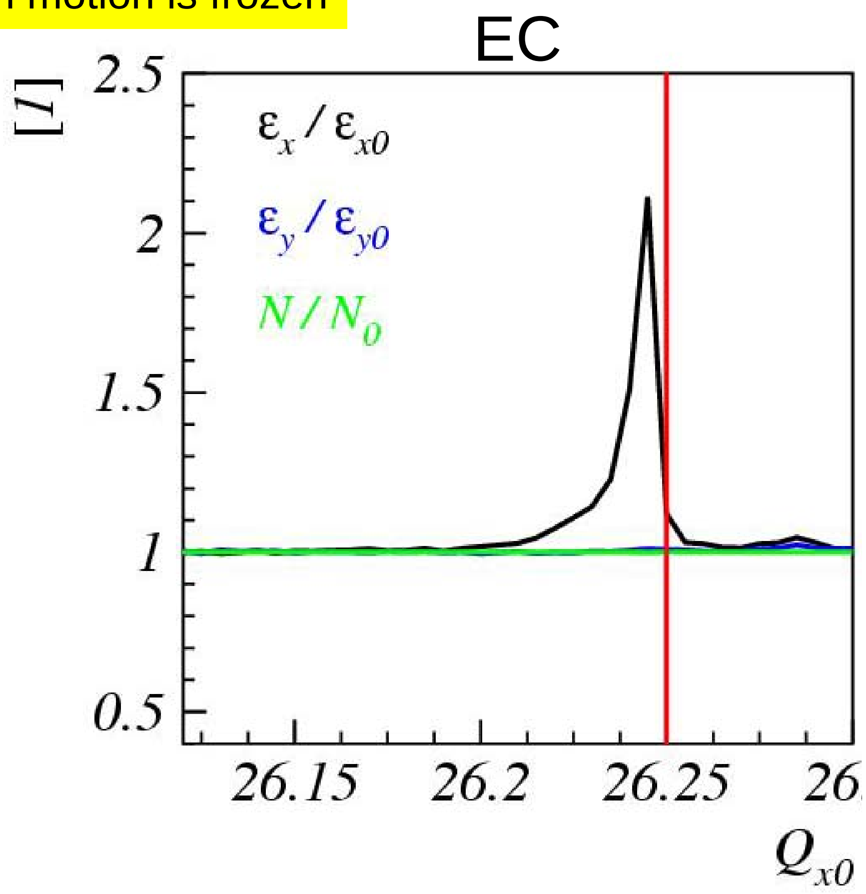
Strength of the resonance is proportional to the Coulomb induced tunespread

Comparison of SC and EC incoherent effects for 2D beams

Structure resonance: 105 EC and SC kicks, $\Delta Q_{sc} = - \Delta Q_{ec} = -0.075$

Synchrotron motion is frozen



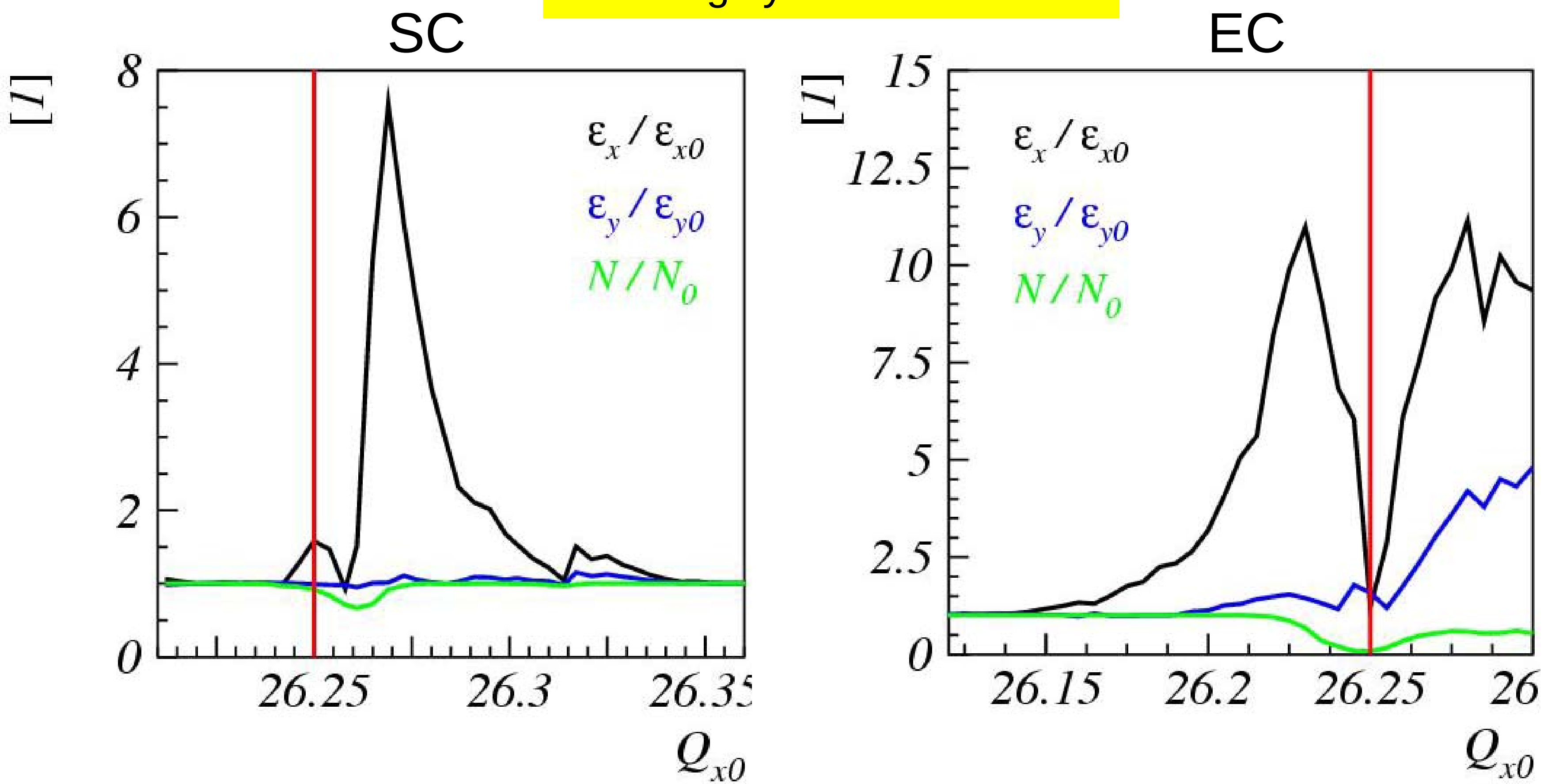


Similar to *I. Hofmann, G. Franchetti, J. Qiang, R. Ryne Proc. 29th ICFA Workshop(AIP, New York, 2003),* ***693****, 65*

Comparison of SC and EC incoherent effects for bunched beams

Structure resonance: 105 EC and SC kicks, $\Delta Q_{sc} = - \Delta Q_{ec} = -0.075$

Including synchrotron motion



Example of incoherent effects

SC incoherent effects in SIS100

G. Franchetti and I. Hofmann, GSI Technical report 2008
G. Franchetti PAC 2005, p. 3807
G. Franchetti et al. EPAC 2006, p. 2793
G. Franchetti PAC 2007, TUZAAB02

EC incoherent effects are suspected to be responsible for the slow emittance growth in RHIC

- *W. Fischer et al., Phys. Rev. ST Accel. Beam 11, 041002 (2008).*
- *S.Y. Zhang and V. Ptitsyn, Phys. Rev. ST Accel. Beam **11**, 051001 (2008).*

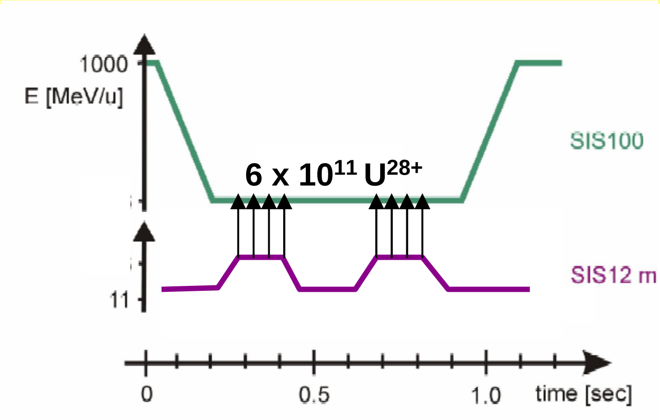
In CERN electron cloud incoherent effects are of relevance for SPS and perhaps LHC

- *E. Benedetto and F. Zimmermann, Proceedings ECLOUD04, CERN Report CERN- 2005-001, p. 81 (2005)..*
- *E. Benedetto, G. Franchetti and F. Zimmermann, Phys. Rev. Lett. **97**, 034801 (2006).*
- *G. Franchetti, I. Hofmann, G. Arduini, E. Benedetto, M. Giovannozzi, T. Linnecar, M. Martini, E. Metral, G. Rumolo, E. Shaposhnikova, F. Zimmermann, LHC Lumi 2006, October 16-20 2006, Valencia, Spain. p. 192.*
- *G. Franchetti and F. Zimmermann, Proc. of CARE-HHH- ADP BEAM07 workshop, Geneva, Switzerland (2007).*

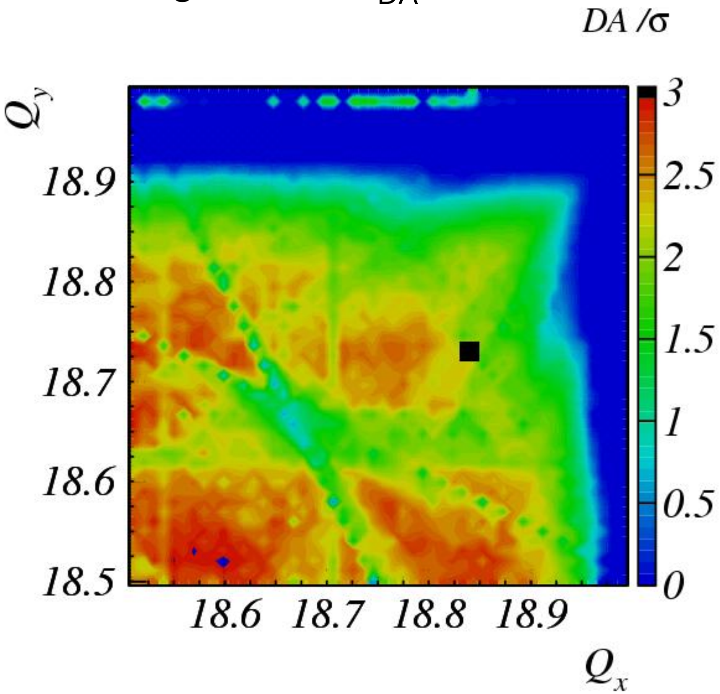
Space charge incoherent effects in FAIR

First bunch @ 150 MeV/u

Nominal N_{ions} = 0.75 x 10^{11}/bunch
Beam1: $\varepsilon_{x/y}$ = 35/15 mm-mrad (2σ) $\Delta Q_{x/y}$= -0.31/-047
Beam2: $\varepsilon_{x/y}$ = 50/20 mm-mrad (2σ) $\Delta Q_{x/y}$= -0.21/-0.24
Turns = 1.2 x 10^5 (1 sec.)



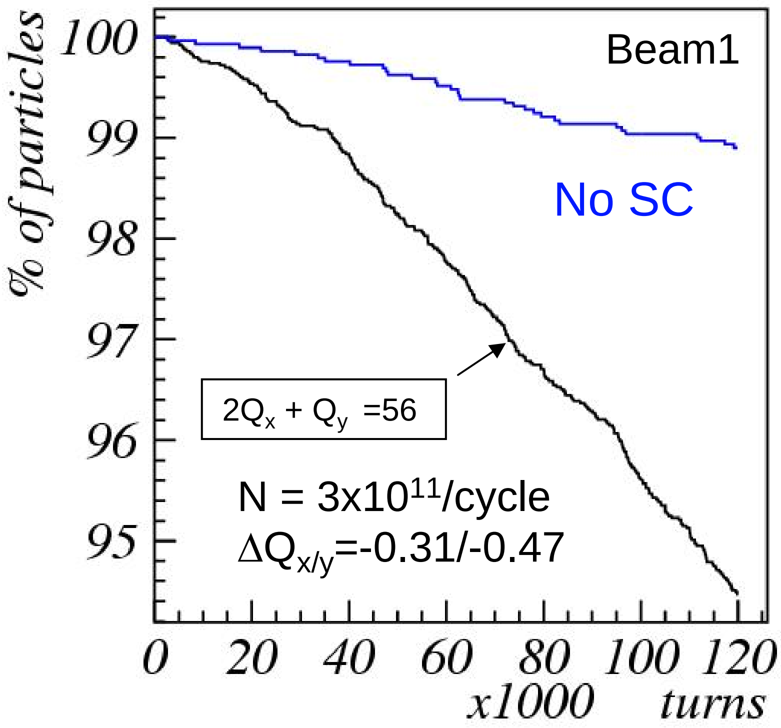
Nonlinear errors in bends and quadrupoles + COD with 16 seeds average DA - $3\sigma_{DA}$.

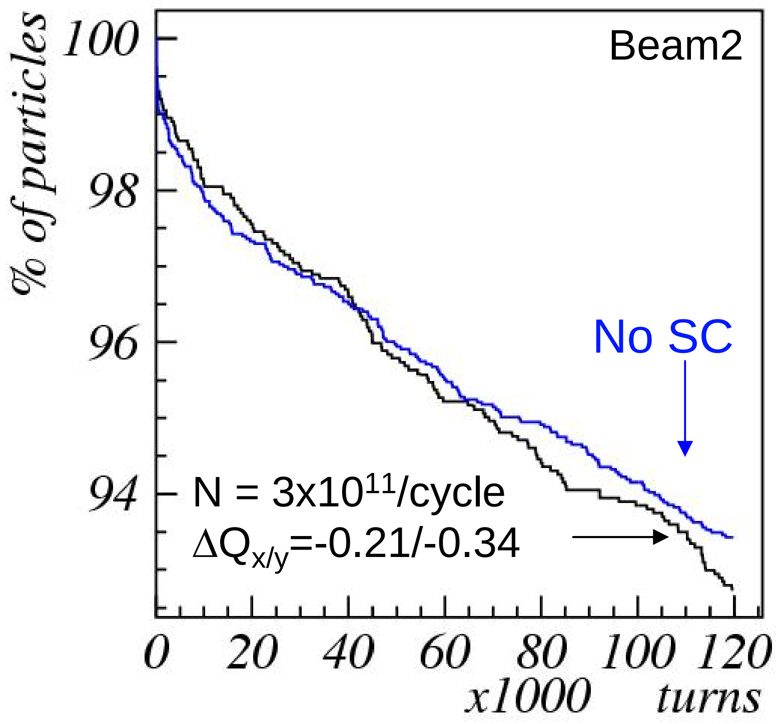


- *P. Spiller et al., MOPC100, these proceedings;*
- *J. Stadlmann et al., MOPC124, these proceedings*
- *P. Spiller, C. Omet et al., MOPC099, these proceedings;*
- *A. Kovalenko, WEPD017, these proceedings;*
- *P. Schnizer et al., TUPP105, WEPD021, these proceedings*
- *E. Mustafin et al., THPP102, these proceedings;*
- *O. Malyshev et al., THPP099, these proceedings;*
- *A.W. Molvik et al., Phys. Rev. Lett.* ***98*** *054801 (2006).*

Beam loss estimates

Take one seed (1mm residual COD, 99% beam loss) + $\langle \delta p/p \rangle_{rms}$ = 5 x10^{-4}



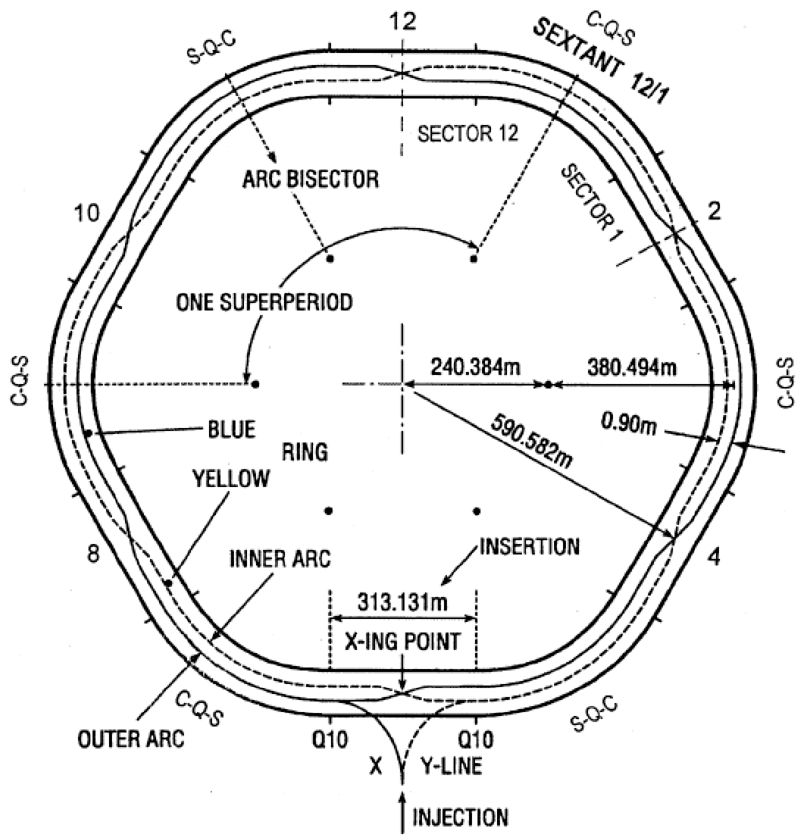


Space charge dominates (incoherent effects)

DA dominates over space charge

Over the full cycle N = 3x10^{11} ~ 3% and for N= 6x10^{11} ~15%

EC incoherent effect in RHIC



*H. Hahn et al. NM A **499** (2003) 245–263*

One electron cloud kick per long dipole

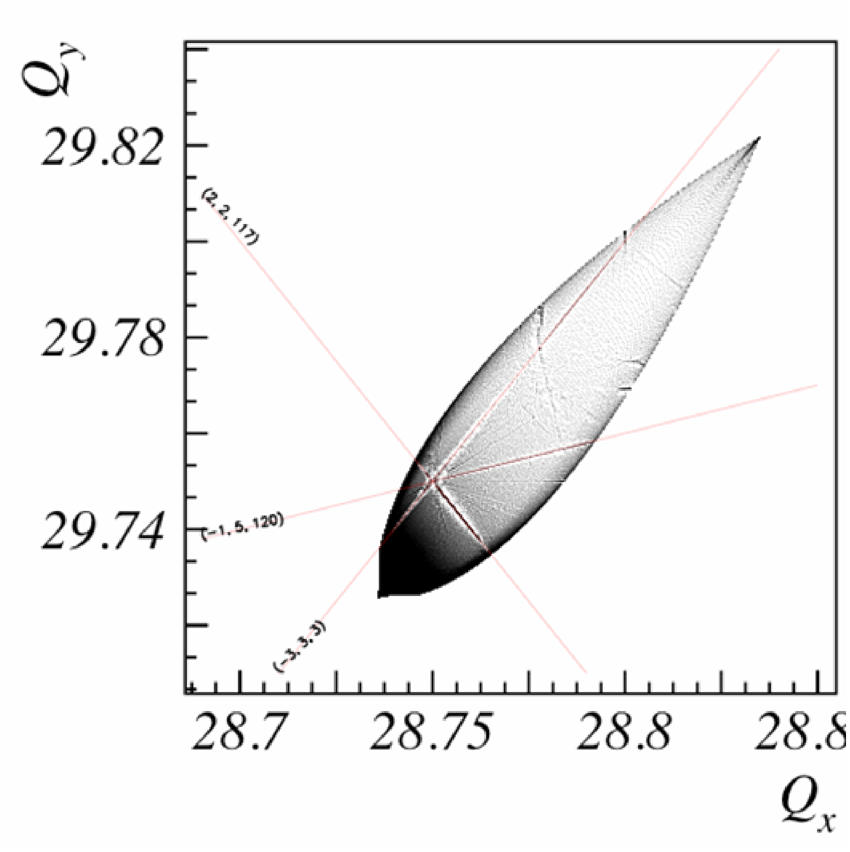
144 EC kicks placed in the correct position of the **BLUE** ring and constant focusing transport in between EC kicks

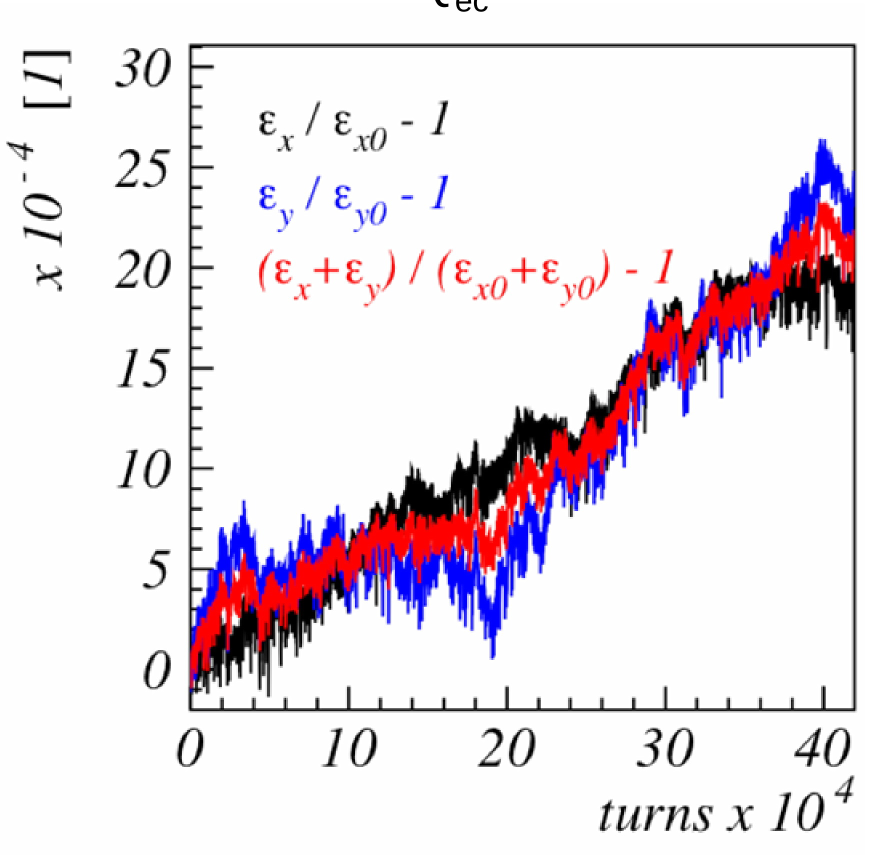
Qx = 28.735
Qy = 29.725

EC incoherent effect in RHIC

Large EC tunespread to detect
EC induced structure resonances

$\Delta Q_{ec} = 0.03$





Exploratory discussion of EC incoherent effects in LHC

Approximated lattice: constant focusing between EC kick

1 EC kick per dipole -> 1152 kicks

Tunes: $Q_x = 64.28$ $Q_y = 59.31$, $Q_s = 1/168$

Assumptions:

1 all EC kicks are equally strong

2 no lattice change of beta is included

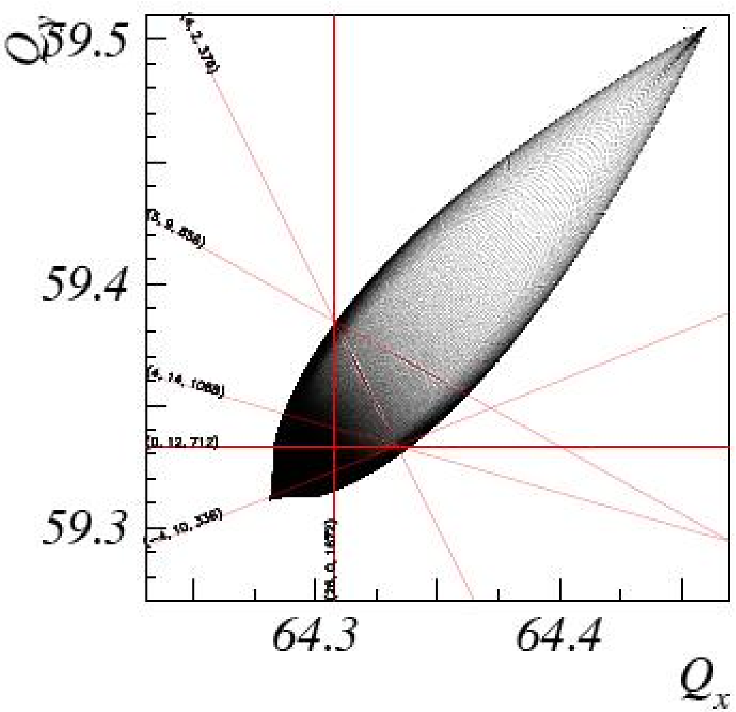
3 no fluctuations of EC included

4 no adjustment of EC rings as function of total integrated detuning

Possible incoherent effects in LHC

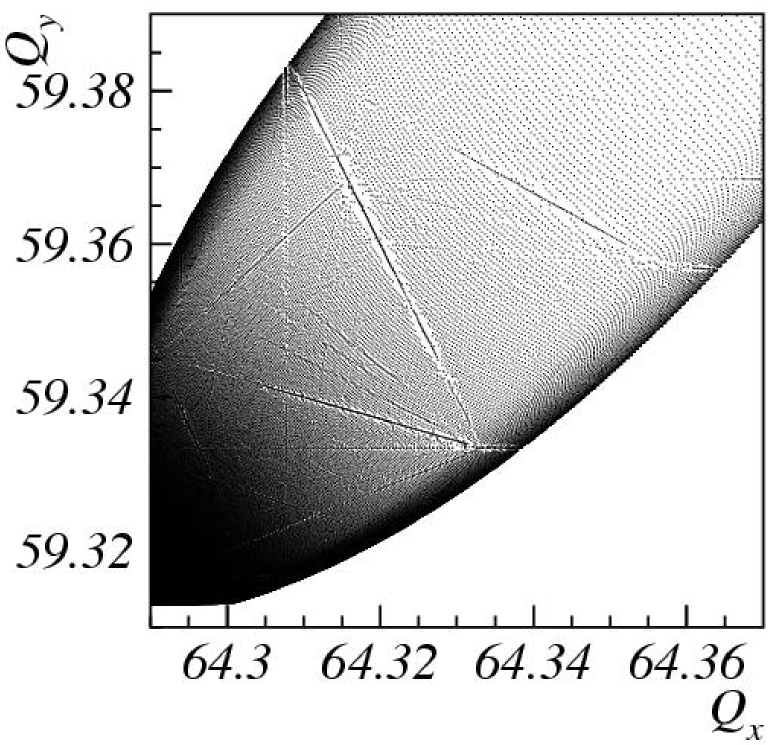
$Q_x = 64.28$ $Q_y = 59.31$

$\Delta Q_{ec} = 0.18$

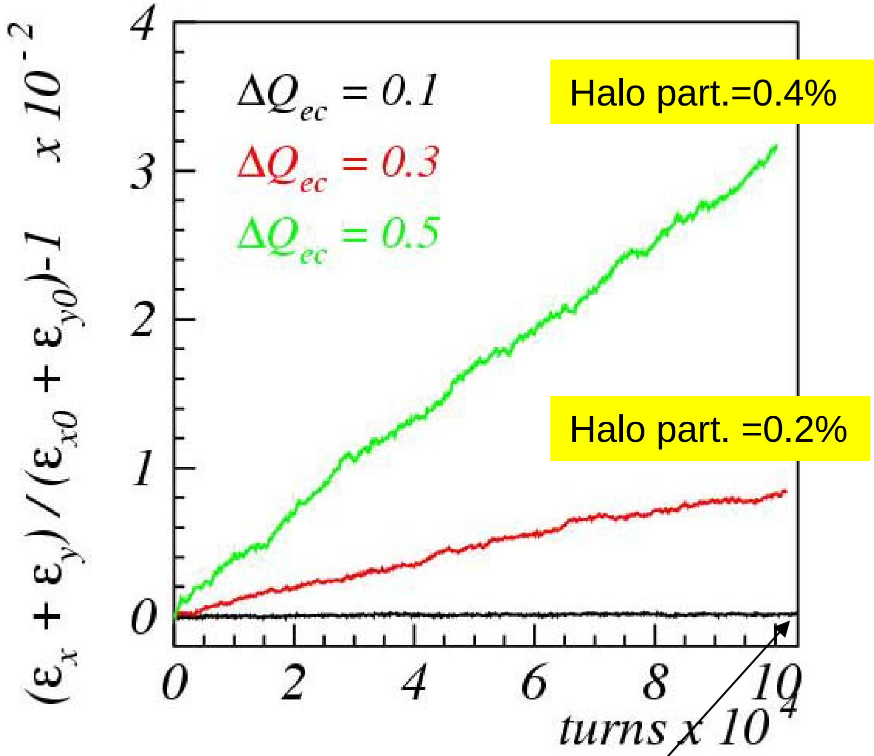


Possible incoherent effects in LHC

Q_x = 64.28 Q_y = 59.31
ΔQ_{ec} = 0.18



Slow emittance growth



emttance growth of 0.04 %

Summary and Outlook

Comparison of SC and EC incoherent effect

We compared SC & EC incoherent effects in terms of beam emittance growth for error resonances and structure resonances. We find that the beam response for EC incoherent effects is understandable in terms of periodic resonance crossing as for SC incoherent effects

High intensity incoherent effects in SIS100

Estimates of long term beam loss for two beams scenario in a lattice with magnet error and a residual 1mm closed orbit distortion are performed. The modeling of full beam intensity needs more realistic ring modeling including residual CO, chromaticity correction, compensation elements and a realistic beam distribution.

Exploratory example of EC incoherent effects in RHIC and LHC

Pinched EC excites several resonances in RHIC which creates slow emittance growth for an integrated tunespread of ΔQ_{ec}=0.03;
In LHC a dense EC induced structure resonance web makes large integrated EC tunespread (ΔQ_{ec} > 0.5) undesirable. A more precise pinched EC modeling is required.

Final remarks

Long term prediction for SC are better understood than EC and experimentally benchmarked.

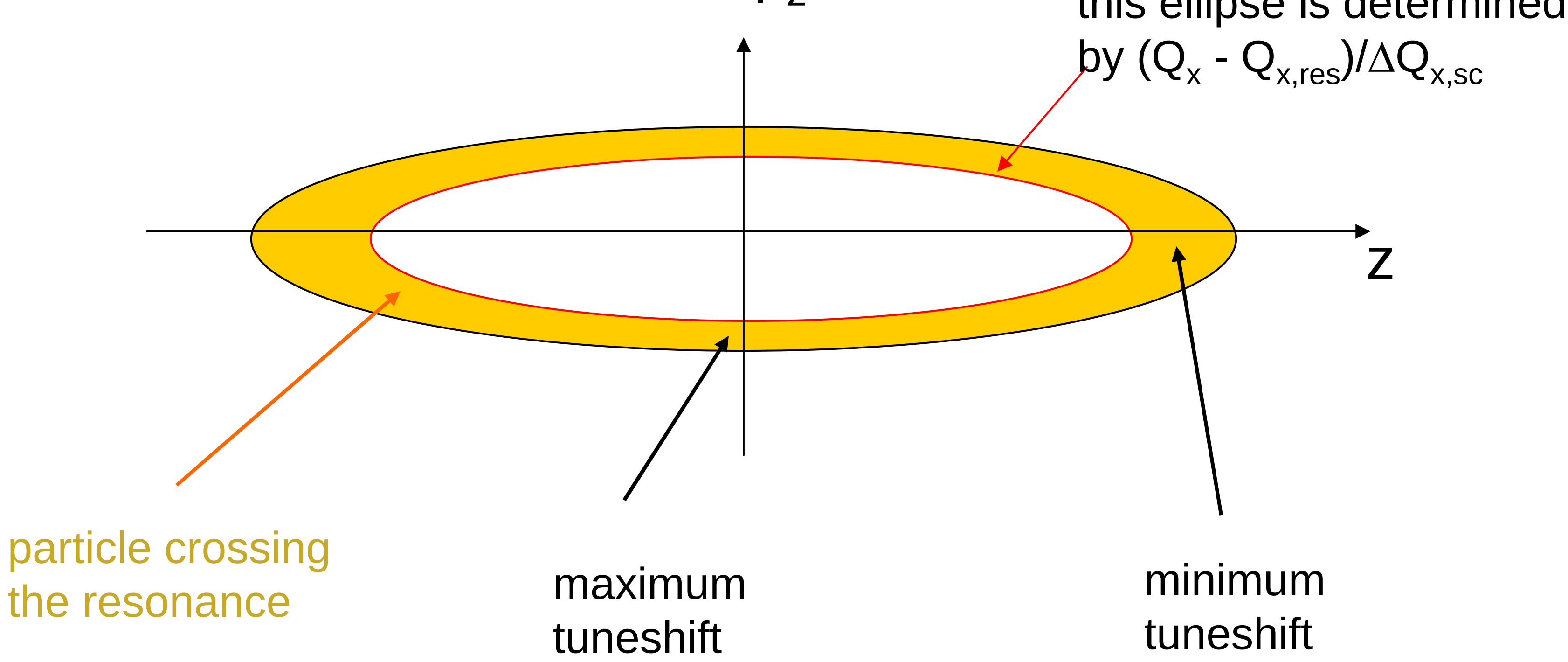
EC incoherent effects need further studies and dedicated experiments in order to validate models for long term predictions.

Thanks to

GSI	O. Choriny, W. Bayer, O. Boine-Frankenheim, C. Omet, B. Franczak, P. Forck, T. Giacomini, I. Hofmann, M. Kirk, H. Kollmus, T. Mohite, A. Parfenova, P. Schuett, P. Spiller
BNL	W. Fischer
CERN	E. Benedetto, O. Bruening,C. Carli, R. Cappi, M. Giovannozzi, M. Martini, E. Metral, R.R. Steeremberg, G. Rumolo, F. Zimmermann
ITEP	P. Zenkevich, A.Bolshakov, V. Kapin
SRI	A.I. Neishtadt
Univ. Bologna	G. Turchetti, C. Benedetti, A. Bazzani

Asymptotic limits

For a Gaussian 3D beam

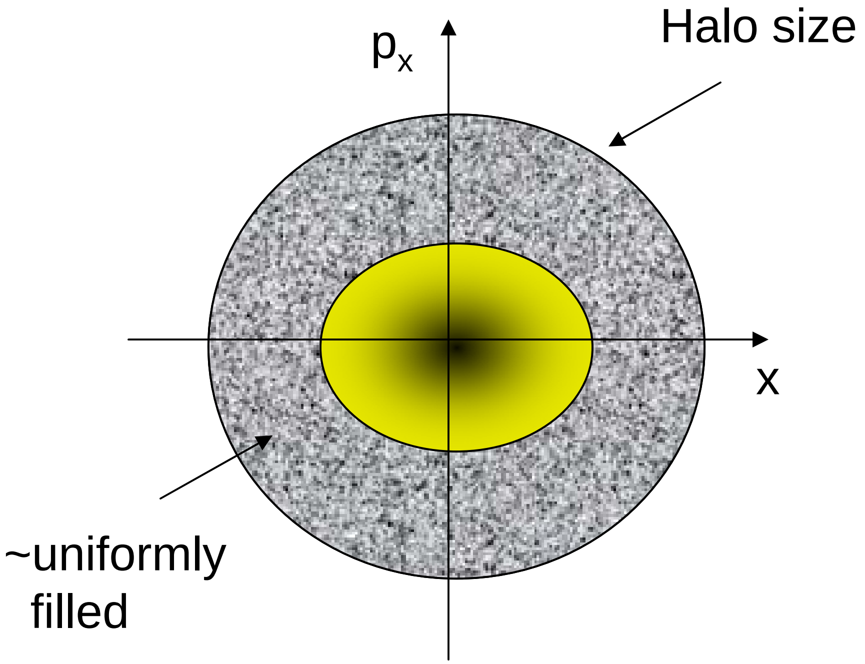


$$\Delta N/N \sim (Q_x - Q_{x,res})/\Delta Q_{x,sc}$$

Asymptotic limits

Estimate of N of particles candidate to be trapped: $$\frac{\Delta N}{N} = \alpha \frac{Q_{x0} - Q_{x,res}}{|\Delta Q_x|}$$

Estimates of halo size: $$\frac{\epsilon_x}{\epsilon_{x0}} \propto \frac{\Delta Q_x}{Q_{x0} - Q_{x,res}}$$



G. Franchetti, I. Hofmann, ICFA-HB2006, Tsukuba, 2006. WEAX01. p. 167

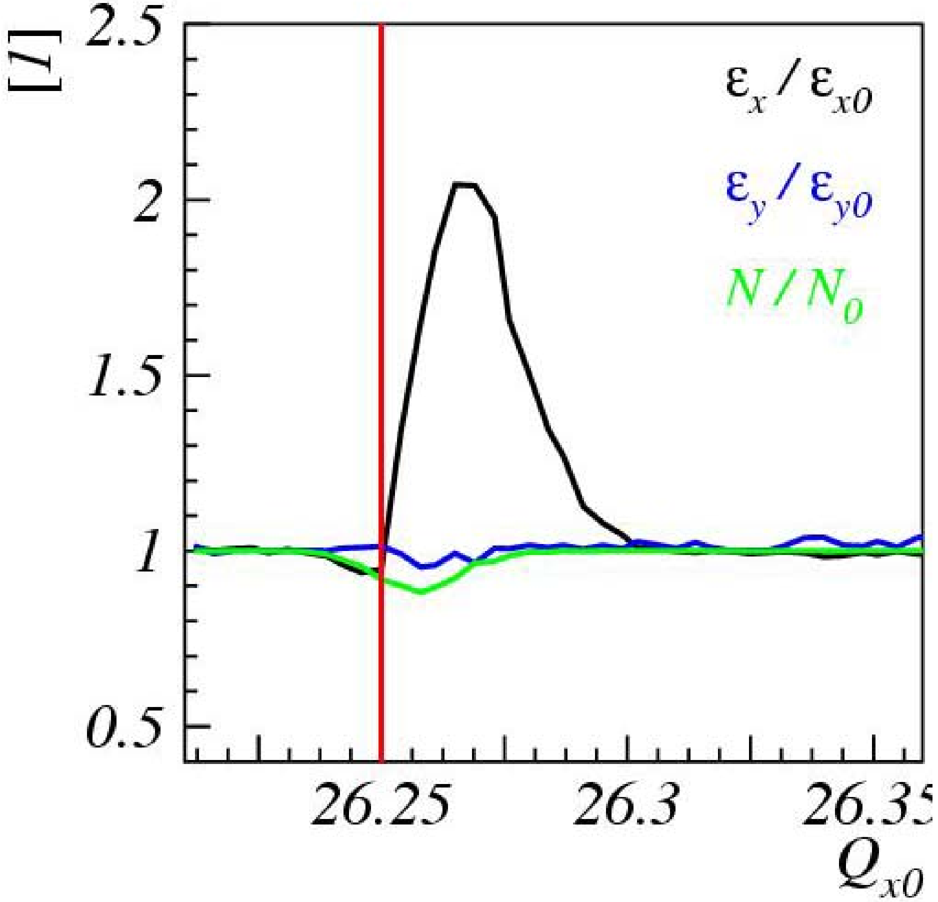
Limits of this model for incoherent effect

Particles driven by a resonance gain transverse amplitude
and via Coulomb force feed back on the space charge strength

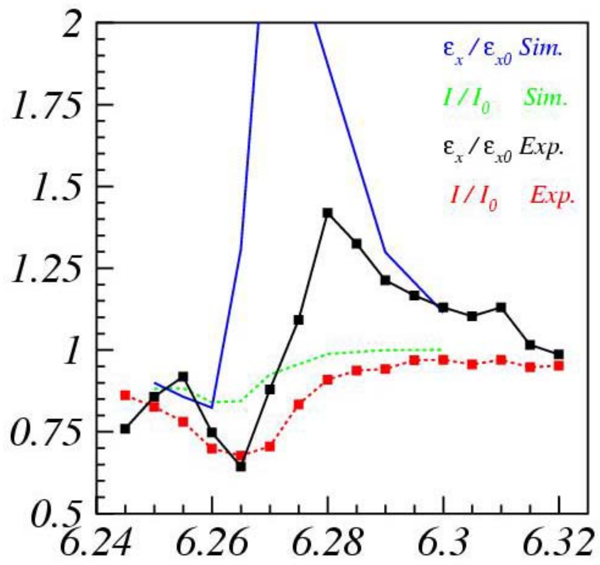
If the amount of particles taking part into incoherent
resonant motion is small, then the core beam motion
can be considered frozen

If many particles are taken by the incoherent resonance,
then the core beam motion changes and the overall
motion becomes coherent

The global picture



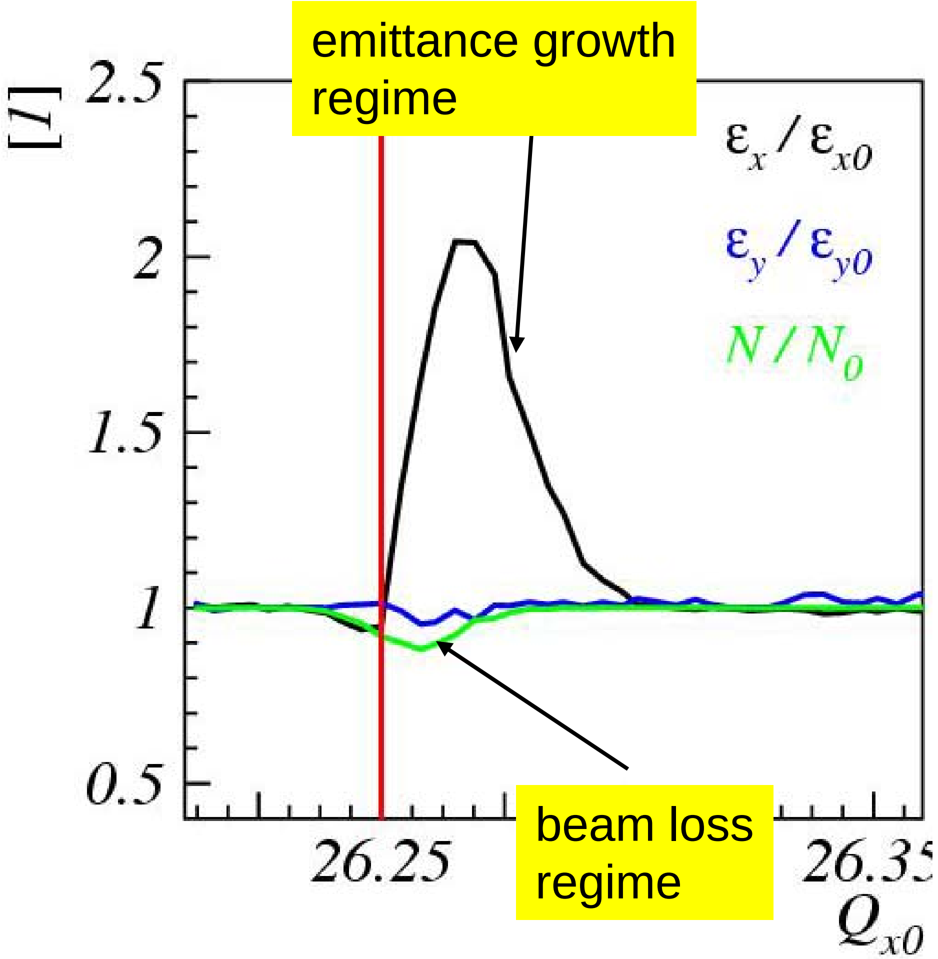
Similar to the results of the CERN-PS benchmarking experiment (2002-2003)



•G. Franchetti, I. Hofmann, M. Giovannozzi, M. Martini, E. Metral Phys. Rev. ST Accel. Beams 6, 124201 (2003).

•E. Metral, G. Franchetti, M. Giovannozzi, I. Hofmann, M. Martini, R. Steerenberg Nucl. Instr. and Meth. A 561, (2006), 257-265.

The global picture



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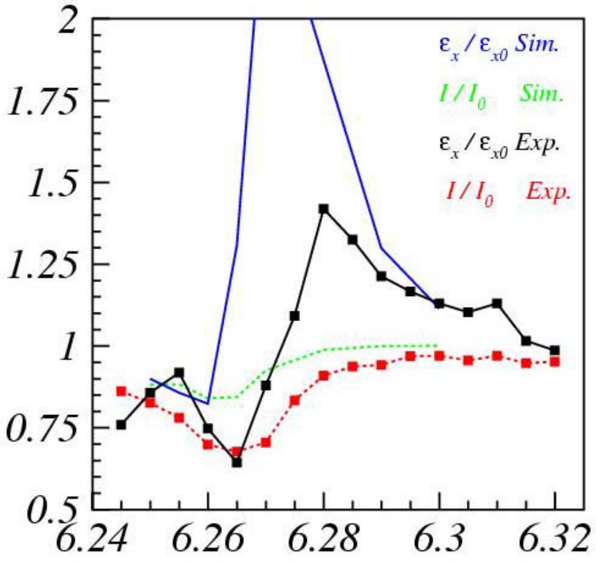


- *G. Franchetti, I. Hofmann, M. Giovannozzi, M. Martini, E. Metral Phys. Rev. ST Accel. Beams 6, 124201 (2003).*
- *E. Metral, G. Franchetti, M. Giovannozzi, I. Hofmann, M. Martini, R. Steerenberg Nucl. Instr. and Meth. A 561, (2006), 257-265.*

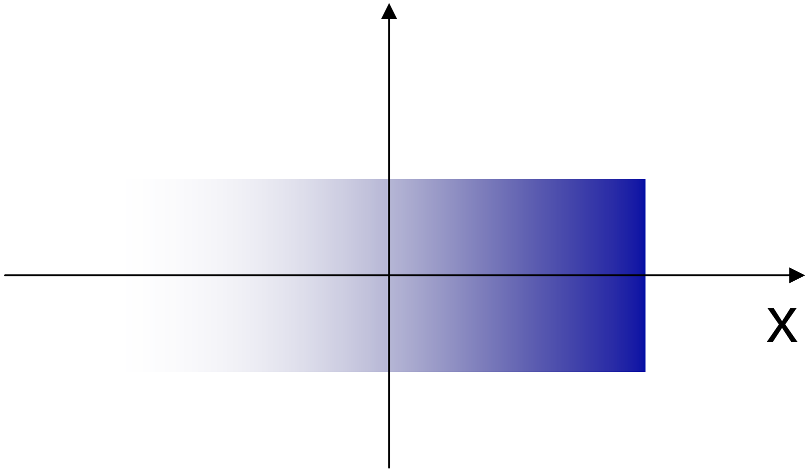
Previous models of pinched EC (frozen)

Varying central density

E. Benedetto et al. Phys. Rev. Lett. 97, 034801 (2006).

Linear varying EC density and varying EC size keeping

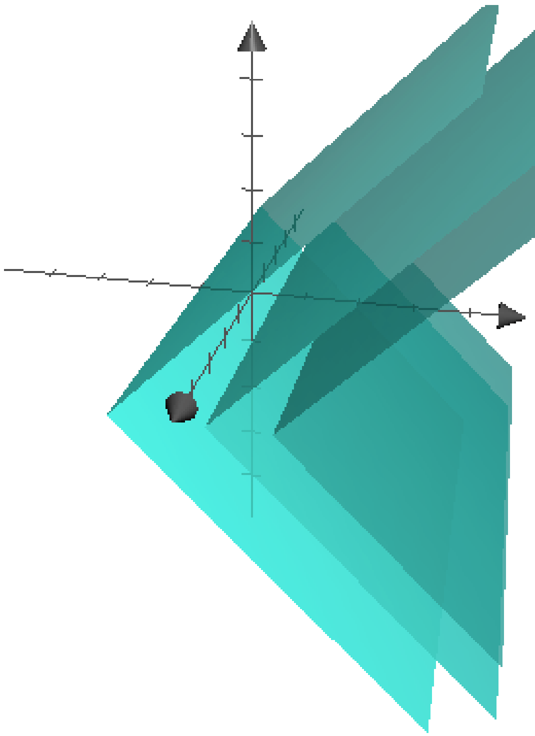
$$\rho_e \sigma_e^2 = \text{const.}$$



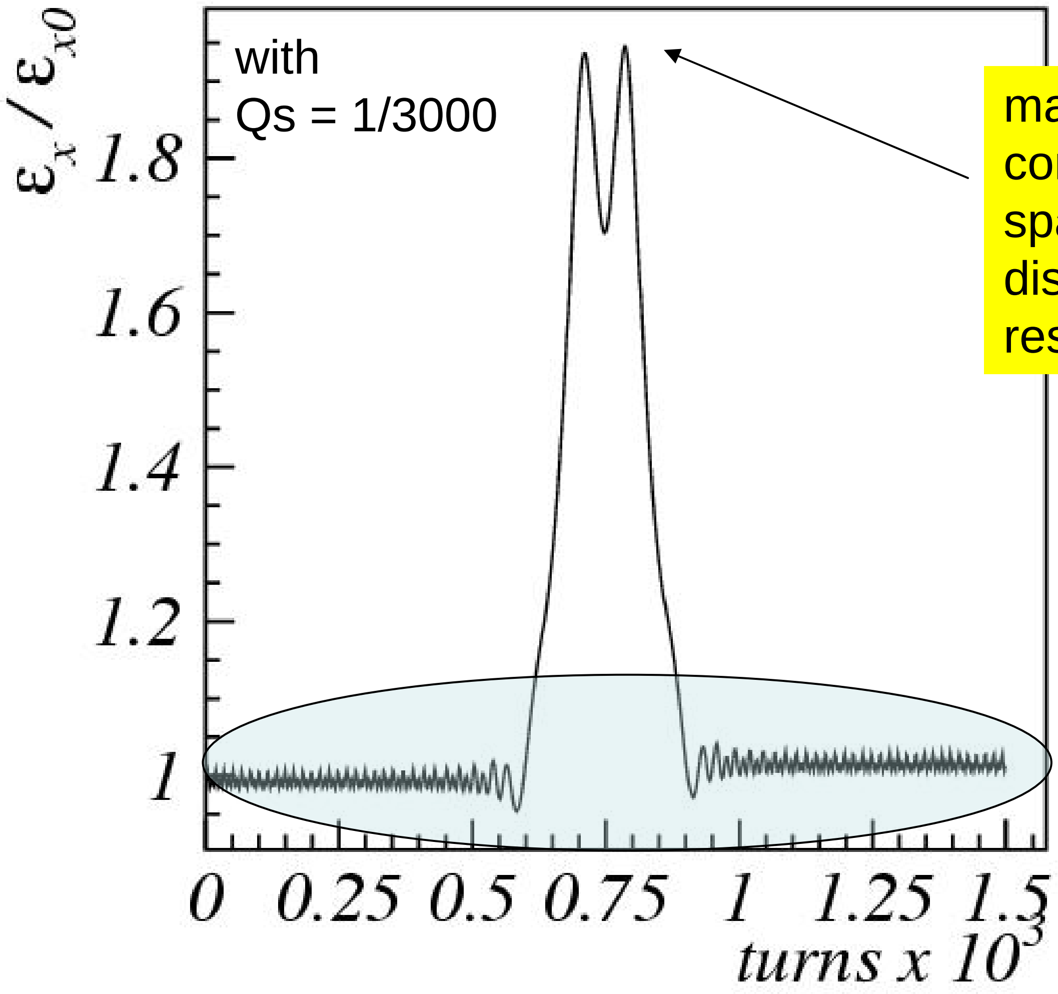
No structured EC pinch modeled

Parallel EC Wall

G. Franchetti and F. Zimmermann
Proc. of Beam 07 , Oct. 1-6, 2007

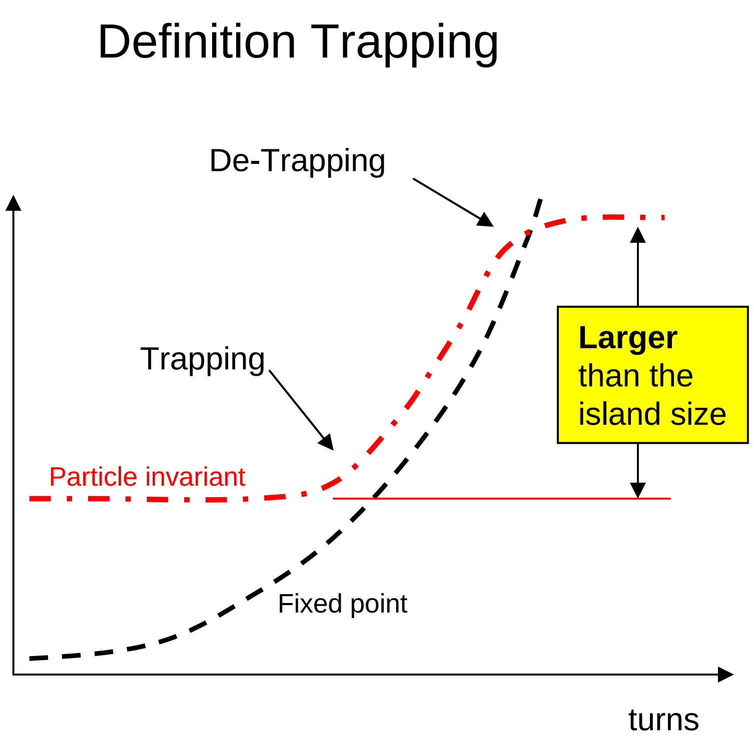


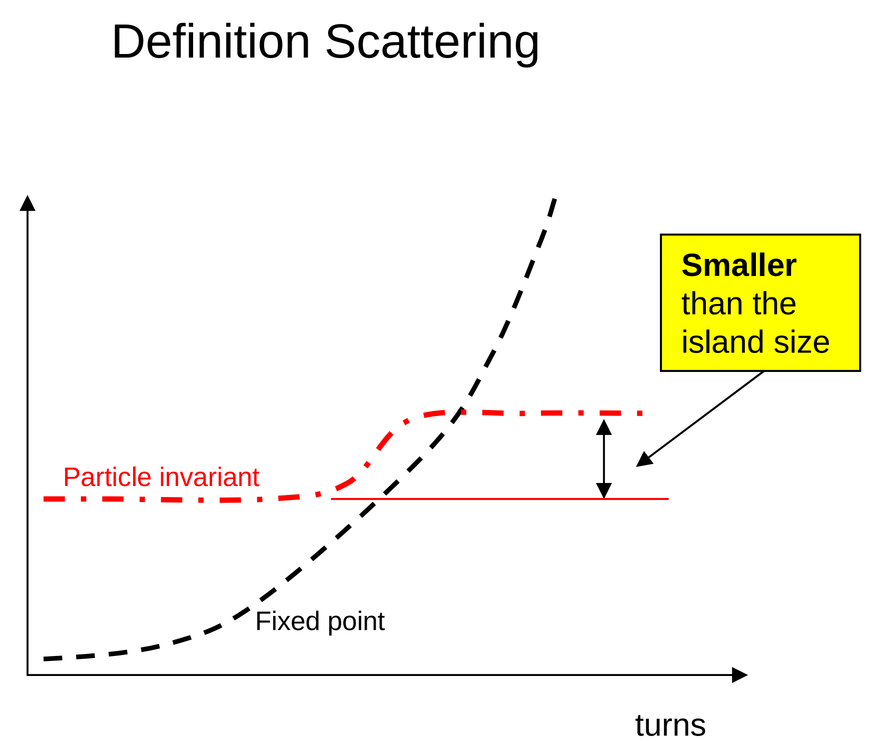
Example of full trapping



maximum amplitude controlled by space charge and distance from resonance

Trapping / Scattering

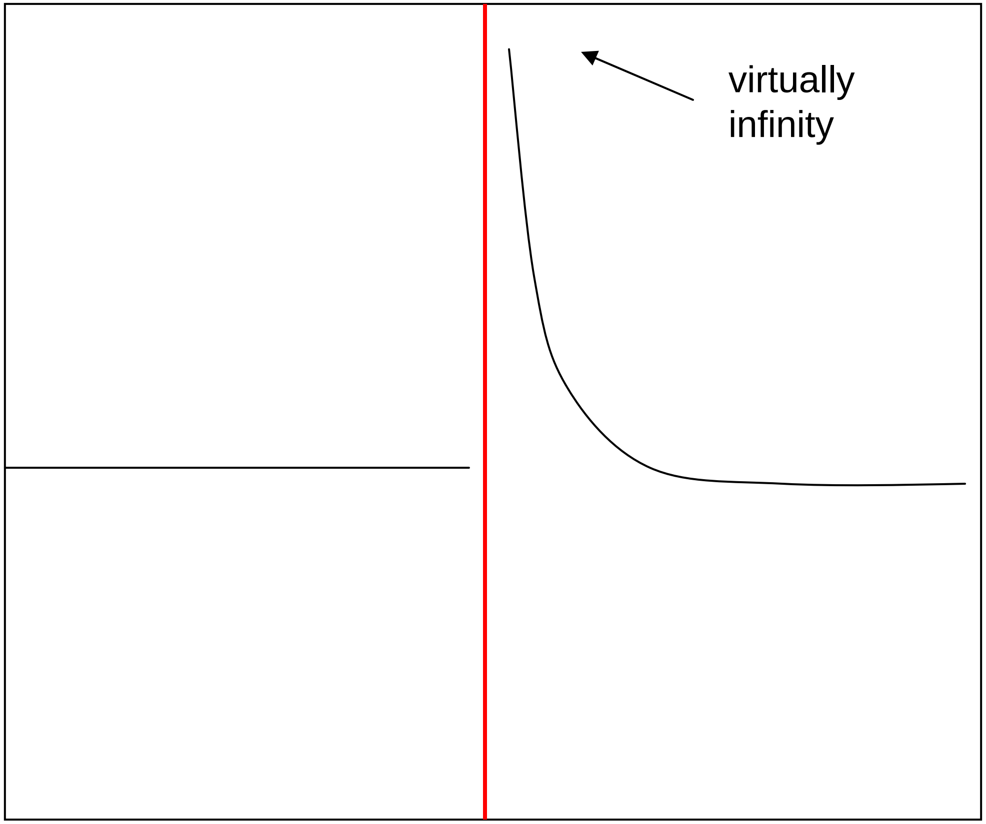




The two regimes are separated by the adiabaticity of the process

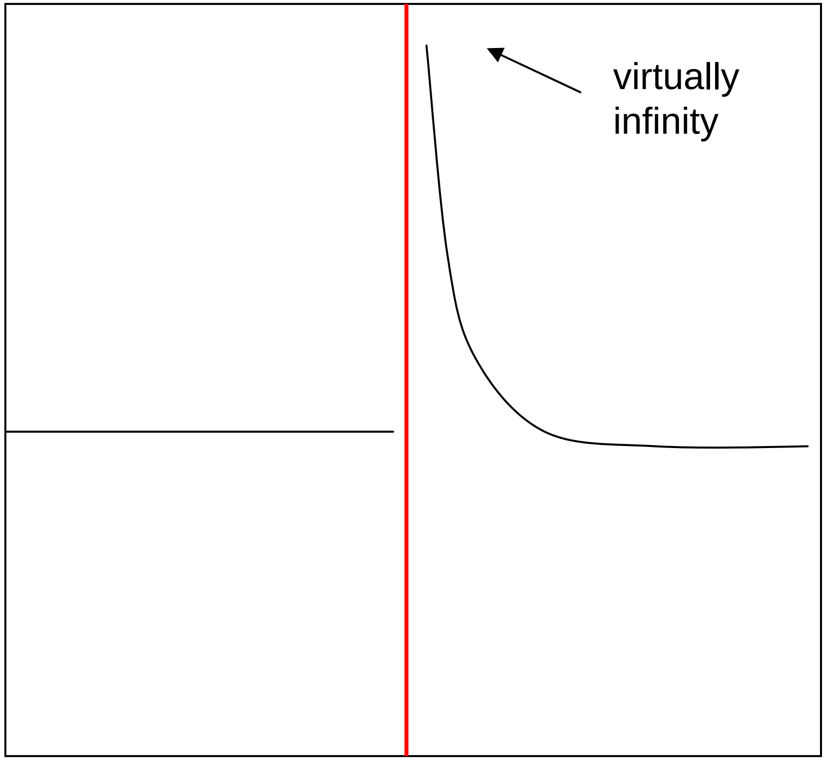
- *A.W. Chao and Month NIM 121, 129 (1974).*
- *A. Schoch, CERN Report, CERN 57-23, (1958)*
- *A.I. Neishtadt, Sov. J. Plasma Phys. 12, 568 (1986)*
- *G. Franchetti, I. Hofmann NIM A **561**, (2006), 195*
- *G. Franchetti et al., HB 2006,*
- *G. Franchetti et al., EPAC 2006,*
- *G. Franchetti PAC 2007*

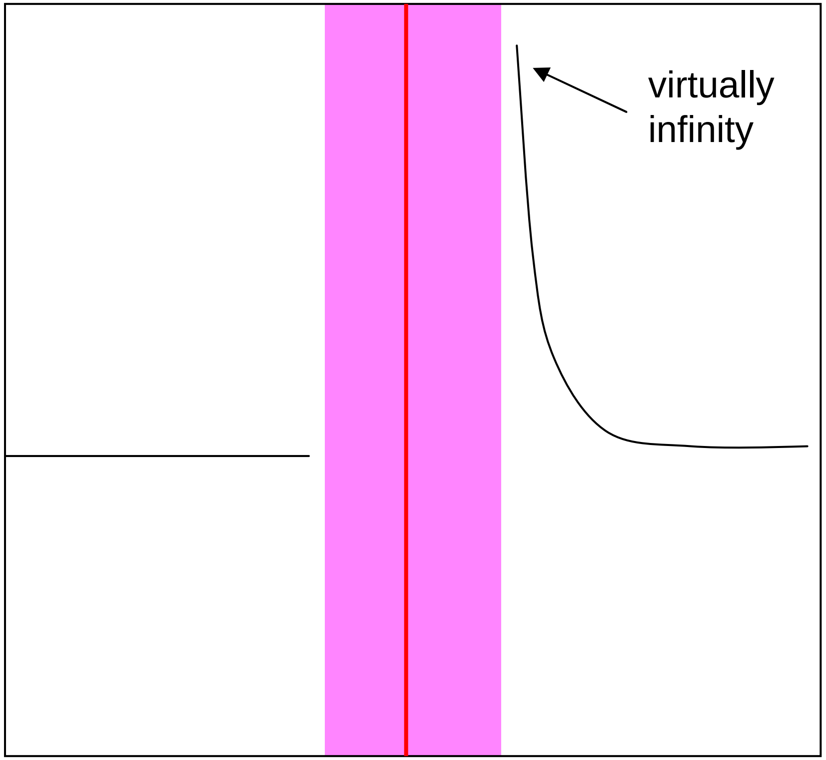
maximum halo amplitude



Chromaticity

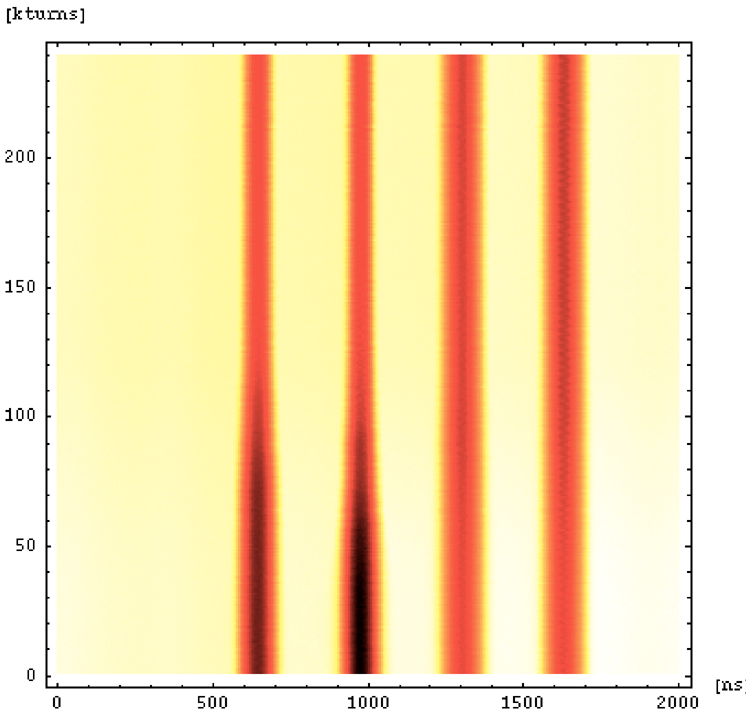
without chromaticity

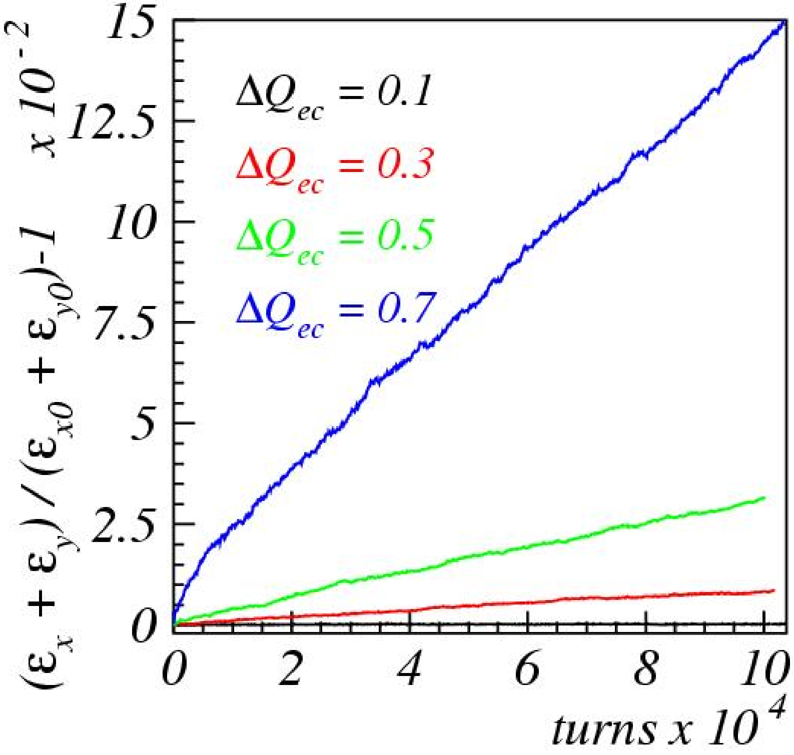




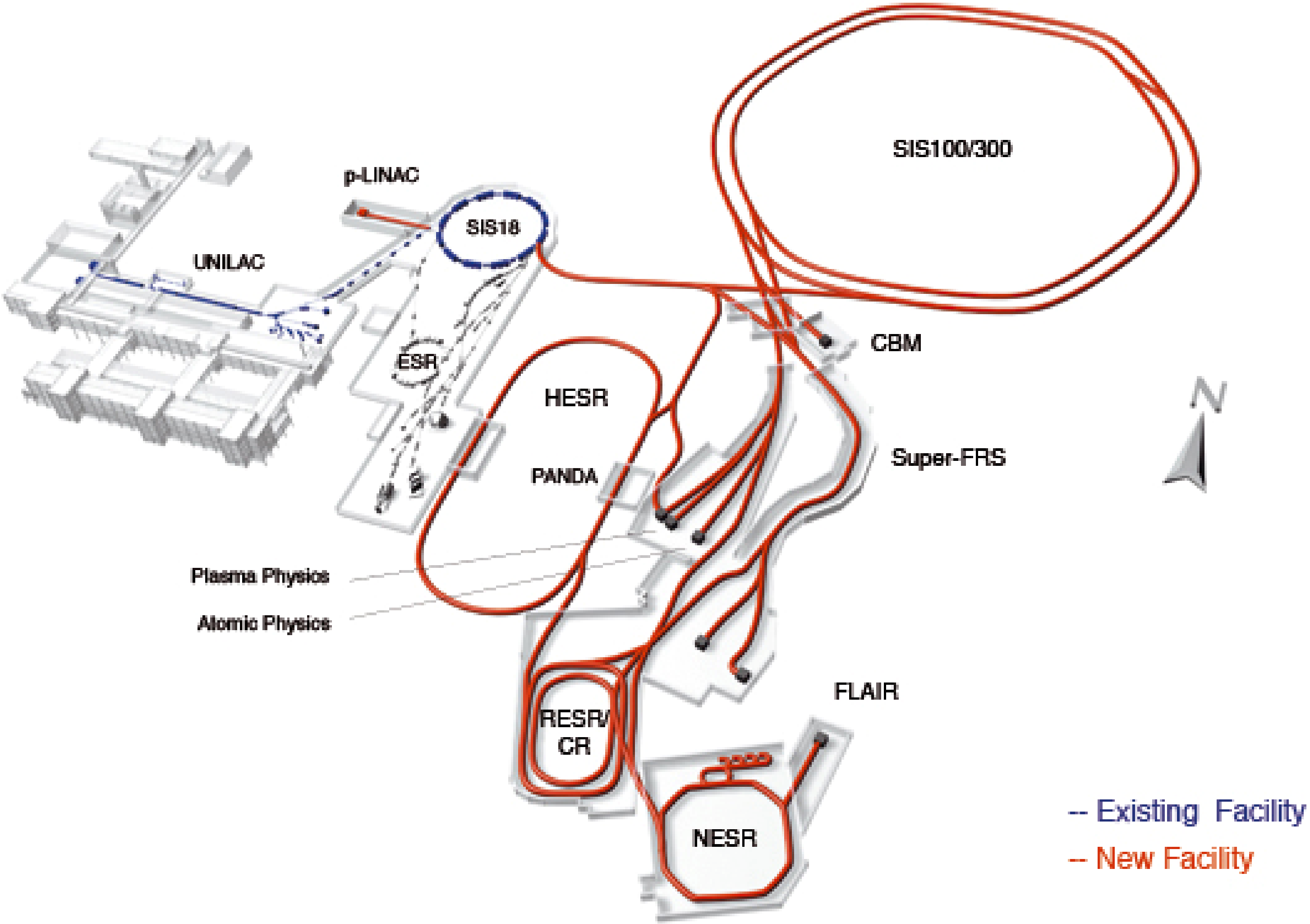
sop-band
of beam loss

Experimental evidences for incoherent space charge effects



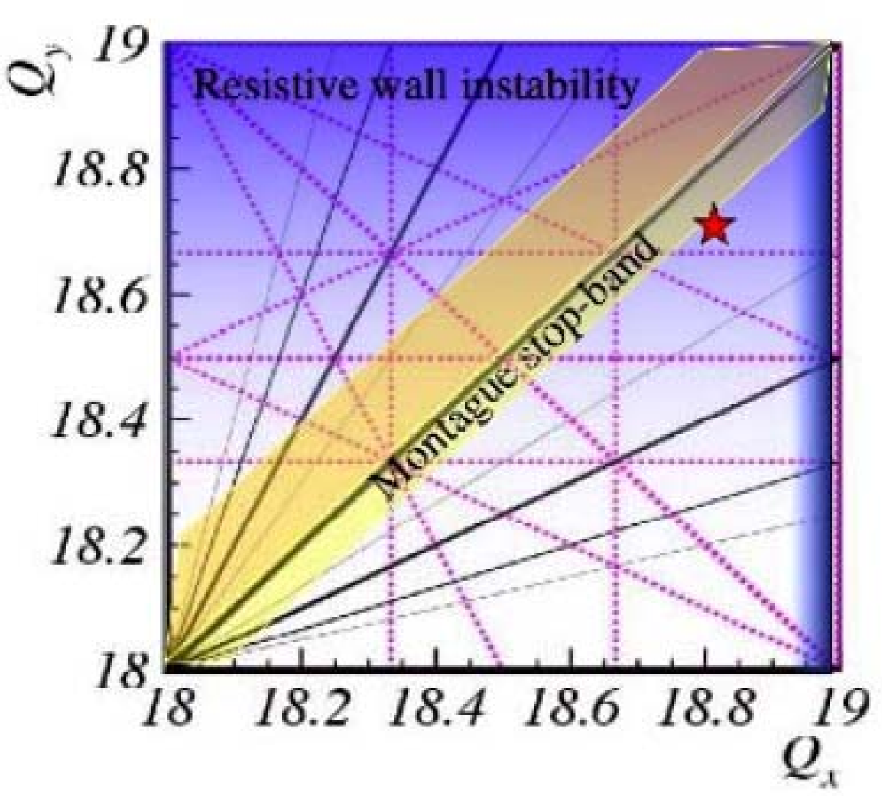


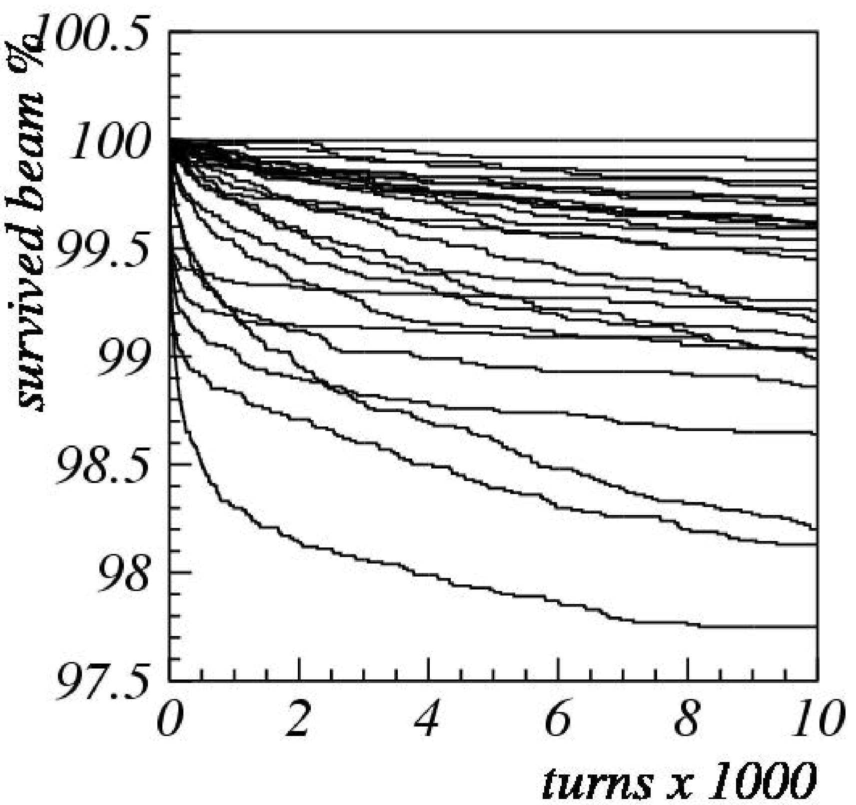
Space charge incoherent effects in FAIR



Fair 2

Qx = 18.84, Qy = 18.73





Incoherent effects driven by structure resonances

It is well known that space charge drives structure resonance

For a stationary beam distribution the space charge force is related to the rms beam envelope

As $E_x(x,y) = E_x(-x,-y)$ an expansion of the Coulomb force is

Example of axe symmetric 2D beam

for a distribution $\rho(r) = \frac{\lambda}{2\pi a^2} \sum_{l=0}^{\infty} c_l \left(\frac{r}{a}\right)^l$ $E_x = \frac{\lambda}{a^2} x \sum_{l=0}^{\infty} c_l \frac{1}{1+l} \left(\frac{r}{a}\right)^{2l}$

but $a = \sqrt{\beta(s)\epsilon}$ the dependence of a from the lattice optics is at the origin of the space charge induced structure resonances

EC incoherent effect in LHC