Incoherent effect of space charge and electron cloud

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26/6/2008
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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
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

Nonlinear Resonances
- single particle motion (incoherent)
- orbit deformations
- long term effects: resonances and dynamic aperture

High intensity + Nonlinear errors
Long storage

High Intensity effects
- many particle force (coherent)
- short term effects
- coherent beam motion
- strong in linac
Example of space charge incoherent effects

Liner lattice + 1 octupole
\[ Q_{x0} = 26.28 \quad Q_s = 1/300 \]
\[ Q_{y0} = 26.1 \]

High intensity bunched beam:
\[ \Delta Q_x = -0.075 \]

Slow emittance growth

\[ +50 \% \]

slow emittance growth
One beam particle motion

$x = 1.8 \sigma_x$
$p_x = y = p_z = p_w = 0$
$z = 3 \sigma_z$

maximum halo amplitude

Scattering

Trapping

$\frac{\epsilon_x / \epsilon_{x,0}}{\epsilon_x}$

0 25 50 75 100 125 150

turns $\times 10^3$
Scattering


1st synch. osc. 2nd synch. osc.

Resonance crossing
Trapping

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

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 \( \frac{\Delta \varepsilon}{\varepsilon \Delta t} \sim 0.4 \)
Evidence of EC induced scattering


[Graph showing x amplitude squared versus number of turns]

HEADTAIL
1 EC Interaction point
LHC @ injection

1 synch. osc.
EC and SC and error resonances

Comparison

Single particle resonances

Studied

High intensity effects

Electron cloud effects

???

???
The problem of long term tracking

Fully self-consistent simulations with the present computer capabilities:
for bunches of $10^6$ macro-particles limits of $\sim 10^6$ 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

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 $3.3\sigma$

Beam pipe at $10\sigma$

$Q_{x0}$ vs $Q_{y0}$

$\varepsilon_x / \varepsilon_{x0}$

$\varepsilon_y / \varepsilon_{y0}$

$N / N_0$
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 and EC + structure resonances

- Structure EC or SC induced resonances
- High intensity effects
- Electron cloud effects

???

???
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

SC kick

SC kick

SC kick

SC kick

SC kick

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

EC kick

EC kick

EC kick

EC kick

EC kick

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

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 PAC 2005, p. 3807
G. Franchetti et al. EPAC 2006, p. 2793
G. Franchetti PAC 2007, TUZAA02

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


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

Space charge incoherent effects in FAIR

First bunch @ 150 MeV/u
Nominal $N_{\text{ions}} = 0.75 \times 10^{11}$/bunch
Beam1: $\varepsilon_{x/y} = 35/15$ mm-mrad $(2\sigma)$ $\Delta Q_{x/y} = -0.31/-0.47$
Beam2: $\varepsilon_{x/y} = 50/20$ mm-mrad $(2\sigma)$ $\Delta Q_{x/y} = -0.21/-0.24$
Turns = $1.2 \times 10^5$ (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. Omer 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;
Beam loss estimates

Take one seed (1mm residual COD, 99% beam loss) + $\langle \delta p/p \rangle_{\text{rms}} = 5 \times 10^{-4}$

Space charge dominates (incoherent effects)

Over the full cycle $N = 3 \times 10^{11} \sim 3\%$ and for $N = 6 \times 10^{11} \sim 15\%$
EC incoherent effect in RHIC

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

\[ \Delta Q_{ec} = 0.03 \]

\[
\begin{align*}
\varepsilon_x / \varepsilon_{x0} - 1 \\
\varepsilon_y / \varepsilon_{y0} - 1 \\
(\varepsilon_x + \varepsilon_y) / (\varepsilon_{x0} + \varepsilon_{y0}) - 1
\end{align*}
\]
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

\[ Q_x = 64.28 \quad Q_y = 59.31 \]
\[ \Delta Q_{ec} = 0.18 \]
Possible incoherent effects in LHC

\[ Q_x = 64.28 \quad Q_y = 59.31 \]
\[ \Delta Q_{ec} = 0.18 \]

Slow emittance growth

\[ \Delta Q_{ec} = 0.1 \]
\[ \Delta Q_{ec} = 0.3 \]
\[ \Delta Q_{ec} = 0.5 \]

Halo part. = 0.4%
Halo part. = 0.2%

Emittance 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 $\Delta Q_{ec}=0.03$;

In LHC a dense EC induced structure resonance web makes large integrated EC tunespread ($\Delta Q_{ec} > 0.5$) 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

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

\[ \Delta N/N \sim \frac{(Q_x - Q_{x,\text{res}})}{\Delta Q_{x,\text{sc}}} \]

this ellipse is determined by \( \frac{(Q_x - Q_{x,\text{res}})}{\Delta Q_{x,\text{sc}}} \)

particle crossing the resonance

maximum tuneshift

minimum tuneshift
Asymptotic limits

Estimate of N of particles candidate to be trapped:

\[ \frac{\Delta N}{N} = \alpha \frac{Q_{x0} - Q_{x,\text{res}}}{|\Delta Q_x|} \]

\[ \frac{\epsilon_x}{\epsilon_{x0}} \propto \frac{\Delta Q_x}{Q_{x0} - Q_{x,\text{res}}} \]

Estimates of halo size:

\[ p_x \]

Halo size

\[ x \]

\[ \sim \text{uniformly filled} \]
Limits of this model for incoherent effect

Particles driven by a resonance gain transverse amplitude and via Coulomb force feedback 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)

\[ \frac{\varepsilon_x}{\varepsilon_{x0}} \]
\[ \frac{\varepsilon_y}{\varepsilon_{y0}} \]
\[ \frac{N}{N_0} \]

\[ \frac{I}{I_0} \text{ Sim.} \]
\[ \frac{I}{I_0} \text{ Exp.} \]

- G. Franchetti, I. Hofmann, M. Giovannozzi, M. Martini, E. Metral
- E. Metral, G. Franchetti, M. Giovannozzi, I. Hofmann, M. Martini,
The global picture

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

Previous models of pinched EC (frozen)

Varying central density


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

with
$Q_s = 1/3000$

maximum amplitude controlled by space charge and distance from resonance
Trapping / Scattering

Definition Trapping

- De-Trapping
- Trapping
- Particle invariant
- Fixed point

Definition Scattering

- Larger than the island size

The two regimes are separated by the adiabaticity of the process

- A.W. Chao and Month NIM 121, 129 (1974)
- G. Franchetti et al., HB 2006,
- G. Franchetti et al., EPAC 2006,
- G. Franchetti PAC 2007
maximum halo amplitude

virtually infinity
Chromaticity

without chromaticity

virtually infinity

sop-band of beam loss

virtually infinity
Experimental evidences for incoherent space charge effects
Space charge incoherent effects in FAIR
$Q_x = 18.84, Q_y = 18.73$

Resistive wall instability

Monague stop band

Survived beam %

$100.5$
$100$
$99.5$
$99$
$98.5$
$98$
$97.5$

$0$
$2$
$4$
$6$
$8$
$10$

$\text{turns} \times 1000$
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 $\rho(r) = \frac{\lambda}{2\pi a^2} \sum_{l=0}^{\infty} c_l \left( \frac{r}{a} \right)^l$ $E_x = \frac{\lambda}{a^2 \Sigma} \sum_{l=0}^{\infty} c_l \frac{1}{1+l} \left( \frac{r}{a} \right)^{2l}$

but $a = \sqrt{\beta(s)\varepsilon}$ the dependence of a from the lattice optics is at the origin of the space charge induced structure resonances
EC incoherent effect in LHC

\[ \frac{(\varepsilon_x + \varepsilon_y)}{(\varepsilon_{x0} + \varepsilon_{y0})^{-1}} \times 10^{-2} \]

\( \Delta Q_{ec} = 0.1 \)
\( \Delta Q_{ec} = 0.3 \)
\( \Delta Q_{ec} = 0.5 \)
\( \Delta Q_{ec} = 0.7 \)