Incoherent effect due to electron cloud

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ECLOUD 2012
8/6/2012 – Isola d’Elba


Thanks: F. Ruggiero
• Introduction to incoherent effects
• EC pinch and characterization of it (attempt)
• Modeling of 3D modeling of EC incoherent effect (attempt)
“Incoherent” effects induced by space charge. Highly relevant for SIS100 in the FAIR project.

Pipe

Slow halo formation

If halo is too large *slow* beam loss take place

Bare tune

Periodic crossing of a resonance

Lattice error or Space Charge Structure Resonance
Transverse-Longitudinal coupling via electron-cloud

The coupling takes place only at the location of an electron cloud.
In the reference frame of the bunch
Electrons have different wavelength according to their amplitude.
Multiple resonance crossing in bunched beams induced by electron cloud

Very complex
Periodic crossing of a resonance

Lattice error or Electron cloud Structure Resonance

Complex structure of amplitude dependent detuning

Pipe

Slow halo formation?

Bare tune
Synergy of electron cloud studies with nonlinear dynamics and space charge

CARE-HHH-APD BEAM'07, 1-6 October 2007 → 1D model (map approach)
Find scaling law for predicting beam behavior after hours of storage

New approach to treat non adiabatic resonance crossing.

Example of non adiabatic crossing of a 4th order resonance

extension of the concept of fix point to non adiabatic varying system
Past modeling relied on analytic models but neglect the full complexity of the pinch.

EC pinch in drift, dipole, quadrupole have different evolution.

Beam off center with respect to the vacuum chamber also alter the pinch structure.
Shift of the beam and shift of an accelerator element

Example with a quadrupole

proton beam

Δyₚ

Δyₚ

Δyₚ

Δxₚ

Δxₚ

Δxₚ

example of shift for a quadrupole

quadrupole
Pinch in a quadrupole

LHC \( \sigma_z = 0.114 \, \text{m} \) \( \text{ntz} = 168 \)

bunch \( \sigma_r = 0.88 \, \text{mm} \) \( \gamma = 450 \)

x-y plane at \( z=0 \)

Beam on axis

Shift \( \Delta x_b = 3 \, \sigma_r \)

the initial distribution is pinched faster
Pinch in a quadrupole

\[ \Delta x_b = 3 \sigma_r \]

Beam on axis

this other part is pinched later

Shift \( \Delta x_b = 3 \sigma_r \)
Pinch in a quadrupole

z-x plane at y=0

Beam on axis

Shift $\Delta x_b = 3 \sigma_r$
beam shifted of $D_{xb} = D_{yb} = 3\sigma_r$
Similarity with other fields

EC pinch in a quadrupole, with beam shifted $D_{xb}=D_{yb} = 3 \sigma$, at $z = 3 \sigma$

Rorschach Test
Incoherent effects are driven by Coulomb force: relevant parameter maximum detuning

Max detuning depends on the gradient created by the electron structure created during the pinch

The gradient created by all the macro-electrons on the beam axis is proportional to the detuning

G. Franchetti et al., PRSTAB 12, 124401 (2009).
Verification in the x-plane

1) take a model of a rod with transverse Gaussian distribution
2) compute maximum tune for all test particles
3) compare it with tune on axis
We take the gradient on beam axis as the major source of the larger detuning among all bunch protons (almost correct).

Electric field modeling

Model one macro-electron as a finite long wire of size zero
Cut-off criteria

Problem: the electric field close to the thin wire diverges → not physical

Cut-off for a uniform distribution

\[ r_{min} = \frac{R}{\sqrt{N}} \]

- \( r_{min} \) = number of macro-electrons
- \( R \) = radius of the vacuum chamber

0.045 for 5x10^5 macro-particles
Characterization through a static indicator

Here the quadrupole is shifted

Here the beam is shifted
Exploring for several displacement

We define

\[ \text{Grad} \equiv \max \left\{ \frac{dE_x(x, y, z)}{dx}, \frac{dE_x(x, y, -3)}{dx} : -3\sigma_z < z < 3\sigma_z \right\} \]

and compute this quantity for several displacement of the beam.
In a dipole

No effect within the range selected due to the nature of the pinch in dipole the result is invariant in almost all the pipe
The previous procedure is apt to characterize the electron pinch beyond the complexity of the pinch itself.

However, the indicator taken is “static”. A test by computing the tune-shift from the dynamics is necessary.
Dynamics including the realistic EC

1) Compute the “normalized transverse force” $E_x,E_y$ created by the passage of the bunch

2) Store the $E_x,E_y$ as function of $x,y,z$ proton position in a 200x200x200 grid

3) EC force acting on the protons is available via a tri-linear interpolation

4) Definition of 3 types of electron cloud kicks deriving from the consistent electron pinch force on the proton.

At the moment the EC pinch does not take into account of the varying beta function ratio characterizing the several section where the EC pinch takes place.

Next is presented a first approach into this study (not completed yet)
Normalized fields acting on protons

In a dipole

direction (electrons uniformly distributed)

a trace of the EC structure is preserved
In a drift

\[ \text{nz} = 10 \]

\[ \text{nz} = 80 \]

the rings in the force are made by the circular shaped structures in x-y
In a quadrupole

$n_x = 10$

$x/\sigma$

$y/\sigma$

$n_x = 70$

$x/\sigma$

$y/\sigma$
Detuning on axis for purpose of benchmarking

On a dipole use of LHC lattice, and added 1 EC kick of the full pinch → betx = 55.7 m, bety = 110.6 m (exit of one dipole)

\[ \Delta Q_x = 6.5 \times 10^{-4} \]
\[ DQ_x = 0.0012 \]

\[ \Delta Q_y = 8.5 \times 10^{-4} \]
\[ DQ_y = 0.013 \]
On a drift use of LHC lattice, and added 1 EC kick of the full pinch → betx = 59 m, bety = 105.6 m (exit of 1 drift)

\[
\begin{align*}
\Delta Q_x & = \text{5.2E-4} \\
\Delta Q_y & = \text{7.6E-4} \\
DQx_0 & = \text{5.2E-4} \\
DQx_{\text{max}} & = \text{0.101} \\
DQy_0 & = \text{7.6E-4} \\
DQy_{\text{max}} & = \text{0.129}
\end{align*}
\]
Detuning on axis for purpose of benchmarking

On a quadrupole

use of LHC lattice, and added 1 EC kick of the full pinch
→ betx = 33.6 m, bety = 162 m (exit of one quadrupole)

\[ \Delta Q_x = 4.32 \times 10^{-4} \]
\[ \Delta Q_x^{\text{max}} = 0.045 \]
\[ \Delta Q_y = 1.01 \times 10^{-3} \]
\[ \Delta Q_y^{\text{max}} = 0.094 \]
Summary and comparison with theory

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<th>( \Delta Q_{-3} )</th>
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<th>( \frac{\Delta Q_{max}}{\Delta Q_{-3}} )</th>
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only EC kicks at the exit of each quadrupole and each dipole and one type of dipole $\sim 1E11$
at different bunch longitudinal section different types of pinch seems to be dominant

\[ z = -1.38 \sigma_r \quad \text{\&} \quad z = -0.72 \sigma_r \quad \text{\&} \quad z = -0.12 \sigma_r \]

FMA is now difficult because the pinch is extremely localized in transverse plane
Emittance growth

1E4 macro-particles
2E6 turns $\rightarrow$ 3 minutes

$DQ_x_{\text{peak}} = 0.0046$
$DQ_y_{\text{peak}} = 0.0045$
$n_e \sim 2 \times 10^{10} \text{ m}^{-3}$

~3 minutes of LHC (Venus transit)
Including EC kick in each drift, dipole, quadrupole
taking into account the length of each element, and assuming the EC density
to be the same
equivalent electron cloud density
ne \sim 5 \times 10^{12} \text{ m}^{-3}
still inconsistent in terms of betx/bety
local ratio
inversion of the emittance growth
x with y. At the moment unexplained
Summary

- The storage of the Ex, Ey forces of the EC pinch is challenging, especially at locations of pinch
- Found no clear correspondence between maximum gradient on axis and maximum tunes on axis: most likely discrepancy due to the grid discretization
- Good benchmarking of tune-shift before pinch
- Slow emittance split, sensitive to EC kicks distribution, and/or EC density. Explanation open.
- Tune-footprint difficult to be used for revealing the presence of structure resonances

To do
- Complete the benchmarking of the model
- Including the effect of the beam shift in the dynamics
- Create an Ex, Ey map which takes into account the local beta function in the EC pinch process: that means find the map from Ex,Ey obtained for betx/bety=1 to Ex,Ey for another betx/bety.
Thanks for the attention