Multiple Resonance Crossings with Space Charge and Electron Cloud

G. Franchetti
EuCARD’s, 2nd Annual Meeting
11.05.2011, Paris
Overview

Resonance crossing phenomena

Space charge multiple resonance crossing

Electron cloud multiple resonance crossing

Conclusions
The dynamics issue

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

**Incoherent Force**

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”

The slow tune modulation creates a regime of resonance crossing
A particle experiences a space charge strength from the local bunch density, which is proportional to the longitudinal position.

Transverse space charge force

\[
F \propto \exp\left[-\frac{1}{2} \left(\frac{z}{\sigma_z}\right)^2\right] \times \frac{1}{r} \left\{1 - \exp\left[-\frac{1}{2} \left(\frac{r}{\sigma_r}\right)^2\right]\right\}
\]

longitudinal modulation \hspace{2cm} transverse
The space charge detuning has different nature from the lattice nonlinear errors induced detuning.
Multiple resonance crossing in bunched beams induced by space charge

Periodic crossing of a resonance

Lattice error or Space Charge Structure Resonance

Slow halo formation

Pipe

x

z

If halo is too large slow beam loss take place

Bare tune
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

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

\[ T \equiv \frac{\partial x_f(n)}{\partial n} \frac{1}{Q_x f(n) \Delta x(n)} \]

T \ll 1 characterize the adiabatic regime

Machine operations typically are in a non adiabatic regime

A.W. Chao and Month NIM 121, 129 (1974).
A. Schoch, CERN Report, CERN 57-23, (1958)
Multiple resonance crossing in SIS100

Mitigation of long term effects

Compensate the resonance $Q_x + 2Q_y = 56$ without exciting the resonance $3Q_x = 56$

Compensation strategy
Cancellation of the driving terms of $Q_x + 2Q_y = 56$ and $3Q_x = 56$ at the crossing of the two resonances

SIS100 resonances for the Standard seed
Beam loss prediction for SIS100

main resonance compensated

Main resonance un-compensated

First bunch

Standard seed

Nonlinearity: Yes
Space charge: Yes
Chromaticity: Yes
Dispersion: Yes
COD: Yes
RF: Yes

Nonlinearity: Yes
Space charge: Yes
Chromaticity: Yes
Dispersion: Yes
COD: Yes
RF: Yes

intensity 5E11

% of particles

0 25 50 75 100 125 150
x1000  turns

0 25 50 75 100 125 150
x1000  turns

error bar
Localized electron cloud

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

Pipe

s

Pipe
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

Structure of EC rings

pinch
EC-pinch in dipoles

For nominal LHC bunch  Based on the "strong field approximation"

\[
\log_{10}(\rho/\rho_0)
\]

Cut at 1 \(\sigma_z\)
Multiple resonance crossing in bunched beams induced by electron cloud

Pipe

Slow halo formation?

Very complex
Periodic crossing of a resonance

Bare tune

Complex structure of amplitude dependent detuning

Lattice error or
Electron cloud
Structure Resonance
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

\[
\begin{pmatrix}
\hat{y}_1 \\
\hat{y}_1'
\end{pmatrix} =
\begin{pmatrix}
\cos \omega & \sin \omega \\
-\sin \omega & \cos \omega
\end{pmatrix}
\begin{pmatrix}
\hat{y}_0 \\
\hat{y}_0' + F(y_0)
\end{pmatrix}
\]
Crossing of the 4th order structure resonance

Trapping process for the 1D electron-cloud map

In red are shown the orbit of the “frozen system”

This resonance crossing is 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

\[ E_r = 0 \]

\[ E_r = -K_{ec} \frac{1}{r} \]

\[ \Delta R \]

Slope (or angle) of the EC ring
Tune footprint

Example for $DQ = 0.2$

Tune-footprint of the full bunch

EC kicks create a web of high order structure resonances

$Q_x$ $Q_y$
Example of an estimate for LHC

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

\[ \Delta \varepsilon_x / \varepsilon_x = 0.06 t_h \]

Simulation DQe = 0.1

\[ \Delta \varepsilon_y / \varepsilon_y \approx 0 \]
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)

<table>
<thead>
<tr>
<th>Source/Feature</th>
<th>Detuning</th>
<th>Amplitude dependence</th>
<th>Driving resonances</th>
<th>Experiment verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromaticity</td>
<td>weak</td>
<td>weak</td>
<td>no (?)</td>
<td>yes</td>
</tr>
<tr>
<td>Space Charge</td>
<td>strong</td>
<td>strong/decrease</td>
<td>yes/no</td>
<td>yes/ongoing</td>
</tr>
<tr>
<td>Electron Cloud</td>
<td>strong/weak</td>
<td>strong/decrease</td>
<td>yes</td>
<td>?</td>
</tr>
<tr>
<td>Nonlinearities</td>
<td>strong/weak</td>
<td>strong/increase</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>
Thanks to

GSI

BNL
W. Fischer

CERN

ITEP
P. Zenkevich, A. Bolshakov, V. Kapin

KEK
K. Ohmi

SLAC/Stanford
A. Chao

SRI
A.I. Neishtadt

Univ. Bologna
G. Turchetti, C. Benedetti, A. Bazzani