Space charge effect on the second order coupled resonance

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The quest of the incoherent effects of space charge

- Study of the space charge on 1D 4th order resonance
- Study of the space charge on 1D 3rd order resonance: proof of principle
- Study of the space charge on 2D 3rd order resonance
- Resonance compensation with space charge
- Experimental discovery of the fixed-lines

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>1 week</td>
<td>12 days (as users)</td>
<td>1 week</td>
<td>~2 days</td>
<td>4 days</td>
</tr>
</tbody>
</table>

PS, SIS18, SIS100

CERN, GSI

IOTA

April 12th 2016
G. Franchetti
TABLE I. Beam and machine parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity $N_p \ [10^{10} \ p]$</td>
<td>55</td>
</tr>
<tr>
<td>Normalized horizontal rms emittance $\varepsilon_x^n \ [\text{mm mrad}]$</td>
<td>3.6</td>
</tr>
<tr>
<td>Normalized vertical rms emittance $\varepsilon_y^n \ [\text{mm mrad}]$</td>
<td>2.2</td>
</tr>
<tr>
<td>Rms bunch length $\sigma_t \ [\text{ns}]$</td>
<td>33</td>
</tr>
<tr>
<td>Rms momentum spread $\frac{\Delta p}{p} \ [10^{-3}]$</td>
<td>0.95</td>
</tr>
<tr>
<td>Horizontal maximum tune spread $\Delta Q_{x, \max}^a$</td>
<td>-0.05</td>
</tr>
<tr>
<td>Vertical maximum tune spread $\Delta Q_{y, \max}^a$</td>
<td>-0.071</td>
</tr>
<tr>
<td>Sextupole current $I_{\text{SX}} \ [\text{A}]$</td>
<td>2</td>
</tr>
<tr>
<td>Harmonic number $h$</td>
<td>8</td>
</tr>
<tr>
<td>RF voltage $V_{\text{RF}} \ [\text{kV}]$</td>
<td>20.5</td>
</tr>
<tr>
<td>Horizontal linear chromaticity $\xi_x^b$</td>
<td>-0.83</td>
</tr>
<tr>
<td>Vertical linear chromaticity $\xi_y^b$</td>
<td>-1.12</td>
</tr>
<tr>
<td>Energy of stored beam $\ [\text{GeV}]$</td>
<td>2</td>
</tr>
<tr>
<td>Turns stored</td>
<td>497646</td>
</tr>
<tr>
<td>Storage time $[\text{s}]$</td>
<td>1.1</td>
</tr>
<tr>
<td>Relativistic $\beta$</td>
<td>0.948</td>
</tr>
<tr>
<td>Relativistic $\gamma$</td>
<td>3.14</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>$1163^{-1}$</td>
</tr>
<tr>
<td>Horizontal flying w. (SS68 at 422.8 m) $\beta_x \ [\text{m}]$</td>
<td>12.40</td>
</tr>
<tr>
<td>Vertical flying w. (SS64 at 397.7 m) $\beta_y \ [\text{m}]$</td>
<td>21.75</td>
</tr>
</tbody>
</table>

$a$ The tune spread is calculated according to Ref. [18].

$b$ $\xi_{x,y} = \frac{Q_{x,y}}{Q_{x,y}} = \frac{\Delta Q_{x,y}}{\Delta p/p}$
PS campaign: “towards the unknown”
Beam Profiles @ (A)
Beam Profiles @ (B)
Code experiment benchmarking
Distance from the resonance

Bare optics

\[ \Delta_{r0} = Q_{x0} + 2Q_{y0} - 19 \]

Bare optics + space charge of one particle at amplitudes X,Y

\[ \Delta_r = \Delta_{r0} + \Delta Q_{sc,x}(X, Y) + 2\Delta Q_{sc,y}(X, Y) \]

Resonance condition \( \rightarrow \) \[ \Delta_r = 0 \]
Resonant particles

\[ \Delta_{r0} = 0.056 \]

\[ \Delta_r, \Delta_{r,sc} \]

\[ X/\sigma_x \]

\[ Y/\sigma_y \]

\[ X_h \]

\[ Y_h \]
Comparison with simulations

(\textbf{a}) \\

(\textbf{b})
Something seems wrong!
The -x- profile does not exhibit an halo that ends at $X_h$
Including the chromaticity

\[ \Delta_r = \Delta_{r0} + \Delta Q_{sc,x}(X,Y) + 2\Delta Q_{sc,y}(X,Y) + Q'_x \delta p/p + 2Q'_y \delta p/p \]

Bare tunes

effect of space charge
AMPLITUDE DEPENDENT

incoherent tune-shift
\[ \Delta Q_{x,\text{max}} \approx -0.05, \quad \Delta Q_{y,\text{max}} \approx -0.071 \]

\[ \mathcal{D}_{r,sc} \approx -0.19 \]

effect of chromaticity
AMPLITUDE INDEPENDENT

consider a test particle with maximum \( dp/p \)

0.037
Expected halo @ 9\sigma
Including chromaticity

No halo in x, but only core growth

Only ~ 5.5σ and not 9σ!
Something seems very wrong! The -x- profile does not exhibit a halo, and the -y- profile have a smaller halo than expected.
with chromaticity

without chromaticity

with chromaticity

\( \varepsilon_{xf} / \varepsilon_{xi} \)

\( \varepsilon_{yf} / \varepsilon_{yi} \)

\( I_f / I_i \)
Coupled dynamics on the resonance

F. Schmidt PhD thesis, and others

G. Franchetti and F. Schmidt

G. Franchetti and F. Schmidt
http://arxiv.org/abs/1504.04389
SPS campaign on May 2015: “Dream of glory”

Experiment organized by F. Schmidt
Space charge induced coupled dynamics in a bunch

longitudinal motion keep frozen, to make retrieve orbits
look at the x-y projection of resonant orbits
two larger resonant orbits: situation very different than 1D resonances. There are infinite fixed lines!!
Transverse space charge is weaker

½ length
two larger resonant orbits: now the amplitude of the orbits is smaller. We still have infinite fixed lines.
Periodic crossing of fixed lines induced by space charge and synchrotron motion
Scattering (of the invariants)
Adiabatic limit

Artificially very slow synchrotron motion

\[
x = \sqrt{\beta_x a_x} \cos(-2t - \alpha + \pi M)
\]

\[
y = \sqrt{\beta_y a_y} \cos(t)
\]
Halo asymmetry explained with fixed lines
A benchmarking on the 3rd order coupled resonance is achieved for the full PS structure.

Outstanding asymmetric halo are formed and decently well retrieved by the simulations.

Thinking in terms of resonance detuning arises paradoxes.

The “fixed-lines” are the new objects that explain the dynamics of the resonance.

“Fixed lines” are measured in the SPS.

Simulations shows that the periodic crossing of the fixed-lines causes the asymmetric halo as result of fixed lines geometry.

Although there are infinite fixed lines, halo diffuses to “one” value \(\rightarrow\) adiabatic limit.

The doors are open for massive studies of all coupled resonances and space charge.