Space charge studies at 160MeV in the CERN PS Booster

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On behalf of the CERN Space-charge Group
In collaboration with the PSB control team and the RF team
# CERN Space Charge Group

<table>
<thead>
<tr>
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</thead>
</table>
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Outline

- Motivations for PSB MD at 160MeV
- PS Booster MD for the PTC-ORBIT code benchmarking
  - Computational tools → PTC-ORBIT code
  - Resonance observations for PSB at 160MeV
  - PTC-ORBIT benchmarking results
  - Extreme space-charge detuning (first attempt)
- Basic plan for nearest Mds
- Summary
Motivations for PSB MD at 160MeV

- LINAC2 (p+ 50MeV) → LINAC4 (h- 160MeV)
  ... very confident to run with \( \Delta Q_y \approx -0.3 \) (and reasonable hope for \( \Delta Q_y \approx -0.36 \))
- PS Booster \( \rightarrow W_{\text{inj}} = 160 \) MeV
  ... very confident to run with \( \Delta Q_y \approx -0.26 \) (with reasonable hope for \( \Delta Q_y \approx -0.30 \) with 180nsec long bunches)
- SPS (Q20 lattice)
  ... present assumption is to run with \( \Delta Q_y \approx -0.15 \)
  ... need to increase \( \Delta Q_y \approx -(0.20 \ldots 0.25) \)

<table>
<thead>
<tr>
<th>25 ns</th>
<th>PSB inj</th>
<th>PSB extr/PSB inj</th>
<th>PS extr/SPS inj</th>
<th>SPS extr/SPS inj</th>
<th>SPS extr/LHC inj</th>
<th>LHC top</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy GeV</td>
<td>0.16</td>
<td>2</td>
<td>26</td>
<td>450</td>
<td>7000</td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td>1</td>
<td>1</td>
<td>72</td>
<td>288</td>
<td>2808</td>
<td></td>
</tr>
<tr>
<td>Ib [e11 p+]</td>
<td>35.2</td>
<td>33.5</td>
<td>2.7</td>
<td>2.4</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>Ib in LHC [e11 p+]</td>
<td>2.9</td>
<td>2.8</td>
<td>2.7</td>
<td>2.4</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>Exyn [mm.mrad]</td>
<td>1.9</td>
<td>2.0</td>
<td>2.1</td>
<td>2.3</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>

\[ B_f = 0.4 \rightarrow \Delta Q_y \approx -0.25 \]
\[ B_f = 0.3 \rightarrow \Delta Q_y \approx -0.37 \]
Motivations for PSB MD at 160MeV

**LHC25 beam**

- Moderate space-charge detuning \((\Delta Q_y \approx -0.25)\)
  - check the estimated space-charge detuning
  - observation the INTEGER and MONTAGUE resonances
  - benchmarking the measured and simulated emittance evolution
  - effect of the linear coupling resonance [1,-1,0]

- Extreme space-charge detuning \((\Delta Q_y \approx -0.40)\)
  - LOW-loss operation at the energy 160MeV
PS Booster: MD for the code benchmarking

\[ Q_y = 4.42 \]
\[ Q_x = 4.225 \]
\[ 160 \text{ MeV} \]
\[ 50 \text{ MeV} \]

Beam profile (Wire-scan...at T ~ 10 shots)

\[ Q_y = 4.42 \]
\[ \sim 600 \text{ ms} \]
\[ \sim 450 \text{ ms} \]

\[ B_I = 0.40, N_0 \sim (150+170) \times 10^{10} \]

\[ B_I = 0.241, N_0 \sim (150+170) \times 10^{10} \]

\[ \text{SHORT} \] bunch ... h=1, \text{‘IN’ phase (8kV+8kV)}

\[ \text{LONG} \] bunch ... h=1, \text{‘ANTI’ phase (8kV+4kV)}

\[ \rightarrow \text{Taken into account the space charge effect in the longitudinal plane} \]

\[ \sim 2.8 \text{ turns MT injection} \]

Horizontal profile: ‘IN’ scan
Vertical profile: ‘IN’ scan

Single bunch intensity
\[ \rightarrow \sim 165 \times 10^{10} \text{ ppb} \]

Normalized 1\( \sigma \) Emittance
\[ H \rightarrow \sim 3.4\pi \text{ mm.mrad} \]
\[ V \rightarrow \sim 1.8\pi \text{ mm.mrad} \]

\[ Q_x = 4.23 \]
\[ Q_y = 4.42 \]

\[ \text{Estimation: } B_I = 0.25 \rightarrow \Delta Q_y (\text{Laslett}) \sim -0.4 \]
Computational tools

**PTC(MADX)-ORBIT code**, developed in collaboration of KEK and SNS.

**Main features of the code:**
- common environment for the single particle and multi particle dynamics, including the collective effects (space-charge, impedance and e-clodes);
- dynamic variation of the machine elements (magnets and RF systems).

The code has been compiled for the CERN lxplus cluster.

**Convergence study** has been performed for the LHC type beam to define the optimum set of the basic parameters for the space-charge model (2.5D), implemented into the ORBIT(MPI) code.
PSB MD: resonance observations at 160MeV

`LHC25' type beam

Q_x = 4.10, Q_y = 4.21

B_r \sim 0.40, \ N_b \sim 170 \times 10^{10}
N_{\text{int}} = 2.8
\varepsilon_{\text{H}} \text{ (norm)} \sim 3.4 \pi \text{ mm.mrad}
\varepsilon_{\text{V}} \text{ (norm)} \sim 1.8 \pi \text{ mm.mrad}

~ 50 msec

Effect of the INTEGER resonance Q_x = 4 (systematic)

LHC25 type beam (B_r = 0.40)

Q_x = 4.10, Q_y = 4.21

Footprint after 1000 turns

PTC-ORBIT

Q_x = 4

Maximum detuning:
\Delta Q_H = -0.16
\Delta Q_V = -0.24
PSB MD: resonance observations at 160MeV

'LHC25' type beam

Effect of the Montague resonance $2Q_x - 2Q_y = 0 \rightarrow$ FIRST trial

$B_r \sim 0.40, N_2 \sim 170 \times 10^{10}$
$N_{\text{proj}} = 2.8$
$\delta_x (\text{norm}) \sim 3.4 \pi \text{ mm.mrad}$
$\delta_y (\text{norm}) \sim 1.8 \pi \text{ mm.mrad}$

$W_{\text{proj}} = 160 \text{ MeV}$
$LHC25 \text{ beam}$
$B_r \sim 0.4$
$Q_x = 4.18 / Q_y = 4.23$

$2Q_x - 2Q_y = 0$

PTC-ORBIT

Alexander Molodozhentsev (KEK), LIU Beam Study Review, August 28, 2012, CERN
PTC-ORBIT benchmarking results

**MD - Beam characteristics – longitudinal**
- h=1 - double harmonic RF +8kV & +4kV in antiphase
- Long bunch ~ B.f. ~0.39
- RMS emittance = 0.161 eVs
- RMS Δp/p = 1.33e-3

**Simulations - Beam characteristics – transverse**

**Simulations - Beam characteristics – longitudinal**
- 500e3 m.particles
- Long bunch ~ B.f. ~0.39
- RMS emittance ~ 0.16 eVs
- RMS Δp/p ~ 1.33e-3

*Thanks to Alexander for the longitudinal distribution*

**Profiles comparison – measured and simulated**
PTC-ORBIT benchmarking results

Effect of [1,0,4] resonance

$LHC25 \text{ beam}$

$W_{\text{kin}} = 160\text{MeV}$

$B_z \sim 0.4$

$Q_x = 4.10 / Q_y = 4.21$

#0 $\rightarrow$ measurements

#1 $\rightarrow$ ideal lattice

#2, #3 $\rightarrow$ lattice with RANDOM errors $\{\delta K1\}_\text{QM}$

#2: 1Sigma $= 1.0 \times 10^{-3}$ (relative value)

#3: 1Sigma $= 5.0 \times 10^{-3}$

Gaussian generator (no cut)

Acceptable agreement between experimental data and simulation results (LHC25 beam)

Maximum random error of the PSB quadrupole magnets $\sim 1.0 \times 10^{-3}$ (1\(\sigma\))
PTC-ORBIT benchmarking results

Effect of the Montague resonance [2,-2,0]

- #0 → measurements
- #1 → ideal lattice
- #2, #3 → lattice with RANDOM TILT of {QM}
- #2: 1Sigma = $2.17 \times 10^{-6}$ rad
- #3: 1Sigma = $4.28 \times 10^{-6}$ rad

Gaussian generator (no cut)

Courtesy V.Forte
PSB MD: resonance observations at 160MeV

MD: extreme space-charge detuning
\[ \Delta Q_y \approx 0.4 \text{ (LHC25 beam) } \]

WITH resonance compensation

\[ Q_x = 4.23 \]
\[ Q_y = 4.42 \]

~ 460ms ~ 600ms

Estimated incoherent space-charge detuning

\[ \rightarrow \text{ Observation at 160MeV: losses < 1%} \]
PSB MD: resonance observations at 160MeV

MD: extreme space-charge detuning $\Delta Q_y \approx -0.4$ (LHC25 beam)

$B_r = 0.241, N_b = 149 \times 10^{10}$

WITH resonance compensations, used for the PSB operation ...

→ observations should be reproduced by the simulations …
Basic plan for nearest PSB MDs

- Tune scan at 160MeV for different space charge detuning by using the LHC25 type beam …

- Observation of the emittance evolution at the 50MeV energy including existing schemes of the resonance compensation to collect information for further simulations…
Summary

• Effects of INTEGRER and Montague resonances at the 160MeV energy has been investigated experimentally to collect data for benchmarking the PTC-ORBIT code.

• Benchmarking the PTC-ORBIT code demonstrates acceptable agreement with the beam observations for the moderate space-charge detuning (V: -0.25).

• The first attempt to use the 'extreme' space charge detuning at the 160MeV energy indicates some promising possibility to reach the space charge detuning of (V: -0.4) with limited emittance blow-up and acceptable particle losses.
THANK YOU FOR YOUR ATTENTION!