PTC-ORBIT Studies for the CERN LHC Injectors Upgrade Project

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Outline

- Motivation
- Computational tools
- ‘Space-charge’ convergence study
- Machine study and the code benchmarking
- ‘Dynamic’ simulations of the Multi-turn injection for the CERN PS Booster
- Observation of the space charge effects for CERN PS and SPS
- Conceptual design of the CERN RCS
Motivation

- CERN LHC (25nsec) beam upgrade scenario (LIU request)

**2011:** ~ $1.1 \times 10^{11}$ with 2.8$\mu$m for 25nsec has been extracted from SPS

**Post LS2 (2019):** $\times 2.4$ times in brightness for 25nsec

A.Molodozhentsev (KEK), ICFA HB12 workshop
Beijing, China, September 17-21, 2012
Motivation

- Space charge detuning estimations for the LHC Injectors

- LINAC2 (p+ 50MeV) → LINAC4 (h 160MeV)
- PS Booster \( W_{\text{inj}} = 160 \text{ MeV} \)
  - very confident to run with \( \Delta Q_y \approx -0.3 \) (and reasonable hope for \( \Delta Q_y \approx -0.36 \))
- PS \( W_{\text{inj}} = 2 \text{ GeV} \)
  - 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 \( \Delta Q_y \approx -(0.20 \ldots 0.25) \)

| \( B_r = 0.4 \) | \( \Delta Q_y \approx -0.25 \) | \( B_r = 0.3 \) | \( \Delta Q_y \approx -0.37 \) |
### Computational tools

**Why PTC-ORBIT?**

- **Real machine with field Imperfections and alignment data**
- **PTC lattice representation**
  - Comprehensive lattice analysis
  - RF cavities (acceleration)
  - NEW!...Time dependent magnets

**ORBIT node**
- PTC as the tracker (6D integrator)

**‘ORBIT’ staff:**
- Injection foil.
- Space charge model.
- Transverse and longitudinal impedance.
- Feedback for stabilization.
- Aperture and collimation.
- Electron cloud model.

**Main feature:**
Common environment for the single particle dynamics (lattice analysis and resonance compensation) and multi particle dynamics (collective effects).
‘Space-charge’ convergence study

**ORBIT(MPI) is the PIC code**
- in particular, FFT Particle-In-Cell without (adapted grid) or with (fixed grid) the boundary
  - Optimum set of the required parameters for the ‘space-charge’ model
    - … avoid artificial emittance growth (‘core’ and ‘halo’ parts of the beam)
    - … reasonable CPU time per the ‘1 turn’ tracking
    - … $N_{mesh}$ (X&Y), $N_{mp}$, $L_{bin}$, $N_{spch}$ should be optimized for beams with different parameters (LHC type or CNGS type)

**Machine lattice:**
- PSB → basic IDEAL lattice without any errors (static lattice)
- PS → basic IDEAL lattice → NO any correctors
- SPS → basic IDEAL lattice
- RCS → basic IDEAL lattice

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**PTC-ORBIT(MPI)**

<table>
<thead>
<tr>
<th>Method</th>
<th>$L_{max} / N_{sp}$</th>
<th>$N_{mesh} (x=y)$</th>
<th>$N_{macro} \times 10^3$</th>
<th>$L_{bin}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSB</td>
<td>Fixed grid</td>
<td>1m / 199</td>
<td>256</td>
<td>1000</td>
</tr>
<tr>
<td>PSB</td>
<td>Adapted grid</td>
<td>3.32m / 2688</td>
<td>64</td>
<td>250</td>
</tr>
<tr>
<td>RCS</td>
<td>Adapted grid</td>
<td>1m / 157</td>
<td>128</td>
<td>500</td>
</tr>
</tbody>
</table>

**LHC type beam**

<table>
<thead>
<tr>
<th>Beam intensity ($\times 10^5$ ppb)</th>
<th>Bunching factor</th>
<th>Tunes</th>
<th>Normalized emittances $1\sigma / \mu m$</th>
<th>Estimated $\Delta Q^{NC, \sigma, V}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PSB 160MeV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHC25 2.475 (1.5 nominal)</td>
<td>0.6 ($T_b = 185$ns)</td>
<td>4.26 / 4.43</td>
<td>0.61 (T = 185ns)</td>
<td>3 / 2 official Excel dataset</td>
</tr>
<tr>
<td><strong>PS 1.4GeV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHC50 0.81 (1.15)</td>
<td>0.174 (T = 90ns)</td>
<td>6.21 / 6.23</td>
<td>0.35 (T = 180ns)</td>
<td>1.45 / 1.32</td>
</tr>
<tr>
<td>SPS 2.0GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHC50 0.27 (1.15)</td>
<td>0.5 (T = 3 ns)</td>
<td>20.15 / 20.23</td>
<td>0.35 (T = 180ns)</td>
<td>2.1 / 2.1</td>
</tr>
<tr>
<td>RCS 160MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2+10^3 (1/2 nominal)</td>
<td>0.3</td>
<td>4.29 / 3.38</td>
<td>0.35 (T = 180ns)</td>
<td>2.5 / 2.5</td>
</tr>
</tbody>
</table>

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Space charge detuning for CERN PS-Booster (160MeV)

![2D histogram](image)

$Q_H / Q_V = 4.26 / 4.43$
‘Space-charge’ convergence study

- RMS and 99% emittance evolution for different sets of the ‘space charge’ module of the code for the case of the lattice tunes $Q_H / Q_V = 4.26 / 4.43$ (CERN PS Booster)

RMS emittance evolution

Evolution of the ‘halo’ part of the beam

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Machine studies (MD-2012) and the PTC-ORBIT code benchmarking

Motivation:
- reproduce the measured beam evolution at 160MeV by the PTC-ORBIT tracking

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Foot print
$Q_H/Q_V=4.18/4.23$

**LHC25 beam**
$B_f \sim 0.4$

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Measured beam profile
‘Tomoscope’ image

Generated beam profile

Generated and measured transverse beam profile at the 160MeV energy

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Machine studies (MD-2012) and the PTC-ORBIT code benchmarking

- taken into account the random error of the quadrupole strength of the PS Booster magnets

- lattice with RANDOM errors \( \{\delta K_1\}QM \)
  - #1: ‘ideal’ lattice
  - #2: \( 1 \text{Sigma} = 1.0 \times 10^{-3} \) (relative value)
  - #3: \( 1 \text{Sigma} = 5.0 \times 10^{-3} \)

- including the random TILT of the PS Booster quadrupole magnets

Up to \( 1 \text{Sigma} = 4.28 \times 10^{-5} \) rad

Linear coupling of the PS Booster: \( \Delta Q_{\text{MIN}} \approx 0.008 \)

- Accuracy of the RMS emittance measurements should be improved …
Multi-turn injection for the CERN PS Booster with LINAC4

- Significant improvement of the efficiency of the MT injection by using the H⁺ stripping injection in the H-plane
- Control over both transverse emittances
- Effects of the edge-focusing of the ‘slow’ bump-magnets, changing during the chicane reduction

KSW Parameters

<table>
<thead>
<tr>
<th></th>
<th>LHC Beam</th>
<th>CNGS Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{1}$</td>
<td>94% $I_{\text{max}}$</td>
<td>71% $I_{\text{max}}$</td>
</tr>
<tr>
<td>$I_{2}$</td>
<td>92% $I_{\text{max}}$</td>
<td>70% $I_{\text{max}}$</td>
</tr>
<tr>
<td>$t_{1}$</td>
<td>7 µs</td>
<td>10 µs</td>
</tr>
<tr>
<td>$t_{2}$</td>
<td>20 µs</td>
<td>49 µs</td>
</tr>
<tr>
<td>$t_{\text{fall}}$</td>
<td>35 µs</td>
<td>64 µs</td>
</tr>
</tbody>
</table>

$L_{\text{max}}$: current corresponding to a bump height at the foil of ~35 mm

Kicks for a 55 mm bump at the foil:
- KSWP16L1: 8.74 mrad → 0.045 T
- KSWP1L4: 2.55 mrad → 0.013 T
- KSWP2L1: 2.55 mrad → 0.013 T
- KSWP16L4: 8.74 mrad → 0.045 T

Functions have to be defined for varying the dI/dt of the KSW during injection.
Different functions for different users → high flexibility is required.
Multi-turn injection for the CERN PS Booster with LINAC4

- Lattice tunes: \( \frac{Q_H}{Q_V} = 4.28/4.45 \)
- \( Q_V \) could be above 4.5 ...
- Compensation the V beta-beating effect
  → Active compensation scheme by using 2 independent families of quads
  → Reduction of the V-beta beat: 35% → 5%
  → Dynamic changing the quad strength during the chicane’s fall from MAX (≈ -80mm) to ZERO

V beta-beating around CERN PS Booster: #1 – before; #2 – after the ‘active’ correction

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Multi-turn injection for the CERN PS Booster with LINAC4

Double harmonic RF system with the longitudinal stacking of the bunches

Particle distribution after 5520t

PTC-ORBIT (space charge → ON)

Longitudinal painting

Further attenuation of space charge effects can be obtained by controlling the distribution, in phase space of injected particles.

Energy of the injected beam will be varied to fill the bucket with an equal density distribution.

Capture efficiency ~ 98%, $B_f \sim 0.6$
Multi-turn injection for the CERN PS Booster with LINAC4

- Transverse emittance evolution (NO FOIL)
- V OFF-set (~3mm) to control the Vertical emittance
- Space Charge effects → ON (adapted grid) ... 35.2e10ppb
- Incoherent space charge detuning < -0.5, Lattice tune $Q_H / Q_V = 4.27 / 4.58$

Effects of FOIL, Aperture limitation, machine imperfections should be analyzed
CERN PS: space charge effects and machine resonances

- Emittance growth near the [0,1,6] resonance has been studied experimentally ... for the code benchmarking

- Resonance Driving Terms:
  - ‘pencil’ beam (LHC-INDIV)
  - different horizontal kick strength

- ‘Realistic’ machine description by using the measured field nonlinearities of the PS magnets ... in progress ... to reproduce the experimental observations.

Tune scan at the energy 2.0GeV
Typical tune-spread H,V ~(-0.18, -0.28)

S. Gilardoni talk

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CERN PS: space charge effects and machine resonances

‘LHC-INDIV’ beam

[1,-1,0] resonance observation

Beam centroid evolution
→ LINEAR coupling → [1,-1,0]

H-kick only

$Q_x = 6.20$
$Q_y = 6.21$

Linear coupling resonance observation (NO correction)

Observation of the [1,-1,0] resonance
→ turn-by-turn data acquisition …

Turn-by-Turn data analysis

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**CERN SPS: space charge effects and machine resonances**

- Tune scan for the Q20 SPS optics at 26GeV
- Single bunch: 2.5-2.7e11 p/b
- Normalized RMS emittance: $1.2\mu$m in both planes
- The incoherent space charge detuning:
  $\Delta Q_H \approx -0.15$, $\Delta Q_V \approx -0.25$.

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*H. Bartosik talk*
RCS conceptual design

Motivations (including the space charge at injection):
- alternative to the CERN PS Booster upgrade (160MeV-2GeV, 10Hz)
- effect the beam envelope modulations on the emittance growth
- effect of the super-periodicity

\[ \Delta Q_y \approx -0.4 \]

\[ Lattice \ tune \ above \ 2Q_y = 7 \]

\[ Including \ the \ Vertical \ beta-beating \ correction \ldots \]

\[ Variation \ of \ the \ beam \ size \ can \ lead \ to \ the \ emittance \ growth: \]

\[ \rightarrow \ the \ ‘TRIPLET’ \ features \ smallest \ variation \ of \ the \ transverse \ emittance \ compared \ to \ the \ ‘DOUBLET’ \ and \ the \ ‘FODO’ \ cell \]

\[ Emittance \ growth \ due \ to \ excitation \ of \ ‘systematic’ \ resonances: \]

\[ \rightarrow \ ‘weak’ \ symmetry \ breaking \ in \ one \ cell \ with \ correcting \ the \ beat-beat \]

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Conclusions

- The performed benchmarking between the measured and simulated beam evolution for the CERN PS Booster at 160MeV shows very good agreement.

- Optimization of main PS Booster setting has been performed to simulate the multi-turn injection process.

- Data accumulation for the further study of the space charge effects for the LHC Injectors has been started to perform extensive simulations during the ‘Shut-Down-1’ period.
Thanks for your attention