PSB injection: beam dynamics studies

C. Bracco, J. Abelleira Fernandez, E. Benedetto, V. Forte,
Outline

• Introduction

• Performed studies:
  – High brightness – small emittance beams
  – High intensity – large emittance beams
  – Perturbations induced by chicane BSW magnets

• Next steps
Longitudinal painting

- 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.

±1.1 MeV energy distribution over a period of **minimum 40 turns**
Transverse Painting Principle

• Horizontal painting bump implemented
• Fill first the centre and then the outer area of the ellipse in the transverse phase space
• Decay time modulation of four kicker magnets (KSW), installed in the PSB lattice, allow to accomplish transverse phase space painting to required emittance and intensity.

Injected Beam

Tracking studies with ORBIT (foil scattering, space charge, aperture model, etc.) ➔ define best parameter and injection scheme
Painting with KSW

Original design for KSW transverse painting

Fast decay (slope 1) ➔ almost constant slope fall until the end of injection (slope 2) ➔ move the beam away from the foil (slope 3) towards negative bump (-9.2 mm = 1/5 BSW bump) ➔ bump to 0 in 1 ms (1/5 BSW decay time) (slope 4)

Distribute particles uniformly in the transverse space ➔ reduce charge density in the core of the bunch ➔ reduce space charge effects
<table>
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<tr>
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**G. Rumolo’s Tables https://edms.cern.ch/document/1296306/1**
# PSB User

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Small Emittance - High Brightness

• How to preserve small emittance?
  – Optimize optics parameters
  – Optimize initial distribution (also longitudinal!)
  – Optimize KSW
  – Minimize foil crossings
  – Optimize PSB working point

What shall we expect in case of errors/non optimal parameters?
Small Emittance - High Brightness

- How to preserve small emittance?
  - Optimize optics parameters
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Small Emittance - High Brightness

• How to preserve small emittance?
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<th>$\beta_x$ [m]</th>
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r.m.s. normalized emittance $\varepsilon_0 = 0.4 \text{ mm mrad}$ (max. from Linac4)

** it depends on $\Delta p/p$

No offset in both x-y plane (-35 mm nominal horizontal KSW bump)

Fully matched optics
Gaussian distribution $x$-$x'$** and $y$-$y'$
Linac4 chopped bunches injection in the PSB without energy modulation

From single Linac4 bunches (thanks to A. Lombardi) It is possible to create injection structures for the PSB, for optimizing...

- the bunch length to minimize the number of turns injected in the PSB for a certain intensity.
- the energy spread to minimize filamentation and peaks in linear density.

*ESME simulations without longitudinal space charge*

Min-max 0.5 MeV (113 keV RMS) - 0.38e-3 dp/p rms – 680 ns – 243 Linac4 bunches

Min-max 1.74 MeV (336 keV RMS) - 1.1e-3 dp/p rms – 616 ns – 220 Linac4 bunches

To inject 1.65e12 p. in the PSB -> 6.6 turns
(@ 220 Linac4 bunches/turn and 1.14e9 p.p.bunch)

Reference:
Linac4 chopped bunches injection in the PSB without energy modulation

- The optimization requires to choose the optimal injection “train” shape to obtain a homogeneous evolution and avoid peaks in the linear density behavior (for lower tune spread due to space charge).
- The 113 keV rms case shows an increase in top linear density of a factor 4 during the first 150 turns.
- The 336 keV rms case shows a nicer and smoother behavior in top linear density (lower).

**After 143 turns**

**113 keV rms**

**336 keV rms**
Small Emittance - High Brightness

- How to preserve small emittance?
  - Optimize optics parameters
  - Optimize initial distribution (also longitudinal!)

| β_x [m] | 5.6 m |
| α_x [rad] | 6.5e-5 |
| D_x [m] | -1.4 m |
| D_x' [rad] | 0.2e-3 |
| β_y [m] | 3.7 m |
| α_y [rad] | 9.6e-5 |
| D_y [m] | 0 |
| D_y' [rad] | 0 |

Δp/p = 1.1 e-3 (336 keV)
Phase = 1.9 rad (616 ns)
Small Emittance - High Brightness

• How to preserve small emittance?
  – Optimize KSW
  – Minimize foil crossings
  – Optimize PSB working point

* 1.65E12 p+ per ring
Small Emittance - High Brightness

- How to preserve small emittance?
  - Optimize KSW
  - Minimize foil crossings
  - Optimize PSB working point? ($Q_H = 4.28; Q_V = 4.55$)

What shall we expect in case of errors/non optimal parameters?

* 1.65E12 p+ per ring
Small Emittance - High Brightness

- Effect of errors and/or non nominal parameters

**End of KSW decay (30 μs)**
- $\varepsilon_f = 0.77$ mm mrad
- $\varepsilon_f = 0.84$ mm mrad

**After 100 μs (stable)**
- $\varepsilon_f = 0.79$ mm mrad
- $\varepsilon_f = 0.85$ mm mrad

a) Ideal case (total intensity = 1.65e12 protons per ring)
b) 25% $\beta_{x,y}$ error & 0.3 m $D_{x,y}$ error
c) 25% $\beta_{x,y}$ error & 0.3 m $D_{x,y}$ error & 2 mm x,y offset
d) 25% $\beta_{x,y}$ error & 0.3 m $D_{x,y}$ error & 2 mm x,y offset & 50% Linac4 current

$\varepsilon_{x,y}$ (BCMS) $\leq$ 1 mm mrad
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*norm. Emittance [mm mrad]*
Assumptions to calculate beam envelope in the injection region (r.m.s normalized emittance 15 x 9 mm mrad):

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<tr>
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<td>orbit</td>
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<td>Max. offset for painting</td>
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<td>Max. Beam env.</td>
<td>±mm</td>
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Beam envelope at the end of injection (KSW bump = 0 mm, BSW bump = 45.9 mm):
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Beam envelope at the end of injection (KSW bump = 0 mm, BSW bump = 45.9 mm):

- BSW4
- H0
- Stripping foil
- BSW3
- BSW2
- Stripping foil
- BSW1

r.m.s norm. emitt. hor = 12 mm mrad

Circulating beam
Beam envelope at the end of injection (KSW bump = -9.2 mm, BSW bump = 45.9 mm):

Circulating beam

H0

BSW4

Dump

BSW3

BSW2

BSW1

Stripping foil

Stripping foil

x [mm]

s [m]

r.m.s norm. emitt. hor = 12 mm mrad

Negative KSW bump

Circulating beam
Beam envelope at the end of injection (KSW bump = -9.2 mm, BSW bump = 45.9 mm):

r.m.s norm. emitt. hor = 9 mm mrad
Injection over 40 turns (1e13 p+ per ring, 40 mA current from Linac4)
Longitudinal painting
Matched optics in beta and dispersion
Initial vertical offset of 7.5 mm

100% $I_{\text{max}} \Rightarrow 60\% I_{\text{max}}$ in 12 $\mu$s ($t_1 = 12$ $\mu$s)
60% $I_{\text{max}} \Rightarrow 59\% I_{\text{max}}$ in 28 $\mu$s ($t_2 = 40$ $\mu$s)
59% $I_{\text{max}} \Rightarrow -0.26\% I_{\text{max}}$ in 15 $\mu$s ($t_3 = 55$ $\mu$s)
Injection over 40 turns (1e13 p+ per ring, 40 mA current from Linac4)
Longitudinal painting
Matched optics in beta and dispersion
Initial vertical offset of 7.5 mm

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Total: 1.1% beam lost
52% of losses occur when KSW $\sim$ constant

Faster decay??
Tradeoff distribution “quality” – losses – foil heating
KSW Envelope Specifications

KSW Magnet Current

LHC- small emittance beams

High intensity – Large emittance

Deviation from reference curve < 1%

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<thead>
<tr>
<th>User</th>
<th># turns</th>
<th>$I_1 [% I_{\text{max}}]$</th>
<th>$I_2 [% I_{\text{max}}]$</th>
<th>$t_1$</th>
<th>$t_2$</th>
<th>$t_{\text{fall const}}$</th>
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Old values
• Edge effects (rectangular magnets)
• Proposed corrugated Inconel vacuum chamber new baseline (ceramic in the original design)
• Influence on beam dynamics of induced Eddy currents:
  – Delay of ~50us
  – Higher order field components (sextupolar)
    • Quadrupolar feed-down
    • Excitation 3rd order resonance
Inconel vacuum chamber

- No showstoppers for the inconel chamber are found, but compensation is required (E. Benedetto et al, @ LIU-PSB Meeting, 26/9/2013)

- Simulations results are valid only in relative, to discriminate between ceramic and inconel chamber
  - optics model as simple as possible
  - no errors except in BSW magnets

**“High brigthness” beam**

- I=3.2e12p
- Ex*=1.2um
- Ey*=1.2um

**“Isolde-like” beam**

- I=1e13p
- Ex*=8.8um
- Ey*=5.7um
Studies on the shape for the chicane ramp down

- Realistic shape with a 125Hz content (So far, assumed linear decay in 5ms)
  
  **Input from D. Aguglia, D. Nisbet**

- Correction for V Beta-Beating has been computed

- Almost identical results (blow-up and/or losses) than with the linear decay

BSW ramp-down function and sextupolar component generated by eddy-currents

Computed strength in the QDE3, QDE14 and in the other quadrupoles
Next Steps

– LHC: possible further optimizations (tune, long. distribution)?

– High intensity beams
  • Agree target values (intensity and emittance!)
  • Define KSW modulations:
    – With/without longitudinal painting (injection turns)
    – Trade-off optimum distribution – minimum losses - foil scattering/heating (all users)
    – Imperfections (delays from eddy currents induced by Ti layer)
    – Other options: mismatch and/or offset (?)
  • Losses in injection region

– Quadrupolar component in BSW1 (C-shaped)
– Final crosscheck with HW experts (specs and tolerances)
Thank you for your attention!
Linac4 chopped bunches injection in the PSB without energy modulation

- Optimize...
  - the bunch length to minimize the number of turns injected in the PSB for a certain intensity.
  - the energy spread to minimize filamentation and peaks in linear density.

**ESME simulations (29.55E11)**

Min-max 0.5 MeV (113 keV RMS) - 0.38e-3 dp/p rms – 680 ns – 243 Linac4 bunches

Min-max 1.74 MeV (336 keV RMS) - 1.1e-3 dp/p rms – 616 ns – 220 Linac4 bunches

**To inject 1.65e12 p. in the PSB -> 6.6 turns**
(@ 220 Linac4 bunches/turn and 1.14e9 p.p.bunch)

Reference:
Linac4 chopped bunches injection in the PSB without energy modulation

From ESME simulations (with longitudinal space charge and I=29.55e11)
Linac4 chopped bunches injection in the PSB without energy modulation

- The longitudinal “islands” creation is an intensity-dependent phenomenon (increases with intensity).
- It happens when the space charge module is activated in ESME (to be understood).

**C275 (injection)**

\[
\begin{align*}
I=0 & \quad I=14.77 \times 10^{11} \text{ p.} \\
I=29.55 \times 10^{11} \text{ p.}
\end{align*}
\]
Injection over 80 turns (2e13 p+ per ring or 20 mA current from Linac4)
Longitudinal painting
Matched optics in beta and dispersion
Initial vertical offset of 6 mm

100% I_{max} \Rightarrow 40% I_{max} in 80 \mu s (t1 = 80 \mu s)
40% I_{max} \Rightarrow -0.26 \% I_{max} in 15 \mu s (t2 = 95 \mu s)