Space Charge Mitigation in PS with Hollow Bunches

MD210: Creation in the PSB
MD211: Behaviour in the PS

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Goals of Study

motivation of hollow bunches

*mitigate* transverse space charge impact at PS injection
and possibly already during PSB ramp

course of action:

1. create hollow bunches in PSB (MD210)
2. transfer to PS (MD211)
3. investigate behaviour during PS RF gymnastics
4. quantify gains during PS injection plateau

⇒ show PS results first!

→ disclaimer: hollow distributions only mediocre quality
(unreliable C16 blow-up, disruptive PSB-PS synchro)
Compared Distributions in PS @C185

**heavily flattened parabolic ("Gauss")**

![Graphs showing distributions](image)

- RMS Emitt. = 0.293 eVs
  - BF = 0.396
  - 90% Emitt. = 1.12 eVs
  - Ne = 1.9E12
  - Mtchd Area = 1.41 eVs
  - Duration = 200 ns
  - RMS dp/p = 1.09E-3
  - fs0;1 = 611;471 Hz

**hollow**

![Graphs showing distributions](image)

- RMS Emitt. = 0.318 eVs
  - BF = 0.446
  - 90% Emitt. = 1.13 eVs
  - Ne = 1.7E12
  - Mtchd Area = 1.36 eVs
  - Duration = 195 ns
  - RMS dp/p = 1.12E-3
  - fs0;1 = 611;477 Hz

- same longitudinal matched 100% emittances (equal $B_L$)

  $\Rightarrow \sim 9\%$ larger r.m.s. emittances in hollow case

- system. higher intensities for Gauss (by 10%, cf. appendix)
Transverse Space Charge

transverse direct space charge:

\[ \Delta Q_{x,y}(z) = -\frac{r_p \lambda(z)}{2\pi \beta^2 \gamma^3} \int ds \frac{\beta_{x,y}(s)}{\sigma_{x,y}(s) (\sigma_x(s) + \sigma_y(s))} \]  

(1)

with (assuming a Gaussian in long. and horiz. plane)

\[ \sigma_{x,y}(s) = \sqrt{\epsilon_{x,y} \beta_{x,y}(s) + D_{x,y}(s)^2 \delta_{\text{RMS}}^2} \]  

(2)

\[ \implies \text{mitigate space charge (lower max } \Delta Q_{x,y} \text{) by} \]

- line density depression \( \lambda_{\text{max}} \sim \lambda(z_{\text{centre}}) \)
- increase momentum spread \( \delta_{\text{RMS}} \)
---

**PS Experiment Overview**

single bunch (ring 3), LHC25 type, minimal changes

<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>long. 100% emittance hollow</td>
<td>$\epsilon_{z,100%}$</td>
<td>$1.43 \pm 0.15$ eV s</td>
</tr>
<tr>
<td>long. 100% emittance Gauss</td>
<td>$\epsilon_{z,100%}$</td>
<td>$1.47 \pm 0.11$ eV s</td>
</tr>
<tr>
<td>PSB horizontal r.m.s. emittance</td>
<td>$\epsilon_x$</td>
<td>$\approx 2.23$ mm mrad</td>
</tr>
<tr>
<td>PSB vertical r.m.s. emittance</td>
<td>$\epsilon_y$</td>
<td>$\approx 2.12$ mm mrad</td>
</tr>
<tr>
<td>intensity hollow</td>
<td>$N$</td>
<td>$(1.661 \pm 0.053) \times 10^{12}$</td>
</tr>
<tr>
<td>intensity Gauss</td>
<td>$N$</td>
<td>$(1.835 \pm 0.034) \times 10^{12}$</td>
</tr>
<tr>
<td>injection plateau energy</td>
<td>$E_{\text{kin}}$</td>
<td>1.4 GeV</td>
</tr>
<tr>
<td>horizontal coh. dip. tune</td>
<td>$Q_x$</td>
<td>6.23</td>
</tr>
<tr>
<td>vertical coh. dip. tune</td>
<td>$Q_y$</td>
<td>6.22</td>
</tr>
<tr>
<td>synchrotron period ($V = 25$ kV)</td>
<td>$Q_{S,0}^{-1}$</td>
<td>725 turns</td>
</tr>
</tbody>
</table>

**Table:** relevant PS beam specifications at injection.
Measured Quantities

for each shot:

- coherent dipolar tune (via PR.BQS72)
- coherent quadrupolar tune (via PR.BQL72)
- intensities via BCT

→ references at C185 and C1350, for each reference time:
  - wire scans in horizontal and vertical plane
  - wall current monitor for tomography (⇒ long. phase space)

3 experiments scanning

1. bunch length \( V_{rf} = 25..80 \text{kV} \)
2. vertical tune \( Q_y = 6.22..6.08 \)
3. intensity (0.5 to 3.3 injected turns)
Bunch Length Scan

- Parabolic bunches
- Hollow bunches
- Parabolic fit with $1\sigma$ c.b.
- Hollow fit with $1\sigma$ c.b.
- Ideal Gaussian profile
- Ideal rectangular profile

$\lambda_{\text{max}}/N [10^{-2}/m] = \Rightarrow$ depression of maximal line density by factor 0.9

$\Rightarrow$ could improve bunching factor even further towards (magenta) ideal rectangular distribution
Results from Bunch Length Scan I

<table>
<thead>
<tr>
<th>ΔQ_y</th>
<th>εfin y [mm mrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>2.0</td>
</tr>
<tr>
<td>0.24</td>
<td>2.5</td>
</tr>
<tr>
<td>0.28</td>
<td>3.0</td>
</tr>
<tr>
<td>0.32</td>
<td>3.5</td>
</tr>
</tbody>
</table>

→ final core emittance for Gaussian space charge shift formulae (1), (2)

→ compares “as if” we had a Gaussian distribution
Results from Intensity Scan I

parabolic bunches
hollow bunches
parabolic fit with 1σ c.b.
hollow fit with 1σ c.b.

$2N/(\epsilon_{x}^{ini} + \epsilon_{y}^{ini}) \ [10^{17} \text{ p}/(\text{m rad})]$ 

→ emittance growth: ratio of core Gauss fits for C1350:C185
How to extract horizontal emittance?!
Horizontal Emittance Determination

- assume betatron distribution $f_\beta$ to be Gaussian
- get momentum distribution $f_\delta$ via tomography / Abel transform from bunch shape monitor
- dispersive distribution $f_{\text{disp}}(x) = \frac{f_\delta(D_x \delta)}{|D_x|}$
- convolute Gaussian with $f_{\text{disp}}$ to fit wire scan
  \[ \Rightarrow \text{find Gaussian } \sigma_{x_\beta} \text{ in least squares approach} \]

\[
x = x_\beta + D_x \delta \quad \text{\(x_\beta, \delta\) indep.} \quad 
\Rightarrow \quad f_x(x) = \int dx' \ f_\beta(x') f_{\text{disp}}(x - x') \\
\text{convolution of profiles}
\]

- $f_x \rightarrow$ wire scan profile, $f_{\text{disp}} \rightarrow$ dispersive distribution
Horizontal Emittance Determination

- Assume betatron distribution $f_\beta$ to be Gaussian.
- Get momentum distribution $f_\delta$ via tomography / Abel transform from bunch shape monitor.
- Dispersive distribution $f_{\text{disp}}(x) = \frac{f_\delta(D_x\delta)}{|D_x|}$.
- Convolute Gaussian with $f_{\text{disp}}$ to fit wire scan.
- Find Gaussian $\sigma_{x_\beta}$ in least squares approach.

![Graph showing horizontal distribution measured: $D_x\delta$ distribution and input: Gaussian $x_\beta$ distribution.](image-url)
Horizontal Emittance Determination

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- get momentum distribution $f_\delta$ via tomography / Abel transform from bunch shape monitor
- dispersive distribution $f_{\text{disp}}(x) = \frac{f_\delta(D_x\delta)}{|D_x|}$
- convolute Gaussian with $f_{\text{disp}}$ to fit wire scan

$\Rightarrow$ find Gaussian $\sigma_{x_\beta}$ in least squares approach
How to create hollow bunches?!
Tomograms Over Process

kinetic energy programme (PSB)

→ dipolar parametric resonance @C575

→ extremely reproducible results @C600

kinetic energy [GeV]
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
ctime [ms]
300 400 500 600 700 800

inj@C275 extr@C805

→

PSB C573 before excitation

PSB C591 after excitation

PSB C800 after synchro, before extraction

PS C171 after transfer

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SC Mitigation in PS with Hollow Bunches
Method: Excitation of Parametric Resonance

**approach:**

- exploit phase-loop to make bunch frame reference oscillate

\[
\phi_{ref}(t) = \phi_s + \hat{\phi}_{drive}\sin(\omega_{drive}t)
\]

\(\frac{\text{driven oscillation}}{}\)

- parametric resonance: \(\omega_{drive} \approx \omega_{s,0}\)

→ use a bit lower \(\omega_{drive} \approx 0.9\omega_{s,0}\) to drive outer particles, bucket non-linearity + space charge \(\Rightarrow \omega_s = \omega_s(J_{long})\)
\[ \phi_{ref}(t) \text{ oscillates for 6 synchrotron periods at } \hat{\phi}_{drive} = 18^\circ \]

\[ \Rightarrow \text{ single-harmonic bucket (cf. LLRF functions in appendix) } \]
PSB: Simulations

Simulations

(a) PSB C575, Gauss. start
(b) PSB C579, after $3.5T_S$
(c) PSB C583, after $6T_S$
(d) PSB C591, filamenting

Measurements

(a) PSB C575
(b) PSB C591

rel. momentum $\delta$

position $z$
PS: Tripple Splitting of Hollow Distribution

Mountain diagram from C1830 to C1890, period of 185 turns

central bunch slightly hollow, others flat

any PS blow-ups before C1900 switched off – otherwise hollow distribution disrupted (cf. PSMD logbook 04.11.)
Conclusion

- hollow bunches release space charge constraints
  (by $\sim 20\%$ (for $\epsilon_y$) even at mediocre quality)
- established *reliable, reproducible* and *minimalistic* hollow bunch creation method (reliable until C16 smoothing)

some interesting aspects:

- convolution approach to extract horizontal $\epsilon_x$ respects non-Gaussian longitudinal distribution
  ($25-35\%$ difference to usual Gaussian formula!)
- triple splitting of hollow bunches
- PSB: C16 blow-up and synchro. to PS need improvement
Thank you for your attention!

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special thanks to PSB / CPS OP teams for their support and kind patience!! ;-}
Different Intensities for Set-ups

PSB injection optimised for Gaussian set-up, missing for hollow set-up, same number of injected turns (2.6) lead to

\[ N_{\text{Gauss}} = (1.835 \pm 0.034) \times 10^{12} \quad \text{vs.} \]
\[ N_{\text{hollow}} = (1.661 \pm 0.053) \times 10^{12} \]

→ need to pay attention for intensity dependent plots!
→ easily correctable in follow-up experiments
Results from Bunch Length Scan II

hollow bunches feature less blow-up for given $N, \epsilon_{x,y}, B_L$
Results from Bunch Length Scan III

\[ \Delta Q_{SC}^x \] for longit. Gauss

\[ \Delta Q_{SC}^y \] for longit. Gauss

\[ \epsilon_x \] @C1350 [umrad]

\[ \epsilon_y \] @C1350 [umrad]

\[ \Rightarrow \] final core emittance for Gaussian space charge shift formulae (1), (2)

\[ \rightarrow \] compares “as if” we had a Gaussian distribution
Results from Vertical Tune Scan

normalised emittances C185

horizontal

vertical

g. emittance [mm mrad]
horizontal
hollow
gauss

vertical tune $Q_y$

normalised emittances C1350

horizontal

vertical

g. emittance [mm mrad]
horizontal
hollow
gauss

vertical tune $Q_y$
Results from Intensity Scan II

\[ \begin{array}{c}
\text{intensity}
\end{array} \]

\[ \begin{array}{c}
depletion \text{ factor}
\end{array} \]

\[ \begin{array}{c}
\text{hollow}
\text{ gauss}
\end{array} \]

\[ \Rightarrow \]

less depletion with increasing intensity due to *decoherence suppression* by longitudinal space charge (cf. appendix)

\[ \rightarrow \]
deployment factor: ratio of maximal density by the zero-amplitude density in the bucket centre

(via angle-integrated phase space density along synchrotron amplitude)
synchronisation loop PSB-PS disrupts hollow distribution in LHC setting (left side)

less gain for the phase synchronisation and earlier timing is better (right side), still not optimal

(cf. PSBMD logbook 26.10.)
Figure: Depression of synchrotron tune by space charge. The 2D simulations consider a line density derivative model for longitudinal space charge during 100 synchrotron periods in the PSB ($\eta < 0$). All simulation runs start from the same initial Gaussian distribution. The theoretical formula is based on a parabolic profile and uses the final r.m.s. bunch length from the simulations.

(a) Depression of the linear synchrotron tune $Q_{s,lin}$ with increasing space charge. Note the increasing final bunch length $\sigma_{z,end}$ as the bucket becomes distorted and narrowed, the initial bunch gets more and more mismatched and filaments.

(b) The synchrotron tune depression inflicted by space charge superposes the inherent non-linearities for larger synchrotron amplitudes (in spatial units of $z_{max}$) towards the bucket separatrix. Here, for $\epsilon_{z,100\%} = 1.2\text{eV}\text{s}$, the central constant tune plateau gets enlarged, correspondingly there is almost no tune spread for a larger range of synchrotron amplitudes.
Figure: Tune footprints for both a Gaussian and a hollow distribution in the PS with the same beam characteristics (intensities, transverse emittances etc.)

(a) Gaussian footprint with $\Delta Q_y^{SC} \approx 0.31$.

(b) Hollow footprint for the same parameters.
optimize phase loop gain such that beam phase really follows sinusoidal signal (cf. PSBMD logbook 20.10. and 02.11.)
PSB: Phase Loop Gain Adjustments II

Phase loop gain (PSB)

- Low gain during excitation (after C575)
- High gain during subsequent blow-ups
- Carefully adjusted gain during PS synchronisation (synchro loop can disrupt distribution)
first blow-up (at C600) after excitation increases matched emittance and smooths distribution

second blow-up (at C700) reshapes to flat-topped profile
C16 modulation frequencies of each blow-up adjusted to resonate on different Hamiltonian contours / synchrotron amplitudes (cf. PSBMD logbook 04.11.)
C02 voltage programme (PSB)

C04 voltage programme (PSB)
PSB: Second-harmonic Relative Phase

relative phase C04 to C02 (PSB)

→ copied from MD_LHC25_EmitBlowUp_A to have constant synchrotron frequency across annulus synchrotron amplitudes during C700 blow-up, not followed up further but possibly interesting! (cf. PSBMD logbook 20.10.)