Hollow Bunches for Potential Space Charge Mitigation

Creation of Hollow Bunches in the PSBooster

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Space Charge Collaboration Meeting
May 21, 2014

Acknowledgements: Christian Carli, Heiko Damerau, Simone Gilardoni, Steven Hancock, Kevin Li, Raymond Wasef

Outline

1. Introduction: Space Charge and Hollow Bunches
2. Simulation Results: Creation of Hollow Bunches
   - Insertion of Empty Phase Space
   - Inversion of Phase Space Contours
   - Parametric Dipolar Excitation
3. Conclusions

Space Charge

- aim: relax space charge impact (i.e. tune spread)

Direct Space Charge – Transverse Tune Spread

$$\Delta Q_{x,y}^{\max} = -\frac{r_p \lambda_{\max}}{2\pi\beta^2\gamma^3} \oint ds \frac{\beta_{x,y}(s)}{\sigma_{x,y}(s) \cdot (\sigma_x(s) + \sigma_y(s))}$$

$$\sigma_{x,y}(s) = \sqrt{\epsilon_{x,y} \cdot \beta_{x,y}(s) + (D_{x,y}(s) \cdot \delta)^2}, \qquad \delta \doteq \frac{\delta p}{p_0}$$

- increase energy $\Longrightarrow$ higher β, γ
- flatten line density and reduce $\lambda_{\max}$
- increase beam size σ through either momentum spread or larger dispersion

} *longitudinally hollow bunches*

Situation at CERN Machines

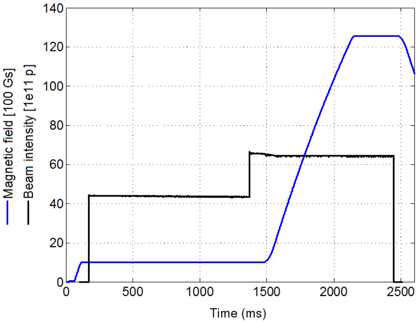

Figure: PS acceleration cycle (LHC type beams)

PS: injection plateau of 1.2 s at $E_{kin} = 1.4\,\text{GeV}$

- presently: $\Delta Q_y^{max} = 0.31$
- future LINAC4: double intensity
  $\Rightarrow \Delta Q_{x,y} \propto N$
  $\rightsquigarrow$ space charge threat

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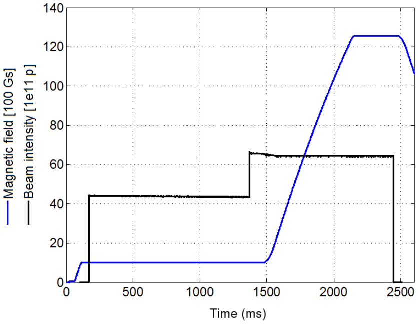

Figure: PS acceleration cycle (LHC type beams)

PS: injection plateau of 1.2 s at $E_{kin} = 1.4$ GeV

- presently: $\Delta Q_y^{max} = 0.31$
- future LINAC4: double intensity
  $\Rightarrow \Delta Q_{x,y} \propto N$
  $\rightsquigarrow$ space charge threat

$\Longrightarrow$ countermeasure: $\Delta Q_y^{max} \propto 1/(\beta\gamma^2)$
increase PSB ejection energy to 2 GeV

$\Longrightarrow$ additional option:
create hollow bunches in PSB and transfer them to PS

How-to on Hollow Bunches

- How to create longitudinally hollow bunches starting from a Gaussian distribution? Several options...

$\longrightarrow$ make use of dual harmonic RF systems

Scalar Potential for Stationary Dual Harmonic RF System

$$U(z) \propto \left[\frac{V_1}{h_1}\cos\left(\frac{h_1 z}{R}+\delta\phi_1\right)+\frac{V_2}{h_2}\cos\left(\frac{h_2 z}{R}+\delta\phi_2\right)\right]$$

$\Longrightarrow$ (adiabatic) manipulation of parameters V_1, V_2, $\delta\phi_1$, $\delta\phi_2$

How-to on Hollow Bunches

- How to create longitudinally hollow bunches starting from a Gaussian distribution? Several options...

⟶ make use of dual harmonic RF systems

- C. Carli suggested two methods in *CERN/PS 2001-073*
  1. insertion of empty phase space into bunch centre
  2. invert phase space distribution: redistribution of phase space contours between bunch centre and periphery

⟹ proof of principle of inversion method 2 in PSB 2001

How-to on Hollow Bunches

- How to create longitudinally hollow bunches starting from a Gaussian distribution? Several options...

$\longrightarrow$ resonant parametric dipolar excitation of bucket phase

Scalar Time-dependent Potential for Dipolar Excitation

$$U(z,t) \propto \cos\left(\frac{hz}{R} + \delta\hat{\phi} \cdot \sin\left(h\,\omega_S t\right)\right)$$

- feasibility in CERN machines investigated by S. Hancock et al. in *CERN/PS 93-18*

$\Longrightarrow$ proof of principle in PS 1993

How-to on Hollow Bunches

- How to create longitudinally hollow bunches starting from a Gaussian distribution? Several options...

$\longrightarrow$ S. Hancock et al. proposed application of a sweeping high harmonic in *CERN/PS 99-36*

$\Longrightarrow$ proof of principle in PS 1998 + acceleration

$\longrightarrow$ phase space painting at H^- injection (LINAC4)

$\longrightarrow$ (...)

General Simulation Parameters

- framework: PyHEADTAIL (development by Kevin Li et al.)

  $\Longrightarrow$ user-friendly port of HEADTAIL to python
- $E_{\text{kin}} = 1.4\,\text{GeV}$, PSB at extraction energy
- $\epsilon_z^{\text{norm}} = 1.2\,\text{eV s}$, initial longitudinal emittance
- $B_L \doteq \frac{4\sigma_z}{\beta c} = 180\,\text{ns}$, initial bunch length
- $V_{\text{rf}} = 8\,\text{kV}$, voltage of fundamental RF system
- $\gamma_{\text{tr}} = 4.05$, operation below transition
- $Q_S = 2.548 \times 10^{-4}$, synchroton period ~ 4000 turns

$\Longrightarrow$ no longitudinal space charge effects included yet

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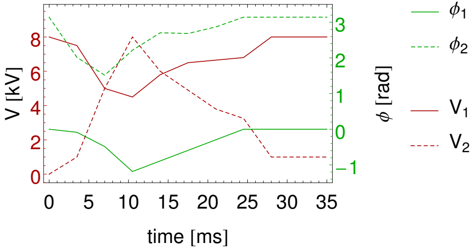
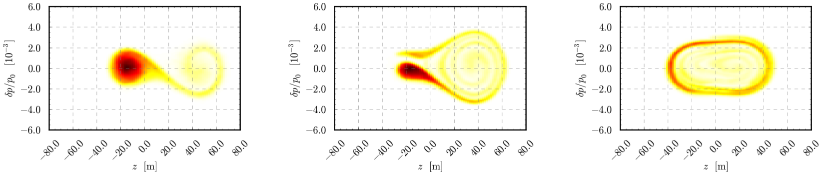
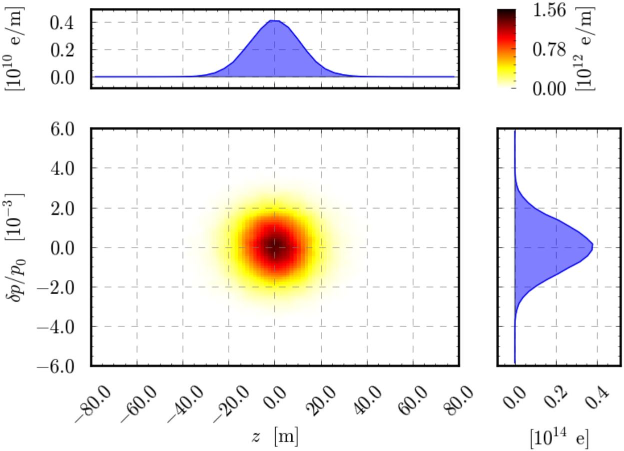
Scheme 1 Parameters

- 70'000 turns, i.e. 35 ms (1 turn $\widehat{=}$ 0.5 μm)

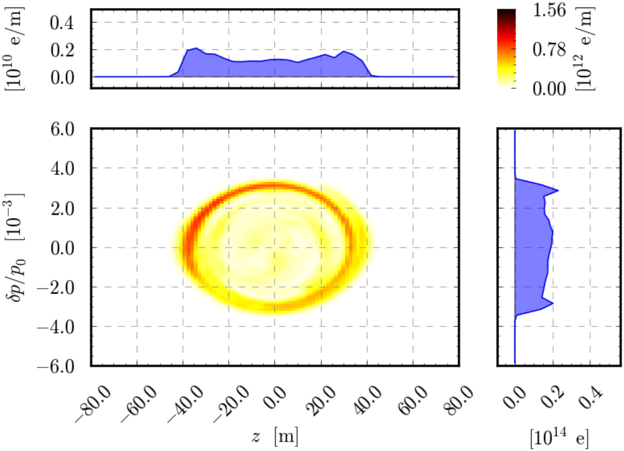




Scheme 1 Results

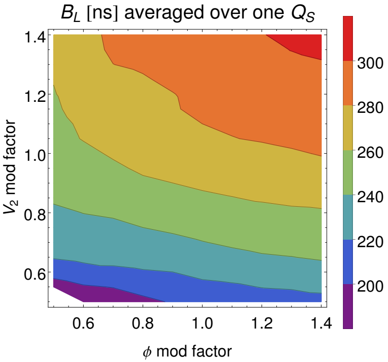


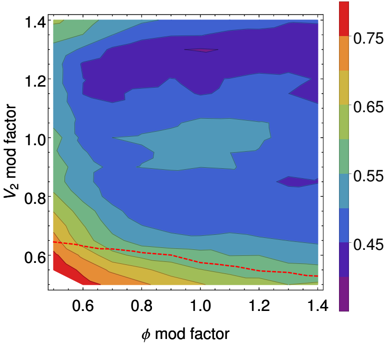
Scheme 1 Results



Scheme 1 Parameter Scan

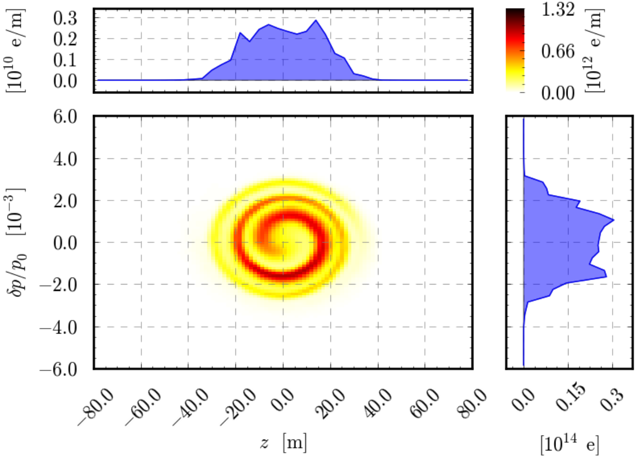
- bunch length B_L gets quite large $\Longrightarrow$ parameter scan
- scan second harmonic voltage V_2 and relative phase ϕ_{12}
- optimise for depression resp. gain factor $\lambda_{\max}^{\text{flat}}/\lambda_{\max}^{\text{gauss}}$





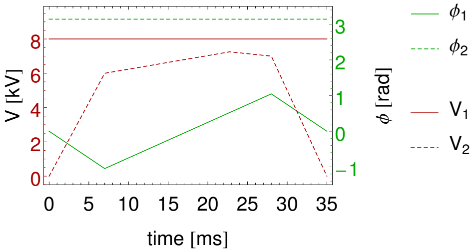
Scheme 1 optimum B_L

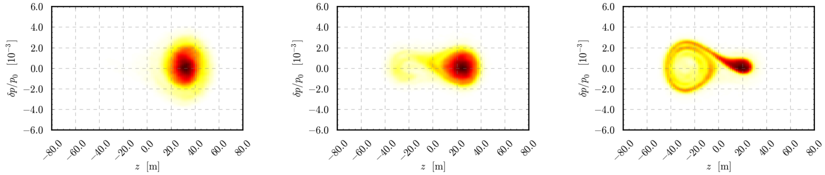
- choose V_2 reduced by 0.5 (leave ϕ_{12}) $\Longrightarrow$ $B_L \approx 60\,\mathrm{m}$ (220 ns)



Scheme 2 Parameters

- 70'000 turns, i.e. 35 ms (1 turn $\widehat{=}$ 0.5 µm)





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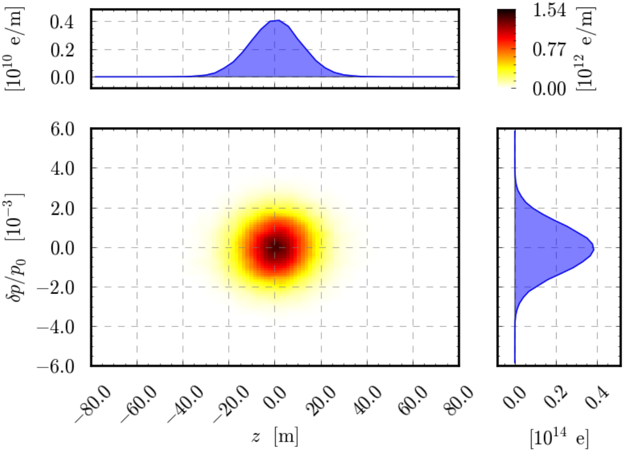

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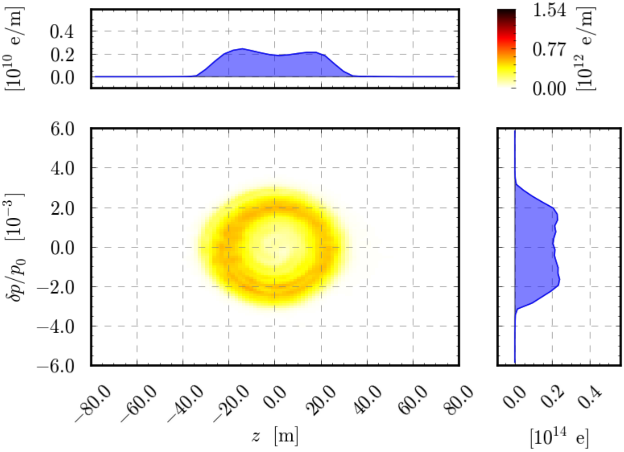
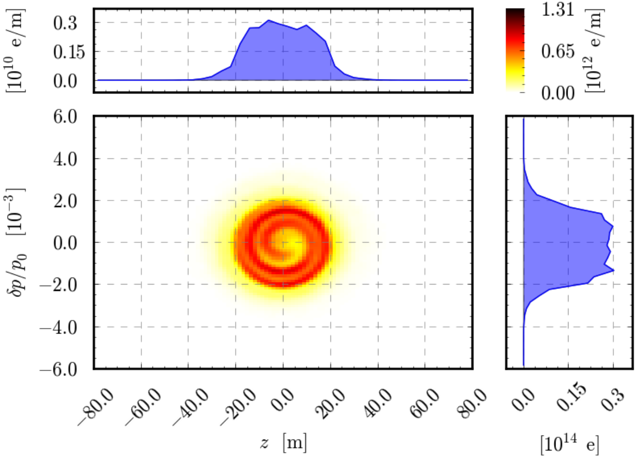


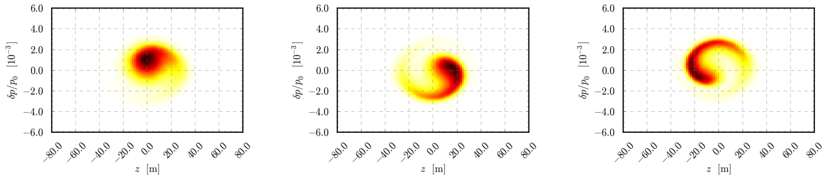
Scheme 2 optimum B_L

- choose V_2 reduced by 0.76 (leave ϕ_{12}) $\Longrightarrow B_L \approx 60\,\text{m}$ (220 ns)



Scheme 3 Parameters

- shake bucket phase with synchroton frequency ω_S of outer particles ($\sim 0.98\,\omega_{S,\mathrm{linear}}$) for n_{shakes} synchroton periods

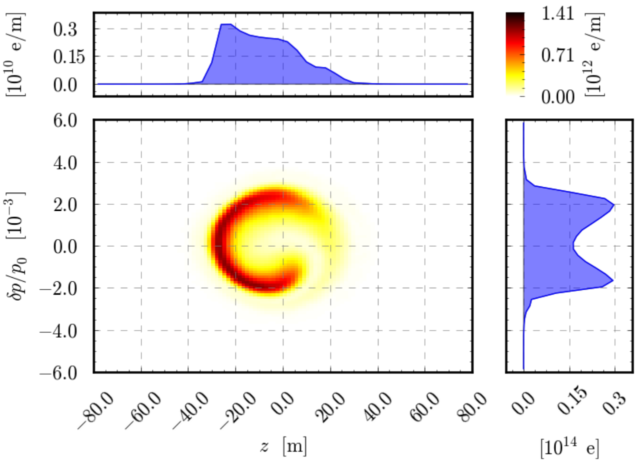


- scan shaking amplitudes $\delta\hat{\phi}$ and shaking periods n_{shakes}
  $\Longrightarrow$ optimum distributions featuring $B_L < 60\,\mathrm{m}$ (220 ns)

$\delta\hat{\phi}$ $[\sigma_z]$	0.5	0.15	0.125	0.1	0.075	0.05	0.025
n_{shakes} $[2\pi/\omega_S]$	5	6	7	9	11	15	25

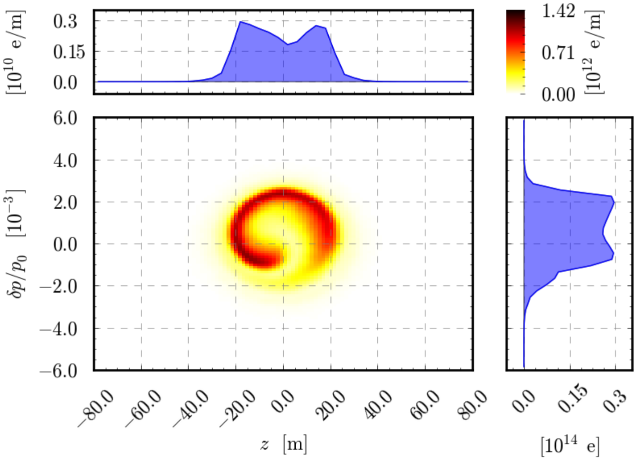
Scheme 3 Results I

- $\delta\hat{\phi} = 0.05$ and $n_{\text{shakes}} = 15$ yields $B_L \approx 60\,\text{m}$



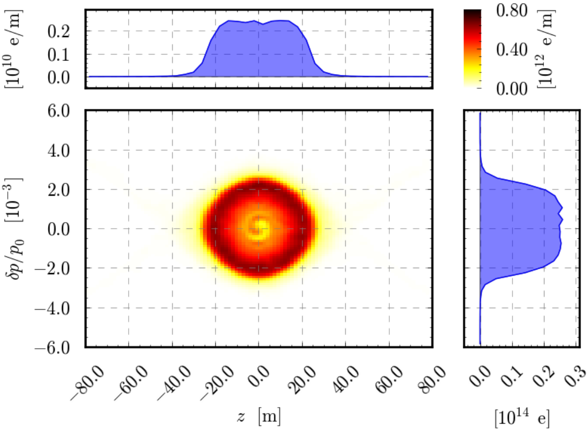
Scheme 3 Results I

- $\delta\hat{\phi} = 0.025$ and $n_{\text{shakes}} = 25$ yields $B_L \approx 55\,\text{m}$



Scheme 3 Results II

- evolution of longitudinal phase space in **PS** after 100 ms for scheme 3 with $\delta\hat{\phi} = 0.025$ and $n_{\text{shakes}} = 25$



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Tune Footprints in PS

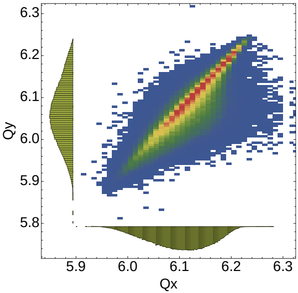

Figure: Gaussian distribution ($B_L = 180\,\text{ns}$)

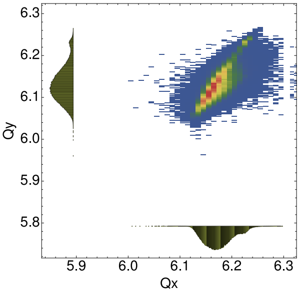

Figure: hollow distribution (parametric excitation method)

$\Longrightarrow$ $\Delta Q_{x,y}^{\text{max}}$ reduced by up to 45% w.r.t. $B_L^{\text{gauss}} = 180\,\text{ns}$ (or 35% w.r.t. $B_L^{\text{gauss}} = 220\,\text{ns}$)

plots: thanks to R. Wasef

Comparison

	scheme 1	scheme 2	scheme 3
V_2 mod factor	0.5	0.76	n.a.
gain $\lambda_{\text{max}}^{\text{flat}} / \lambda_{\text{max}}^{\text{gauss}}$ (w.r.t. $B_L^{\text{gauss}} = 220\,\text{ns}$)	$\approx 80\%$	$\approx 90\%$	$\approx 75\%$

- scheme 1 very sensitive to slight changes in trim functions
- scheme 2 has been successfully tested in PSB by C. Carli

  $\Longrightarrow$ not feasible during acceleration (phase lock of RF systems)
- scheme 3 has been successfully tested in PS by S. Hancock

  $\Longrightarrow$ in principle feasible during acceleration
- hollow bunches have never been used operationally at CERN!

Perspectives

simulation projects:

- explore feasibility of parametric excitation method during acceleration in PSB
- investigate smoothing of excited bunch (scheme 3) by sweeping high-frequency modulation
- implement longitudinal space charge and study impact
- study behaviour during later RF gymnastics

experimental projects:

- hollow bunches scheduled for MDs in autumn 2014

Thank you for your attention!

Any comments, suggestions, objections?

Please write to me: oeftiger@cern.ch