Hollow Bunches for Space Charge Mitigation

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Motivation

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In the context of **strong space charge regime** with **LHC Injectors Upgrade** (LIU) beam parameters: mitigate detrimental space charge impact due to integer resonance at PS injection plateau

Content of this talk:

1. proof of principle (2015)
   - establish hollow bunch production procedure
   - SC mitigation with hollow bunches
2. recent advances for reliable production (2016)

Situation at PS

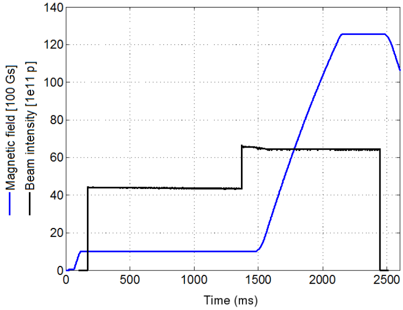

Figure: (old) PS cycle structure

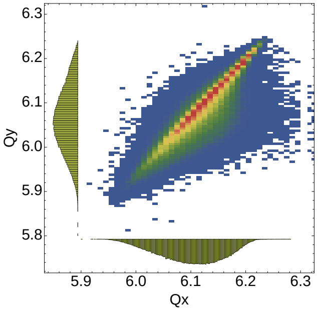

Figure: Gaussian footprint with $\Delta Q_y^{SC} \approx 0.31$.

- LHC-type beams: 1.2 s injection plateau in PS waiting for 2nd batch
- LIU upgrade: 2× higher N, same $\epsilon_{x,y}$

$\Longrightarrow$ higher space charge (SC) tune spread

$\longrightarrow$ resonances: upper limit $8Q_y = 50$ vs. lower limit $Q_y = 6$

How-To: Mitigate Space Charge

detuning from transverse direct space charge

$$\Delta Q_{x,y}(z) = -\frac{r_p \lambda(z)}{2\pi\beta^2\gamma^3} \oint ds \frac{\beta_{x,y}(s)}{\sigma_{x,y}(s)\left(\sigma_x(s)+\sigma_y(s)\right)} \quad (1)$$

with beam sizes

$$\sigma_x(s) = \sqrt{\beta_x(s)\frac{\epsilon_x}{\beta\gamma} + D_x(s)^2 {\delta_{\mathrm{rms}}}^2}, \quad \sigma_y(s) = \sqrt{\beta_y(s)\frac{\epsilon_y}{\beta\gamma}} \quad (2)$$

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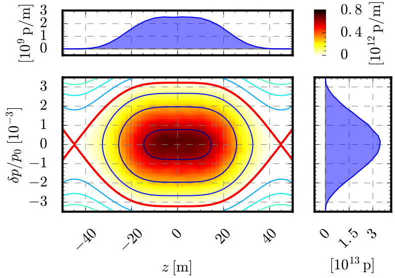
- line charge density depression $\lambda_{max} \sim \lambda(z_{centre})$
- enlarging momentum spread δ_{rms}

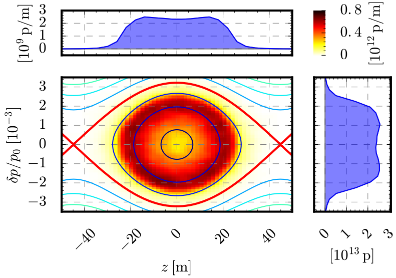
mitigate space charge via *flat beam profile*:

1. standard approach: double harmonic RF systems
2. novel approach: hollow phase space distribution

1. double-harmonic RF bucket



2. hollow distribution



Hollow Bunches

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1. double-harmonic RF bucket

– additional RF systems

– precise phase alignment across machines

2. hollow distribution

+ single-harmonic RF

– creation reportedly often suffers from instabilities

Hollow Bunches

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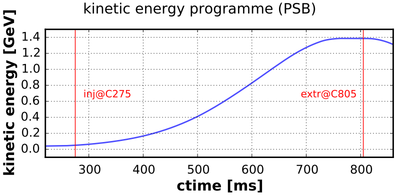
1. double-harmonic RF bucket

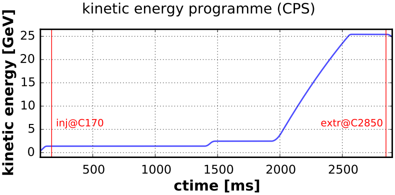
- − additional RF systems
- − precise phase alignment across machines
- + lower λ_{max}

2. hollow distribution

- + single-harmonic RF
- − creation reportedly often suffers from instabilities
- + lower λ_{max}
- + larger momentum spread δ_{rms}
- ⇒ larger horizontal beam size $\sigma_x = \sqrt{\beta_x \epsilon_x / (\beta\gamma) + D_x^2 \delta_{\text{rms}}^2}$

Creation in CERN's PS Booster (PSB)





Strategy:

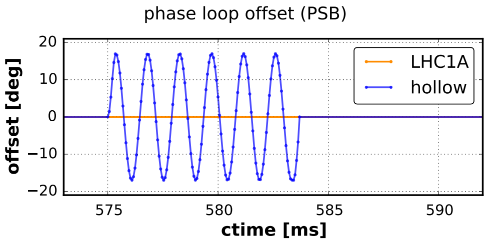
1. start from usual LHC beam production cycle
2. add hollowing process during PSB ramp
   - ⟶ enables creation without instabilities!
   - ⟶ solidly reproducible results!
3. excite **dipolar parametric resonance** to deplete distribution
4. transfer hollow bunches to PS

$\Longrightarrow$ mitigate space charge during PS injection plateau

Method: Excitation of Parametric Resonance

Exploit phase feedback loop to make bucket phase reference oscillate:

$$\phi_{ref}(t) = \phi_s + \underbrace{\hat{\phi}_{drive}\sin(\omega_{drive}t)}_{\text{driven oscillation}} \tag{3}$$

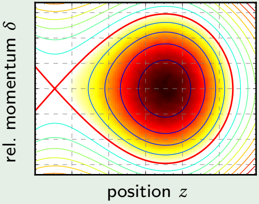


- parametric resonance: $m\omega_{drive} \stackrel{!}{=} n\omega_{s,0}$

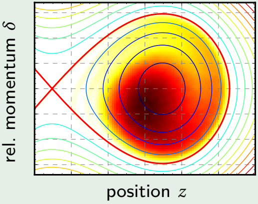
⟶ excite $m = 1, n = 1$ dipolar resonance $\Longrightarrow$ only one filament

⟶ use $\omega_{drive} \approx 0.9\,\omega_{s,0}$ to excite slightly outside centre,
RF bucket non-linearity + space charge $\Longrightarrow \omega_s = \omega_s(J_{long.})$

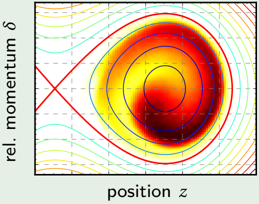
PyHEADTAIL Simulations Incl. Space Charge



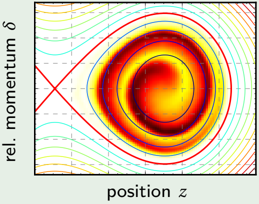
(a) start from Gaussian



(b) excitation for $3.5T_S$

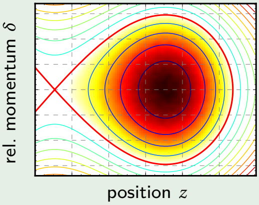


(c) after $6T_S$ excitation



(d) filamenting

PyHEADTAIL Simulations Incl. Space Charge



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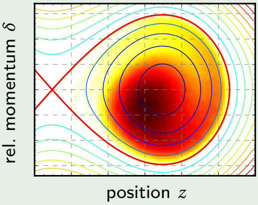

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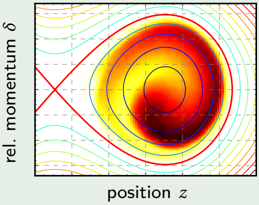

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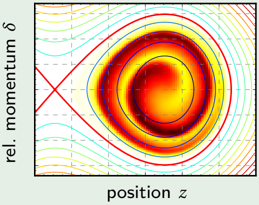

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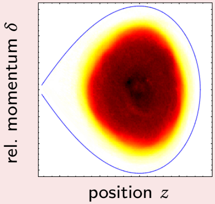
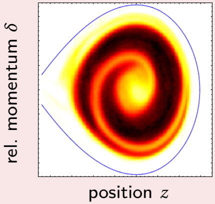
PSB Measurements

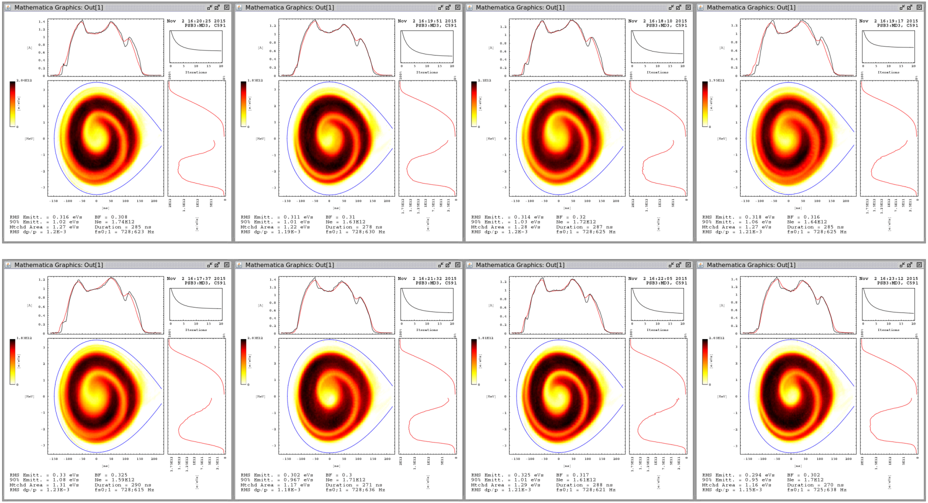


(a) start from Gauss.



(b) filamenting

Some consecutive shots:



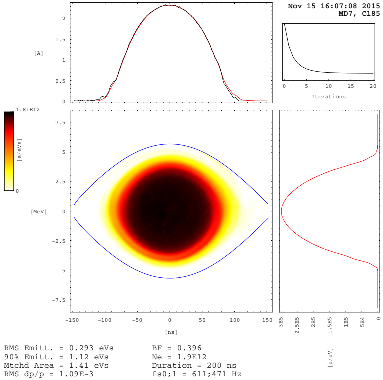
PS Experiment Overview

⟶ single bunch (ring 3), `LHC25` type, minimalistic changes

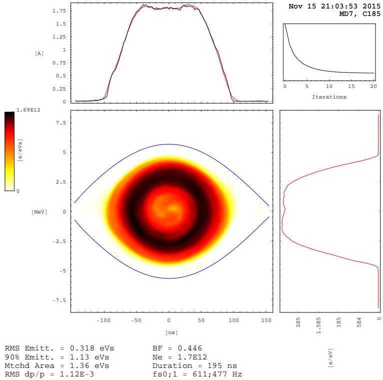
parameter	symbol	value
long. 100% emittance hollow	$\epsilon_{z,100\%}$	$1.43 \pm 0.15\,\mathrm{eV\,s}$
long. 100% emittance Gauss	$\epsilon_{z,100\%}$	$1.47 \pm 0.11\,\mathrm{eV\,s}$
PSB horizontal r.m.s. emittance	ϵ_x	$\approx 2.23\,\mathrm{mm\,mrad}$
PSB vertical r.m.s. emittance	ϵ_y	$\approx 2.12\,\mathrm{mm\,mrad}$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

Table: relevant PS beam specifications at injection.

heavily flattened parabolic ("Gauss")



hollow

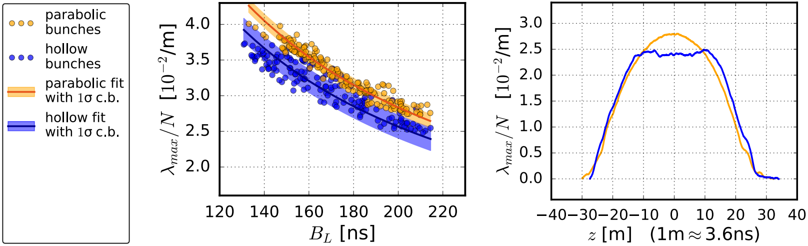


- same longitudinal matched 100% emittances (equal B_L)

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

Transfer to PS: Bunch Length Scan

scan bunch length B_L to vary space charge $\Delta Q_{x,y} \propto \lambda_{\max} \propto 1/B_L$:
compare hollow to standard parabolic (Gaussian-type) bunches



- maximal bunch length restricted by PSB recombination kicker window (PSB has 4 rings whose $h = 1$ bunches need to be enchained for PS)

$\Longrightarrow$ **reduce** maximal line density by factor $\mathbf{0.9}$ for hollow bunches (unrealistic rectangular extreme case gives factor $\sqrt{2\pi}/4 \approx 0.63$)

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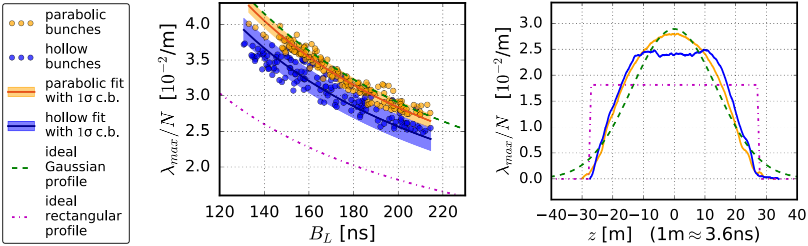

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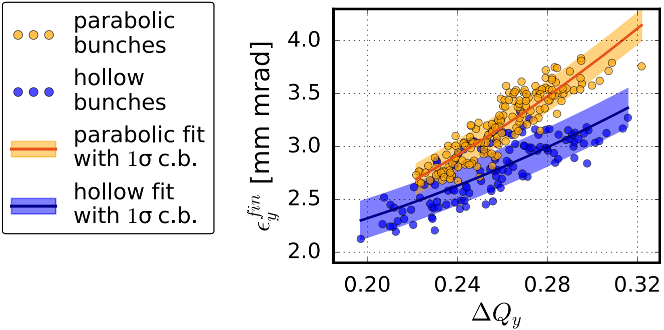


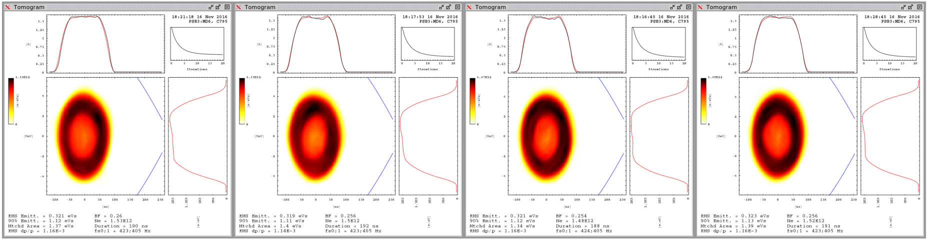
- high vertical SC tune spreads lead to blow-up from integer resonance

⟹ final core emittance for *reference* Gaussian space charge shift (computed using injection values for each shot in formulae (1), (2))

⟶ read this plot as "to what extent does the longitudinal distribution **improve PS transmission** compared to a Gaussian distribution?"

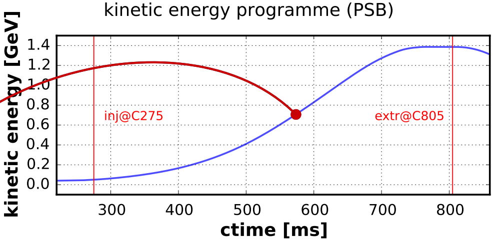
2016 Results: “Nominal-like” Hollow Bunches

Produced hollow bunches with longitudinal matched area of ~1.4 eVs at ~0.32 eVs RMS emittance (nominal 0.25 eVs):

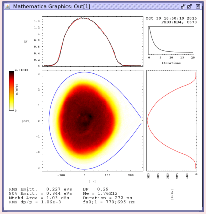


minimalistic changes to operational LHC cycle

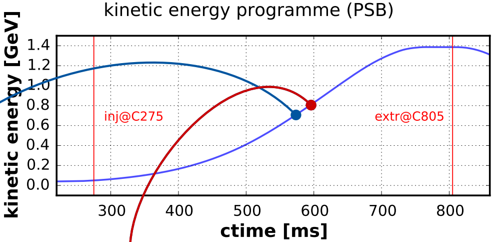
1. adiabatic change from $h = 2$ to $h = 1$ (after nominal C16 blow-up)
2. sinusoidal phase loop offset excites **dipolar parametric resonance**
3. second C16 blow-up to flatten / smoothen phase space distribution



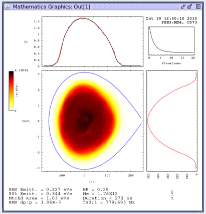
PSB C573



before excitation

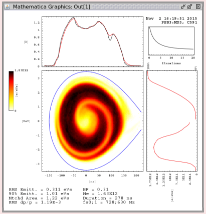


PSB C573

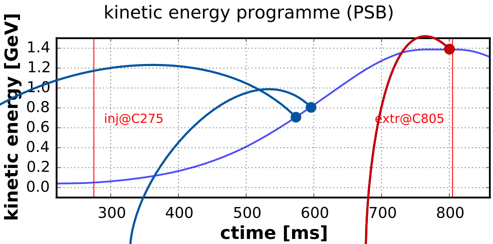


before excitation

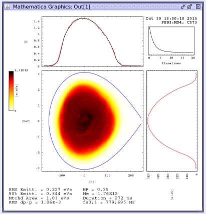
PSB C591



after excitation

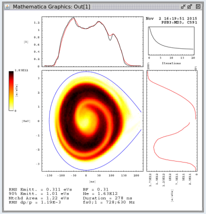


PSB C573



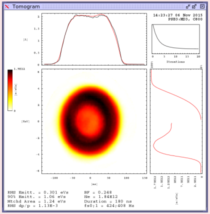
before excitation

PSB C591



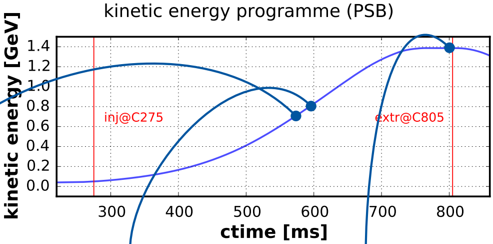
after excitation

PSB C800

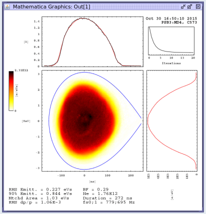


after synchro,
before extraction

Tomograms Over Process

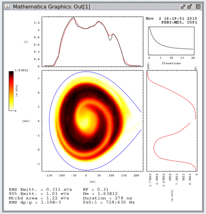


PSB C573



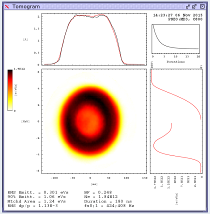
before excitation

PSB C591



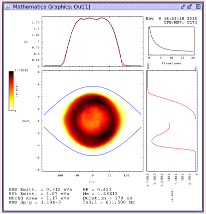
after excitation

PSB C800



after synchro, before extraction

CPS C171



after transfer

2016 Results: Large Emittance Hollow Bunches

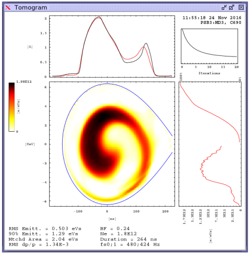
How to achieve large longitudinal emittances (towards LIU goal 3 eVs)?

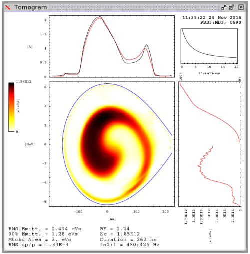
- later times in PSB cycle: more available RF bucket area

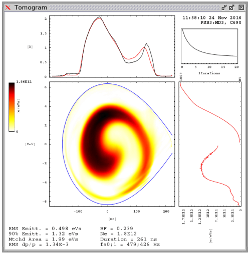
$$\left(\frac{\Delta E}{E_0}\right)_{\max} \propto \frac{1}{\sqrt{-\eta}} \quad \text{for} \quad \phi_s = \text{const} \quad \text{and} \quad \eta < 0 \rightarrow \text{increasing} \qquad (4)$$

⟶ move parametric resonance from C575 to C675 (extraction: C805)

⟹ easily obtain 0.5 eVs RMS longitudinal emittance (2 eVs matched area) after excitation (double RMS emittance compared to nominal)







Summary and Outlook

We have seen

- hollow bunches mitigating space charge impact of integer resonance
  - ⟶ lower ϵ_y transmitted through PS injection plateau (compared to nominal parabolic bunches) for same injected $\epsilon_{x,y}$, N and B_L
- continuous and reliable hollow bunch production possible

Next steps:

- PSB: finalise large ϵ_z hollow bunches (towards LIU goal)
  - ⟶ improve resonance excitation to even larger synchrotron amplitudes
  - ⟶ investigate high-harmonic phase modulation settings for smoothing
- PS: space charge study
  - now much cleaner hollow bunch production: narrower error bars
  - ⟶ more accurate figure of improvement over parabolic bunches
  - ⟹ demonstrate **higher intensity reach** at same extracted emittance

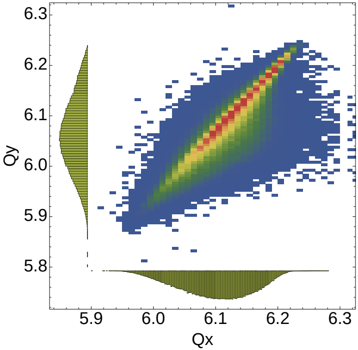
Thank you for your attention!

Acknowledgements:
Maria-Elena Angoletta, Hannes Bartosik, Michael Betz, Christian Carli, Heiko Damerau, Alan Findlay, Simone Gilardoni, Cedric Hernalsteens, Alexander Huschauer, Michael Jaussi, Kevin Li, Giovanni Rumolo, Guido Sterbini, Raymond Wasef

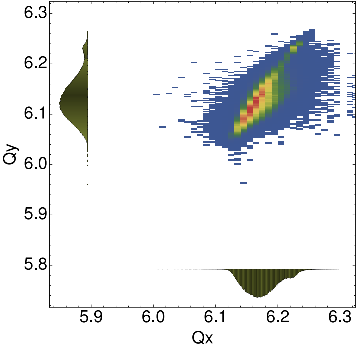
special thanks to PSB / CPS OP teams for their support and kind patience!! ;-)

Space Charge Tune Spreads

Figure: Tune footprints for both a Gaussian and a hollow distribution in the PS with the same beam characteristics (intensities, transverse emittances etc.)

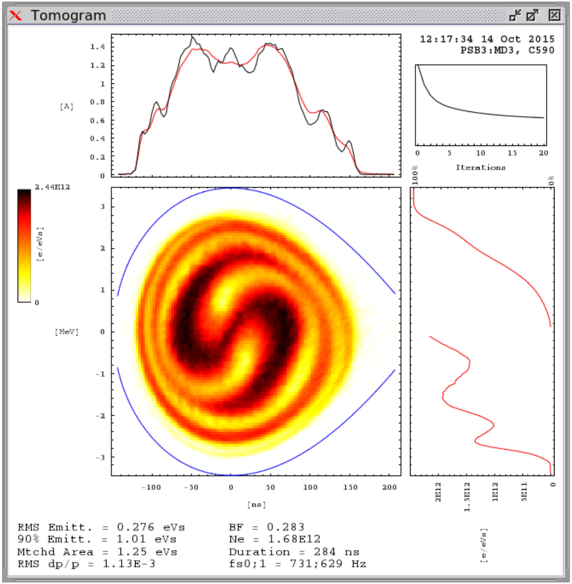


(a) Gaussian footprint with $\Delta Q_y^{SC} \approx 0.31$.

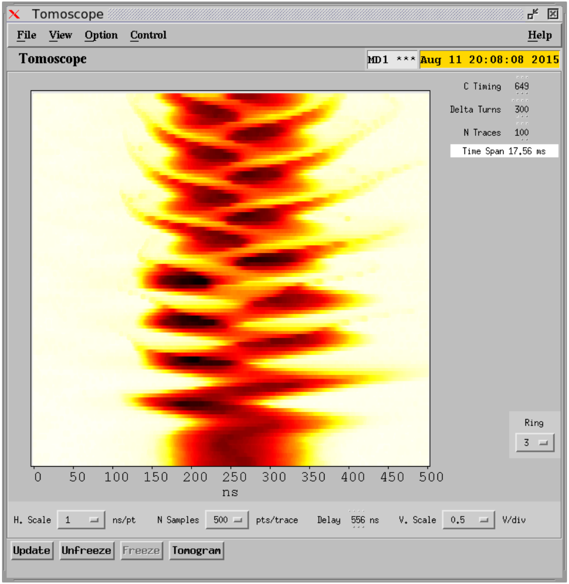


(b) Hollow footprint for the same parameters.

1 : 2 Parametric Resonance Creates 2 Filaments

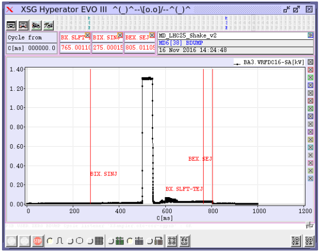


Waterfall Plot During 1:1 Parametric Resonance



Lessons Learned

1. as we need consecutive C16 blow-ups: make C16 transparent in between active times via non-integer harmonic values (e.g. $h = 9.5$) to minimise induced voltage (Alan Findlay)



2. need to minimise cross-dependency of radial and phase loop feedback systems (to cleanly excite dipolar resonance):
   - ⟶ bad idea: switching off radial loop entirely during hollowing procedure (⇒ persistent beam loss afterwards)
   - ⟶ per default, PSB radial loop at unnecessarily strong gain
   - ⟶ low radial loop gain allows to reliably excite to 0.5 eVs RMS emittance
   - ⟶ on top, low biquad corrector gain for (i.) weaker immediate radial loop reaction and (ii.) overall less noisy radial position

Horizontal Emittance Determination

- assume betatron distribution f_β to be Gaussian
- get momentum distribution f_δ 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_{disp} to fit wire scan

$\Longrightarrow$ find Gaussian σ_{x_β} in least squares approach

sum of independent random variables

$$x = x_\beta + D_x\delta \quad \overset{x_\beta,\delta \text{ indep.}}{\Longrightarrow} \quad f_x(x) = \underbrace{\int dx' \; f_\beta(x') f_{\text{disp}}(x - x')}_{\text{convolution of profiles}}$$

$f_x \rightarrow$ wire scan profile, $\quad f_{\text{disp}} \rightarrow$ dispersive distribution

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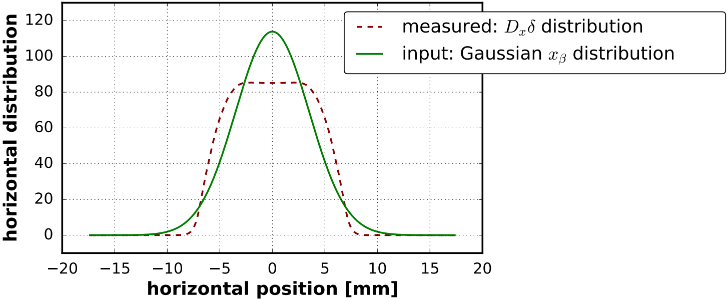

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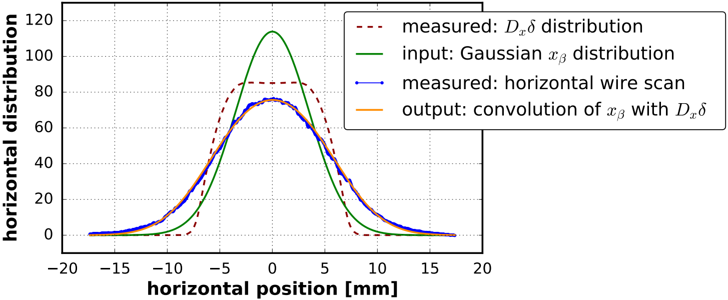
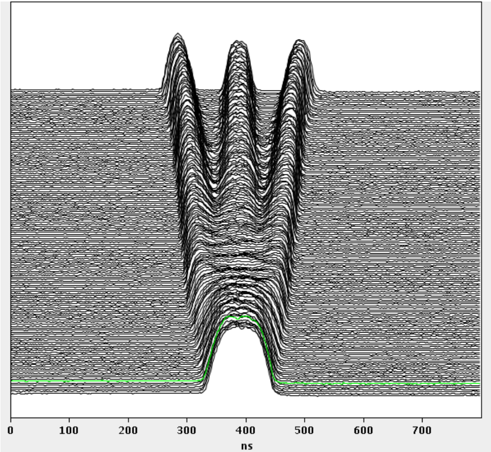
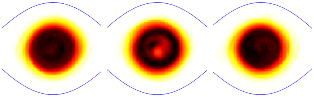


PS: Tripple Splitting of Hollow Distribution





central bunch slightly hollow, others flat

Mountain diagram from C1830 to C1890, period of 185 turns

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