

HOLLOW BUNCHES PRODUCTION

S. Hancock, A. Oeftiger

Abstract

Hollow bunches address the issue of high-brightness beams suffering from transverse emittance growth in a strong space charge regime. During the Proton Synchrotron (PS) injection plateau, the negative space charge tune shift can push the beam onto the $Q_y = 6$ integer resonance. Modifying the longitudinal bunch profile in order to reduce the peak line charge density alleviates the detrimental impact of space charge. To this end we first produce longitudinally hollow phase space distributions in the PS Booster by exciting a parametric resonance with the phase loop feedback system. These inherently flat bunches are then transferred to the PS, where the beam becomes less prone to the emittance growth caused by the integer resonance.

During the late 2016 machine development sessions in the PS Booster we profited from solved issues from 2015 and managed to reliably extract hollow bunches of 1.3 eV s matched longitudinal area. Furthermore, first results to create hollow bunches with larger longitudinal emittances towards the LHC Injector Upgrade project goals proved successful. Here, we present the ingredients to the established hollow bunch procedure, showing the few involved changes to the PS Booster cycle for nominal LHC beam production. We also discuss challenges related to the competing phase loop and radial loop feedback systems: their mutual responses can effectively inhibit the excitation of the parametric resonance which should deplete the core of the initially parabolic bunches.

INTRODUCTION

The impact of transverse space charge can be mitigated by flattening the usually parabolic longitudinal bunch profile. Consequently, the peak beam self-field around the longitudinal peak line density decreases. The direct space charge tune spread for bunched beams can thus be reduced, which helps to find good machine tunes minimising the interaction with betatron resonances. The latter can result in transverse emittance growth as well as beam losses, which is detrimental to beam quality. The most common approach to achieve a flat bunch profile is to use a second RF system in bunch lengthening mode.

In view of the LHC Injectors Upgrade (LIU), the intensity of the nominal Large Hadron Collider (LHC) beams is to be increased twice while keeping the same transverse emittances [1]. These high-brightness beams are expected to encounter a strong space charge regime during the Proton Synchrotron (PS) injection plateau. Transverse space charge inflicts a negative tune shift on the beam, which in the case of the PS can shift the beam into the vertical integer betatron resonance stop-band $Q_y = 6$. At the same time, the PS structure resonance $8Q_y = 50$ puts an upper limit to the bare machine tune in this tune diagram quadrant: peri-

odic trapping of halo particles [2] leads to intolerable beam losses [3]. Thus, the machine tune should remain slightly below $Q_y = 6.25$ while emittance growth due to the integer stop-band needs to be minimised. Hollow Bunches provide a solution to this problem by shrinking the overall space charge tune spread at PS injection.

This paper summarises the current status of MDs 210 and 211. Section I explains the theoretical considerations behind hollow bunches. In section II we outline the 2015 proof of concept experiments: (i.) production of $\epsilon_{z,100\%} \approx 1.3$ eV s hollow bunches in the PS Booster with a minimalistic set of changes to the presently operational nominal LHC beam production scheme and (ii.) first experimental quantification of the improved emittance preservation in the PS. Section III then reports on the 2016 advances on the study with improved reproducibility of the delivered hollow bunches in terms of longitudinal parameters, since some machine issues found in 2015 have been resolved in the meantime. First results to produce larger hollow bunches towards the $\epsilon_{z,100\%} = 3$ eV s LIU goal are reviewed. Section IV finally discusses the necessary ingredients to reach this goal, in particular how to avoid beam-induced voltage in the high frequency RF cavities as well as the mutual response of the radial and phase loop feedback systems which may affect the longitudinal parametric resonance excitation to create hollow bunches.

I. THEORETICAL CONSIDERATIONS

The transverse incoherent space charge tune spread along a transversely Gaussian distributed bunch reads

$$\Delta Q_u^{\text{SC}}(z) = -\frac{r_p \hat{\lambda}(z)}{2\pi \beta^2 \gamma^3} \oint ds \frac{\beta_u(s)}{\sigma_u(s) (\sigma_x(s) + \sigma_y(s))} \quad (1)$$

with $u = x$ for the horizontal and $u = y$ for the vertical plane. z denotes the longitudinal position with respect to the RF bucket centre, r_p the classic proton radius, q the elementary charge, $\hat{\lambda}(z)$ the line density in m^{-1} , β the beam speed in units of c , γ the relativistic Lorentz factor, s the position around the accelerator, $\beta_{x,y}(s)$ the local betatron functions, and $\sigma_{x,y}(s)$ the local transverse root mean square (RMS) beam sizes. In presence of dispersion $D_x(s) \neq 0$, the momentum distribution contributes to the horizontal beam size,

$$\sigma_x = \sqrt{\beta_x \epsilon_x / (\beta \gamma) + D_x^2 \delta_{\text{RMS}}^2} \quad , \quad (2)$$

where $\epsilon_{x,y}$ denotes the normalised transverse RMS emittances and $\delta_{\text{RMS}} \doteq \langle (p - p_0) / p_0 \rangle$ the RMS momentum deviation.

Since $\Delta Q_{x,y}^{\text{SC}} \propto 1/(\beta \gamma^2)$, it is foreseen to step up the PS injection energy from $E_{\text{kin}} = 1.4$ GeV to 2 GeV as the major measure to mitigate space charge. The total bunch length B ,

already exploits the time window given by the rise time of the PS Booster recombination kicker magnet and cannot be further increased to reduce $\hat{\lambda}_{\max}$. Bunch reshaping is hence a good option to support the raise in injection energy to decrease $\Delta Q_{x,y}^{\text{SC}}$ while fixing $\epsilon_{x,y}$, B_L and intensity N . This is where the concept of hollow bunches comes in, offering a few advantages over usual double-harmonic flattening:

1. By producing an inherently flat longitudinal phase space distribution upstream in the PS Booster, the PS can profit directly starting from injection instead of first having to adiabatically ramp up the double harmonic in bunch lengthening mode. Double-harmonic shaped bunches can in principle also be transferred directly. However, this requires precise relative phase alignments of the additional RF systems in both PS Booster and PS to avoid longitudinal mismatch. In contrast, hollow bunches can be transferred in a single-harmonic RF bucket between the machines without further adaptation.
2. The unused second harmonic voltage is available for bunch shortening instead which hence allows for larger longitudinal emittances at the same B_L . NB: the LIU goal is to reach a matched 100 % emittance of $\epsilon_{z,100\%} = 3 \text{ eV s}$ (the present LHC beams feature 1.3 eV s at PS injection).
3. In addition to reducing $\hat{\lambda}_{\max}$, hollow bunches feature a larger momentum spread δ_{RMS} . Due to Eq. (2) the horizontal beam size enlarges which provides another knob to reduce $\Delta Q_{x,y}^{\text{SC}}$.

Starting from 2015, MD 210 has set up hollow bunch production in the PS Booster and MD 211 has demonstrated the subsequent benefit in terms of transverse emittance preservation throughout the PS injection plateau. The present approach to create hollow phase space distributions goes back to an idea of Ref. [4]. The idea is to deliberately excite a longitudinal *dipolar parametric resonance*. For this purpose the phase loop feedback system can be used, which aligns the RF reference phase ϕ_{RF} with the longitudinal centre-of-gravity of the bunch. The dipole mode of the longitudinal parametric resonance can be excited by phase modulation [5]. The initially parabolic bunch has its centre depleted as the core particles are excited to higher synchrotron amplitudes during a few synchrotron periods. We modulate the phase loop offset around the synchronous phase ϕ_s :

$$\phi_{\text{RF}}(t) = \phi_s + \hat{\phi}_{\text{drive}} \sin(2\pi f_{\text{drive}} t) \quad . \quad (3)$$

To excite the beam core, the driving frequency needs to satisfy the resonance condition

$$mf_{\text{drive}} \approx nf_{s,0} \quad (4)$$

with $f_{s,0}$ denoting the linear synchrotron frequency. In reality, longitudinal space charge will reduce the RF phase focusing below transition. The synchrotron motion in the

RF bucket centre slows down correspondingly, which translates to lower resonant driving frequencies around $f_{\text{drive}} \lesssim 0.95f_{s,0}$ in our case. The integer numbers m and n characterise the $m : n$ parametric resonance, where for us $m = 1, n = 1$ proves to be most useful as only a single filament is excited. This bunchlet wraps around the emptied centre and would filament for a too long time before it effectively forms a smooth ring in phase space, given the time to extraction. The filamentation process can be enhanced by smoothing by high frequency phase modulation to achieve a stationary distribution within the PS Booster cycle, which features the aforementioned lower $\hat{\lambda}_{\max}$ and larger δ_{RMS} . In contrast to many other hollow bunch creation techniques (cf. chapter 5 in Ref. [6] for an overview), our approach can be implemented during the acceleration ramp rendering it a versatile tool to mitigate the impact of transverse space charge.

II. PROOF OF CONCEPT IN 2015

Production of Hollow Bunches

In August 2015, the radial loop feedback system has been used in a first attempt to drive a dipolar longitudinal parametric resonance [7]. The new digital low-level RF (LLRF) system of the PS Booster allowed to program a sinusoidal offset vector in the radial feedback. At this point the phase loop steering system only supported a fixed register value for the phase offset, i.e. exciting the resonance directly with the phase loop was not yet feasible. Nonetheless, one may control the longitudinal phase indirectly via the radial position: in order for the radial loop to steer the radial beam position, the feedback corrects the RF frequency programme. Non-adiabatic changes of the RF frequency affect the beam phase. Therefore, a sinusoidal radial steering at about the synchrotron frequency translates to a sinusoidal phase steering. We used this mechanism to excite the dipolar longitudinal parametric resonance as the waterfall plot in Fig. 1 shows. The bunch centre indeed depleted within a few synchrotron periods, hence demonstrating the conceptual feasibility of producing hollow phase space distributions in this manner.

However, the indirect approach via the radial loop proved to be rather ineffective: the phase loop acted against the excitation and limited the finally reached full longitudinal emittances (the ‘‘matched area’’ in tomoscope terms). For further details on the experiment results with the radial loop we refer the interested reader to Ref. [7]. The close link of radial and phase loop feedback systems and their mutually damping effect should play a role again at a later stage in 2016, as explained below and in section IV.

Later, the phase loop control system was extended to support offset vectors as well. This enabled us to directly program a sinusoidal beam phase steering in order to excite the resonance. In October and November 2015, a procedure was established to create hollow bunches via the dipolar resonance in the PS Booster [6, appendix A]. The goal was to involve a minimalistic set of changes to the conventional LHC nominal beam production scheme in the PS Booster

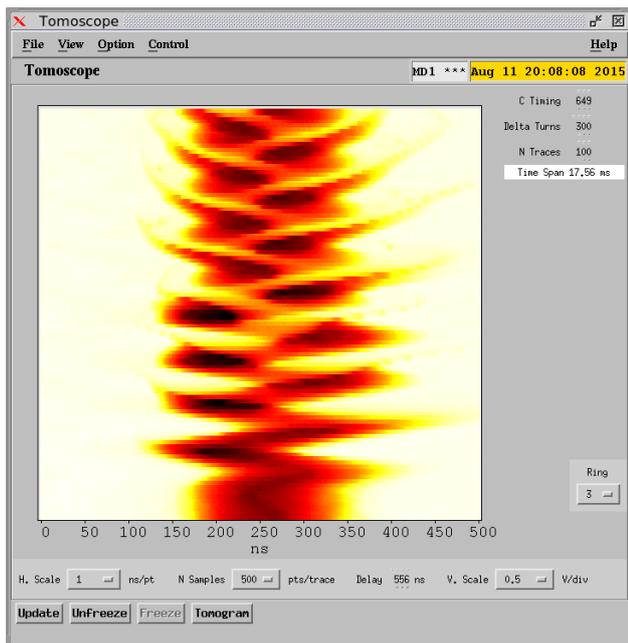


Figure 1: Waterfall view showing the profile evolution of an excited longitudinal phase space distribution. Turns increase towards the top and the colour range from black via red to white indicates decreasing line charge density. The initially parabolic profile in the lower part is excited during four synchrotron periods and then begins to filament in the upper half of the plot (to eventually become a hollow bunch).

in order to ease possible operational implementation. The following changes enabled a continuous delivery of hollow bunches to the PS:

1. adiabatic powering down of the second harmonic RF system C04 to provide single-harmonic parabolic bunches at c-time C575 (the double-harmonic RF bucket is required to reduce transverse space charge impact during the first part of the PS Booster cycle);
2. sinusoidal beam phase steering during 6 synchrotron periods (i.e. 9 ms) to excite bunch core particles to higher synchrotron amplitudes during the dipolar parametric resonance, thus depleting the RF bucket centre;
3. low phase loop gain during the resonance excitation and high gain afterwards; and
4. two further subsequent phases of high frequency phase modulation with the C16 RF systems at $h = 9$ in order to smooth the filamenting phase space distribution.

In contrast to the previous experiment with the radial loop, the phase loop approach provided highly reproducible results at a fixed time instant directly after the parametric resonance. Consecutive shots exhibited the same filamenting phase space distribution at c-time C591. Furthermore, the measured tomograms closely resembled simulations for the exact same time span including the resonance excitation and subsequent filamentation [8, Fig. 3d vs. Fig. 5b].

However, the outcome of the smoothing process varied on a shot-to-shot basis due to the fluctuating effectiveness of the high frequency C16 RF systems (problem 1). Later, during 2016 it has been found that the initial phase of the C16 wave has been randomly distributed for subsequent pulses [9–11]. Varying this initial phase changes the resonance conditions for the phase modulation [12]. Thus, the extracted hollow bunches in 2015 had fluctuating longitudinal parameters in terms of the matched 100 % emittance as well as the RMS emittance (as the finally achieved thickness of the hollow phase space ring varied).

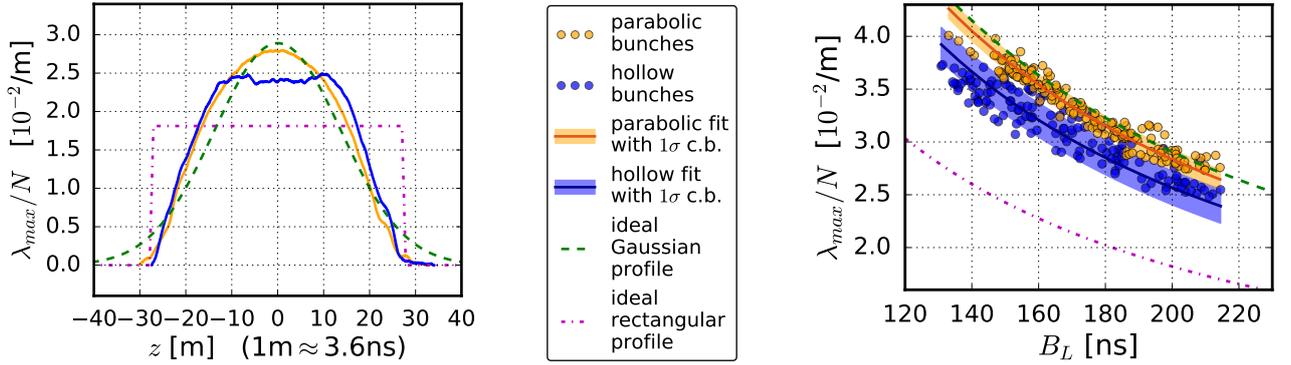
Moreover, hollow bunches proved to be more sensitive to the extraction synchronisation loop action. The synchronisation loop settings (including its gain) at the time have had quite a strong impact on the beam (problem 2). In particular, the sudden RF phase synchronisation disrupted the longitudinal phase space distribution: the centre-of-gravity was relocated, which is much more visible in a hollow distribution than compared to a usual parabolic distribution (although both are affected in the same way). Consequently the filamenting phase space density in the bucket centre increased resulting in non-flat-topped bunch shapes. Weaker synchronisation loop gain (as a first remedy) and a lower phase loop gain improved the situation in 2015 for the time being.

Space Charge Mitigation

Towards the end of beam time in 2015 we injected into the PS hollow bunches created as described above with moderately stable longitudinal parameters. The goal of the experiment was to assess how much hollow bunches improve the transmitted beam quality through the 1.2 s long PS injection plateau of the nominal LHC beam production scheme. We compared the transverse emittance growth of standard parabolic bunches to hollow bunches for given injected $\epsilon_{x,y}$, N and B_L . The results have been thoroughly discussed in Ref. [6, chapter 5] and presented in Refs. [8, 13]. Here we shall briefly outline relevant outcomes of the experiment.

Two measured examples of these bunch shapes are presented in Fig. 2a. A Gaussian and a rectangular bunch profile are plotted as ideal upper and lower limits of the peak line density. A rectangular profile of $4\sigma_z$ length correspondingly allows for a factor $\sqrt{2\pi}/4 \approx 0.63$ smaller $\hat{\lambda}_{\max}$ than the Gaussian profile. NB: a rectangular profile is an extreme case which can only be implemented in a double-harmonic bucket in bunch lengthening mode. In a single-harmonic bucket geometry one necessarily ends up with a finitely inclined flank of the profile. Here, the goal is to receive single-harmonic bunches in the PS, which is why the effective lower limit in the peak line density lies above the rectangular factor 0.63.

In order to vary the space charge strength, we compressed the injected bunches to bunch lengths between $130 \text{ ns} \leq B_L \leq 220 \text{ ns}$. Fig. 2b plots the measured peak line densities of the prepared parabolic and hollow bunches. The 1σ confidence band of the hyperbolic fit of the hollow bunch peak line densities is about twice as wide as in the parabolic case, which comes from the shot-to-shot fluctuating efficiency of



(a) Bunch shape comparison for equal B_L : measured examples and ideal limit cases.

(b) Measured peak line densities over total bunch length (with 1σ confidence bands and limit cases).

Figure 2: Comparison between peak line densities of parabolic and hollow bunches.

the high frequency phase modulation (cf. problem 1). The fits indicate 10 % lower peak line densities for the flat-topped bunches compared to the parabolic ones.

The essential goal is to compare the impact of space charge for both beam types. The vertical space charge detuning is stronger due to the smaller beam size (as $D_y = 0$ while the transverse emittances are the same), which explains why the vertical (and not the horizontal) integer resonance stop-band is the limiting factor. In order to assess the expected improvement of the eventually transmitted transverse emittances, we can refer to the maximal tune spread via Eq. (1) which unifies the initial B_L , N and $\epsilon_{x,y}$ in one quantity. B_L remained constant during the injection plateau and there were only marginal losses (constant N) but $\epsilon_{x,y}$ would grow due to the integer stop-band. To evaluate the reference Gaussian tune spread $\Delta Q_y^{\text{SC}}|_{\text{max,Gauss}}$, we fixed a peak line density of

$$\hat{\lambda}_{\text{max}} = \frac{N}{\sqrt{2\pi}B_L/4} \quad . \quad (5)$$

In reality, the direct space charge tune spread of the hollow bunches is around $0.88 \Delta Q_y^{\text{SC}}|_{\text{max,Gauss}}$ due to the larger momentum spread δ_{RMS} and the lower peak line density λ_{max} . On the contrary, the parabolic bunches are represented quite well by the Gaussian formula with a factor 0.97 lower real tune spread. The Gaussian tune spread therefore serves as a reference to evaluate how much transmission improves by using hollow bunches instead of parabolic bunches.

The measured final vertical emittances at the end of the injection plateau are presented in Fig. 3 along with empirical fits and their 1σ confidence bands. We concluded that for the same injected intensity, transverse emittances and (compressed) bunch length, hollow bunches indeed lead to lower final vertical emittances than parabolic bunches. Thus, hollow bunches provide a viable means to mitigate bunch core emittance growth coming from the integer resonance stop-band.

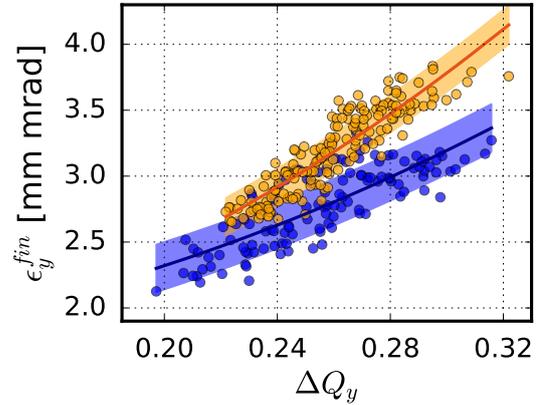


Figure 3: Transmitted vertical emittance at the end of the injection plateau over reference Gaussian space charge tune spread via Eqs. (1), (5) (for the legend cf. Fig. 2).

III. RELIABLE PRODUCTION IN 2016

During the first half of 2016, problem 1 and 2 as described in section II have been solved by the RF team:

1. The phase of the C16 RF systems can be reset to the same value at the start of each pulse (even for changing harmonics, this has been implemented with a new firmware upgrade on June 7), which renders the high frequency phase modulation reproducible.
2. The extraction synchronisation loop (in particular the phase synchronisation) has been optimised to avoid disruption of the longitudinal phase distribution.

This enabled us to reliably extract well-defined longitudinal parameters from the PS Booster: implementing the settings of the previous year stably produced hollow bunches at $\epsilon_{z,100\%} = 1.3 \text{ eV s}$ equivalent to nominal LHC-type beams.

In the following subsection we list the exact changes to the operational LHC1A cycle (at the end of 2016) to obtain these hollow bunches. We continue using ring 3 (implementing

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the concept on all four rings should be straightforward). In a next step we present the $\epsilon_{z,100\%} = 2 \text{ eV s}$ approach.

Optimal Settings for $\epsilon_{z,100\%} = 1.3 \text{ eV s}$

The last beam modification during nominal LHC beam production in the PS Booster cycle is the longitudinal blow-up at c-time C500 by high frequency phase modulation. To this end, the C16 RF systems pulse during 50 ms at a voltage of $V_{C16} = 1.3 \text{ kV}$ at harmonic $h = 9$. The phase modulation uses $\hat{\phi} = 180^\circ$ modulation depth. Furthermore, the modulation frequency follows the decreasing linear synchrotron frequency by $1.75f_{s,0}$ (taking into account only the fundamental voltage of the C02 RF systems).

The starting point for the hollowing is again a single-harmonic RF bucket, i.e., after the longitudinal blow-up at c-time C550 we adiabatically ramp down the C04 RF systems to 0.5 kV during 20 ms. The fundamental C02 RF systems remain at 8 kV throughout the cycle. The initial longitudinal phase space distribution should exhibit as large a central black patch of constant phase space density as possible in the tomogram at c-time C573 directly before the parametric resonance (cf. Fig. 5a). This ensures a well-defined ring in longitudinal phase space afterwards, making the flanks of the flat-topped bunch profile as steep as possible. The above blow-up settings yield a parabolic bunch of $\epsilon_{z,100\%} = 1.1 \text{ eV s}$. At c-time C575, when the resonance excitation starts, the available RF bucket area is 1.8 eV s .

The ingredients to turn the parabolic bunch into a hollow one comprise [14]:

- phase loop gain at 0.4 throughout the cycle;
- 6 synchrotron periods of phase loop excitation starting at c-time C575 and ending 8.7 ms later (cf. Fig. 4) with
 - modulation depth of around $\hat{\phi}_{\text{drive}} \approx 17^\circ$,
 - modulation frequency of $f_{\text{drive}} = 690 \text{ Hz}$,
 - phase loop gain of 0.2 during the excitation; and
- smoothing of the filament with a second 50 ms long C16 pulse of high frequency modulation at c-time C600 with
 - voltage of 1 kV,
 - modulation depth of $\hat{\phi} = 180^\circ$, and
 - modulation frequency of $0.65f_{s,0}$ ($1.35f_{s,0}$ also works).

Fig. 5 presents tomographic reconstructions of the longitudinal phase space at important points during the cycle. The lower right sub-plot (obtained with the “specialist” tomography setting) shows the synchrotron amplitude projection for the phase space distribution in Figs. 5b and 5c. Towards the bucket centre, the phase space density clearly decreases. Especially for the non-stationary filament in Fig. 5b, the synchrotron amplitude projection provides a good tool to optimise for the resulting hollow bunches at the end of the cycle. The final bunch profile in Fig. 5c should feature steep

flanks and a steady flat top. The thickness of the excited filament and the minimal amount of particles left in the bucket centre have to be carefully adjusted to obtain an optimal bunch shape.

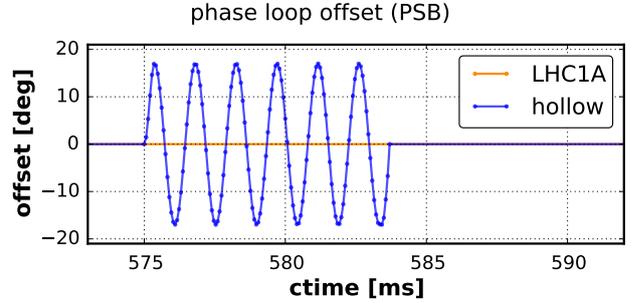


Figure 4: 6 synchrotron periods of phase modulation.

The third smoothing C16 pulse (at C700) from the 2015 set-up is not needed any more, as the blow-up works more reliably now due to the fixed initial relative phase of the C16 to C02. In general we found that, the more concise and well-defined the smoothing, the less the resulting longitudinal parameters seem to fluctuate. Fig. 5d shows an example of a hollow bunch with $\epsilon_{z,100\%} = 1.3 \text{ eV s}$ at c-time C795 10 ms before extraction [15].

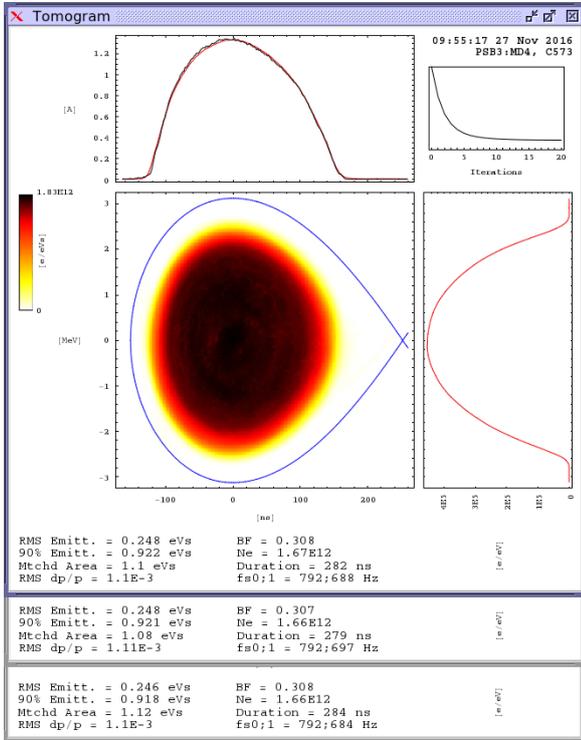
Settings for $\epsilon_{z,100\%} = 2 \text{ eV s}$

The energy acceptance $(\Delta E/E_0)_{\text{max}}$ in an accelerating single-harmonic RF bucket is given by [16, Eq. (65)]:

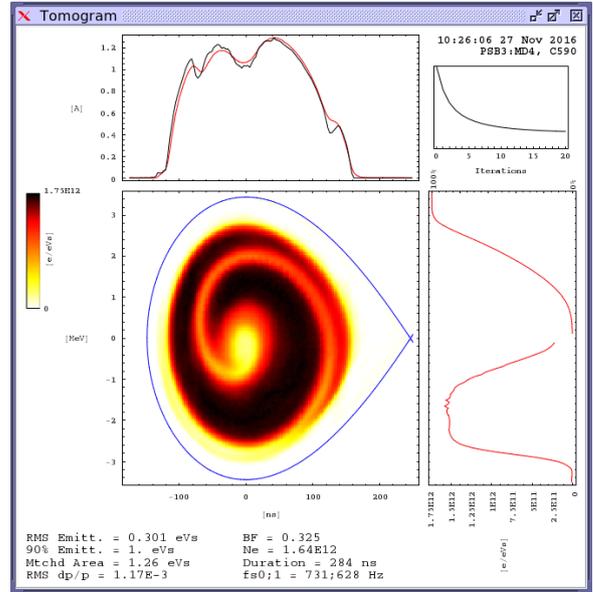
$$\left(\frac{\Delta E}{E_0}\right)_{\text{max}} = \pm \beta \sqrt{-\frac{eV}{\pi h \eta E_0}} \times \sqrt{2 \cos(\phi_s) + (2\phi_s - \pi) \sin(\phi_s)}, \quad (6)$$

where $\eta = \gamma_t^{-2} - \gamma^{-2}$ denotes the slippage factor with the transition energy γ_t and $E_0 = \gamma m_p c^2$ the total beam energy. For a fixed synchronous phase ϕ_s , the energy acceptance hence monotonically increases on the interval $1 \leq \gamma < \gamma_t$. This entails that the RF bucket area grows towards the end of the PS Booster cycle while, at the same time, the already blown-up longitudinal emittance remains constant. Therefore, the larger available RF bucket area at later c-times offers more space for the dipolar parametric resonance to excite the filament to larger synchrotron amplitudes. The achieved hollow bunches after smoothing should thus reach larger longitudinal emittances if the excitation is shifted towards the end of the PS Booster cycle.

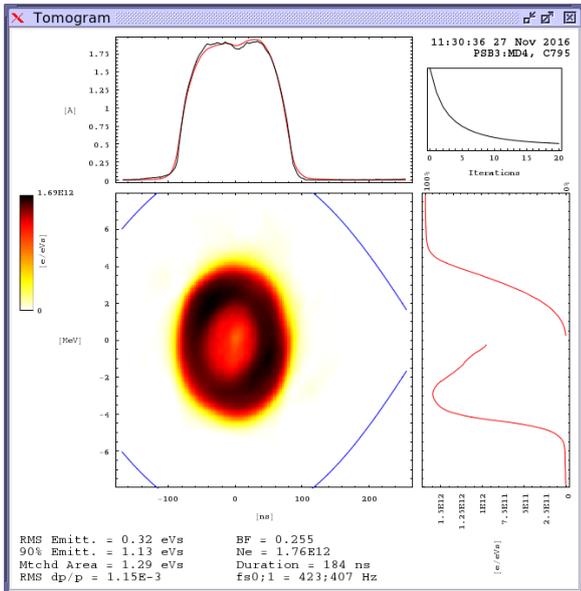
The parametric resonance should be followed by 50 ms of high frequency modulation for smoothing. The latter should finish before the radial loop may move the beam from the fixed radial position at 0 mm to the final -2 mm during some 20 ms before the synchronisation loop sets in. The first step of the synchronisation loop, the frequency steering, starts at c-time C775. Just as a remark, the second step is the phase alignment to the PS, which happens 7 ms to 10 ms after the revolution frequency of the PS Booster has been adapted to



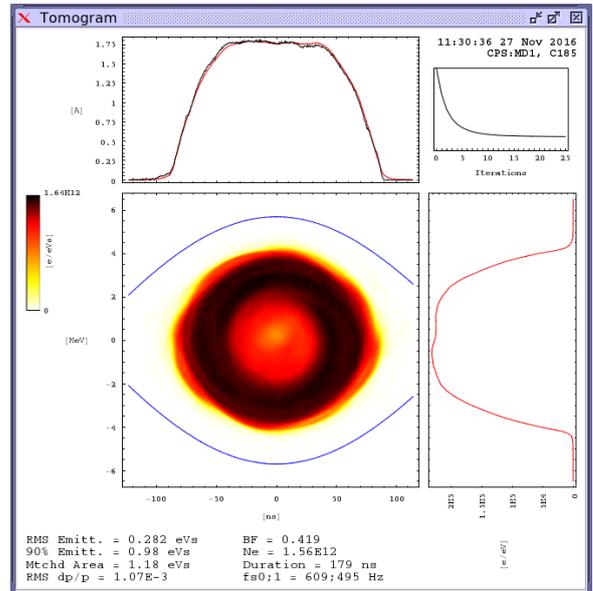
(a) The initial parabolic phase space distribution in a single-harmonic RF bucket at C573.



(b) The filamenting phase space distribution at C590 after 6 synchrotron periods of parametric resonance excitation.



(c) The smoothed final hollow phase space distribution at C795 after subsequent C16 pulses (10 ms to extraction).



(d) The received hollow bunch in the PS at C185 (15 ms after injection).

Figure 5: Snapshots of the longitudinal phase space distribution during creation of hollow bunches with the 2016 set-up.

the PS. Subtracting the 20 ms radial steering and the 50 ms C16 pulse from c-time C775 hence requires the parametric resonance excitation to finish at the latest at c-time C705. To extract larger longitudinal emittance, we also need to set up the second harmonic in bunch shortening mode at the end of the cycle in order to avoid beam loss of too long bunches interfering with the recombination kicker rise time window.

Following the same set-up (canonical blow-up, single-harmonic RF bucket) as for the excitation starting at c-time C575, we have achieved first good results starting at C675: the synchrotron frequency in the single-harmonic RF bucket with $V_{h=1} = 8$ kV amounts to $f_0 = 504$ Hz at this point. It is crucial to remove the interference of the radial loop feedback system (see section IV) to avoid complete suppression of the dipolar resonance excitation. A scan to determine the window of resonant frequencies f_{drive} reveals sharp edges (clearly defined to 1 Hz [17]):

$$408 \text{ Hz} < f_{\text{drive}} < 440 \text{ Hz} \quad . \quad (7)$$

Promising and reproducible first results from the excitation at this late point of the cycle have been achieved with $f_{\text{drive}} = 420$ Hz, $\hat{\phi}_{\text{drive}} = 45$ deg and 5 synchrotron periods duration (i.e. 12 ms) [18]. At the end of the 2016 run we were hence in a position to produce excited filaments at 0.5 eV s RMS longitudinal emittance (twice the nominal LHC beam-type value), while the matched 100 % longitudinal emittance reached 2 eV s. Fig. 6 demonstrates an example tomogram with the reconstructed longitudinal phase space. The effective blow-up due to the hollowing from the initial 1.1 eV s to 2 eV s is a step towards the LIU goal of injecting 3 eV s bunches into the PS.

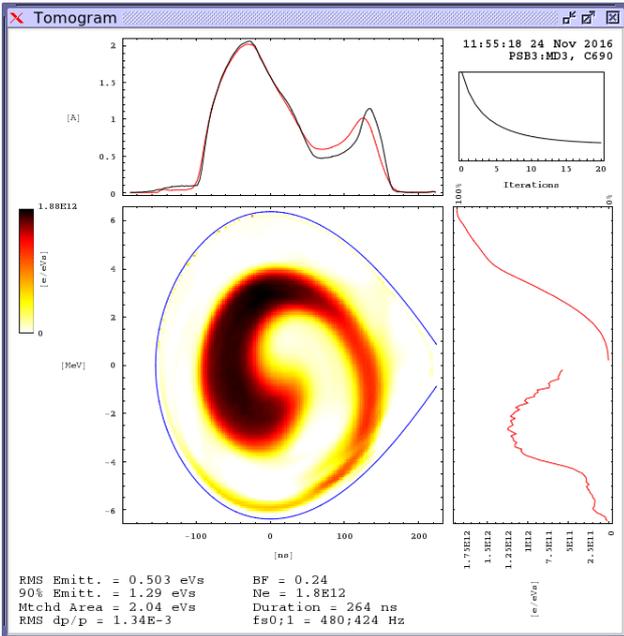


Figure 6: Longitudinal phase space after late resonance excitation starting at C675, showing a large excited filament (matched 100 % emittance of 2 eV s).

IV. LESSONS LEARNED

C16 Induced Voltage and its Harmonic Setting

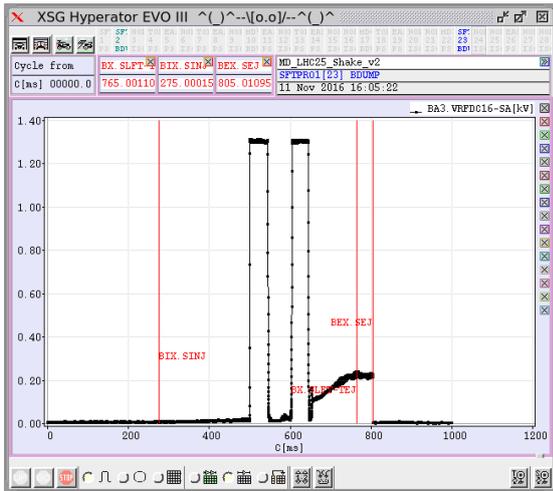
The C16 RF systems are used to smooth the excited bunch filament in a second pulse (the first one provides the canonical longitudinal blow-up for LHC beam production). It is important to control the high frequency modulation well in order to obtain well-defined longitudinal bunch parameters (RMS and 100 % emittances as well as momentum spread). We have noted a significant impact on reproducibility if the C16 cavities are left in a resonant state from the first blow-up onwards, i.e. when the programmed harmonic is an integer of the revolution frequency (which is the presently employed setting in operation). Fig. 7a shows the measured beam induced voltage in the C16 RF systems rising up to some 0.2 kV after the second pulse when the harmonic is left on $h = 9$.

Tuning the C16 to some non-integer multiple of the revolution frequency makes the cavities transparent to the beam. Unwanted further resonance effects distorting the longitudinal distribution can thus be suppressed. The higher the non-integer harmonic, the better the suppression seems to work. However, the C16 high frequency RF systems naturally have an upper limit: we find significant induced voltage by the beam passage when the frequency programme exceeds a certain frequency at around 17 MHz when programming $h = 10.5$. We achieved the best results at $h = 9.5$ in between the two first C16 pulses and again after the second one as shown in Figs. 7b and 7c.

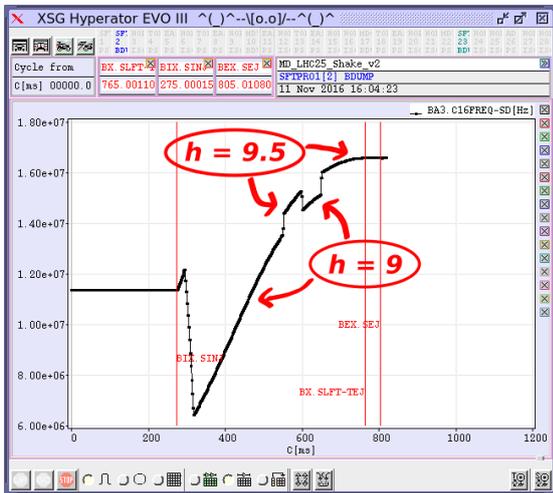
Cross-dependency of Radial and Phase Loop Feedback

The action-reaction coupling between the phase loop and radial loop feedback systems becomes more and more pronounced towards the end of the cycle. While the damping reaction of the radial loop to the excitation of the parametric resonance is present but limited around c-time C575, it effectively inhibits the resonance driving at later c-times around C675. The excitation works fine if we switch off the radial loop altogether, however, switching it back on afterwards may result in beam losses.

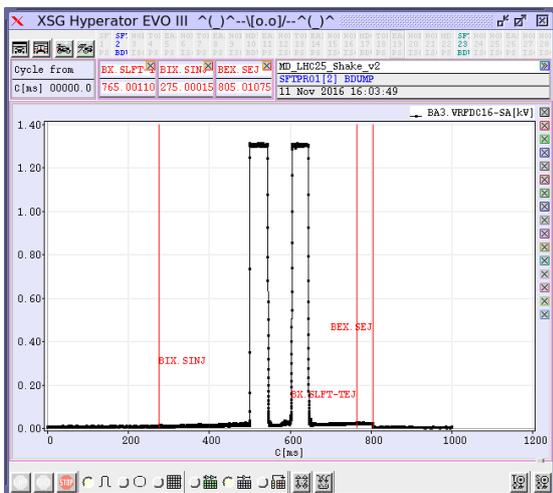
Simply reducing the radial loop gain directly (up to 2 orders of magnitude) unfortunately did not suffice to avoid the damping. Instead, we found that the radial loop biquad corrector has a strong influence on the immediate reaction of the radial loop. By reducing the biquad corrector gain (from the previous setting of 2.2 to 0.15), the coupling between the two feedback systems could finally be significantly reduced. Together with a half of the radial loop gain (1.5 instead of the canonical 3), this eventually enabled the excitation of the parametric resonance to deplete the phase space distribution [18]. At the same time, the radial loop steering behaved much smoother with less fluctuations across the entire cycle than before, which suggests that the radial loop in the canonical setting for LHC beam production acts overly strong.



(a) Measured C16 voltage while remaining on $h = 9$ after second smoothing pulse, clear sign of induced voltage after C650.



(b) Frequency programme avoiding induced voltage by setting a non-resonant $h = 9.5$ after C650.



(c) Measured C16 voltage without induced voltage after C650.

Figure 7: How to minimise induced voltage in the high frequency RF system.

Fig. 8 shows the feedback loops’ final steering on the scope for the optimal gain settings found to produce the large emittance hollow bunches (cf. Fig. 6).

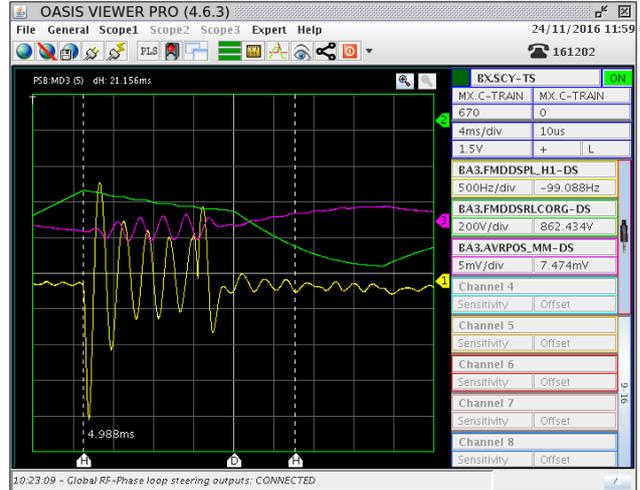


Figure 8: The final steering inputs for the phase loop (yellow) and the radial loop (green) along with the measured radial beam position (magenta) during the parametric resonance excitation around c-time C675.

The yellow curve for the phase loop clearly exhibits the 5 synchrotron periods long sinusoidal offset to drive the parametric resonance. At the sudden end of the excitation, the phase loop’s own feedback input makes it recapture the oscillating bunch, resulting in the last 180° shifted oscillation before it fluctuates around the programmed default phase offset of zero. The magenta curve marks the measured radial position of the beam, which shows the sinusoidal radial offset due to the RF frequency change caused by the phase loop steering. Note the 90° shift between the radial position and the phase loop curves: the phase loop provides the external driving and we expect the actual bunch phase to be shifted by 90° in case of resonant beam reaction to the driving frequency. This translates to the radial position oscillation in phase with the longitudinal bunch centre-of-gravity. The green curve represents the radial loop steering with negligible reaction to the phase loop’s oscillating steering. Our weak corrector gain settings indeed work as the radial loop does not inhibit the excitation process any more.

CONCLUSION

During MD 210, hollow bunches have been successfully produced in the PS Booster by means of exciting a longitudinal dipolar parametric resonance with the aid of the phase loop feedback system. We have presented the minimalistic set of changes to the LHC1A cycle for nominal LHC beam production which allows to extract hollow bunches with a matched longitudinal emittance of $\epsilon_{z,100\%} = 1.3 \text{ eV s}$. The space charge mitigating effect of hollow bunches during the PS injection plateau has been demonstrated in the context of MD 211. We have outlined a strategy to produce larger

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longitudinal emittances with first results featuring a matched area of 2 eV s.

Crucial ingredients for the larger longitudinal emittances is to remove the response of the radial loop to the sinusoidal phase loop steering. The corresponding lower radial biquad corrector gain also led to a much smoother action of the phase loop compared to the fluctuating reaction under the strong setting of the nominal LHC1A cycle. Furthermore, the C16 needs to be set to a non-integer harmonic during the later part of the cycle to avoid a back reaction on the beam.

Next steps include implementing the smoothing of the large emittance hollow bunches. To this end, the second harmonic in bunch shortening mode might already be used during the resonance excitation: the correspondingly larger synchrotron frequency gradient across RF bucket should provide quicker filamentation. Furthermore, exciting the bunch core by a frequency band of phase loop noise instead of a single frequency might provide a more smooth hollowing procedure, which could avoid the radial loop interference as the bunch centre-of-gravity would not be as strongly affected.

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