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LONGITUDINAL EMITTANCE BLOW-UP AND PRODUCTION OF FUTURE LHC BEAMS

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Abstract

During Long Shutdown 2 the RF systems of the PSB will be replaced with broadband Finemet systems, there will also be an energy increase and many other modifications. This note summarises studies that were done to investigate how to meet the emittance requirements for the LIU-PSB baseline and a possible use of the broadband cavities to improve the capture process.

The LIU-PSB baseline requires longitudinal emittance blow-up to 3 eVs with 205 ns bunch length at extraction. The current ferrite RF systems were used, with phase modulation of a high harmonic, to produce 2.8 eVs bunches with 220 ns bunch length, as this is the largest that can currently be transferred to the PS. Larger emittances were possible, demonstrating the ability to reach the LIU-PSB baseline in the future, which is confirmed in simulation.

The broadband impedance of the Finemet was exploited to allow RF voltage to be supplied on three harmonics (h=1, h=2, h=3), as opposed to the usual 2. For high intensity beams this lead to an improved capture efficiency for the same total voltage, and future studies are planned to demonstrate if there is an effect on extracted transverse emittance.

INTRODUCTION

This paper describes two sets of MDs, the first is dedicated to the production of high emittance bunches for the LIU-PSB [1] program, the second is an investigation into the use of three harmonics at capture to produce longer and flatter bunches than otherwise possible.

At current extraction kinetic energy of 1.4 GeV the longest bunch that can be delivered from the PSB to the PS is 220 ns. On the flat top with both C02 (h=1) and C04 (h=2) operating at 8 kV in bunch shortening mode this gives a longitudinal emittance of 2.8 eVs.

Losses early in the cycle are partially due to the large transverse tune spread at low energies. Since the transverse tune spread is proportional to the longitudinal line density it follows that a reduction in the line density will reduce the losses. The new HLRF Finemet systems that will be installed over LS2 allow the possibility to arbitrarily divide voltage across multiple harmonics, therefore allowing three harmonics to be used during capture, rather than two as used in current operations [2, 3].

2016 MDS

This section summarises the two MDs carried out during 2016, the first related to production of large emittance bunches, the second to demonstration of triple harmonic capture using the Finemet test cavity in ring 4.

Longitudinal Emittance Blowup

The objective of these MDs was to demonstrate the potential for a more optimised application of operational emittance blow-up to reach the LIU-PSB baseline of 2.8 eVs with nominal LHC intensities. Phase modulation of a high harmonic is used operationally in the PSB for either emittance blow-up, as in nominal LHC cycles, or longitudinal shaving, as in LHCINDIV type cycles. Phase modulation works by producing resonances between the high harmonic and the synchrotron motion of particles within the bunch. The induced resonances cause particles to move towards larger synchrotron amplitudes, therefore increasing the emittance of the bunch.

The ratio of synchrotron frequency distribution within the bunch (ω_s) and the modulation frequency of the high harmonic (Ω) determines the strength and positon of resonances. Since there is no flat portion in the PSB cycle the emittance blowup is done on the fly, leading to a constant change in ω_s. Under these conditions relating the small amplitude synchrotron frequency (ω_{s0}) to Ω through a constant multiplier (M) is beneficial, and the condition $\Omega = M\omega_{s0}$ is imposed.

For a fixed voltage in the PSB the bucket area continually grows during acceleration, therefore the relative spread of synchrotron frequencies is reduced, as shown in figure 1a. Under these conditions the number of resonances for a given M will decrease during acceleration. For these MDs the constant voltage was replaced with a constant bucket area during emittance blowup. By applying a constant bucket area the relative spread $\frac{\omega_{s0}}{\omega_s}$ is maintained (figure 1b), therefore induced resonances will persist allowing more effective blowup.

Due to the presently available voltage in the machine the bucket area does not become sufficient to contain 2.8 eVs until near the end of the cycle. Therefore for these studies blowup was performed in three steps, with bucket areas set to 3 eVs, 4 eVs and 5 eVs, giving both time and sufficient acceptance for blowup.

Figure 2 shows the voltage functions used for the three RF systems (C02, C04 and C16) during emittance blowup and up to extraction. The 1st harmonic (C02) shows three sections where the voltage is reduced through time, these are the fixed bucket area sections. The 2nd harmonic (C04) is ramped down during blowup to remove the effect it has on ω_s, before being ramped up in bunch shortening mode for extraction. The high harmonic (C16) is maintained at a fixed multiple of the C02 voltage during blowup, before being ramped up afterwards to help improve filamentation of the bunch.

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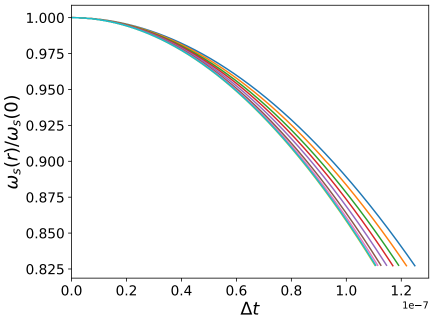
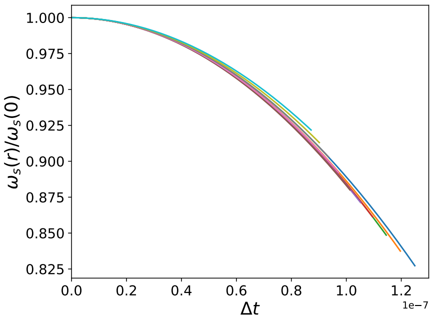
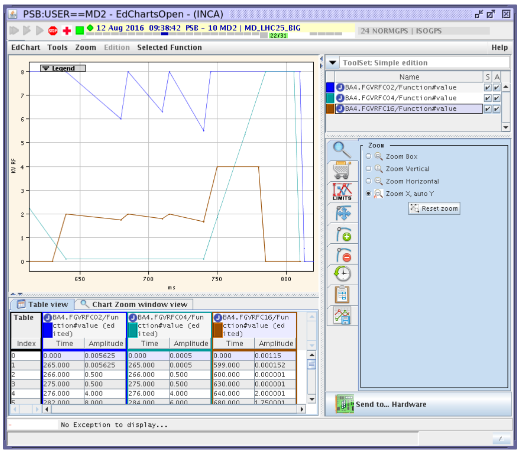


(a) Fixed voltage



(b) Fixed bucket area

Figure 1: Relative synchrotron frequency distribution ($\frac{\omega_s}{\omega_{s0}}$) with constant 8 kV vs constant bucket area during acceleration.



Name	S	A
🟦 BA4.FGVRFC02/Function#value	✓	✓
🟩 BA4.FGVRFC04/Function#value	✓	✓
🟫 BA4.FGVRFC16/Function#value	✓	✓

Table	BA4.FGVRFC02/Function#value (edited)		BA4.FGVRFC04/Function#value (edited)		BA4.FGVRFC16/Function#value (edited)	
Index	Time	Amplitude	Time	Amplitude	Time	Amplitude
0	0.000	0.005625	0.000	0.0005	0.000	0.00115
1	265.000	0.005625	265.000	0.0005	599.000	0.000152
2	266.000	0.500	266.000	0.500	600.000	0.000001
3	275.000	0.500	275.000	0.500	630.000	0.000001
4	276.000	4.000	276.000	4.000	640.000	2.000001
5	282.000	8.000	284.000	6.000	680.000	1.750001

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No Exception to display...
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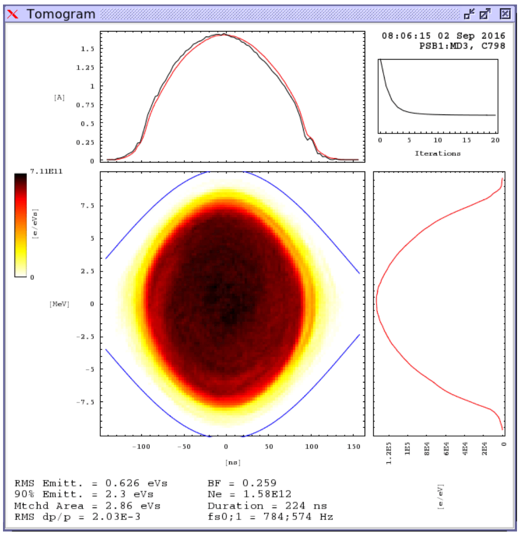
Figure 2: Voltage functions used for the three RF systems during and after longitudinal emittance blowup.

As all three fixed bucket area sections are independent from each other the modulation frequency and amplitude is different for all three. Due to the current LLRF operational conditions the optimum value of M in each section cannot be pre-calculated, instead an empirical scan was used to achieve desired effects.

The blowup was set up in each ring in a series of MDs, demonstrating the efficacy of the principle and the ability to achieve required similarity between the rings. Figure 3 shows the tomographic reconstruction of phase space prior to extraction in ring 1. The other rings were similar in both appearance and numbers, however further work is needed to achieve uniform characteristics.



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RMS Emitt. = 0.626 eVs      BF = 0.259
90% Emitt. = 2.3 eVs        Ne = 1.58E12
Mtchd Area = 2.86 eVs       Duration = 224 ns
RMS dp/p = 2.03E-3          fs0;1 = 784;574 Hz
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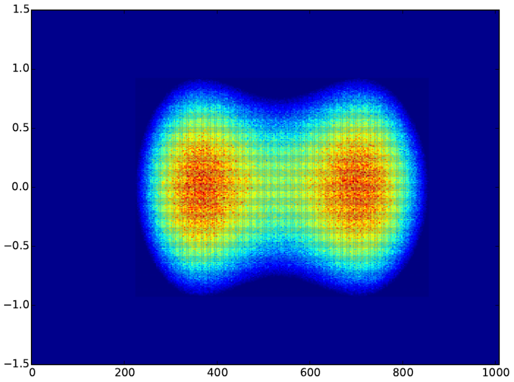
Figure 3: Phase space at extraction of the 2.8 eVs bunch in ring 1.

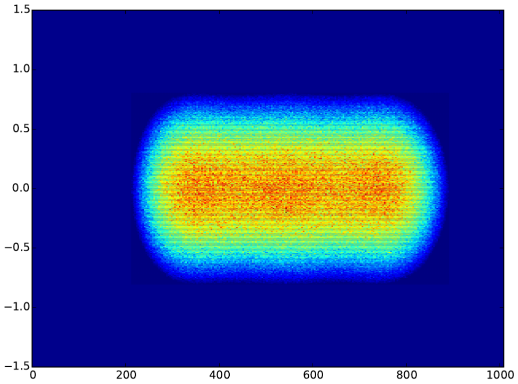
Triple Harmonic Capture

Due to a hardware fault the MD described in this section was limited to approximately 1 hour in length. However, it demonstrated the ability to use three harmonics during capture with minimal difficulty, and also showed that it may enable reduced losses in the early part of the PSB cycle. Large transverse space charge forces in the first tens of ms of the ramp lead to significant tune spreads, and correspondingly large losses. To reduce this effect the longitudinal line density can be reduced, increasing the bunching factor and decreasing the tune spread. For high intensity bunches the current operational condition is to use the 1st and 2nd harmonic in bunch lengthening mode, with 8 kV on both harmonics. The voltages and phases used provide maximum bucket area, and also reduce the line density of the beam. From simulations it was seen that maintaining the 16 kV total voltage, but including a third harmonic could reduce the line density by approximately 20% as shown in figure 4.

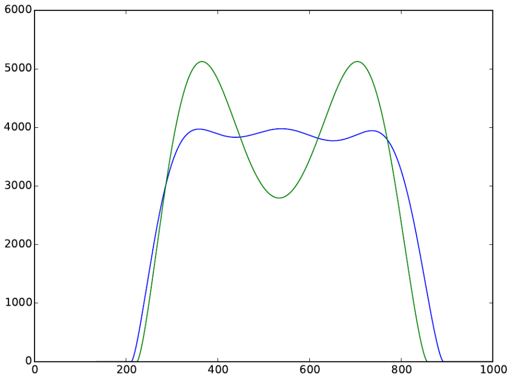
Using the ring 0 LLRF beam control, which controls the ring 4 HLRF systems, the beam was captured first with the standard 8 kV + 8 kV on C02 and C04, after which the Finemet system was enabled and the voltage was redistributed to 6.4 kV + 6.4 kV + 3.2 kV on C02, C04 and Finemet h=3 respectively. After carefully aligning the phases to give the standard profile with two harmonics and the flattest bunches possible with three harmonics the tomoscope waterfall plots shown in figure 5 were obtained. Figure 5a shows the standard double peaked structure assosciated with a phase space distribution like that in figure 4a, whereas figure 5b shows a significantly flatter profile, as would be caused by the distribution in figure 4b.



(a) Double harmonic



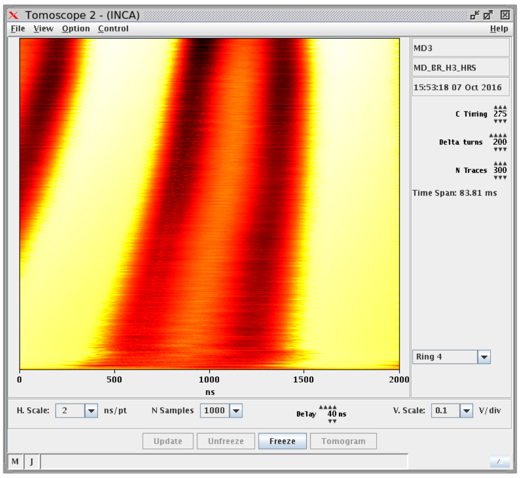
(b) Triple harmonic



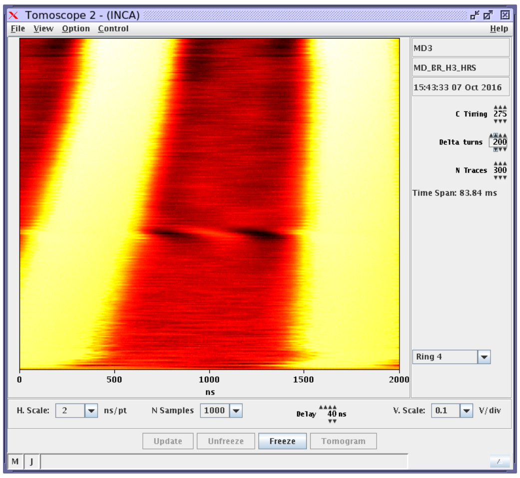
(c) Line densities

Figure 4: Simulated phase space with two harmonics, three harmonics, and corresponding line densities.

After setting up the voltages and phases correctly in each case the BCT traces for a series of shots were recorded. Figure 6 shows the recorded intensities with two (red) and three (blue) harmonics. As can be seen the use of three harmonics enabled reliably higher intensities with approximately 10% difference on average. Whilst the difference here is small it should be stressed that approximately one hour of beam time was used, and further improvements are expected to be possible.


MD3
MD_BR_H3_HRS
15:53:18 07 Oct 2016
C Timing 275
Delta turns 200
N Traces 300
Time Span: 83.81 ms
Ring 4
H. Scale: 2 ns/pt
N Samples 1000
Delay 40 ns
V. Scale: 0.1 V/div

(a) Double harmonic


MD3
MD_BR_H3_HRS
15:43:33 07 Oct 2016
C Timing 275
Delta turns 200
N Traces 300
Time Span: 83.84 ms
Ring 4
H. Scale: 2 ns/pt
N Samples 1000
Delay 40 ns
V. Scale: 0.1 V/div

(b) Triple harmonic

Figure 5: Waterfall plots of capture and the early part of the cycle with 2 and 3 harmonics.

PLANS FOR 2017

Both the longitudinal emittance blow-up and triple harmonic studies discussed have significant room for further research. This section discusses some of the work that is intended to be carried out during the 2017 run.

Longitudinal Emittance Blowup

In most current operational cycles blow-up is performed with voltage on both h=1 and h=2, as well as the high harmonic, with h=2 in bunch lengthening mode. The disadvantage of using h=2 in bunch lengthening mode is that both ω_s and ω_{s0} are extremely sensitive to small changes in relative phase. However, if bunch shortening mode is used the sensitivity is greatly reduced, and is concentrated at large synchrotron amplitudes. Repeating the 2016 studies but with h=2 in bunch shortening mode is therefore planned for 2017, it is hoped that this will allow blowup to happen faster than with only h=1.

An alternative to phase modulation of a high harmonic is to use phase noise. Band limited white noise injected onto

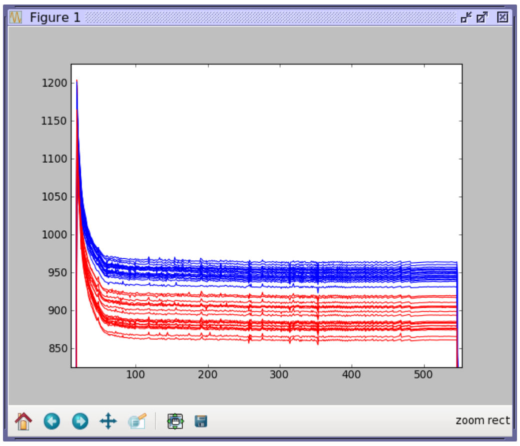


Figure 6: Recorded BCT traces for capture with two harmonics (red) and three harmonics (blue).

the main harmonic is currently used in both the SPS and LHC for emittance blowup to great effect [4]. The hardware capability exists to do this in the PSB, but it has not yet been tested. Simulations show that it should be effective after LS2, but machine measurements are needed for validation [5].

Triple Harmonic Capture

As a continuation of the first validation of triple harmonic capture further studies are intended to quantify the effect on the tune spread in two ways. First the transverse emittance can be measured at the end of the cycle, since the emittance growth appears to be driven by space charge effects lower values are expected. Alternatively the working point can be moved towards resonances that are known to be damaging, it would be expected that incoherent losses will be reduced with triple harmonics compared to double harmonics as the footprint should be smaller.

These tests should be performed with a variety of combinations of voltages on the three harmonics. Equal bucket area and equal total voltage between $V_{h1} = V_{h2}$, $V_{h1} = 2V_{h2}$ and $V_{h1} = V_{h2} = 2V_{h3}$, which will allow comparison between the standard double lobed structure used in operation now, a flat double harmonic profile and the flattened triple harmonic profile.

CONCLUSION

Two sets of MDs from 2016 have been discussed. Longitudinal emittance blowup studies have demonstrated an optimisation of operational norms, which demonstrated the ability to reach the LIU-PSB baseline for the first time. The blow-up was applied in all four rings to confirm efficacy and reproducibility, and whilst improvements are still possible the system was shown to be effective. Secondly the use of three harmonics, rather than the standard two, during capture and early in the cycle was shown. Using three harmonics allows longer and flatter bunches than otherwise possible, and it was shown that this can give better transmission than otherwise possible.

ACKNOWLEDGEMENTS

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