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NEW LONGITUDINAL BEAM PRODUCTION METHODS IN THE CERN PROTON SYNCHROTRON BOOSTER

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Abstract

As part of the LHC Injectors Upgrade (LIU) project, significant improvements were made to the CERN Proton Synchrotron Booster (PSB) during the 2019/2020 long shutdown, including a new Finemet-based wideband RF system, renovated longitudinal beam control, and a new magnetic cycle. To meet the requirements of the diverse experimental programme, the PSB provides beams with intensities spanning three orders of magnitude and a large range of longitudinal emittances. To maximise the brightness, in particular for the LHC beams, the voltages at low energy are designed to reduce the impact of transverse space charge using a second RF harmonic in bunch lengthening mode. At high energies, the risk of longitudinal microwave instability is avoided by optimising the longitudinal distribution to raise the instability threshold. RF phase noise is applied to provide controlled longitudinal emittance blow-up and to shape the longitudinal distribution. This paper discusses the design of the RF functions used to meet the beam specifications, whilst ensuring longitudinal stability.

INTRODUCTION

The CERN Proton Synchrotron Booster (PSB) is the first synchrotron in the LHC injector chain and has undergone major upgrades as part of the LHC Injectors Upgrade project [1]. The parameter space of operational beams includes single bunch intensities from $\mathcal{O}\left(10^{10}\right)$ to $\mathcal{O}\left(10^{13}\right)$, with longitudinal emittances, ε_l, between 0.3 and 3 eVs. To meet the challenging requirements for the High Luminosity LHC, the brightness of LHC physics beams is to be doubled, and the extraction kinetic energy increased from 1.4 GeV to 2 GeV. This paper details the proposed RF voltage functions for the production of some of the main physics beams required from the PSB.

The PSB accelerates beam from 160 MeV to 2 GeV in 530 ms with a 1.2 s repetition rate. Moments in the cycle are referred to in "C-Time", which indicates time in ms relative to the start of the cycle. The acceleration cycle is shown in Fig. 1 in kinetic energy and as a ratio of $\beta\gamma^2$ to the value at injection, for space charge scaling. The two highlighted sections show where transverse space charge (grey) and longitudinal stability (orange) have been the primary considerations in cycle design. To produce the required longitudinal emittance, controlled longitudinal emittance blow-up is applied. After a successful reliability run in 2018, the decision was taken to use RF phase noise, which can be injected into the beam phase loop or the cavity set point, for blow-up in the PSB [2].

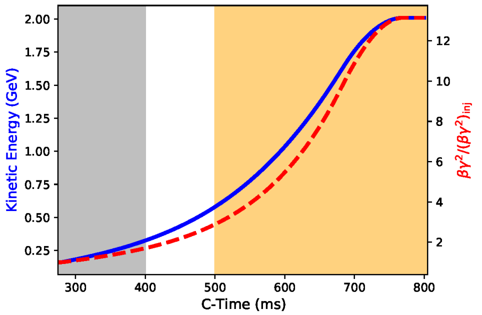


Figure 1: Kinetic energy (solid blue line) and $\beta\gamma^2/(\beta\gamma^2)_{\mathrm{inj}}$ (dashed red line) for the 2 GeV PSB magnetic cycle.

TRANSVERSE SPACE CHARGE

One of the main performance limitations for high brightness and high intensity synchrotrons at low and medium energy, such as the PSB, is the transverse space charge effect in combination with betatron resonances. The space charge force introduces an incoherent tune shift according to

$$\Delta Q_{x,y} = -\frac{r_0 \lambda}{2\pi e \beta^2 \gamma^3} \oint \frac{\beta_{x,y(s)}}{\sigma_{x,y}(s)(\sigma_x(s)+\sigma_y(s))} ds, \quad (1)$$

where, r_0 is the classical particle radius, λ the longitudinal line density, e the elementary charge, β, γ the relativistic factors and $\beta_{x,y}$, $\sigma_{x,y}$ the transverse β-functions and beam sizes, respectively [3]. This shift leads to a spread in the transverse tune space, which can result in beam degradation such as transverse emittance blow-up and losses.

In the PSB, the excitation of multiple high order betatron resonances is observed [4]. In addition, the resonances at integer tunes are expected to be excited by random machine errors as well as in fourth order by space charge due to the lattice periodicity of 16 [5]. Hence, it is essential to keep the space charge tune spread as low as possible. However, as seen from Eq. (1), for given machine and beam specifications, the only parameter that can be adjusted is the longitudinal line density, λ, which can substantially reduce the maximum space charge tune shift [6].

Figure 2 shows the estimated incoherent space charge tune spread [7] for the nominal LIU LHC filling cycle, assuming a Gaussian longitudinal distribution in single RF (gray) or double RF in bunch lengthening mode (green). As observed in simulations, transverse emittance blow up is expected in the case that the tune footprint extends beyond the resonances at integer tunes as shown here for the Gaussian longitudinal distribution in a single harmonic RF bucket. On the other hand, these resonances can be avoided using a double harmonic RF bucket and the beam brightness is conserved.

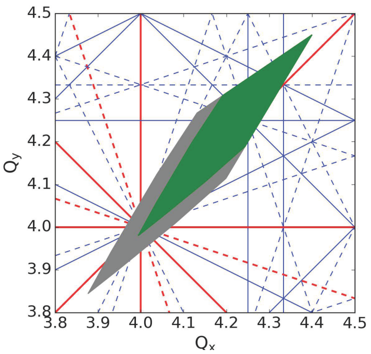


Figure 2: Estimated space charge tune spread for the LIU LHC25ns beam using a Gaussian longitudinal distribution in single harmonic (grey) and double harmonic (green) RF system. Resonances up to 4th order are plotted, normal in solid lines and skew in dashed, systematic in red and non-systematic in blue.

LONGITUDINAL MICROWAVE INSTABILITY

The upgrade from tuned ferrite-loaded RF cavities to broadband Finemet-loaded cavities causes a substantial change in the longitudinal impedance of the PSB. The cavities plus space charge are the most significant impedances by a large margin, with the Finemet cavities contributing more than the previous ferrite cavities. Servoloops operating on the Finemet cavities suppress the beam induced voltage at and near specified harmonics. When designing the beam production scheme, the number of servoloops was not yet defined, so a conservative estimate of the first 8 harmonics was used [8]. There is a strong impedance peak at about 18 MHz, which is well above the operating frequency range, where the impedance is broadband and covered by the servoloops. The impedance (Z/n) of the Finement and space charge at flat top, with servoloops acting on the first 8 revolution frequency (f_{rev}) harmonics, sampled at multiples of f_{rev}, is shown in Fig. 3.

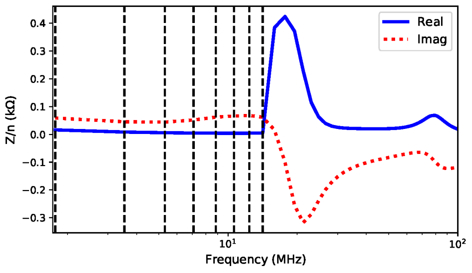


Figure 3: Longitudinal impedance (Z/n) of space charge and the Finemet cavities at flat top, with the servoloops reducing the impedance at $h = [1..8]$, indicated by the vertical lines.

The instability threshold, with constant ε_l, can be raised in two ways. The longitudinal phase space distribution can be optimised. With the current PSB impedance model this requires a parabolic line density, which will be given by controlled longitudinal emittance blow-up. Additionally, the energy spread can be increased either with a high voltage at $h = 1$ or with voltage at $h = 2$ phased to shorten the bunch.

PRIMARY BEAM TYPES

Across beams for user facilities and machine studies, the PSB can produce an almost limitless variety of longitudinal parameters at extraction. This section covers the main types that are needed for user facilities and downstream accelerators, and how they will be produced in the PSB.

The intermediate and high intensity beams have two or three main segments, shown in Fig. 4, with purposes indicated in Table 1. How these are applied in each case is detailed in the relevant sections.

Table 1: Beam Parameters and Main Sections of the Voltage Programs for Medium and High Intensity Beams

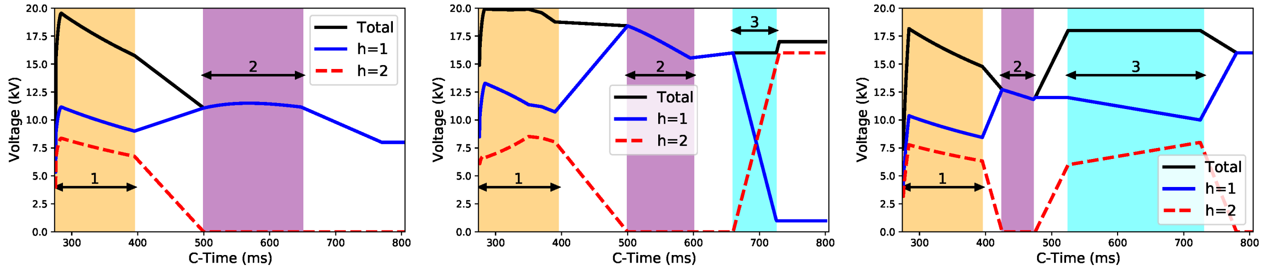
	LHC Multi-Bunch	nTOF	SFTPRO
# of bunches	1	1	2
Intensity, N_b	3.2×10^{12}	8.5×10^{12}	2.5×10^{12}
Emittance, ε_l	3	1.7	1.3
Section 1	Bunch lengthening (double-harmonic)		
Section 2	Controlled longitudinal emittance blow-up		
Section 3	-	Bunch shortening	Splitting

In addition to the intermediate and high intensity beams, very low intensity beams with small longitudinal emittance for the LHC are produced differently. These are discussed at the end of the section.

LHC Multi-Bunch

Two LHC multi-bunch beams are required from the PSB, known as “BCMS” and “LHC25”, which go through different manipulations in the PS [9]. In the PSB, these will be produced in a similar way, but with different intensity and ε_l. The method of producing the LHC25 with ε_l =3 eVs will be discussed here, but the principle is the same for all variants. The RF voltage function for the full cycle is shown in Fig. 4(a). Since this beam will be used for luminosity production in the LHC, where brightness is paramount, mitigating the space charge induced transverse blow-up is vital, therefore two RF harmonics are used in anti-phase to lengthen the bunch and reduce the line density. Thanks to the wideband Finemet cavities, it will be possible to add further harmonics, using three harmonics ($h = 1 + h = 2 +$ h=3) will be tried in the future for further bunch flattening and space charge reduction.

If additional time is needed for blow-up, or space charge is a problem later into the cycle than expected, these two sections can be stretched. There is also a possibility to add voltage at a higher harmonic (e.g. $h = 3$ in phase) during blow-up to increase the synchrotron frequency spread, which would make it easier to reach the target longitudinal emittance of 3 eVs.



(a) LHC Multi Bunch (b) SPS Fixed Target Protons (c) neutron Time-of-Flight

Figure 4: RF voltage functions for main intermediate and high intensity beam types.

High Intensity Single Bunch

The highest intensity beam extracted at 2 GeV is the one for the nTOF facility. This beam is most susceptible to microwave instability due to the high intensity (8.5×10^{12} protons) and the high energy at extraction. A second burst of $h = 2$, this time in phase, is applied to further increase the energy spread and raise the microwave instability threshold, which was shown to be necessary for stability with the BLonD tracking code [10]. The RF voltage functions are plotted in Fig. 4(c).

A similar beam is required at 1.4 GeV for the ISOLDE facility, which is produced in a similar way but the instability threshold is higher due to the lower energy, therefore the second harmonic after blow-up is not required.

SPS Fixed Target Protons

The SPS Fixed Target Proton beams (SFTPRO) are the only beams where two bunches are extracted from each PSB ring. The beam is therefore split longitudinally during acceleration. The full RF voltage functions are shown in Fig. 4(b), a non-constant ratio between the harmonics during section 1 is used to increase the bucket area at the cost of slightly increased space charge effects.

Ideally, the longitudinal splitting would take place at the end of the cycle. However, because the splitting process temporarily flattens the bunch and reduces the energy spread, it could easily become unstable. The chosen time of splitting is a compromise between minimising the risk of instability and waiting until as close to extraction as possible as accelerating in $h = 2$ is more difficult.

LHC Single Bunch

Two LHC single bunch beams are produced by the PSB, the LHCINDIV and LHCPILOT, which only differ slightly in the longitudinal plane. For both beams, the main challenge is producing the very small emittance and low intensity in a controlled and reproducible way. The specifications at extraction are 0.2 eVs and $0.5 - 2 \times 10^{10}$ protons per bunch for LHCPILOT and 0.3 eVs and $2 - 12 \times 10^{10}$ protons per bunch for LHCINDIV. The full function for the main harmonic in both cases is shown in Fig. 5. At injection, the RF voltage is 2.5 kV to allow a small amount of beam to be injected with $\varepsilon_l \approx 0.3$ eVs. Thereafter, the cycle is constructed from the sections indicated by the numbers in Fig. 5:

1. Fast adiabatic voltage increase for the start of acceleration to maintain the bucket area.
2. Fixed synchrotron frequency, during which a high harmonic is phase modulated for controlled emittance blow-up and longitudinal shaving.
3. Acceptance choke to remove additional unwanted beam and set the final ε_l.
4. Constant acceptance to preserve Landau damping; the acceptance can be adapted to match the ε_l if necessary.
5. Linear change in the synchronous phase to prevent a dipole kick from the large ramp rate decrease on the approach to the flat top.

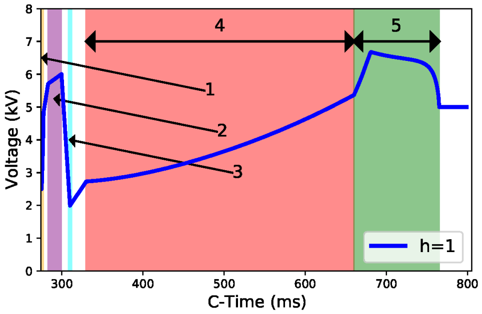


Figure 5: Voltage function used for LHCINDIV production.

CONCLUSION

After the upgrades during Long Shutdown 2, the operational capabilities and flexibility of the CERN PS Booster have been significantly increased, in part due to the new Finemet based RF systems. This paper explored the method used to design voltage functions for the main beam types required for operational users. This required considering space charge mitigation, controlled longitudinal emittance blow-up and longitudinal microwave instability. The PSB is in the process of being commissioned and the proposed functions are being tested with beam and optimised.

REFERENCES

[1] J. Coupard *et al.*, “LHC Injectors Upgrade, Technical Design Report, Vol. I: Protons”, CERN, Geneva, Switzerland, Rep. CERN-ACC-2014-0337, 2014.

[2] S. C. P. Albright and D. Quartullo, “Time Varying RF Phase Noise for Longitudinal Emittance Blow-Up”, in *Proc. 10th Int. Particle Accelerator Conf. (IPAC’19)*, Melbourne, Australia, May 2019, pp. 3954–3957. `doi:10.18429/JACoW-IPAC2019-THPRB067`

[3] K. Schindl, “Space Charge”, CERN, Geneva, Switzerland, Rep. CERN/PS 99-012(DI), 1999.

[4] A. Santamaría García *et al.*, “Identification and Compensation of Betatronic Resonances in the Proton Synchrotron Booster at 160 Mev”, in *Proc. 10th Int. Particle Accelerator Conf. (IPAC’19)*, Melbourne, Australia, May 2019, pp. 1054–1057. `doi:10.18429/JACoW-IPAC2019-MOPTS086`

[5] F. Asvesta, “Space Charge and Lattice Driven Resonances at the CERN Injectors”, PhD thesis, National Technical University of Athens, 2020.

[6] A. Oeftiger, “Space Charge Effects and Advanced Modelling for CERN Low Energy Machines”, PhD thesis, Ecole Polytechnique, Lausanne, 2016.

[7] F. Asvesta and H. Bartosik, “Resonance Driving Terms From Space Charge Potential”, CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2019-0046, 2019.

[8] M. E. Angoletta *et al.*, “Control and Operation of a Wideband RF System in CERN’s PS Booster”, in *Proc. 8th Int. Particle Accelerator Conf. (IPAC’17)*, Copenhagen, Denmark, May 2017, pp. 4050–4053. `doi:10.18429/JACoW-IPAC2017-THPAB141`

[9] H. Damerau, A. Findlay, S. S. Gilardoni, and S. Hancock, “RF Manipulations for Higher Brightness LHC-type Beams”, in *Proc. 4th Int. Particle Accelerator Conf. (IPAC’13)*, Shanghai, China, May 2013, paper WEPEA044, pp. 2600–2602.

[10] CERN Beam Longitudinal Dynamics code BLonD, `http://blond.web.cern.ch`