BEAM-LOADING COMPENSATION AT TRANSITION CROSSING FOR MIXED INTENSITY BUNCHES

O. Smedt[1,2], A. Lasheen*[1], H. Damerau[1]
[1]European Organization for Nuclear Research, Geneva, Switzerland
[2]École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

Abstract

To produce beam for the nTOF and East Area experimental facilities at CERN, the Proton Synchrotron (PS) simultaneously accelerates two bunches with very different intensities. This combined acceleration cycle gains time and flexibility for beam sharing across the accelerator complex. However, to fulfil the demanding beam requests for future facilities like the Search for Hidden Particles (SHiP) experiment, a higher bunch intensity delivered to nTOF is essential to maintain the average flux at a reduced repetition rate. This further increases the intensity difference with respect to the low-intensity bunch for the East Area. In this contribution, longitudinal dipole oscillations triggered by the intensity-dependent phase jump at transition crossing are exposed. A mitigation technique is derived analytically and demonstrated in beam tests, by tuning one cavity of the main RF system to a separate harmonic of the revolution frequency. This allowed the elimination of dipole oscillations at transition crossing and the preservation of beam quality, even with a significant increase of the nTOF bunch intensity.

INTRODUCTION

For the beam delivery to the East area experimental facility [1], a particle bunch of 2.2 to 8 × 10^{11} protons per bunch (p/b) is accelerated in the PS ('EAST bunch'). To run the PS more efficiently, a second bunch can be simultaneously accelerated for the nTOF facility [2]. This parasitic bunch has an intensity of up to 6 × 10^{12} p/b ('parasitic TOF bunch'). When a cycle is dedicated to the nTOF facility the equivalent bunch ('dedicated TOF bunch') has a higher intensity of 8.4 × 10^{12} p/b.

The SHiP experiment in the North Area of the SPS will require around two million cycles from the PS per year [3], equivalent to 28 days of dedicated operation of the PS. Servicing SHiP should ideally not affect the average proton flux to other facilities. This is partly achieved by raising the parasitic TOF intensity to the same intensity as on the dedicated cycle. The 40 % intensity increase would allow one dedicated TOF cycle to be removed for every four EAST cycles, without affecting the average proton flux to the nTOF facility. During typical operation of the PS, this change could shorten the supercycle by 5 %.

The parasitic TOF intensity is currently limited by dipole oscillations at transition crossing, induced by the difference in beam loading between the TOF and EAST bunches. These dipole oscillations cannot be mitigated by the beam phase loop, as they only occur for the less intense EAST bunch. The dipole oscillations decohere, resulting in emittance dilution. A mountain range plot of the EAST bunch at transition crossing is shown in Fig. 1. After transition crossing, the inter-bunch distance oscillates with an initial amplitude of 37 ns. The longitudinal RMS emittance is 0.38 eVs 170 ms after these oscillations begin.

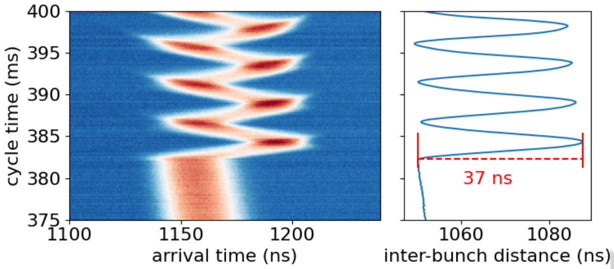

Figure 1: Mountain range plot of an EAST bunch (left) when a parasitic TOF bunch is present in the cycle. Transition crossing occurs at 382 ms with respect to the cycle start. The inter-bunch distance (right) is measured between the centres of two Gaussian profiles, fitted to each bunch. The measurement was performed with an EAST intensity of 2.2 × 10^{11} p/b and TOF intensity of 6 × 10^{12} p/b.

In this contribution we analyse the dipole oscillations, and develop a procedure to predict their amplitude. A method for their compensation is proposed and validated with beam tests, making use of existing RF hardware and leveraging the beam induced voltage. The implication of these optimizations on beam extraction is discussed.

DERIVATION OF DIPOLE OSCILLATION AMPLITUDE

The dipole oscillations are caused by the intensity dependent synchronous phase shift which is different for the EAST and TOF bunches. Through energy conservation the synchronous phase, ϕ_s, is known to satisfy

$$V_{\mathrm{ind}}(\phi_s) + V_{\mathrm{RF}}(\phi_s) = \frac{\delta E_s}{e}, \tag{1}$$

where δE_s is the energy gain per turn of the synchronous particle, e is the elementary charge, $V_{\mathrm{ind}}(\phi)$ is the beam induced voltage, and $V_{\mathrm{RF}}(\phi)$ is the voltage of the RF system without beam. The phase ϕ is with respect to the principle harmonic of the RF system, h. With knowledge of the beam induced voltage, this equation can be solved for the buckets of the TOF and EAST bunches to obtain $\phi_{s,\mathrm{TOF}}$ and $\phi_{s,\mathrm{EAST}}$.

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[*] alexandre.lasheen@cern.ch

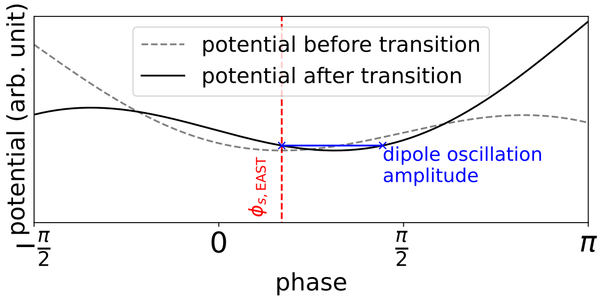

Figure 2: Longitudinal potential in the EAST bucket before and after transition crossing. The bottom of the potential well moves almost instantly at transition. Therefore, the EAST bunch becomes offset with respect to its potential well. Beam induced voltage from both bunches is accounted for in the potential.

At transition energy, a jump in RF phase by $\pi - 2\phi_s$ must be performed to preserve phase stability. Since ϕ_s is different for the two bunches, one bunch will necessarily be misaligned with respect to its stable phase after the jump. As the TOF bunch is more intense than the EAST bunch by an order of magnitude, its signal dominates the measured beam phase. The beam phase loop of the PS acts to stabilize the measured beam phase. Hence the effective phase jump is always $\pi - 2\phi_{s,\mathrm{TOF}}$. The longitudinal potential well $U(\phi)$ after this jump can be calculated as

$$U(\phi) = \frac{e}{2\pi h} \int V_{\mathrm{ind}}(\phi) + V_{\mathrm{RF}}(\phi) - \frac{\delta E_s}{e} d\phi. \qquad (2)$$

Above transition the EAST bunch starts at $\phi_{s,\mathrm{EAST}}$, and the dipole oscillation amplitude can be estimated to be the width of the potential, $U(\phi)$, at this point (Fig. 2). For the configuration shown in Table 1, corresponding to the measurement in Fig. 1, the amplitude of dipole oscillations should be 0.87 rad of RF phase corresponding to 36 ns. The calculation was done using the impedance of the main accelerating cavities [4]. Repeating the prediction with varying TOF and EAST intensities, it is clear that the dipole oscillation amplitude should scale approximately linearly with the difference in intensity of the two bunches (Fig. 3).

COMPENSATION OF OSCILLATIONS

To equalize the ideal phase jump at transition, the difference in energy loss from beam induced voltage must be compensated. The main RF system of the PS consists of ten tunable ferrite-loaded cavities, each with an RF voltage of up to 20 kV. The resonance frequency can be controlled from 2.8 MHz to 10 MHz [5]. By pulsing one of these main cavities at a harmonic which advances in phase by an odd integer times π radians between the bunches, additional voltage can be provided to the TOF bunch and removed for the EAST bunch. For the current bunch spacing of four RF periods, harmonic, $h = 7$ has the correct phase advance. A similar compensation scheme has been applied to counteract transient beam loading at transition crossing for asymmetric filling patterns [6]. For maximum compensation, the crest and trough of the detuned voltage should be aligned with TOF and EAST bunches both before and after transition. Therefore, the phase is not switched at transition. With one cavity tuned to harmonic $h = 7$, the voltage on the principal harmonic, $h = 8$ is reduced by 10 % around transition crossing. The contribution from the detuned voltage ensures that the bucket area for the TOF bunch remains almost unchanged, while the bucket area for the EAST bunch shrinks by 40 %.

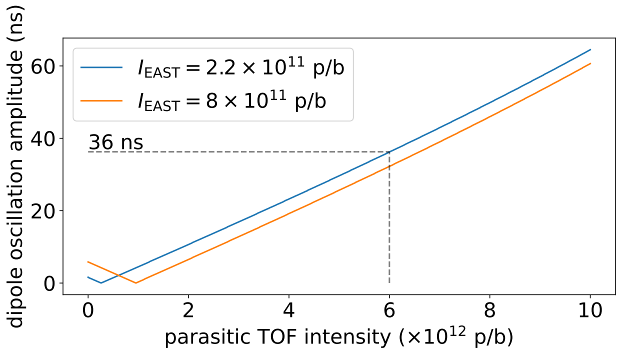

Figure 3: Expected dipole oscillation amplitude calculated using the parameters in Table 1, but varying TOF and EAST intensities.

Table 1: Parameters at transition crossing for the EAST cycle, as it is currently implemented in operation. The quoted intensities are the smallest EAST and highest parasitic TOF intensities which are accelerated in operation.

Description	**Variable**	**Value**
TOF bunch intensity	I_{TOF}	6×10^{12} p/b
EAST bunch intensity	I_{EAST}	2.2×10^{11} p/b
TOF bunch RMS length	σ_{TOF}	15.5 ns
EAST bunch RMS length	σ_{EAST}	11.5 ns
Synchronous energy gain	δE_s	101.5 keV
Main RF voltage	$V_{h=8}$	200 kV
Main RF harmonic	h	8
Main RF frequency	f_{RF}	3.8 MHz
Bunch spacing in RF periods	n_{periods}	4

The analytical considerations from the previous section, are still valid with the modified RF voltage. For any voltage amplitude, V_{det} and phase, ϕ_{det} of the detuned cavity the residual dipole oscillation amplitude can be predicted (Fig. 4, left).

Calculations predict that at a voltage of $V_{\mathrm{det}} = 18$ kV and a phase of $\phi_{\mathrm{det}} = 50°$, the dipole oscillations are completely eliminated for the bunch intensities shown in Table 1. Beam tests showed that a slightly higher voltage of $V_{\mathrm{det}} = 20$ kV was required. This is the maximum available voltage. Thus perfect compensation would not be possible at a parasitic TOF bunch intensity of 8.4×10^{12} p/b, in this configuration.

Additional voltage can be sourced from the beam induced voltage. At the current bunch spacing of four RF periods, the beam induced voltage of the TOF bunch fully decays

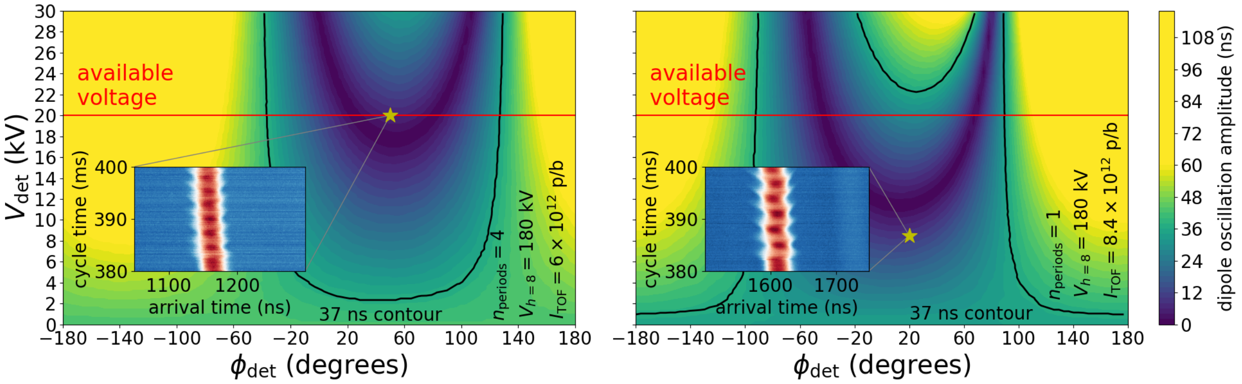

Figure 4: Estimated amplitude of residual dipole oscillations when detuning one of the main cavities to compensate the difference in beam induced voltage. The left contour shows the configuration were the bunch spacing and TOF intensity is unchanged from Table 1. The right contour shows the configuration were the bunch spacing is reduced and TOF intensity increased. The compensation scheme necessarily decreases the voltage on the principle harmonic to $V_{\text{h=8}} = 180\,\text{kV}$. All parameters other than n_{periods}, I_{TOF}, and $V_{h=8}$ are taken from Table 1. The black line indicates the dipole oscillation amplitude observed in Fig. 1 corresponding to the settings in Table 1. The insets show measured mountain range plots of the EAST bunch at transition close to the expected ideal settings of phase and voltage for the detuned cavity.

before the passage of the EAST bunch. However, measurements indicate that strong beam induced voltage persists up to 500 ns behind the parasitic TOF bunch [4]. The beam induced voltage can therefore extract energy from the EAST bunch, if it is placed in the bucket just after the TOF bunch.

With this method it is possible to reduce the required voltage from the detuned cavity. It enables perfect compensation of dipole oscillations even at an increased parasitic TOF intensity of 8.4×10^{12} p/b (Fig. 4, right). The change of bunch spacing also necessitates that the detuned cavity is pulsed at harmonic, $h = 12$ instead of $h = 7$ to ensure the correct phase advance between the bunches.

This result is counter-intuitive as the typical approach when tackling beam induced voltage is to space the bunches to decouple their dynamics. In this case it is beneficial to intentionally place the EAST bunch in the wake-field induced by the parasitic TOF bunch.

Detuning one of the main cavities for operational beam production will not be feasible until 2028, when all of the main cavities will become individually tunable. An attempt was made to partially compensate dipole oscillations by utilizing a wideband cavity with a bandwidth of 0.5 to 5 MHz [7]. Beam induced voltages caused by the large impedance of the cavity made it unsuited for this purpose, in the present configuration.

IMPLICATIONS FOR TOF EXTRACTION

The parasitic TOF bunch is extracted before the EAST bunch and requires a bunch rotation triggered by a phase jump to achieve a short extracted bunch length. The bandwidth of the main RF system does not allow for the bunch rotation to be applied to a single bunch only. After the TOF bunch extraction, a second bunch rotation is therefore performed to stop the quadrupole oscillations induced in the EAST bunch by the first rotation. The large longitudinal emittance of the EAST bunch in the presence of the parasitic TOF, limits the best achievable bunch compression, due to losses and filamentation from non-linear synchrotron motion. For this reason the rotation performed on the parasitic and dedicated TOF bunches have previously been different.

With the elimination of the dipole oscillations, a post transition RMS emittance of 0.21 eVs was achieved in comparison to 0.38 eVs, representing an almost two fold reduction. A bunch rotation with more aggressive compression could thus be found for the cycle. The settings for the bunch rotation performed on the dedicated TOF were copied to the EAST cycle and applied to the parasitic TOF bunch. This allowed the dedicated and parasitic versions of the TOF bunch to match in both intensity and longitudinal profile at the moment of extraction. The change did not lead to a discernible decrease in EAST bunch quality, although work is still ongoing to study the implications.

CONCLUSION

Transition crossing with bunches of very different intensity without dipole oscillations has been demonstrated in the PS, by applying beam loading compensation. By detuning a cavity and changing the bunch spacing, the synchronous phase shifts were equalized. With this compensation in place the emittance of EAST bunches could be reduced by a factor of two, despite a 40 % increase in TOF bunch intensity. This increases the average proton flux which the PS is capable of producing and will be implemented operationally in 2028.

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