

BEAM MANIPULATIONS WITH BARRIER BUCKETS IN THE CERN PS

M. Vadai*¹, A. Alomainy, Queen Mary University of London, London, UK

H. Damerau, S. Gilardoni, M. Giovannozzi, A. Huschauer CERN, 1211 Geneva 23, Switzerland

¹also at CERN, 1211 Geneva 23, Switzerland

Abstract

A barrier bucket scheme is being considered to reduce losses during the Multi-Turn Extraction from the CERN Proton Synchrotron to the Super Proton Synchrotron for the fixed-target physics programme. For effective loss reduction, the extraction kicker has to be triggered during the gap at the time of the longitudinal barrier. Initial beam studies at injection energy and with low intensity beams allowed to fully qualify an existing wide-band cavity to generate one or multiple beam synchronous pulses per turn. Bunch-length stretching and shortening have been exercised with barriers moving in azimuth with respect to the beam. The encouraging results obtained at injection energy guided the implementation of a de-bunching manipulation at higher energy to move all bunches into a single barrier bucket. Beam measurements at a momentum of 14 GeV/c, varying intensity and the width of the barrier, demonstrate that a quasi-constant longitudinal line density and an almost fully depleted gap can be achieved at highest intensities. The contribution summarises the results of the beam studies at high energy together with some observations related to the Multi-Turn Extraction.

INTRODUCTION

A prototype low-level radiofrequency (LLRF) system has been developed [1] in combination with a wide-band Finemet[®] cavity, which is normally part of a longitudinal feedback system at the CERN Proton Synchrotron (PS) [2]. The aim is to reduce beam losses of fixed target beams at extraction from the PS by creating a gap in the coasting beam with a so-called barrier bucket [3]. Creating an isolated pulse for the barrier bucket requires a wide-band RF system. The Finemet[®] cavity has a suitable frequency range and gap voltage to be operated as a barrier bucket system by installing an additional LLRF system. Before testing the new setup at extraction energies and with high-intensity beams, initial beam tests at low energy and low intensity allowed to qualify the parameters of the system, as well as to perform the integration for machine development purposes.

Systematic tests performed with azimuthally-moving potential barriers confirmed the theoretically predicted barrier speed limits with respect to the adiabaticity of the changes. Having achieved promising results at low energies, studies at extraction energy with beam were performed without the integration of the Multi-Turn Extraction (MTE) [4, 5] scheme to validate the barrier waveform generator at 14 GeV/c momentum. Re-bucketing at flat top was exercised and the performance of the barrier bucket system is reported with

different beam intensities including the good performance at highest intensities.

Longitudinal Dynamics in a Barrier Bucket

A barrier bucket is a long, flat RF bucket in the longitudinal plane of a synchrotron, which is made by isolated RF pulses at a wide-band cavity gap. The potential created by the sinusoidal RF pulses forces the particles confined by it to form a long, flat bunch. Two basic features of the barrier buckets are illustrated in Fig. 1: (i) the reflection region, where the longitudinal dynamics is similar to a conventional RF bucket; (ii) the drift region, where the energy change of the particles is ideally zero, since no RF voltage is present in the cavity gap.

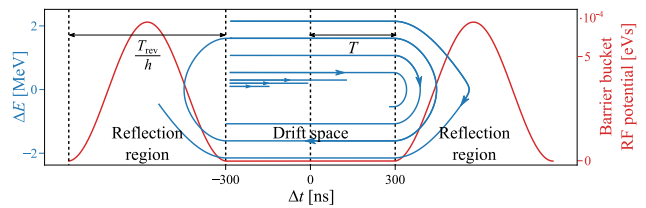


Figure 1: The RF potential (red) due to the pulsed RF voltage and the trajectories (blue) in the ΔE , Δt phase space. T is the time measured from $\Delta t = 0$ to the barrier. $2T$ is the duration of the drift space. T_{rev} is the revolution period of the synchrotron and h is the harmonic number corresponding to the length of the reflection region.

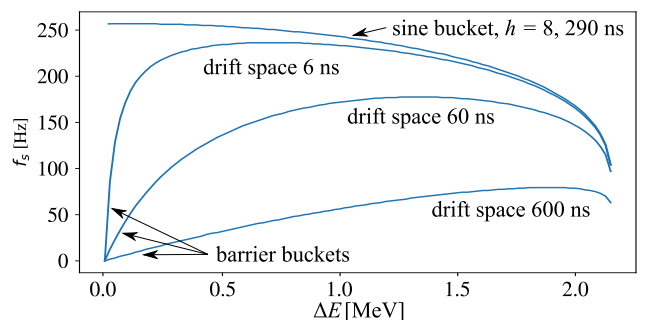


Figure 2: The synchrotron frequency dependence on ΔE during the expansion and compression operations for the different phases of the manipulation. The peak RF voltage is ≈ 4 kV.

Compared to a sinusoidal bucket the introduction of the drift space increases the period of the oscillations for a particle having a non-zero energy offset. To highlight this difference, the synchrotron frequency as a function of energy for a barrier bucket and a sinusoidal bucket are compared in Fig. 2. The presence of the drift space results in a different

* mihaly.vadai@cern.ch

synchrotron frequency variation with energy offset. The shape of the frequency curve depends on the length of the drift space relative to the length of the reflection region [6]. The increase in the synchrotron frequency with the energy deviation becomes nearly linear for longer barrier buckets.

Limit on Barrier Speed

The duration of the drift space ($2T$, see Fig. 1) can be changed to check adiabaticity limits for the barrier bucket beam manipulations. Since the conventional estimation methods for the adiabaticity of beam manipulations do not apply to a barrier bucket because of the different synchrotron frequency spread, a different approach suggested in [6] was used. While compressing the beam in a barrier bucket, the incremental change of energy of the particles having the maximum energy offset during the compression should be sufficiently small compared to the total beam spread in order to avoid emittance growth. The speed of the azimuthally-moving voltage pulse is $|dT/dt|$, where T is half of the duration of the drift space. The result of the estimation is that the barrier pulse speed should be $|dT/dt| \ll 1.4 \times 10^{-4}$. This was calculated for a proton beam at 1.4 GeV kinetic energy E_k and at 2.1 MeV corresponding to the beam spread in the barrier buckets generated in the PS.

BEAM STUDIES AT INJECTION ENERGY

The proton beam at $E_k = 1.4$ GeV was injected into a bucket formed by the two barrier pulses placed directly next to each other. Then the RF bucket was stretched by symmetrically moving the barrier-generating potentials and compressed again the same way using two different schemes as illustrated in Fig. 3 with examples of experimental data from the PS. During the measurements with the first scheme, the beam was kept between the barriers for as long as it was possible within the cycle, roughly for 1 s (Fig. 3 left and centre plots). With the second scheme, the whole operation lasted for twice the expansion time only (Fig. 3 right plot). The latter did not include the intermediate barrier bucket phase.

The fine details of the filamentation could be observed in the mountain-range plot captured with a shorter time scale on the right-hand side of Fig. 3. In the left and central images the acquisition having a longer time scale sub-samples the synchrotron motion, therefore it does not resolve this detail. However, since the acquisition is happening over a longer period of time, the picture shows an overall larger bunch length due to the advanced phase of the filamentation.

The barrier azimuthal speed range in the tests performed corresponds to $1 \times 10^{-6} < |dT/dt| < 3 \times 10^{-5}$. The duration of compression and expansion, t_c , was varied in a range of 10 ms to 300 ms. In all cases the bucket was stretched to a maximum drift space of 600 ns corresponding to $T = 300$ ns and compressed back again. Although the upper speed is still well below the optimistically defined limit, it became clear during the tests that approaching even a tenth of this

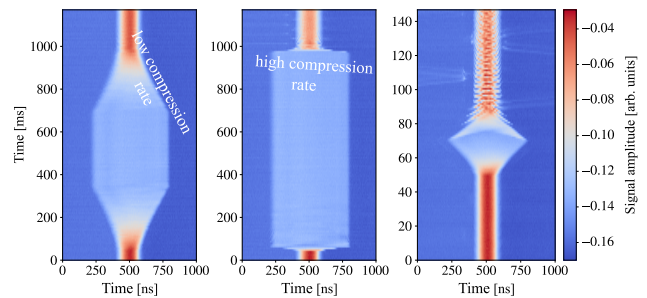


Figure 3: Examples of adiabatic (left) and non-adiabatic beam manipulations (centre and right plots) using two schemes. The excursions of the barriers are the same, but the expansion and compression times are different: 300 ms for the left and 20 ms for the centre and right plots at $E_k = 1.4$ GeV and at 1×10^{11} particles per pulse (ppp) intensity.

value results in a significant perturbation of the bunch profile. Similar observations have been reported in [7].

Performing Gaussian fits to the beam distribution before and after the compression, the bunch lengths before the expansion operation and after the compression are compared for two schemes of barrier motion, and the results are shown in Fig. 4. It is clear that once even the tenth of $|dT/dt|$ is approached, the difference in the bunch length increases significantly. In addition, the data taken for the shorter beam manipulations show that the bunch length spread increases for larger barrier speeds as a result of quadrupolar oscillations of the final bunch. This view of the experimental data in Fig. 4 supports the same, expected conclusion as suggested by Fig. 3, i.e. approaching the optimistically-defined barrier speed limit results in a non-adiabatic compression.

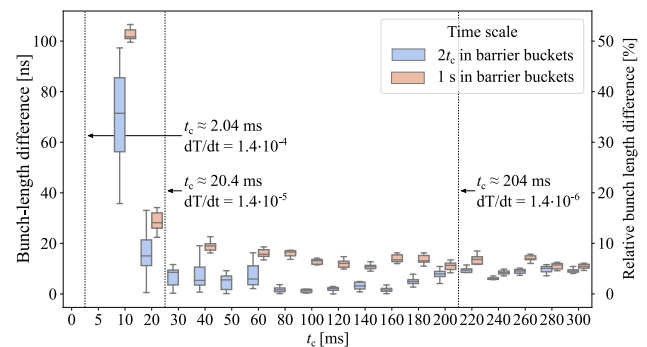


Figure 4: Difference of initial (200 ns) and final bunch length vs. compression time, t_c . Once the compression speed, dT/dt , becomes too fast, the bunches are perturbed after the manipulation. This results in an increased bunch length after filamentation.

BEAM STUDIES AT HIGH ENERGY

Beam tests at a flat top of 14 GeV/c momentum were performed in view of the foreseen operational conditions at extraction. The nominal MTE cycle was modified not to include the transverse splitting, which allowed the effects of the longitudinal manipulation alone to be seen.

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A re-bucketing manipulation was performed at higher intensities, since this is similar to the foreseen application. Since the duration of the gap created is small compared to the duration of the drift space, the synchrotron frequencies are low in such a barrier bucket. The shape of the synchrotron frequency spread vs. ΔE is similar to the long drift space depicted in Fig. 2. Since the time is too short for a full de-bunching, dynamic effects play a role in shaping the longitudinal profile near extraction as shown in Fig. 5.

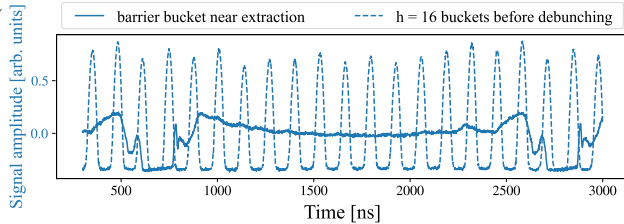


Figure 5: Line density in the barrier bucket at a momentum of 14 GeV/c before extraction at 3×10^{12} ppp. The initial conditions before rebucketing are shown with the dashed blue line.

Re-bucketing at Flat Top (14 GeV/c)

One barrier waveform creating a gap corresponding to $h = 7$ (see Fig. 1) or 300 ns was generated per turn. The intensity was increased, but because the ratio of the reflection region to the drift space was very similar to the previous high-energy tests, the synchrotron frequencies were still low in the barrier buckets at extraction. Hence the initial position of the potential barriers has an effect on the symmetry of the profile at extraction. To mitigate the uneven reflections caused by an asymmetrically-placed potential barrier, the gaps were placed between two bunches at $h = 16$. The gap was created by lowering the amplitude of the main RF system at $h = 16$ and at the same time increasing the amplitude of the wide-band system as shown in Fig. 6.

Intensity-related Observations

Figure 7 shows results of the measurements with the beam intensity increased at flat top. Only the beam intensity was changed, the barrier parameters and the system and cycle settings were the same. The gap and the flat longitudinal intensity are well preserved even at highest intensities, indicating that the beam induced voltage is small compared to the voltage driven by the amplifier. Particle tracking studies are foreseen to investigate how the beam intensity affects the longitudinal profile.

CONCLUSIONS

The results of beam tests at low and high intensities performed in the CERN PS were presented with a prototype barrier bucket system. Adiabaticity limits with azimuthally-moving barriers were studied for bunch compression and expansion. High energy and higher intensity tests were performed at 14 GeV/c momentum. They confirmed that a

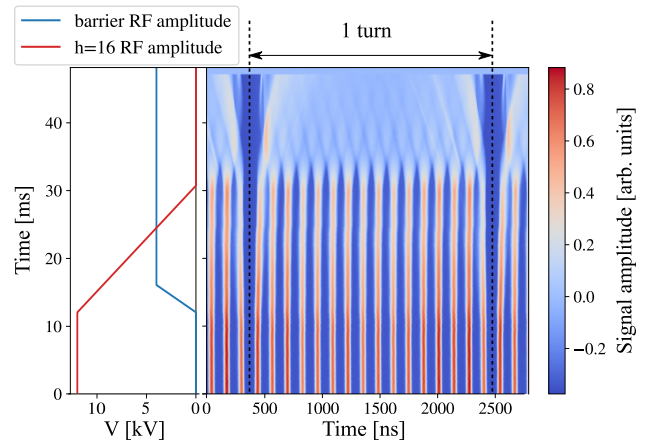


Figure 6: Re-bucketing the beam into a barrier bucket within the time available before extraction (3×10^{12} ppp). The dynamics of the re-bucketing was driven by the decrease of the $h = 16$ RF voltage.

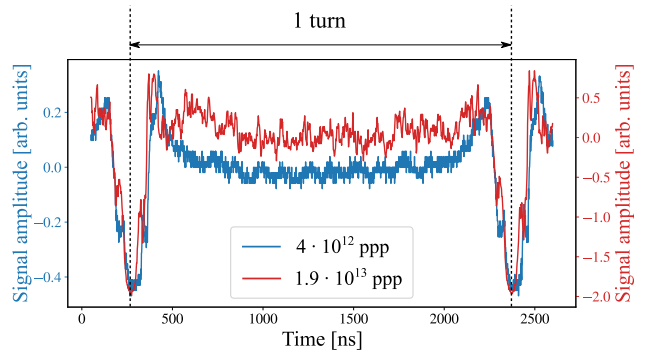


Figure 7: Longitudinal beam profiles at 14 GeV/c for two different intensities. The bunch profile is closer to a flat distribution at high beam intensities.

longitudinal gap as means of reducing the beam losses at extraction can be made in the beam distribution. Encouraging observations related to intensity effects were reported. Further studies will be required to investigate the scheme especially in the view of the intensity effects and the configuration at the start up after the CERN Long Shutdown 2.

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