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IMPROVED ANTIPROTON PRODUCTION BEAM AT CERN

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Abstract

Antiprotons are generated at CERN by extracting a high-intensity proton beam from the Proton Synchrotron (PS) onto a target. The resulting antiprotons are captured in the Antiproton Decelerator (AD) ring. As the AD is about three times shorter than the PS, the entire primary proton beam must be compressed to less than one third of the PS circumference. The previous batch compression brought four bunches injected from the PS Booster (PSB) into consecutive RF buckets at a harmonic number of 20. An improved injection and compression scheme has been developed and commissioned to deliver five bunches to the AD. It became feasible thanks to the upgrades of the injector complex for the High-Luminosity LHC (HL-LHC). One of the four PSB rings delivers twice higher intensity in two bunches, and an optimized sequence of nine different RF harmonics has been set up to obtain five bunches within one quarter of the PS circumference. The contribution summarizes the main changes to the antiproton production beam, as well as the experience of the first year of operation. Results of beam tests with increased total intensity are presented.

INTRODUCTION

Sending the 26 GeV/c high-intensity proton beam from the CERN PS on a target produces antiprotons at an average momentum of 3.57 GeV/c. These are then captured, cooled and decelerated in the Antiproton Decelerator (AD) [1], before they are transferred to the Extra Low ENergy Antiproton (ELENA) ring [2] for further reduction of their energy. The AD has been built as a modified version of the Antiproton Collector (AC) ring [3], which was part of the antiproton accumulation complex for the Super Proton Synchrotron (SPS) $p\bar{p}$ collider [4]. The circumference of about 182.4 m remained unchanged when moving from AC to AD. It had been chosen to allow single-turn injection of a bunch train extending over one quarter of the $2\pi 100$ m long PS. Concentrating all particles in this fraction of the PS circumference was motivated by the length of the PS Booster (PSB). With the circumference of each of its four stacked rings corresponding to exactly one quarter of the PS circumference, its harmonic number was initially $h_{\mathrm{PSB}} = 5$, which matched the four times larger harmonic number for acceleration in the PS at that time.

At the transfer between PS and AD, the harmonic number of the primary proton beam is therefore still $h_{\mathrm{PS}} = 20$. The design harmonic number of the AD, $h_{\mathrm{AD}} = 6$, leaves one empty bucket for the fall time of the AD injection kicker in addition to the up to five filled buckets.

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However, with the conversion of the PS complex for the production beams in view of the LHC [5], the original schemes to generate five bunches at PS extraction [6, 7] became impossible. The main harmonic number of the PSB was changed to $h_{\mathrm{PSB}} = 1$, which reduced the number of bunches to the AD to four, one bunch from each ring of the PSB, limiting the maximum total primary beam intensity.

With the recent improvements of the injector complex in the framework of the LHC Injectors Upgrade (LIU) project [8], the beam brightness in PSB and PS has been doubled. As a byproduct two bunches with sufficiently small transverse emittance can therefore be delivered by one ring, while the other three accelerate just one bunch with very similar characteristics, re-enabling the transfer of in total five bunches to the PS. Beyond the special injection scheme of 2 + 1 + 1 + 1 bunches into consecutive buckets at $h_{\mathrm{PS}} = 8$, this contribution presents an upgraded RF manipulation to concentrate the bunch train initially distributed over $5/8^{\mathrm{th}}$ of the circumference to only one quarter.

BEAM PRODUCTION IN PSB AND TRANSFER TO PS

To obtain five bunches from the four PSB rings, the 3rd ring from the bottom, in which the beam is vertically at the same level as in the PS, is set up to deliver two bunches. As a result, the intensity delivered from Linac4 to ring 3 is twice higher than in the other rings. However, the beam is still captured in one bucket and then symmetrically split [9,10] by increasing the RF harmonic from $h_{\mathrm{PSB}} = 1$ to $h_{\mathrm{PSB}} = 2$ when approaching the flat-top. Only one bunch is accelerated and extracted from the remaining three rings. Figure 1 illustrates the PSB-to-PS transfer scheme.

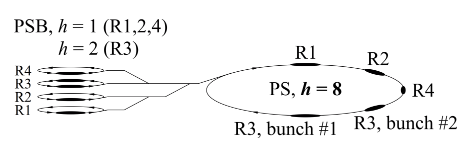

Figure 1: Injection scheme of five bunches from the four PSB rings (2 + 1 + 1 + 1). The two bunches from ring 3 are followed by one bunch from each of the remaining three rings. The order of rings is defined by the recombination kickers in the transfer line between PSB and PS.

The transverse emittance in the PSB is ideally proportional to the beam intensity, and hence twice larger emittances would be expected from the ring delivering two bunches [11]. To preserve the brightness in ring 3 and to equilibrate the emittances of all rings, the main parameters, i.e. tunes, resonance compensation [12] and painting [13], at injection have to be modified accordingly. Figure 2 shows

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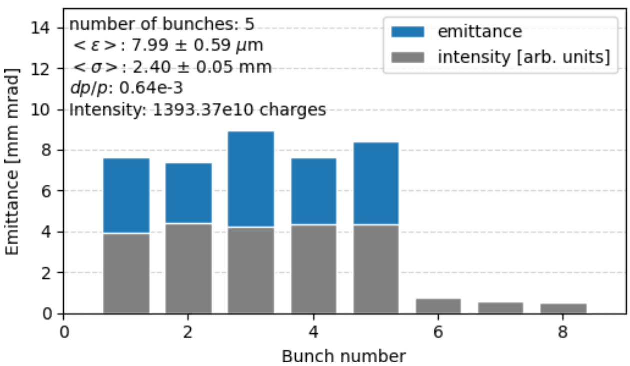

Figure 2: Horizontal beam size, σ, and normalised emittance, ε, of the five bunches measured by the wire scanner at PS flat-top. The total intensity was about $1.4 \cdot 10^{13}$ p/p (protons per pulse) equally distributed over the five bunches (data from April 2022). The first two bunches (#1 and #2) are both generated in ring 3 of the PSB.

the results of a bunch-by-bunch horizontal emittance measurement at flat-top in the PS. In the vertical plane the average emittance is $\varepsilon_{\mathrm{V}} \simeq 4.7$ m. This demonstrates that the emittances of the first two bunches are not any larger than the following ones. When increasing the total intensity to $1.8 \cdot 10^{13}$ p/p (protons per pulse), emittances grow to $\varepsilon_{\mathrm{H}} \simeq 9.4$ m and $\varepsilon_{\mathrm{V}} \simeq 6.3$ m, remaining acceptable for the transfer line from the PS towards the AD and the antiproton production target.

BATCH COMPRESSION IN THE PS

At constant average beam energy, the harmonic number of a bunched beam can be changed by slowly increasing the RF voltage at a final harmonic and thereafter decreasing the voltage at the initial one. As the distance between bunches is directly proportional to the period of the RF wave, increasing the harmonic number compresses the length of a bunch train. Sequentially raising the harmonic number in several steps to approach bunches is referred to as batch compression [14].

Since 2006, the harmonic number sequence for the batch compression of four consecutive bunches at the 26 GeV/c flat-top was $h_{\mathrm{PS}} = 8 \rightarrow 9 \rightarrow 11 \rightarrow 13 \rightarrow 15 \rightarrow 17 \rightarrow 20$. When incrementing the harmonic number by two units, the initial bunch train must cover less than half of the circumference. With equal RF voltages on both harmonics, h_1 and $h_2 = h_1 + 2$, the envelope of the RF amplitude is modulated around the circumference, with two nodes of zero net voltage. With five bunches extending over $5/9^{\mathrm{th}}$ of the circumference at the start of the second step, $h = 9 \rightarrow 11$, this RF manipulation would fail (Fig. 3). Several sequences were analyzed in terms of area of the five buckets throughout the entire batch compression manipulation, while minimizing the number of additional harmonic number steps to reduce complexity and duration of the process. With two additional steps, the new harmonic number sequence becomes $h_{\mathrm{PS}} = 8 \rightarrow 9 \rightarrow 10 \rightarrow 11 \rightarrow 12 \rightarrow 14 \rightarrow 16 \rightarrow 18 \rightarrow 20$. Figure 4 summarizes the normalized bucket area of the five central buckets during the improved batch compression.

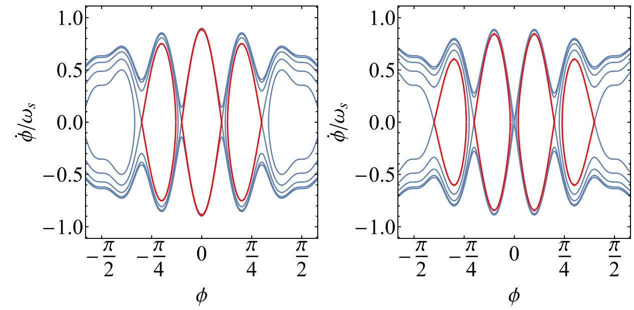

Figure 3: Longitudinal phase space when RF voltages are equal at $h = 9$ and $h = 11$. While at maximum four bunches (red separatrix contours) are available (left), not more than three buckets exist when the relative RF phases are chosen to obtain a batch compression symmetric around a centre bucket (right).

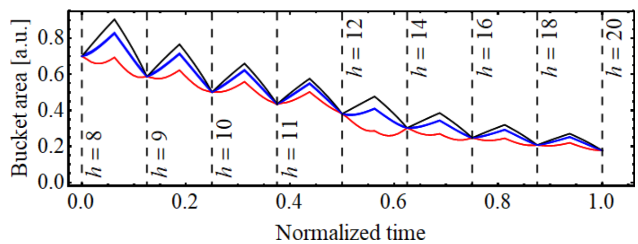

Figure 4: Normalized bucket area of outer (red), middle (blue) and central (black) buckets for the upgraded harmonic number sequence.

Nine of the ten ferrite-loaded cavities, tunable from 2.8 MHz to 10 MHz, are split into three equal groups. While two groups are active simultaneously for each handover, the third group is already tuned to the subsequent harmonic number [15]. To suppress the strong transient beam loading due to the partially filled ring, the cavities are equipped with 1-turn delay feedback [16, 17] to reduce their impedances. Following the new harmonic number sequence the batch compression is extremely clean (Fig. 5). Only at highest intensities beyond $2 \cdot 10^{13}$ p/p, about 40% above the one achievable with the previous four-bunch scheme (some $1.5 \cdot 10^{13}$ p/p), few particles ahead of the batch escape from the buckets during the harmonic handover from $h = 16$ to $h = 18$, causing additional beam loss at extraction.

Following the batch compression, the bunches are synchronized with an external reference at $h = 20$, which also pilots the capture RF system ($h_{\mathrm{AD}} = 6$) in the AD [18]. Prior to extraction, the bunches are compressed by stretching the longitudinal distribution at the unstable fixed-point with subsequent bunch rotation [19].

Bunch length and shape slightly degrade (Fig. 6) due to transient beam loading and a high frequency instability during the final bunch rotation. The outer bunches of the batch compression suffer most.

FIVE BUNCHES IN AD

Adding one more bunch in the AD halves the gap duration for the injection kicker, and its fall time had to be carefully

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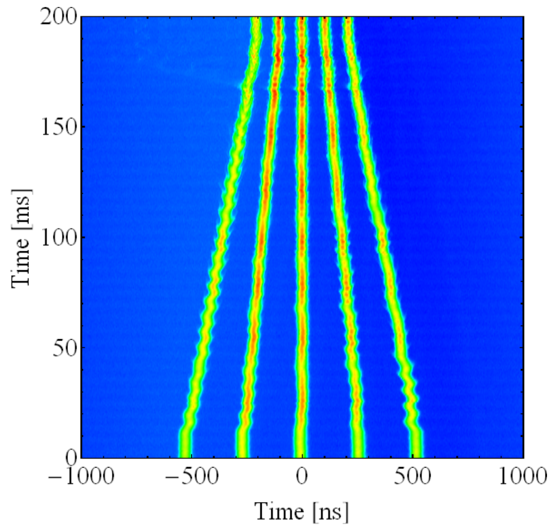

Figure 5: Mountain range plot of the batch compression of five bunches, measured at a total intensity of $2.1 \cdot 10^{13}$ p/p. The harmonic number sequence is $h_{PS} = 8 \rightarrow 9 \rightarrow 10 \rightarrow 11 \rightarrow 12 \rightarrow 14 \rightarrow 16 \rightarrow 18 \rightarrow 20$.

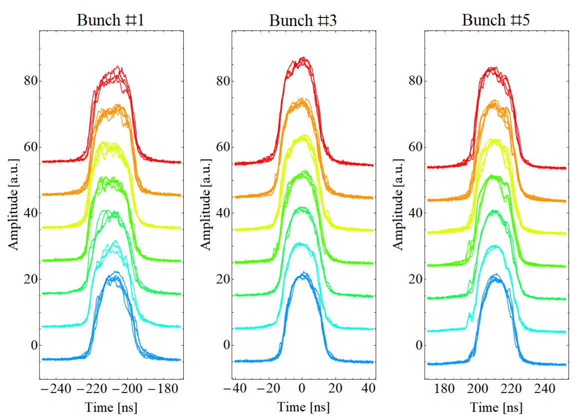

Figure 6: Bunch profiles at extraction with increasing intensity from $1.6 \cdot 10^{13}$ p/p (blue) to $2.1 \cdot 10^{13}$ p/p (red).

aligned with the only remaining empty bucket. A typical mountain range plot of the longitudinal beam signal during the first milliseconds after injection is shown in Fig. 7, and

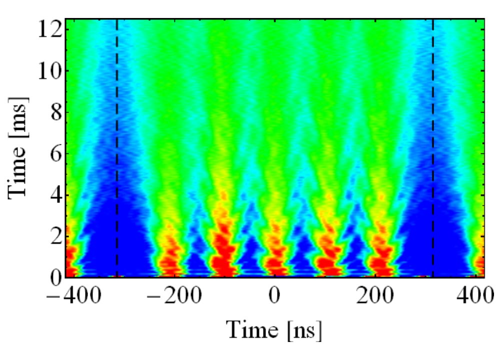

Figure 7: Mountain range plot of five bunches observed after injection into the AD. The first beam profiles of the acquisition are perturbed by debris from the target. The dashed lines mark one revolution period (629 ns) of the AD.

no noticeable beam loss is caused by the shorter kicker gap.

The antiproton bunches have the same time structure as the primary beam extracted from the PS. To rapidly reduce their momentum spread, the bunches are firstly rotated in the longitudinal phase space [15, 19] and then slowly debunched adiabatically with the capture RF cavities of the AD [18].

INTENSITY RAMP-UP

Thanks to the optimized harmonic number sequence of the batch compression in the PS, especially avoiding the large step from $h = 17$ to $h = 20$, the batch compression became significantly more robust. Additionally, distributing the intensity over more bunches allows to favourably increase the total intensity compared to the previous four-bunch scheme. The beam loss from injection to extraction in the PS remains very small, well below 2%, even at the highest intensities of $2.1 \cdot 10^{13}$ p/p, and also the transmission in the transfer line to the target is only slightly reduced. The target itself, as well as the radiation in the experimental area downstream of the target zone, now become the main limitations.

The intensity of the primary proton beam on target (Fig. 8) was ramped up while carefully monitoring the antiproton yield, resulting in about $3.5 \cdot 10^7$ $\bar{p}$/p at injection into ELENA at the end of the 2022 run, produced by almost $1.8 \cdot 10^{13}$ p/p accelerated in the PS and $1.6 \cdot 10^{13}$ p/p on target.

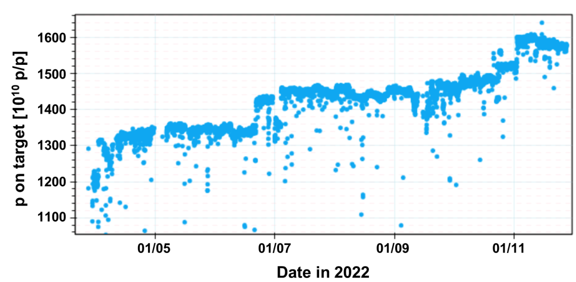

Figure 8: Intensity increase of the primary proton beam on target during the 2022 run.

CONCLUSIONS

Driven by the LIU project, the brightness in the PSB with Linac4 injecting at 160 MeV has doubled. Two bunches can therefore be produced in a PSB ring with sufficiently small transverse emittances for the transfer line and the antiproton production target. Hence the PSB can deliver five bunches with one transfer to the PS. The batch compression at the PS flat-top has been redesigned for the longer train, also making it more robust against transient beam loading. Up to 40% higher total intensities have been demonstrated at PS extraction. Already with a partial increase 20% more antiprotons are achieved in the AD. The intensity ramp-up will continue in 2023, and future studies will explore the full potential of the novel operational beam production scheme.

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