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INTENSITY REACH OF THE BARRIER-BUCKET MULTI-TURN TRANSFER FOR FIXED-TARGET PROTON BEAM FROM PS TO SPS

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Abstract

Fixed target beams are extracted in five turns from the Proton Synchrotron (PS) at CERN to fill almost half the circumference of the Super Proton Synchrotron (SPS) with each transfer. To avoid beam loss during the rise time of the extraction kickers a longitudinal gap is generated with an RF barrier-bucket scheme. However, the synchronization of the gap with the PS extraction and SPS injection kickers requires the RF system to operate without any beam feedback during the transverse splitting process at the flat-top. Low RF voltage is moreover required during the process to keep a small momentum spread. Both conditions are unfavorable for longitudinal stability and a campaign of beam measurements has been performed to explore potential intensity limitations. Up to $3.3 \cdot 10^{13}$ protons have been accelerated and remained longitudinally stable at high energy. Longitudinal coupled-bunch instabilities occurring at the intermediate plateau below transition energy are moreover cured by a dipole-mode feedback system initially developed for LHC-type beams. The contribution summarizes the results of the beam tests, probing the limits of the fixed-target proton beam production.

INTRODUCTION

With its circumference of 6.9 km the Super Proton Synchrotron (SPS) at CERN is eleven times larger than its injector, the Proton Synchrotron (PS). To avoid too many transfers to fill the circumference of the SPS, a Multi-Turn Extraction (MTE) scheme is applied to transfer a coasting beam within five turns from the PS [1]. At the flat-top momentum of 14 GeV/c the beam is split transversely into four islands and a central core. During the splitting the bunches are longitudinally held at low RF voltage at harmonic $h = 16$ to keep small momentum spread. In the past they were completely debunched prior to extraction, and most of the beam loss during the rise time of the extraction kickers was captured by a dummy septum. These extraction losses have recently been removed by debunching into a barrier-bucket [2], introducing a longitudinal gap during the rise time of the kickers. The combined extraction barrier-bucket MTE process did not only allow to retract the dummy septum, which increased the acceptance of the extraction channels for all fast extraction beams, but it also paves the way to an intensity increase of the fixed-target beam for the SPS.

Past high-intensity study campaigns were compromised by the maximum intensity reach of the PS Booster (PSB), and two injections with a 1.2 s long flat-bottom were necessary to reach well above $3 \cdot 10^{13}$ protons after injection in the PS [3]. In this experimental configuration up to $3.9 \cdot 10^{13}$ protons have been accelerated on $h = 8$ with more than $4.2 \cdot 10^{13}$ protons injected [4]. Following the connection of Linac4 and the important upgrades in the framework of the LHC Injector Upgrade (LIU) project [5], the PSB can comfortably extract intensities above $4 \cdot 10^{13}$ protons, well beyond the present intensity limit in the PS.

ACCELERATION CYCLE

The PSB delivers eight bunches in total, two from each ring, which are accelerated in the PS (Fig. 1) on $h = 8$ to an

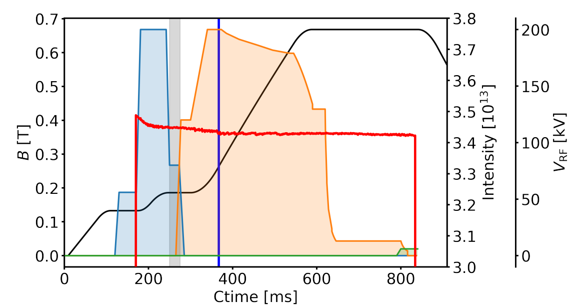

Figure 1: Bending field, B (black) together with the RF voltage, V_{RF} programs at $h = 8$ (blue) and $h = 16$ (orange) for the barrier-bucket MTE cycle. Cycle time (Ctime) refers to the time with respect to the start of the cycle, injection being at 170 ms, i.e. C170. The RF voltage to generate the barrier-bucket (green) is only activated shortly before extraction. The grey shaded area marks controlled longitudinal blow-up with a high-harmonic RF system. The transition energy is crossed about 200 ms after injection (blue vertical line). The transverse splitting of the MTE takes place during the long flat-top with low RF voltage at $h = 16$.

intermediate plateau at a kinetic energy of 3.1 GeV. At this plateau controlled longitudinal blow-up [6] and a bunch-pair splitting [7] from $h = 8$ to 16 is performed to reach the longitudinal beam conditions for crossing transition energy and acceleration to the flat-top.

The transverse splitting of the MTE only works with a beam of low momentum spread. Consequently the RF voltage must be small ($V_{\mathrm{RF}} \simeq 12$ kV from one single cavity) during the about 150 ms of the process. These are very unfavourable conditions for the evolution of longitudinal coupled-bunch instabilities, and quadrupolar coupled-bunch bunch oscillations had been previously observed at intensities as low as $1.7 \cdot 10^{13}$ protons [8]. An important reduction

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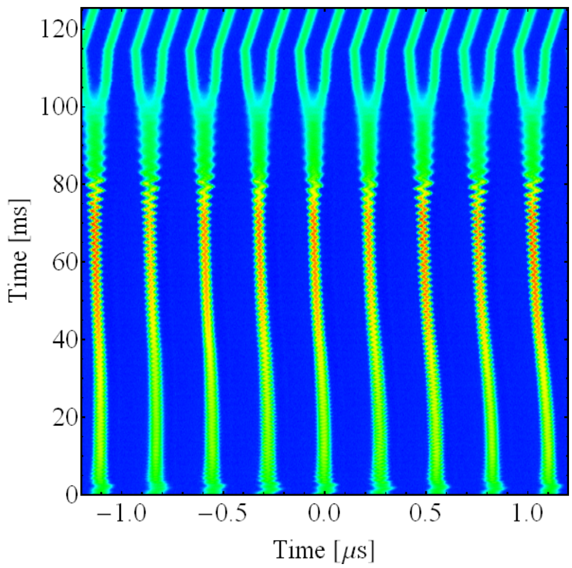

Figure 2: Evolution of the measured bunch profiles from injection at time zero (C170) to the end of intermediate plateau. The total beam intensity for the example measurement was about $3 \cdot 10^{13}$ protons. The horizontal time range covers slightly more than one revolution period, i.e. the last bunch (right) is first bunch (left) one turn later, and the overall shift of the bunches to the left during acceleration is caused by uncompensated delay of the observation trigger.

of the RF cavity impedances by evolved feedback has been achieved with the upgrades in the framework of the LIU project [5, 9]. However, the synchronization of the barrier-bucket with the kicker rise times and the circulating beam in the SPS requires the critical low-voltage phase to be performed at fixed RF frequency. This practically excludes the application of a beam phase loop, as well as conventional feedback to improve longitudinal stability.

Front Porch

To fit the time required for the barrier-bucket manipulation and synchronization within the constraint of the overall cycle duration (1.2 s), the low- and medium energy parts are compressed as much as possible (Fig. 1). Hence no controlled longitudinal emittance blow-up to modify the distribution for improved longitudinal stability can be applied before the arrival on the intermediate plateau (Fig. 1, grey shaded area). Strong dipole coupled-bunch oscillations evolve before the bunch-pair splitting, as illustrated in Fig. 2. The dipole coupled-bunch oscillations rising before the bunch-pair splitting are probably seeded by the residual phase and energy errors of the bunches injected from the four different PSB rings. Increased controlled longitudinal emittance blow-up starting from the arrival at the plateau stabilizes them, but at the expense of a longitudinal emittance too large for transition crossing on harmonic $h = 16$.

Similar oscillations were already observed in the past [10]. The coupled-bunch feedback [9] originally developed to stabilize LHC-type beams accelerated at $h = 21$ has been successfully reconfigured. Synchrotron frequency side-bands of

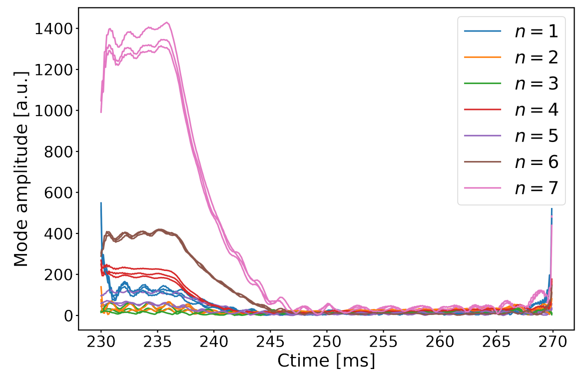

Figure 3: Damping of the coupled-bunch instabilities by the feedback in mode domain for $2 \cdot 10^{13}$ protons (three cycles). The mode number, n indicates a phase advance of $\Delta\phi = 2\pi n/h$ from bunch to bunch. The amplitudes are derived from the synchrotron frequency side-bands [11].

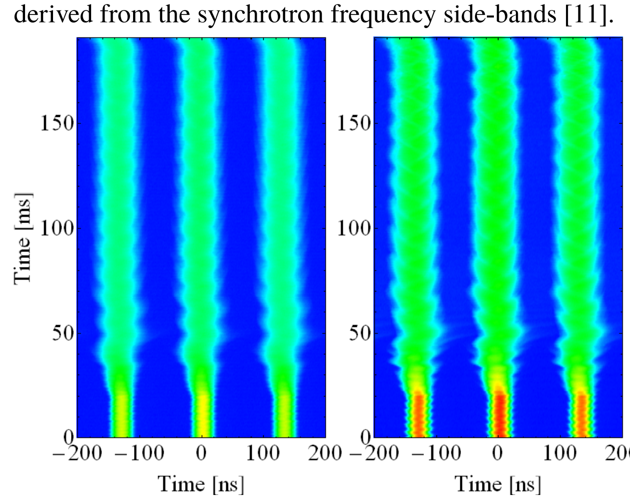

Figure 4: Bunch profile evolution of three out of 16 bunches ($h = 16$) during the long flat-top. The beam intensity was $2.5 \cdot 10^{13}$ (left) and $3.3 \cdot 10^{13}$ (right) protons. The handover from the conventional to the barrier-bucket RF system takes place just after the end of the acquired time window (Fig. 1, around C800).

the revolution frequency harmonics are detected as a signature of the coupled-bunch oscillation modes at $4 \ldots 7 f_{rev}$ and corrected at $4 \ldots 1 f_{rev}$ by a wide-band Finemet longitudinal kicker (Fig. 3). The dipole oscillations are fully suppressed, and the feedback has margin for further intensity increase or reduction of the longitudinal emittance.

Flat-top

The evaluation of the longitudinal stability during the transverse splitting for the MTE was a major motivation for the campaign of high-intensity studies. In the absence of feedback due to the frozen RF frequency, any instability can develop freely. Figure 4 illustrates the longitudinal stability during the long period with low RF voltage for the transverse splitting and at fixed frequency, as required for the synchronized extraction. The RF voltages still decreases during the initial part and then stays constant at about 12 kV. Small dipole oscillations are triggered by the switch-over from

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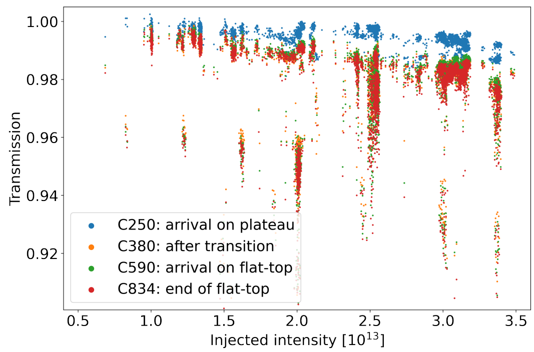

Figure 5: Transmission versus injected beam intensity at relevant times in the cycle, indicated by their Ctimes (milliseconds with respect to the start of the cycle).

beam-controlled acceleration to fixed frequency, just after arrival at flat-top. At an intensity of $2.5 \cdot 10^{13}$ protons (left) these oscillations smear out due to the non-linearity of the synchrotron frequency distribution. Close to the highest measured intensity of $3.3 \cdot 10^{13}$ protons (right) these oscillations tend to persist, indicating the vicinity of the instability threshold. Note that also the initial longitudinal emittance was larger at higher intensity, indicated by the longer bunches. At both intensities the beam quality was nonetheless sufficient for a clean barrier-bucket MTE extraction.

INTENSITY RAMP-UP AND TRANSMISSION

The beam intensity has been varied from about 2 to $3.4 \cdot 10^{13}$ protons while minimizing losses throughout the acceleration cycle. The tests were interrupted by a coincidental vacuum leak due to a non-conform RF bypass [12], until all other of these units had been checked.

Figure 5 summarizes the transmission until several key moments in the acceleration cycle versus intensity. The main beam losses take place during first part of the acceleration, before the arrival at the intermediate plateau (blue, C250), as well as during the re-acceleration and after transition crossing (orange, C380). Beyond transition energy almost the entire beam is brought up to the arrival at the flat-top (green, C590) and to extraction (red, C834). An example of the intensity along the entire cycle for the maximum of almost $3.5 \cdot 10^{13}$ injected is shown in Fig. 1. Even in this intensity regime of about 1.5 times the highest operational values, an overall transmission of almost 98% can be maintained. Performance through the entire chain is analyzed in [13].

BEAM STRUCTURE AT EXTRACTION AND TRANSFER TO SPS

Prior to extraction, the 16 bunches are debunched into the barrier-bucket [2]. Pre-distortion of the RF drive signal to the wide-band amplifier and cavity system must be applied for a sinusoidal voltage at the gap of the Finemet cavity in all cases. Although adapting this voltage function to include beam loading was not easily possible for technical reasons,

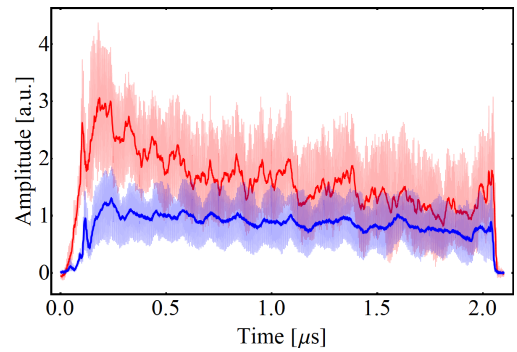

Figure 6: Bunch profiles few turns before extraction at $1.2 \cdot 10^{13}$ (blue) and $3.0 \cdot 10^{13}$ protons (red). The thin, shaded traces show the original bunch profiles recorded with a sampling rate of 4 GS/s, while a moving average (factor of 20) has been applied to obtain the dark lines. The large spread is caused by a 200 MHz structure imprinted intentionally by dedicated RF cavities. It is essential for the downstream SPS to capture and observe the beam.

intensity scans were performed with the program optimized without beam.

The resulting typical bunch shapes few turns before extraction are compared for two extreme intensities in Fig. 6 [14]. At lower intensity (blue) the long bunch at extraction is almost perfectly flat. However, for an intensity of $3.0 \cdot 10^{13}$ protons the bunch profile exhibits a strong asymmetry, with significantly more particles trapped towards the head of the bunch. With increasing beam intensity the beam induced voltage also rises proportionally, requiring an intensity optimization of the pre-distorted drive signal to the wideband cavity.

No systematic beam studies have yet been performed in the SPS, but up to $2.7 \cdot 10^{13}$ protons were injected (single transfer) during a preliminary test. The transient beam loading due to the additional gaps from the barrier-bucket can be handled by the upgraded RF system of the SPS without issues and leaves sufficient headroom for future intensity increase.

CONCLUSIONS

Exploring intensity limitations of the barrier-bucket MTE beam in the PS is essential input for future fixed-target proton physics. Longitudinal stability must be maintained during the transverse splitting at flat-top, where the RF frequency is frozen and conventional feedback cannot be applied. A maximum intensity of $3.3 \cdot 10^{13}$ protons has been reached reliably and with acceptable losses at the 2%-level. Future studies foresee the optimization of the transverse parameters and a further increase in intensity. The focus will thereafter move to the SPS, pushing intensity ideally up to the limitation of its beam dump.

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