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PROGRESS IN THE BEAM PREPARATION FOR THE MULTI-TURN EXTRACTION AT THE CERN PROTON SYNCHROTRON

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A new type of extraction based on beam trapping inside stable islands in the horizontal phase space will become operational during 2008 at the CERN Proton Synchrotron. A series of beam experiments was carried out to prove lossless capture with high intensity and multi-bunched beams, up to 1.5 × 10^{13} protons per pulse, in preparation of the extraction commissioning. These fundamental steps for the new Multi-turn Extraction are presented and discussed in details.

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A new type of extraction based on beam trapping inside stable islands in the horizontal phase space will become operational during 2008 at the CERN Proton Synchrotron. A series of beam experiments was carried out to prove loss-less capture with high intensity and multi-bunched beams, up to 1.5×10^{13} protons per pulse, in preparation of the extraction commissioning. These fundamental steps for the new Multi-turn Extraction are presented and discussed in details.

INTRODUCTION

A new multi-turn extraction (MTE) [1] is due to become operational during 2008 at the CERN Proton Synchrotron (PS) [2], in order to replace the Continuous Transfer (CT) between the PS and the Super Proton Synchrotron (SPS) at 14 GeV/c [3]. The key feature of such a new scheme is the beam splitting and trapping inside four stable islands of the horizontal phase space, which are generated by non-linear magnetic elements (sextupoles and octupoles) and separated by sweeping the horizontal tune through the one-fourth resonance, $Q_x = 6.25$. The combined use of non-linear magnetic fields and programmable corrector quadrupoles allows to create five separate beamlets (four in the islands plus one in the core) without any interaction of the beam with the accelerator hardware. This is of great help reducing beam losses at extraction. Indeed, during the traditional CT the beam is shaved and separated by an electrostatic septum. The interaction between the beam and the septum blade is source of important beam loss, at the septum as well as in the immediate downstream sections, part of the beam hitting the blade and hence being reflected with irregular trajectories [4]. Moreover, the beamlets generated through the MTE are better matched in terms of optics and RMS parameters compared to the slices created during the CT [2].

Dedicated measured campaigns in the PS have been carried out since 2002 in order to assess both the feasibility and the robustness of the beam splitting. This was a critical point before the design and the installation of any new hardware. After a loss-free beam splitting in five beamlets was proved and shown reliable [5], a design study was launched for the replacement of the CT with the new MTE. Among other items, a new orbit bump (slow and fast) had to be designed and realized around the extraction channel, while new enlarged vacuum chambers had to be placed in the extraction region in order to provide sufficient clearance to the five beamlets.

The beam preparation has been a crucial activity, together with the hardware installation and upgrade. In particular, the loss-less beam splitting had to be realized under new conditions. First, the long magnetic cycle of 2.4 s used during the past experimental campaigns had to be replaced by an operational one of 1.2 s, out of which only 50-90 ms (corresponding to about $24 - 34 \ \times 10^3$ turns at 14 GeV/c) are available for the splitting. Second, the new PS configuration differs from the ones used in the past. Among other items, the non-linear magnetic elements used for the capture were upgraded and displaced. Additional non-linear forces can be applied by means of extra coils mounted on the pole faces of the combined function main dipoles: the existing system with three independent currents was upgraded to control independently five physical parameters (such as tunes, chromaticities plus one additional free parameter) by means of five new separate circuits [6]. Third, the loss-less beam splitting, so far tested with a single-bunch beam of about 3×10^{10}, had to be retrieved with a four-bunch beam of 1.5×10^{13} protons per pulse. These and other aspects are reported in this paper with the results achieved so far, together with an outlook at the completion of the beam commissioning.

2007 CAMPAIGN

The first part of the 2007 run was devoted to the commissioning of the new five-current working point tuning system, which allows the simultaneous setting of tune and chromaticity in both planes, plus one additional free parameter. The old three-current system allowed the adjustment of the transverse tunes and of chromaticity in one plane only. The new system inevitably modified both the linear and the non-linear settings of the PS. This affected also the beam splitting, whose parameters (mainly the currents of corrector quadrupoles, sextupoles and octupoles) had to be reprogrammed. Due to some technical issues that arose with the new tuning system, a loss-less beam splitting could be achieved only towards the end of the summer. Meanwhile, dedicated experiments were carried out to exploit the possibility of splitting the beam in various numbers of beamlets while crossing resonances different from the one-fourth. The main results are reported in Ref. [7].

The next step was to obtain a loss-free beam splitting with a four-bunch beam of 1.5×10^{13} protons per pulse. Such intensity is achieved by injecting in the PS four bunches from the four rings of the PS booster (PSB). It is worth mentioning that the nominal beam to be injected from the PSB into the PS will eventually be of eight bunches, even though with the same intensity per pulse. This will be obtained by doubling the PSB harmonic number from h=1 to h=2. At the beginning of November a

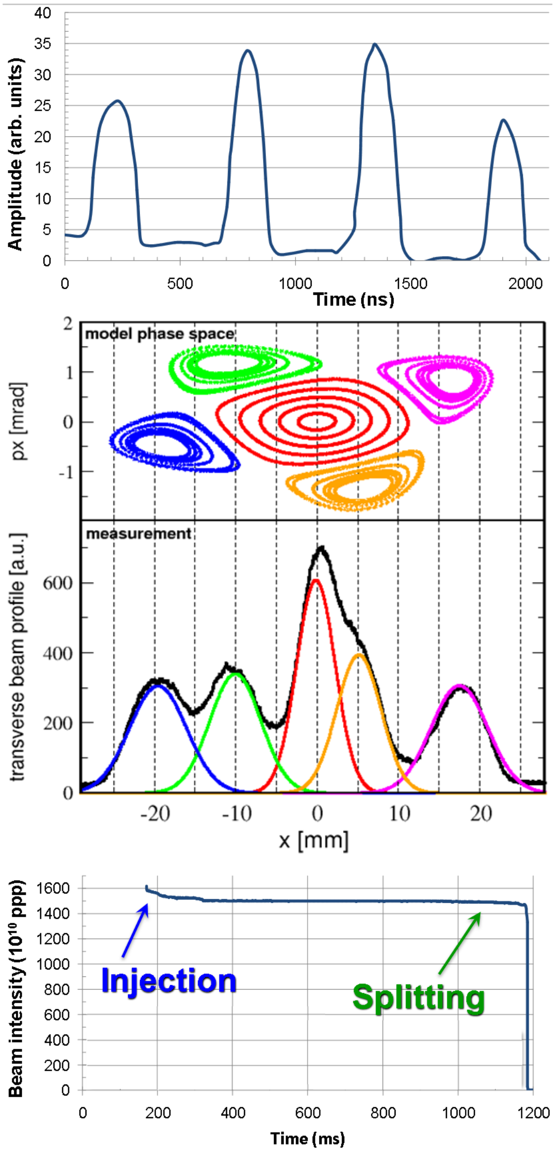

Figure 1: The four-bunch beam structure (top) together with the horizontal beam profile measured at the end of the capture (center), and the beam intensity registered by the current transformer (bottom). The measured profile is compared with the model phase space.

four-bunch beam of 1.48×10^{13} proton per pulse was successfully split without any measurable loss. This is documented by the three pictures of Fig. 1. In the upper plot the four bunches are shown along the PS circumference (one turn corresponds to 2.1 μs at 14 GeV/c). In the centre figure, the horizontal beam profile measured with a flying wire scanner at the end of the capture process is shown, together with a multi-Gaussian fit [7] that clearly show the presence of four islands surrounding the beam core. In the upper part of the picture the phase space portrait at the location of the wire scanner, computed by using the PS model, is displayed. The peaks in the measured profile match very well the positions of the islands in the model phase space. In the lower figure, the beam intensity measured by a current transformer over the entire PS cycle (of 2.4 s, even though the beam is extracted after 1.2 s) proves that the splitting is loss free. Small losses towards the end of the cycle appear because the beam is eventually merged together before the extraction, by rapidly crossing the resonance in the opposite direction. This gymnastic will however not be performed during the operational MTE and that loss is of no concern.

A special measurement was carried out in order to validate the preservation of the vertical emittance during the beam splitting. Non-linear coupling between the transverse planes induced by sextupoles and octupoles is expected to be small, the ratio between the two beta functions being $\beta_y/\beta_x \simeq 0.5$ at their location. Any unexpected emittance growth in the vertical plane would however be of concern, in terms of vertical clearance in the PS extraction channel, as well as in the downstream SPS. Measurements show that the vertical profile remains well fitted by a Gaussian whose RMS size increase of about 4.5%. This means that the emittance growth is $\delta\epsilon_y/\epsilon_y = 2\delta\sigma_y/\sigma_y \simeq 9\%$, which is acceptable.

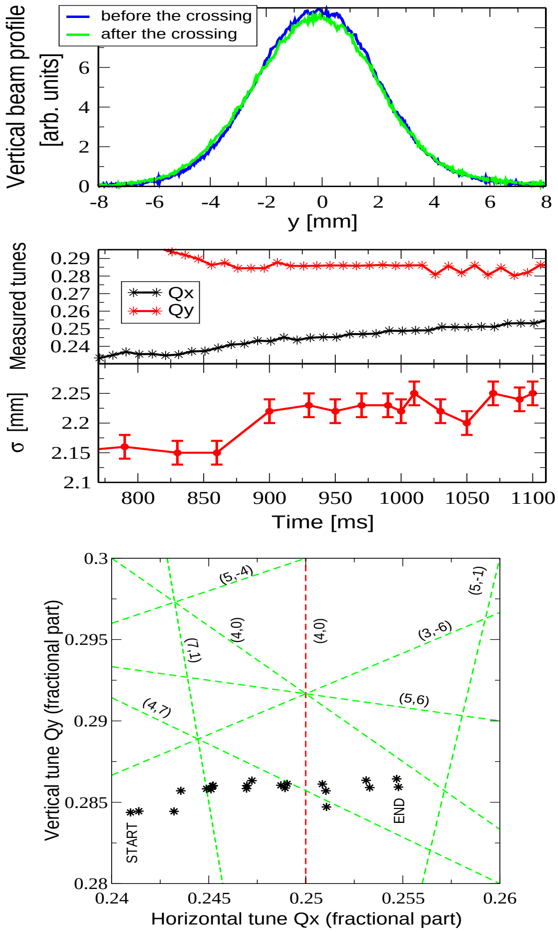

Figure 2: Vertical beam profile measured before and at the end of the capture (top). Variation of the RMS beam size and tune variation during the resonance crossing (centre): for each point, three measurements were taken. The resonance is crossed when the fractional part of the horizontal tune $Q_x = 0.25$ (bottom).

2008 STARTUP

From the splitting process point of view, the most important aspect of the new PS configuration is the installation in the PS straight sections SS39 and SS55 of two independent new octupoles, that replace an old SPS-type installed in the straight section SS21. The 2.4m-long section SS21 houses now one of the three new kickers required for the new MTE fast bump. Each octupole has been installed next to a sextupole and the horizontal phase advance between the two pairs is of 2π. An additional family of corrector octupoles is available for a fine tuning of the non-linear parameters. First, the tune dependence on the momentum offset $\Delta p/p$ was measured with all non-linear elements switched off, see upper plots of Fig. 3. By fitting the curve with a polynomial curve, the MADX-PTC [8] non-linear lattice model of the bare PS could be inferred by using the technique described in [9]. The same measurement was then repeated by powering separately each octupole and sextupole. In the centre plots of Fig. 3 the chromaticity curve is plotted for the case with one sextupole powered with 251 A. By using the PS model previously calculated, MADX-PTC computed the sextupole current that best reproduces the new first-order term of the polynomial expansion. The same procedure was eventually repeated for the second sextupole and for the two octupoles (the second-order polynomial term is used in this case), showing an overall go od agreement between set and measured currents.

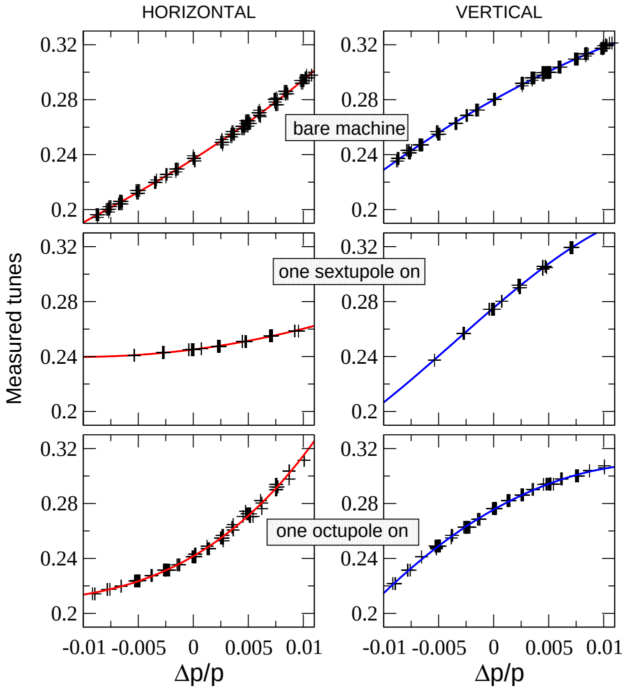

Figure 3: Measured chromaticity for three different machine settings: bare machine with all non-linear elements switched off (top), with one sextupole powered with 251 A (centre), and with one octupole powered with -100 A (bottom).

COMPLETION OF THE BEAM COMMISSIONING

The beam commissioning has been separated in two phases. In the first one, the beam splitting with a four-bunch beam will be resumed under operational conditions. Meanwhile, a pencil beam will be used to commission the new extraction slow bump. In the second phase, the new fast bump will be tested, again using a pencil beam. First extraction tests will then be performed sending the ejected beamlets on a beam dump in the transfer line between the PS and the SPS. Once the extraction from the PS will be well tuned, the five beamlets will be injected into the SPS. There, first-turn measurements of the beamlets' trajectories will be used to match the transfer line optics (for the first tests, the same optics of the CT will be used). It is already expected to have a beamlet-dependent trajectory in the transfer line (as well as in the SPS) as result of a non-perfect closure of the beamlets orbit in the PS. This is an intrinsic feature, the beamlets experiencing different feed-down fields according to their horizontal displacement. Nevertheless, dedicated kickers exist in the transfer line, that are able to impart a turn-by-turn variable deflection [10]. The correction of the beamlets' trajectory will then become the last step to guarantee an operational multi-turn extraction.

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