FIRST RESULTS FOR THE BEAM COMMISSIONING OF THE CERN MULTI-TURN EXTRACTION

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Abstract

The Multi-Turn Extraction (MTE), a new type of extraction based on beam trapping inside stable islands in horizontal phase space, has been commissioned during the 2008 run of the CERN Proton Synchrotron. Both single- and multi-bunch beams with a total intensity up to 1.4 10^{13} protons have been extracted with efficiencies up to 98%. Furthermore, injection tests in the CERN Super Proton Synchrotron were performed, with the beam then accelerated and extracted to produce neutrinos for the CERN Neutrino-to-Gran Sasso experiments. The results of the extensive measurement campaign are presented and discussed in detail.

INTRODUCTION

Already early in 2001, a new extraction method has been proposed based on beam splitting into stable islands [1]. The main ingredient of the novel extraction is that the beam is separated in transverse phase space using nonlinear magnetic elements (sextupoles and octupoles) to create stable islands. A slow (adiabatic) horizontal tune-variation is programmed to cross an appropriate resonance, in the Proton Synchrotron (PS) case the 1/4. The five equally-populated beamlets resulting from the splitting process are extracted one by one on successive turns, thanks to slow and fast bumps which deflect the beam over five turns toward the extraction line. The goal of the extraction is to provide beam to the Super Proton Synchrotron (SPS) at 14 GeV/c for the CERN-to-Gran Sasso Experiment and for fixed-target experiments, reducing to a minimum the losses in the PS with respect to the existing extraction. A detailed description of the method and hardware implementation required in the PS can be found in [2]. The different steps which led to the first extraction ever realised with this method are described in the following. In May and June 2008, beam splitting was resumed using the newly installed sextupoles and octupoles, achieving a loss-free capture with a single bunch of about 3 10^{12} protons. At the same time the new extraction slow bump was commissioned so that it was ready for the extraction tests in July 2008 when the new kicker Pulse Forming Networks (PFN), completed and hardware-commissioned, became available for the beam tests. Then, on 1 August, five beamlets with almost the same intensity were successfully created from a single bunch of 3 10^{12} protons and extracted in the first part of the transfer line, TT2, to the Super Proton Synchrotron (SPS). The rest of the commissioning period until the end of the SPS-physics run on 3 November 2008 was dedicated to studying the best longitudinal structure for beam delivery and injection into the SPS, and it included a campaign of measurements of the optical parameters in the transfer line between the PS and the SPS machines. These various steps of the beam commissioning are described in the following sections.

NON-LINEAR MAGNETIC ELEMENTS

The stable islands are created by a set of dedicated non-linear elements: in total two independent octupoles and four sextupoles connected in two independent groups have been installed, together with new power converters, during the PS shutdown 2007-2008 [3]. The magnetic multipole effective strengths have been cross checked by measuring the horizontal and vertical non-linear chromaticity for a given set of currents. The measurements have been then fit with a MADX model of the PS to deduce the expected current provided by each power converter. One example of the measurements for an octupole is shown in Fig. 1 together with the fit from the model. The results of this campaign proved that all the sextupole plus one octupole strengths are well within the specifications, whereas the second octupole is delivering a lower gradient by about 20%. Further investigations showed that the magnet gradient is within specification [3] and the power converter is also delivering the required current. The reduction in octupolar strength is most probably related to a magnetic feed-down effect produced by an orbit distortion in the section of the magnet.

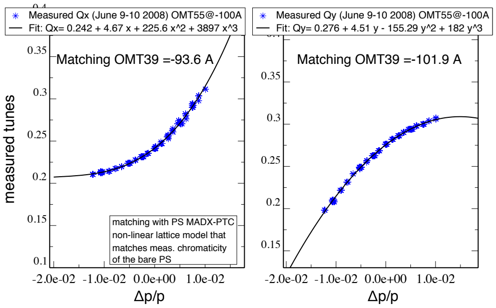

Figure 1: Example of non-linear chromaticity measurement for one of the MTE octupoles.

SLOW AND FAST BUMP

Once the beamlets are generated, they are separated by means of a tune variation to accomodate between two islands the blade of the extraction septum. At this stage, a slow bump 7.5 ms long[1] pushes the beamlets towards the septum blade. The jump of the blade is produced by a set of kickers which fire during the last five turns, with one PS turn ≈ 2.1 μs long. The new slow bump has been designed to ensure at the same time the bump closure over 7.5 ms and to optimise the beam clearance in the extraction region. These two goals have been realised by installing six independent bumpers. Fig. 2(left) shows the measured orbit at the maximum bump height with respect to the expected bump, demonstrating a very good agreement between the two. During the bump rise time, the beam is no more centered with respect to the main magnets over about 12 sections in the region of the extraction. The PS is composed of 100 combined function dipoles (Main Units, MU) interleaved by 100 Straight Sections (SS) in which auxiliary magnets are installed. The control of the linear and nonlinear working point is performed by powering four extra coils mounted on top of each of the MU poles and one supplementary winding of the main coil. The feed-down of those fields induces a variation of the horizontal tune of the order of 1.5 10^{-3}.This variation reduces the clearance available between the islands for the septum blande at extraction. A tune correction, as presented in Fig. 2(right), has been implemented to compensate for this effect. The extraction proper is realised by firing five kickers (KFA): those in SS13, SS21 and SS9 deflect the beam constantly for five turns creating a closed bump, whereas those in SS4 and SS71 are used on top of the others to extract the central island during the last turn. The commissioning of the new kickers, with the PFNs available since the beginning of July 2008, started with the strength calibration tests. The successful results are presented in Fig. 3(left), in which the predicted trajectory distortion induced by one of the kickers for a given strength has been compared with the expected one. Then the kicker timings and strengths have been finely adjusted to achieve the bump closure and the correct bump amplitude (see the results in Fig. 3, right).

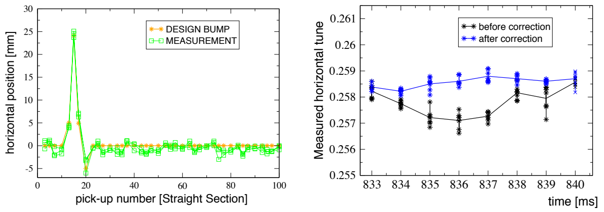

Figure 2: Beam trajectory at the maximum of the extraction bump (left) and tune compensation during the bump rise (right).

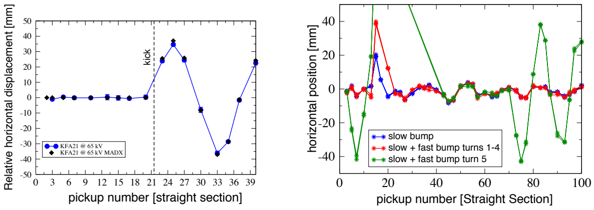

Figure 3: Tests of the new KFA21 calibration (left). The trajectories during the turn before the firing of the fast kickers, the first four extraction turns, and the last turn show the precise closure of the slow and fast bump (right).

EXTRACTION AND LOSS OPTIMISATION

The first real MTE extraction has been performed on 1 August, when a single bunch beam of about 3 10^{12} protons has been sent to an external dump in the PS-SPS transfer line. Fig. 4 (left) shows the measured horizontal beam profile of the beamlets in the PS at the end of the splitting process and prior to extraction. A fit of the five beamlets is also superimposed. Fig. 4 (right) shows the intensity signal of a pick-up in the PS-SPS transfer line of the extracted beam. Each of the five peaks corresponds to a beamlet extracted over a single turn. The distance between them corresponds to the PS revolution time of 2.1 μs. As expected, the five peaks feature about the same intensity, a clear sign that the equally populated islands were correctly extracted. The rest of the commissioning was devoted to the preparation of the operational magnetic cycle, the study of the extraction with multi-bunch beam and the determination of the most suitable longitudinal structure to be injected in the SPS. This has been another crucial point of the study. The beamlet formation, in fact, is not sensitive to the number of bunches in the machine, but it is sensitive to the beam momentum spread, since via chromaticity a large momentum spread creates a large tune modulation, inducing trapping/detrapping phenomena and reducing the capture efficiency. The losses at extraction, however, depend on the bunch spacing due to the finite rise time of the kickers. In particular, the kicker rise time is longer than the h=8 PS bunch spacing, the rise time being about 350 ns and the bunch spacing about 260 ns. This implies that a

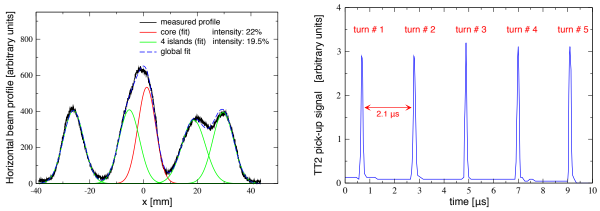

Figure 4: Transverse profile of the beamlets before extraction (left) and intensity signal of a pick-up in the PS-SPS transfer line of the extracted beam.

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[1] duration counted from zero bump current up to the maximum current.

part of the beam will be intercepted by the extraction septum during the kicker rise. The situation becomes worse if the h=16 harmonic is preferred or if the beam is debunched: the losses are nearly doubled going from 0.6% of the circulating intensity for h=8 up to 0.9% and 1% for the h=16 and debunched cases, respectively [2]. A detailed series of studies, presented in [4], has been done by injecting a beam in the SPS with different longitudinal structures from the PS and assessing the dependence of the losses as a function of the harmonic number and the RF voltage at extraction. The outcome is that a debunched beam is the most suitable for the SPS, even if this choice does not minimise the losses in the PS. For these reasons, a MTE debunched extraction, see Fig. 5(left), has been prepared after the end of the SPS run 2008, increasing the extracted intensity to 1.4 10^{13} protons. The extraction efficiency, expected to be up to 97-98%, turned out to be on average about 93%, but with peaks up to 99%. These fluctuations were correlated with a beam instability due to a slightly negative value of the chromaticity just prior to the resonant crossing. For the nominal extraction case, with an efficiency of about 98%, the beam loss pattern has been compared to the five turn extraction currently in use, the Continuous Transfer Extraction (CT) [5], which should be replaced by MTE. In the CT case, the beam is split in five slices by an electrostatic septum in SS31. As expected, (see Fig. 5, right), the MTE beam losses are concentrated in the extraction region, whereas for the old extraction losses of typically 5-6% of the circulating intensity are spread out over the entire machine circumference [5]. Losses during the CT extraction are generated first by the interaction of protons with the blade of the electrostatic septum in SS31. Moreover, particles scattered at the septum generate losses in the region between SS40-45 and SS72-76.

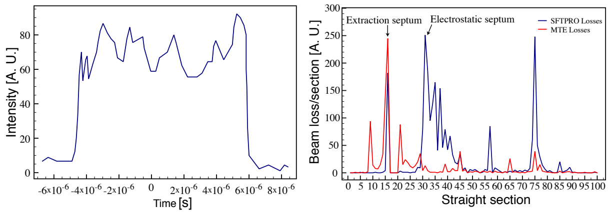

Figure 5: Intensity of a MTE debunched beam extracted over five turns measured by a transformer in the PS-SPS transfer line (left). Beam losses at each PS SS for the MTE beam compared to a CT extracted beam for the same intensity (right). The sizable reduction is apparent.

SPS INJECTION TESTS

During the last part of the CNGS run, it was finally possible to inject a MTE h=16 bunched beam in one of the CNGS SPS cycles. The total intensity injected was about 1.4 10^{13} protons. The two batches, each one of about 0.7 10^{13} protons, each one five PS turns long (presented in Fig. 6) had the last PS ejected turn with a larger intensity than the other four. This was due to a change in the beam radial position induced by the synchronization between the two machines. The variation of the radial position changes the capture process as the non-linear magnetic components changes due to different feed down effects. The proton beam in the SPS could be injected, accelerated and extracted towards the CNGS target. Neutrinos could also be produced during the last night of the CNGS run. Losses in the SPS were measured during the CNGS cycle and compared to the beam injected with a similar method currently in use [4]. Larger losses have been observed for the MTE, corresponding to about 23% of the injected intensity [4], to be compared with 8% for the other method. The injection losses were likely a consequence of an optical mismatch. Extraction losses were due to an instability causing a vertical emittance blow-up.

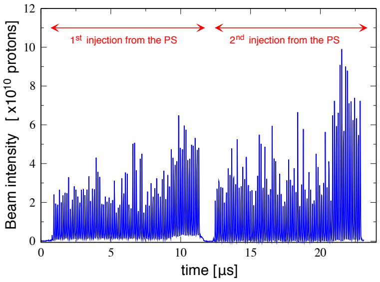

Figure 6: SPS ring transformer showing a double batch MTE injected beam.

CONCLUSIONS

The MTE commissioning proved for the first time the possibility to extract beamlets produced by beam splitting into stable islands. MTE extracted beam was delivered to the SPS for the last night of the CNGS run, with about a quarter of the nominal intensity. Later in the PS run, the maximum intensity extracted was raised to 1.3-1.4 10^{13}, with extraction losses in the PS limited to about 1% of the circulating beam in the best case.

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