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SLOW EXTRACTION AT THE SPS: EXTRACTION EFFICIENCY AND LOSS REDUCTION STUDIES

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INTRODUCTION

Elevated activation levels in LSS2 were first reported during an intervention on the SPS extraction septum (ZS) in September 2015. The increase was attributed to higher intensity Fixed Target (FT) operation and poorer extraction efficiency, and reported to the IEFC [1]. Since this event the awareness of the impact of slow extraction losses on the operation and maintenance of the SPS has been heightened. This is particularly pertinent in light of tightening limits on dose to personnel and recent requests for increased intensities, as well as ambitious future experimental proposals in the North Area (NA), such as the SPS Beam Dump Facility (BDF) [2]. To follow up these issues the SPS Losses and Activation Working Group (SLAWG) was formed.

The MD programme for 2016 was originally foreseen to test the faster spill on a 1.2 second flat-top for the BDF and benchmark simulations of the extraction process, but this was not possible due to the restrictions imposed by the TIDVG. Nevertheless, during operational set-up and re-alignment of the electrostatic septum (ZS) the extraction efficiency could be studied parasitically. The first re-alignment of the ZS actually took place during dedicated MD time in May, before moving to physics time.

The application of bent crystals used in different configurations and modes of operation for slow extraction is being studied [3, 4]. Bent crystals offer promising solutions for reducing the activation of the SPS LSS2 extraction region that is induced by the small fraction of beam that unavoidably impinges the ZS during the conventional resonant slow extraction process. In 2016, the slow extraction of a low intensity coasting 270 GeV proton beam into the TT20 extraction line towards the NA of the SPS was demonstrated in dedicated MDs using the extraction septa in LSS2 and a bent crystal, provided by the UA9 collaboration as part of their experimental installation in LSS5.

TIDVG Restrictions

The TIDVG fault in 2016 limited the scope of slow extraction MD plans. Extraction tests that could be carried out as part of operational set-up were carried out, such as the alignment of the ZS, checking spiral step size, extraction bump amplitude, profile measurements, aperture measurements, etc. The following MDs were largely put on hold or severely limited due to the intensity limit:

- MD181: Deployment of new SPS BDF cycle and extraction tests
- MD183: Deployment of new SPS BDF optics for TT20
- MD186: Investigation of slow-extraction losses and optimisation studies

Fortunately, the restriction on single-bunch coasting MD's at 270 GeV was relaxed and crystal-assisted slow extraction MDs could be carried out:

- MD953: Crystal-assisted slow extraction through LSS2

The requests for the MD programme in 2017 will reflect the time lost in 2016.

MD186: INVESTIGATION OF SLOW EXTRACTION LOSSES AND OPTIMISATION STUDIES

Extraction losses at the ZS were improved in 2016 with beam-based alignment campaigns, however a local hotspot discovered in the end-of-year RP survey indicated that the losses had been pushed downstream. Although the TPST is a dedicated absorber the situation must be better ameliorated in 2017 and studies are on-going to understand the cause of the hotspot. The re-alignments were slow, taking over 8 hours. With the possibility to scan the up and the downstream ends of each of the 5 ZS tanks it was challenging to minimise the measured loss on BLMs in an efficient manner. This type of alignment is a potential use case for machine learning algorithms, which will be pursued to improve the efficiency in 2017. It is also expected to re-align by moving the beam instead of the ZS to correct for orbit drifts.

The extraction inefficiency could be measured parasitically as ZS position was scanned during the realignments and could therefore be carried out despite the TIDVG restrictions. The objective was to experimentally quantify the efficiency of the SPS slow extraction process and make a first attempt to calibrate the secondary emission foils (BSI) foils in TT20 using the ring BCT. The BSI foils are used to determine transmission through the NA transfer lines and to determine the Protons on Target (POT) sent to the experiments. Significant discrepancies in the calibration of these foils have been reported but the source of the discrepancy is not understood. The titanium foils in the first two BSI's of the TT20 extraction line, which are normally permanently inserted into the extracted beam, were used in the calibration tests, as shown in Fig. 1: BSI.210216 (used for the servo spill control) and BSI.210279.

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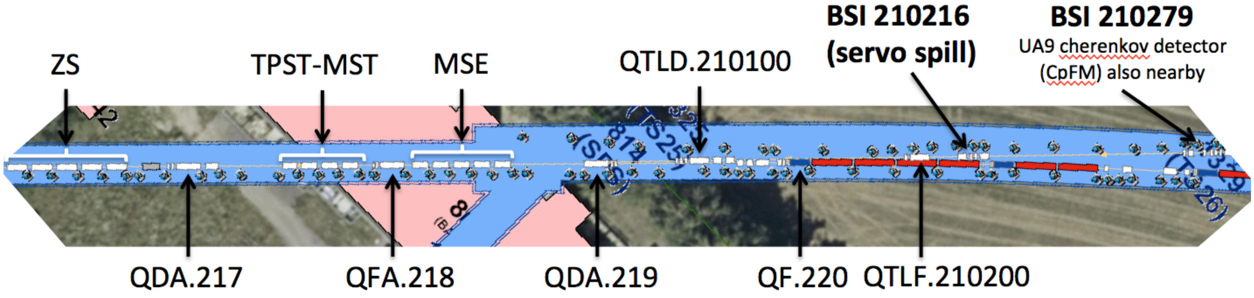


Figure 1: Layout of the LSS2 extraction region and location of the BSI's.

Extraction Inefficiency Measurement Concept

The inefficiency measurement used the more reliable ring BCT intensity measurement to calibrate both the BLMs and BSIs as the extraction efficiency was deliberately varied by misaligning the ZS. The concept relies on the assumption that losses do not appear somewhere that the BLM system does not cover and that the results can be extrapolated over a rather large range. The concept is based on investigations made at the AGS in Brookhaven during the 1980's [5], as shown in Fig. 2.

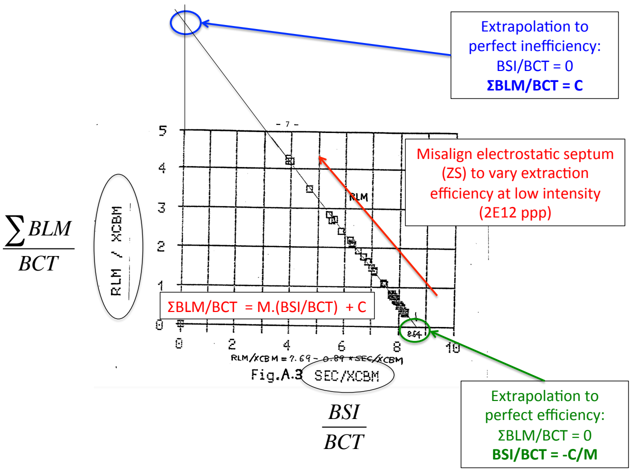


Figure 2: Measurement concept with AGS data [5].

The septum is deliberately skewed, as is done anyway to find the optimum position during re-alignment, and the resulting beam losses are correlated to the measured beam intensity extracted into the transfer line, normalised to the total intensity in the ring before extraction measured on the BCT. The correlation is closely linear and one can compute the extraction efficiency and check the calibration of the BSI against the BCT by extrapolating and computing the intercepts with each of the axes as shown in Fig. 2.

A low intensity beam of 2×10^{12} ppp was extracted during the MD to avoid damaging the ZS and to avoid unnecessary activation. It was important to remove the beam intensity lost at injection and dumped after the extraction to properly normalise the loss and extracted beam intensity data. A total of 160 shots were measured as the downstream end of the ZS girder was scanned by ±1.5 mm, i.e. both towards and away from the circulating beam. A screenshot of the ZS scan application is shown in Fig. 3, where the BLM response is recorded as function of the downstream girder position.

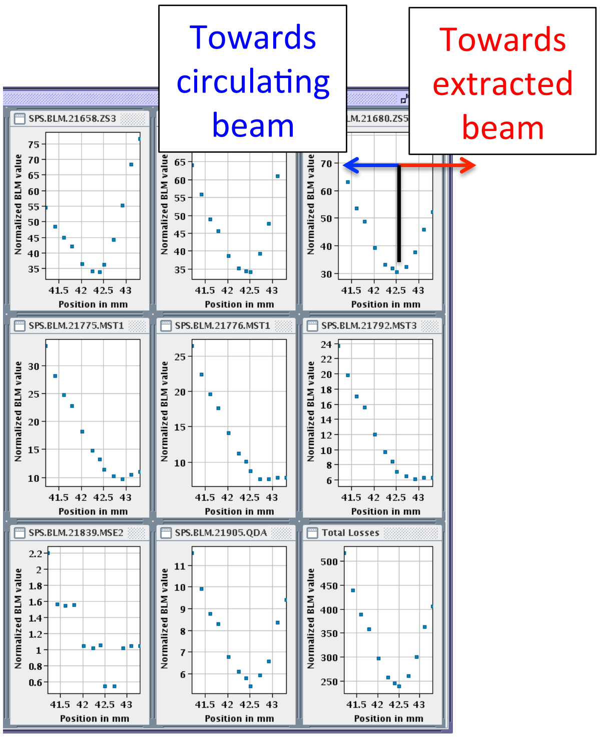


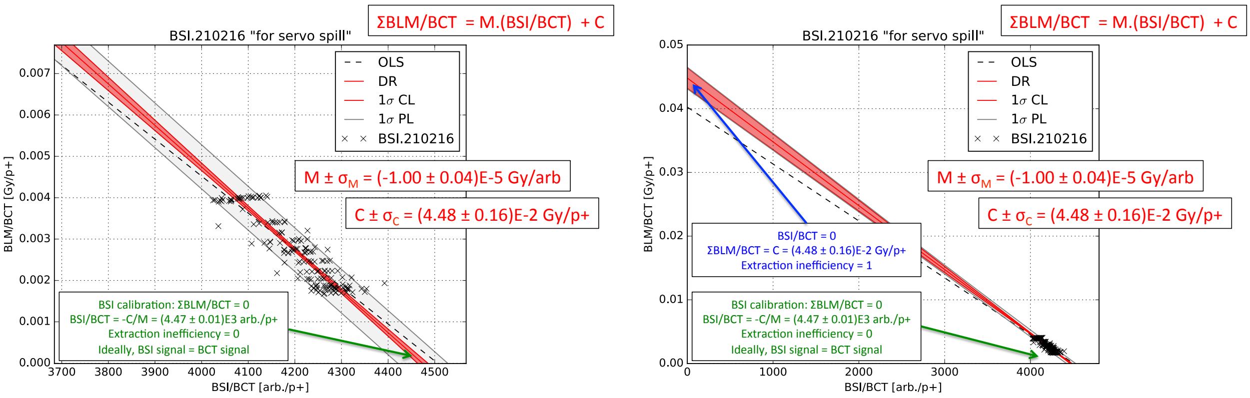
Figure 3: Screenshot of the ZS scan application for girder movement. The normalised loss (per extracted proton) measured on different BLMs in LSS2 are displayed as a function of the downstream ZS girder position.

Extraction Inefficiency Results

The results collected on the two different BSIs are shown in Figs. 4 and 5, and summarised in Table 1. In order not to introduce any additional non-linear effects it was decided not to adjust the gain of the BSI even though relatively low intensities were being extracted. This is the source of the poor signal-to-noise on the BSI measurement data. The measurement errors in both the BLM and BSI measurements

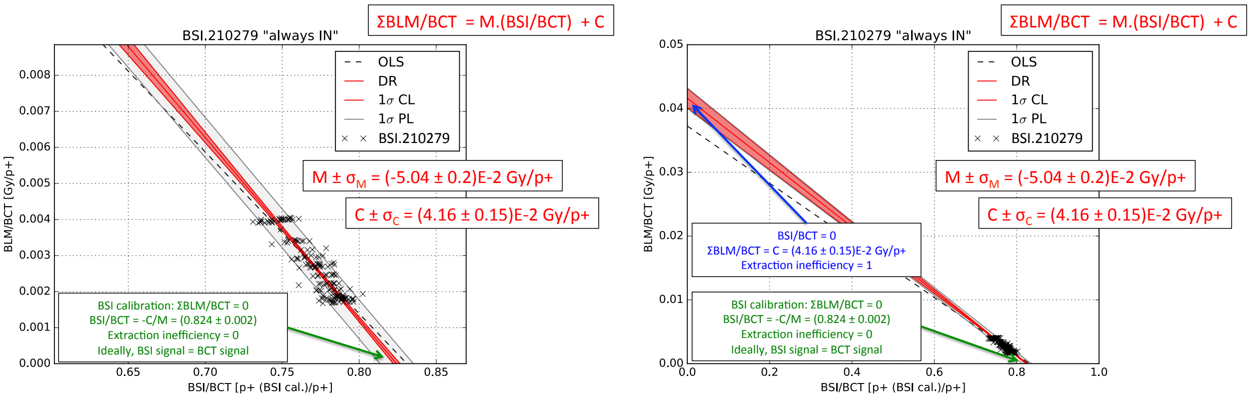
Table 1: Summary of extraction inefficiency measurements

BSI #	Comment	Extraction Inefficiency [%]	Calibration Error
210216	servo spill, Ti, always IN	4.0 ± 0.2	n/a
210279	second in TT20, Ti, always IN	3.6 ± 0.2	−17.6 ± 0.2



(a) Zoomed. (b) Extrapolation.

Figure 4: Results for BSI.210216 (used for the servo spill control): downstream girder position scanned ±1.5 mm.



(a) Zoomed. (b) Extrapolation.

Figure 5: Results for BSI.210279: downstream girder position scanned ±1.5 mm.

were taken carefully into account when carrying out the least-squares regression analysis:

$$\frac{\sum BLM}{BCT} = M\frac{BSI}{BCT} + C \qquad (1)$$

The extraction inefficiency was computed by normalising the sum BLM signal for the well-aligned case with the extrapolated y-intercept:

$$\text{Ext. inefficiency} = \frac{\left.\frac{\sum BLM}{BCT}\right|_{\text{ZS aligned}}}{C} \qquad (2)$$

The electronics of BSI.210216 used for the spill control is different to the other BSI's in the line and is not used for intensity measurements, only spill fluctuations, therefore no calibration constant is available to compare with the ring BCT. The calibration of BSI.210279 showed a discrepancy of close to 18% compared to the BCT, as shown by the intercept of the regression with the horizontal axis. In both cases the slow extraction inefficiency was measured at approximately 4.0%.

Discussion & Outlook

Care must be taken in the interpretation of the results as systematic errors are rather unknown, e.g. transmission losses between the SPS and the BSI location will systematically shift the calibration measurements. However, an 18% loss of beam intensity between the ring and the transfer line is unlikely and doesn't agree with the measured 4% extraction inefficiency. In order to better understand the calibration of the BSI, the titanium foil in question (in BSI.210279), was removed from TT20 and installed in TT10 during the shutdown where a BCT is present. Dedicated measurements of its secondary emission yield are planned in 2017 to further investigate these results.

MD953: CRYSTAL-ASSISTED SLOW EXTRACTION AT THE SPS

The possibility of extracting highly energetic particles from the SPS by means of silicon bent crystals has been explored since the 1990's. The channelling effect of a bent crystal can be used to strongly deflect primary protons and hence direct them onto an internal absorber or, with additional deflection elements, eject them from the synchrotron. Many studies and experiments have been carried out to investigate crystal channelling effects. As summarised in [6–9], diffusion extraction of 120 and 270 GeV proton beams has already been demonstrated in the SPS with dedicated experiments located in the ring. At present in the SPS, the UA9 experiment is performing studies to evaluate the possibility to use bent silicon crystals to steer particle beams in high energy accelerators [10–14]. Recent studies on the feasibility of extraction from the SPS have been made using the UA9 infrastructure with a longer-term view of using crystals to help mitigate slow extraction induced activation of the SPS. During three dedicated MD sessions in 2016 the possibility to eject particles from the SPS and into the extraction channel in Long Straight Section (LSS) 2 using the bent crystals was tested.

Extraction Concept

The location of the bent crystals in LSS5 is 3.5 km from the slow extraction channel in LSS2, which makes the extraction process highly sensitive to the working point of the machine. The crystals are positioned on the inside of the ring and deflect inwards. Detailed studies [15] failed to identify a suitable working point that provides the required phase advance for the channelled beam to jump the wires of the electrostatic septum, on the outside of the ring, on the first turn. However, they did identify the potential of the operational Fixed Target working point ($Q_x = 26.62$, $Q_y = 26.58$) to extract the beam at the ZS on the second turn, with a fractional phase advance of 252°. The extraction scheme chosen is shown schematically in Fig. 6, where the electrostatic and magnetic septa (ZS, MST and MSE) are shown, along with a dedicated Cherenkov for Proton Flux Measurement (CpFM) detector installed upstream of the extraction dump (TED) in the TT20 transfer line. The channelled beam performs almost 41 betatron oscillations before reaching the ZS.

With the machine configured to store a single bunch at constant energy, the transverse halo can be slowly and non-resonantly extracted as it diffuses into the crystal, is channelled and deflected into the extraction septa. The advantage of such an extraction concept for these first development tests is that the channelled beam passes the UA9 experimental area a second time, allowing the exploitation of the specialised beam diagnostics systems to verify the phase advance of the channelled beam in the absence of suitable systems in LSS2.

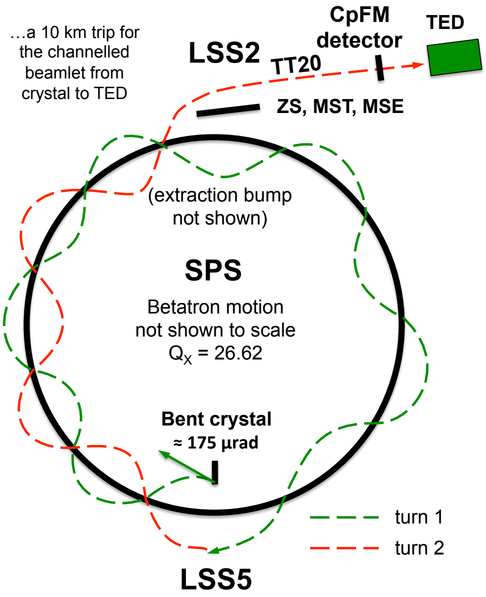


Figure 6: Schematic of the crystal-assisted extraction scheme.

In order to simulate the dynamics of the extraction, the SPS was implemented in MADX and particle tracking carried out in combination with the `pycollimate` [16] scattering routine, where the crystal interaction was modelled using single-pass UA9 measurement data [17]. More details of how the simulations were implemented are found in [15]. The presentation of the beam at the entrance to the ZS is shown in Fig. 7 after being tracked through the crystal and the SPS, where the distribution is approximated as a hollow halo beam to save computation time. In Fig.7 the crystal is aligned at -6σ with a channelling angle of -160 μrad, where positive denotes a direction towards the outside of the ring. The simulations were used to design the LSS2 extraction bump, ensuring its closure, and to set the strengths of the extraction septa such that the channelled beam enters TT20 on the nominal trajectory.

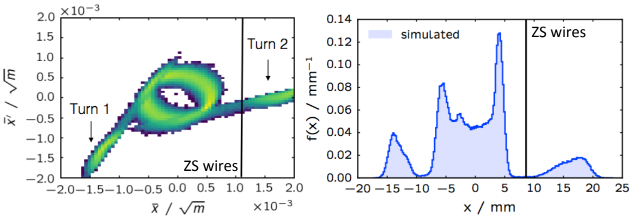


Figure 7: Beam distribution (hollow halo approximation) at ZS: normalised phase space (left) and horizontal projection (right) [15].

Experimental Setup

A schematic view of the UA9 installation is shown in Fig. 8 comprising two goniometers for a multi- and a single-crystal setup, different detectors used to precisely align the crystals to the beam and to measure different observables, as well as absorbers and scrapers to intercept the channelled beam. The collimators and absorbers are named TCXHW, TCSM, TACW and TAL, and all of them are equipped with LHC Beam Loss Monitors (BLMs), which are significantly more sensitive than the standard SPS BLMs. The TCSM is an LHC prototype collimator with two horizontal jaws, composed of 1 m long blocks of graphite, and equipped with a Beam Position Monitor (BPM) at its entrance. The TACW is an old SPS collimator, which was equipped with a single 60 cm tungsten jaw to suit the needs of the UA9 experiment, used to stop the crystal-channelled beam during data taking. The experimental installation starts with the TCXHW, a 10 cm long double-sided tungsten scraper, and terminates with a station in the high dispersive area, which includes the TAL (10 cm long double-sided tungsten scraper) and a Roman Pot containing two Timepix high-precision pixel detectors [18, 19]. In conjunction with UA9's absorbers and scrapers, the channelled beam could be stopped from circulating after a given number of turns and its position and transverse size measured on its return to LSS5, turn-by-turn. To directly detect the presence of channelled beam in the TT20 extraction line a dedicated CpFM detector [20,21] was installed that is capable of measuring single-particle events and therefore very low extraction rates.

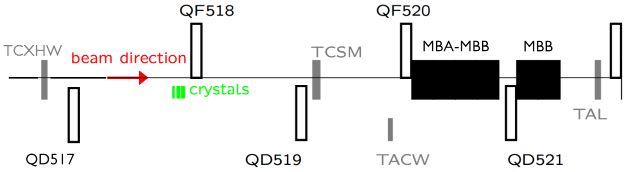


Figure 8: Schematic of the UA9 experiment's installation.

Experimental Results

A low intensity LHC-type single-bunch of 1.6×10^{10} protons was used throughout the tests in order to guarantee the protection of the fragile wires of the ZS from damage. The effect of the imperfect closure of the LSS2 extraction bump was tested and shown not to significantly perturb the channelling efficiency. The BPM at the TCSM observed a 0.1 mm movement as the extraction bump was powered to its nominal value of 57 mm at the ZS, inducing a spike in the channelling rate and increasing BLM readings in LSS5. To avoid this type of dynamic effect it was decided to turn on the extraction bump before aligning the crystal with the beam. The alignment of the UA9 equipment was carried out as usual [22]. The crystal was positioned at 6σ and aligned by scanning the angle of its goniometer and using scintillators and BLM loss levels as observables to determine the optimal orientation of the crystal. The bending angle of the crystal used was measured in a previous MD in 2016 as 175 ± 2 μrad, consistent with [10]. Once the TACW absorber was retracted and the channelled beam was free to circulate, it was immediately detected by the CpFM in the TT20 extraction line. After small steering corrections the beam could be centred on the nominal beam axis at the CpFM. The extraction could be ceased by reinserting the TACW and stopping the channelled beam in LSS5 as shown in Figs. 9 and 10.

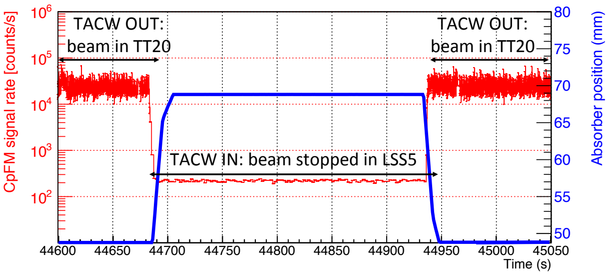
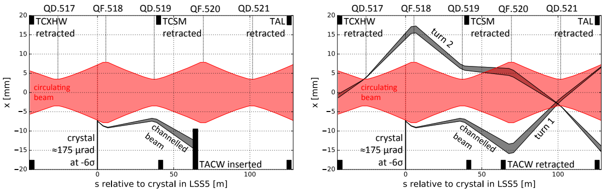


Figure 9: TT20 CpFM signal rate (red) vs. TACW position (blue) [21].



(a) TACW IN. (b) TACW OUT.

Figure 10: LSS5 absorber configuration for extraction.

The horizontal beam size of the extracted beam at the CpFM was also measured at $\sigma = 0.6$ mm by scanning the quartz bar of the CpFM through the extracted beam in the horizontal plane, as shown in Fig. 11. The signal reaches its maximum value when the quartz bar samples the entire beam. The calibration of the CpFM is on-going in order to quantify the exact extraction rate in terms of protons extracted per second.

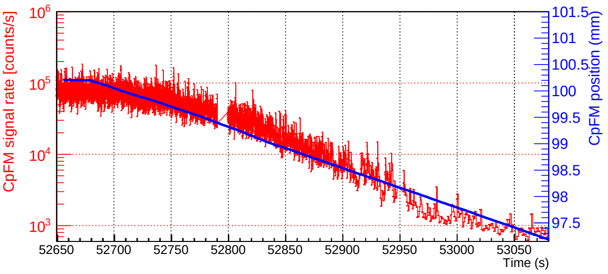
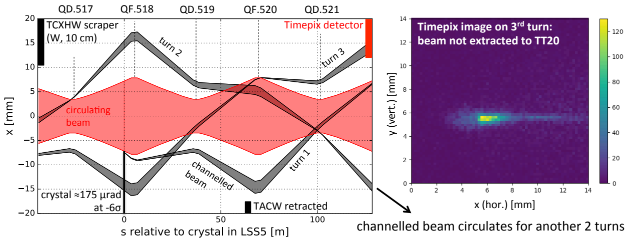


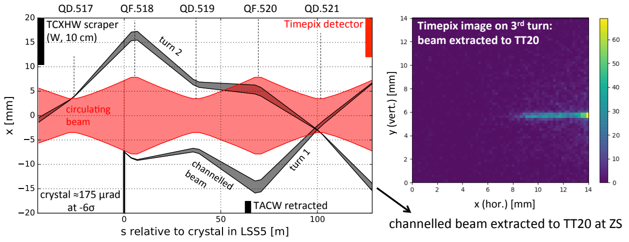
Figure 11: TT20 CpFM signal (red) and position (blue) vs. time as it is moved out of the extracted beam [21].

Further tests were made to guarantee that the extracted beam was indeed channelled by the crystal. These involved (i) inserting the outer TCSM jaw and TAL inner jaw to stop the channelled beam on the second turn in LSS5, also allowing beam profiles to be reconstructed, (ii) changing the angular alignment of crystal and (iii) adjusting the diffusion rate by exciting the beam with the transverse damper and checking the measured extraction rate on the CpFM. The aforementioned direct checks using the CpFM behaved as expected with the most elegant validation being an indirect measurement carried out with the Timepix detector. With the extraction bump turned off, and the TCXHW inserted to intercept the channelled beam from circulating after its fourth pass of LSS5, the channeled beam was imaged on the Timepix detector on its third pass of LSS5, as shown in Fig. 12(a). When the extraction bump was turned on the channelled beam disappeared from the image as it was pushed over the septum wires of the ZS and extracted into TT20, as shown in Fig. 12(b). The extraction was again confirmed by the CpFM.



channelled beam circulates for another 2 turns

(a) Extraction bump OFF.



channelled beam extracted to TT20 at ZS

(b) Extraction bump ON.

Figure 12: Timepix images showing the disappearance of the channelled beam in LSS5 when extracted in LSS2.

Conclusion & Outlook

The non-resonant crystal-assisted slow extraction of a 270 GeV proton beam from the SPS towards the North Experimental Area has been demonstrated during dedicated MD tests in 2016. The low intensity beam was extracted from the halo of a circulating LHC-type single-bunch of 1.6×10^{10} protons and its presence validated and characteristics probed with a dedicated CpFM detector in the extraction line. This is the first time in the SPS that a bent crystal has been used in conjunction with the extraction systems to bring the beam into a transfer line towards an experimental area. In light of future experimental requests for Fixed Target physics at 400 GeV, this is an important step in the application of bent crystals at the SPS for the mitigation of slow extraction induced activation.

The MD programme will continue in 2017 to increase the extraction rate, characterise the extracted beam, quantify and compare the losses for different extraction techniques, and calibrate the CpFM with a beam synchronous trigger to improve the signal-to-noise ratio. The application of bent crystals to shadow the wires of the ZS during a conventional resonant slow extraction is being actively studied [23] and the installation of a dedicated crystal to test this proposal in MD sessions is presently being discussed.

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