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MD#4164: Separatrix folding with octupoles during slow extraction at SPS

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Resonant slow extraction, third-integer, extraction loss reduction, octupoles, phase space folding, separatrix arms

Summary

The powering of the SPS main focusing octupole circuit (LOF) during third-integer slow extraction was tested to reduce the density of the extracted beam impinging the wires of the electrostatic extraction septum (ZS). This note briefly summarises the results of the slow extraction tests carried out on 26th September and 1st November 2018 with 400 GeV protons, including the pre-requisite studies and tests needed to perform the test safely, concluding with the demonstration of a ~ 40% reduction of the specific (per extracted proton) beam loss at the ZS in Long Straight Section (LSS) 2.

1. Introduction

Slow extraction using the third-integer resonance and thin electrostatic septa is a process with inherent beam loss, resulting in activation of the machine, reduced component lifetime and severe limitations on personnel access and maintenance. In view of tightening restrictions on dose-to-personnel for the necessary hands-on maintenance of accelerator equipment, and ever-increasing experimental requests for higher slow-extracted proton flux to the North Area, the SPS Losses and Activation Working Group (SLAWG) [1] has been established to investigate, implement and follow-up various methods to reduce the induced radioactivity in LSS2, and the SPS in general.

One of the techniques pursued in recent years is the application of higher-order multipole fields to manipulate the spatial density of the beam presented to the extraction septum [2-3] and, in particular at the SPS, the application of octupolar fields. In the present operational scenario four extraction sextupoles (LOE) are used to drive the third-integer resonance and increase the amplitude of particles on outward spiralling separatrices, which closely resemble straight lines in phase space. In this scenario, the spatial density of the beam at the septum drops off quadratically with amplitude. When strong octupolar fields are added, one can curve the phase space separatrix presented to the septum and manipulate it such that, after optimisation and at the expense of a larger extracted beam emittance, the spatial density projection of the extracted beam is peaked inside the extraction channel rather than at the septum wires. The lower density at the septum wires reduces the number of protons interacting with the wires during extraction, reducing the overall beam loss and activation. A full discussion on the technique of applying high-order multipoles to third-integer slow extraction can be found in [4], which includes a theoretical treatment backed-up with simulations and error studies.

2. Machine protection aspects

As the application of octupoles during slow extraction has potentially serious machine protection implications, a detailed procedure [5] was prepared and approved to establish safe parameters and minimise the risk to the machine during the tests, with potential for future operational deployment. The procedure was presented and approved at the 167th SPS and LHC Machine Protection Panel Meeting.

The main risk was identified as accidently trapping the beam in the machine at large amplitudes, increasing the density and collimating/extracting the beam directly on the ZS wires. The damage limit of the ZS wires could be estimated from past incidents and flying wire Machine Development (MD) tests carried out in the 1990's. The beam intensity typically used for alignment and setting-up of the SFTPRO cycle is 2×10^{12} protons, which is at the estimated damage limit for the 60 μm diameter wires in the first ZS tanks, should the entire beam be bumped into the wires. In order to mitigate the risk, a very low intensity (VLI) version of MTE at $1 - 5 \times 10^{11}$ ppp was prepared in the injectors. An intensity on the higher end of this scale was needed in order to attain a high-enough signal-to-noise ratio on the beam profiles measurements taken with the beam instrumentation in LSS2 (BSG – SEM wire grids).

The use of the VLI MTE beam meant that other high intensity beams were forbidden in the SPS super-cycle (to protect the LLRF electronics when attenuators are removed to tune the VLI beam) and the MD had to be scheduled accordingly to take place in parallel to other low intensity MD's. When extracting with octupoles, the TCSM was positioned to limit the beam size of the extracted beam in the horizontal plane and protect and shadow the cathode of the ZS. In addition, the MD could not be carried out in parallel to LHC filling with the TCSM inserted. The current comparator for the SIS interlock triggering the PS internal dump will be set to limit the intensity extracted from the PS. The entire MD was carried out with the TT20 TED inserted.

3. MD programme and conditions

The MD tests were performed on the mornings of 26th September and 1st November, totalling no more than 8 hours, reduced by the availability of the injector chain on those days.

The MD goals were to:

- Demonstrate and understand the possibility to resonantly drive the beam to large amplitude with the sextupoles and trap it there with the octupoles, checking the strength of the multipole terms with those implemented in simulation;
- Demonstrate clear changes in the extracted beam profile and extraction losses in LSS2 with varying octupole and sextupole strengths;
- Test a knob to rotate the phase of the sextupole resonant driving term;
- Iteratively find a combination of sextupole and octupole strengths and ZS alignment for which losses are lower than nominal.

The tests were carried out with a single injected batch of approximately 5×10^{11} ppp, extracted on a spill with a flat-top duration of 4.8 seconds and with the recently developed

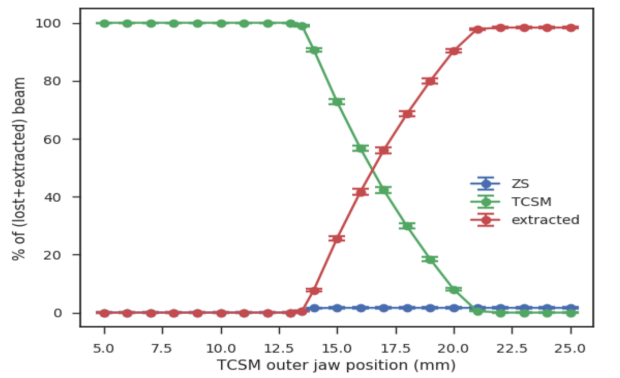
Constant Optics Slow Extraction (COSE) [6], rather than the traditional tune sweep method. In the traditional scheme, the resonant tune is changed by changing the QF strength only. While this does achieve the goal of changing the tune, it also changes the optics as seen by the extracted particles. With the COSE method, all magnets are scaled in strength synchronously, so that at any time during the extraction, all extracted particles of different momenta see the same optics throughout the spill.

The LOF magnets used in the MD are installed near focusing quadrupoles with a large horizontal beta-function (85 – 105 m) and are suitable for use in the extraction scheme investigated here. It should be pointed out that this MD took place after the 2018 Injector Technical Stop 2 and the reconfiguration of the SPS main octupole circuits [7], where all 24 LOF magnets were connected to the same power supply and 6 cabled with the opposite polarity.

The MD was split into two parts. In order to safely check the effective strength of the resonant driving term and octupoles, a first step was carried out with the extraction bump off and the TCSM inserted to same aperture as the ZS wires. The octupole strength could then be safely scanned for different sextupole strengths and safe limits understood by observing the beam loss pattern measured at the TCSM that replaced the ZS as the aperture bottleneck. The second part of the MD proceeded with extraction and the TCSM retracted to shadow the cathode, measuring the effect of the combined sextupolar and octupolar fields, whilst slow extracting the beam through LSS2 into TT20 and onto the TED, with the predetermined limits on the octupole strength.

4. TCSM alignment with ZS wires

With the machine nominally set up and slow-extracting to the TT20 TED, the outer TCSM jaw was inserted and moved into the separatrix arm as it made its final turn in the machine before reaching the ZS. The simulated and measured loss response and extracted intensity is shown in Figures 1 and 2, respectively.



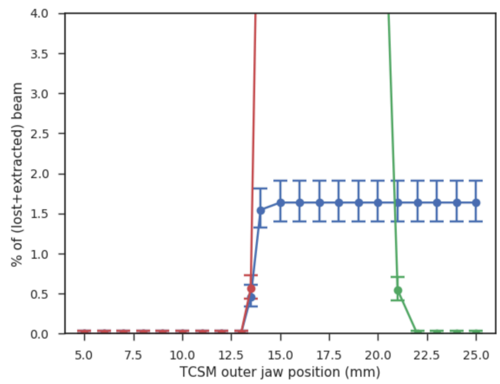


Figure 1 – Simulated evolution of losses during a scan of the outer TCSM jaw position while slow extracting with nominal multipole strengths (zoomed on right).

The measurement allows to the place the TCSM at the same aperture as the ZS wires (representing the horizontal aperture limit in the machine) and to measure the position of the end of the separatrix arm at the TCSM (size of the spiral step). As the TCSM intercepts the separatrix arm, the amount of beam extracted decreases while losses on the TCSM increase, until finally a sharp drop in losses at the ZS is observed. This drop was measured at a position between 12 – 13 mm in the machine. This is in rough agreement (considering various misalignment tolerances) with the expected aperture from scaling the distance between the circulating beam centre and the

ZS wires (~ 26 mm) by the square root of the beta functions at the different locations (~ 100 m at the ZS and ~ 25 m at the TCSM). Contrary to the simulated data, the ZS losses in the measurement do not drop immediately to zero, but rather stay at about 15% of their initial value before dropping to zero between 7 – 9 mm. This is due to the fact that the TCSM is not a black absorber, as simulated, but a ~ 1 m long carbon block.

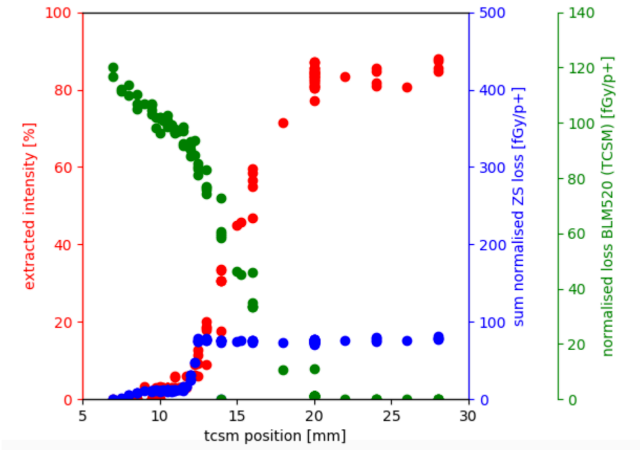


Figure 2 – Measured evolution of beam loss during a scan of the outer TCSM jaw position while slow extracting with nominal sextupole strength.

5. Verification of beam trapping

With the extraction bump in LSS2 turned off and the bottleneck transferred from the ZS wires to the TCSM the critical octupole settings could be safely identified by varying the focusing octupole strength (LOF->K) and observing the beam loss at the TCSM along with beam intensity trapped and dumped internally at the end of the flattop. At low octupole settings, the beam is slow-extracted onto the TCSM. As the octupole strength is ramped (either positive or negative) the separatrix arms bend, eventually trapping the beam in the machine when the octupole strength is high enough. The measured data is compared to simulation in Figure 3. When the beam loss reduces at the TCSM and the dumped intensity increases, the beam is trapped at large amplitude. The interpretation of the measured loss signal at the TCSM is complicated by the changing impact position and beam angle, which determine the development of the particle shower detected at the BLM. Nevertheless, the onset of trapping was very well predicted by simulation for both positive and negative values. The same exercise was repeated for stronger sextupole strength and demonstrated that higher octupole strengths are needed to trap the beam. The limits set on the octupole strength to avoid trapping the beam close to the aperture defined by the TCSM (and therefore ZS wires) for different sextupole settings are collected in Table 1.

The intensity evolution, as measured on the ring BCT as a function of the octupole strength is shown in Figure 4.

Data from the rest-gas ionisation monitor (BGI) was taken to observe the effect of the capture process on the transverse beam distribution in the horizontal plane, as shown in Figure 5. During the nominal slow extraction, without octupoles, the horizontal beam size of the circulating beam remains constant throughout the extraction and the intensity decreases linearly through the spill. However, when the octupoles are strong enough to trap the beam, the beam size increases as beam is trapped at large amplitude instead of extracted, which significantly changes the distribution of the beam intensity in the horizontal plane. Trapping of the beam is clearly demonstrated, but some parts of the distribution are missing, since the beam was not aligned to the centre of the detector.

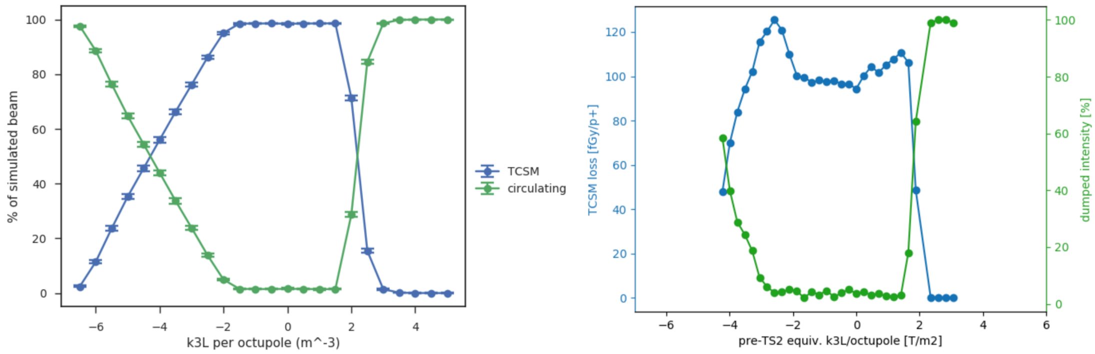


Figure 3 – Beam loss at the TCSM and intensity left circulating at the end of the flat-top (and subsequently dumped) as a function of octupole strength, with the TCSM at the ZS equivalent aperture (left – simulation, right – measurement)

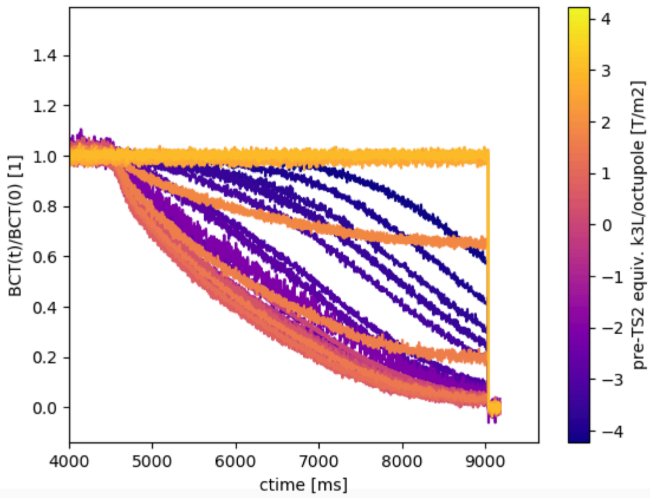
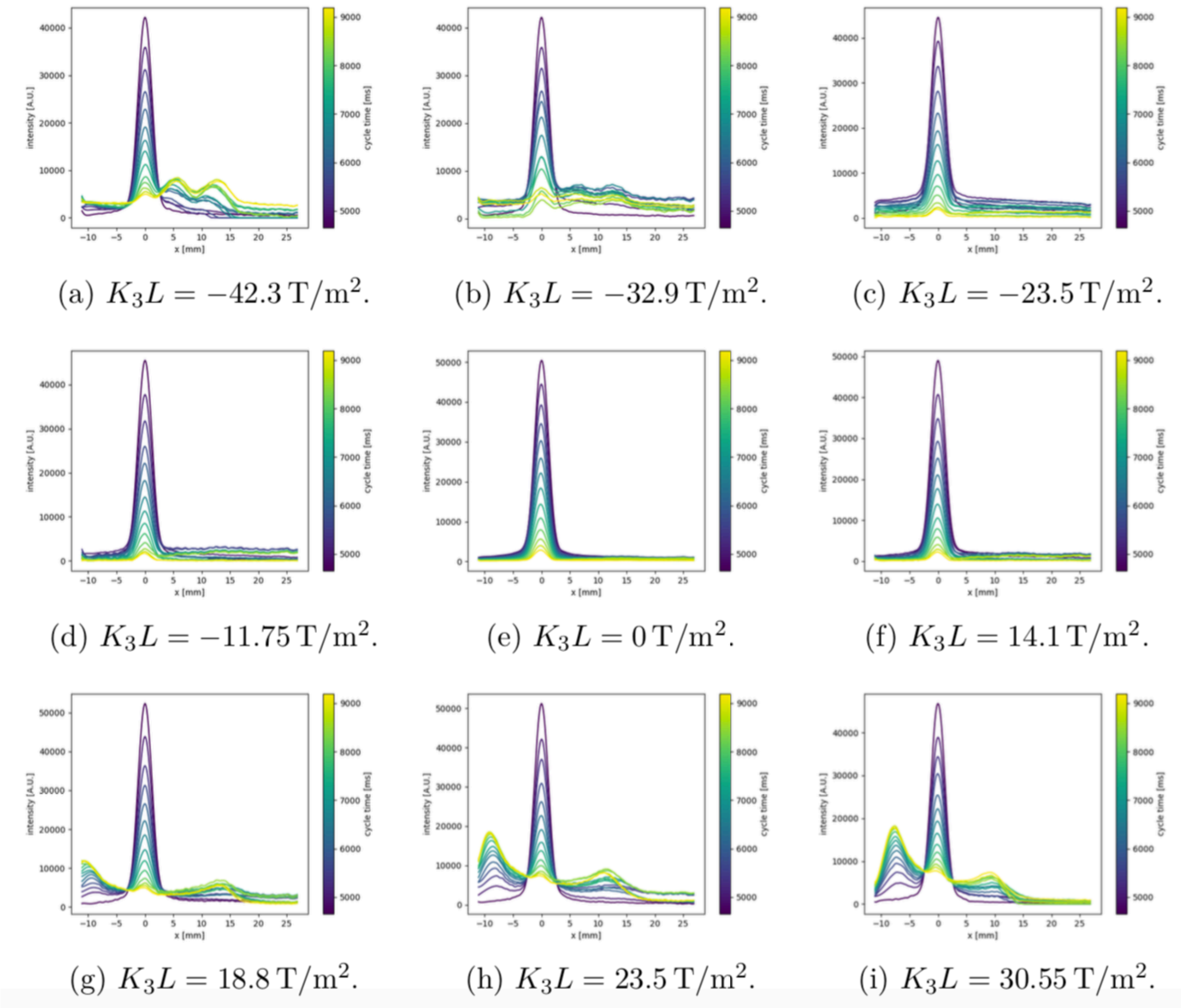


Figure 4 – Beam intensity measured by the ring BCT along the flat-top as a function of the applied octupole strength, with the sextupoles powered nominally.

Table 1 – Safe LSA limits for the octupole strength for different sextupole strengths, determined by the observed onset of trapping. The pre-TS2 equivalent strength is listed for the octupoles.

Sextupole strength $k_2L/(k_2L)_{ref}$	**Lower limit of octupole strength k_3L per LOF [T/m^2]**	**Upper limit of octupole strength k_3L per LOF [T/m^2]**
0.95	-2.5	1.5
1.4	-4.0	2.0
2.1	-4.0	4.0



(a) $K_3L = -42.3\,\mathrm{T/m^2}$. (b) $K_3L = -32.9\,\mathrm{T/m^2}$. (c) $K_3L = -23.5\,\mathrm{T/m^2}$.

(d) $K_3L = -11.75\,\mathrm{T/m^2}$. (e) $K_3L = 0\,\mathrm{T/m^2}$. (f) $K_3L = 14.1\,\mathrm{T/m^2}$.

(g) $K_3L = 18.8\,\mathrm{T/m^2}$. (h) $K_3L = 23.5\,\mathrm{T/m^2}$. (i) $K_3L = 30.55\,\mathrm{T/m^2}$.

Figure 5 – Evolution of measured beam profiles throughout the extraction for different octupole strengths, at nominal sextupole strength. (K_3L listed as pre-TS2 per octupole equivalent.)

6. Rotation of the resonant driving term

The angle at which the extracted separatrix arm presents itself to the ZS changes as a function of the applied octupole strength. In the first tests this caused inhibitive beam loss measured at the TPST. As realignment of the extraction channel would be prohibitively time consuming a knob was created to rotate the phase angle of the resonant driving term using two other groups of extraction sextupoles (LOE) without changing the amplitude of the driving term. The driving term rotation knob, described in [4], has the effect of rotating the angle of the separatrix arms without moving the beam centre and applied as follows,

- k2L_124 := 1.98904E−2 * knob_ang [deg] * *knob_strength*
- k2L_424 := 1.98904E−2 * knob_ang [deg] * *knob_strength*
- k2L_206 := −9.13846E−3 * knob_ang [deg] * *knob_strength*
- k2L_324 := −9.13846E−3 * knob_ang [deg] * *knob_strength*

- k2L_506 := −9.13846E−3 * knob_ang [deg] * *knob_strength*
- k2L_624 := −9.13846E−3 * knob_ang [deg] * *knob_strength*

where *knob_strength* is given relative to the nominal sextupole strength of the main four main LOE's (k2L_106, k2L_224, k2L_406, k2L_524).

All power converters needed for the rotation knob were available for operation, except for sextupole 324. Hence, the rotation knob was slightly altered to use only the other five sextupoles. The knob allows for large adjustments of the resonance angle, with only small changes to the resonance strength, as demonstrated both in simulation and in the machine. When the rotation knob was applied to the nominal extraction, the spiral step is largely unaffected while a big movement is seen 90° downstream, as shown in Figure 6, indicating the extracted beam angle, and not position, at the ZS was changed, as would be expected when only resonance angle is changed.

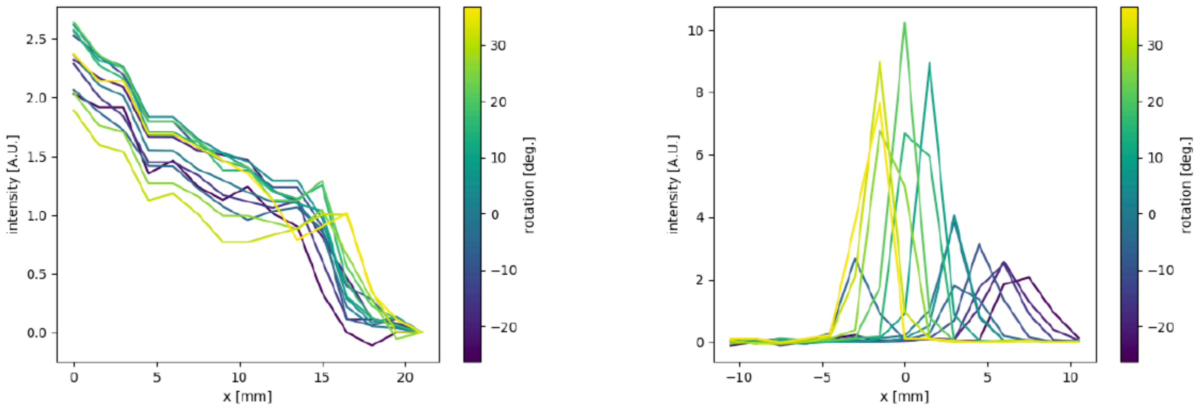


Figure 6 – Extracted beam as measured on the extraction grids for different settings of the driving term rotation knob, without octupoles, at nominal extraction sextupole strength (left – ZS entrance (BSGH216), right – approx. 90 deg downstream of the ZS entrance inside the MSE (BSGH218)).

Figure 7 shows a comparison between the knob and the ZS girder alignment, where swinging the downstream end of the ZS girder changes its angle relative to the beam. This knob is not only convenient for correcting the beam angle with added octupoles, but could also be useful in nominal operation for quick re-alignment purposes.

7. Resonant extraction with octupoles

The ability to rotate the resonant driving term was an important pre-requisite to demonstrate the full potential of such a loss reduction technique because mechanical realignment of the extraction channel would have been prohibitively time-consuming with the limited amount of MD time available. This is shown in Figures 8 and 9, where the changing beam position at BSGH218 located about 90 deg. phase advance downstream of the ZS inside the MSE is evident.

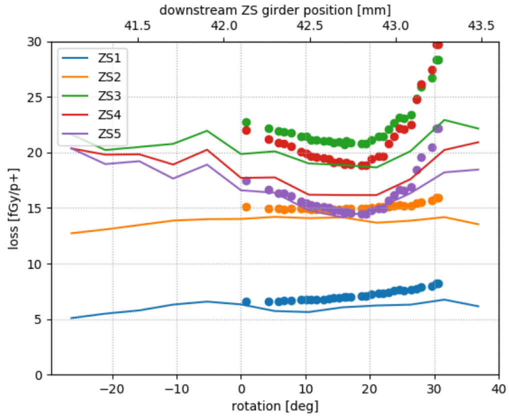


Figure 7 – Measured normalised losses on the ZS BLMs during a scan of the driving term rotation knob (solid lines, lower horizontal scale) compared to those during an earlier scan of the downstream ZS girder position (dots, upper horizontal scale).

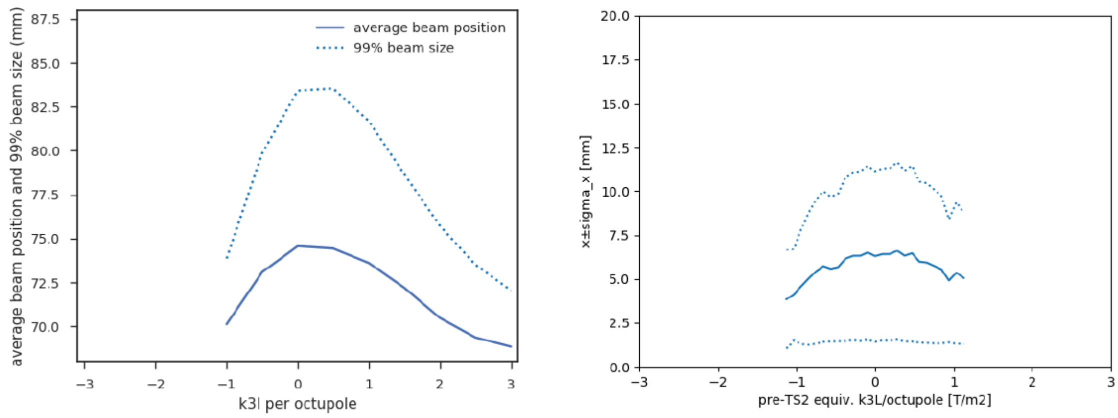


Figure 8 – Horizontal beam profiles at ZS entrance (BSGH216) with varying octupole strength, using nominal sextupole strength and ZS alignment (left – simulation: average position and 99% beam size, right – measurement: average position and rms beam size).

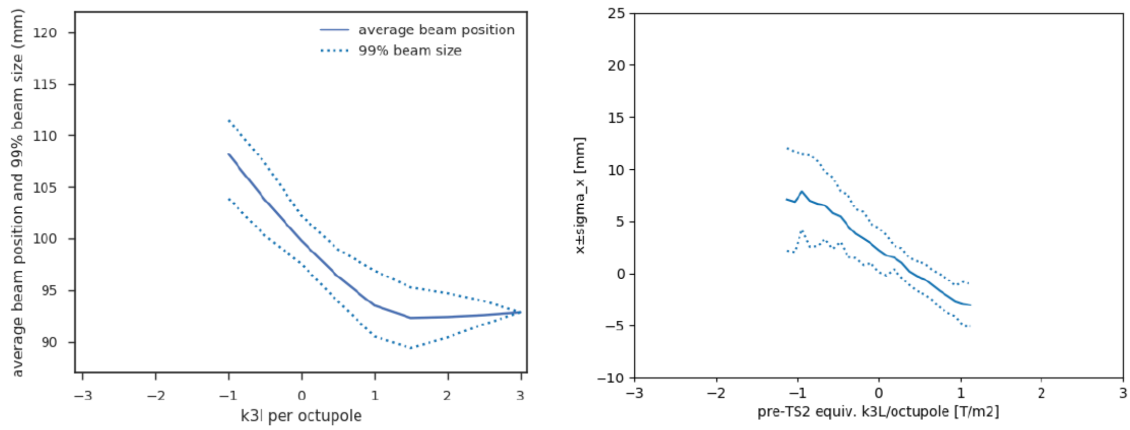


Figure 9 – Horizontal beam profiles ~ 90 deg. downstream of the ZS entrance inside the MSE (BSGH218) with varying octupole strength, using nominal sextupole strength and ZS alignment (left – simulation: average position and 99% beam size, right – measurement: average position and rms beam size).

Although it would have been preferable to scan all multipole parameters the limited time meant that only a few combinations of octupole and sextupole strengths, which performed well in simulation, were tested. For each setting, a scan of the angular rotation knob was performed in order to minimise the sum of the normalised losses at the ZS BLMs. Only a single configuration with positive octupole strength was tested, as time was limited. For the tested strength, only a marginal improvement in ZS losses was seen. For the tested configurations with negative octupole strengths, the relative loss reduction was similar on all ZS tanks and in the best case reduced by 42%, with the settings applied collected in Table 2. The modified beam density distribution at the ZS entrance is shown for the best case in Figure 10, where a clear reduction in the beam density close to the ZS wire location and an increased density is evident well inside the extraction aperture.

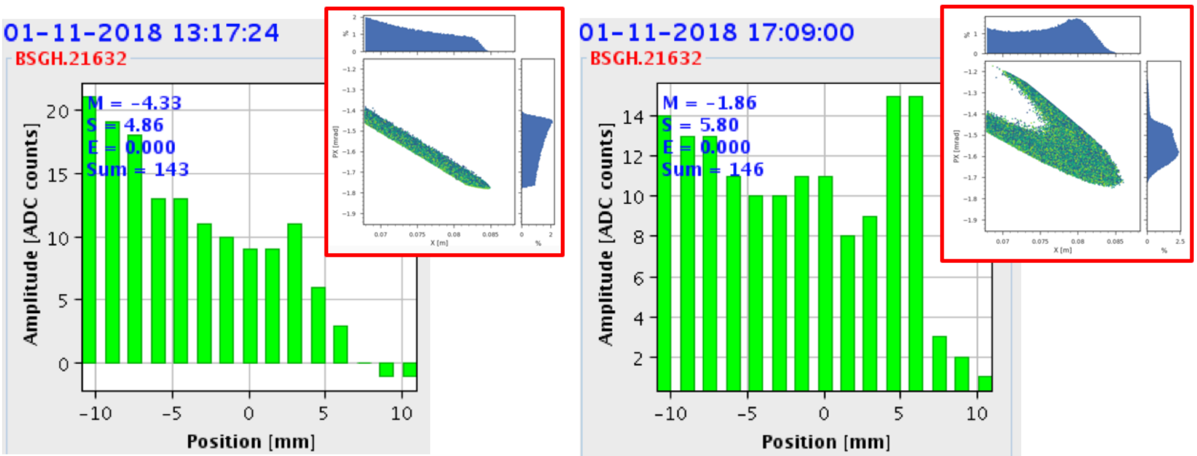


Figure 10 – Horizontal beam profiles at the ZS entrance (BSGH216) for the nominal extraction (left) and in the best case (right) with the simulated phase space shown inset in both cases (ZS wires located at ~ - 9 mm).

For the best-case scenario, unlike for the other configurations, the rotational knob could not be used to fully minimise the beam loss at both the ZS and downstream in LSS2. As the beam was rotated, the ZS losses decreased but the loss signal at BLM.219 increased, most likely caused by the beam scraping on the downstream end of the MSE. The beam loss pattern in the LSS2 and TT20 BLM's is shown in Figure 11. The ZS loss is significantly reduced but the extracted beam appeared to scrape the outside of the downstream end of the MSE, inducing beam losses measured on the BLM at QDA.219. The aperture in LSS2 along with the measured beam profile at the BSGH218 is shown in Figure 12. Due to the limited time available during the test it was not possible to attempt to reduce the beam loss observed downstream by steering or realigning the extraction channel.

8. Conclusion and outlook

The first tests applying octupolar fields during slow extraction to manipulate the phase space density of the beam at the ZS successfully demonstrated the feasibility of the principle and validated the simulation tools used to design the extraction scheme. In the best case, the losses at the ZS were reduced by ~ 42% with carefully chosen multipole strengths. To implement the scheme in operation, further study and optimisation in the machine, e.g. steering, alignment of extraction septa, etc., will be needed in Long Shutdown 2 and during Run 3 to ensure that the increased horizontal transverse emittance can be transported out of LSS2, split in TT20 and transported to the production targets. In addition, the machine protection aspects of an operational implementation will need careful consideration.

Slow extraction with octupoles was tested with success in combination with a thin, bent crystal shadowing the wires of the ZS, the details of which are reported elsewhere. This important result demonstrates that different techniques can be combined in the quest for the factor of 4 – 5 reduction in the specific extraction loss needed to welcome the proposed Beam Dump Facility at CERN, which is requesting far higher extracted proton fluxes in the future.

Table 2 – Optimised ZS losses for several combinations of octupole and sextupole strengths. The pre-TS2 equivalent strength is listed for the octupoles.

Sextupole strength $k_2L/(k_2L)_{ref}$	Octupole strength k_3L per LOF [T/m^2]	Rotation angle [deg.]	Beam loss ZS1-5 [fGy/p+]	Beam loss BLM.219 [fGy/p+]
0.95	0.0	15.8	69.4	2.7
0.95	1.13	-35.8	67.8	3.6
1.4	-1.65	50.0	47.0	10.0
2.1	-1.50	14.2	43.7	9.9
2.1 (best-case)	**-1.65**	**28.5**	**40.2**	**18.5**

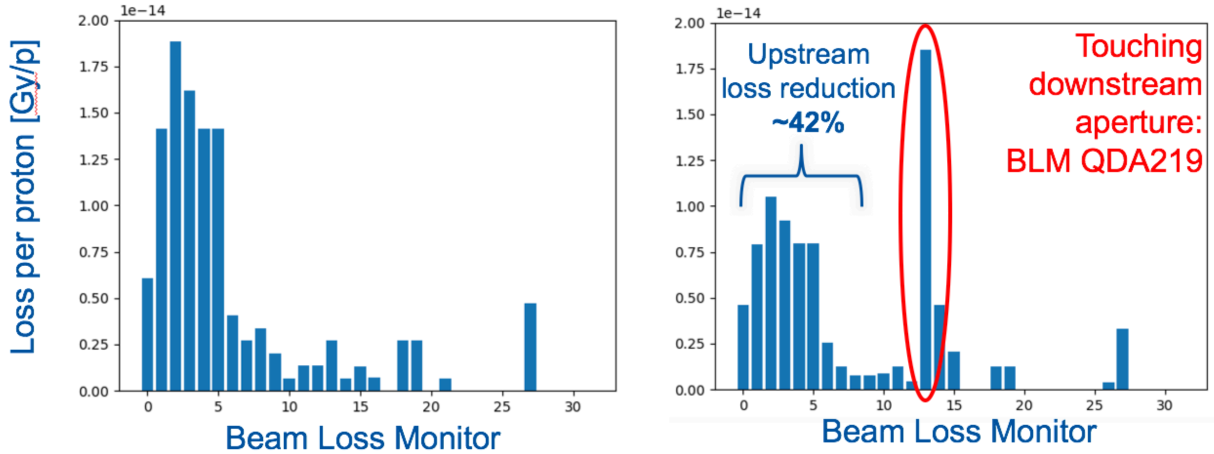


Figure 11 – Beam loss profile along LSS2 and TT20 for the nominal extraction (left) and in the best case (right).

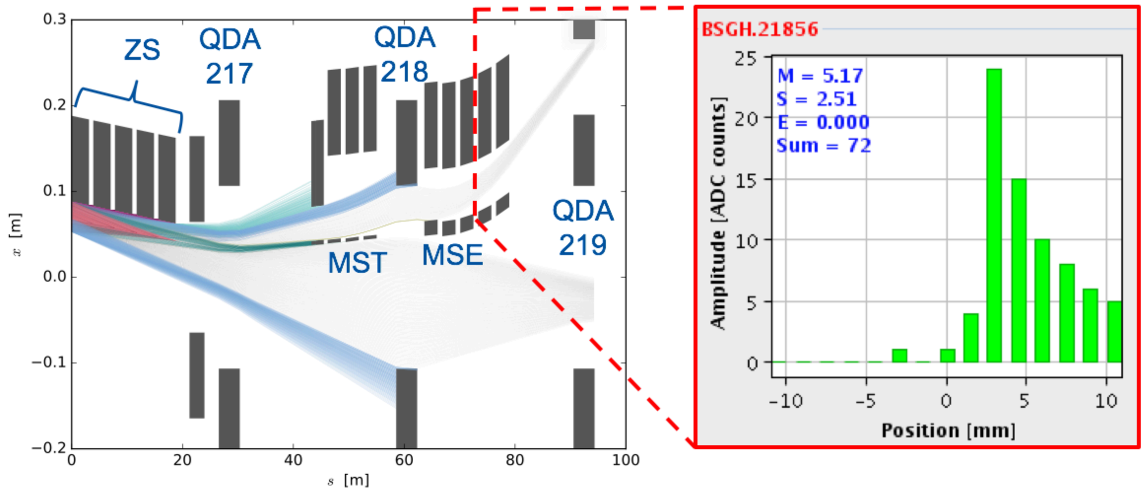


Figure 12 – LSS2 aperture and measured beam profile at BSGH218, showing the extracted beam positioned well towards the outside of the extraction aperture.

6. Acknowledgement

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