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CH-1211 Geneva 23
Switzerland

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Injector MD Procedure – SPS

SEPARATRIX FOLDING WITH OCTUPOLES DURING RESONANT SLOW EXTRACTION

Abstract

This note summarises the Machine Development (MD) studies proposed to test the folding of the separatrix arms during resonant slow extraction by using octupoles. The objective is to demonstrate a changing extracted beam profile at the electrostatic septum (ZS) and downstream thereof, and to understand the impact on the changing extraction beam loss measured in LSS2. In the long term this method is expected to reduce losses during extraction on the SFTPRO user at the electrostatic septum by reducing the density of the beam impinging on the wires. The octupole folding concept is introduced and the damage limits of the ZS wires are outlined before the proposed steps of the MD programme are described, along with the necessary modifications to the machine protection systems.

Prepared by:	***Checked by:***	***Approved by:***
M.A. Fraser **L.S. Stoel** **F.M. Velotti**	**B. Balhan** **H. Bartosik** **K. Cornelis** **B. Goddard** **V. Kain** **S. Readelli** **J. Storey**	**J. Wenninger** **D. Wollmann** **J. Uythoven** **M. Zerlauth**

Distribution list:

SPS machine supervisors, SPS operators, SPS Loss and Activation Working Group invitation list

History of Changes

Rev. No.	***Date***	***Pages***	***Description of Changes***
0.1	16-Aug-2018	All	First draft

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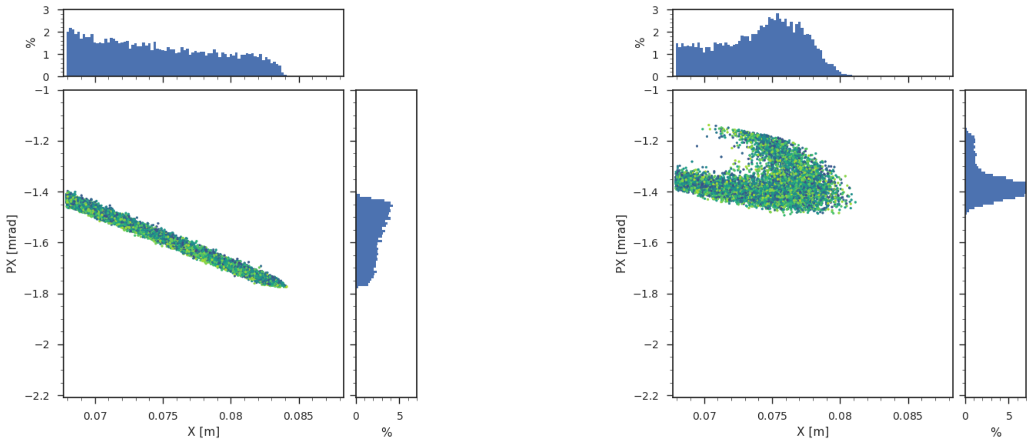
1. INTRODUCTION

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.

In the current operational scenario four extraction sextupoles are used to drive out particles on the separatrix, which is a straight line in phase space in this case. Moreover, in this scenario the spatial density of the beam at the ZS drops off quadratically with distance to the beam centre. Simulation results for the extracted beam at the ZS with its spatial and angular density projections is shown in Figure 1a.

When strong octupolar fields are added, one can curve the separatrix in phase space. Additional sextupole strength is then required to keep the extracted beam size the same. After optimizing, this allows for an extracted beam whose spatial density projection is peaked inside the extraction channel rather than at the septum wires. The lower density at the ZS wires then causes less protons to interact in the wires, reducing overall losses and activation. An example of simulated beam extracted this way is shown in Figure 1b.



(a) Nominal extracted beam (b) With octupoles

Figure 1 – Simulated extracted beams for the nominal case (a) and with added octupoles and increased sextupole strength (b) (k3L=-2.0 m^{-3} per LOF magnet, extraction sextupoles at 2.6x nominal strength).

Error studies have shown that even with large changes in octupole and sextupole strength, the orbit is not expected to change significantly (see appendix A.2). The resonance driving term however is affected. The resonance driving term is mainly determined by the sextupole strength (as per design), but in the case of a non-zero closed orbit it may differ in both strength and angle from the theoretical expectation. In the presence of a non-zero closed orbit the changing octupole strength will also change the driving term angle and strength somewhat (see appendix A.3). Even though simulations show the impact of the octupoles on the resonance driving term is small, the first part of the MD will be dedicated to understanding the impact of applying octupoles at resonance without extracting.

Simulations have shown that for very large octupole strengths a significant amount of beam can stay trapped in the machine at large amplitudes, due to the separatrix being folded back further than the extraction aperture allows. This effect is shown in appendix B.1 and will also be studied in the first part of the MD.

The separatrix arms are expected to both bend and rotate compared to their nominal position. This changes the angle at which particles reach the ZS wires, and the angle at which they travel through the extraction channel. This would require an adjustment of the downstream ZS girder position, realigning the wire array with the beam angle, as well as monitoring of losses in the rest of the extraction channel during the MD.

The recently developed Constant Optics Slow Extraction (COSE) [2] will be used for this MD, rather than the traditional (and currently operational) 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 other optics parameters. With the COSE method, all magnets are scaled in strength synchronously, so that at any time during the extraction, all extracted particles see the same optics throughout the spill. This method has been tested and implemented during several MDs in 2018, and the Autospill application has been upgraded to enable an easy set-up of this extraction.

A full optimization of a slow resonant extraction with octupole folding of the separatrix would require either the realignment of the LSS2 magnetic septa, or an additional knob to change the beam angle in the extraction region. In this MD however, we will not attempt such a full optimization yet and focus rather on verifying our understanding of the extraction dynamic in the presence of octupolar fields.

The MD goals are to:

- Demonstrate the and understand the possibility to resonantly drive the beam to large amplitude with the sextupoles and trap it there with the octupoles.
- Demonstrate clear changes in the extracted beam profile and extraction losses in LSS2 with varying octupole and sextupole strengths.
- Iteratively find a combination of sextupole strength, octupole strength and ZS alignment for which losses are lower than or comparable to nominal.

2. ZS DAMAGE LIMITS

An incident in 2007 [3] involving damage to the ZS and flying wire MD’s in the 1990’s [4] give indications for the damage limits of the ZS.

2.1 SUMMARY OF 2007 INCIDENT DAMAGING ZS1

At the end of the 2007 physics run, a 90 mm bump was erroneously applied during the ramp, bumping two consecutive cycles containing a circulating beam of 9E12 protons over the ZS wires in a few ms breaking wires in the first tank (ø = 60 μm). The incident occurred as a result of superimposing two bumps of nominal amplitude. The bump speed was 0.3 mm/ms. The beam was swept over the wires in about 9 ms, for $\pm 4\sigma$. The beam was dumped on losses but the reaction time of the TT20.BLM.210222 was too slow sampling at 20 ms. Since this event TT20.BLM.210222 was connected to the fast BLD system, with µs reaction time, the status of the extraction bumper (ON/OFF) are surveyed in SIS and limits placed on the extraction bump amplitude in LSA (120% of their nominal value).

2.2 FLYING WIRE MD’S

ZS (W26Re) wires were flown through circulating proton beams in the SPS at speeds varying from 0.6 to 6 m/s in the horizontal plane. First tests were carried out at injection energy using a set-up of 4 wires (2x 60 μm and 2x 110 μm). Several attempts were made to break the wires with even a 2.3E12 SFTPRO beam failing to break the wires at the slowest scan speed; beam was quickly scattered out of the SPS because of the number of wires. Some modification to the surface of the wires was observed in electron microscopy but the wires remained intact.

Tests with a single 110 μm wire and circulating LHC bunches at 450 GeV/c broke near the middle of its passage with 7.3E12 protons, i.e. a single batch of 72 bunches, at 0.7 m/s. The **damage limit was therefore estimated at 1.9E12 circulating protons for a 60 μm wire at 0.7 m/s**. The beta-function used at the wire-scanner is 3 times smaller than at the first ZS tank, giving some margin in this number. The wires that were broken were shown to have melted due to beam induced heating. These results showed reasonable agreement with simulations and were extrapolated for single-pass damage limits for the design of LHC fast extraction regions, put at about a factor 10 higher.

It should be pointed out that reference [3] implies a single-bunch with 7.3E12 protons was circulating, although this, most obviously, appears to be a typo. We infer that this intensity refers to a train of 72 circulating bunches of close to 1.0E11 ppb.

2.3 RELEVANCE TO THE PROPOSED MD

The expected movement of the beam due to octupole feed-down to the orbit is negligible, hence the application of octupoles does not risk bumping the circulating beam into the ZS. In order to check the impact of imperfections on the effective strength of the resonant driving term, the first step of the MD will be carried out with the TCSM inserted and the extraction bump off to set limits on the range of octupole strengths applied, ensuring that no significant fraction of beam can be captured at amplitudes near the ZS wires.

3. DETAILED STEPS TO BE TAKEN BEFORE, DURING AND AFTER THE MD

3.1 STEPS TO BE TAKEN BEFORE THE MD

A very low intensity (VLI) version of MTE at 1 – 5E11 ppp has been prepared in the injectors, to help mitigate the risk to the ZS wires. The beam intensity typically used for alignment and setting-up of the SFTPRO cycle is 2E12 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. The reduction to 5E11 ppp should keep the intensity just high enough that the SEM grids in the extraction area give reliable data, but low enough to be below the expected damage threshold. Use of this beam means that other high intensity beams may be limited in the SPS super-cycle (to protect the LLRF electronics when attenuators are removed for the very low intensity MTE beam), and the MD will be scheduled accordingly to take place in parallel to low intensity ion MDs.

3.2 PREPARATION OF THE MD

Number of MD’s	1
Time required per MD [h]	10
Beam required	SFTPRO1 (Slow extraction MD cycle)
Beam energy [GeV]	400
Bunch intensity [#p]	**VLI MTE at ~5E11 ppp**
Extracted spill length [s]	~ 4.8 s
Number of batches	1 batch from PS
Transv. emittance [m rad]	< 8E-6
Orbit change [yes/no]	No
RF system change [yes/no]	Tuning needed by RF expert for very low intensity MTE

What else will be changed?	LOF->K and EXTR_SEXT knobs will be varied, as well as the ZS downstream girder position. The momentum sweep for the extraction may be trimmed if necessary. The TCSM will be inserted and aligned with the beam during the MD.
Extraction configuration	TT20 TED IN

Table 1: SPS machine parameters during the MD

3.3 STEPS TO BE TAKEN DURING THE MD

The MD will be split into two parts. The first part will focus on verifying our understanding the stabilizing/trapping effect of the octupoles applied during slow extraction in combination with the extraction sextupoles. In this first part the extraction bump will be off, so that the beam will either stay trapped or be lost on the TCSM collimator, which will be inserted for this purpose. The second part of the MD will then proceed to measure the effect of the combined sextupolar and octupolar fields on the extracted beam whilst slow extracting the beam through LSS2, with predetermined limits on the octupole strength.

The current comparator for the SIS interlock triggering the PS internal dump will be set to limit the intensity extracted from the PS. TT20 TED inserted IN beam.

3.3.1 EXTRACTION SET-UP

1. Verify set-up of the COSE extraction of the the VLI-MTE beam in SPS. The RF gymnastic should be off, and Autospill (and trim of the initial tune) can be used to obtain a nominal spill.
2. Realign the ZS downstream position to minimize loss. (The optimum is known to differ a bit between COSE and the operational extraction scheme.)
3. Measure the beam profile and extraction losses as reference, to enable fair comparison of observables later on.
4. Set up the BGI to measure circulating beam size throughout the flat-top.
5. Increase normalized loss interlock limits in the ZS region by a factor 10. Lower the absolute loss interlock limits to correspond to this normalized loss limit, or to 5x lower than nominal if no normalized loss limit exists. (See Tables 2 and 3.)
6. Verify the LSS2 BLM fast hardware interlock, i.e. lower the interlock threshold to below the expected losses and check that the beam is inhibited.

3.3.2 TCSM ALIGNMENT

1. On a cycle-by-cycle basis, move in the outer jaw of the TCSM by 1 mm at a time.
2. Find the TCSM aperture at which the extracted beam and ZS losses are exchanged with slow losses on the TCSM. This is expected to be at 13 mm.
3. Move in the inner TCSM jaw to match the position of the outer jaw, symmetrically w.r.t. the beam.
4. Verify that there is no significant beam loss at injection for these TCSM settings. (As expected.) If high injection losses are seen, move out the inner jaw slightly and bump the beam away from the outer jaw at injection.

The simulated result of this procedure can be found in appendix B.2.

3.3.3 MD1: VERIFICATION OF BEAM TRAPPING

1. With the TCSM aligned as per section 3.3.2, turn off the extraction bump.
2. Increase the focusing octupole strength (LOF->K) in steps of 0.3 m^{-4} until a few steps beyond the strength where nearly all of the beam intensity stays trapped in the ring, referred to as the 'critical octupole strength' below. (Expected at roughly 4.2 m^{-4}.) (Note: The remaining beam is by default always dumped at the end of the flattop.)

3. Quantify the beam size (new emittance) at the end of the flattop on the BGI for the trapped beam at critical octupole strength.
4. Return to zero octupole strength and set the sextupole strength to 1.4x nominal. Repeat steps 2-3, the octupole strength needed to observe trapping is expected to be almost twice as high now.
5. Return to zero octupole strength and nominal sextupole strength. Repeat steps 2-4, except now *decreasing* the octupole strength in steps of -0.3 m^{-4}.
6. Inhibit the beam. Restore the octupole and extraction bumps back to their nominal values and move the TCSM back out.

The simulated result of this procedure can be found in appendix B.3.

3.3.4 MD2: RESONANT EXTRACTION WITH OCTUPOLES

1. Add LSA interlocks on LOF->K corresponding to the limits found in MD1 for nominal sextupole strength. Add LSA interlocks on the extraction sextupole knob to be between 0.99 and 1.41.
2. **Octupole scan:** Decrease LOF->K in steps of -0.3 m^{-4}, while measuring beam profiles at BSGH.216 and BSGH.218 and the beam losses around the ring, until the limit defined in MD1. If either of the conditions below occur, the scan should be stopped even if the limit was not reached:
   a. Normalized losses at the ZS or TPST are significantly increased. (Up to the adjusted loss interlock limits.)
   b. The extracted beam at the upstream end of the ZS extends less than 5 mm past the wires, i.e. the "effective spiral step" is less than 5 mm. (Nominal 15 mm.)
3. **Girder scan:** At this maximum acceptable LOF->K setting, perform a downstream ZS girder scan to minimize losses. (We expect it needs to move by about 1.5 mm.)
4. **Sextupole scan:** (Only if the higher sextupole scan in MD1 behaved as expected.) Now increase the extraction sextupole knob in steps of 0.05. Stop when 1.4x nominal sextupole strength is reached or either of these holds:
   a. The extracted beam at the upstream end of the ZS extends more than 18 mm past the wires. (Nominal 15 mm, maximum 20 mm.)
   b. Significant losses at non-nominal loss locations are observed.
5. **Girder scan:** At the combination of octupole and sextupole strength obtained, perform a downstream ZS girder scan to minimize losses. (We expect it needs to move by only a few hundred micron.)
6. Inhibit the beam, then set the sextupole and octupole knobs back to nominal, as well as the downstream ZS girder position.
7. Repeat steps 2-5, but *increasing* LOF->K in steps of 0.3 this time.

A simulated version of this MD is presented in appendix B.4, showing the evolution of the main observables as well as the underlying phase space distributions.

3.4 STEPS TO BE TAKEN AFTER THE MD

After the MD double-check that nominal values are restored for:

1. The LOF->K and EXTR_SEXT knobs
2. The downstream ZS position
3. The normalized and absolute loss interlock limits in the ZS region

and that the LSA limits on LOF->K and EXTR_SEXT are removed.

4. CHANGES OF MACHINE PROTECTION SETTINGS DURING MD

4.1 CHANGES TO BEAM INTENSITY LIMITS

The intensity sent from the PS can be interlocked by setting correctly the current comparator and the PS internal dump.

4.2 CHANGES TO BLM INTERLOCKS

Normalized loss interlock limits in the ZS region will be increased by a factor 10, while absolute loss limits will be decreased to match this threshold at an intensity of 5E11 p+/cycle. The absolute loss limit for BLMs in LSS2_TT20 and BA2 will be reduced by a factor 5 if no normalized loss limit is defined. An overview of nominal and MD loss limits is given in tables 2 and 3. Note that the normalized loss interlock will only inhibit the *next* beam, while the absolute loss interlock will trigger a beam dump based on the SPS BLMs.

	Norm lim (Gy/p+)	MD norm lim (Gy/p+)	Abs lim (mGy)	MD abs lim (mGy)
ZS1	8.80 E-15	8.80 E-14	225	44
ZS2	1.85 E-14	1.85 E-13	455	92.5
ZS3	2.35 E-14	2.35 E-13	690	117.5
ZS4	2.42 E-14	2.42 E-13	615	121
ZS5	2.12 E-14	2.12 E-13	545	106
TCE	-	-	525	105
TPST	1.85 E-14	1.85 E-13	205	92.5
MST1.21775	-	-	200	40
MST1.21776	-	-	328.2	65.64
MST3.21792	-	-	160	32
MST3.21796	-	-	150	30
MSE1	-	-	50	10
MSE2	-	-	50	10
QDA.219	-	-	149	29.8
MBE.210330	-	-	150	30
QNLF.211600	-	-	264.6	52.92
QTLD.210280	-	-	261.8	52.36
BLM.211106	-	-	291	58.2
Other LSS2_TT20	-	-	100	20

Table 2: Changes to LSS2_TT20 normalized and absolute BLM limits

	Norm lim (Gy/p+)	MD norm lim (Gy/p+)	Abs lim (mGy)	MD abs lim (mGy)
217	-	-	150	30
218	-	-	300	60
Other BA2	-	-	100	20

Table 3: Changes to BA2 normalized and absolute BLM limits

5. CONCLUSIONS

A procedure to investigate the use of octupoles during slow extraction to reduce extraction losses in LSS2 has been prepared, and this procedure has been simulated. A VLI MTE beam of ~5E11 ppp has been prepared and tested to mitigate the risk of damaging to the ZS or other aperture limits. The procedure explicitly makes use of constant small steps, so that shot-by-shot changes will be small and high loss scenarios can be avoided.

6. REFERENCES

[1] M.A. Fraser and B. Goddard, SPS Losses and Activation Working Group (SLAWG) meeting series, https://indico.cern.ch/category/7887/

[2] F.M. Velotti, "Constant Optics Slow Extraction (COSE)", SLAWG meeting #29, 23 May 2018, https://indico.cern.ch/event/730812/contributions/3012443/attachments/1654671/2648336/cose.pdf.

[3] J. Wenninger, "SPS Machine Protection and Incidents in 2007", CERN-AB-Note-2008-003, CERN, Geneva, Switzerland, 2008.

[4] G. Ferioli et al., "Energy Deposition in a Septum Wire", CERN SL-Note-01-029 MD, CERN, Geneva, Switzerland, July 2001.

A. ERROR STUDIES

Simulations investigating feed-down effects due to the non-zero closed orbit for various octupole and sextupole settings have been carried out.

A.1 STUDY SET UP

In order to investigate the impact of the non-zero closed orbit in SPS, error studies were carried out in which the quadrupoles were randomly misaligned horizontally, with an RMS of 150 um and 500 seeds. A histogram of the resulting non-closure at resonance as measured at the horizontal BPMs is shown in Figure 2. Other error tolerances on the quadrupole alignment were considered, but 150 um agrees both with the expected SPS quadrupole misalignment and with the usual observations of the RMS orbit of a few mm, as measured on the BPMs.

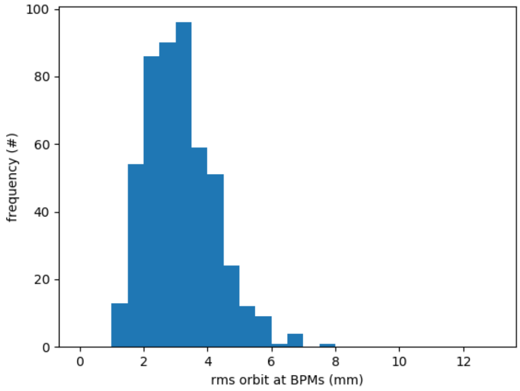
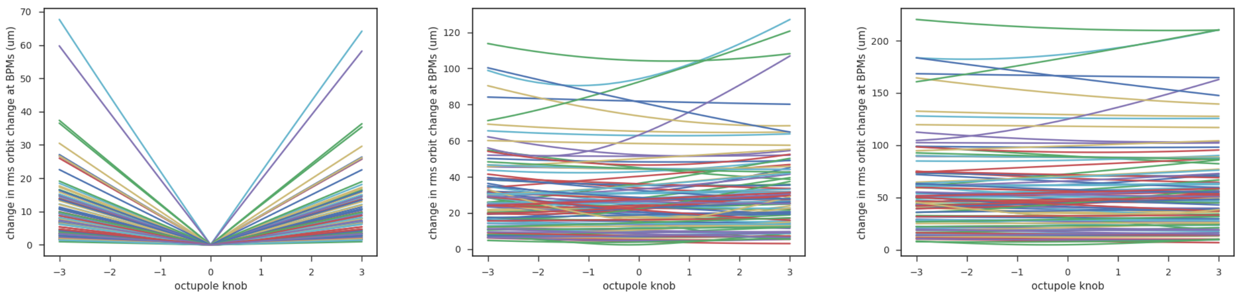


Figure 2 – RMS orbit for different quadrupole misalignments

A.2 ORBIT MOVEMENT

Subsequently, the change in orbit at resonance with changing octupole and sextupole strength was studied for 100 seeds. The reference for each realization of the misalignment was its orbit at nominal sextupole strength with the octupoles turned off. As can be seen in Figure 3, these changes are small, especially when compared to the nominal non-closure. Based on these simulations, we expect the movement of the beam at the ZS to be less than 0.3 mm and 10 urad even in the worst case.



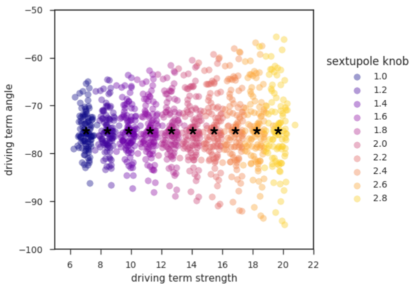
(a) Nominal sextupole strength (b) 1.8x nominal sextupole strength (c) 2.6x nominal sextupole strength

Figure 3 – RMS change in orbit with sextupole and octupole strength. (Octupole strength in K3L per LOF octupole.)

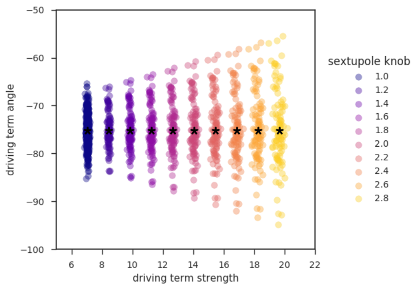
A.3 DRIVING TERM

A non-zero closed orbit will affect the resonance driving term as well as the change in the resonance driving term with varying octupole and sextupole strength due to feed down. Results of the error study are shown in Figure 4. Some of the strengths shown in the figure are much higher than those that will be used in the MD, but the general behaviour is well demonstrated. We see that

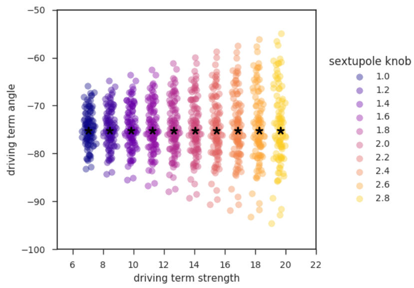
- The driving term strength is mainly determined by the sextupole strength, as it should be, with only small variations due to the orbit.
- The octupole strength will feed down to the driving term strength, but the difference will only be a few percent even for high octupole strengths. Whether the driving term strength will increase or decrease with increasing octupole strength depends on the exact orbit in the machine.
- The angle of the driving term depends on the exact orbit in the machine. For a perfect closed orbit the angle would be fixed with varying sextupole strength, but with a non-zero closed orbit the angle may go up or down with increasing sextupole strength, depending on the exact orbit.
- Feeddown from the octupoles may lead to an additional change in driving term strength, but this change is small compared to the uncertainty in angle from the non-zero closed orbit. The sign, once more, depends on the exact orbit.



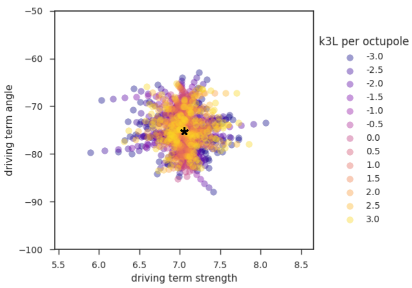
(a) Varying sextupole strengths, at k3L = -2.0 m^{-3} per LOF magnet



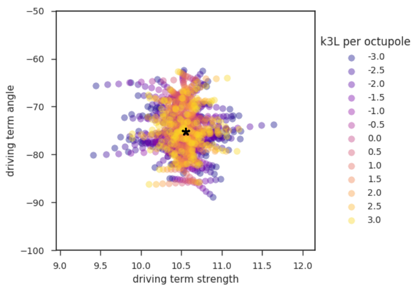
(b) Varying sextupole strengths, with the octupoles off



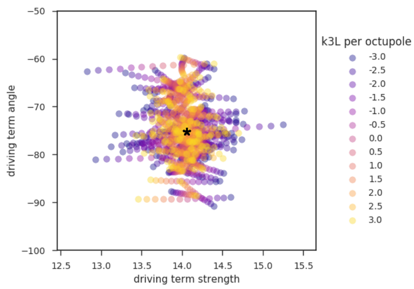
(c) Varying sextupole strengths, at k3L = 2.0 m^{-3} per LOF magnet



(d) Varying octupole strength, at nominal sextupole strength



(e) Varying octupole strength, at 1.5x nominal sextupole strength



(f) Varying octupole strength, at 2.0x nominal sextupole strength

Figure 4 – Driving term strength and angle for several realizations of non-zero orbits with varying octupole and sextupole strength. (The value of 1.0 for the sextupole knob in these plots corresponds to the nominal value.)

B. SIMULATED MD RESULTS

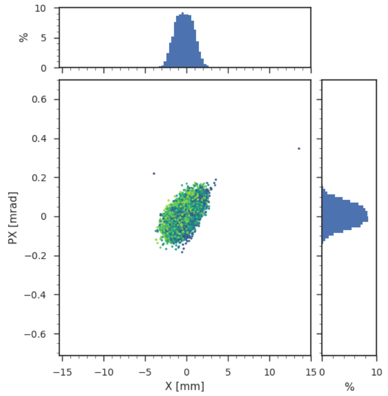
B.1 SIMULATED BEAM TRAPPING

A significant amount of beam stays trapped in the machine during extraction when the octupole strength is very high. For certain values of sextupole and octupole strengths a large amount of beam can build up at large amplitudes, posing a potential mechanism by which the circulating beam can touch the ZS wires.

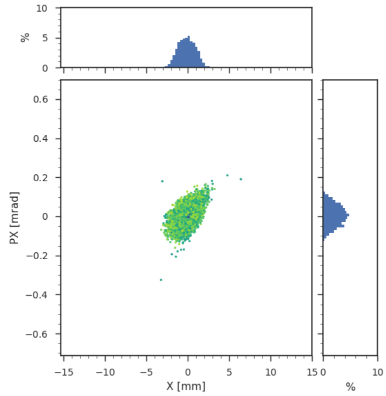
The initial part of the MD is designed to avoid any risk from this beam trapping effect. The bottleneck is transferred from the ZS wires to the TCSM, before the LSS2 extraction bump is turned off. With this set up the critical settings can be safely identified and avoided in the later part of the MD.

For completeness, we present the beam trapping effect as it would happen with the extraction bump active and the TCSM out. The mechanism behind this effect is that the beam is driven out of the centre of phase space by the sextupoles, but stabilized by the octupoles at an amplitude that is within the machine acceptance. The simulated beam throughout the extraction is shown for several octupole strengths, at nominal sextupole strength in Figure 5. The beam presented here is at the TCSM.

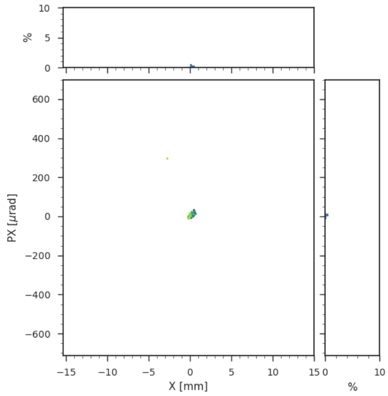
From this figure we see that for low octupole strengths, beam is extracted nominally, with only a few particles at very small amplitudes surviving until the end of the flat-top (Figure 5.a.3). For higher octupole strengths, some beam starts to become trapped at large amplitudes, and at high strengths most of the beam remains in the machine until the end of flat-top, trapped at high amplitudes (Figure 5.c.3).



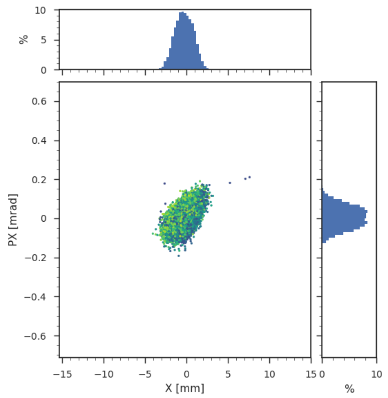
(a.1) k3L=1.0 m^{-3} per LOF magnet, start extraction



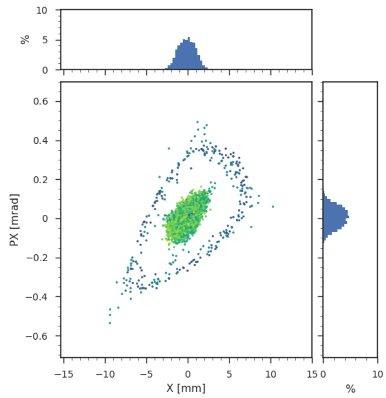
(a.2) k3L=1.0 m^{-3} per LOF magnet, mid extraction



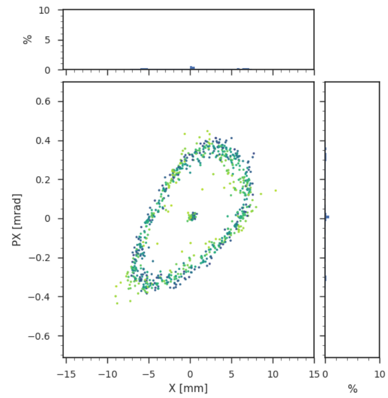
(a.3) k3L=1.0 m^{-3} per LOF magnet, end extraction



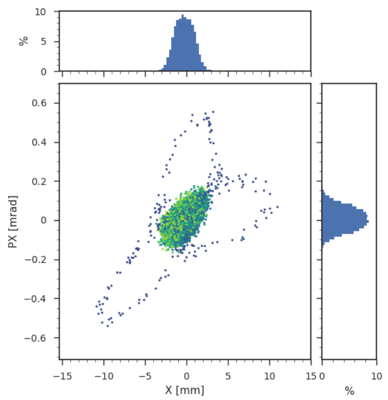
(b.1) k3L=2.0 m^{-3} per LOF magnet, start extraction



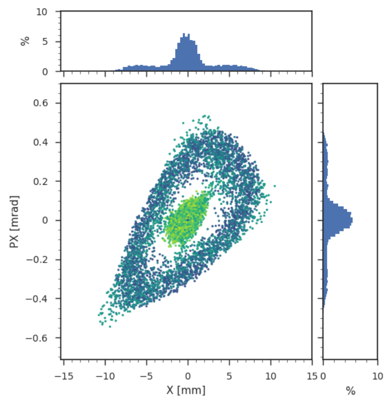
(b.2) k3L=2.0 m^{-3} per LOF magnet, mid extraction



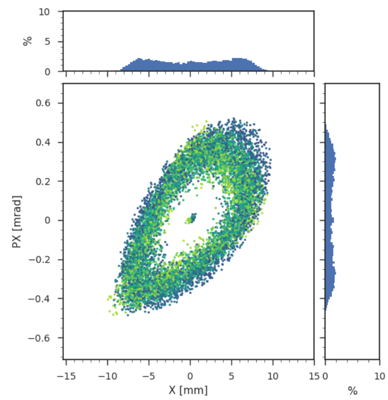
(b.3) k3L=2.0 m^{-3} per LOF magnet, end extraction



(c.1) k3L=3.0 m^{-3} per LOF magnet, start extraction



(c.2) k3L=3.0 m^{-3} per LOF magnet, mid extraction

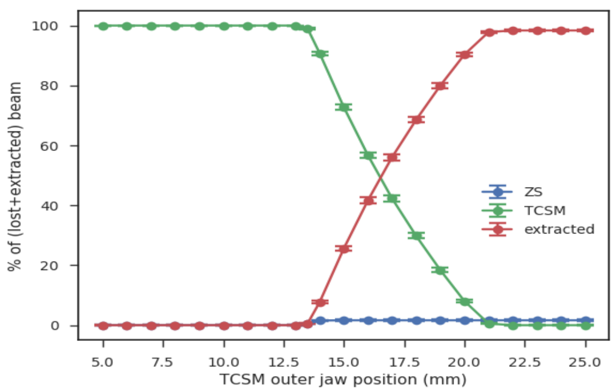


(c.3) k3L=3.0 m^{-3} per LOF magnet, end extraction

Figure 5 – Horizontal phase-space view of the circulating beam at the TCSM location during extraction for several octupole strengths at nominal sextupole strengths. Simulated particles are coloured by momentum from blue (low) to yellow (high).

B.2 TCSM ALIGNMENT

Simulated losses for the TCSM alignment procedure outlined in section 3.3.2 can be found in Figure 6. As the outer TCSM jaw is bought in and starts intercepting the spiral 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 between 14 and 13 mm. This agrees with the expected aperture from scaling the distance between the the circulating beam centre and the ZS wires (~26 mm) by the square root of the beta functions (~100 m at the ZS and ~25 m at the TCSM).



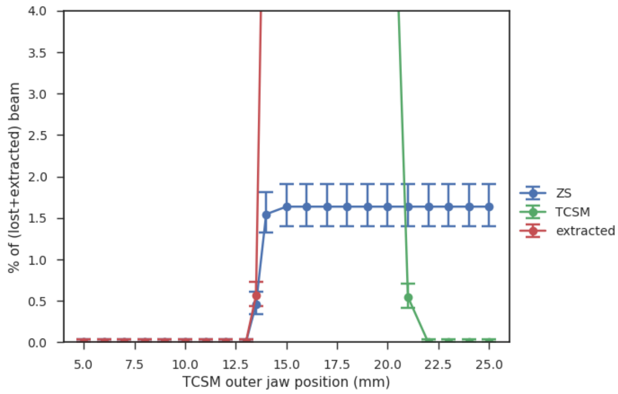


Figure 6 – Evolution of losses during a scan of the outer TCSM jaw position while slow extracting with nominal multipole strengths. (Full view on the left with zoomed view on the right.)

B.3 MD1: VERIFICATION OF BEAM TRAPPING

Simulated results for the MD outlined in section 3.3.3 can be found in Figures 7 and 8. In the simulated procedure the extraction bump is off and the TCSM jaws are inserted at ±13.0 mm. When the octupoles are off, all beam is slowly lost on the TCSM, but when the octupole strength is increased sufficiently we see more and more beam that stays trapped in the machine.

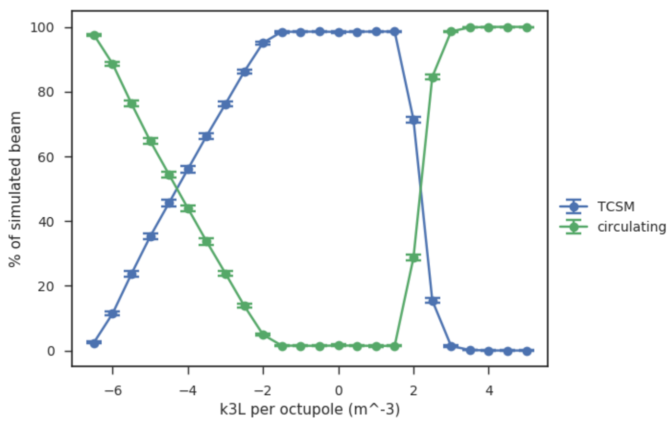


Figure 7 – Simulated particles lost at the TCSM or still circulating at the end of the simulation as a function of octupole strength, with the TCSM at ±13.0 mm.

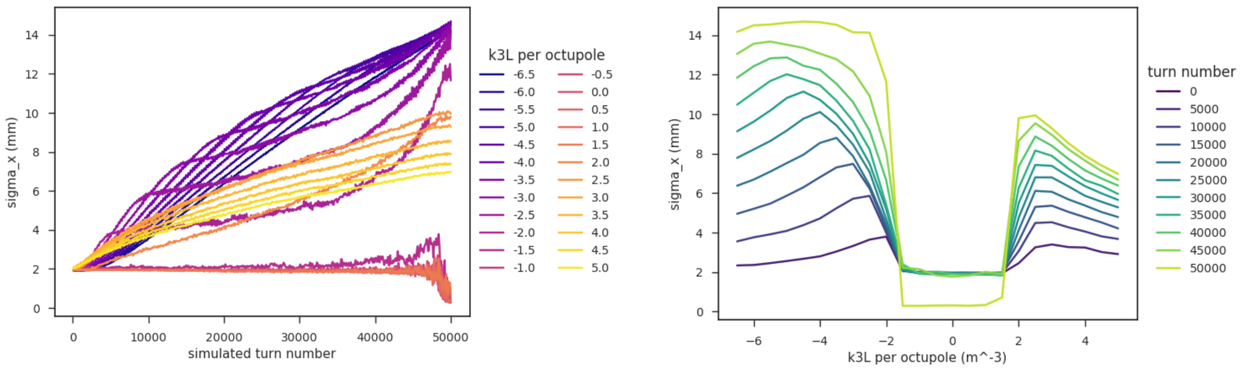
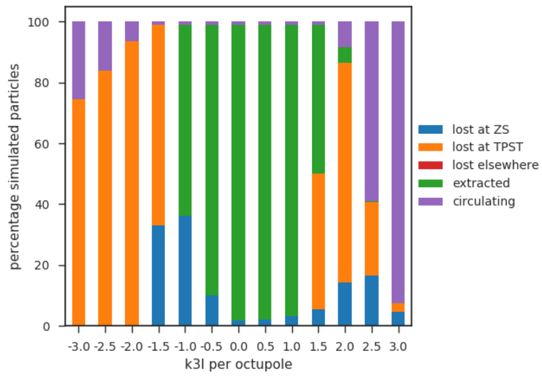


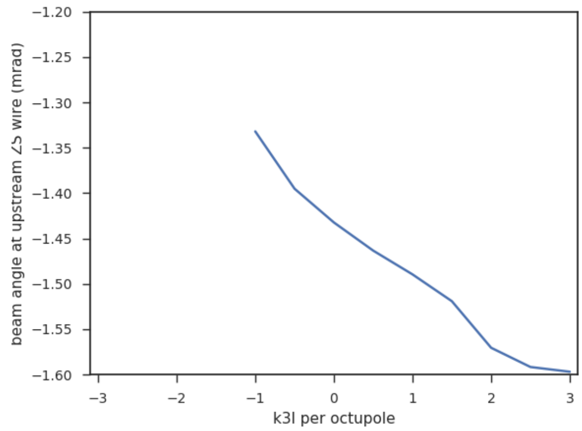
Figure 8 – Two different views of circulating beam sizes at the BGI throughout the flattop for different octupole strengths, with nominal sextupole strength.

B.4 MD2: RESONANT EXTRACTION WITH OCTUPOLES

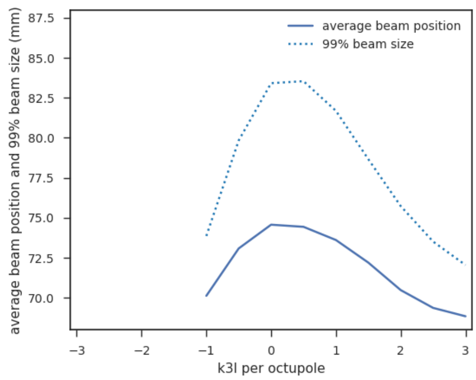
Simulations of the octupole and sextupole strength scans proposed in section 3.3.4 were carried out, but with a larger step size and a larger scan range. The evolution of beam losses as well as the changes in the beam profiles at the grids are shown in Figures 9-11. These figures show the proposed sextupole and octupole scans. The simulated phase space at the upstream end of the ZS for a few important settings is shown in Figure 12.



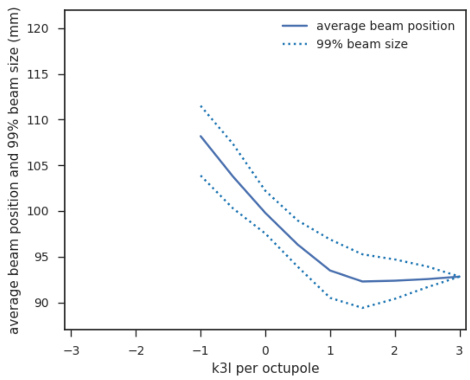
(a) Loss profile



(b) Beam angle at the upstream ZS wire

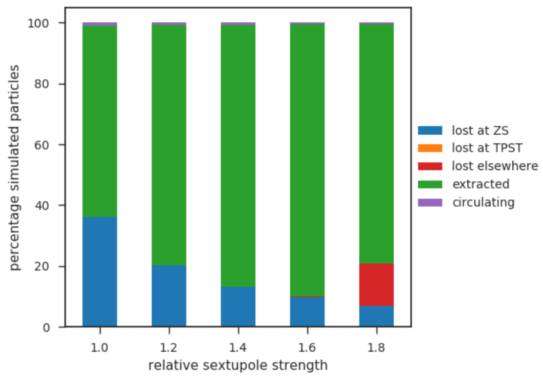


(c) Beam profile at BSGH.216

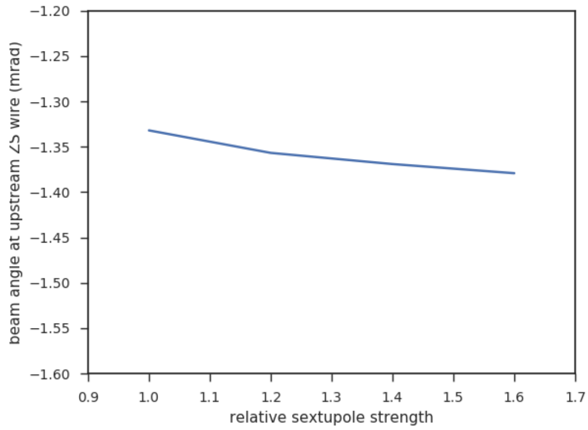


(d) Beam profile at BSGH.218

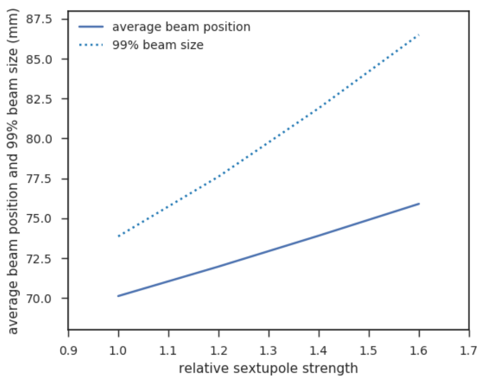
Figure 9 – Simulated octupole strength scan at nominal sextupole strength and ZS alignment.



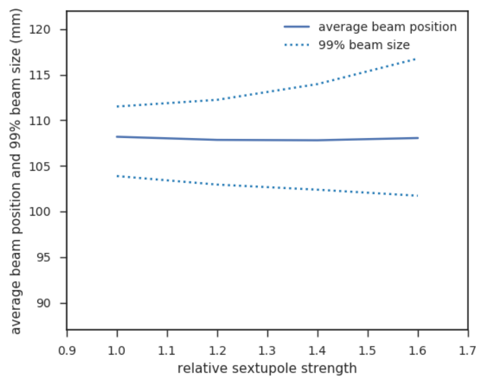
(a) Loss profile



(b) Beam angle at the upstream ZS wire

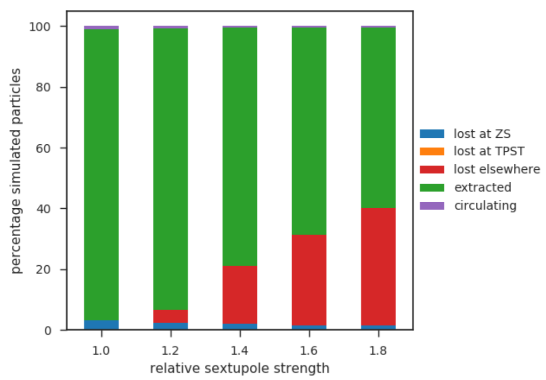


(c) Beam profile at BSGH.216

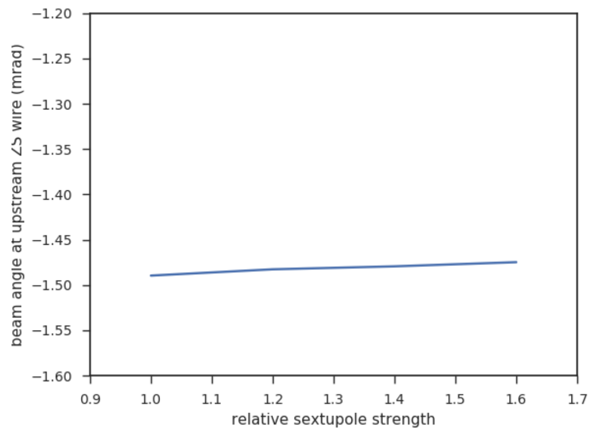


(d) Beam profile at BSGH.218

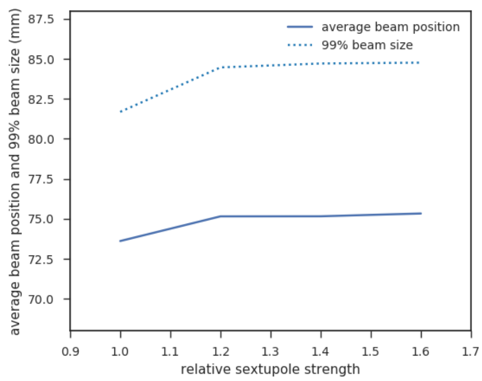
Figure 10 – Simulated sextupole strength scan at k3L=-1.0 m^{-3} per octupole with nominal ZS alignment.



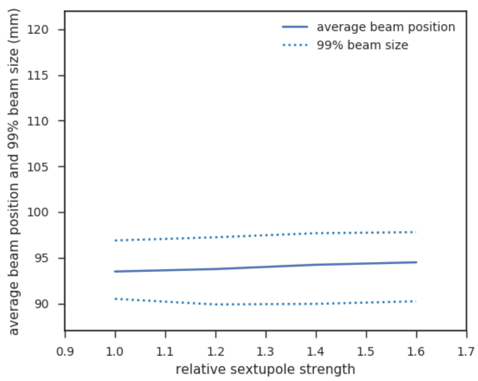
(a) Loss profile



(b) Beam angle at the upstream ZS wire

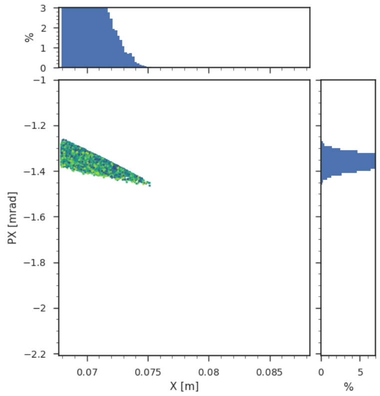


(c) Beam profile at BSGH.216

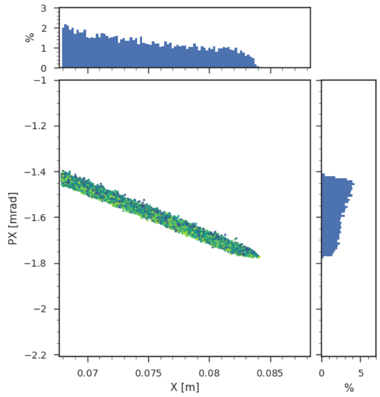


(d) Beam profile at BSGH.218

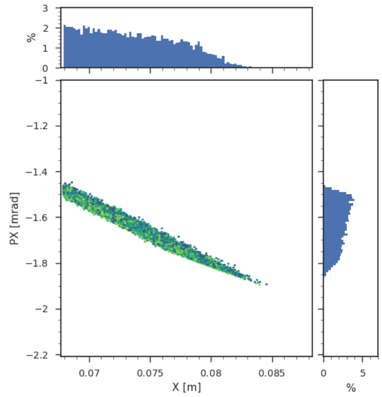
Figure 11 – Simulated sextupole strength scan at k3L=+1.0 m^{-3} per octupole with nominal ZS alignment.



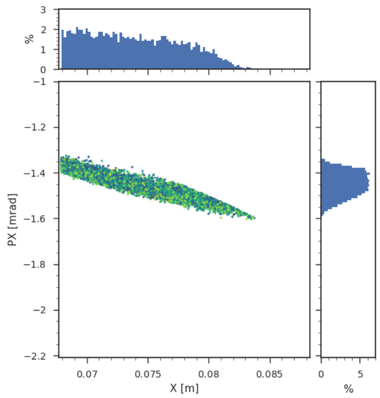
(a) Nominal sextupole strength, k3L=-1.0 m^{-3} per LOF



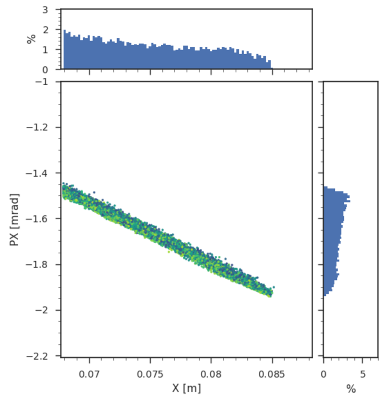
(b) Nominal extraction



(c) Nominal sextupole strength, k3L=+1.0 m^{-3} per LOF



(d) 1.4x nominal sextupole strength, k3L=-1.0 m^{-3} per LOF



(e) 1.2x nominal sextupole strength, k3L=+1.0 m^{-3} per LOF

Figure 12 – Simulated horizontal phase space at the upstream end of the ZS for several octupole and sextupole settings.