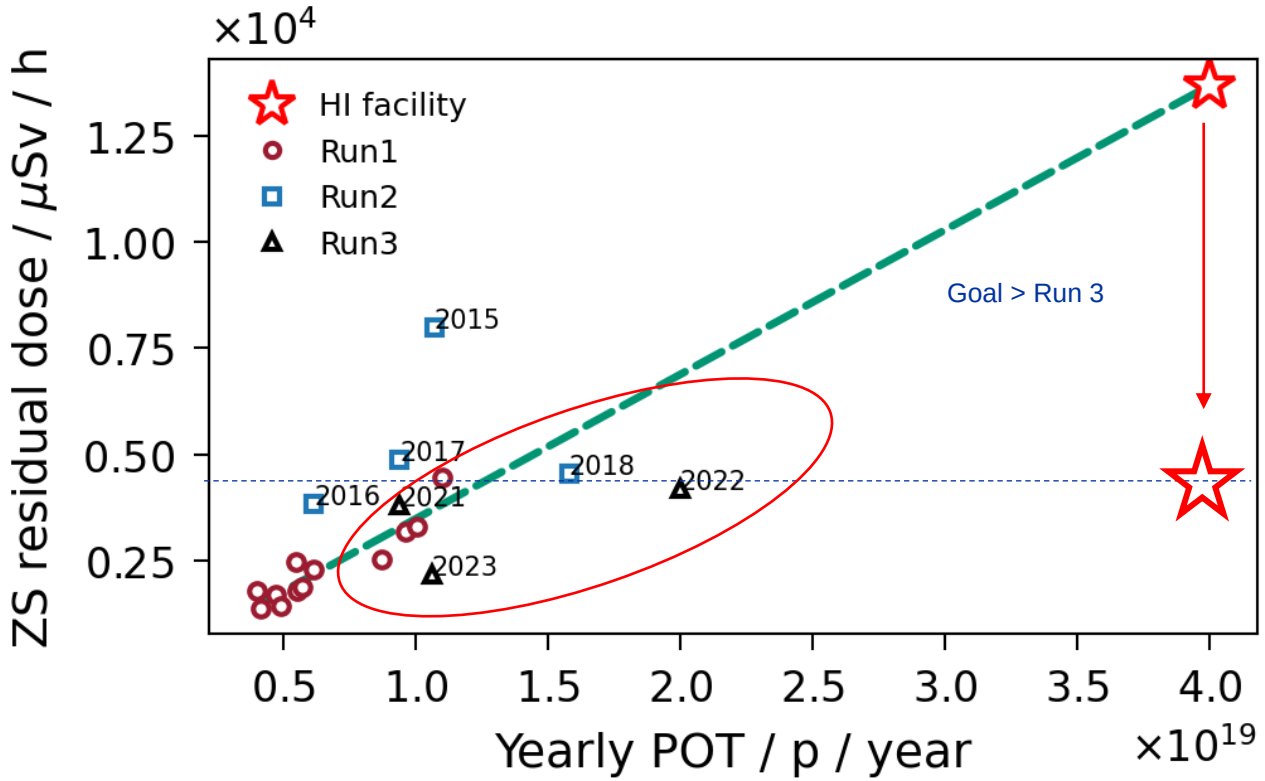
Octupole assisted slow extraction MD 2024

Aleksandr Gorn, Matthew Alexander Fraser, Francesco Maria Velotti, Pablo Aruttia (SY-ABT-BTP)

02.02.2025

Slow extraction in LSS2: ZS activation problem



- Beam losses on ES cause activation and, thus, limit max POT.
- We need to significantly reduce these losses (x4) to keep the dose at the level of Run 3.

Octupole folding technique

The idea of the octupole folding is to reduce the beam density on the ZA blade folding the beam in phase space together with increasing the spiral step.

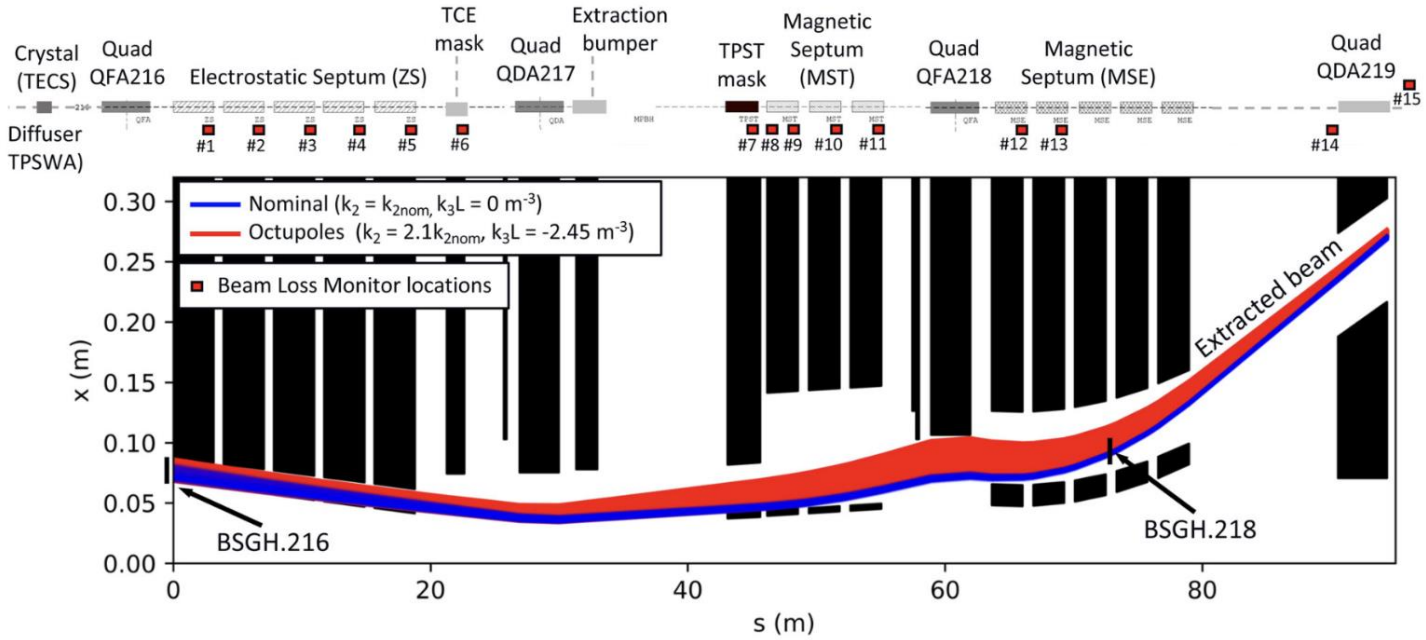
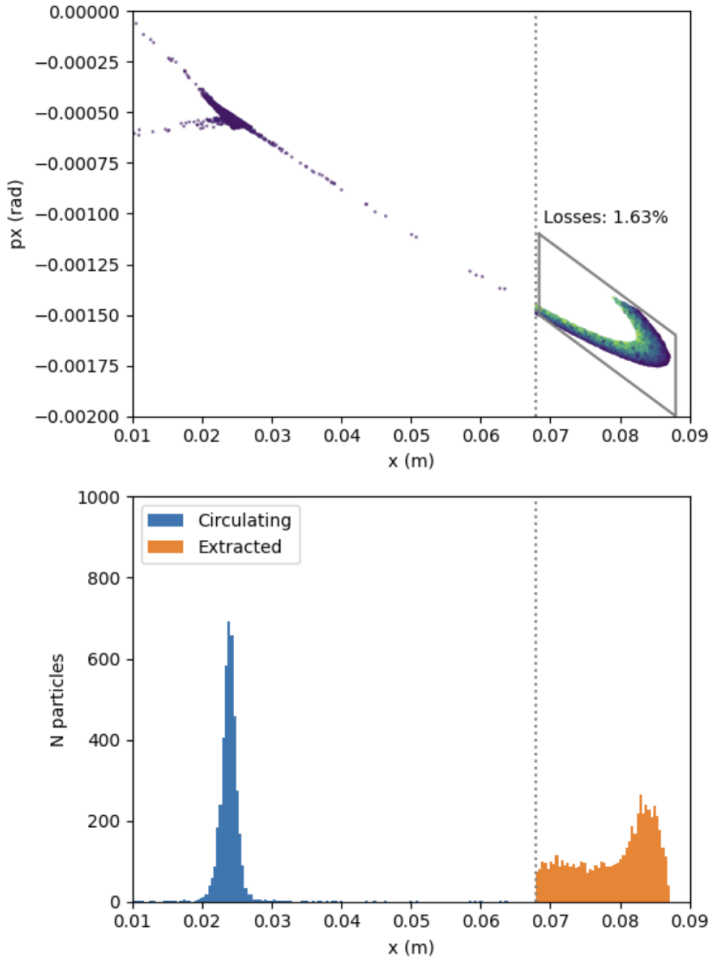


FIG. 17. Extracted beam trajectories along LSS2 with the multipoles powered ($k_2 = 2.1k_{2,\mathrm{nom}}$ and $k_3L = -2.45$ m^{-3}).



Losses in LSS2 during nominal operation

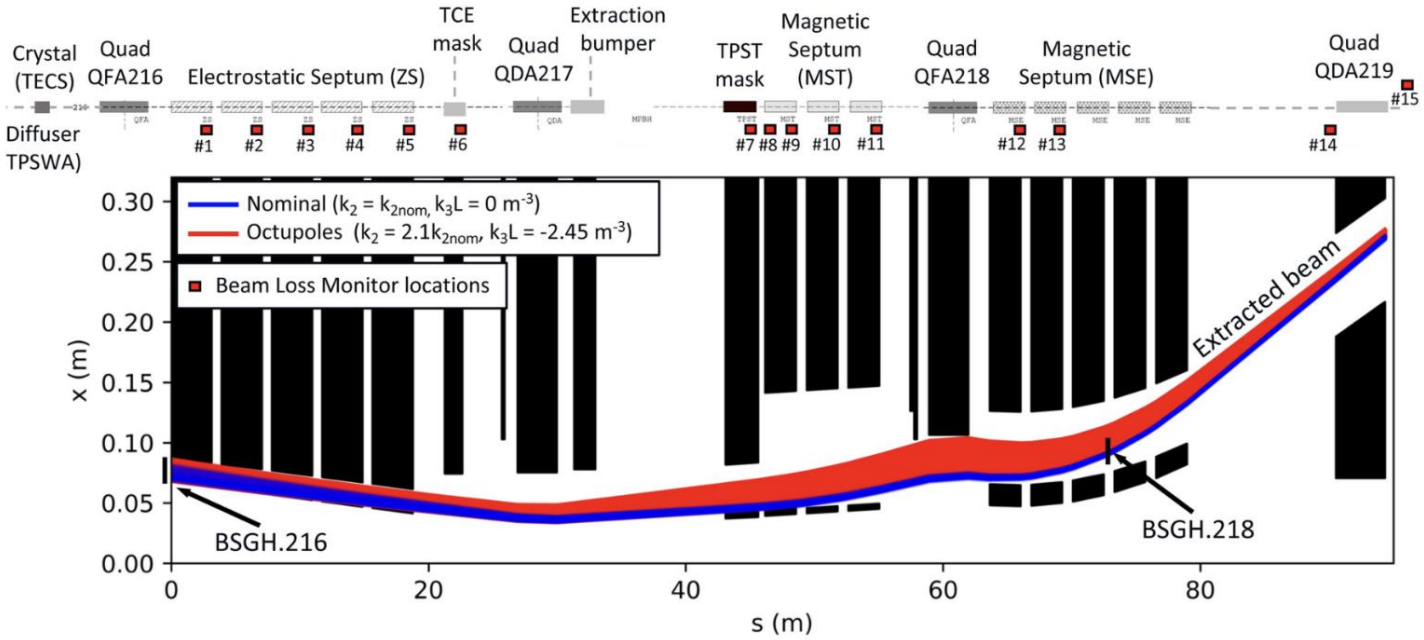
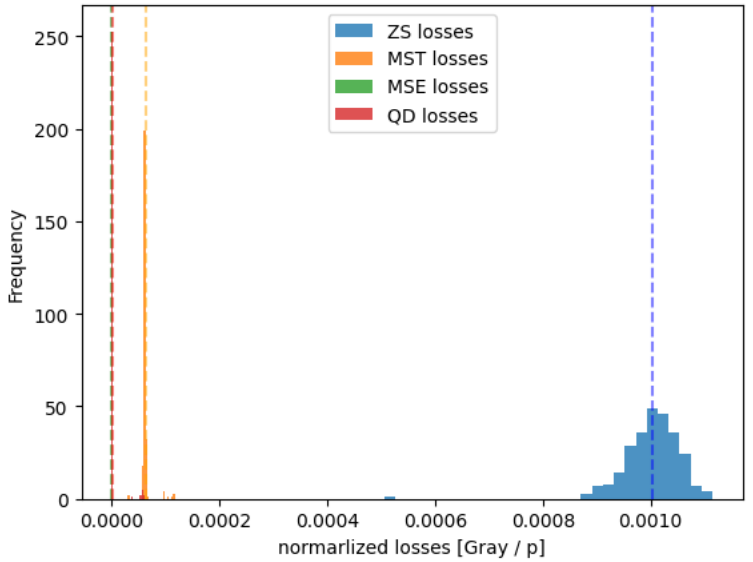
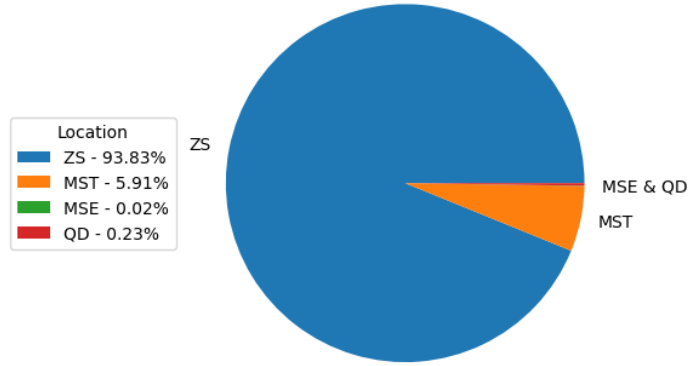


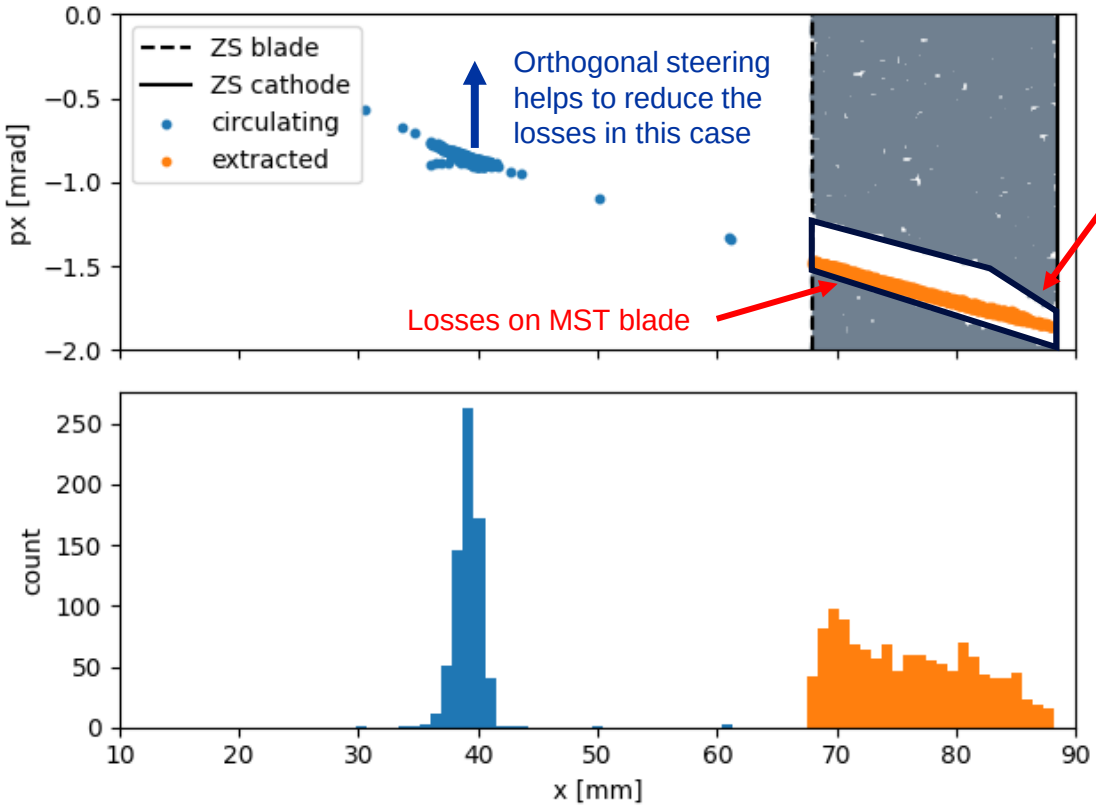
FIG. 17. Extracted beam trajectories along LSS2 with the multipoles powered ($k_2 = 2.1k_{2,\mathrm{nom}}$ and $k_3L = -2.45$ m^{-3}).



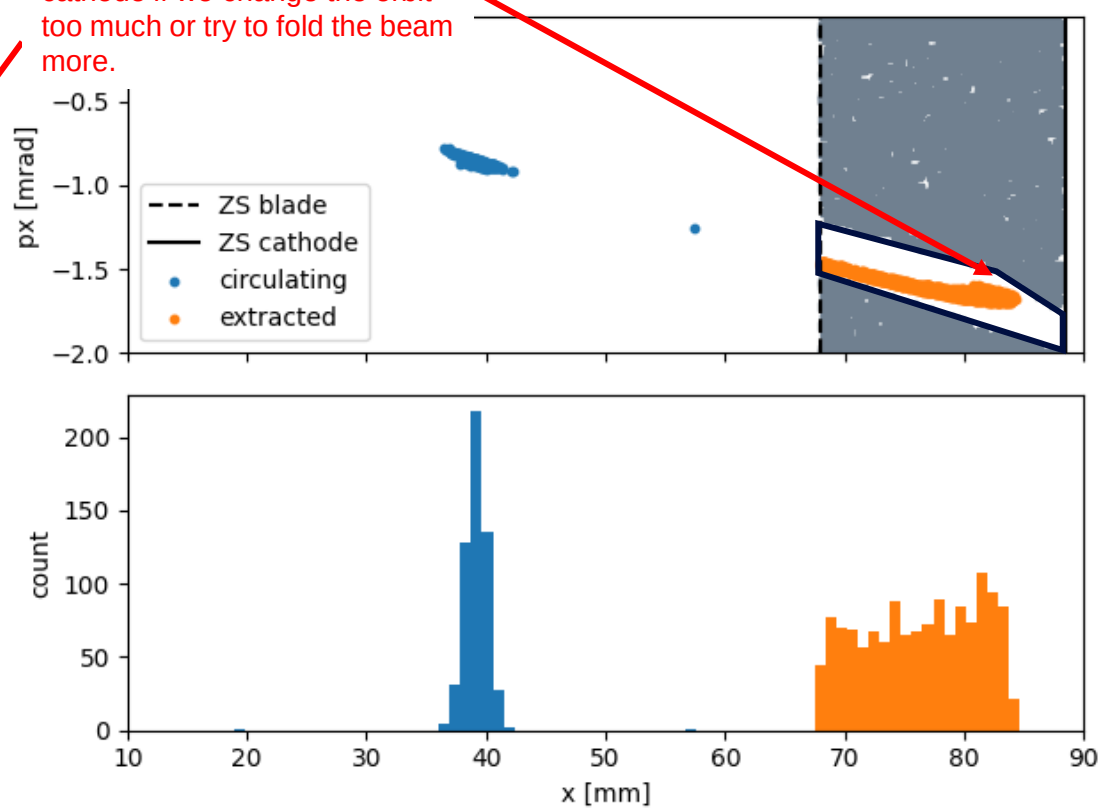


ZS has the highest level of losses in LSS2.

Extraction line acceptance



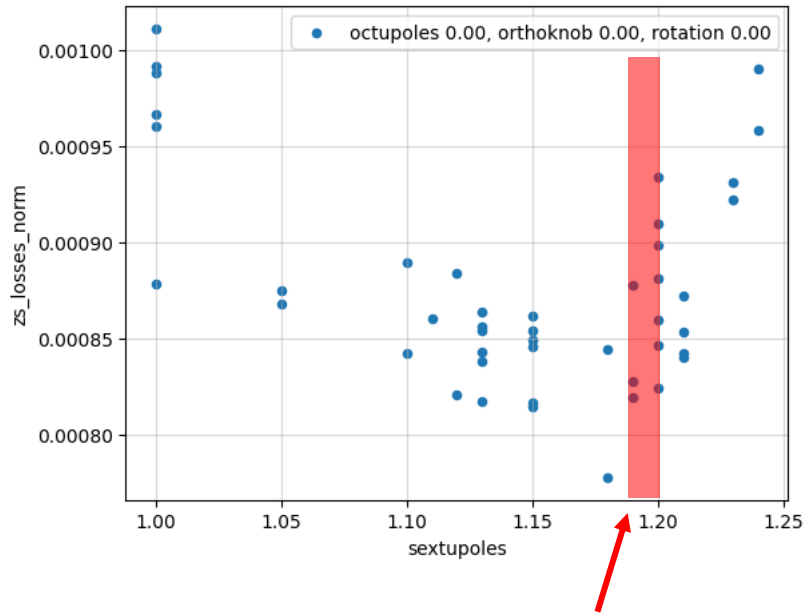
On the other hand at some point we start hitting the ZS cathode if we change the orbit too much or try to fold the beam more.



The main challenge of octupole folding is to find the balance between the sextupole strength, separatrix rotation and octupole strength.
The higher the first two, the longer the spiral step. The stronger the octupoles, the higher the angular spread.

Loss reduction

Knob	Value
Octupole strength	0
Sextupole strength	1 - 1.25
Separatrix rotation	0
Extraction bump	1
Orthogonal steering angle [urad]	0
Girder downstream position [mm]	42.82



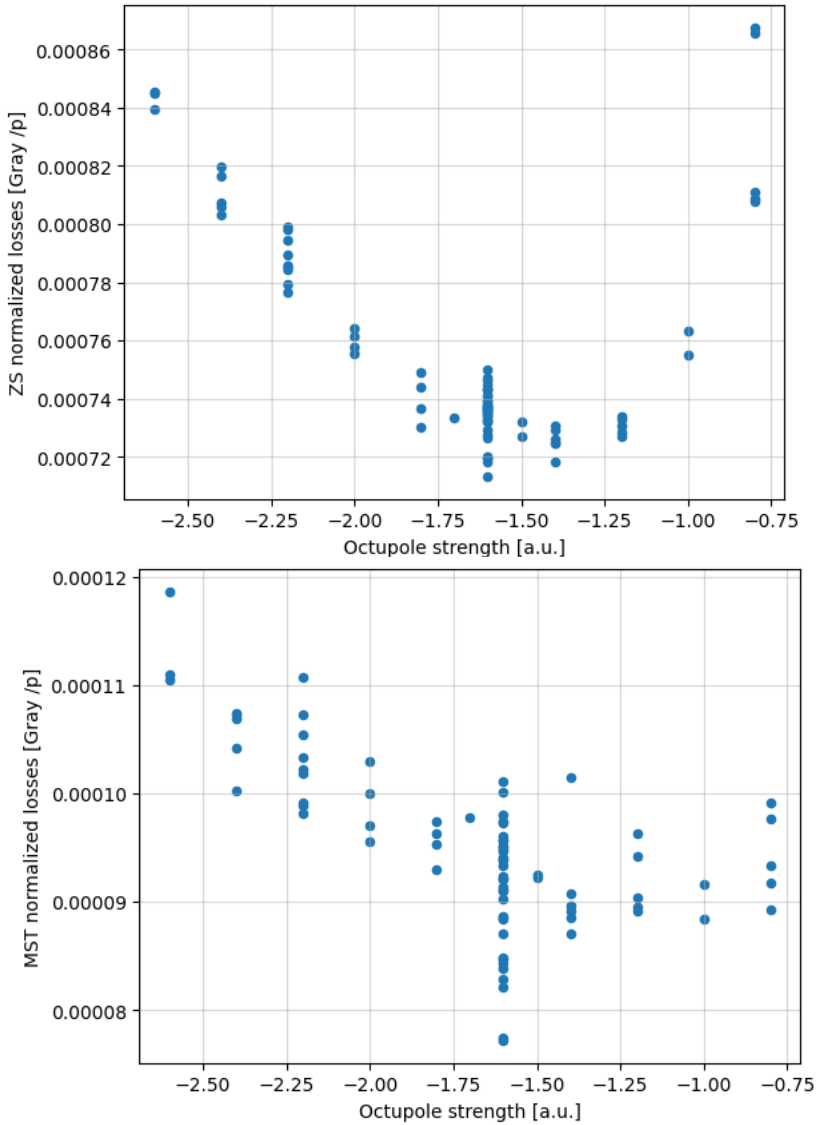
At this point (~1.19-1.2) the beam starts hitting the ZS cathode

First, we started with the scan of the extraction sextupole strength to find the maximum achievable spiral step before we turn on octupoles.

Loss reduction

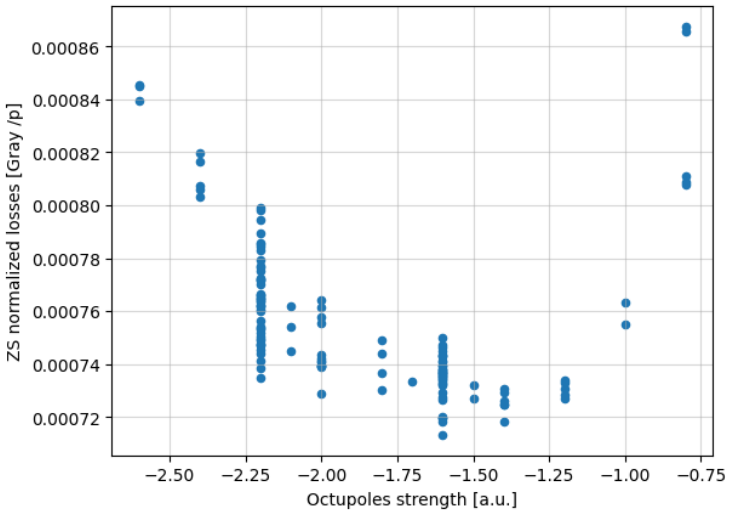
Knob	Value
Octupole strength	-1.6
Sextupole strength	1.3
Separatrix rotation	15
Extraction bump	1.03
Orthogonal steering angle [urad]	-24 (Minimum possible)
Girder downstream position [mm]	42.82

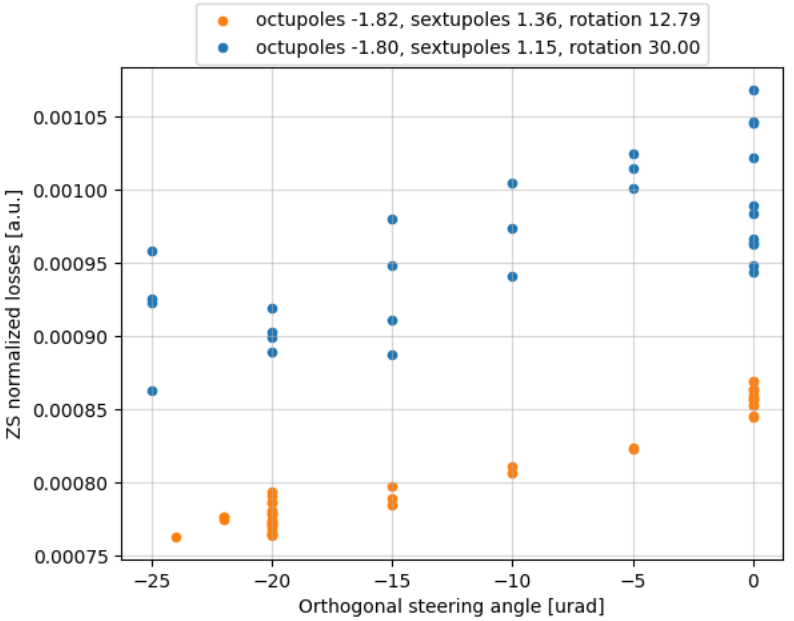
Then we started to increase the octupole strength strength together with the spiral step.



Loss reduction

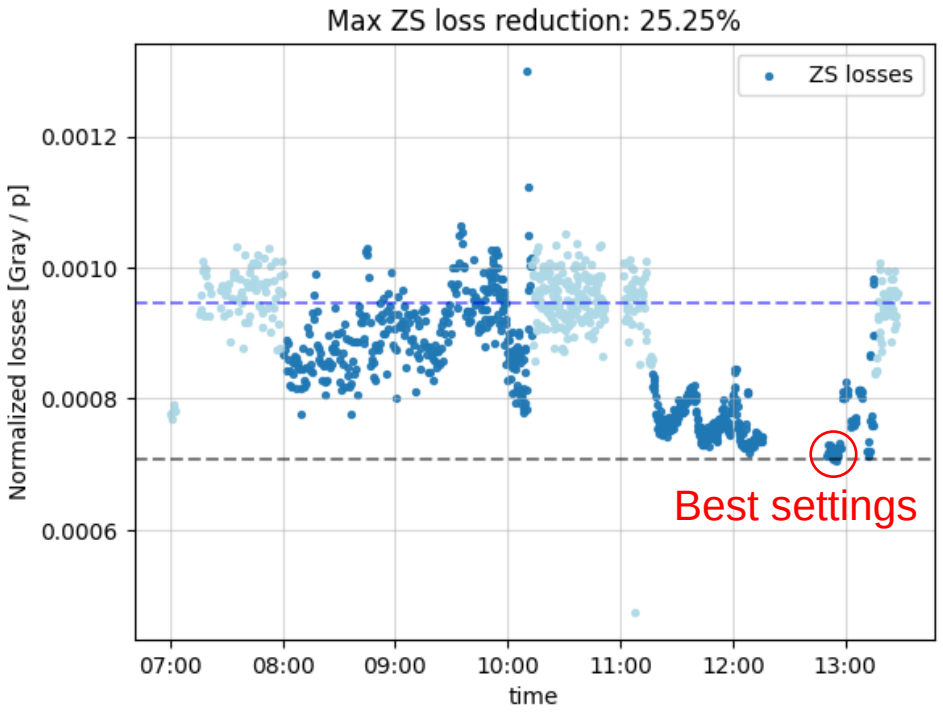
Knob	Value
Octupole strength	-1.6
Sextupole strength	1.3
Separatrix rotation	15
Extraction bump	1.03
Orthogonal steering angle [urad]	-24 (Minimum possible)
Girder downstream position [mm]	42.82

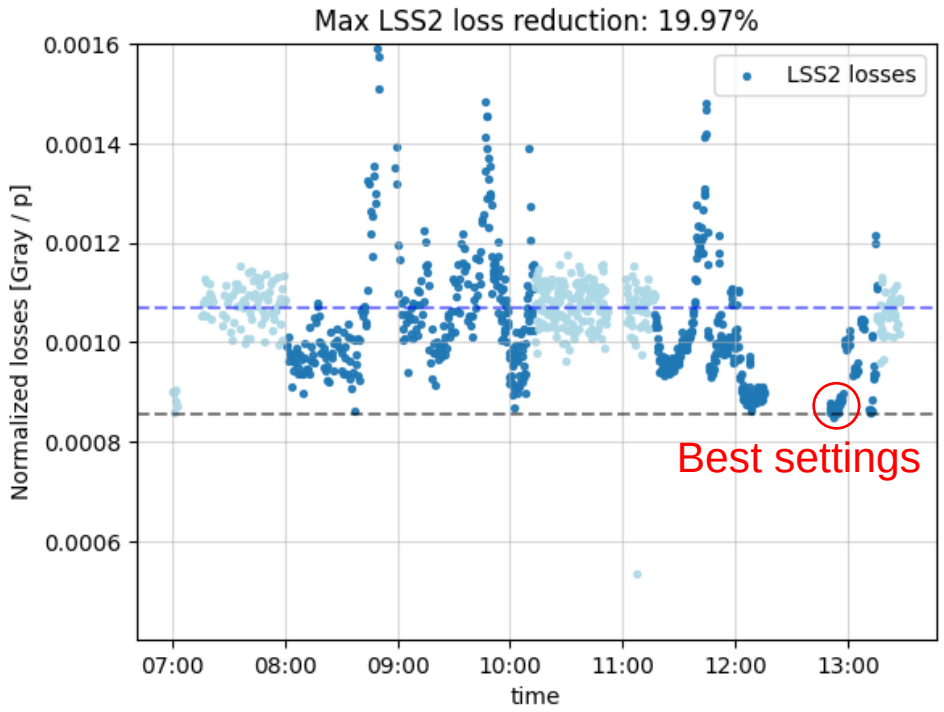




However, octupoles increase the beam angular spread and the angle at the ZS -> Decided to use the orthogonal steering to compensate that. -> Did not minimize the losses fully, because reached the maximum possible corrector strength.

Loss reduction

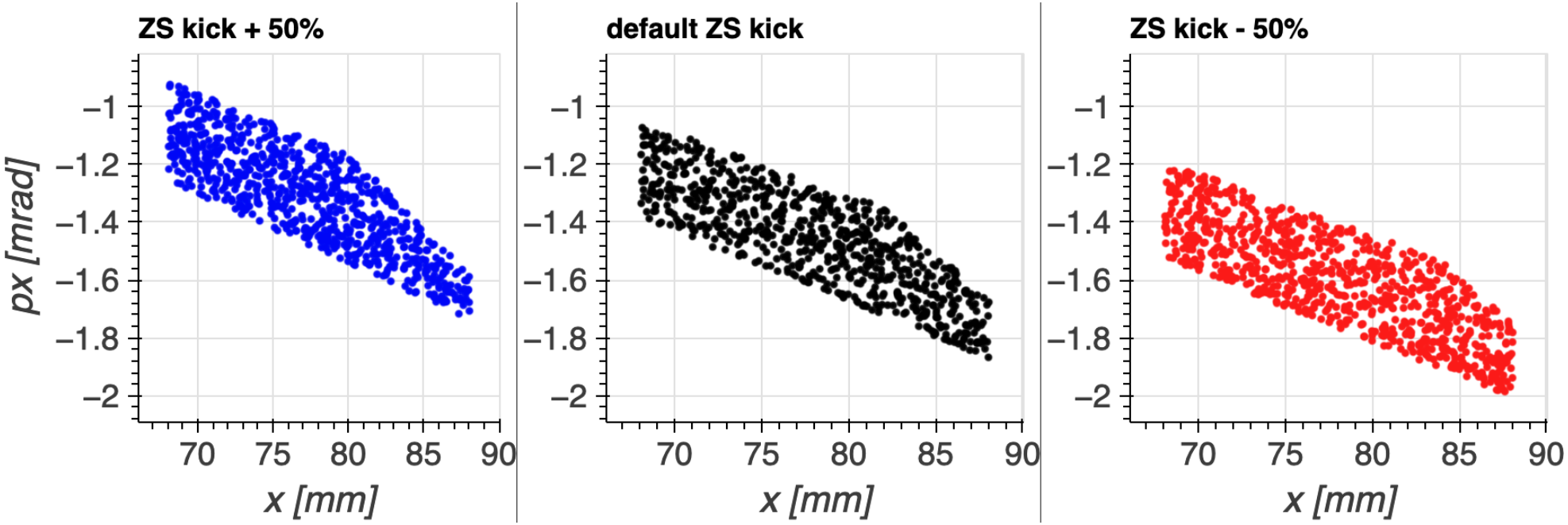




During MD in 2024 we managed to reduce the losses at the ZS by 25% and total losses in LSS2 by 20%.

Influence of ZS kick on the acceptance

Default ZS kick = 0.440 mrad



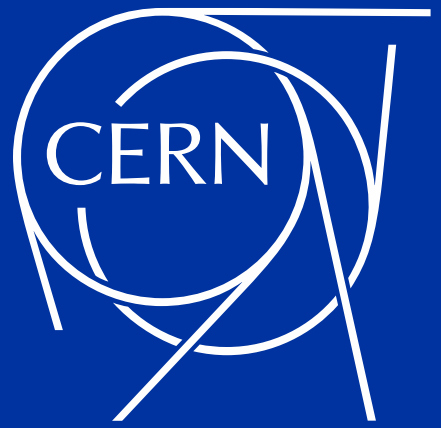
Reducing of the kick at the ZS allows to increase the acceptance of the LSS2 for the folded beam. -> Can try to achieve further loss reduction.

Summary

- Reasonable loss reduction in LSS2 (20-25%) can already be achieved using the octupole folding approach.
- Orthogonal steering was very important, and we did not reach the optimum, because the correctors were at the limit of their strength.

Next steps

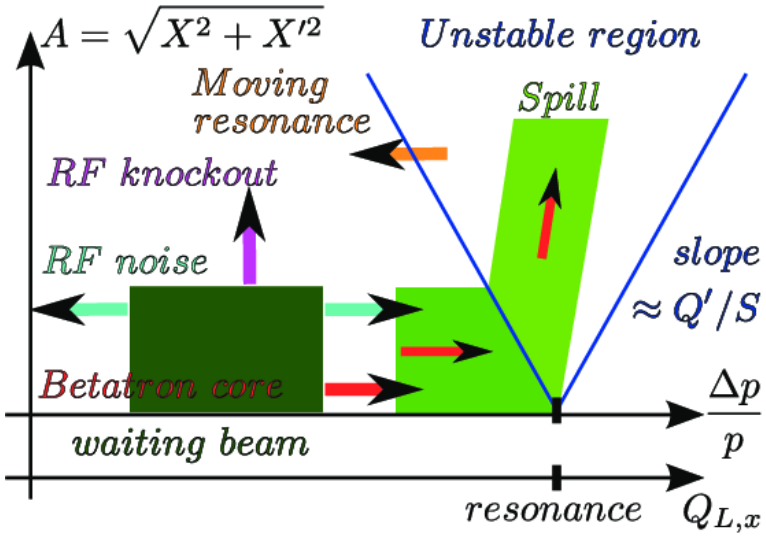
- We need to check if changing the ZS voltage can help to reduce the losses even more (1 MD slot).

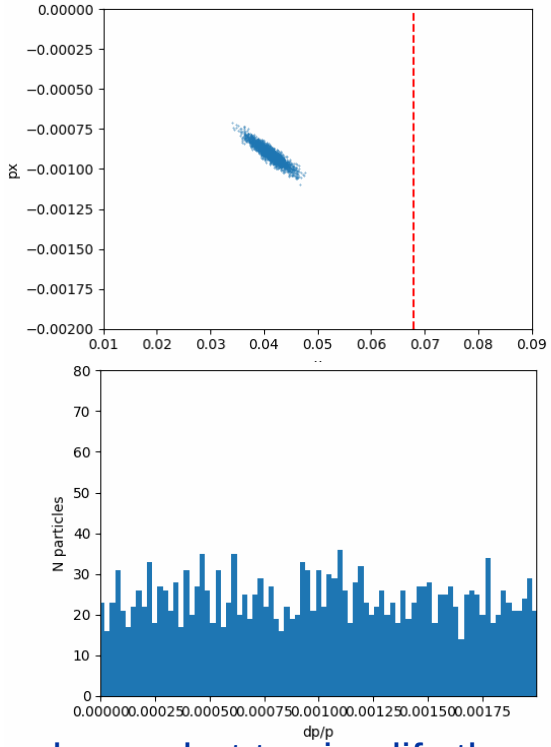


Thanks for your attention!

Slow extraction model

COSE: Constant Optics Slow Extraction





In the machine COSE is used to extract the beam, but to simplify the study, we do not change the reference momentum in the model and focus on the transverse beam dynamics.

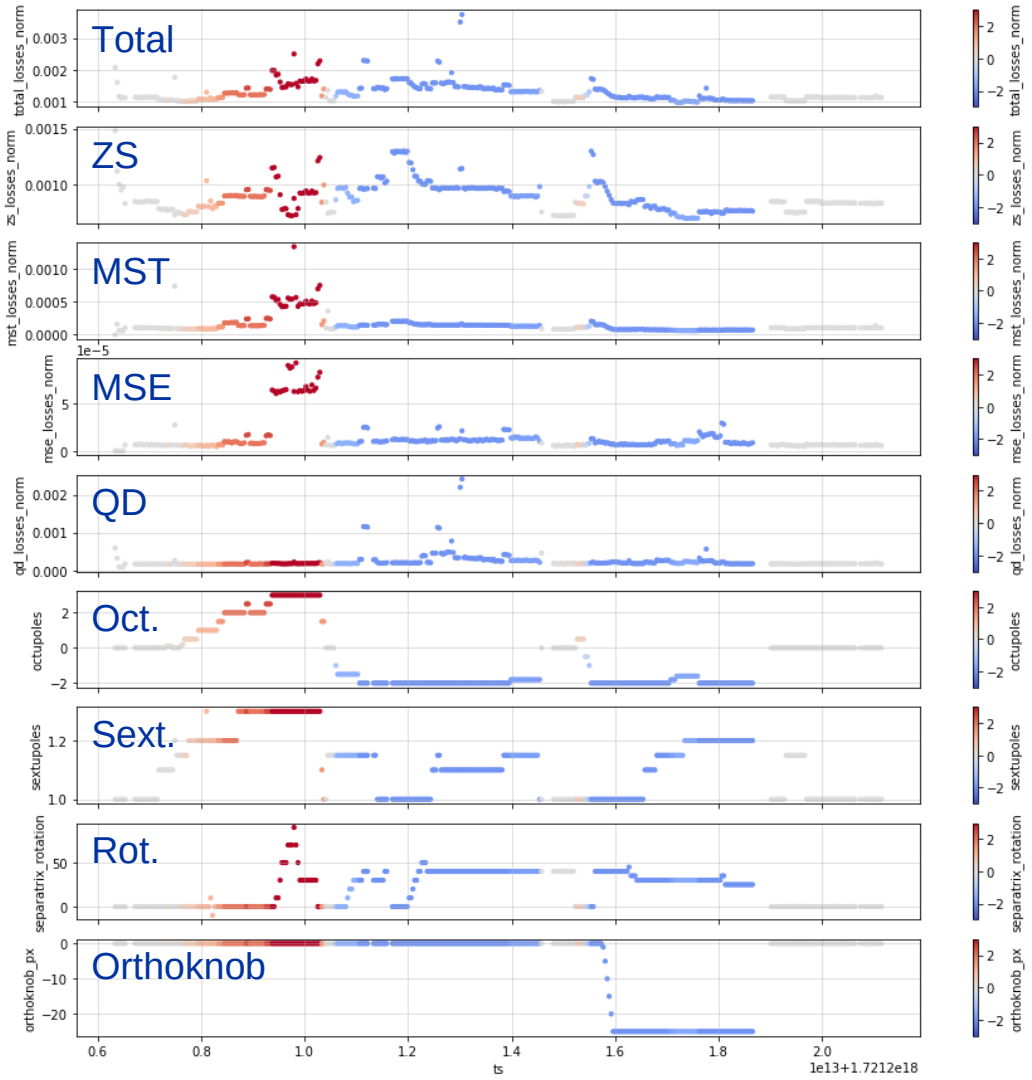
Model is based on the Francesco's Xsuite example for the slow extraction.

Machine parameters are taken from *M. Fraser, et al.*, *Phys. Rev. Accel. Beams* ***22***, 123501

TABLE I. Machine parameters for slow extraction at SPS.

Parameter	Unit	Value
Particle	p	
Nominal spill intensity	10^{13}	3–4
Spill length	s	~1–10
Momentum (p_0)	GeV/c	400
Relativistic factor ($\beta_r\gamma_r$)		426
Magnetic rigidity ($B\rho$)	Tm	1334
Momentum spread ($\Delta p/p_0$)	‰	[−1.5, 1.5]
Horizontal emittance (rms, norm.) ($\varepsilon_{x,n}$)	μm	8
Horizontal emittance (rms, geom.) ($\varepsilon_{x,g}$)	nm	19
Vertical emittance (rms, norm.) ($\varepsilon_{y,n}$)	μm	5
Vertical emittance (rms, geom.) ($\varepsilon_{y,g}$)	nm	12
Horizontal tune (on resonance) (Q_x)		80/3
Vertical tune (Q_y)		26.58
Horizontal chromaticity ($\xi_x = Q'_x/Q_x$)		−1.0
Vertical chromaticity ($\xi_y = Q'_y/Q_y$)		0.5

MD setup



Knobs that we touched:

- Extraction sextupole strength
- LOF strength
- Separatrix rotation
- Orthoknob px
- MSE strength
- MST strength
- Made a couple of bumps downstream MSE

Our approach was to localise the source of losses and try to minimize them.

Data can be split into 3 sets depending on our approach:

1. Positive LOF strength
2. Negative LOF strength
3. Octupoles off

Extraction line acceptance

Apertures for the ZS, MST and MSE blades are taken from acc-models-sps.

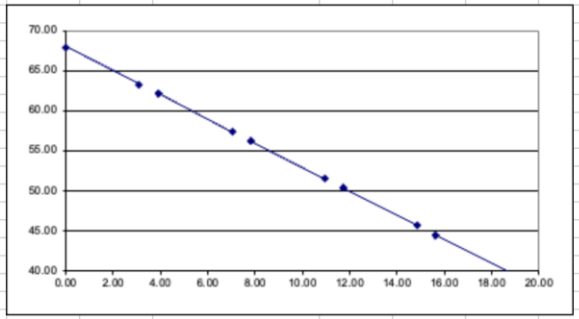
ZS_LSS2

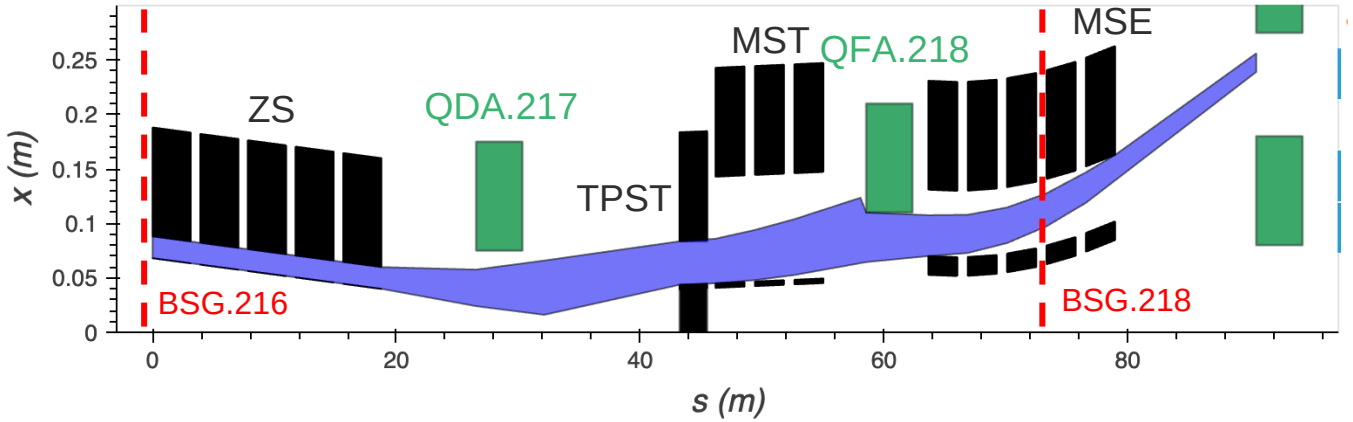
Valeur entrée software	68.00	<===	IN
Valeur sortie software	39.80	<===	OUT

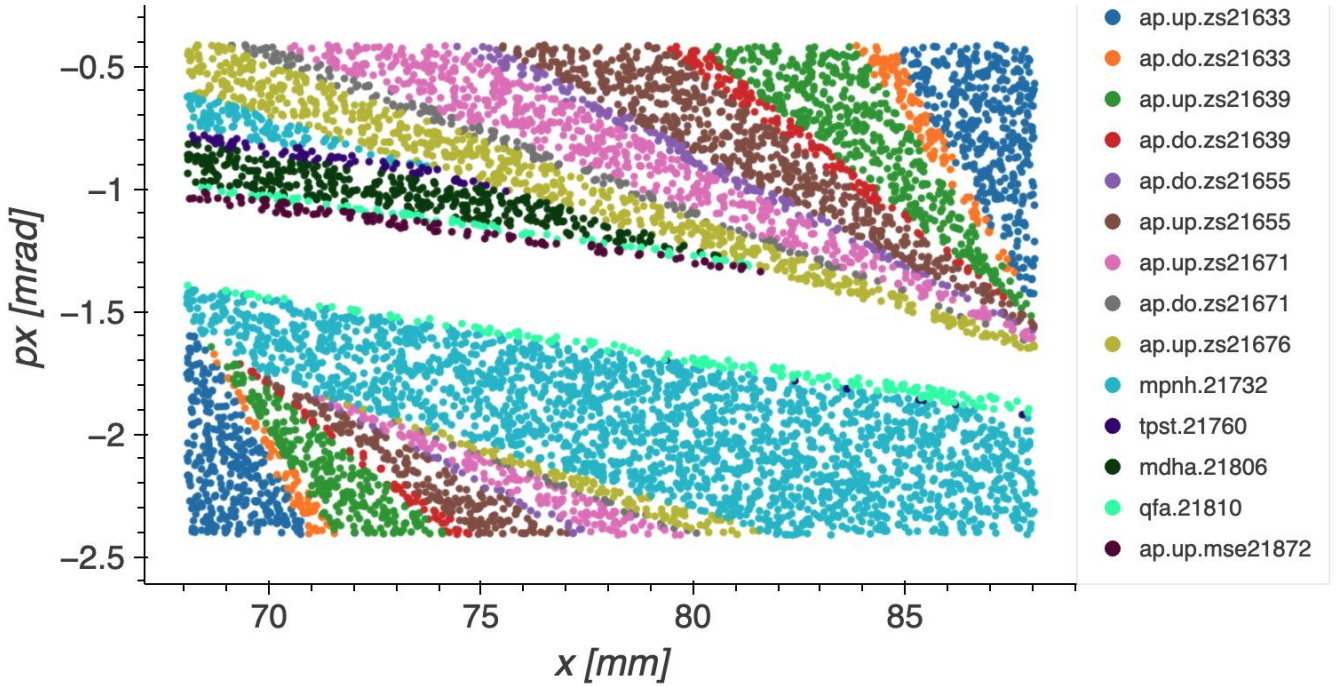
calcul position reel		
	a	-1.50
	b	68.00
épaisseur septum ZS 1-2		0.06
épaisseur septum ZS 3-5		0.1

	x	y=ax+b	position + epaisseur
ZS 21633	0.00	68.00	68.06
	3.10	63.34	63.40
ZS 21638	3.91	62.12	62.18
	7.01	57.45	57.51
ZS 21655	7.82	56.23	56.33
	10.92	51.57	51.67
ZS 21671	11.73	50.35	50.45
	14.83	45.68	45.78
ZS 21676	15.64	44.46	44.56
	18.74	39.80	39.90

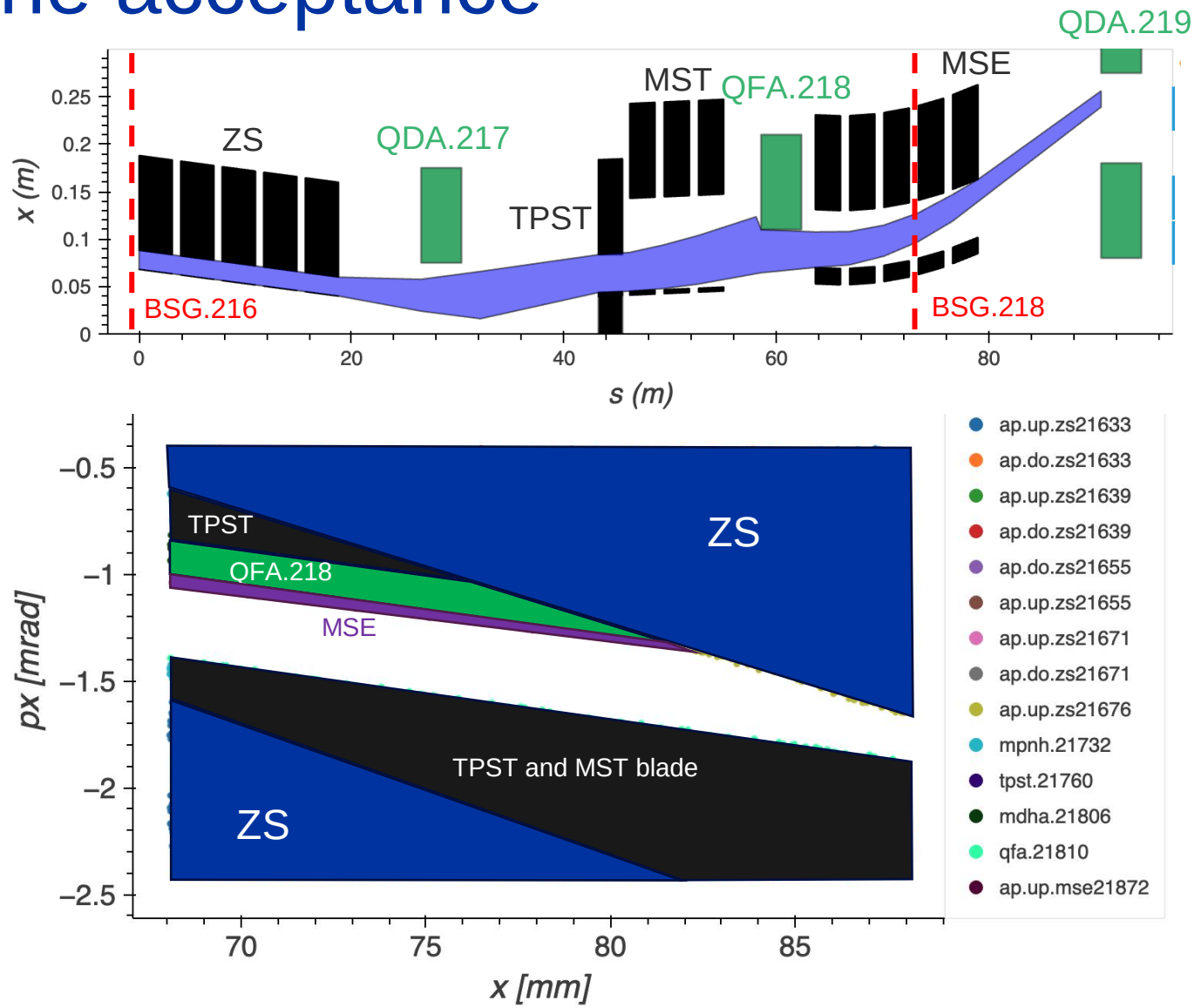
position septa





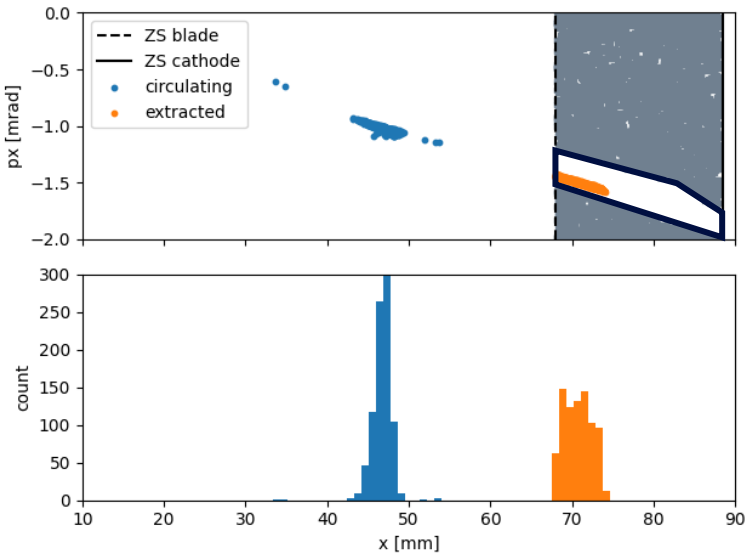


Extraction line acceptance

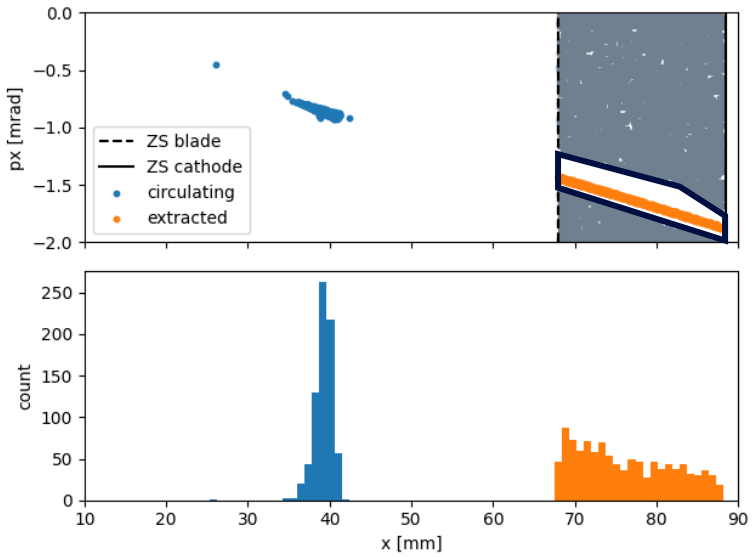


Matching the extraction bump

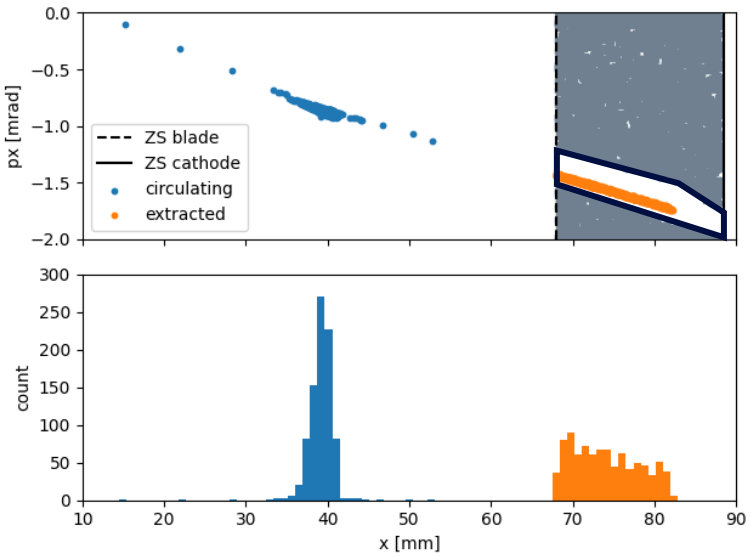
Knob / Parameter	Value
Extraction sextupoles	1.0
Octupoles	0
Extraction bump	1.0 (≈48 mm)



Knob / Parameter	Value
Extraction sextupoles	1.2
Octupoles	0
Extraction bump	0.84 (≈39 mm)

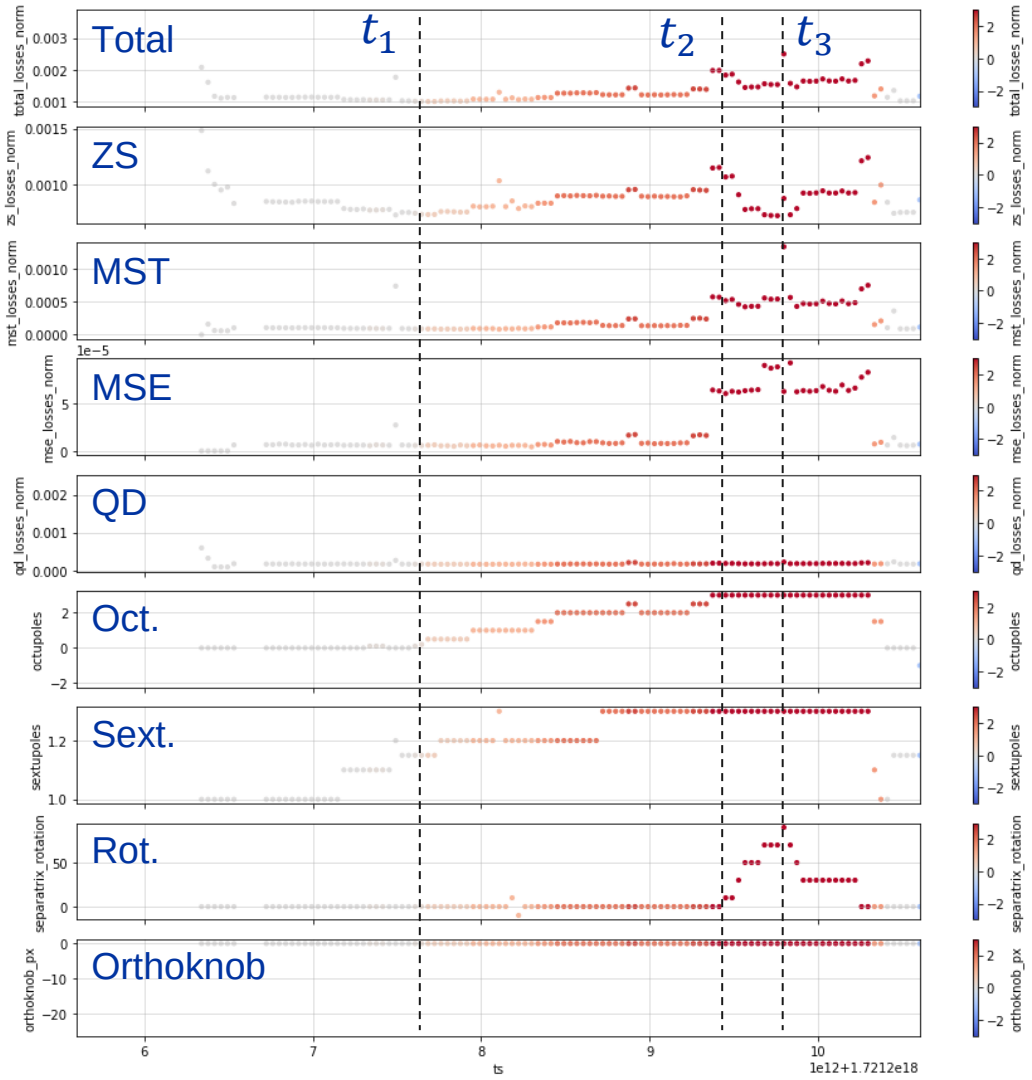


Knob / Parameter	Value
Extraction sextupoles	1.0
Octupoles	0
Extraction bump	0.84 (≈39 mm)



Extraction bump strongly impact on the spiral step. Level of losses at ZS starts to grow since we increase the sextupole strength up to ≈1.2 (+20% to the nominal value), which indicates that the spiral step is close to the size of the gap between the ZS blade and the cthode. Extraction bump is tweaked in the model to match this condition.

Positive octupole strength



t_1 - increased sextupole strength together with LOF k.

- Slightly lower losses at ZS

t_2 - further increase

- High losses everywhere

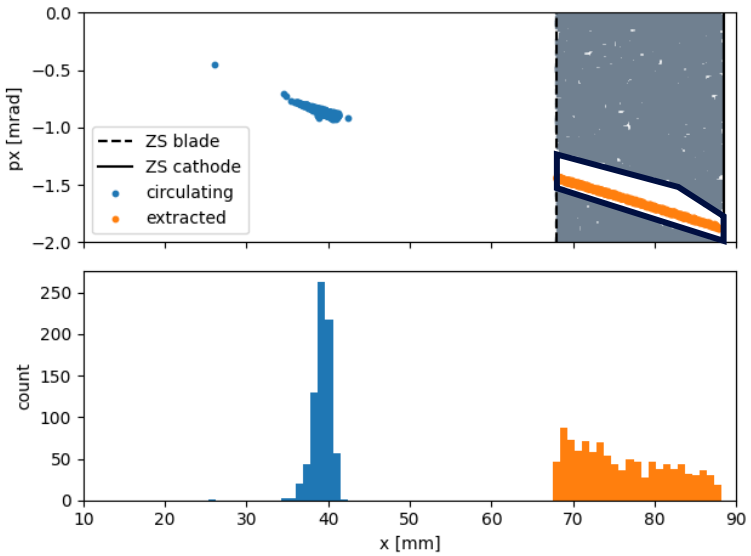
t_3 - steered the beam with separatrix rotation knob

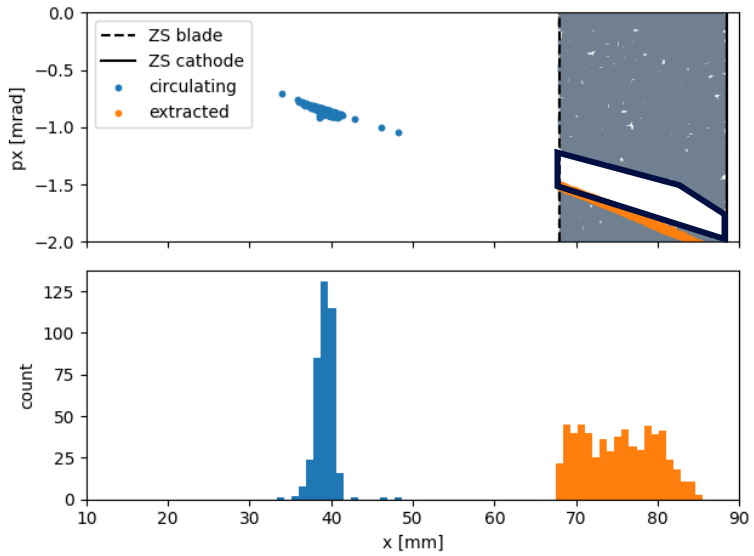
- Low losses at ZS, but extremely high at MST and MSE

Positive octupole strength

Knob / Parameter	Value
Extraction sextupoles	1.2
Octupoles	0
Extraction bump	0.84 (≈39 mm)

Knob / Parameter	Value
Extraction sextupoles	1.2
Octupoles	2.5
Extraction bump	0.84 (≈39 mm)

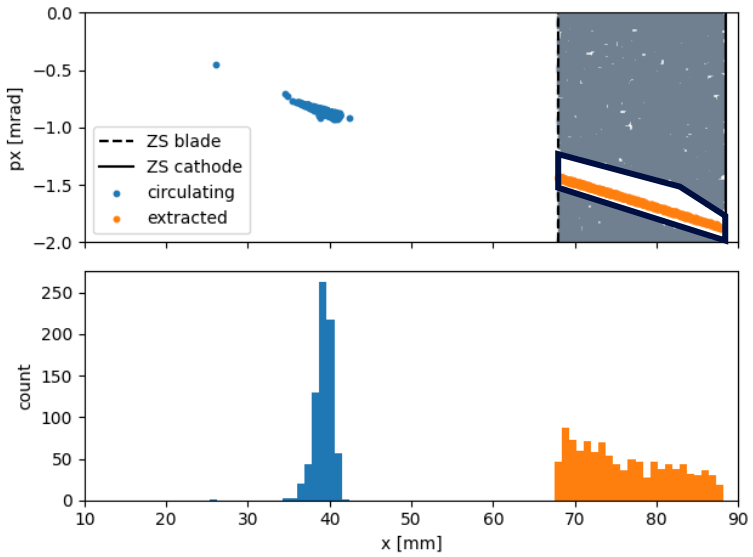




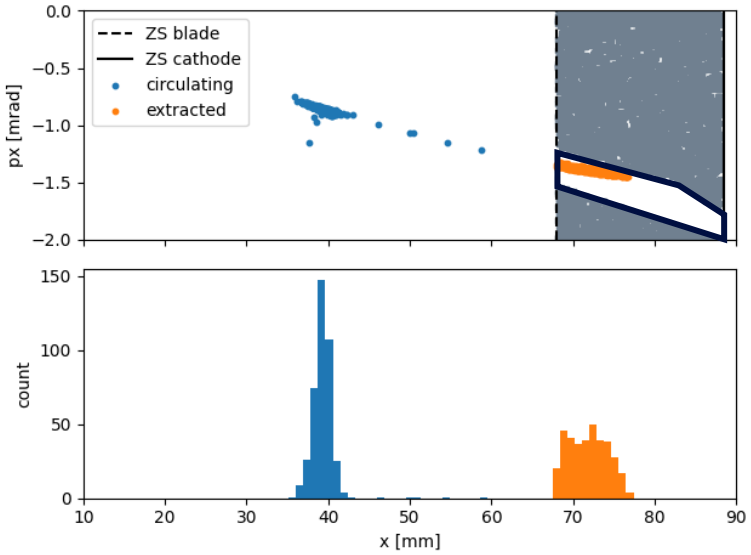
Positive octupole strength folds the beam to the wrong direction in the phase space. Although we can try to compensate it with the separatrix rotation, but this correction is too big for the existing sextupoles in the ring and we do not use the acceptance efficiently in this case.

Negative octupole strength

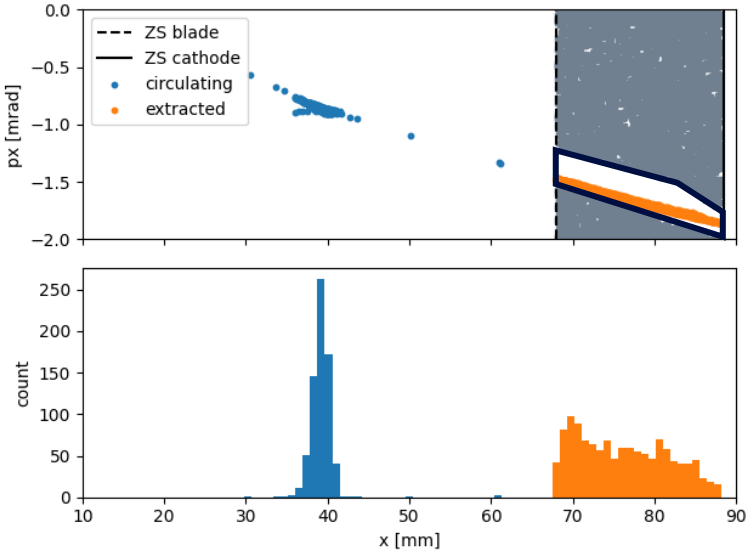
Knob / Parameter	Value
Extraction sextupoles	1.2
Octupoles	0
Extraction bump	0.84 (≈39 mm)
Sep. rotation	0



Knob / Parameter	Value
Extraction sextupoles	1.2
Octupoles	-2.0
Extraction bump	0.84 (≈39 mm)
Sep. rotation	0

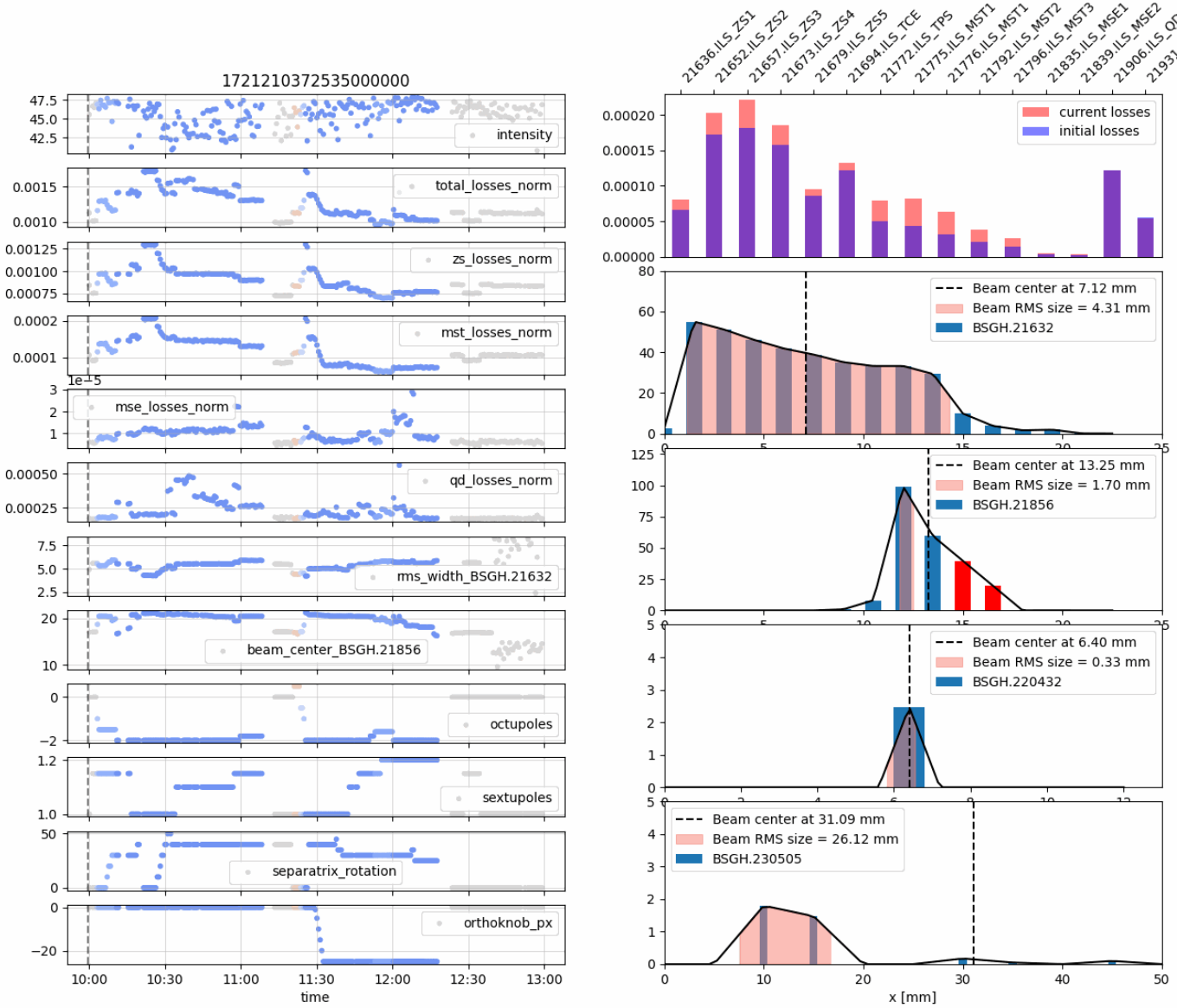


Knob / Parameter	Value
Extraction sextupoles	1.2
Octupoles	-2.0
Extraction bump	0.84 (≈39 mm)
Sep. rotation	50



The main challenge of octupole folding is to find the balance between the sextupole strength, separatrix rotation and octupole strength.
The higher the first two, the longer the spiral step. The stronger the octupoles, the higher the angular spread.

Measurements



Settings with the minimum losses

Knob / Parameter	Value
Extraction sextupoles	1.15
Octupoles	-1.8
Extraction bump	0.84 (≈39 mm) ?
Sep. rotation	40
Orthonob [urad]	20

The minimum losses during MD (-10-12% at ZS) were achieved by changing the angle of the beam at the ZS towards more positive value and conpensating this by encreasing the MST strength.

We did not manage to achieve better loss reduction due to limits of the orthogonal steering.