FLASH extraction from the NIMMS Helium Synchrotron

R. Taylor, E. Benedetto, J. Borburgh
H. Huttunen, K. Palskis, S. Detsi

5th Slow Extraction Workshop

14th February 2024

Outline

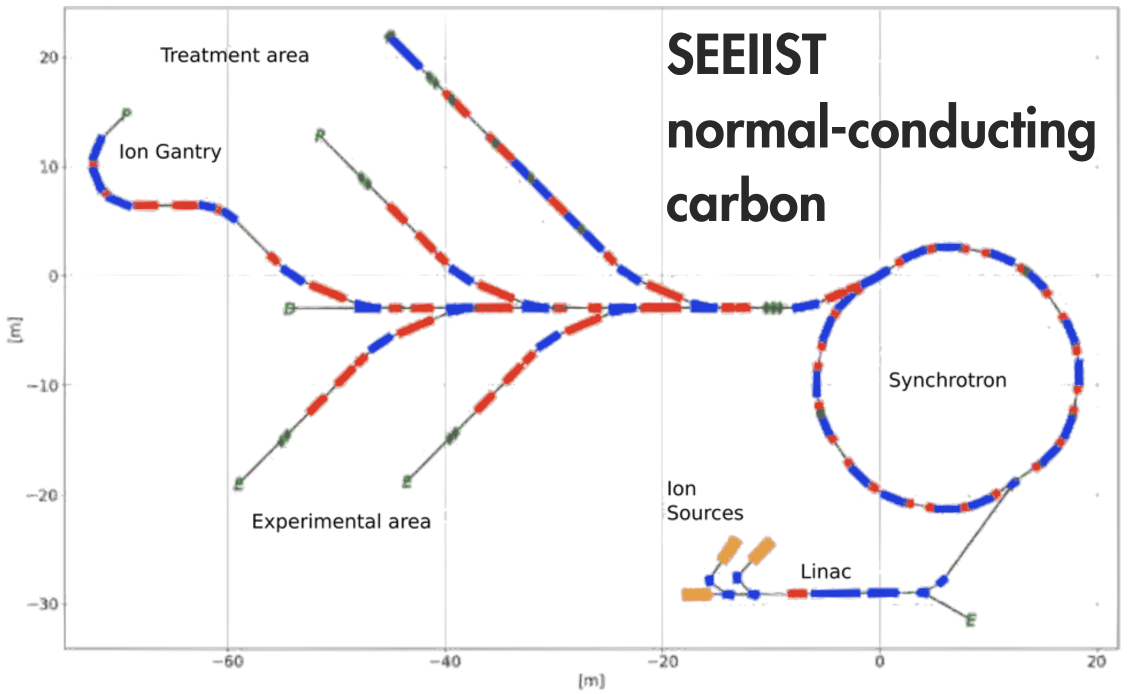
1 FLASH

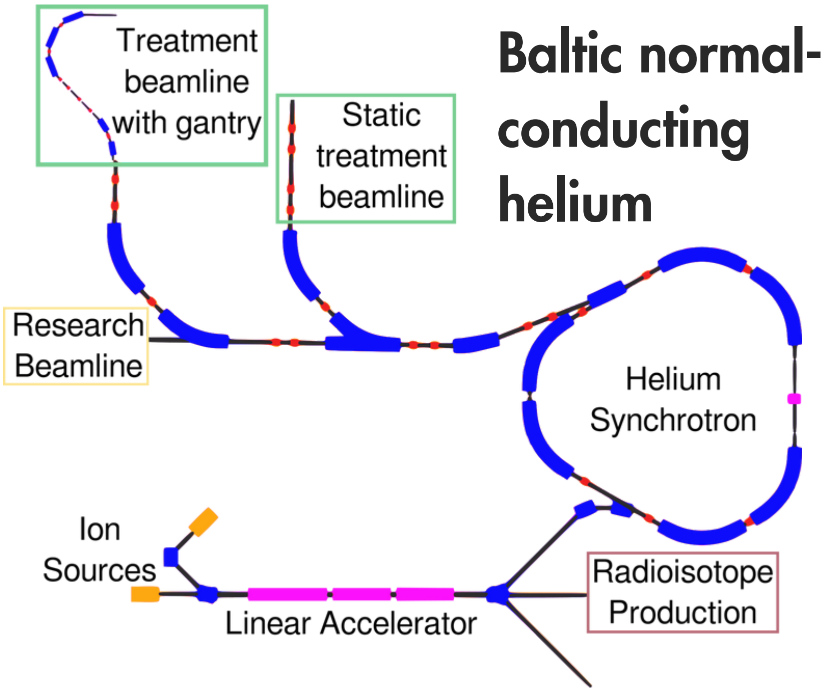
2 Normal-conducting carbon

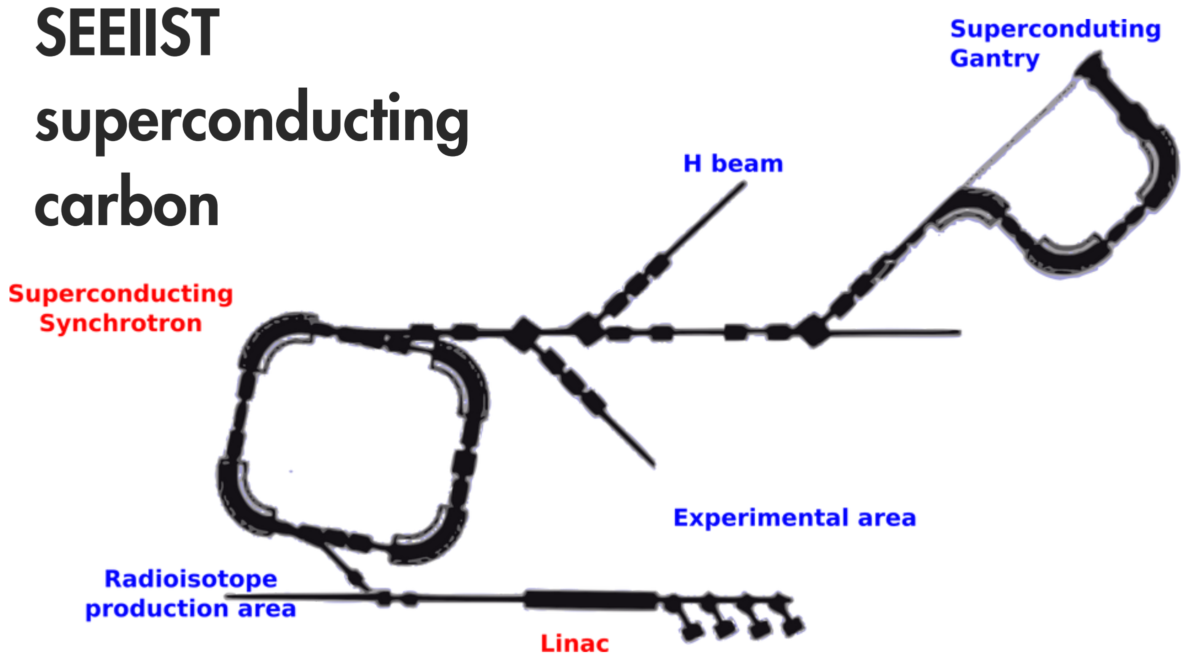
3 Normal-conducting helium

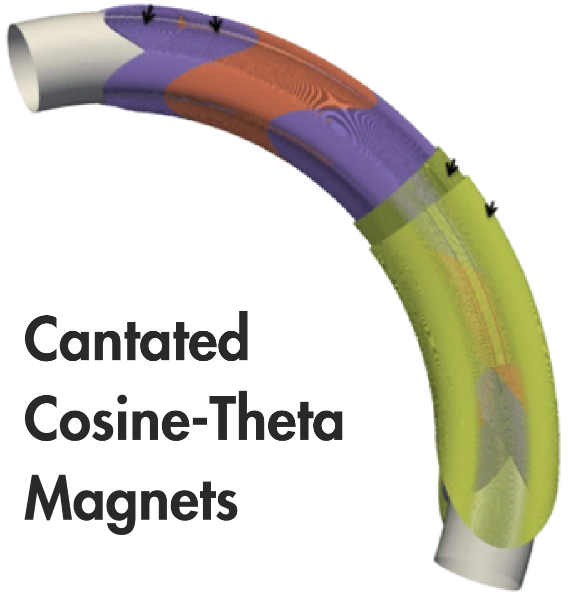
- a Fast quadrupole-driven spills
- b Fast RF-KO spills

NIMMS Next Ion Medical Machine Study:
Accelerator Toolbox at CERN









- NIMMS has a variety of **designs** available.
  - Used to research wide variety of **radiotherapy** concepts.
- Consider slow extraction needs first, then machine around it.

Five SX projects explored:

PIMMS Proton Ion Medical Machine Study

NIMMS Next Ion Medical Machine Study

HIT Heidelberg Ion Therapy Facility

PS CERN Proton Synchrotron

LhARA Laser-hybrid Accelerator for Radiobiological Applications

FLASH Requirements

High dose rate (>40 Gy/s) reduces toxicities to healthy tissue, but preserves damage to tumour tissue.

Higher Intensities

- FLASH effect defined by dose rate.
  - Intensity affects **volume** of tumour that can be irradiated.
- **Extraction limitation: Consistent intensity**
- Higher intensities from x20 Multi-Turn Injection.
  - Higher **horizontal emittance**.
  - Also for MEE up to 20x steps.

Faster Timescales

- Flexible timescales to adapt to field of FLASH radiobiology.
  - <100 ms often cited minimum rate.
- **Extraction limitation: Hardware** and response of system.
  - Beam dynamics simulations indicate **response time** required from extraction system.

Simplified Example:

Tumour volume: 1 litre **Total Dose:** 2 Grey

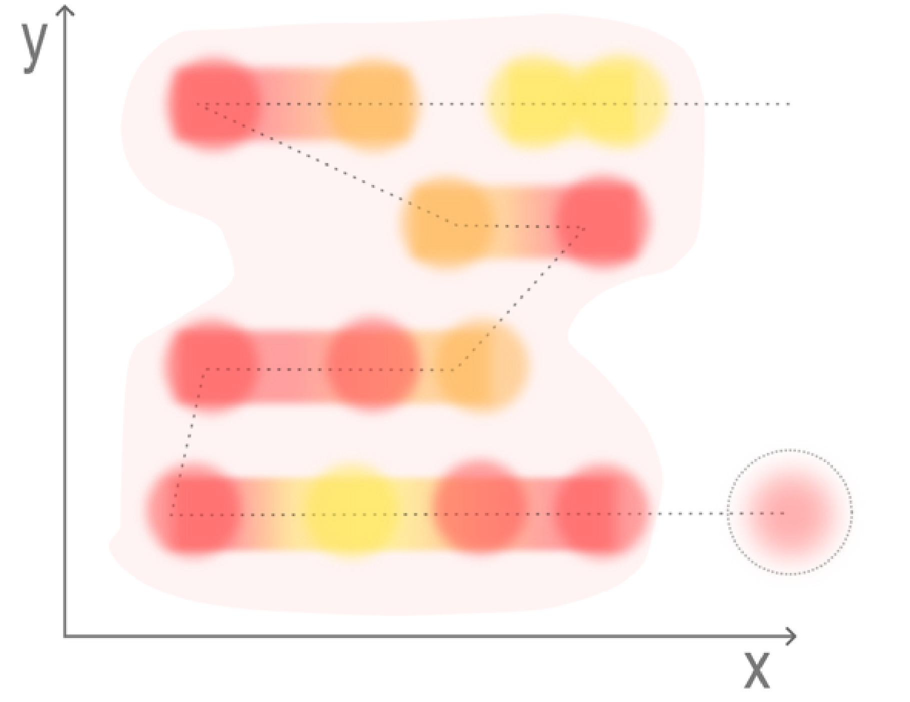
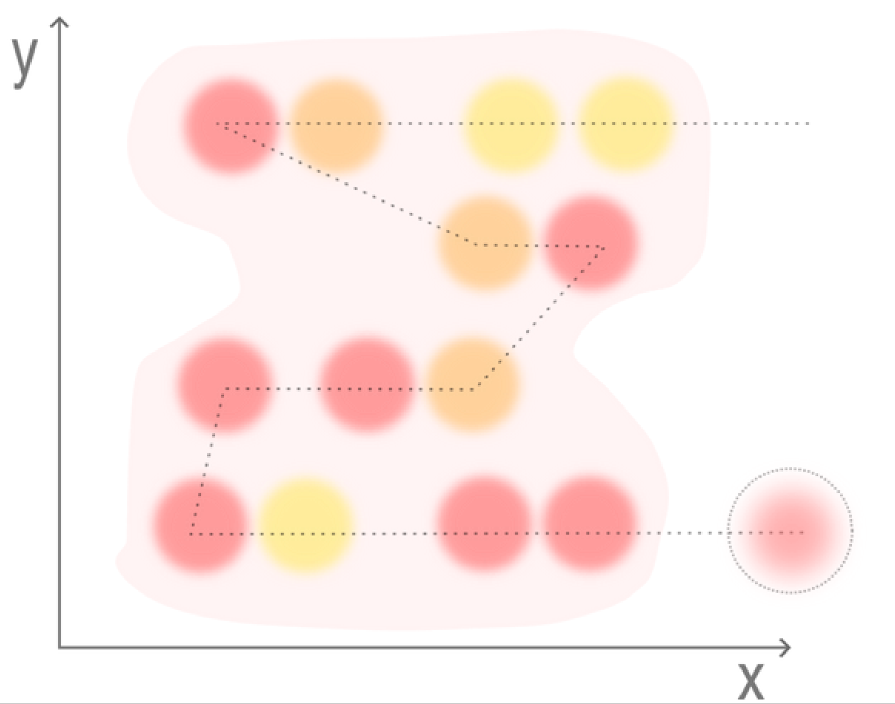
Minimum rate: 40 Gy/s **Corresponding spill length:** 50 ms

This would not result in FLASH
Not a simple mathematical prediction

FLASH Delivery

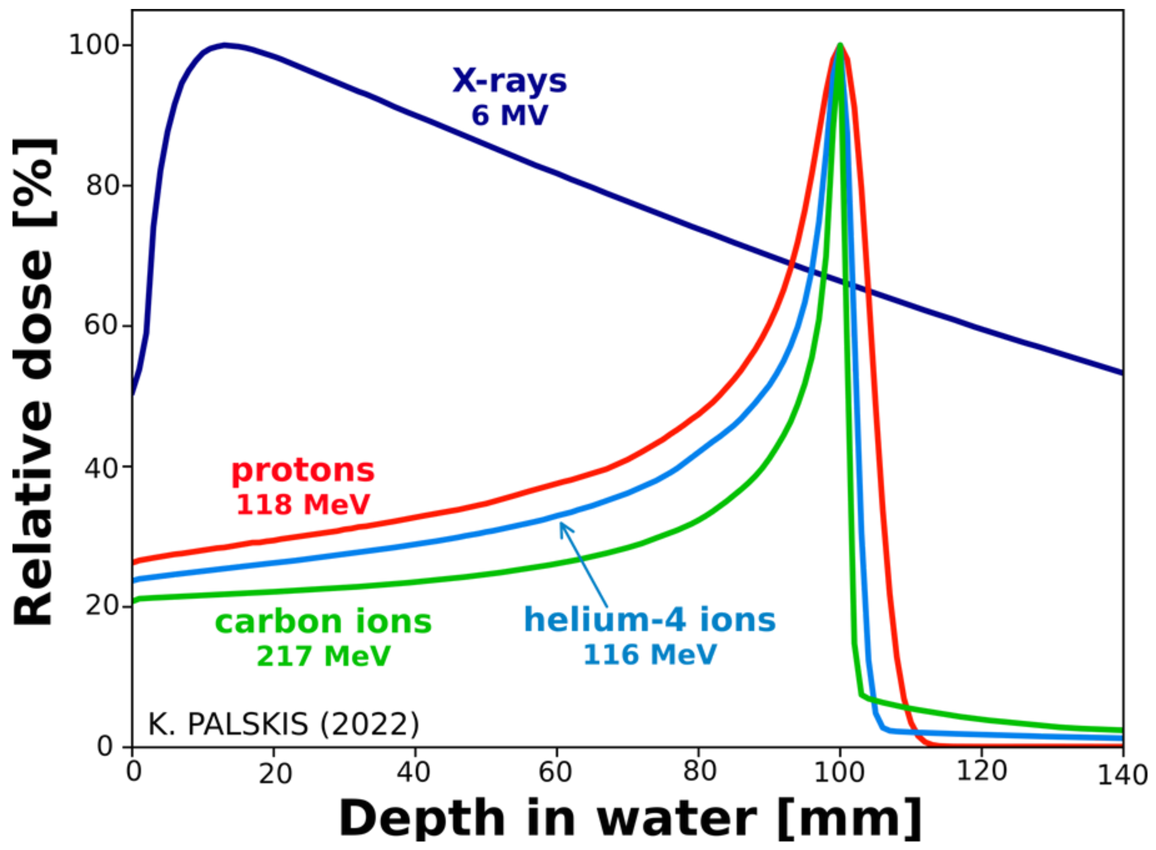
Entire dose must be delivered within the time-frame. Different existing ways to deliver hadron therapy beams.

Two active scanning methods, both requiring fast-responding quadrupole & scanning magnets.

Raster Scanning	Spot Scanning
Scan across **whole plane**	Individual **shots** applied
	
Slower scan for higher intensities	More shots for higher intensities
<100 ms continuous dose	~1 ms bursts over <100 ms
Uniform spill essential	Consistency per shot > uniformity within shot

Longitudinal delivery: Either

- **Shoot-through**, using the entry-way dose
  - 8-10 Gy delivered to normal tissue (FAST-01)
  - Requires higher energy beams
  - Must go through patient
- **Spread-out Bragg Peak**, with 3D range modulators for energy depth



FLASH Requirements

Correspondance from K. Palskis

Helium Synchrotron example:

Revolution frequency: 3.00 MHz

Dose rate delivered as a function of time:

Time [ms]	Turns	8 Gy	10 Gy
500	1,500,000	16 Gy/s	20 Gy/s
100	***300,000***	***80 Gy/s***	***100 Gy/s***
10	30,000	800 Gy/s	1000 Gy/s
0.00033	1	2.4E7 Gy/s	3.0E7 Gy/s

		Helium
Intensity		8.2E10
Energy		220 MeV/u
Max Field [cm]	Shoot 8 Gy	5.72
	Shoot 10 Gy	5.12
	SOBP 8 Gy	6.61
	SOBP 10 Gy	5.92
Volume [l]	SOBP 8 Gy	0.29
	SOBP 10 Gy	0.20

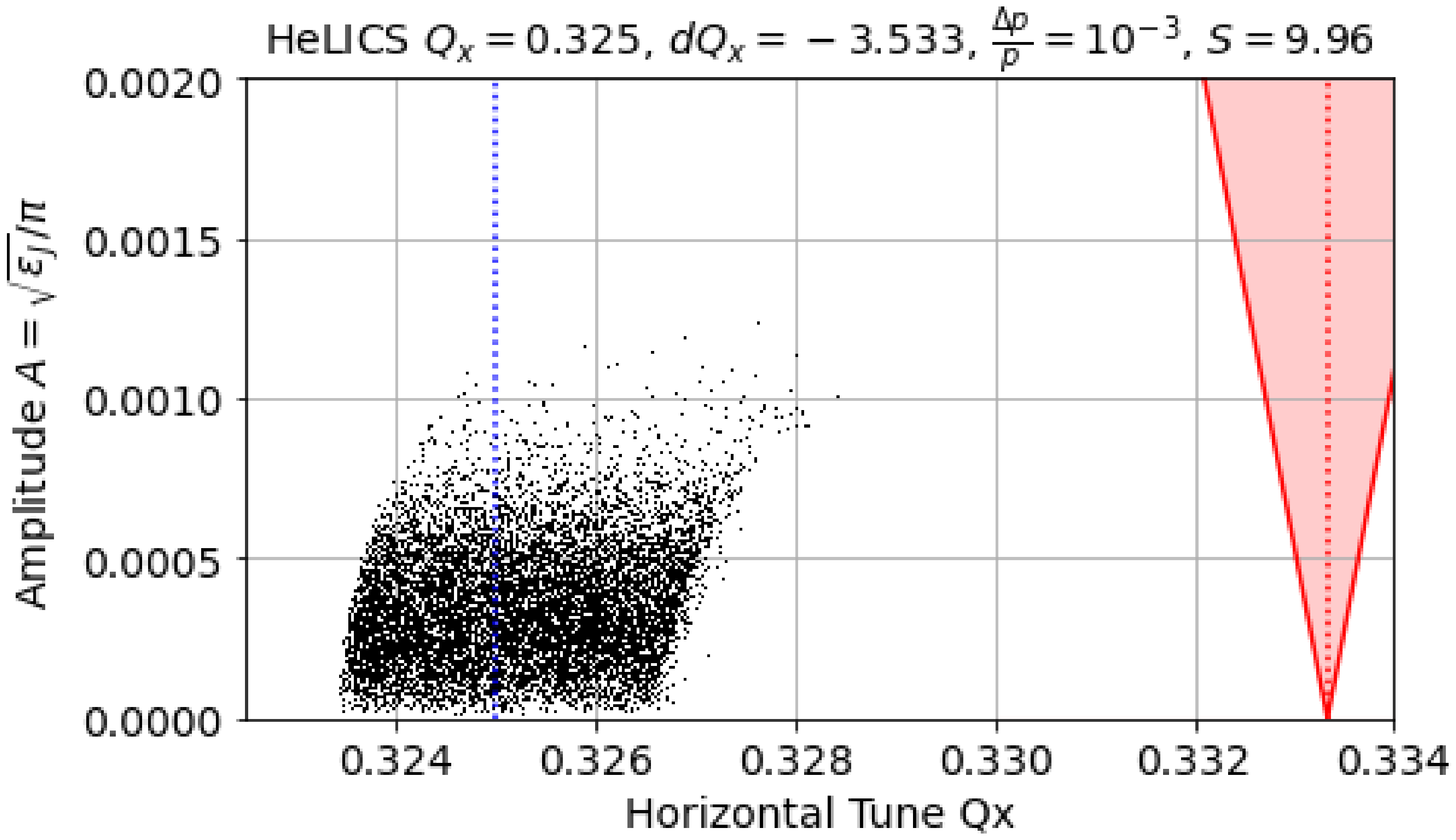
Delivering to volumes of ~5x5x5cm

FLASH Extraction

Momentum Driven

Hardware limit: Magnet ramp rate *[T/m/s]*

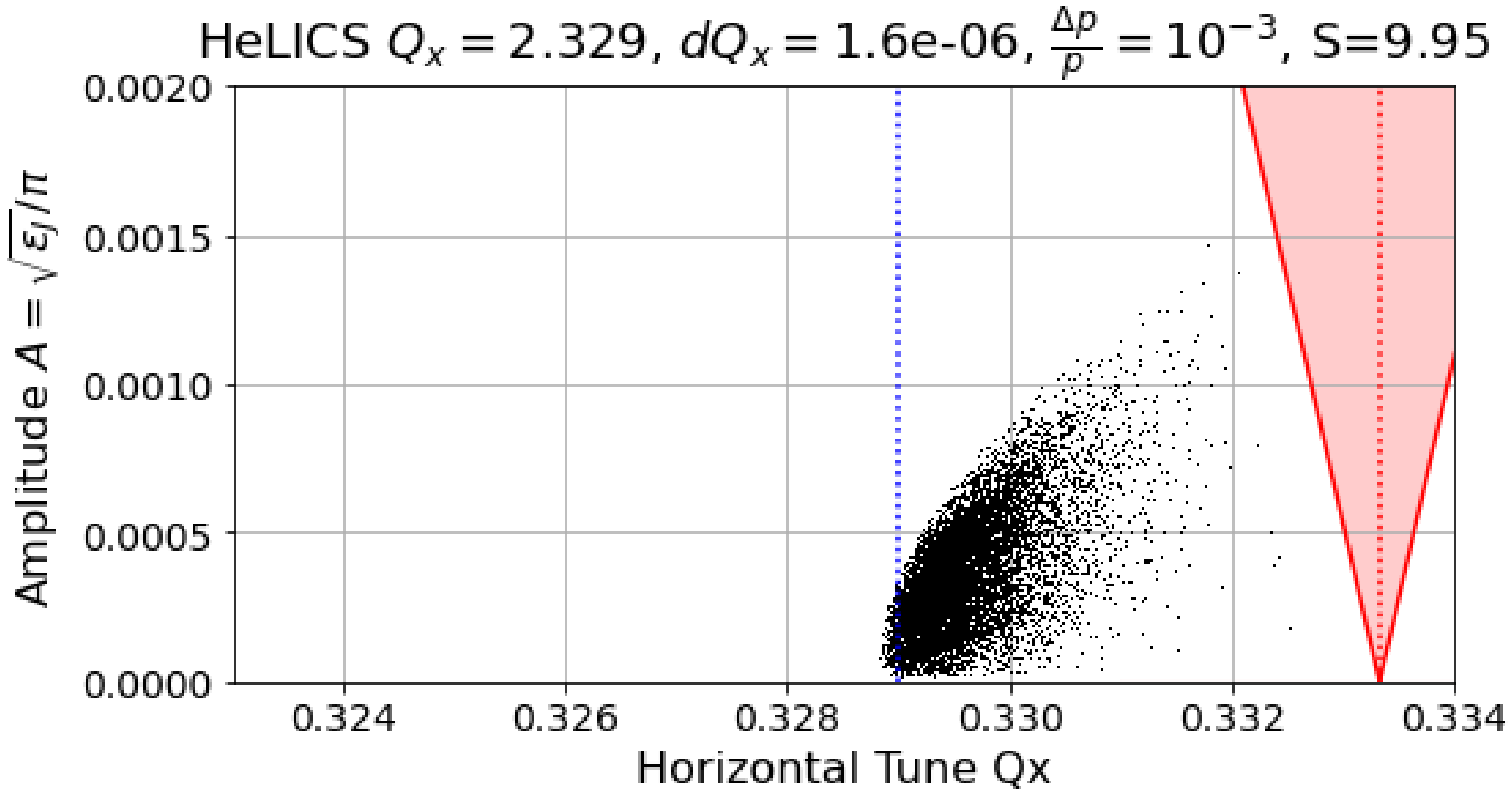
Aim to reduce time by reducing tune spread and reduce distance to resonance.



Amplitude Driven

Hardware limit: Voltage *[kV]*, response time

Exponentially increases kick at lowest amplitudes.
Feedback systems have limited resolution.



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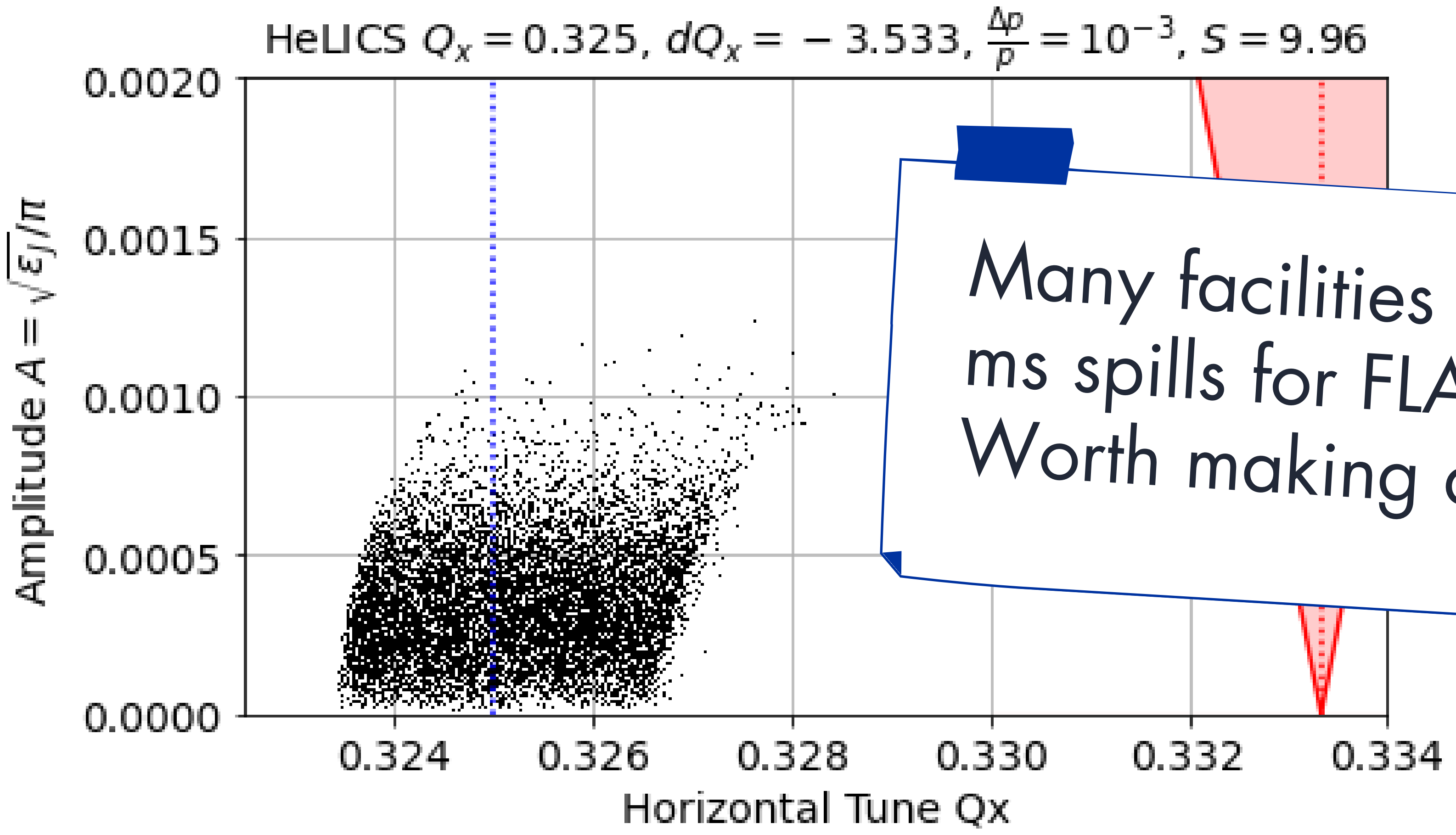

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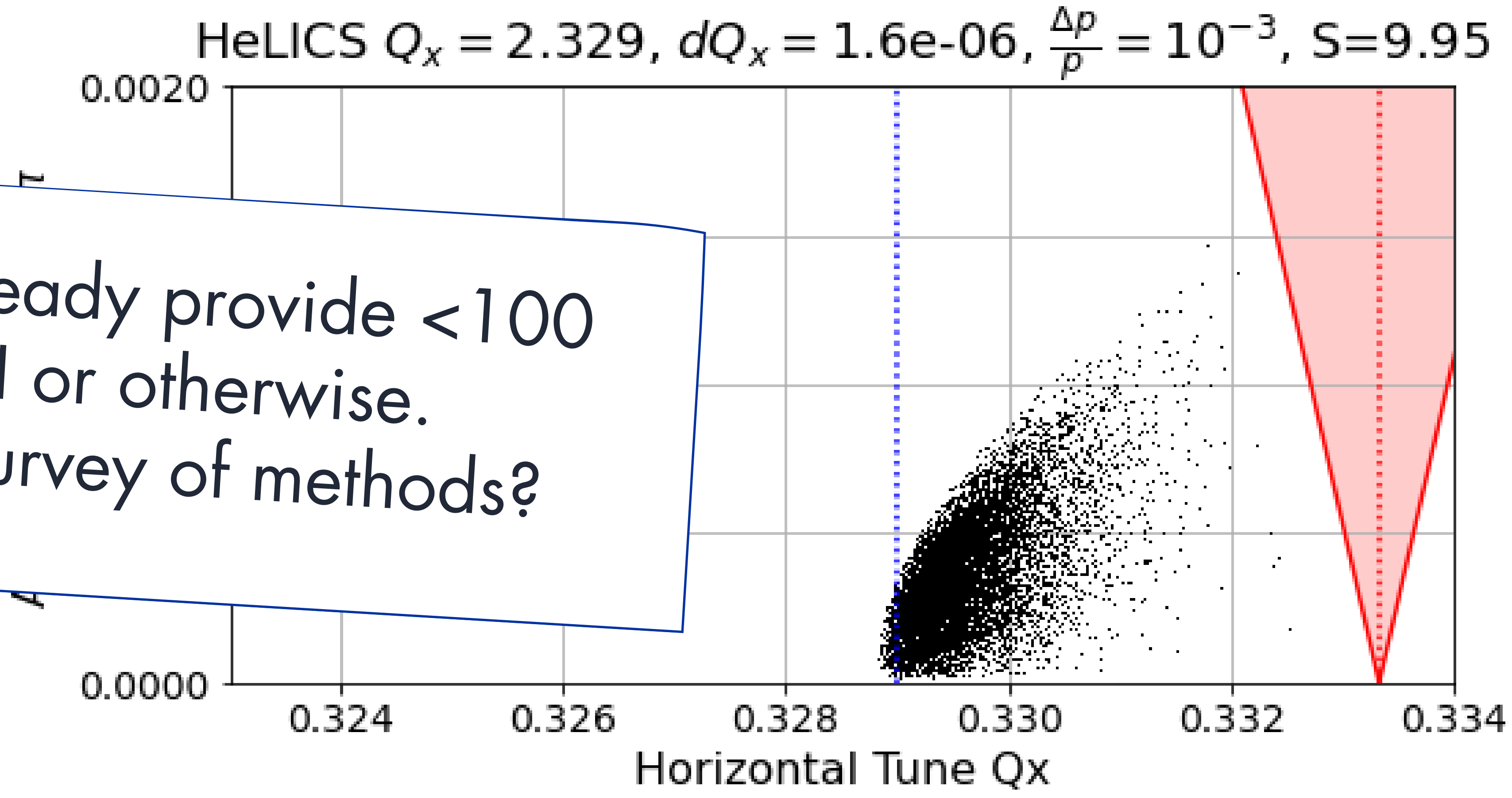
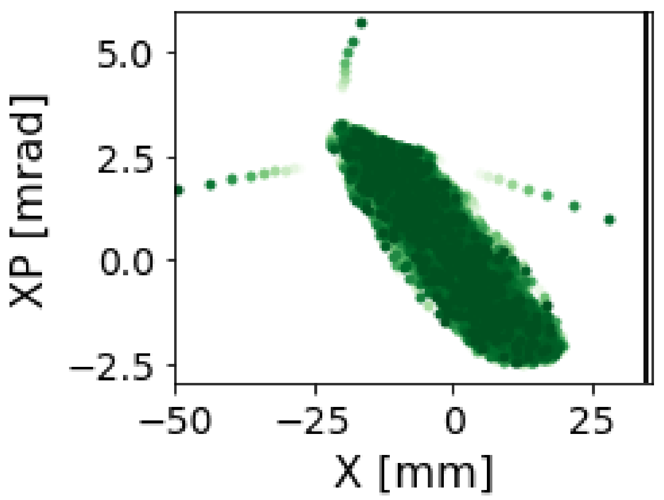
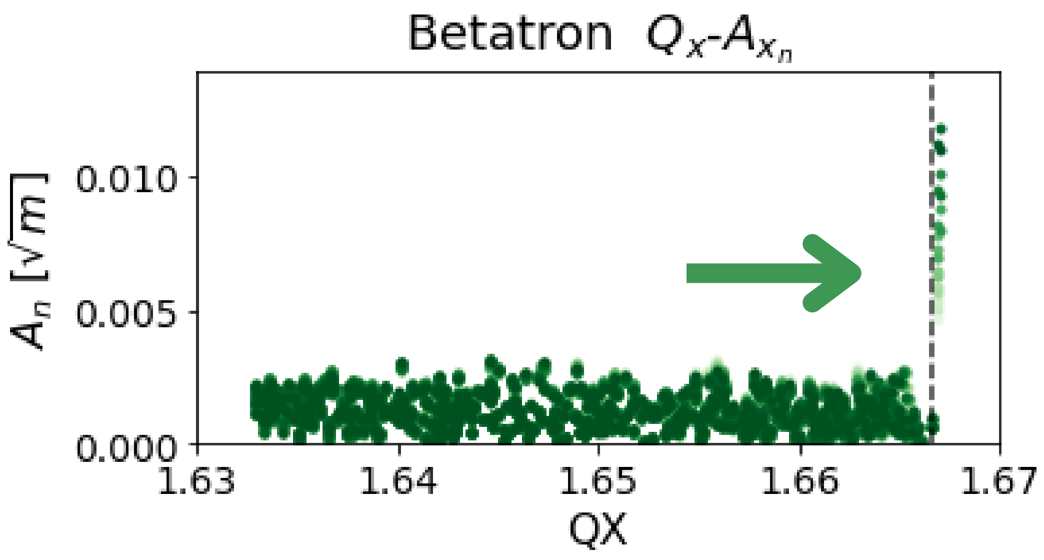


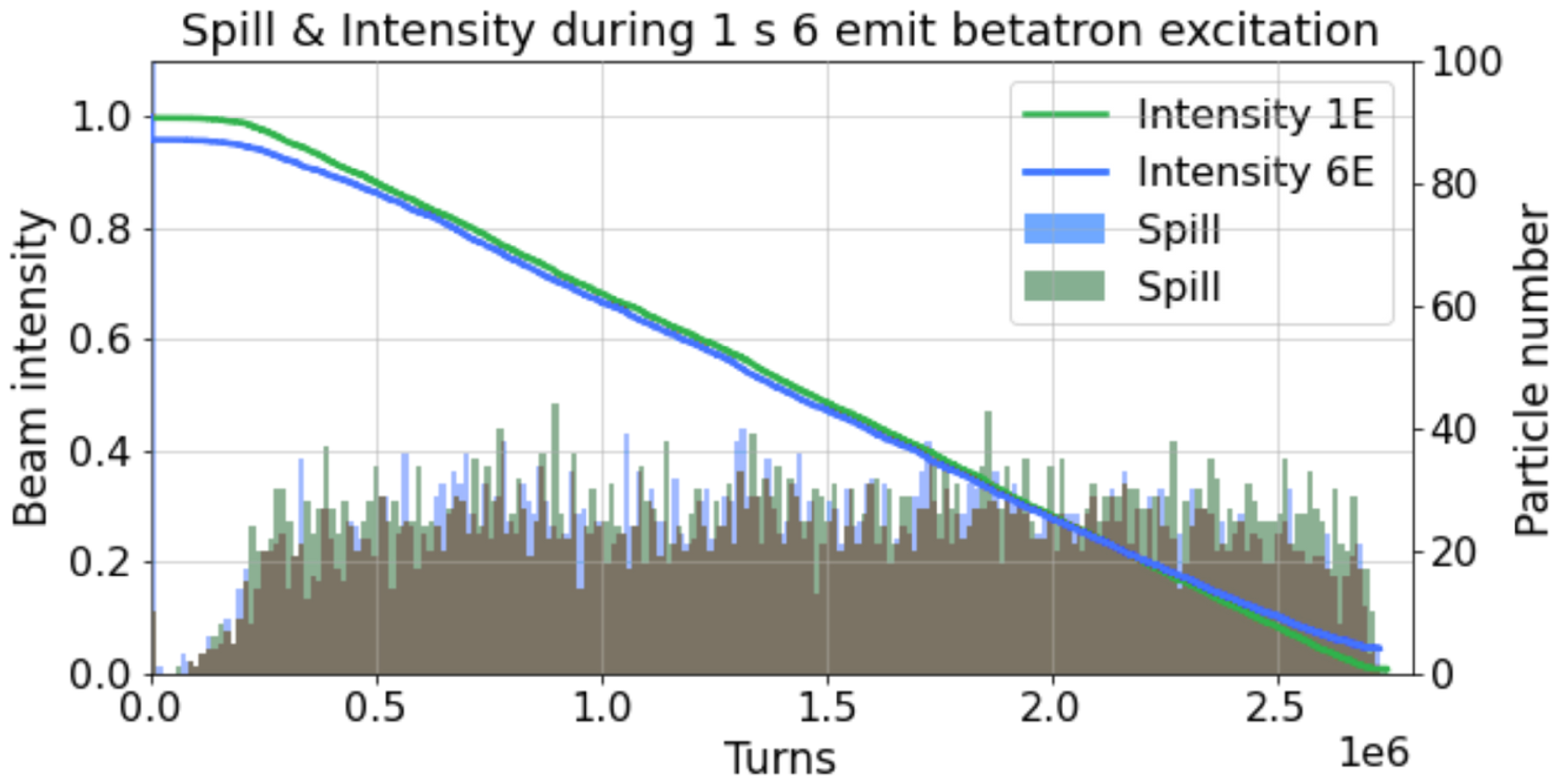
Many facilities already provide <100 ms spills for FLASH or otherwise. Worth making a survey of methods?

NC C6+: Betatron Core

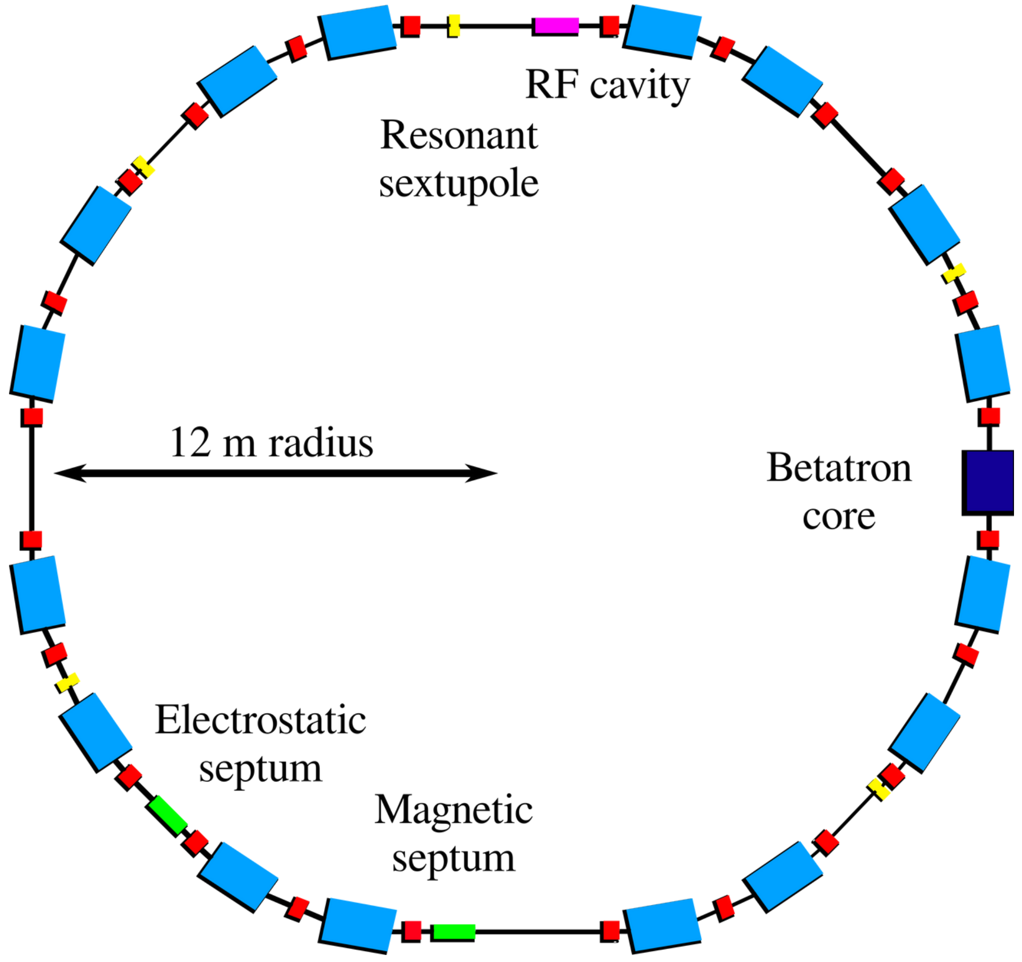




- Establishing benchmark with existing PIMMS literature.
- **Betatron core** extraction for 20x turns of MTI resulting in **εx < 6 π.mm.mrad**.
- Simulation of 5E4 particles for 2.8E6 turns in Maptrack.
    - No dependence with εx expected.

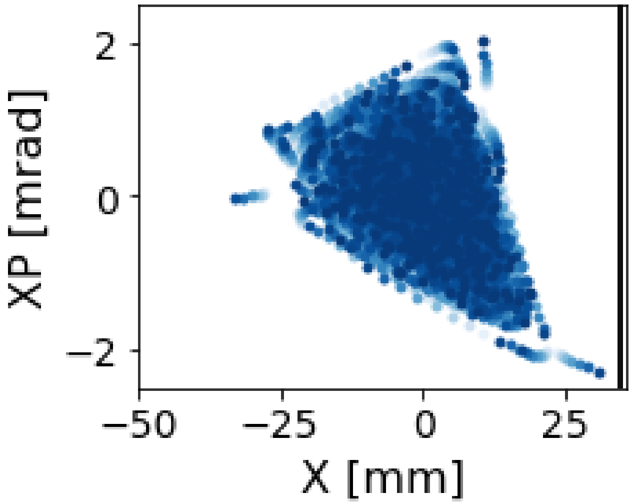


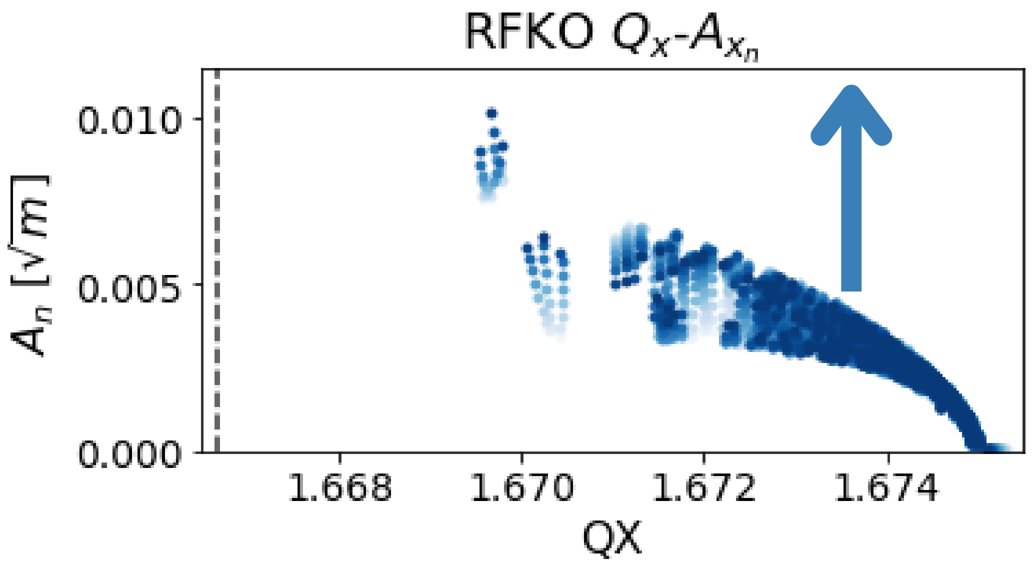
PIMMS lattice taken as baseline of study, adapted for needs of NIMMS.

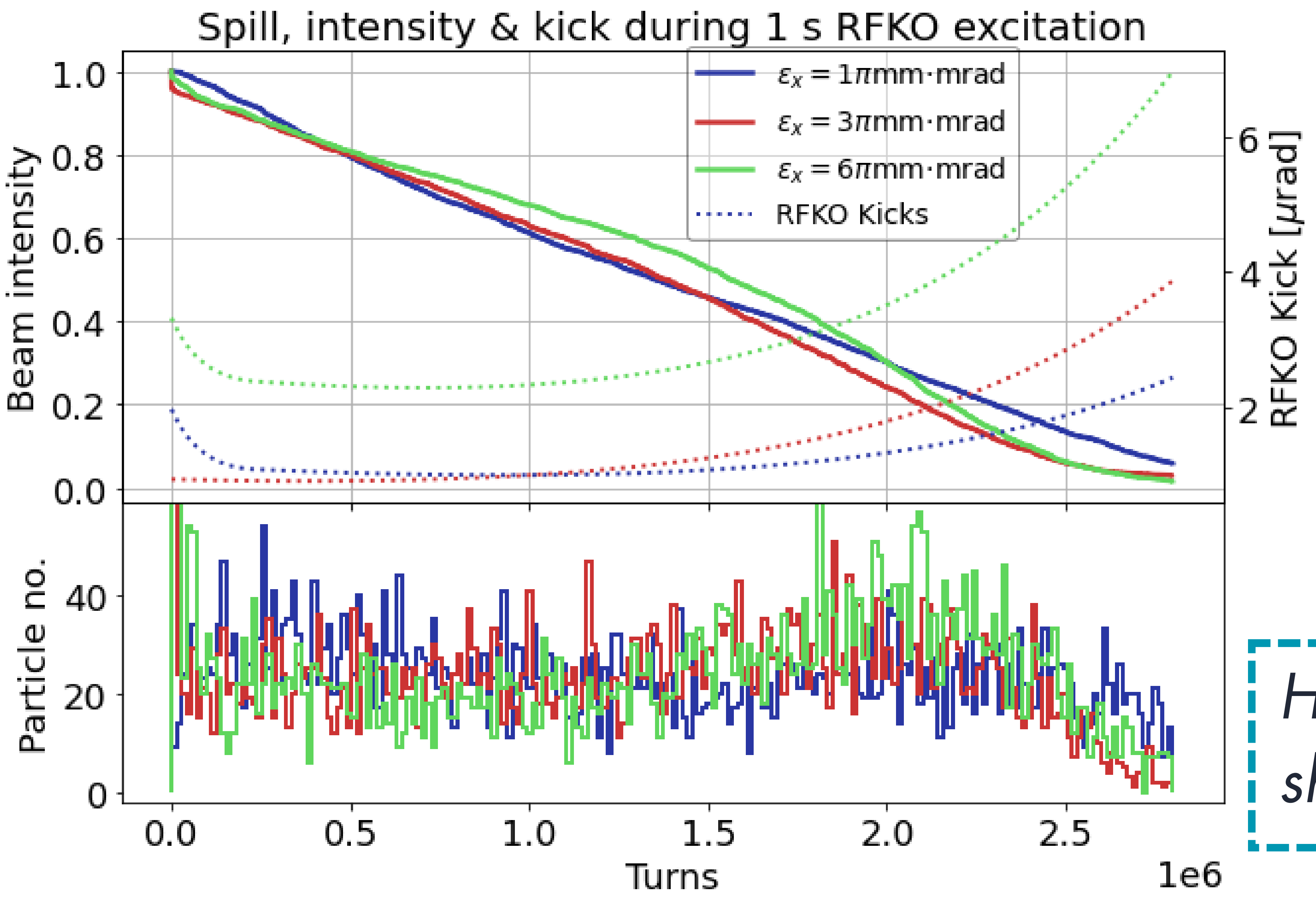


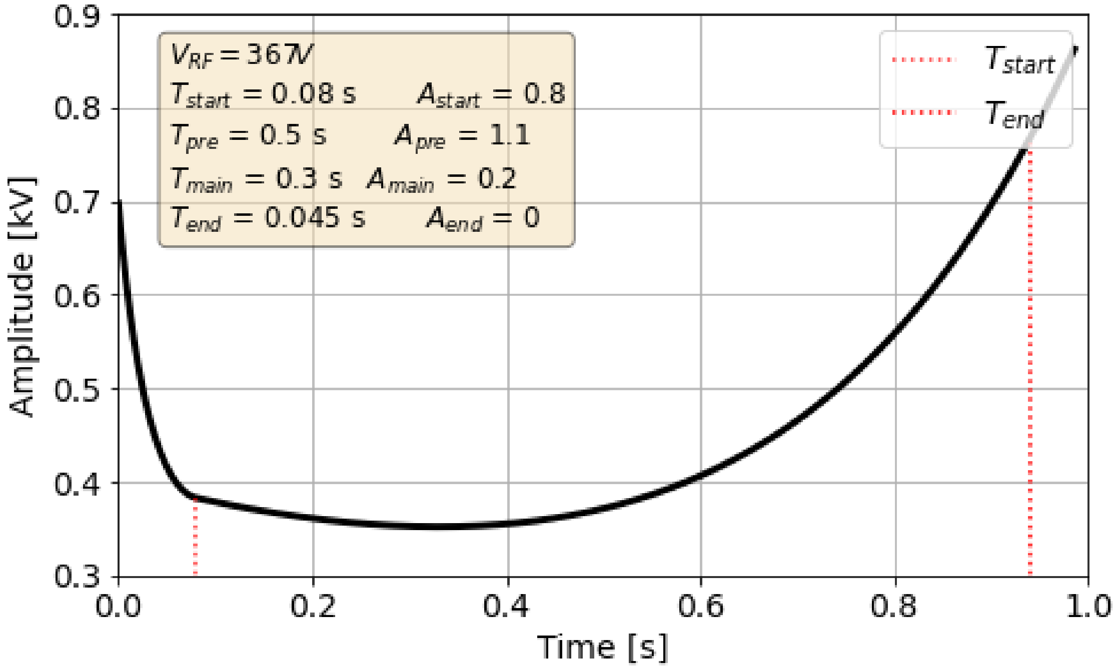
NC C6+: RF-KO

- **RF-KO** excited added to Maptrack.
  - FM at Qx frequency with ΔQx gaussian BW.
  - AM varying exponentially via *C. Schömers*
- Simulation of 5E4 particles for 2.8E6 turns in Maptrack.

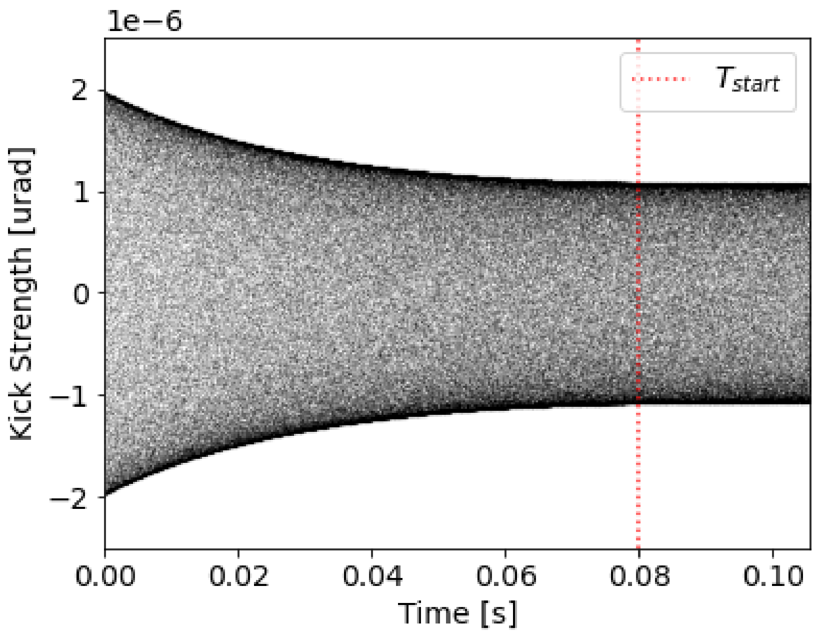






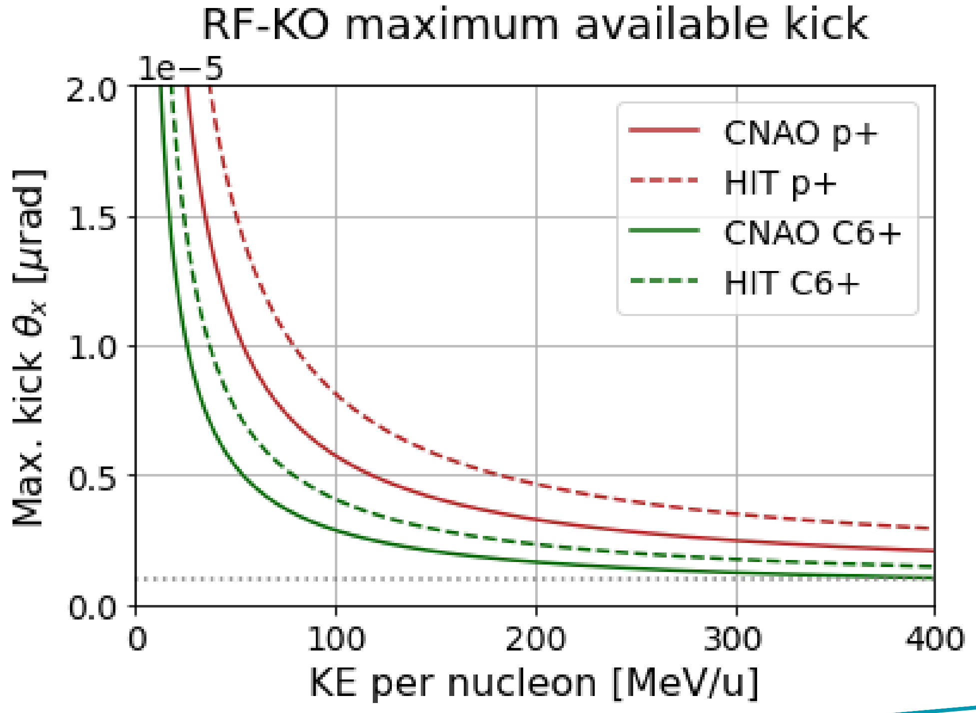


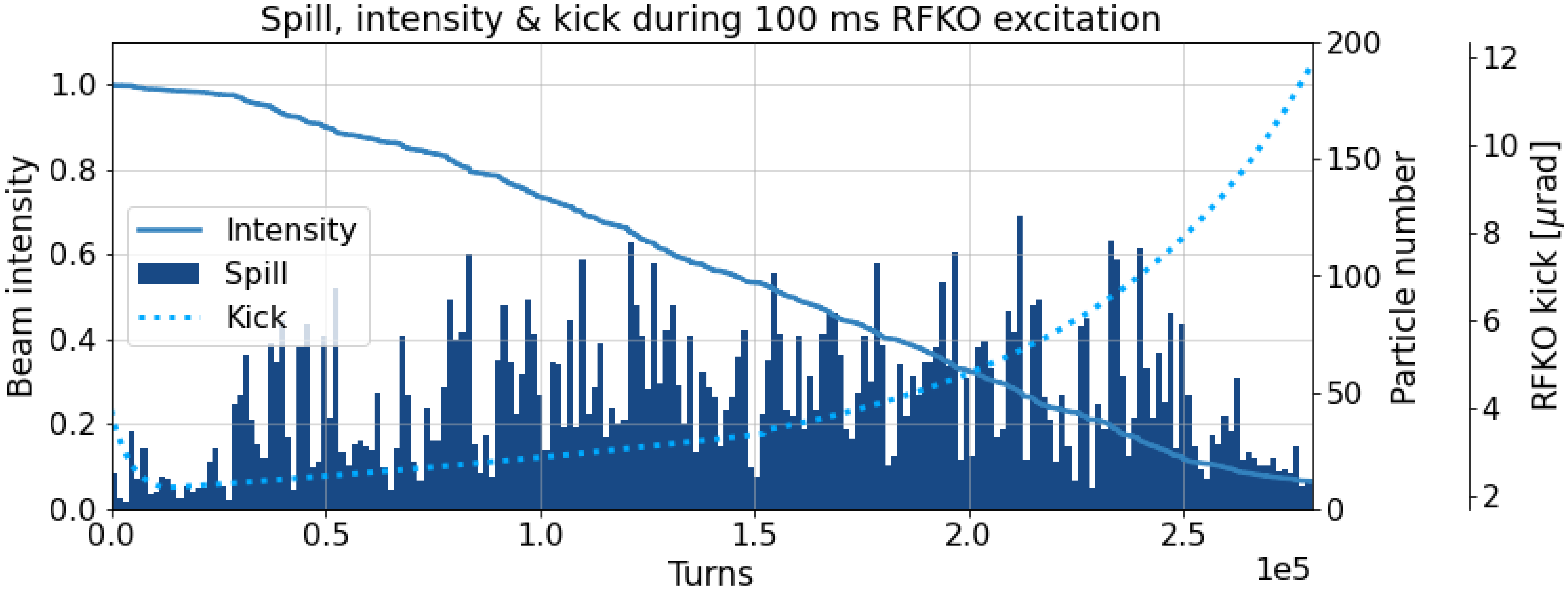
High εx requiring tune shift, higher baseline AM.



NC C6+: Fast RF-KO

- Repeated simulation increasing extraction rate x10
- Simulation of 1E5 particles for 2.8E5 turns in Maptrack.
  - Higher AM exponent at tail to extract complete beam.



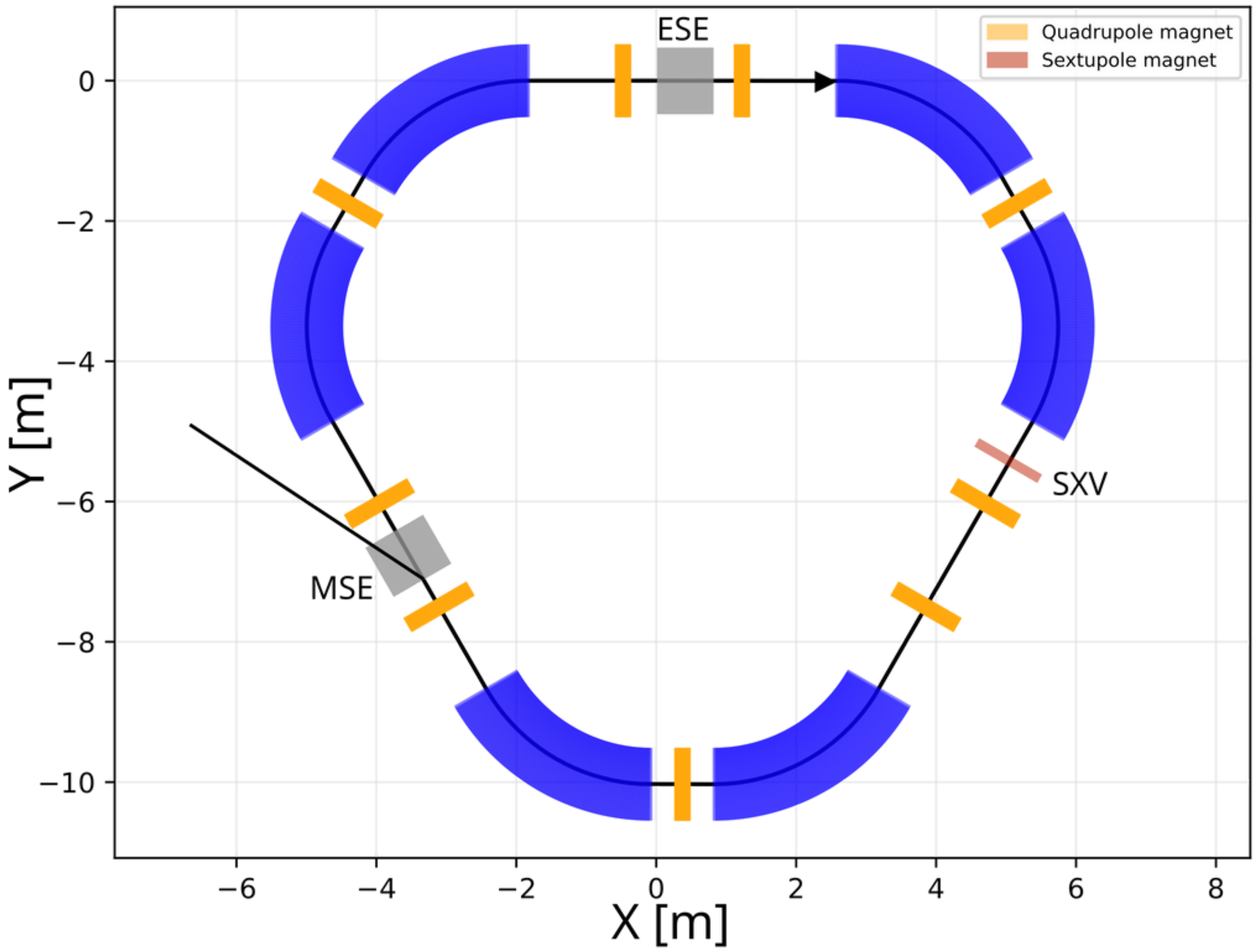


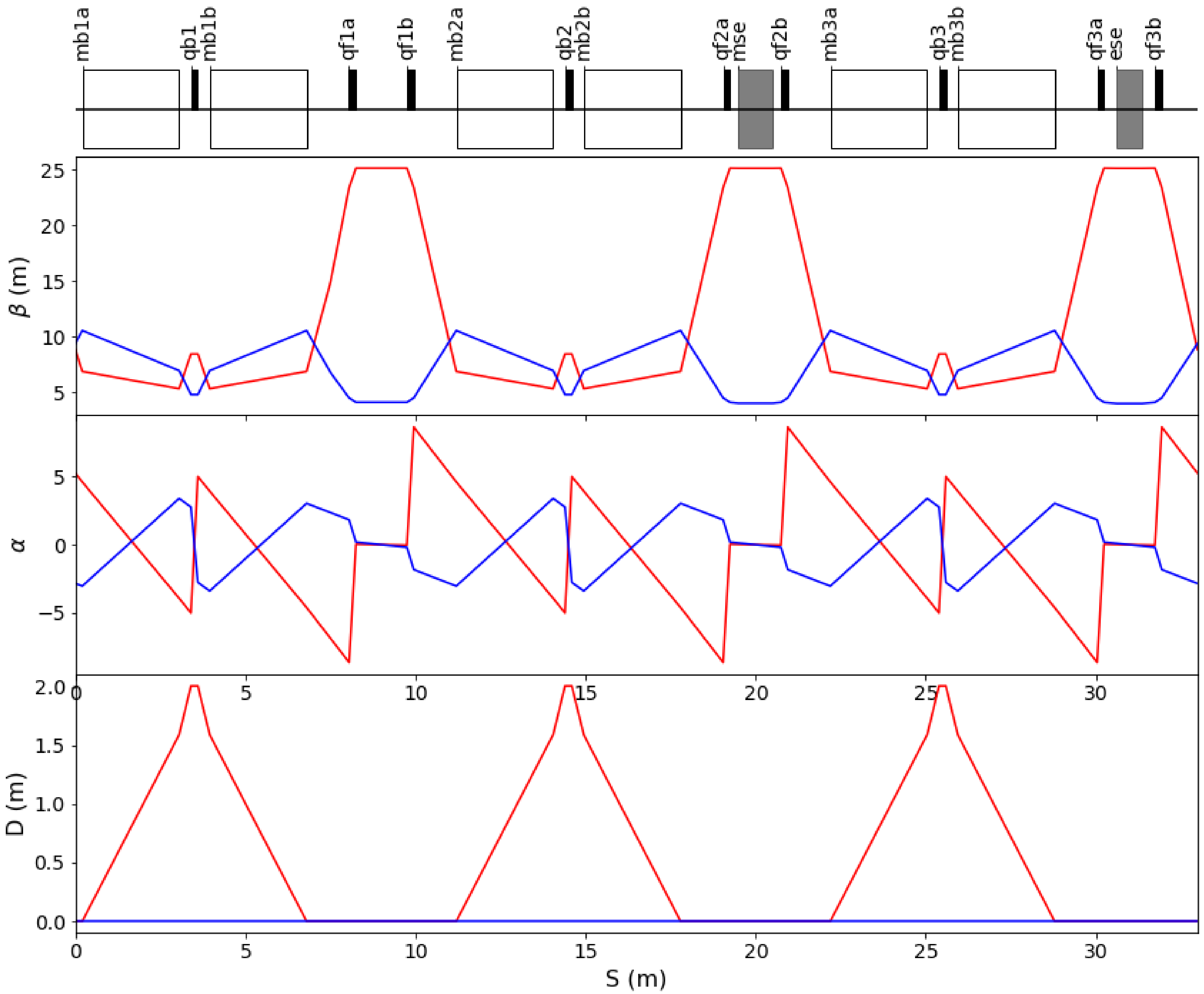
12 urad kick for 400 MeV/u C6+ beam equivalent to 4 kV exciter.

HeLICS Helium Light Ion Compact Synchrotron

Initial optics released *Feb 2023*

- Qx = 2.666
- dQx = -5.56
- Circum = 32.9 m





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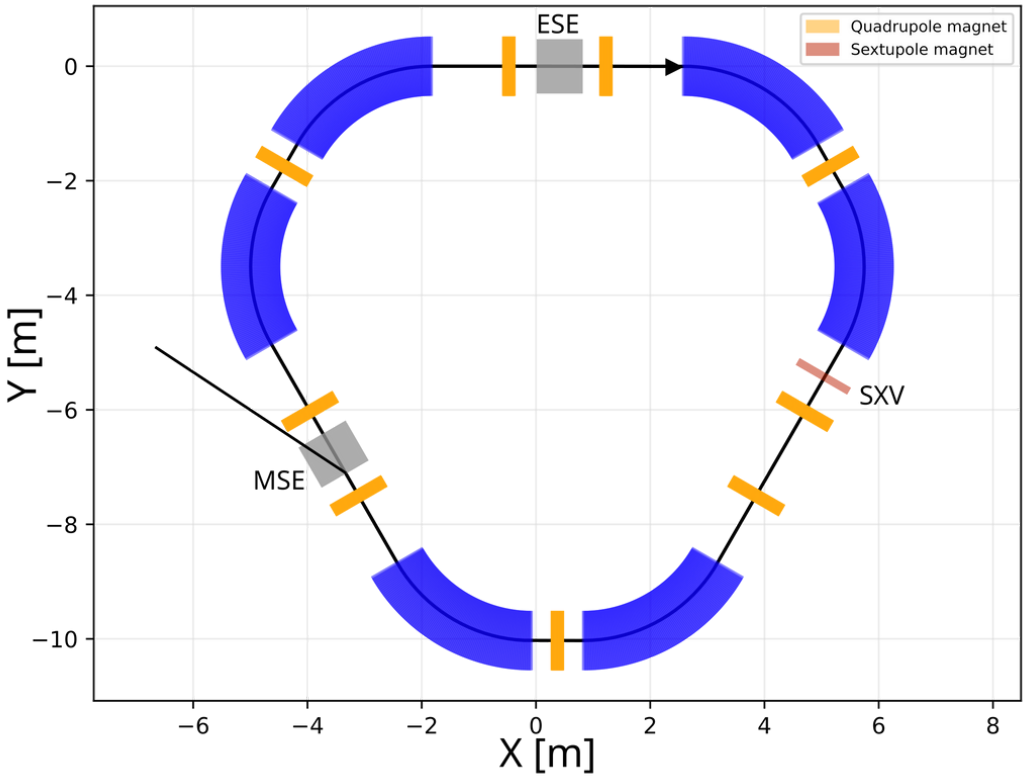
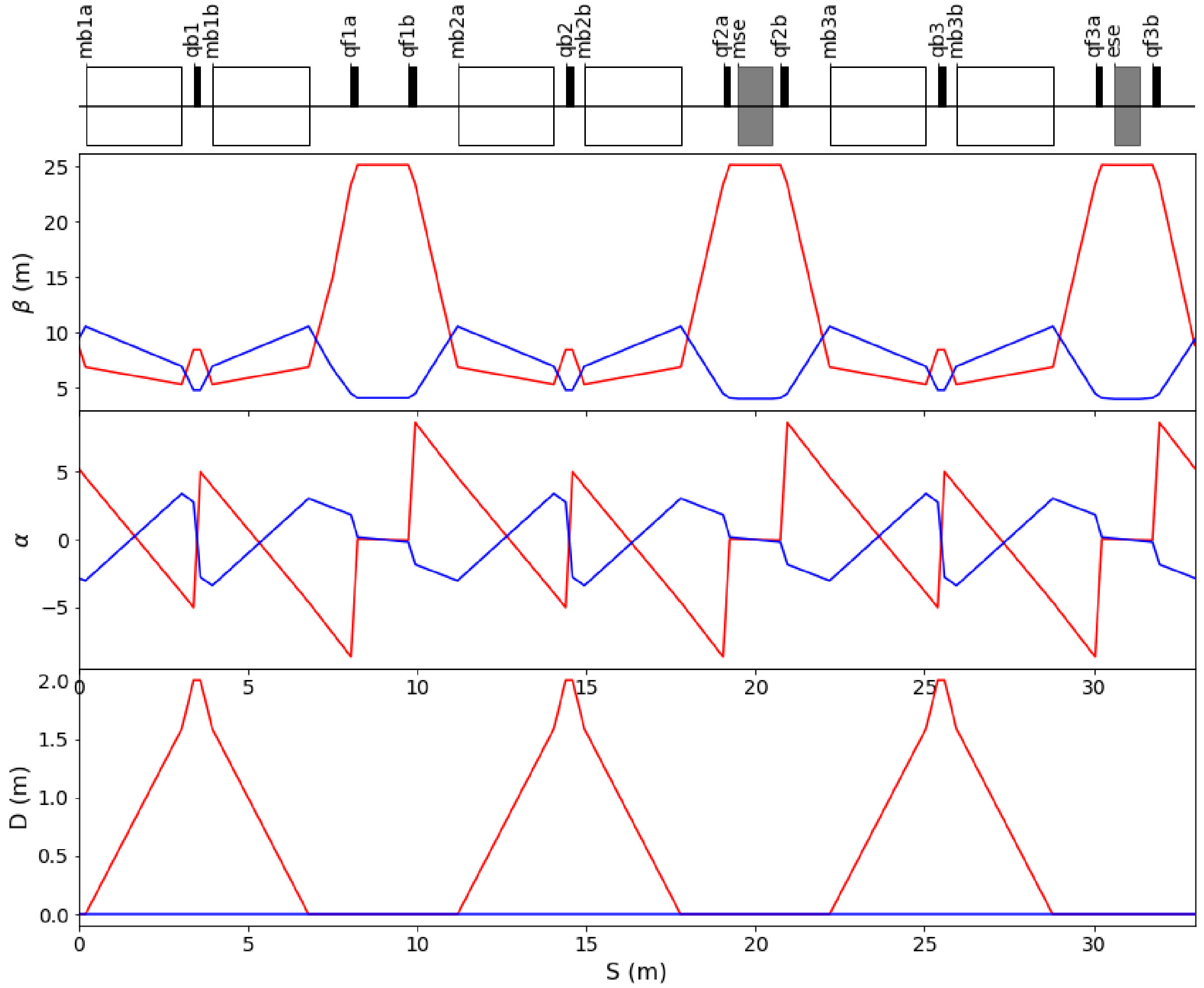
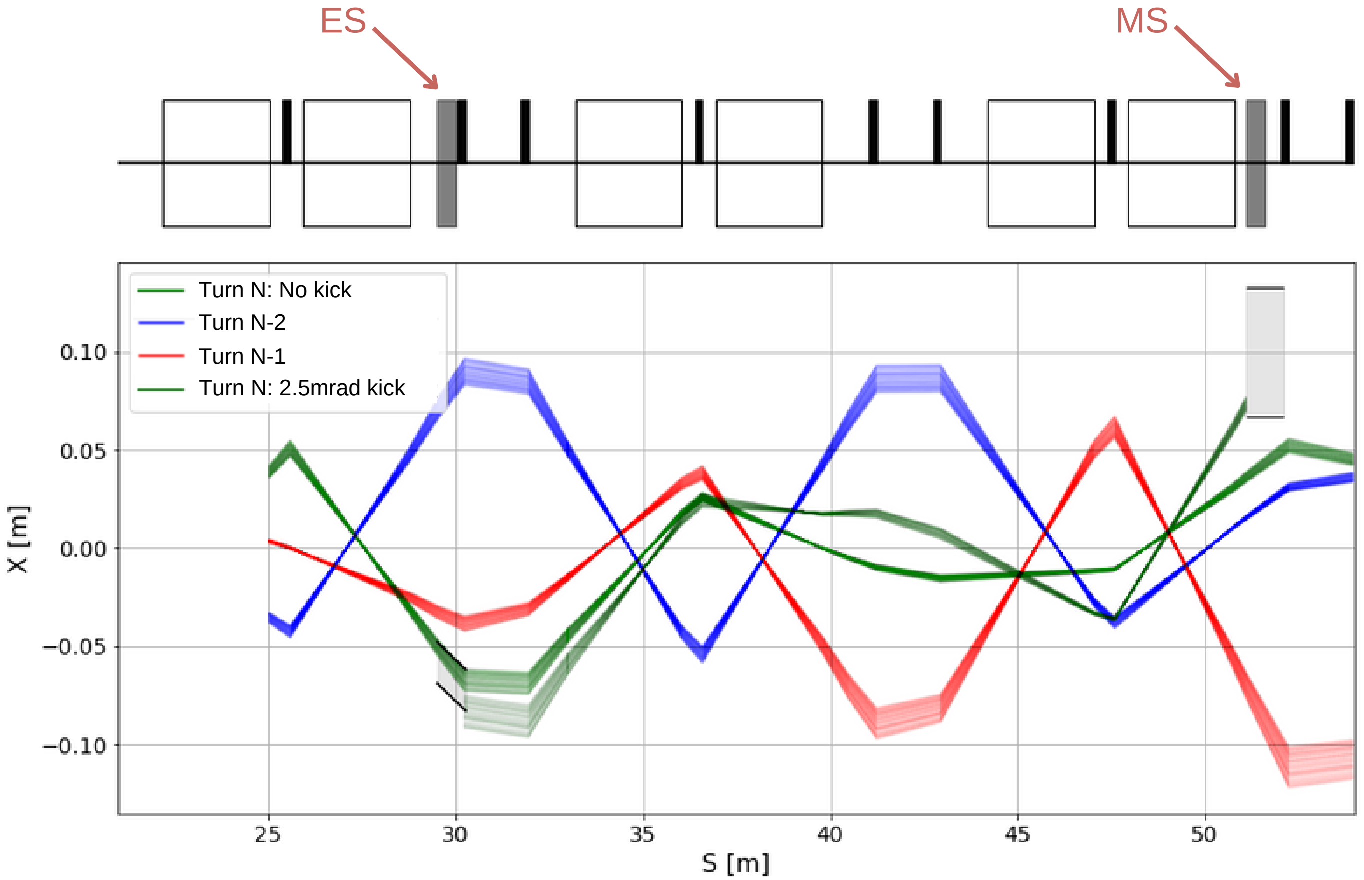
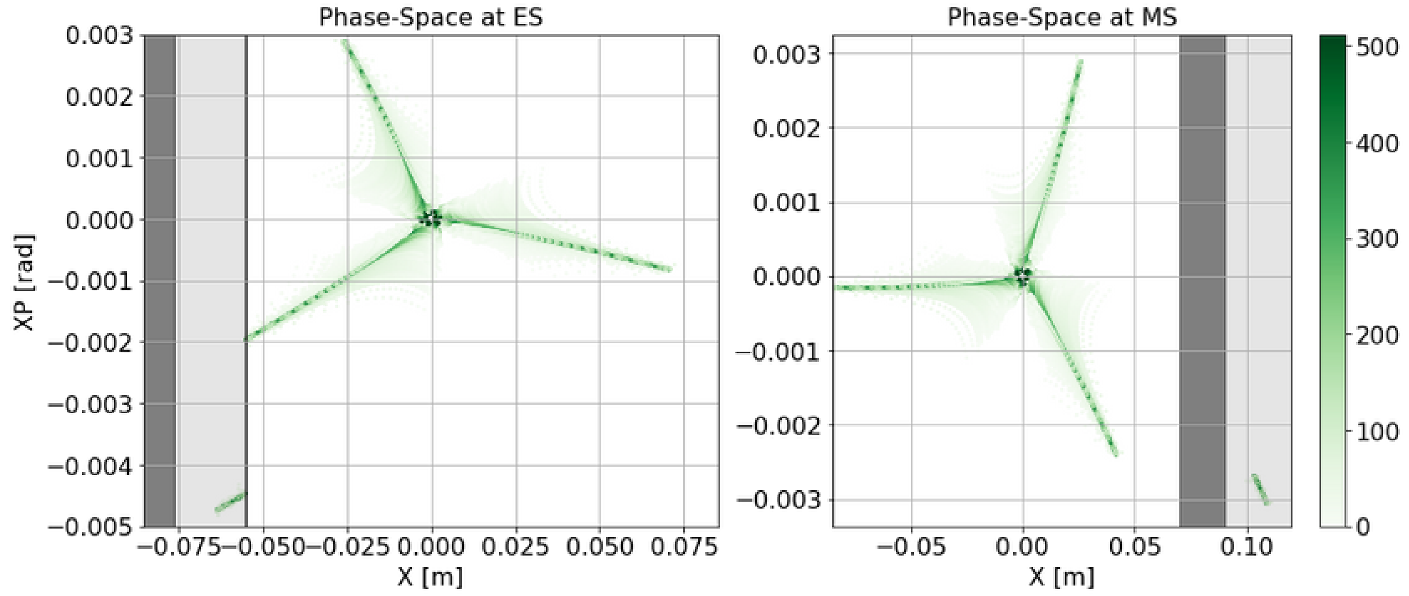




Extraction schematic set up *Spring 2023*





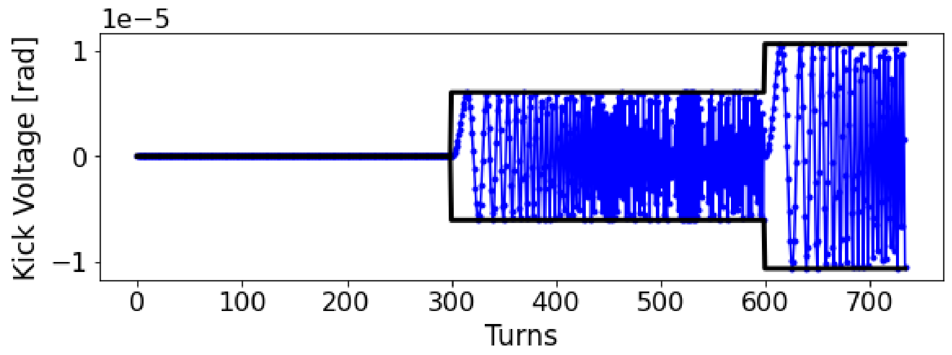
HeLICS

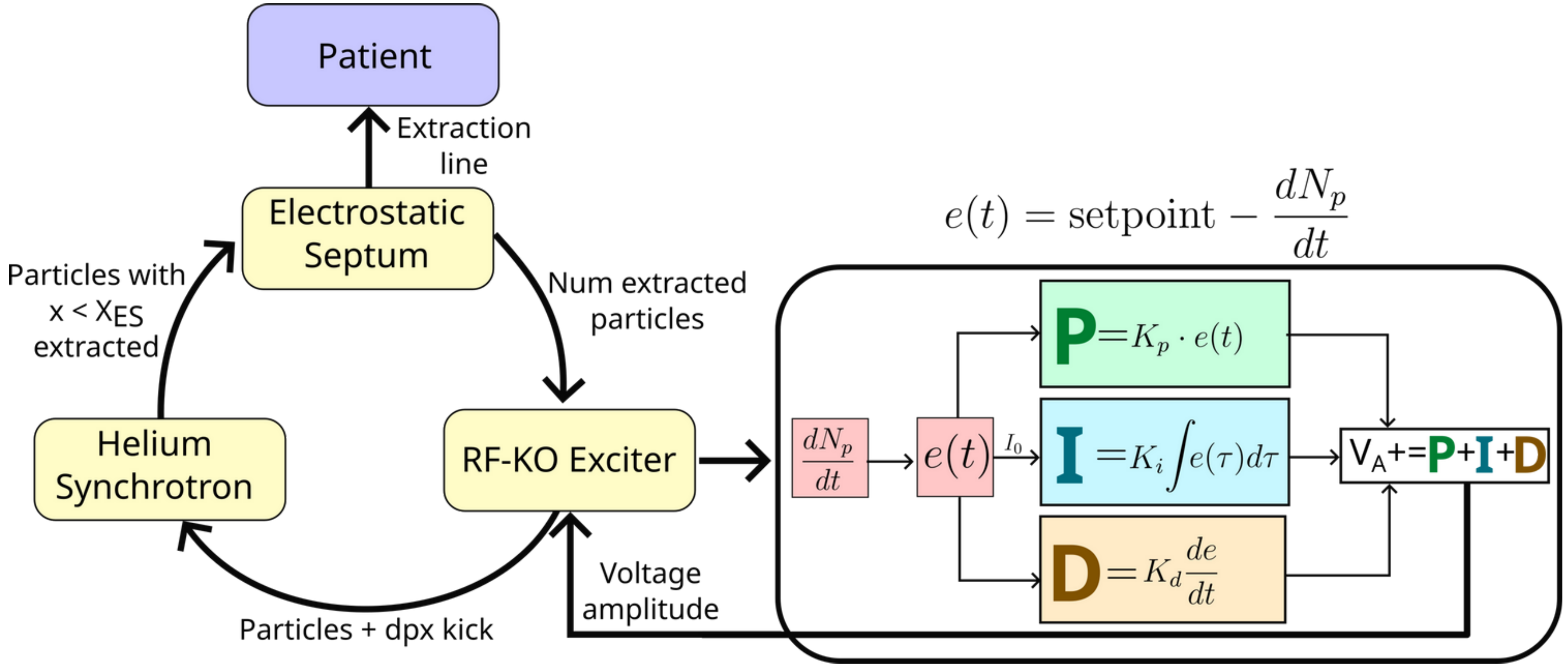
RF-KO Controller

S. Detsi, R. Taylor

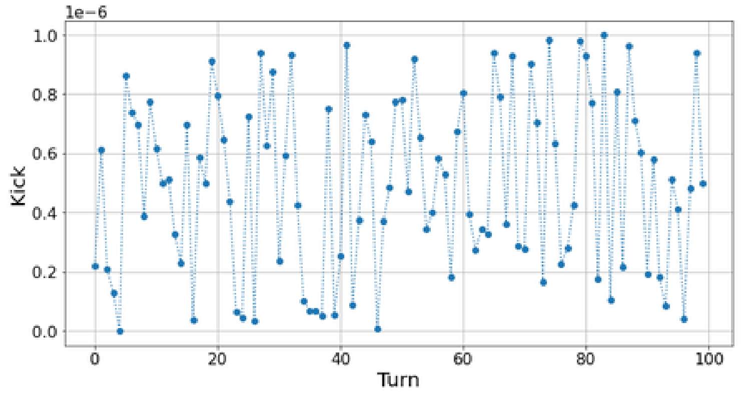
Amplitude Modulation: *Controlled by PID limit*

- Written in C, incorporated as Xsuite element
- Particles lost from septa every time window, compares to setpoint: N_particles/N_turns
- Time window: 100 μs = 300 turns

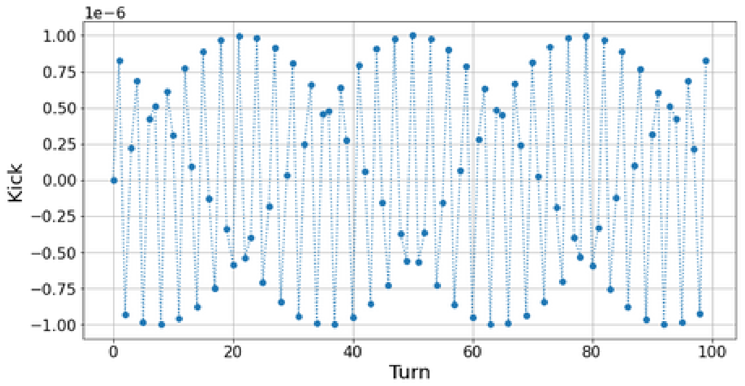




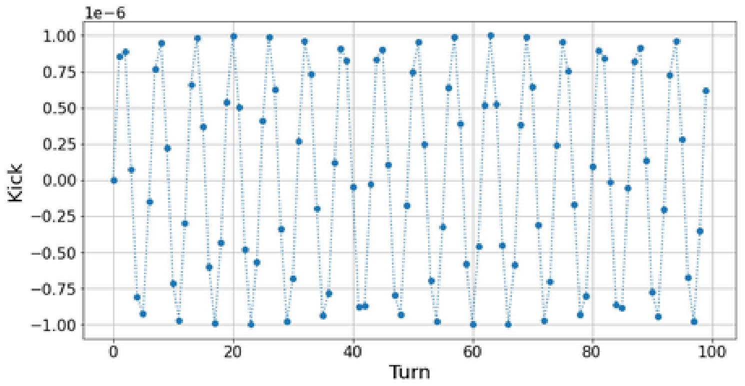
Frequency Modulation: Defined by user



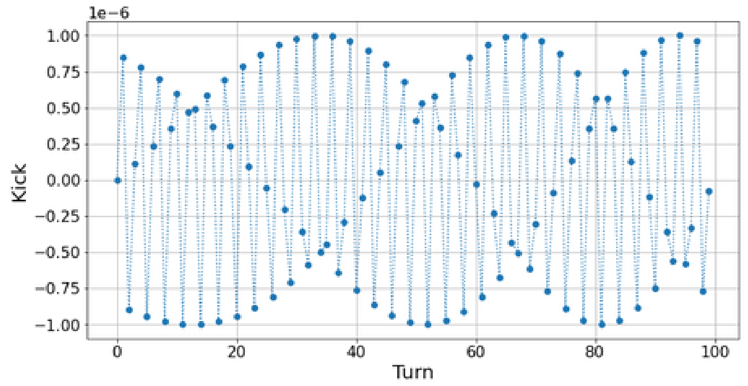
Random noise



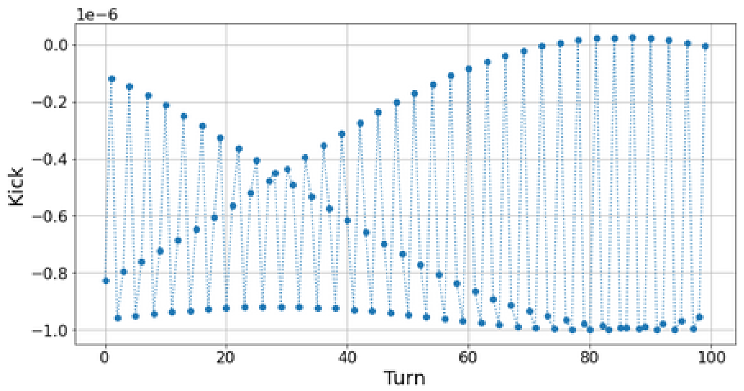
Sin(Qx)



Sin + dQx bandwidth



Chirp



Modulation Signal

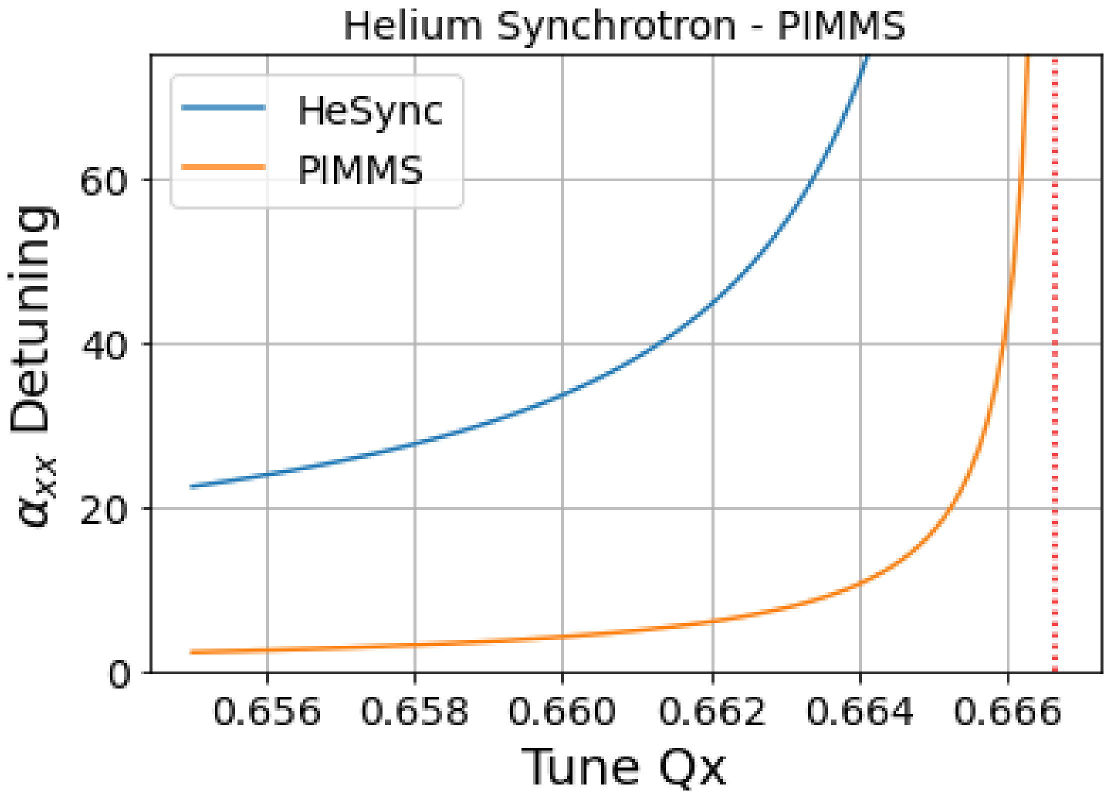
HeLICS Amplitude Detuning

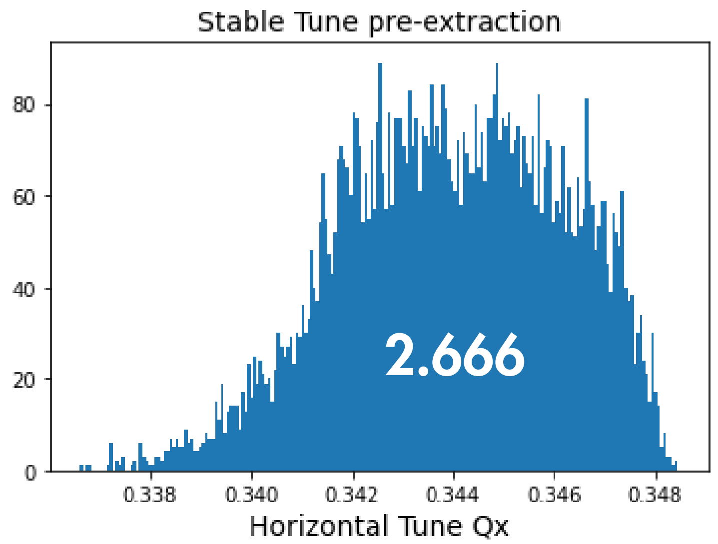
Quadrupole-driven extraction & amplitude detuning explored in *Autumn 2023*

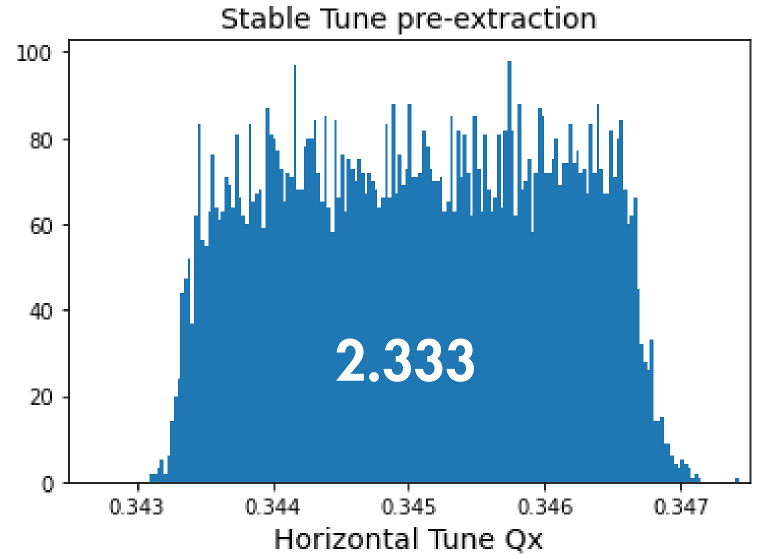
- Amended by using updated optics (H. Huttunen)

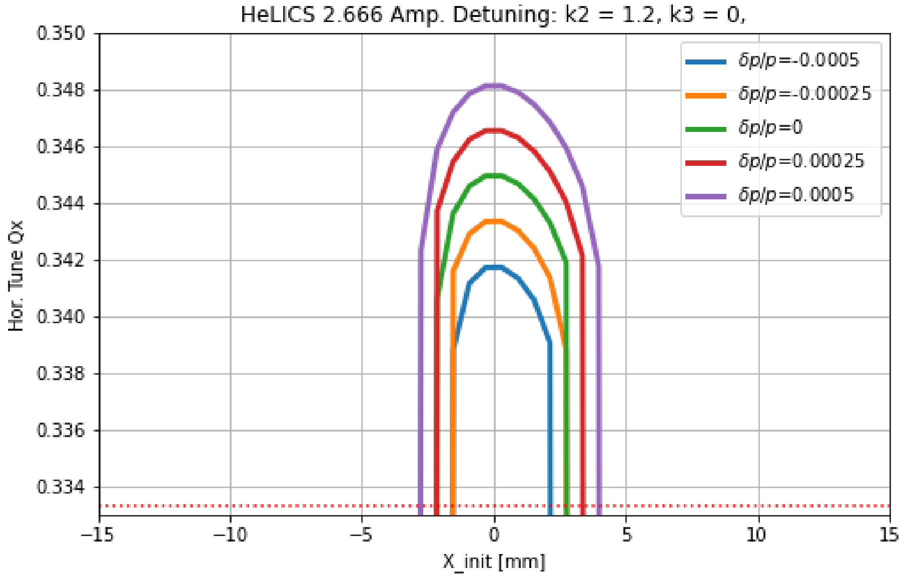
Sexupole detuning term: S.Y. Lee 3rd ed. pg 198

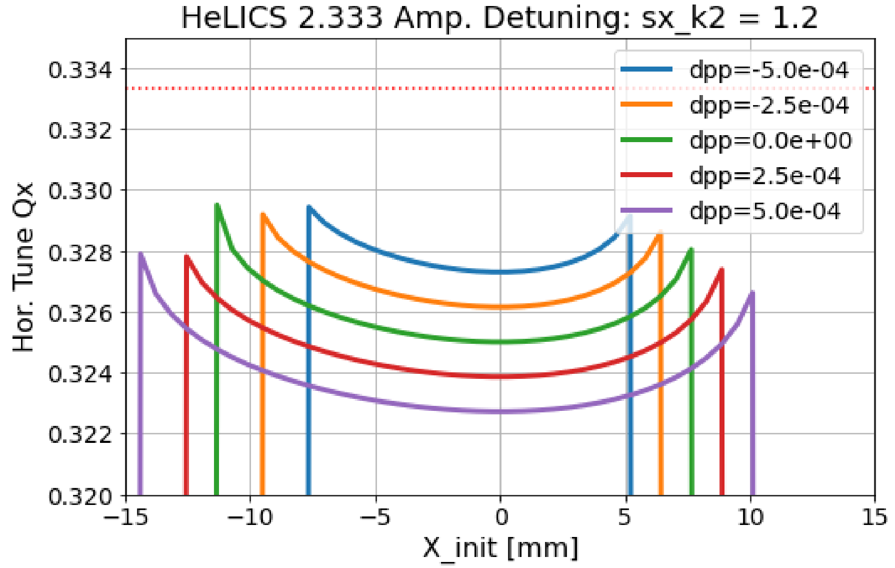
$$\alpha_{xx} = \frac{1}{64\pi} \sum_{ij} S_i S_j \beta_{x,i}^{3/2} \beta_{x,j}^{3/2} \left[\frac{\cos 3(\pi\nu_x - |\psi_{x,ij}|)}{\sin 3\pi\nu_x} + 3\frac{\cos(\pi\nu_x - |\psi_{x,ij}|)}{\sin \pi\nu_x} \right]$$

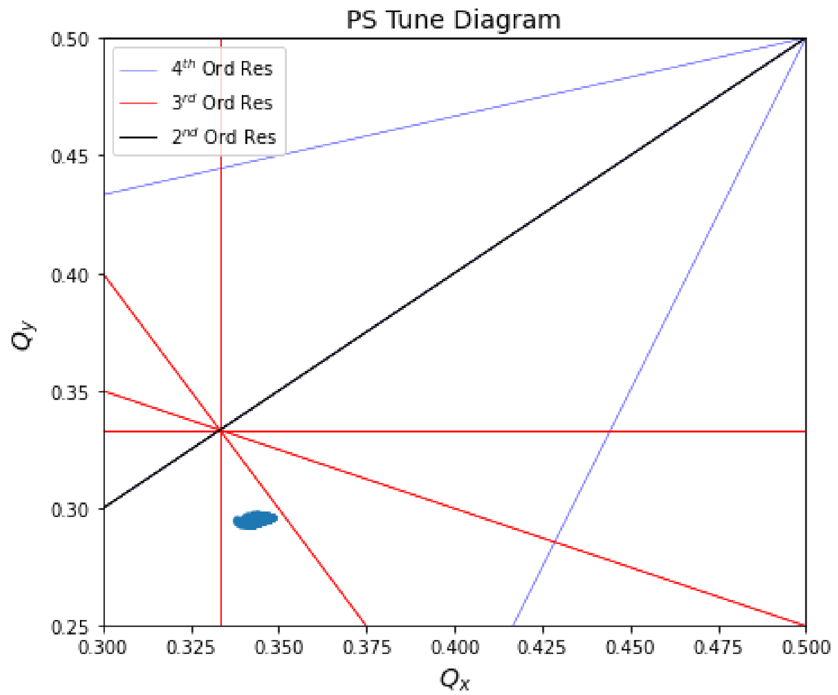


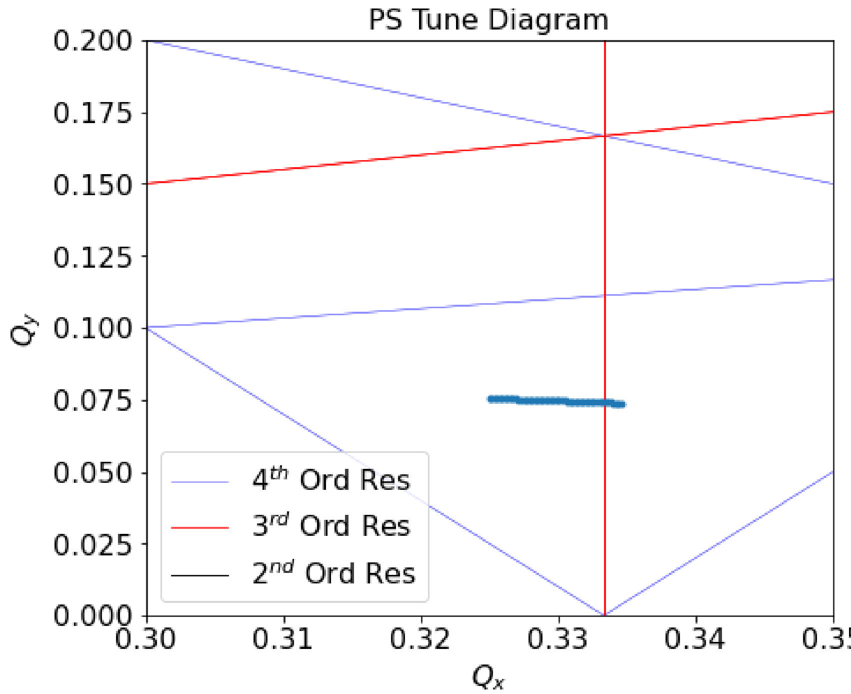










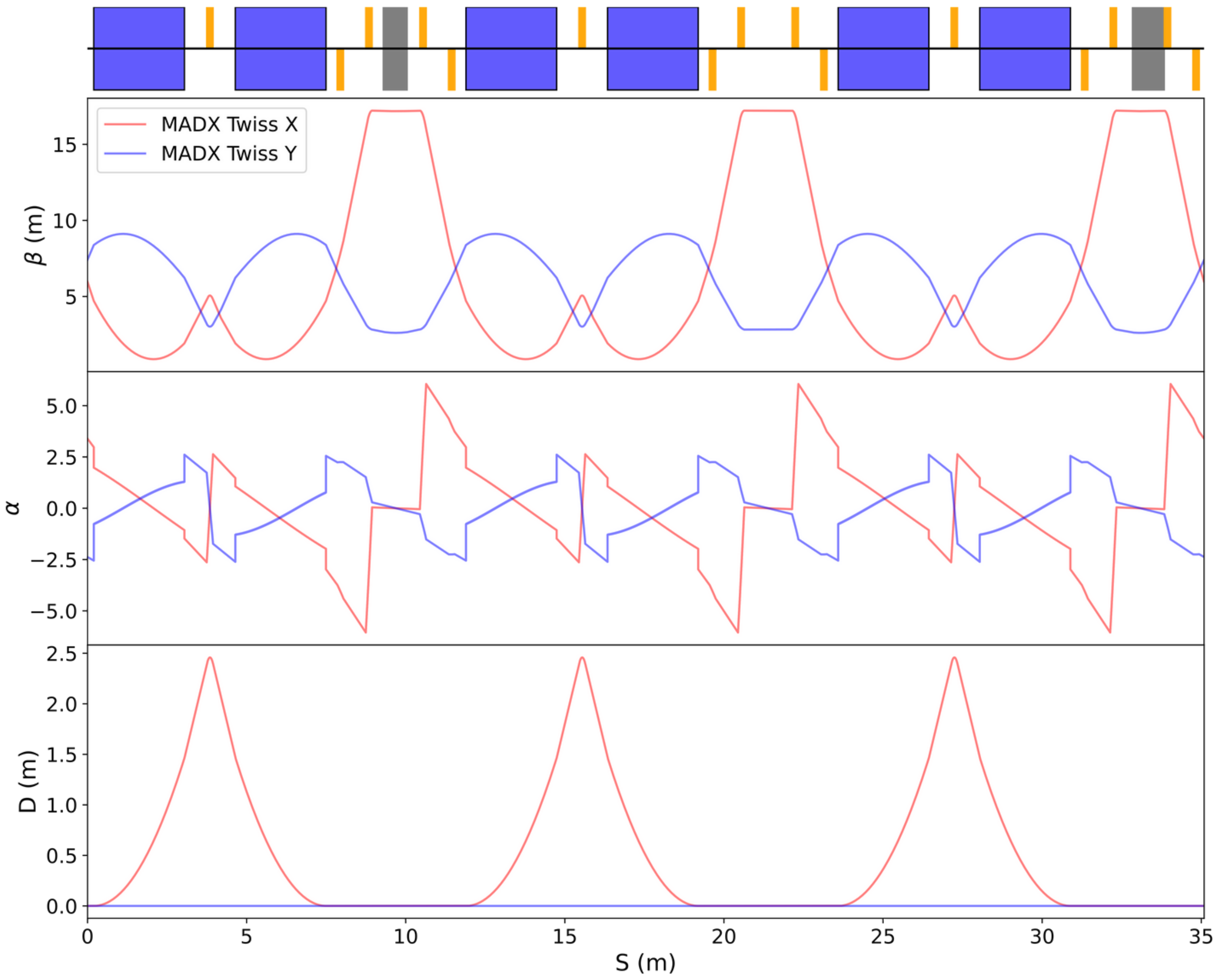


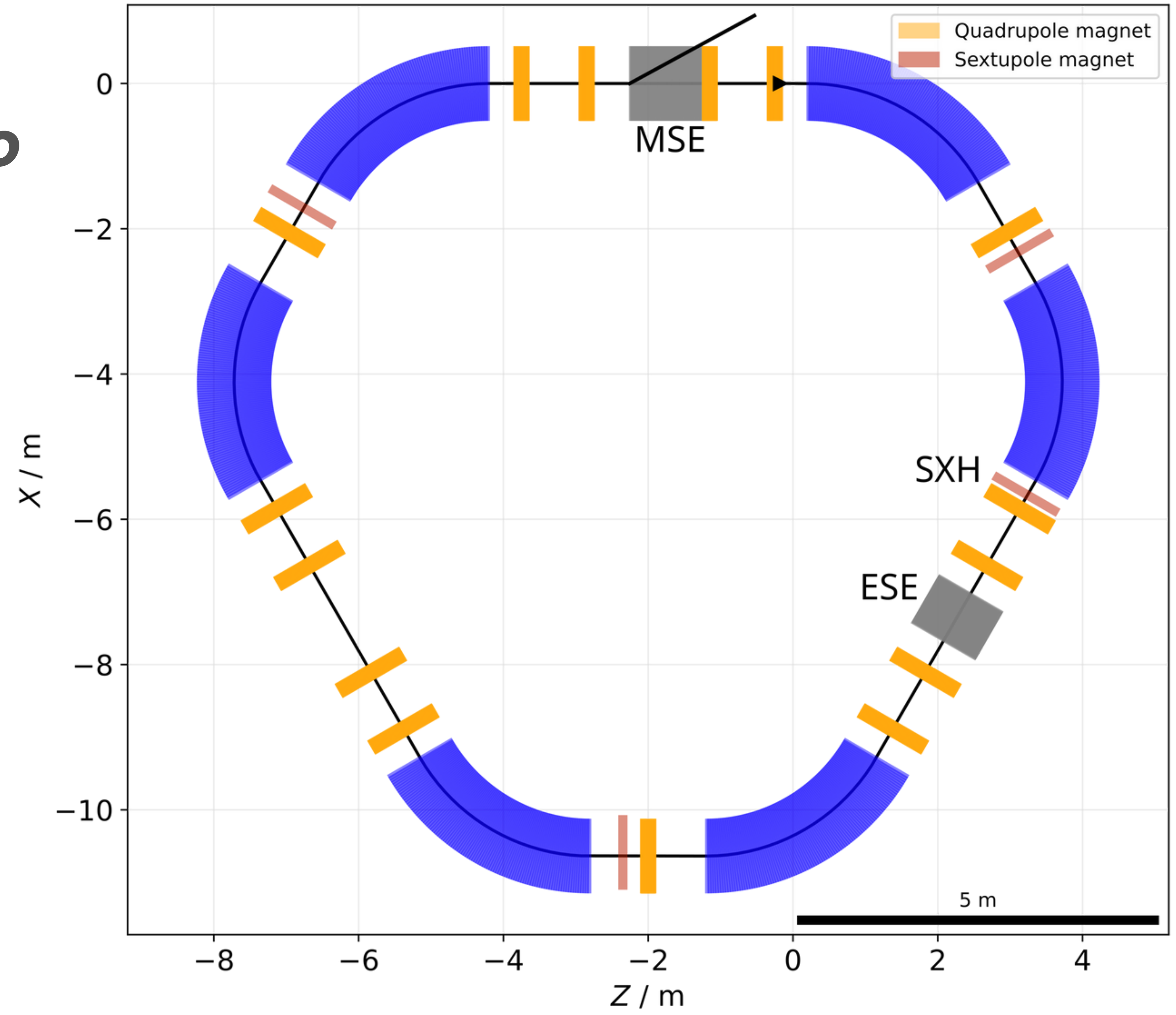
HeLICS

Current Status

H. Huttunen, F. Asveta, E. Benedetto

- Defocusing quads were added
- k1 in combined function dipoles were reduced





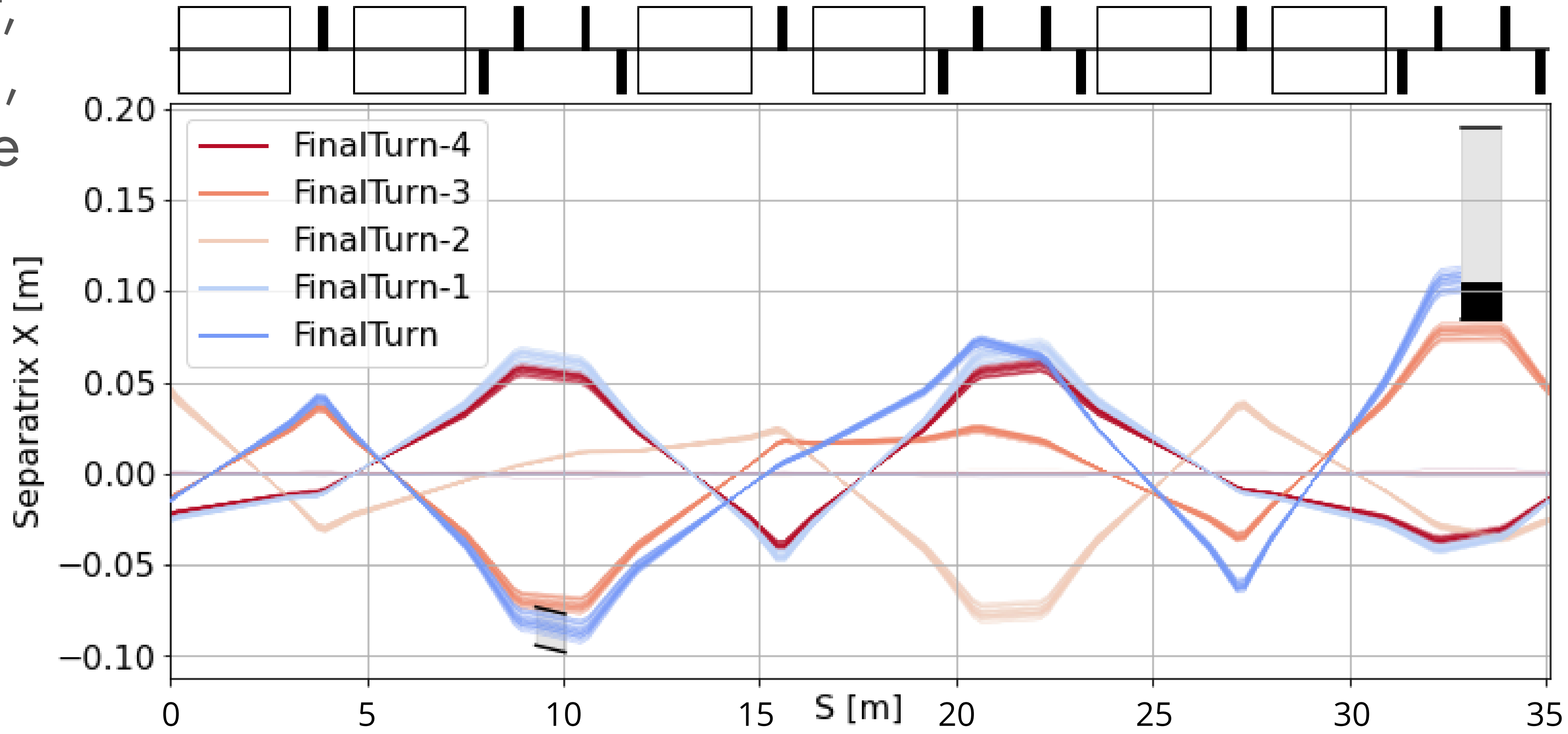
Qx = 2.333	Circum = 35 m
Qx′ = -3.09 (natural)	E_max = 220 MeV/u
εnx = 3 π.mm.mrad	dpp = 10^{-3} (in sim)
εny = <1 π.mm.mrad	β_{rel} = 0.329

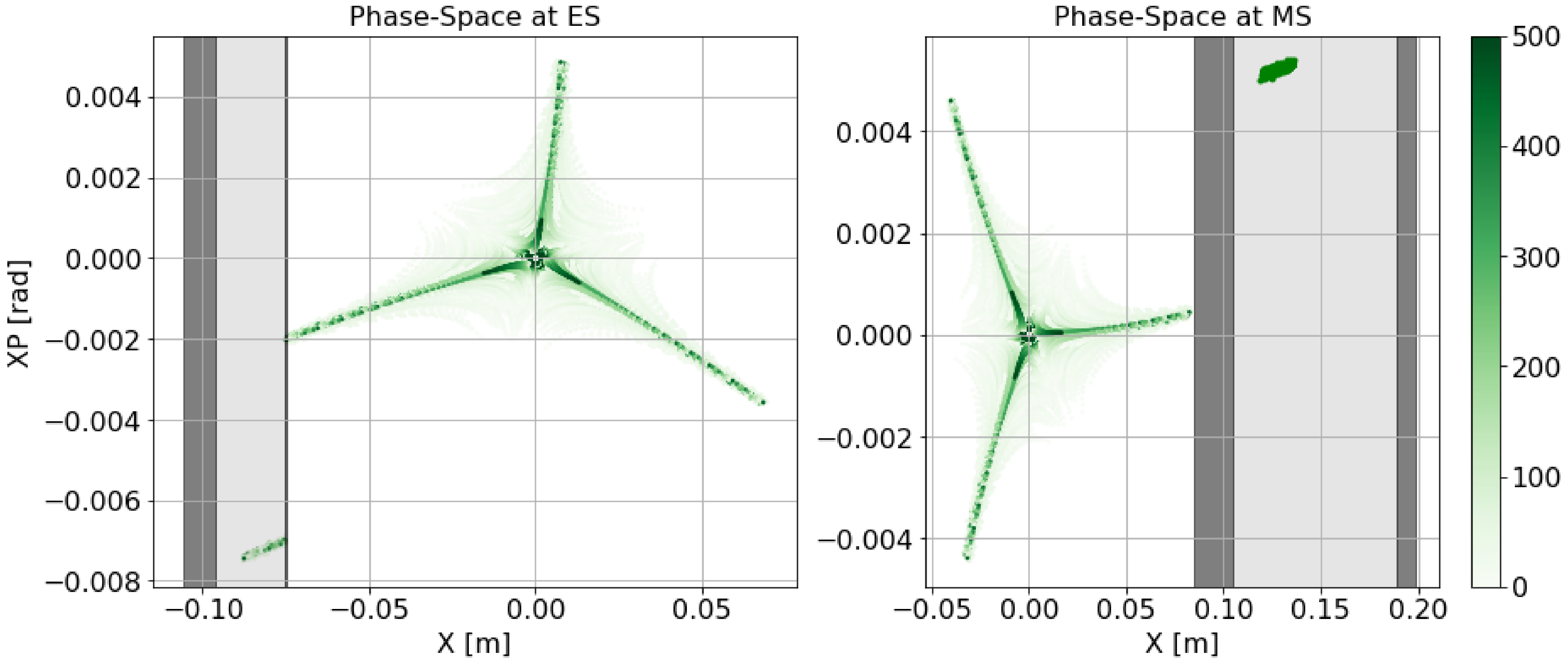
HeLICS

Septa created as **Xsuite element**, providing kick in ES field region, and loss flags at anode/cathode and MS extracted beam.

Designs from *J. Borburgh*	ES	MS
Deflection angle [mrad]	2.5	100
Physical length [mm]	750	1000
Active length [mm]	550	910
Gap height [mm]	35	35
Gap width [mm]	21	84
Septum thickness [mm]	0.2	20

	Value
Sextupole Strength k2L	1.2
Spiral Step [mm]	12
ES Offset [mm]	75
MS Offset [mm]	85





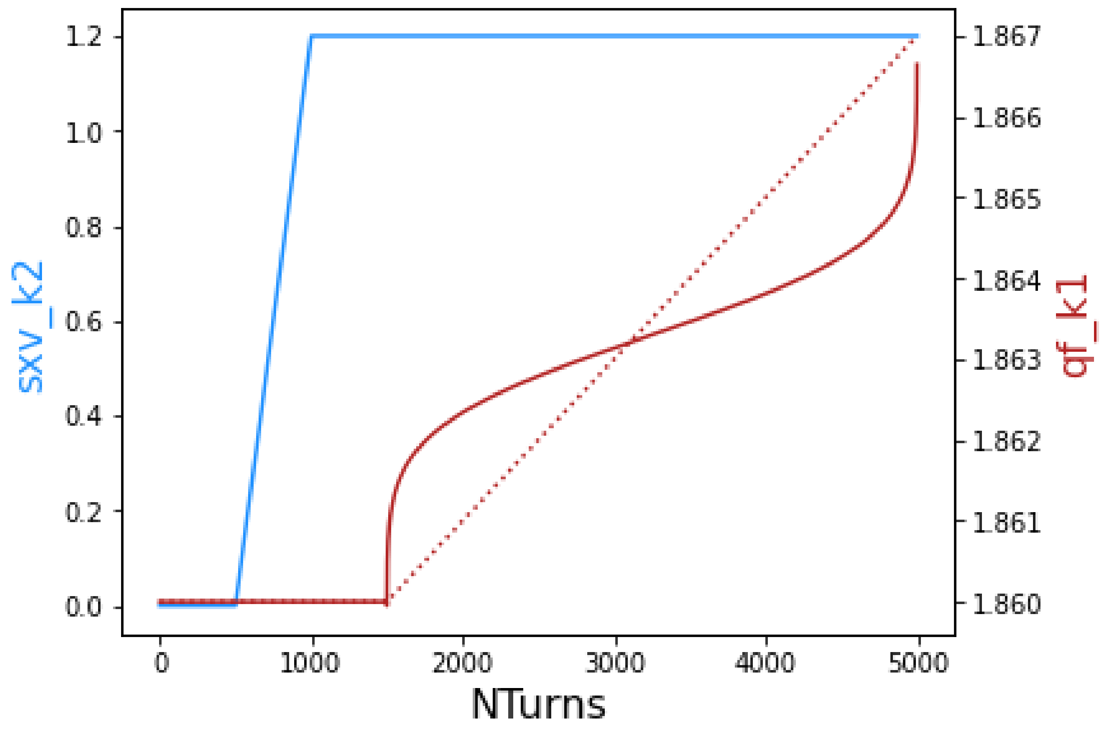
HeLICS: Quad-driven

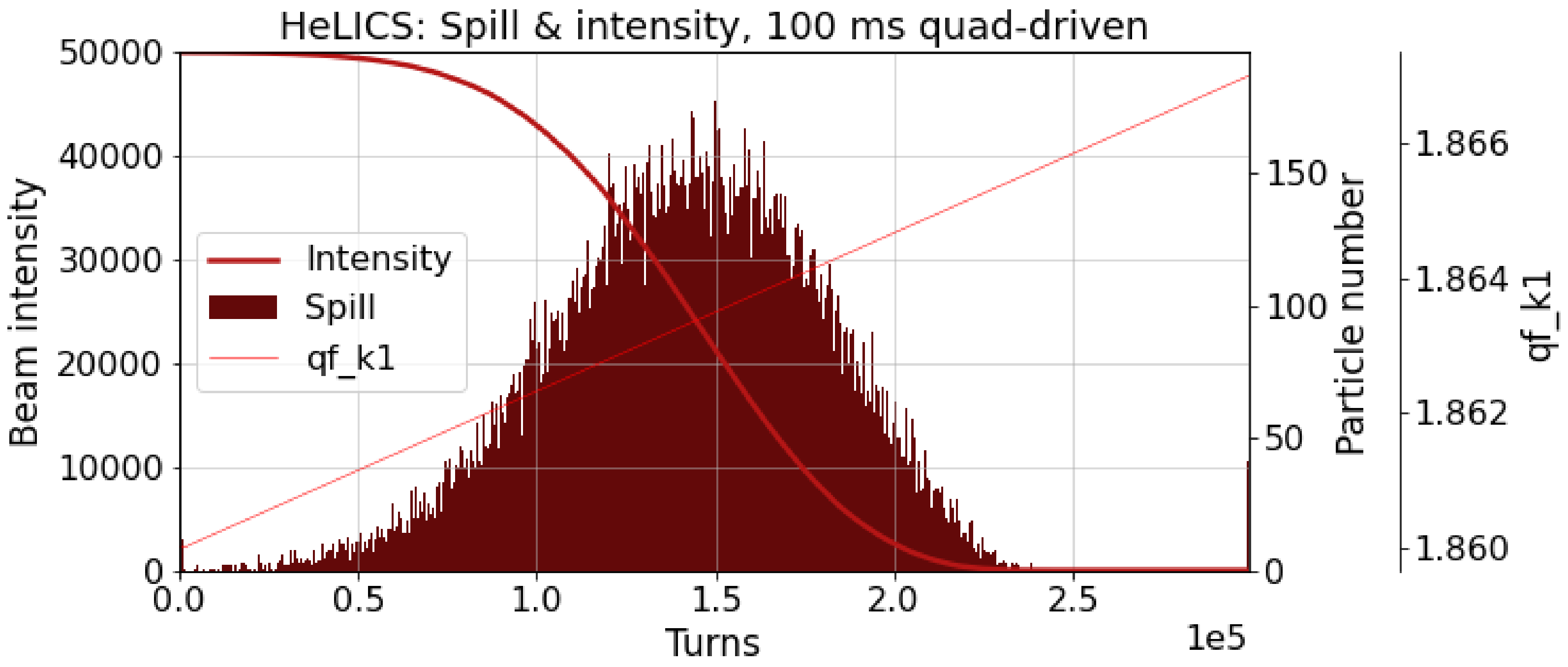
Uses k2 ramp of 0.006 - equivalent to *0.027 T/m* for 4.5 Tm beam rigidity. Throughout 100 ms gives rate of ***0.27 T/m/s***

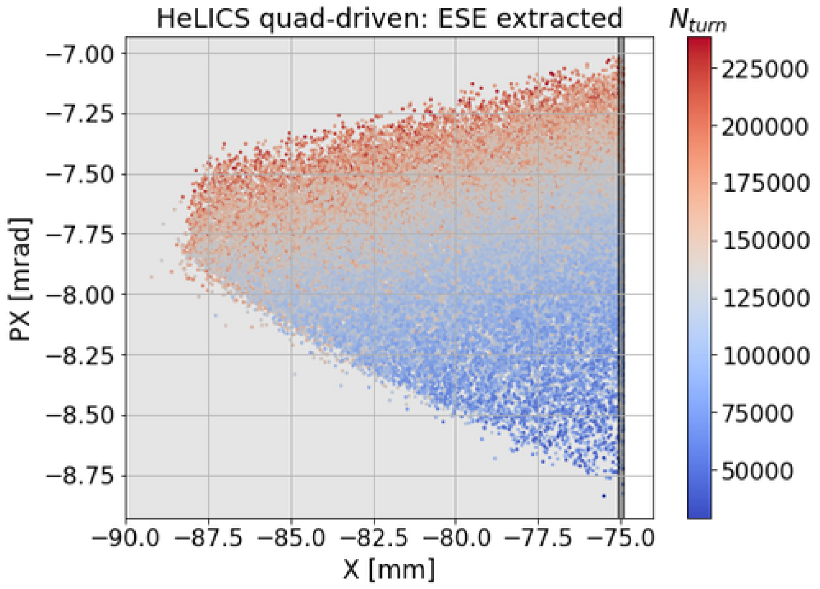
XSuite: 5E4 particles for 3E5 turns

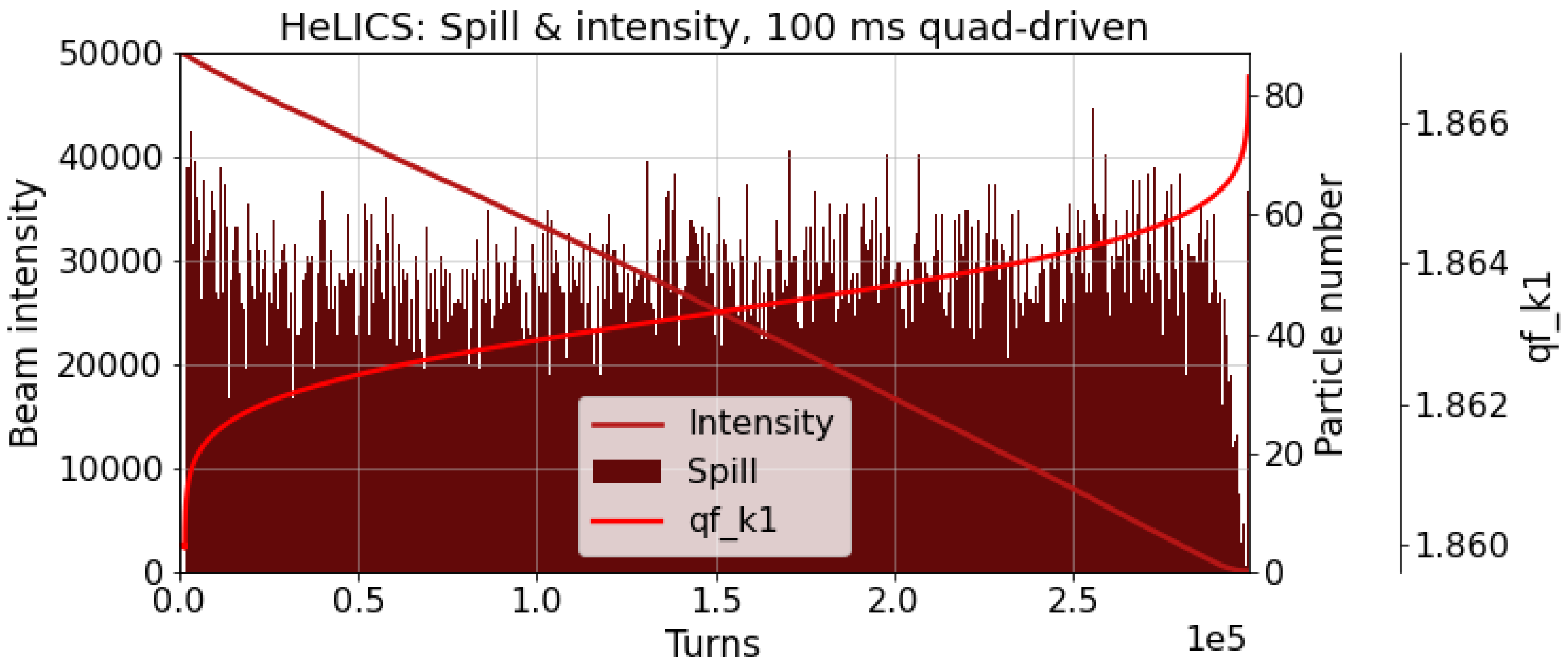
Small tune spread and **linear** quad ramp: Highly dependant on **beam density function**.

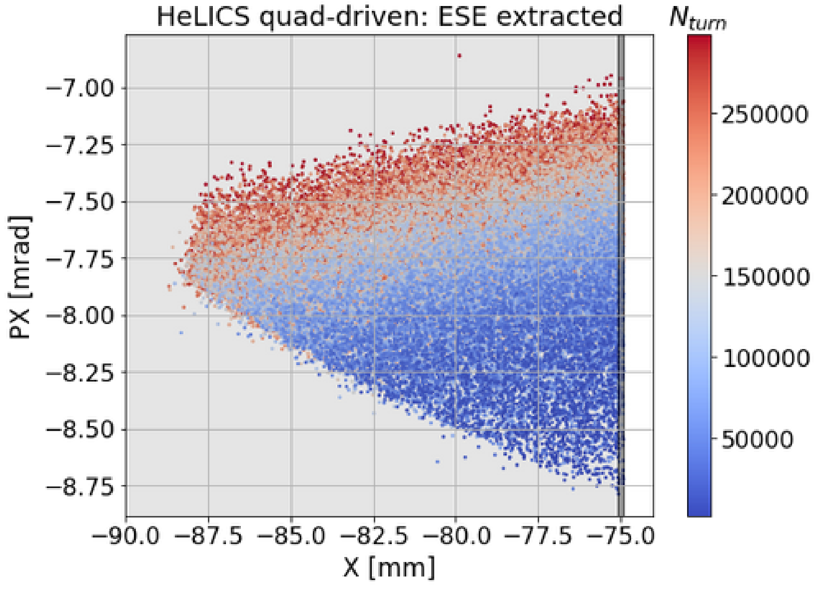
Matched to **Gaussian CDF**. Inverse ppf function as quad ramp rate.







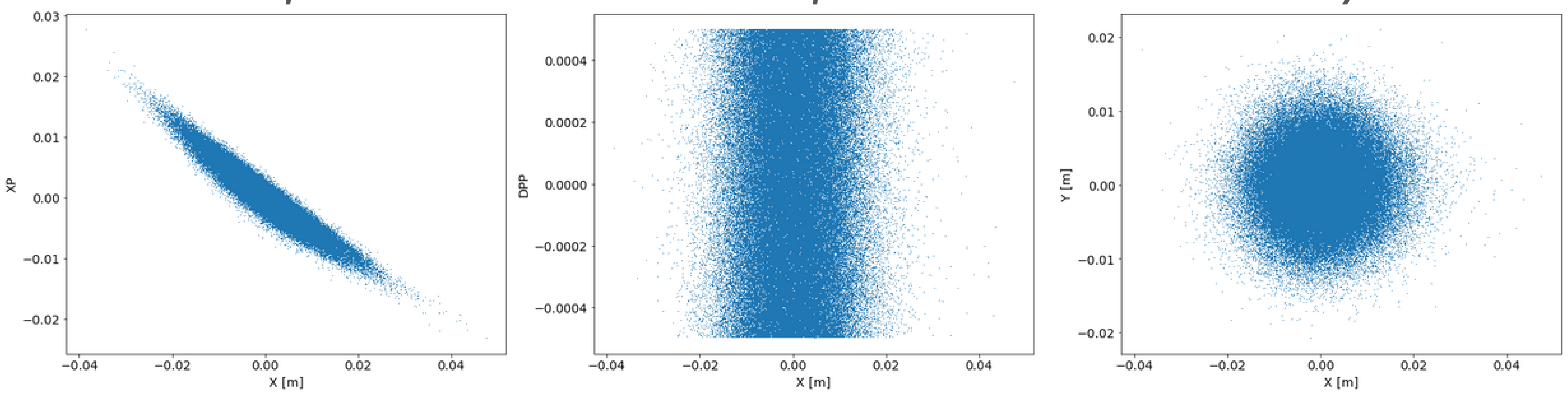




Little effect on extracted beam at ES

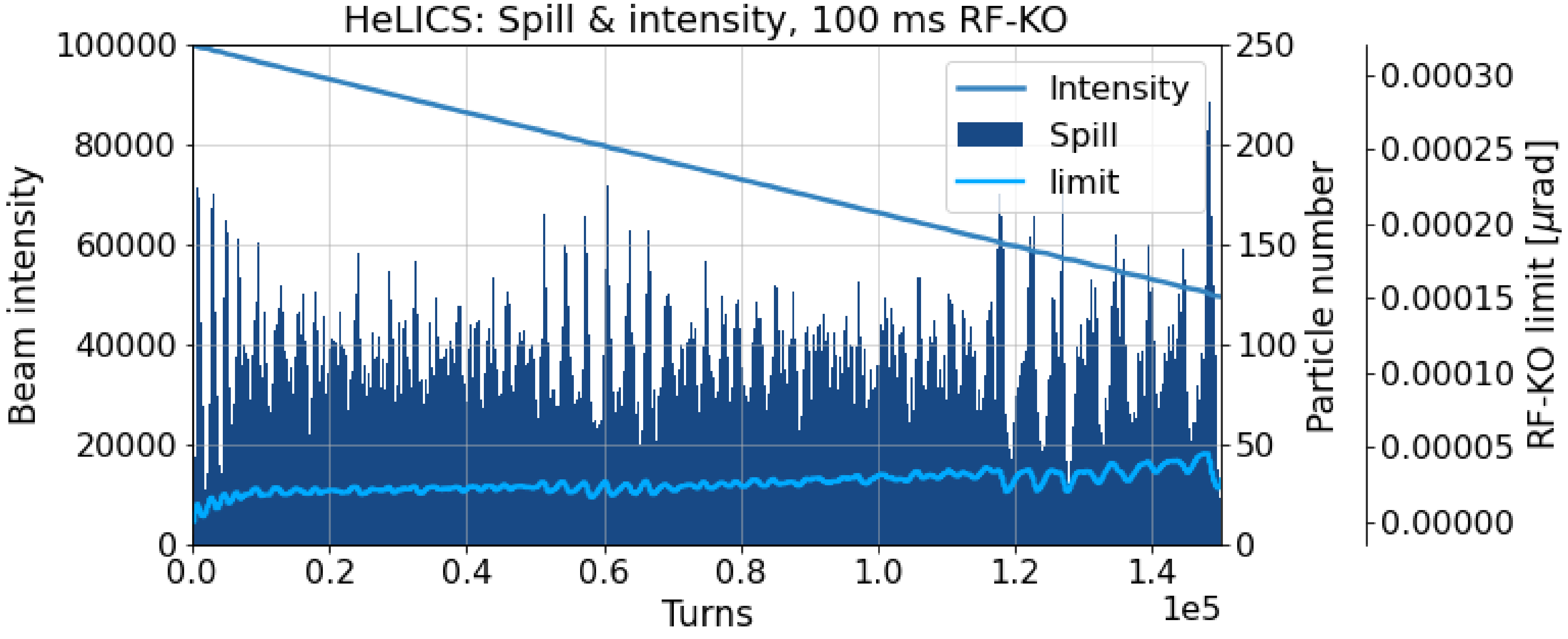
HeLICS: RF-KO

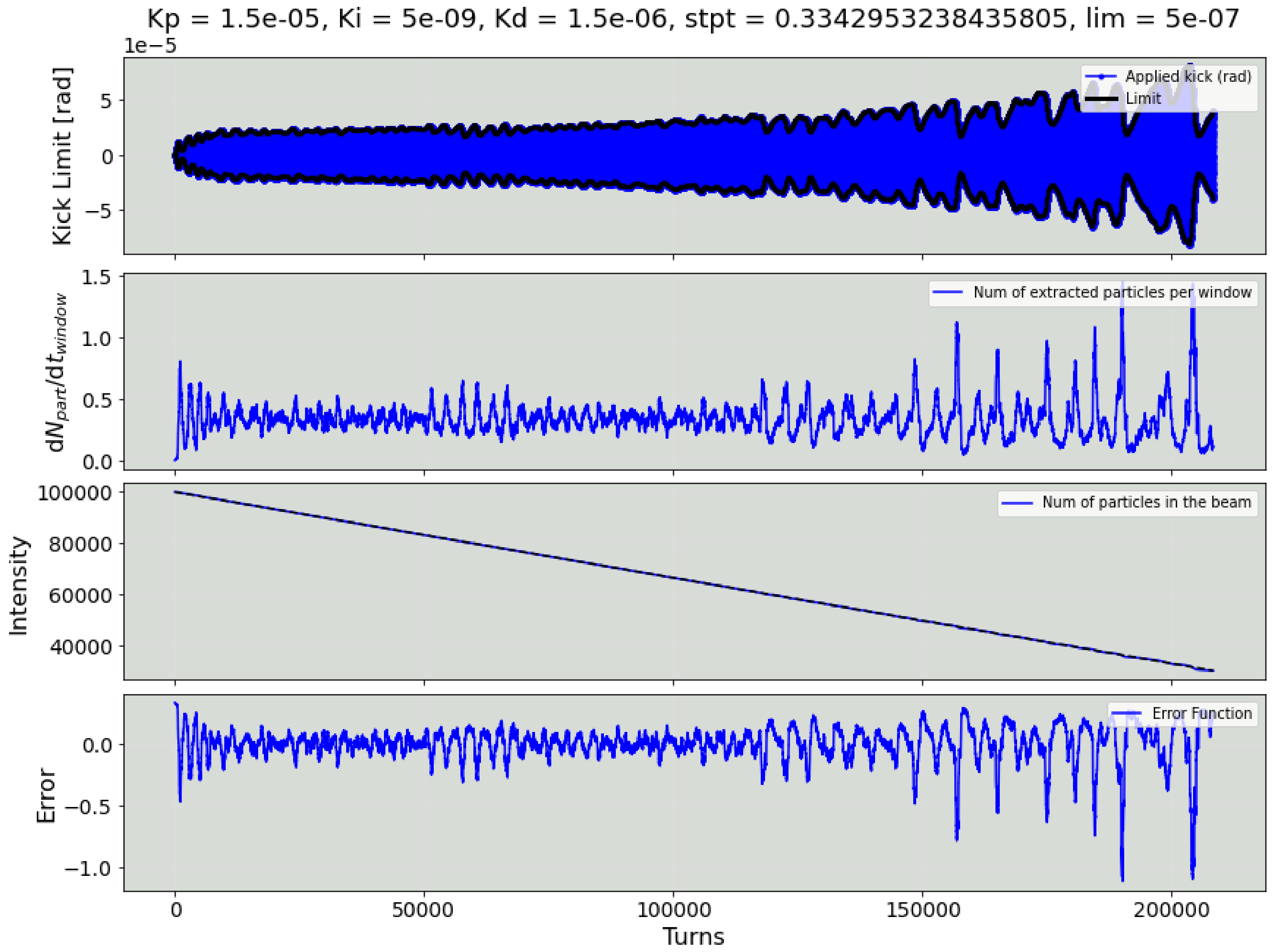
Initial beam:



XSuite: 1E5 particles for 3E5 turns

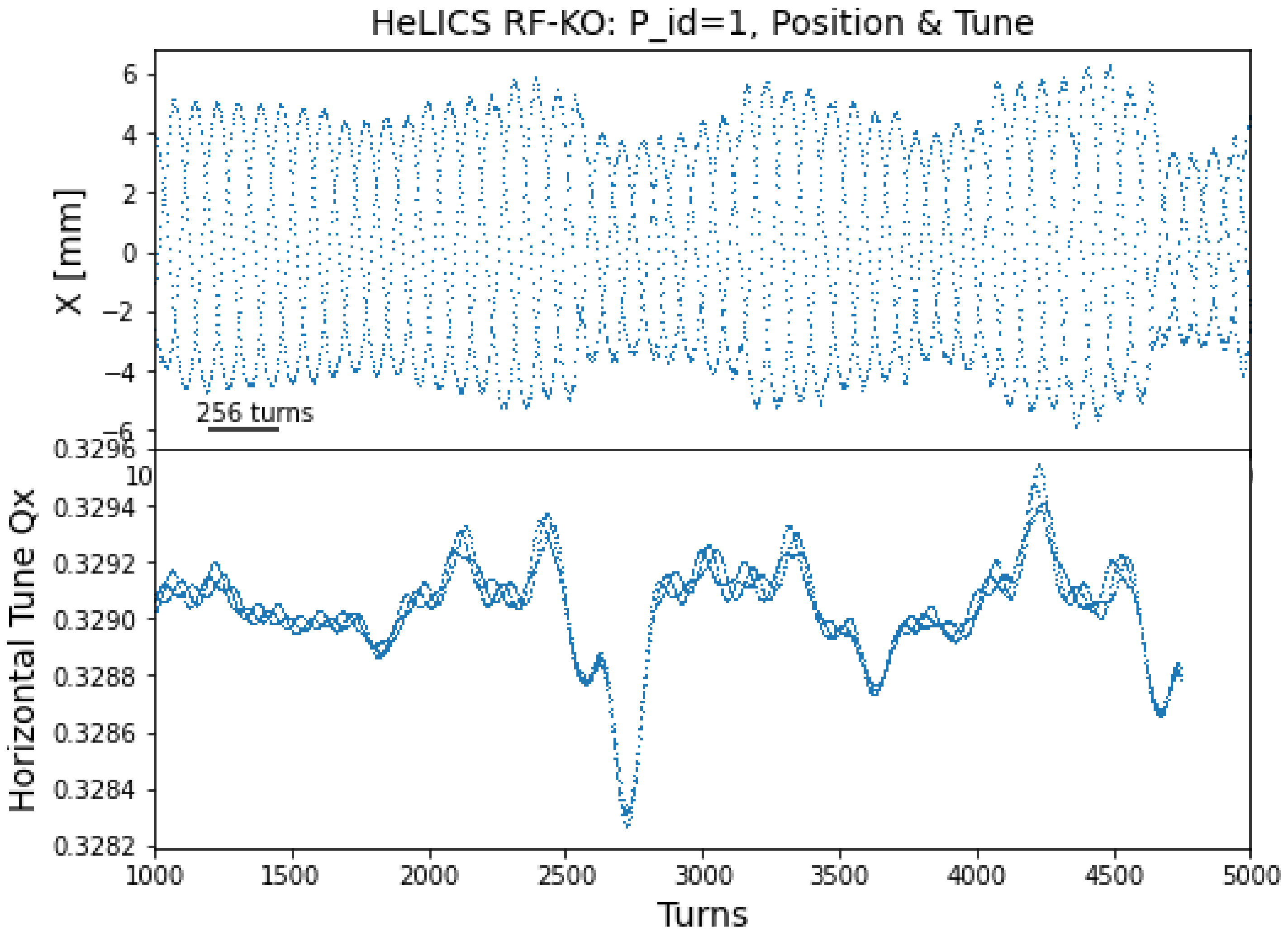
- Linear chirp across beam tune.
- Ripples from high Ki and low Kd settings.
- Integration with Xsuite allows for easy connection with PID optimisation algorithms.

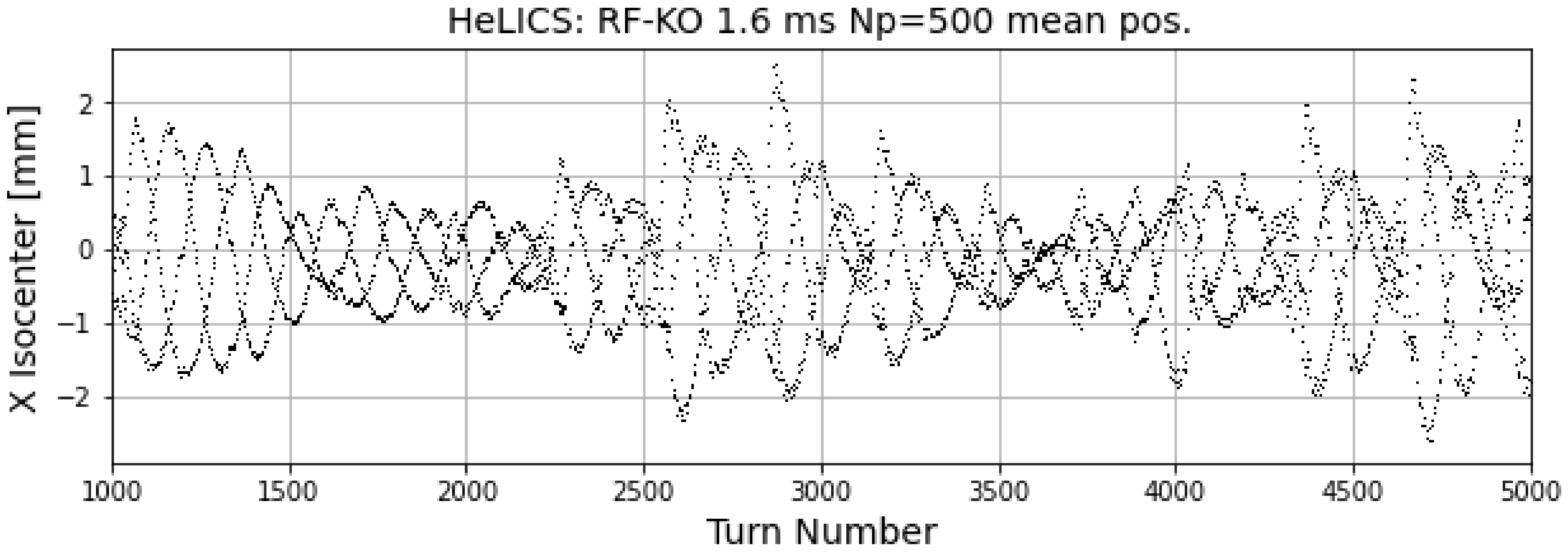


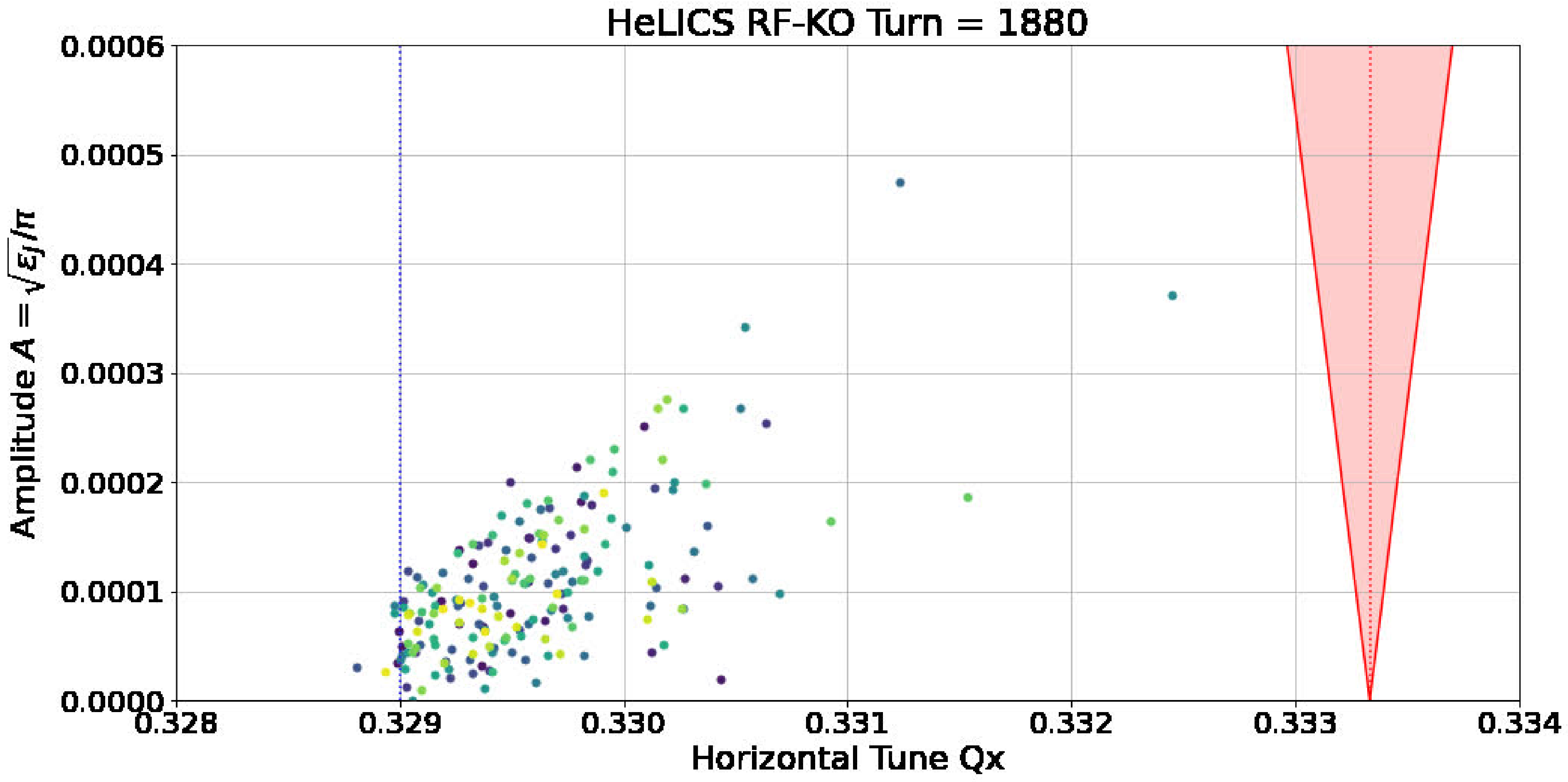


HeLICS: RF-KO

256 turn NAFF window scrolling every 1 turn





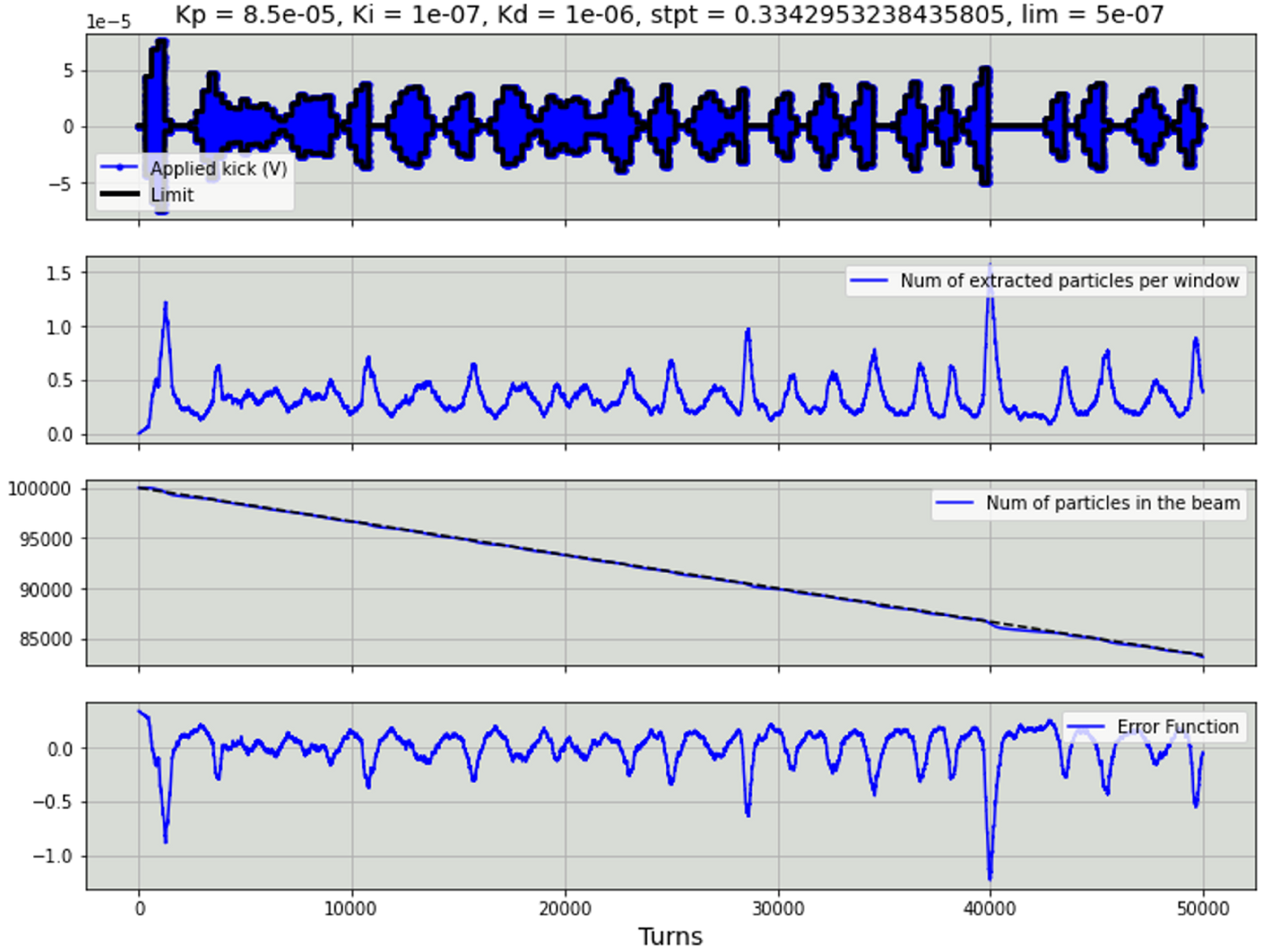


256 turn NAFF window scrolling every 10 turns

HeLICS: Burst RF-KO

Preliminary

- Use of a controller to vary voltage burst applied to RF-KO.
- Follows the set-point, so still extracts the same amount of dose in the same time, but varies intensity on a shot to shot scale.
- Time between pulses limited only by time resolution of exciter.



SX R&D Overview

	MA	CNAO	HIT	HIMAC	PS	SPS	GSI	J-PARC	NIMMS
Quad-Driven	[12]				[13]	[6]	[14]	[15]	✓
Betatron Core	[16]	[17]							
RF-KO	[18]	[19]	[20]	[11]			[21]		✓
COSE	[12]				[22]	[23]			
Quad + RF-KO					[24]			[25]	
Noise++			[26]	✓			✓		✓
Empty-Bucket	[27]	[28]			[29]	[30]			
Burst Extraction	[31]				[32]				✓
MEE	[33]	✓	[34]	[35]					✓
Octupole Folding					[Ch.7]	[36]			
Crystal Channelling						[37]			
Helium	[38]	✓	[39]	✓					✓
FLASH	[40]		[41]	✓					✓

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Summary

NIMMS facilities need **flexible extraction methods** to provide the beams needed to answer unsolved radiobiological questions.

Baseline slow extraction design to provide **FLASH-like** intensities and timescales. These parameters are categorised.

First extraction schematic of HeLICS applied.

Exploring extraction methods <100 ms from the new HeLICS lattice.

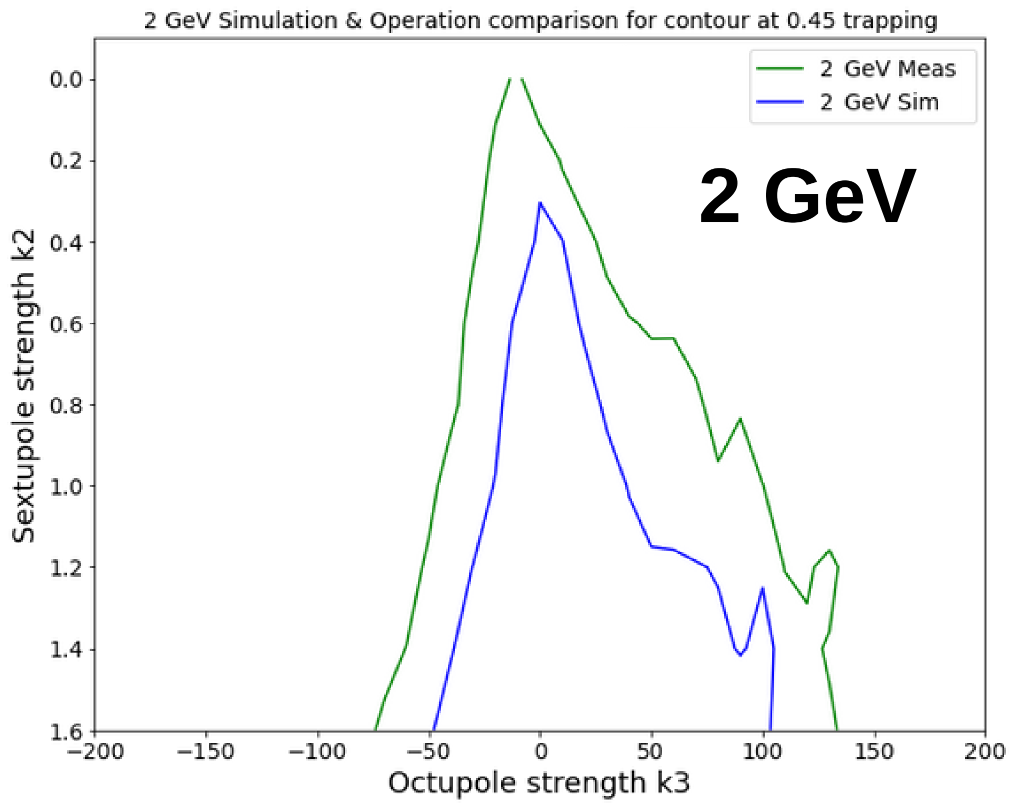
PhD concluding March 2024

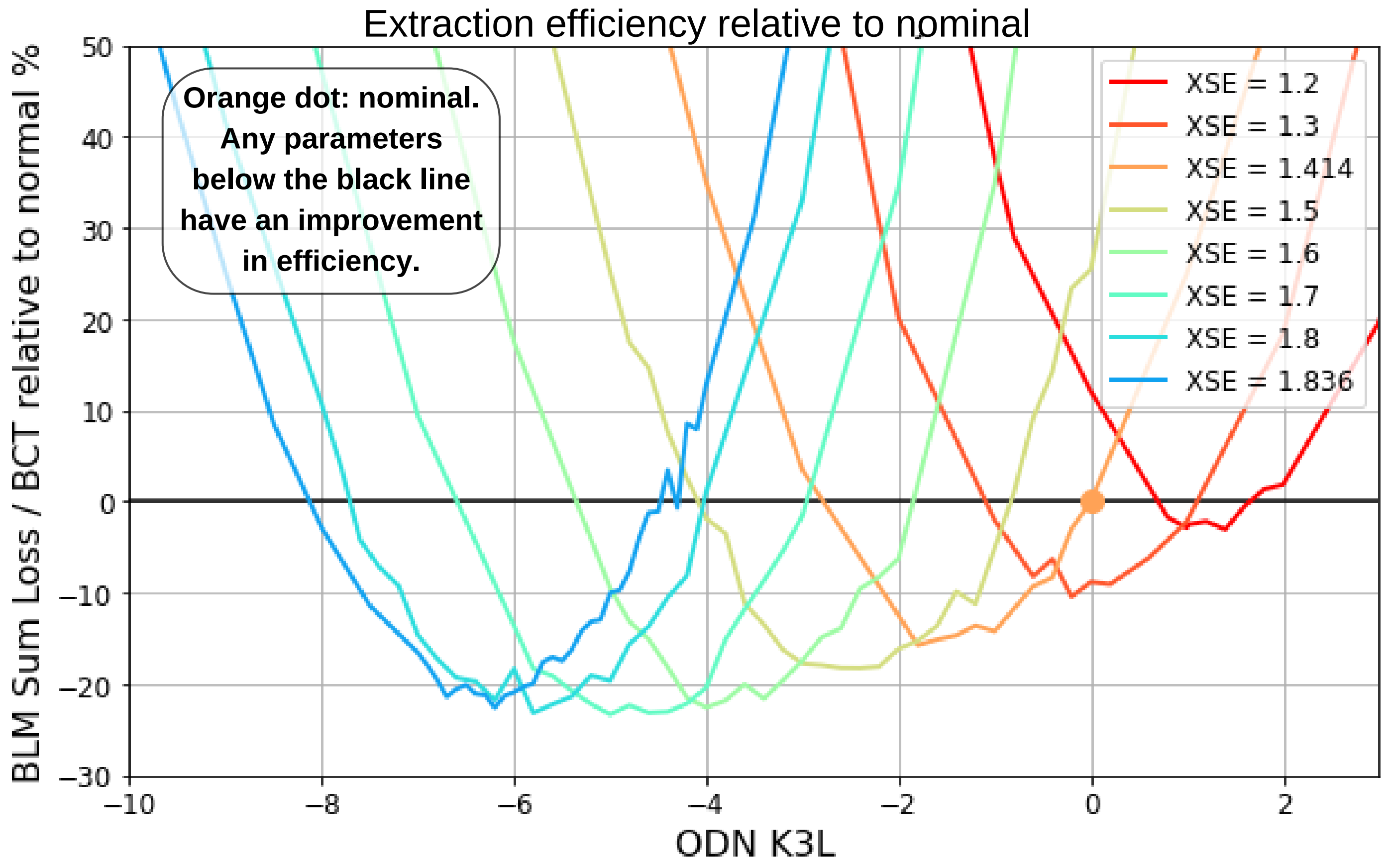
Next: Comparison with burst extraction (RF-KO or phase displacement). Downstream, dosimetry & integration.

Thank you, questions welcome

Background

- Want to **reduce losses** during **slow extraction** to the East Area
  - Targeting losses at electrostatic septum (SEH23) and magnetic septum (SMH57)
- ***2021 MD*** established PS octupole model using trapping
- ***2022 MD*** found good setting for beam loss reduction
  - East23 cycle introduced a lot of changes.
    - Using ***2023 MD*** to explore relations between parameters

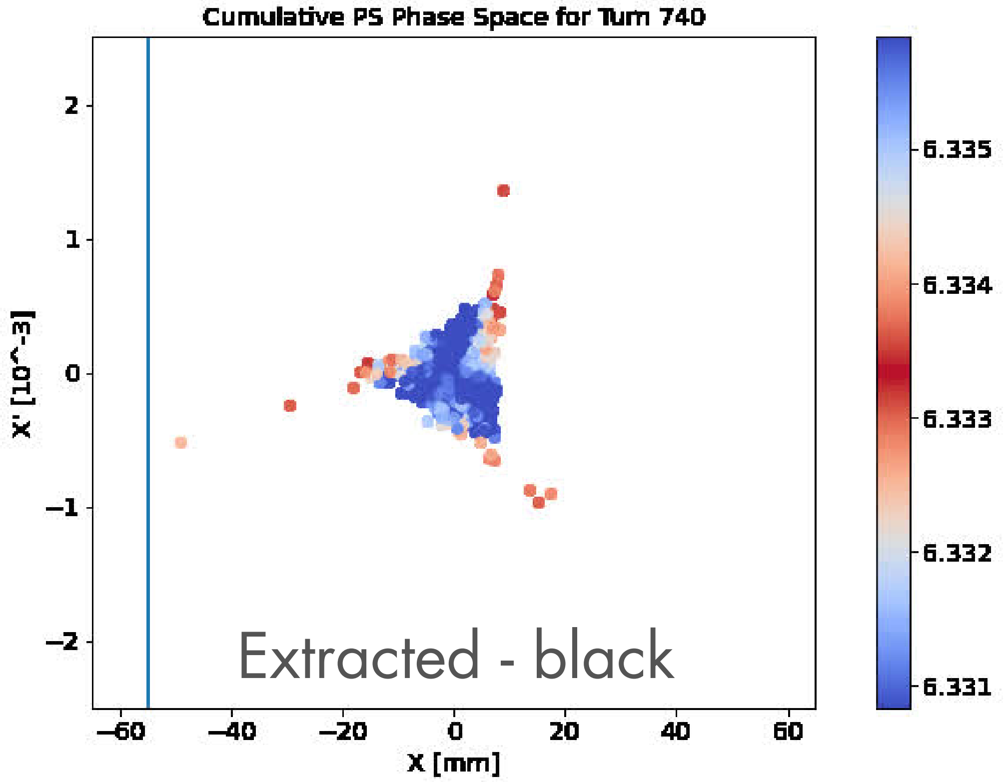




PS
CERN Proton Synchrotron

Applied strong octupole components to the PS during extraction. Aiming to measure the formation of islands:

- Changed k2 and k3 in machine.
  - Measured extraction ratio.
- Good comparison with simulations.
  - Difference due to PFW k3 modelling.
- Future applications with crystal channelling.



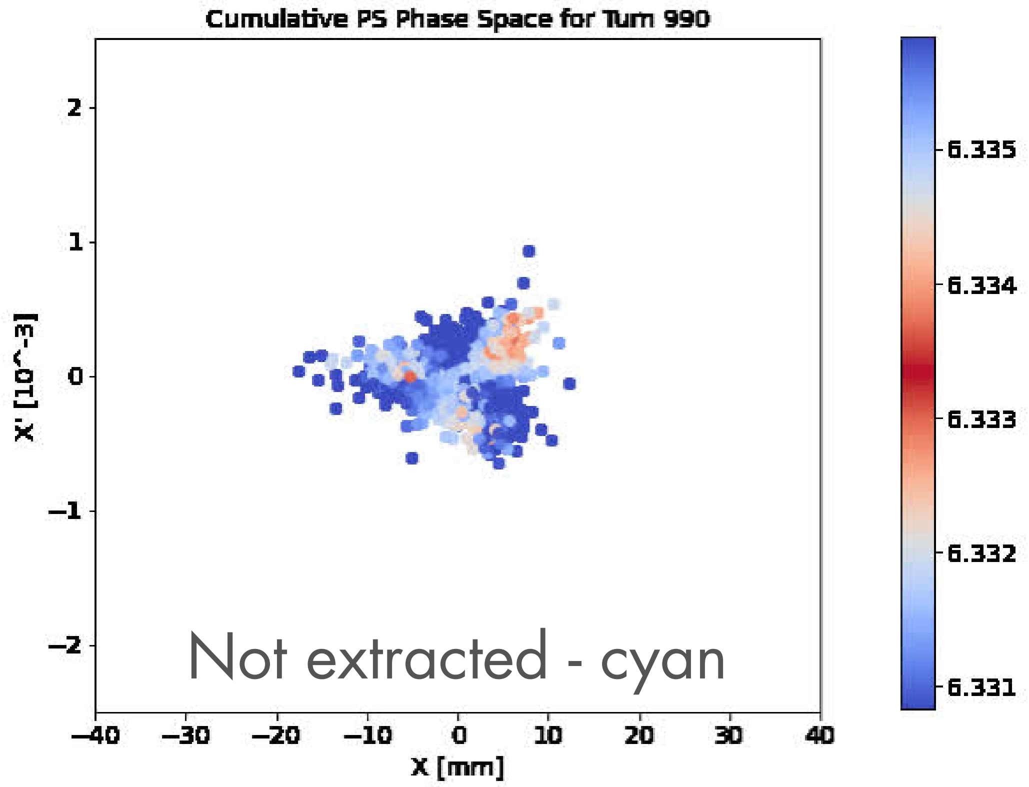
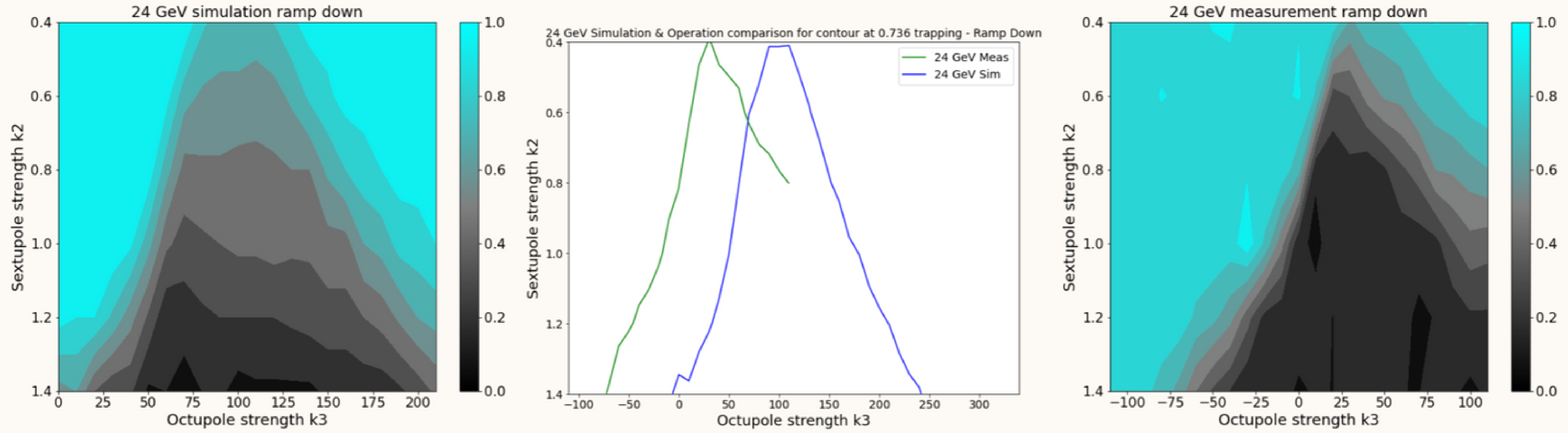
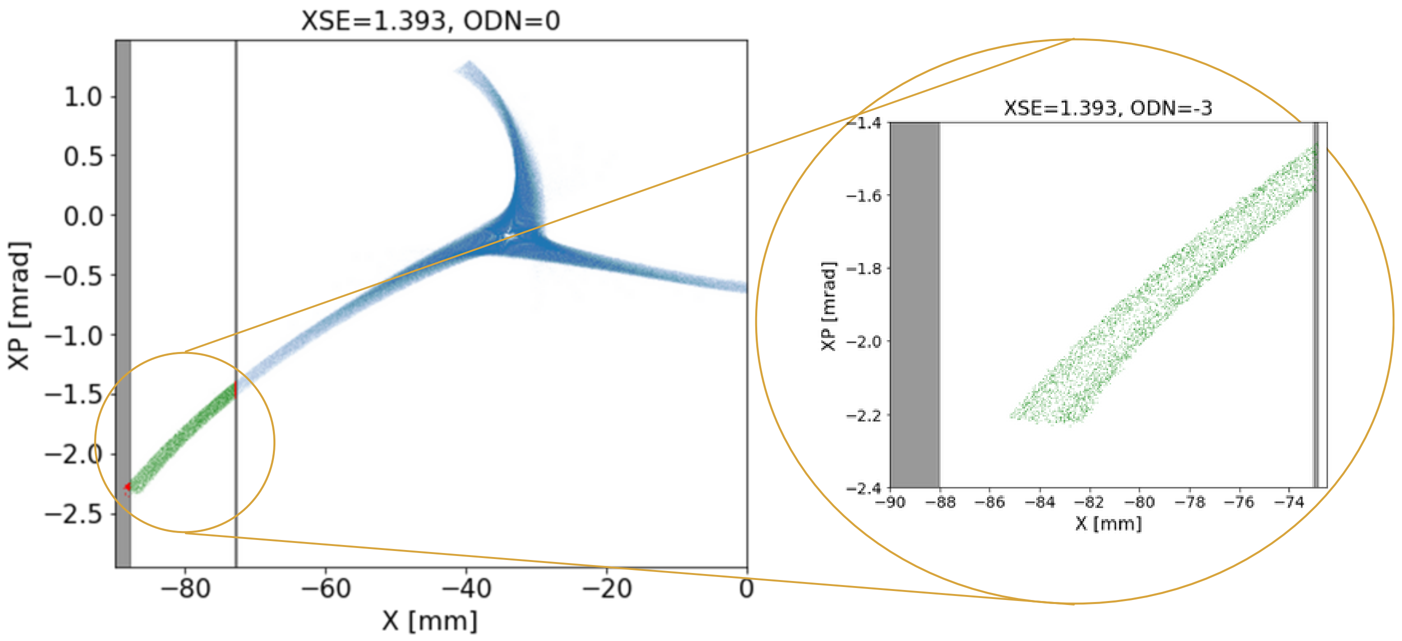


Figure 7.4.: 24 GeV Simulation and Measurement comparisons



PS
CERN Proton Synchrotron

Repeated procedure, now using octupoles to **fold separatrix**.



Reducing **losses** on the extraction **septa**:

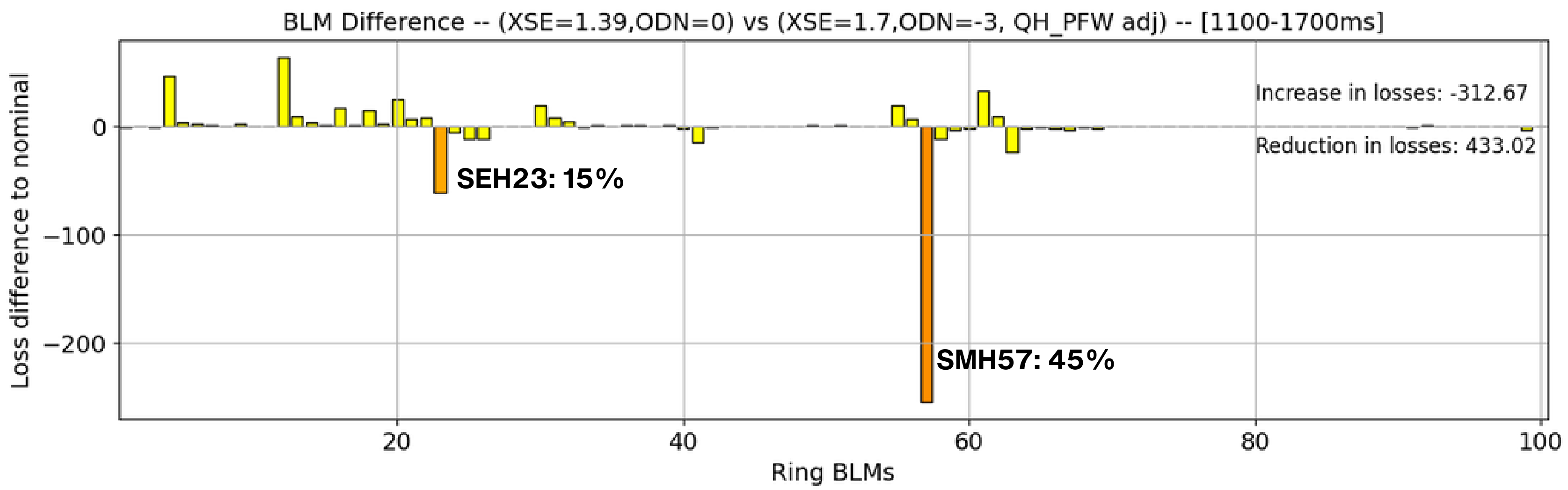
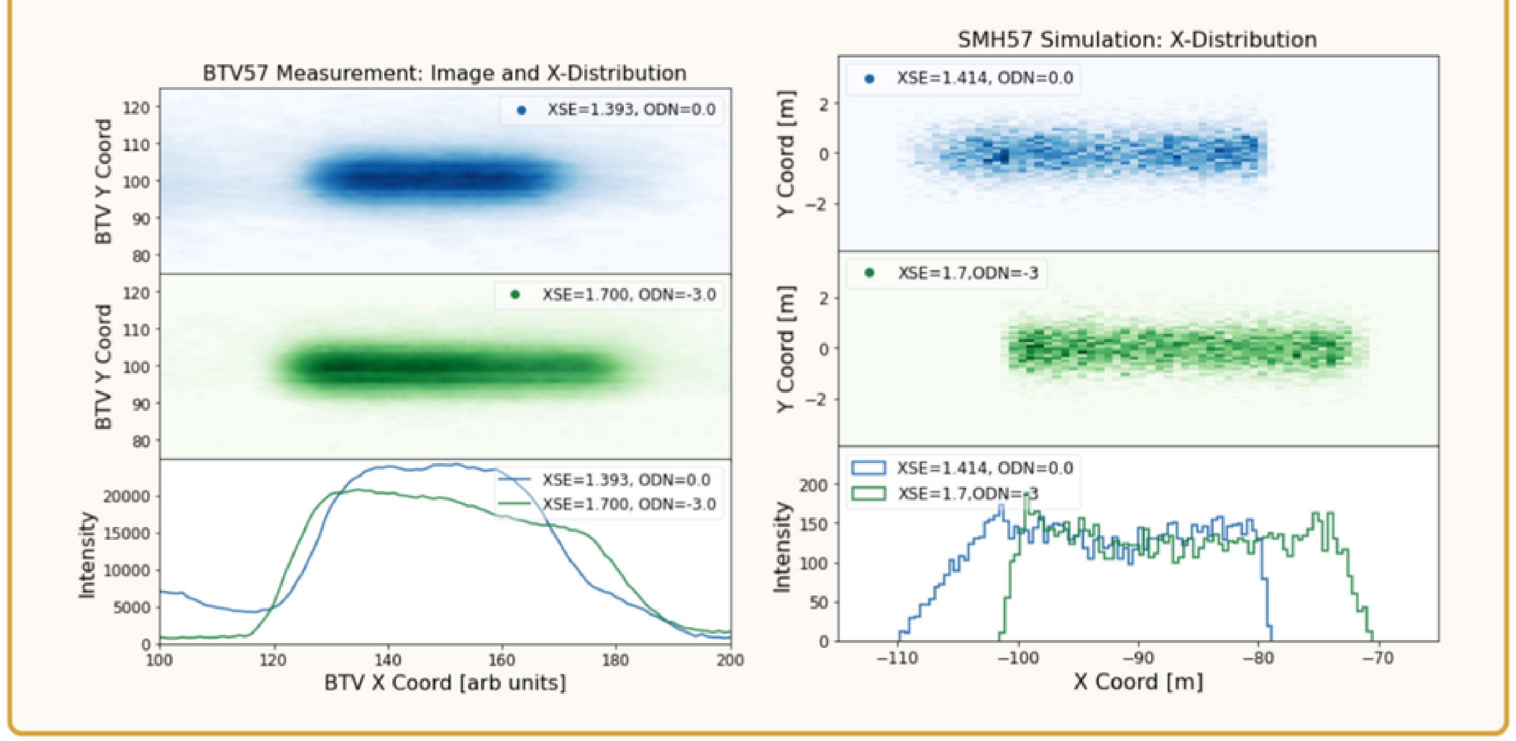
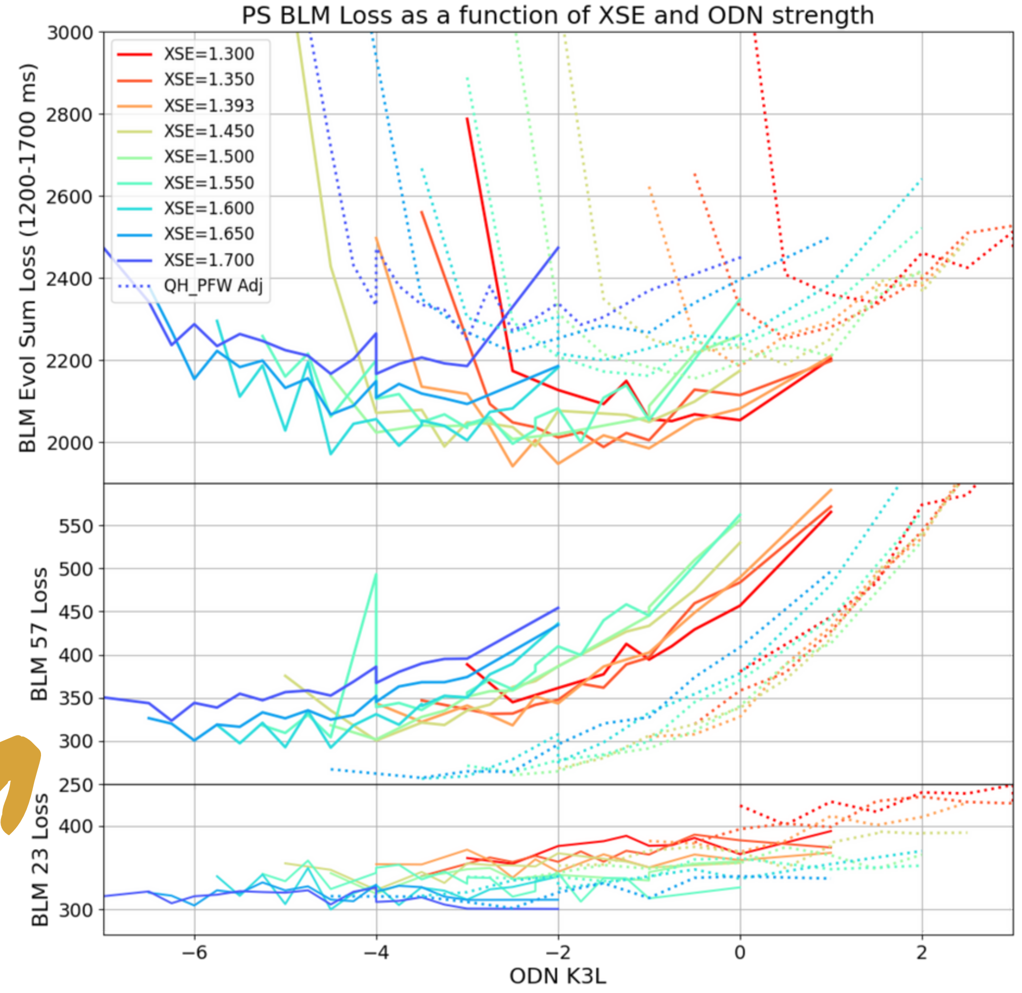


Figure 7.13.: Measurement & Simulation Comparison of BTV57 with and without ODN



- Changes distribution of extracted beam.
- Requires downstream steering via algorithm.
- Turn reduced losses into improved extraction efficiency.

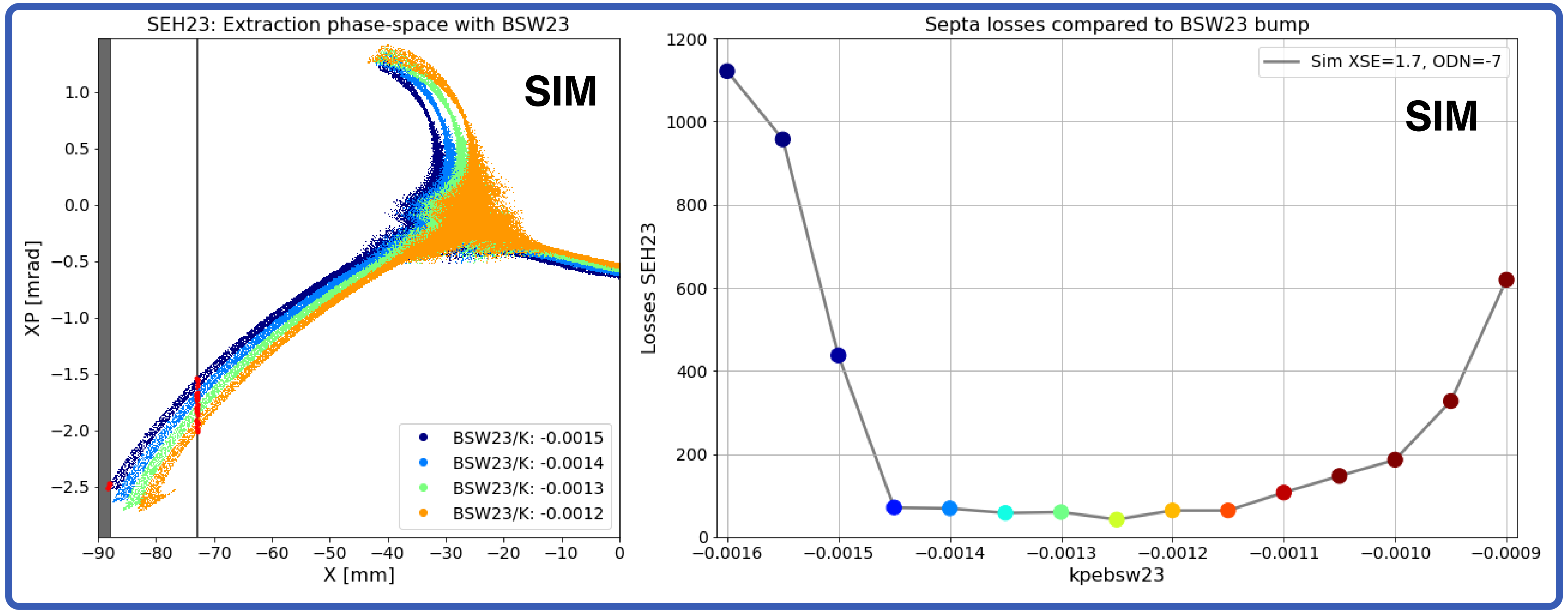


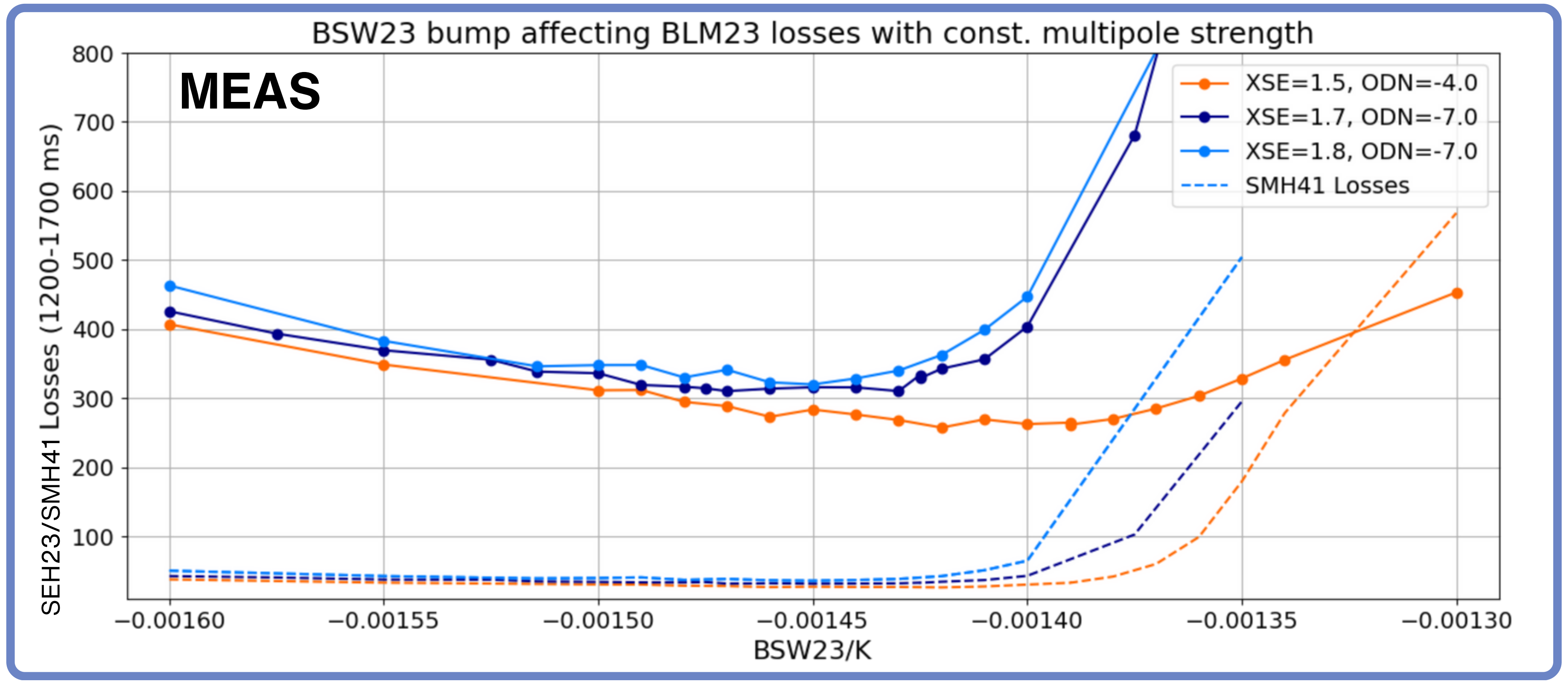
4

Consider BSW bump effects

Extraction bump further from septum will:

- Increase spiral step.
- Increase space for curvature.





Weaker bump gives low BLM23, but increases BLM41.

- YASP/DZH for correction affects BLM23 again.