Most material for this presentation is taken from:
https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.28.021002

ESRF | The European Synchrotron

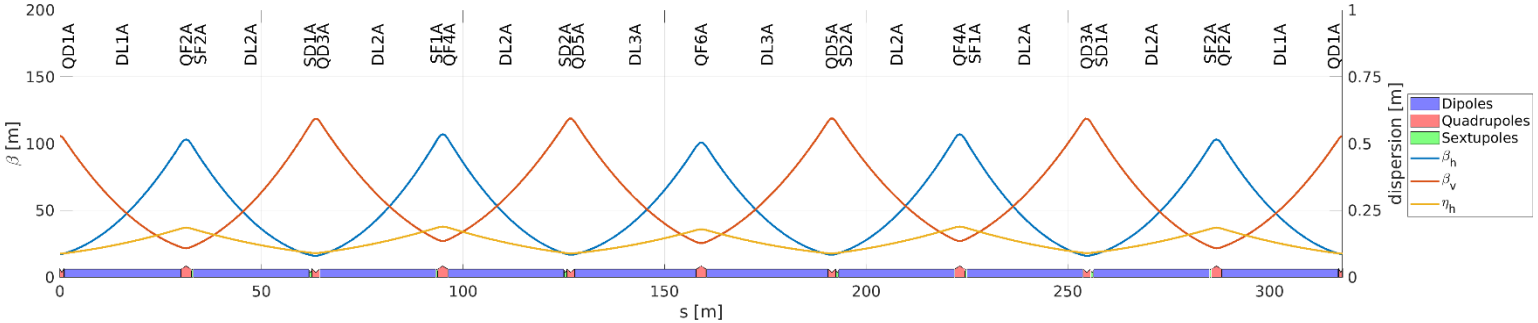
FCC-ee
Local Chromaticity Correction (LCC) optics
Status and plans

K.André, P.Raimondi, S.Liuzzo, S.White

Many thanks to the the members of *FCC-ee design, tuning, integration* groups for the constructive and valuable help.

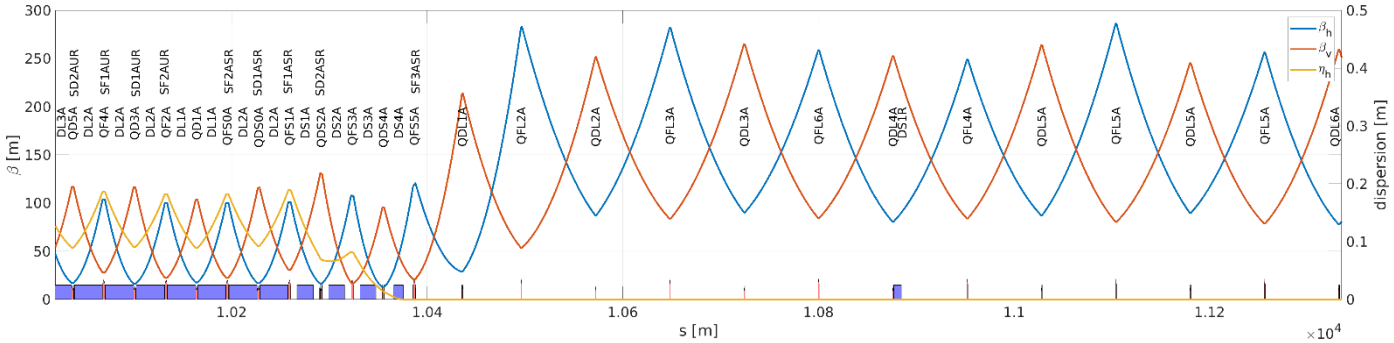
LCC OPTICS

Hybrid Focussing Defocussing (HFD) arcs

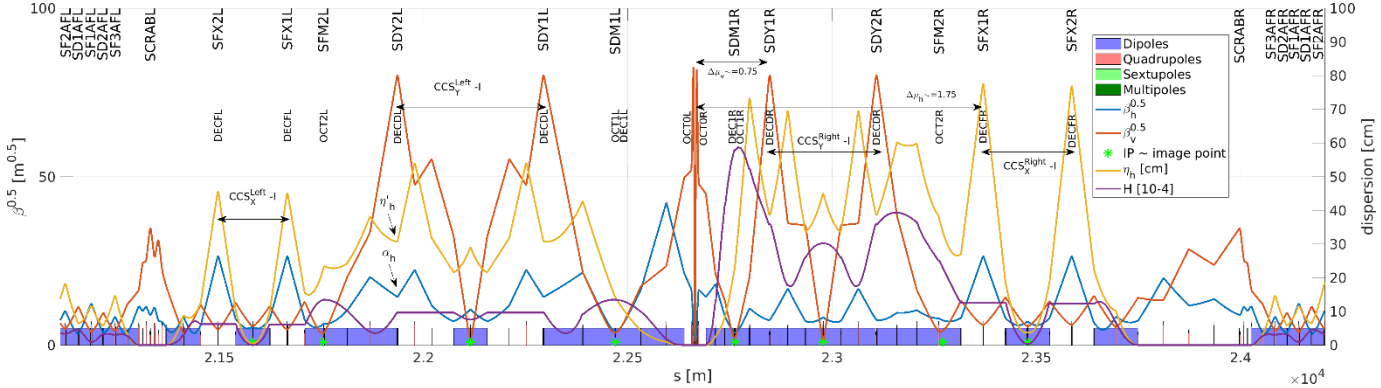


Long straight sections (LSS) fulfilling the *Transparency Conditions.*

https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.26.021601



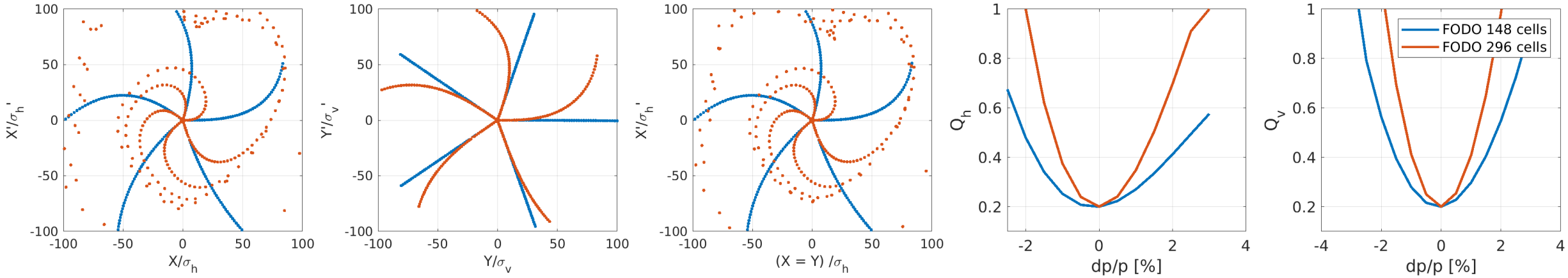
Final Focus optics fulfilling the *Transparency Conditions* and integrating all IP requirements



ACHROMATICITY AND ANHARMONICITY IN A FODO LATTICE

A lattice is considered **anharmonic** when transverse dynamics scale linearly with respect to x and y actions.

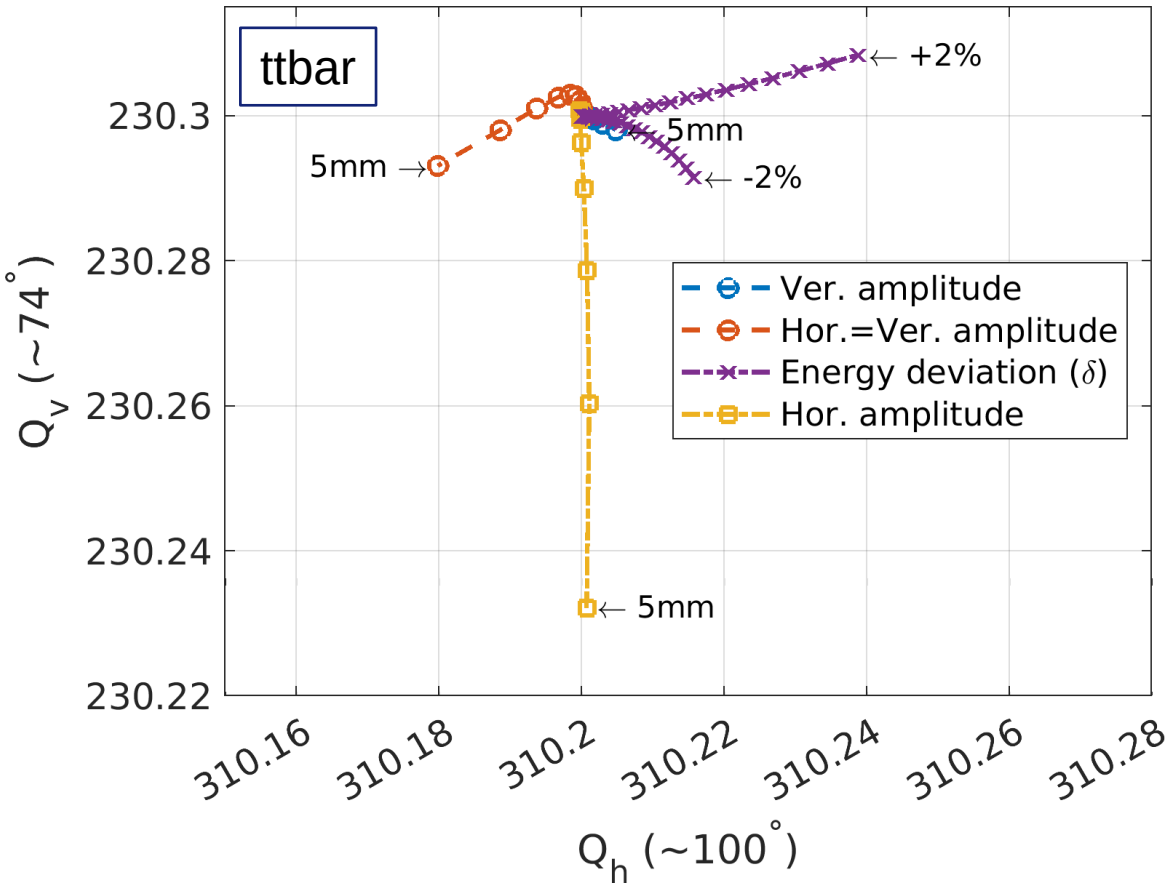
A lattice is considered **achromatic** if the variation of the main optics parameters, such as the tunes ($Q_{h,v}$) and the optics (β, α) at the interaction point (IP), has a small dependency on the variation of energy, ideally above 2% at Z and 3% at ttbar energy



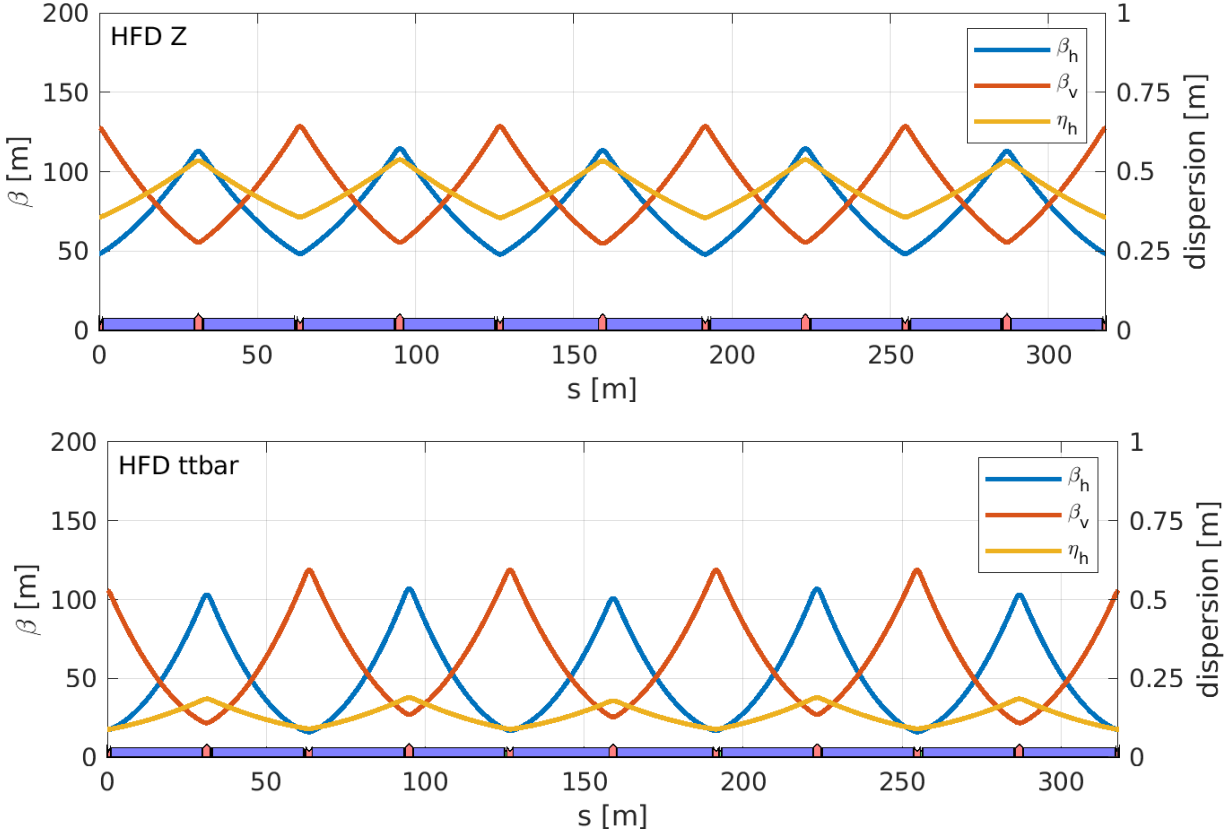
At large amplitude, the nonlinear contributions transform the initial coordinates distributed on a straight line into a curve with nonzero second and higher order polynomial components. The more a lattice is anharmonic, the more the coordinates at each of the five turns will be close to straight lines.

HYBRID FOCUSING DEFOCUSING (HFD) ARC CELLS

Very small tune footprint



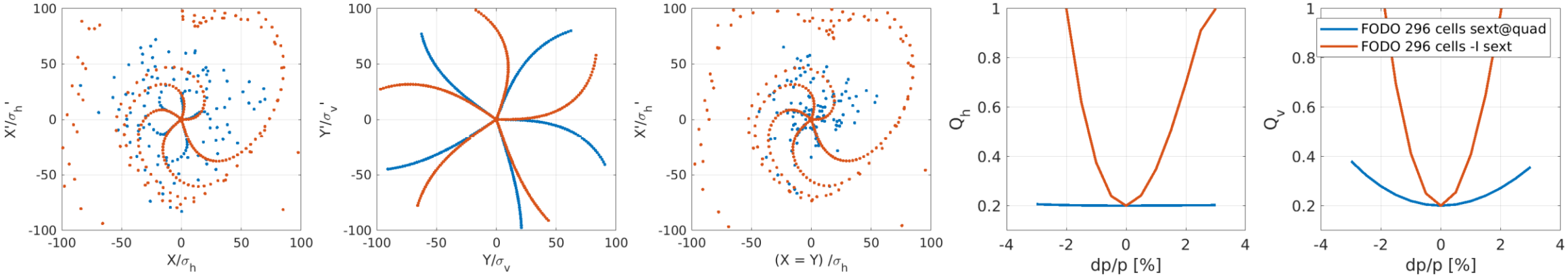
Same magnets layout at both energies



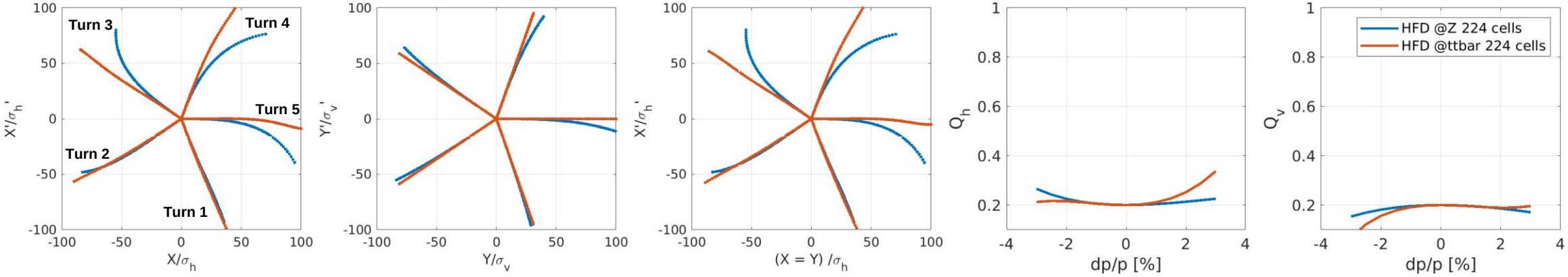
6 quadrupole families instead of 2 in a FODO cell
3 sextupole families instead of 2 in a FODO cell

ACHROMATICTY AND ANHARMONICTY IN THE ARCS OF THE LCC OPTICS

In a FODO arc cell, sextupoles with –I transformation help for anharmonicty, but worsen the achromaticty



In a HFD arc cell, anharmonicty and achromaticty are optimal at both energies and are unaffected by the long straight section insertions following the *transparency conditions* principles.

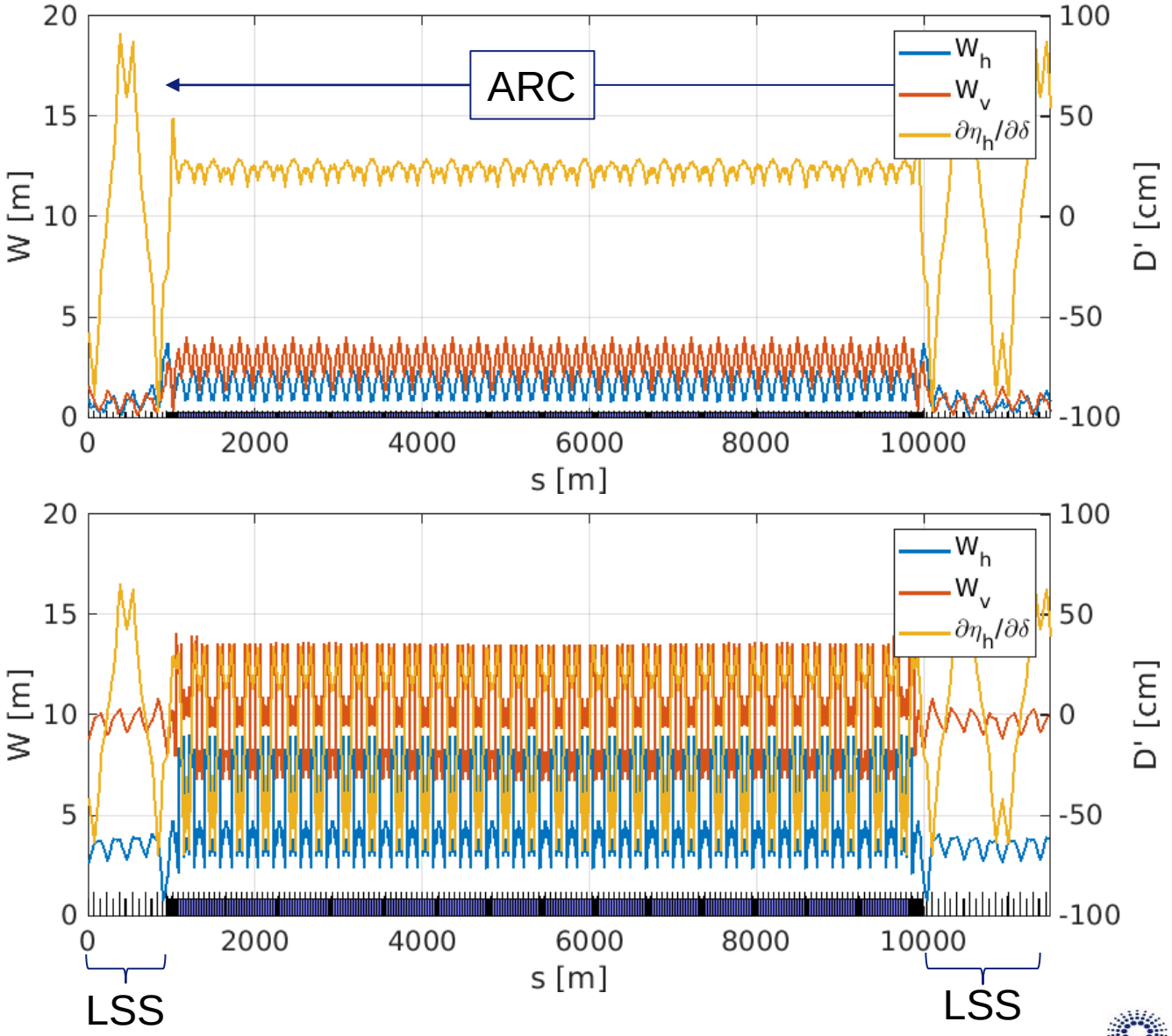


LONG STRAIGHT SECTIONS AND TRANSPARENCY CONDITIONS

Sextupole ON

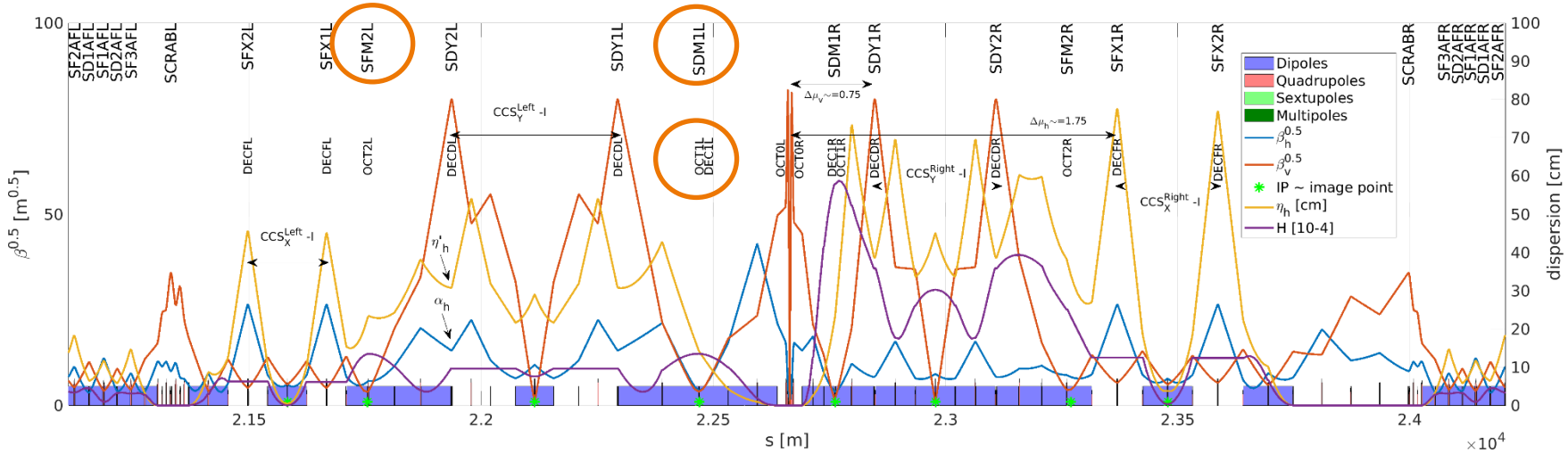
Transparency conditions are fulfilled when including the Long Straight Section (LSS), The off-energy optics (W and second order dispersion) remains periodic with sextupoles turned on/off.

Sextupole OFF

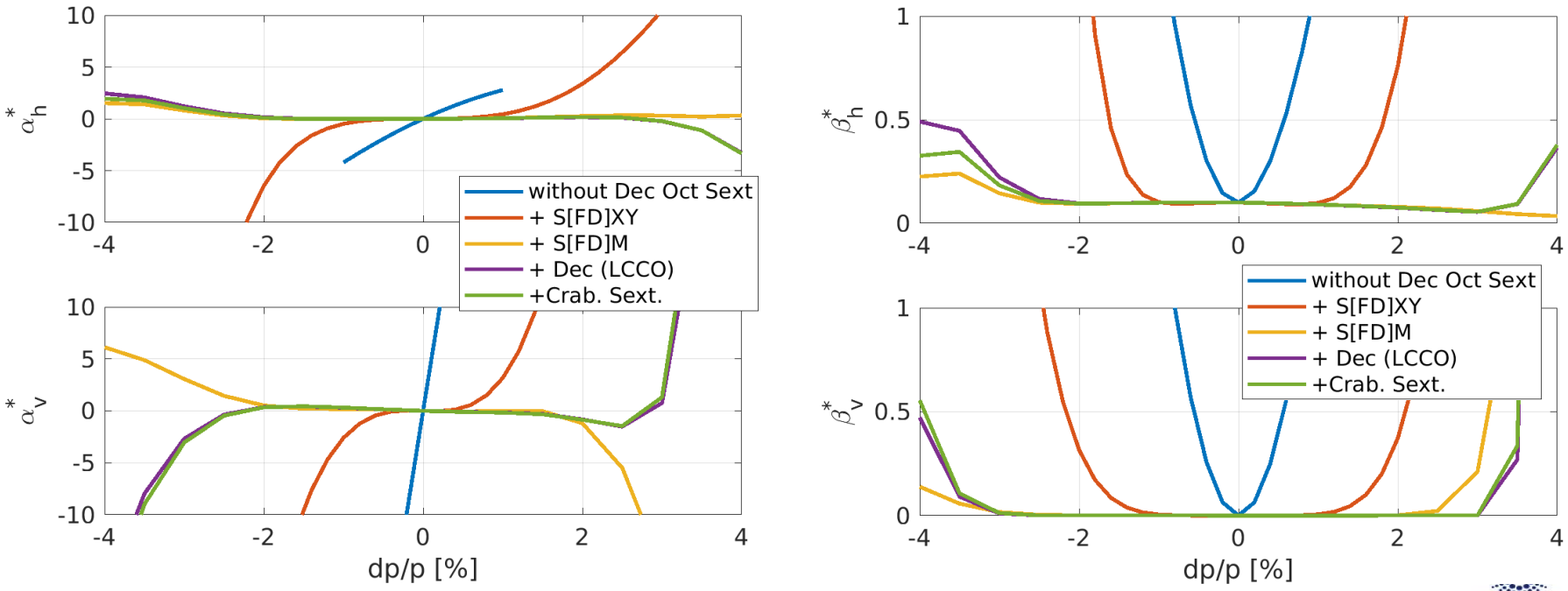


FINAL FOCUS

Sextupoles, octupoles and decapoles at **IP image point** correct third, fourth and fifth order chromaticity at the IP and optimize off-energy optics at the crab sextupoles.

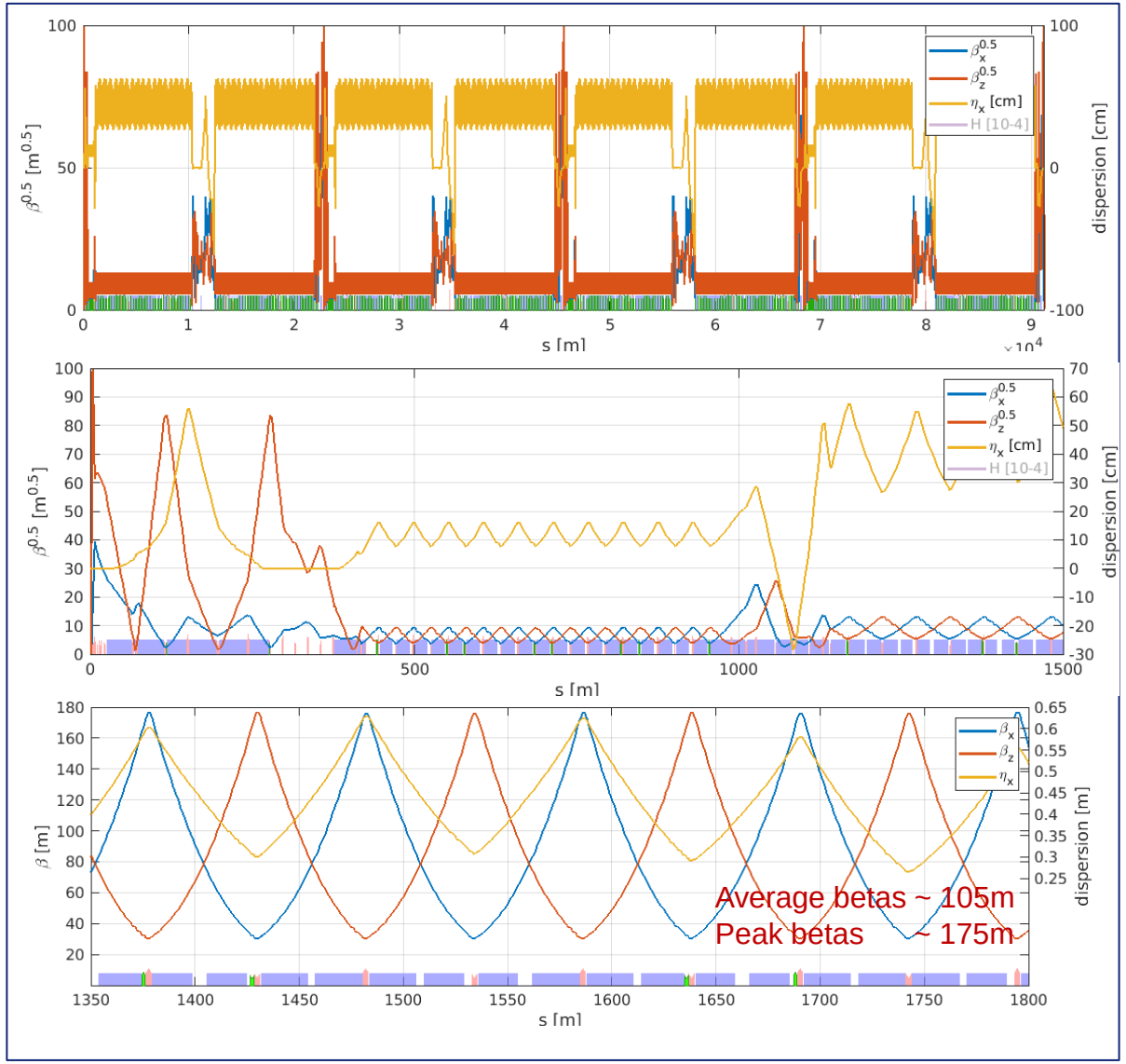


The long sextupole aberrations is mitigated by de-tuning the –I transformation in the chromaticity correction sections (linear optics)

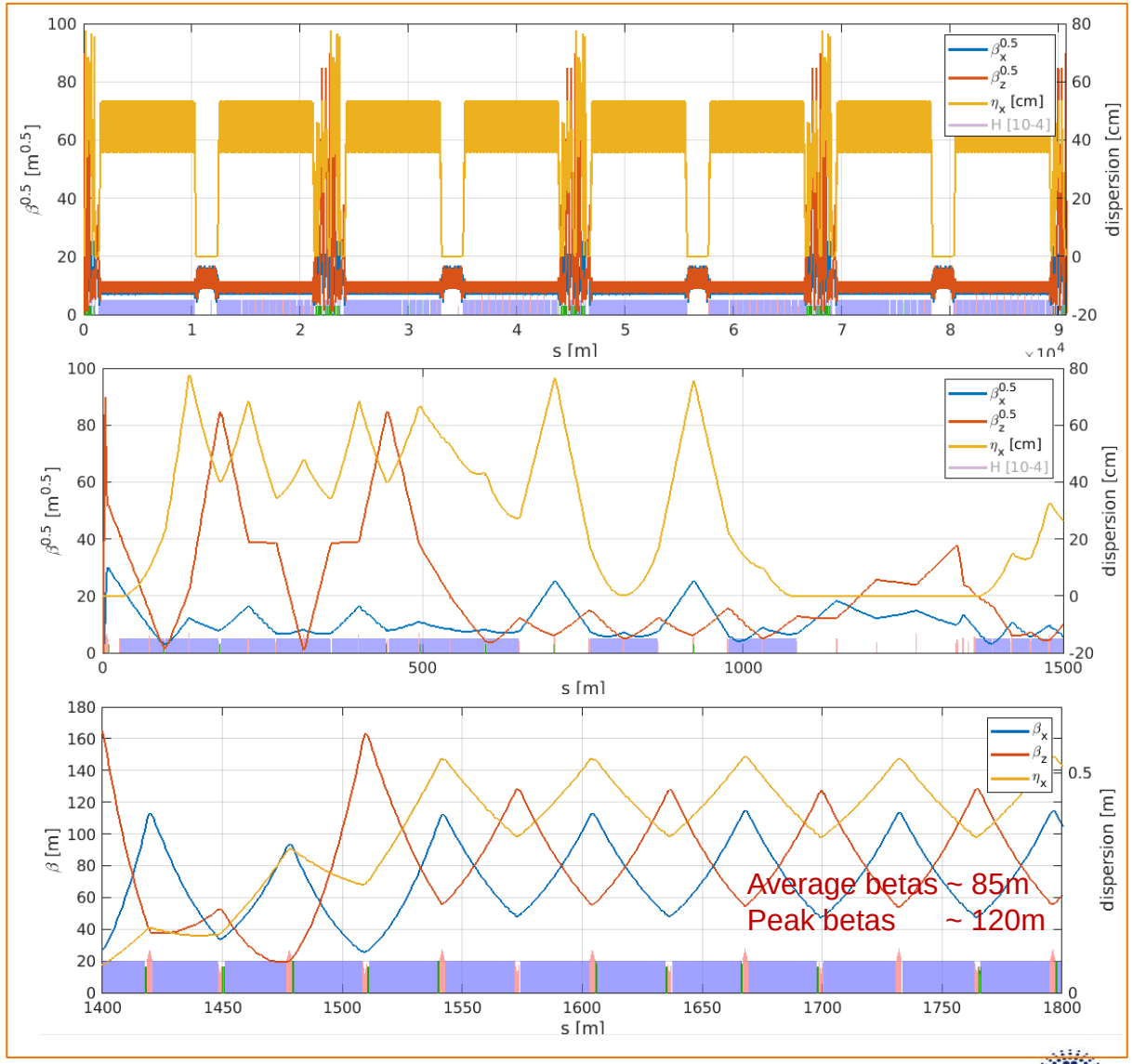


OPTICS FOR FCC-EE: LATTICE LAYOUT FOR ARCS AND FINAL FOCUS

GHC-V22 (K.Oide, https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.19.111005)

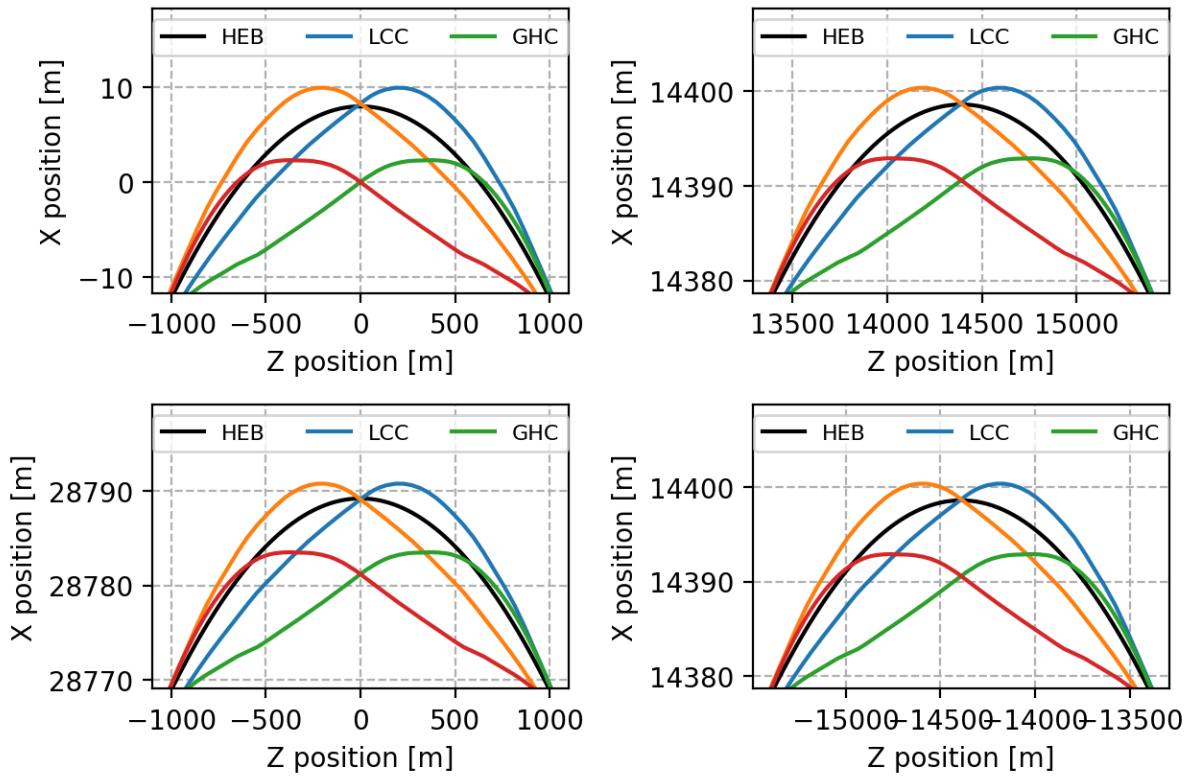


LCC-89 (P.Raimondi, https://indico.cern.ch/event/1326738/timetable/#45-alternative-optics-and-vari)

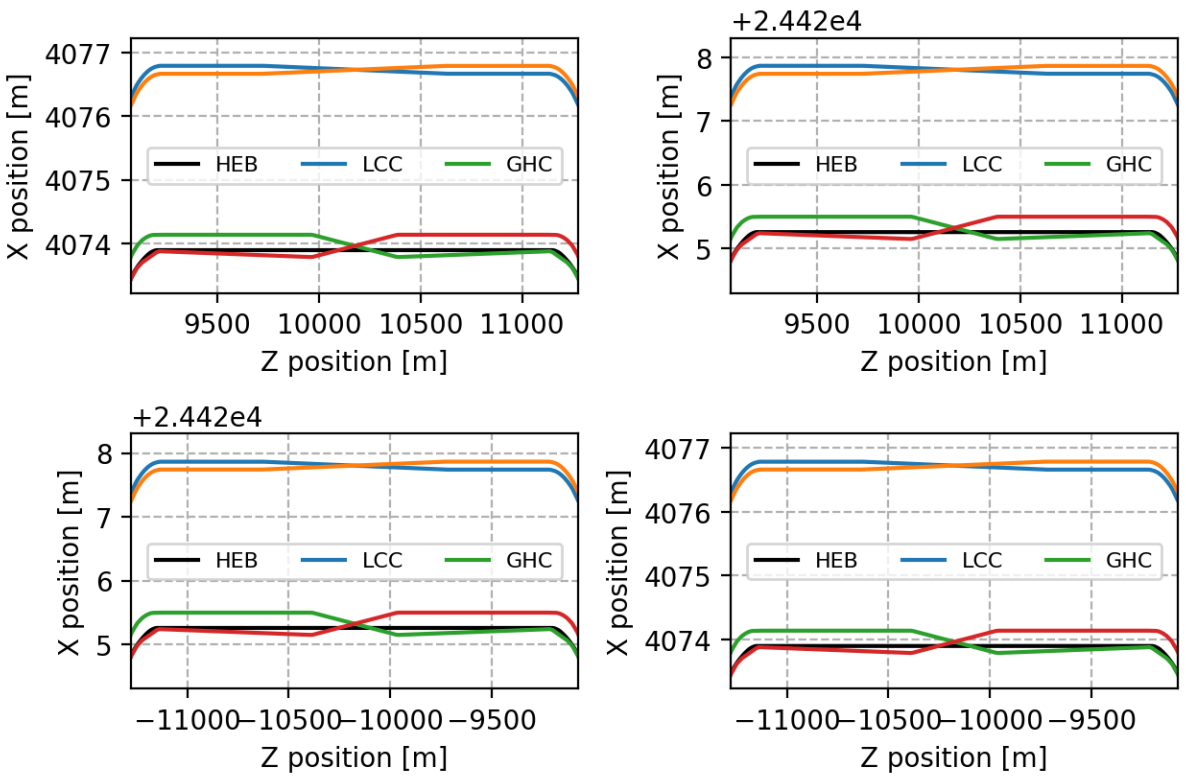


FOOTPRINTS

Overlap of experimental insertions between GHC, LCC and booster
IP_A is at (x,z)=(0,0)



Overlay of technical insertions between GHC, LCC and booster
IP_A is at (x,z)=(0,0)



About 7m offset w.r.t. GHC footprint at each interaction points and 3m in the technical straight sections.

BEAM PARAMETERS

Outdated

	units	V22@Z 45.6 GeV	LCC-89@Z 45.6 GeV
circumference	m	9.1174e+04	9.0659e+04
momentum compaction		2.8448e-05	2.8968e-05
tunes		214.26 214.38	198.20 174.30
chromaticity		-0.0183, -0.0782	-0.2942 1.0593
damping time	seconds	0.7102 0.7117 0.3549	0.8037 0.8037 0.4018
energy spread		3.9182e-04	**3.7148e-04**
bunch length	mm	3.2	**3.0**
hor. nat. emittance	pm rad	706	**676**
energy loss / turn	MeV/turn	39.0	**34.3** (lower power)
RF voltage	MeV	200	200
harmonic number		135000	135000

Python Accelerator Toolbox tracking: 6D = including synchrotron radiation and RF

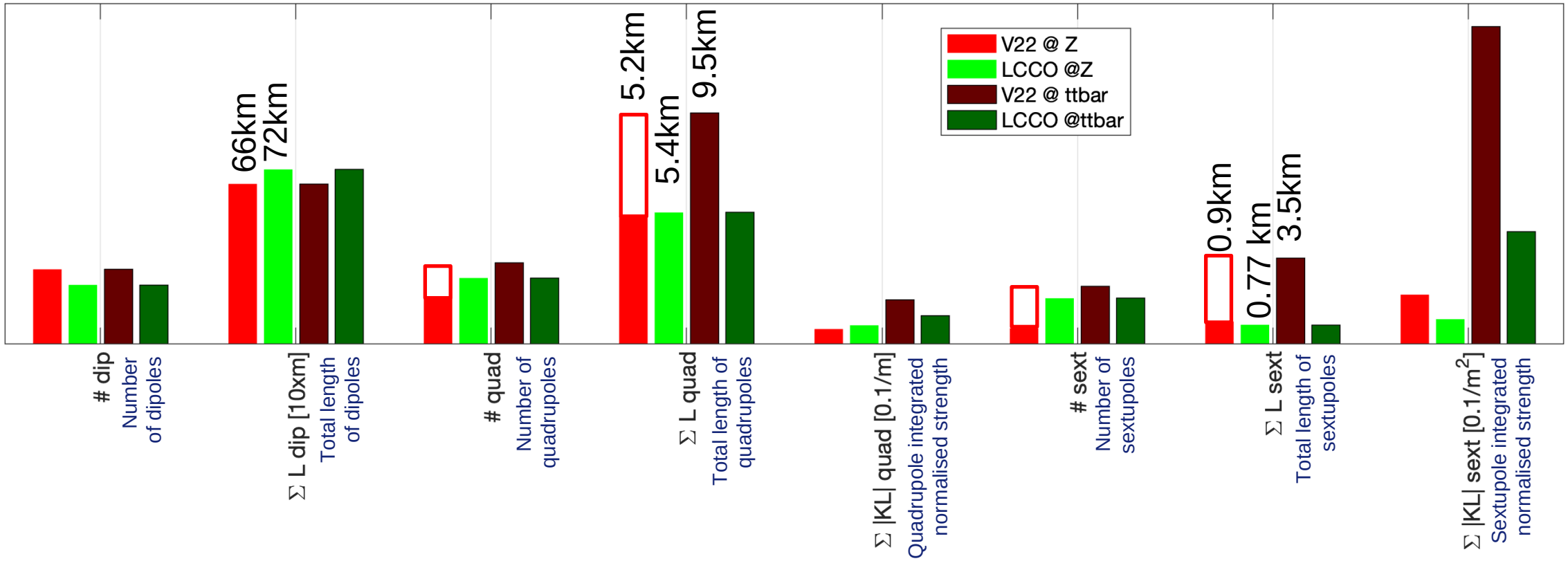
Quantum diffusion is not included in the following studies (although available).

https://github.com/atcollab/at

Fully benchmarked with MADX-PTC

COMPARISON OF THE NUMBER OF MAGNETIC ELEMENTS AND GRADIENTS

includes Crab sextupoles

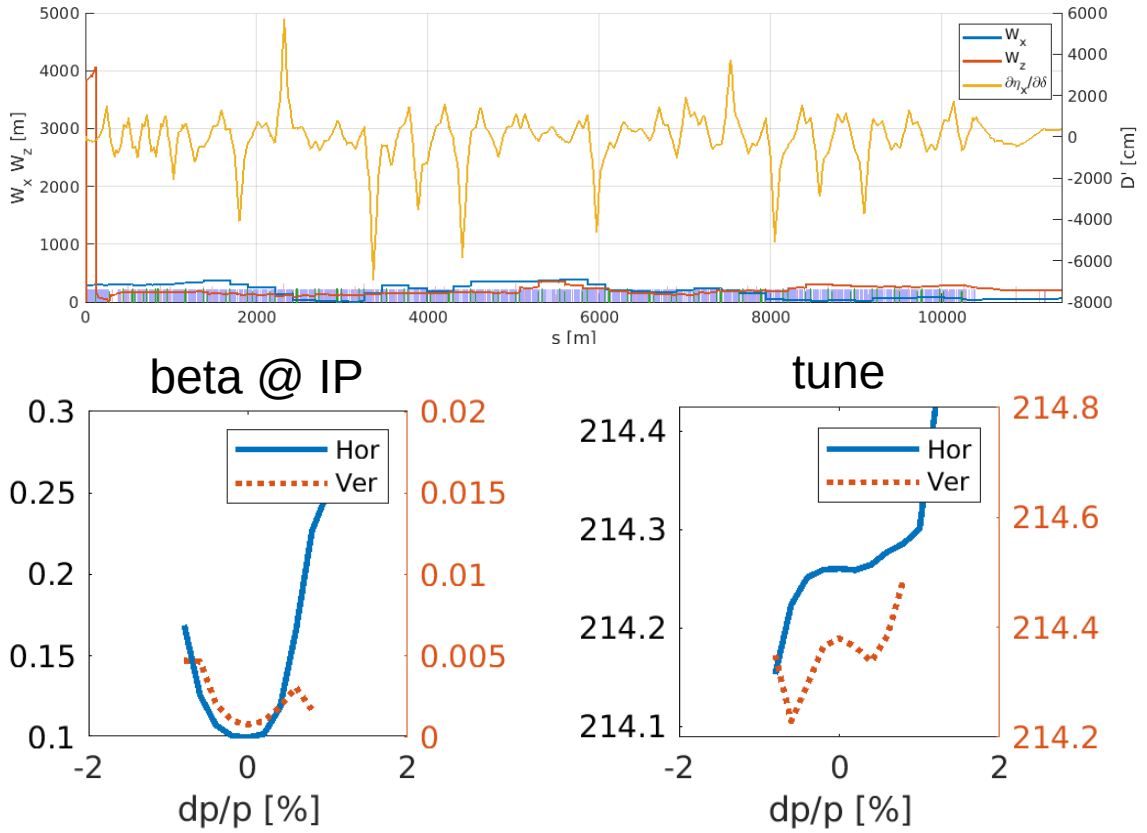


- Only the magnet gradients change in LCC between Z and ttbar.
- The white boxes for V22 baseline correspond to magnets turned off at Z, which are turned on at ttbar.
- LCC's sextupoles at <u>ttbar</u> have**: 1) smaller KL, 2) there are ~500 less and 3) they are shorter.**

machfs/liuzzo/FCC/89a2/ANALYSIS/CompareSextupole.m

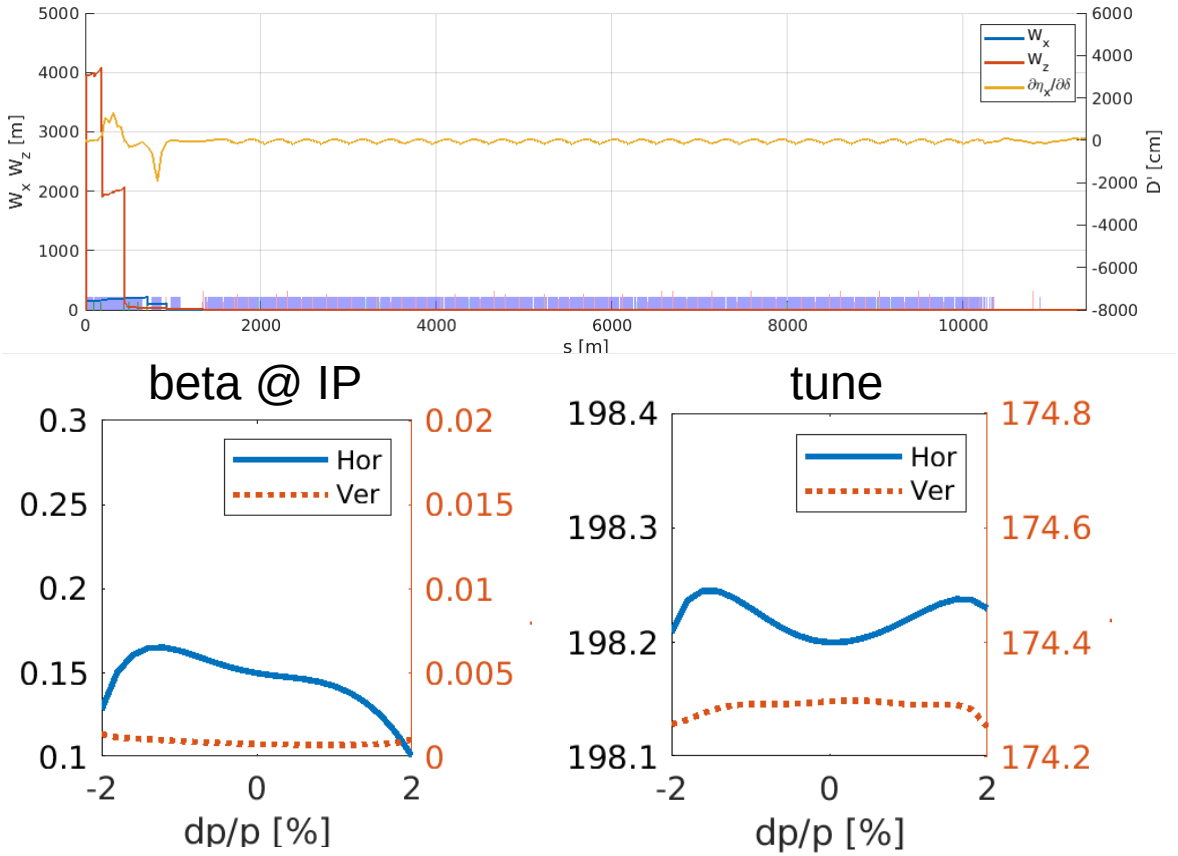
OFF ENERGY ELECTRON BEAM OPTICS: W FUNCTIONS, IP OPTICS AND PHASE ADVANCE AT CRAB SEXT.

GHC-V22 (K.Oide, https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.19.111005)



Missing line = Optics computation failed

LCC-89 (P.Raimondi, https://indico.cern.ch/event/1326738/timetable/#45-alternative-optics-and-vari)

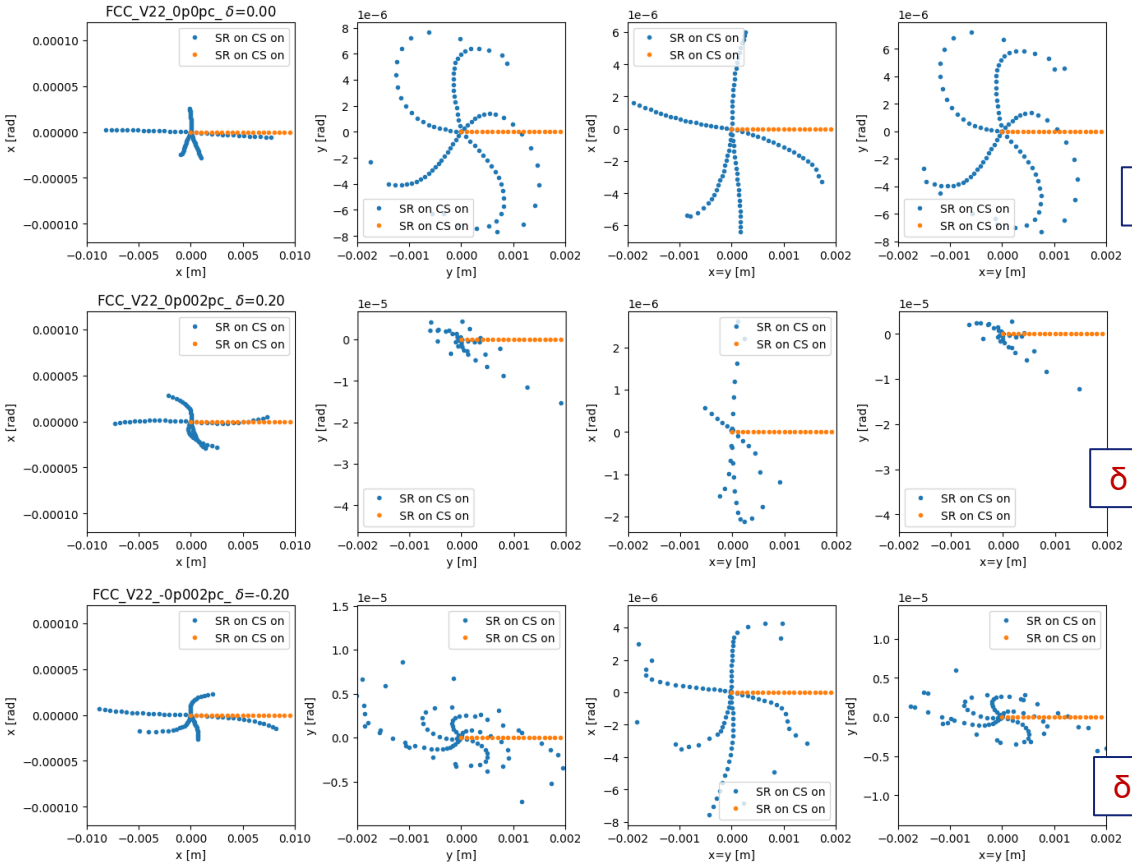


Negligible luminosity loss due to energy dependent beta

PHASE SPACE EVOLUTION OVER 5 TURNS ON AND OFF ENERGY

No SR in dipoles (no effect)

GHC

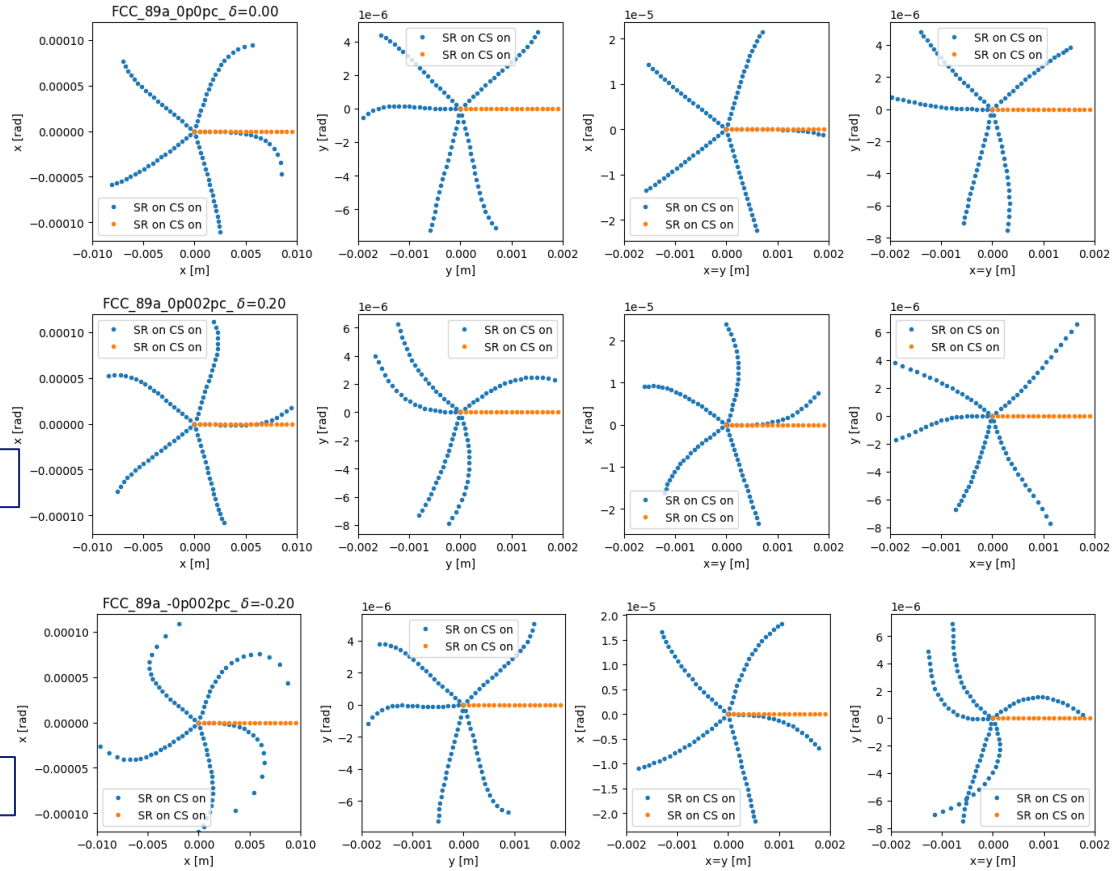


δ = 0

δ = +0.2%

δ = -0.2%

LCC



Synchrotron radiation and crab sextupoles **turned on**

The “starfish” plots provide a “quick” overview of the combined effects of all the resonant driving.

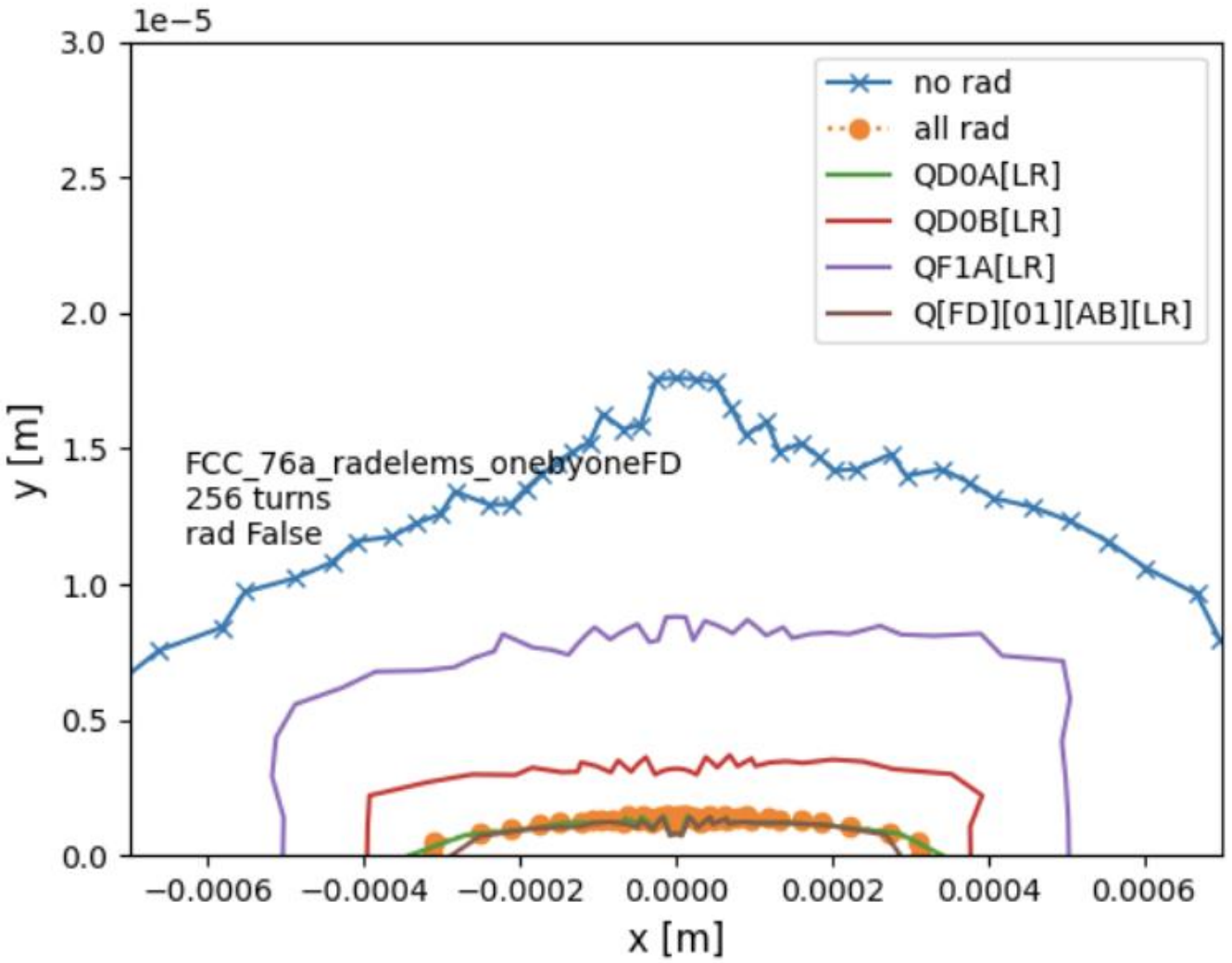
SYNCHROTRON RADIATION IN FINAL DOUBLET QUADRUPOLES

LCC76

Magnet	Dip	Qarc	Qff	Qfd	ALL
Q[FD][01][AB][LR]	YES				YES
QD0A[LR]		YES			YES
QD0B[LR]			YES		YES
QF1A[LR]				YES	YES

The dynamic aperture is dominated by synchrotron radiation in the final quadrupole doublet.

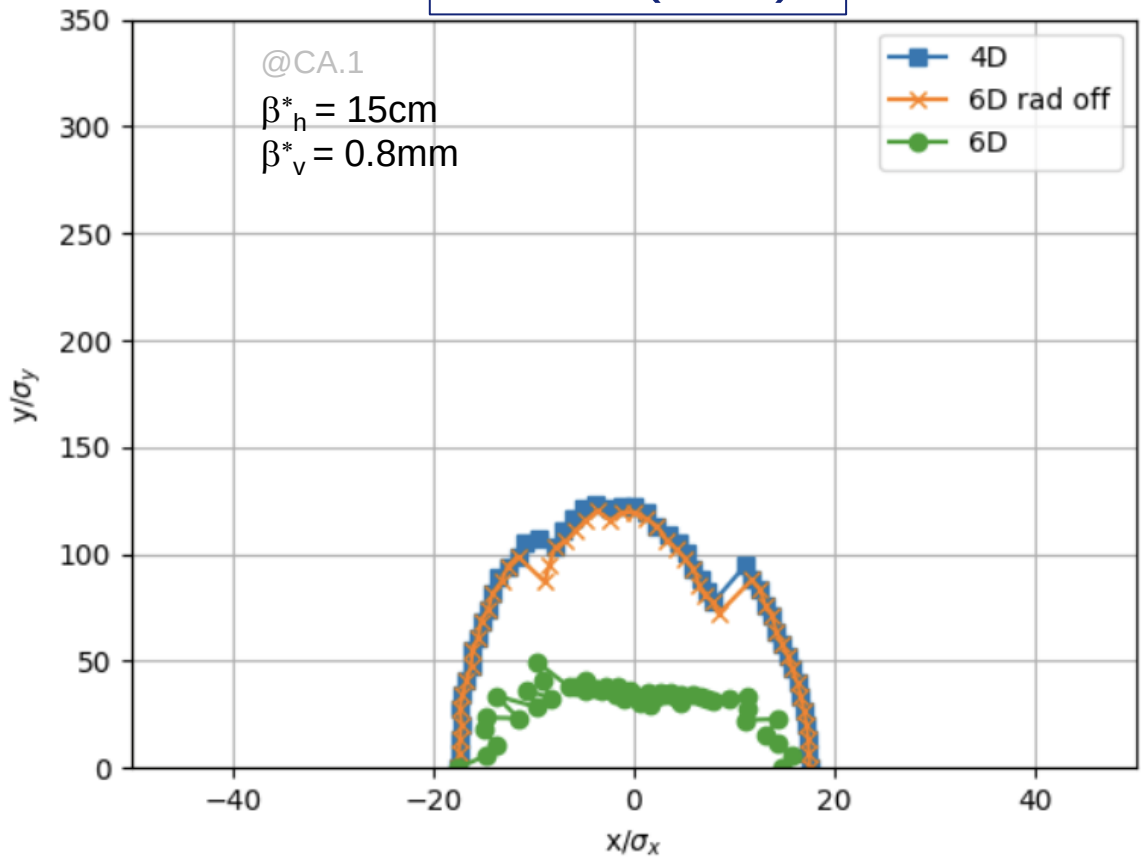
Subsequently, the gradient of the FD has been reoptimized to minimize the effect of SR. (~few percent gain).



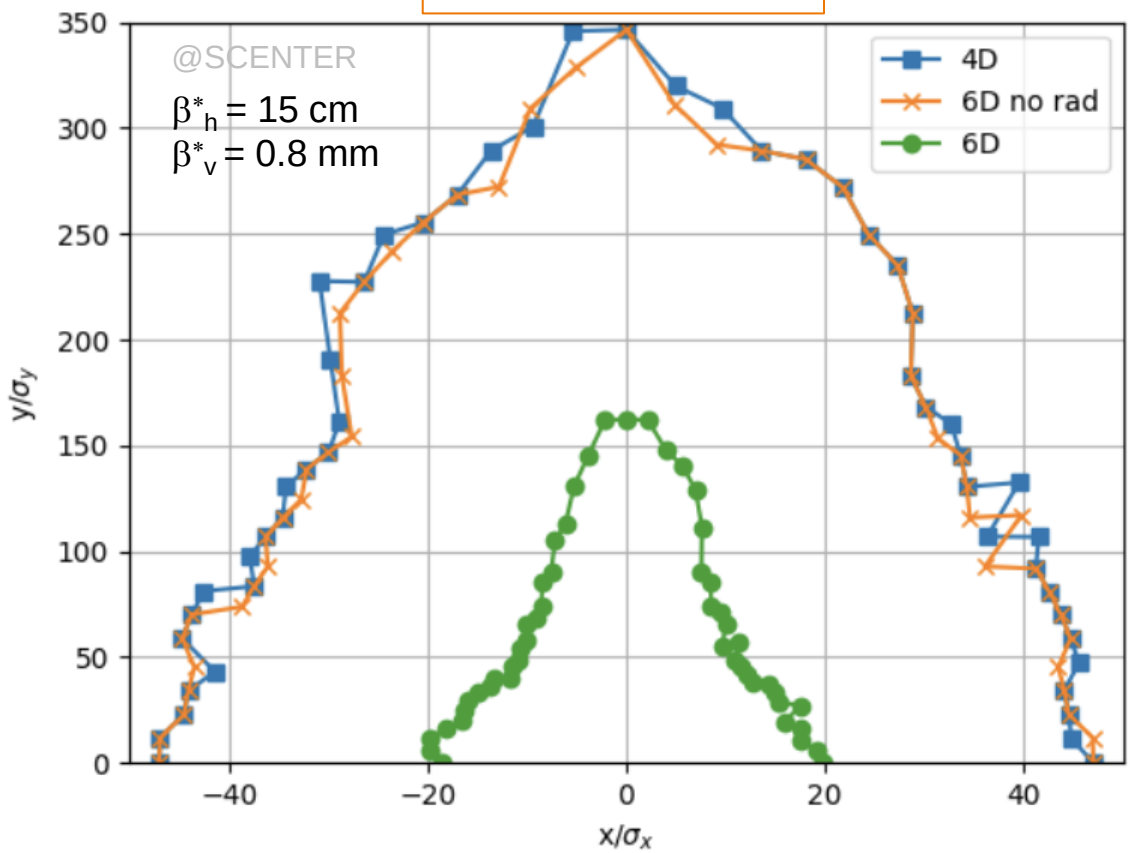
SYNCHROTRON RADIATION IN FINAL DOUBLET QUADRUPOLES (QUANTUM DIFFUSION)

6D tracking for 2350 turns, with quantum diffusion (1 seed) starting from straight section**, Crab sext. ON,** ε_v = 0.2% ε_h

GHC (V22)

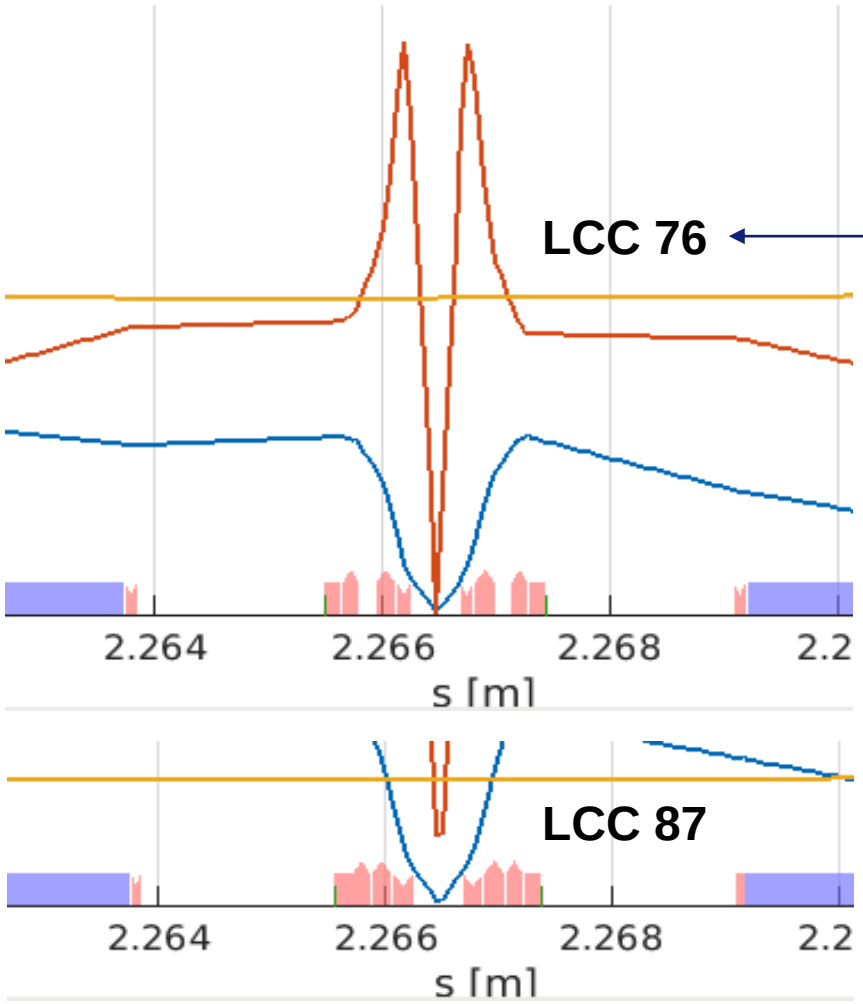


LCC



LCC includes countermeasures (decapoles) for synchrotron radiation in Final Doublet.

MODIFIED LAYOUT AND ADDITIONAL DECAPOLES TO MITIGATE FINAL DOUBLET SYNCHROTRON RADIATION

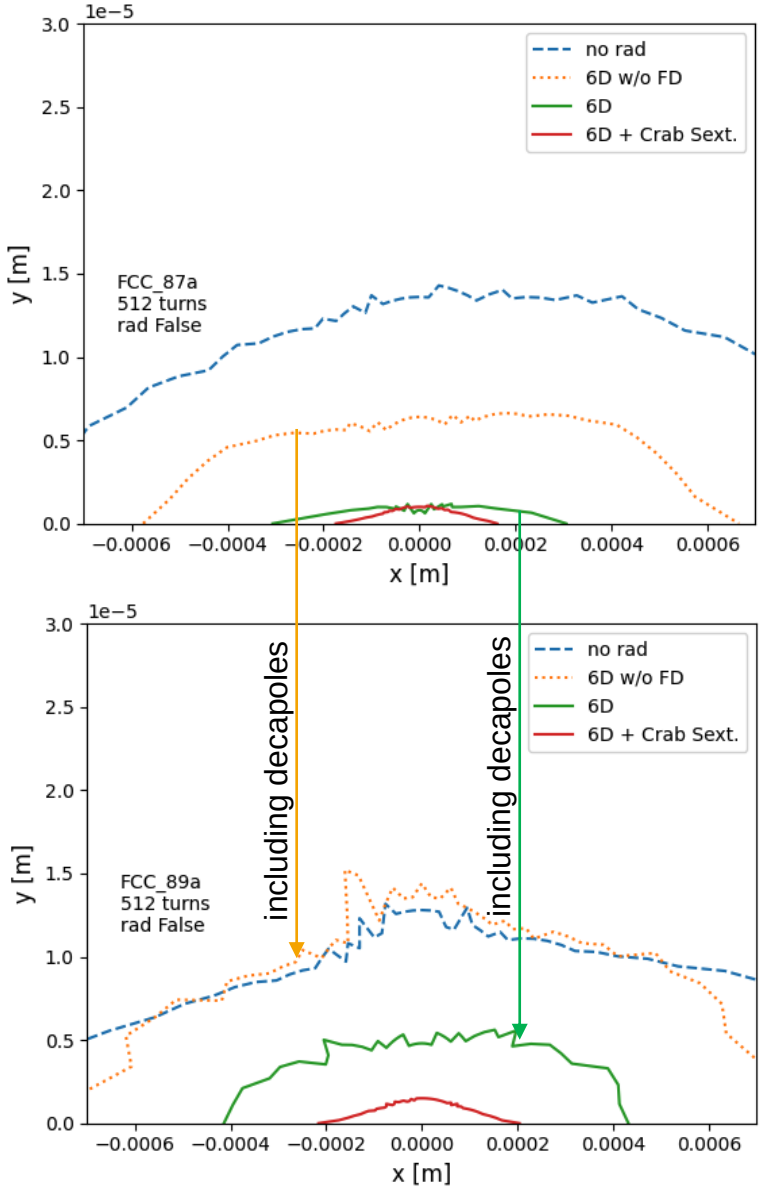


LCC 87 = FD optimized to reduce SR and DA-shrinkage due to SR

LCC 89 = + 3 DECAPOLE pairs in the Final Focus section.

The effectiveness of the DECAPOLES is evident.

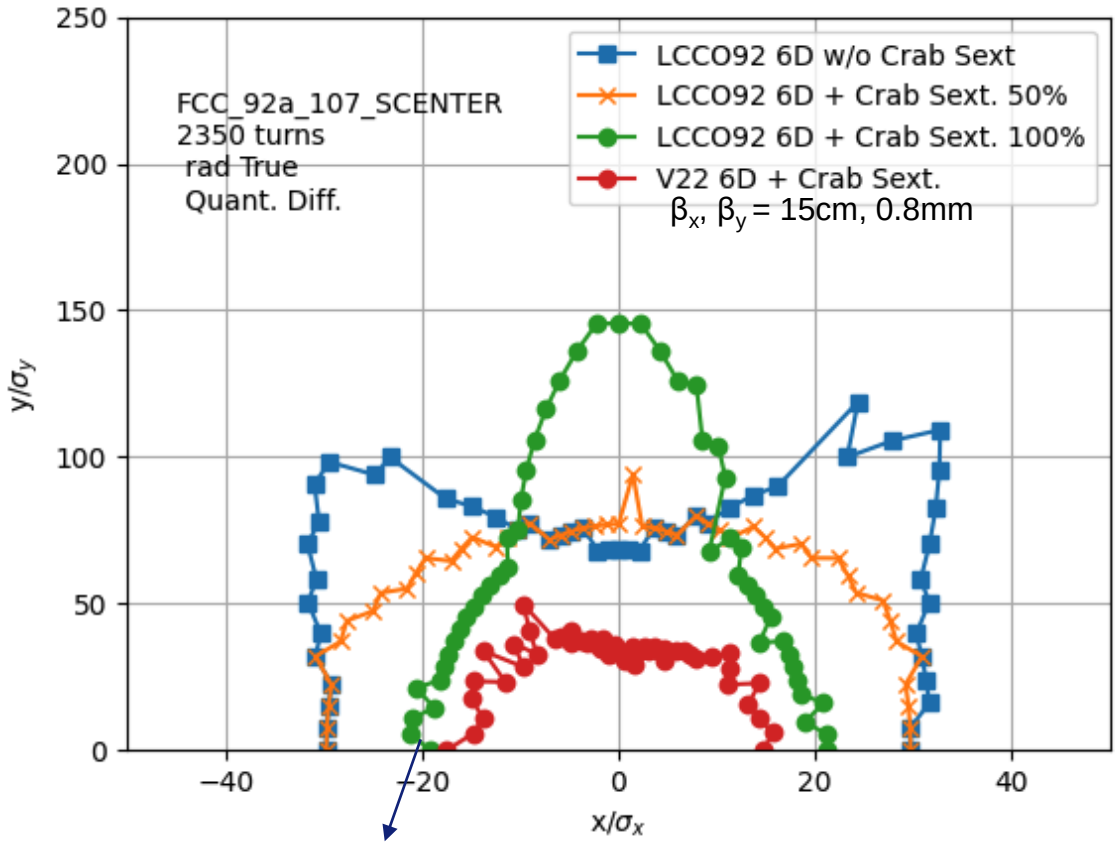
This is arguably the first time that the degradation due to the quadrupoles-SR and, in particular, final-doublet-SR is effectively addressed.



More details available here: indico link

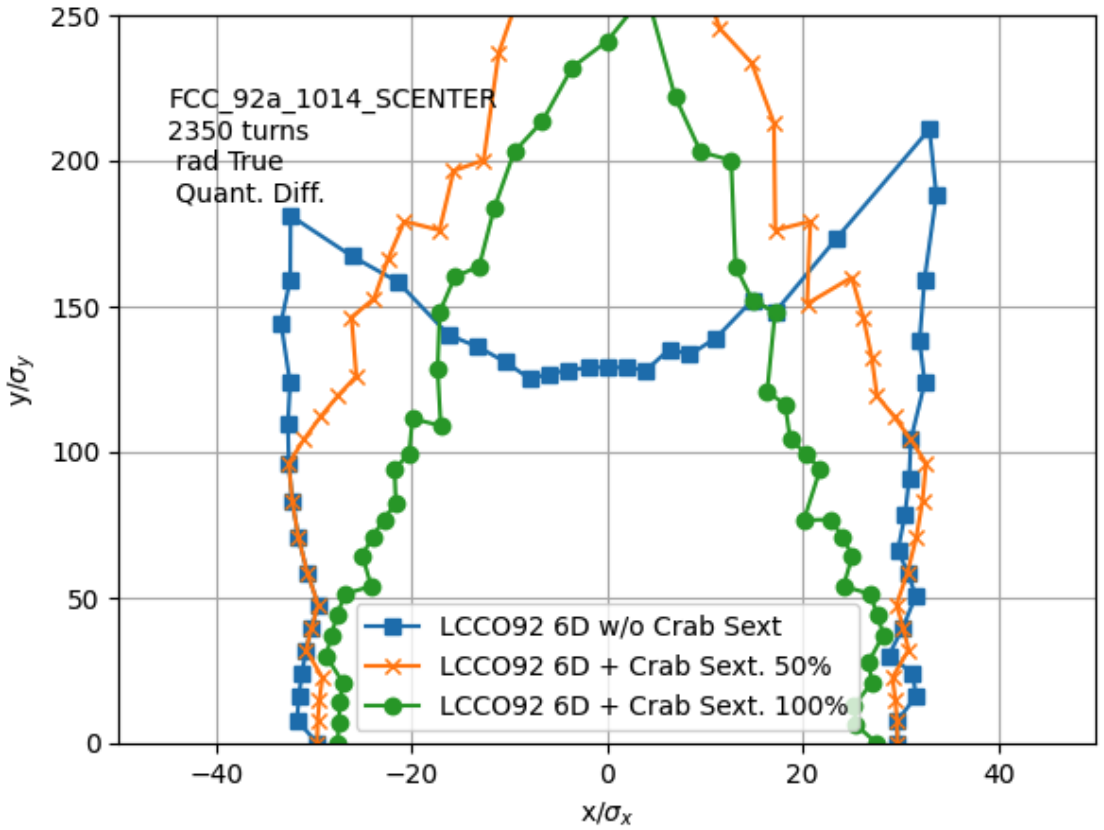
COMPARISON BETWEEN NOMINAL AND RELAXED OPTICS

Nominal β* **β^*_h=10cm, β^*_v=0.7mm**



→ LCC92 with **β^*_h=10cm, β^*_v=0.7mm** gives a DA larger horizontally and vertically with respect to GHC(V22) featuring **β^*_h=15cm, β^*_v=0.8mm**.

Relaxed β* **β^*_h=10cm, β^*_v=1.4mm**



- **Relaxed optics** obtained by only changing 2x6 quadrupoles in the FF entrance/exit.
- **Decapoles** optimized only for "Crab Sextupoles set to 100%" (80% of geometric value).

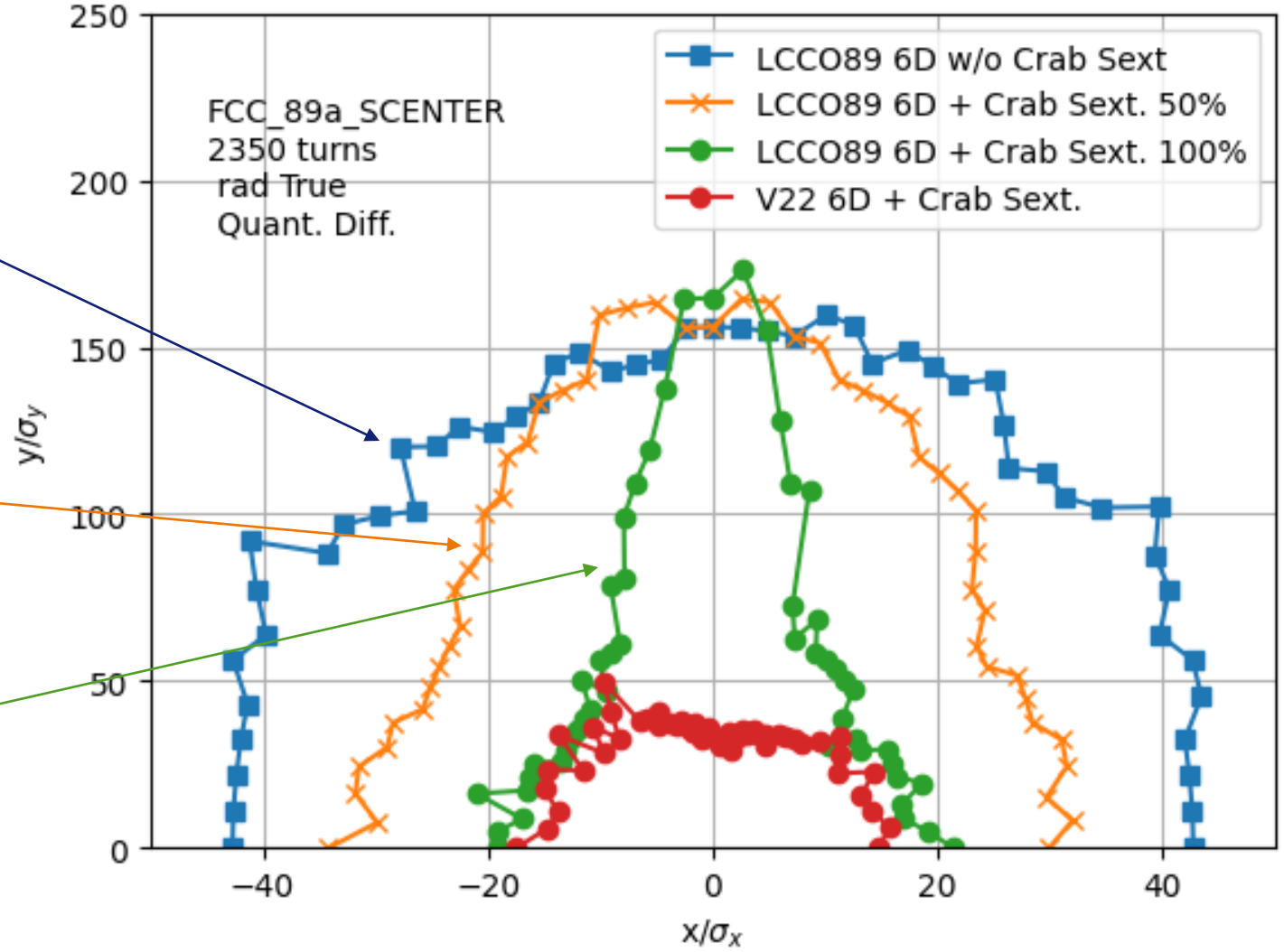
DYNAMIC APERTURE AT STRAIGHT SECTION

Crab 100% = 80% of the geometric value (eq. to GHC)

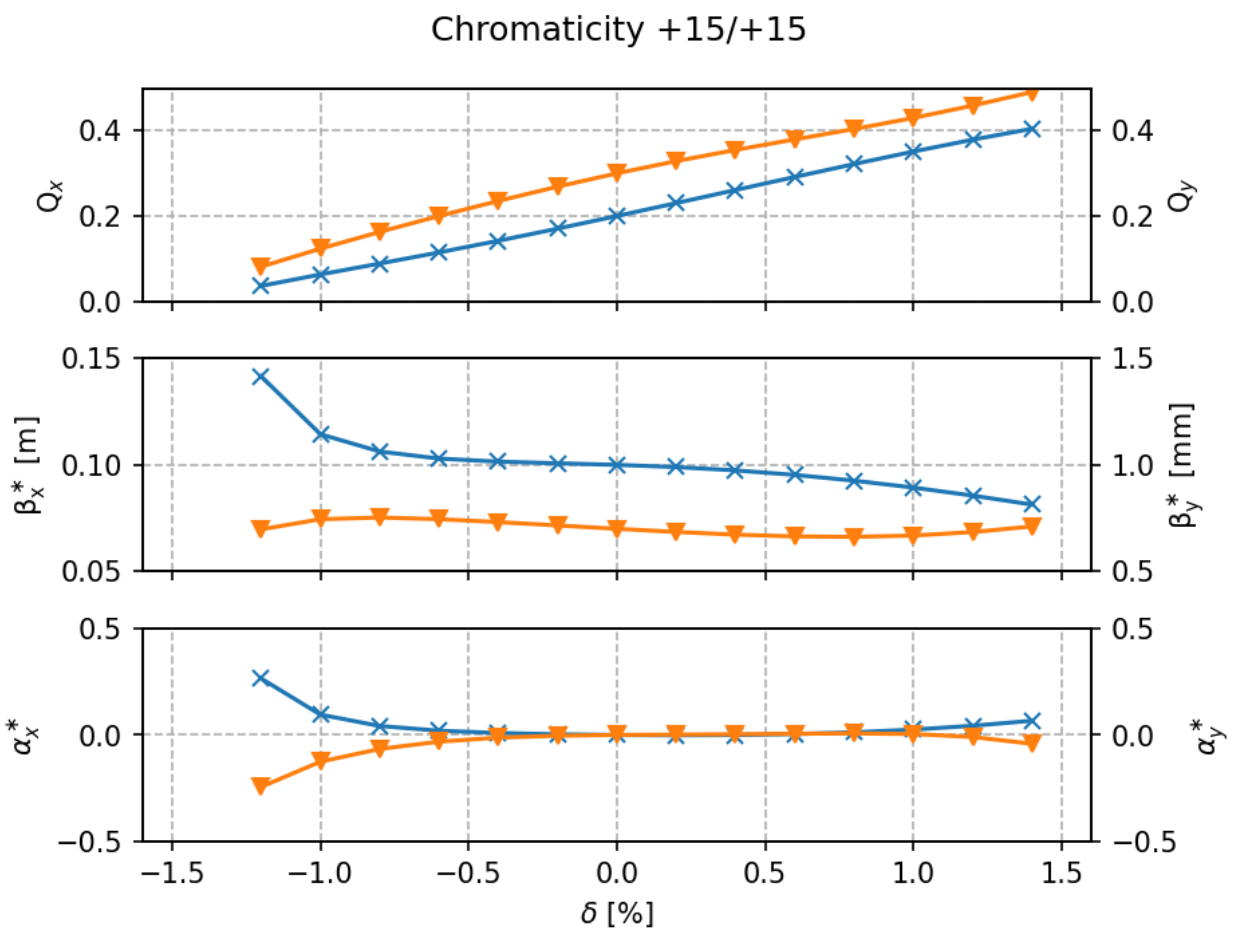
Commissioning

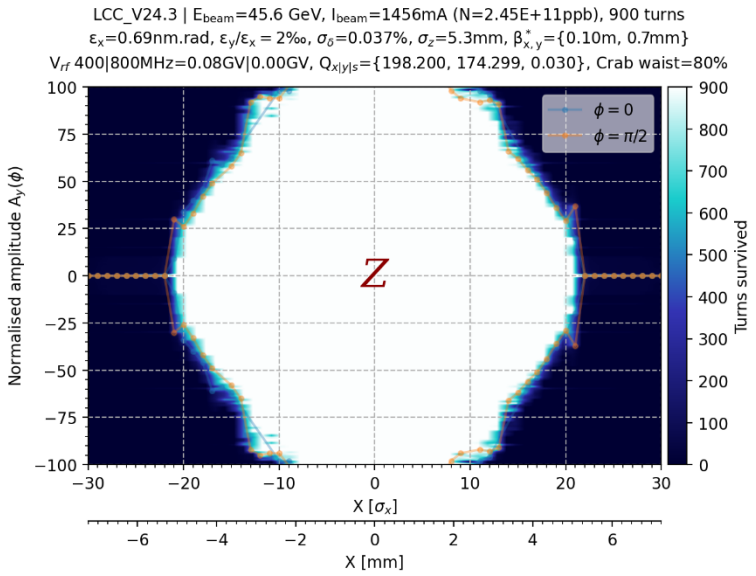
Tuning with progressive increase of Crab sextupoles strength.

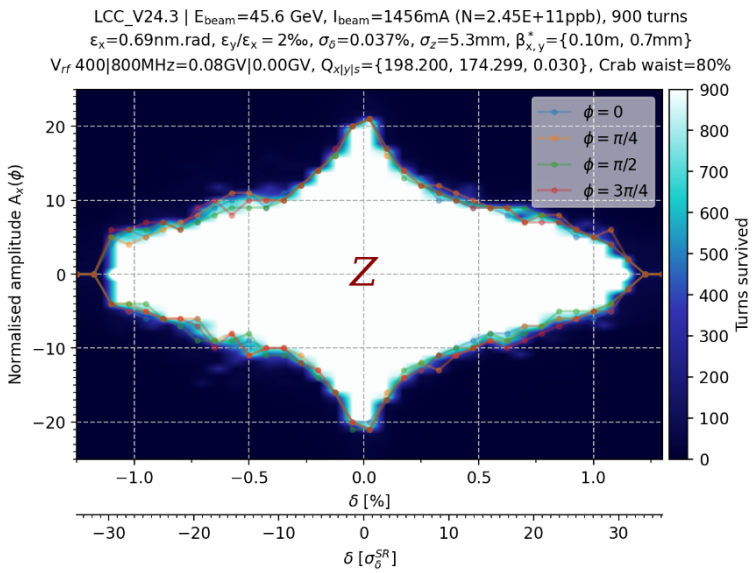
Final configuration for Luminosity production.



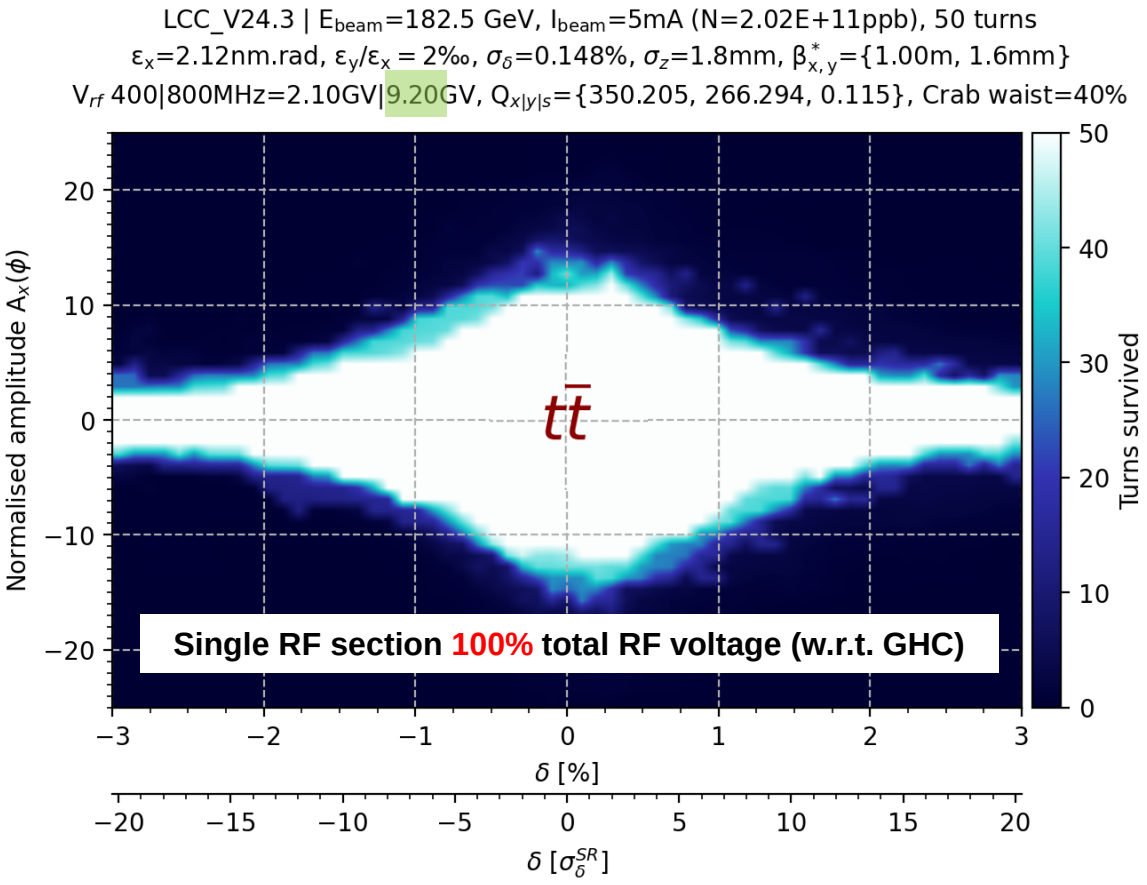
DYNAMIC APERTURE WITH HIGHER CHROMATICITY MITIGATING COLLECTIVE EFFECTS

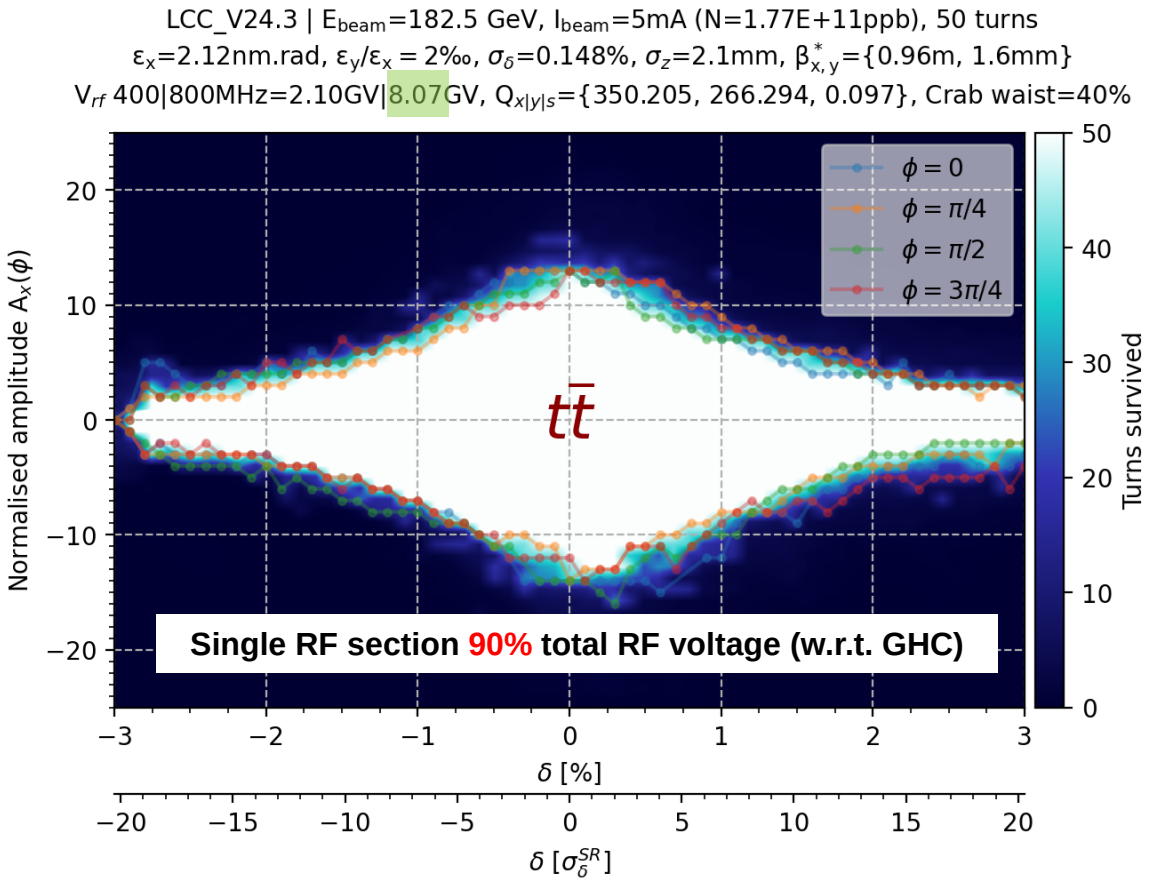






OFF-ENERGY DYNAMIC APERTURE WITH REDUCED RF VOLTAGE

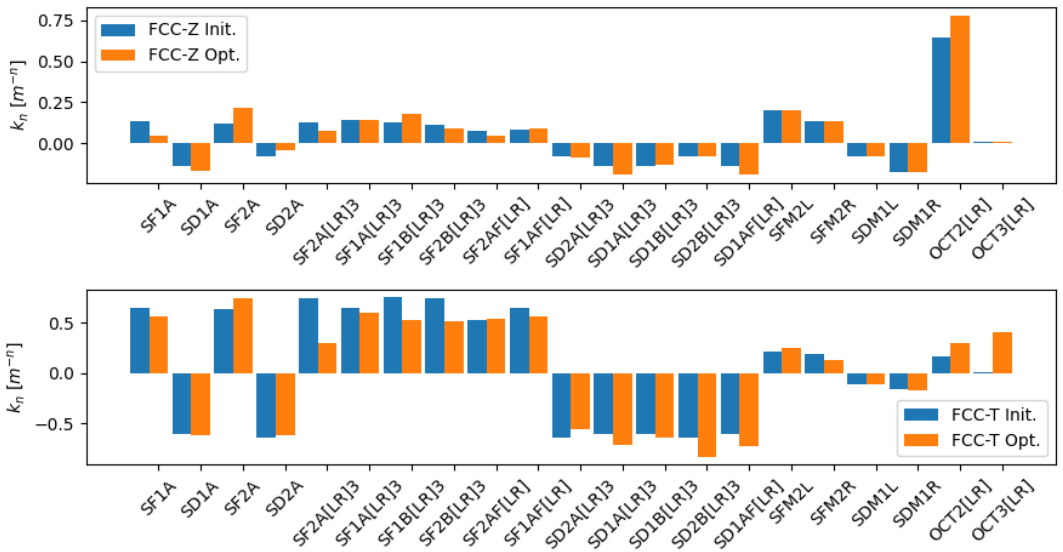




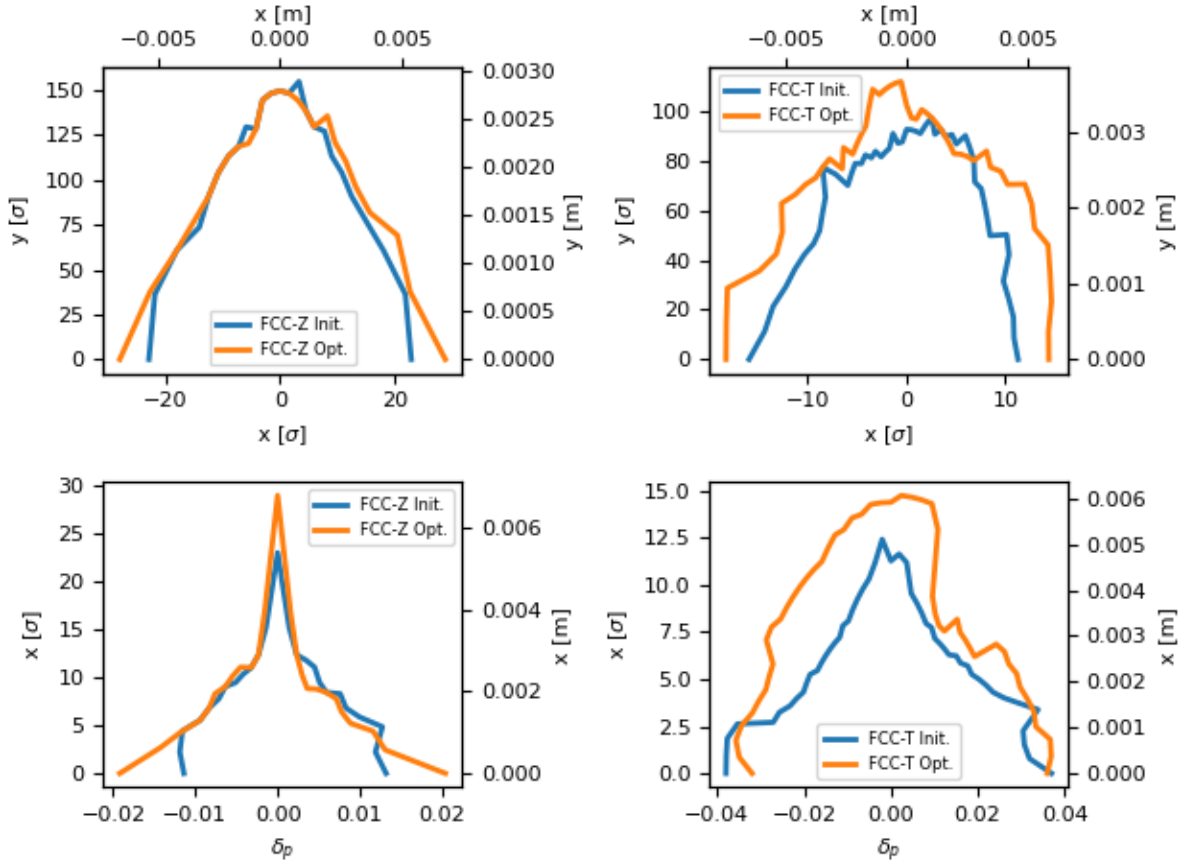
- Optimization of magnet strengths to be performed,
- Reduces the required space for 800MHz RF cavities.

OPTICS OPTIMIZATIONS - I

Multi-objective optimization (DA & MA) with NSGA-II of non-linear elements in LCC.



Pre- and post- optimization magnet strengths for Z (top) and ttbar (bottom).

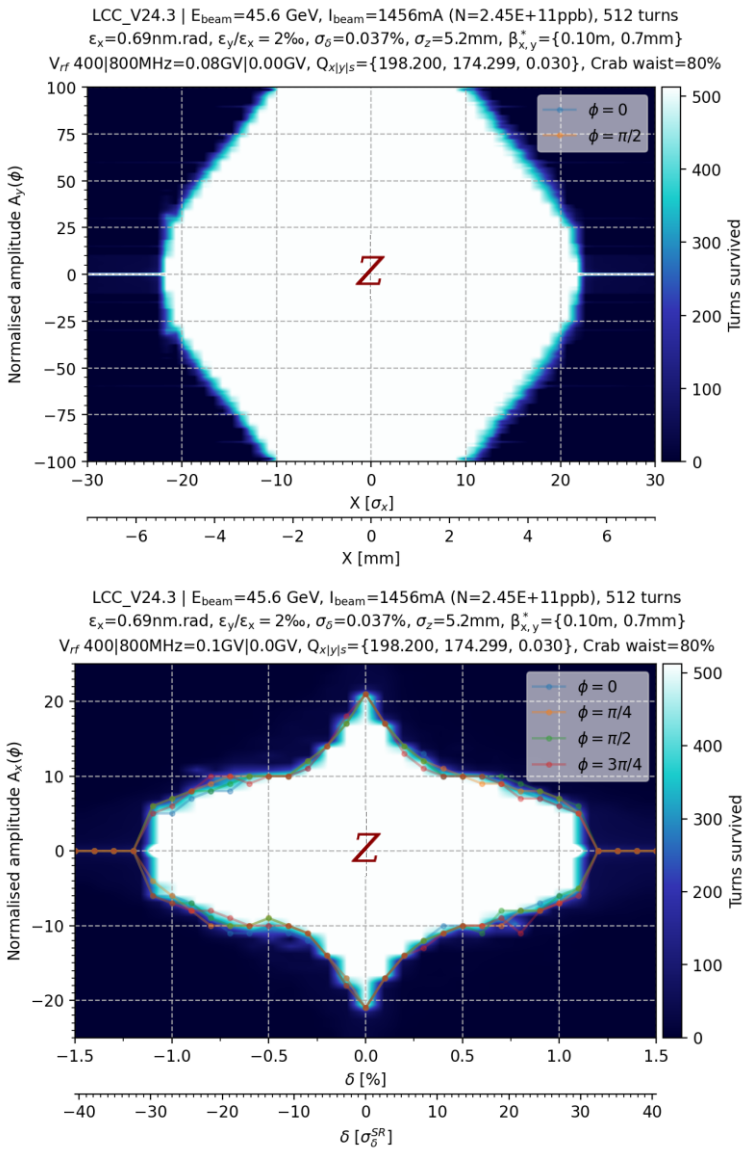


Pre- and post- optimization DA and MA for Z (left) and ttbar (right).

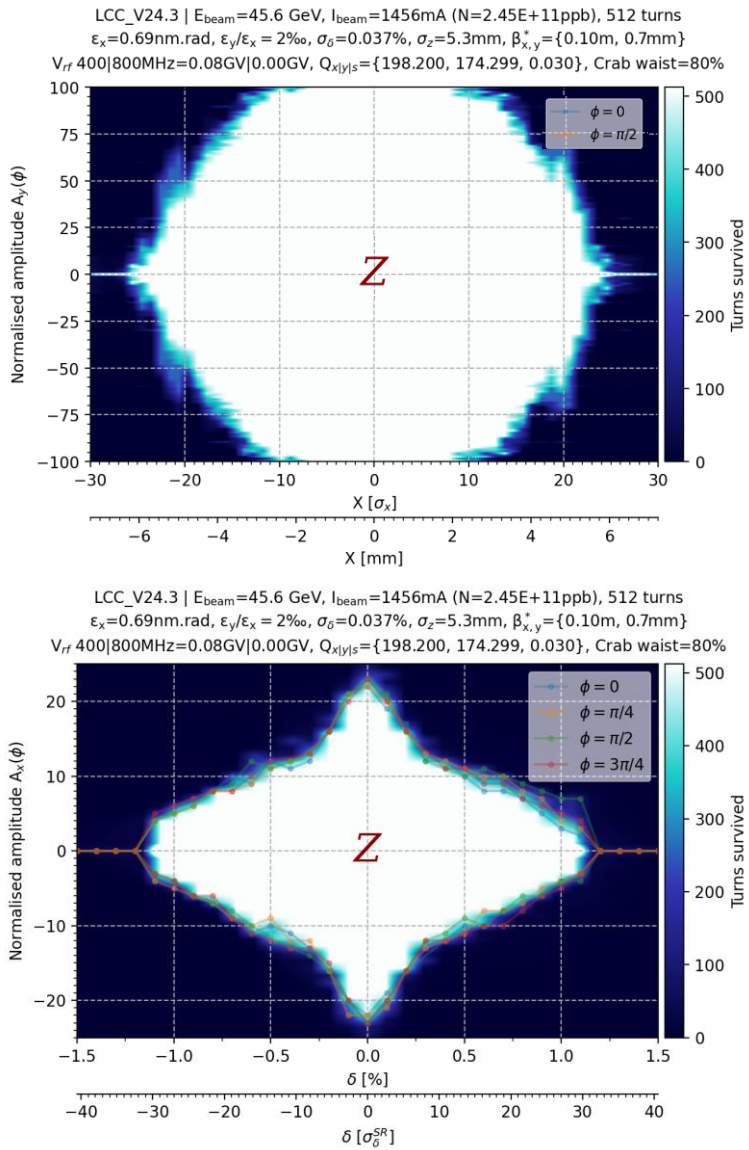
OPTICS OPTIMIZATIONS - II

Results of initial magnet strengths optimization from S.White performed with pyAT for the Z-pole energy, implemented in Xsuite.

Nominal magnet strengths (v92a)



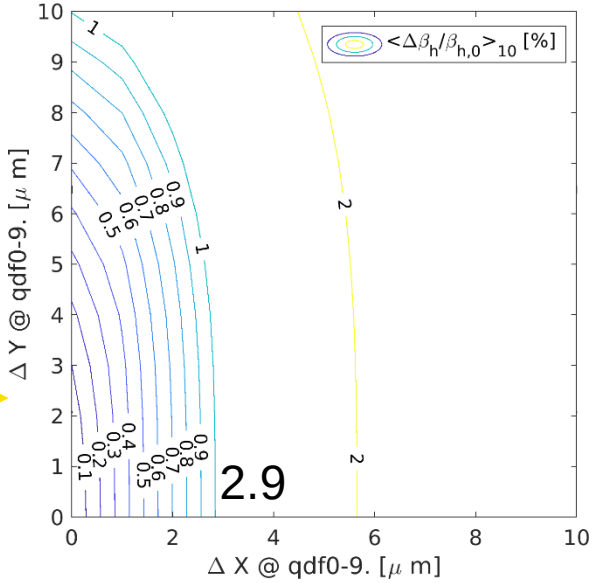
Optimized magnet strengths (v92a)

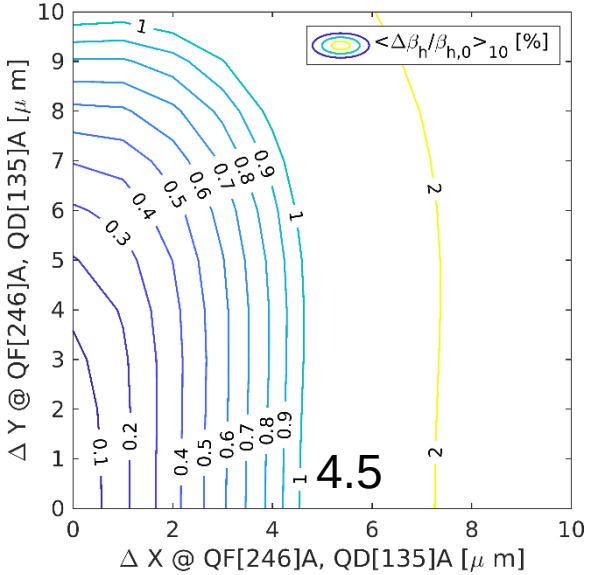


ARC ALIGNMENT SENSITIVITIES

			Orbit		$\Delta\beta/\beta$		$\Delta\eta$	
			H	V	H	V	H	V
Criteria			100 μm	100 μm	1%	1%	1 mm	1 mm
Optics	E_0	#	Arc quadrupoles sensitivity (μm)					
GHC	Z	1420	1.9	1.9	2.9	0.7	0.1	0.1
LCC	Z	2168	2.0	1.6	4.5	0.38	0.8	0.25
GHC	$t\bar{t}$	2836	1.3	1.5	1.5	0.5	0.12	0.2
CEPC	$t\bar{t}$	3460	0.70	0.83	0.4	0.1	0.09	0.07
LCC	$t\bar{t}$	2168	1.4	1.0	2.1	0.41	1.2	0.32
			Arc sextupoles sensitivity (μm)					
GHC	Z	600	>100	>100	17	8.5	3.1	2.6
LCC	Z	1792	>100	>100	>100	47	14	10
GHC	$t\bar{t}$	2336	>100	>100	10	7.0	7.5	10
CEPC	$t\bar{t}$	1024	>100	>100	6.4	4.8	3.1	4.4
LCC	$t\bar{t}$	1792	>100	>100	24	12	12	12

The contour plot shows the horizontal beta-beating for:
- GHC (top),
- LCC (bottom).





LCC ARC errors sensitivities are generally better or similar

FINAL FOCUS ALIGNMENT SENSITIVITIES

			Orbit		$\Delta\beta/\beta$		$\Delta\eta$	
			H	V	H	V	H	V
Criteria			100 μm	100 μm	1%	1%	1 mm	1 mm
Optics	E_0	No.	FF quadrupoles sensitivity (μm)					
GHC	Z	436	0.65	0.15	1.2	0.065	0.04	0.014
LCC	Z	532	0.57	0.11	0.63	0.035	0.18	0.018
GHC	$t\bar{t}$	480	2.0	0.35	2.1	0.25	0.23	0.08
CEPC	$t\bar{t}$	228	0.8	0.2	0.65	0.18	0.12	0.024
LCC	$t\bar{t}$	532	1.3	0.27	1.4	0.14	0.65	0.08
			FF sextupoles sensitivity (μm)					
GHC	Z	16	>10	>10	>10	0.25	>10	1.2
LCC	Z	72	>10	>10	>10	0.7	8	1.8
GHC	$t\bar{t}$	16	>10	>10	>10	0.50	>10	2.6
CEPC	$t\bar{t}$	52	>10	>10	9.5	1.3	>10	3.8
LCC	$t\bar{t}$	72	>10	>10	>10	1.6	>10	3.9

~3x better for LCC

FF quadrupole errors sensitivities are generally better for GHC optics

FF sextupole errors sensitivities are generally better for LCC optics

Orbit in FF sextupoles must be maintained at this level during operation (a fast orbit feedback is needed)

FUTURE WORK

Detailed commissioning simulations studies to compare with the Feasibility Study Report results featuring the GHC lattice, including alignment and field errors.

Design and optics matching of required technical straight sections.

Study of the impact of tuning knobs and beta squeezing on realistic lattice scenarios (errors and corrections)

Assess the impact of beam-beam effect on tolerances.

Study minimal correction schemes and tuning strategies.

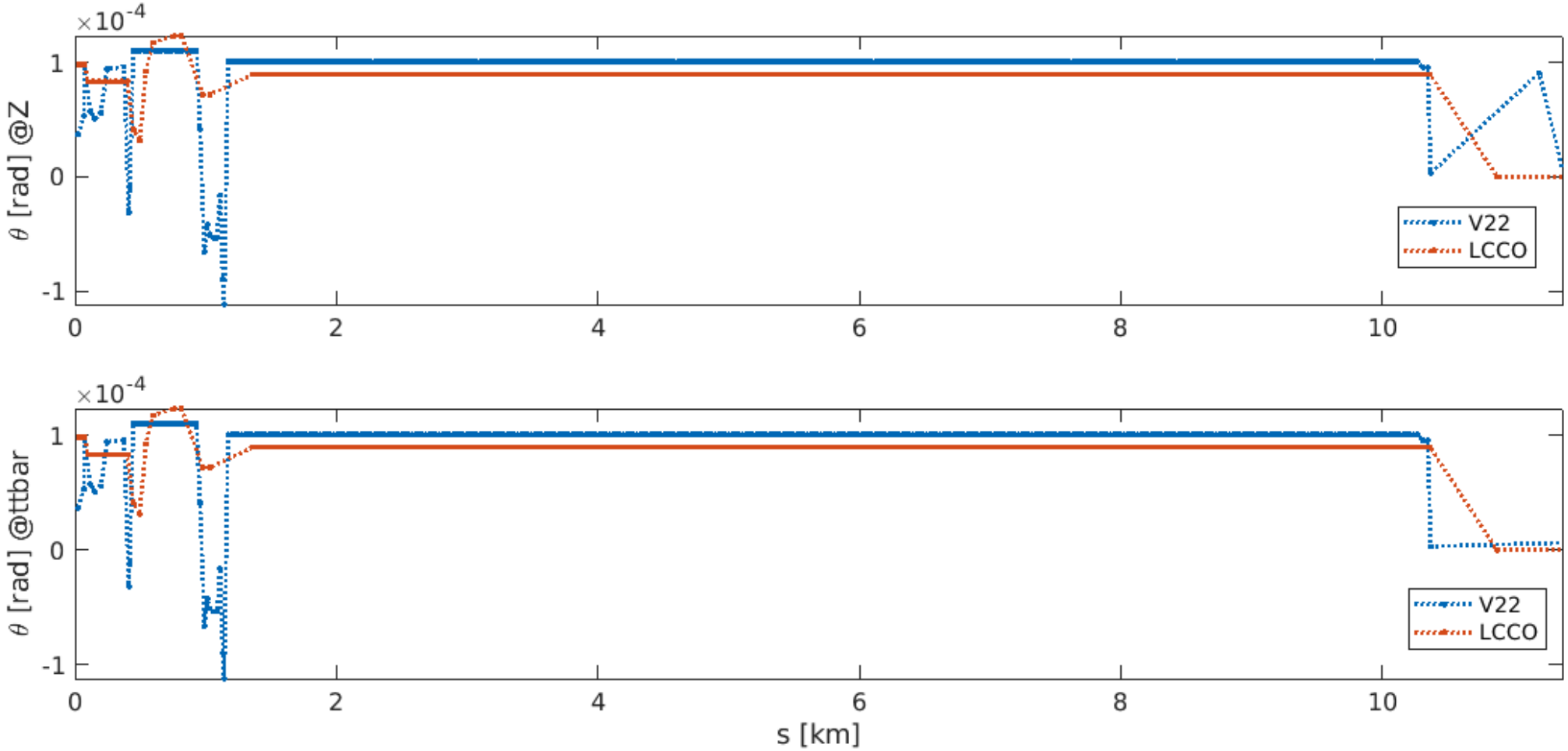
Contribute to the Tuning and Layout & Accelerator Design activities to finalize the optics development in view of a comparison with the baseline.

CONCLUSIONS

- **Large orthogonality of many fundamental quantities, that can be varied separately with no need to retune other quantities: *e.g. arc chromaticity, machine tunes, individual IP betas, individual CS pairs, …***
- **The LCC optics include unprecedented solutions to deal with the effect of synchrotron radiation in the Final Focus quadrupole doublet largely benefiting the higher energies operation.**
- **Beam parameters: comparable to GHC, smaller energy loss per turn for LCC.**
- **Number of magnets: at ttbar the LCC optics has less magnets with smaller gradients.**
- **Dynamic Aperture: larger DA on-energy and off-energy for the LCC optics, particularly vertically. It is expected to be larger also for ttbar thanks to much smaller sextupole strengths.**
- **Errors sensitivities: better sextupoles sensitivity for LCC optics (due to lower gradients). Both V22 and LCC optics show issues with long range errors, mostly driven by the Final Focus system.**
- **Random alignment errors: FF and final doublet errors are dominating.**

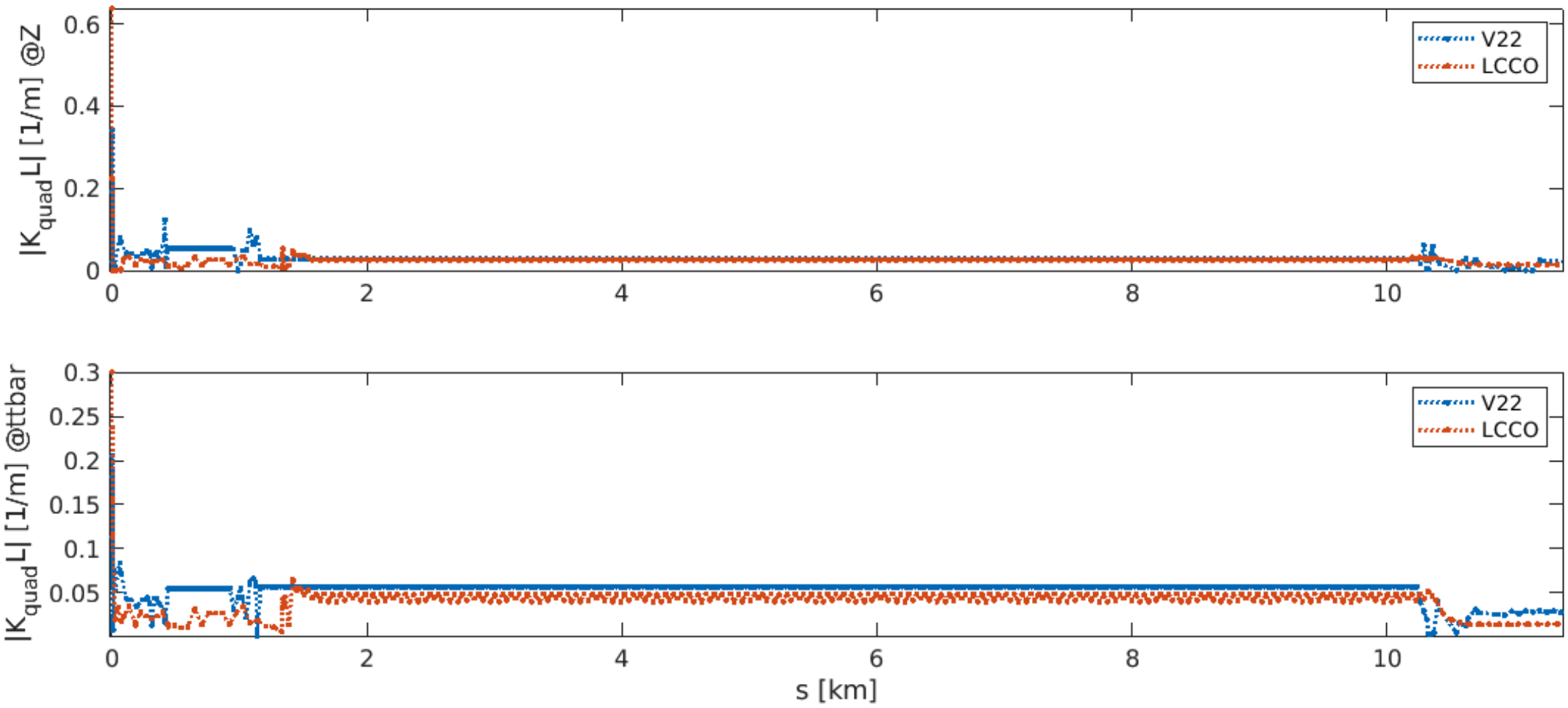
Thank you for your attention !

DIPOLE FIELDS (1 OCTANT)



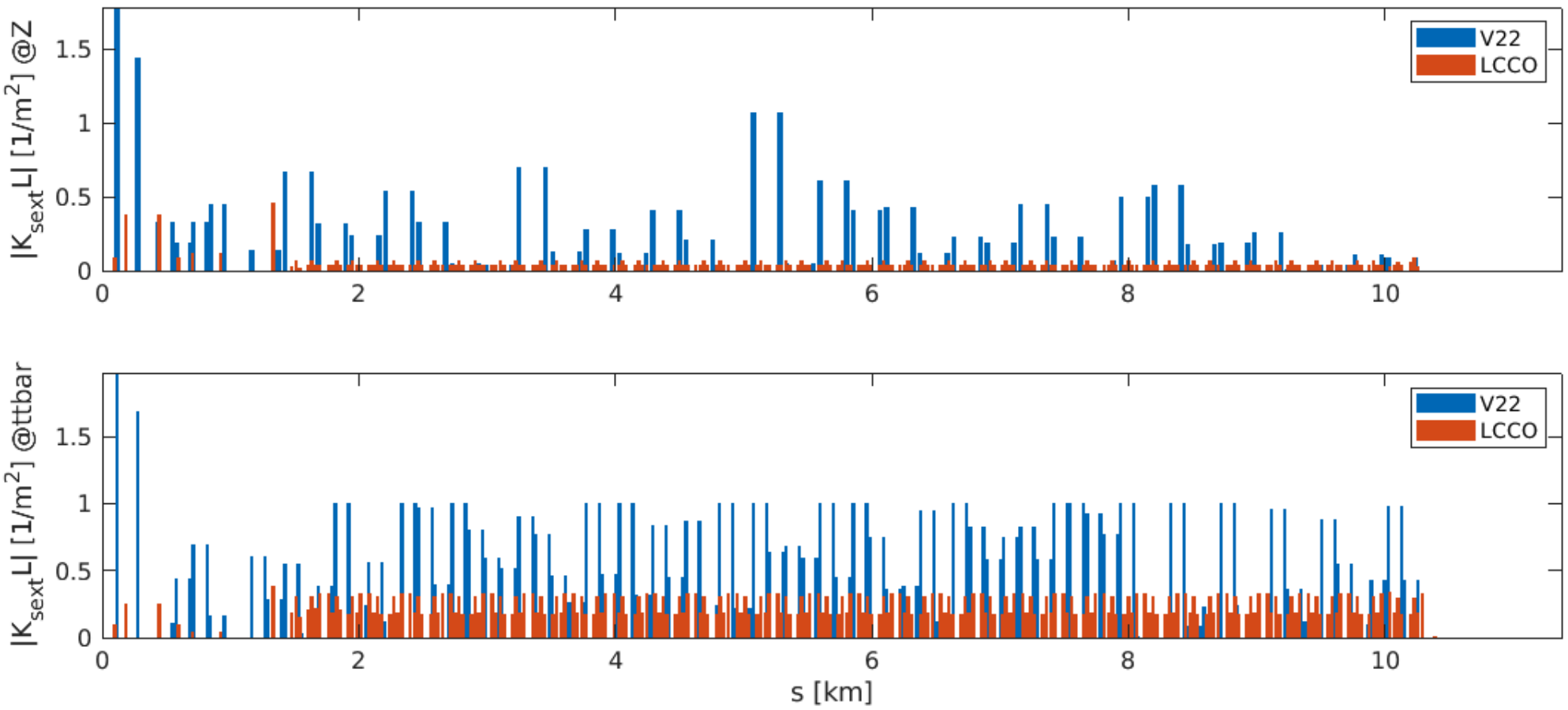
No negative angle bends for LCCO optics → easier synchrotron radiation absorption scheme

QUADRUPOLE GRADIENTS (1 OCTANT)



Lower gradients for quadrupoles for LCC optics (apart from the final doublet)

SEXTUPOLES GRADIENTS (1 OCTANT)



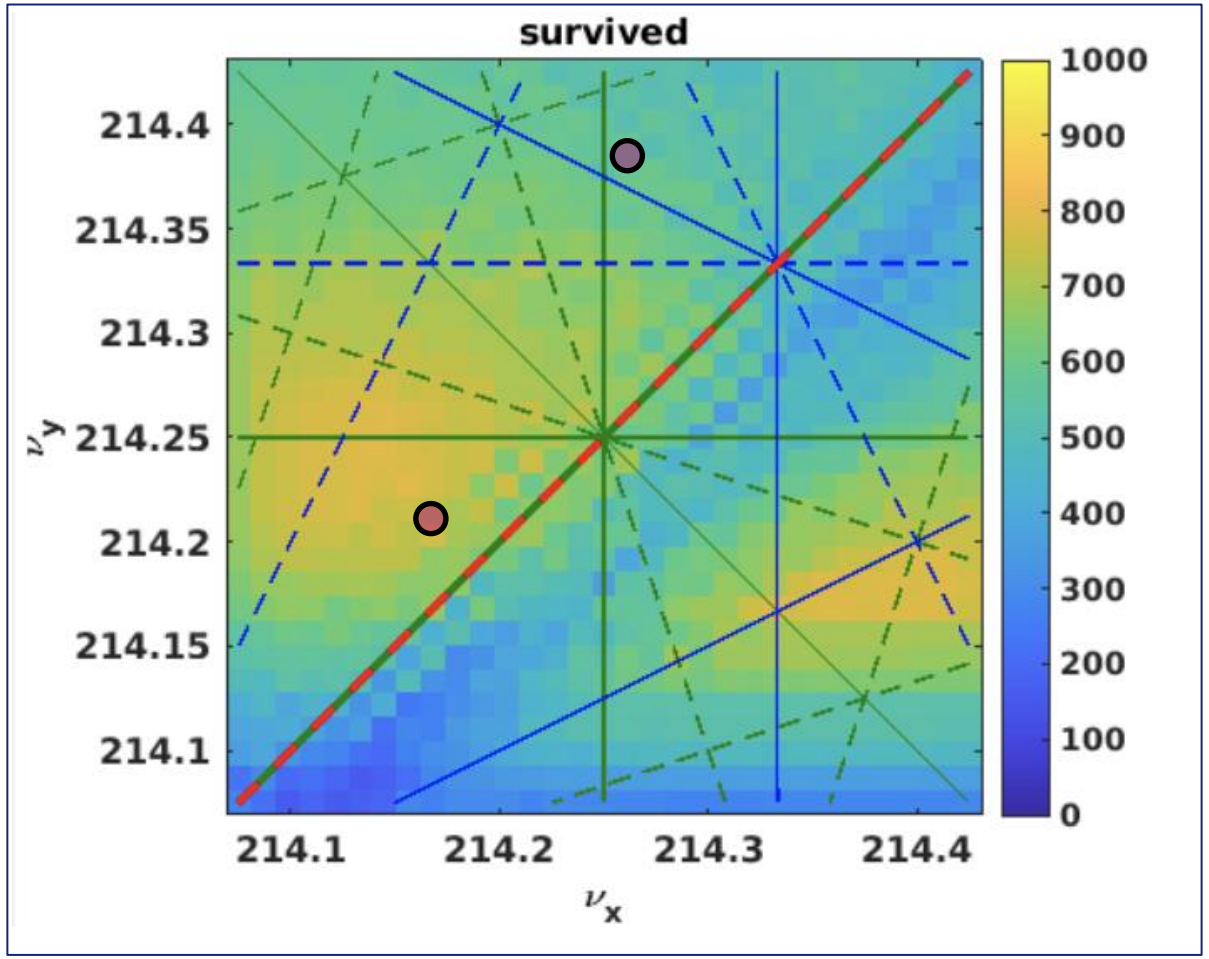
904 m
773 m

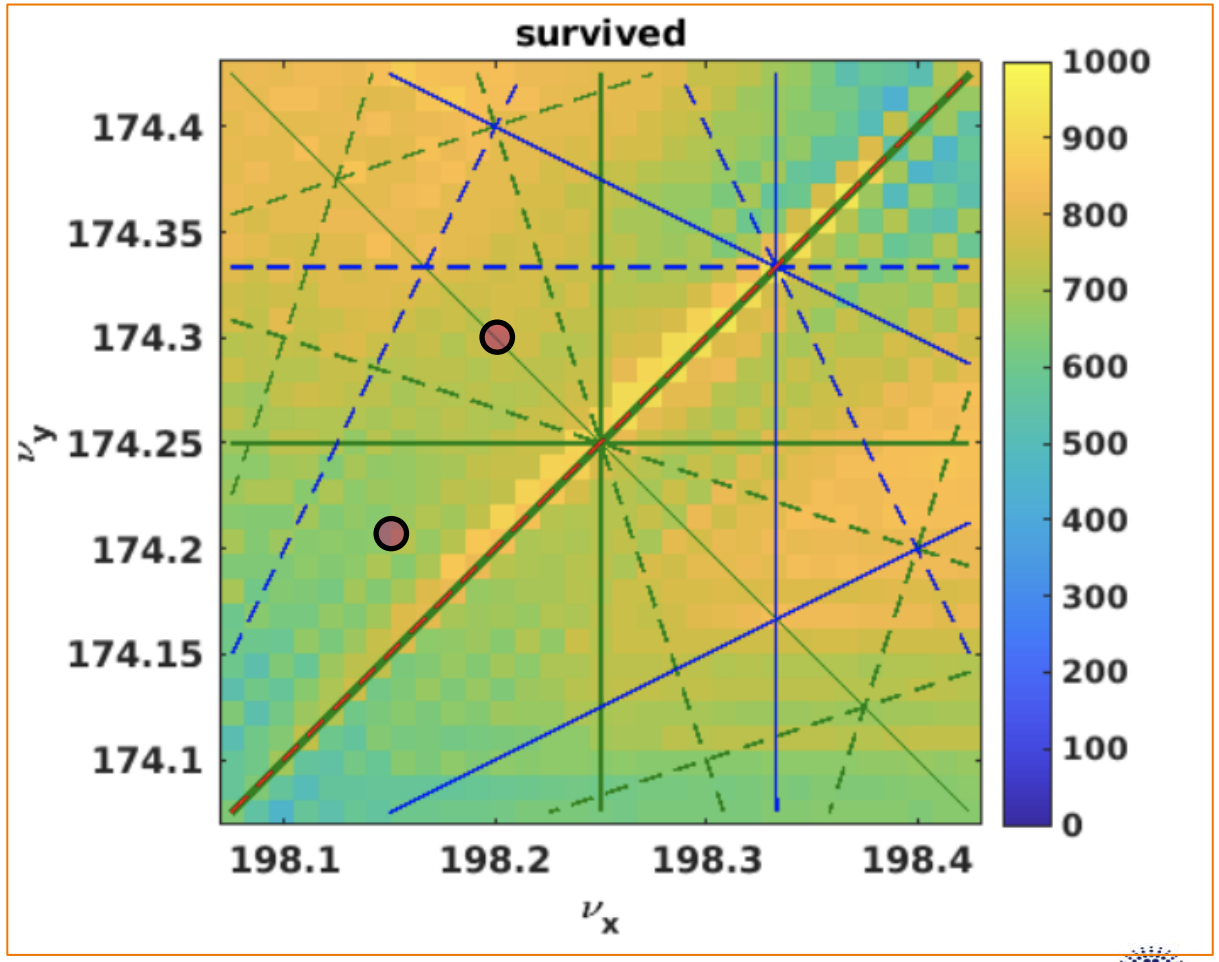
3506 m
773 m

Smaller sextupole gradients ➔ Usually better performances.

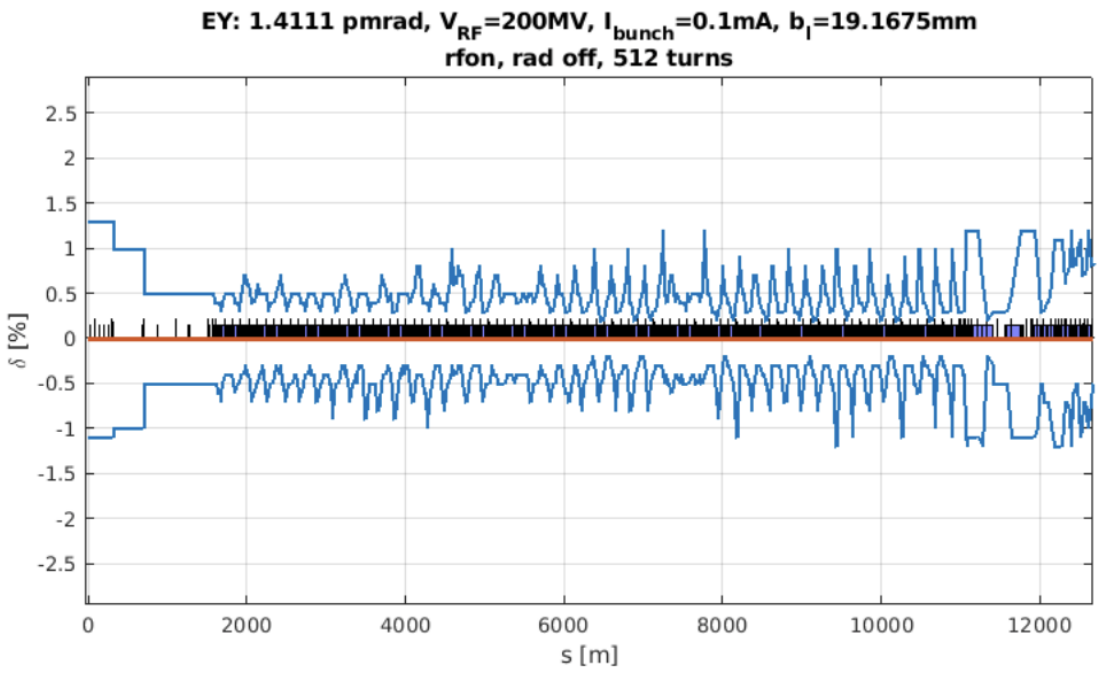
STABILITY ABOUT TUNE WORKING POINT

Track a 3D grid of 1000 particles of size: $20\sigma_x$ x $20\sigma_y$ x 0.002 $\delta p/p$ for 512 turns for different tunes.
Tune varied using ARC quadrupoles. Chromaticity corrected to initial value after tune change.
Small (10 nm) random errors added to all elements (to emphasize resonance lines).





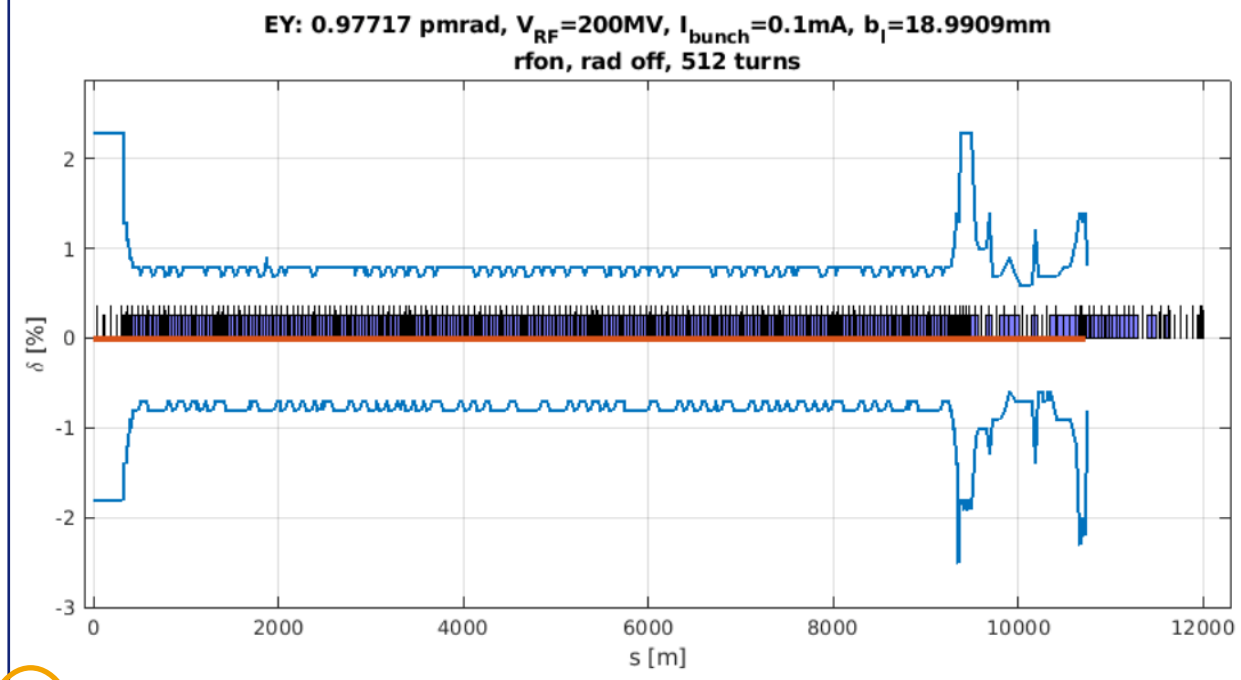
LOCAL MOMENTUM ACCEPTANCE NO SYNCHROTRON RADIATION (OPTIMISTIC)



6.5h

GHC (V22)

$$\tau_{Tou.,bunch} \propto \frac{\delta^3 \sqrt{\epsilon_v}\sqrt{\epsilon_h}\sigma_l}{I_{bunch}}$$



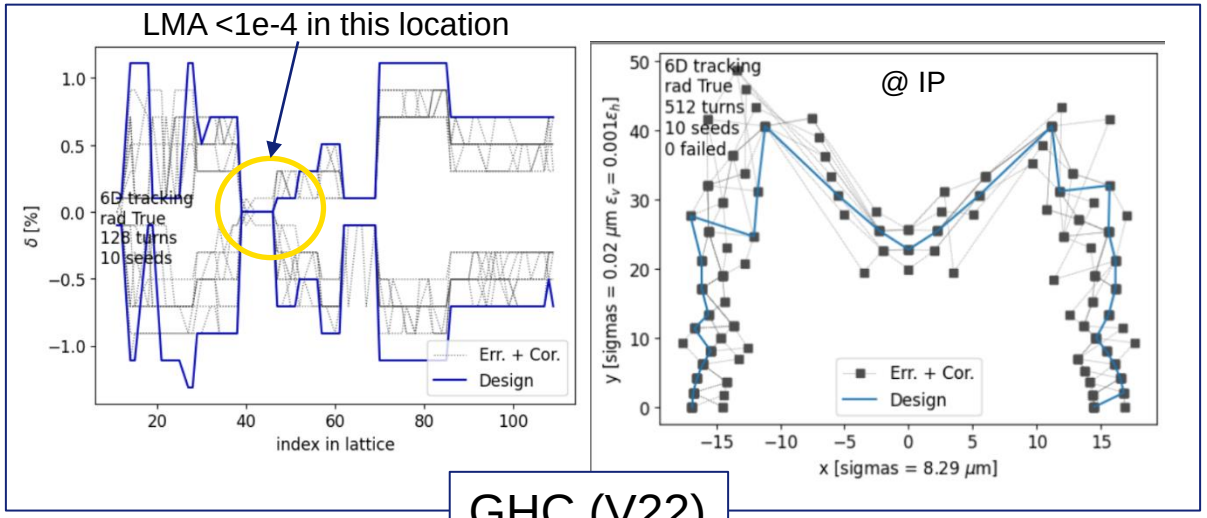
12.2h

LCC (76a)

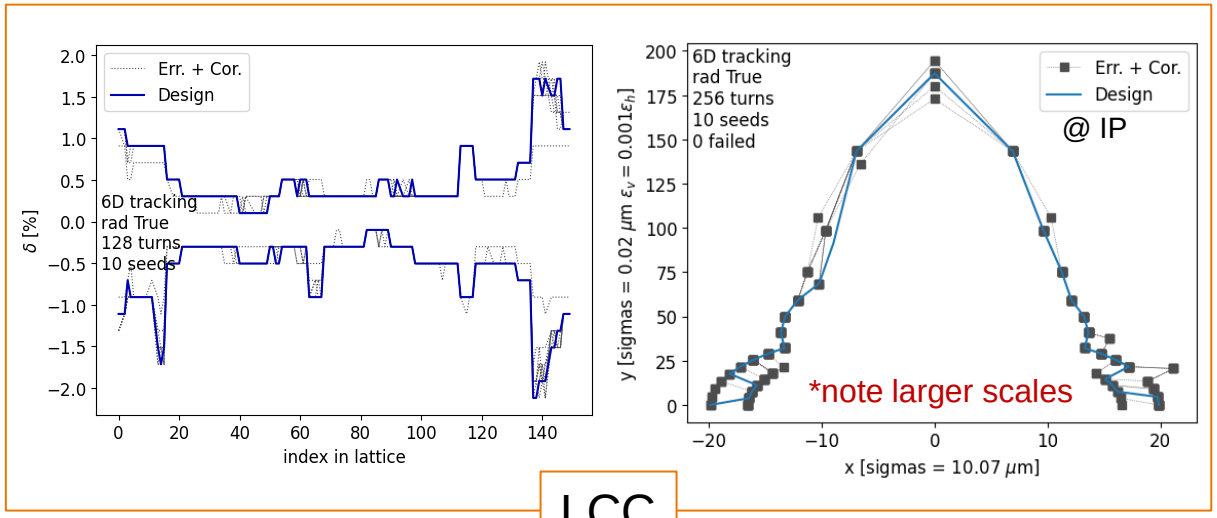
Small momentum acceptance locations have large impact on final Vacuum and Touschek Lifetime

ERROR TOLERANCES: COMMISSIONING SIMULATIONS

Set errors and apply correction sequence: beam threading (first turns), orbit, tunes, optics, coupling, etc…



GHC (V22)

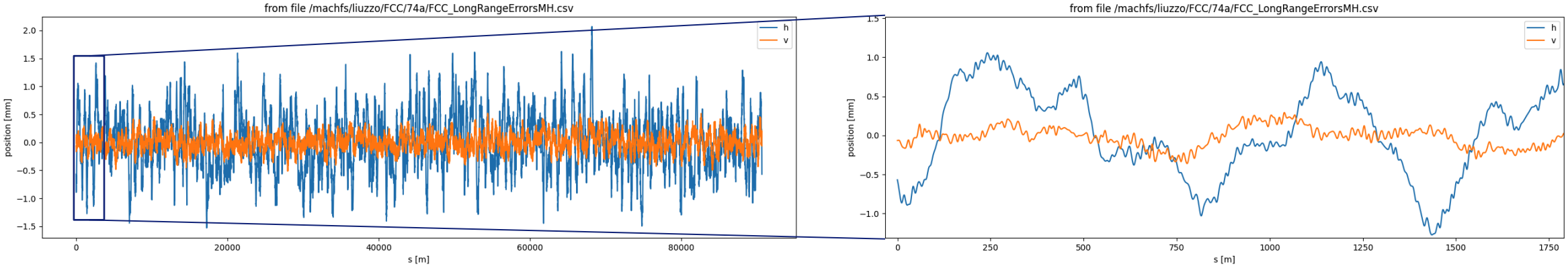


LCC

10um random errors only in the ARCS quadrupoles and sextupoles already impact DA, LMA and optics parameters. Errors larger than 30um seldom make it through first turns beam threading.
Final focus errors are even more demanding (<10um) and dominated by the final doublet errors.

Work in progress to define tolerated errors and commissioning procedures.

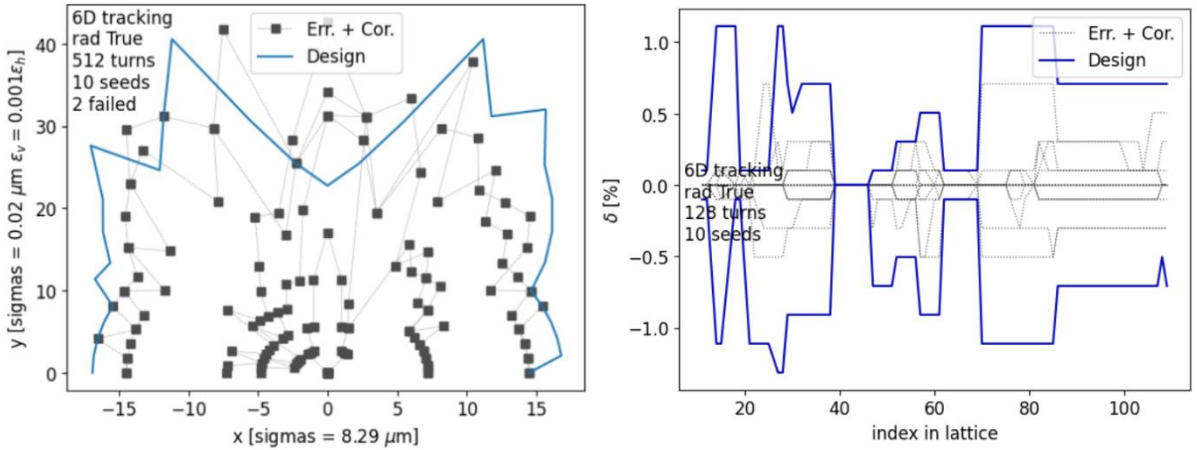
LONG RANGE ERRORS TOLERANCES



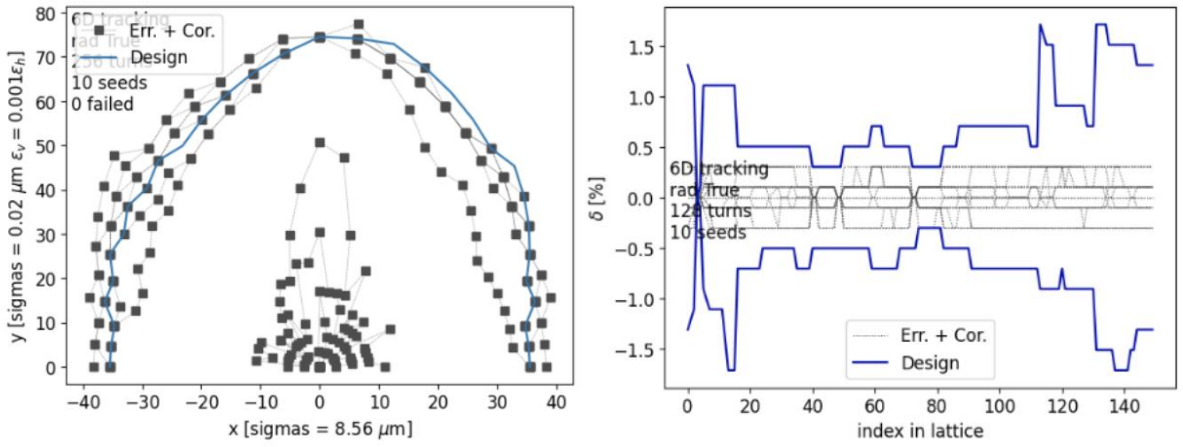
Errors defined following indications by alignment experts. Presently feasible with state of the art technology.

~10% of these errors already leads to several failing seeds and zero LMA. Final focus errors are the main offenders.

GHC (V22) 1/10 seeds survived



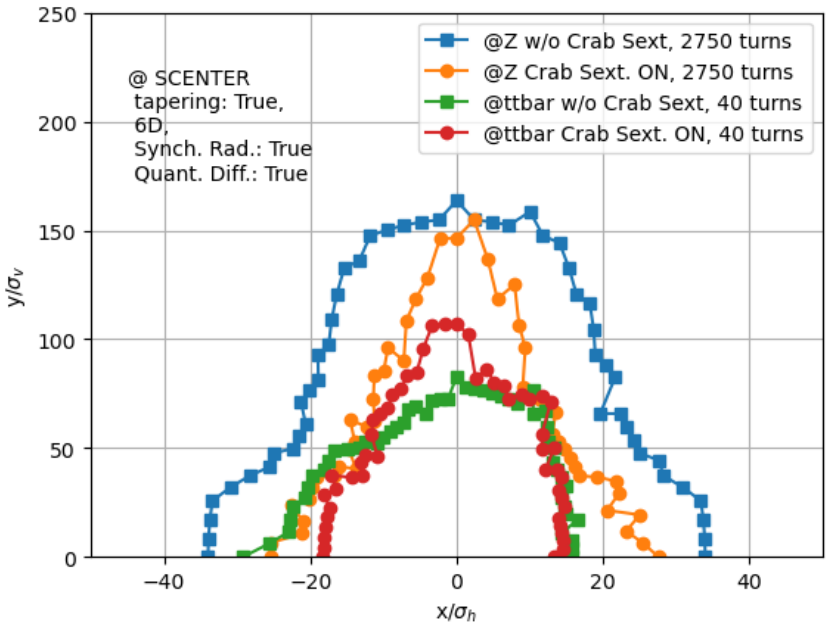
LCCv76 6/10 seeds survived

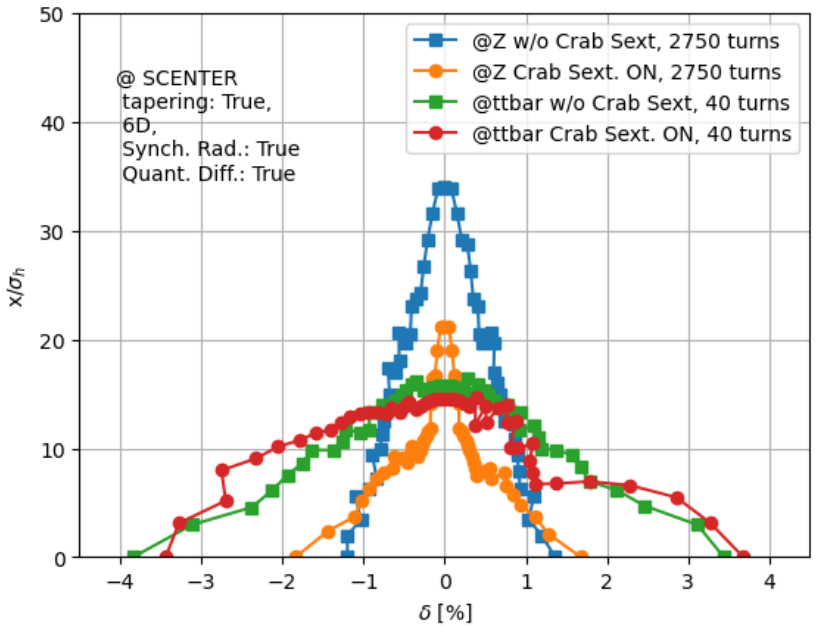


Same study with relaxed optics should be performed

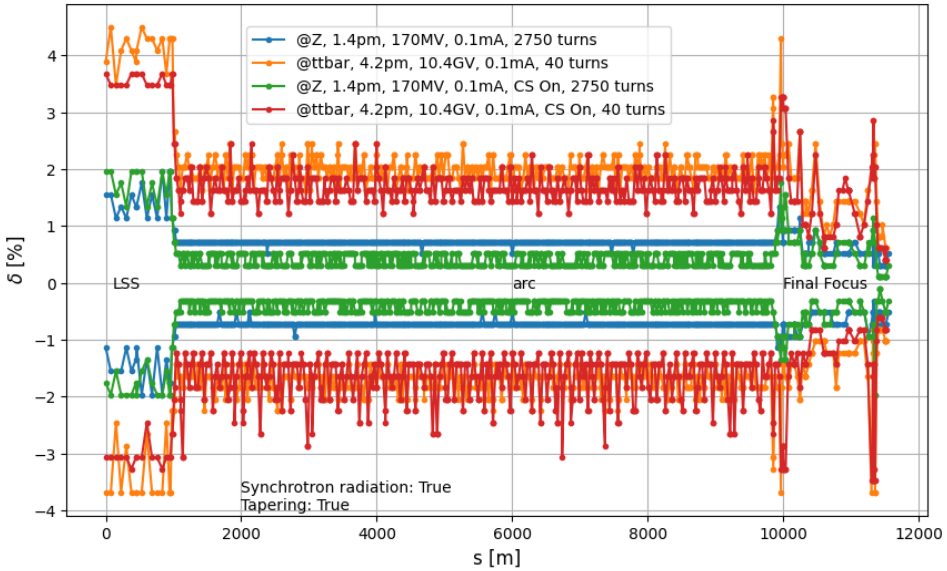
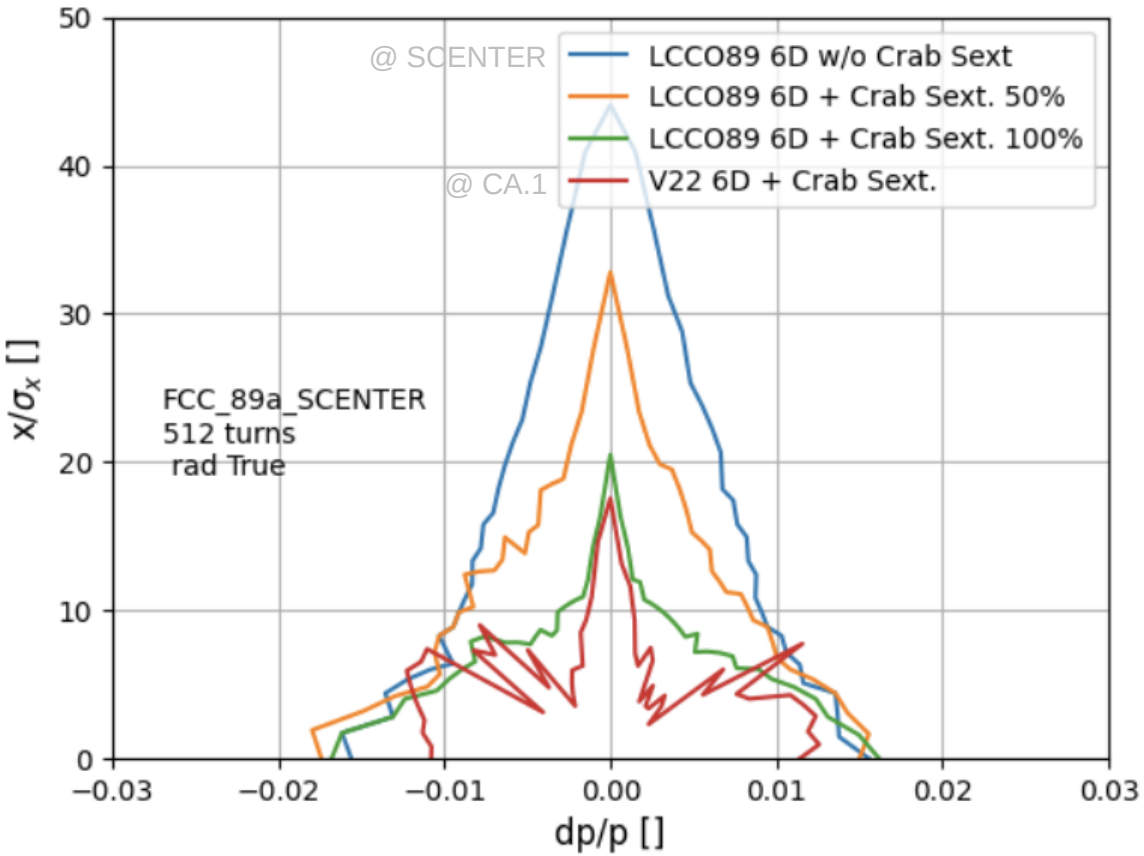
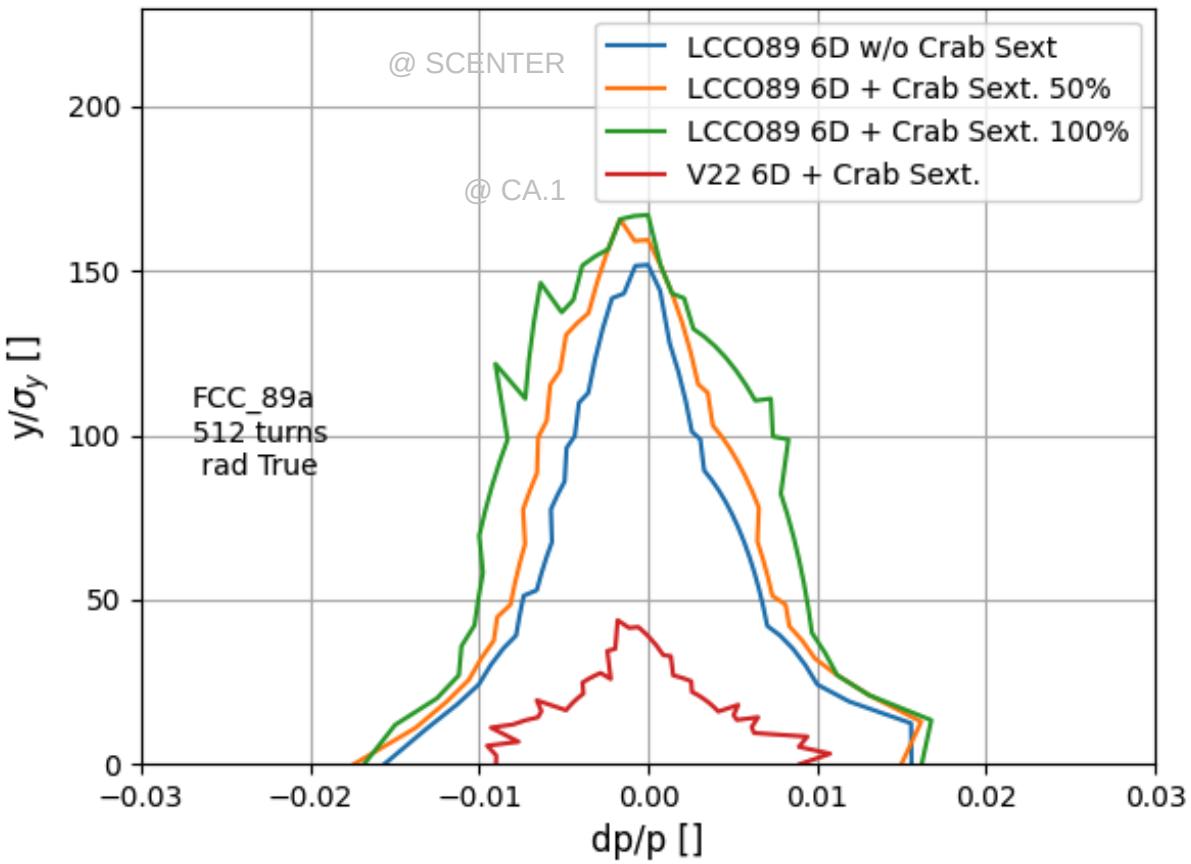
DYNAMIC APERTURE AND MOMENTUM APERTURE FOR Z & TTBAR LATEST VERSION (LCC 92 JAN 2025)

The effects of crab sextupoles is the next effect to be investigated.





Momentum acceptance is in general lower in dispersive or very chromatic regions because off-energy particles will exercise simultaneously betatron and chromatic oscillations.



OFF-ENERGY DYNAMIC APERTURE