7th FCC Physics Workshop, Annecy, 1 Feb, 2024

ESRF | The European Synchrotron

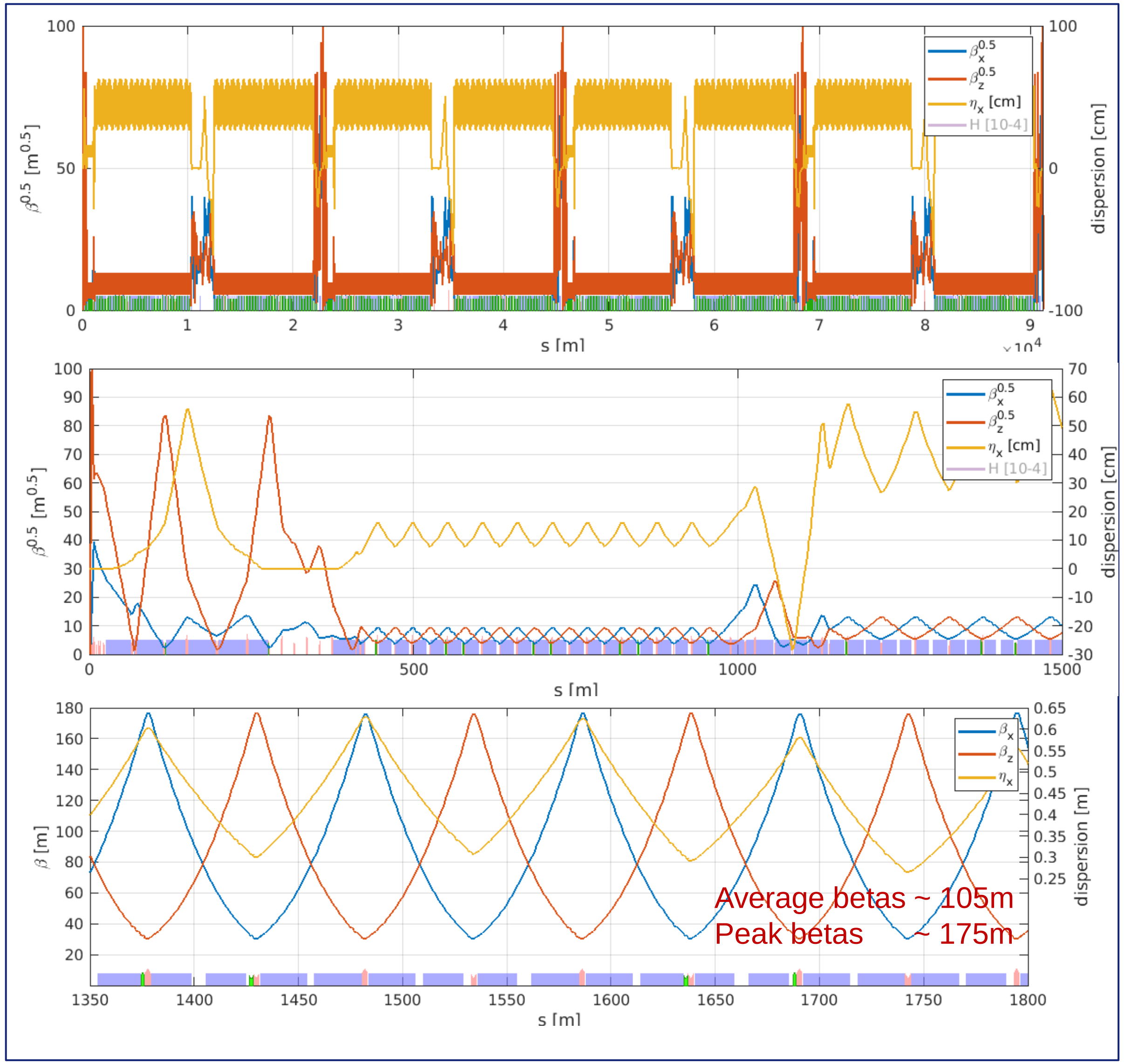
Optimization of machine performance at the Z-pole: COMPARISON OF OPTICS

S.M.Liuzzo, ESRF, Grenoble
P.Raimondi, CERN, Geneva and SLAC, California, USA
M.Hofer, CERN Geneva

Many thanks to the all the members of *FCC-ee optics* and *FCC-ee tuning* groups for the constructive and valuable help.
Many thanks to the ESRF computing cluster resources and the colleagues making those resources available.

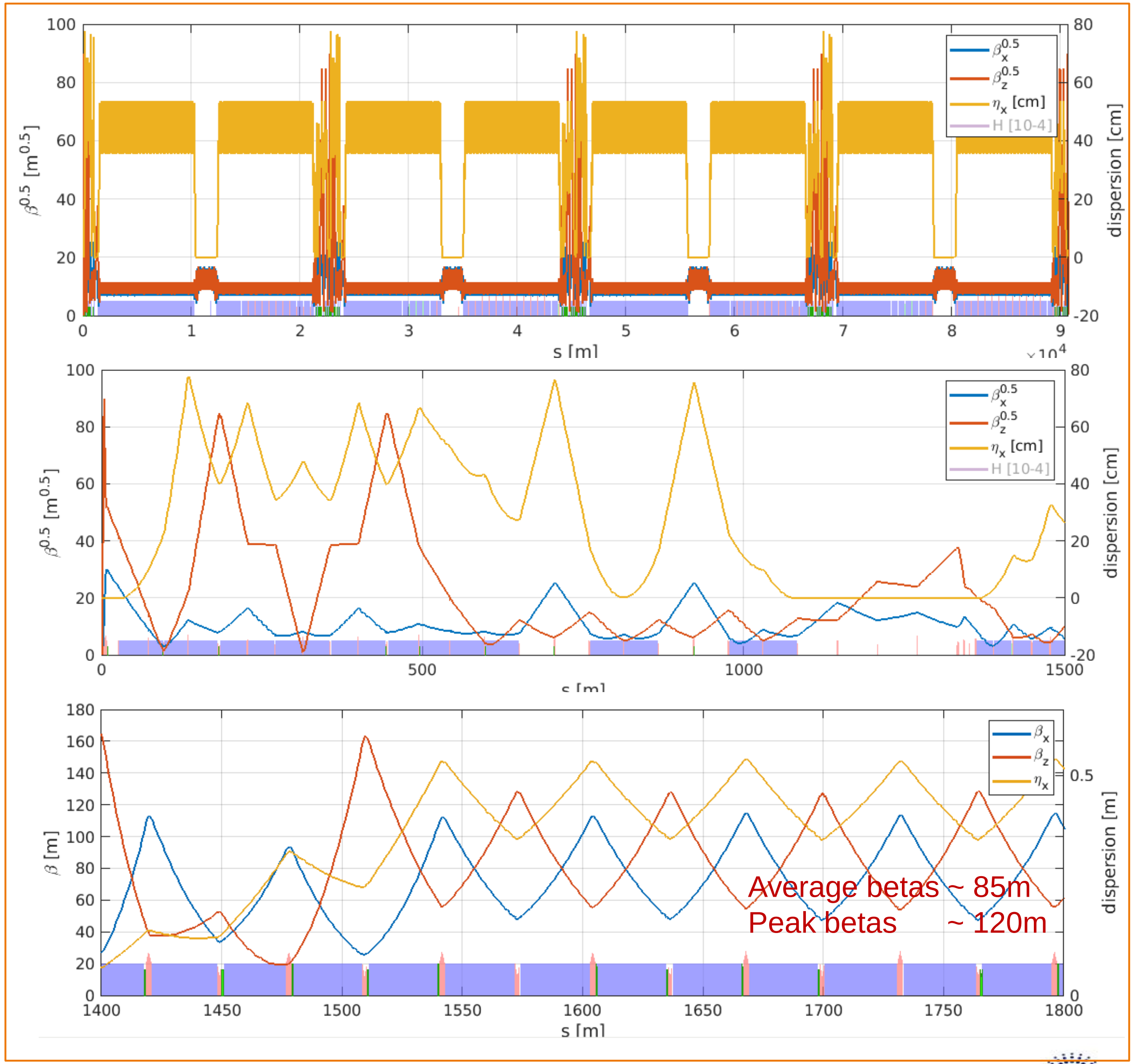
PRESENT OPTICS FOR FCC-EE: LATTICE LAYOUT FOR ARCS AND FINAL FOCUS

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



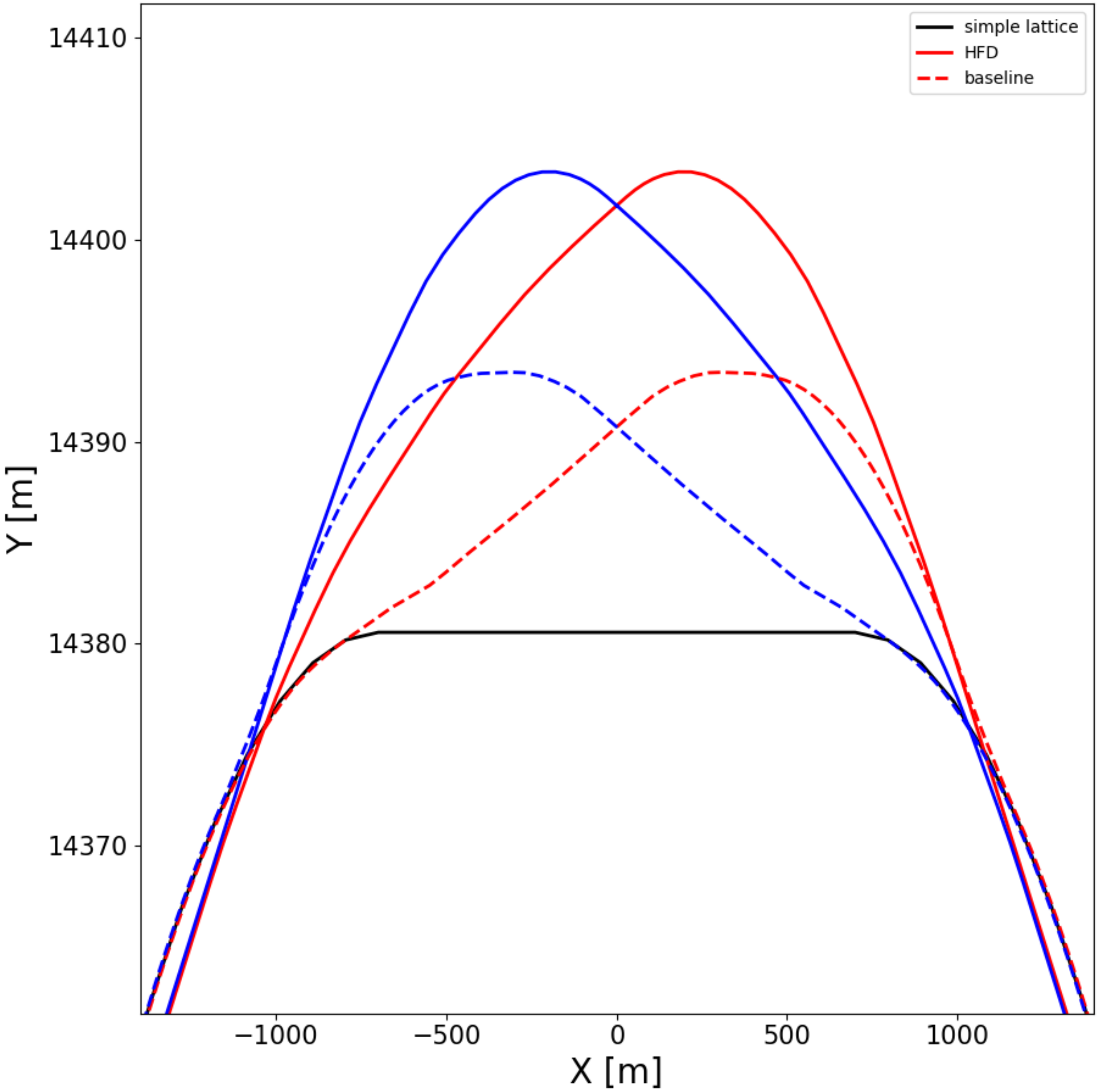
Average betas ~ 105m
Peak betas ~ 175m

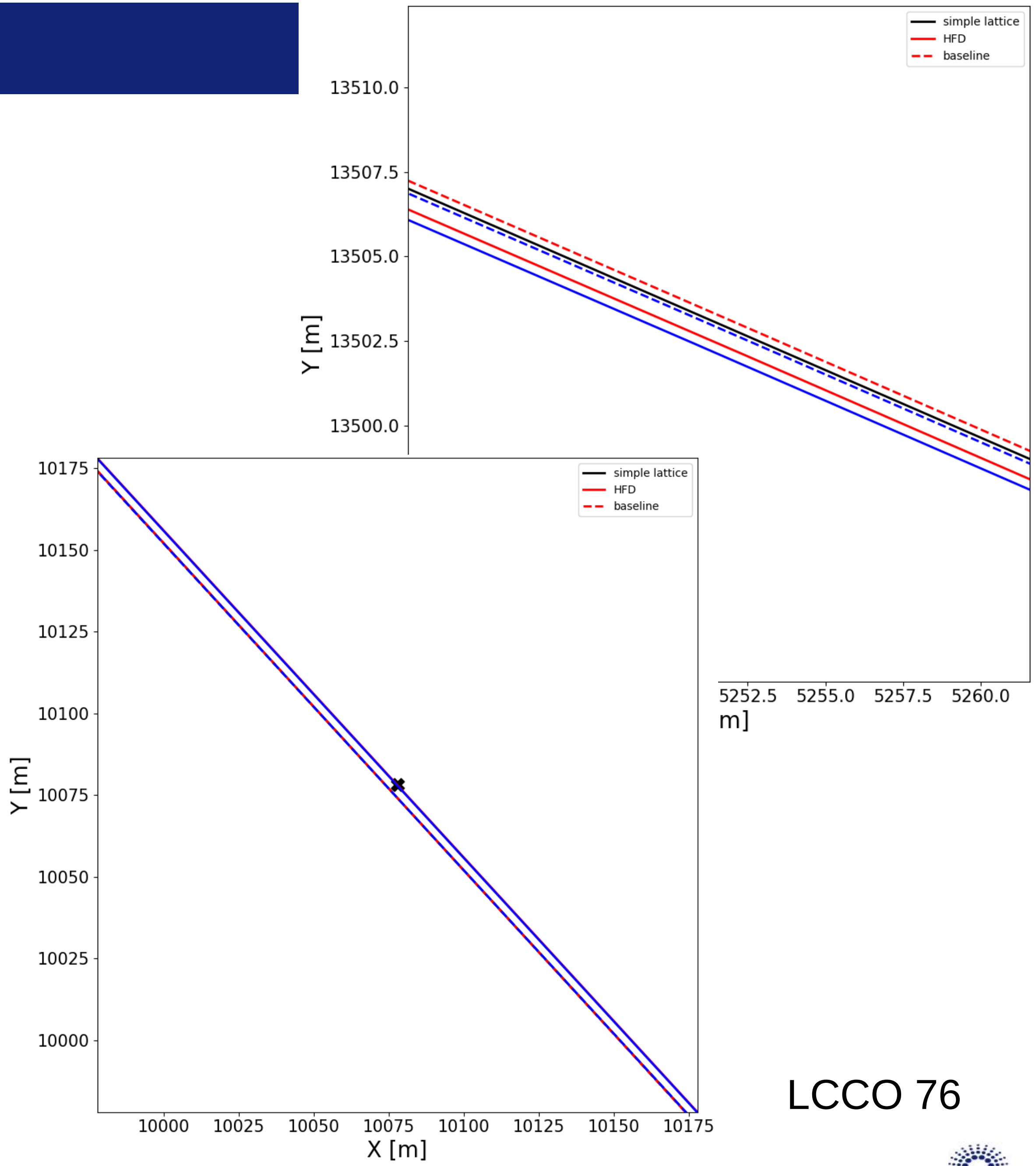
LCCO-89 (P.Raimondi, https://indico.cern.ch/event/1326738/timetable/#45-alternative-optics-and-vari)



Average betas ~ 85m
Peak betas ~ 120m

FOOT-PRINT





LCCO 76

BEAM PARAMETERS

	units	V22@Z 45.6 GeV	LCCO-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

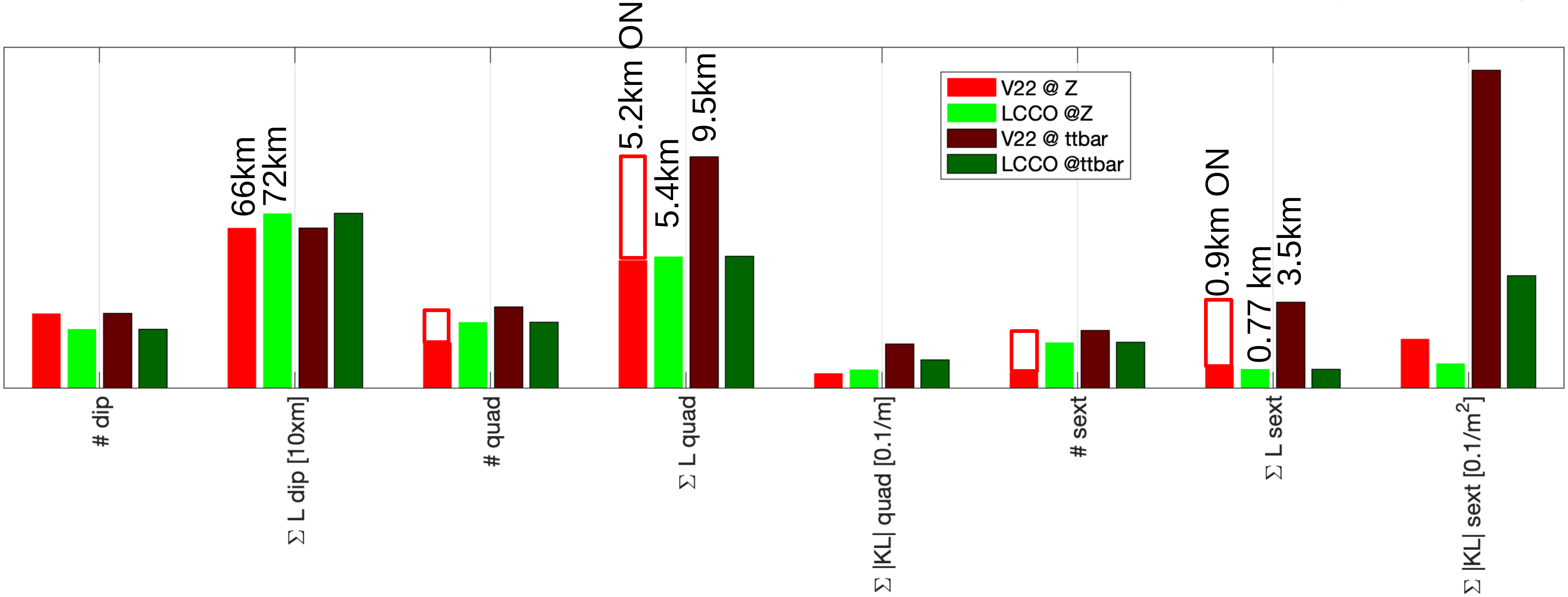
Quantum diffusion is not included in the following studies (available).

https://github.com/atcollab/at

Fully benchmarked with MADX-PTC

NUMBER OF MAGNETIC ELEMENTS AND GRADIENTS

Including Crab sextupoles

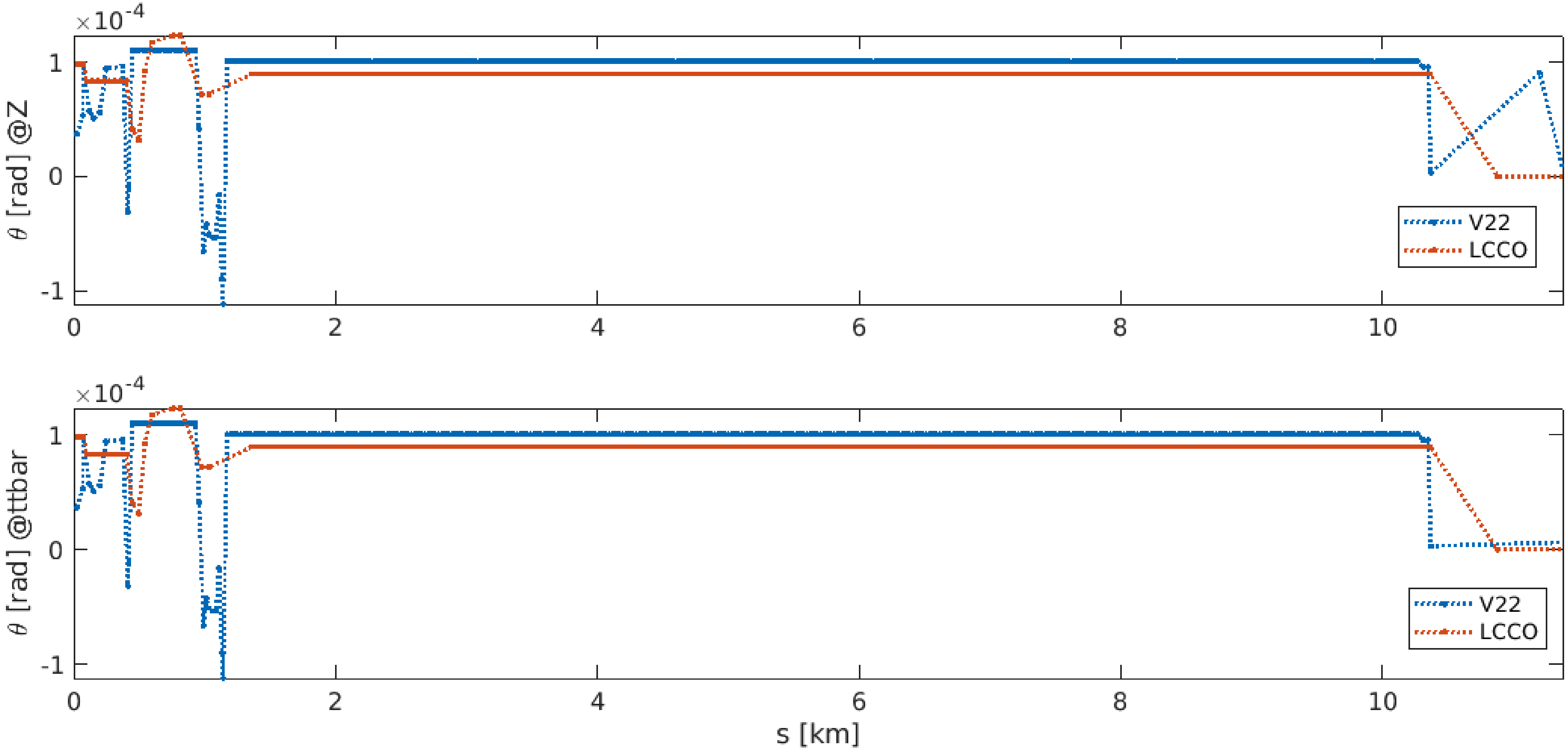


Only magnet gradients change. White boxes for baseline correspond to magnet off at Z.

LCCO sextupole's at ttbar have**: 1) smaller KL, 2) there are ~500 less and 3) they are shorter.**

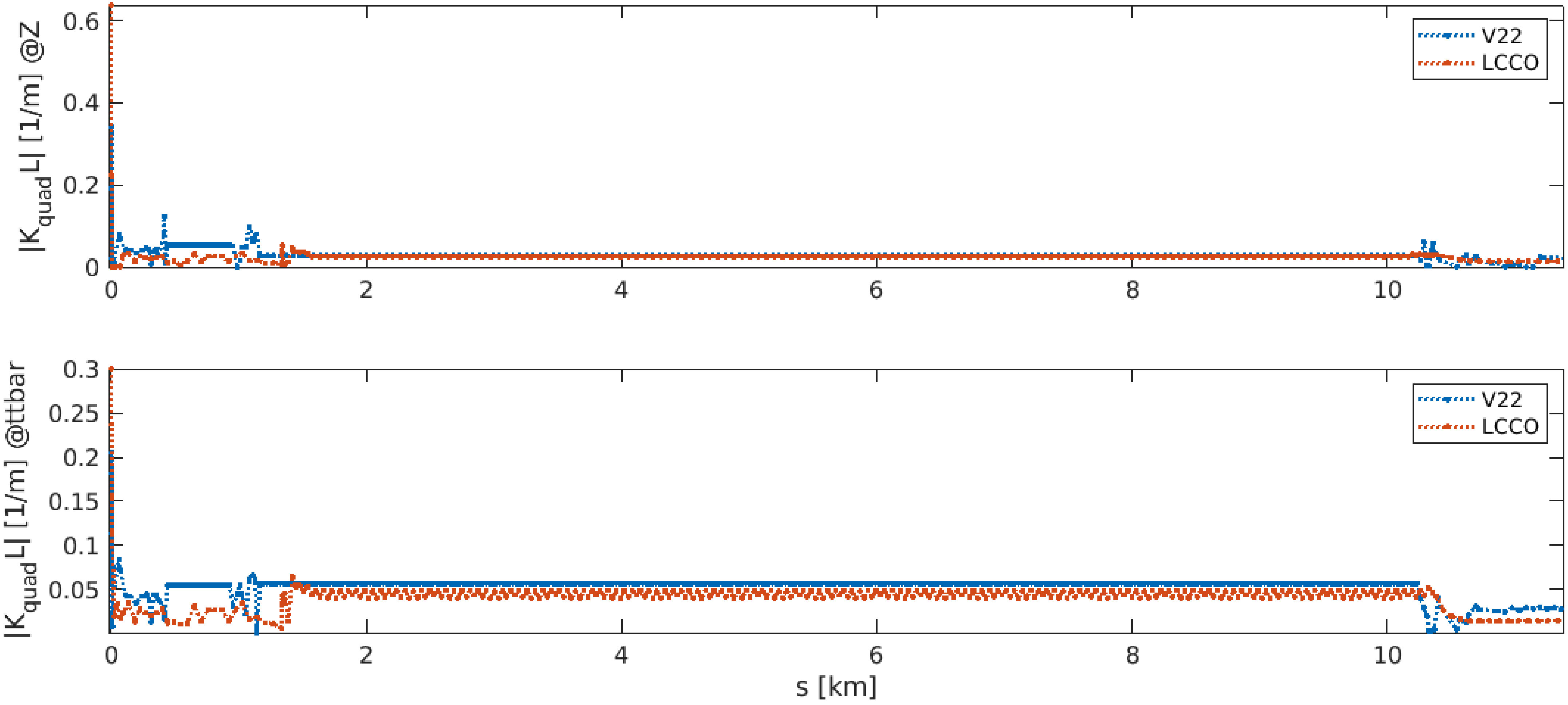
machfs/liuzzo/FCC/89a2/ANALYSIS/CompareSextupole.m

DIPOLE FIELDS (1 OCTANT)



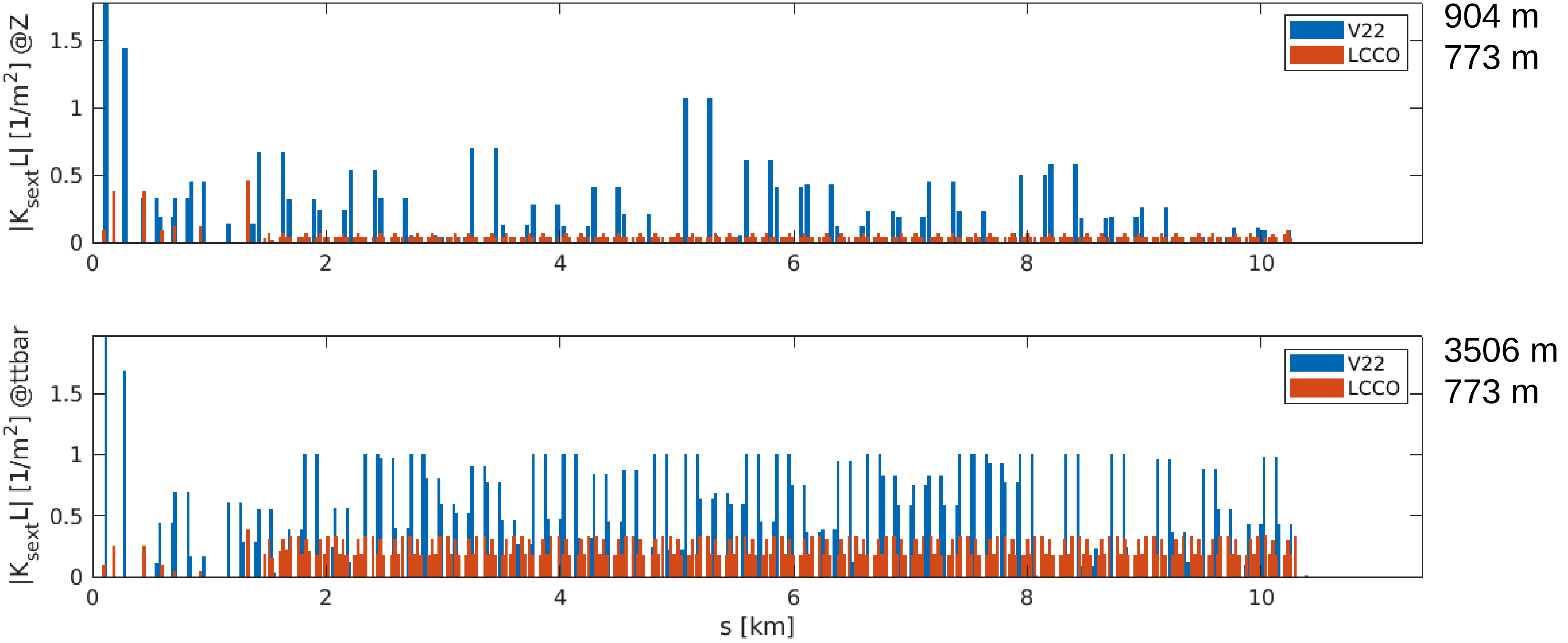
No negative angle bends for LCCO optics → easier synchrotron radiation absorption scheme

QUADRUPOLE GRADIENTS (1 OCTANT)



Lower gradients for quadrupoles for LCCO optics (apart final doublet)

SEXTUPOLES GRADIENTS (1 OCTANT)



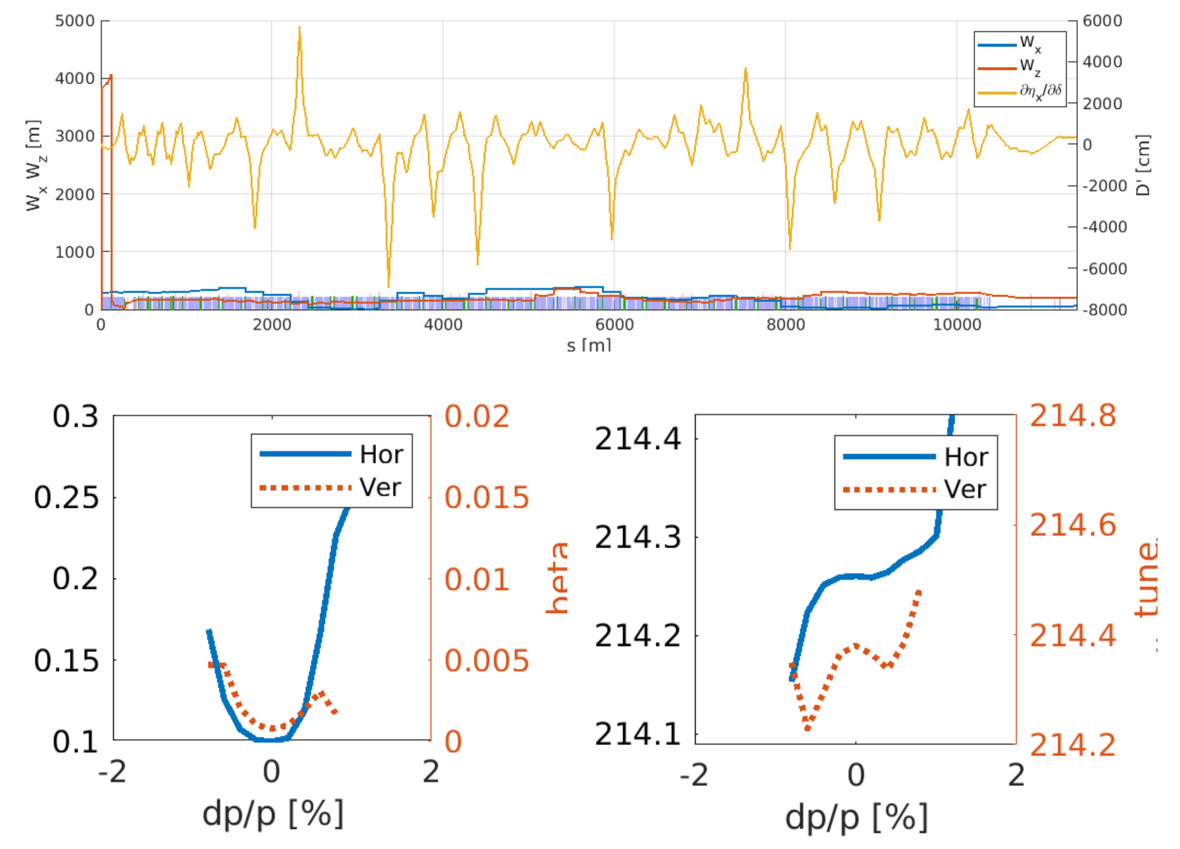
904 m
773 m

3506 m
773 m

Smaller sextupole gradients ➔ Usually better performances.

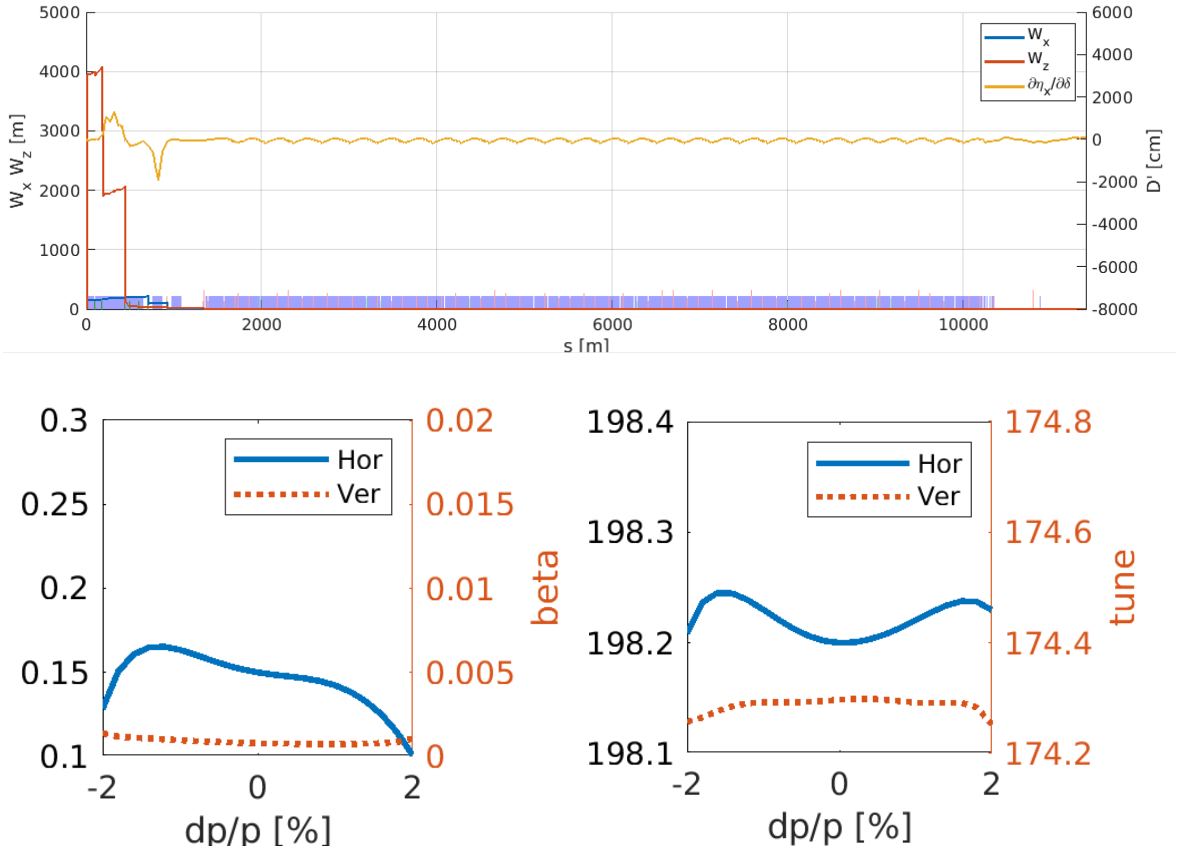
OFF ENERGY ELECTRON BEAM OPTICS: W FUNCTIONS, IP OPTICS AND PHASE ADVANCE AT CRAB SEXT.

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



Missing line = Optics computation failed

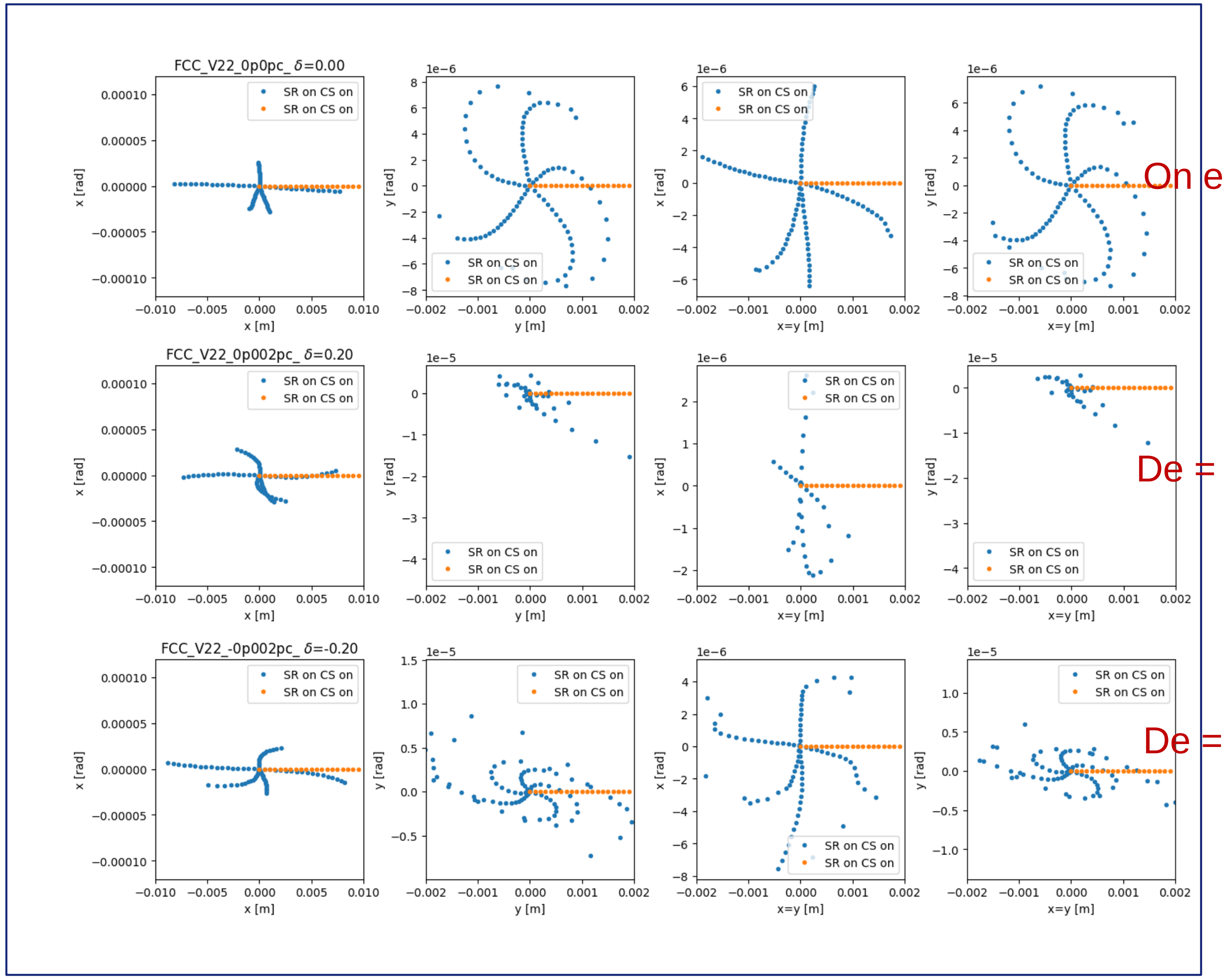
LCCO-89 (P.Raimondi, https://indico.cern.ch/event/1326738/timetable/#45-alternative-optics-and-vari)



* Negligible luminosity loss due to energy dependent beta*

PHASE SPACE EVOLUTION OVER 5 TURNS ON AND OFF ENERGY

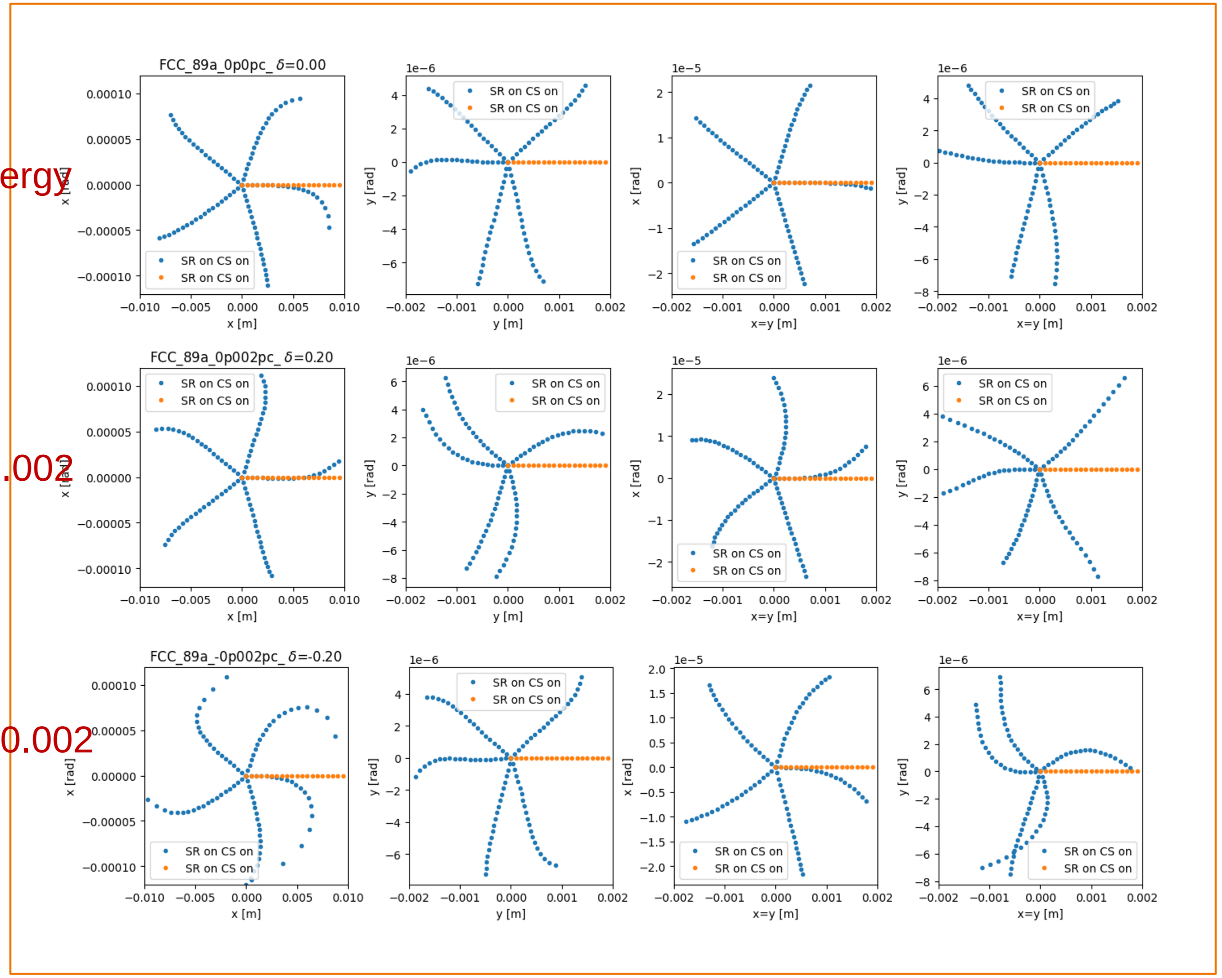
No SR in dipoles (no effect)



On energy

De = 0.002

De = -0.002



SYNCHROTRON RADIATION AND CRAB SEXTUPOLES ON

Starfish plots provide a “quick” overview of the combined effect of all the resonant driving

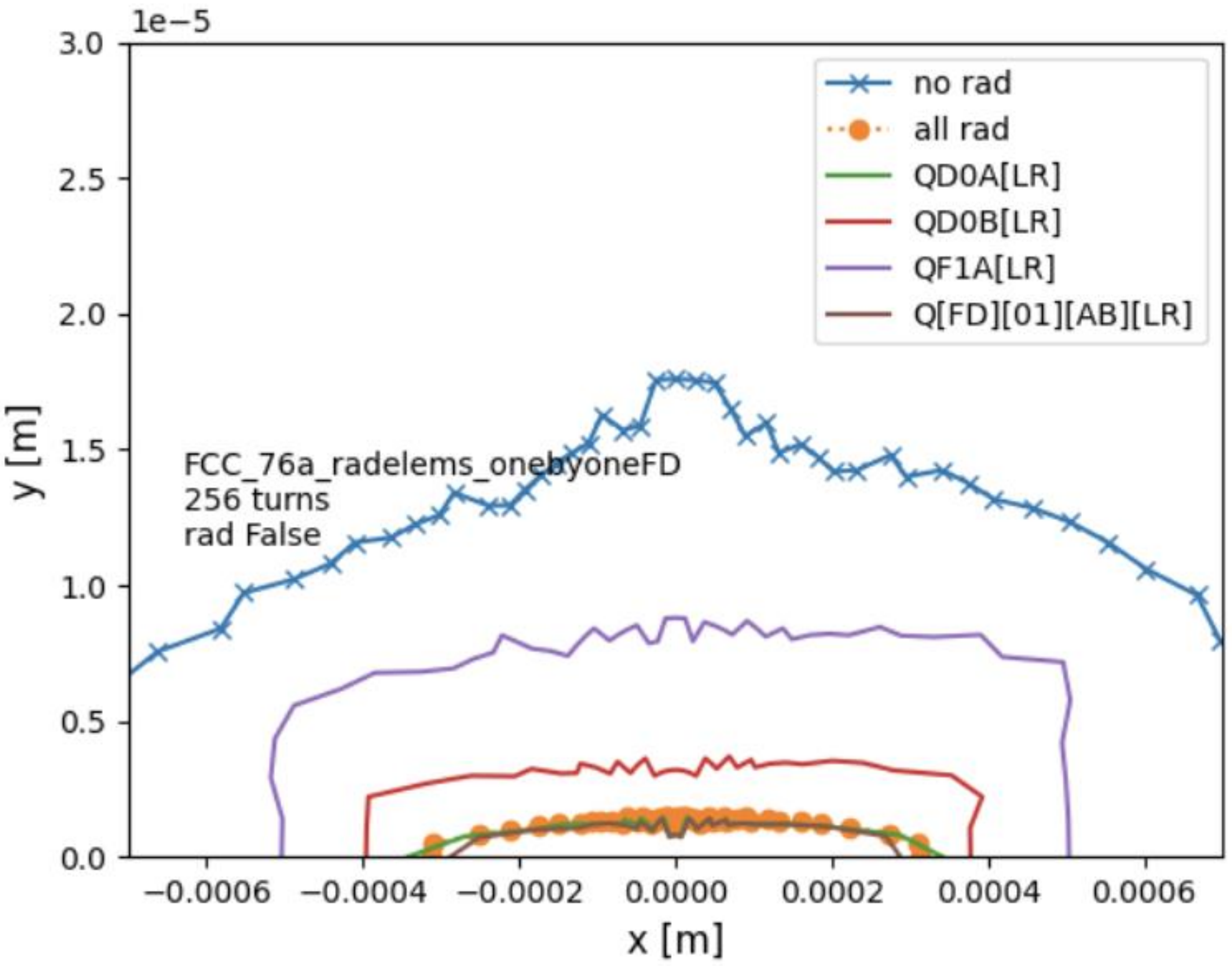
RADIATION IN FINAL DOUBLET QUADRUPOLES

LCCO76

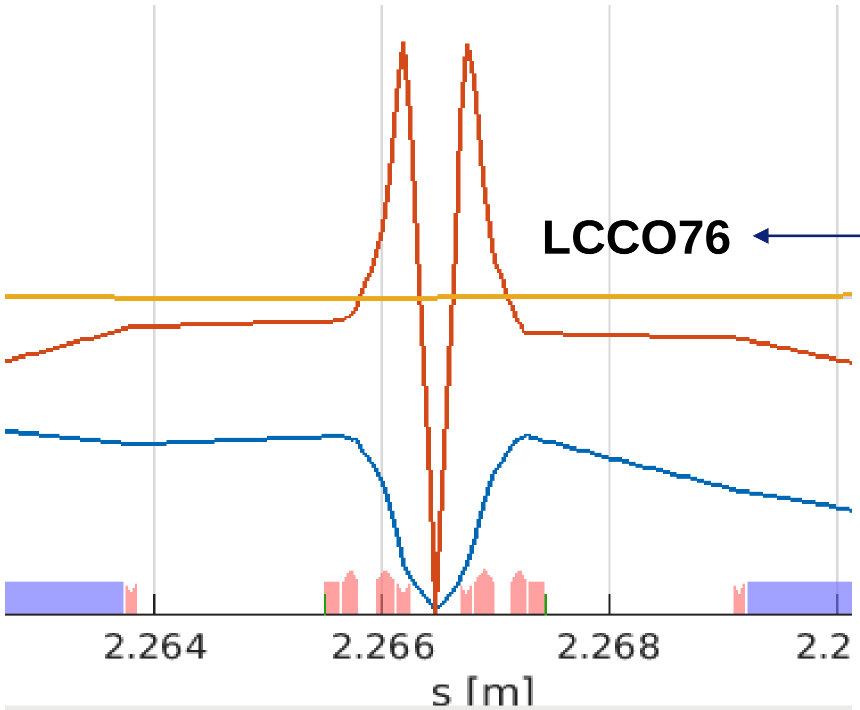
Magnet	Dip	Qarc	Qff	Qfd	ALL
Q[FD][01][AB][LR]	YES				YES
QD0A[LR]		YES			YES
QD0B[LR]			YES		YES
QF1A[LR]				YES	YES

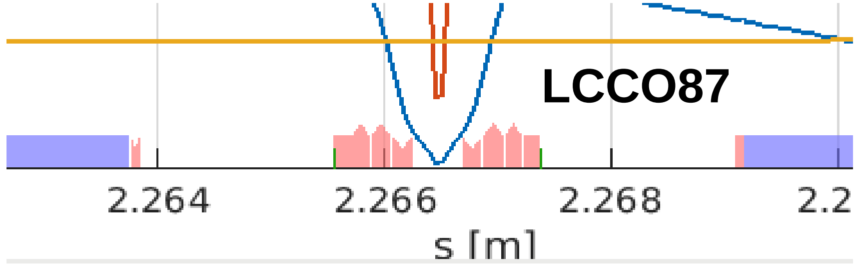
DA is dominated by synchrotron radiation in the final quadrupole doublet.

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



MODIFIED LAYOUT AND ADDITIONAL DECAPOLES TO MITIGATE FINAL DOUBLET SYNCHROTRON RADIATION



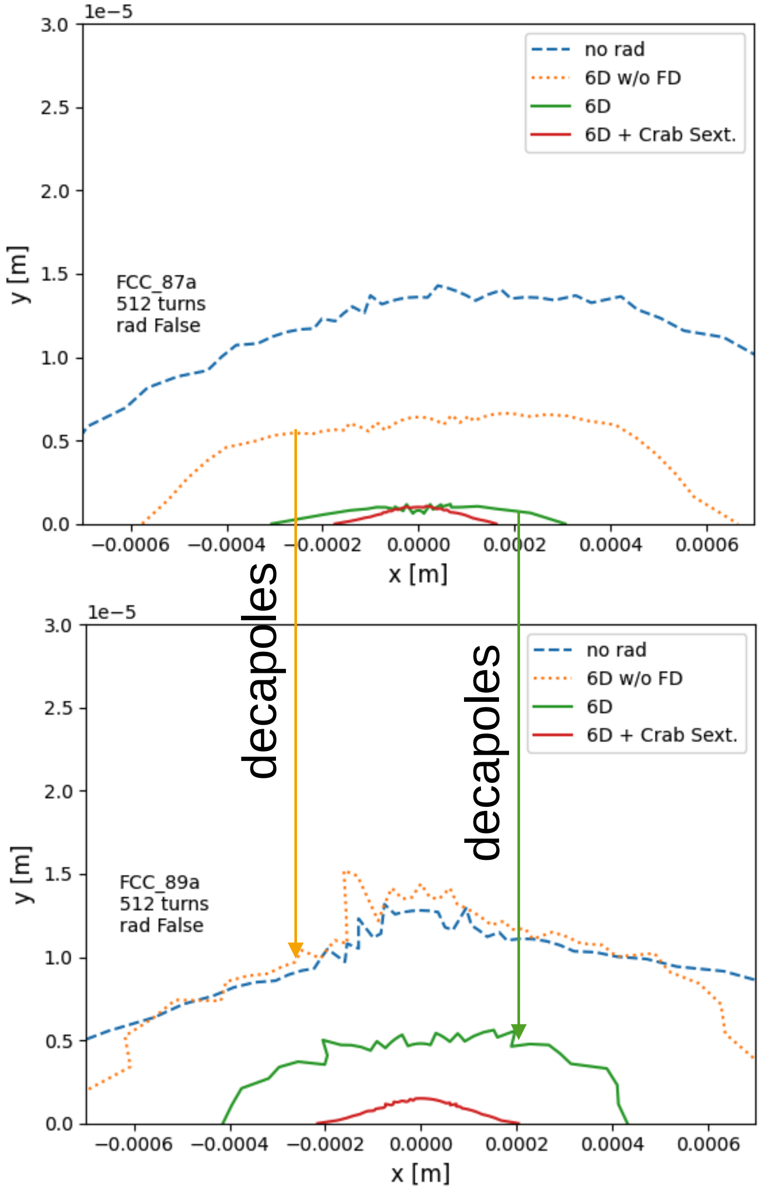


LCCO87 FD optimized to reduce SR and DA-shrinkage due to SR

LCCO89 = + 3 DECAPOLE pairs to in the Final Focus

The effectiveness of the DECAPOLES is evident.

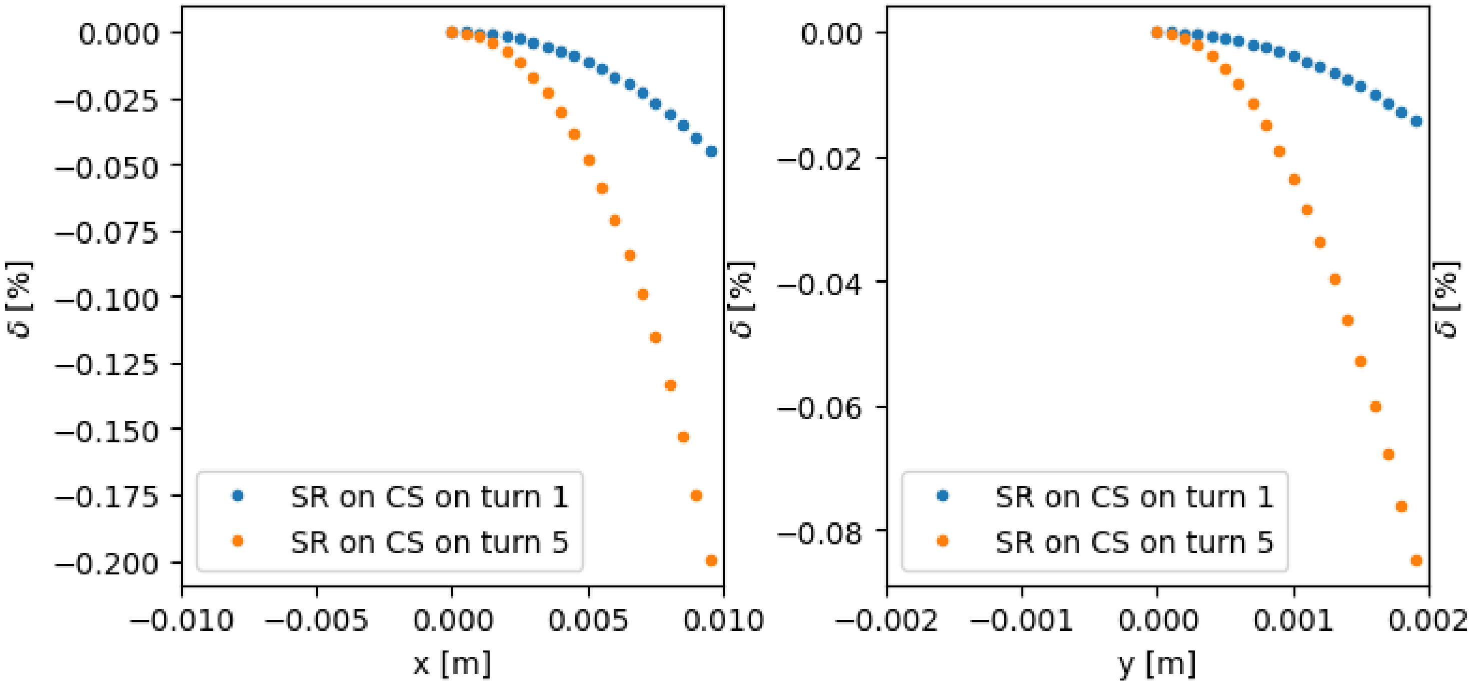
This is probably the first time that the degradation due to the quadrupoles-SR and FD-SR in particular is very effectively addressed



ENERGY LOSS DUE TO FINAL DOUBLET RADIATION

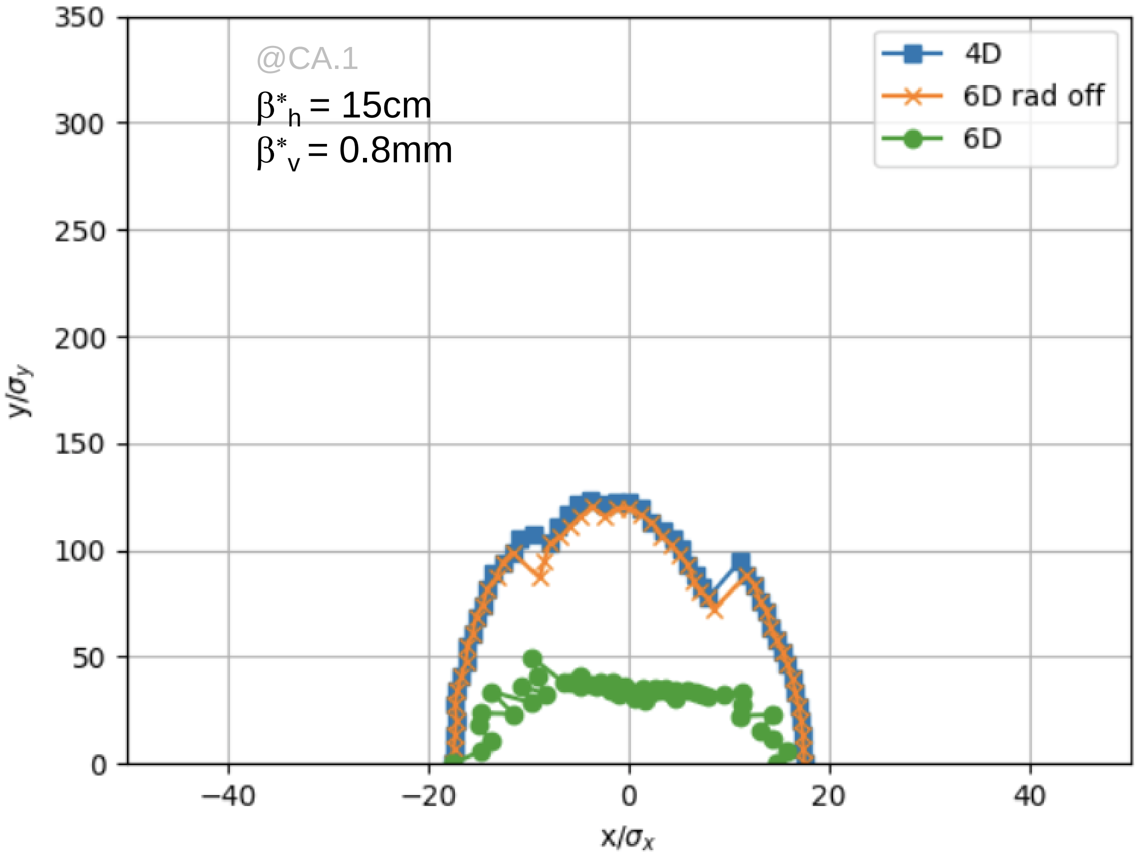
Energy loss induced by final doublet SR only.

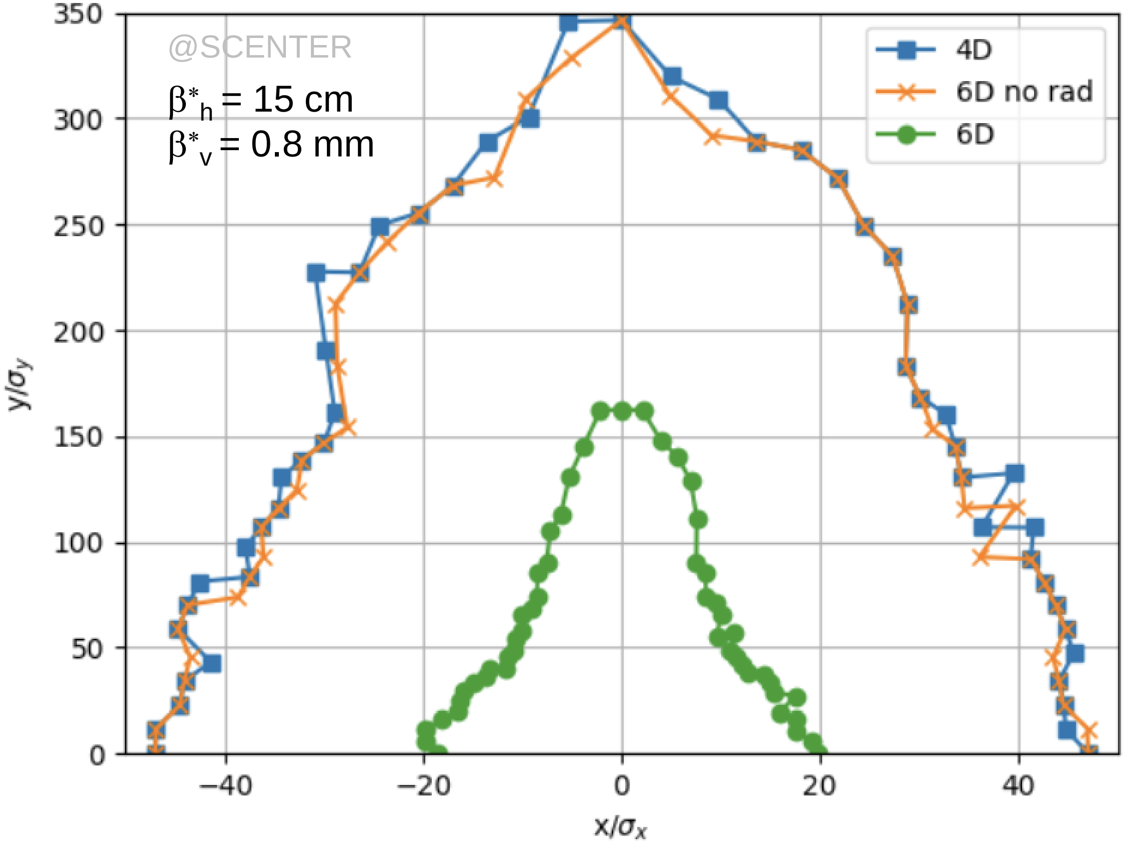
Similar for the two lattices.
After 160 turns the beam loses 2% and is lost out of MA.
The RF helps to recover the energy loss and the DA might improve by optimizing the RF voltage



DYNAMIC APERTURE

6D tracking for 2350 turns, with quantum diffusion (1 seed) starting from straight sections, Crab sext. ON. $\varepsilon_v = 0.2\% \, \varepsilon_h$





LCCO includes countermeasures (decapoles) for synchrotron radiation in Final Doublet

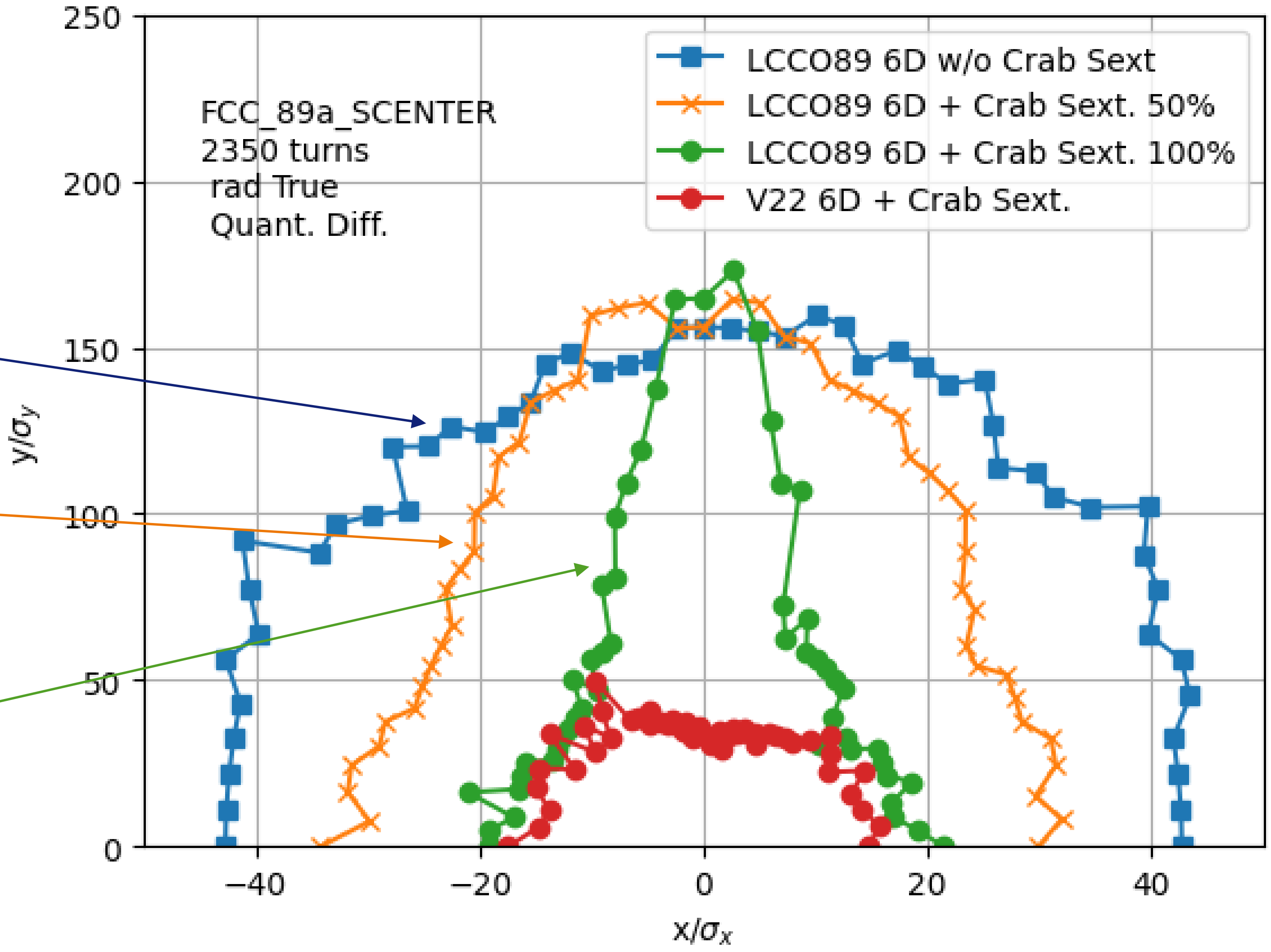
DYNAMIC APERTURE AT STRAIGHT SECTION

Crab 100% = 80% of geometric value

Commissioning

Tuning with progressive increase of Crab sextupoles.

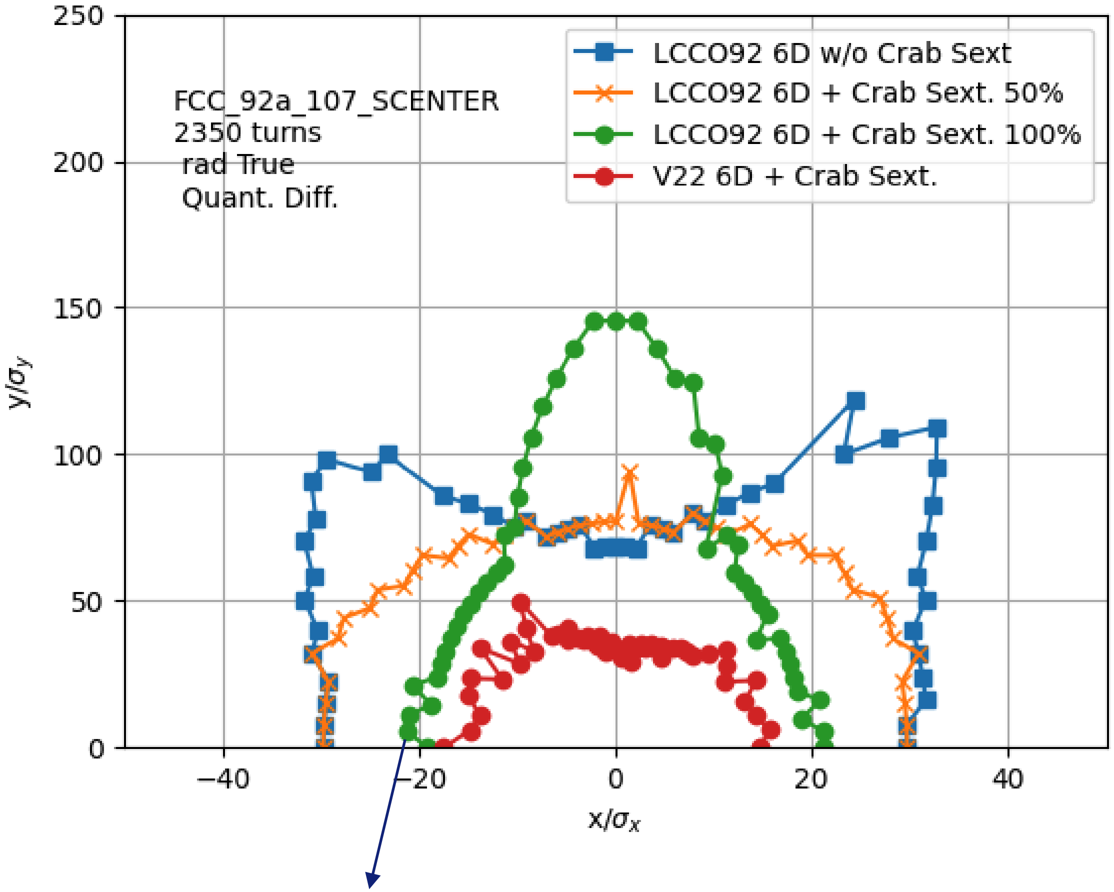
Final configuration for Luminosity production.

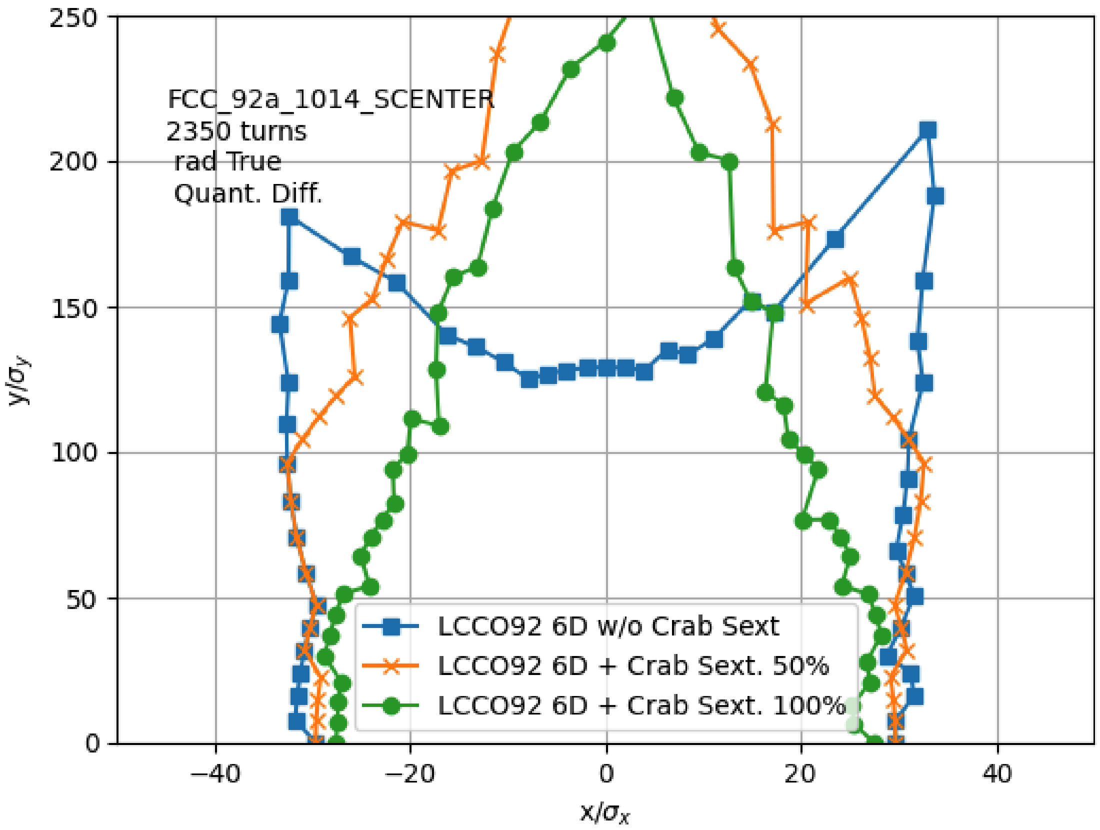


UP TO DATE IP BETA* AND CORRESPONDING RELAXED OPTICS LCCO92

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

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

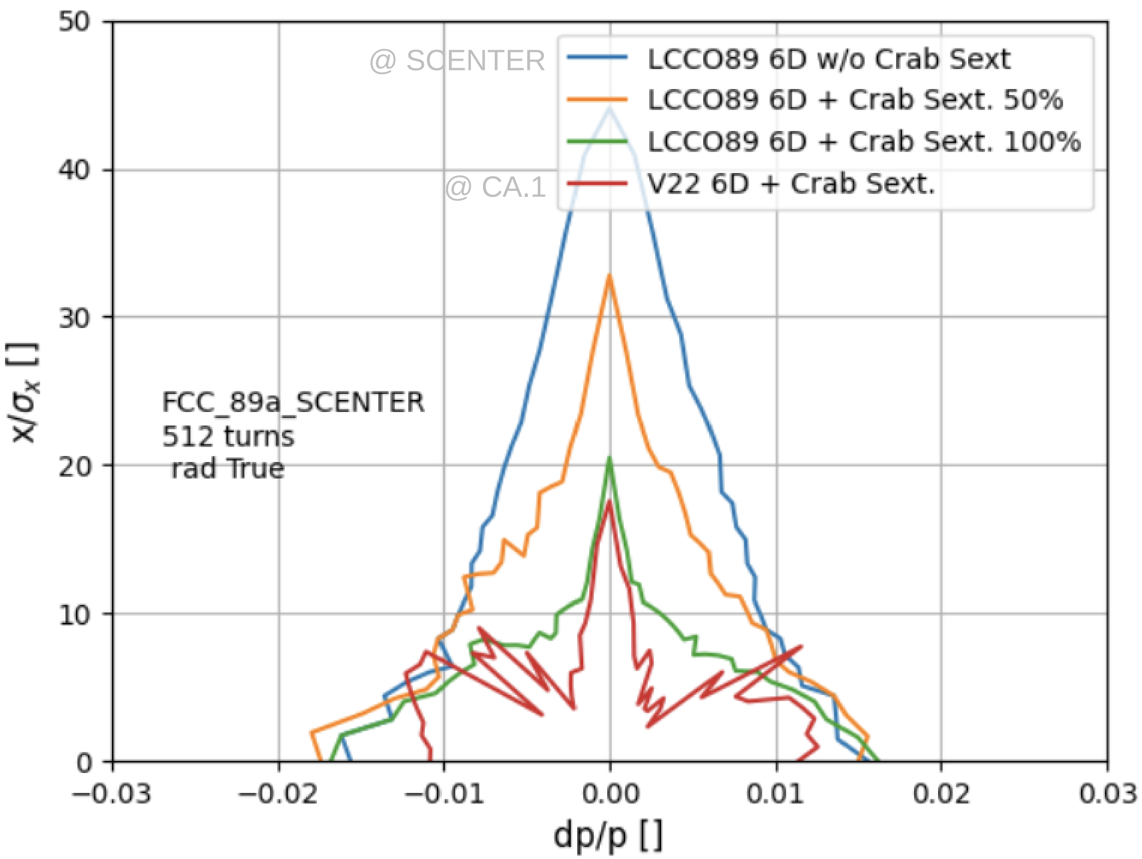


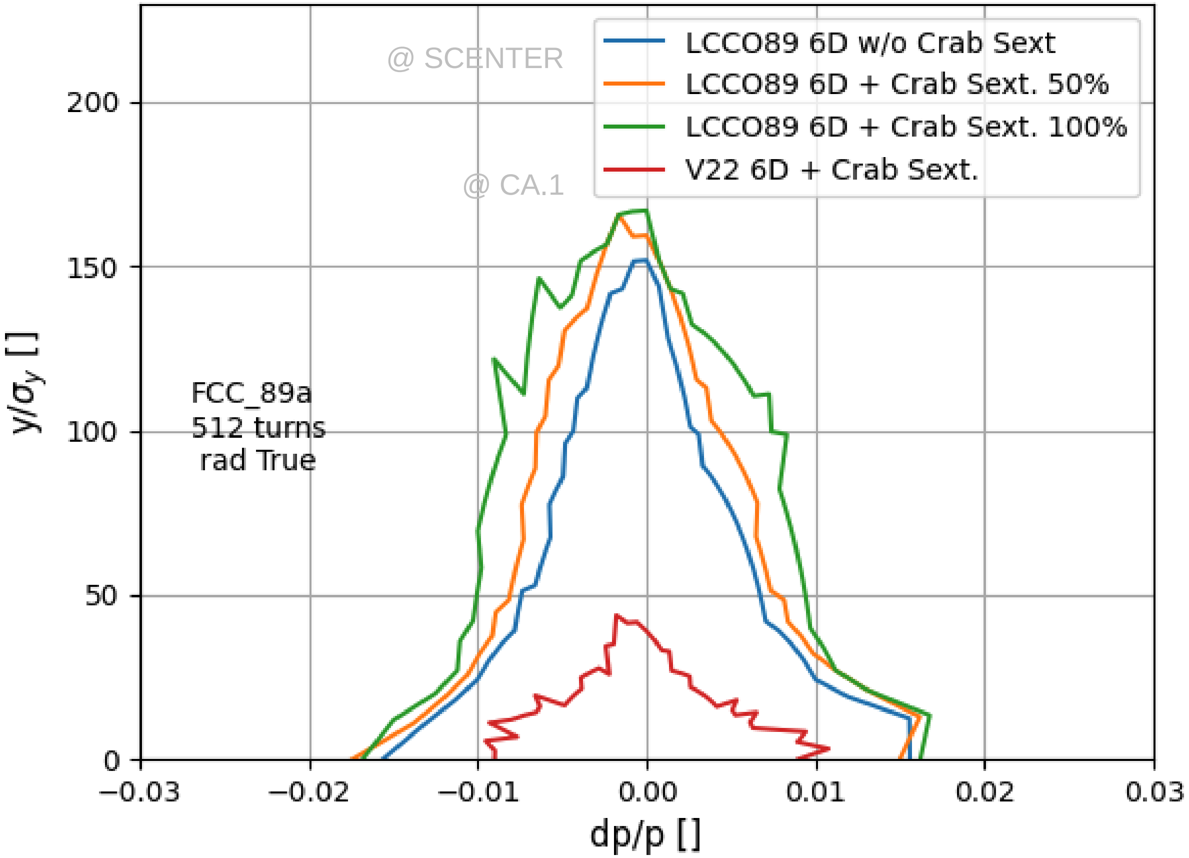


β^*_h=10cm, β^*_v=0.7mm give DA larger in Hor. and Ver. with respect to **β^*_h=15cm, β^*_v=0.8mm**

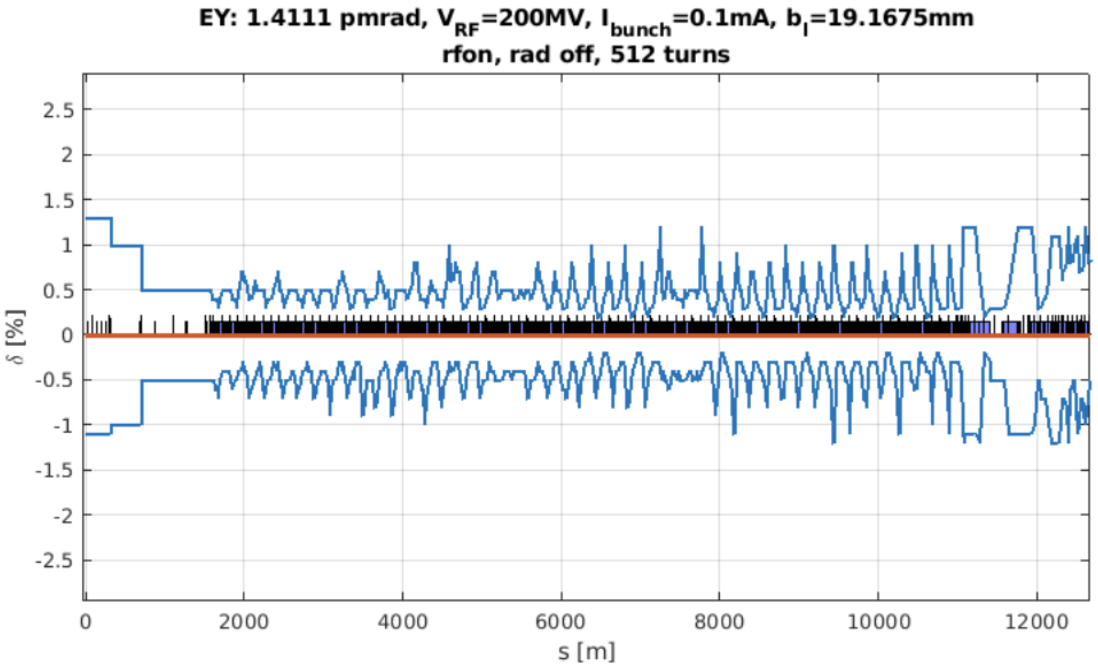
Decapoles optimized ONLY for “CRAB Sext. 100%” (80% of geometric value)

OFF-ENERGY DYNAMIC APERTURE

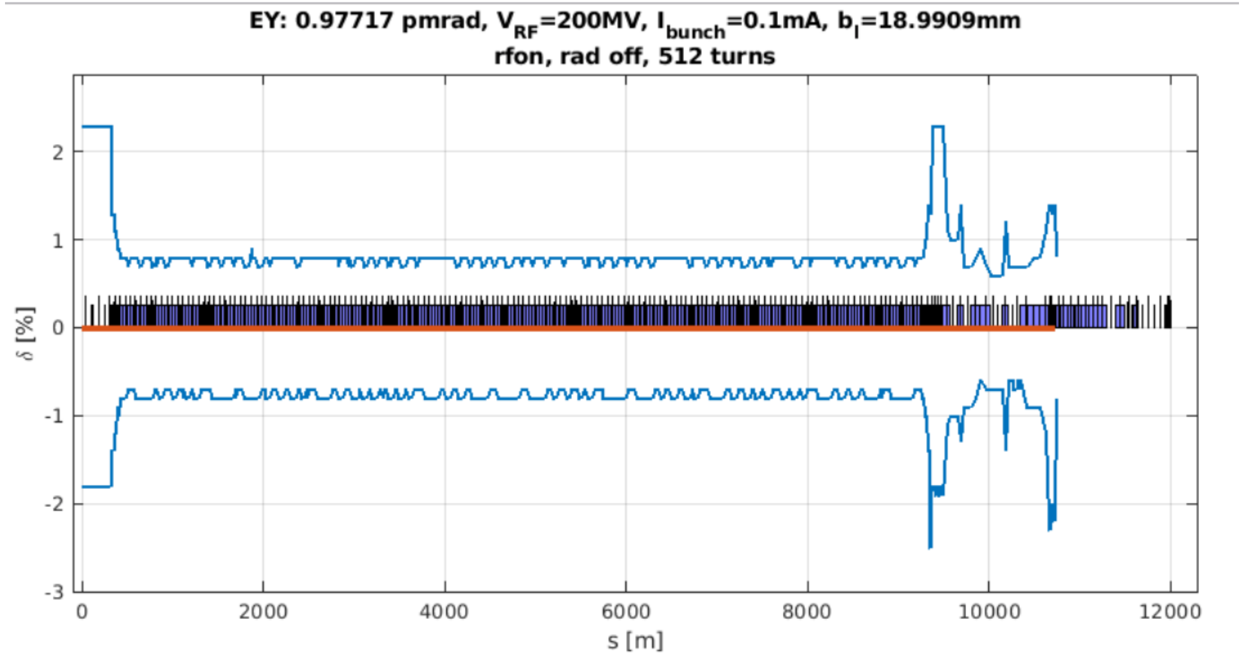




LOCAL MOMENTUM ACCEPTANCE NO SYNCHROTRON RADIATION (OPTIMISTIC)


EY: 1.4111 pmrad, V_{RF}=200MV, I_{bunch}=0.1mA, b_l=19.1675mm
rfon, rad off, 512 turns

LCCO 76


EY: 0.97717 pmrad, V_{RF}=200MV, I_{bunch}=0.1mA, b_l=18.9909mm
rfon, rad off, 512 turns

6.5h

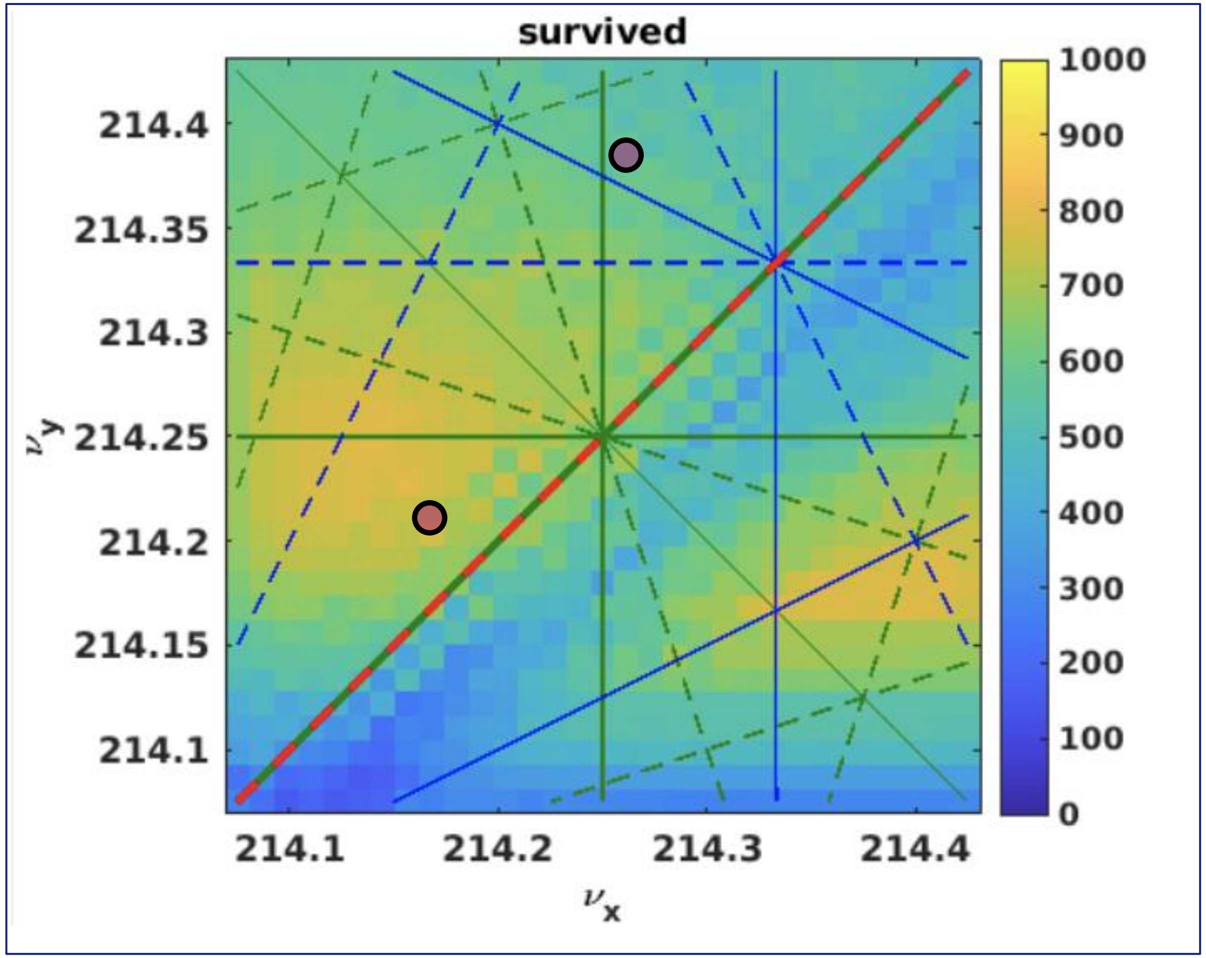
$$\tau_{Tou.,bunch} \propto \frac{\boxed{\delta^3}\sqrt{\epsilon_v}\sqrt{\epsilon_h}\sigma_l}{I_{bunch}}$$

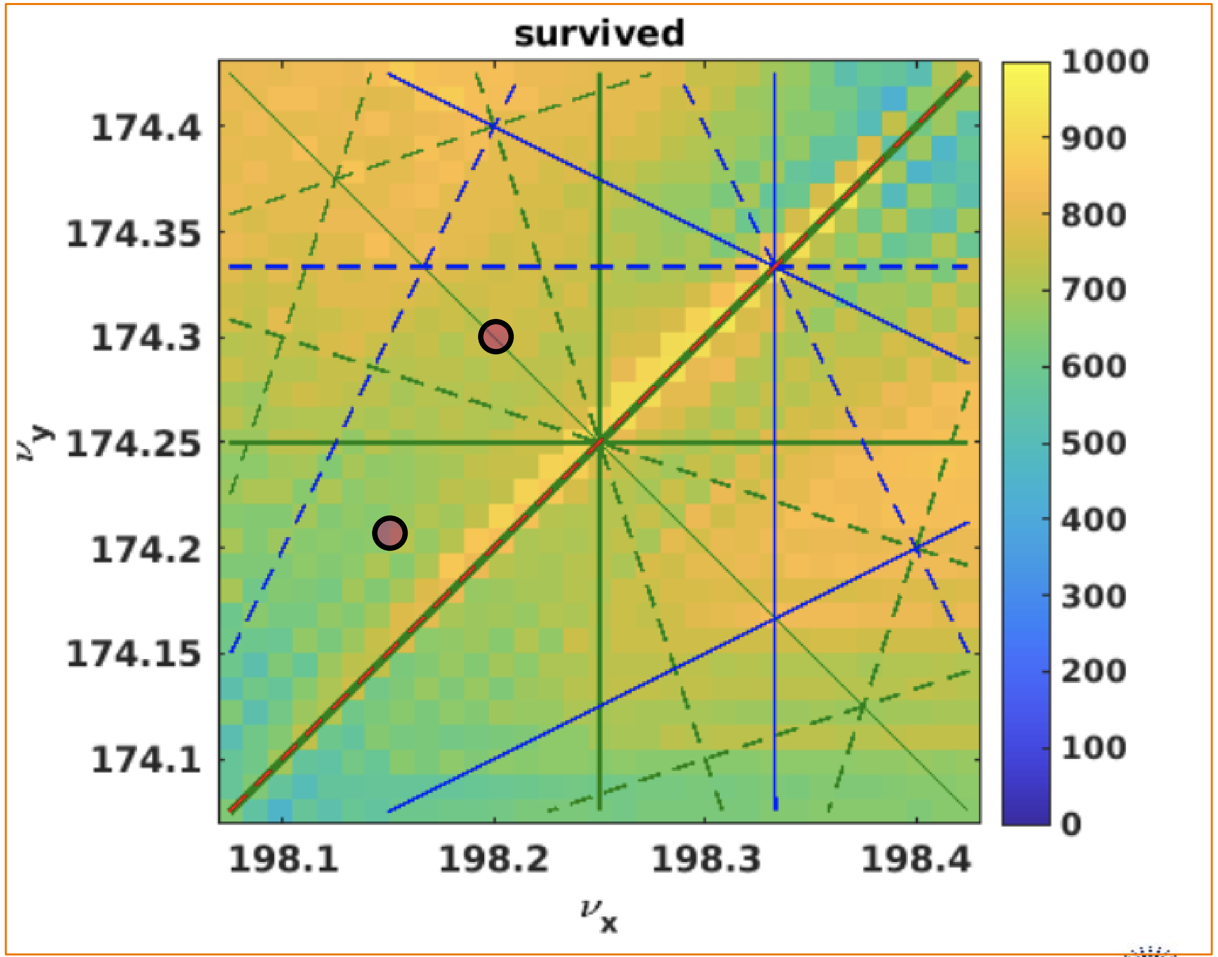
12.2h

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

STABILITY ABOUT TUNE WORKING POINT

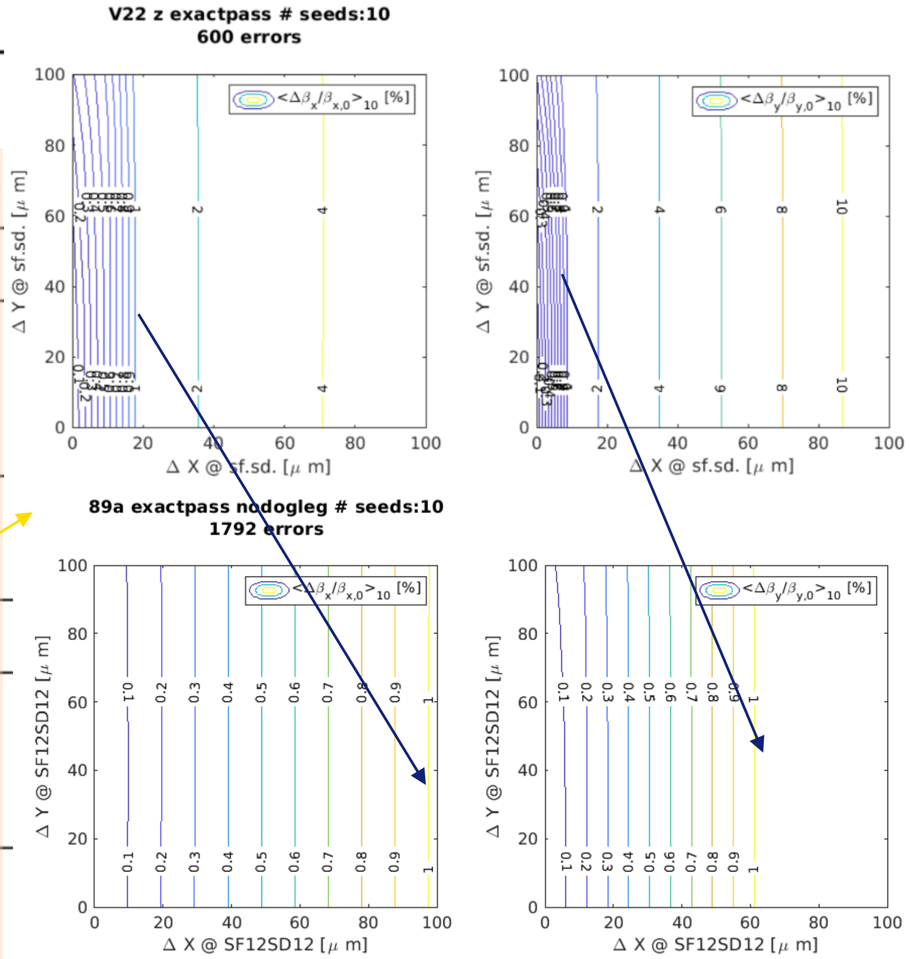
Track a 3D grid of 1000 particles of size: $20\sigma_x$ x $20\sigma_y$ x 0.002 $\delta p/p$ for 512 turns for different tunes.
Tune varied using ARC quadrupoles. Chromaticity corrected to initial value after tune change.
Small (10 nm) random errors added to all elements (to emphasize resonance lines).





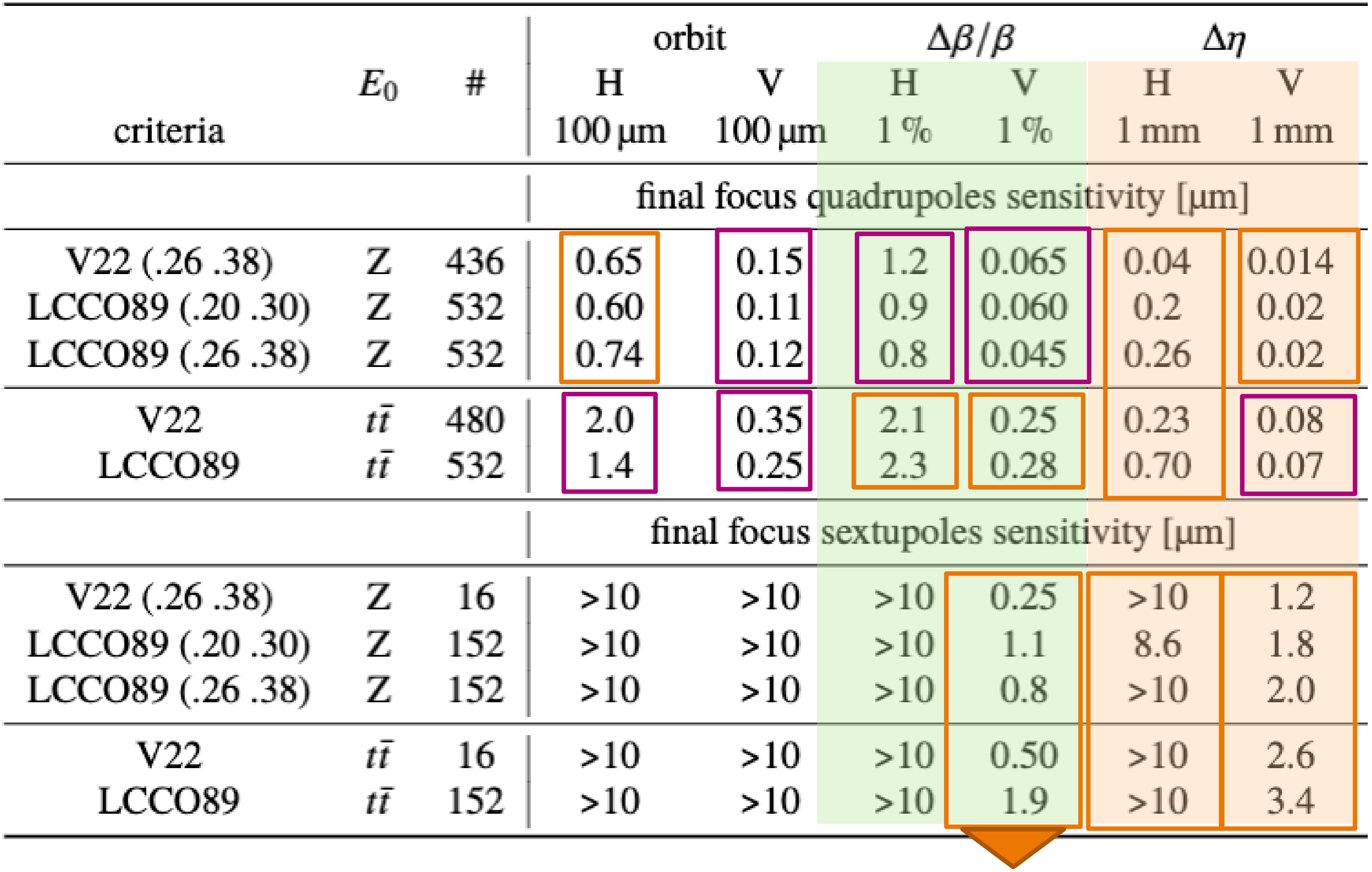
ARC ALIGNMENT SENSITIVITIES

criteria	E_0	#	orbit		$\Delta\beta/\beta$		$\Delta\eta$	
			H	V	H	V	H	V
			100 µm	100 µm	1 %	1 %	1 mm	1 mm
			arc quadrupoles sensitivity [µm]					
V22 (.26 .38	Z	1420	1.9	1.9	2.9	0.7	0.1	0.1
LCCO89 (.20 .30)	Z	2168	1.7	1.4	5.3	0.4	0.2	0.24
LCCO89 (.26 .38)	Z	2168	2.0	1.6	6.1	0.5	0.9	0.26
V22	$t\bar{t}$	2836	1.3	1.5	1.5	0.5	0.12	0.2
LCCO89	$t\bar{t}$	2168	1.3	0.9	2.1	0.45	1.0	0.3
			arc sextupoles sensitivity [µm]					
V22 (.26 .38)	Z	600	>100	>100	17	8.5	3.1	2.6
LCCO89 (.20 .30)	Z	1792	>100	>100	97	61	12	10
LCCO89 (.26 .38)	Z	1792	>100	>100	>100	46	14	10
V22	$t\bar{t}$	2336	>100	>100	10	7.0	7.5	10
LCCO89	$t\bar{t}$	1792	>100	>100	22	15	12	11



LCCO ARC errors sensitivities are always better (apart sextupoles induced vertical dispersion)

FINAL FOCUS ALIGNMENT SENSITIVITY



			orbit		$\Delta\beta/\beta$		$\Delta\eta$	
	E_0	#	H	V	H	V	H	V
criteria			100 µm	100 µm	1 %	1 %	1 mm	1 mm
			final focus quadrupoles sensitivity [µm]					
V22 (.26 .38)	Z	436	0.65	0.15	1.2	0.065	0.04	0.014
LCCO89 (.20 .30)	Z	532	0.60	0.11	0.9	0.060	0.2	0.02
LCCO89 (.26 .38)	Z	532	0.74	0.12	0.8	0.045	0.26	0.02
V22	$t\bar{t}$	480	2.0	0.35	2.1	0.25	0.23	0.08
LCCO89	$t\bar{t}$	532	1.4	0.25	2.3	0.28	0.70	0.07
			final focus sextupoles sensitivity [µm]					
V22 (.26 .38)	Z	16	>10	>10	>10	0.25	>10	1.2
LCCO89 (.20 .30)	Z	152	>10	>10	>10	1.1	8.6	1.8
LCCO89 (.26 .38)	Z	152	>10	>10	>10	0.8	>10	2.0
V22	$t\bar{t}$	16	>10	>10	>10	0.50	>10	2.6
LCCO89	$t\bar{t}$	152	>10	>10	>10	1.9	>10	3.4

Better for V22

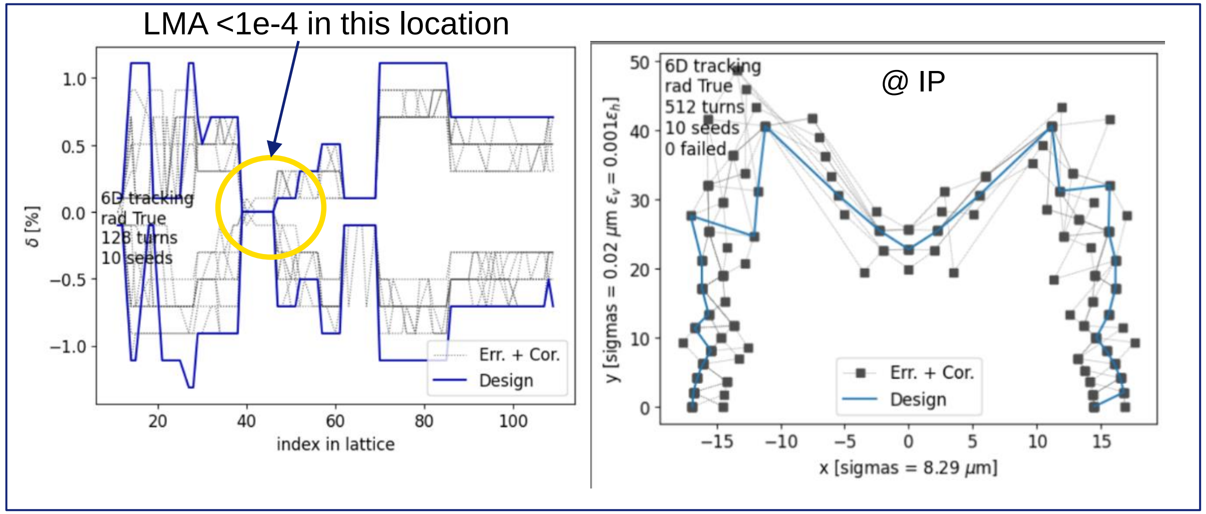
Better for LCCO

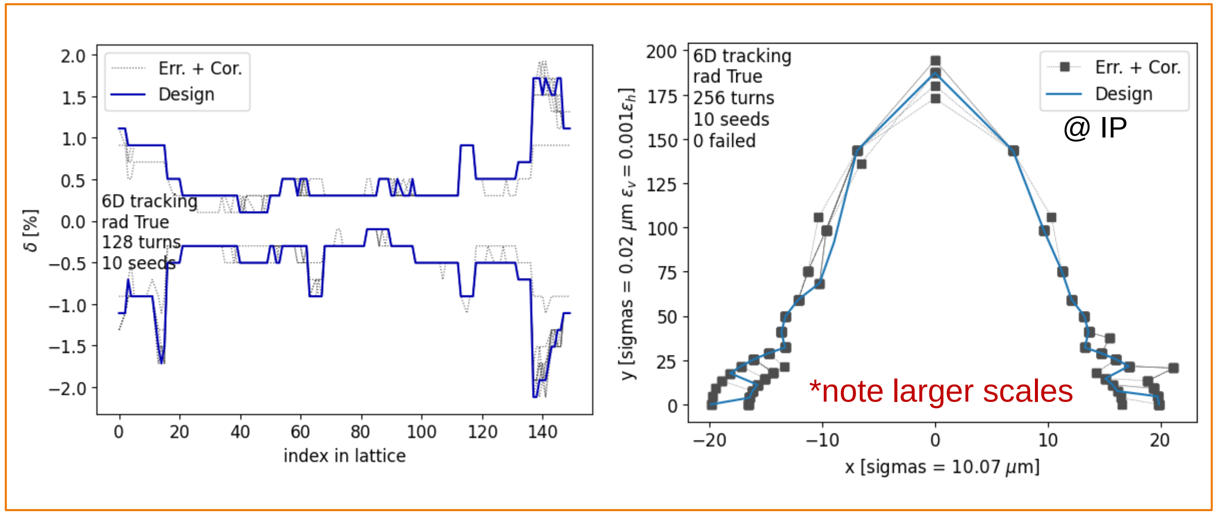
~4x better for LCCO

Orbit in FF sextupoles has to be maintained at this level during operation

ERROR TOLERANCES: COMMISSIONING SIMULATIONS

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





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).
This **is in contrast with previous tracking** simulations results*, see tables below for V22.

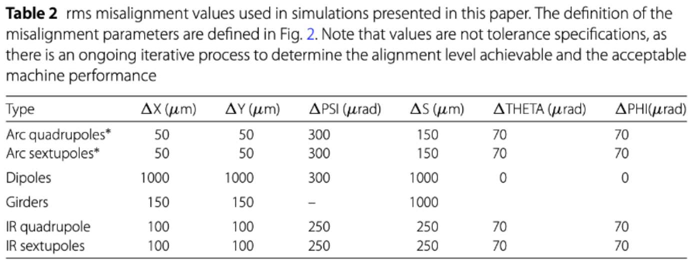


Table 2 rms misalignment values used in simulations presented in this paper. The definition of the misalignment parameters are defined in Fig. 2. Note that values are not tolerance specifications, as there is an ongoing iterative process to determine the alignment level achievable and the acceptable machine performance

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI(μrad)
Arc quadrupoles*	50	50	300	150	70	70
Arc sextupoles*	50	50	300	150	70	70
Dipoles	1000	1000	300	1000	0	0
Girders	150	150	–	1000		
IR quadrupole	100	100	250	250	70	70
IR sextupoles	100	100	250	250	70	70

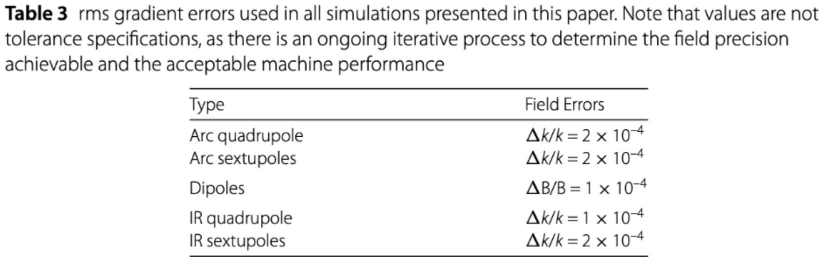


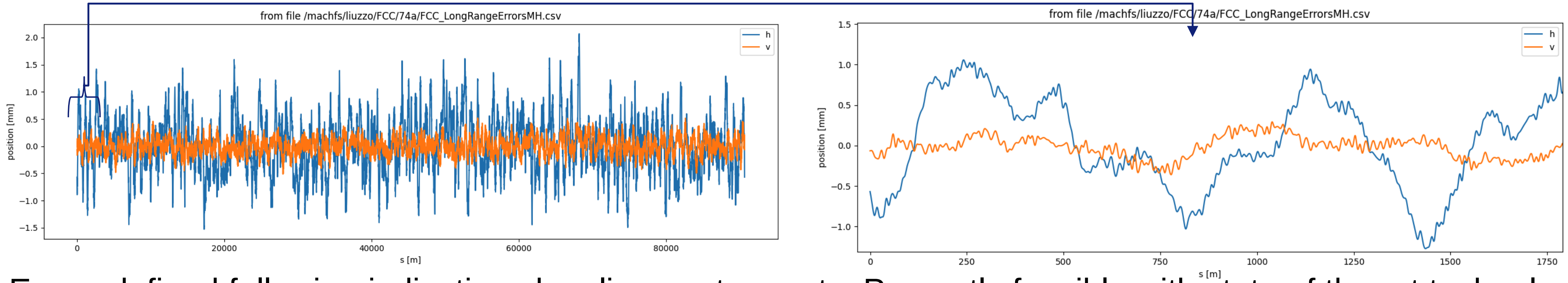
Table 3 rms gradient errors used in all simulations presented in this paper. Note that values are not tolerance specifications, as there is an ongoing iterative process to determine the field precision achievable and the acceptable machine performance

Type	Field Errors
Arc quadrupole	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	$\Delta B/B = 1 \times 10^{-4}$
IR quadrupole	$\Delta k/k = 1 \times 10^{-4}$
IR sextupoles	$\Delta k/k = 2 \times 10^{-4}$

Work in progress to define tolerated errors and commissioning procedures.

* T. K. Charles et al. https://link.springer.com/content/pdf/10.1140/epjti/s40485-023-00096-3.pdf

LONG RANGE ERRORS TOLERANCES



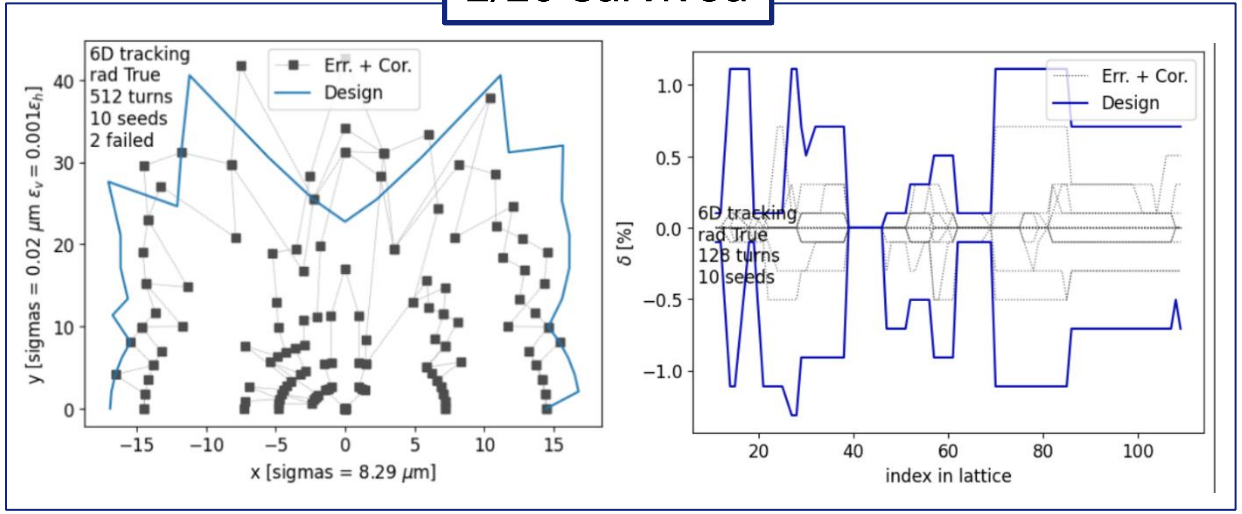
Errors defined following indications by alignment experts. Presently feasible with state of the art technology.

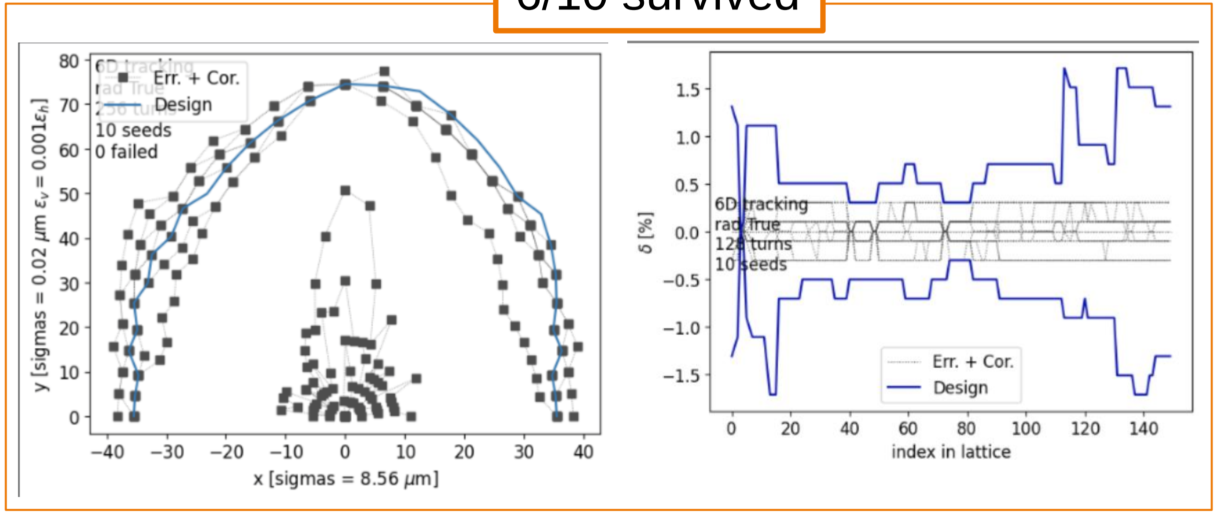
~10% of these errors already leads to several failing seeds and zero LMA. Final focus errors are the main offenders.

1/10 survived

6/10 survived

LCCO 76





Same study with relaxed optics should be performed

CONCLUSIONS

Beam parameters: comparable, better energy loss per turn for LCCO

# of magnets: comparison at t-tbar LCCO optics has less magnets with smaller gradients. Lower power needed.

DA: larger DA on energy and off energy for LCCO optics. Expected to be larger also for ttbar due to much smaller sextupole strengths.

Lifetime: Better for LCCO. Result shown are optimistic.

Errors sensitivities: better sextupoles sensitivity for LCCO optics (due to lower gradients).

Long range errors: 10% of the expected survey/long range errors give already several failing error seeds in both cases.

Random alignment errors: discrepancy among results presented here (very stringent alignment tolerances) and past studies (relaxed alignment tolerances).

LCCO optics appears to be better than the actual baseline optics V22 under all beam dynamics points of view.

LCCO optics include solutions to deal with the effect of synchrotron radiation in the Final Focus quadrupole doublet.

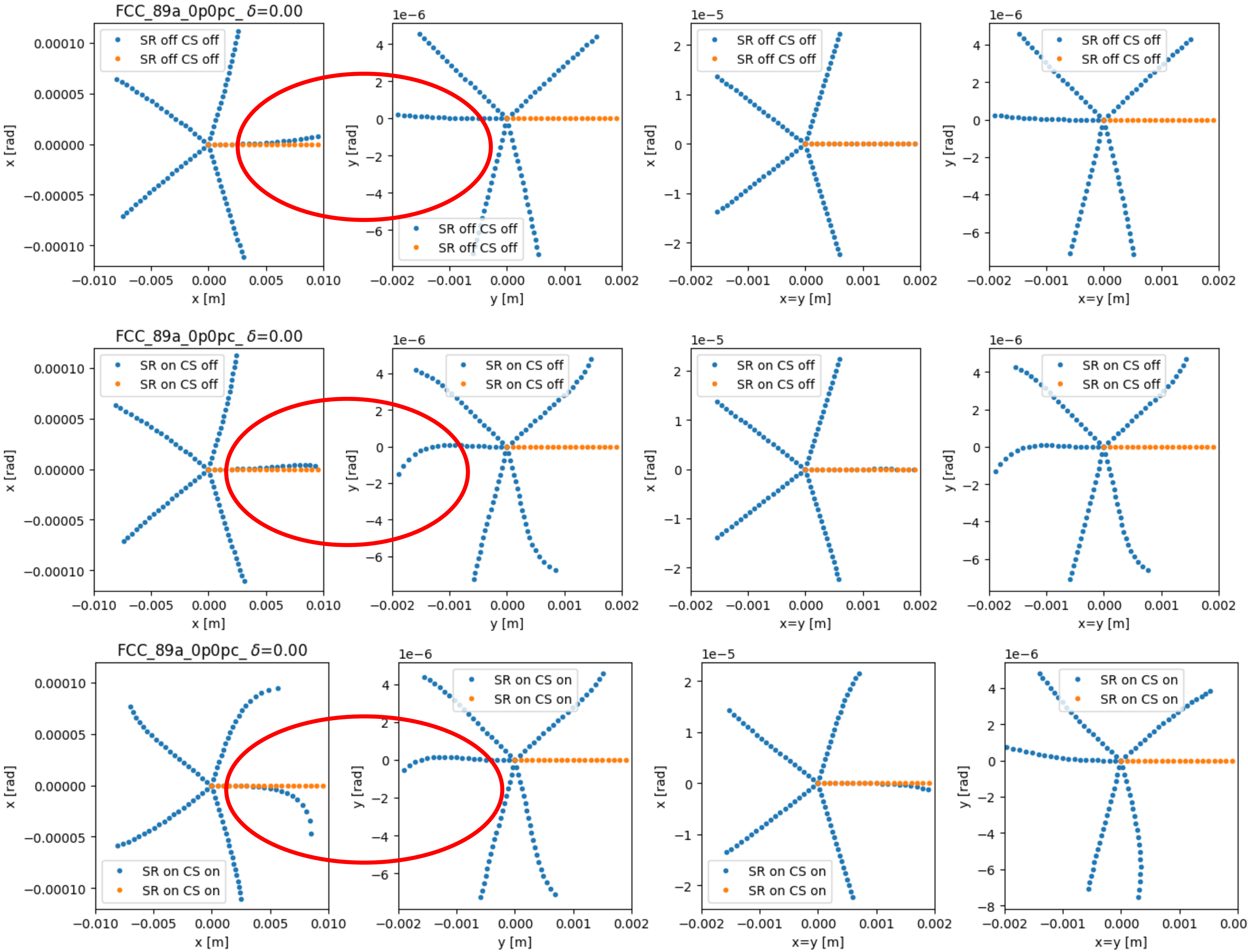
Both V22 and LCCO optics show issues with long range errors, mostly driven by Final Focus.

BACKUP

LAST OFFENDER IN DA OPTIMIZATION = CRAB SEXTUPOLES

Remaining aberration only due to Crab Sextupoles.

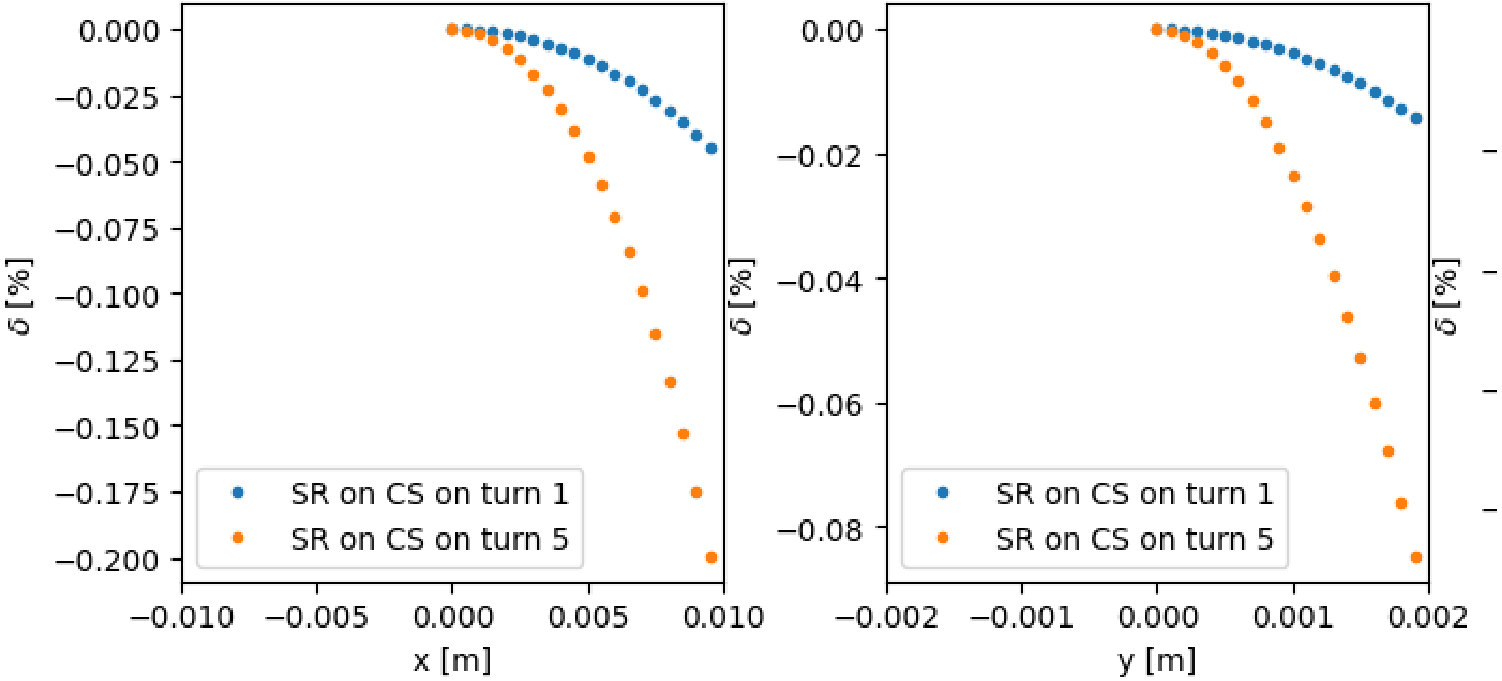
If fixed DA will further improve



ENERGY LOSS DUE TO FINAL DOUBLET RADIATION

Energy loss induced by final doublet SR only.

Similar for the two lattices.
After 160 turns the beam loses 2% and is lost out of MA.
The RF helps to recover the energy loss.



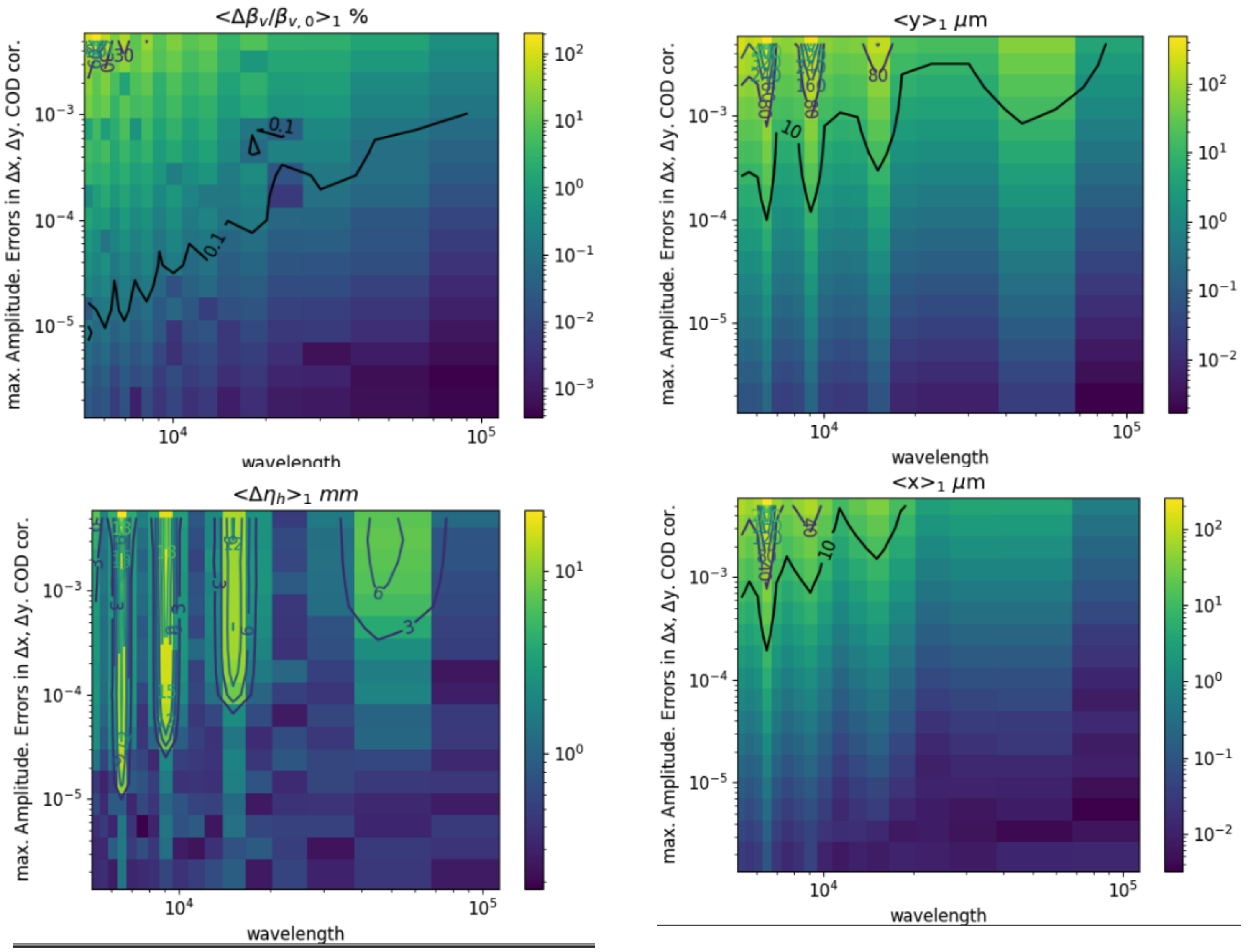
WAVE ERRORS

LCCO74 @ Z

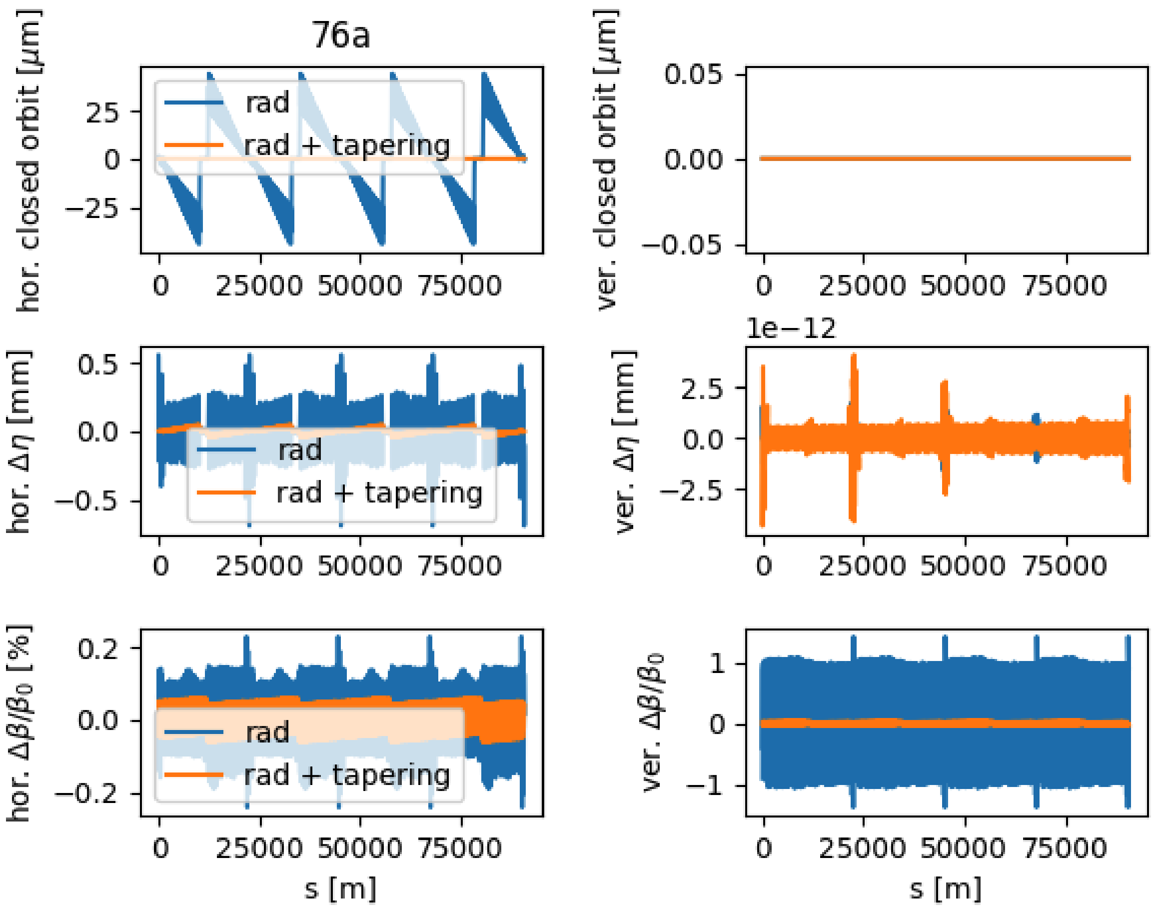
Scan wave of errors in amplitude and frequency ~~and correct orbit (only orbit)~~

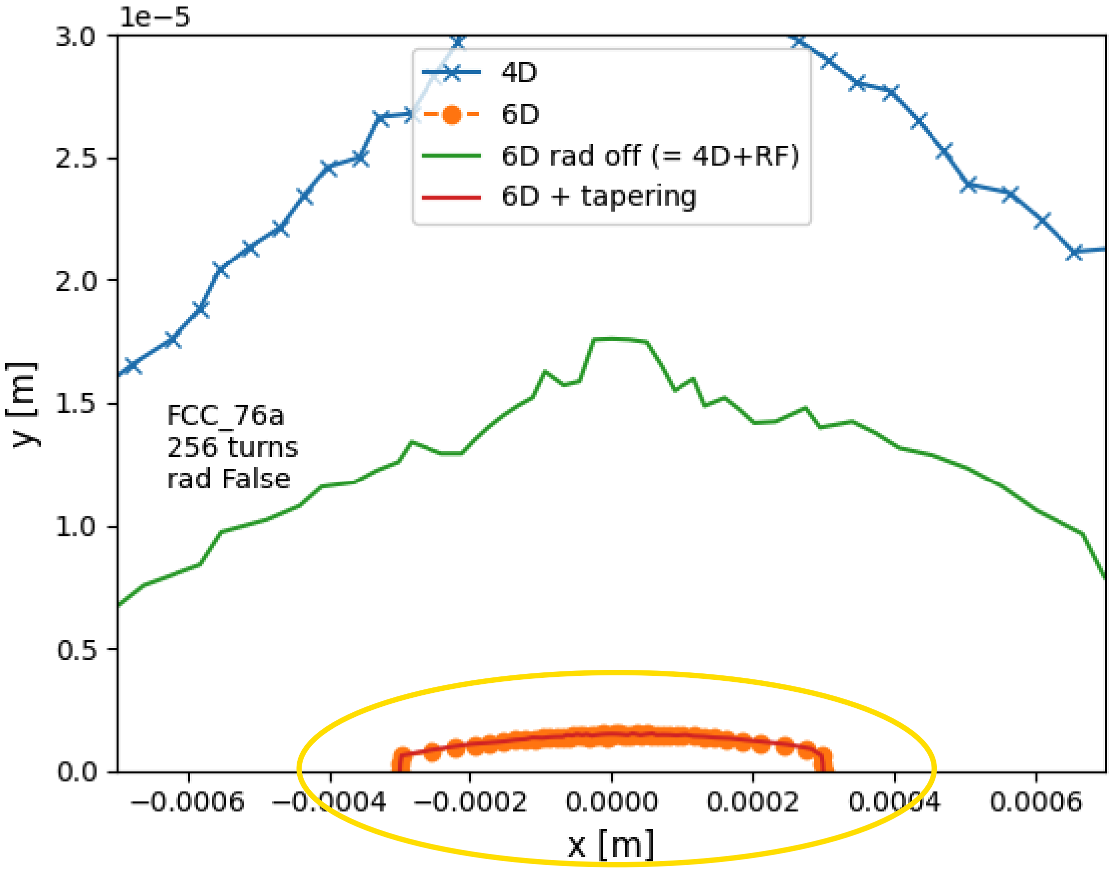
Golden orbit = Assigned Errors at BPMs

Error waves frequency fractions of the total length (always closed continuous and derivable)



GRADIENTS TAPERING

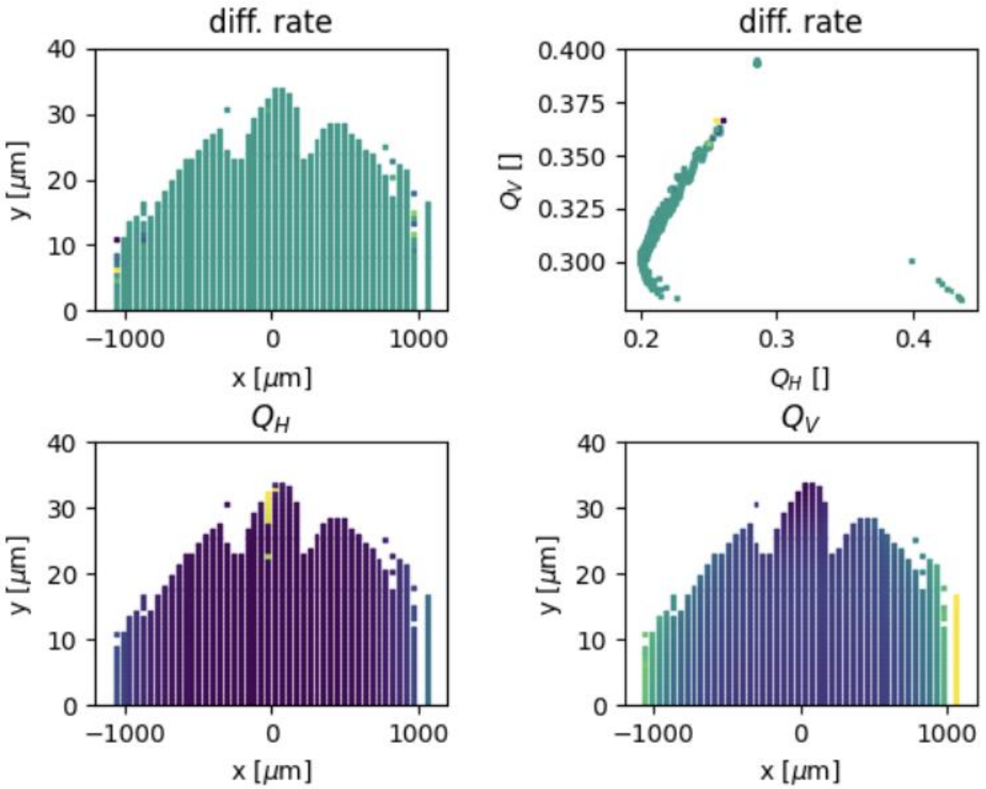




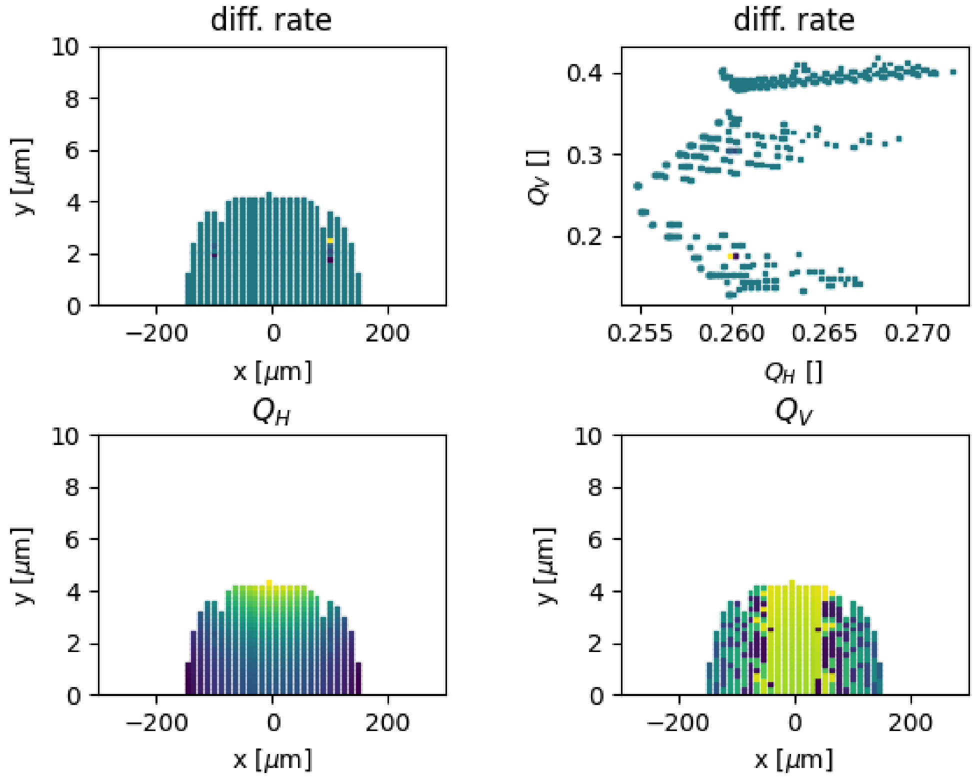
Introducing gradients *tapering* to follow the energy loss of the beam along the accelerator has small impact on 6D DA with synchrotron radiation @Z.
To be reassessed for the solutions with larger DA (V89).
At ttbar the tapering could be more relevant.

FREQUENCY MAP ANALYSIS FOR LCCO76 AND V22 @Z 4D

LCCO76



V22



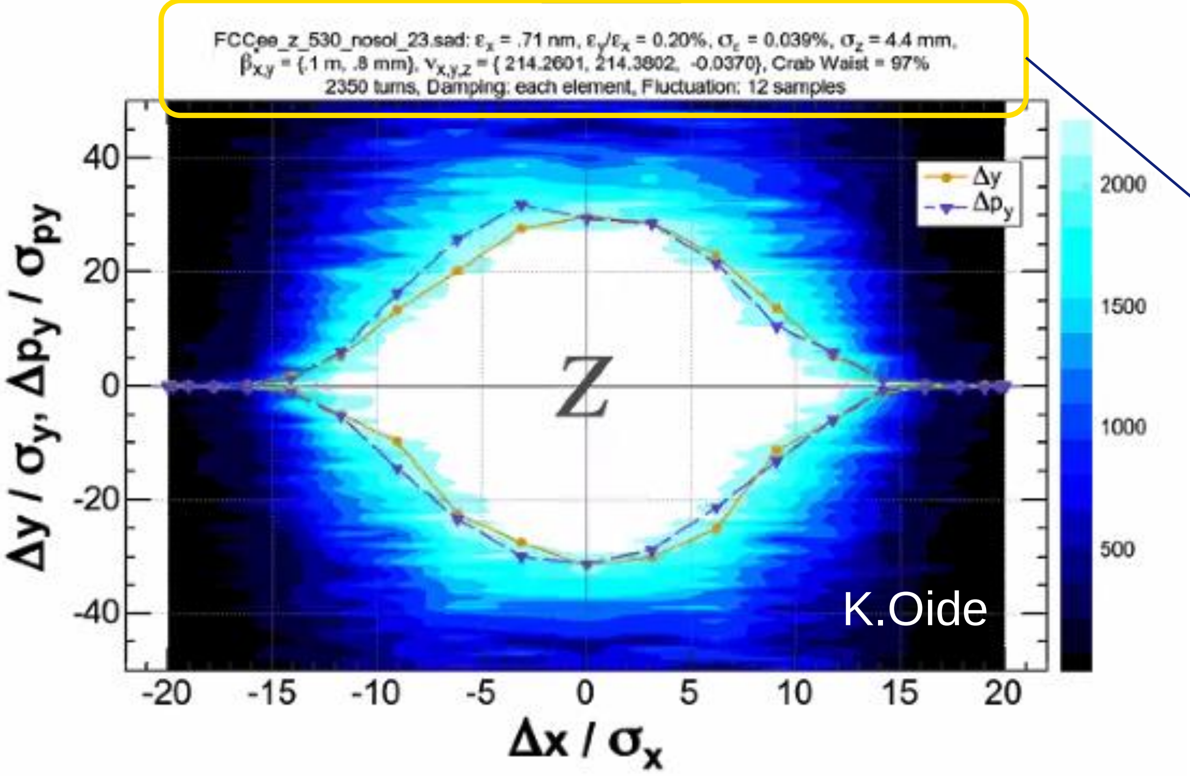
UPDATE FOR 89 OLD, Crab On.

Check scales

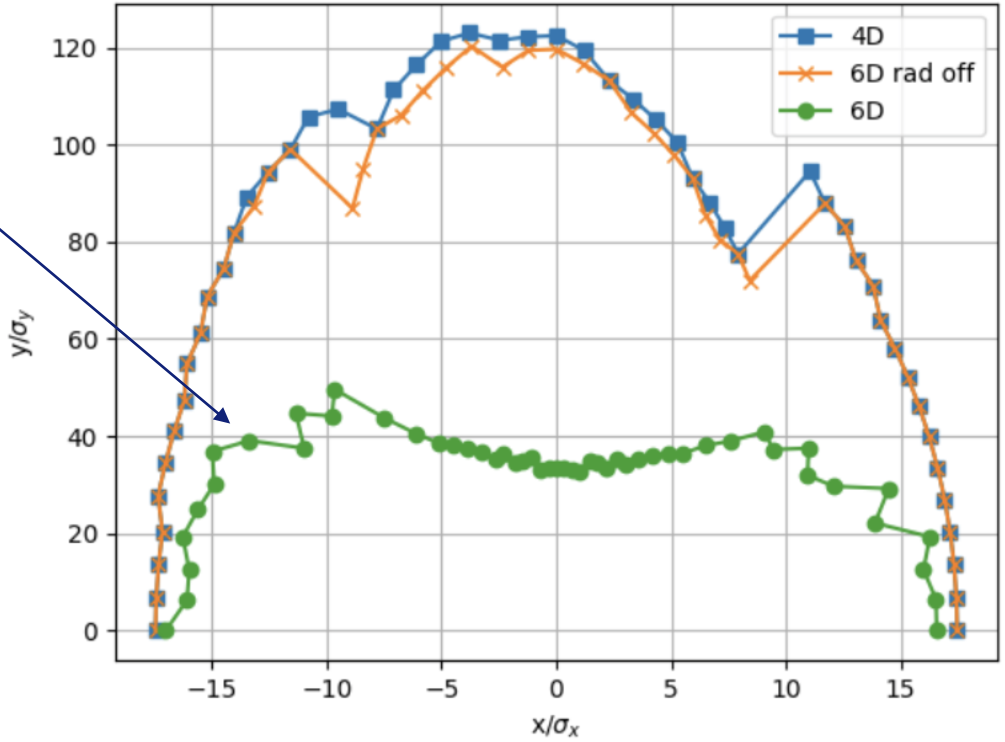
COMPARISON OF AT AND SAD DA COMPUTATIONS FOR V22

fluctuation == quantum diffusion in AT **not included**

SAD



AT



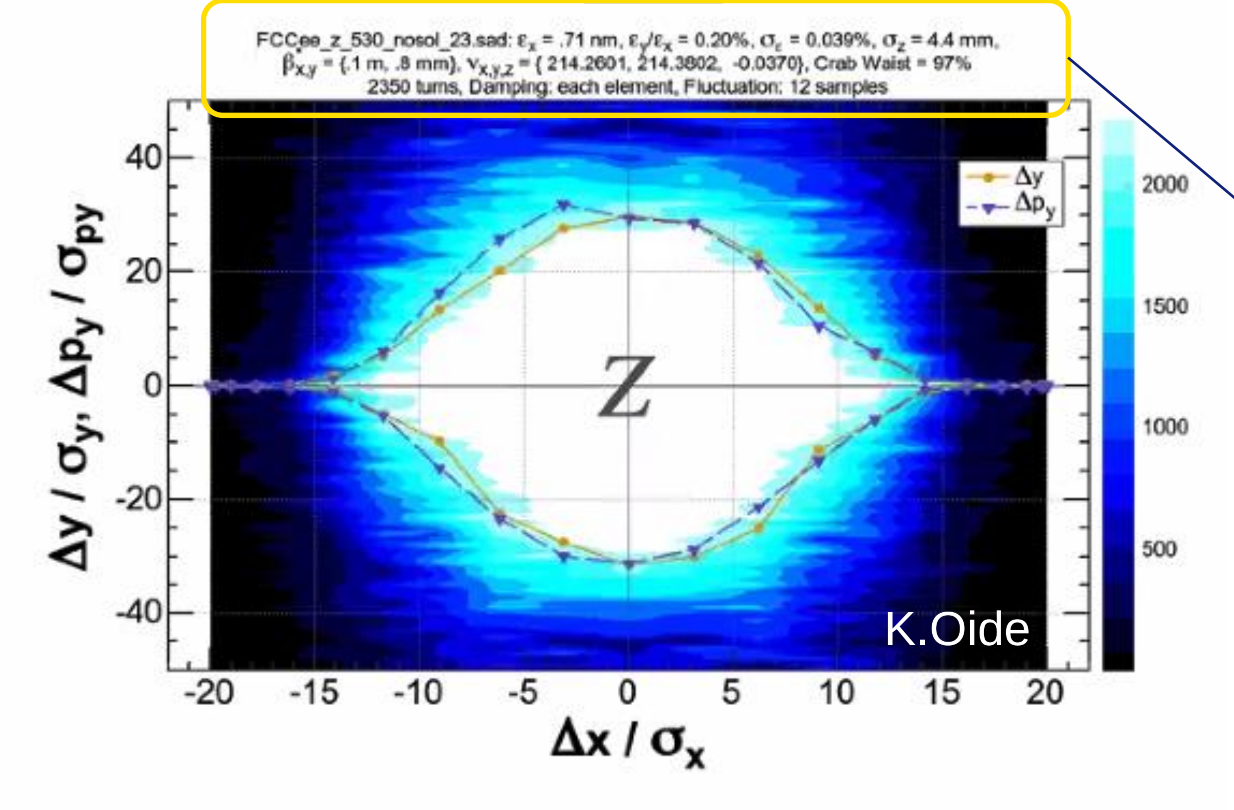
Radiation in all elements, exact integrators, 2350 turns, Ey/Ex = 0.2%

damping at each element in AT is assumed as Radiation at each element.

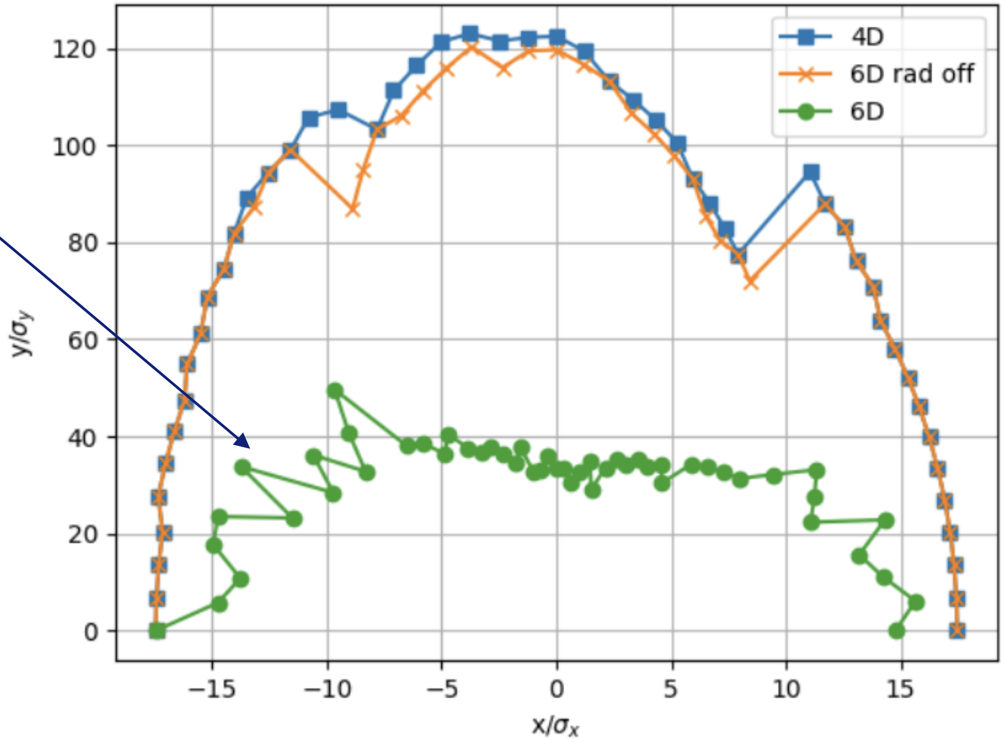
COMPARISON OF AT AND SAD DA COMPUTATIONS FOR V22

fluctuation == quantum diffusion in AT **included**

SAD



AT



V22 β^*_h=10cm, β^*_v=0.8mm

FCCee_z_530_nosol_23.sad

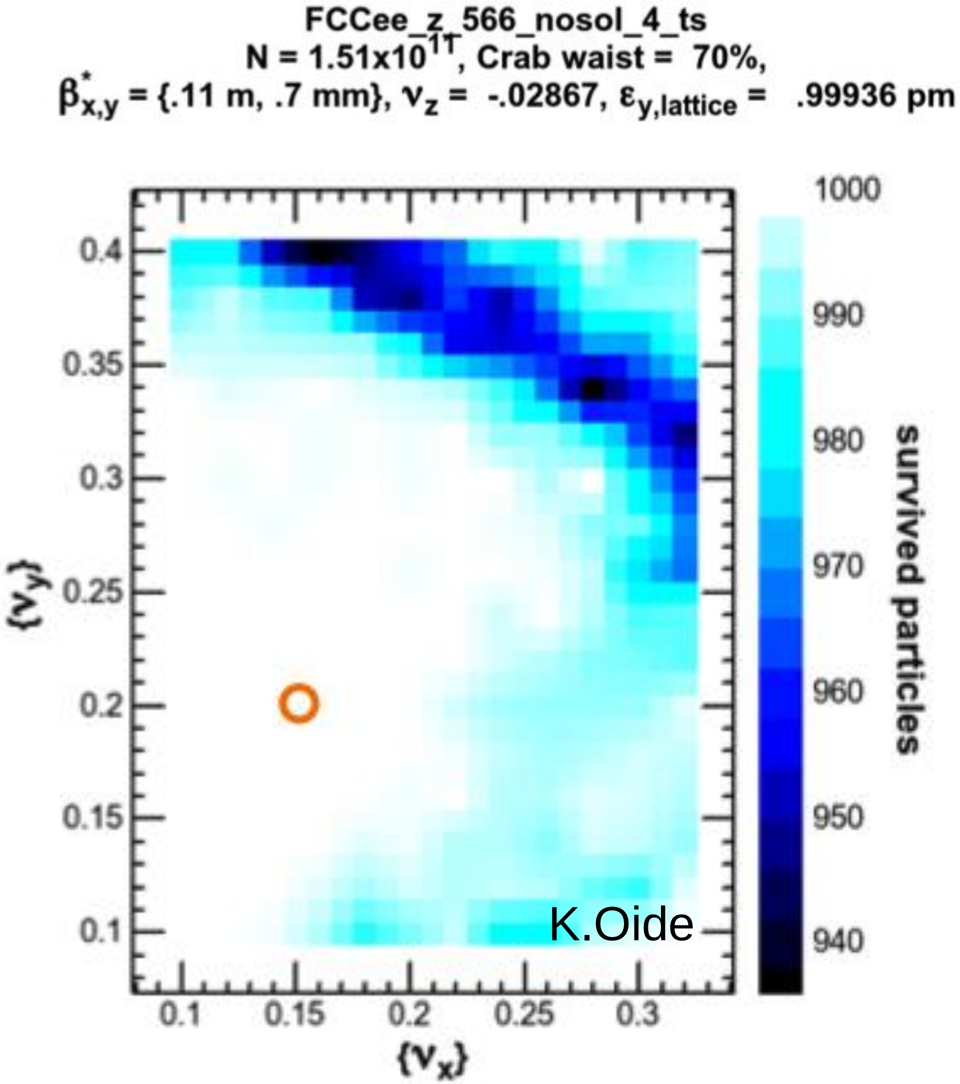
β^*_h=10cm, β^*_v=0.8mm

Radiation in all elements, exact integrators, 2350 turns, Ey/Ex = 0.2%

damping at each element in AT is assumed as Radiation at each element.

TUNE WORKING POINT SCAN FOR V22

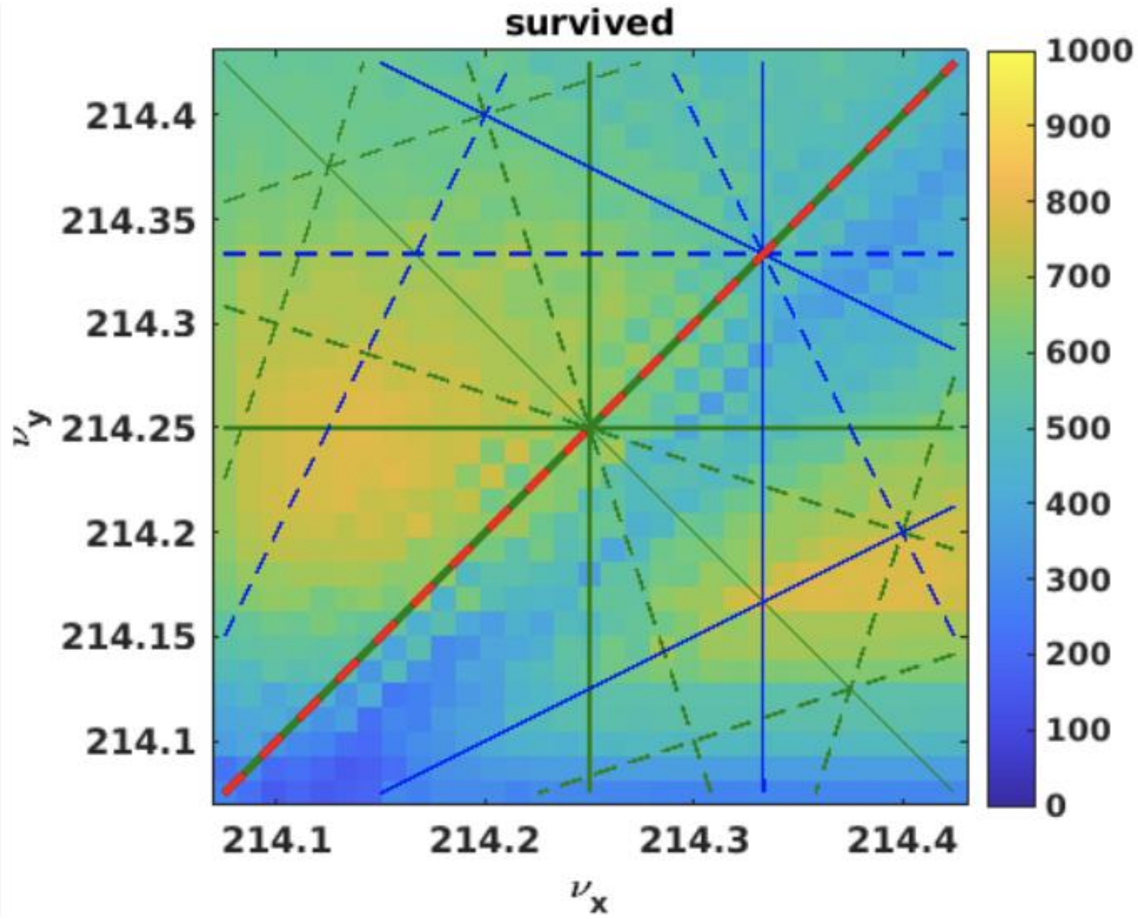
SAD



K.Oide

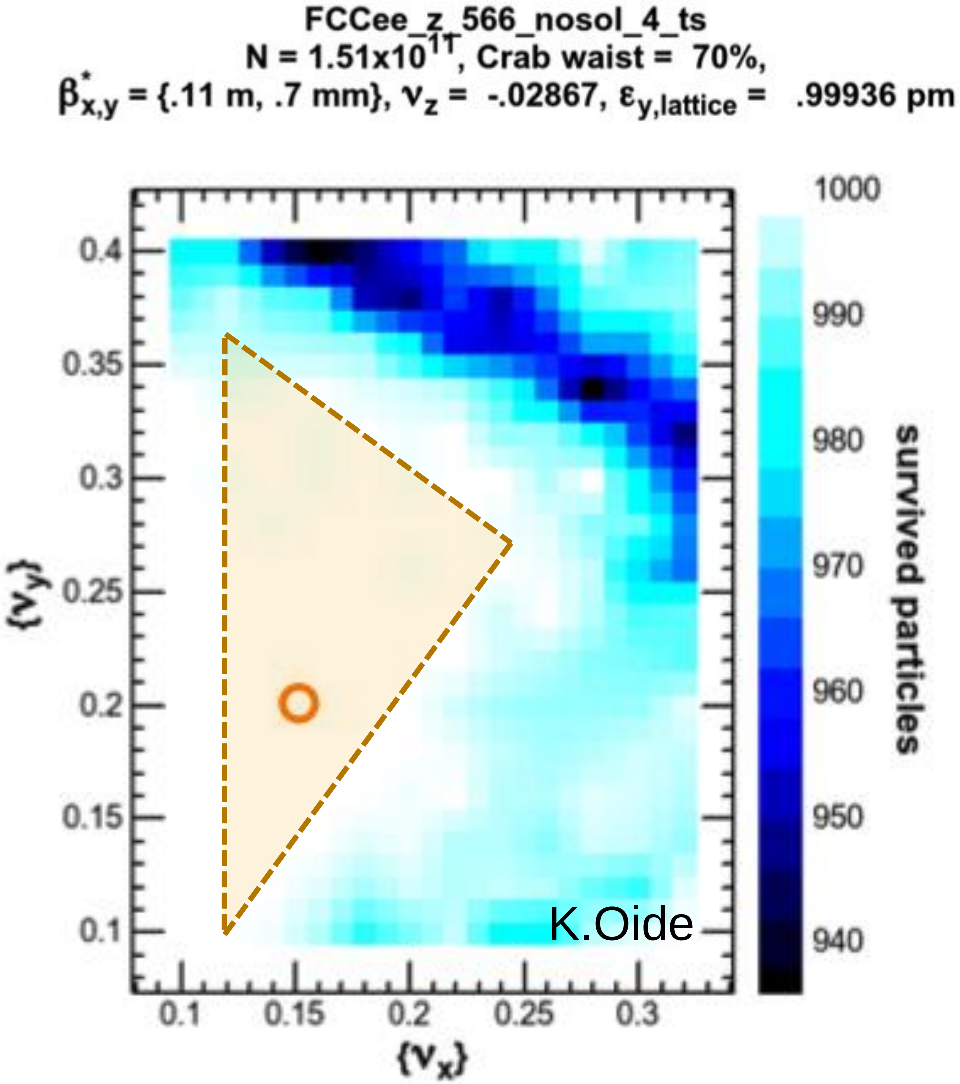
AT

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).



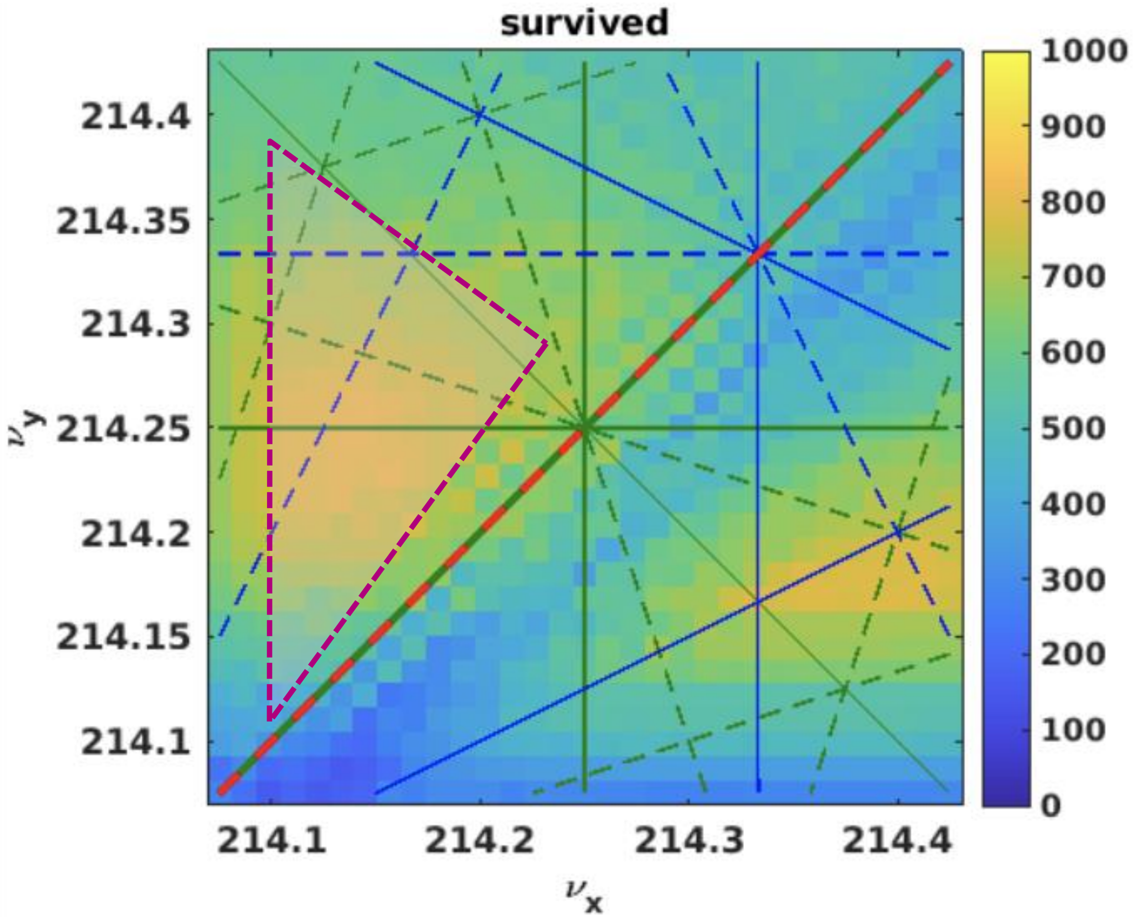
TUNE WORKING POINT SCAN FOR V22

SAD



AT

Track a 3D grid of 1000 particles of size: 20σ_x x 20σ_y x 0.002 δp/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 ANGULAR ACCEPTANCE

Normalized with $\sigma_{x'}(s)$ WITH RADIATION

Comments by P.Raimondi:

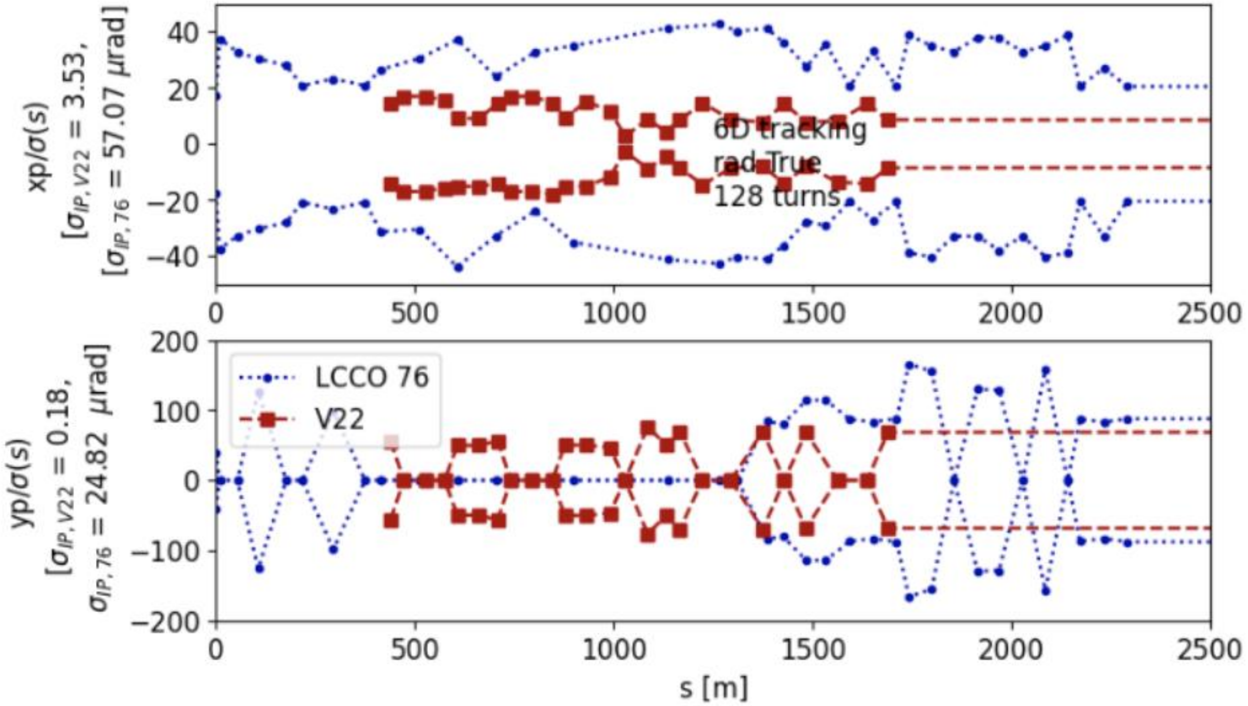
Local angular acceptance could be useful to understand/identify possible bottlenecks in transverse DA in the ring.

Small values could be critical for local gas- bremstralung or for local instabilities (e-cloud, TMCI, etc…)

Local angular acceptance is in principle constant.

If the phase space is locally distorted in general it decreases.

(eg: larger value of alpha, or strong local sextupole/high order aberrations).



SEVERAL locations with ZERO* Angular acceptance

* Smaller than the minimum step of the grid