Local Chromatic Correction
Arc & Final Focus FCC Optic

FCC Workshop

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Outline

- LCCO rationale
- Ring and Final Focus layout
- Hardware requirements
- Performances
- Conclusions

Local Chromatic Correction Optic

LCCO based on the development of optics solutions that allow/rely on chromatic and harmonic corrections as local as possible. This has led to the development of:

HFD ARC lattice.
The lattice has been optimized by introducing a “beta&phase-modulation” and relies on 4 sextupole families that results in a second-order achromat and nearly anharmonic lattice. The lattice is periodic over 5 Hybrid-FODO cells.
The optimized phase advance for ttbar operations is about 100/74.
A weaker lattice that utilizes all the ttbar magnets that has a phase advance of about 51/44 is achromatic and anharmonic as well. It is considered to be used for Z operations and all modes that require a large momentum compaction.
Both lattices have a MA in excess of +/-3%,

Long Straight Section matching
The insertion of the straight sections is performed by requiring the “Transparency Conditions” (APS prize @IPAC2024)
This allows the virtually transparent insertion of any SS in a Ring, without any significative degradation of Its characteristics (DA/MA, detuning etc), neither requiring the introdusction of sextupole families.
The TCs can be applied for any given SS, provided that 4 quadrupoles/side are available to match the conditions.

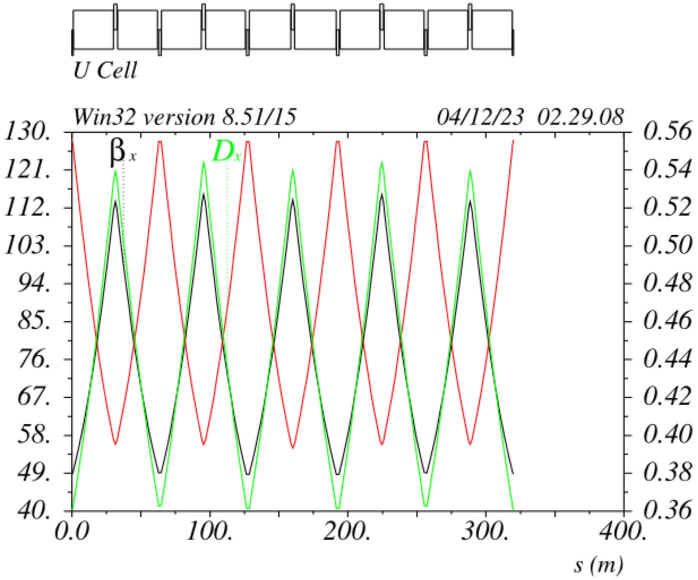
Final Focus.
LCCO requirements are fulfilled by correcting the low-beta IP chromaticity in the FF in both planes and nearly entirely.
LCCO also results in the need of placing the Crab sextupoles in a nearly “chromatic-free” region: the FF outer ends.
This solution has been developed for the SuperB and has been adopted by CEPC as well.

Ring layout v_74 ttbar

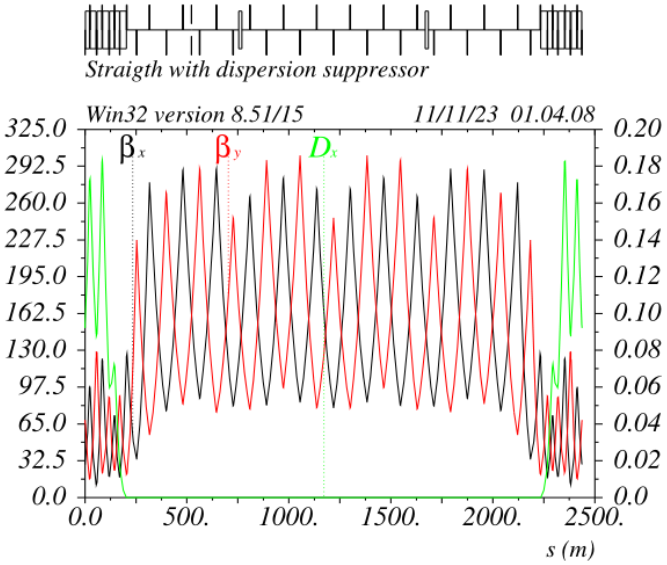
V_74 optic matches the baseline layout:

- LSS 2032m long as baseline
- ARCs bending radius as baseline
- FF section length set to match overall ring circumference: 90658.609m (tunnel length 90657.609)

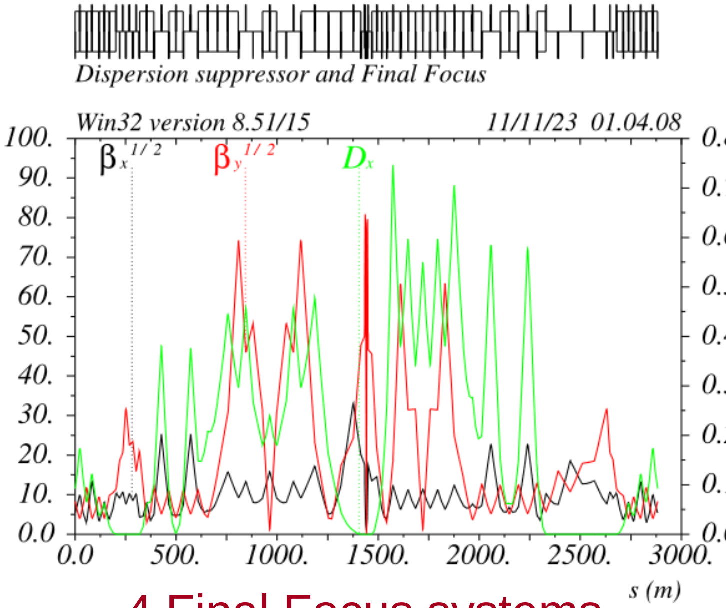
Specialized LSS optics (injection, collimation, RF) presently not included.



30 cells/octant

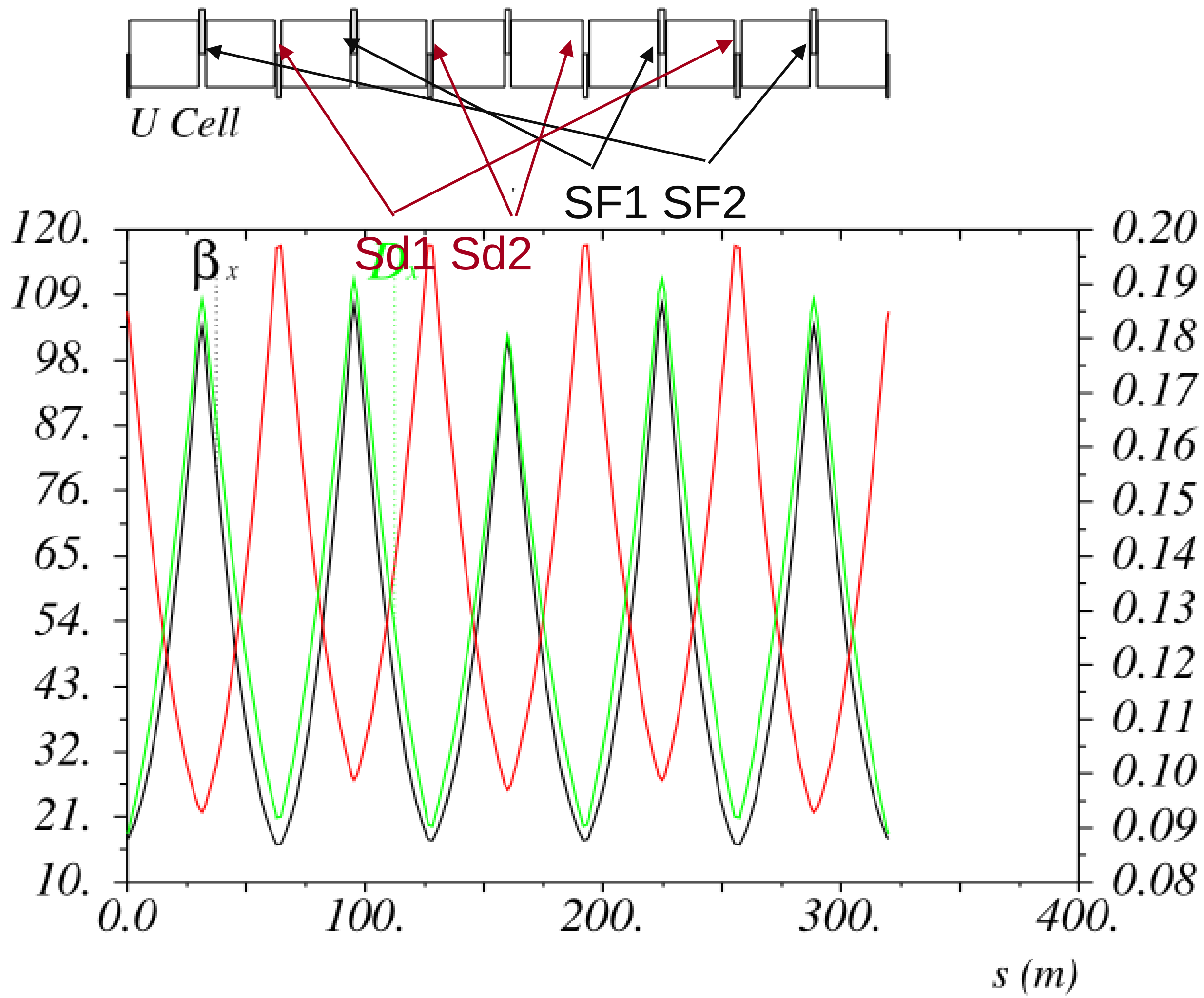


4 Long Straight Sections



4 Final Focus systems

HFD_100/74 ttbar mode

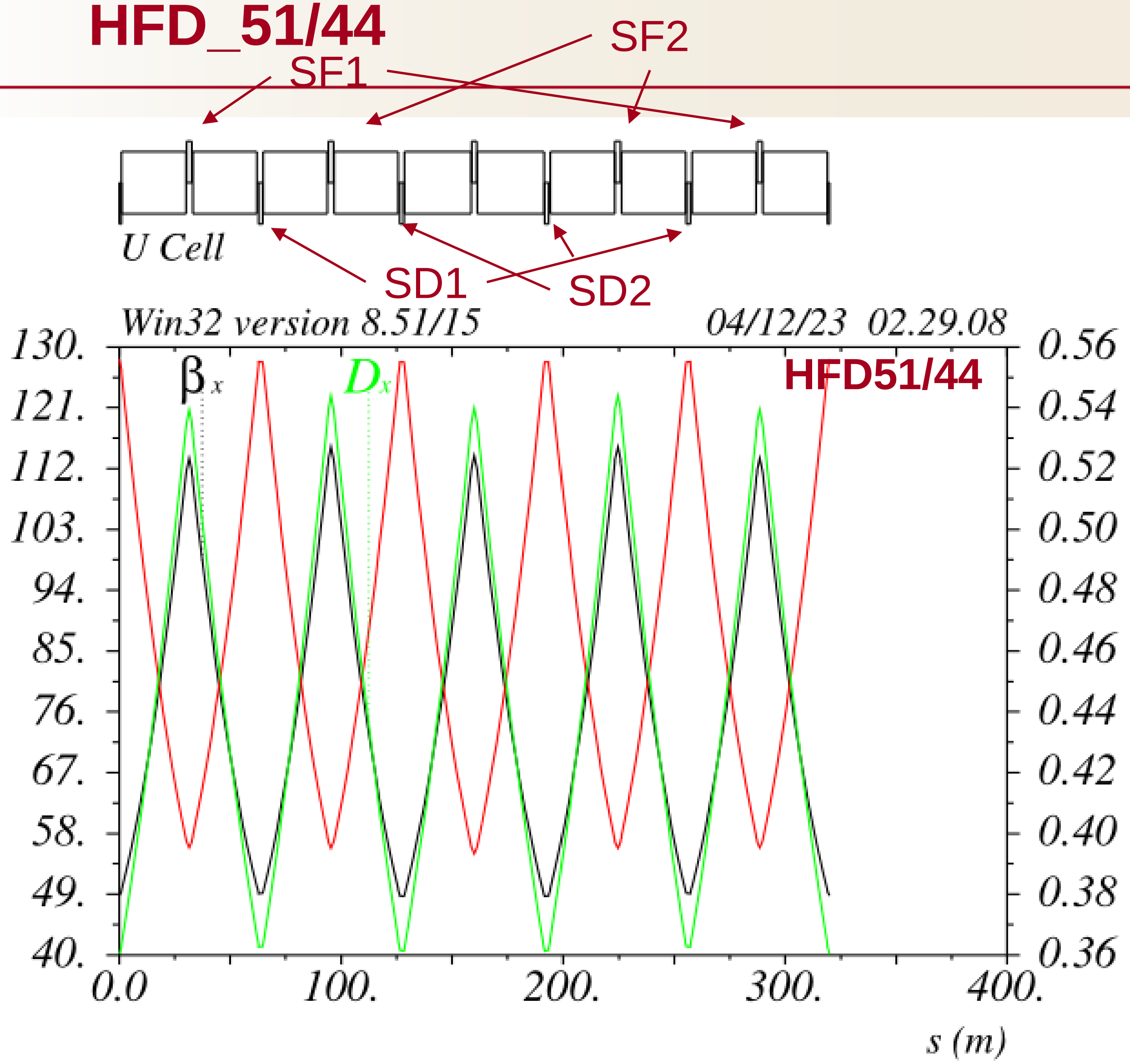


Intrinsic ARC emittance @ttbar is 1.74nm
Vertical chromaticity is close to the minimum
Lattice is very periodic, beta modulation around 5%

The matching conditions are:
mux, muy, x_det, x_det'', y_det, xy_det, Qx'',Qy'',
Ex_min (2 conditions)
Variables are:
QD1/QF2/QD3/QF4/QD5/QF6
2 Dipole pairs relative lengths (3 families deltas+/-3%)
2 sexts families

Sextupoles pairs are placed left-right symmetric and also their position wrt the nearby quad (before or after) has been chosen to minimize aberration

HFD_51/44 — Z mode



Given the additional degree of freedom from the 4 sexts families, good tunes working points do exist almost continuously.

HFD_51/44 delivers:

Ex = 0.70nm   Alphac =3.30e-5

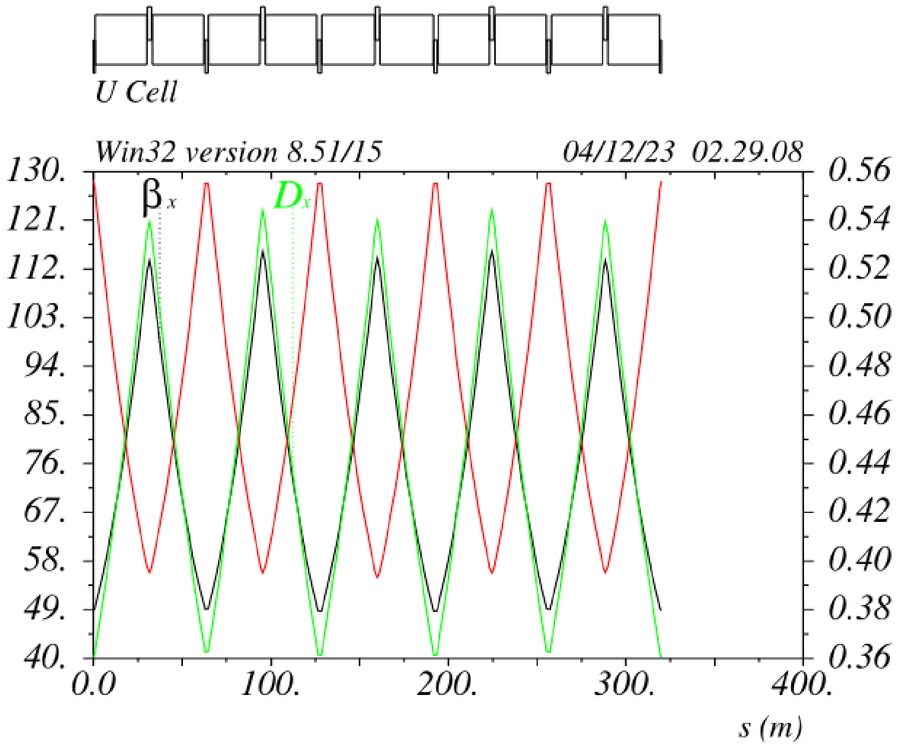
(Ex = 0.69nm   Alphac =2.94e-5 for full ring)

Muy has been chosen as best compromise between chromaticities, detunings and sensitivitiy to collective effects.

Peak betas are very similar to the HFD100/74 (Long9090 FODO has twice larger betas wrt Short9090)

ARC layout

Z and ttbar mode



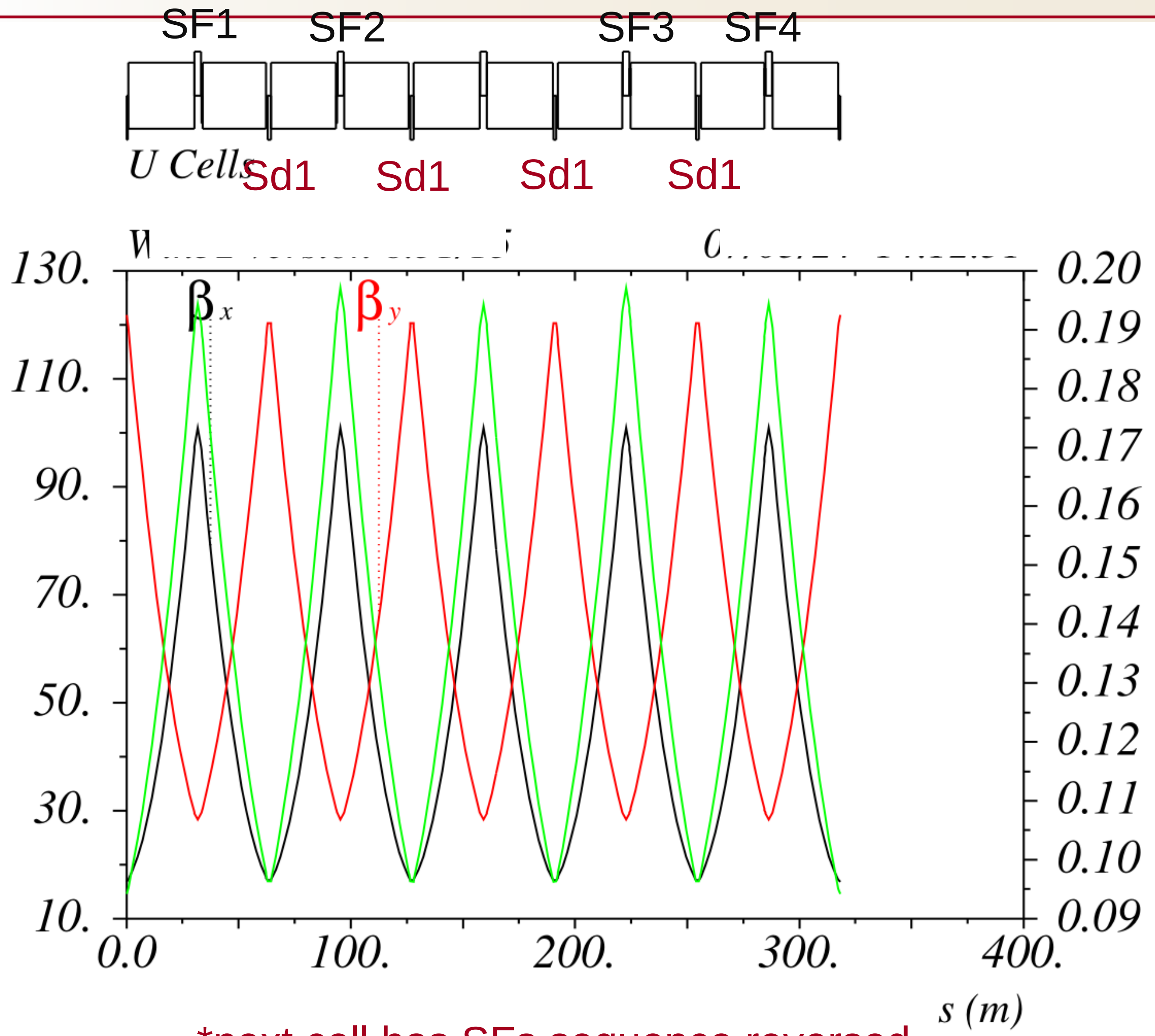
- The arc is a standard FODO sequence with two missing sextupole for every 10 quads.
- BPMs are placed at each sextupole location (between sext and quad)
- The sextupoles are the ones presently designed and the foreseen trimming coils are all what is needed for orbit and optic correction.
- Sextupoles are 0.40/0.50m long, power consumption is < 5MW
- Quads are 2.4/1.8m long and should consume about 5Kw each, 2240 per ring are needed => 23MW@ttbar
- Dipoles are about 29.6m Long

In the case of HTS option the sextupoles are wrapped around the quadrupoles.

In principle by shifting the arc longitudinally by 30m, the QF will overlap with the QD.
In this case it could be possible to use a 1.8m twin quad as in the baseline + a 0.6m QF on one side only.
Pros and cons of this possibility should be carefully quantified.

ARC completely periodic lattice

v_94b @ttbar



*next cell has SFs sequence reversed

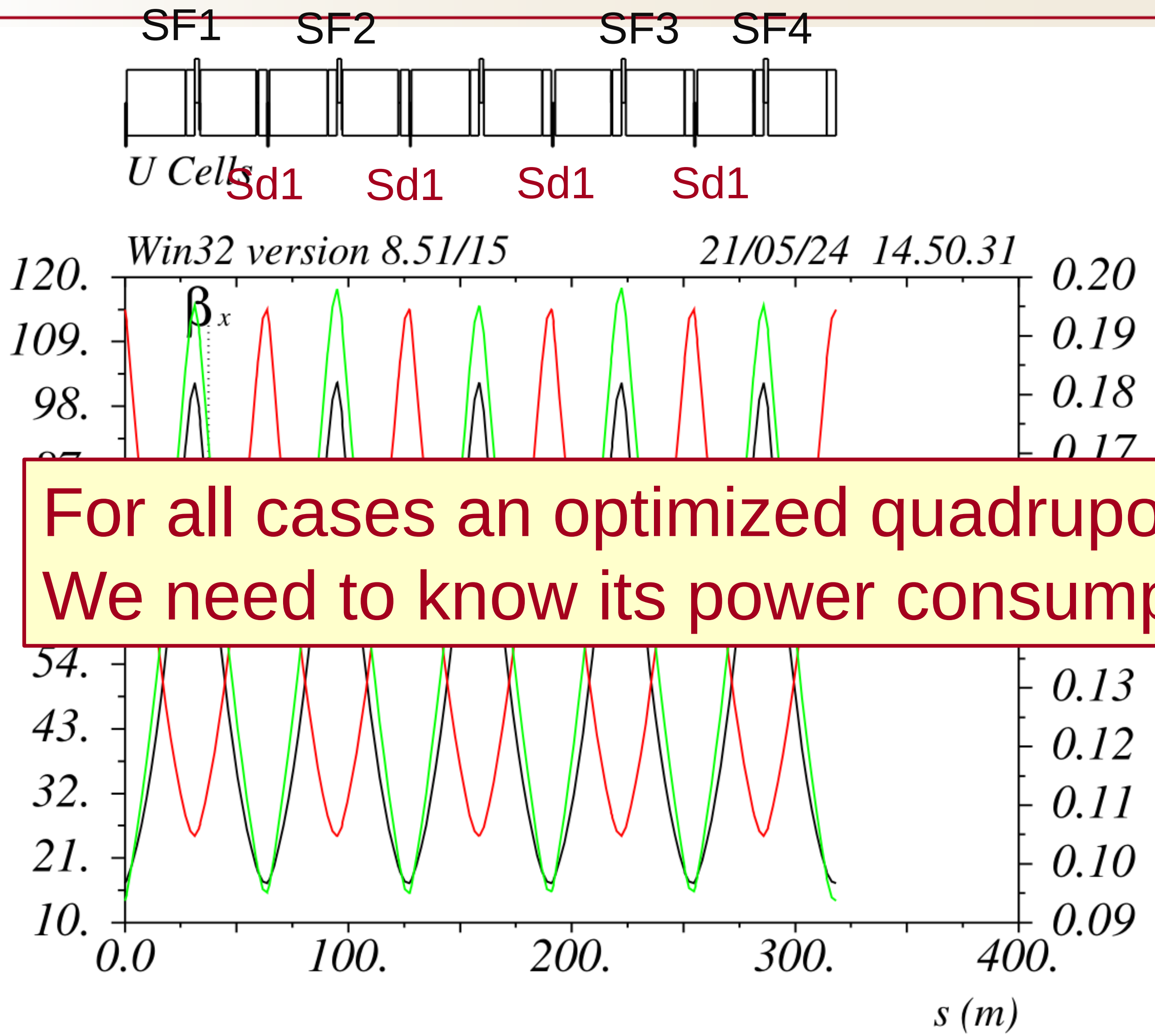
With an additional sextupole family there are enough DOF to correct all the dominant RDTs/aberrations. Sexts modulation ~20%

V_94b is completely periodic and has weaker quads and sextupoles wrt v_92b4. Non-linear dynamic is also better. (100/65 cell advance)

V_94 is compatible with twin quads:
The e+&e- arcs can be shifted by ~30m to have
The QDs and QFs will be aligned, the twin quad can be used, with an additional short QF quad (60cm) to make up for the x/y tune difference.
The complete tunability of the lattice is preserved

V_94 has not been released yet

ARC completely periodic lattice with weak and long twin quads



Twin quads are about 5m long, gradients ~3T/m

~60cm QFs are also included

Eloss/turn is 5% larger (8%lower wrt GHC) wrt v_92

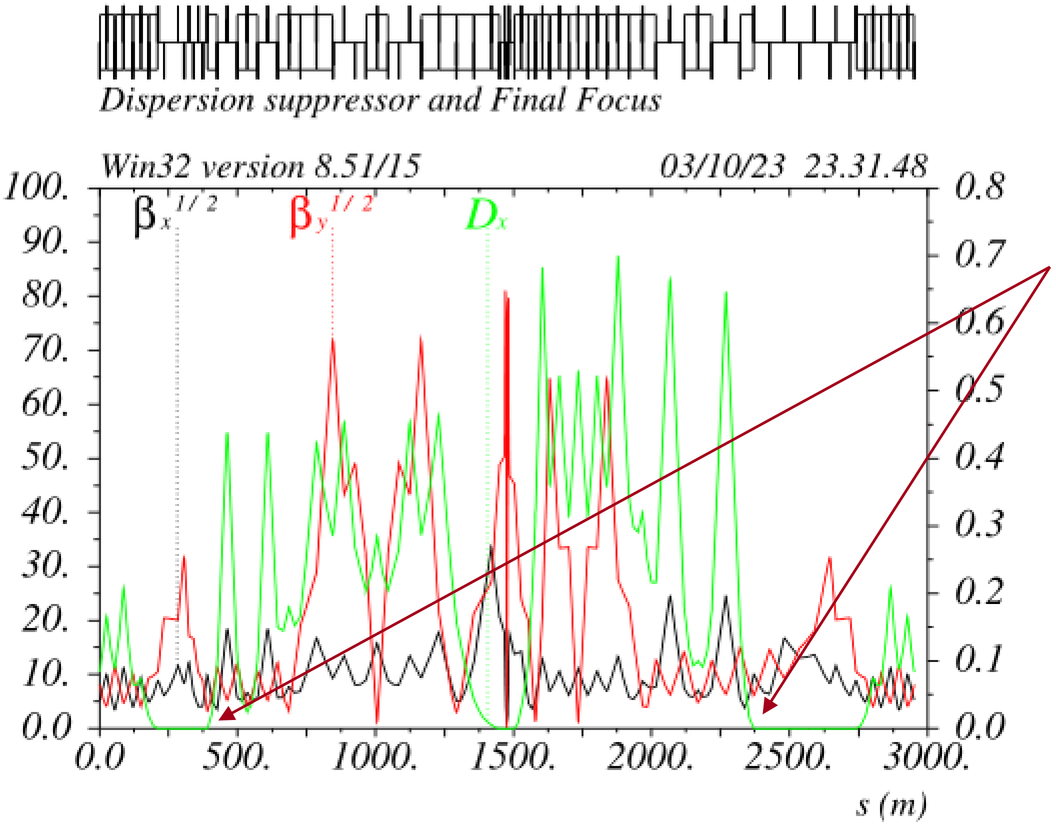
For all cases an optimized quadrupole design (with 4 coils) is needed
We need to know its power consumption wrt twin-quad

Eloss due to the ARC quads become negligible (compared to the FD eloss)

HTS solution allows flexibility in the best overalp of B/Q/S fields, and in optimizing the quads lenghts

*next cell has SFs sequence reversed

Local Chromatic Compensation FF asymmetric layout ttbar optic



The FF geometry is adjusted in order to recover entirely the beams separation. Dipoles ARCs modification is not necessary.

Beams start to split @300m and are back @2300m (Present separation in the ARCs is set to 40cm)

CCsX_Left section is short and has "strong bends"

CCsY_Left section is long and has "weak bend"

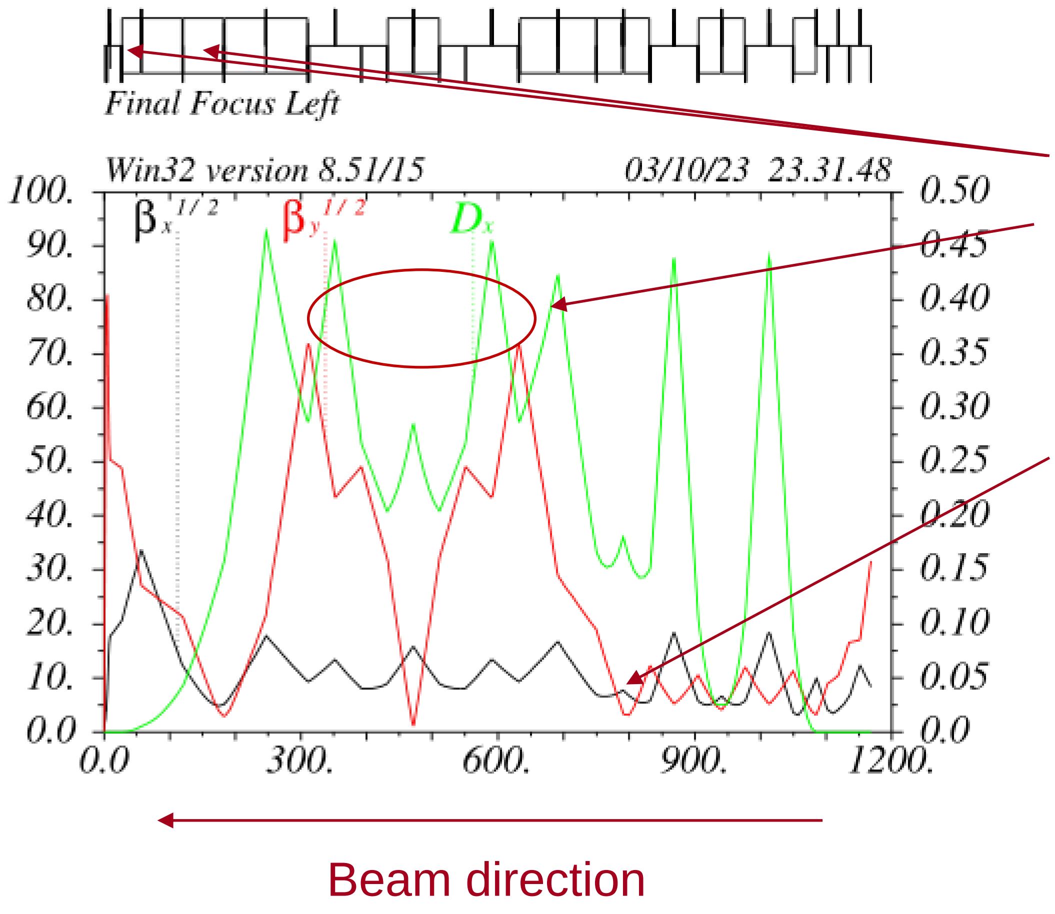
CCsY_Right section is short and has "strong bends"

CCsX_Right section is long and has "weak bend"

Details in next slides

Left Final Focus

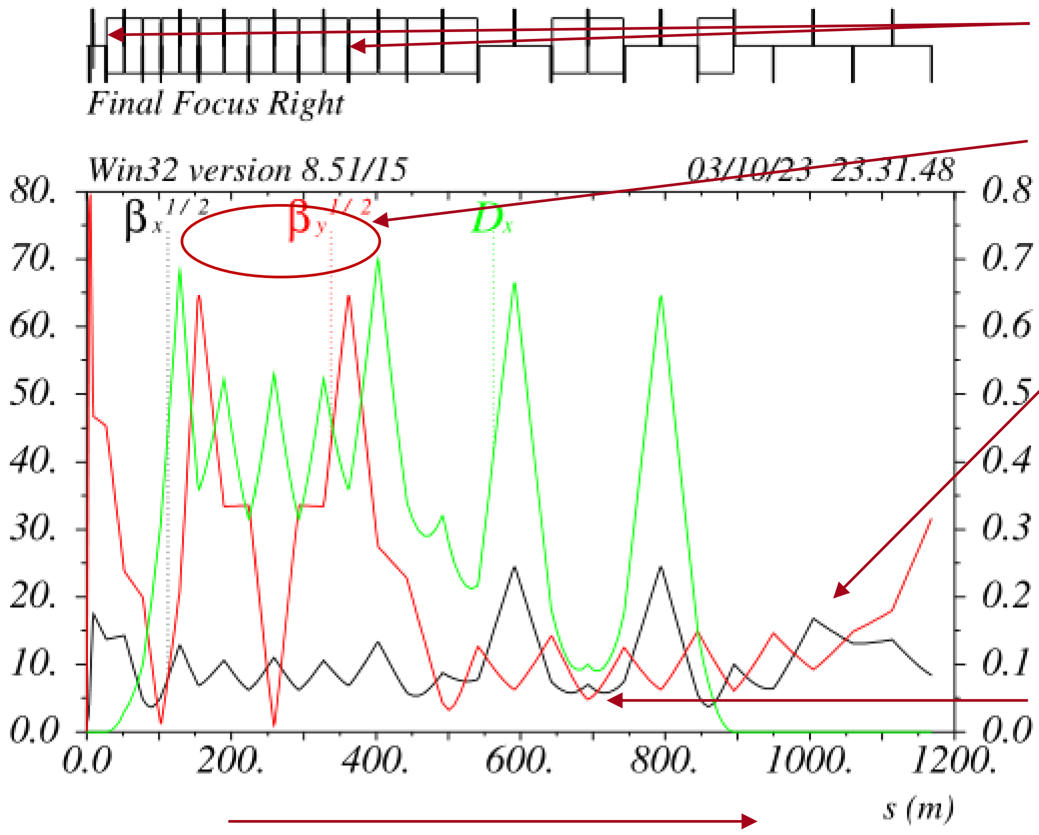
ttbar optic



- Last 3 dipoles EC~130KeV
- CCSy optic has the largest dispersion (so far) for a given bend angle in the –I, presently Dx=0.303m@SDs
- “Standard” non-linear optimization is performed as usual
- Betas&Alfas at IP-phase sextupoles are optimized to reduce the DA reduction from Crab sextupoles
- CCSy/x_L/R lengths and ratio between their total bend angles are optimized to have maximum dispersion on CCSy_Left and minimum overall emittance growth and radiation
- CCSy sextupoles (0.6m long) are very weak Ks_madx~0.7 @ttbar, Ks~0.9 @Z. In fact ARCs sextupoles can be used in the FF as well

Right Final Focus

v_67 ttbar optic



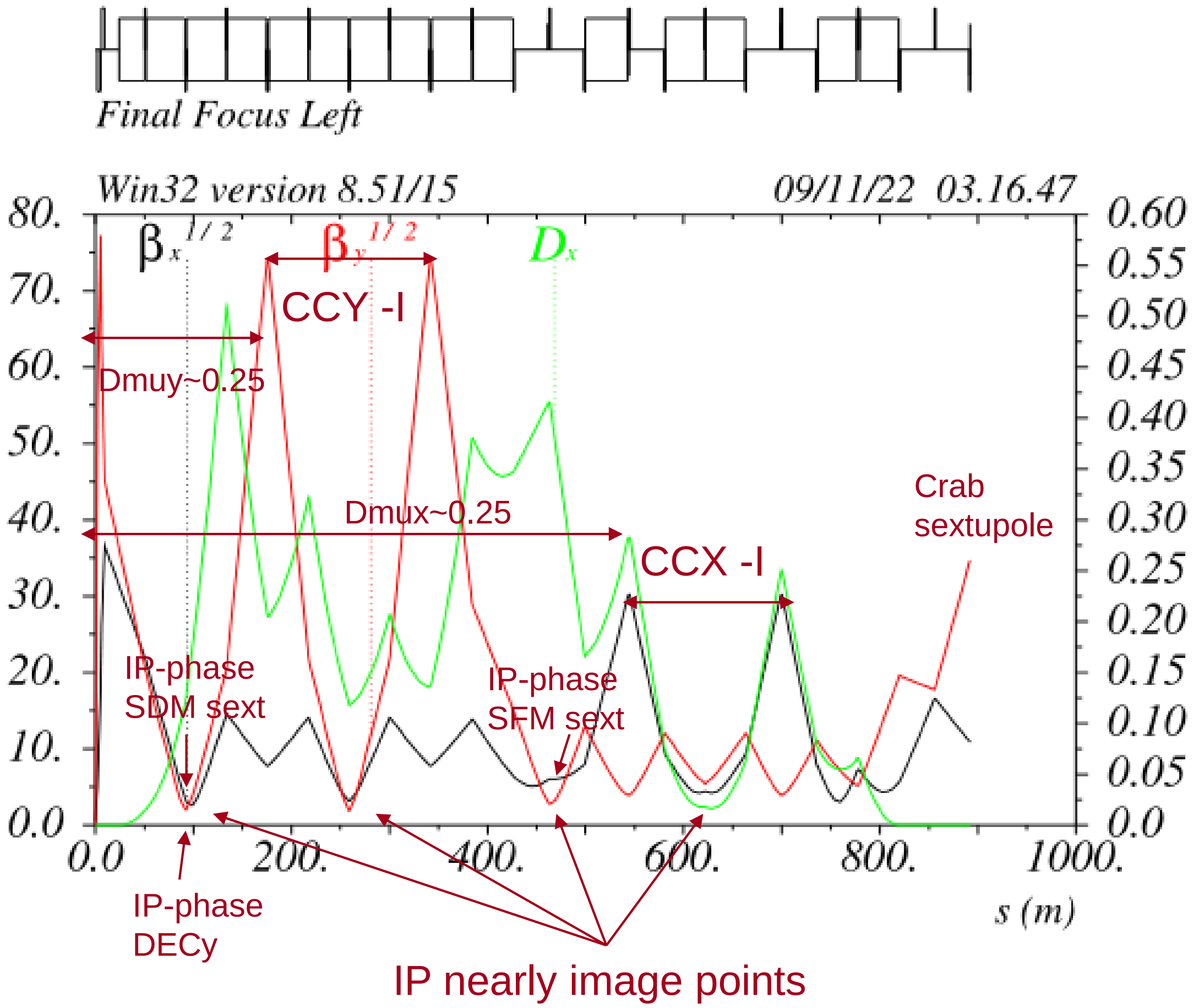
Beam direction

- All dipoles in the CCSy have same field, best configuration to recover the beams separation
- CCSy optic has the largest dispersion (so far) given the above requirement in the –I, presently Dx=0.370m@SDs
- “Standard” non-linear optimization is performed as usual
- CCsX has been shortened and pushed back, helping to recover the geometry. Incidentally this has originated a very long dispersion free straight section, ~400m when included the ARC DS part
- Two drift sections about 100m long are also present in the CCsX “-I”

- Alfay in the CCSx_LR is not zero to symmetrize the F_LR non linear optic

- Long dipoles free sections are present in both FF arms, a section compatible with the polarimeter could be developed (DSs could be considered as well)

Final Focus chromatic and geometric aberration tuning knobs



Main aberrations tuning knobs:

1) Main Sextupoles SDy and SFx
2) SDy&SDx phase advance wrt IP
3) IP-phase sextupoles SDM and SFM
4) Etaxp@ CCSY and CCSX
5) Decapoles y (&x)
6) Phase advance between –I sextupole pairs

Final Focus chromaticity compensation

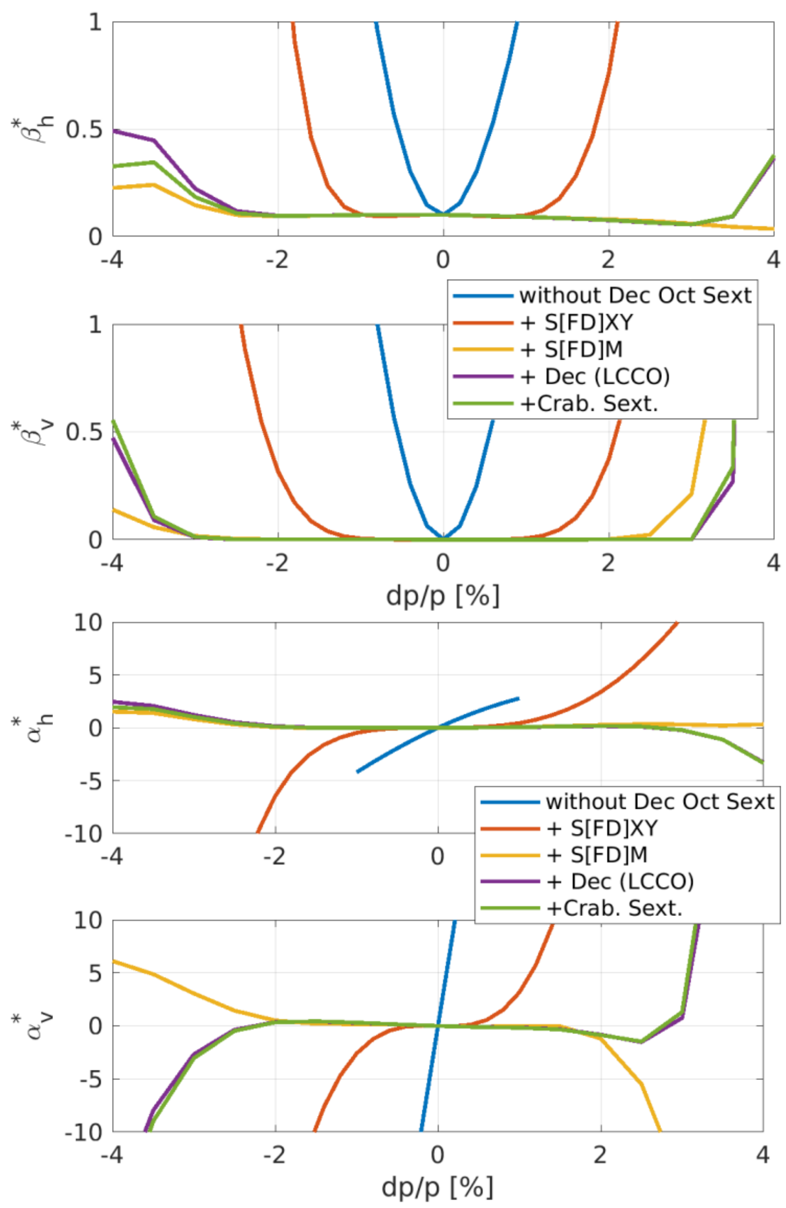


FIG. 15. $\beta*$ at IP (top) and $\alpha*$ at IP as a function of the energy deviation considering only the FF optics turning on progressively the multipoles for non-linear corrections.

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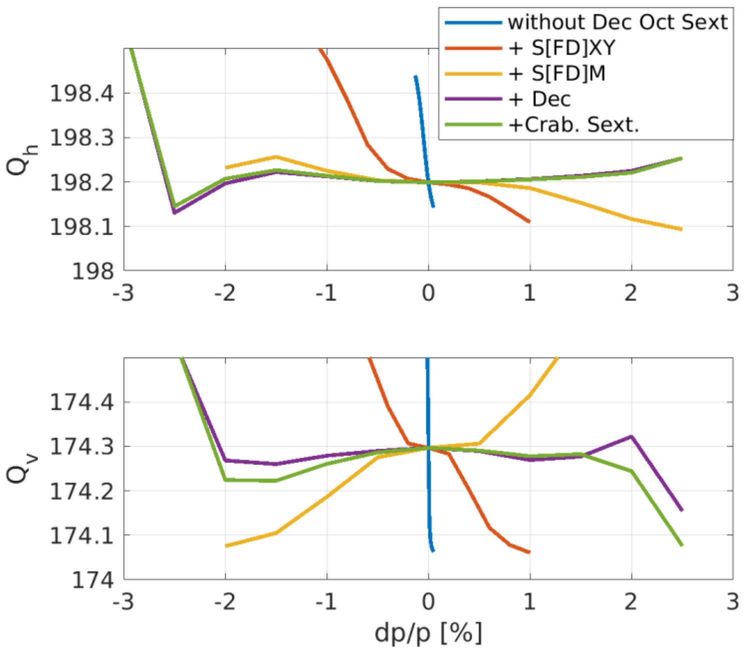
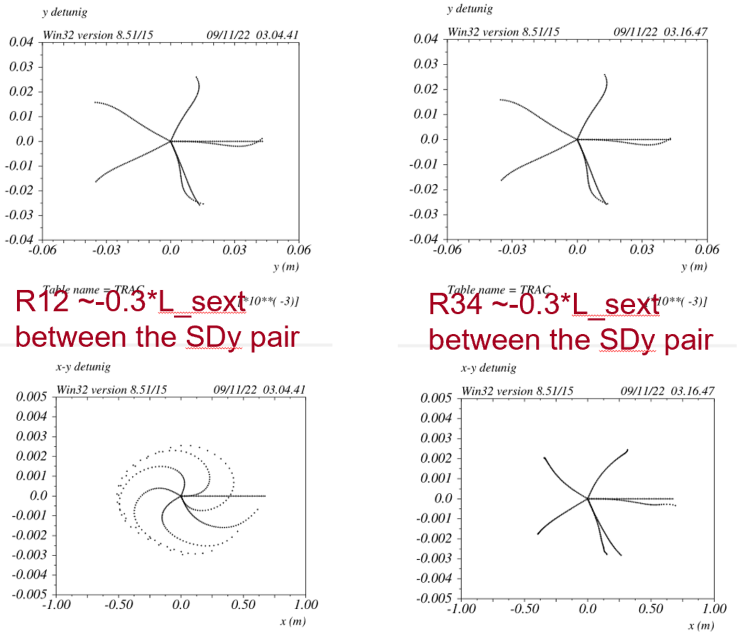


FIG. 14. Tunes vs momentum introducing one by one the non-linear multipoles in the Final Focus optics. Results are obtained by 6D particle tracking without synchrotron radiation.



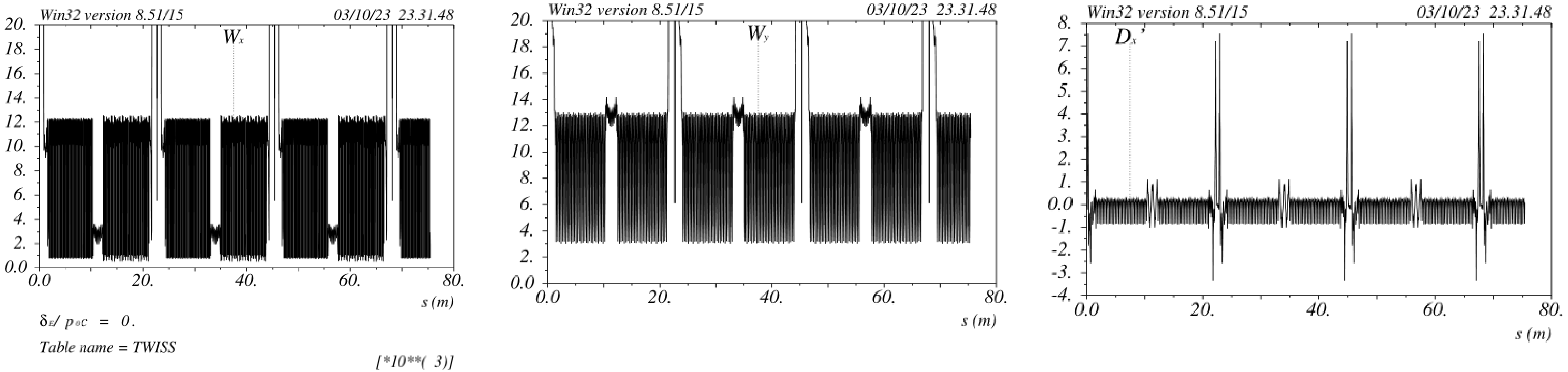
R12 ~-0.3*L_sext between the SDy pair

R34 ~-0.3*L_sext between the SDy pair

Higher order effects are optimized by prper dimensioning of dipoles and beta functions

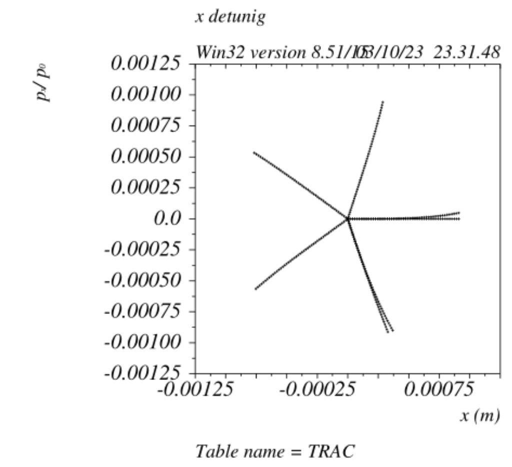
Full ring chromatic properties

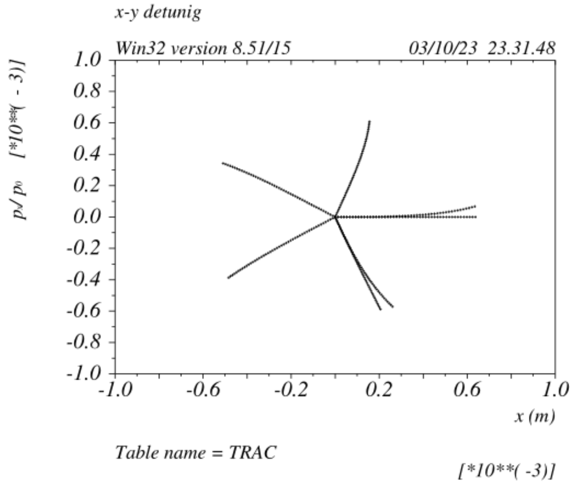
ttbar optic

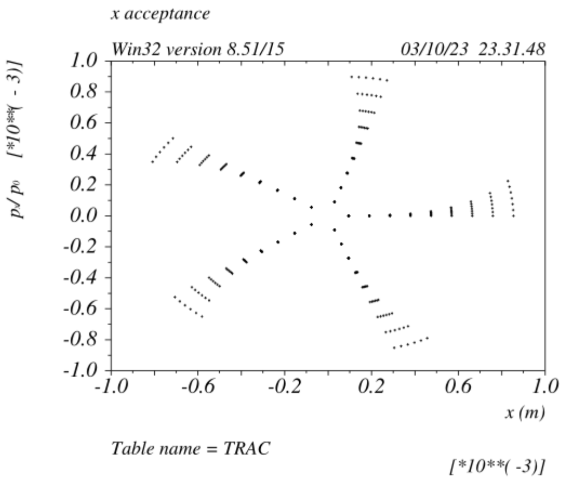


Chromaticity in the ARCs is periodic and about 12 in both planes
This is extremely beneficial to reach and maintain top performances in a very short time
No sextupole families are needed to correct the chromaticity from the IPs
Because the “Full Achromat” FF property, there is no need to change the ARCs&FF sextupoles (and CS) setting when the beta-squeeze is done with the beta-matching quads
This is extremely beneficial to reach top performances, it will be extremely useful to level the luminosity on the 4 IPs as well.

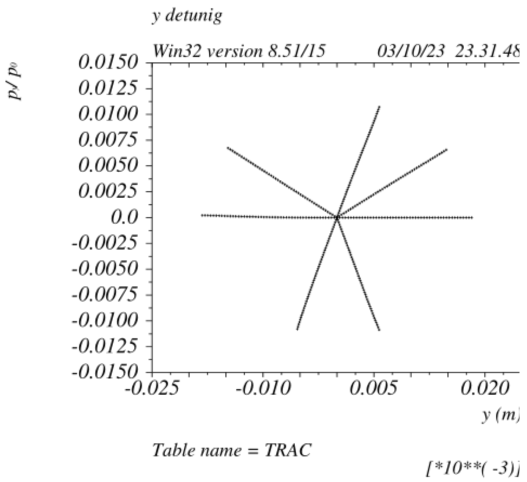
Full ring transverse DA v_67 ttbar optic

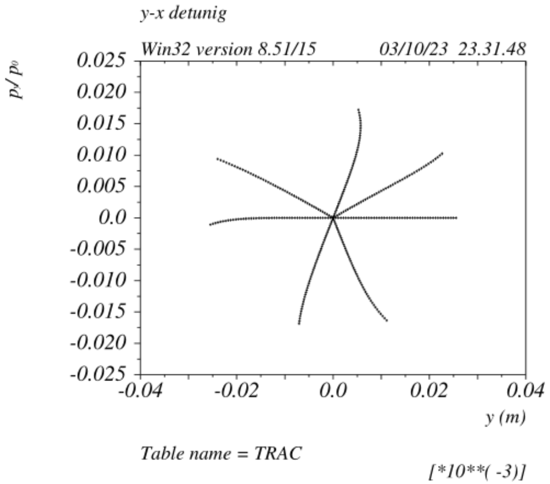


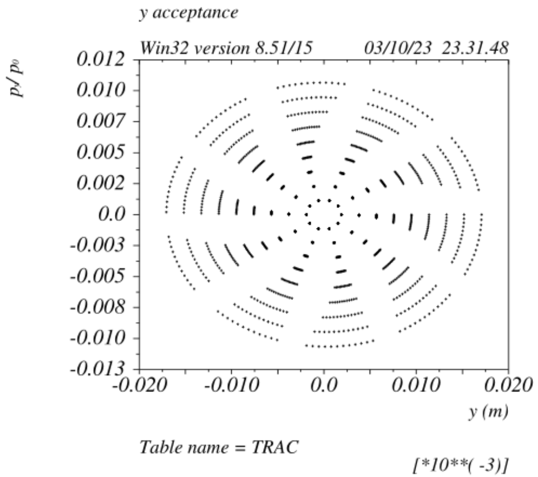




On energy dynamic is linear.
“Resonances” are virtually not existing.
Extremely favourable dynamics to minimize BeamBeam degradation (DS)







The quest/dream for a “quasi” time-independent trajectory is at reach!

Cancelation of the Energy dependent Y & XY detuning with decapoles: restoring the CCs sexts “-I” condition for off energy particles

The trick adopted is to use the Left and Right decapoles pairs to cancel “globally” the detuning: FFL&R instead of FFL and FFR individually.

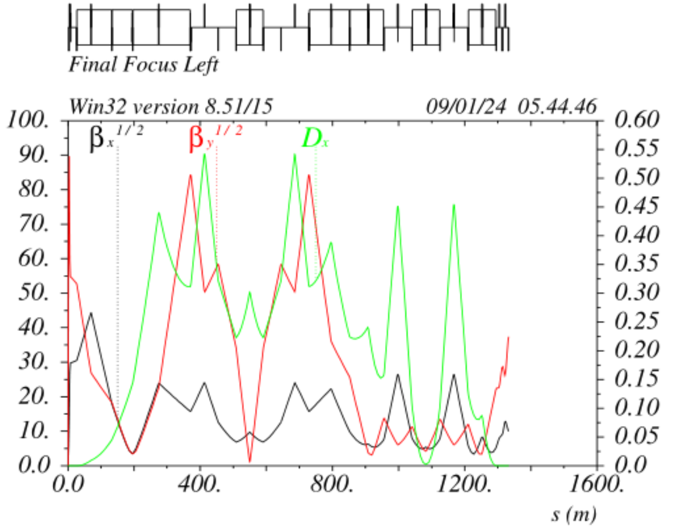
1) CCSy_Left decapoles are negative and cancel de_xy_detuning
2) CCSy_Right decapoles are positive and cancel de_y_detuning
3) CCSx_L&R decapoles are positive and cancel de_x_detuning

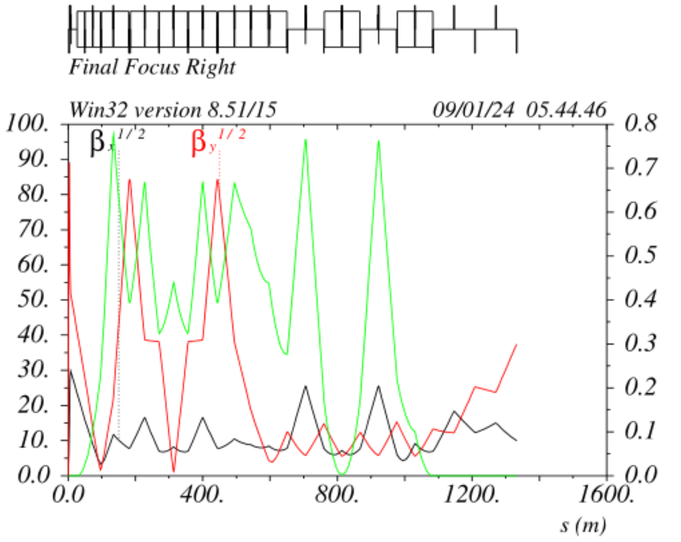
Betax/y@CCSyL/R are set to maximize the decapole effectiveness:

CCSy_L:	betay=7100m, betax=250m	dx=0.30m	K4L_DECDL ~	-2200
CCSy_R:	betay=7100m, betax=65m	dx=0.40m	K4L_DECDR ~	+3000
CCSx_L&R	betay~30, betax~650	dx~0.60m	K4L_DECFL&R ~	+500

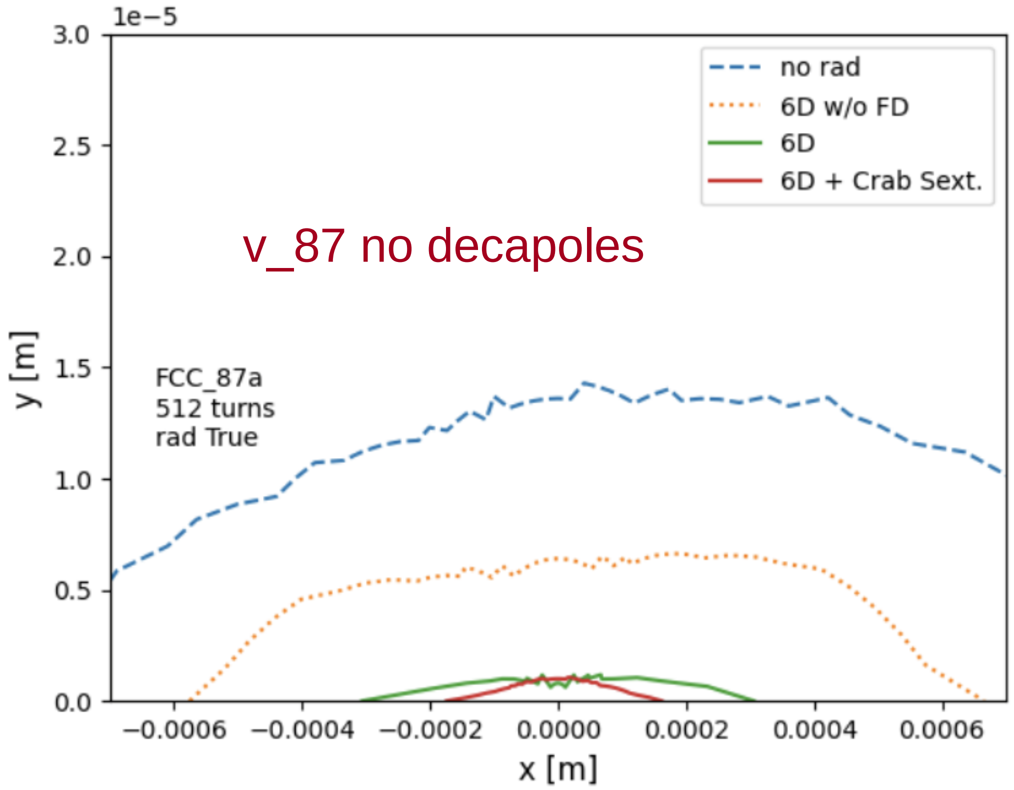
Given the very high order of the aberration the decapoles pairs are very orthogonal

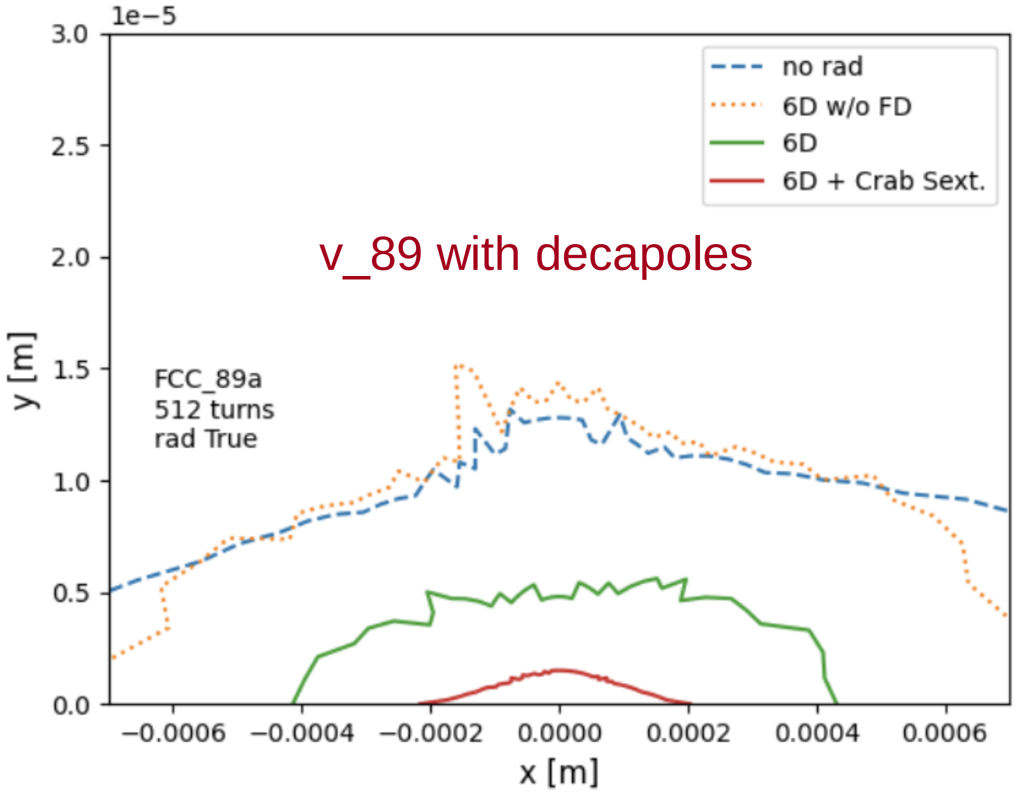
The transverse (mainly vertical) residual nonlinearities of the CCSy decapoles are canceled altogether because the opposite sign of the Left/Right ones.
The are no side effects on the DA and on on_energy detunings
The third order chromaticity is weakily effected, this result in a small change in the IP_phase sextupoles settings. Makes the x-IP_phase_sextupoles 10% weaker





Dynamic aperture without and with Synchrotron Radiation





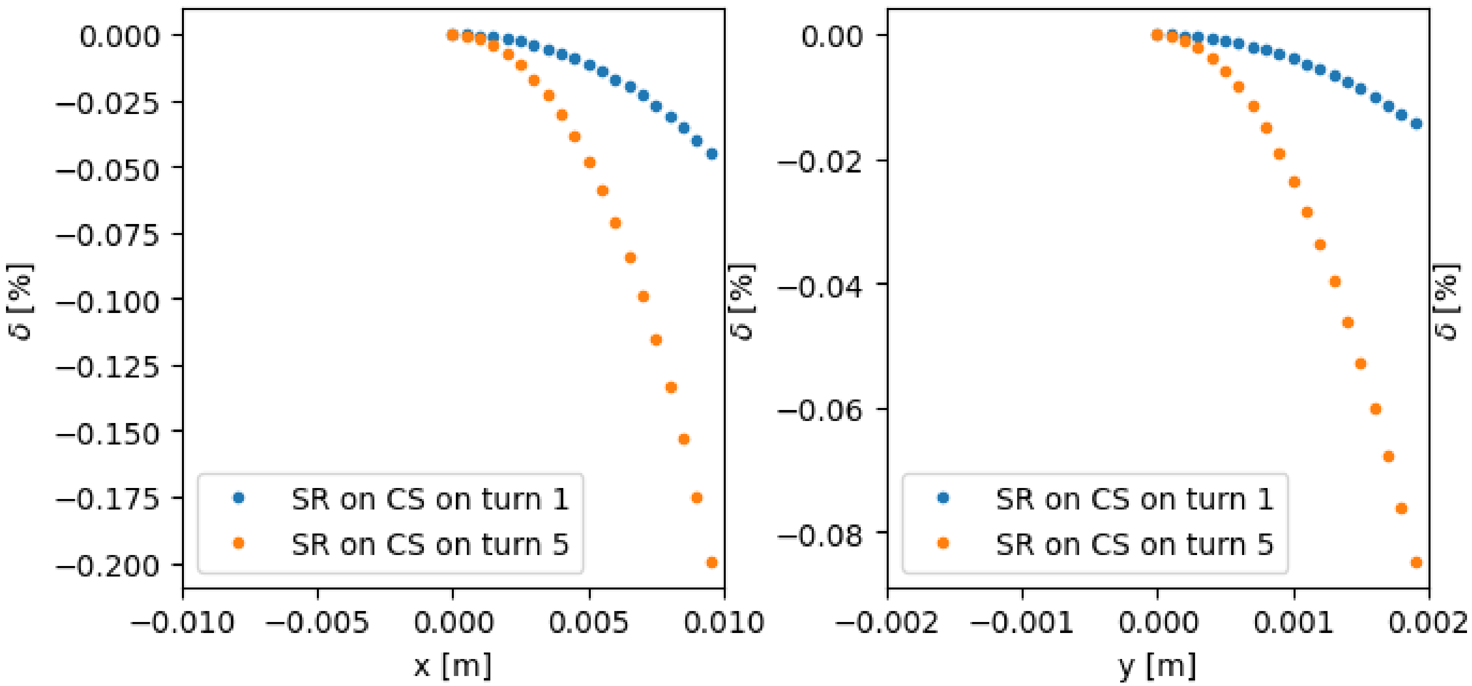
The effectiveness of the decapoles is evident
This is probably the first time that the degradation due to the quadrupoles-SR and FD-SR in particular is very effectively addressed

S Liuzzo

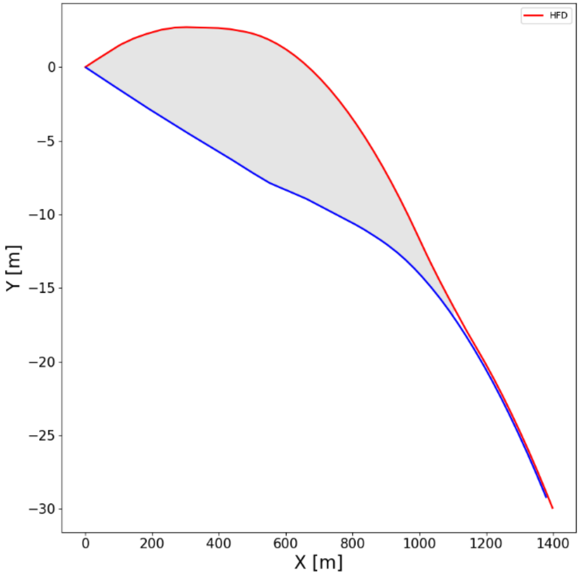
Energy loss due to Final doublet radiation (Z mode)

Energy loss induced by final doublet SR only.

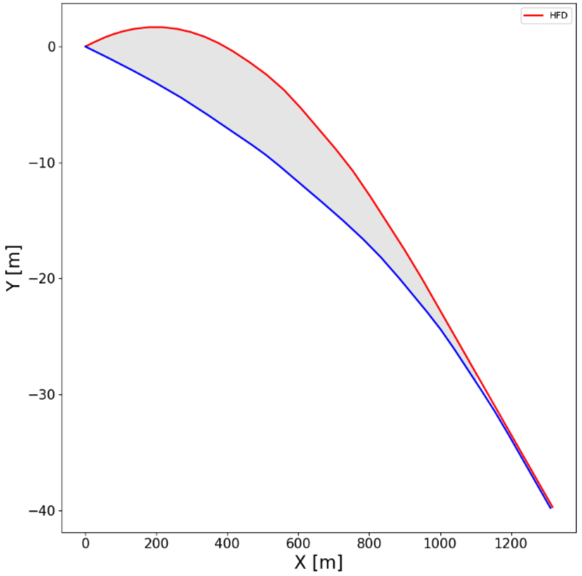
Similar for the two lattices.
After 160 turns the beam loses 2% and is lost out of MA.
The RF helps to recover the energy loss and the DA might improve by optimizing the RF voltage



FF layout v_89



Baseline: area 6640m2
Max separation 9.6m



LCCO: area 4960m2
Max separation 7m

IP offset wrt to baseline is around 11m

There are no reverse bends thus simplifying the SR radiation handling for the distributed absorbers

The stronger dipoles are in the CCSy_R just downstream the IP, they are anyway about 10% weaker wrt the ARCs ones.

The “Soft bend” upstream the IP is about 230m long and has an Ec~130KeV @ttbar

Overall the ratio FF_Eloss/FF_bend_angle is very similar to the ARC one.

There are no superconducting magnets required except the FD ones (this might change if some zero-leakage quadrupoles are needed). FF sextupoles@ttbar have k_values around 1 (1.5@Z) and are 60cm long.
FF quads are shorter and weaker wrt ARC’s

Beam parameters

	units	GHC@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

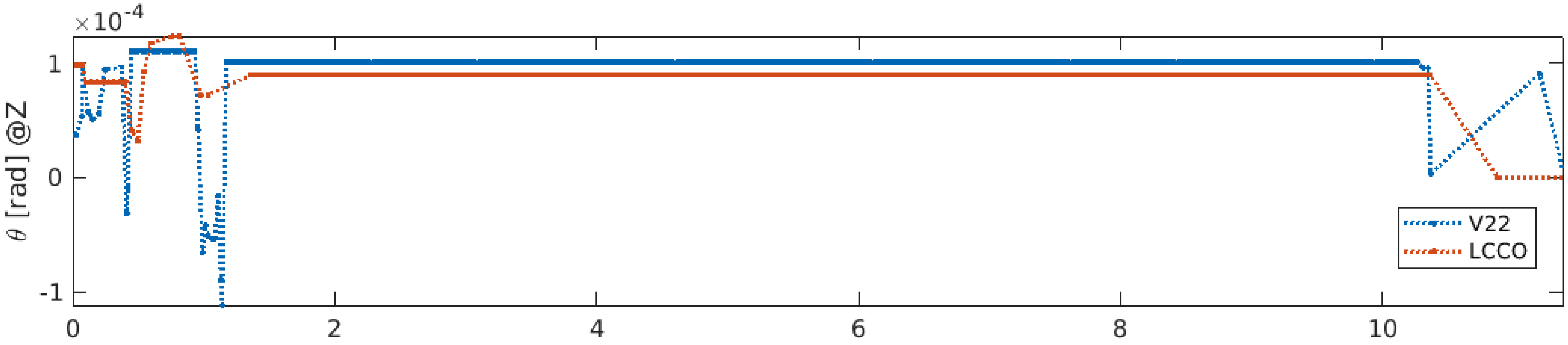
Quantum diffusion is not included in the following studies (available).

https://github.com/atcollab/at

Fully benchmarked with MADX-PTC

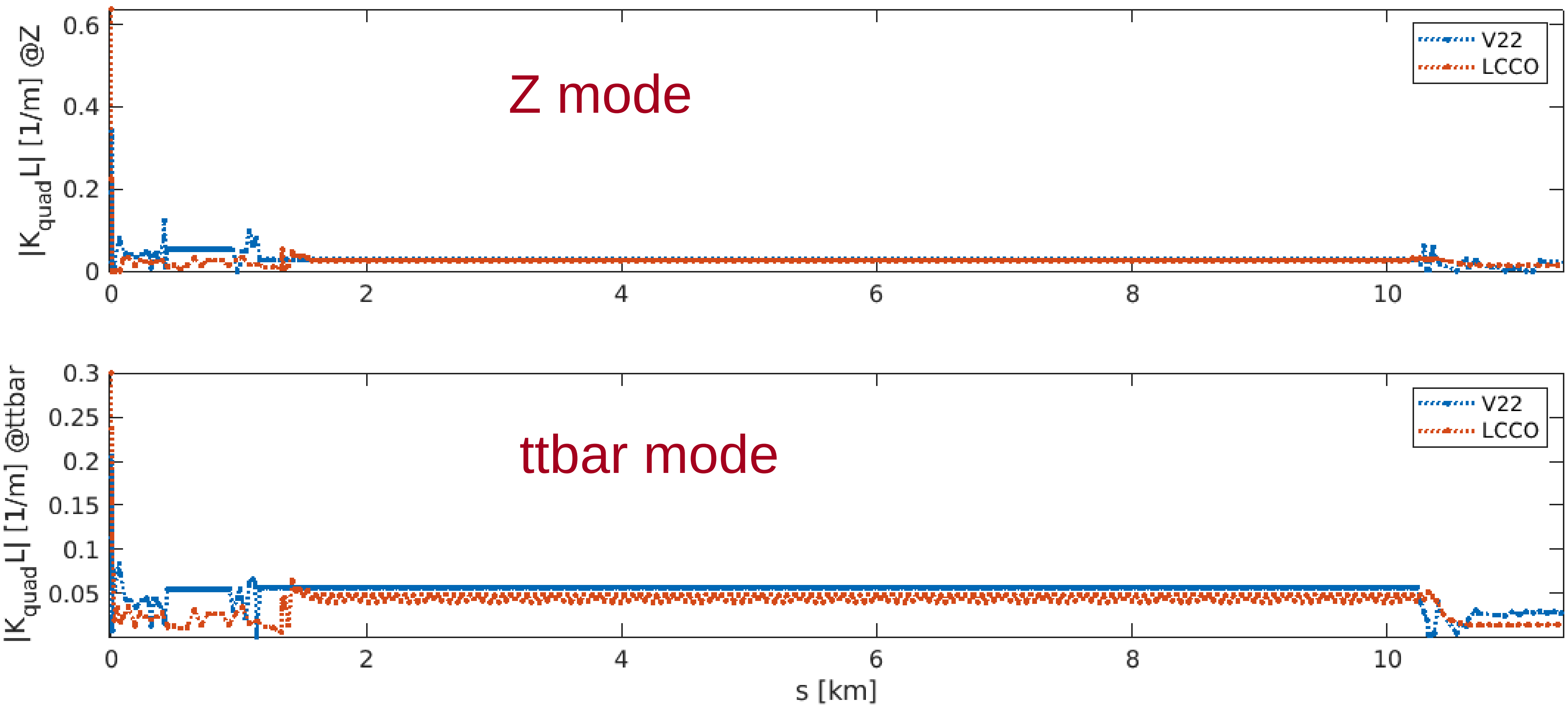
DIPOLE FIELDS (1 octant)

Z&ttbar mode



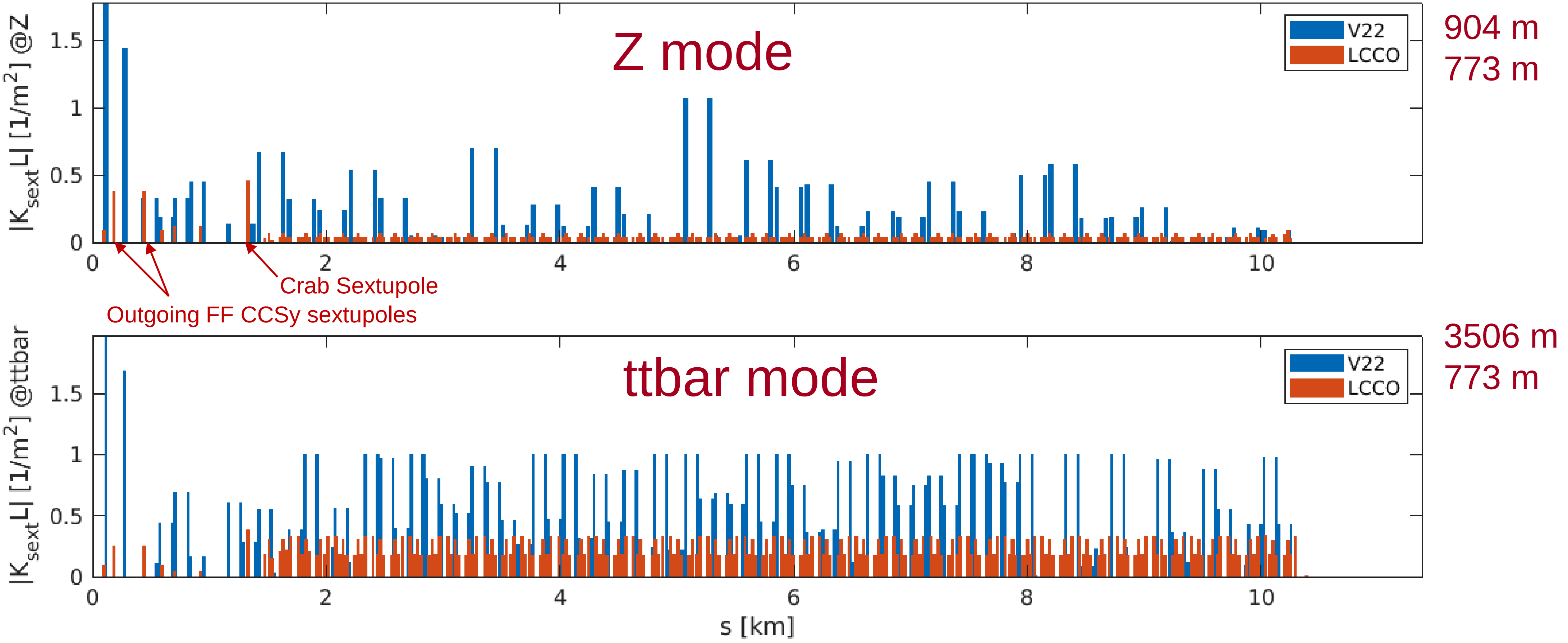
No negative angle bends for LCCO optics → easier synchrotron radiation absorption scheme

QUADRUPOLE GRADIENTS (1 octant)



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

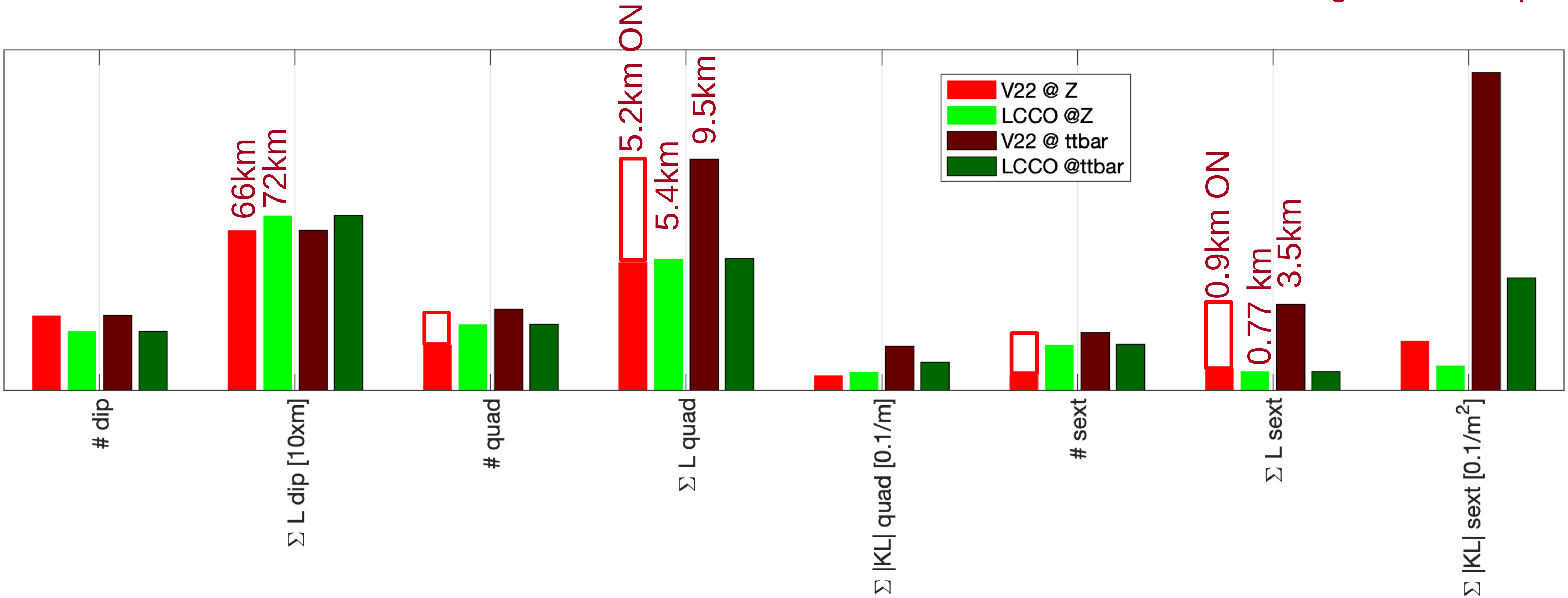
Sextupoles gradients (1 octant)



Smaller sextupole gradients ➔ Relaxed requirements and tolerances.

Number of magnetic elements and gradients

Including Crab sextupoles

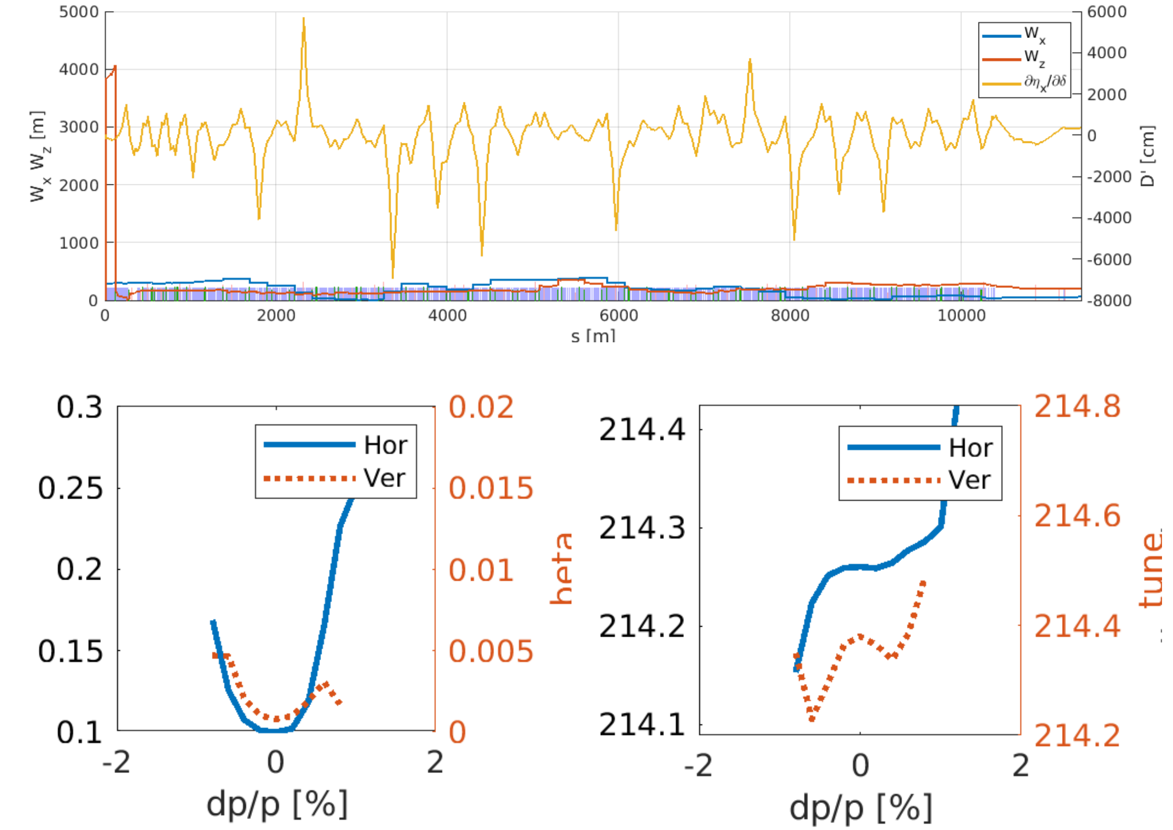


Only magnet gradients change. White boxes for baseline correspond to magnet off at Z
LCCO needs about half total quadrupole length and about four times less total sextupole length
LCCO needs about 60% of BPMs and correctors wrt baseline as well
LCCO requires about 13% less RF power and voltage wrt baseline

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

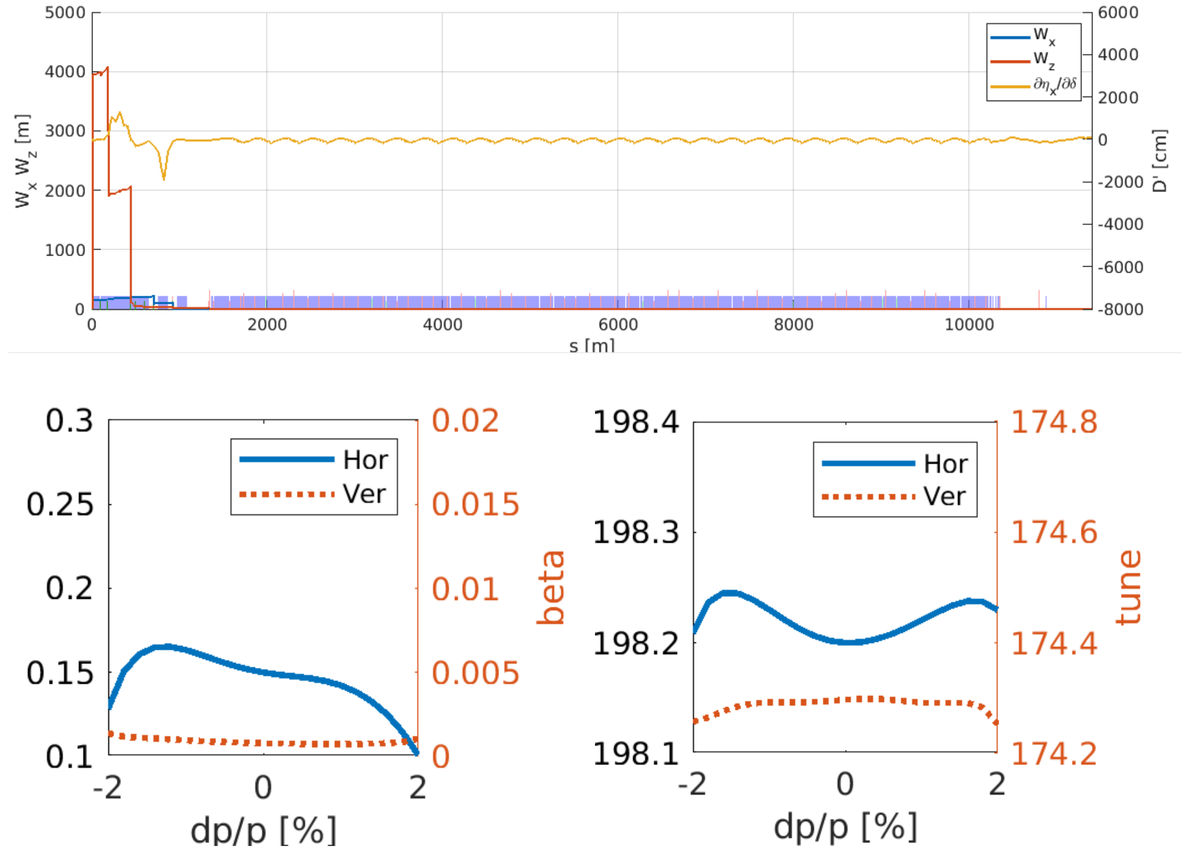
Off energy electron beam optics: W functions, IP bandwidth

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)

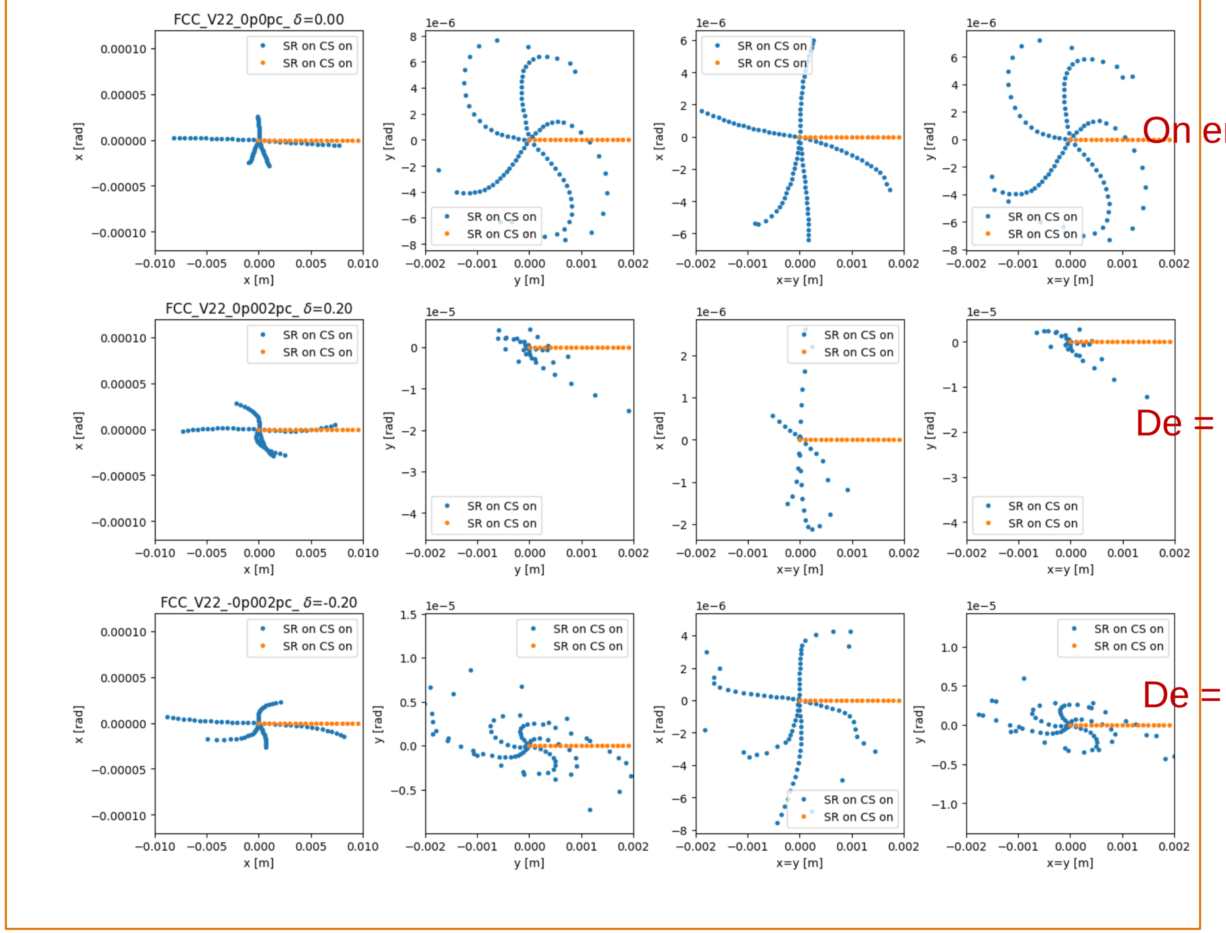


- Negligible luminosity loss due to energy dependent beta*
- Energy loss @IP does not cause betatron oscillations

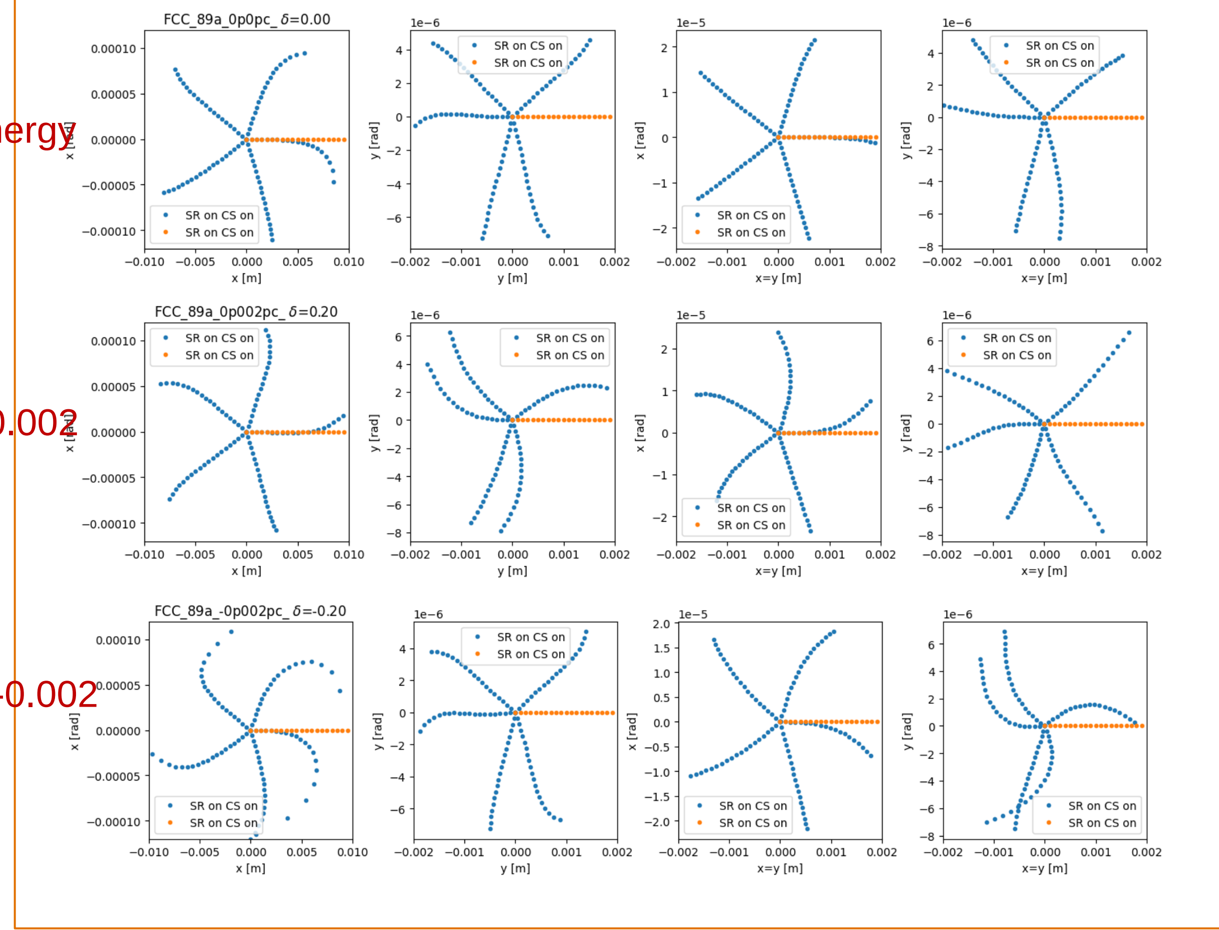
Phase space evolution over 5 turns on and off energy

No SR in dipoles (no effect)

GHC



LCC



On energy

De = 0.002

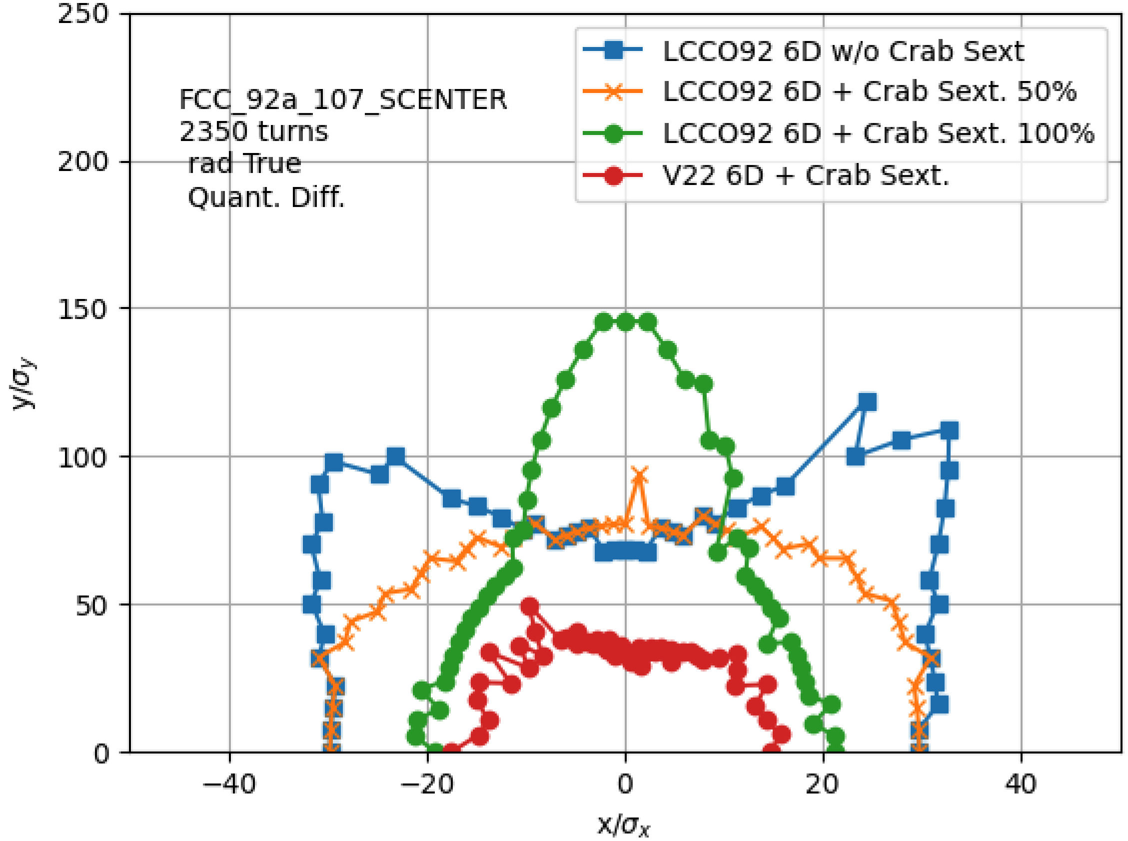
De = -0.002

SYNCHROTRON RADIATION AND CRAB SEXTUPOLES ON

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

Up to date IP beta* and corresponding Relaxed optics LCCO92

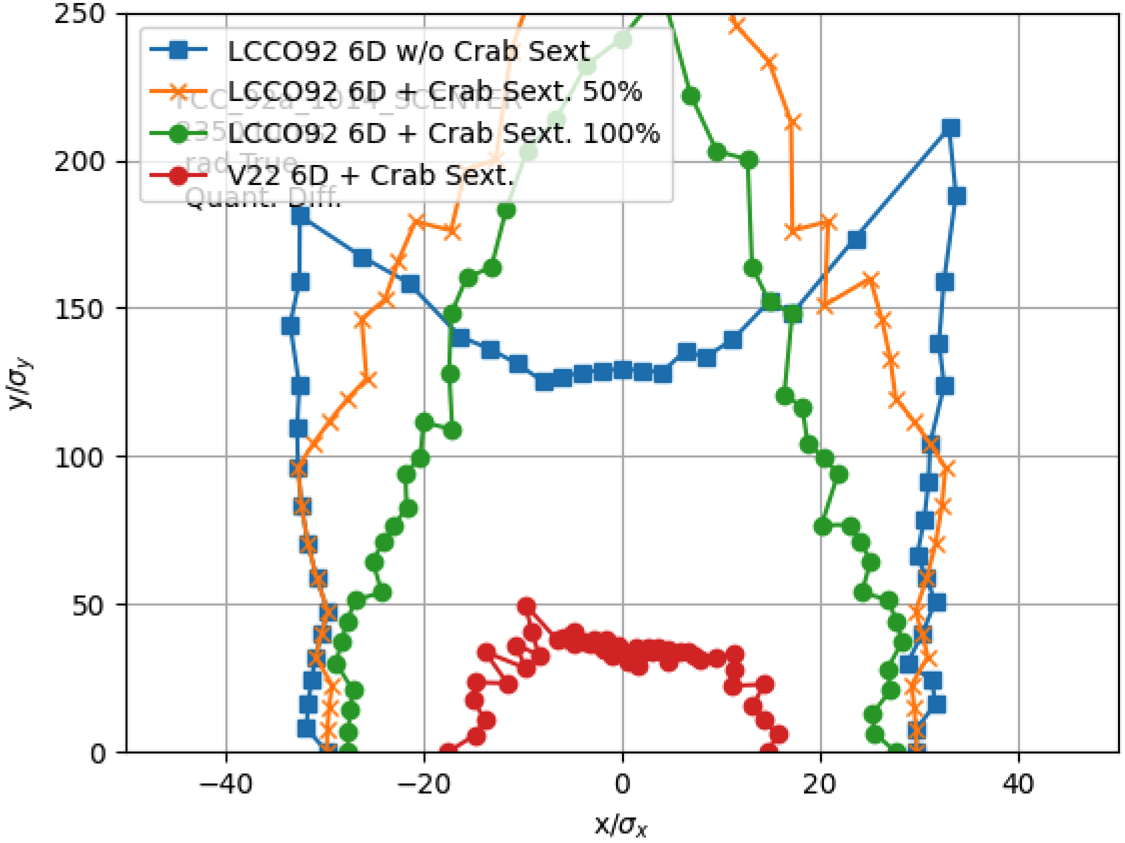
Present baseline beta*: β^*_h=10cm, β^*_v=0.7mm



*LCC vertical collimator gaps ~3 times larger wrt GHC

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

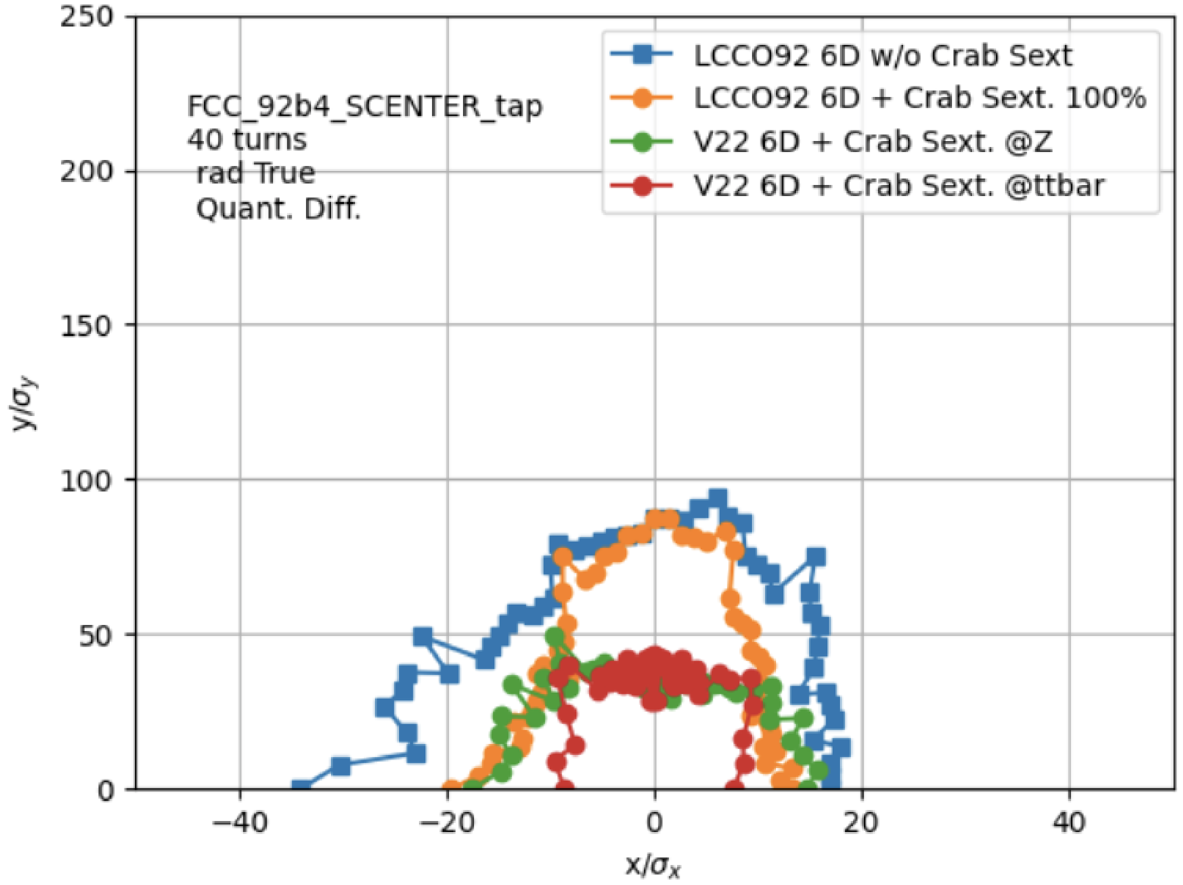
Relaxed beta optic obtained by changing 2*6 beta matching quads only at FF entrance



*Decapoles settings optimized only with CS on

LCC DA @ ttbar vs GHC (v22)

V_92b4

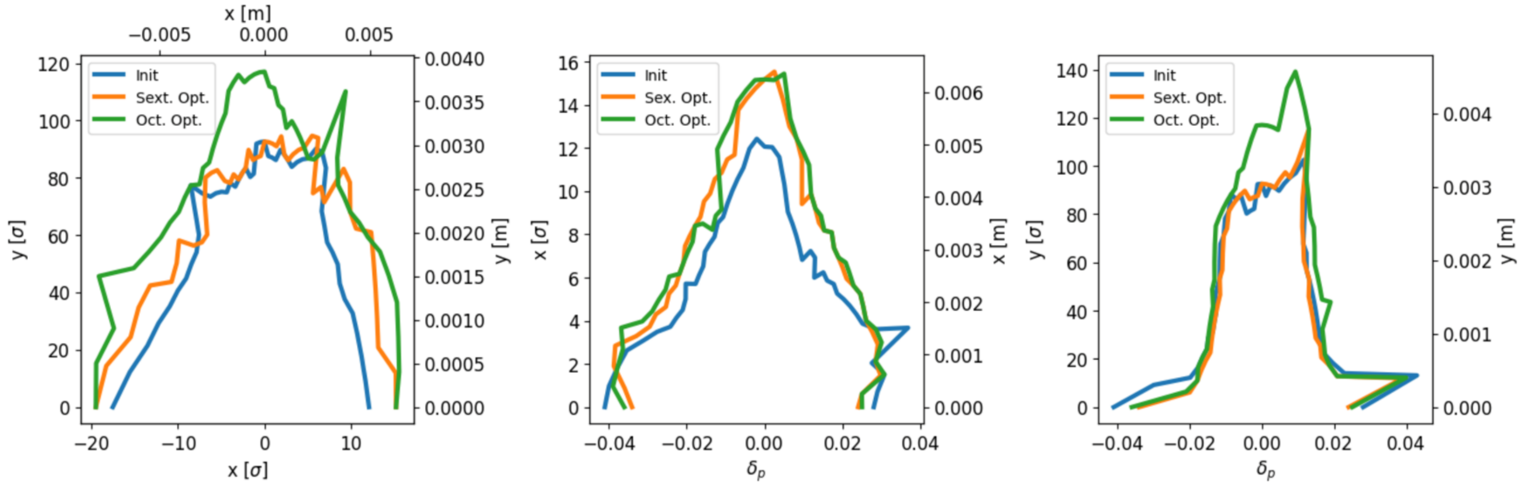


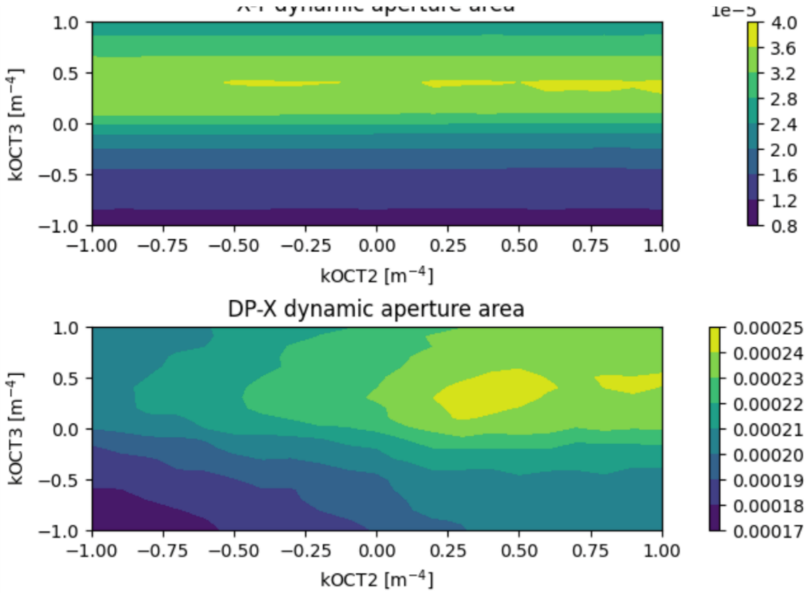
ttbar DA dominated by SR effects,
Need to simultaneously improve:
- MA
- DA
- Minimize eloss of axis (quadrupoles gradients)

Lattice optimization for ttbar is still on a “fast track”

Optimization with tracking

S White

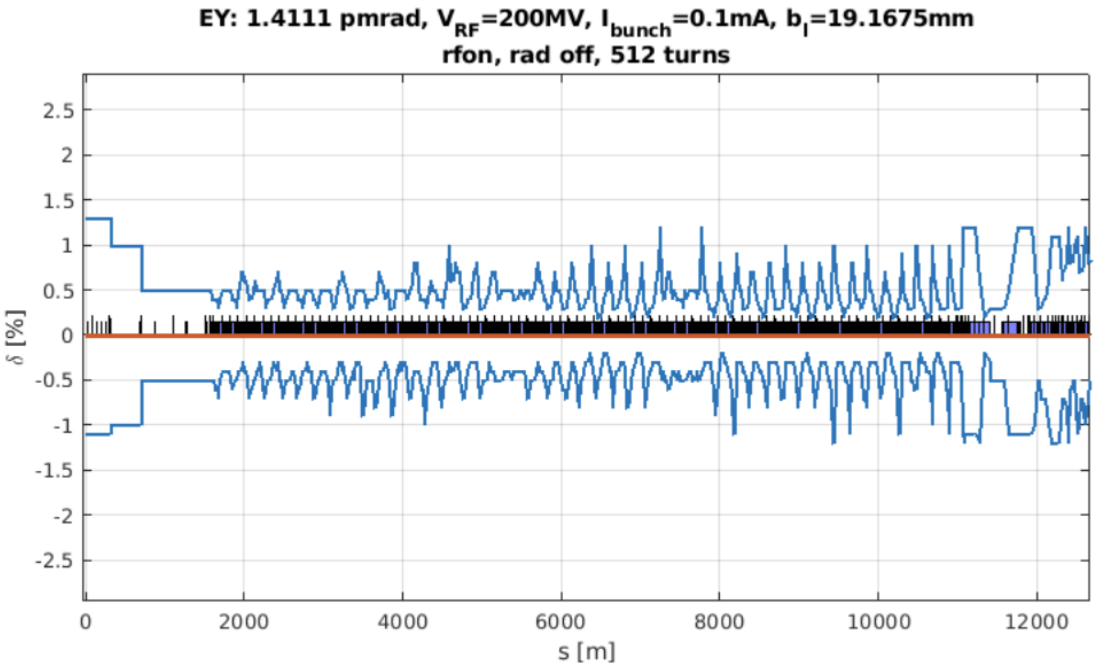




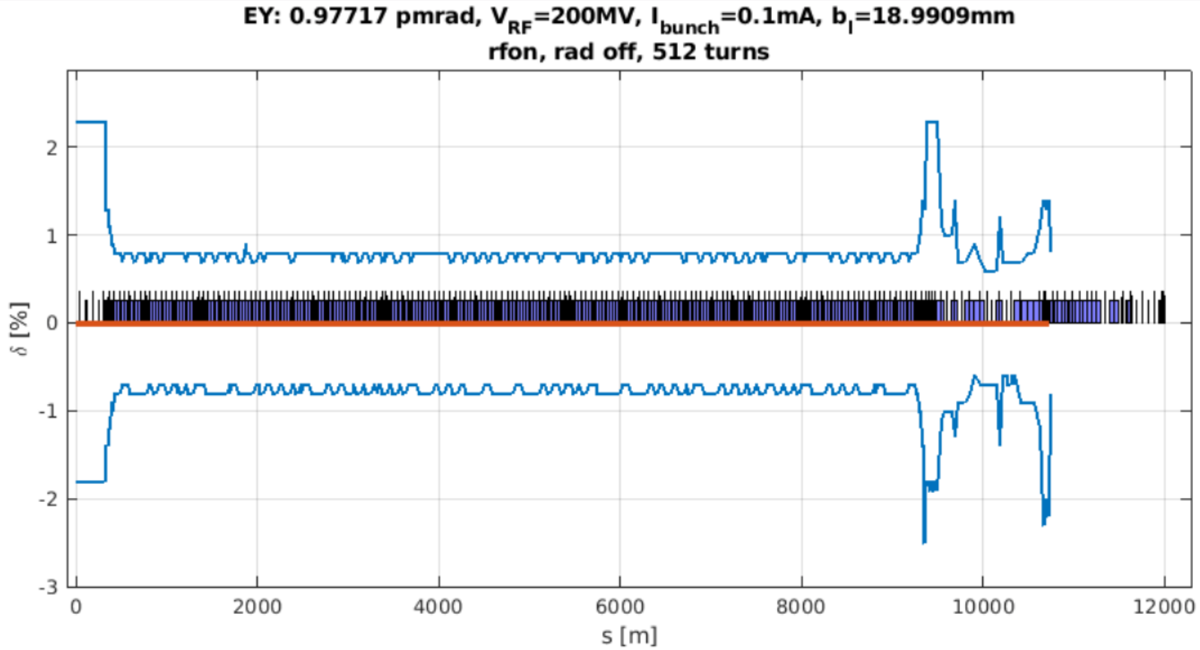
Optimization with numerical tracking further improve DA&MA
Preliminary results show a potential of 20%-30%

- Main RDTs/aberrations are set to optimal values (~0) with nearly orthogonal knobs/sexts/octs/decs
- Their settings can be computed very much analytically
- However there is always some trade-off among them, numerical opptimization with tracking is very effective to optimize this trade-off

Local Momentum Acceptance no synchrotron Radiation (OPTIMISTIC)



LCCO 76



6.5h

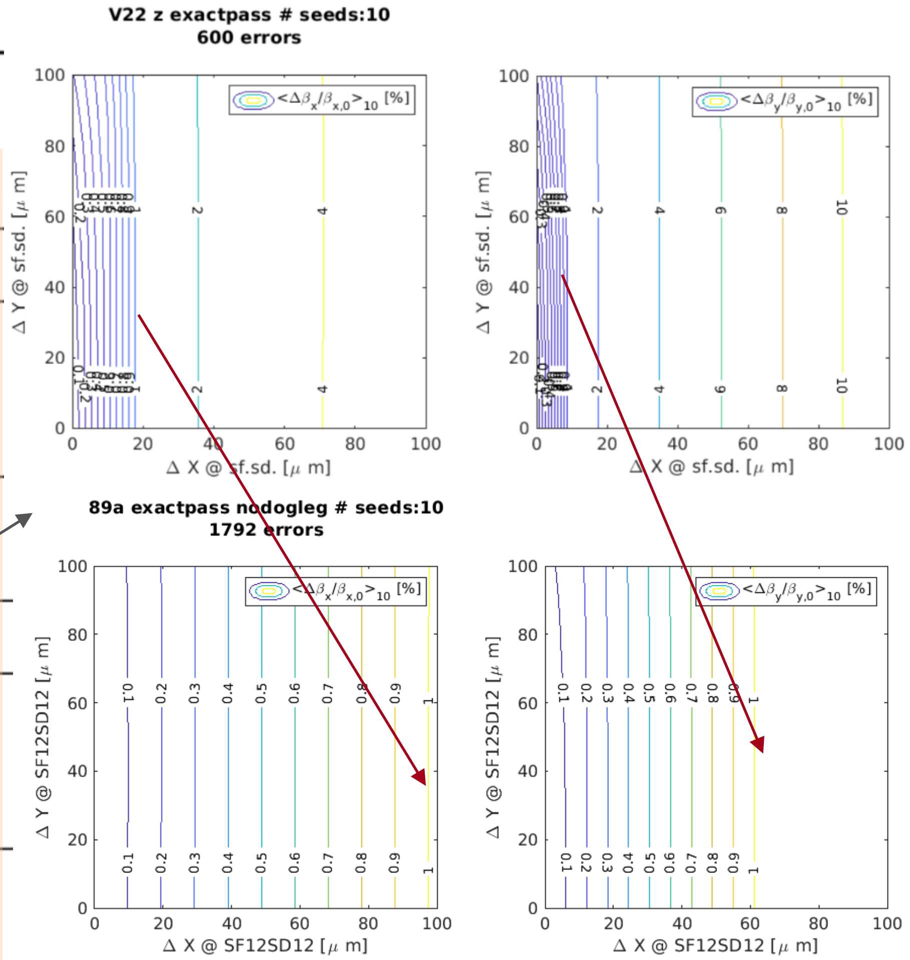
$$\tau_{Tou.,bunch} \propto \frac{\delta^3 \sqrt{\epsilon_v}\sqrt{\epsilon_h}\sigma_l}{I_{bunch}}$$

12.2h

Small momentum acceptance locations have large impact on final Vacuum and Touschek Lifetime
LMA with errors further shrinks

Arc alignment sensitivities

criteria	E_0	#	orbit H 100 µm	orbit V 100 µm	$\Delta\beta/\beta$ H 1 %	$\Delta\beta/\beta$ V 1 %	$\Delta\eta$ H 1 mm	$\Delta\eta$ V 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

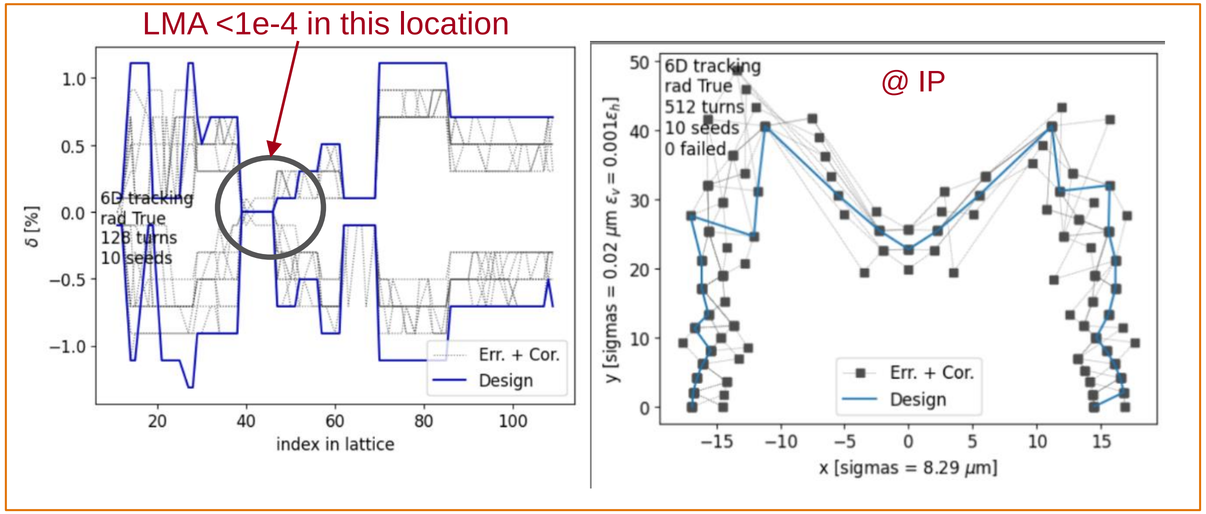
criteria	E_0	#	orbit H 100 µm	orbit V 100 µm	$\Delta\beta/\beta$ H 1 %	$\Delta\beta/\beta$ V 1 %	$\Delta\eta$ H 1 mm	$\Delta\eta$ V 1 mm
			final focus quadrupoles sensitivity to (hor., ver.) alignment [µm]					
V22 (.26 .38)	Z	436	0.8	0.1	(1.5, 1.2)	0.05	(0.025, 0.025)	0.01
LCCO89 (.20 .30)	Z	532	0.6	0.1	0.3	«0.1	0.04	0.01
LCCO89 (.26 .38)	Z	532	0.6	0.12	0.6	<0.01	0.06	<0.01
V22	$t\bar{t}$	480	2.0	0.35	2.1	0.22	0.24	0.04
LCCO89	$t\bar{t}$	532	1.4	0.25	2.3	0.04	0.24	0.05
			final focus sextupoles sensitivity to (hor., ver.) alignment [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

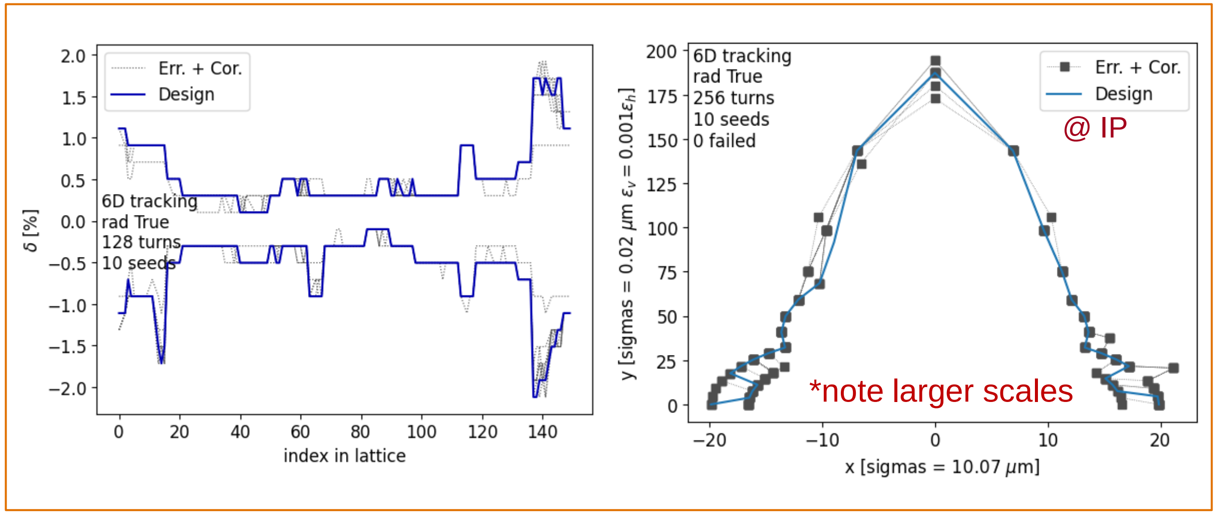
~4x better

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

Some LCCO highlights

- ARC tuning nearly identical to the EBS one (highest energy ring with lowest horizontal emittance existing so far), correctors (H/V/S) are trim coils on sextupoles
- FF tuning knobs are very standard and can be built accordingly to the SLC/NLC/LEP ones
- Large orthogonality of many fundamental quantities, that can be varied separately with no need to retune other quantities:
  - ARC chromaticities
  - Machine tunes
  - FF chromaticities
  - Individual IP betas
  - Individual CS pairs
  - Local FF tuning knobs
- All requirements on tolerances and stabilities for LCCO are very relaxed (M Hofer S Liuzzo)

Summary (1)

- The LCC beam dynamics is extremely well understood and optimized
- The understanding of the quads SR on beam dynamics has lead to unprecedented means to mitigate the related DA deterioraton. This will be potentially even more beneficial to the higher energies operation.
- DA/MA exceeds the baseline, particularly in the vertical plane.
- There is only one very well identified aberrations that makes the CS detrimental to the DA. The reduction of this effect seems possible.
- Hardware requirements for LCC are much less demanding wrt GHC

Summary (2)

SLAC

- LCC includes all the know-how and experience acquired in designing, building, commissioning and operating most of the high-energy and high-luminosity linear and circular colliders of the past 30 years.
- Many innovative solutions developed in the very active (and forefront) Synchrotron Radiation Accelerator community are utilized as well
- LCC hardware requirements are in line with standard (and cheap) solutions adopted for most of the colliders built so far, in particular LEP
- LCC is an invaluable opportunity to further progress in Accelerator Physics and push forward the frontier of High Energy Science