Optics tuning and correction for future circular colliders workshop, CERN, 26-28 June 2023

ESRF | The European Synchrotron

FCC-ee optics tuning simulations

S.Liuzzo, A.Franchi, S.White (ESRF)
P.Raimondi (SLAC, CERN, ESRF)
M.Hofer (CERN)

OUTLINE

1. **Lattices used : V22 (z and t-tbar) HFD-51 (z and ttbar) HFD-61 (z and ttbar)**
2. **Sensitivity to sextupole and quadrupole alignment errors (no corrections) for ARC and FF**
3. **Commissioning simulations**
   1. Optics parameters after corrections
   2. Dynamic apertures with errors

References:

R.Tomas et al., Progress of the FCC-ee tuning working group WEPLO23, IPAC2023

A.Franchi et al. Analytic derivative of orbit response matrix and dispersion with thick error sources and thick steerers implemented in python, MOPLO69, IPAC2023

S.Liuzzo et al., Commissioning simulations tools based on python Accelerator Toolbox, MOPA142, IPAC2023, IOP

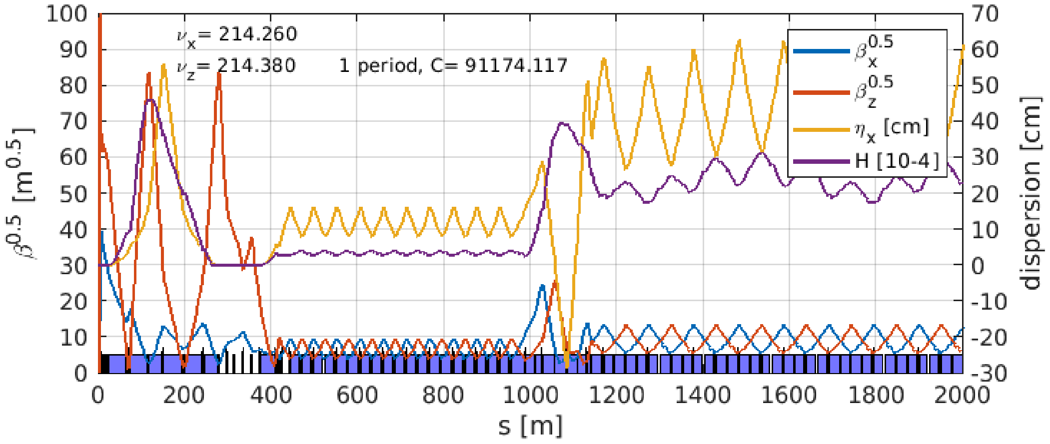
A.Franchi et al., Analytic formulas for the rapid evaluation of the orbit response matrix and chromatic functions from lattice parameters in circular accelerators, https://arxiv.org/abs/1711.06589

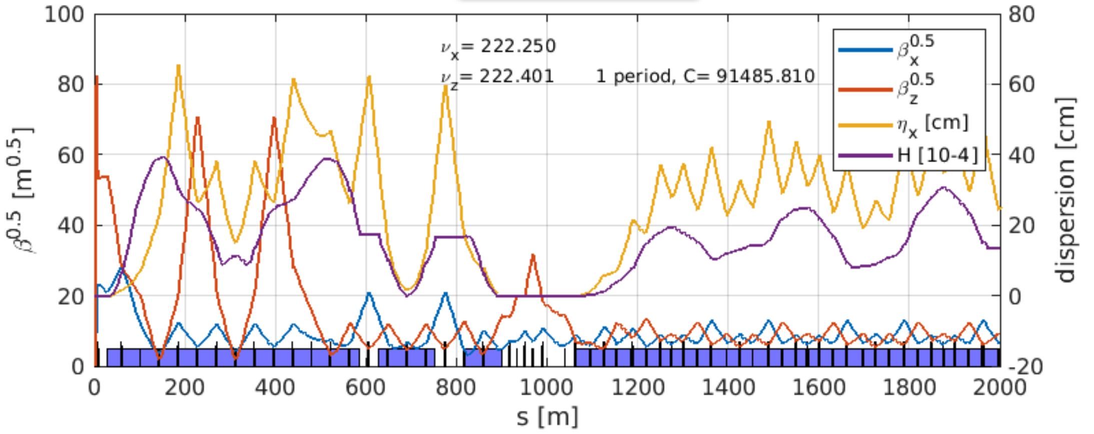
J Safranek, Experimental determination of storage ring optics using orbit response measurements, NIM-A, 1997,https://doi.org/10.1016/S0168-9002(97)00309-4.

LATTICES USED

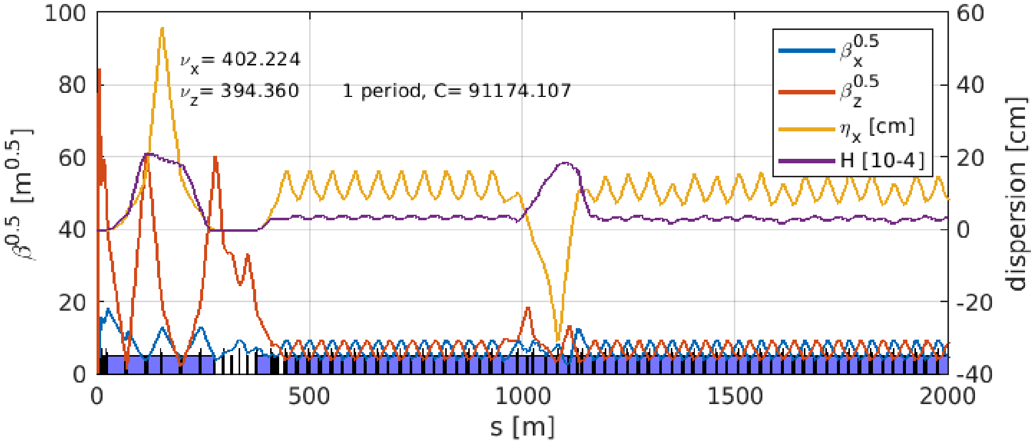
V22 First 2 km (over ~91km) HFD-61

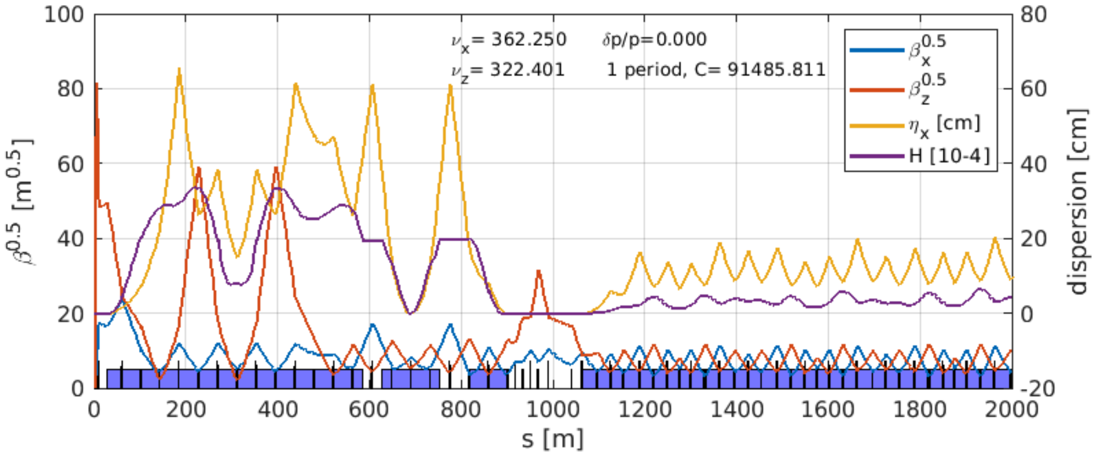
Z





t-tbar





Software used for all simulations is **Accelerator Toolbox (python and matlab)**. + Exact Hamiltonian integrators

Tracking has been benchmarked with MADX-PTC in several occasions.

https://github.com/atcollab/at

1) Scan alignment errors in given locations and store (horizontal and vertical):

- **Orbit**
- **Dispersion**
- **Beta-beating**
- **Emittance**

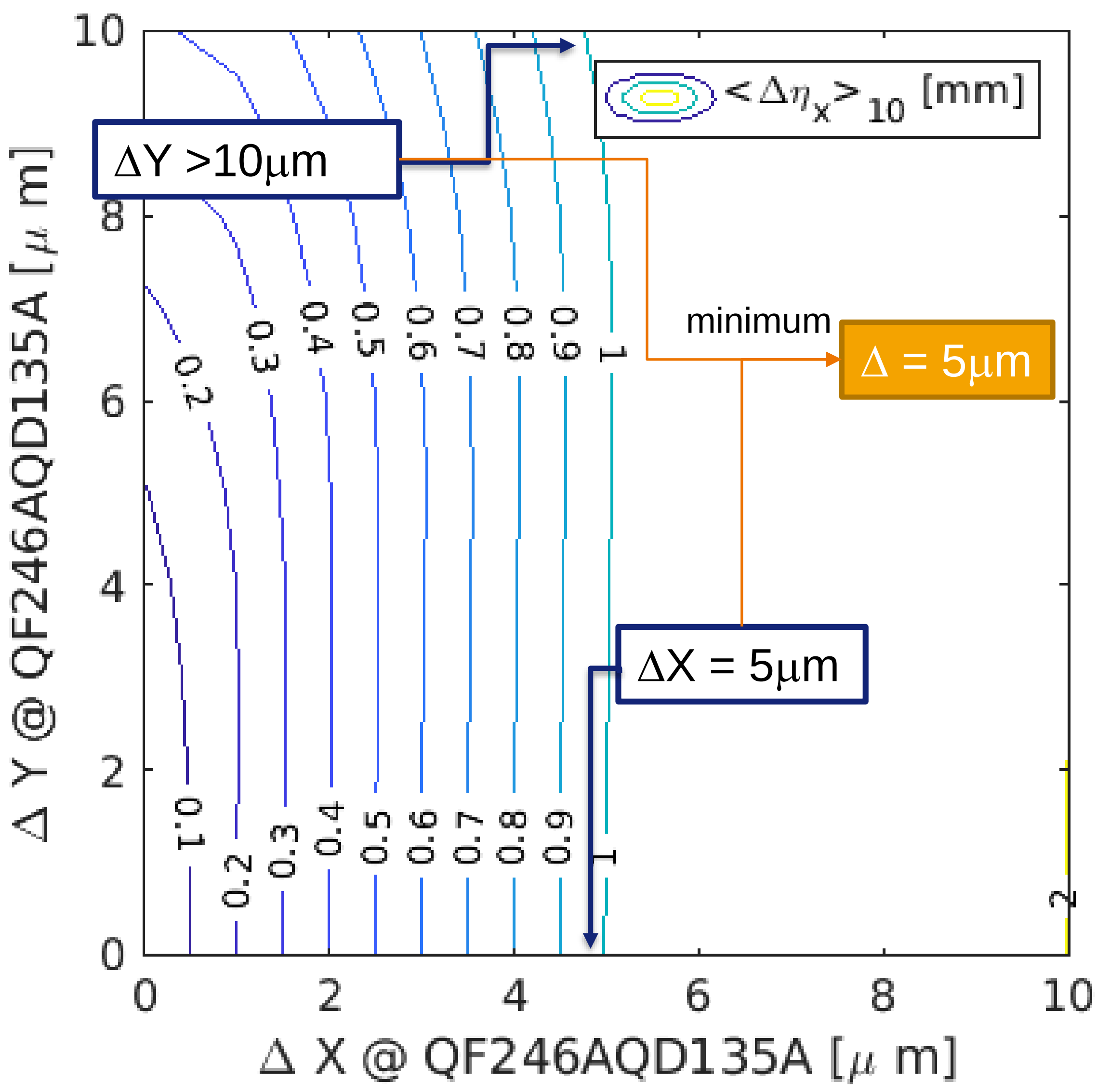
rms along the ring, averaged for 10 error seeds.

<u>NO CORRECTIONS</u>

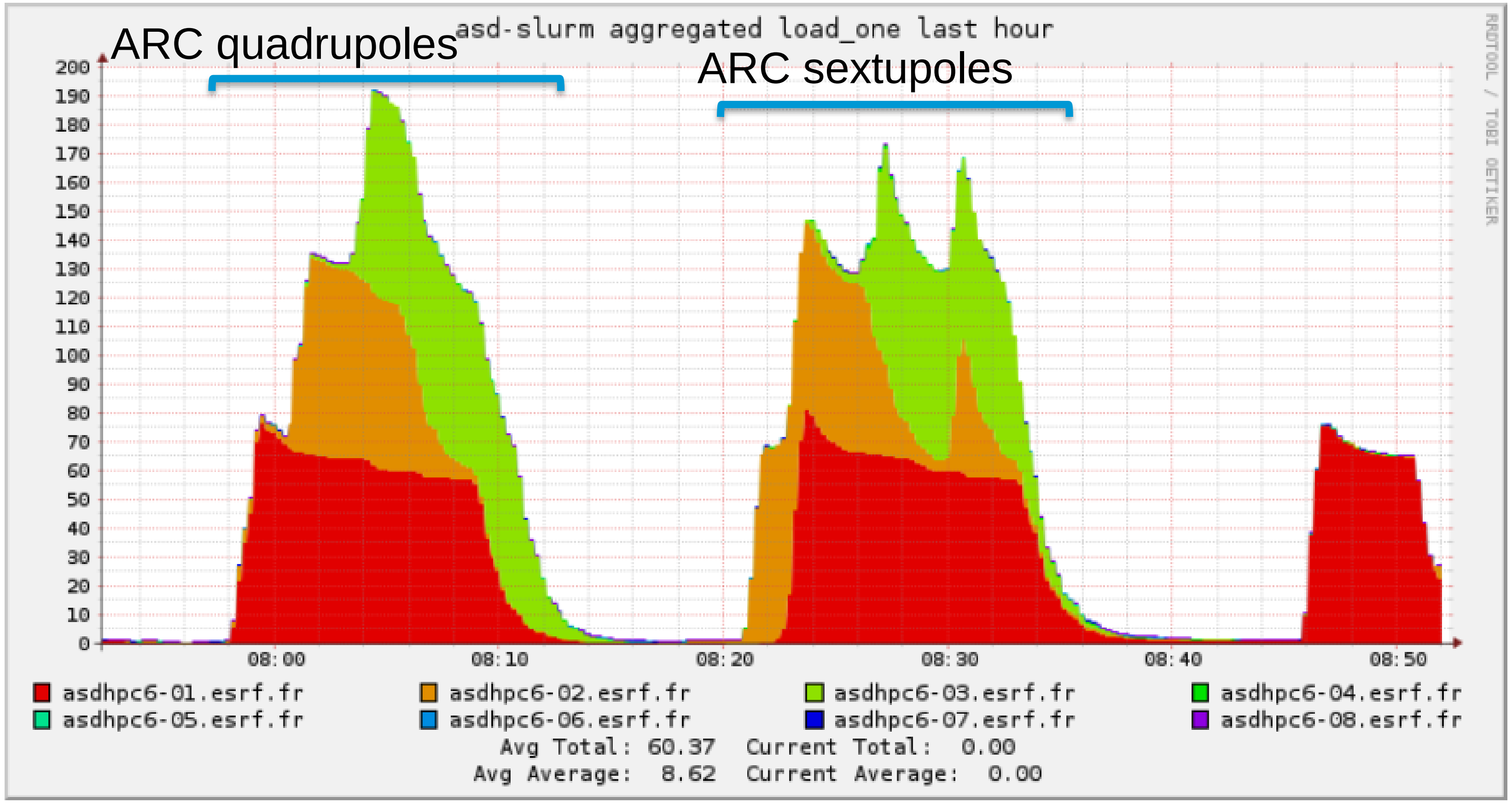
2) Extract values of errors that provide

- **0.1 mm Orbit**
- **1 mm hor. dispersion**
- **1 mm ver. dispersion**
- **1% Beta-beating**
- **1% hor. emittance increase**
- **Ver. emittance = 0.1% hor. Emittance**

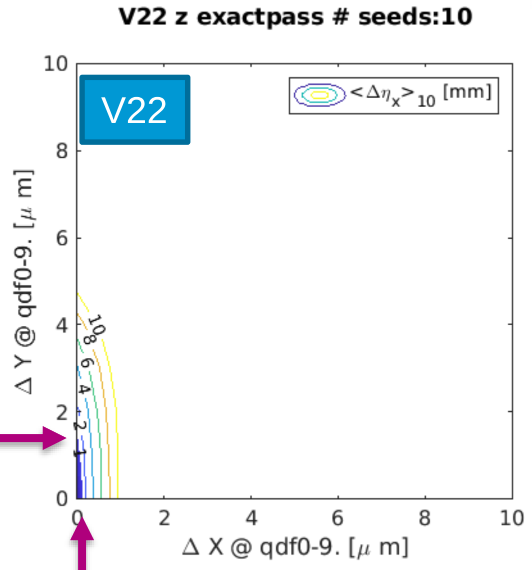
A simple tool to compare tolerances for different lattices

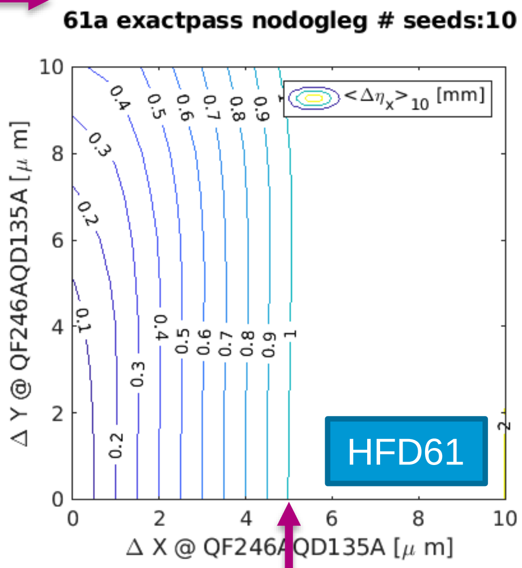


CLUSTER USAGE FOR SENSITIVITY PLOTS



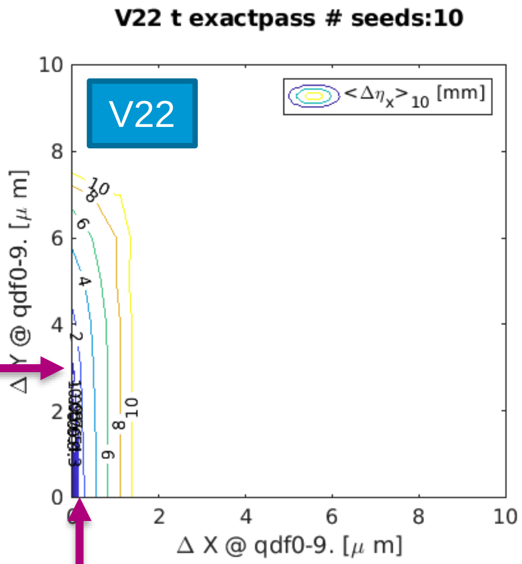
Rather fast (with the ESRF computing cluster). May be run often and for several lattice options.
Much longer time to extract and summarize the results in human readable tables.

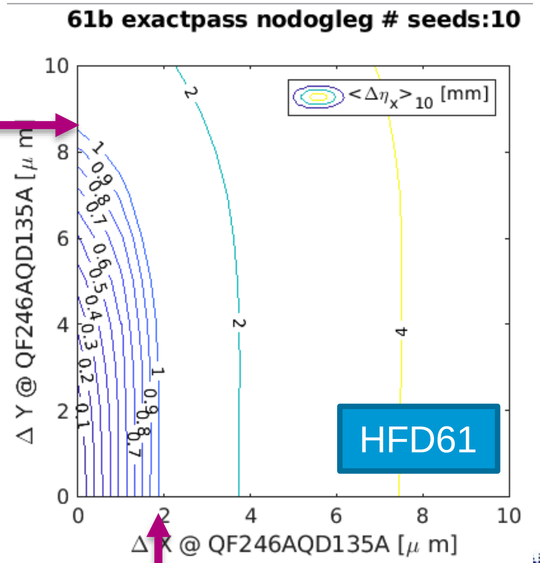

V22 z exactpass # seeds:10
V22
$<\Delta\eta_x>_{10}$ [mm]
Δ Y @ qdf0-9. [μ m]
Δ X @ qdf0-9. [μ m]


61a exactpass nodogleg # seeds:10
HFD61
$<\Delta\eta_x>_{10}$ [mm]
Δ Y @ QF246AQD135A [μ m]
Δ X @ QF246AQD135A [μ m]

@ Z

@ ttbar


V22 t exactpass # seeds:10
V22
$<\Delta\eta_x>_{10}$ [mm]
Δ Y @ qdf0-9. [μ m]
Δ X @ qdf0-9. [μ m]


61b exactpass nodogleg # seeds:10
HFD61
$<\Delta\eta_x>_{10}$ [mm]
Δ Y @ QF246AQD135A [μ m]
Δ X @ QF246AQD135A [μ m]

SUMMARY SENSITIVITY TO ARC ERRORS

HFD61 **is less sensitive to errors in the ARCS** than the baseline lattice for for all parameters studied.

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	$\Delta\epsilon$ H 1‰ϵ_h	$\Delta\epsilon$ V 1‰ϵ_h
			arc quadrupoles sensitivity [µm]							
V22	Z	1420	1.9	1.9	2.9	0.7	0.1	0.1	3.0	1.0
HFD61	Z	2408	8.4	7.5	>10	3.0	5.0	1.6	>10	2.7
V22	$t\bar{t}$	2836	1.3	1.5	1.5	0.5	0.12	0.2	0.5	0.17
HFD61	$t\bar{t}$	2408	2.8	3.1	4.2	1.5	1.9	1.0	>10	0.8
			arc sextupoles sensitivity [µm]							
V22	Z	600	>100	>100	17	8.5	3.1	2.6	90	39
HFD61	Z	912	>100	>100	60	26	10	16	>100	>100
V22	$t\bar{t}$	2336	>100	>100	10	7.0	7.5	10	27	26
HFD61	$t\bar{t}$	912	>100	>100	19	8	10	11	78	48

SUMMARY TABLE OF ERROR SENSITIVITY: NOT-ARC == FINAL FOCUS AND STRAIGHT SECTIONS

The Final Focus* magnets are more sensible especially in the V plane
Sensitivity to sextupole errors is similar.
Sensitivity to quadrupole errors is better for V22@Z and for HFD61@ttbar

7 nano-meter vertical quad alignment error ➔ 1mm rms Hor. Dispersion, 1% hor. Emittance etc. ...

Not-ARC

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	$\Delta\epsilon$ H 1‰ϵ_h	$\Delta\epsilon$ V 1‱ϵ_h
			final focus quadrupoles sensitivity to (hor., ver.) alignment [µm]							
V22	Z	436	0.8	>10	(1.5, 1.2)	0.05	(0.025, 0.025)	0.01	(1.2, 1.0)	0.008
HFD61	Z	524	0.8	0.19	(1.7, 1.0)	0.06	(0.4, 0.007)	0.004	(5.5, 0.007)	0.006
V22	$t\bar{t}$	480	2.0	0.35	2.1	0.22	0.24	0.04	1.1	0.06
HFD61	$t\bar{t}$	524	2.8	0.40	4.2	0.3	1.1	0.1	2.1	0.01
			final focus sextupoles sensitivity to (hor., ver.) alignment [µm]							
V22	Z	16	>10	>10	>10	0.25	>10	1.2	>10	>10
HFD61	Z	152	>10	>10	>10	0.25	9	2.2	>10	>10
V22	$t\bar{t}$	16	>10	>10	>10	0.50	>10	2.6	>10	8
HFD61	$t\bar{t}$	152	>10	>10	>10	0.45	>10	3.7	>10	>10

Sensitivity to sextupole misalignment primarily dominated by the low-beta chromatic correction

* assuming that the FF focus magnets are the most relevant contributors.

* N.B.: SEXTUPOLE “RAMP” is not needed. Replaced by realistic trajectory steering. EBS was commissioned sextupoles on.

V22@Z

pyAT

a) 1 **BPM** and 1 corrector for each quadrupole

b) Set 10um rms alignment **errors** in ARCS quadrupoles and sextupoles

c) Correction loop (repeated 2 times):

~30min

1. Trajectory steering *, find closed orbit
2. Orbit correction
3. Tunes correction
4. Chromaticity correction
5. (not done, no BPM errors BBA)
6. Optics and coupling correction (“LOCO-like”, 18 steerers) using Analytic Jacobians with thick quad. and thick steerers corrections

+ >3h

d) Evaluate lattice properties (DA, MA, optics, emittances, etc…)

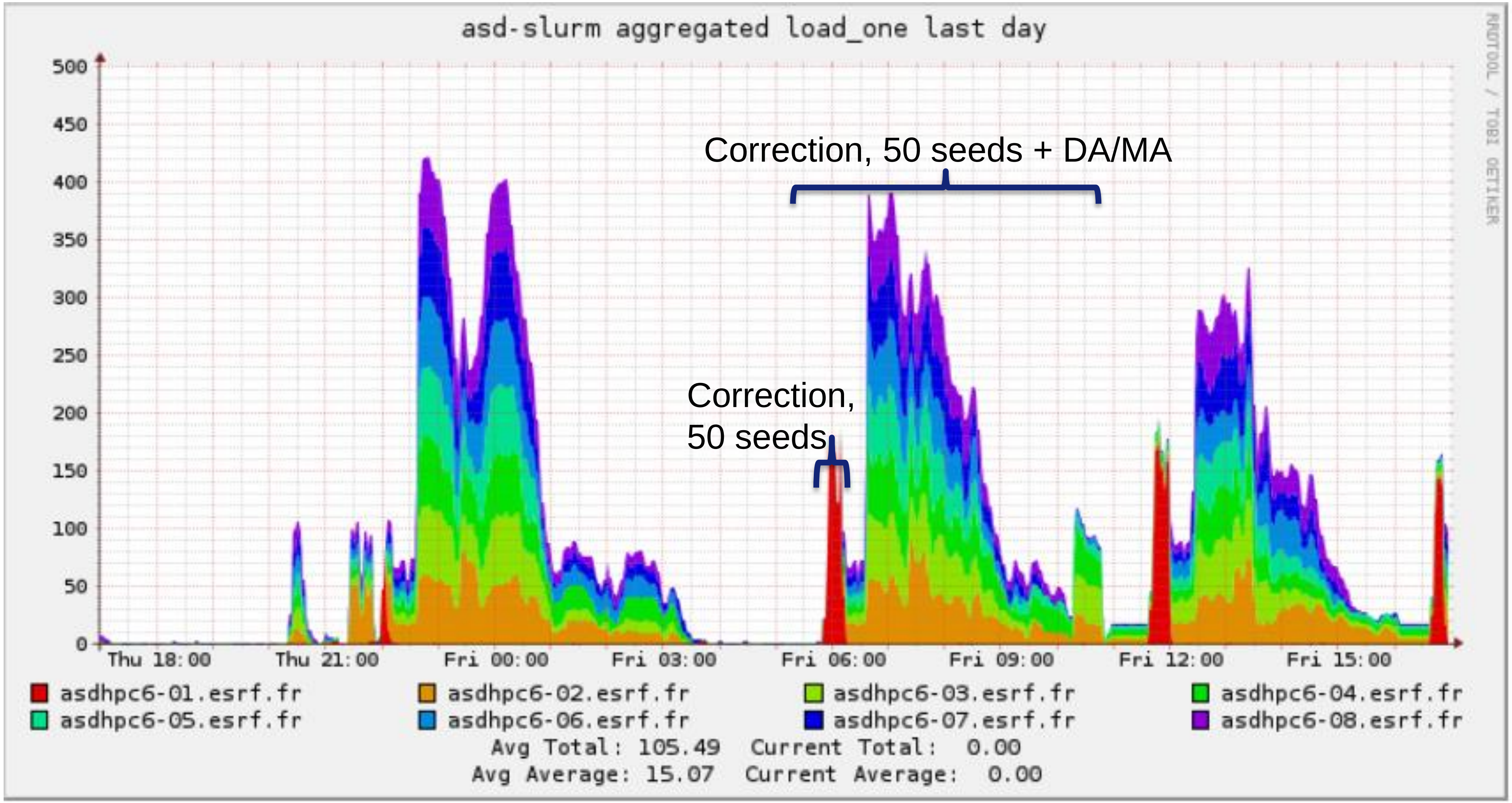
~ 4h to get commissioning simulations data for 50 seeds using the ESRF computing cluster

Table 3: β-beating, dispersion and emittances after correction of 10 μm random alignment errors on dipole quadrupole and sextupole magnets for the FCC-ee lattice using analytic ORM derivative (1856 BPMs, 18 steerers). The input lattice is tested: without radiation, with radiation and with radiation and tapering. Reference lattice is in all cases without radiation.

$\langle std \rangle_{50}$ units	$\frac{\Delta\beta_h}{\beta_{h,0}}$ %	$\frac{\Delta\beta_v}{\beta_{v,0}}$ %	$\Delta\eta_h$ mm	$\Delta\eta_v$ mm	$\Delta\epsilon_v$ pm rad
4D err	3.63	61.37	118.7	82.36	-
4D cor	0.84	4.24	25.67	9.58	0.71
6D err	3.60	59.45	120.54	82.45	-
6D cor	0.81	4.29	26.0	9.57	0.17
6D err + tapering	3.61	61.33	119.59	82.96	-
6D cor + tapering	0.82	4.22	26.03	9.65	0.18

A.Franchi et al. Analytic derivative of orbit response matrix and dispersion with thick error sources and thick steerers implemented in python, MOPLO69, IPAC2023

CLUSTER USAGE FOR COMMISSIONING SIMULATIONS AND DA/MA COMPUTATION

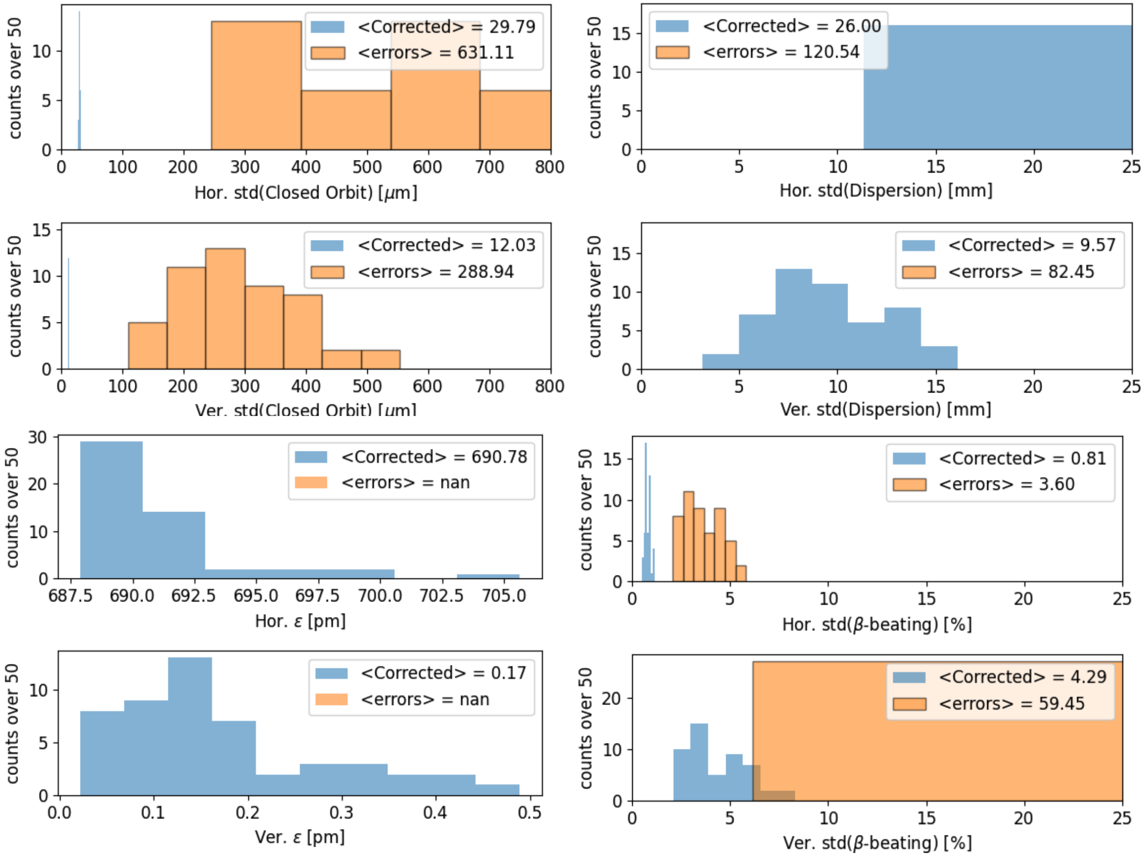


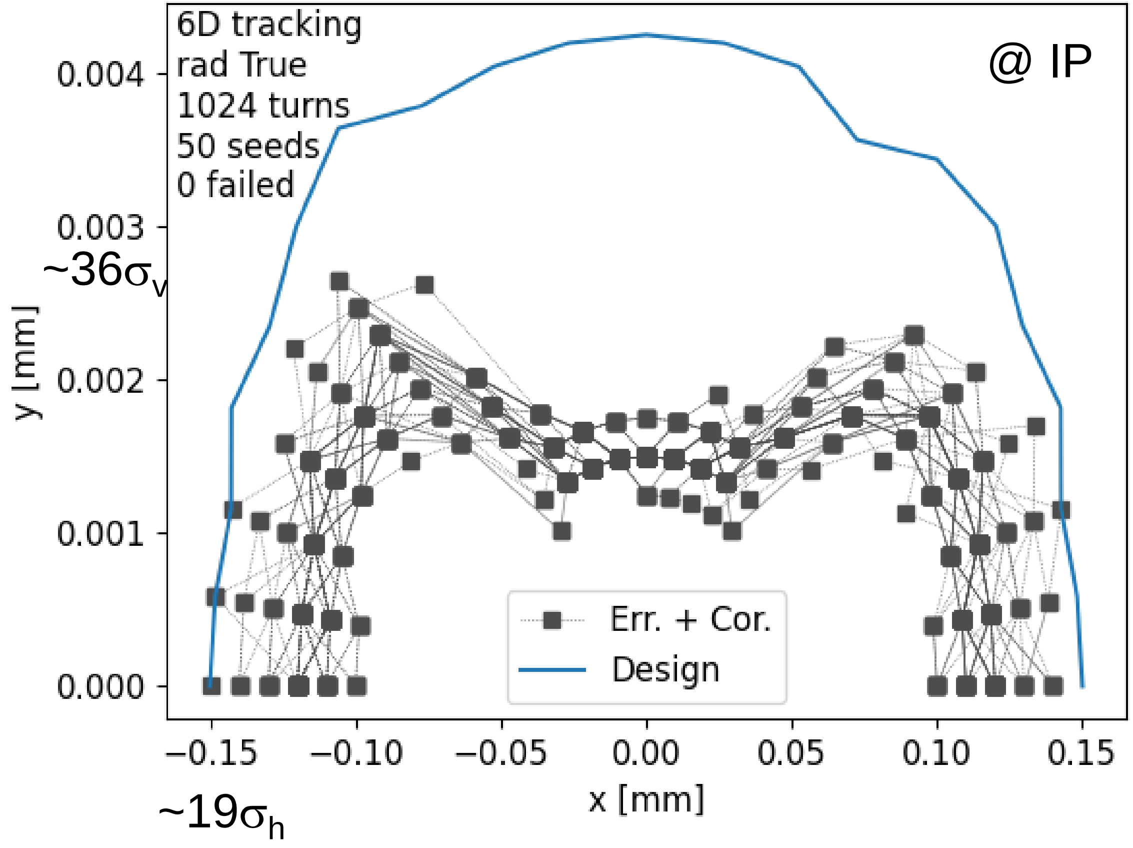
Significant amount of time, man power and computing resources spent for FCC-ee studies

BPMS: 1856
correctors: 1856

normal quad: 1496
skew quad: 632

pyAT





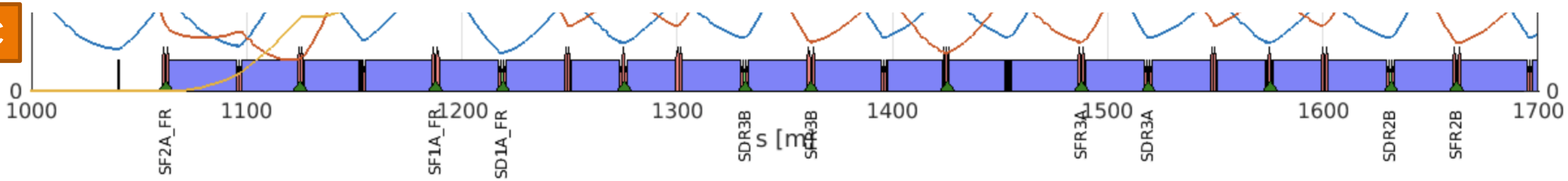
S.Liuzzo et al., Commissioning simulations tools based on python Accelerator Toolbox, MOPA142, IPAC2023, IOP

R.Tomas et al., Progress of the FCC-ee tuning working group WEPLO23, IPAC2023

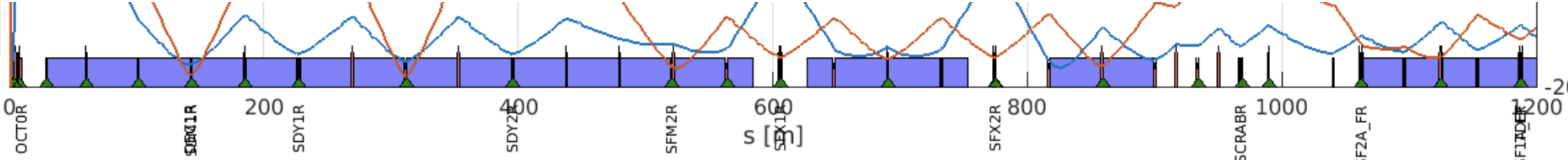
ASSUMPTION (as for EBS): **SEXTUPOLES ARE THE MAIN SOURCE OF OPTICS ERRORS**

~ 2 BPMs per **sextupole** : @ sextupole and 1 between 2 consecutive sextupoles: **1732 BPM**
1 H/V corrector at every **sextupole** : **1064 correctors**
(1 corrector per BPM will also be analyzed (1732 BPM / 1732 cor) and 1 BPM/COR per sextupole (1064 BPM / 1064 COR)
Normal and skew quad at every **sextupole** : **1064 Norm/Skew quad**

ARC

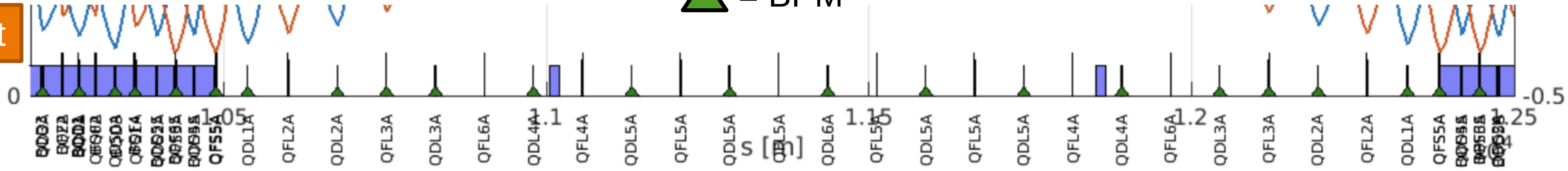


Final Focus



= BPM

Straight



COMMISSIONING SIMULATIONS FOR HFD-61@Z: SIMULATIONS RESULTS

HFD-61@Z

pyAT

a) ~2 **BPM** and 1 corrector for each Sextupole

b) Set 10um rms alignment **errors** in ARCS quadrupoles and sextupoles

c) Correction loop (repeated 2 times):

Parameters identical to V22 correction

1. Trajectory steering *, find closed orbit
2. Orbit correction
3. Tunes correction
4. Chromaticity correction
5. (not done, no BPM errors BBA)
6. Optics and coupling correction ("LOCO-like", 8 steerers) using Analytic Jacobians with thick quad. and thick steerers corrections

d) Evaluate lattice properties (DA, MA, optics, emittances, etc…)

```
correcting trajectory
- - -- - -- - -- - -- - -
Closed Orbit: True
Final Hor. orb  | std: 8.62e+03 microm  |  (min, max) (-2.12e+04, 5.59e+03)
Final Ver. orb  | std: 8.43e+03 microm  |  (min, max) (-2.12e+04, 3.62e+03)

Fitting Tune...
- - -- - -- - -- - -- - -
Initial value [222.24990804 222.40033254]
Final value [222.25006598 222.40097606]

Fitting Chromaticity...
- - -- - -- - -- - -- - -
Initial value [0.41061787 0.66738543]
Final value [0.39133633 0.46618063]

correcting orbit
- - -- - -- - -- - -- - -
Hor. orbit | std: 1.08e+03 microm  |  (min, max) (-3.05e+03, 3.2e+03)
Ver. orbit | std: 661 microm  |  (min, max) (-5.27e+03, 5.59e+03)
Final Hor. orb | std: 26.2 microm  |  (min, max) (-109, 91.8)
Final Ver. orb | std: 28.1 microm  |  (min, max) (-133, 156)

correcting optics
- - -- - -- - -- - -- - -
Before - fitted quadrupole errors correction:
beta-beating:     H 0.61%      V 1.22%
delta dispersion: H 2.11mm     V 4.13mm
emittance:  H 542.09pmrad  V 0.94pmrad
After -fitted quadrupole errors correction:
beta-beating:     H 0.19%      V 0.21%
delta dispersion: H 2.14mm     V 4.13mm
emittance:  H 542.09pmrad  V 0.96pmrad
…
```

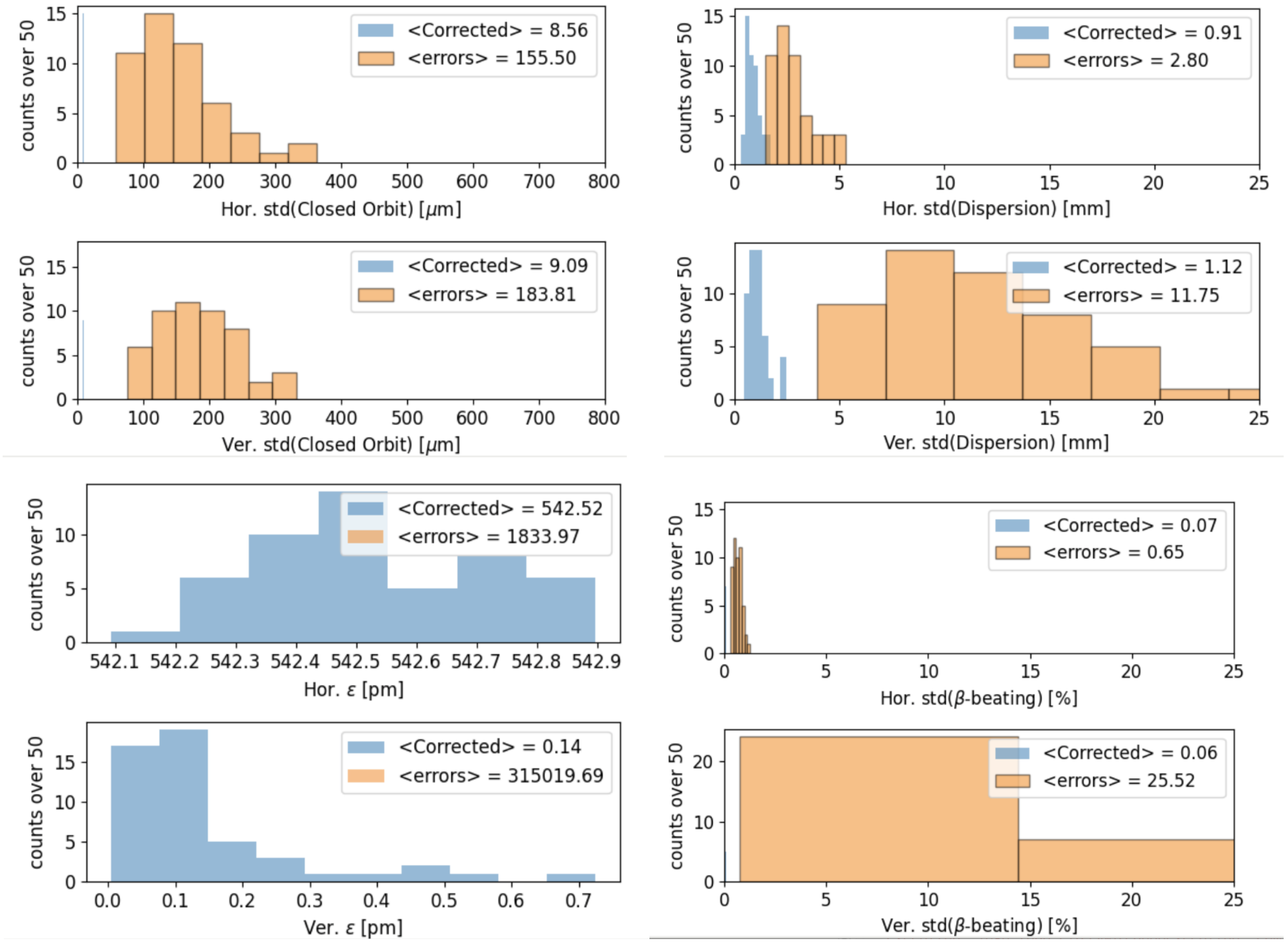
Closed orbit from start!

Small beta-beating and dispersion/emittance deviation

DA AND LATTICE PROPERTIES AFTER COMMISSIONING-LIKE CORRECTION: HFD61@Z

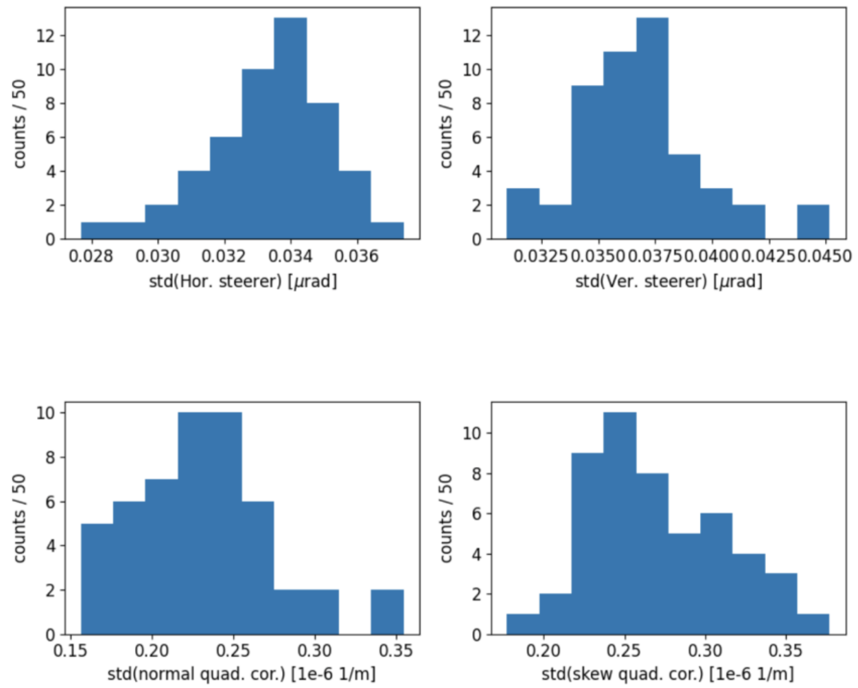
RF ON, Radiation ON, Tapering ON, Sext ON, Oct ON, …
CrabSext OFF, Fringe fields OFF, Solenoid OFF, Spin OFF

10 µm alignment errors in ARCS's quad. and sext.



All parameters are well corrected and correctors strengths are small.

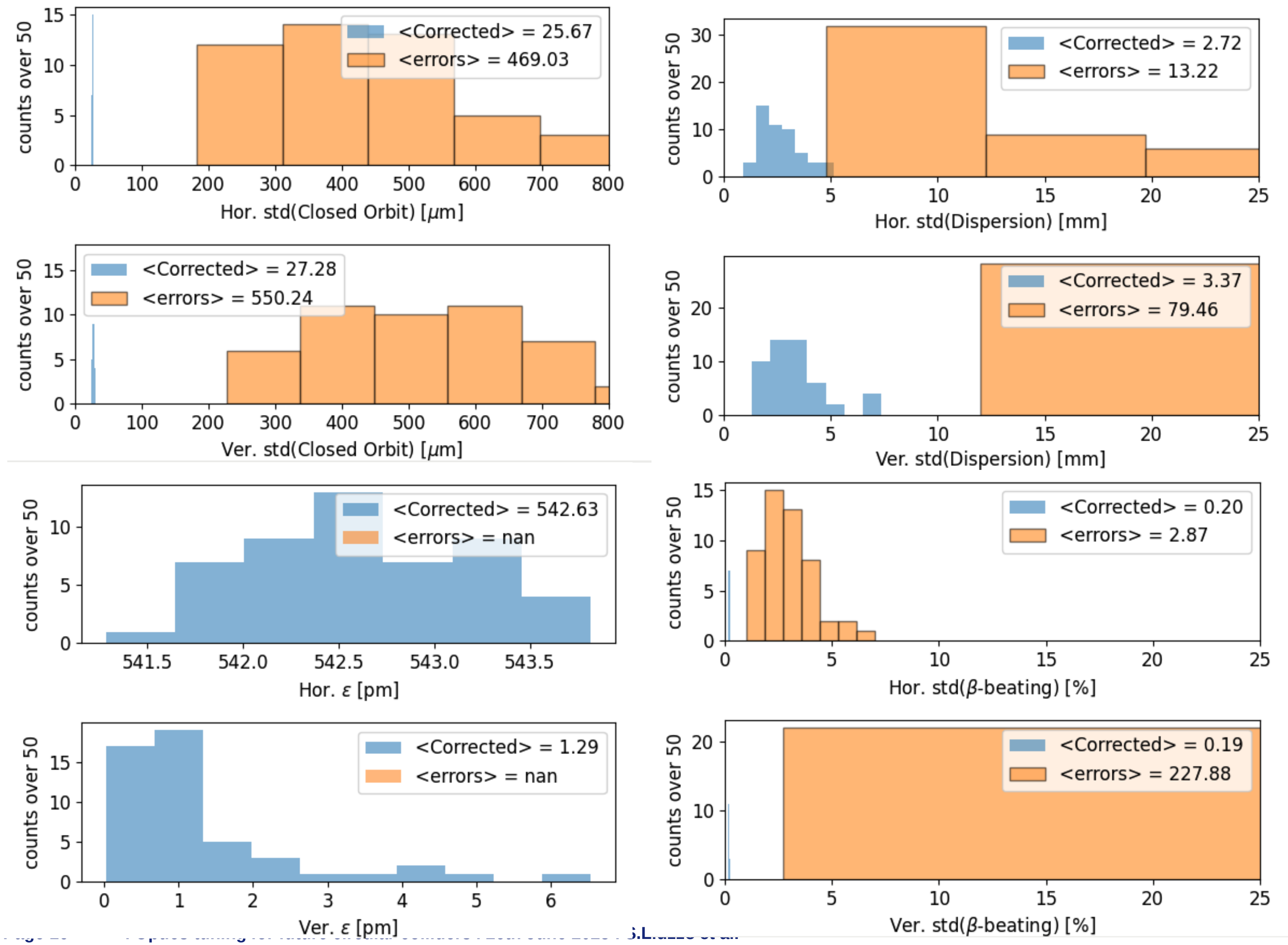
It seems possible to increase the errors set in the lattice ARCS.

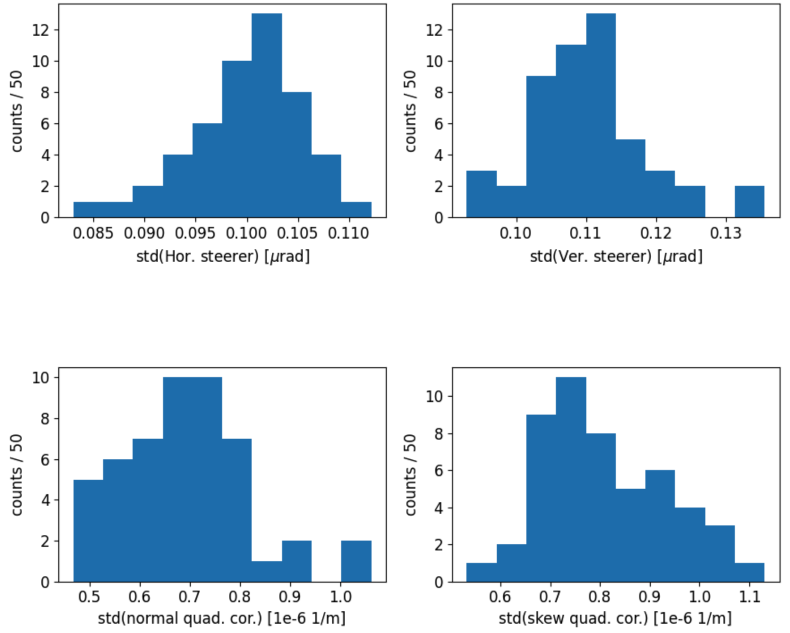


DA AND LATTICE PROPERTIES AFTER COMMISSIONING-LIKE CORRECTION: HFD61@Z

RF ON, Radiation ON, Tapering ON, Sext ON, Oct ON, …
CrabSext OFF, Fringe fields OFF, Solenoid OFF, Spin OFF

30 μm alignment errors in ARCS's quad. and sext.

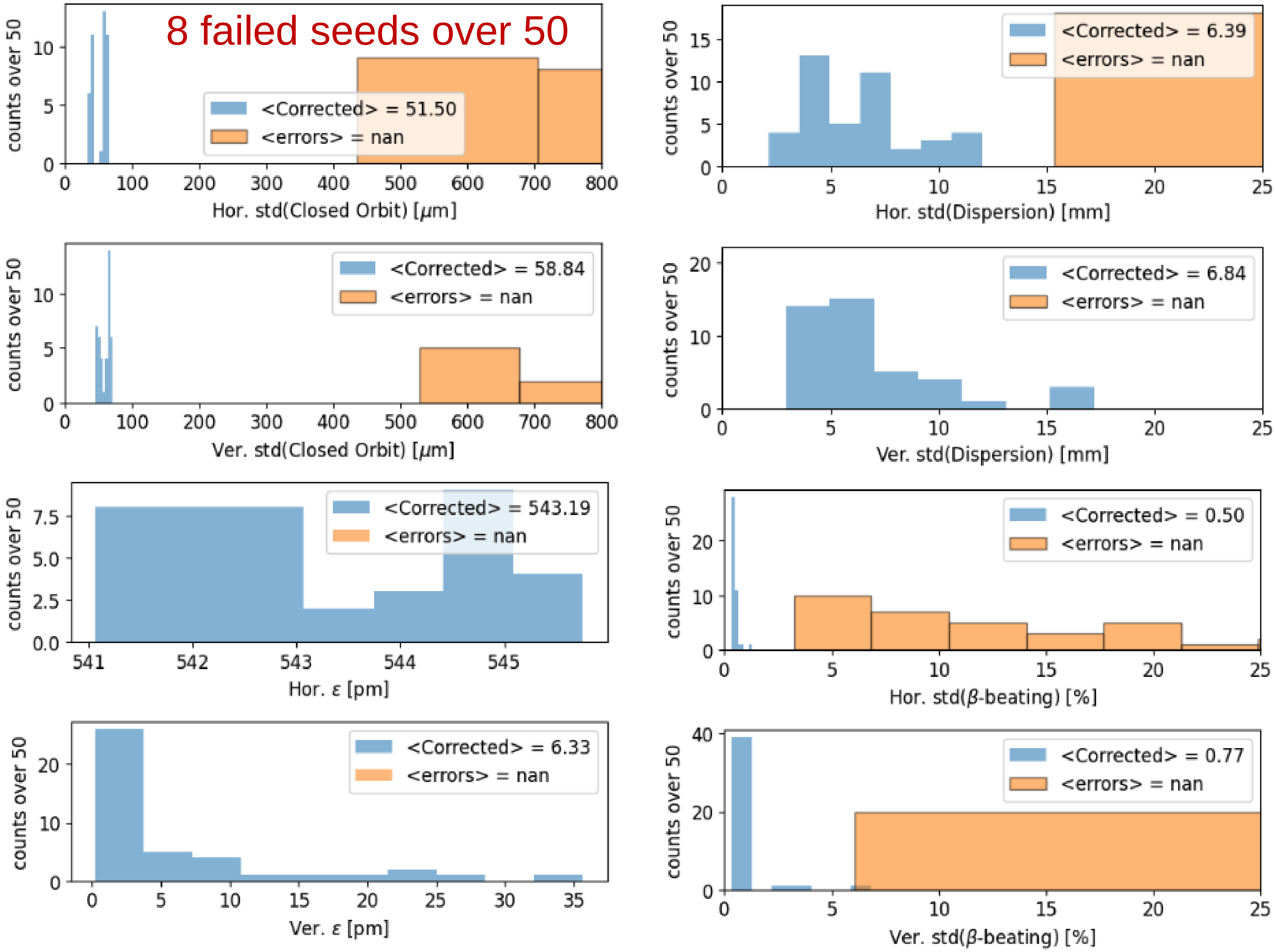




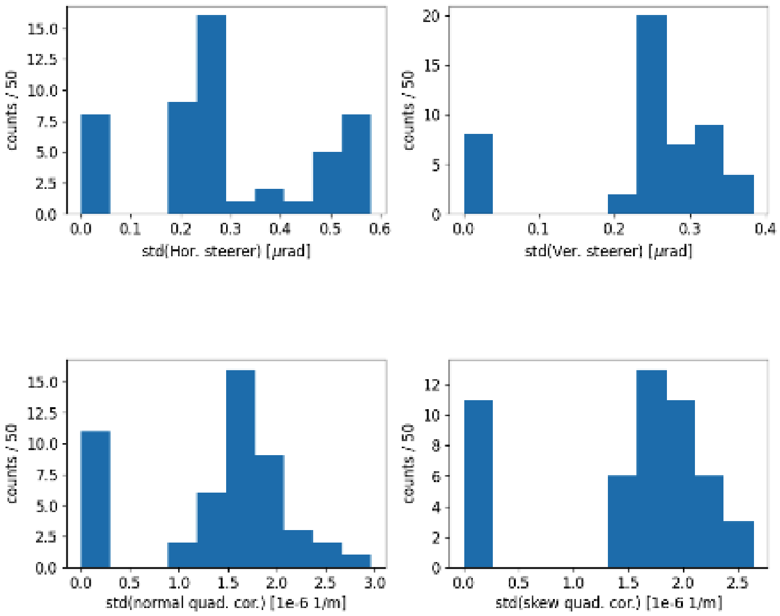
DA AND LATTICE PROPERTIES AFTER COMMISSIONING-LIKE CORRECTION: HFD61@Z

RF ON, Radiation ON, Tapering ON, Sext ON, Oct ON, …
CrabSext OFF, Fringe fields OFF, Solenoid OFF, Spin OFF

70 µm alignment errors in ARCS's quad. and sext.



Beam is stored with > 500um closed orbit.
300um BPM offsets are probably tolerable to store the beam. (To be checked)
As for Synchrotron light sources, beam can be stored with BPM offsets (c.o.d. ~ (300^2 + 500^2) and as a second stage standard BBA (based on closed orbit) takes place.



COMMISSIONING SIMULATIONS COMPARISON TABLE

Summary of above plots:

Only errors in ARCS

Gaussian errors, no truncation.

NO ERRORS in Final Focus.

RF ON

Radiation ON

Tapering

Identical correction procedure

Identical correction parameters (eigenvectors, weights, etc…)

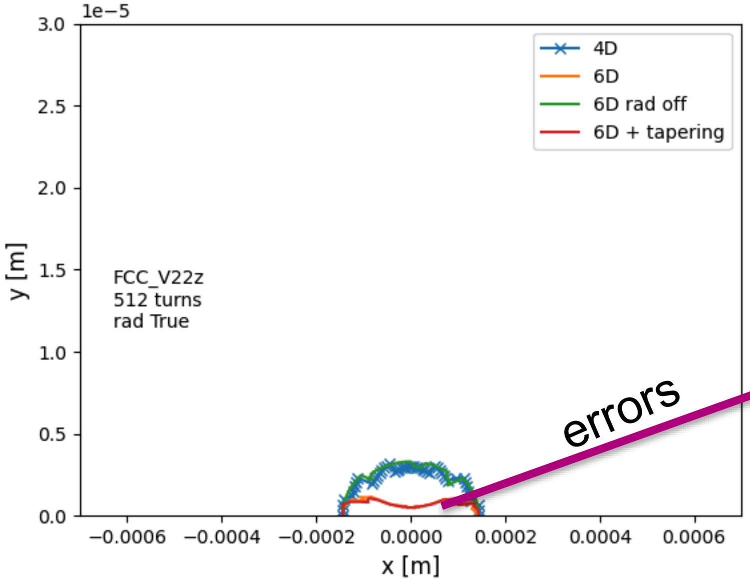
Average over 50 seeds of standard deviations of parameters along the ring.

$\langle std \rangle_{50}$	Δx	Δy	$\frac{\Delta\beta_h}{\beta_{h,0}}$	$\frac{\Delta\beta_v}{\beta_{v,0}}$	$\Delta\eta_h$	$\Delta\eta_v$	$\Delta\epsilon_h$	$\Delta\epsilon_v$
units	µm	µm	%	%	mm	mm	pm rad	pm rad
V22 @Z 10 µm								
err	631.1	288.94	3.6	59.45	120.54	82.45	-	-
cor	29.79	12.03	0.81	4.29	26.00	9.57	690.78	0.17
HFD-61 @Z 10 µm								
err	155.50	183.81	0.65	25.52	2.8	11.75	1833.97	-
cor	8.56	9.09	0.07	0.06	0.91	1.12	542.52	0.14
HFD-61 @Z 30 µm								
err	490.03	550.24	2.87	227.88	13.22	79.46	-	-
cor	25.67	27.28	0.20	0.19	2.72	3.37	542.63	1.29
HFD-61 @Z 70 µm							8 failed seeds	
err	-	-	-	-	-	-	-	-
cor	51.50	58.84	0.5	0.77	6.39	6.84	543.19	6.33

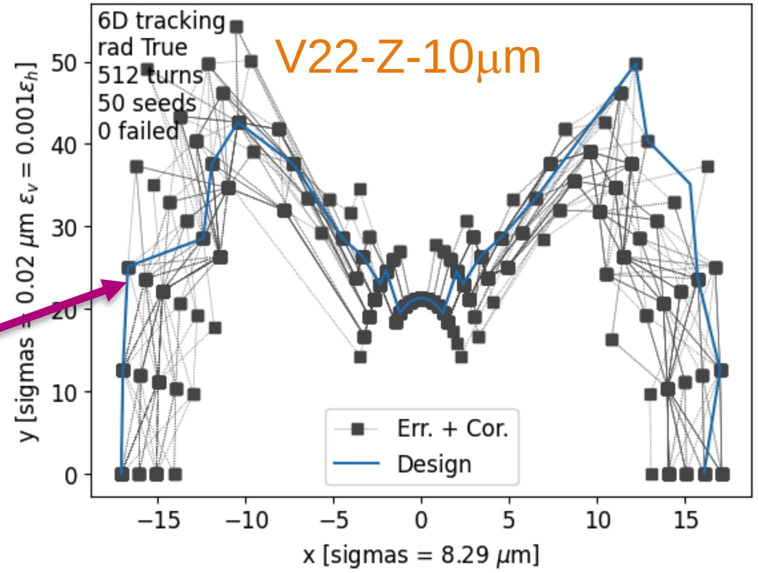
RADIATION has a severe effect on Dynamic Aperture

Errors further reduce Dynamic Aperture

With radiation HFD~=V22



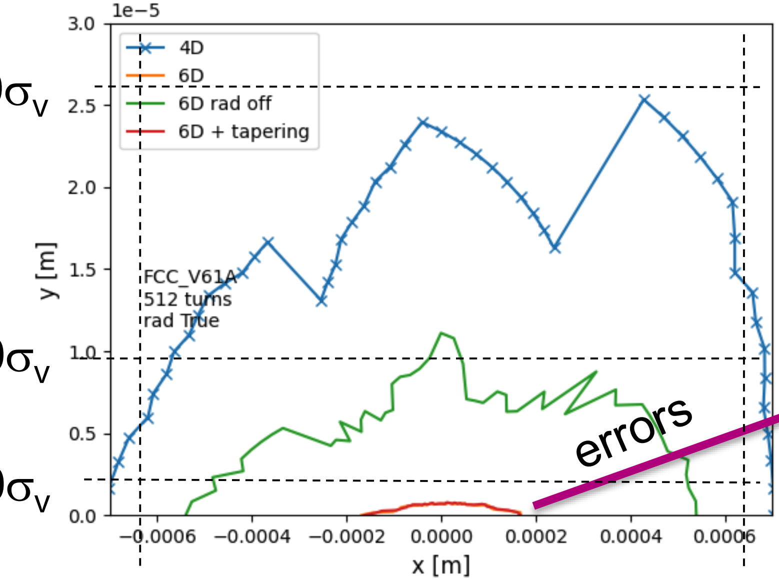
DA for the 50 error seeds of previous slide



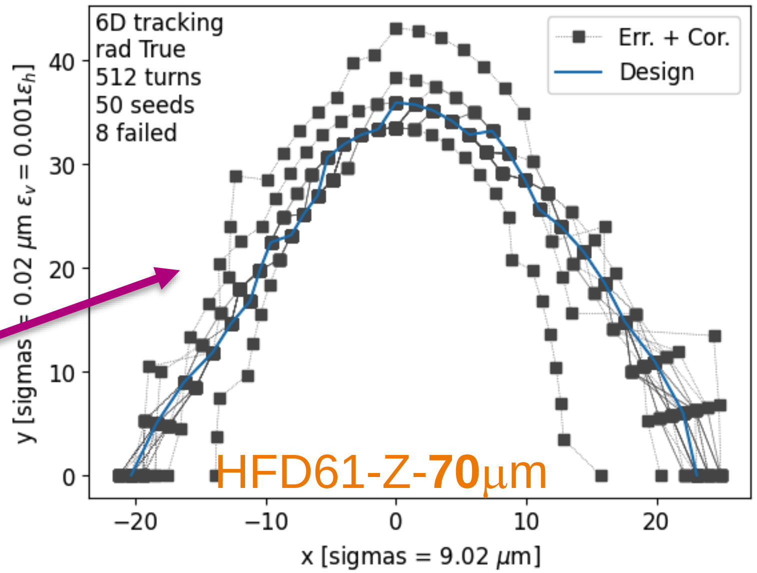
$600\sigma_v$

$\sim150\sigma_v$

$\sim50\sigma_v$



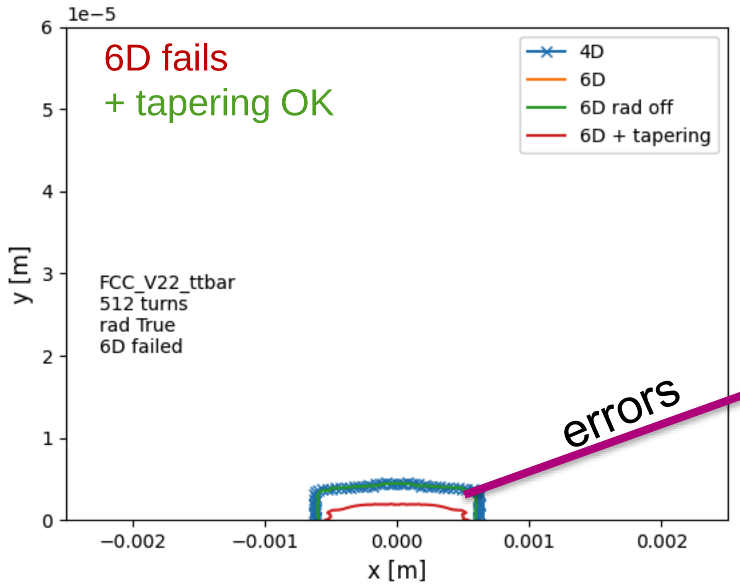
$\sim50\sigma_h$ $\sim50\sigma_h$

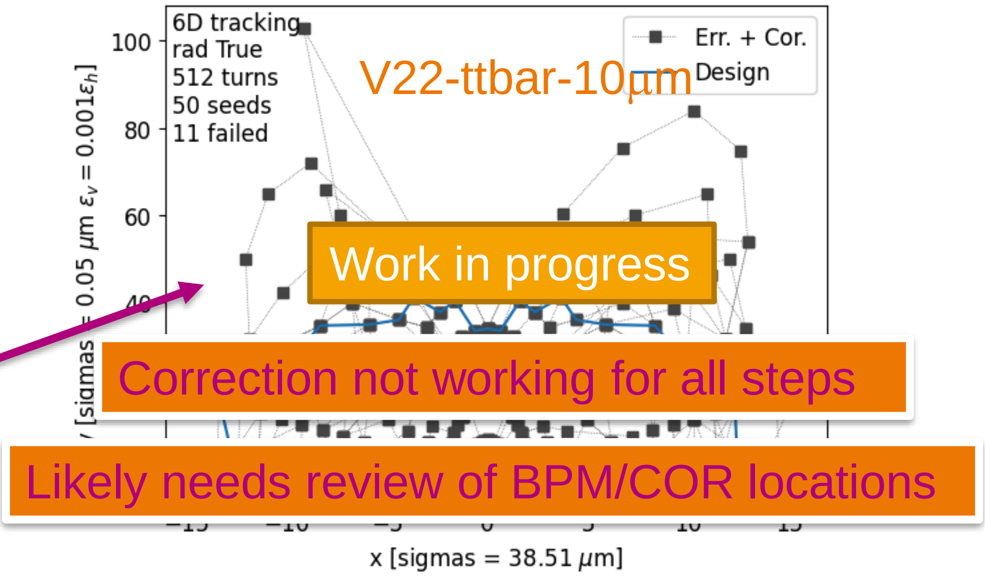


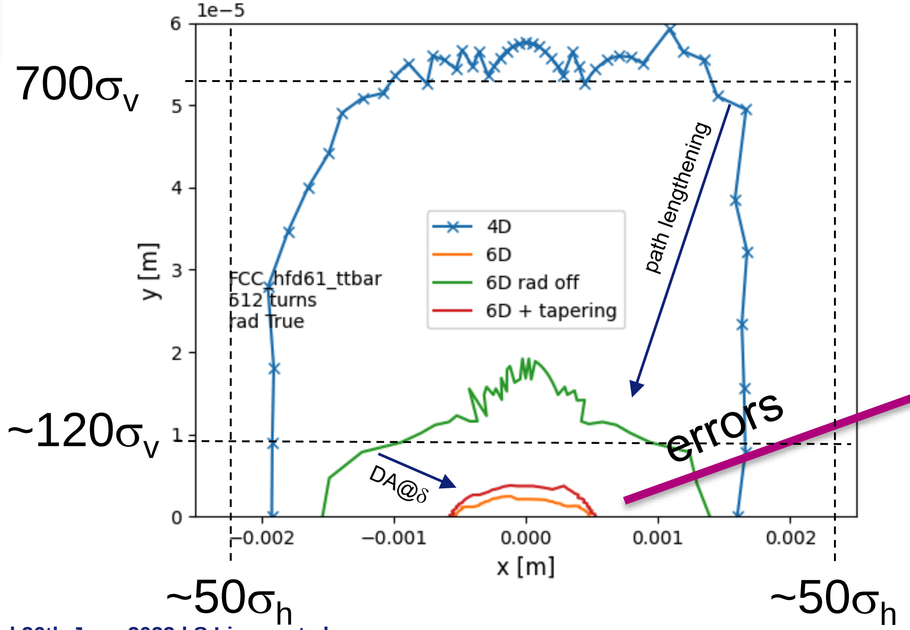
RADIATION has a severe effect on Dynamic Aperture

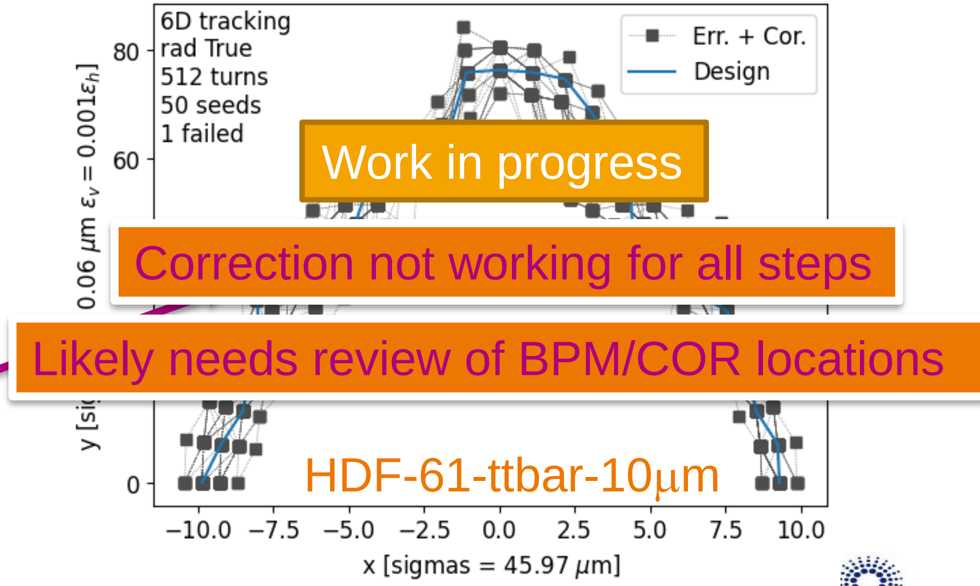
See P.R. presentation, due to off-energy x-y DA

Errors further reduce Dynamic Aperture ?









HFD lattice appears less sensible to errors in the ARCs.

Final Focus sensitivity larger than ARCs.

Commissioning simulations @Z for V22 and HFD lattice show that HFD lattice may tolerate about 3 times as large alignment errors in the arcs after correction of trajectory, orbit, tune, chromaticity optics and coupling. More could be possible after ad-hoc correction tuning.

HFD lattice commissioning simulations are performed with a smaller number of BPM & correctors. In fact may need correctors at all BPM locations also for HFD lattice (1732 correctors).

Optics and coupling corrections are performed as in synchrotron light sources (LOCO-like, reduced 8-steerers ORM) and using Analytic Jacobians (see talk by A.Franchi on Wednesday)

Further commissioning simulations runs:

for ttbar lattices

with 300 um BPM offsets (no BBA)

with 1064 BPM/COR or 1732 BPM/COR

DA convergence studies are ongoing (S.White) and indicate that larger number of turn for the DA could be needed (4096 instead of 512). However, DA tracking for 4096 turns without radiations takes 1.5h using the 128 cores of a 2022 HPC.

Replace all normal and skew quadrupole corrections by H/V offsets at the sextupoles. If this is successful, no need of quadrupole independent Power Supplies.

BACKUP

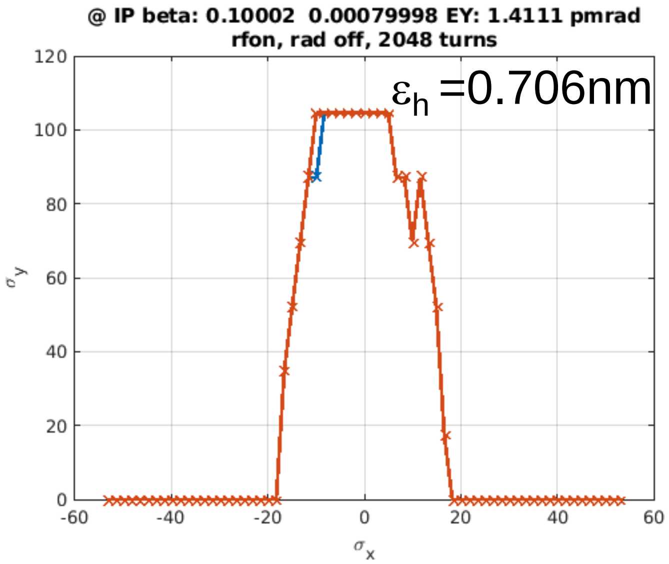
COMPLETE TABLE OF ERRORS SENSITIVITY

	E_0	c.o.d.		$\Delta\beta/\beta$		$\Delta\eta$		ϵ		failed seeds
		H	V	H	V	H	V	H	V	
criteria		100 µm	100 µm	1 %	1 %	1 mm	1 mm	1 %	0.1 %ϵ_h	>0
arc quadrupoles (hor., ver.) misalignment [µm]										
V22	Z	(1.9 , >10)	(>10 , 1.9)	(2.9 , 10.0)	(0.7 , 6.8)	(0.1 , 1.5)	(>10 , 0.1)	(3.0 , 9.0)	(>10 , 1)	(- , -)
HFD61	Z	(8.4 , >10)	(>10 , 7.5)	(>10 , >10)	(3 , >10)	(5 , >10)	(>10 , 1.6)	(>10 , >10)	(>10 , 2.7)	(- , -)
V22	t	(1.3 , 8)	(>10 , 1.5)	(1.5 , 7.5)	(0.5 , 2.2)	(0.12 , 3.2)	(>10 , 0.2)	(0.5 , 7.3)	(10 , 0.17)	(- , 5)
HFD61	t	(2.8 , >10)	(>10 , 3.1)	(4.2 , >10)	(1.5 , >10)	(1.9 , 8.5)	(>10 , 1.0)	(>10 , >10)	(>10 , 0.8)	(- , -)
arc sextupoles (hor., ver.) misalignment [µm]										
V22	Z	(>100 , >100)	(>100 , >100)	(17 , >100)	(8.5 , >100)	(3.1 , 65)	(>100 , 2.6)	(90 , >100)	(>100 , 39)	(- , -)
HFD61	Z	(>100 , >100)	(>100 , >100)	(60 , >100)	(26 , >100)	(10 , >100)	(>100 , 16)	(>100 , >100)	(>100 , >100)	(- , -)
V22	t	(>100 , >100)	(>100 , >100)	(10 , 95)	(7 , 85)	(7.5 , 90)	(>100 , 10)	(27 , 100)	(>100 , 26)	(- , -)
HFD61	t	(>100 , >100)	(>100 , >100)	(19 , >100)	(8 , >100)	(10 , >100)	(>100 , 11)	(78 , >100)	(>100 , 48)	(-, -)
final focus quadrupoles (hor., ver.) misalignment [µm]										
V22	Z	(0.6 , 1.1)	(>10 , >10)	(1.5 , 1.2)	(0.05 , 0.5)	(0.05 , 0.025)	(>10 , 0.01)	(1.2 , 1.0)	(>10 , 0.008)	(2 , 0)
HFD61	Z	(0.8 , 0.8)	(>10 , 0.19)	(1.7 , 1.0)	(0.06 , 0.8)	(0.4 , 0.007)	(>10 , 0.004)	(5.5 , 0.007)	(7 , 0.006)	(5 , 2)
V22	t	(2.0 , 2.5)	(>10 , 0.35)	(2.7 , 2.1)	(0.26 , 0.22)	(0.24 , 0.26)	(>10 , 0.04)	(0.07 , 1.1)	(>10 , 0.06)	(- , 2)
HFD61	t	(2.8 , 3.0)	(>10 , 0.4)	(4.8 , 4.2)	(0.3 , 4.1)	(1.7 , 1.1)	(>10 , 0.1)	(>10 , 2.1)	(>10 , 0.01)	(9 , 7)
final focus sextupoles (hor., ver.) misalignment [µm]										
V22	Z	(>10 , >10)	(>10 , >10)	(>10 , >10)	(0.25 , >10)	(>10 , >10)	(>10 , 1.2)	(>10 , >10)	(>10 , >10)	(8 , -)
HFD61	Z	(>10 , >10)	(>10 , >10)	(>10 , >10)	(0.25 , >10)	(9 , >10)	(>10 , 2.2)	(>10 , >10)	(>10 , >10)	(- , -)
V22	t	(>10 , >10)	(>10 , >10)	(»10 , »10)	(0.5 , >10)	(>10 , >10)	(>10 , 2.6)	(>10 , >10)	(>10 , 8)	(- , -)
HFD61	t	(>10 , >10)	(>10 , >10)	(>10 , >10)	(0.45 , >10)	(>10 , >10)	(>10 , 3.7)	(>10 , >10)	(>10 , >10)	(- , -)

https://www.overleaf.com/project/6486d06cdae28cd6dacf0fd3

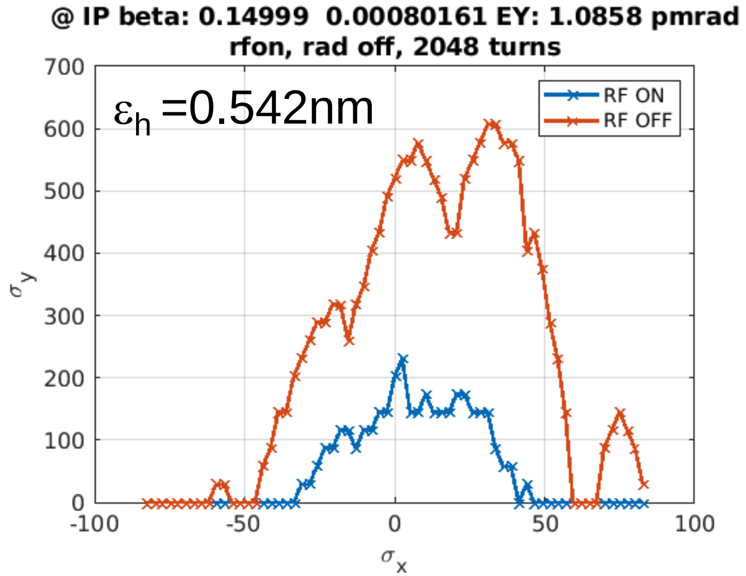
DA FOR THE 4 LATTICES

Z

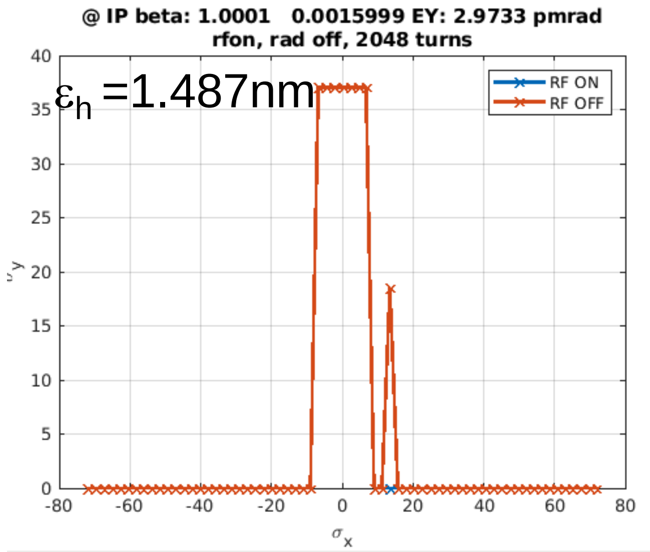


V22

HFD

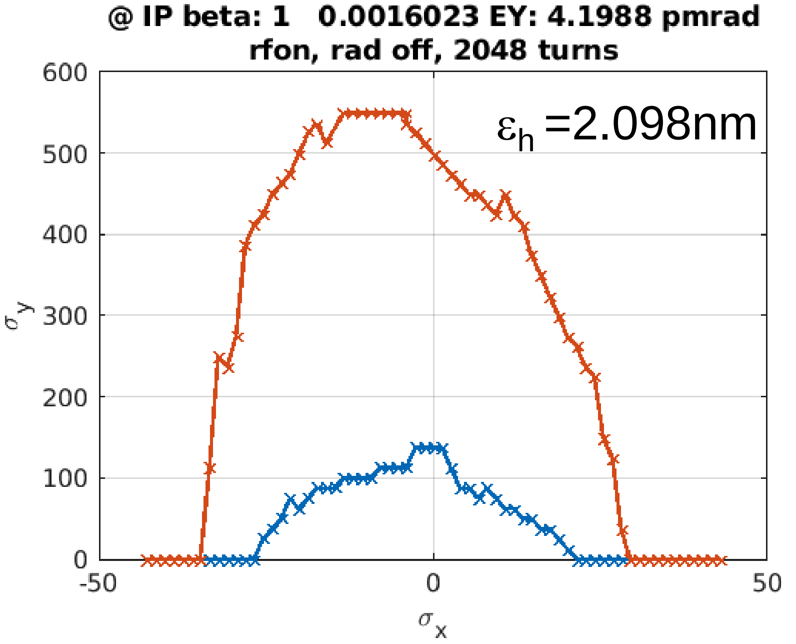


ttbar



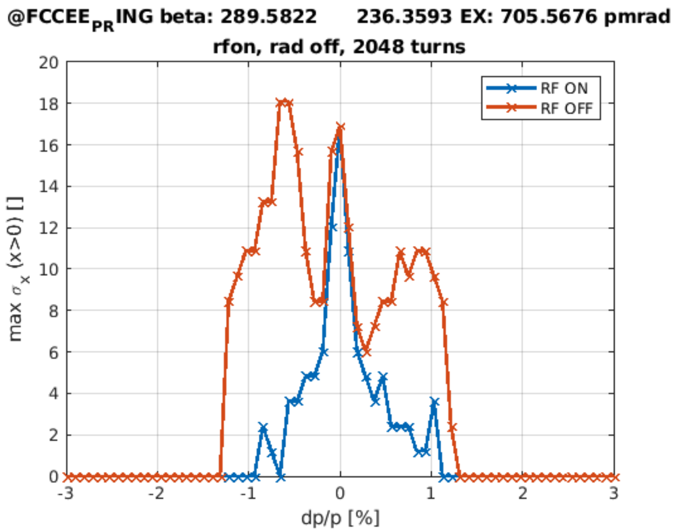
V22

HFD



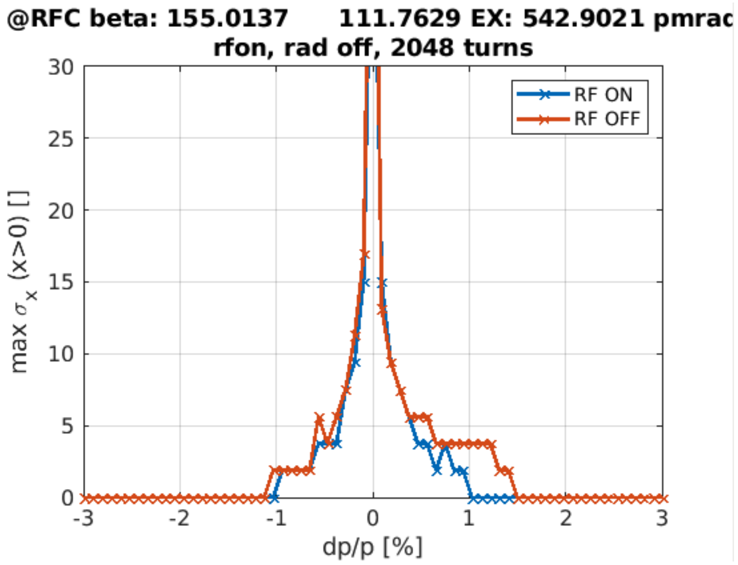
ε_v =0.2% ε_h

Z

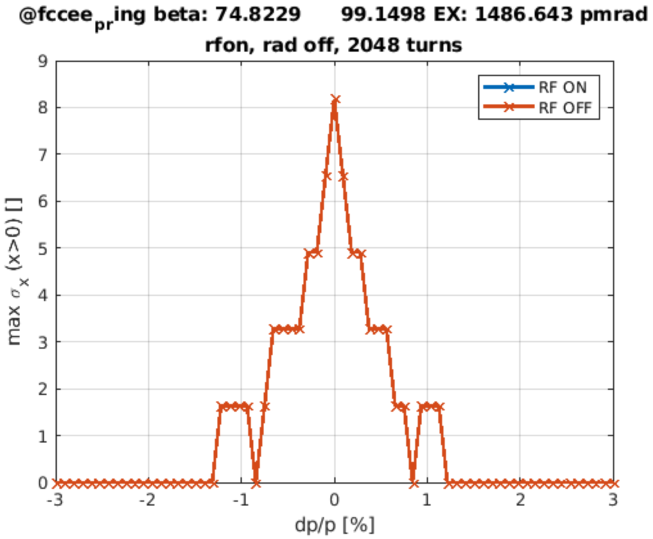


V22

HFD

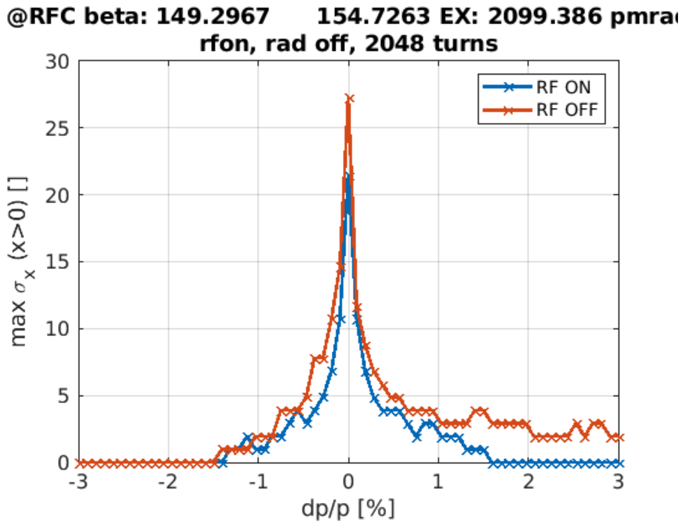


ttbar



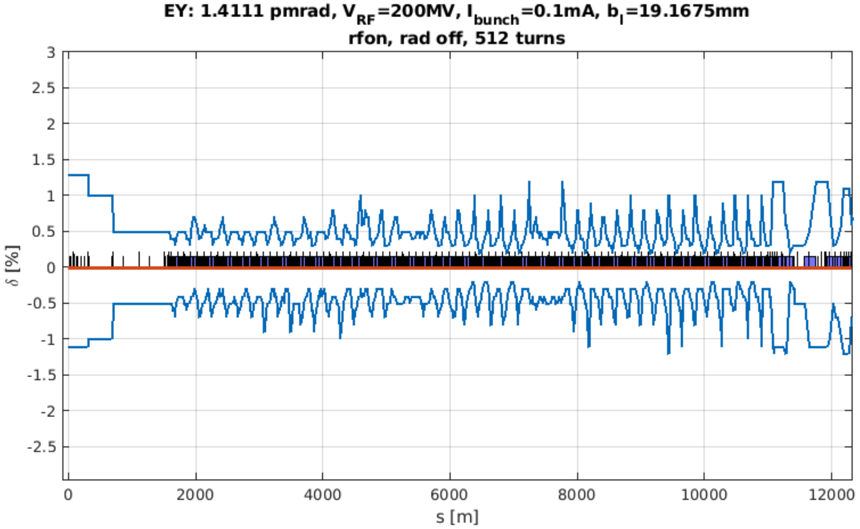
V22

HFD



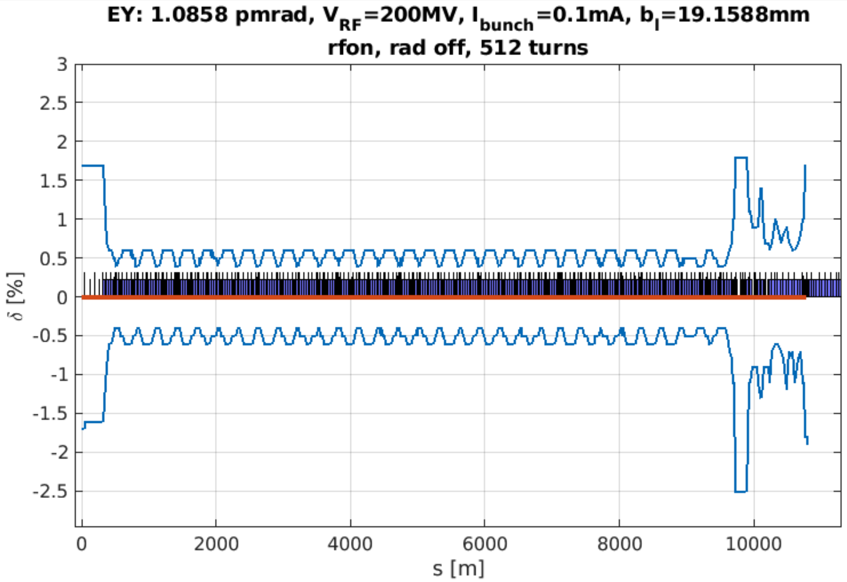
LOCAL MOMENTUM ACCEPTANCE FOR THE 4 LATTICES

Z

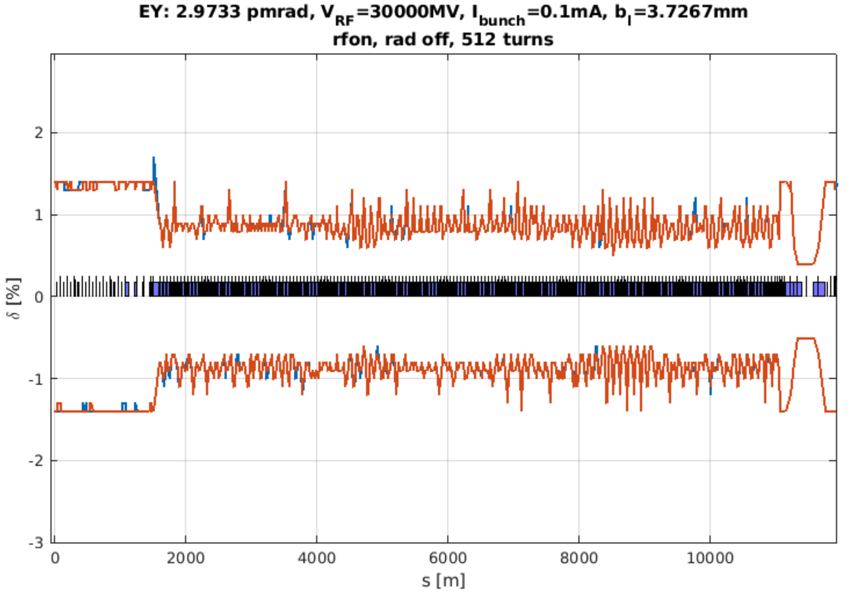


V22

HFD

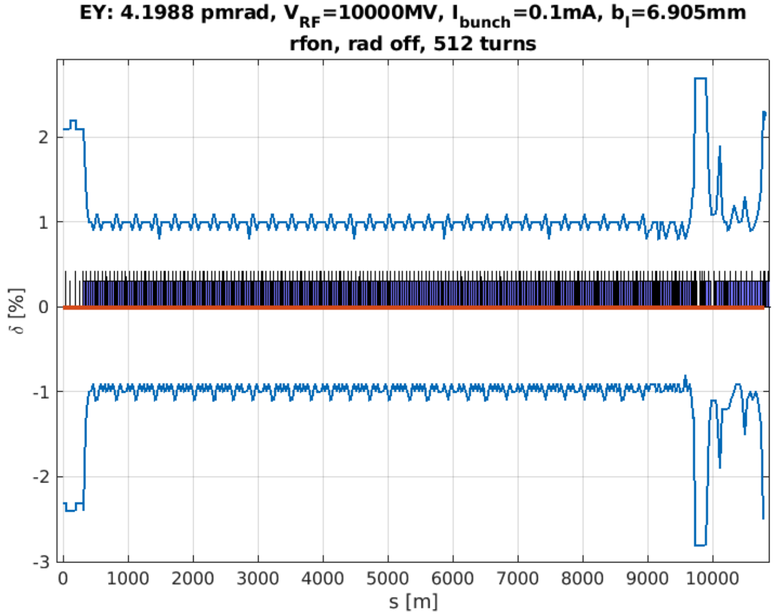


ttbar



V22

HFD



Simulations data in:

/machfs/liuzzo/FCC/**/ANALYSIS

/machfs/liuzzo/FCC/**/Errors