

FCC lattice evolution

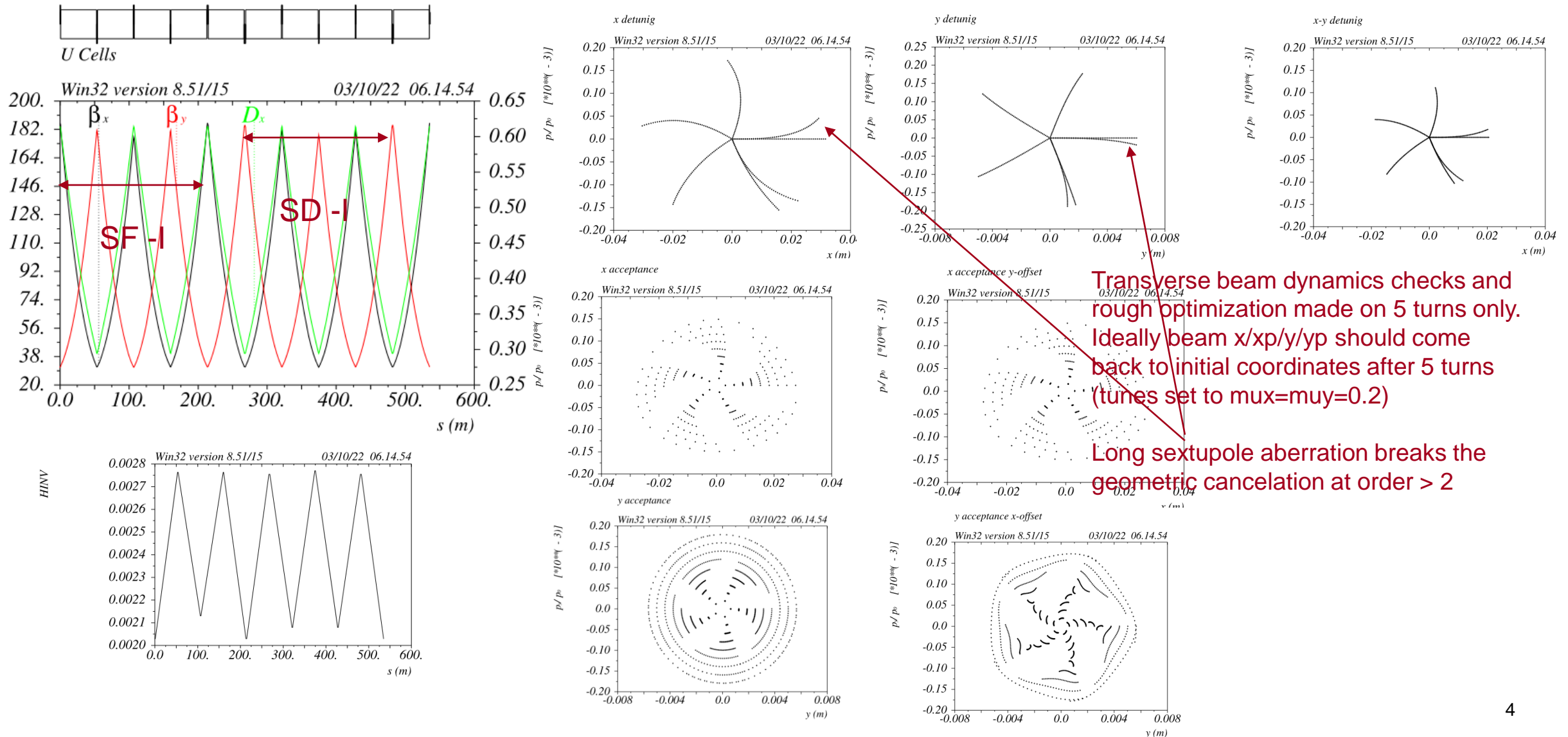
FCC week
London, June 8th , 2023

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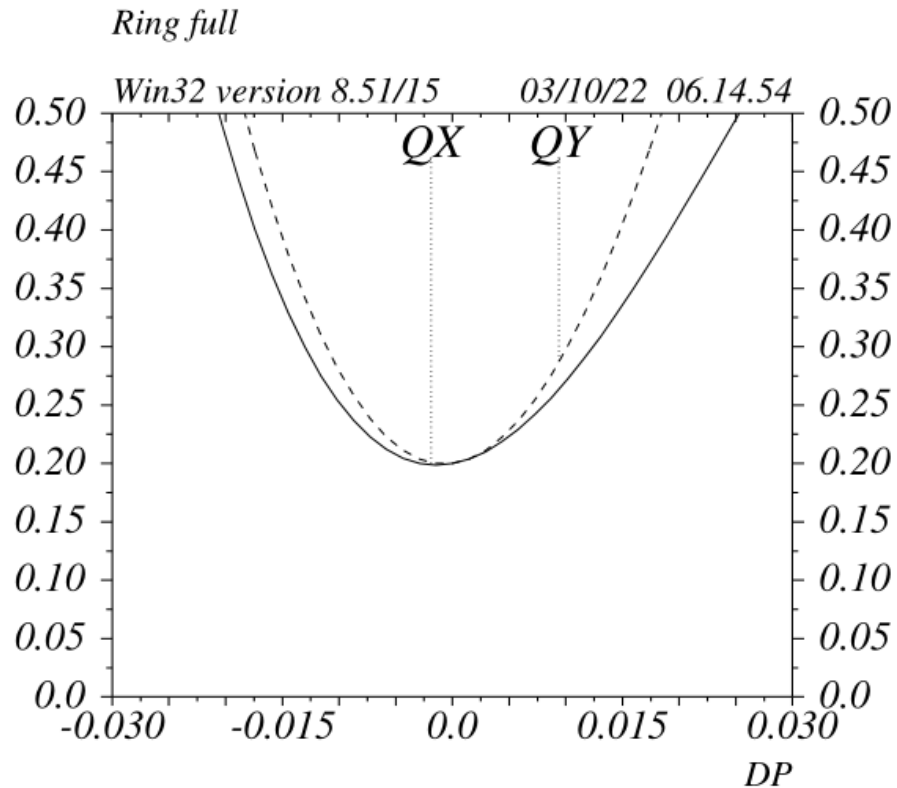
- Collider design strategy
- ARC lattice
- Straight sections matching
- Final Focus
- Performances
- Conclusions

- Improve as much as possible the ARC lattice achromaticity and anharmonicity
- Develop methods in to insert straight sections with minimum impact on the ring performances related to its periodicity
- Design achromatic and anharmonic Final Focus System that relies minimally on ARC sextupoles for DA&MA optimization
- Develop methodologies and solutions to accommodate all the necessary lattice adjustments (crossing angle, LSS requirements etc) with minimal impact on beam dynamics and parameters

ARC lattice 148 long cells made of FODO9090 (~80KM)



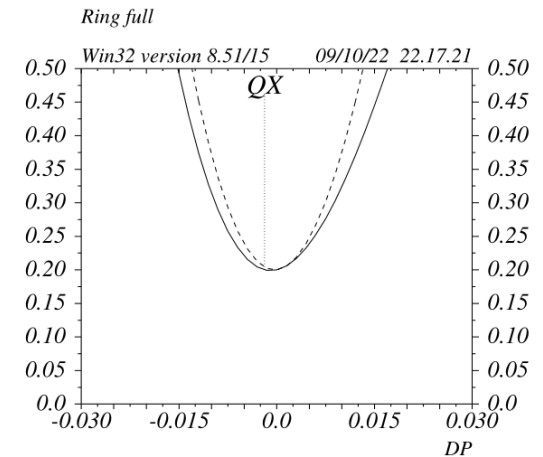
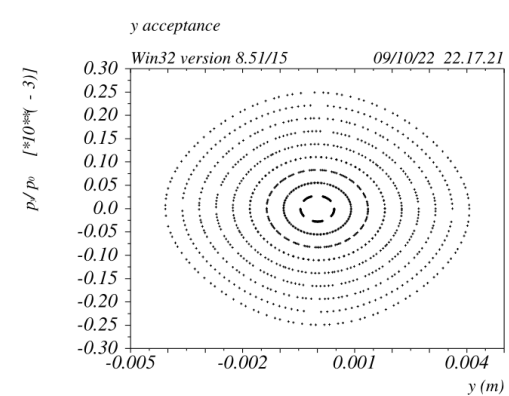
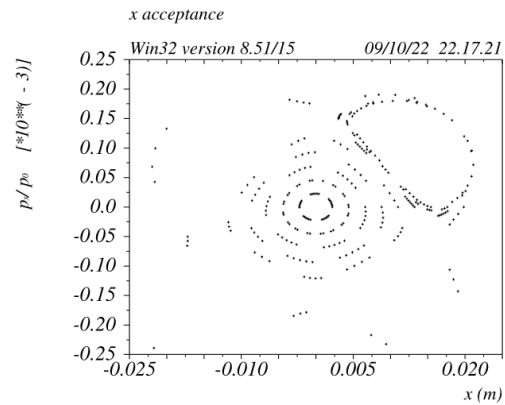
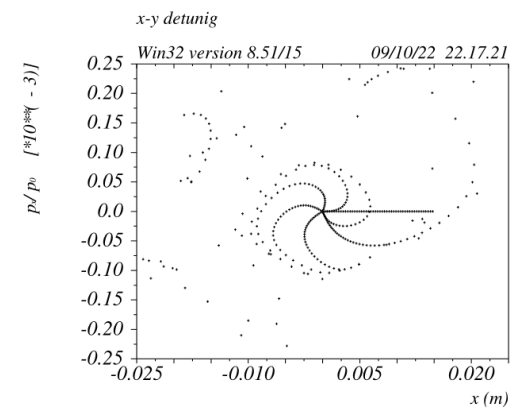
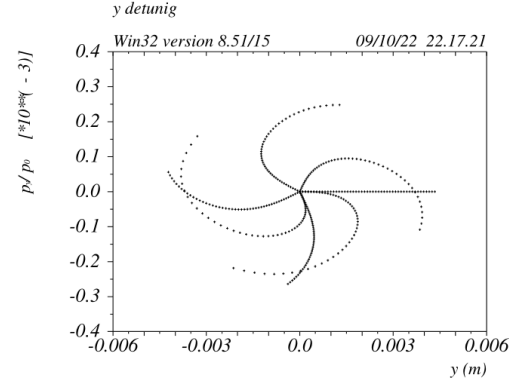
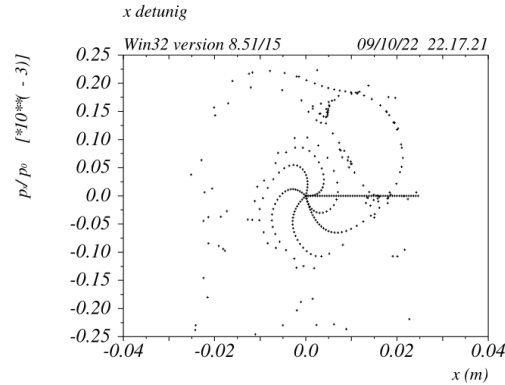
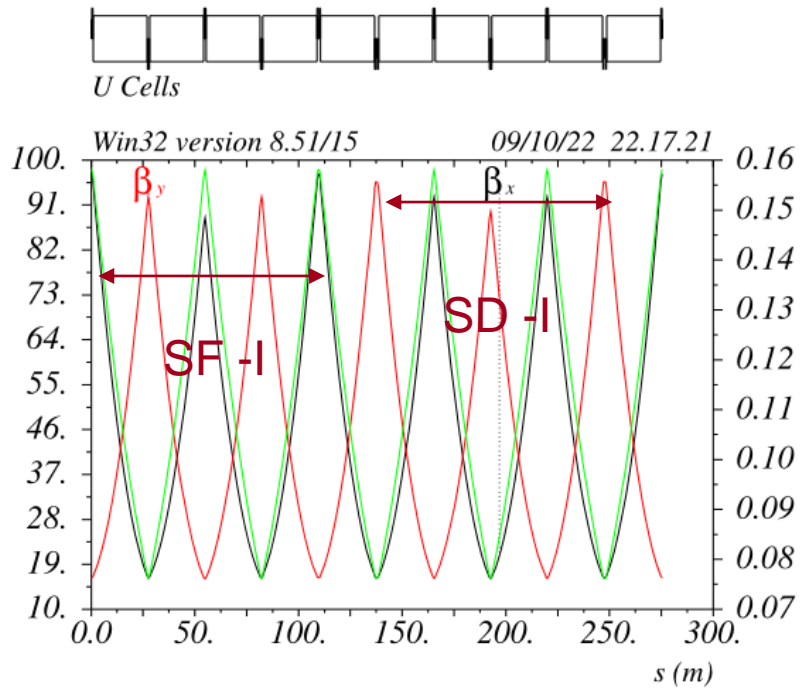
ARC lattice: 148 long FODO9090



FODO9090 cell is only a first order Achromat
Placing sextupoles at every quads will cancel the 2nd order chromaticity (SOC) but then the cell will not longer be anharmonic
EA, defined by the tune footprint to be contained in one quadrant, is around +/-1.5%

*CEPC approach is to cancel the SOC with sextupole families encompassing on 8 cells

ARC lattice 296 short cells made of FODO9090 (~80KM)



Aberrations become more severe with more cells

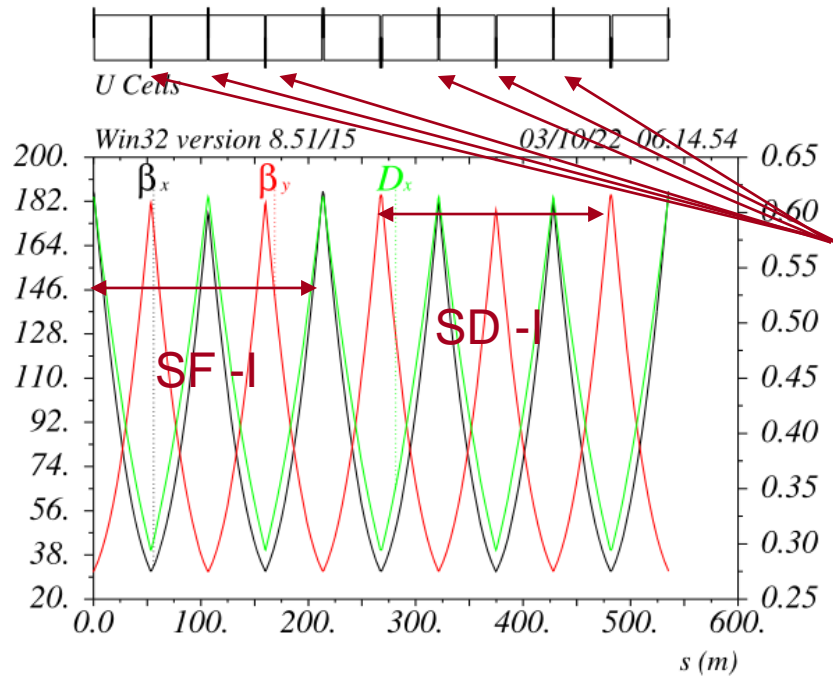
In general, multiplying the number of cells by a factor 2:

- Emittance decreases by 2^3 (8)
- Quadrupoles gradient doubles and number of quadrupoles double
- Quads power consumption increases by a factor 4 (supposing twice longer quads)
- Sextupole gradients increase by 2^3 and number of sextupoles doubles
- Sextupoles power consumption increases by a factor 16 (supposing 8 times longer sexts)
- EA decreases by a factor 2
- DA decreases by a factor $> 2^3$

- Cost and power consumption of quadrupoles scales with $1/E_{mix}^2$
- Cost and power consumption of sextupoles scales with $1/E_{mix}^4$

To limit the number of cells the intrinsic arc cell emittance should be as small as possible
Emittance increase due to insertions (e.g. FF) should be as small as possible

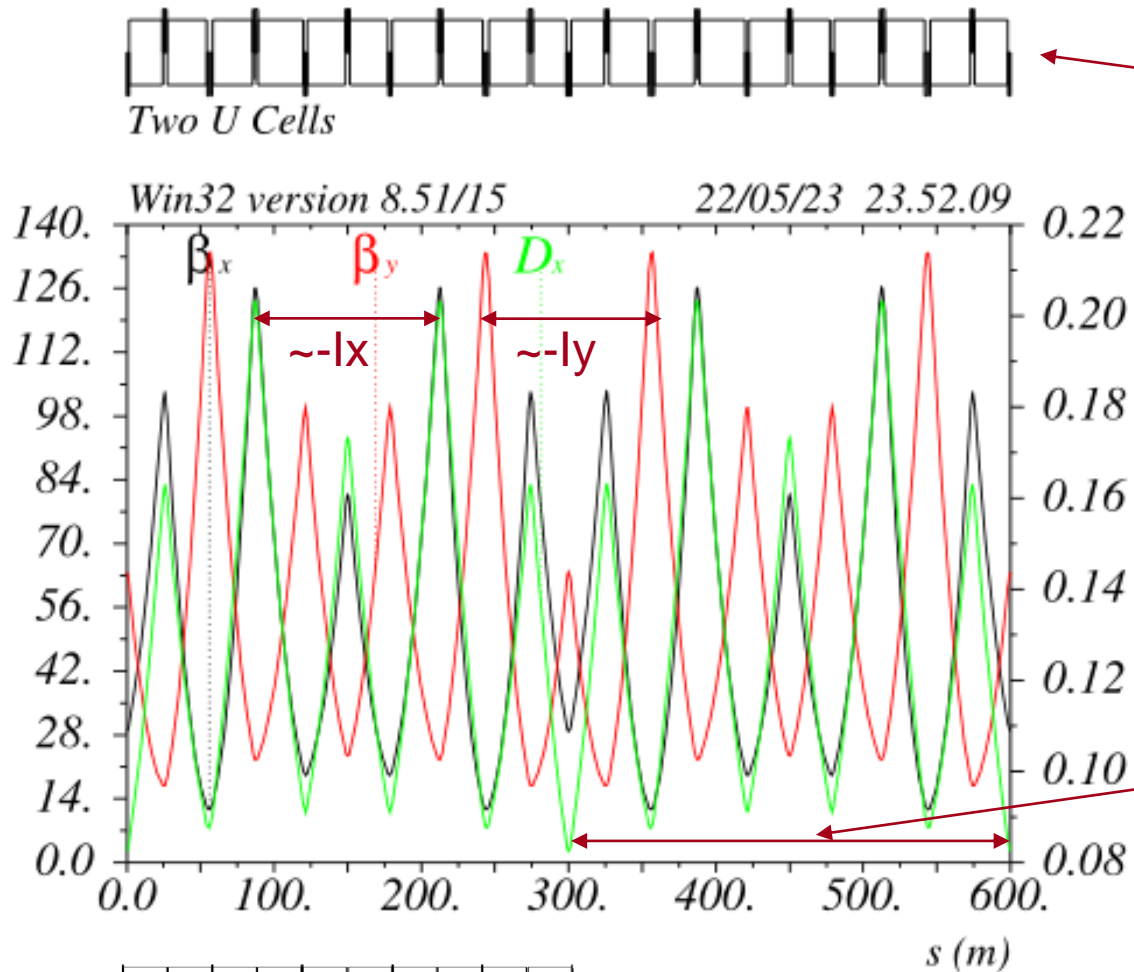
FODO9090 optimization



Ultimate source of SOC is uncorrected chromaticity and second order dispersion originated by the quads with no nearby sextupoles (QWOS)

In fact it is possible to remove the second order chromaticity while still maintaining the (geometric) properties of the non-interleaved sextupoles scheme

Hybrid FoDo lattice: the evolution of the FODO90990 (ttbar case)



Two cells are displayed

One cell is built with the following matching constraints:

Mux => minimize emittance

Muy => minimize Y chromaticity

Dmux between SFs => zero X-detuning

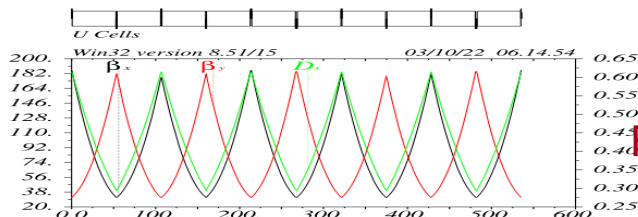
Dmuy between SFs => zero XY-detuning

Dmuy between SDs => zero Y-detuning

Betay @ SD => zero second order y chromaticity

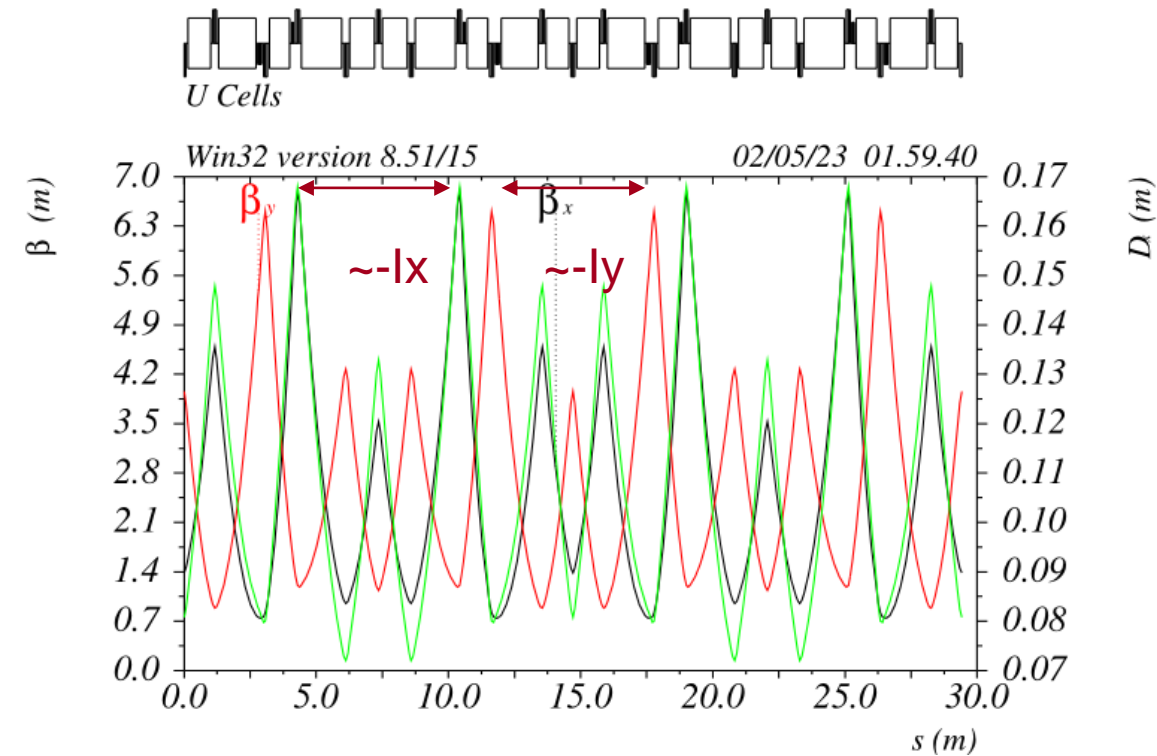
Betax @ SF => zero second order x chromaticity

One "cell" consists of 10 dipoles and 10 quadrupoles
6 quadrupoles (remaining 4 quads are paired) are varied to match the constraints
plus the relative length of the dipoles in between the sextupoles pairs



HFD lattice matching routine

CELL



This routine generates a linear and second order achromatic lattice

```
vary, DL12, step=.001
```

```
vary, KQD1, step=.001
vary, KQF2, step=.001
vary, KQD3, step=.001
vary, KQF4, step=.001
vary, KQD5, step=.001
vary, KQF6, step=.001
```

```
constrai, SD1A[2], bety = bysu, mux = mux_sd/2, muy = muy_sd/2
constrai, SF1A[2], betx = bxsu, mux = muxu/2-mux_sf/2
```

```
constrai, #e, mux = 2*muxu, muy = 2*muyu
```

```
lmdif, tolerance = 1e-10, calls = 2000
```

```
endmatch
```

Insert Long Straight section: Transparency Conditions

In the middle of the cell, supposing the Arc+half SS being a single pass line, the optics must satisfy these constraints:

0) $\alpha_x = \alpha_y = \alpha_{px} = 0$ (beta matching conditions)

1) $dmux = 0 + N$ (wrt the standard cell)
 $dmuy = 0 + M$

These conditions ensure that the Arc periodicity is kept for the on-energy electrons

2) $dW_x = dW_y = ddp_x = 0$ ($\phi_x = \phi_y = 0$, m_{dx} notation)

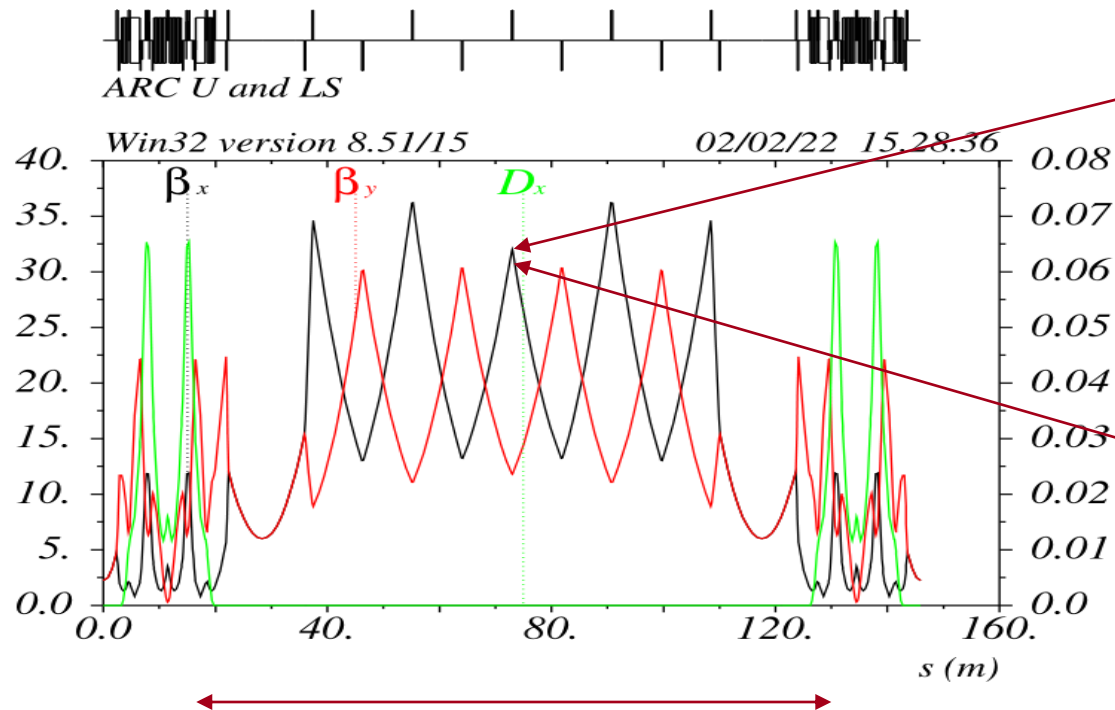
The first order derivatives wrt energy are also set to 0

These conditions ensure that the full periodicity is kept for the off-energy electrons as well (at first order)

All these conditions can be achieved by properly adjusting the linear matching

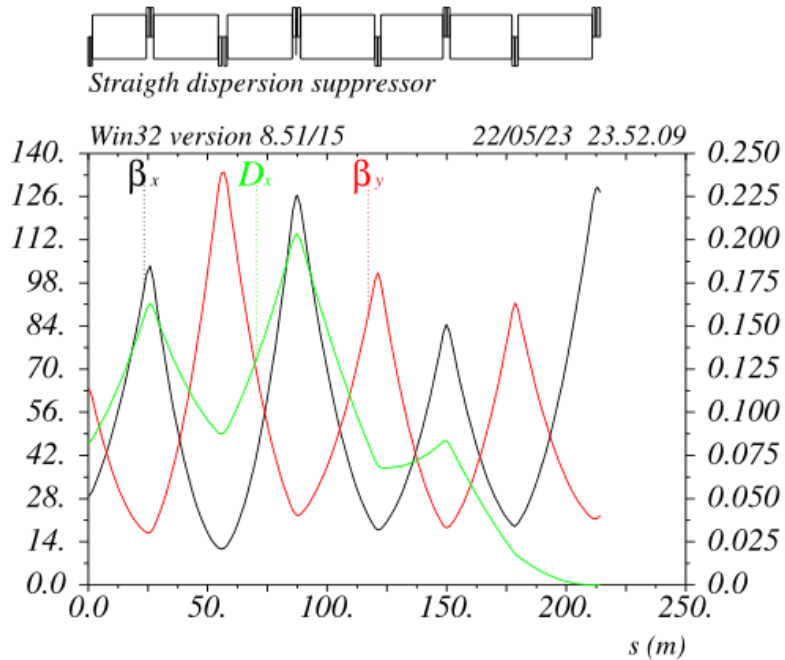
3) For a superperiodic lattice (eg: ARCs+SSs) the phase advance between ARCs must be far from 0 and 0.5
(Integer part of the tunes should not be multiple of the superperiodicity)

In general, the overall chromaticity of the section should be minimized as much as possible.



Only the linear optic between the last and first sextupoles of the adjacent arcs is modified

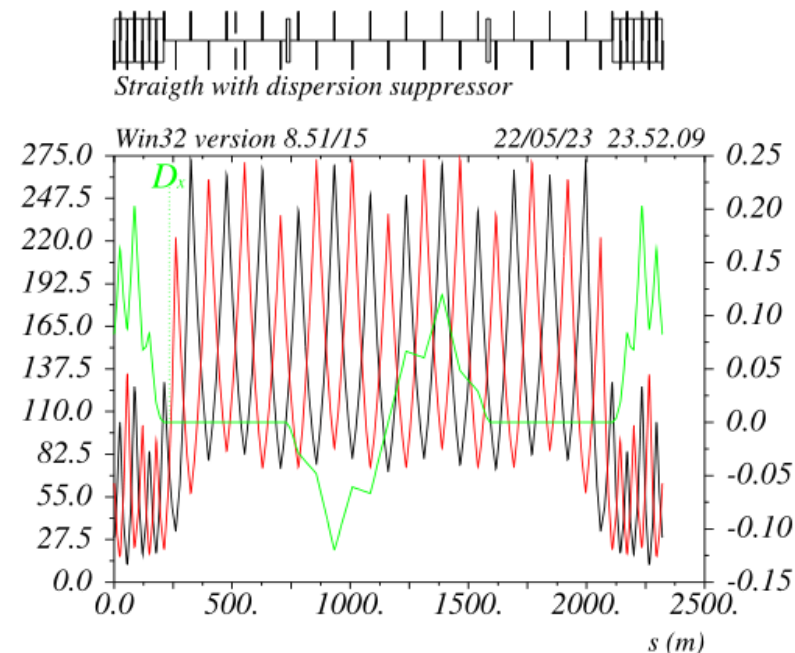
Dispersion suppressor and Long Straight



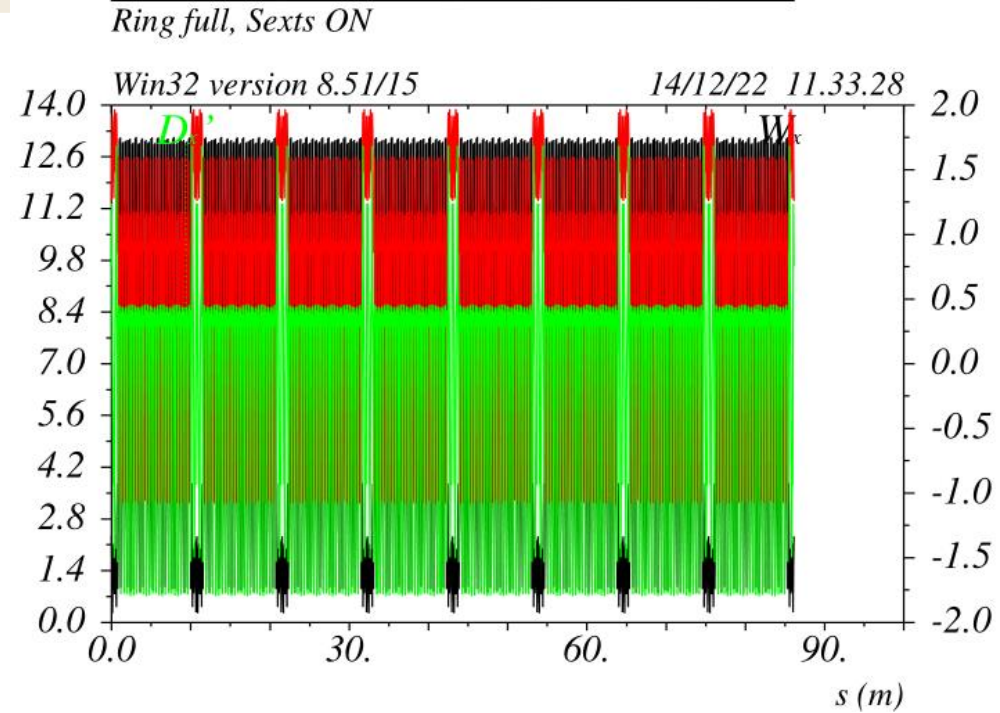
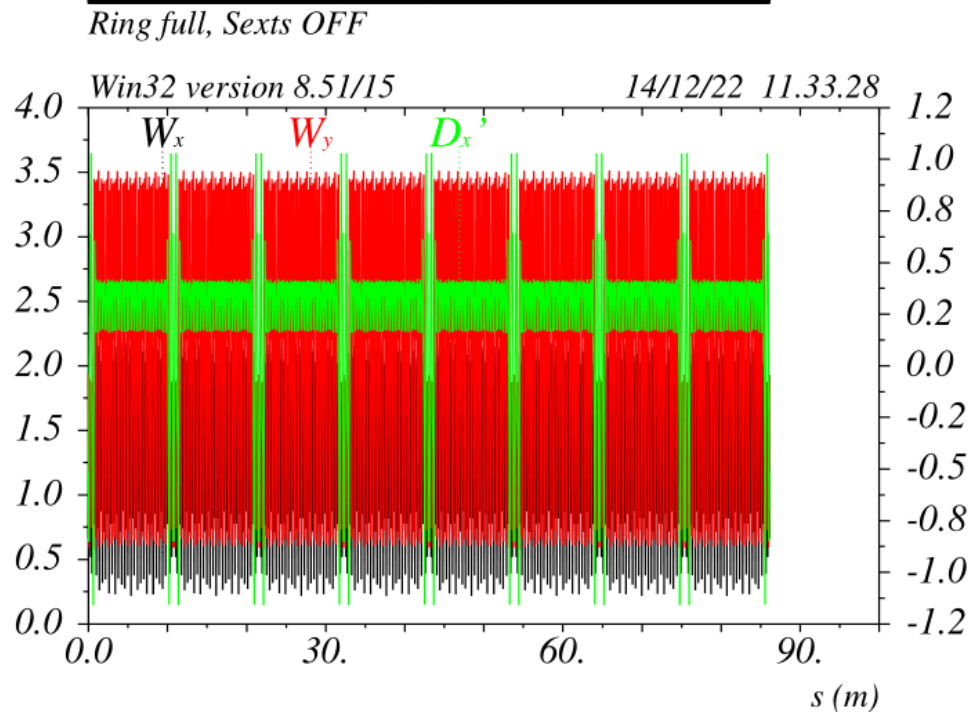
In order to match first and second order dispersion the last 4 dipoles have half the field of the ARC ones

At the end of the DS there is a quasi-image point of the last SF, a sextupole in this location can be used to round the X phase space in the straight section

Example of LSS with a "quasi-fodo"
 $D_{mux}=+3$ $D_{muy}=+3$



HFD + Straight Section



Matching with TCs guarantees the periodicity of the chromatic functions.

They remain periodic with sextupoles OFF and ON

No sextupole families are needed to restore chromatic properties up to the third order

ARCs+LSs+FFDS (no Final focus) dynamic properties

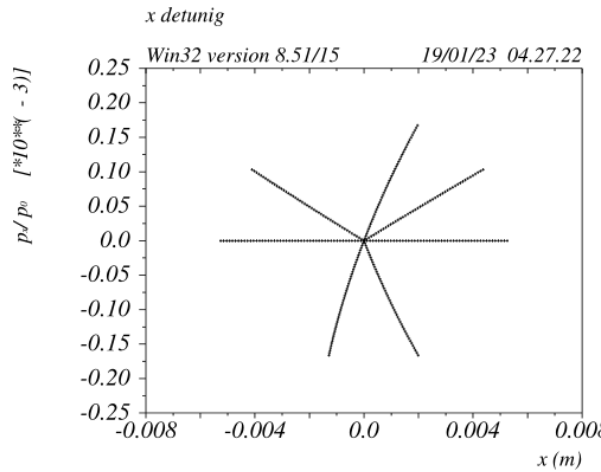


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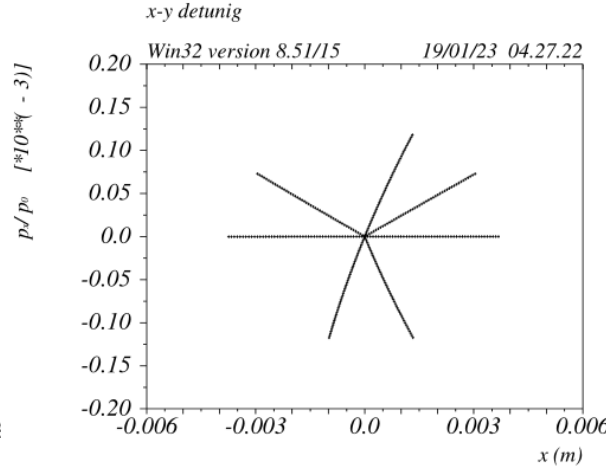


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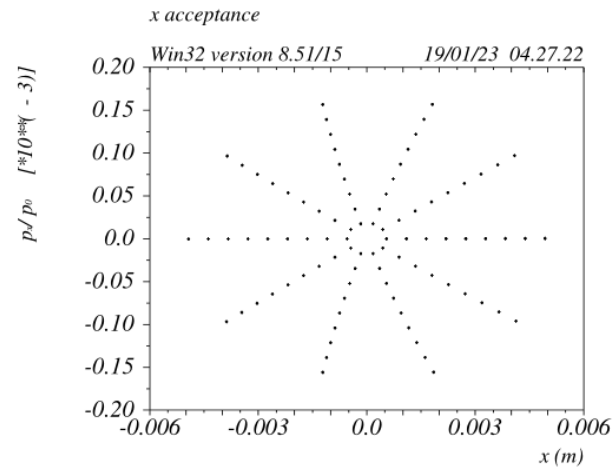


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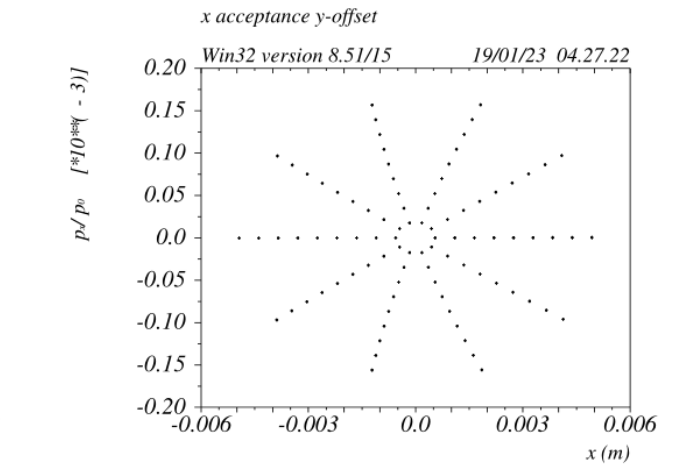
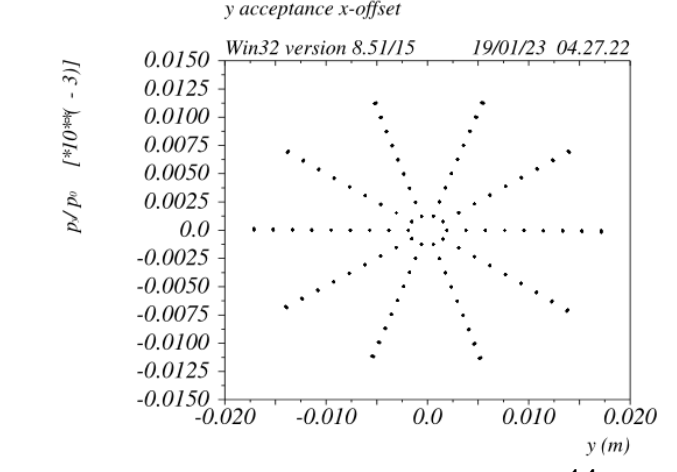
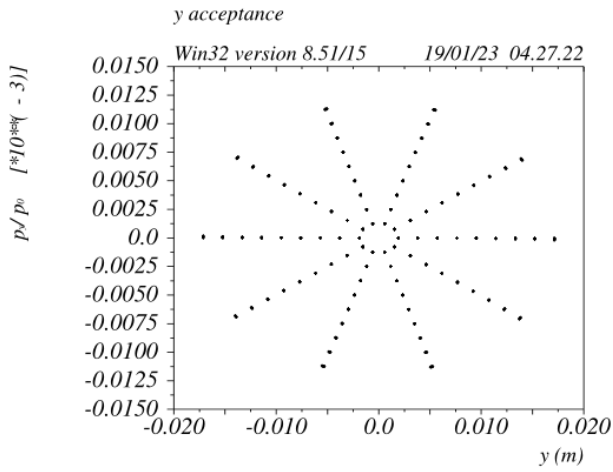
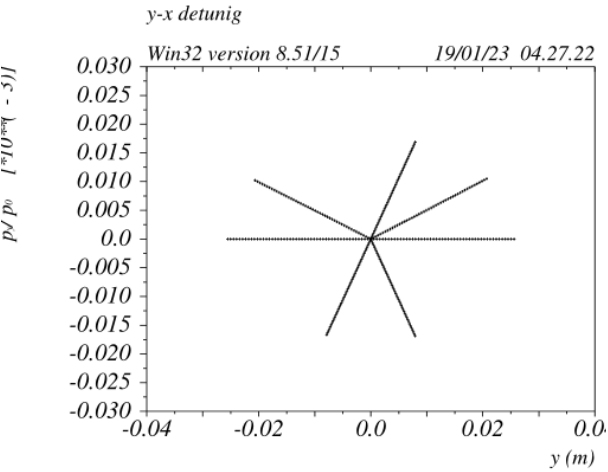
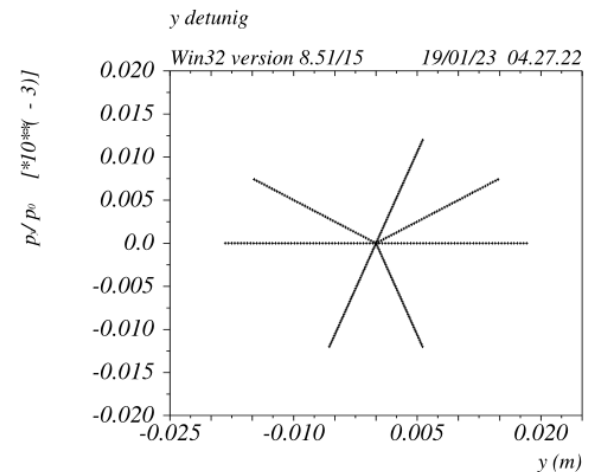
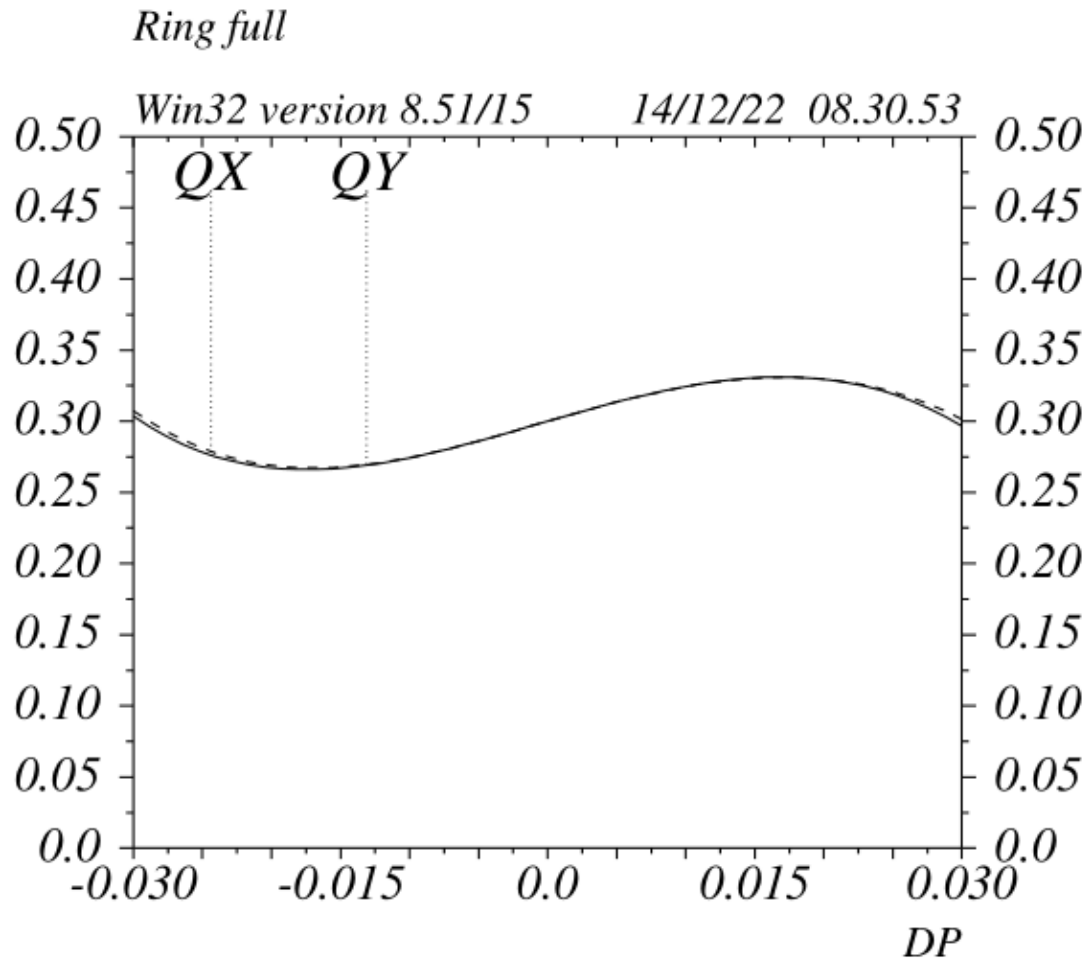


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betax= 30m betay = 1450m (FF entrance, crab sext location)



HFD Energy Acceptance

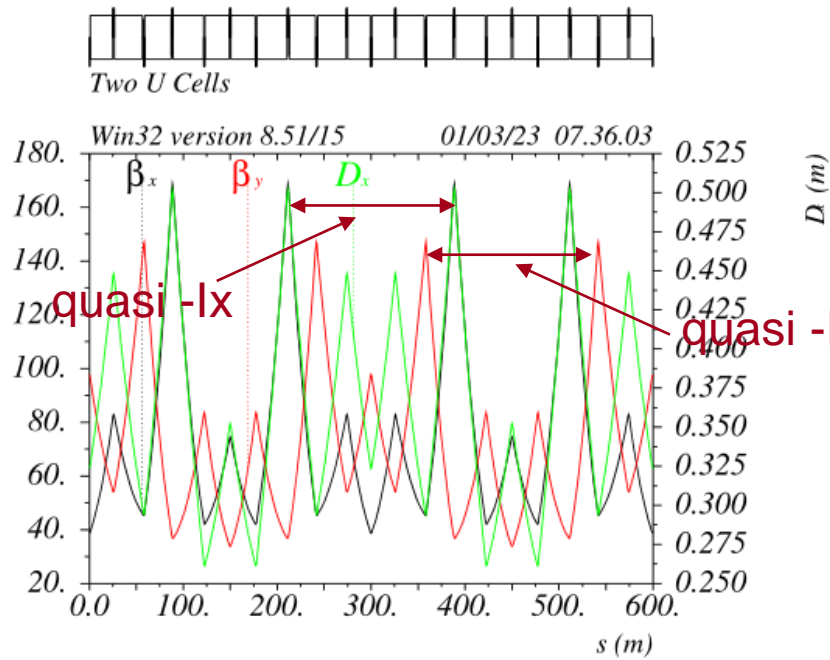


The ARC+LSS has zero second order chromaticity in both planes, only third and higher orders remain.

In principle paired-decapoles placed at the sextupole locations can remove the third order chromaticity (not needed for FCC) as well

These properties can be maintained for a very large number of cells.

HFD lattice optimization: (short) HFD4545 for Z (Long FODO9090 Baseline)



The trick of canceling the linear detuning by adjusting the phase between the sextupole pairs can be applied for any given Cell phase advance. It works better (less linear detuning as starting with and residual non-linear detuning) if the fractional X-cell phase advances is around $\pi/2$

The cell has been optimized around:

$\text{mux_C} = 1.235$ $\text{muy_C} = 1.251$ (~45deg/plane between consecutive QFs)

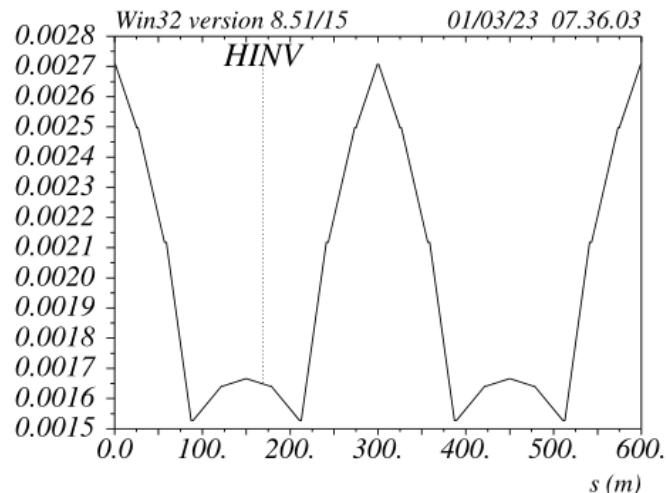
The matching routine is the one shown on the previous slide.

The sextupoles become very weak, Ks about 5 times weaker wrt to tbar optics, no detuning is visible up to 100sigmas

The DA/MA is extremely large, possibly larger wrt to HFD9090

A small second order chromaticity remains to keep betax below 170m.

Natural chromaticity is much lower wrt LONG FODO9090



Z ARCs dynamic properties

v_51a1

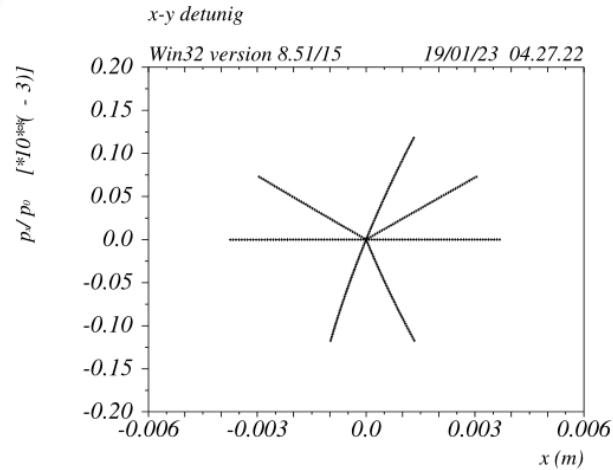


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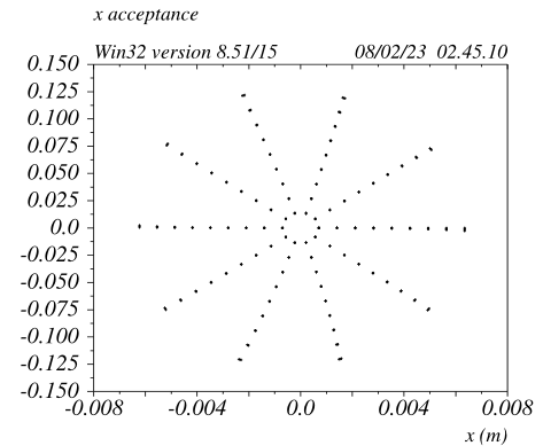
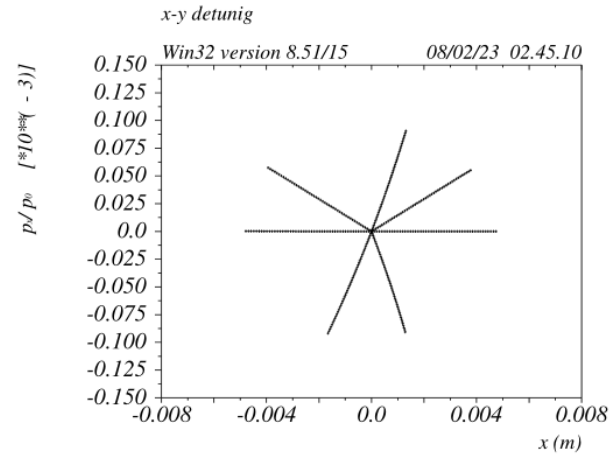


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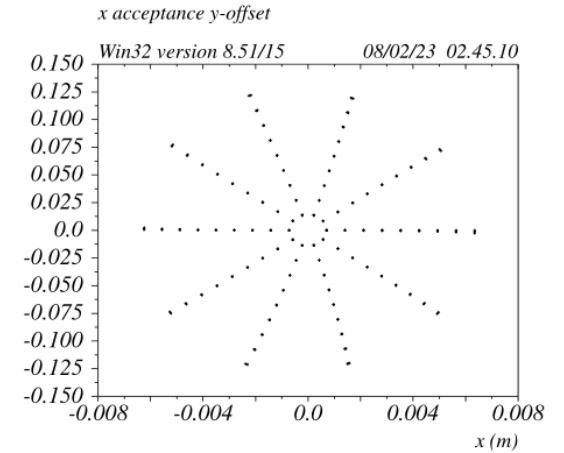
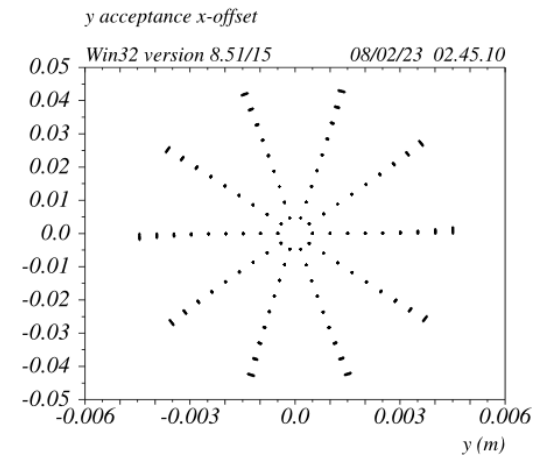
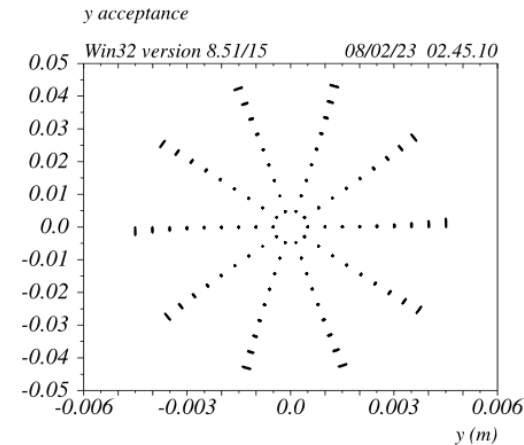
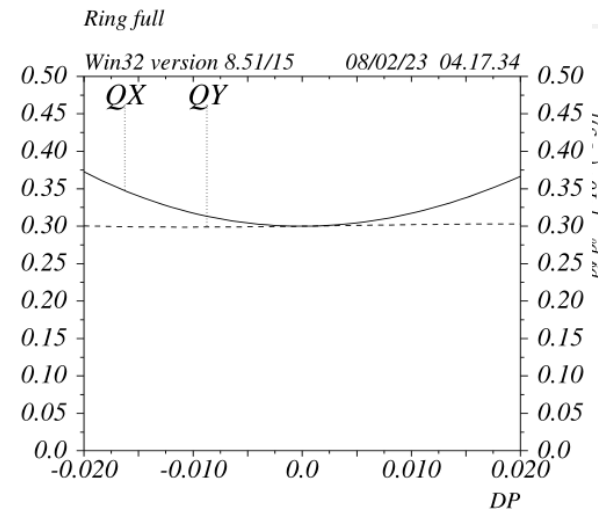
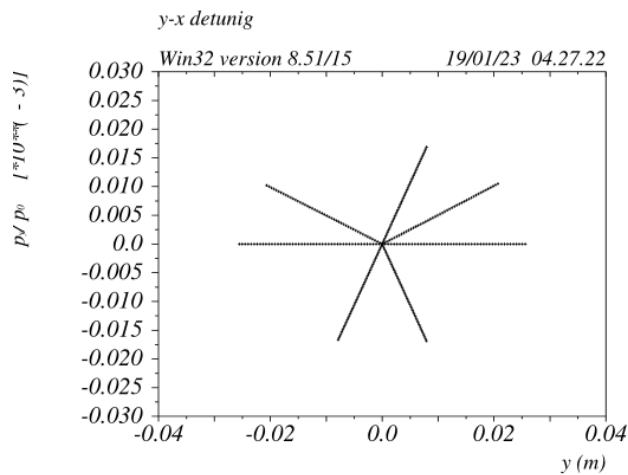


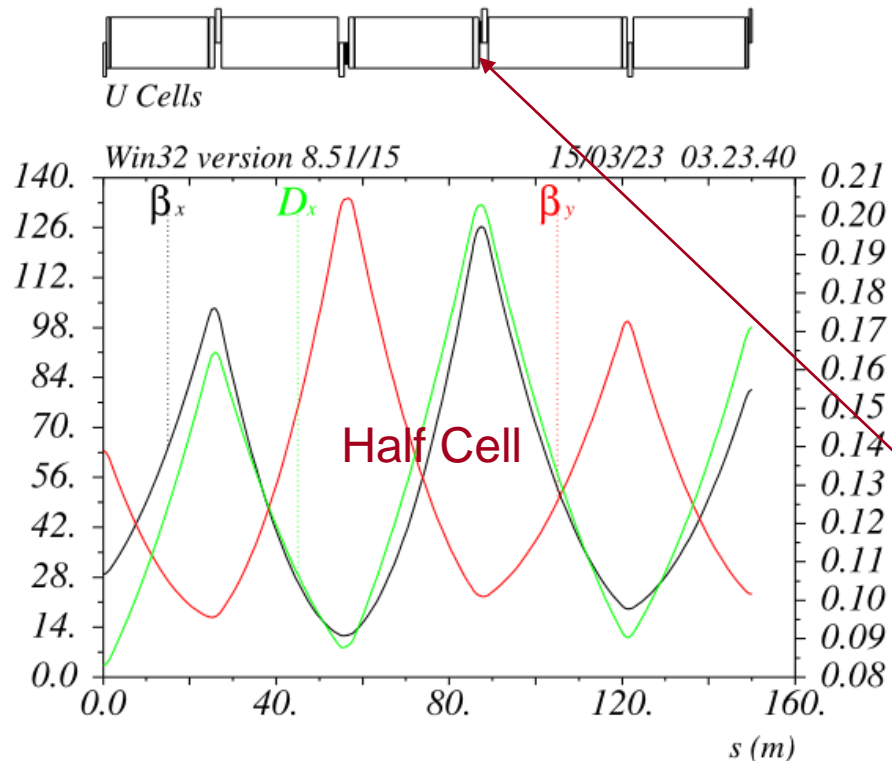
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betax= 45m betay = 100m

HFD4545 dynamic properties are comparable to HFD9090



ARC half cell layout



Optimal complement of corrector and bpm's might be smaller wrt baseline

ARC quads are pairs ~1.2m long with gradients around 12T/m @ttbar

Quads are not paired between the two rings

Total number of ARC quads ~250*20=5000 per ring, ~10000 total

It would be interesting to see if it is possible to conceive a quad that needs 1-2Kw@ttbar

(ESRF HG-quad, 0.49m long, G=90T/m, bore radius~12.5mm, needs~1.5Kw, APS HG-quads are even more efficient)

If a power efficient design is found, the QDs can be twice shorter => twice less => 7500 quads total

ARC sextupoles (at the moment) have all the same strength, apart the "matching section" ones

Sextupoles sit in between two quads

SFs are 0.38m long $K_s \sim 0.146$ @Z $K_s \sim 0.685$ @ttbar

SDs are 0.77m long $K_s \sim 0.125$ $K_s \sim 0.70$

Total number of ARC sextupoles ~250*4=1000 per ring ~2000 total

Sextupoles total power consumption is a very small fraction wrt to quads

In order to minimize synchrotron radiation, one of

the two quads could be offset by ~2-4mm => ~3% less U0

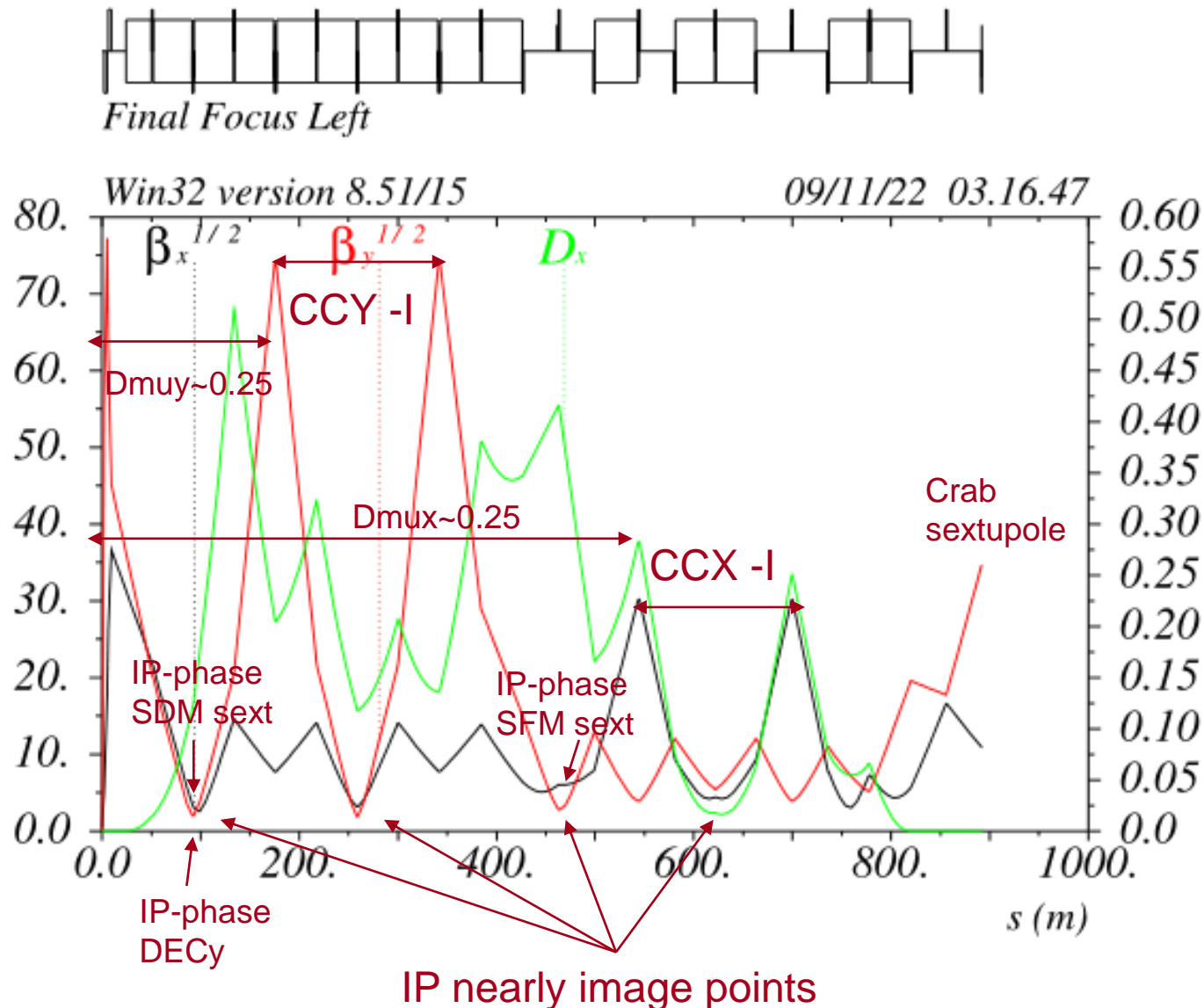
With HTS, the quads dipole field can be superimposed to all the ARC quads.
In this case the ARC dipole filling ratio will be > 0.99 for all modes

- Highly anharmonic and second order achromatic ARC cells can be developed with minor modification of the Oide FODO9090 cell.
- HFD matching works well to build quasi-linear-lattices for a large range of cell phase advances
- Overall ring MA above $\pm 5\%$ can be achieved for a ring composed of up to ~ 300 cells
- Potential use for low emittance rings and even SLSs can be conceived and should be further explored.
- A very simple and analytical method to insert sections in the ARC preserving the ring DA&MA is used
- Rings with generic straight section insertions with performances comparable to a fully periodic structure can be made

- Half FF is defined as a telescope that starts from the ARC-DSS and ends to the IP
- The crab sextupole is placed at the beginning of the FF to minimize its impact on MA
- The FF is built to be as much as possible an high order Achromat in both planes.
- In the following it will be described how to optimize the FF system, defining all the related tuning knobs and their effect on overall performances
- This methodology can be applied very generally to any low beta insertion
- By construction, the FF_Left+FF_Right is an identity transformation and can be readily inserted in the ring according to the TCs criteria

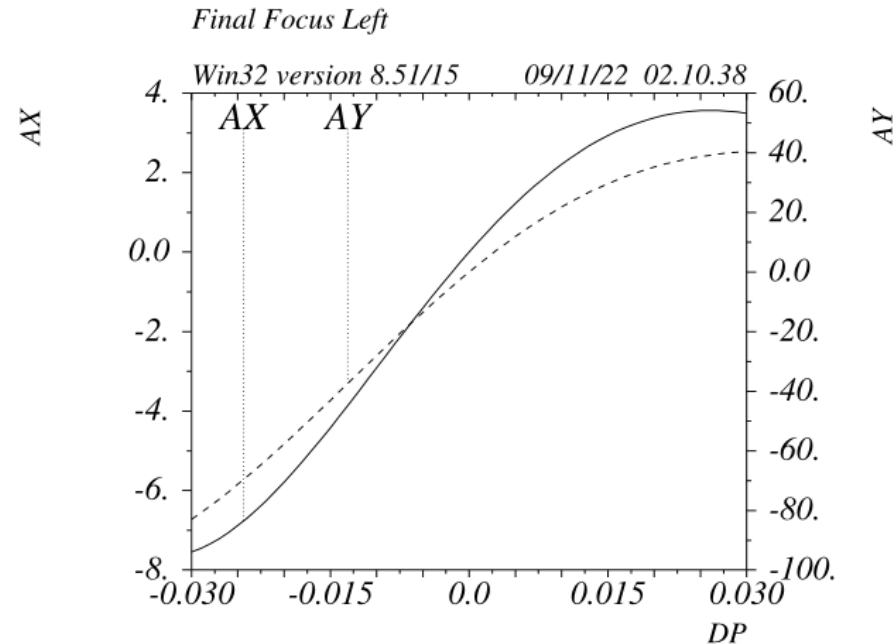
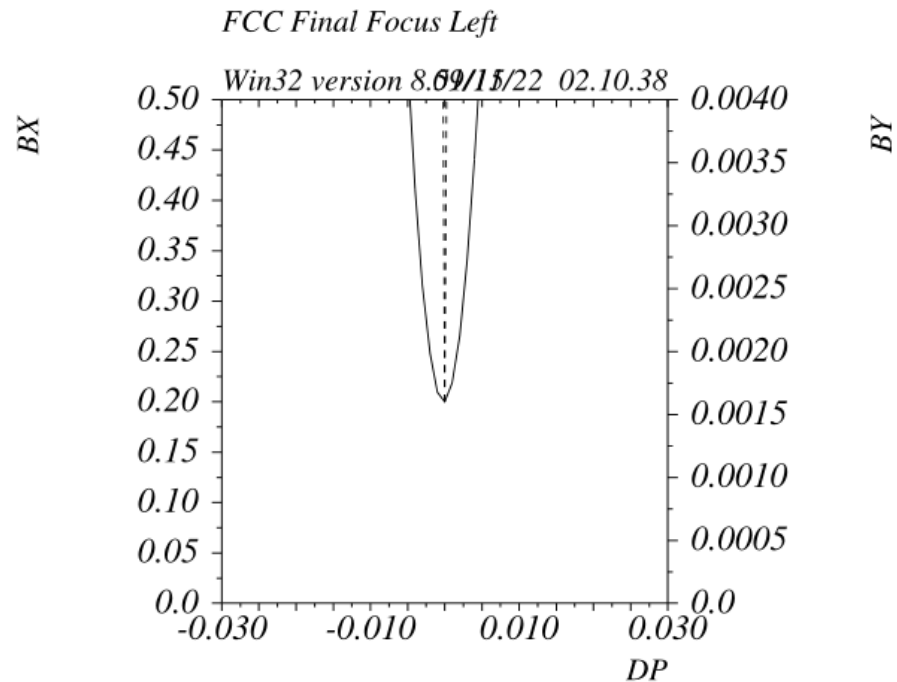
Final Focus: NLC FF => LCC FF for Circular colliders

v_23c



The effect of all these elements/quantities will be described, together with the results of their optimization:

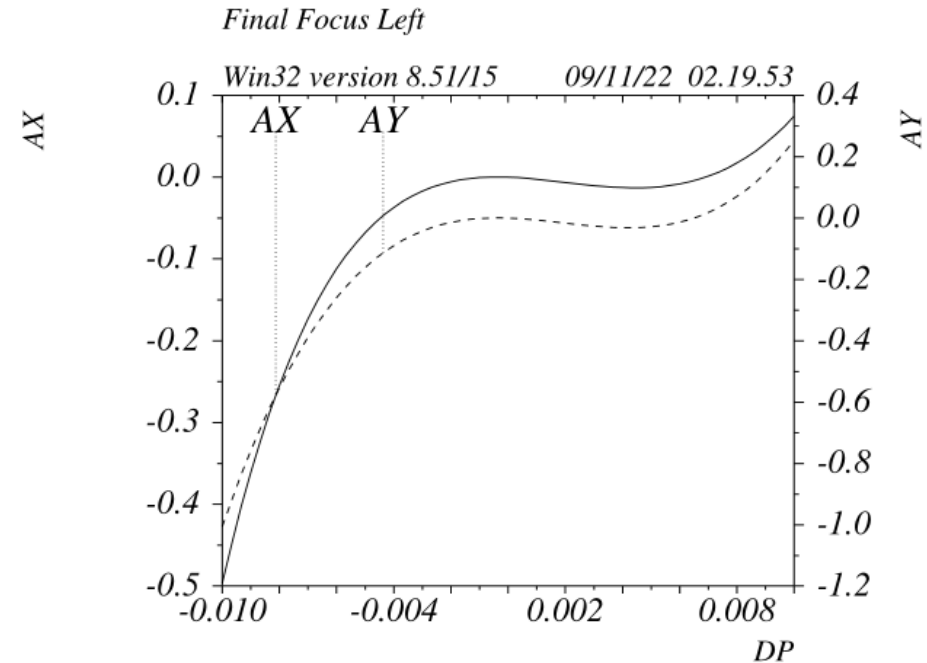
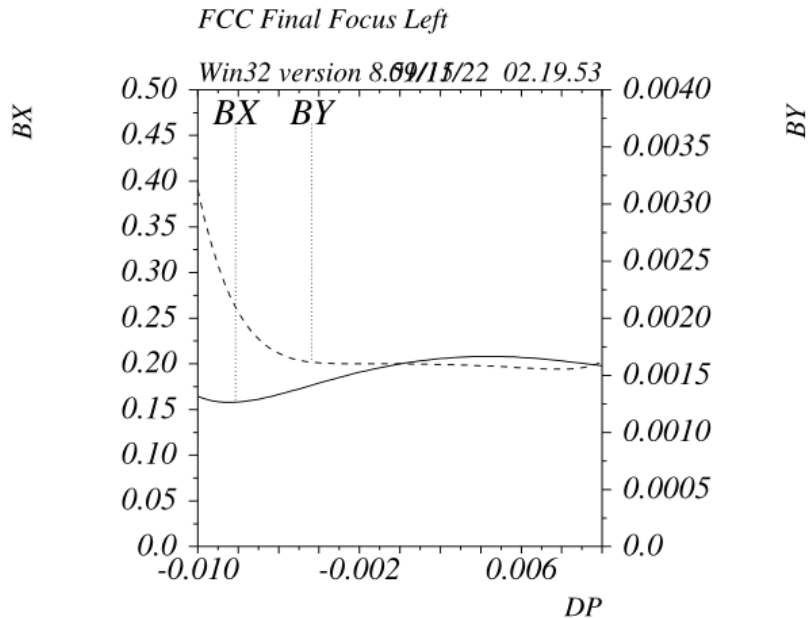
- 1) Main Sextupoles SDy and SFx
- 2) SDy&SDx phase advance wrt IP
- 3) IP-phase sextupoles SDM and SFM
- 4) Etaxp@ CCSY and CCSX
- 5) Decapole y (&x)
- 6) Phase advance between -I sextupole pairs



All sextupoles OFF

FF BandWidth (or MA) without chromatic compensation is infinitesimal

Final Focus with up to First Order Chromatic Correction v_23c

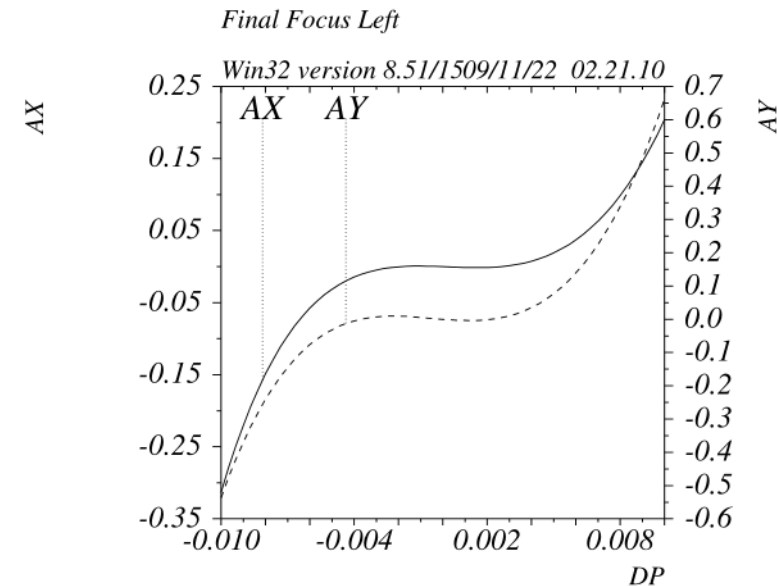
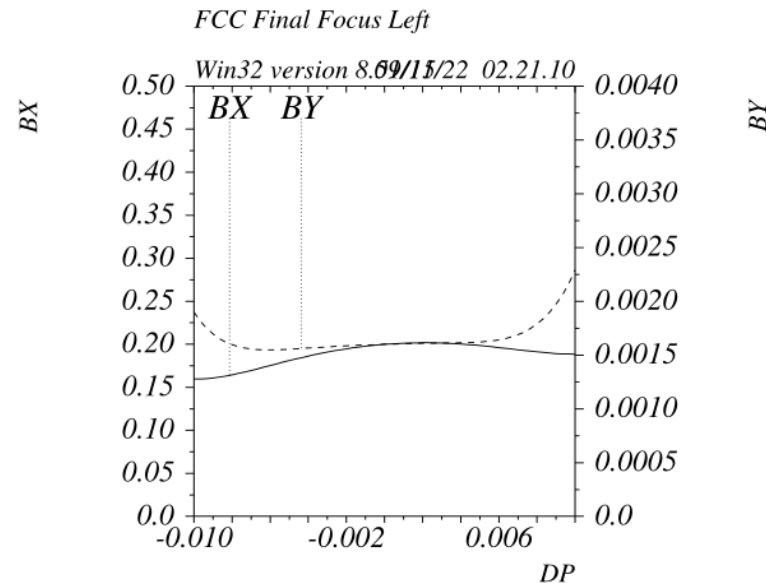


Only the main SDy and SFx pair are set in order to zero the derivatives of α_{fy} & α_{fx} wrt energy.

The horizontal scale is +/-1% (not 3% as in the previous plots)

Higher order terms (at least second and third) remain

Final Focus with up to Second Order Chromatic Correction v_23c



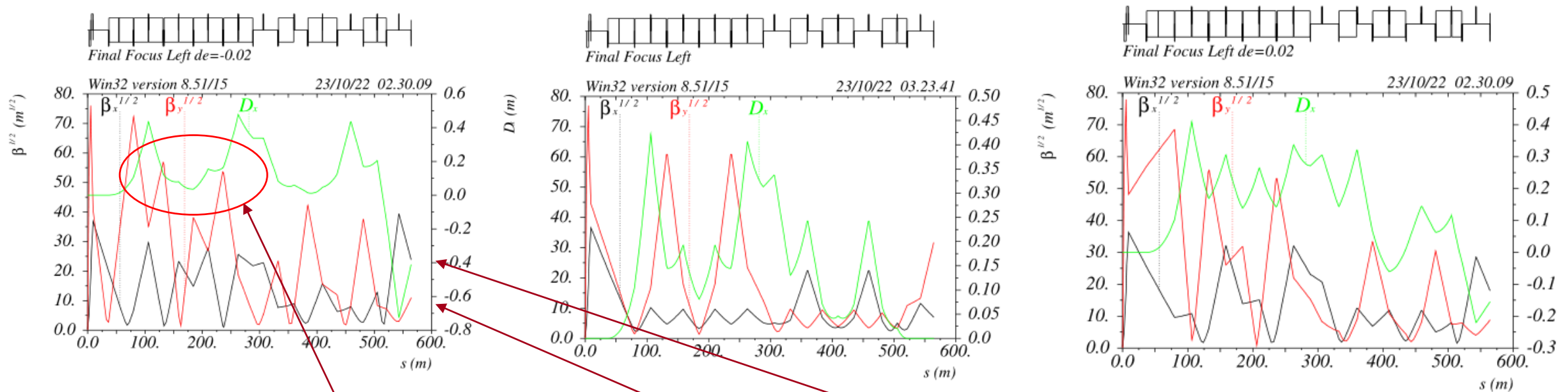
The phase advance between the sextupole pairs wrt the IP is optimized in order to zero the second order chromaticity. Optimal value is close but not equal to 0.25, the reason is that the overall contributions (vector-like) to the FF chromaticity are not necessarily at 90deg wrt IP

The optimal phases are set with simple linear optics matching.

The present FF quadrupole complement allows the change of these phases while maintaining all the other parameters unchanged (betas dispersions, other phases etc...)

Higher order terms (third very visible) remains

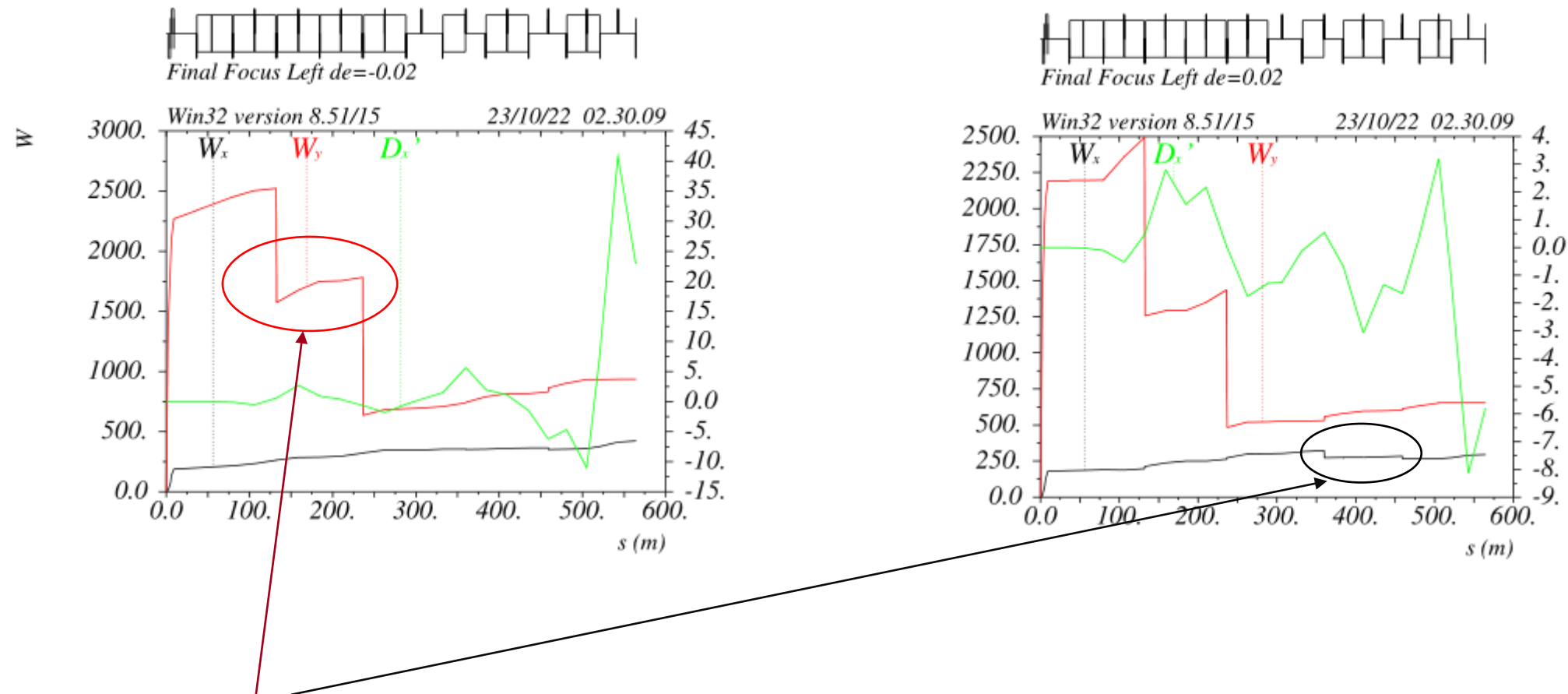
Final Focus with first order chromatic correction v_17e



Chromatic behaviour for off energy beam much heavily affected by third order chromaticity
betas&alfas @CS are still way off (but less way off): betay@CS~100, betax@CS~400

The reason is that the betafunctions on the sextupoles for off energy particles are lower (nominal etay@SD=3600), so they do not correct the chromaticity effectively anymore (also the relative phase wrt FD changes)

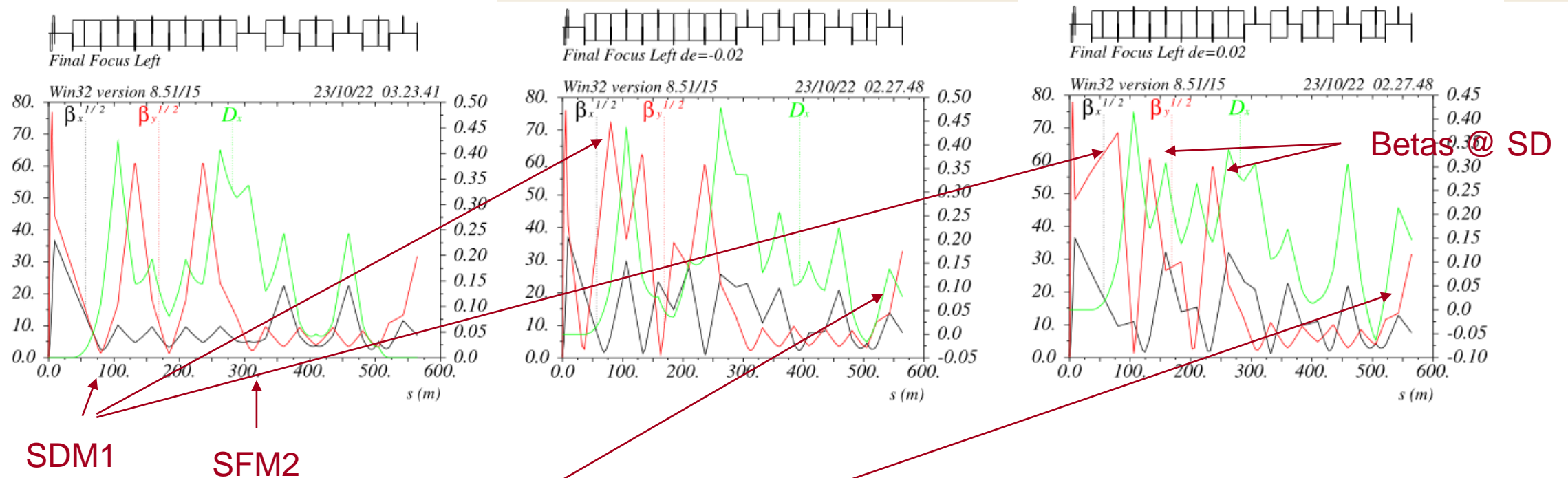
Final Focus with first order chromatic correction v_17e



Sextupoles becomes less effective in correcting the chromaticity for off energy electrons

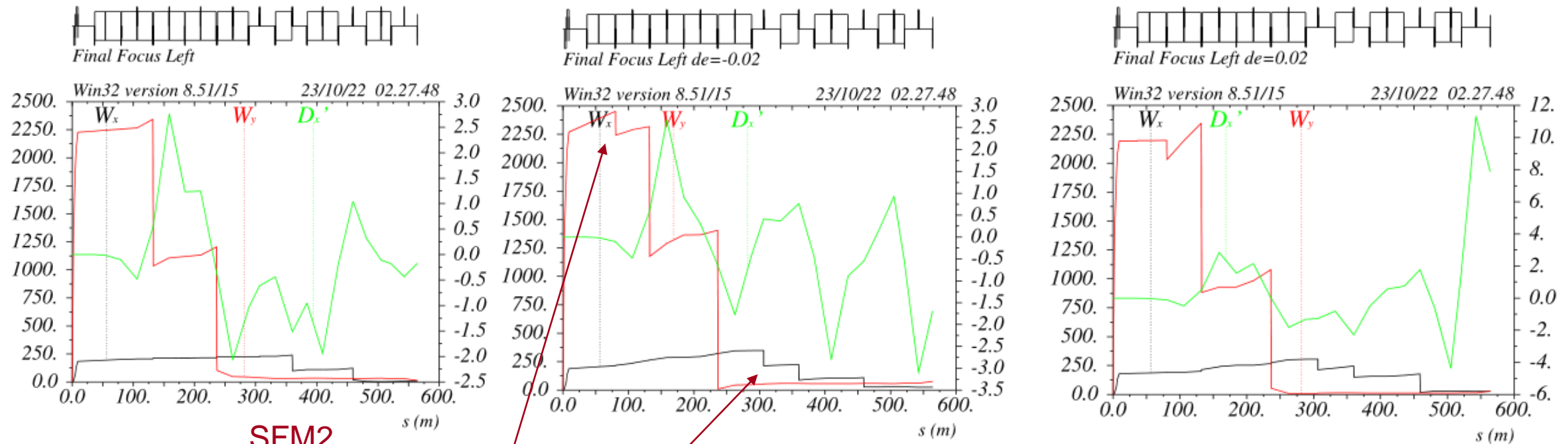
Final Focus with second order chromatic correction

v_17e



The two additional weak sexts are added in the IP image points outside the -I pairs
They preserve the -I's and are at low beta locations, so they do not harm the FF Anaharmonicities

For off energy electrons they are at extremely large betas locations, they successfully restore the nominal betas and phase advance on the main sextupoles for all energies
The betas @ CS are nominal for all energies as well !



Chromaticities are well corrected for off energy beam as well

The contribution of the IP-Phase Sextupoles for off energy beam is evident

Final Focus with up to Third Order Chromatic Correction v_23c

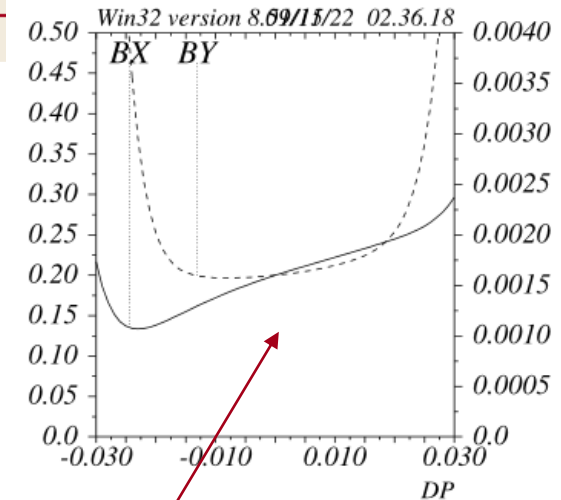
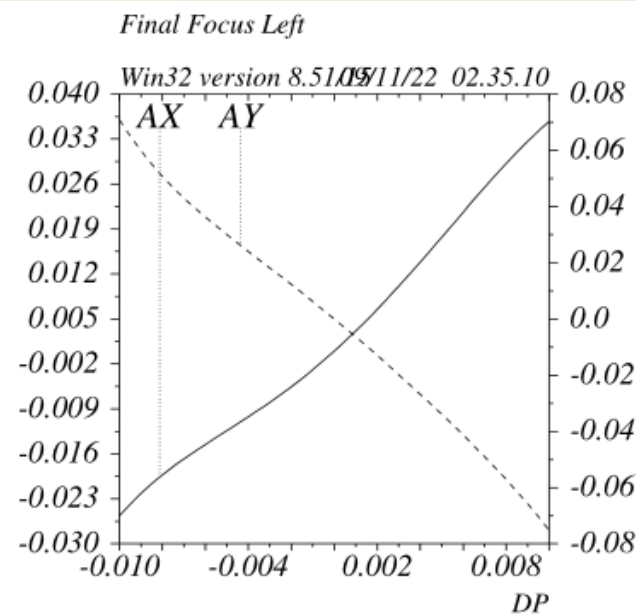
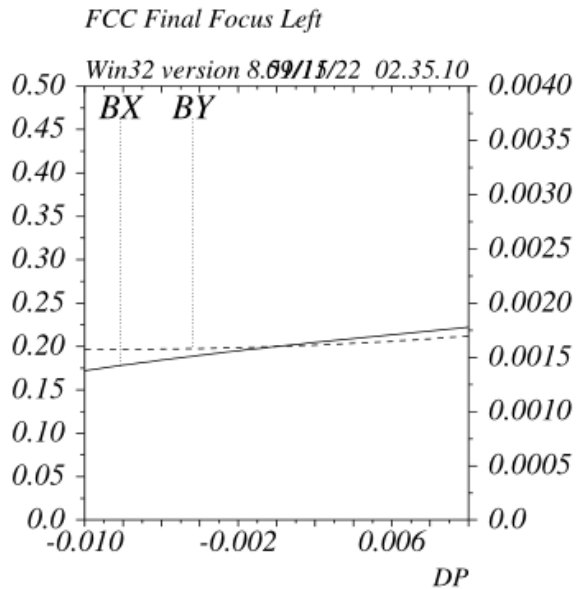
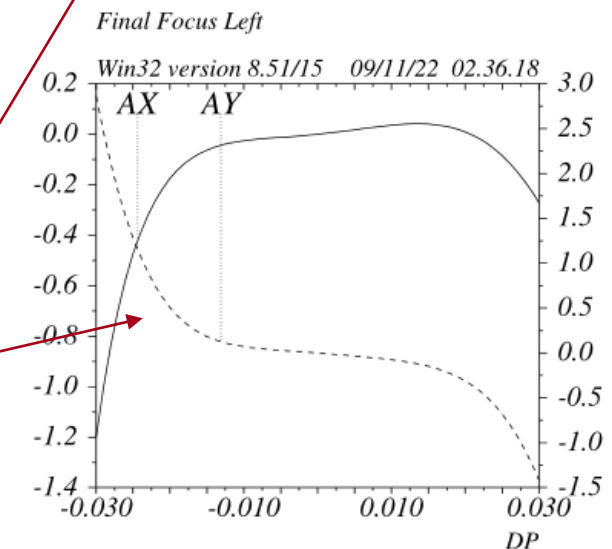
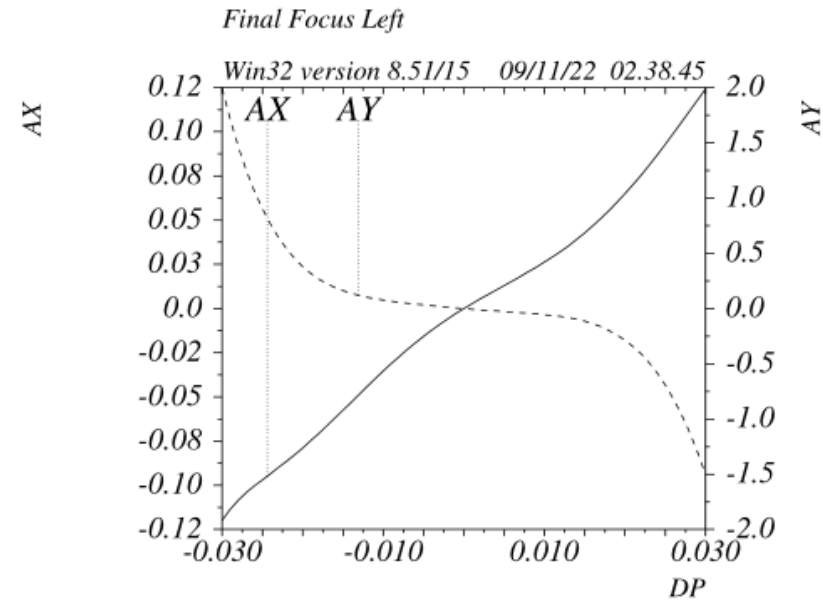
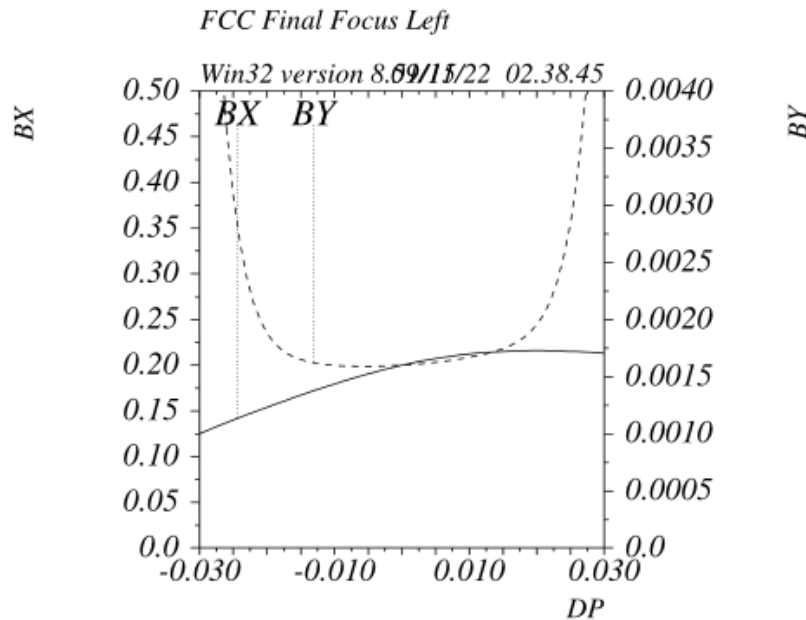


Table name = SPECIAL

The IP-phase SDM and SFM sextupoles make the FF a third order achromat (on Nov 3rd presentation it was shown how)
To match the ARCs Ws, a linear chromaticity different from zero has been set.
On a large scale are visible the remaining terms above the third and their effect on the BW



Final Focus with up to Fourth Order Chromatic Correction v_23c

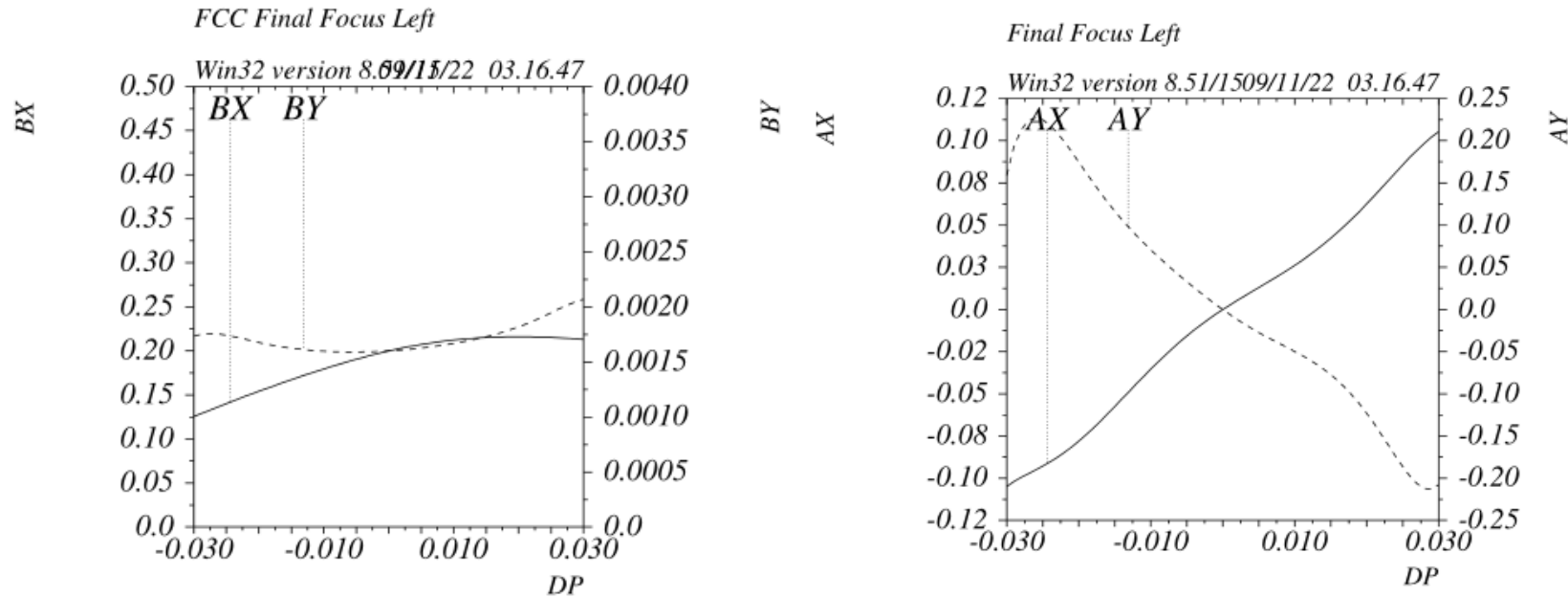


By having different horizontal dispersion across the sextupole pairs the fourth order chromaticity is canceled. The quantity that is optimized are the ϵ_{txp} in the middle of the CCSy and CCSx.

The present FF quadrupole complement allows the change of both ϵ_{txp} while maintaining all the other parameters unchanged

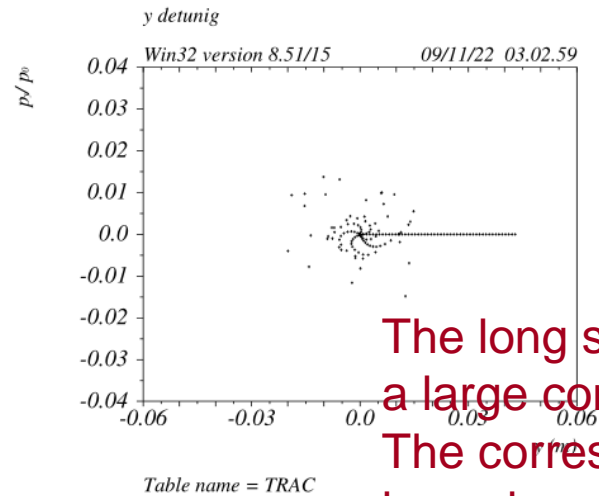
Fifth order terms in the vertical is visible

Final Focus with up to Fifth Order Chromatic Correction v_23c

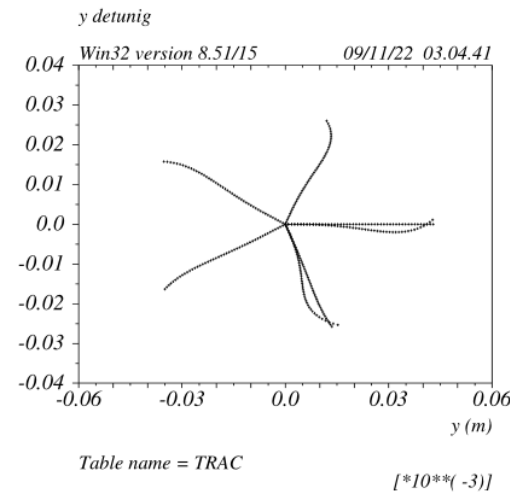


A (DECy K4L~300 in MADX units) decapole at the same location of the SDM can cancel the fifth order chromaticity very effectively

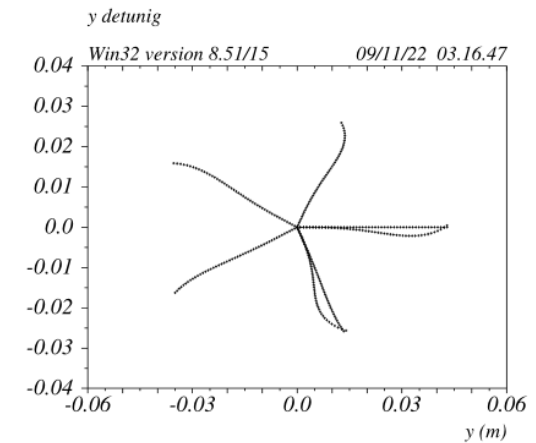
Final Focus geometric aberrations v_23c



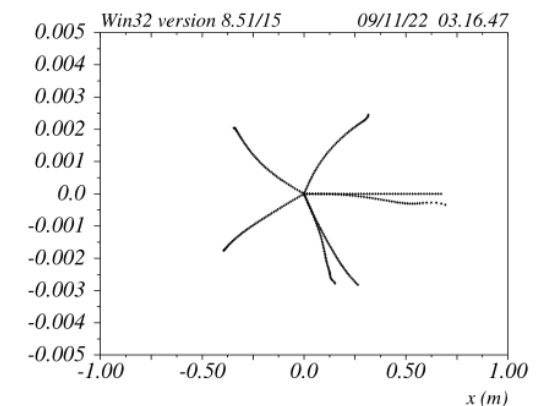
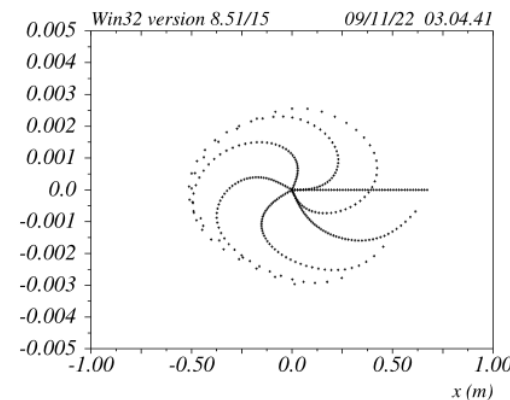
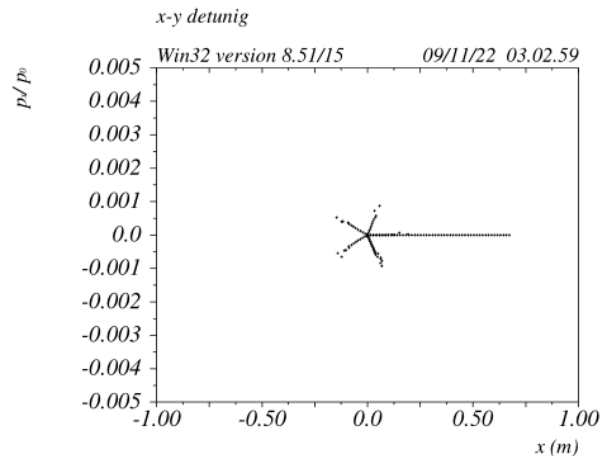
The long sextupole aberration has a large contribution on DA. The corresponding detunings can be reduced by “breaking” the –I between the SDs and SFpairs



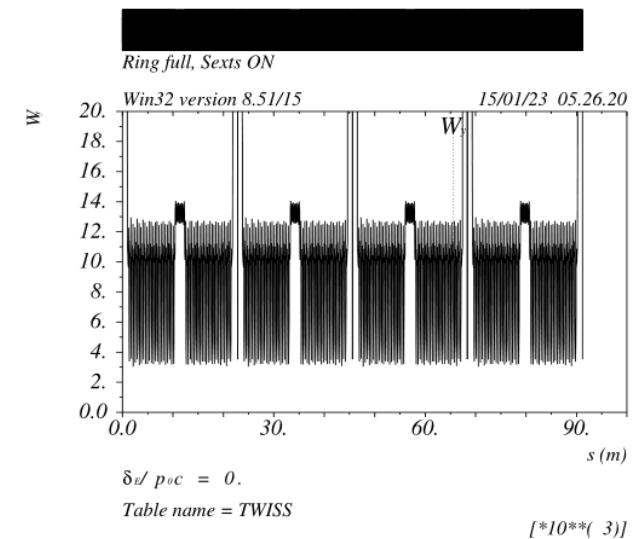
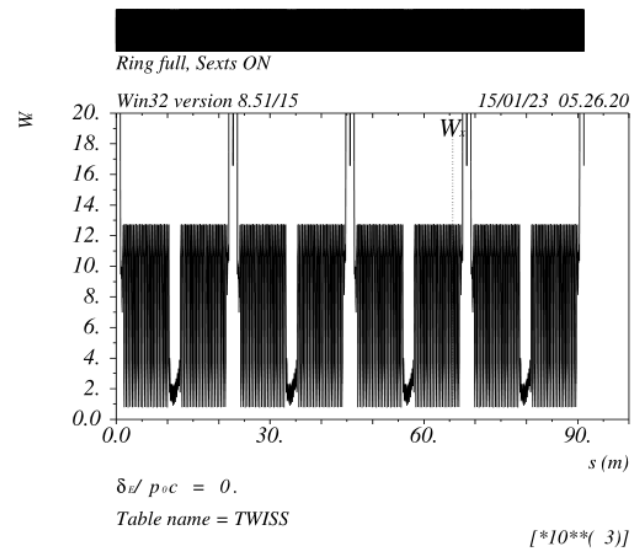
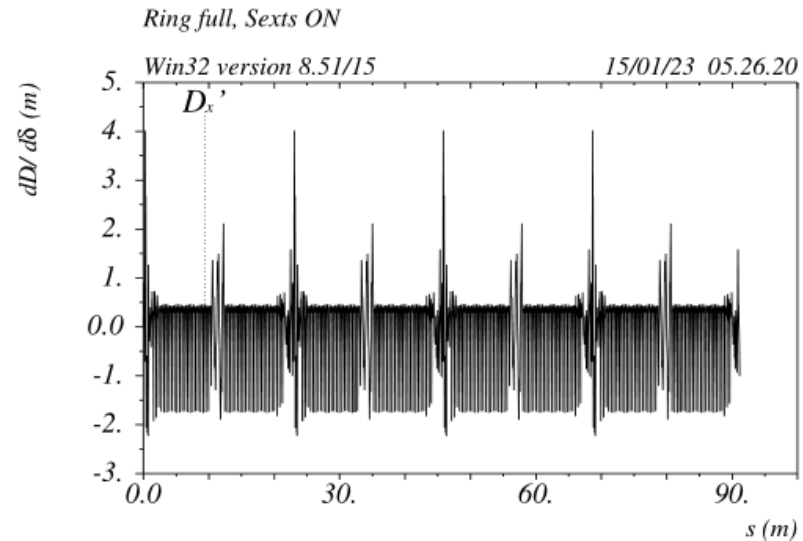
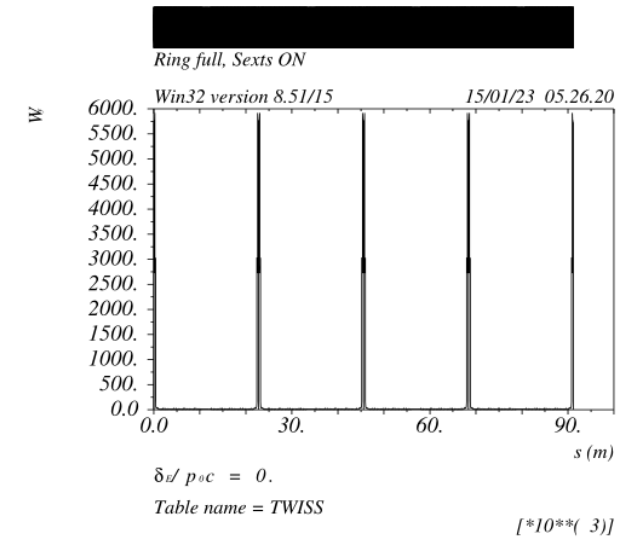
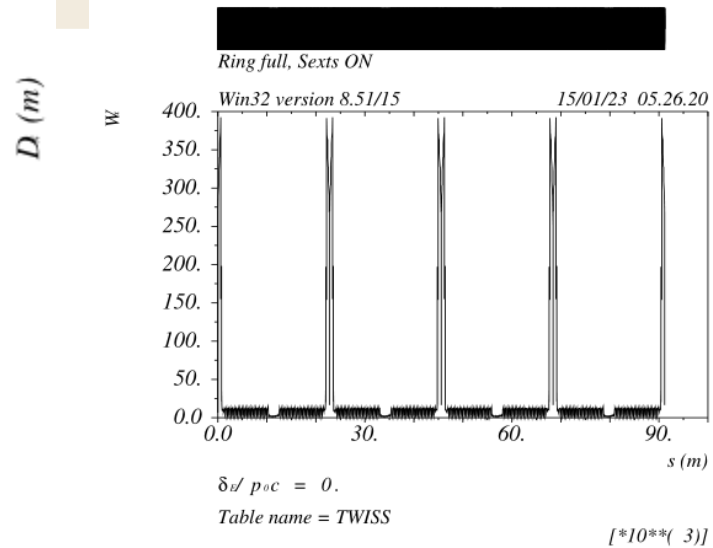
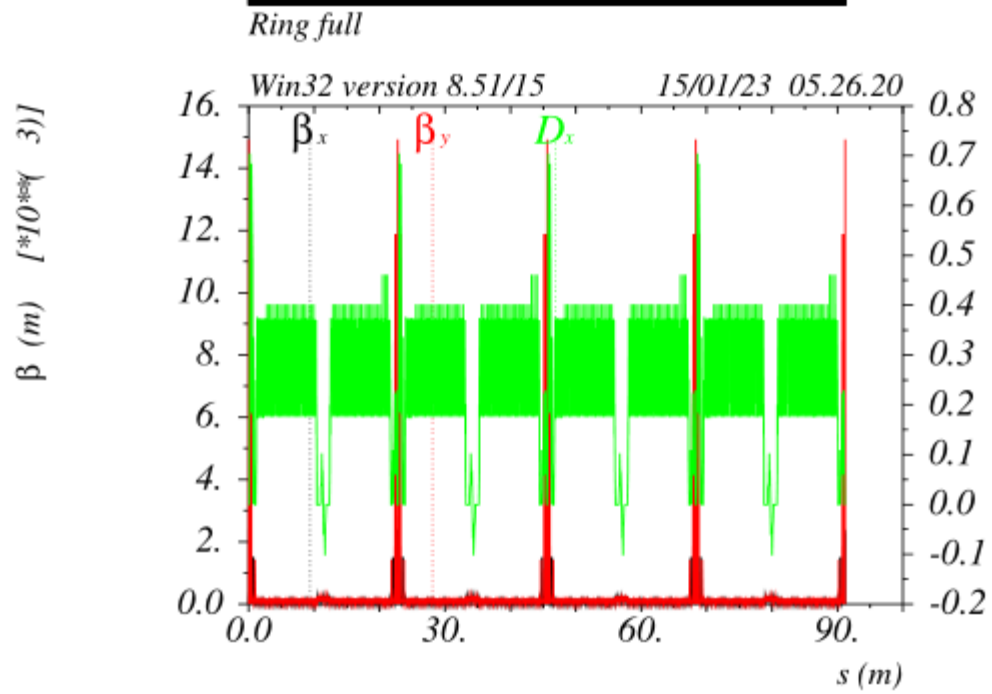
R12 $\sim -0.3 \cdot L_{\text{sext}}$ between the SDy pair



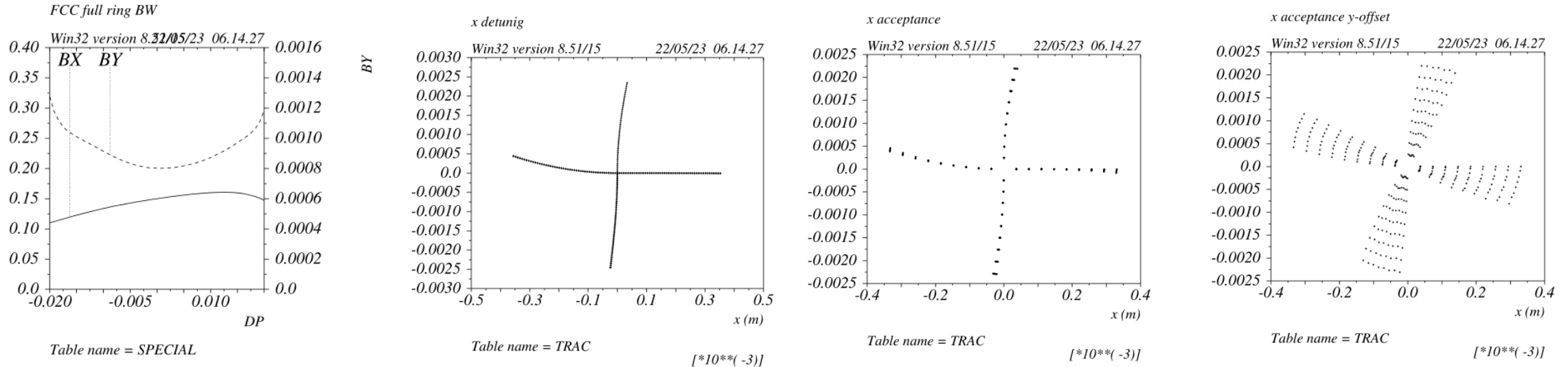
R34 $\sim -0.3 \cdot L_{\text{sext}}$ between the SDy pair



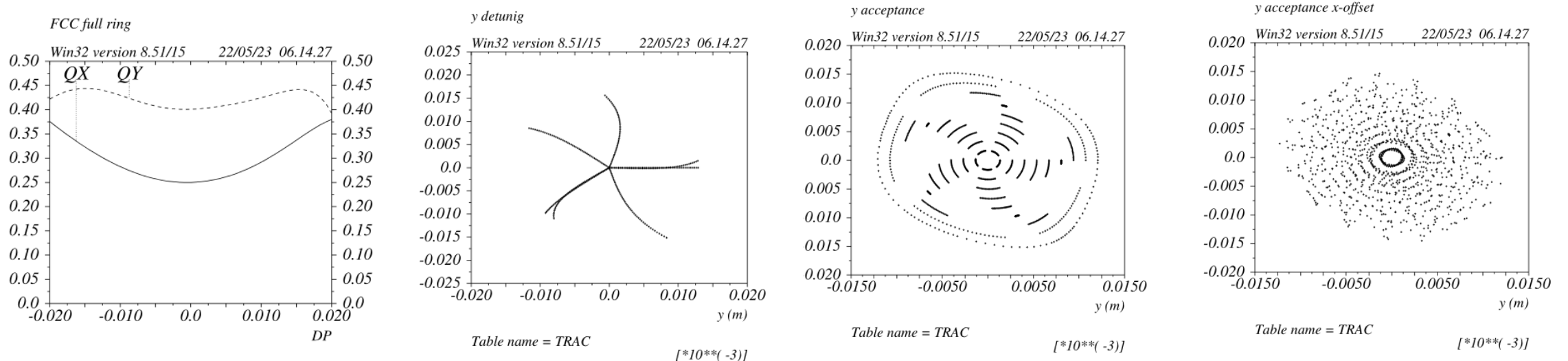
Ring optics and chromatic properties v_42a1



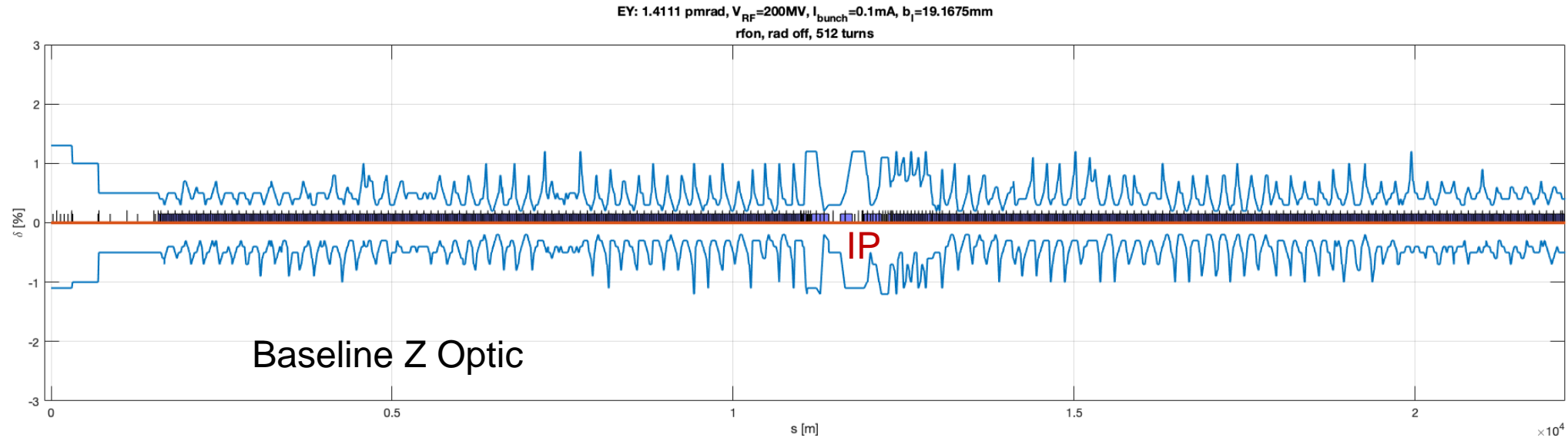
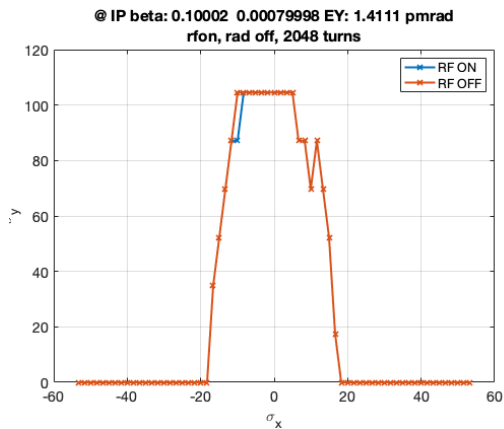
Ring optics and chromatic properties v_61a @Z



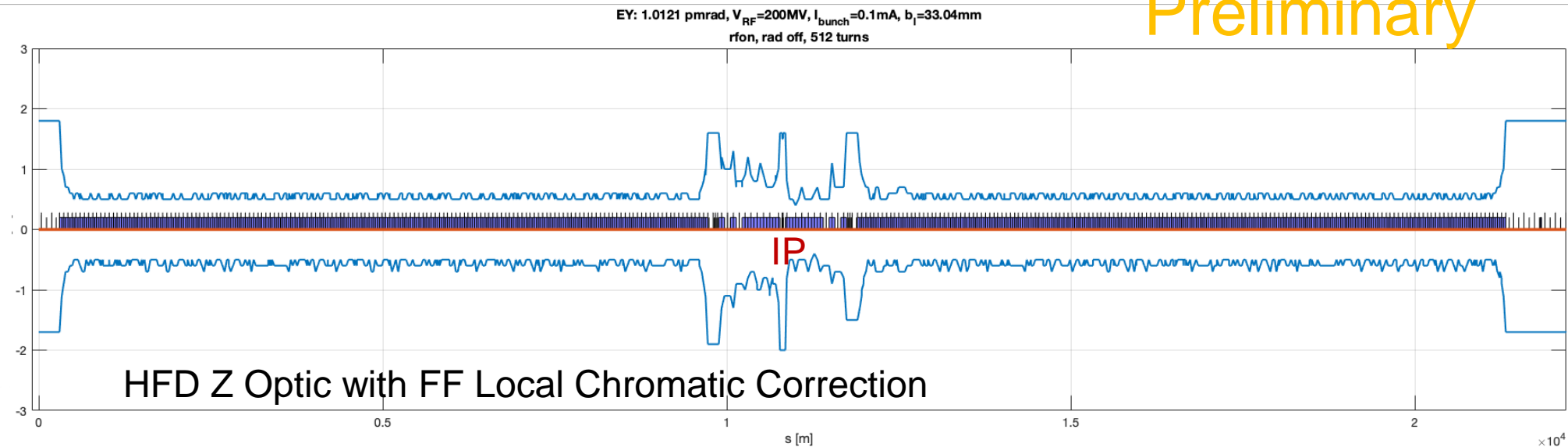
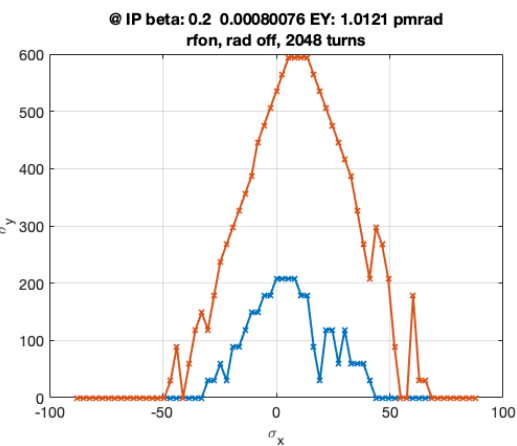
Detailed studies will be presented by M. Hofer



DA and Local Momentum Acceptance (Perfect lattice)



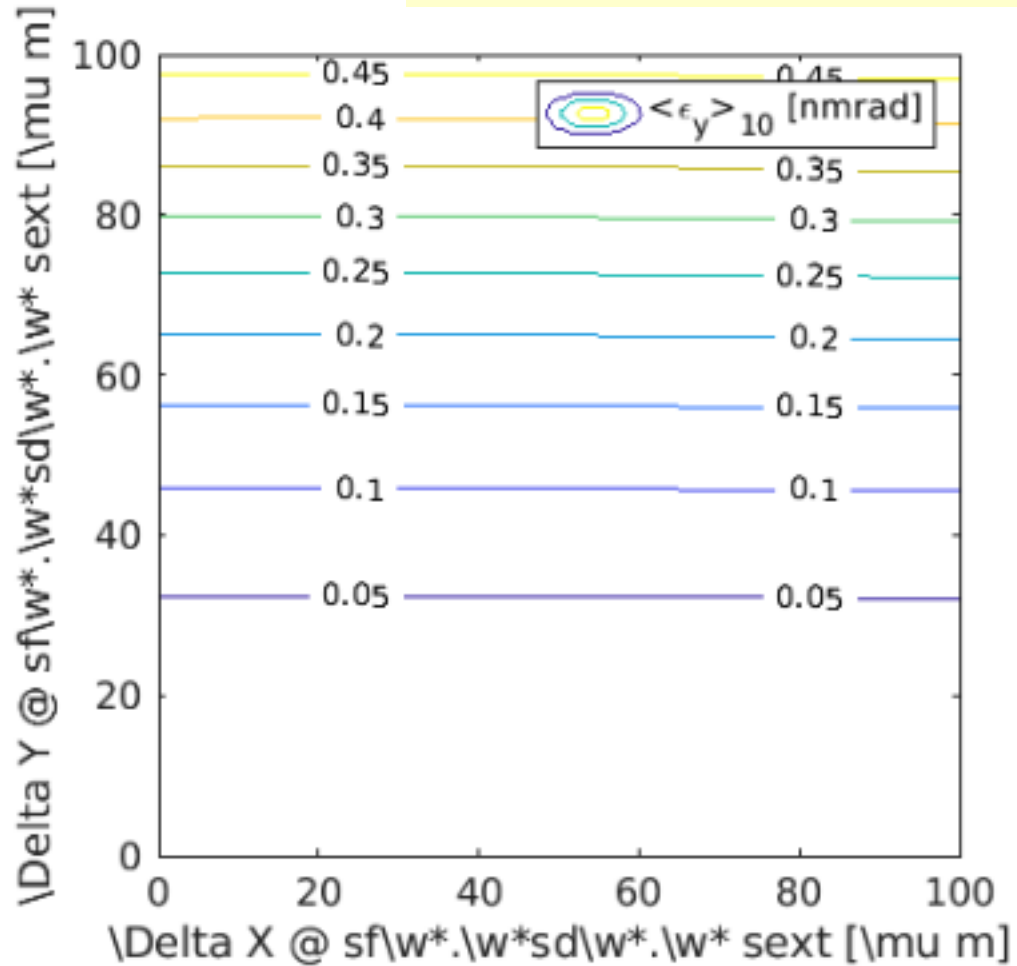
Baseline Z Optic



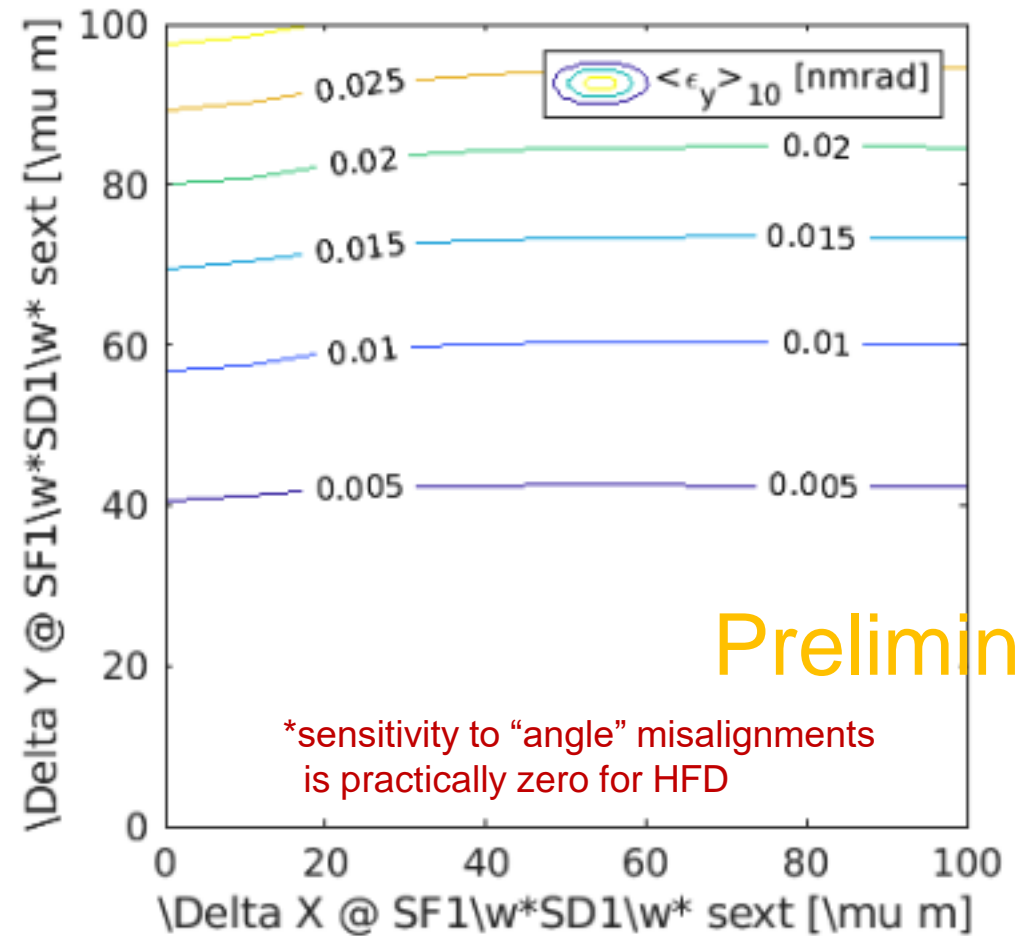
HFD Z Optic with FF Local Chromatic Correction

Preliminary

Achieving small vertical emittance is easier with lower sensitivity to errors



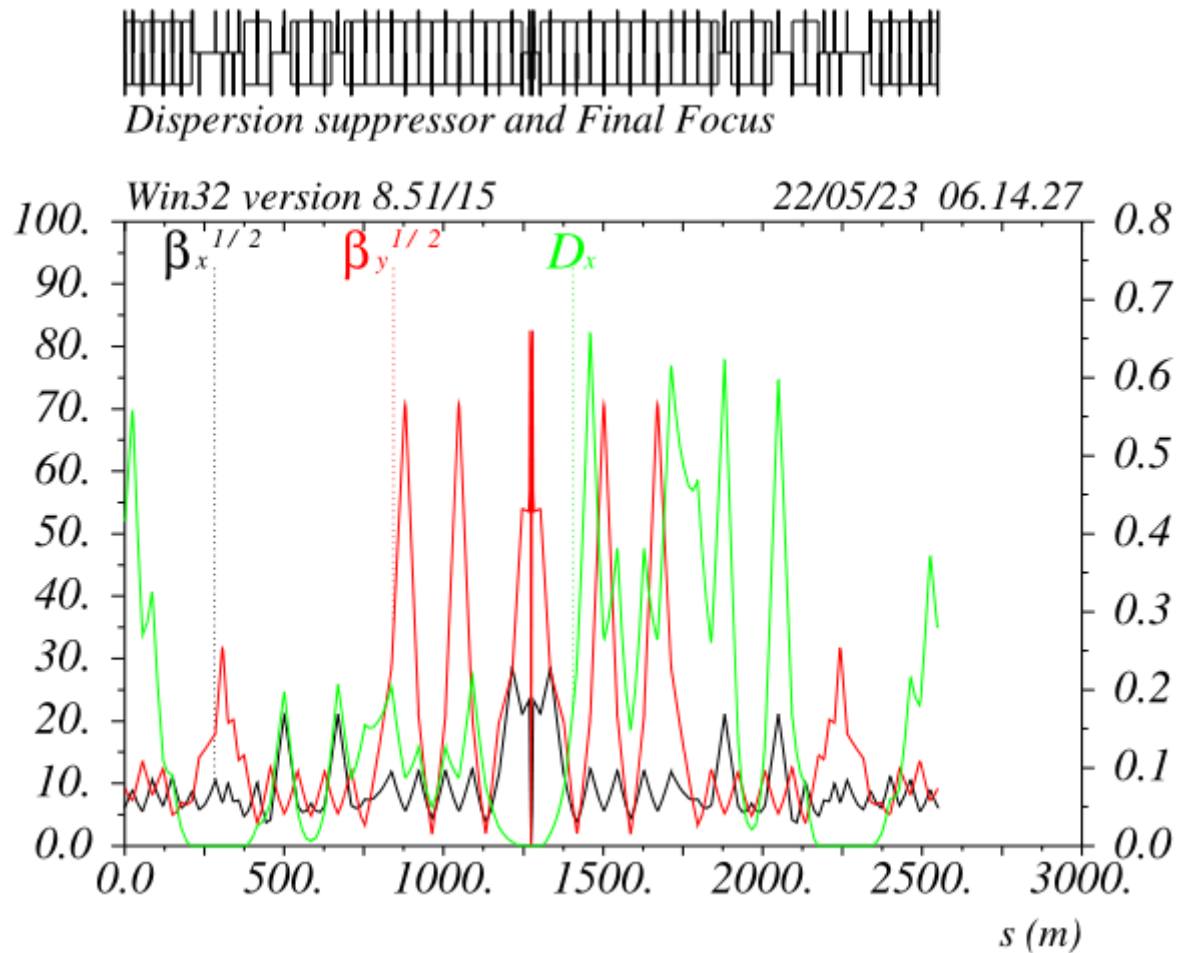
Baseline Z Optic



Preliminary

HFD Z Optic with Local Chromatic Correction

FF layout



Present layout is Left-Right symmetric

Dipoles have all the same (ARC) sign, on the left are ~ 3 times weaker wrt right to make up for the X-angle.

FF has a net bend angle of about 85mrad, this value is optimized based on the overall layout constraints

Last two arc dipole bending angles (~+/-10%) are used to match the layout and two rings separation.

Last two arcs sextupoles are also used (~20% max modulation) to compensate for the resulting high order dispersion asymmetry and the residual aberrations leaking outside the FF (mostly high order dispersion due to the dipole asymmetry)

Layout is being optimized based on SR handling requirement (see Kevin talk) as well

Full ring general parameters

Z lattice:

$E_x = 0.528\text{nm}$

$J_x = 1.00$

$\text{Alphac} = 2.37\text{e-}5$

$U_0 = 34.38\text{MeV}$

$\text{Sig_E} = 3.82\text{e-}4$

$\text{Betay}^* = 0.8\text{mm}$

$\text{Betax}^* = 0.15\text{m}$

ttbar lattice:

$E_x = 2.03\text{nm}$

$J_x = 1.00$

$\text{Alphac} = 0.901\text{e-}5$

$U_0 = 8.78\text{GeV}$

$\text{Sig_E} = 1.50\text{e-}3$

$\text{Betay}^* = 1.6\text{mm}$

$\text{Betax}^* = 1.0\text{m}$

Machine parameters consistent with baseline
for all modes

Z lattice:

$E_x = 0.343\text{nm}$

$J_x = 1.54$

$\text{Alphac} = 2.37\text{e-}5$

$U_0 = 33.06\text{MeV}$

$\text{Sig_E} = 4.29\text{e-}4$

$\text{Betay}^* = 0.8\text{mm}$

$\text{Betax}^* = 0.15\text{m}$

With offset quads

With HTS U_0 is further
reduced by ~3%

ttbar lattice:

$E_x = 2.03\text{nm}$

$J_x = 1.00$

$\text{Alphac} = 0.901\text{e-}5$

$U_0 = 8.46\text{GeV}$

$\text{Sig_E} = 1.45\text{e-}3$

$\text{Betay}^* = 1.6\text{mm}$

$\text{Betax}^* = 1.0\text{m}$

With offset quads

- ARC optic very linear, max number of cells primarily dominated by cost, power consumption and tolerances considerations.
- ARC local chromatic compensation is very beneficial in order to reach desired performances and reduce sensitivity to errors and drifts.
- FF is the most aberration free telescope up to date. It can be adopted for any (green field) circular collider. Since it has been optimized for $t\bar{t}$ operation, the Left-FF could be readily adopted for a medium energy Linear collider as well, and possibly for a TeV-scale LC with moderate lengthening
- The FF has been optimized to have the Crab-Sextupoles smallest possible impact on DA&MA

FF sextupoles effect on DA&MA and mismatch

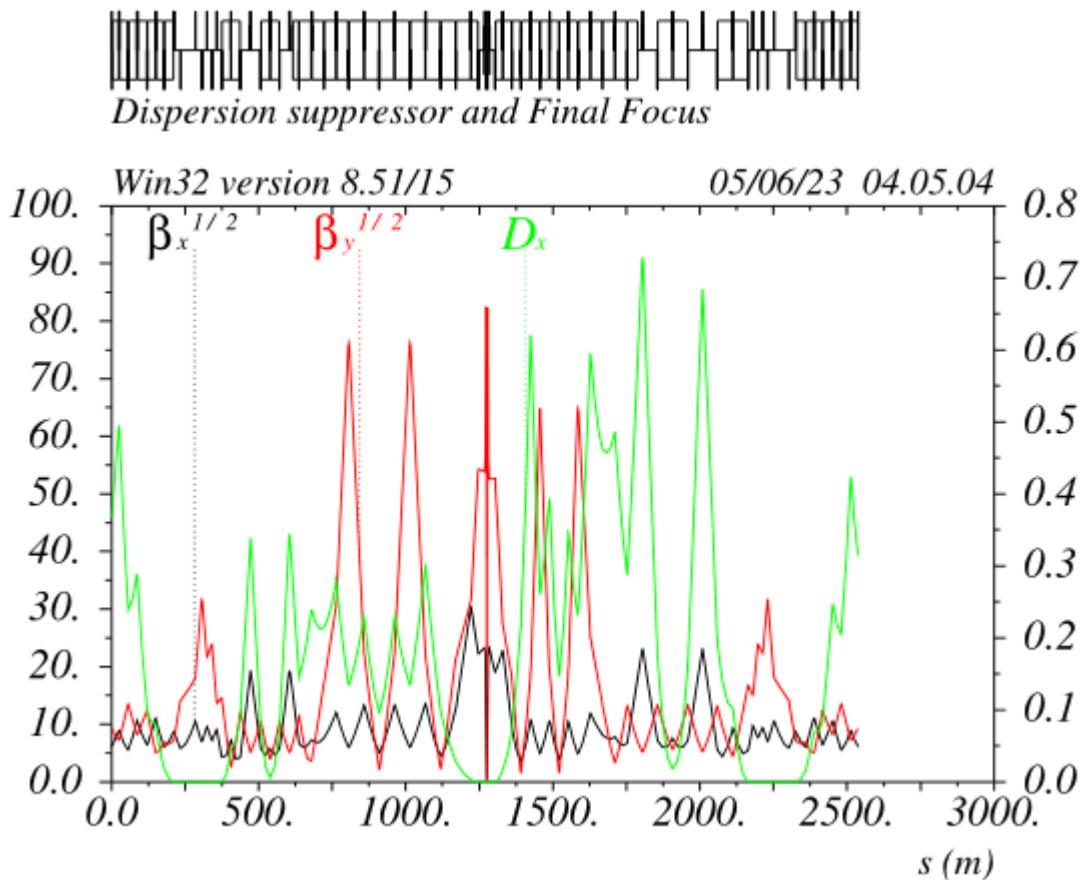
- FF sextupoles strength driven by the low-beta chromaticity (given)
- Bigger betas at sextupoles do reduce the sextupole strength but have little effect on error sensitivity
- Larger dispersion at sextupoles reduces their strength as well and consequently:
 - inversely decreases the waist shift (betatron mismatch) due to horizontal orbit error
 - inversely decreases the coupling due to vertical orbit error
 - inversely² (or more) decreases the residual non-linear geometric (and some chromatic) aberrations
 - the dispersion mismatch due to orbit errors is not affected

Larger dispersion is in general beneficial (if can be created without generating dispersion-related aberrations and keeping the SR in check)

LCCFF has in average higher SDs dispersion wrt to baseline, it should have correspondingly better sensitivities (to be checked).

Given the left-right dispersion ratio~3, the Left-FF SDs sensitivities dominate

FF asymmetric layout under study



An asymmetric layout (a-la-CEPC) is under study

Left: CCSx shorter, and stronger dipoles
CCSy longer, dipole field unchanged
Right: CCSy shorter, stronger dipoles
CCSx longer, weaker dipoles

It is possible to make the AsymmFF entrance-exit optically symmetric up to the:

- fifth order (chromatically)
- fourth order (geometrically)

Given the high degree of symmetry, this FF could work as well as the full symmetric one.

The layout shown has a 20% CCS length modulation. Performances seem very promising and will be further optimized and studied.

Conclusions

- HFD lattice has a very large DA&MA and very high filling ratio
- Transparency conditions allow the insertion of any kind of Straight Section with negligible impact on DA&MA
- LCCFF is a very powerful telescope with very efficient built-in compensation of high order aberrations
- Dipole filling ratio can be made asymptotically close to 1!
- HFD&LCCFF could ameliorate/alleviate many of the requirements on hardware and power consumption.
- Machine tuning and ramp-up time could benefit as well

Please refer to M.Hofer/D.Shatilov for detailed machine performances studies