# FCC lattice evolution

FCC tuning workshop

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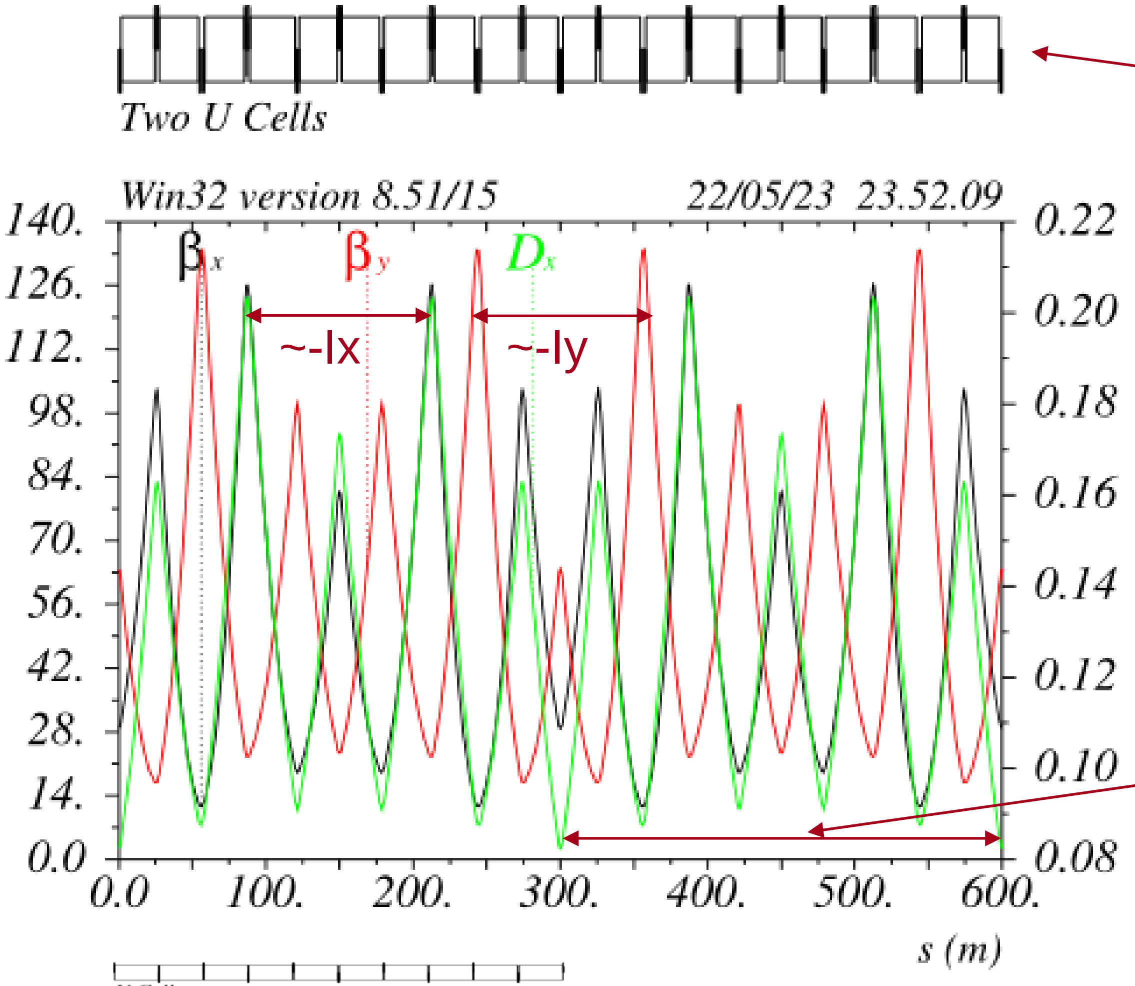
Office of Science

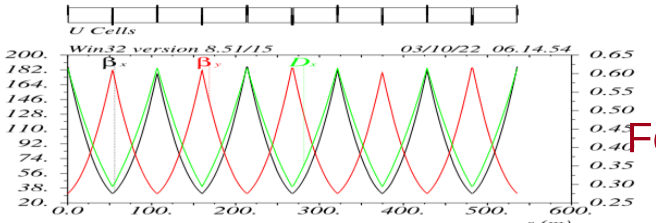
SLAC NATIONAL ACCELERATOR LABORATORY

# Outline

- HFD ARC lattice recap and work in progress
- Local chomatic compensation Final Focus recap and work in progress
- Action items

# Hybrid FoDo lattice: the evolution of the FODO9090 (ttbar case)




Fodo9090

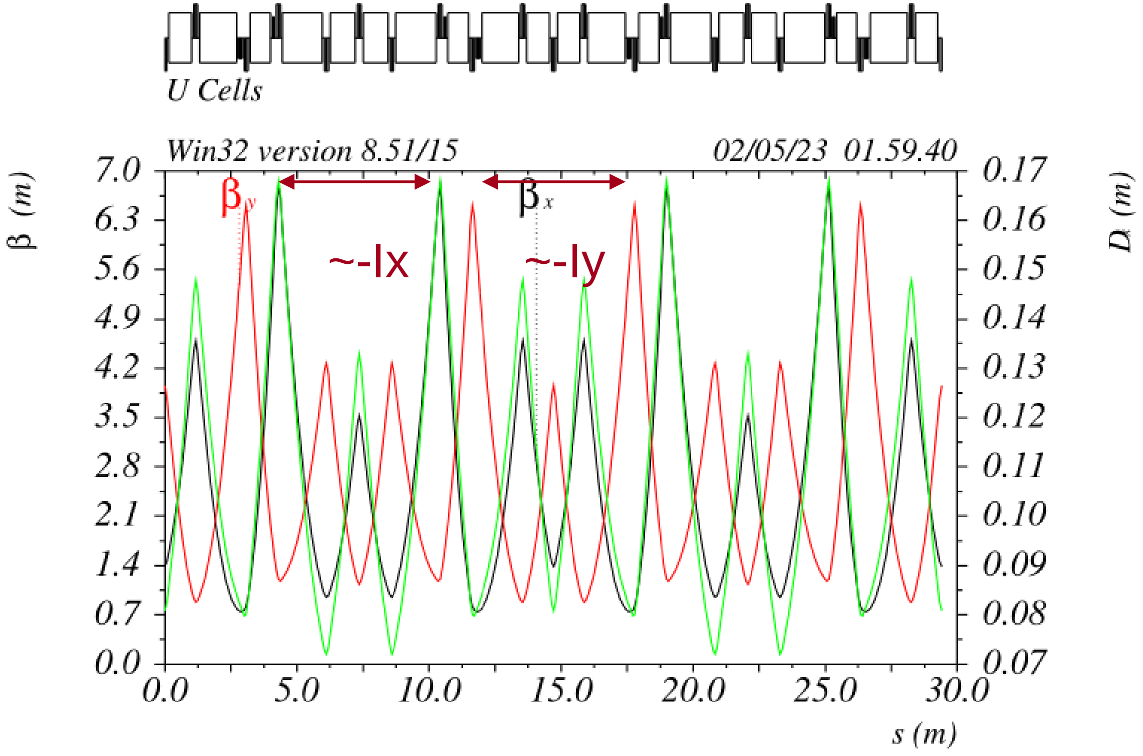
Two cells are displayed

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

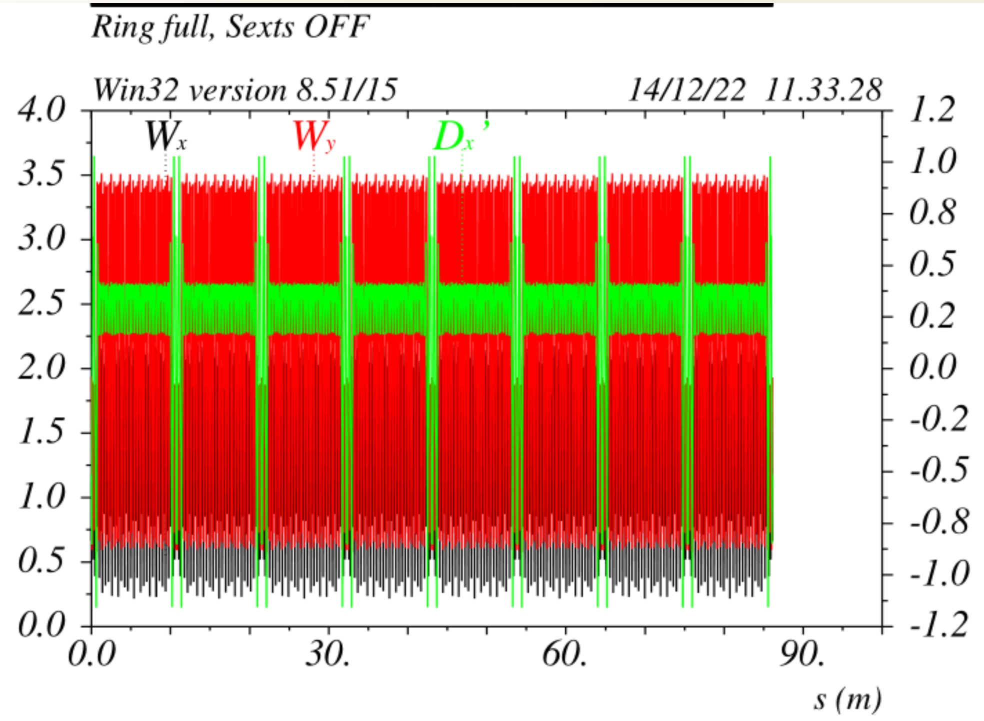
# HFD lattice matching routine

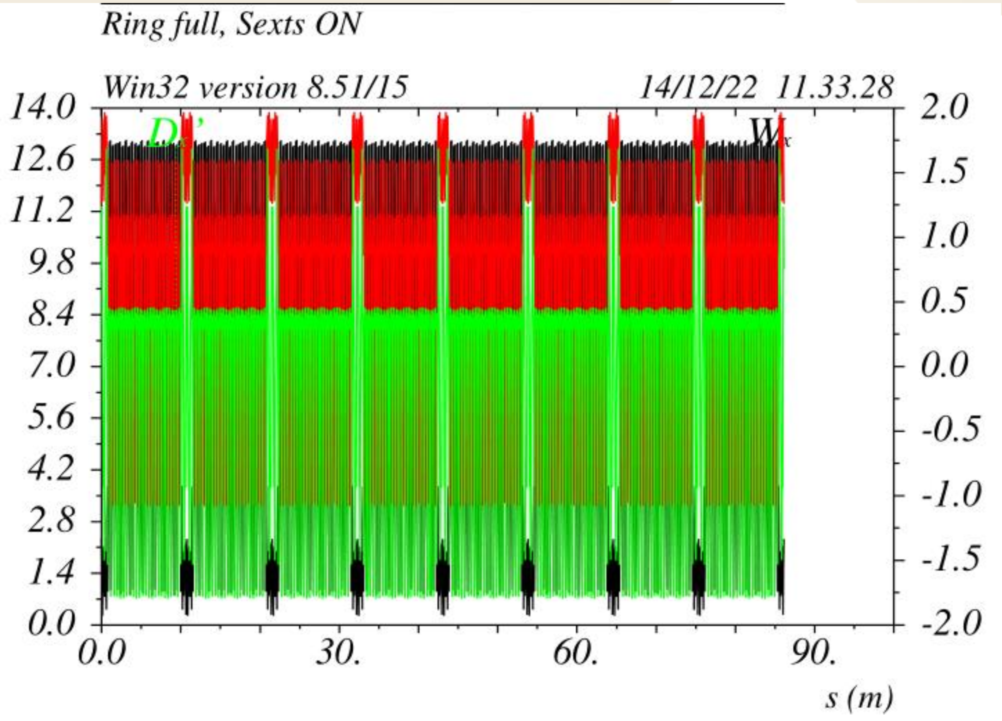



This routine generates a linear and second order achromatic lattice

```
CELL

  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
```

# 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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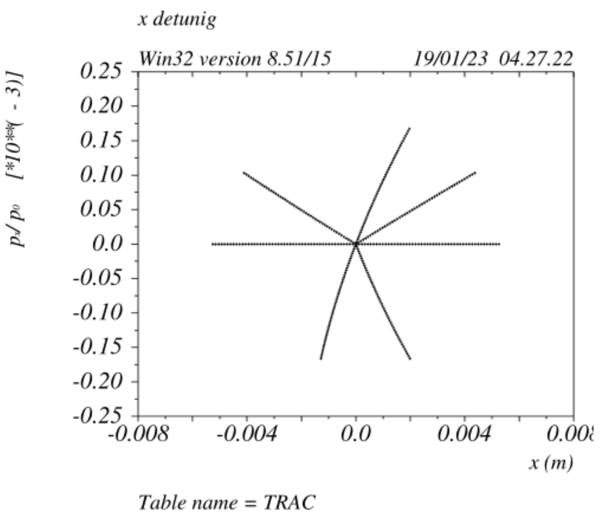
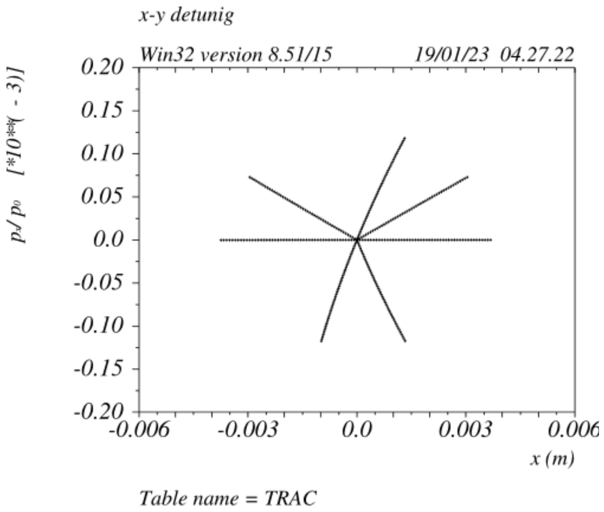
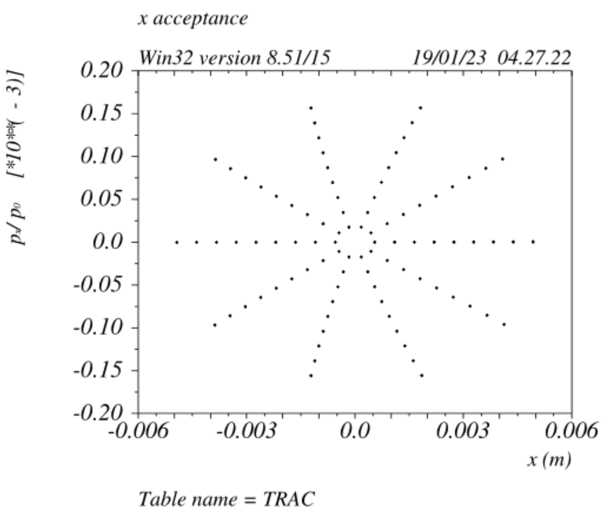
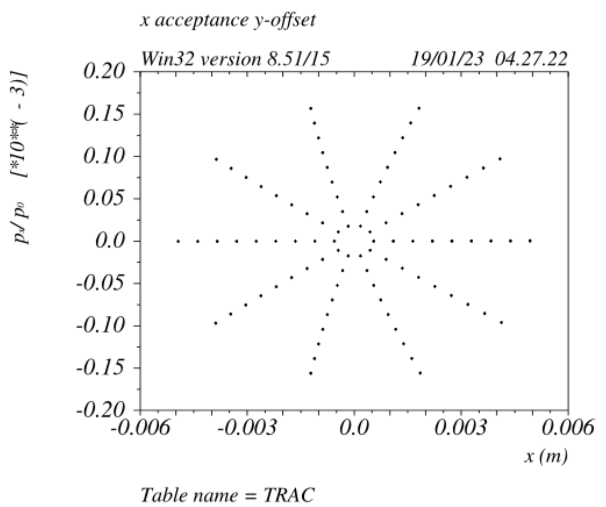
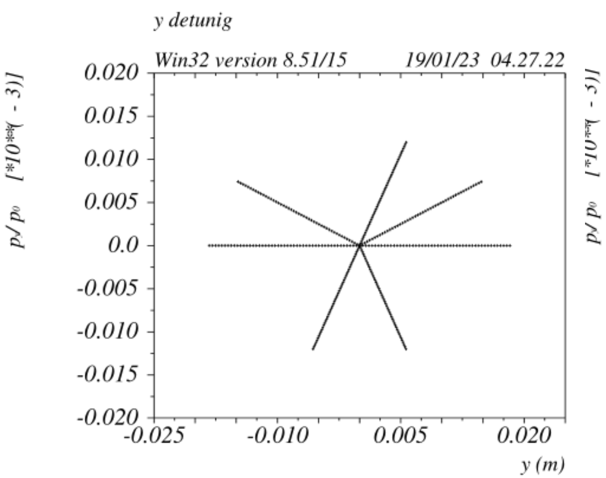


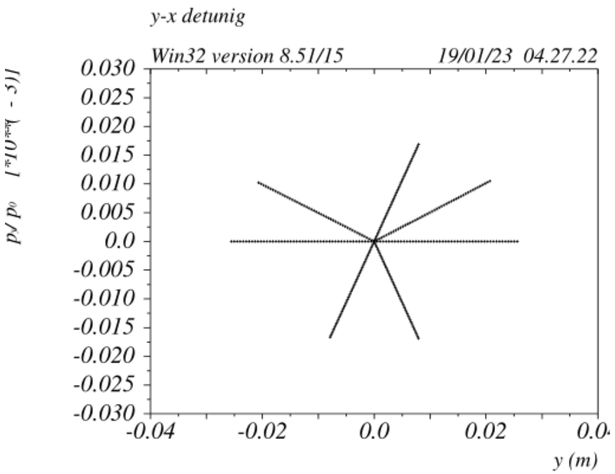



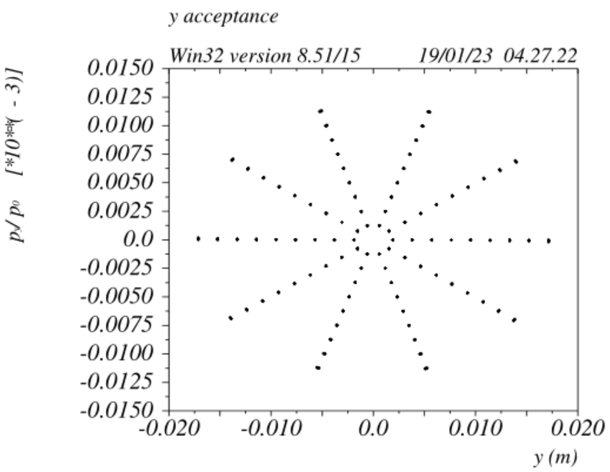



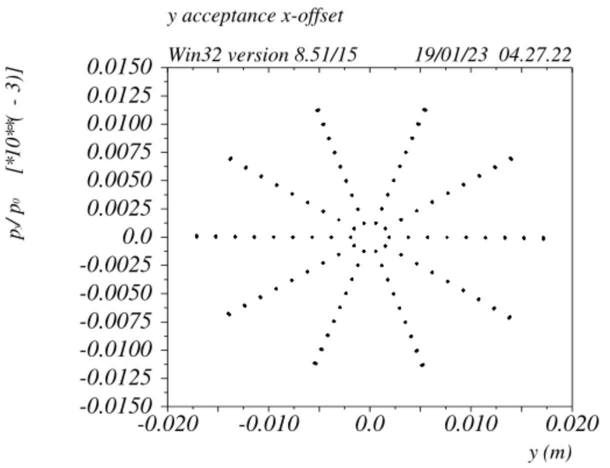




betax= 30m betay = 1450m (FF entrance, crab sext location)

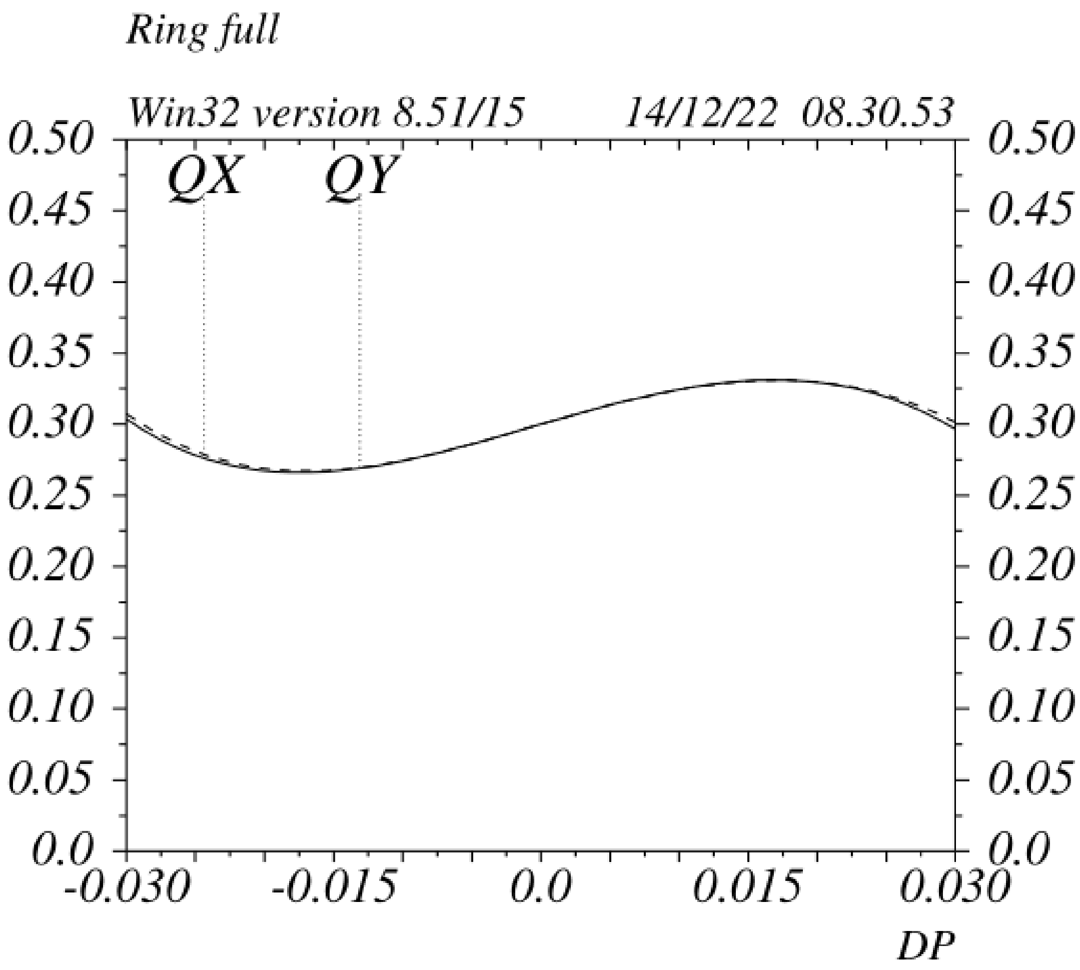


# HFD Energy Acceptance

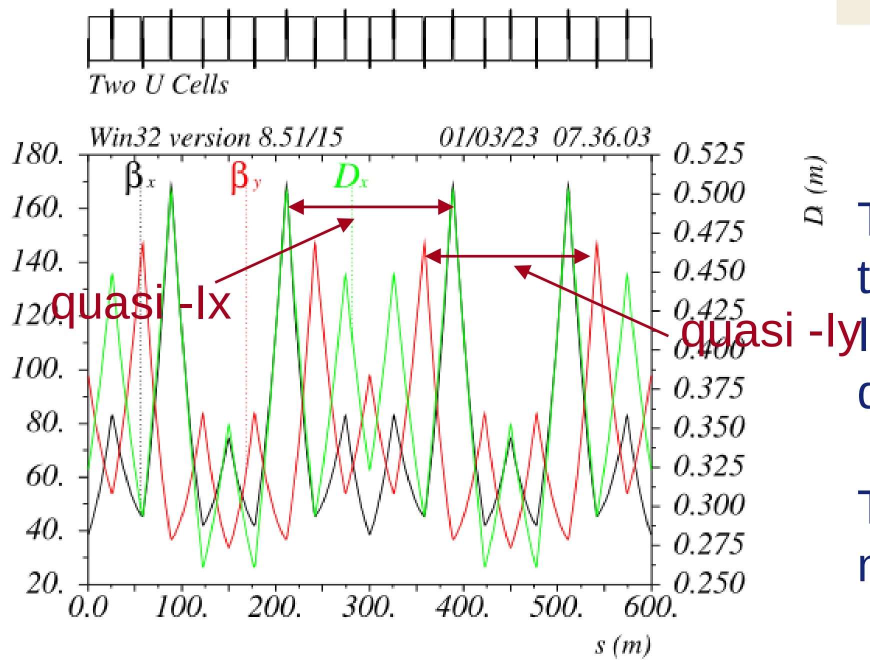


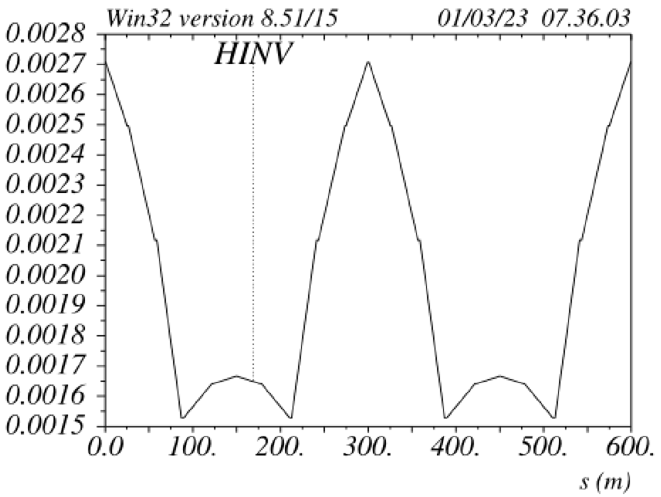

The ARC+LSS has zero second order chromaticity in both planes, only third and higher orders remain.

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

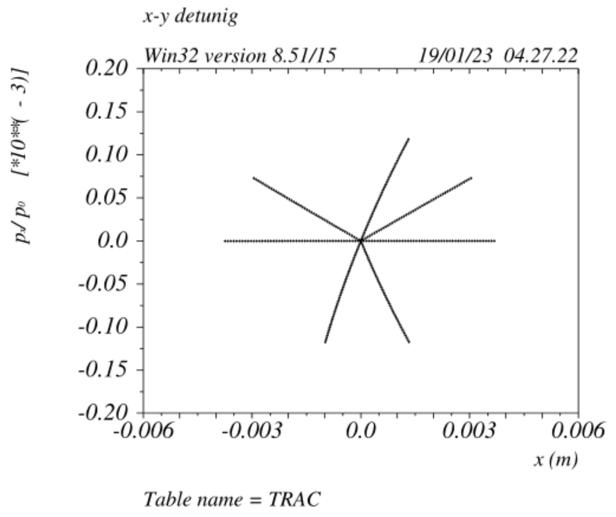
The cell has been optimized around:
mux_C = 1.235 muy_C = 1.251 (~45deg/plane between consecutive QFs)

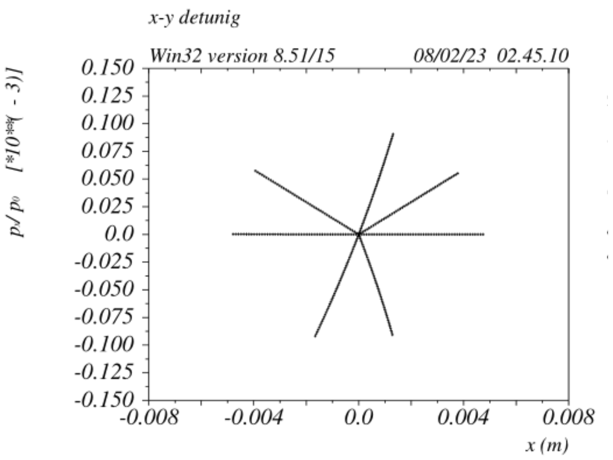
The matching routine is the one shown on the previous slide.

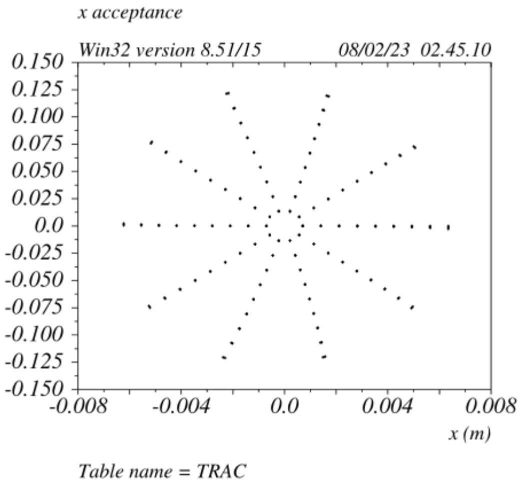
The sextupoles become very weak, Ks about 5 times weaker wrt to ttbar optics, no detuning is visible up to 100sigmas
The DA/MA is extremely large, possibly larger wrt to HFD9090
A small second order chromaticity remains to keep betax below 170m.

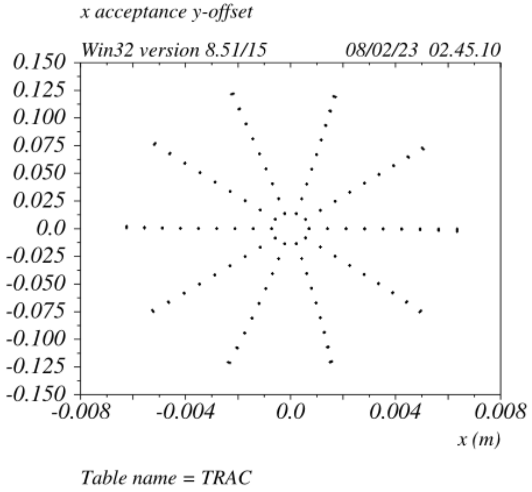
Natural chromaticity is much lower wrt LONG FODO9090

# Z ARCs dynamic properties v_51a1

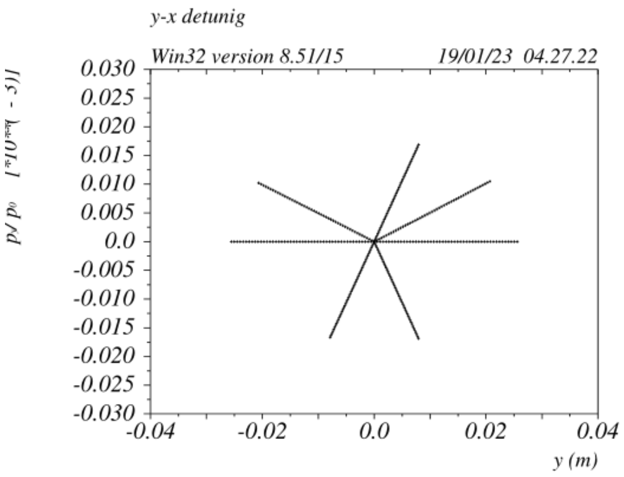


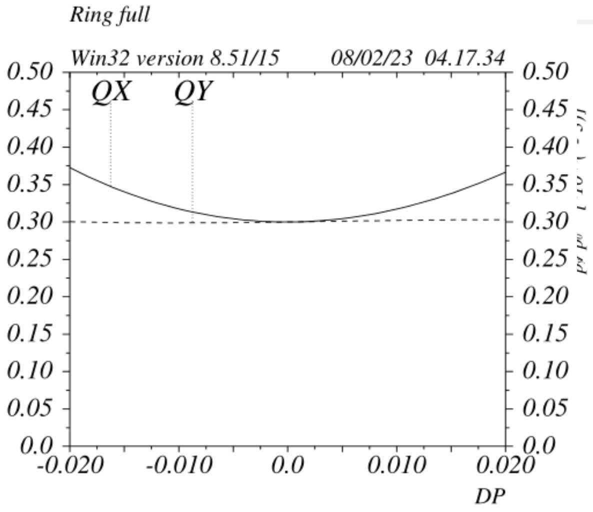



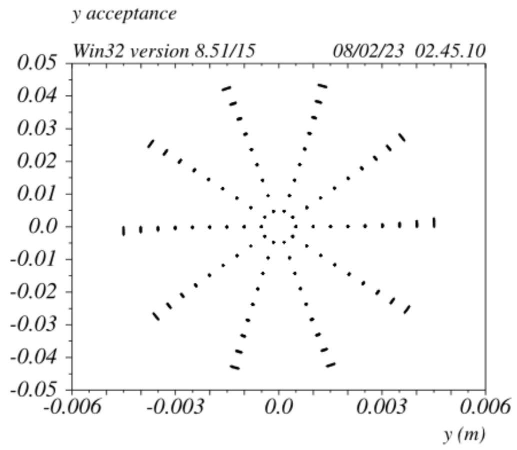



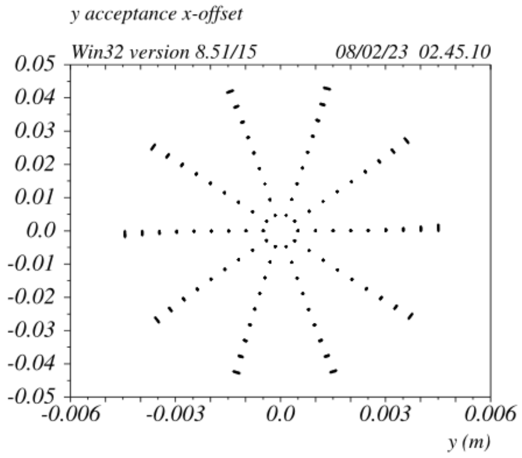




betax= 45m betay = 100m HFD4545 dynamic properties are comaparble to HFD9090

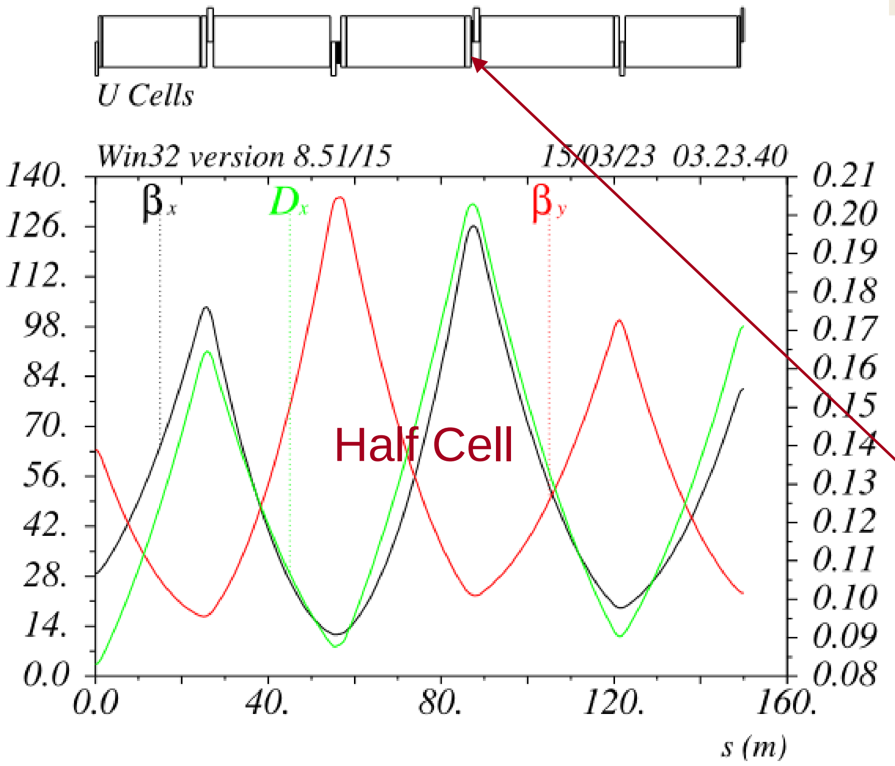


# ARC half cell layout




Optimal complement of corrector and bpms 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 Ks~0.146 @Z Ks~0.685 @ttbar

SDs are 0.77m long Ks~-0.125 Ks~-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

# HFD work in progress

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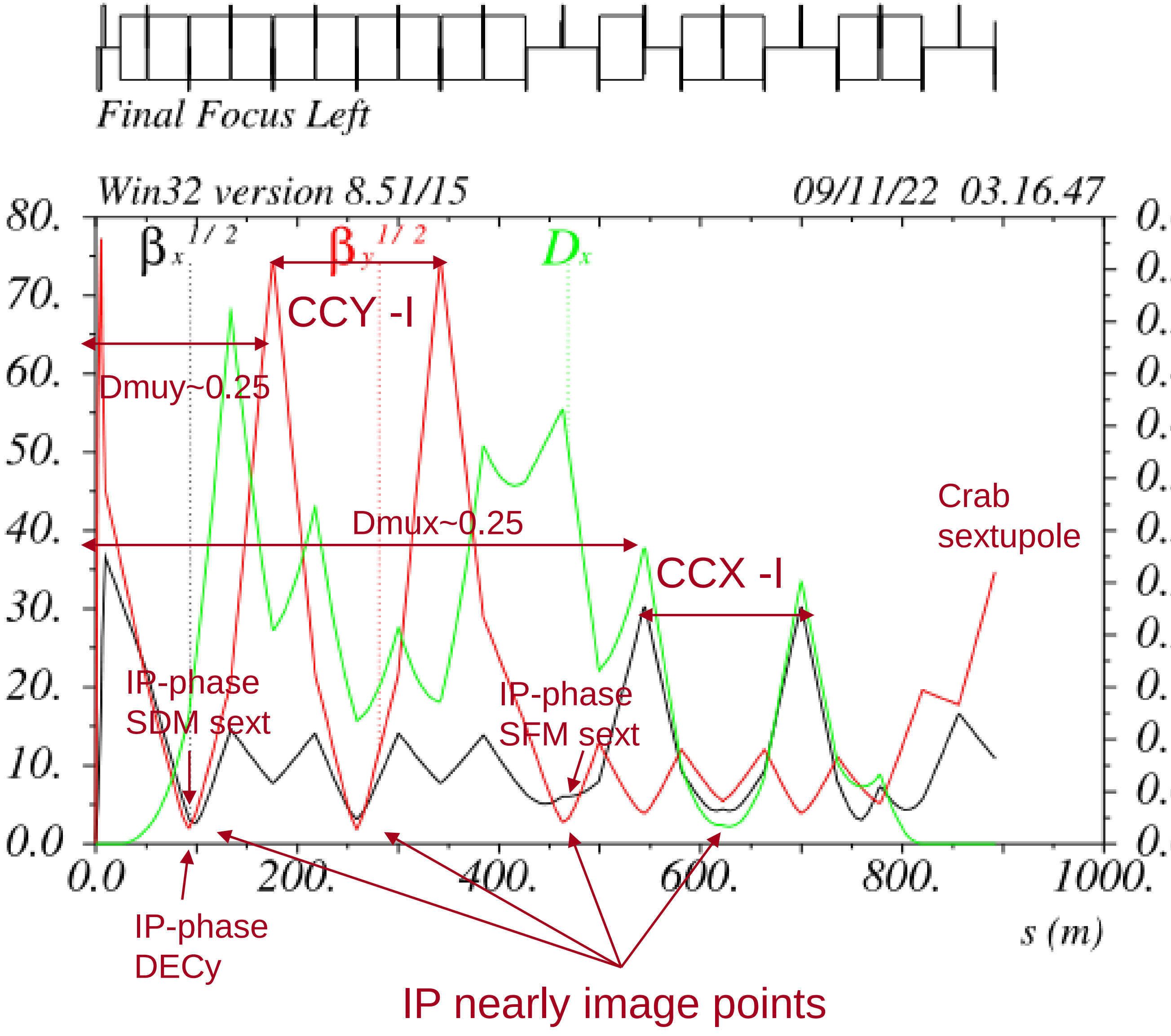
- HFD4545 (Z mode) is being reoptimized in order to improve emittance, alphac and Local Momentum Acceptance (by flattening curl-H)
- HFD9090 (high energy mode) is the ultimate? T Raubenheimer suggested to investigate the possibility of lowering the vertical tune as much as possible using the HDF matching, that seems to be able to generate anharmoninc and second oreder chromatic corrected lattices for a wide range of phase advances. A much lower vertical tune could further reduce the integrated quadrupoles and sextupole gradients => lower cost/power consumption and possibly better performances
- Full characterization of lattice and tuning is under study by M Hofer and S Liuzzo.

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

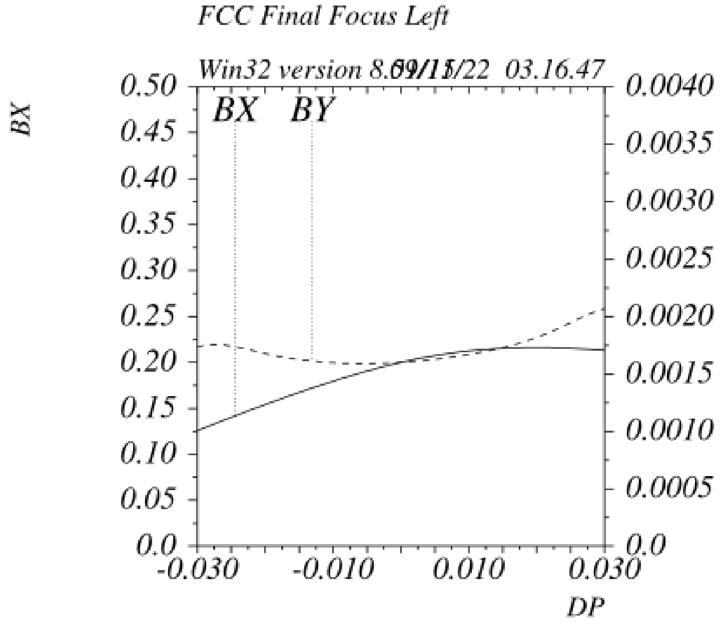


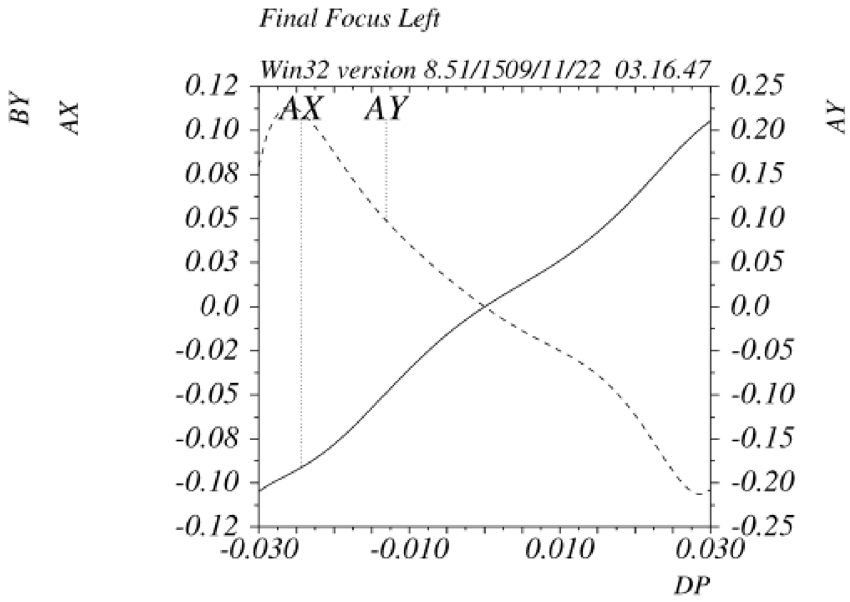

The FF system has built 5 tuning knobs that make it a quasi-fifth order achromat and produce very little detuning

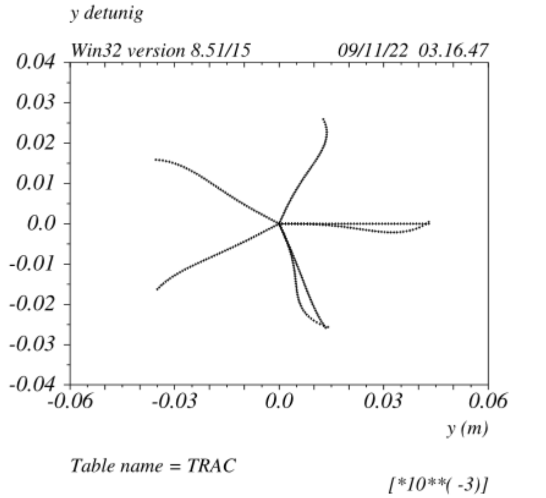
1) Main Sextupoles SDy and SFx
2) SDy&SDx phase advance wrt IP
3) IP-phase sextupoles SDM and SFM
4) Etaxp@ CCSY and CCSX
5) Decapole y (&x)
(for chomaticity)

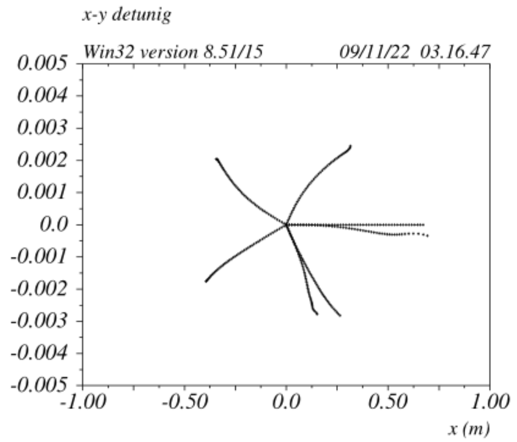
6) Phase advance between –I sextupole pairs
(for detuning)

# Final Focus with up to Fifth Order Chromatic Correction v_23c



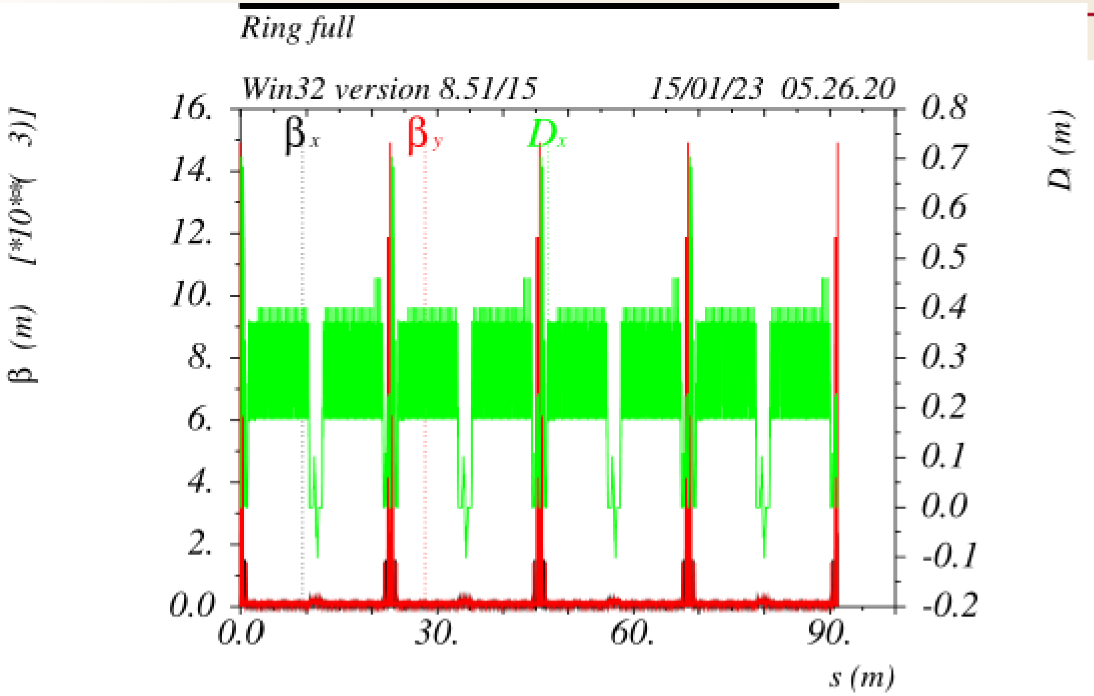



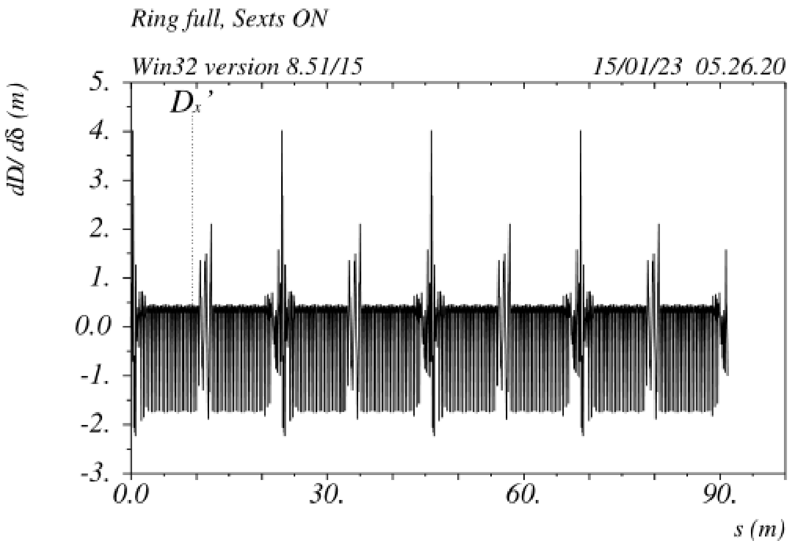



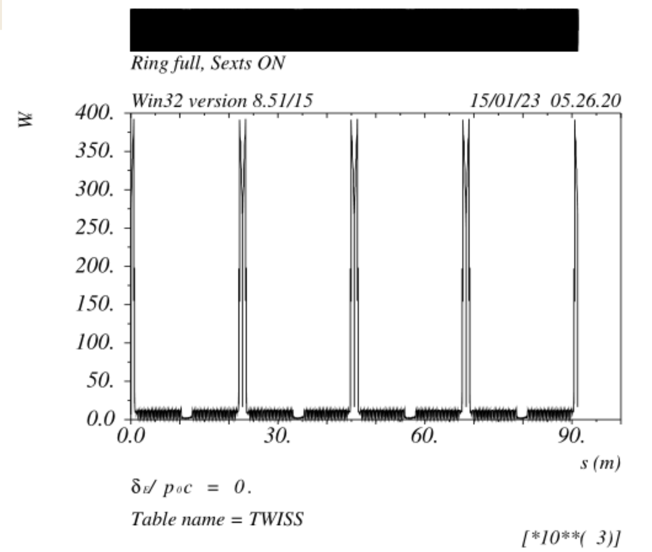



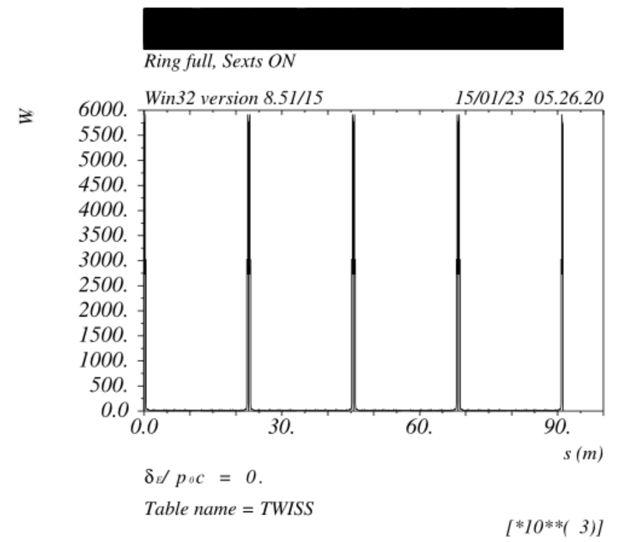

The Final Focus can be made linear very effectively, by local compensating or not creating high order aberrations. ~95% of the job is done with optimized linear matching and 3 sextupoles/plane

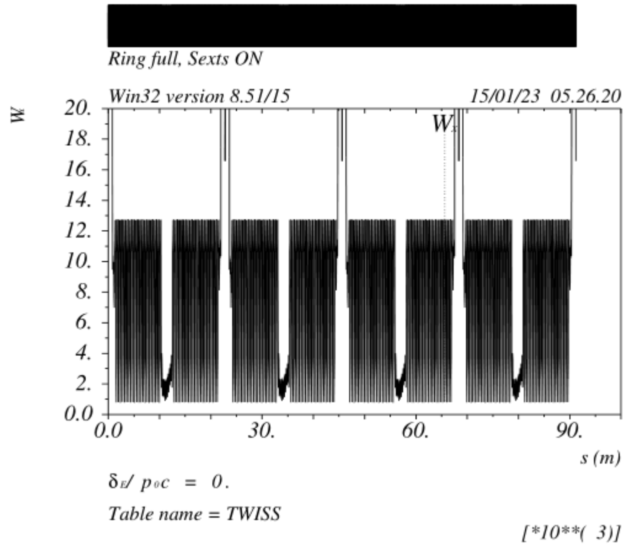
# Final Focus and Long Straight section are “transparently” inserted

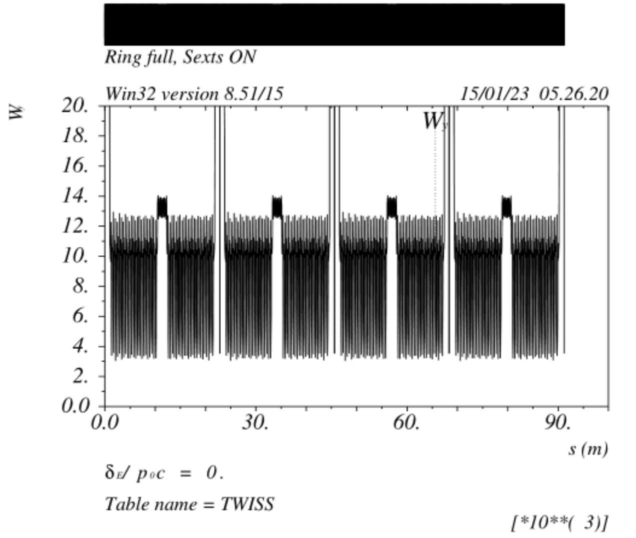


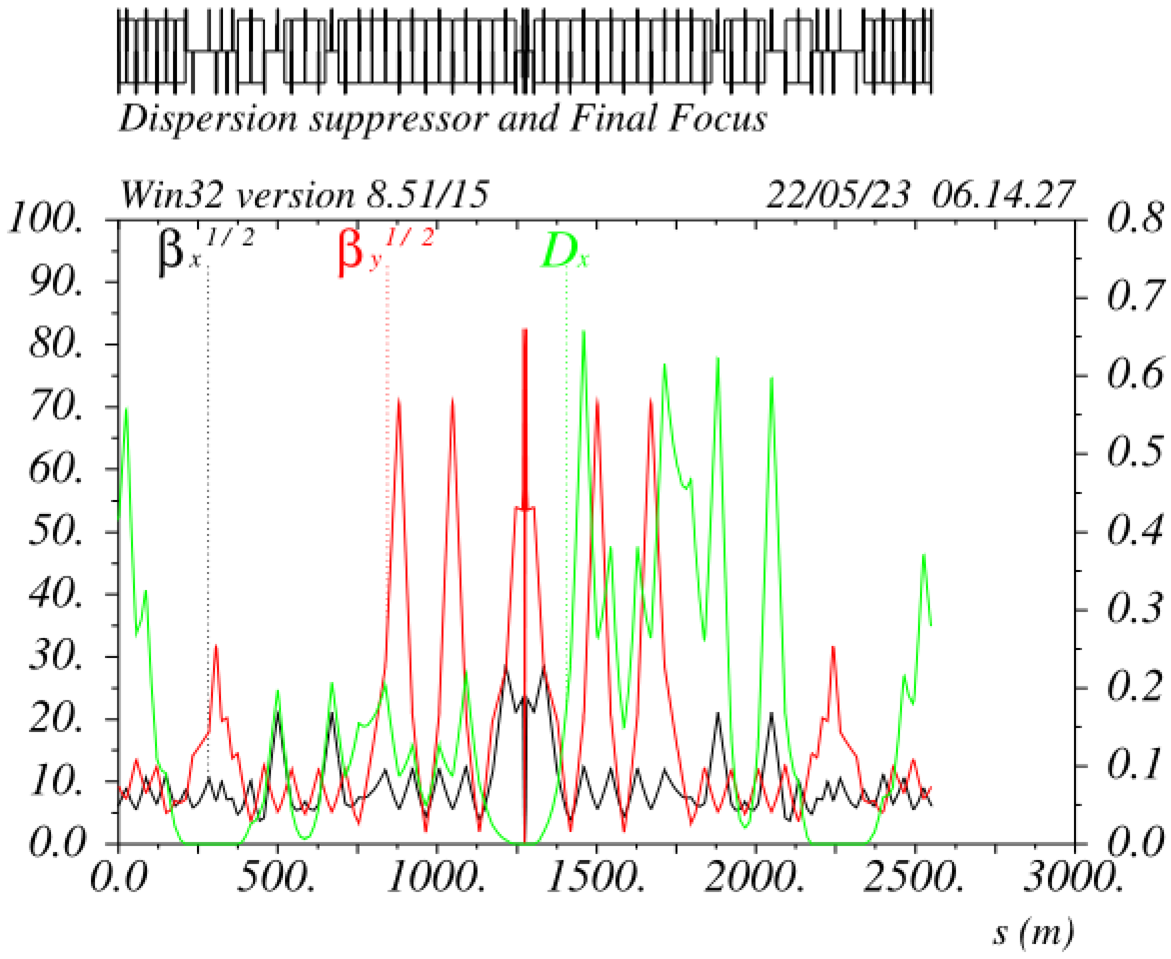



# FF layout v_61a (Z mode)




V_61a 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 optimzed 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)

Dipoles complement is optimized based on SR requirement

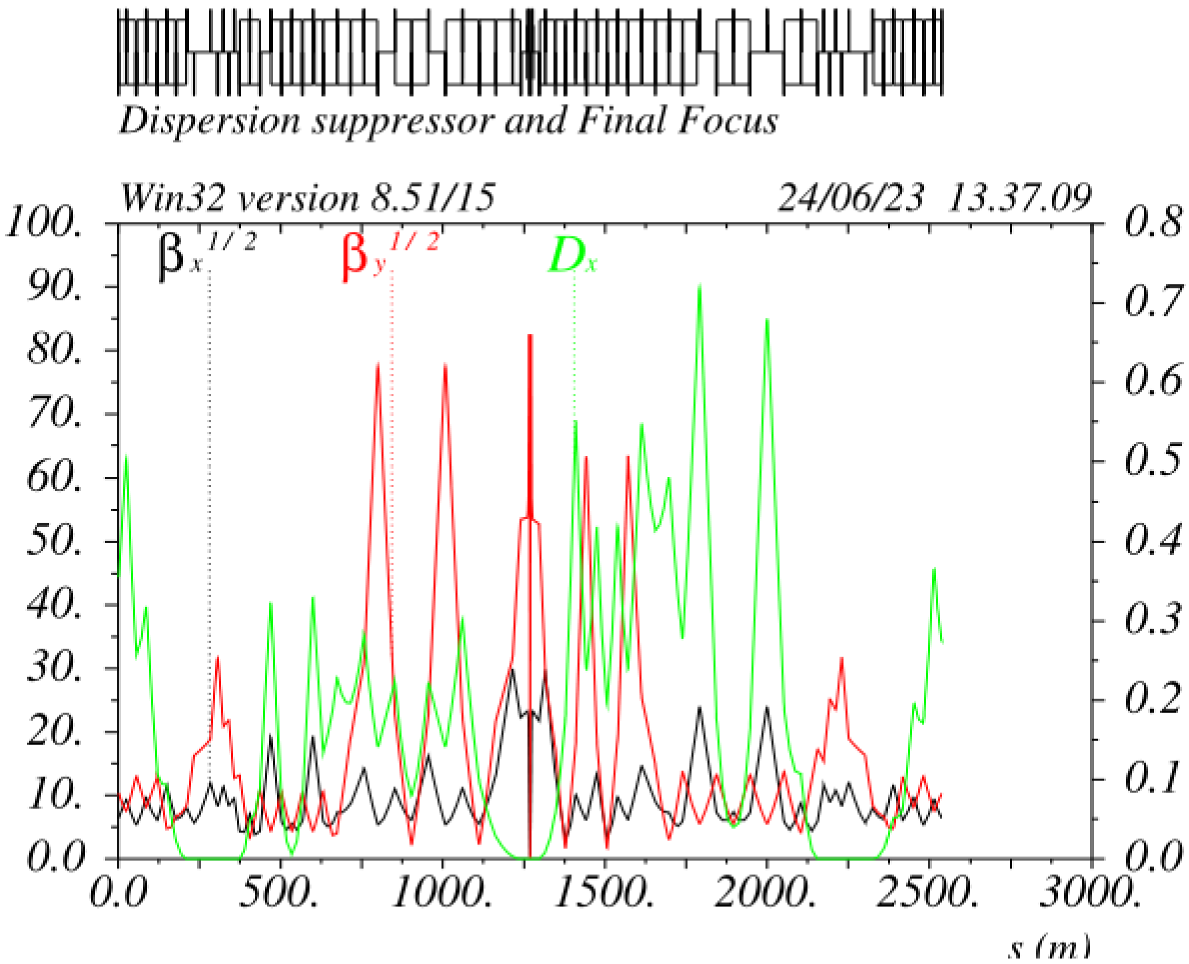
# FF sextupoles effect on DA&MA and mismatch

- 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 consequentely:
  - inversely decreases the waist shift (betatron mismatch) due to horizontal orbit error
  - inversely decreases the coupling due to vertical orbit error
  - inversely^2 (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)

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

# FF asymmetric layout under study



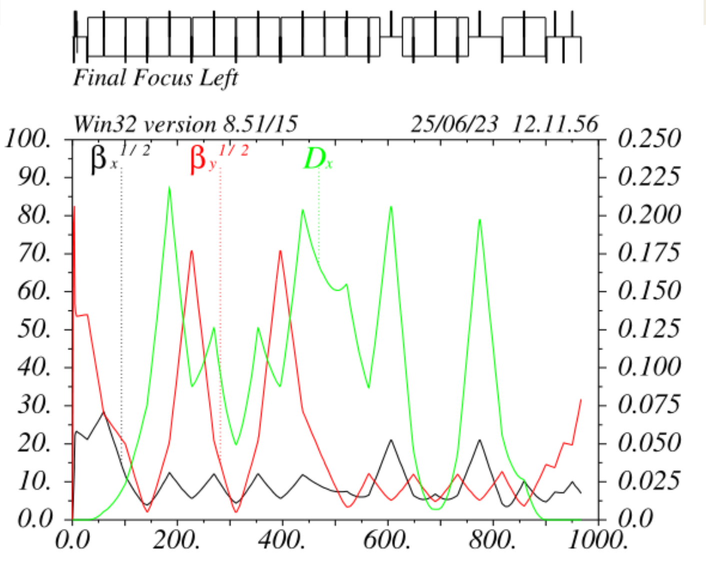

An asymmetric layout (a-la-CEPC/FCC_baseline) is under study

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

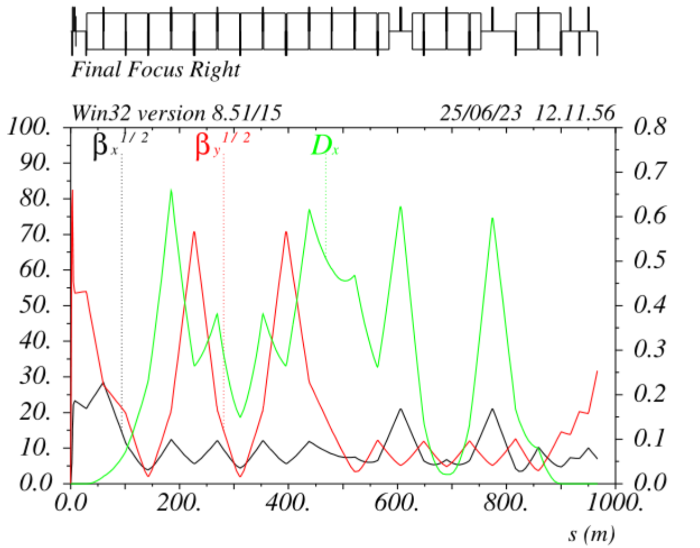
It is possible to make the whole AsymmFF entrance-exit optically symmetric up to the:
- fifth order (chromatically)
- fourth order (geometrically)

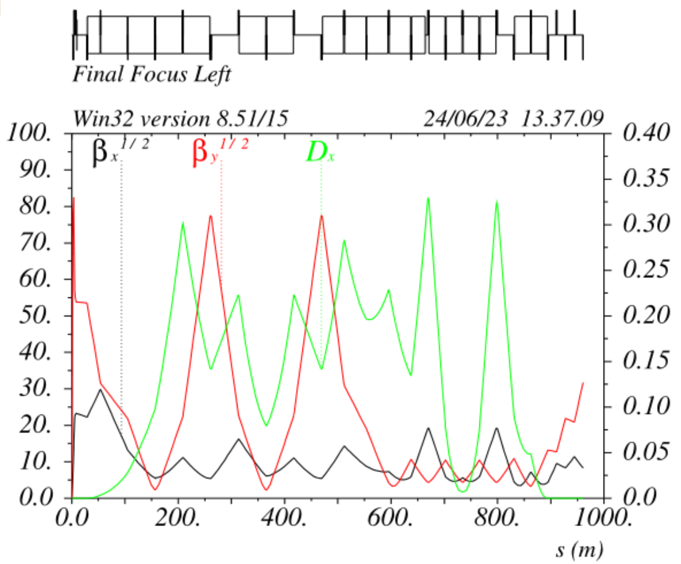
The layout shown has a +-25% CCS length modulation.

# FF asymmetric layout under study v_65a

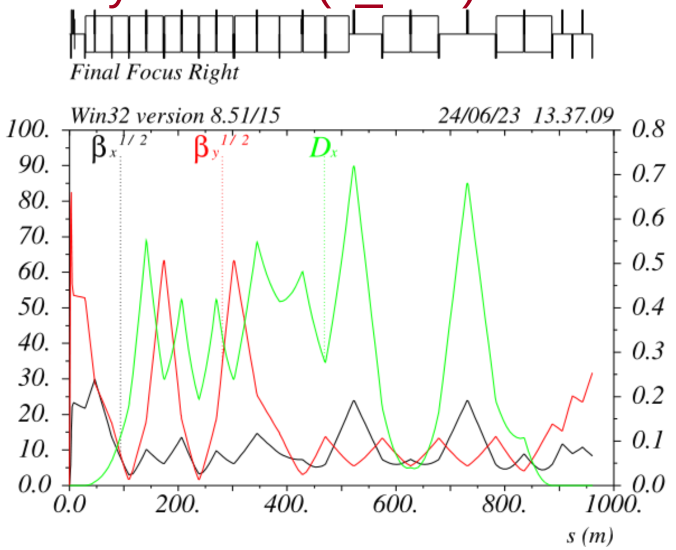



Symmetric (v_61a)




Asymmetric (v_65a)



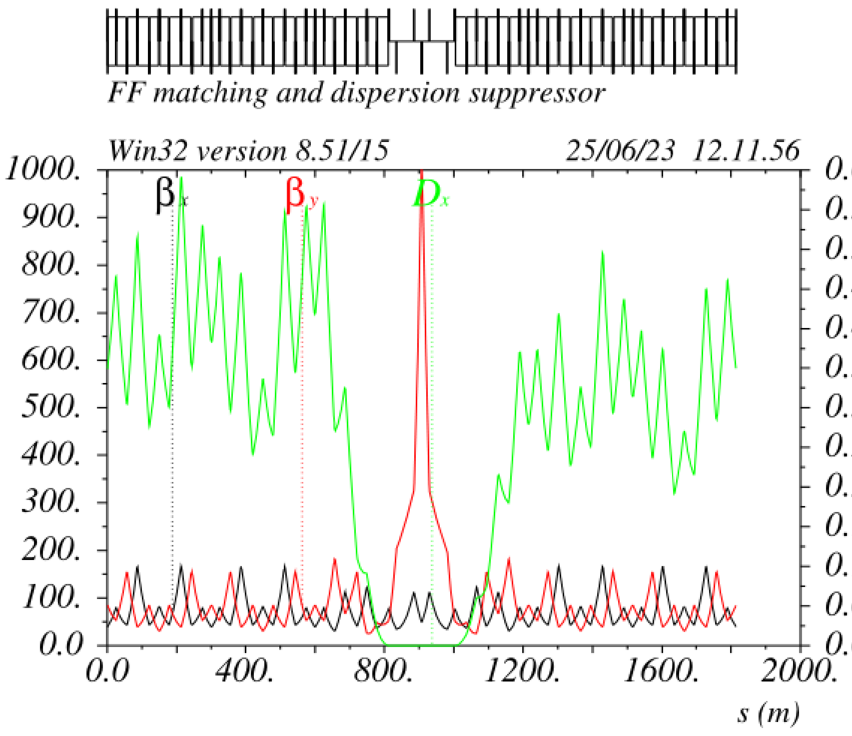

FFL Y-sextupoles are 2 times weaker (K2Ls very similar on both FF sides) because 65% larger dispersion and 25% larger betay
Tolerances should be relaxed accordingly

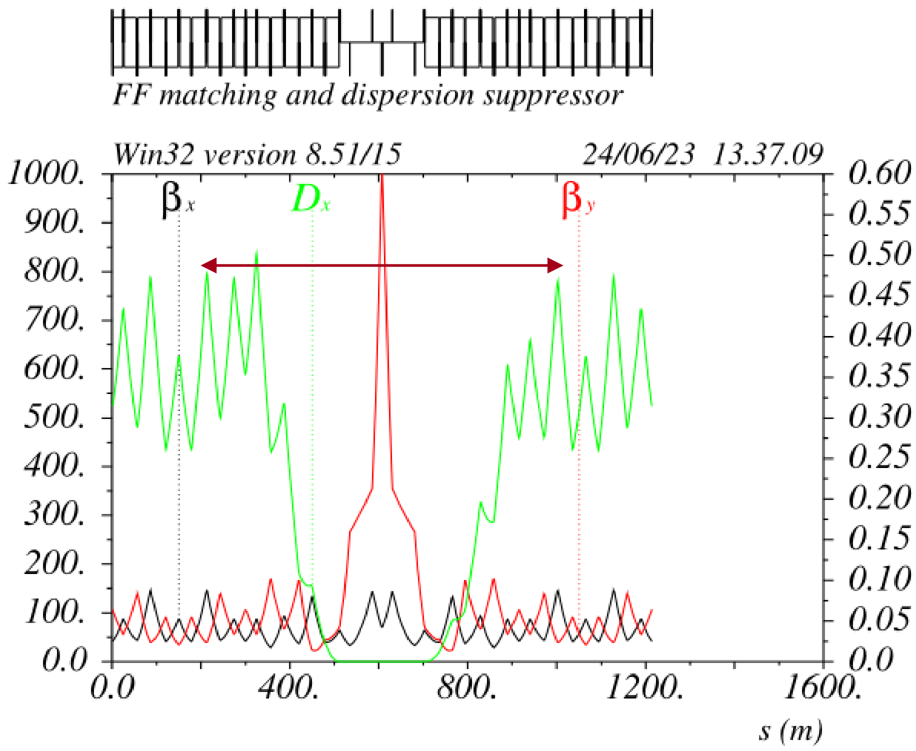
FFL decapole is 3 times weaker as well

In general all sextupoles are weaker and more left-right symmetric

DA/MA with tracking seems larger

# ARC dipoles umbalance for layout recovery v_65a



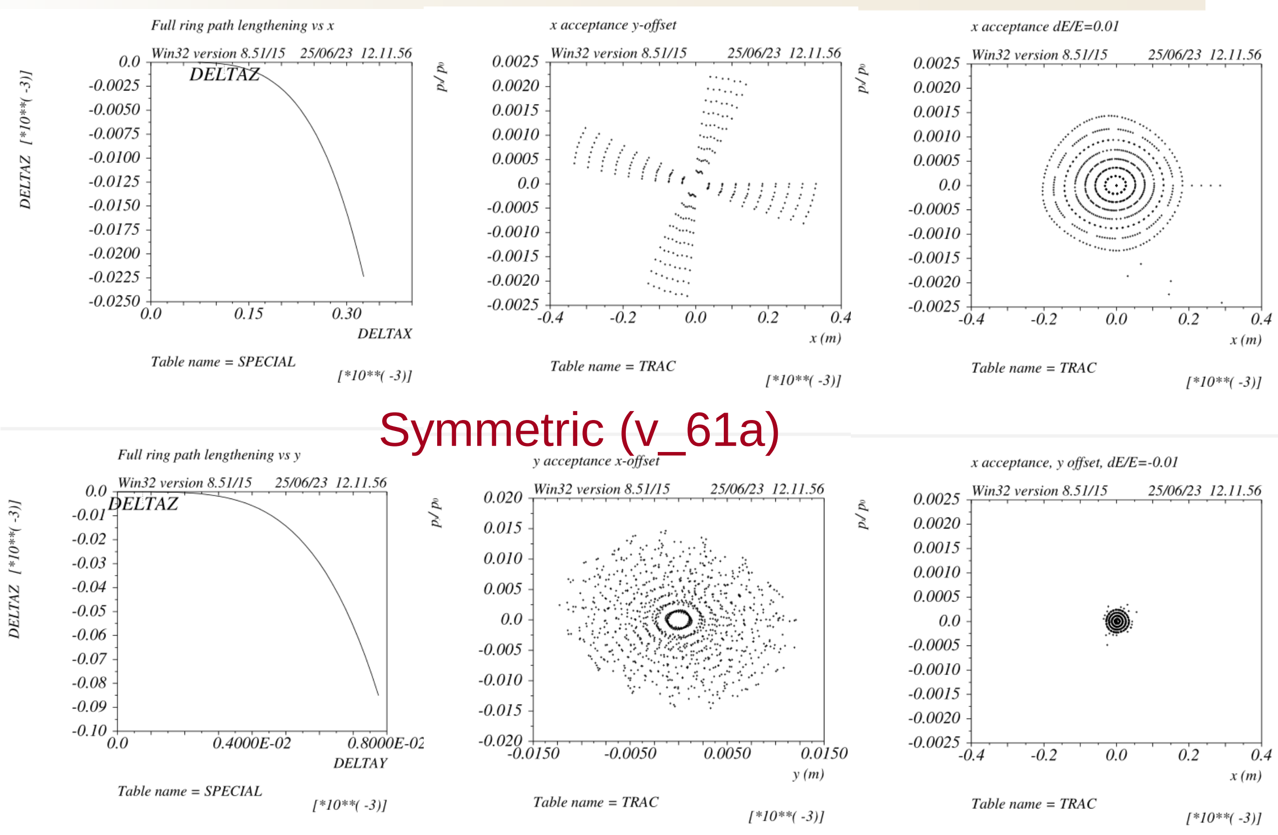

Symmetric (v_61a)

Asymmetric (v_65a)

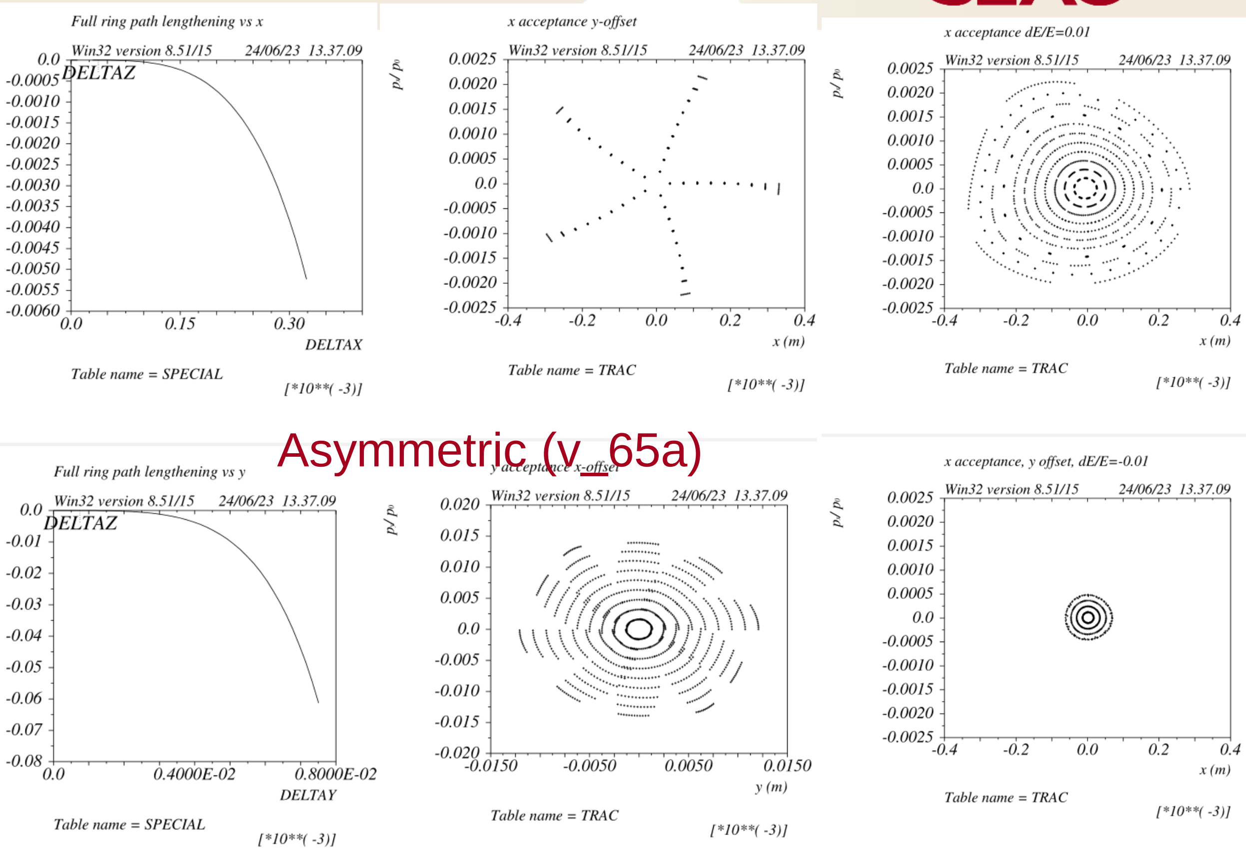
For the symmetric case the last 800m of the ARC dipoles are rescaled (~+/-10%)

For the asymmetric case only the last 250m of the ARC dipoles are rescaled (~+/-10%)

# Beam dynamics




Symmetric (v_61a)

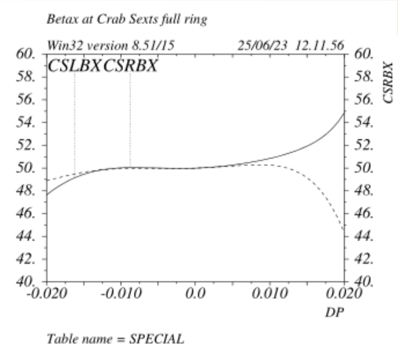


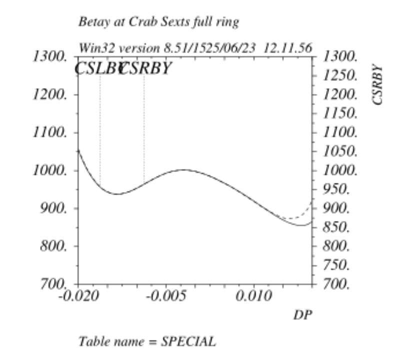

Asymmetric (v_65a)

Lower path lengthening vs amplitude reduces the DA shrinking from 4D to 6D
Transverse linearity is improved, now tracking is completely linear for offset beam as well
Off momentum transverse DA almost doubled, this also should reduce the 4D to 6D DA shrinkage

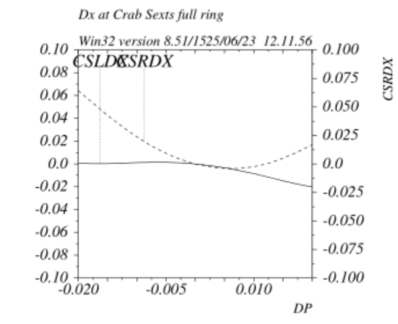
*Off momentum tracking shown is done with mad8, not accurate for high chromaticity rings

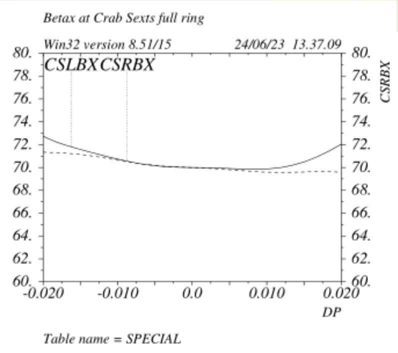
# Crab sextupoles

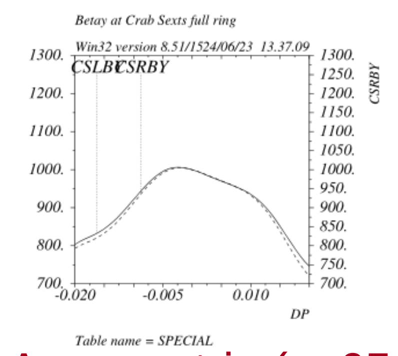


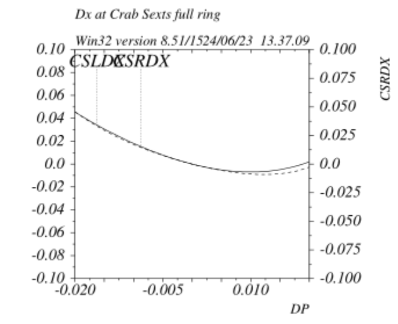

Symmetric (v_61a)




Asymmetric (v_65a)

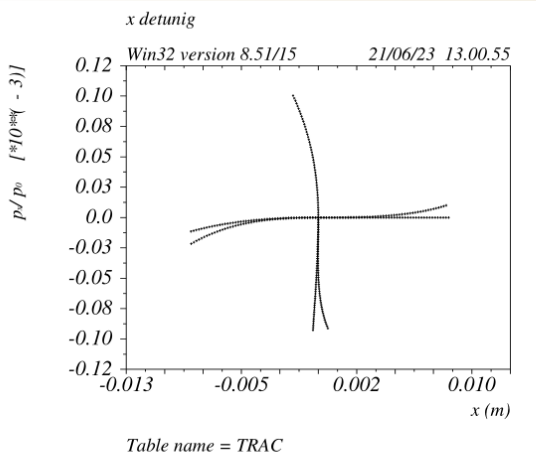


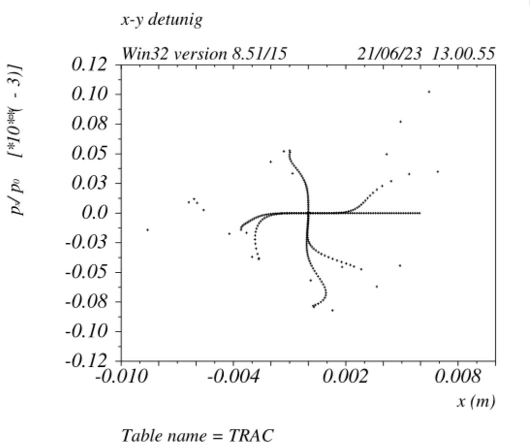

In order to reduce the impact of CS on BW, betas have to be as constant as possible.
High order dispersion should be small and equal on the two CSs.
For v_65a there is no change in the BW for CS on/off

(v_61a dynamic betay is flatter because the last two arc sextupoles optimization)

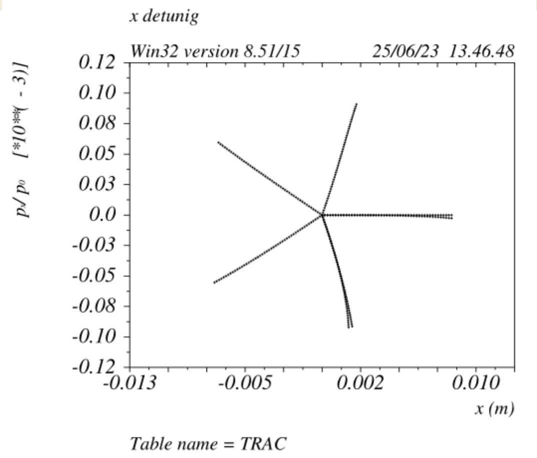
Higher betax@CS might be beneficial to reduce sensitivities

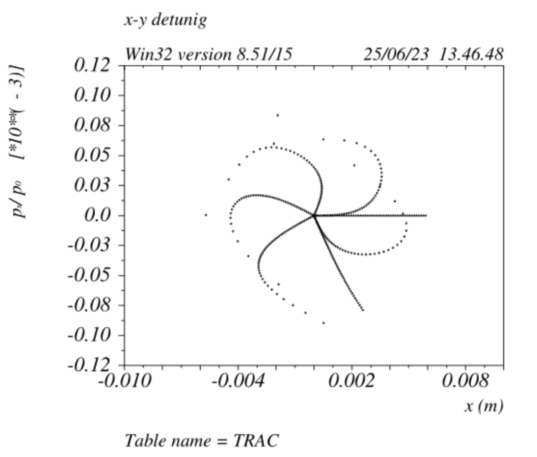
# Detuning from Crab sextupoles



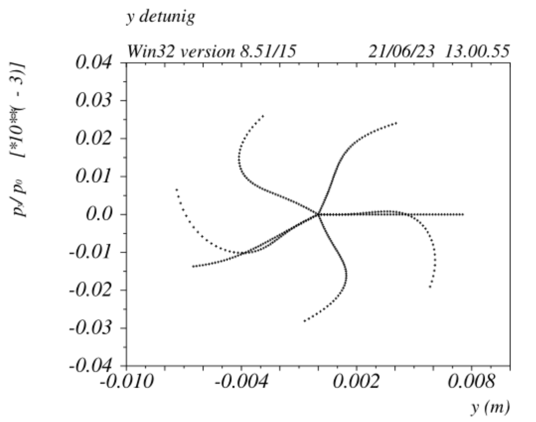



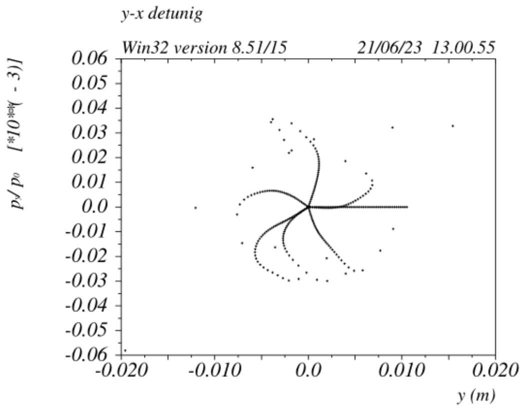

Symmetric (v_61a)

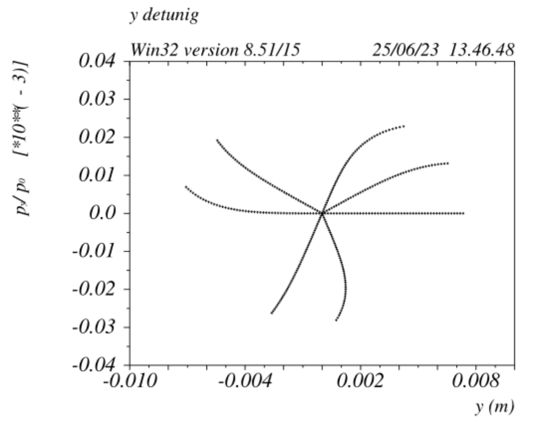


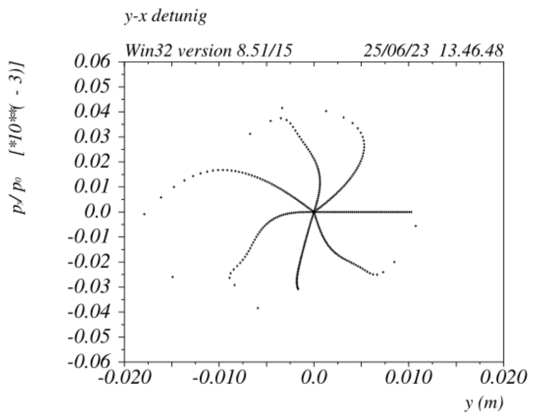




Asymmetric (v_65a)




Detuning from crab sextupoles further reduced.

X-Y detuning (v_65a) almost entirely due to IP_phase_SFs, it might be further improved

DA shrinkage due to CS is reduced as well

# Action items

- Furter improve HFD ARC lattice (in particular explore low y-tune for ttbar)
- Further improve FF lattice, in particular optimize FF-Right dipoles profile
- Further characterize lattice performances and benchmark different versions

  (M Hofer S Liuzzo)
- Study tuning procedures optimized for HFD/LCCFF (S Liuzzo)
- Perform 6D-DA optimization by using the last two ARC sextupoles + FF sextupoles (S White)