ARC and Long Straight Sections beam dynamics studies

December 7th,2022

Pantaleo Raimondi

SLAC National Accelerator Laboratory

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Premise

This work has been triggered by M Benedikt and F Zimmermann, they did ask me to investigate the possibility of relaxing tolerances on machine errors, specifically alignment requirements.

About 3 presentations (minimum) are required to explain in a reasonably analytical/exhaustive way the proposed solution to this not trivial problem.

outline

- Objectives
- ARC lattices & beam dynamics
- Straight sections matching and beam dynamics
- Conclusions

Ultimate objectives

- increase DA&MA and lifetimes
- reduce accelerator number of components
- reduce magnet families
- reduce integrated gradients requirements
- increase tolerances on errors (gradients & misalignments)
- relax requirements for tuning

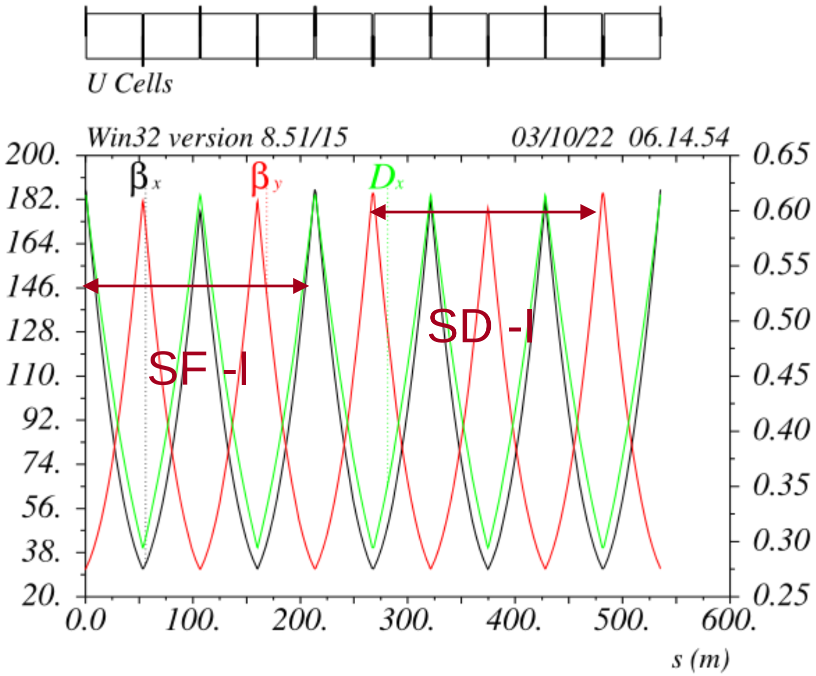
In the following these objectives are being addressed through lattice design optimization

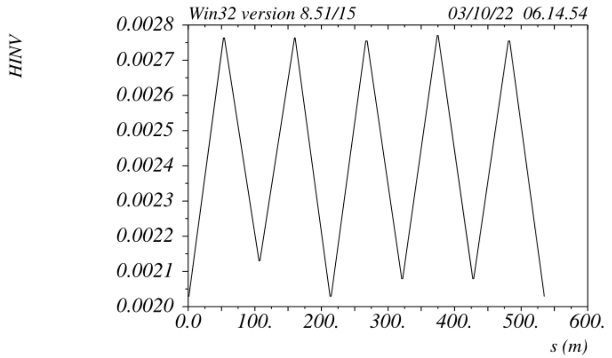
Strategy

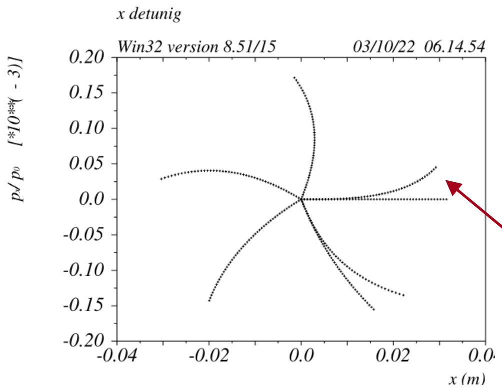
Modular FCC lattice design

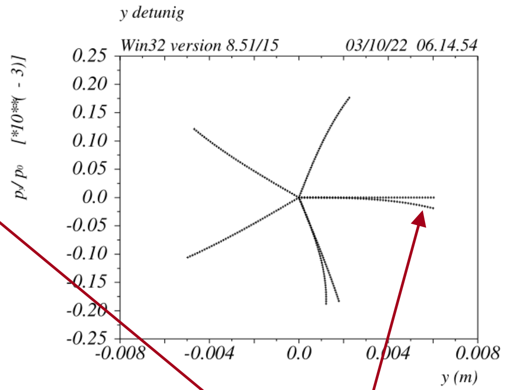
- Develop an “Ultimate ARC” lattice made by the best possible Achromat&Anharmonic Cell
- Develop a method in order to insert straight sections with minimum impact on breaking of the ring periodicity
- Design the best possible Achromat&Anharmonic Final Focus system that does not relies on ARC sextupoles for DA&MA optimization
- Develop methodology and solutions to accommodate all the necessary lattice adjustments (crossing angle, LSS requirements etc) with minimal impact on beam dynamics and parameters

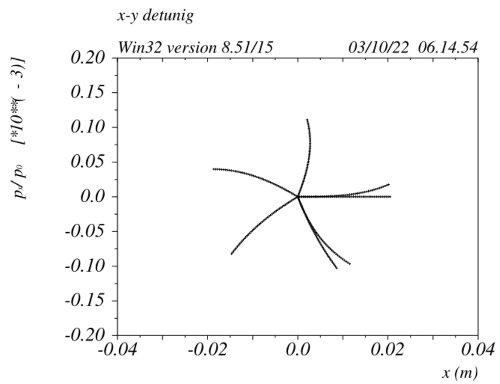
ARC lattice 148 long cells made of FODO9090 (~80KM)

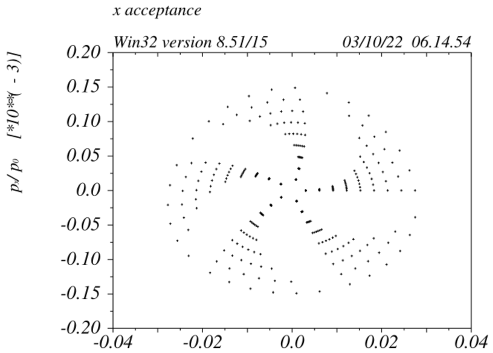


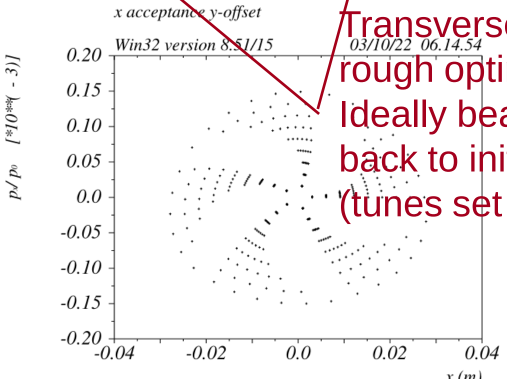




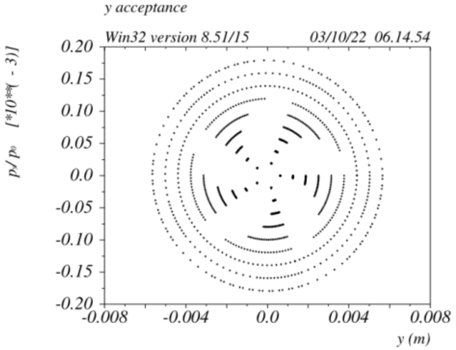


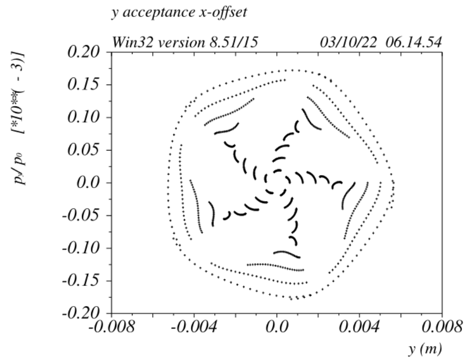






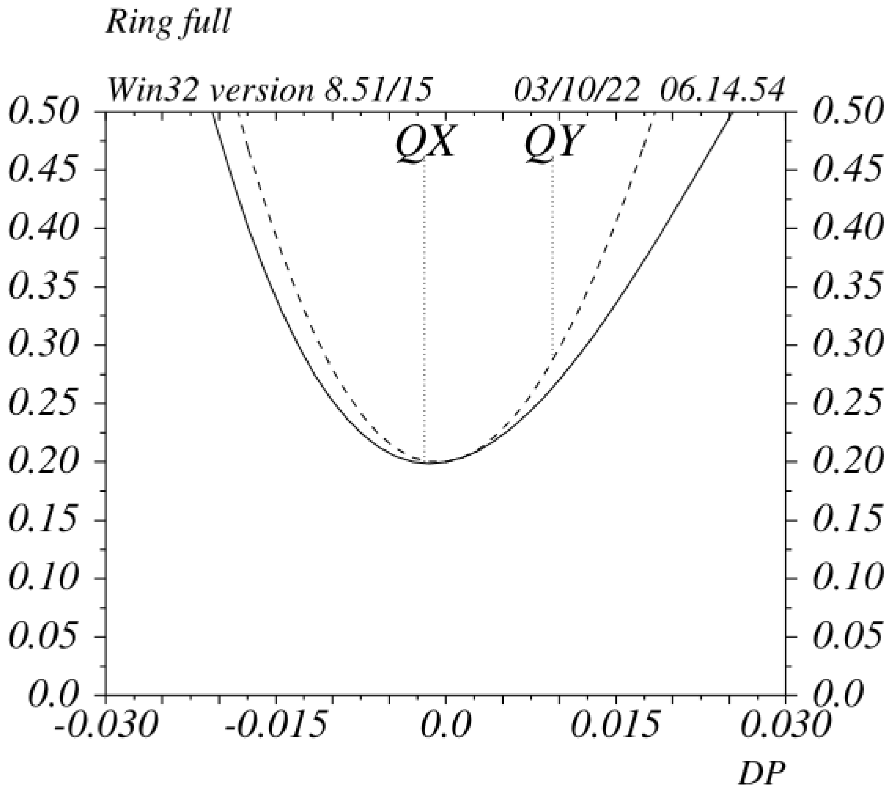
Transverse beam dynamics checks and rough optimization of 5 turns.
Ideally beam x/xp/y/yp should come back to initial coordinates after 5 turns (tunes set to mux=muy=0.2)





FODO 9090 is very anharmonic !!!

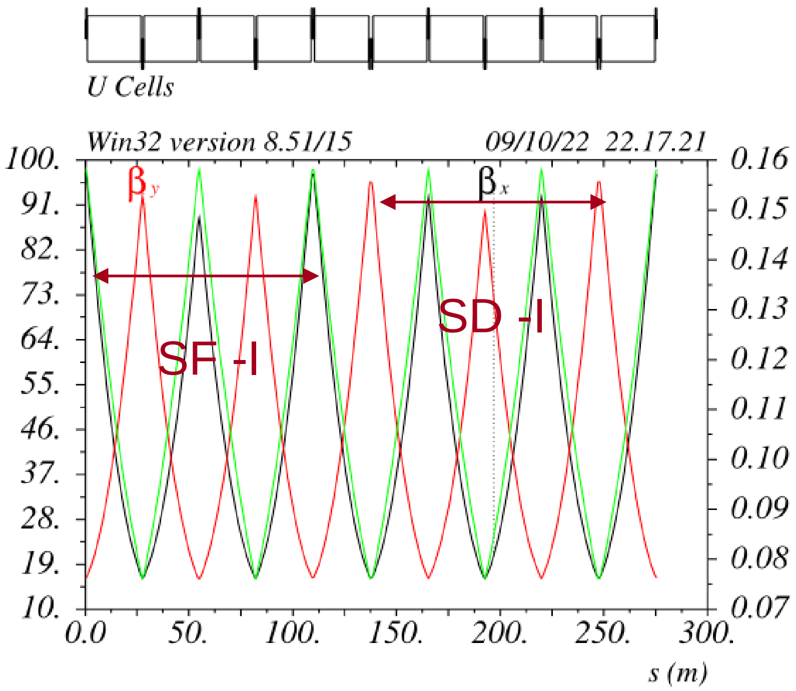
ARC lattice: 148 long FODO9090

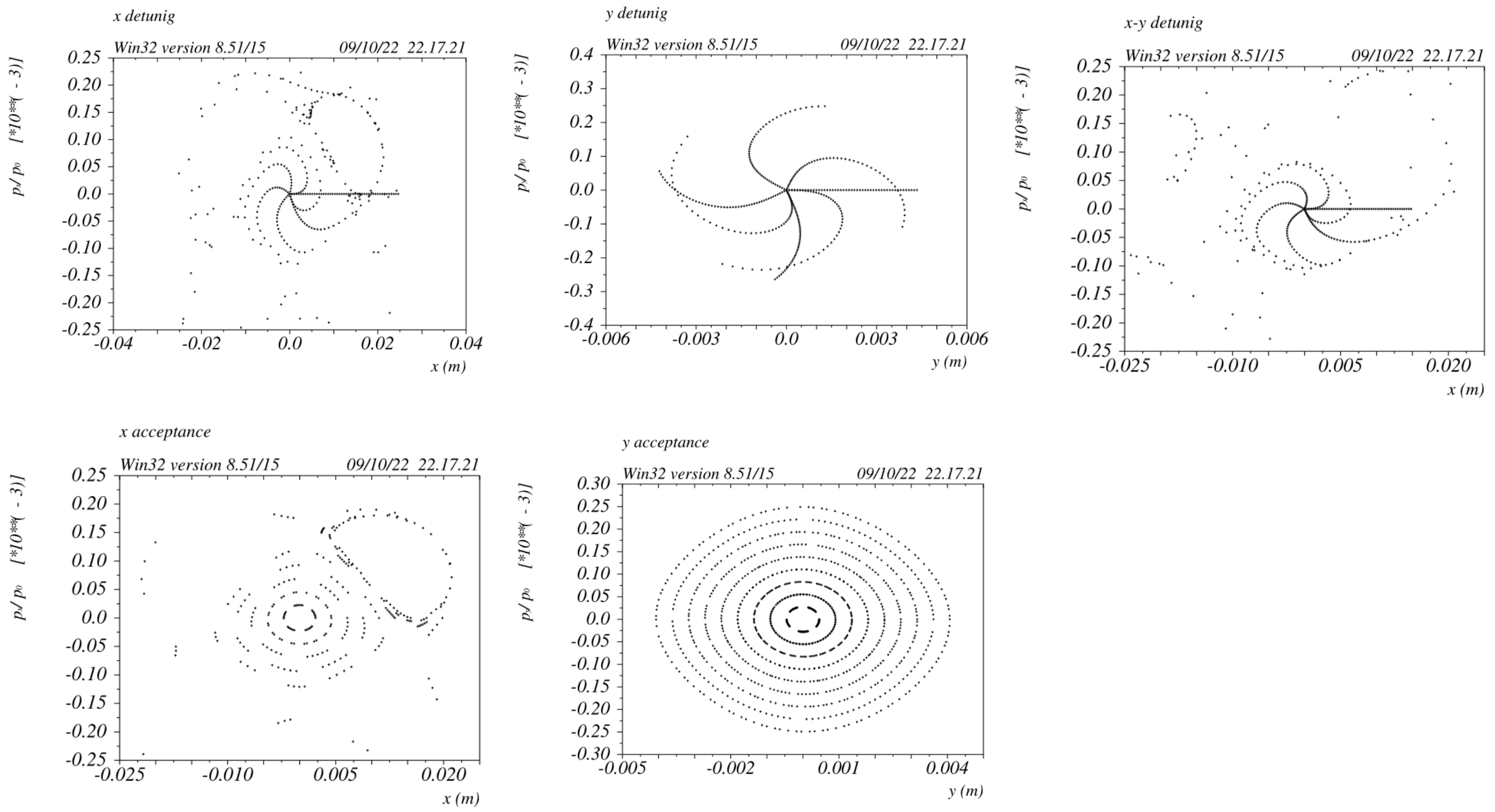


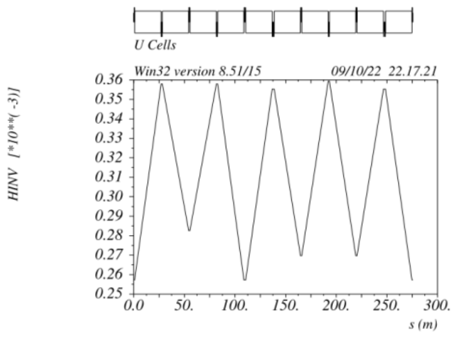
FODO9090 cell is only a first order Achromat
Placing sextupoles at every quads will cancel the 2nd order chromaticity (SOC) but then the cell will not be Anharmonic
EA (defined by the tune footprint to be contained in one quadrant) is around +/-1.5%

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

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



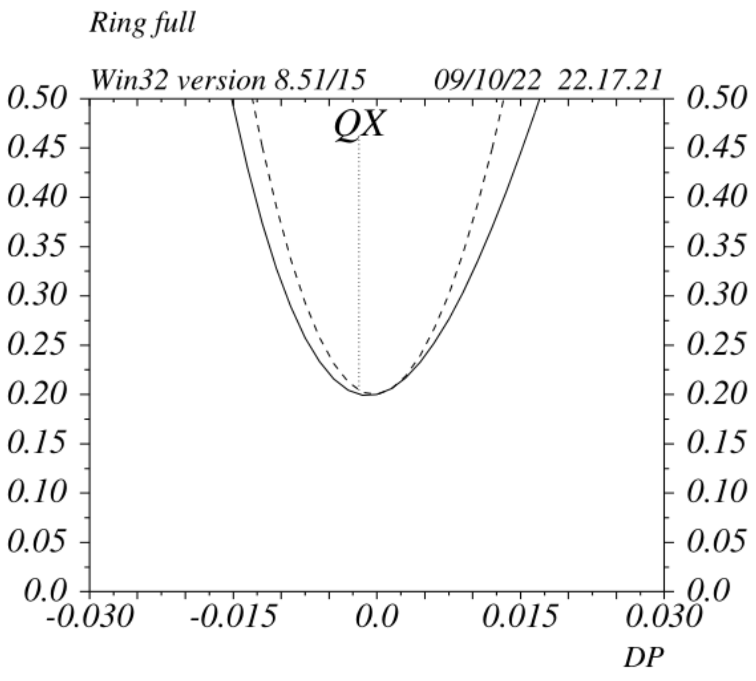




FODO 9090 is not Anharmonic, some contribution comes from the long sextupole aberration.

The sensitivity to the –I condition is larger wrt the Long-FODO9090

ARC lattice: 296 short FODO9090



EA (defined by the tune footprint to be contained in one quadrant) is around +/-0.75%

ARC lattice scaling laws

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

FODO9090 with	74 cells has an EA of about	+/- 3.0%
	148	+/- 1.5%
	296	+/- 0.75%
	592	0.00% (runaway case)

ARC lattice scaling laws

In fact the length of magnets/sextupoles grows much faster then linear/linear^3 and in particular the sextupoles reach the asymptotic limit first.

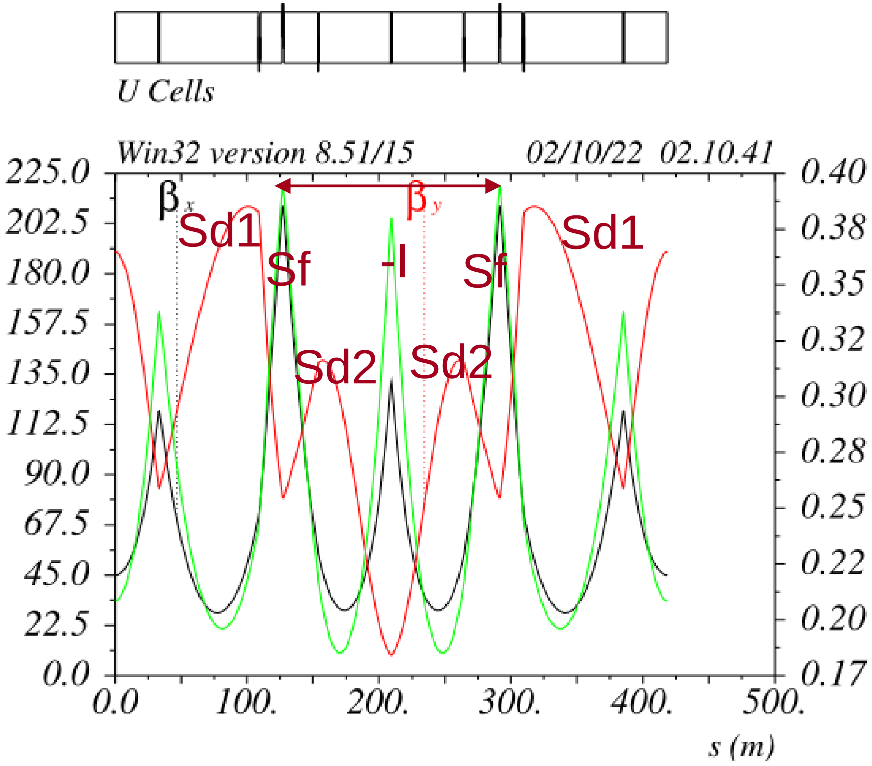
Sexts become longer => there is less space for the other magnets => betas and dispersion decreases => sextupoles need to be even longer => with 592 cells the sextupoles take a large fraction of all the available space

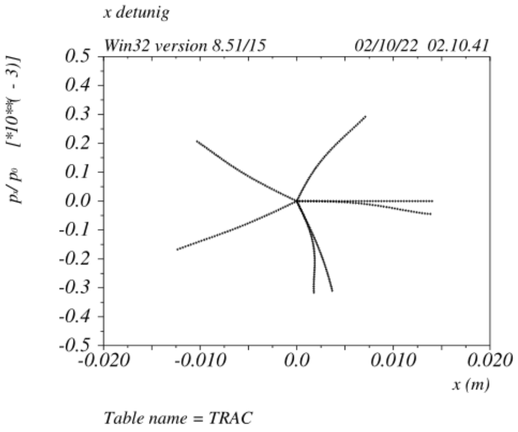
EBS (H7BA) is made of 32 cells, the limit for acceptable performances (DA<3%, MA<100sigmas) is around 40-45cells
Petra4 (H6BA) is made of 72cells, the limit is around 80-90cells

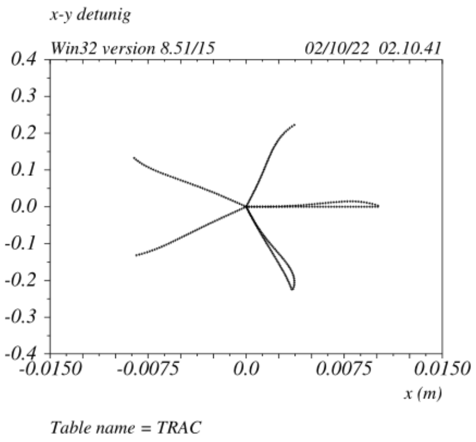
With the same SLSs criteria the limit for acceptable performances of the FODO9090 is ~100

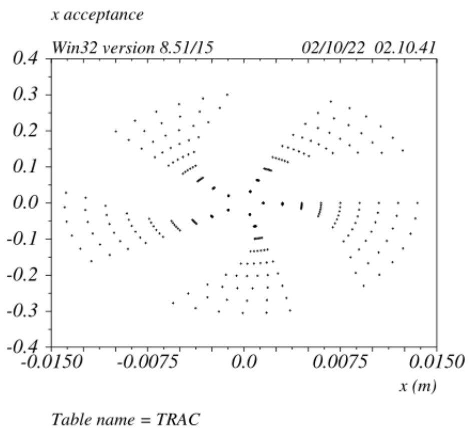
The scaling laws do not depend from ring size, a 200Km ring does not allows twice the number of cells. The only difference is that it pushes a little further the asymptotic limit, since there is more space for the extremely long sextupoles.

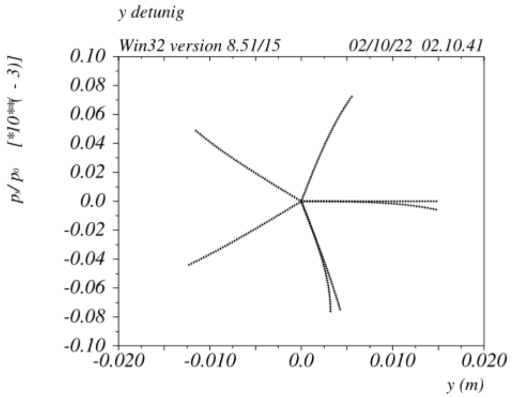
ARC lattice 192 long cells made of HMBA (~80KM)

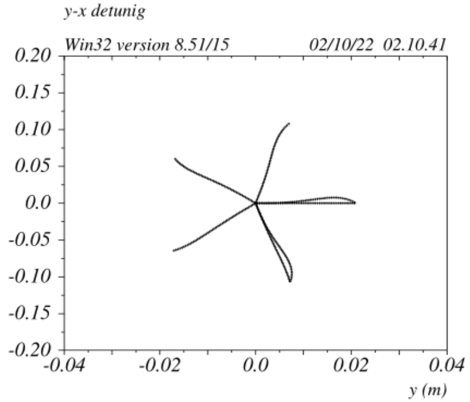


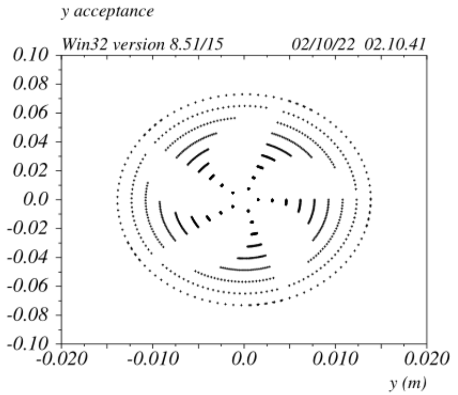








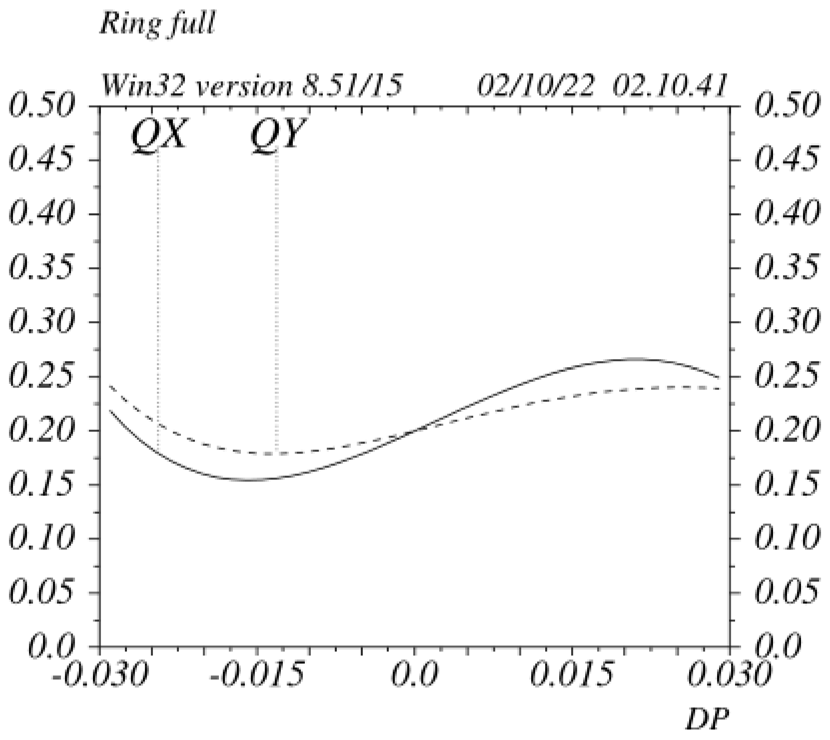




HMBA is Anharmonic
R12s&R34s in the –I are optimized
Sd1 and Sd2 are optimized

ARC lattice 192 long cells made of HMBA (~80KM)

SLAC

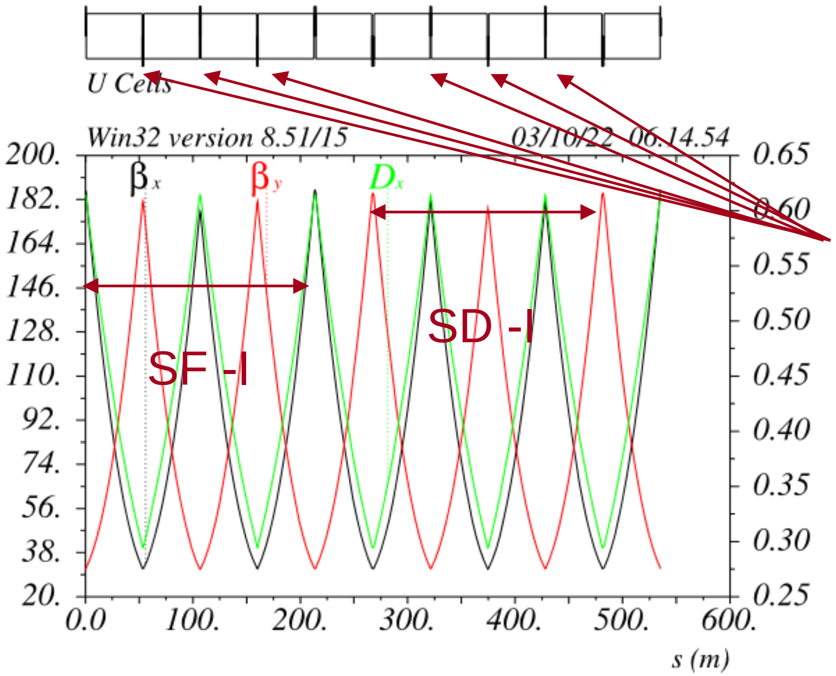


HMBA is Achromatic up to the third order
HMBA breakdown is around 200 cells

HMBA is just a proof of principle that a A&A cell can be made
However it is an adaption from optics developed for SLSs

Definitely it is not the best solution for a "standalone" ARC

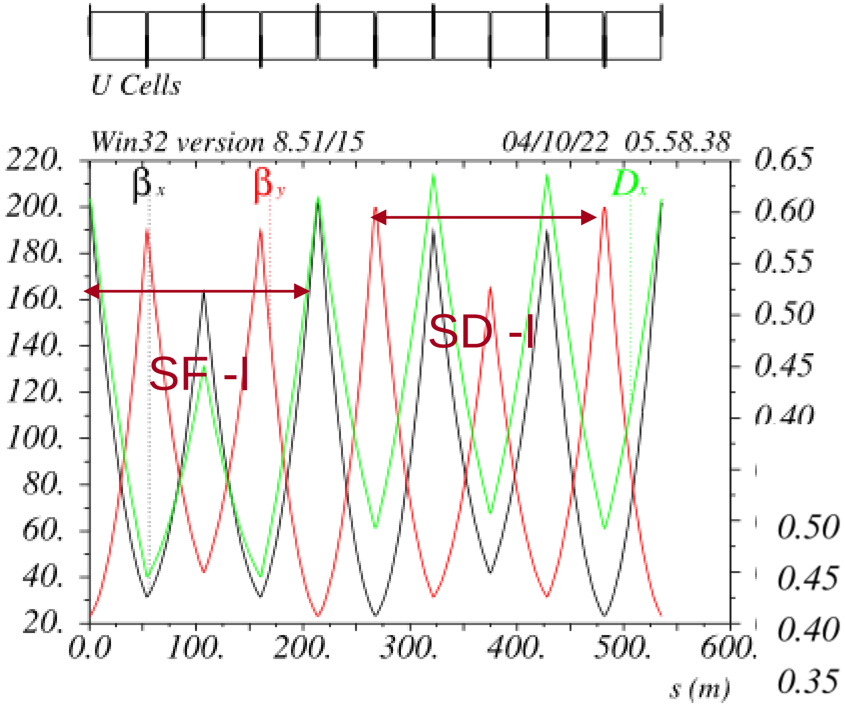
FODO9090 optimization

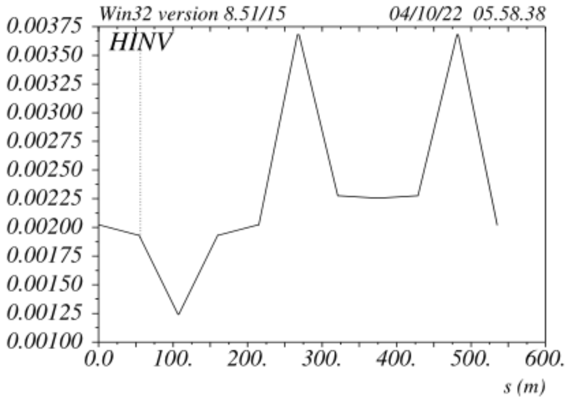


Ultimate source of SOC is uncorrected chromaticity and second order dispersion originated by the quads with no nearby sextupoles (QWOS)

Can this effect/source be reduced?

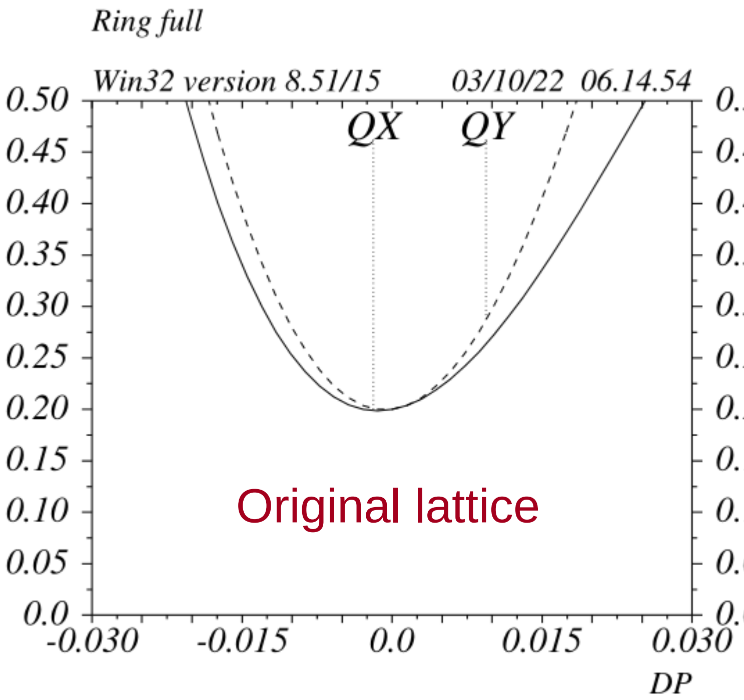
FODO9090 optimization v_2a

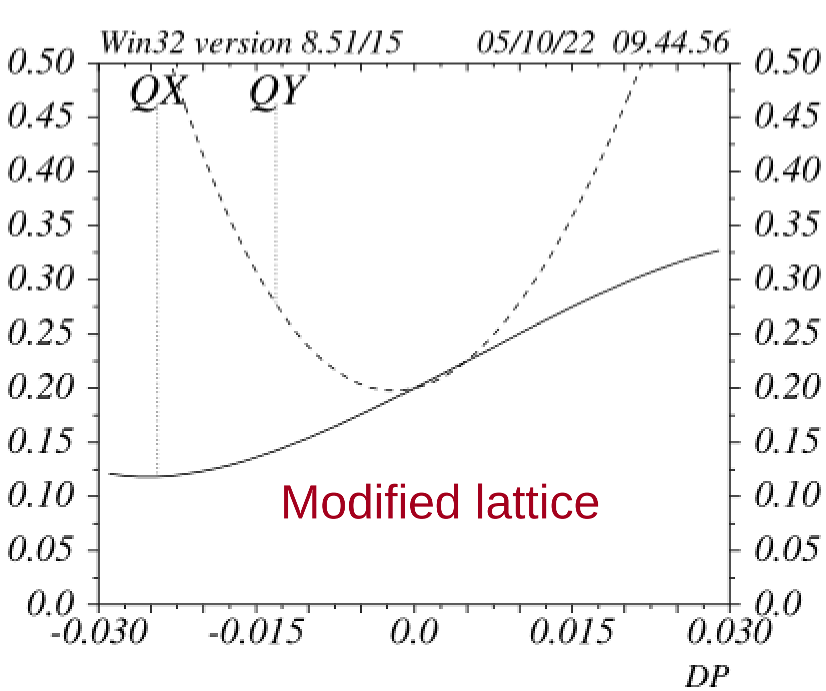




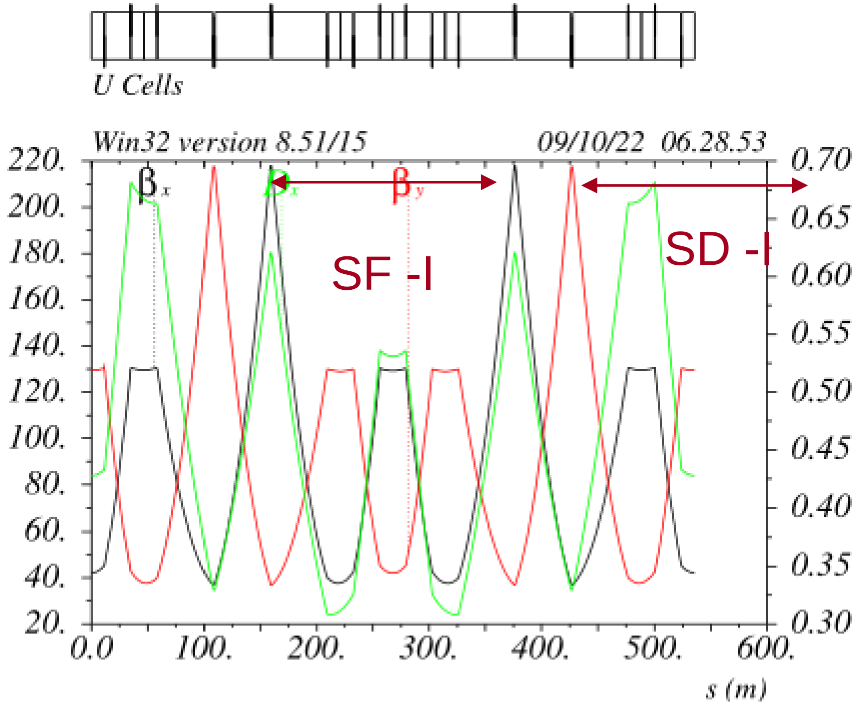
Phase advance between the –I pairs has been increased, this decreases the betafunctions&dispersion on the QWOS

EA is about +/-2.2%
Cell is Anharmonic

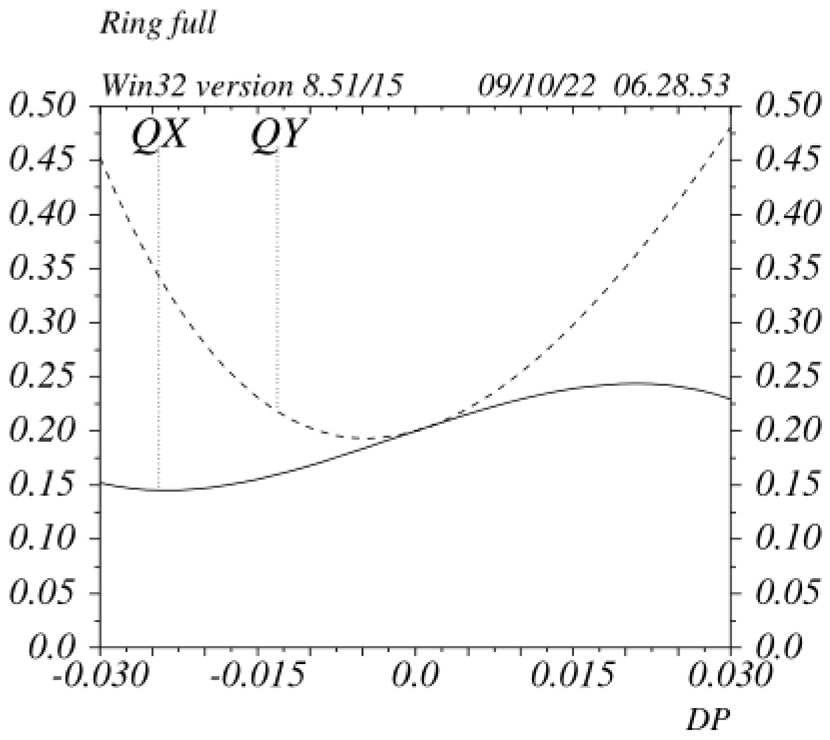




HFD optimization v_5a3



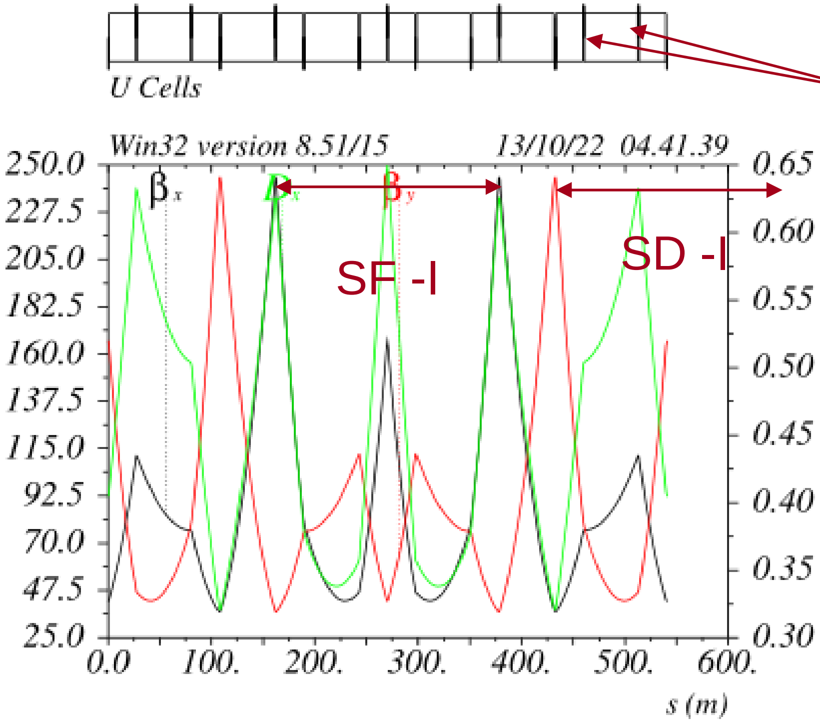
Betas and dispersion have been further decreased on the QWOS by splitting them.
Overall chromaticity is also lower, and the reductions come from less chromaticity from QWOS



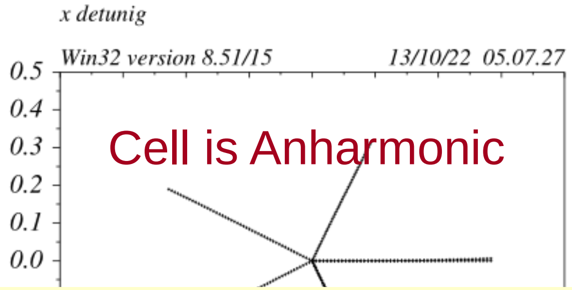
EA is about +/-3.2%

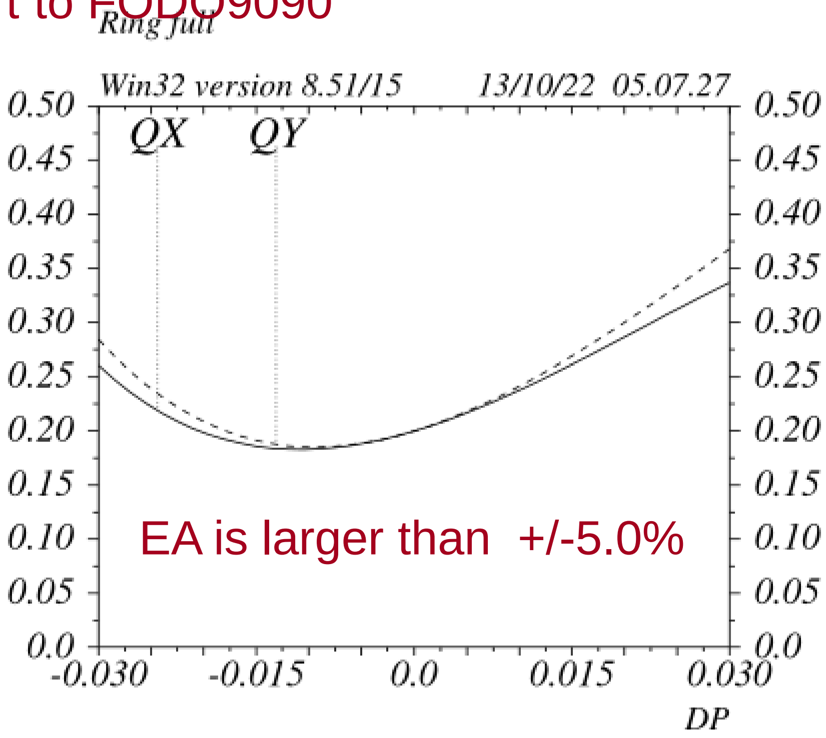
Cell is Anharmonic

HFD optimization v_11a1



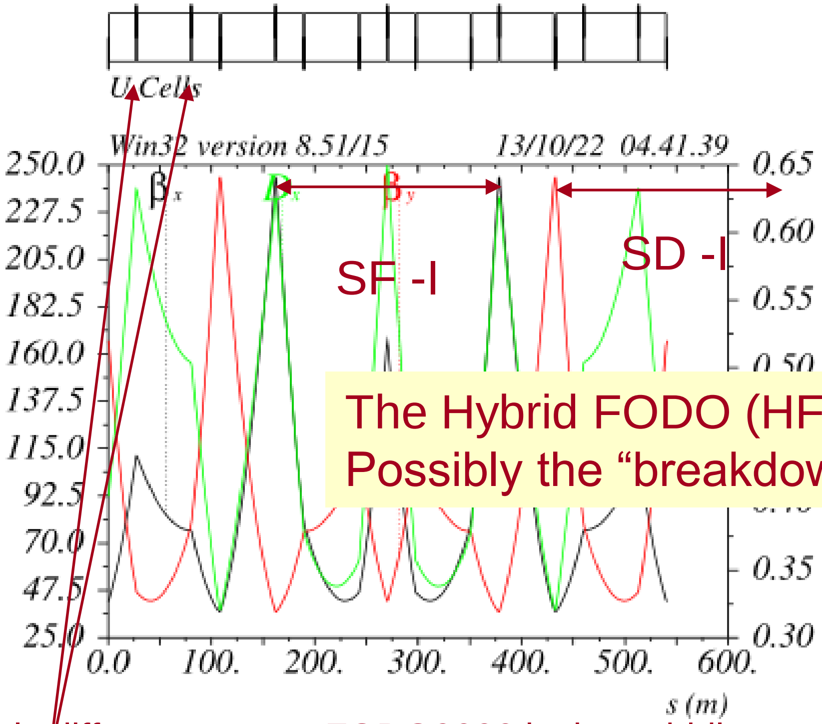
Middle quad has been replaced by two quads, dipoles are 25m and 50m long, their respective lengths have not been optimized.
Betas at QWS and cell phase advance are the only optimized variables.
Sextupoles are 20% weaker wrt to FODO9090

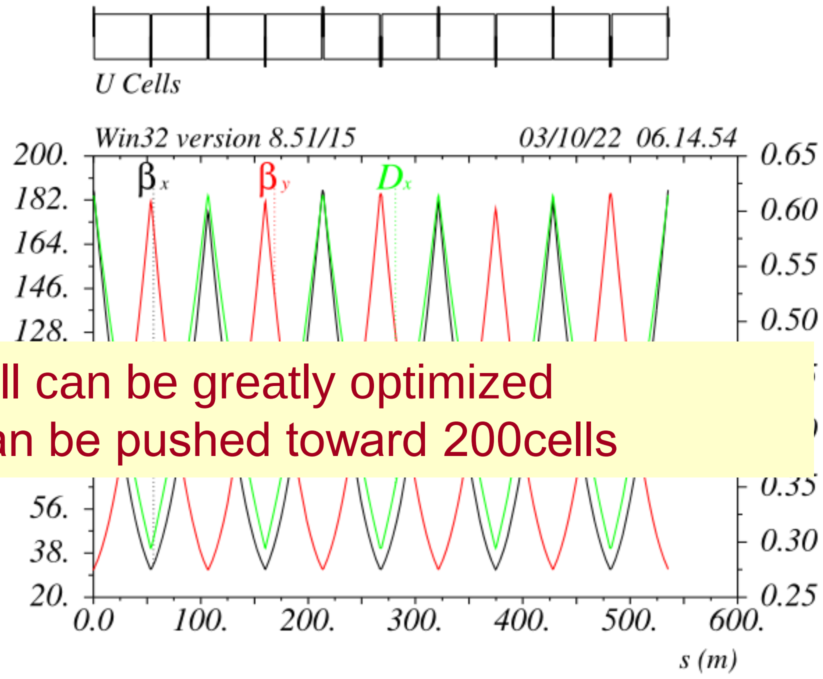




At least for me this is the first time that I see a second order Achromat and Anharmonic cell
For the case shown the compatibility with the present layout has been retained (only usable when run in long/long mode).
It is also compatible with e-&e+ rings quads pairing

HFD optimization v_11b1

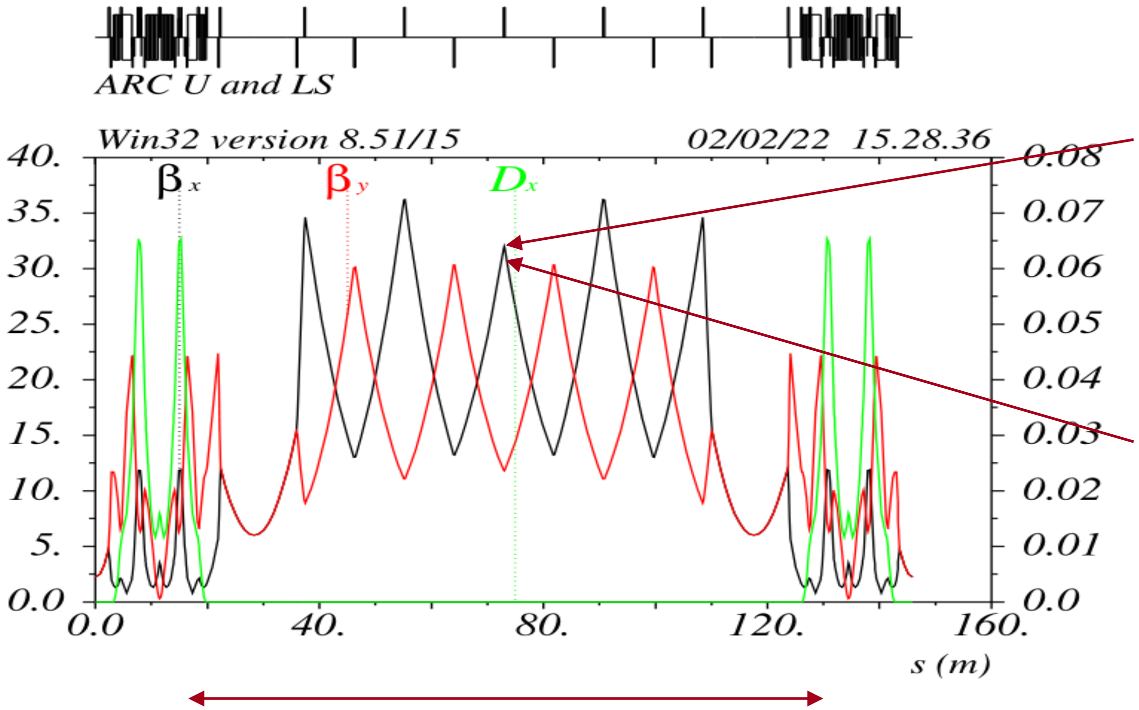




The Hybrid FODO (HFD) cell can be greatly optimized
Possibly the “breakdown” can be pushed toward 200cells

Only difference wrt to FODO9090 is that middle
quad-pair in the –I is split in two (distance roughly optimized)
This adds an additional degree of freedom:
Overall cell phase advances and betas@sexts are free parameters and can be optimized for emittance&beam dynamics.
No sexts families are needed to improve the DA&MA and LMA is maximal
The benefits should overcome the additional complexity
Very interestingly the optics naturally develops the betas&dispersion bump at the sextupole locations, improving their effectiveness
This is one of the key ingredient of the H7BA lattice (EBS) leading to the need of just 6 sestx/cell, despite the increased complexity.
(current 7BA designs do require about 21-25 sextupoles and many octupoles)

Insert Long Straight section: Transparency Conditions



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

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

1) dmux = 0 +N (wrt the standard cell)
   dmuy = 0 +M/2 ("/2" comes from Hamiltonian reasoning)
   alphax=alphay=dpx=0

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

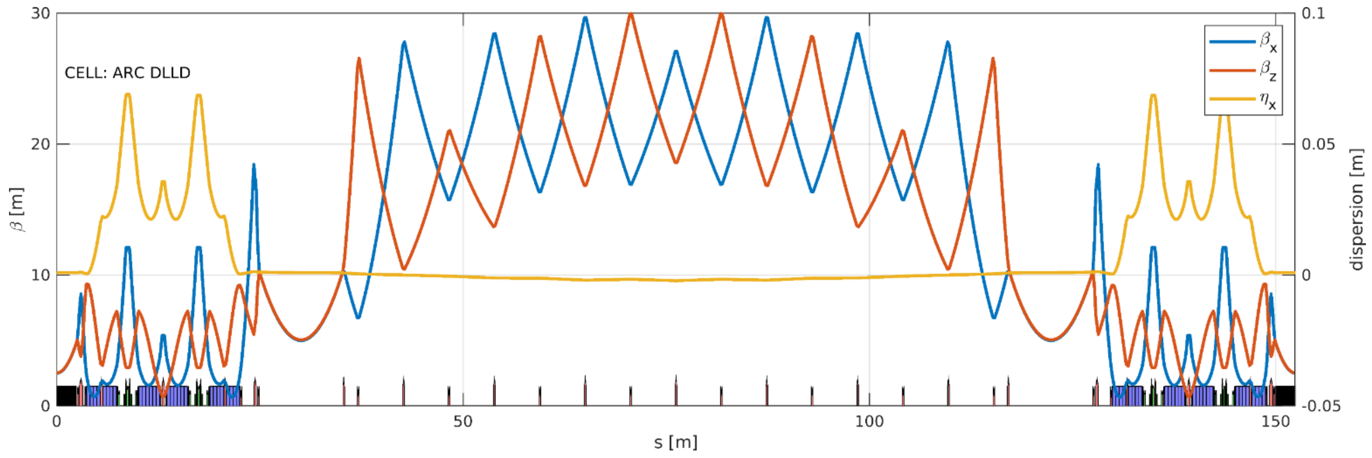
2) dWx=dWy=ddpx = 0

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

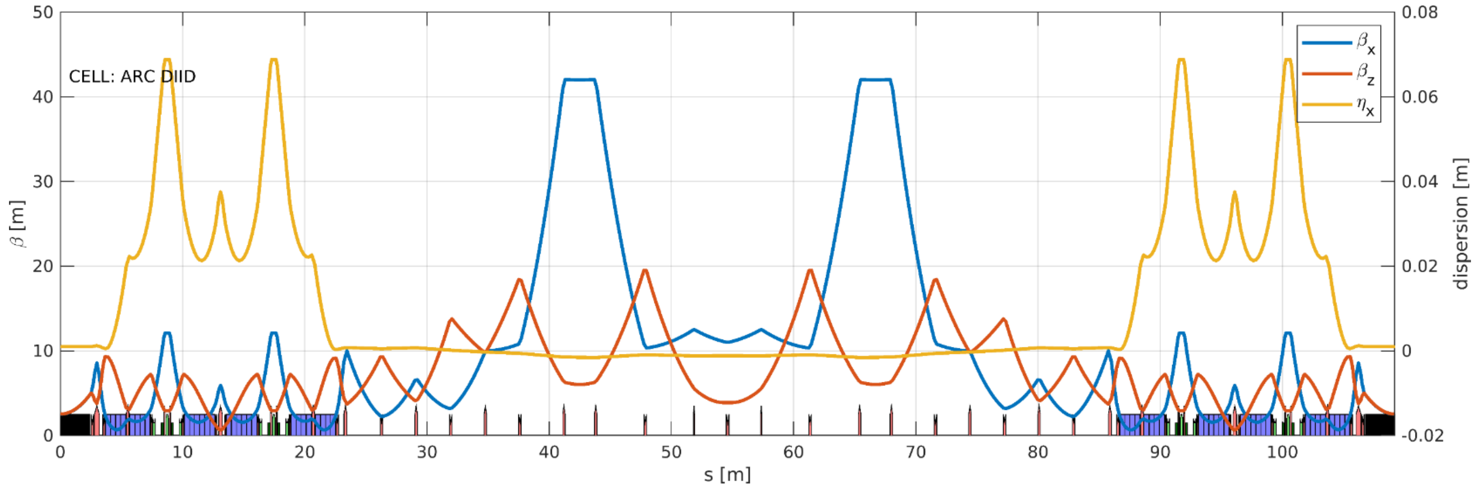
3) For a superperiodic lattice (eg: ARCs+SSs) the phase advance between ARCs must be far from 0 and 0.5
   (Integer part of the tunes should not be multiple of the superperiodicity)

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

Petra4 examples



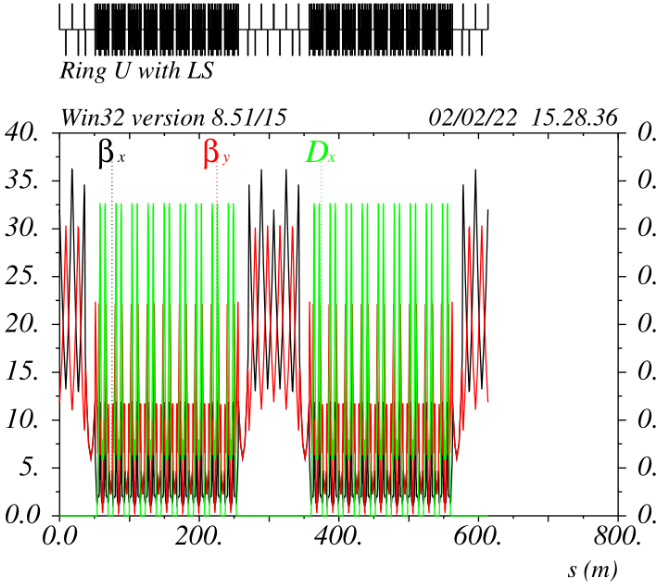
Double minibeta section

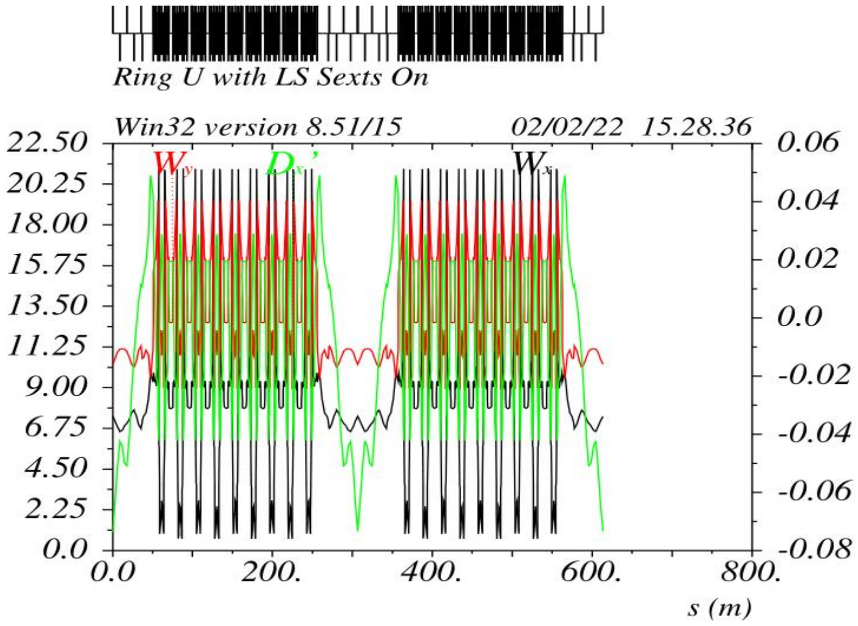


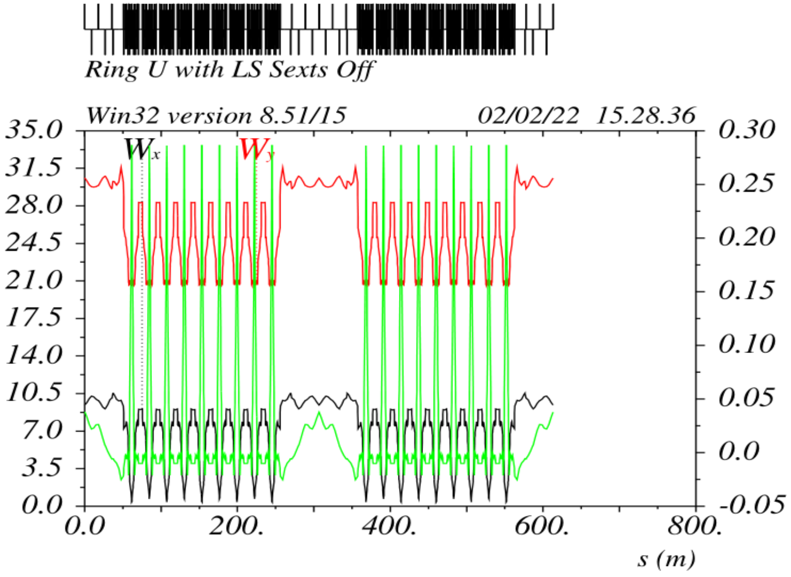
Injection section

TCs can be met almost independently of the optics requirements in the Long Straight Sections

CHROMATIC FUNCTIONS WITH INSERTIONS WITH TCS (PETRA4)







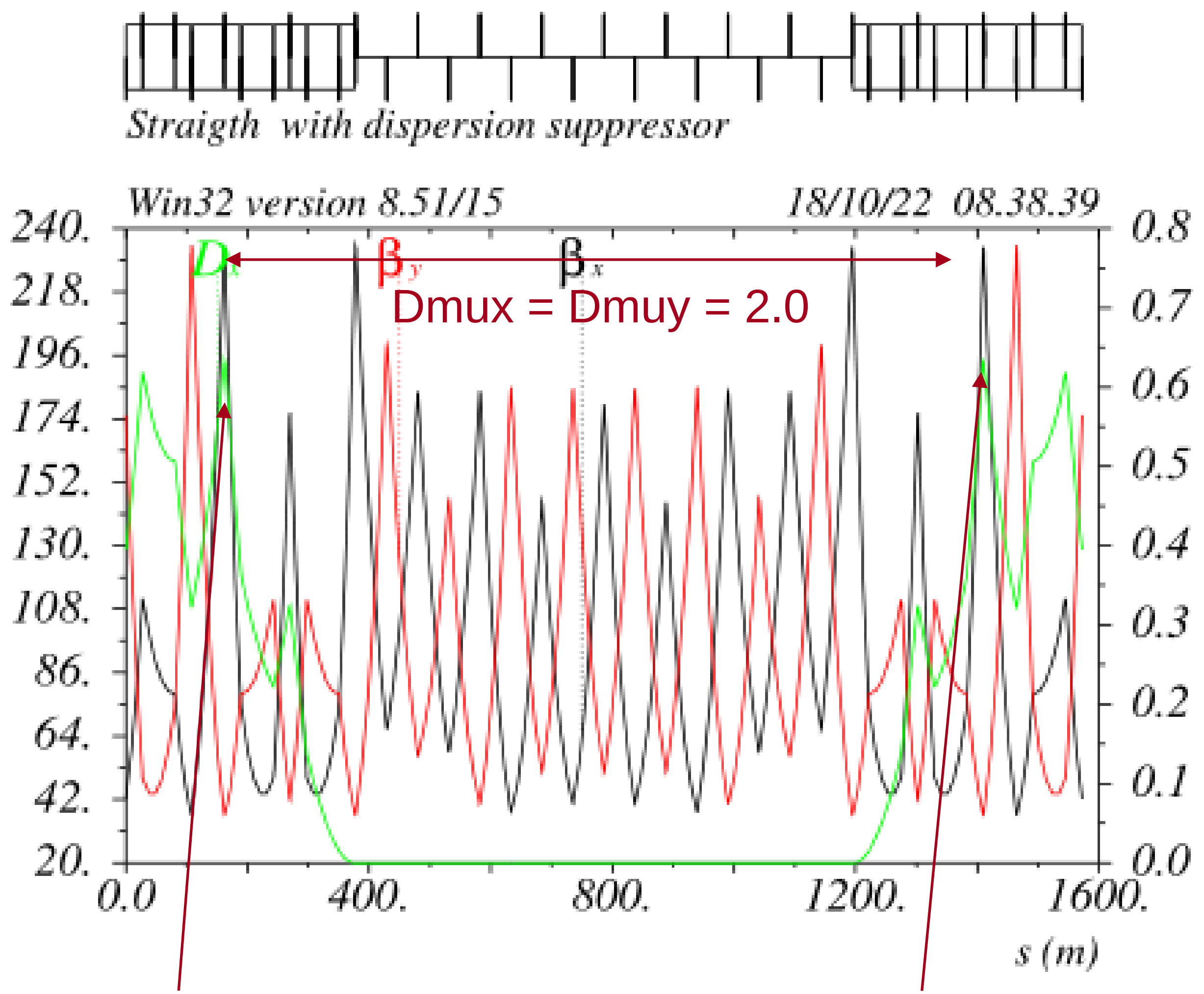
With the transparency conditions everything remains periodic in the arcs:

Betax and betay

Wx and Wy with sextupoles off and on

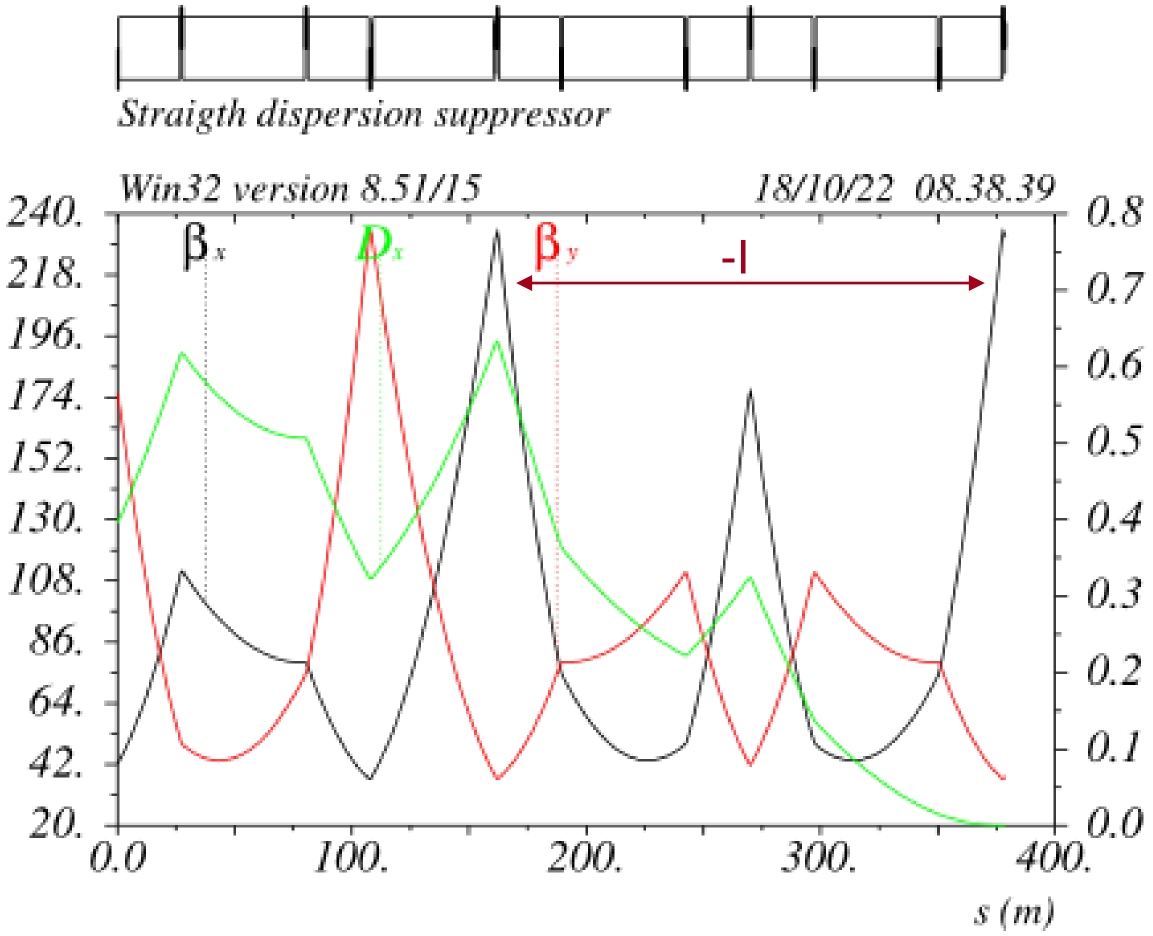
No sextupoles families are needed, however with sextupole families (found by MOPSO for example), the DA and MA reaches values very close to the periodic ring.

Long straight insertion with TCs V_15a2



The last SF of the left ARC pairs with the first SF of the right ARC as for the “standard” SFs ARC pairs

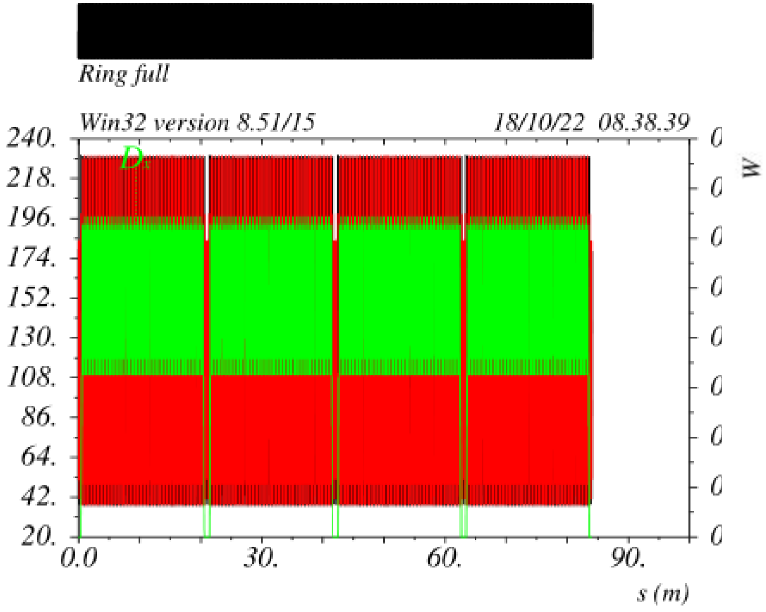
Long straight insertion with TCs V_15a2

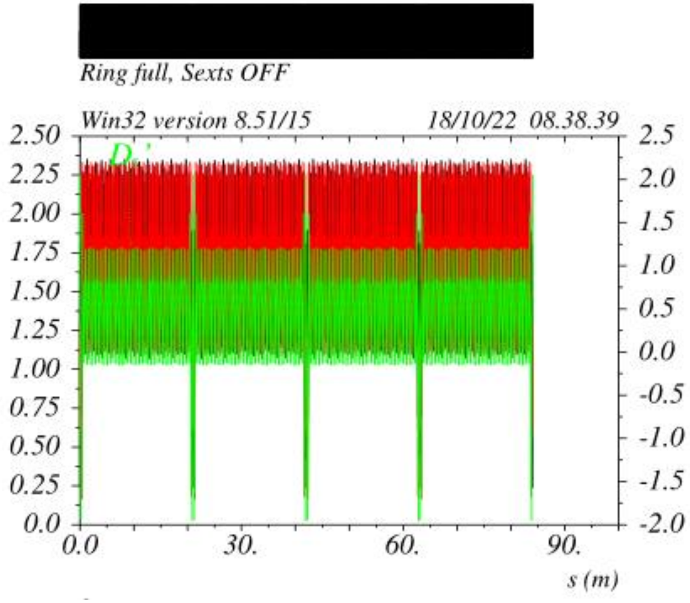


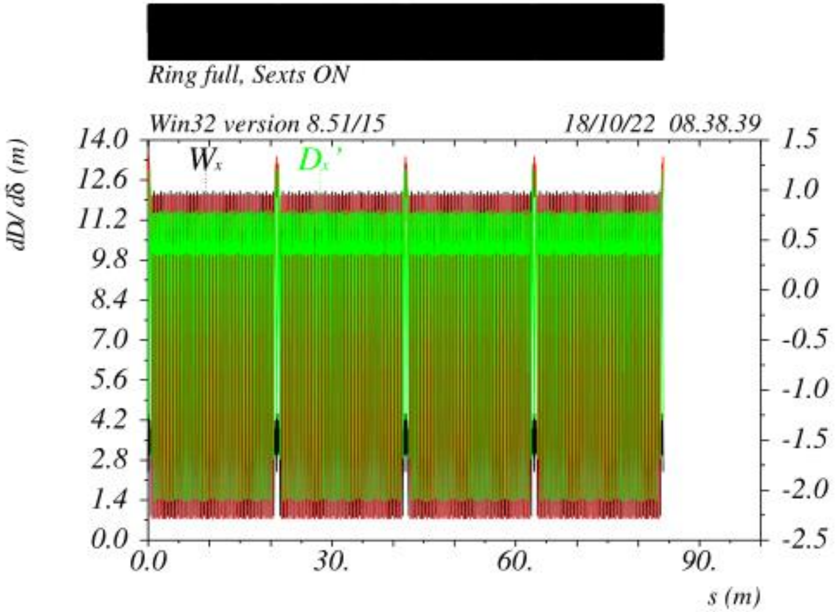
In order to match the second order dispersion the "missing dipole" scheme does not work
The solution chosen is to have:
- the total bend angle of the DS ~ half of the nominal
- the first 3 dipoles have a different bend angle wrt the last 3, the value is defined by requiring the second order dispersion match

Finally the end of the DS is at –I wrt last ARC SF
This means that if an "harmonic" sextupoles is placed there, there is no need of
the transparency condition dmux=dmuy=2

Ring with Long straight insertion v_15a2

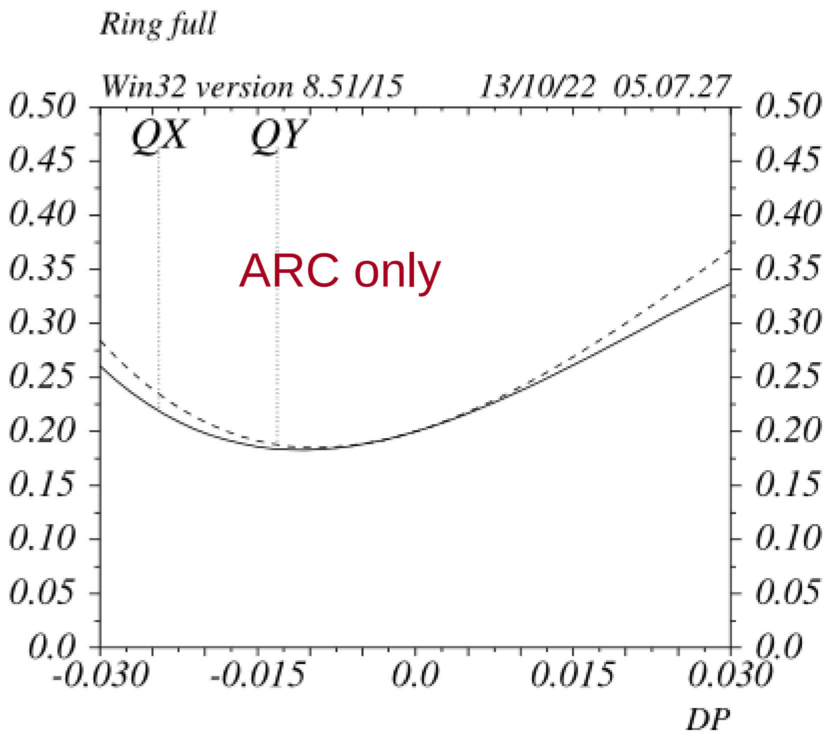


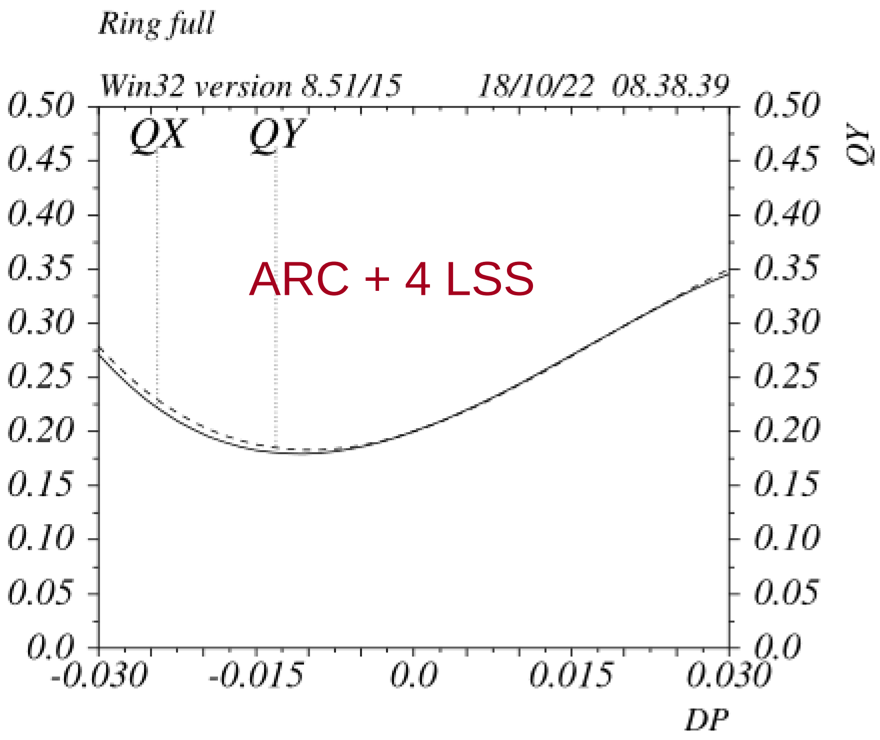




The ARC beta functions and their derivatives wrt energy are fully periodic.
They are periodic with sexts off and on by construction.
The LSS do increase the total chromaticity by about 5%, the ARC sextupoles are rescaled correspondingly.
No sextupole families are needed although sextupole families with a moderate modulation (~5%) could further improve performances

Ring with Long straight insertion v_15a2





The LSS insertion has a minimal impact on performances
Sextupoles are about 5% stronger wrt ARC alone
(SDs: integrated Ks~0.12 SFs: integrated Ks~0.06 (madx units))

Conclusions

- Highly anharmonic and second order achromatic ARC cells can be developed with minor modification of the Oide FODO9090 cell.
- Overall ring MA above +-/5% can be achieved for a ring composed of up to ~200cells
- 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 has been described
- ARCs with generic straight section insertions with performances comparable to a fully periodic structure can be made