Update on FCC with Local Chromatic Correction design studies

January 19th,2023

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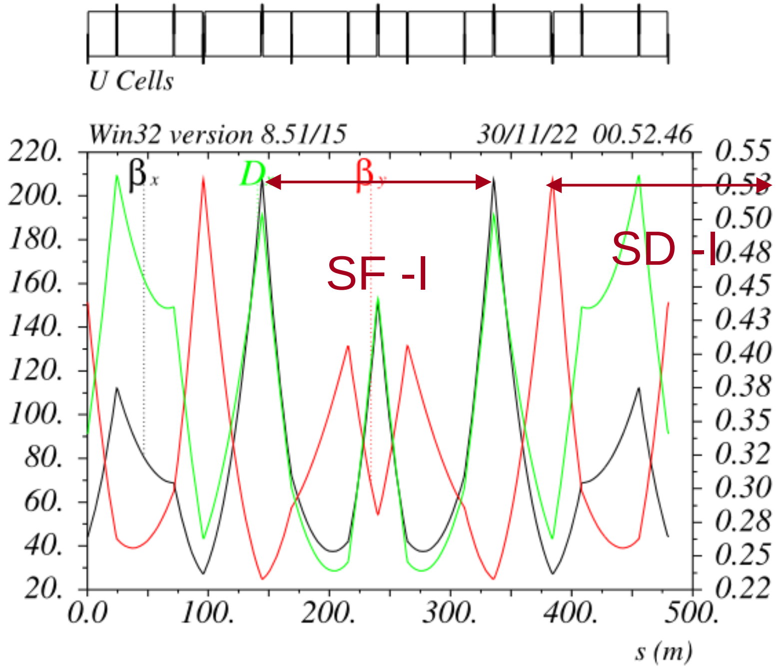
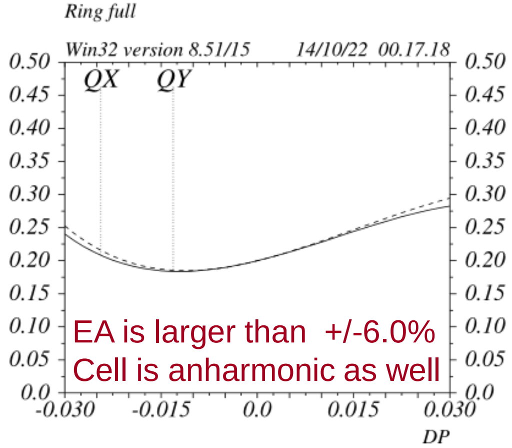
SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- ARC cell optimization
- Subsystems integration strategy
- Long straight sections optimization
- FF optimization
- ARC to FF matching
- Z-W-H-ttbar optics
- Parameters table
- To do list

HFD lattice general specs v_32a1 Dec. 2022





Octant composed of 20 cells 480m long: 9.6km total length
Total number of cells: 160
200m of the dispersion suppressor cell roll into the LongSS
A weak gradient has been added to all the dipoles: K_mad=6.1e-5
(to be checked overall benefits and feasibility)

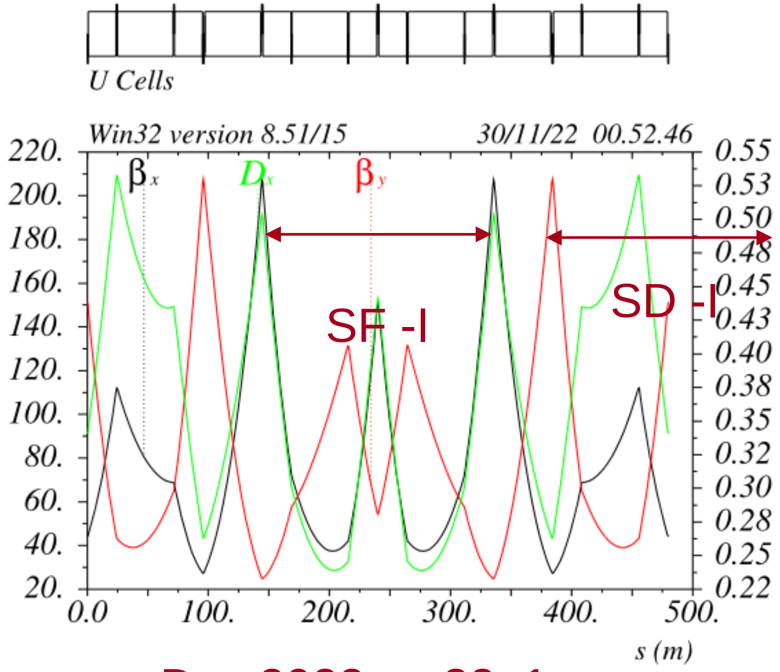
The ARC lattice can be the same for all modes
(with some readjustement of beam parameters)

Quads ~0.5-1mt long Kmad ~0.033 (20T/m@ttbar)
SF Sexts ~0.3mt long Kmadx~0.24 (145T/m^2@ttbar)
SD sexts ~0.6mt long Kmadx~0.24 (0.29T@45mm radius)

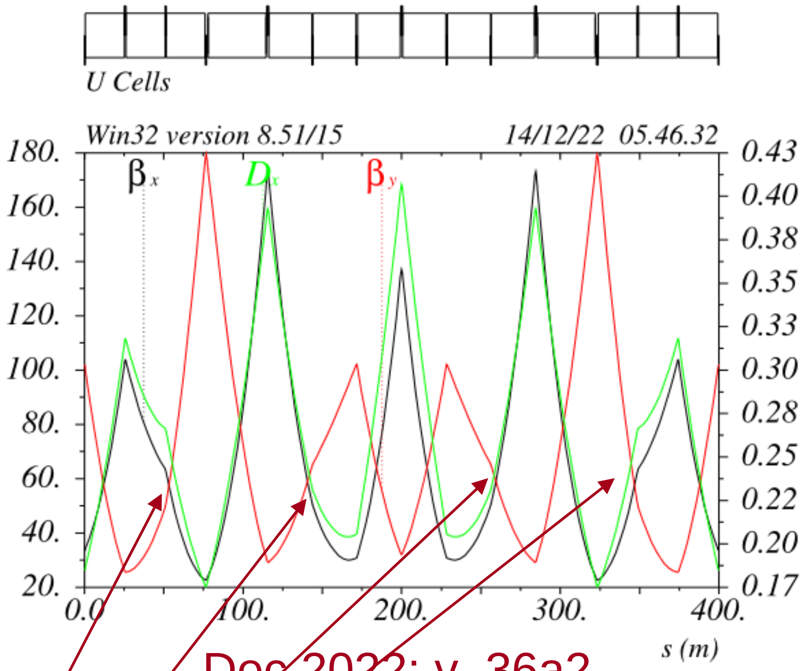
Jx = 1.5, Jy = 1.0, Jz = 1.5
Alphac = 2.57e-5
Ex = 0.34nm @ 45.5GeV Ex = 5.44nm @ 182GeV
U0 = 31.8MeV U0 = 8.141GeV

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

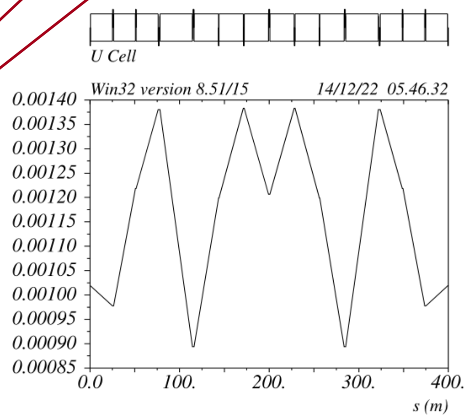
HFD lattice optimization



Dec 2022: v_32a1
480m*160 cells total



Dec 2022: v_36a2
400m*192 cells total



Optimized:

- Dipole lengths
- mux&muy
- Betax&betay @ sexts

betas@sexts are set to zero the II order chromaticities

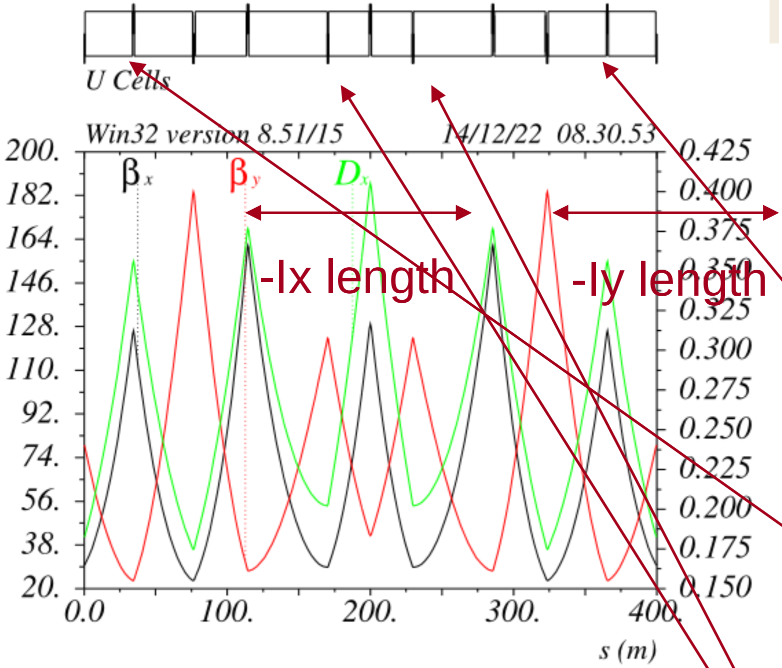
Dipole lengths and tunes to get the minimum emittance

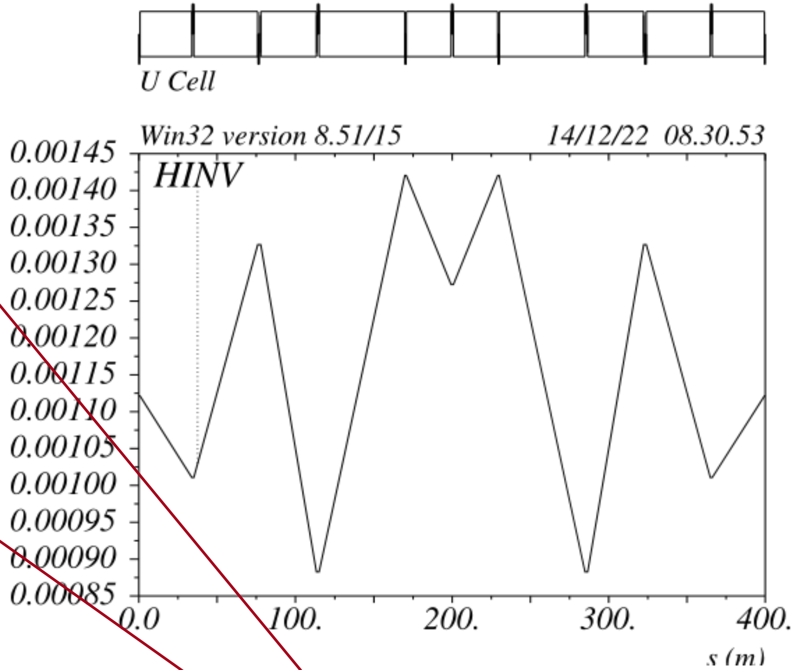
(Only the integer part (mod4) of the full ring tunes is optimized)

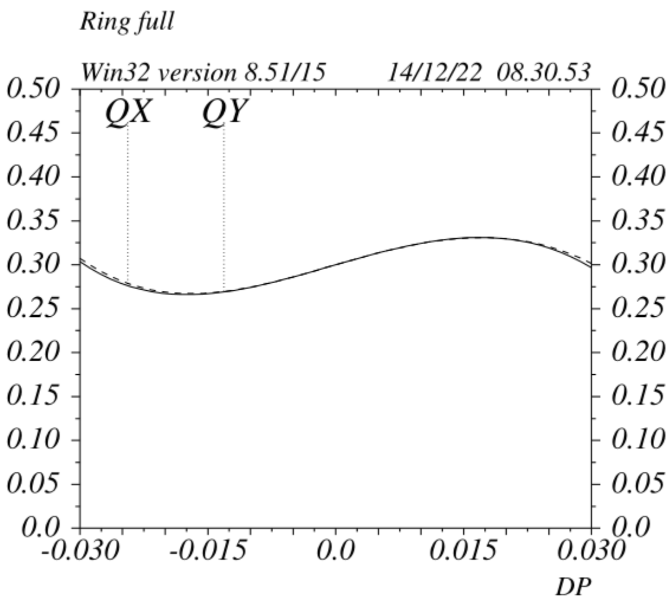
Because high betas@sexts, sexts strength do grow slower wrt to the (number of cells)^3

Some quads becomes weak and could be effectively removed

HFD lattice optimization



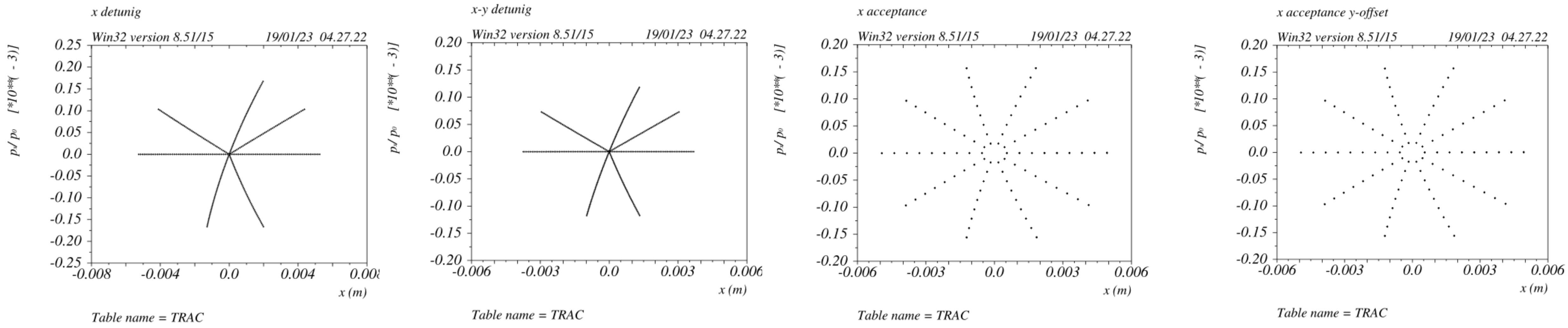




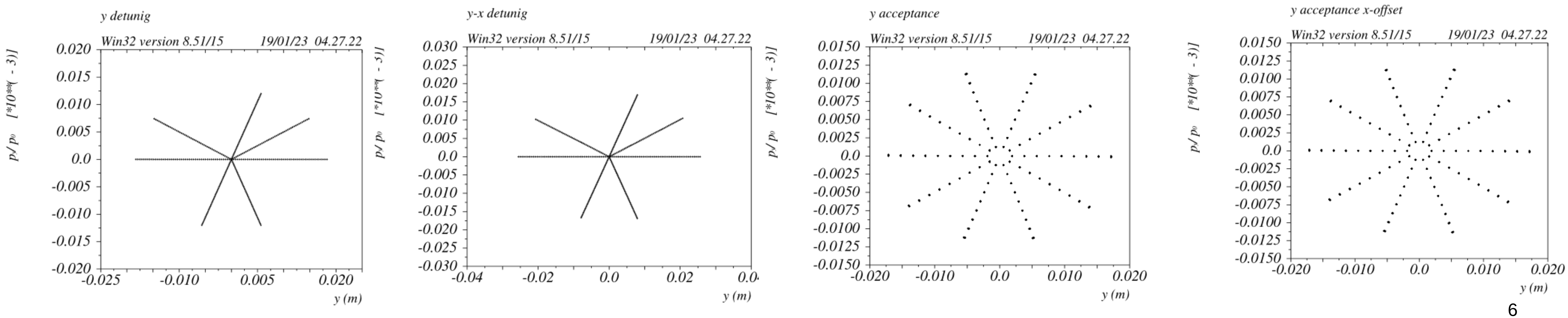
Jan 2023: v_42a1
400m*192 cells total
(minus 8 cells at the FFs sides)

Cell structure is identical to FODO9090
Dipoles in the cell have different lengths (same fields):
-Ix and -Iy sections overall dipole length and dipole length between the SD&SF has been optimized for emittance
QD in the –Ix and QF in the –Iy are positioned in order to zero the II order chromaticity
R12s/R34s between the sexts are set ~1/3 sexts_length to compensate for the long sexts aberration
Detuning is zeroed, DAx/y exceeds several hundred sigmas

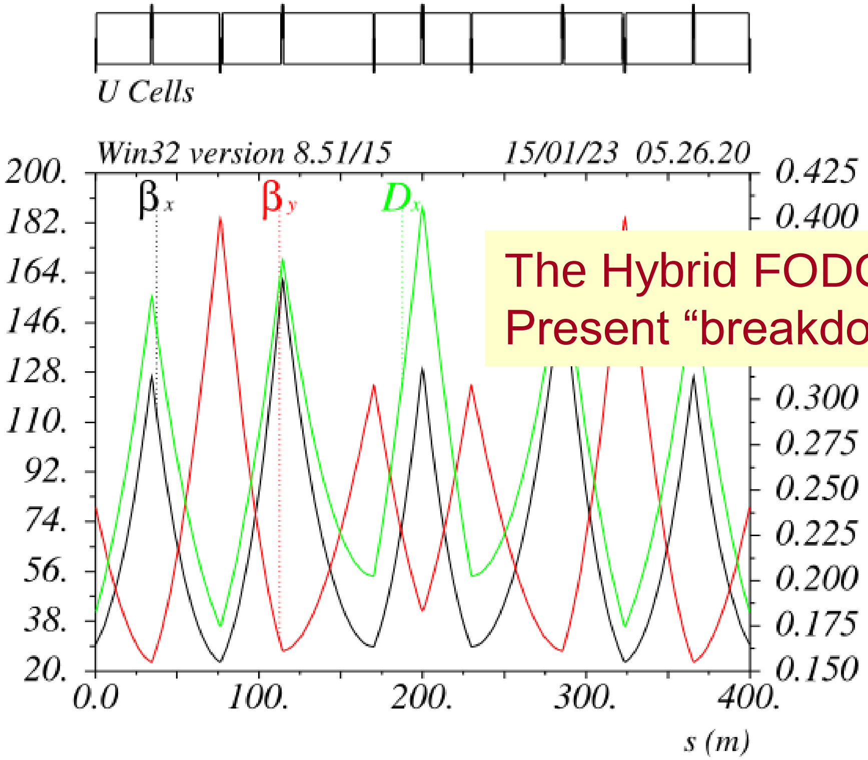
ARCs+LSs+FFDS (no Final focus) dynamic properties



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



HFD lattice general specs v_42a1



Octant composed of 24 cells 400m long: 9.6km total length
Total number of cells: 192 (minus 2*4 at the FFs sides)
200m of the dispersion suppressor cell roll into the LongSS
A weak gradient has been added to all the dipoles: K_mad=12.0e-5

The Hybrid FODO (HFD) cell can be further optimized
Present “breakdown” is above 200-240cells

ttbar)
SF Sexts ~0.3mt long Kmadx~0.32
SD sexts ~0.6mt long Kmadx~0.32 (~0.4T@45mm radius)

Jx = 1.7, Jy = 1.0, Jz = 1.3
Alphac = 1.78e-5
Ex = 0.17nm @ 45.6GeV   Ex = 2.72nm @ 182.5GeV
U0 = 31.8MeV   U0 = 8.141GeV

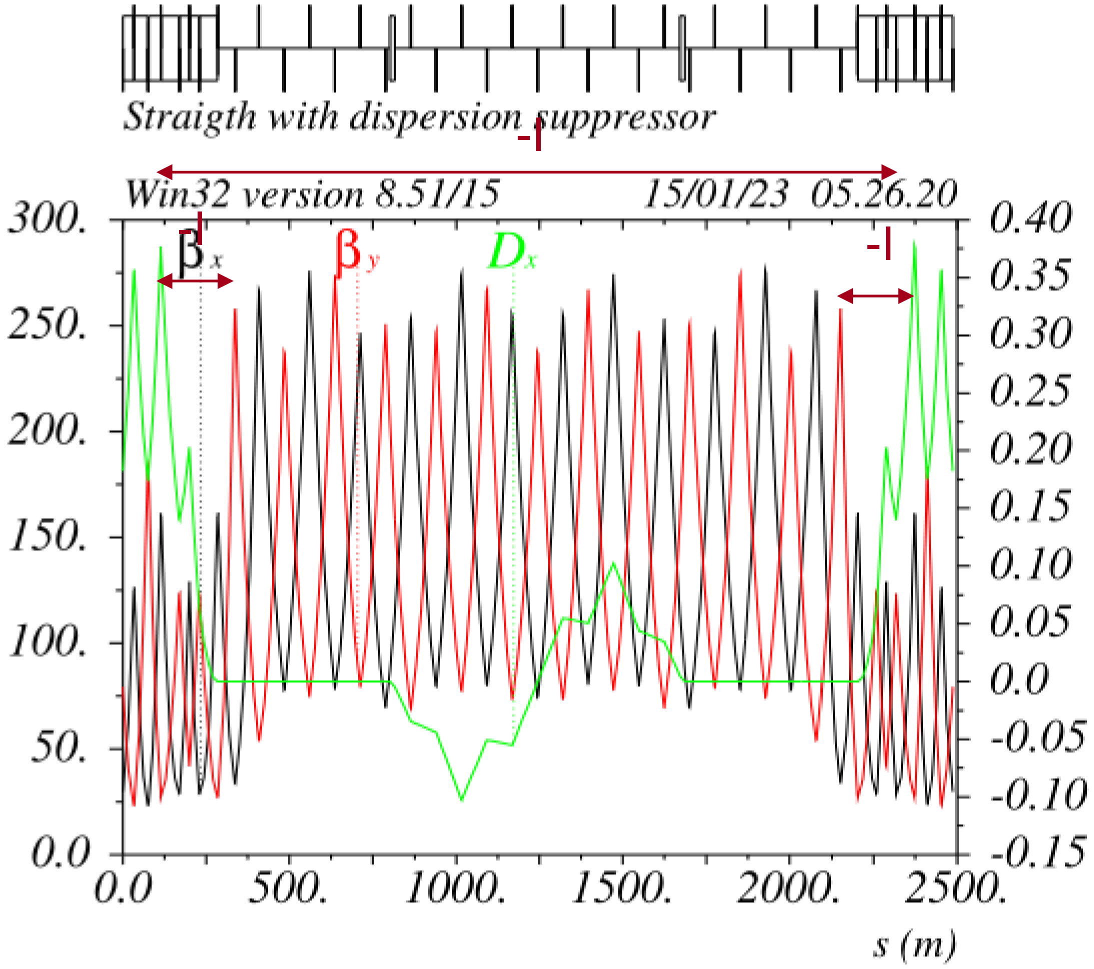
- For now it is being studied the possibility of maintaining the same ARC lattice for all modes (the advantages and related beam parameters will be described later)
- However the ARC can be made such it delivers Ex~1.5nm@ttbar with:
about 25% more cells and ~1.7times stronger sexts (still ~ 5 times weaker wrt present lattice).
In this case, since its structure is identical to the short FODO9090, it can provide a larger emittance/alphac with the same detuning done to go from the short to the long FODO9090

Subsystem integration strategy (repeat)

Subsystems integration made according to (as much as possible):

- Using TCs criteria
- Minimum emittance dilution
- Minimum energy loss increase
- Minimum impact on natural chromaticities
- Maintaining optics symmetries
- Develop specific solutions to compensate for asymmetries (only dipoles for now)
- Step-by-step optimization and impact evaluation on ring properties

Asymmetric Long straight insertion with TCs v_42a1



Long straight sections all identical with a dogleg to recover the proper layout, in particular:

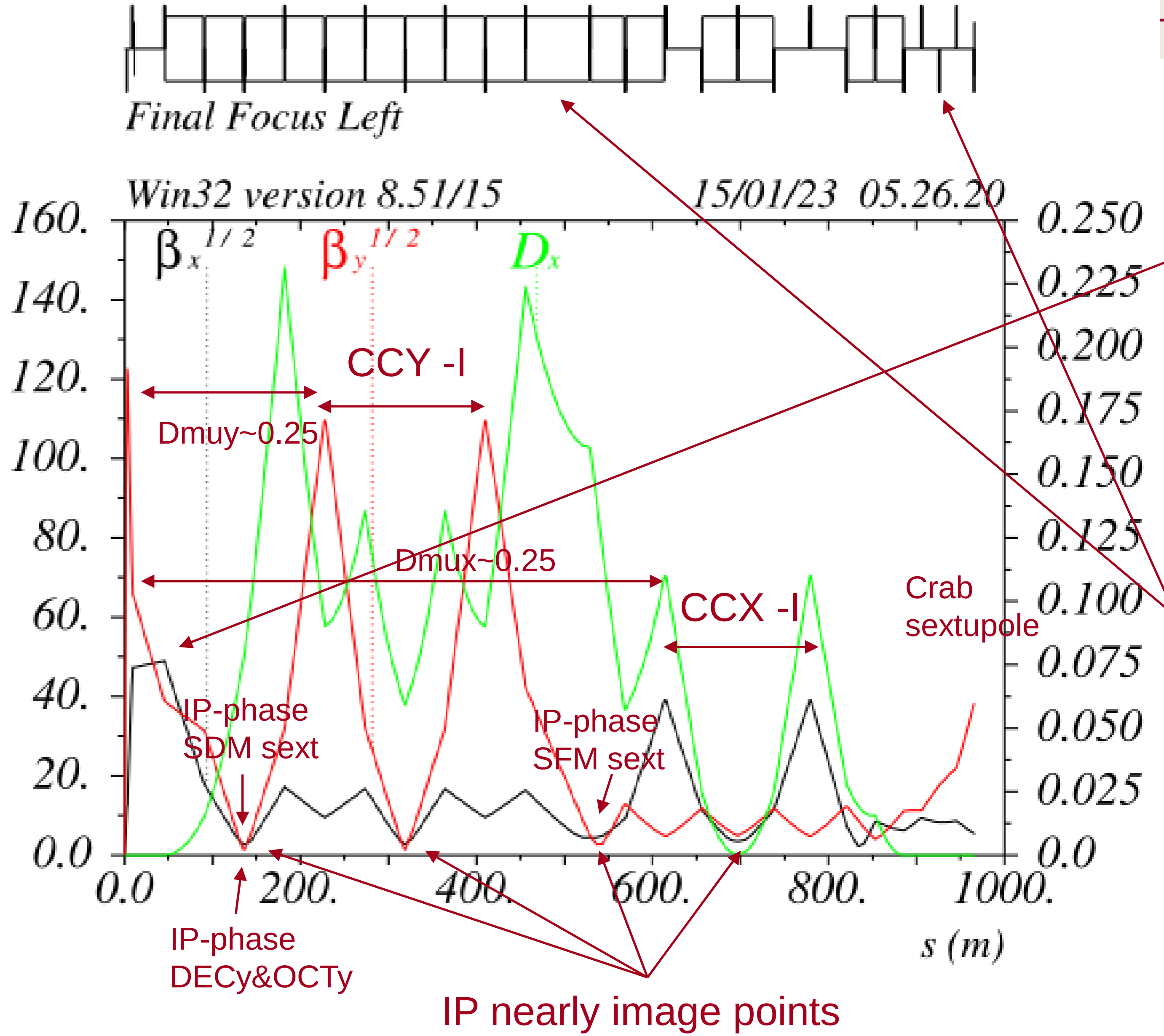
- Complementary crossing angles
- Distance between rings
- Overall ring length (~91.17Km)

TCs technique for the insertion has been already discussed in previous presentations

Specific LSs can be designed and inserted with TCs as needed

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

Final Focus with 5th order chromatic correction v_42a1



Changes wrt to v32a1:

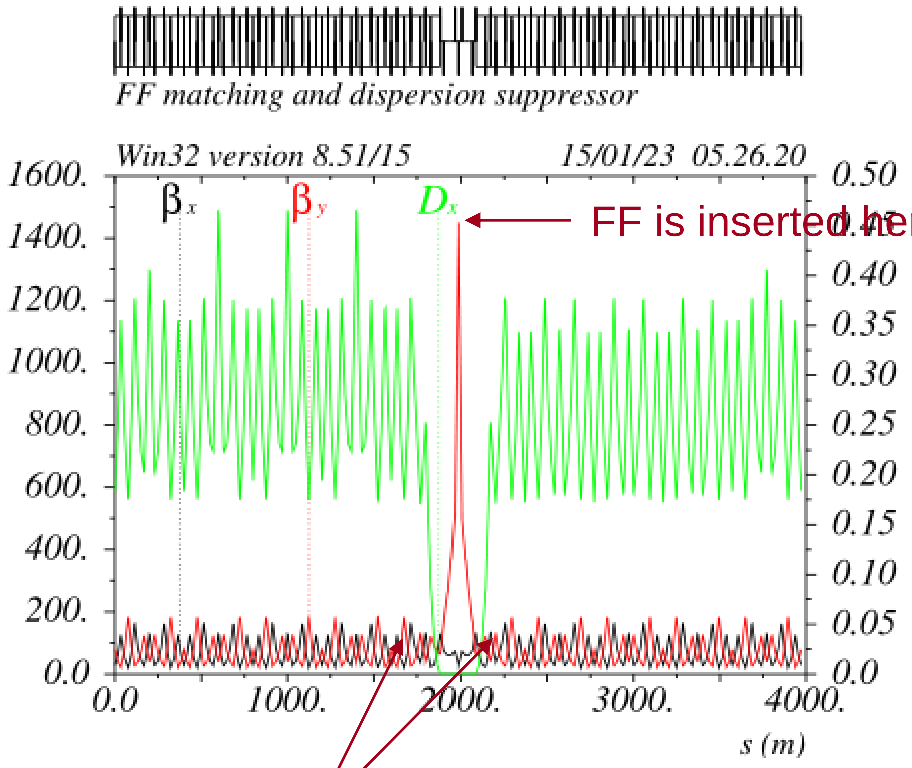
Added QF2:
- improved matching (in particular for Z-ttbar changes)
- reduced dipole BS field (EC~170KreV)
- increased distance FD-BS (~40m)

Added OCTy&OCTx:
- fourth order chromaticity corrected with OCTs and not with etap => no ddx generated, larger BW

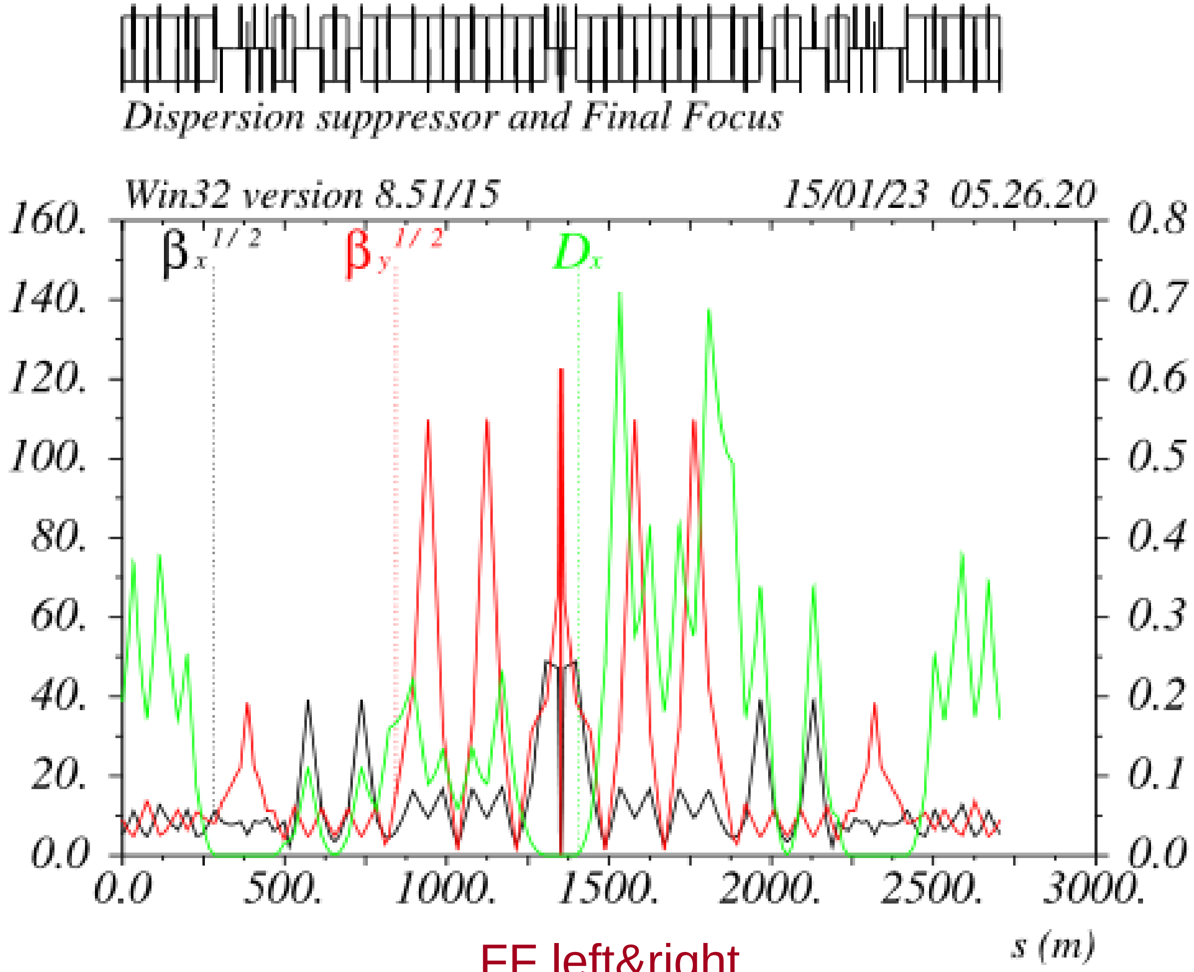
Removed QD9:
- better matching and weaker SFM, larger DA

Added QD18&QF19:
- improved matching (dipole angles not part of the matching anymore)

ARC to Final Focus match v_42a1



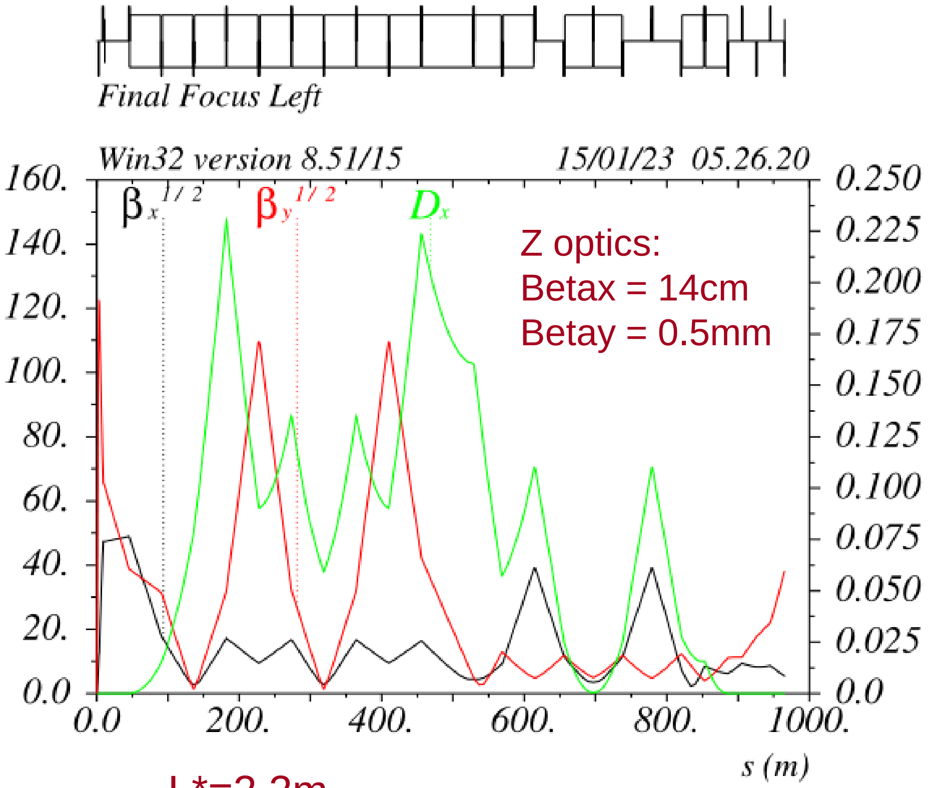
FF is inserted here

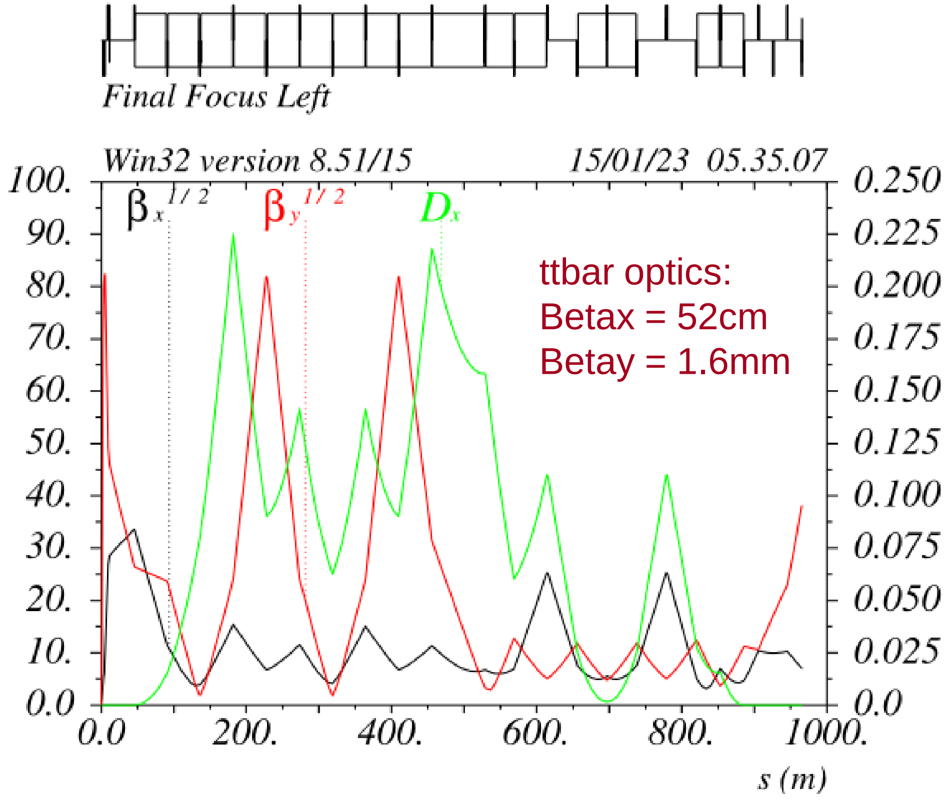


Last ARC SF sextupole is retuned to match ddx in the FF.
Retuning of the last SFs&SDs ARC sexts pairs will further improve the MA. This should be possible since the FF BW is much larger wrt full ring BW.

FF left&right
FF has mirrorlike K_Quads symmetry

Final Focus for different energies

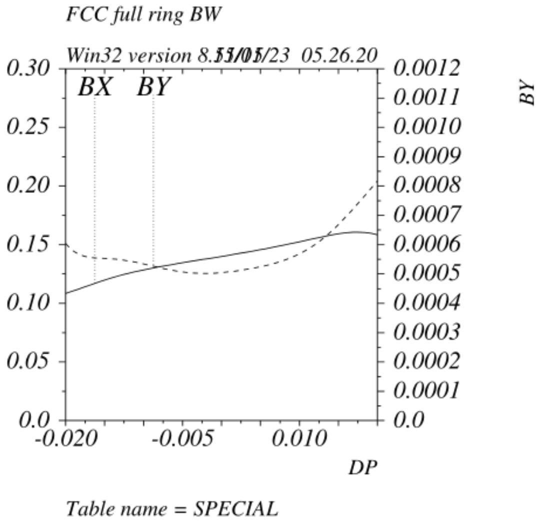


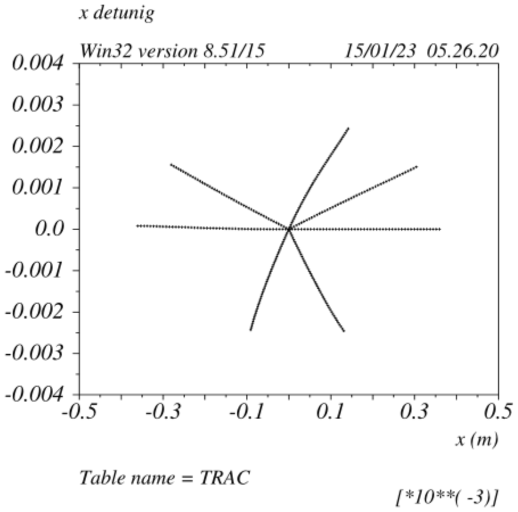


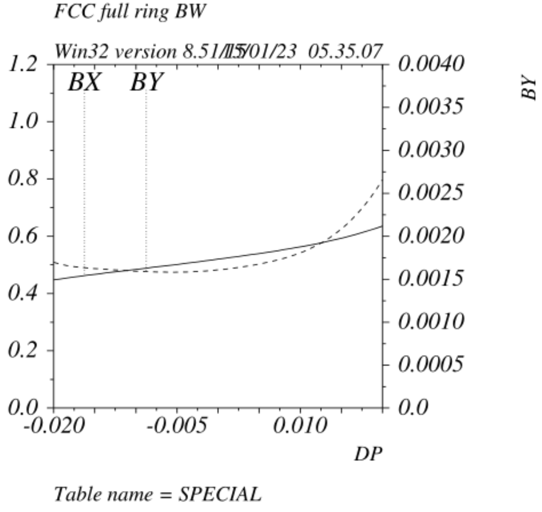
L*=2.2m
QD0 is made of QD0a&QD0b each 1.355m long (15cm apart) (left=right)
Distance between QD0b and QF1a is 3.05m
QF1 is made of QF1a&QF1b each 1.445m long (15cm apart) (left=right)

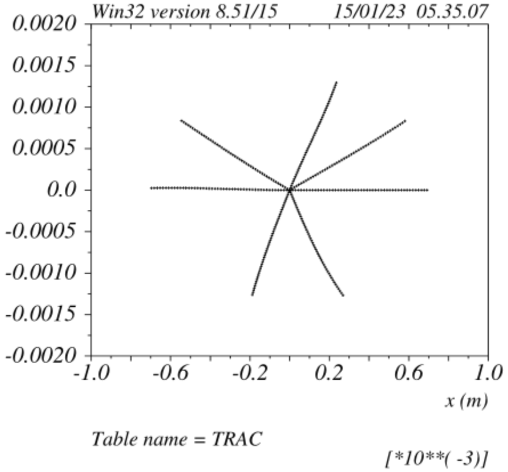
K_QD0a=K_QD0b and K_QF1a=K_QF1b @ H&ttbar   K_QD0a/b~95T/m @ttbar
QD0b and QF1b are off for Z&W (about 20%gain in y-chromaticity)
K_QD0a~95T/m @W&ttbar   K_QF1 at least twice weaker

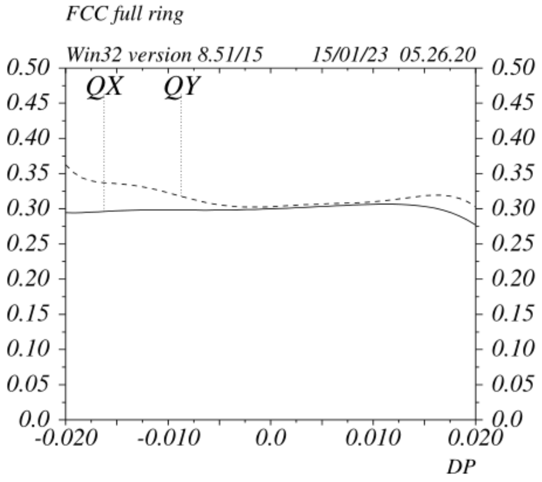
Full ring DA&MA v_42a1 & v_42b1

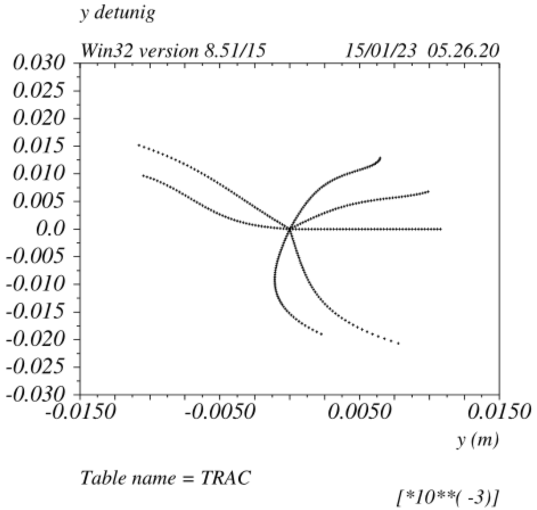


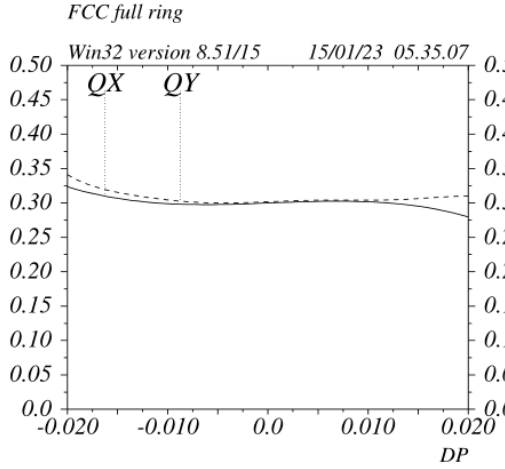


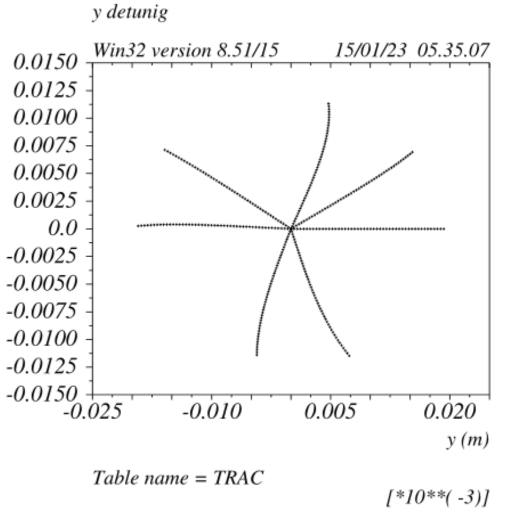




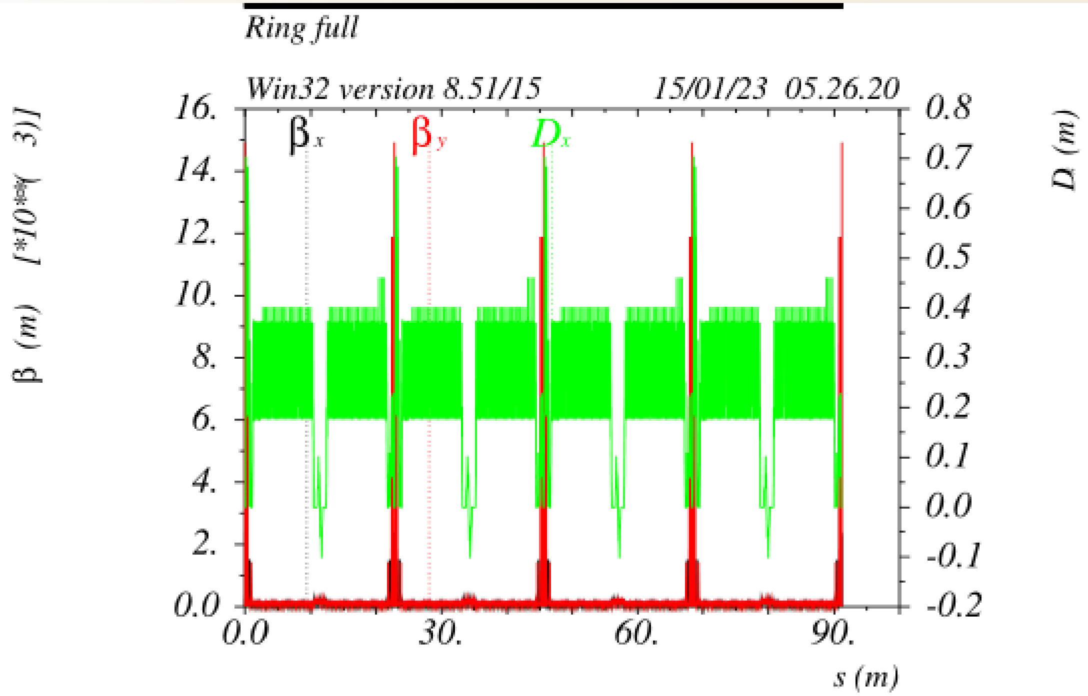


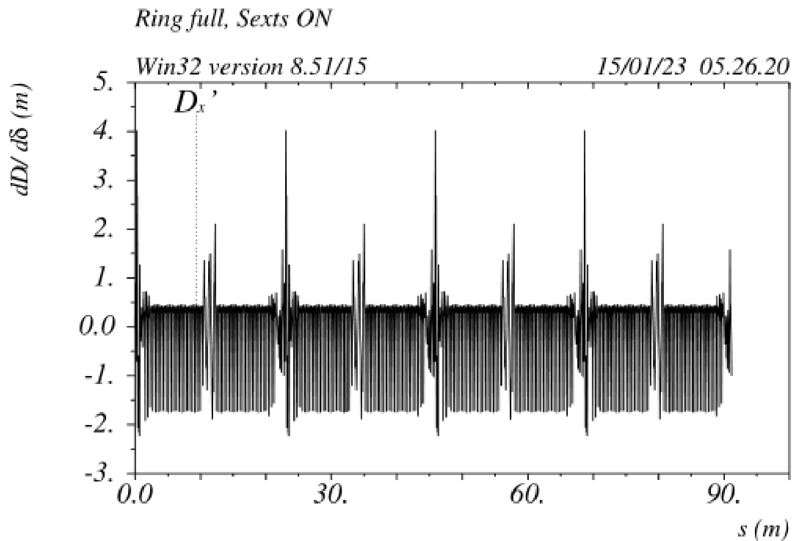


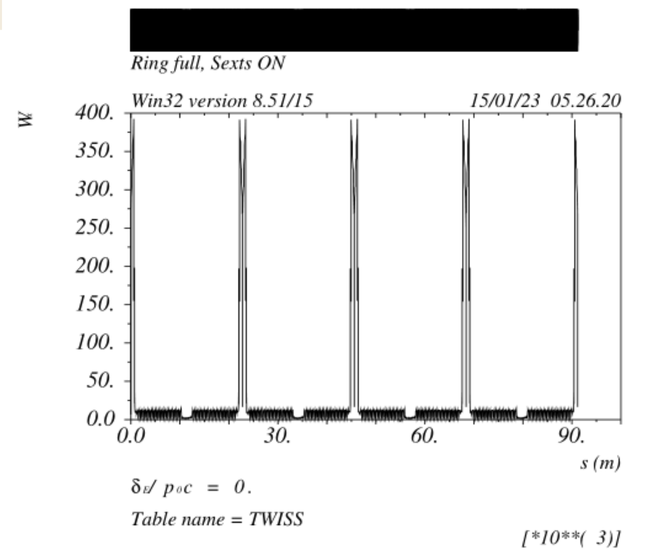


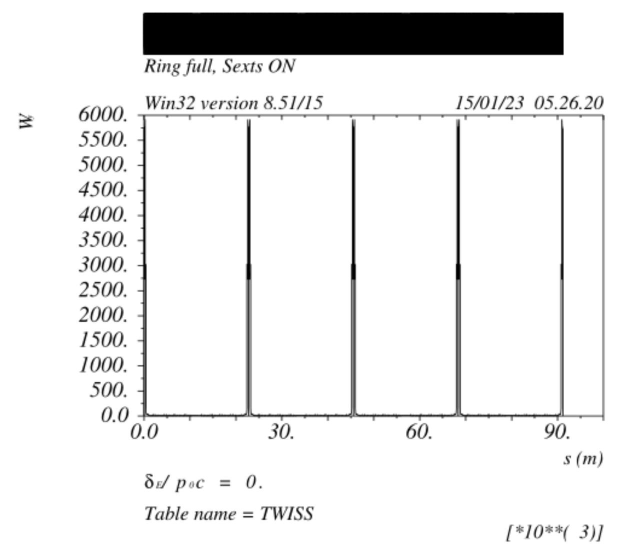


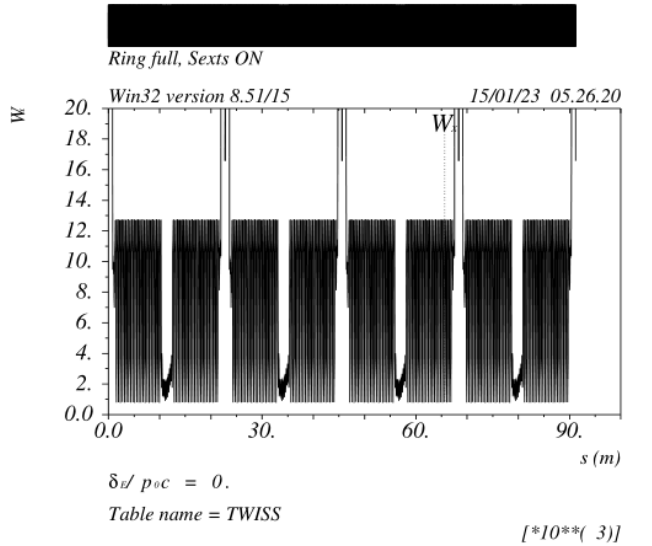
Ring optics and chromatic properties v_42a1

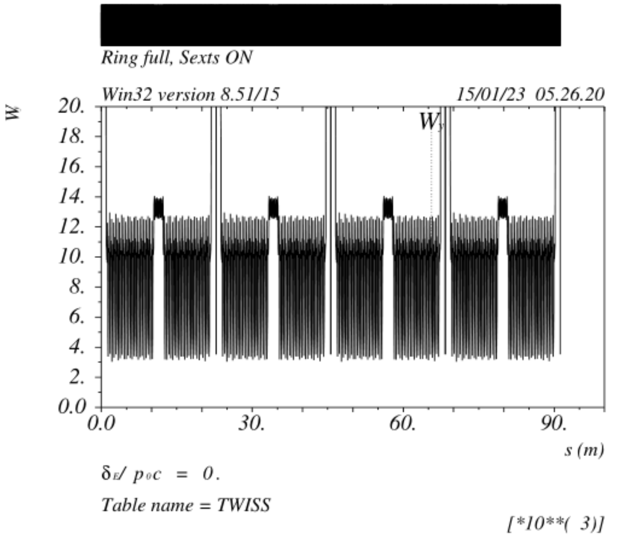




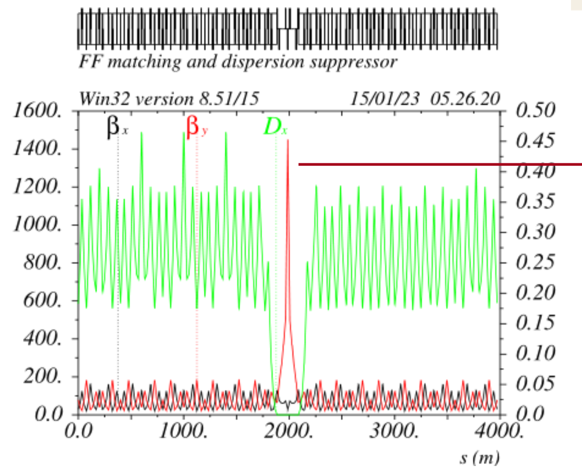


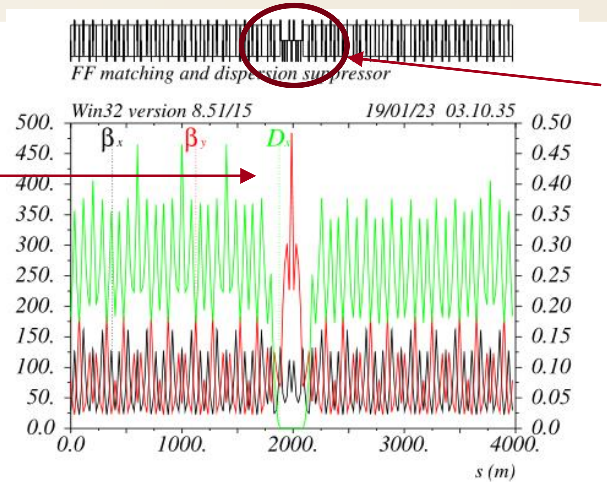




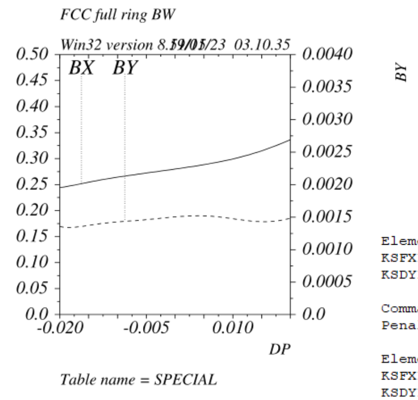


FF properties: Changing beta*   v_42a1





With the 8 matching quads upstream the FF, the IP betas can be changed at will and just a minor retuning of the Sextupoles in order to recover the TCs is needed

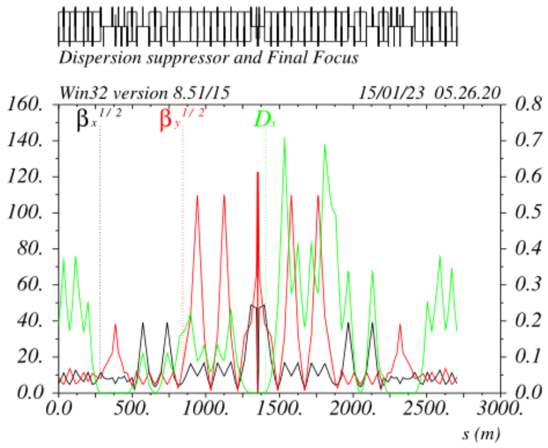


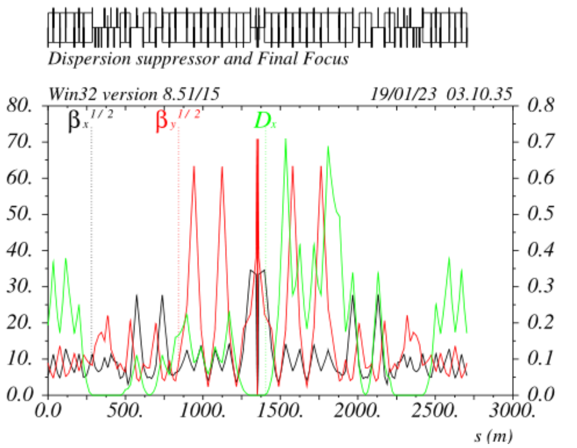
In this example:
betax is doubled
betay is tripled

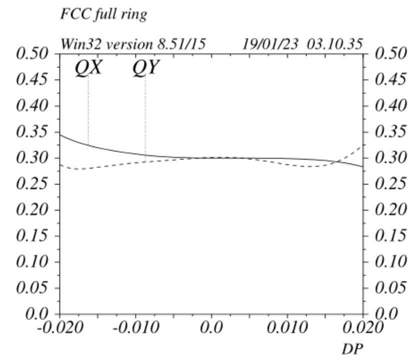
```
! bx=14cm  by = 0.5mm
 KQDM10L =  -4.179726E-02
 KQFM9L  =   2.812699E-02
 KQDM6L  =  -1.361338E-02
 KQFM5L  =   2.969904E-02
 KQDM4L  =  -2.871961E-02
 KQFM3L  =   3.506099E-02
 KQDM2L  =  -5.194422E-02
 KQFM1L  =   3.134378E-02

! bx=28cm  by = 1.5mm
 KQDM10L = -4.092830E-02
 KQFM9L  =  2.936331E-02
 KQDM6L  = -2.576348E-02
 KQFM5L  =  3.341134E-02
 KQDM4L  = -3.265595E-02
 KQFM3L  =  3.430527E-02
 KQDM2L  = -4.449499E-02
 KQFM1L  =  3.072792E-02
```

FF sexts

```
Element              attribute                  value
KSFX1L                                          2.377443E+00
KSDY1L                                         -4.923311E+00

Command: LMDIF                     Time:         1.078
Penalty function:                          8.617927E-23

Element              attribute                  value
KSFX1L                                          2.368825E+00
KSDY1L                                         -4.848025E+00
```

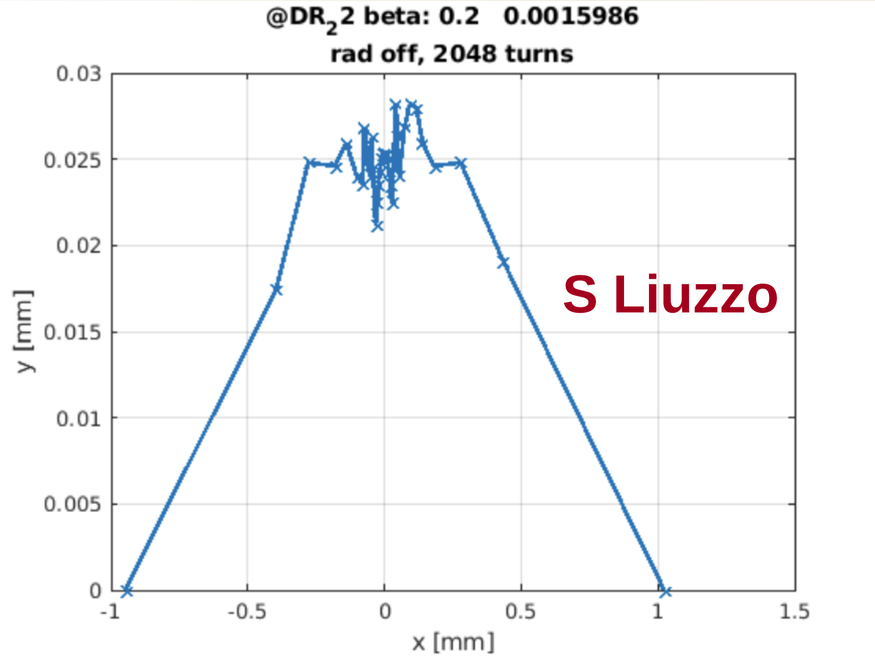







```
! sextupoles, octupoles and decapoles for full ring bx=14cm by=0.5mm
KSF1 = 0.6350*sxt_on
KSF1_SL = 0.7140*sxt_on
KSF1_SR = 0.5560*sxt_on
KSF1_FL = (0.2350-0.0300)*sxt_on
KSF1_FR = (0.2350+0.0300)*sxt_on

KSD1   = -0.6530*sxt_on

! sextupoles, octupoles and decapoles for full ring bx=28cm by=1.5mm
KSF1 = 0.6500*sxt_on
KSF1_SL = 0.7290*sxt_on
KSF1_SR = 0.5710*sxt_on
KSF1_FL = (0.2100-0.0300)*sxt_on
KSF1_FR = (0.2100+0.0300)*sxt_on

KSD1   = -0.7080*sxt_on
```

Transverse beam dynamics v_34a1



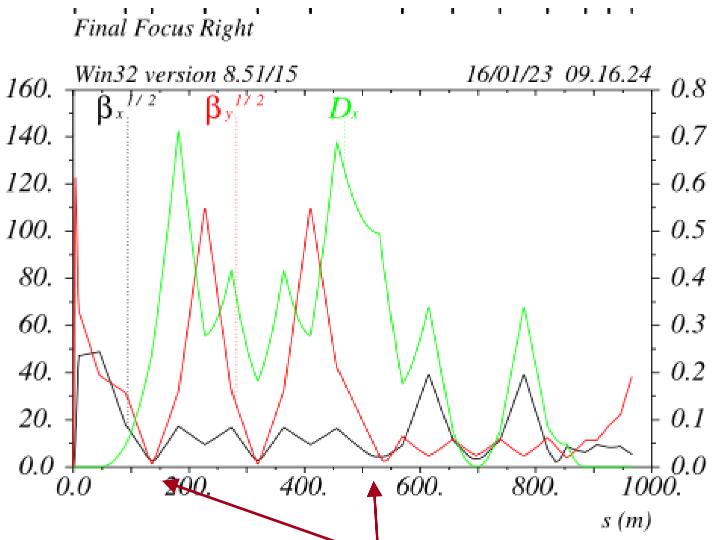
Transverse acceptance transported to the ARC with betax_max~betay_max~200m is about:

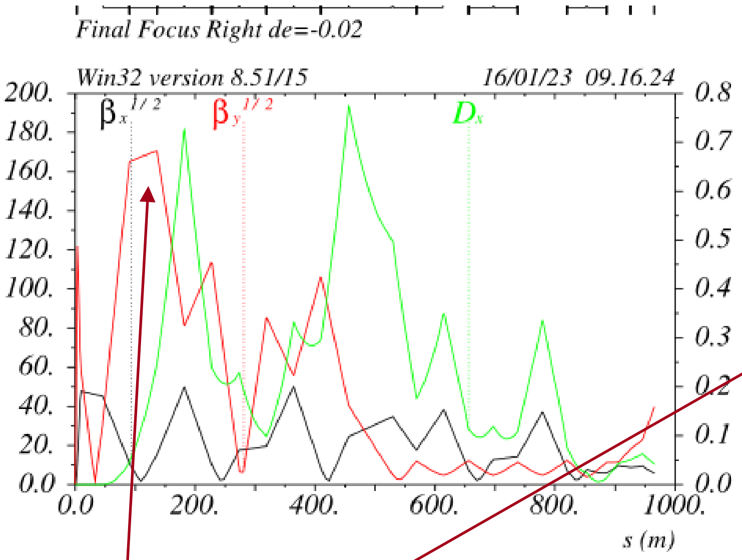
30mm/9mm x/y respectively (tracking with AT/PTC)

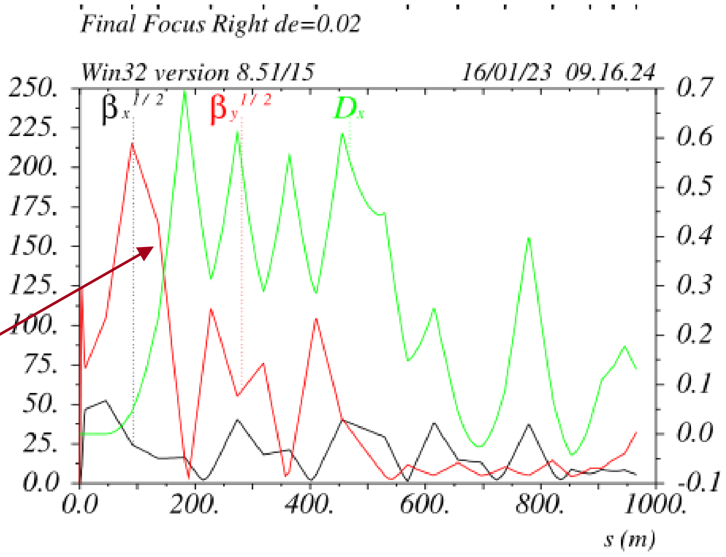
Injection requirements and efficiency will improve

Collimation system can greatly benefit from improved DA
Impedance contribution from collimators will decrease as well

Non-linear beam dynamic and collimation







Chromatic dbetas are very small everywhere except near the IP (unavoidably)

Very interestingly the largest chromatic betas are at the first image point downstream the IP
A collimator in this location is the most non-linear collimator we can imagine (Wy~several thousands)
It could be extremely effective in collimating off-energy large y-amplitude particles with negligible impact on impedance and lifetime
The third image point could work for the horizontal as well

Machine parameters

The FCC-LCC optics can be made to match almost exactly the present machine parameters.
However the LPA&CW scheme has the property that the luminosity increases with 1/Emix if betay* can be (indefinitelyt) lowered with srqt(Emix).
FCC-LCC has a very large BW, it is worth to explore its performances with parameters optimized with lower Emix and betay* at Z/W.

Main advantages could be:

- same optics for all cases,
- reduced tuning and peak luminosity ramp-up time
- reduced number of ARC magnets
- weaker ARC gradients
- relaxed ARC tolerances
- reduced magnet power consumption
- reduced synchrotron radiation
- reduced beam current
- reduced beam power
- reduced collective effect, in particular instability thresholds
- reduced accelerator cost and operation costs

If detailed studies prove this possibility unfeasible, FCC-LCC can be updated to match the present parameter

Parameters table

(Bold: computed values)		FCCee Z	FCCee W	FCCee H	FCCee ttbar
Parameter	Units				
LUMINOSITY	$cm^{-2}\ s^{-1}$	**1.83E+36**	**1.95E+35**	**6.93E+34**	**1.21E+34**
Pinch effect Shatilov		**1.93E+36**	**2.05E+35**	**7.27E+34**	**1.27E+34**
Energy	GeV	45.6	80	120	182.5
Circumference	m	91170	91170	91170	91170
X-Angle (full)	mrad	30	30	30	30
β_x @ IP	m	0.13	0.16	0.2	0.52
β_y @ IP	mm	0.5	0.8	1.1	1.6
Coupling (full current)	%	0.1	0.1	0.1	0.1
Emittance x (without IBS)	nm	0.19	0.57	1.24	2.83
Emittance x (with IBS)	nm	0.19	0.57	1.24	2.83
Emittance y	pm	**0.188**	**0.57**	**1.24**	**2.83**
Momentum compac	mm	1.78E-05	1.78E-05	1.78E-05	1.78E-05
Bunch length (zero current)	mm	3.7	3.9	4.2	4.7
Bunch length (in collision)	mm	10.9	7.02	6.1	5.3
Beam current	mA	720	70	23	4
Number of bunches	#	16000	1000	200	20
RF frequency	Hz	4.00E+08	4.00E+08	4.00E+08	4.00E+08
Revolution frequency	Hz	**3.29E+03**	**3.29E+03**	**3.29E+03**	**3.29E+03**
Harmonic number	#	**121644**	**121644**	**121644**	**121644**
N. Particle/bunch	#	**8.553E+10**	**1.330E+11**	**2.186E+11**	**3.801E+11**
σ_x @ IP	microns	**4.94**	**9.55**	**15.75**	**38.36**
σ_y @ IP	nm	**9.70**	**21.35**	**36.93**	**67.29**
σ_x @ IP	cm	**0.000494**	**0.000955**	**0.001575**	**0.003836**
σ_y @ IP	cm	**0.00000097**	**0.00000214**	**0.00000369**	**0.00000673**
$\sigma_{x'}$ @ IP	microrad	**38.0**	**59.7**	**78.7**	**73.8**
$\sigma_{y'}$ @ IP	microrad	**0.019**	**0.027**	**0.034**	**0.042**
Piwinski angle	rad	**33.07**	**11.03**	**5.81**	**2.07**
σ_x effective	microns	**163.59**	**105.74**	**92.85**	**88.28**
σ_x effective	cm	**0.0164**	**0.0106**	**0.0093**	**0.0088**
Hourglass reduction factor		0.950	0.950	0.950	0.950
Tune shift x		**0.0021**	**0.0055**	**0.0100**	**0.0392**
Tune shift y		**0.1354**	**0.1354**	**0.1356**	**0.1426**
Energy Loss/turn	MeV	31.8	300	1530	8150
SR power loss	MW	**22.90**	**21.00**	**35.19**	**32.60**
RF Wall Plug Power (SR only)	MW	**45.79**	**42.00**	**70.38**	**65.20**

SLAC

Given the more relaxed optics the coupling is supposed to be (at least) a factor 2 better wrt present assumptions: ~1.0e-3
This should be carefully estimated with simulations and comparison with the present optic

The table is extremely preliminary

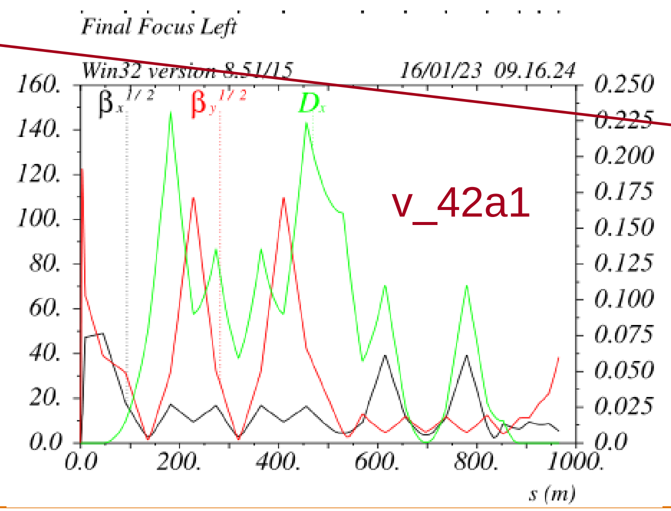
All parameters need to be readdressed/reassessed/verified/reoptimized

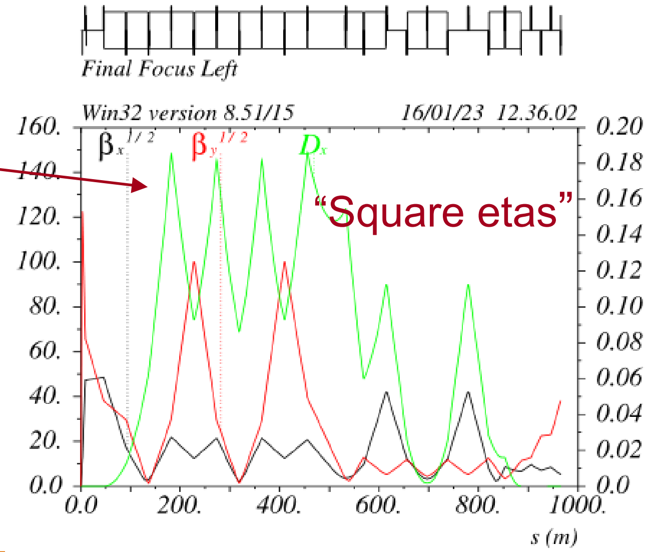
Optics evolution to do list

The arc HFD lattice can be easily modified to match the present emittances/alphac, however it will be a suboptimal solution, since it will correspond to a machine that does not exploit the full potential of its optical properties, in particular betay* will be limited by the horizontal emittance and not by DA&MA requirements.

The FF dipoles profile should be further optimized in order to reduce the SR power/fan from the dipoles upstream the FF. Presently Ec~170KeV, this value at the moment is not a compromise with SR requirements, it is very much the optimal from optics considerations.

The FFTB (John Irwin design) had “square etas” across the CCSy => much weaker dipoles upstream the IP. I have still been unable to achieve the maximum BW in this configuration (**for the full ring**), mainly because of not optimal compensation of high order dispersion contributions from quads and dipoles

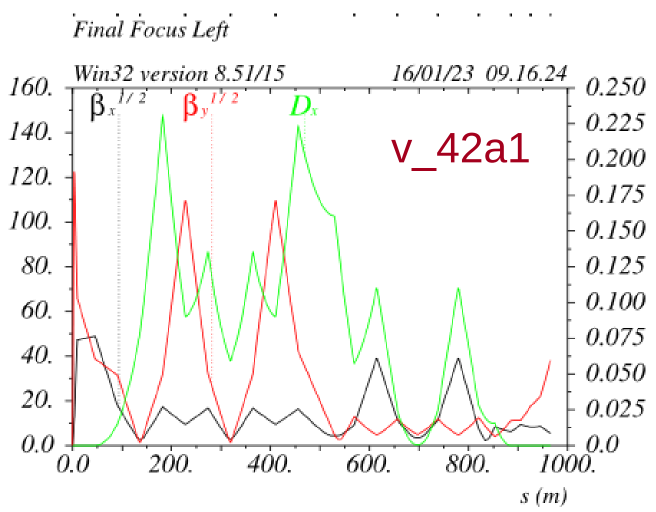




Optics evolution to do list

Total FF bend angle can be decreased as well, in general this results in:

- Weaker dipoles
- Stronger CCS(y) sextupoles and smaller (alignment) tolerances
- Smaller DA (linearly) and smaller MA (weak dependance)



Effect on DA of FD (just QD0) fringe fields and its compensation not included so far

Effect on DA/MA of Crab Sexts and its compensation not included so far

Ring DA is primarly determined by the CCSy long sexts aberration (LSA).

All the sexts in the rings are paired and the relative LSA effect is negligible.

LSA compensation from CCSy sexts could be further improved with additional non-linear elements and additional optics tricks.

Back up

Conclusions

The exploitation of novel methods to insert specific optical segments in a periodic ARC lattice with minimum impact of optical properties leads to:

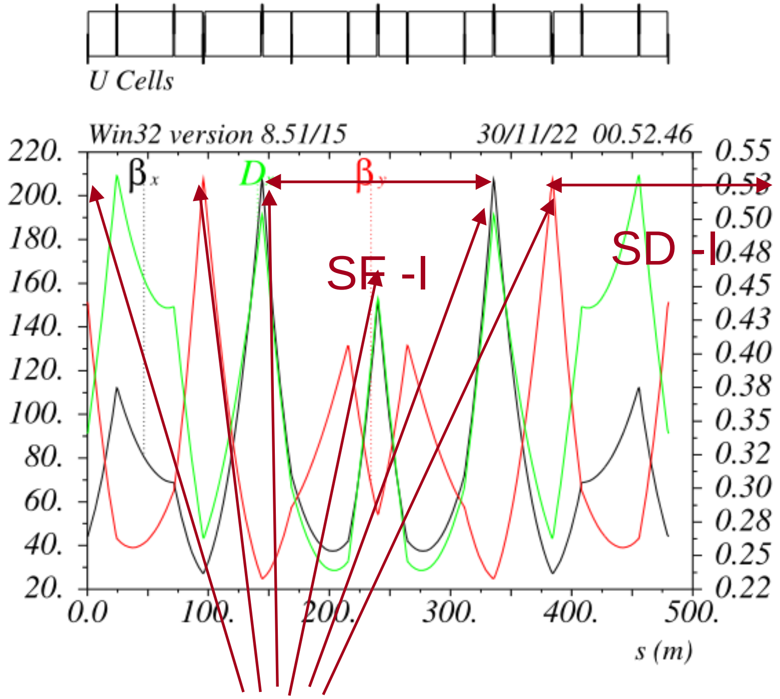
- Improvements in overall machine performances
- Simplifications of the overall optic
- Better understanding of the beam dynamics of specific subsystems and the resulting machine as a whole
- Relaxed requirements on accelerator components, in particular magnets gradients and tolerances
- Simplification of tuning procedures
- Increase the likelihood of reaching “close to ideal” machine parameters

FCC case has been used just as an example to demonstrate the effectiveness of this method.

Very generally it could be applied for the design of a large variety of new accelerators, further extending their ultimate performances.

The possibility to effectively implement it for FCCee will require a much more careful and detailed study.

ARC orbit and betabeating/dispersion/emittance control



ARCs betabeating, dispersion and coupling correction can be performed as with current machines, eg EBS:

- the reconstructed errors (quads and skews) are supposed to be originated only at the sextupole locations,
- the correction applied is = -errors.
- The correction can be applied just by changing the reference orbit on the sextupole BPMs (that will generate the required quads and skew components) as for the LEP-DFS case

…to be checked

In principle BPMs and correctors could be placed only on the high-beta locations:
6 BPMs and correctors(x&y) per ARC cell => ~960 total for the ARCs
Orbit will be controlled at the sextupoles (angle at the sextupole will not be controlled, but sexts are ~0.3-0.6m long)
A “small” orbit distorsion will remain across the “low-beta” quads, the distorsion is of the order of the quad rms-misalignment (~100-200um) and should have negligible consequences on machine performances
Sextupoles are weak and trimming coils on the sextupoles could provide the maximum corrector strength required, resulting in saving in number of components and increasing the main dipoles filling factor