



# Status of the FCC-ee lattice design and the chromaticity correction scheme in the arcs

**Bastian Haerer (CERN, Geneva; KIT, Karlsruhe)**  
**for the FCC-ee lattice design group**





# 1) Chromaticity correction

Thanks a lot to Anton, who provided me with his macros and gave me a lot of advise!!!



# Chromaticity

$$\varphi(\delta) = \varphi_0 + \frac{\partial \varphi}{\partial \delta} \delta + \frac{\partial^2 \varphi}{\partial \varphi^2} \delta^2 + \dots$$

The first three orders, as derived by A. Bogomyagkov:

$$\begin{aligned}\frac{\partial \varphi_y}{\partial \delta} &= \frac{1}{2} \int_0^\Pi \beta_y (K_1 - K_2 \eta_0) ds, \\ \frac{\partial^2 \varphi_y}{\partial \delta^2} &= -2 \frac{\partial \varphi_y}{\partial \delta} - \int_0^\Pi \beta_y K_2 \eta_1 ds + \frac{1}{2} \int_0^\Pi \beta_y b_{y,1} (K_1 - K_2 \eta_0) ds, \\ \frac{\partial^3 \varphi_y}{\partial \delta^3} &= 6 \frac{\partial \varphi_y}{\partial \delta} - \int_0^\Pi \beta_y (K_1 - K_2 \eta_0) (a_{y,1}^2 + b_{y,1}^2) ds + \\ &+ 3 \int_0^\Pi \beta_y (K_2 \eta_1 - K_2 \eta_2) ds + \frac{3}{2} \int_0^\Pi \beta_y b_{y,2} (K_1 - K_2 \eta_0) ds.\end{aligned}$$

(A. Bogomyagkov: “Crab waist interaction region for FCC-ee and the arc second attempt”, presentation in the FCC-ee meeting no. 13, 09 February 2015)



# FCCee: Natural Chromaticity

	no IRs	4 IRs	$\Delta Q$ (1.5 %)
$Q_x$	498.85	502.16	
$Q_x'$	-554.93	-603.80	-9.06
$Q_x''$	1587.57	-8258.29	-0.93
$Q_x'''$	-8071.77	-1.4e+08	-79.31
$Q_x^{''''}$	-3.27e+09	-2.1e+12	-4.43e+03
$Q_y$	331.24	334.28	
$Q_y'$	-458.98	-2044.43	-30.67
$Q_y''$	1086.30	-8.4e+06	-944.12
$Q_y'''$	-4547.47	-2.0e+11	-1.10e+05
$Q_y^{''''}$	-3.62e+09	-6.5e+15	-1.37e+07

$$Q(\delta) = Q_0 + Q' \delta + Q'' \delta^2/2 + \dots$$



# Montague functions

- Chromatic variables

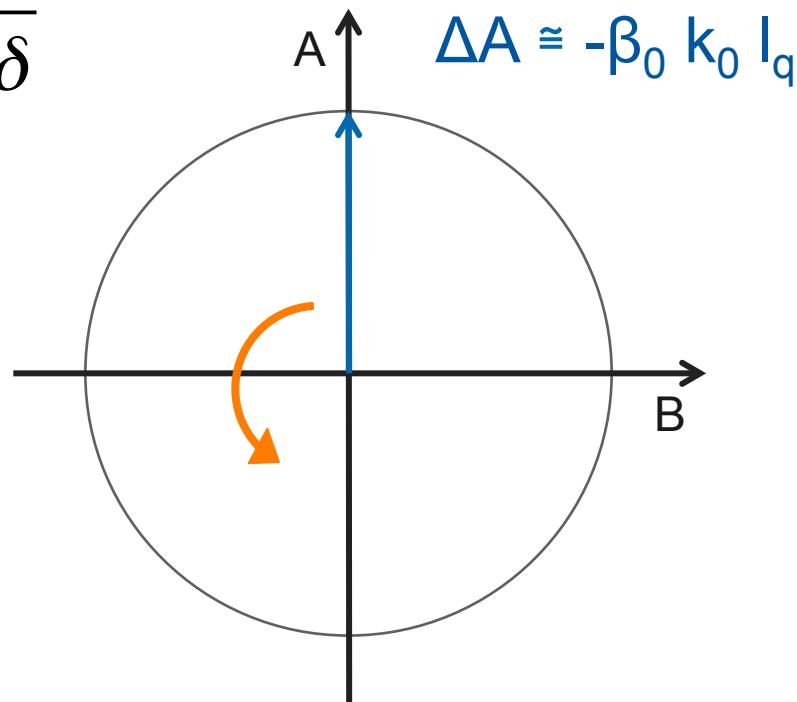
$$B = \frac{1}{\beta} \frac{\partial \beta}{\partial \delta}$$

$$A = \frac{\partial \alpha}{\partial \delta} - \frac{\alpha}{\beta} \frac{\partial \beta}{\partial \delta}$$

- W-vector

$$\vec{W} = \frac{1}{2} (B + iA)$$

$$= \frac{1}{2} \sqrt{A^2 + B^2} e^{i2\psi}$$

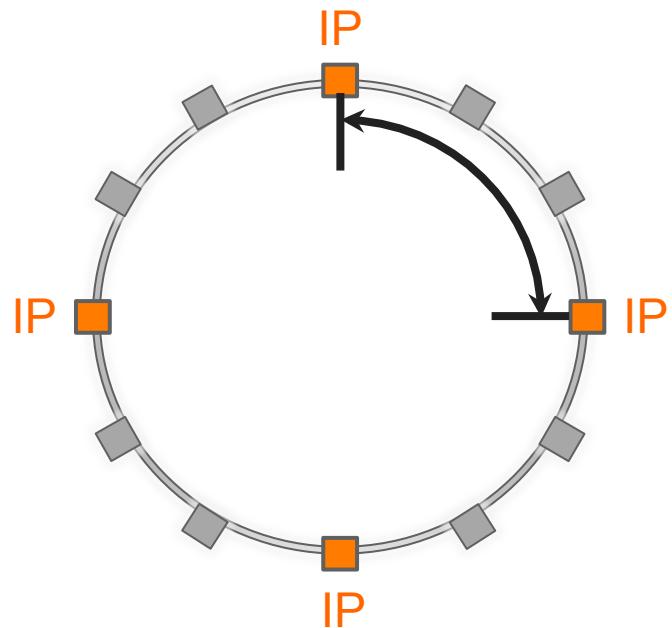


Oscillates with twice the phase advance!

# FCC-ee Lattice V15

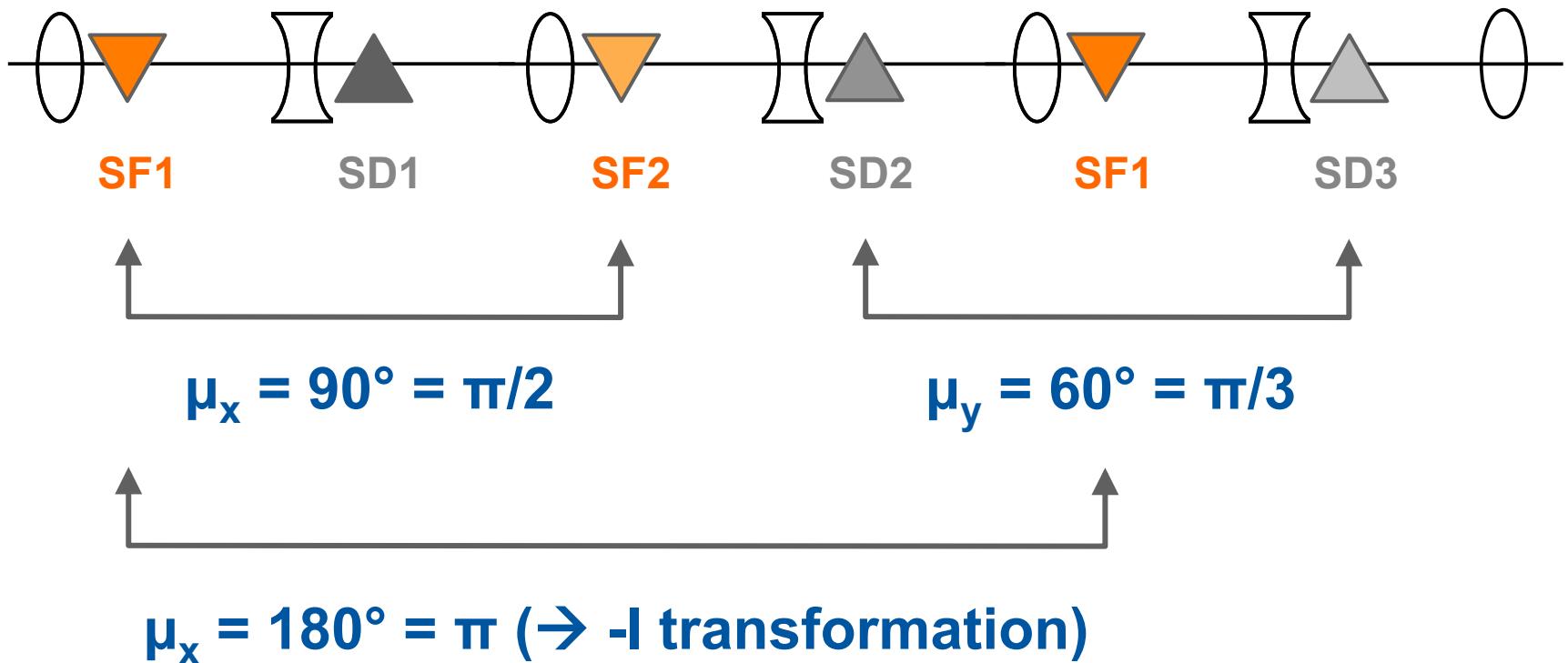
Circumference: 100 km  
Arc length: 6.8 km  
Straight section length: 1.5 km

4 LEP-like mini-beta insertions!



B = bending magnet, Q = quadrupole, S = sextupole

# FCC-ee sextupole scheme



Even number of sextupoles per family!

# -I transformation

- Sextupoles of each family are in phase

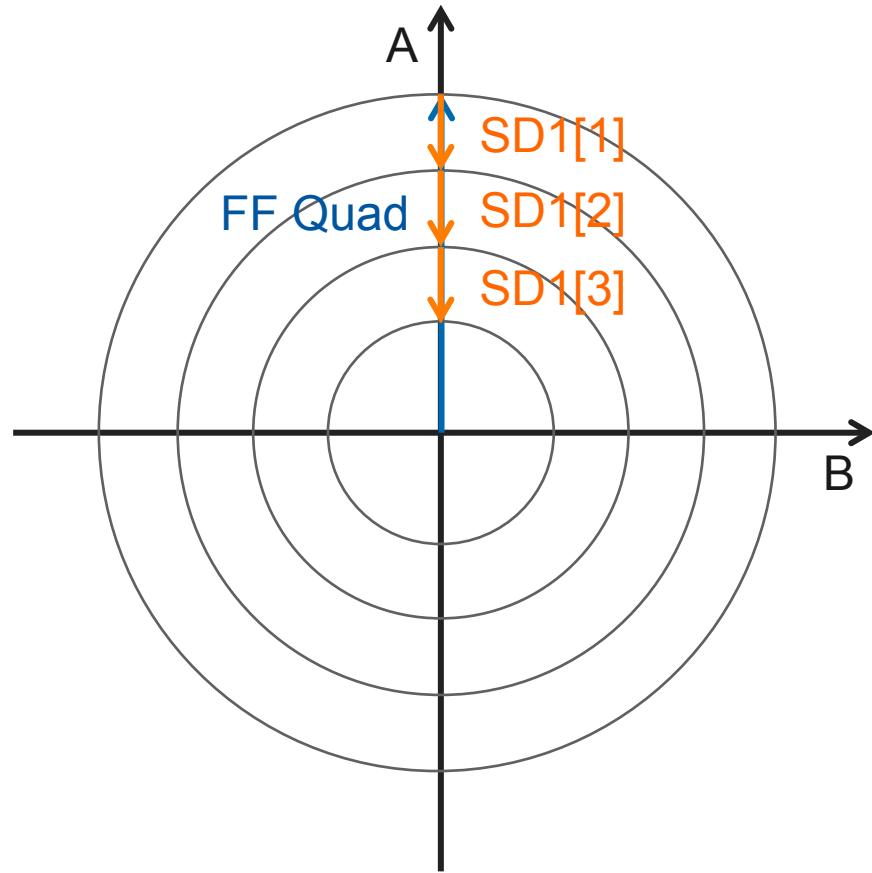
→ Even number:

$x, y, x', y'$

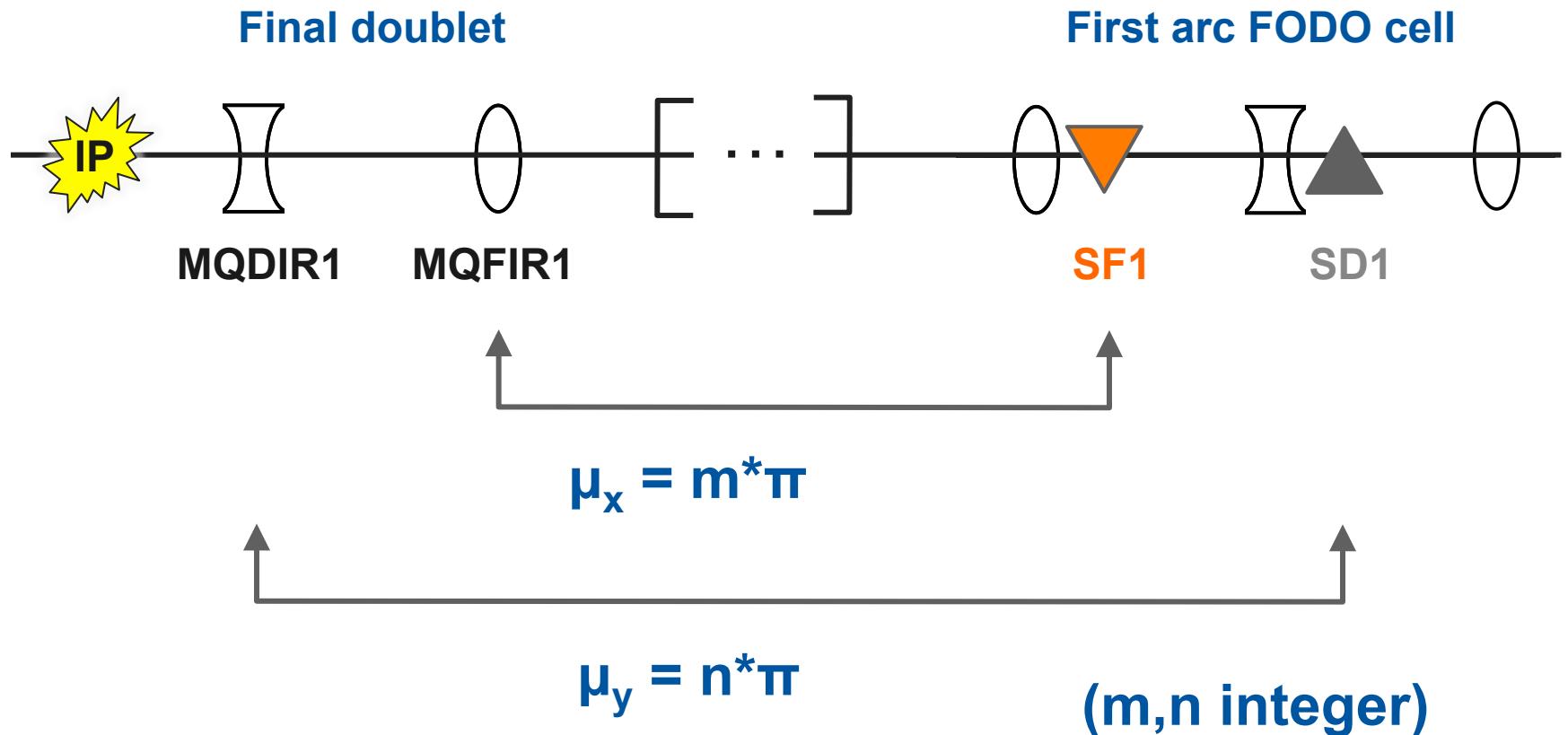
stay the same

→ W-vector

rotates by  $2\pi$



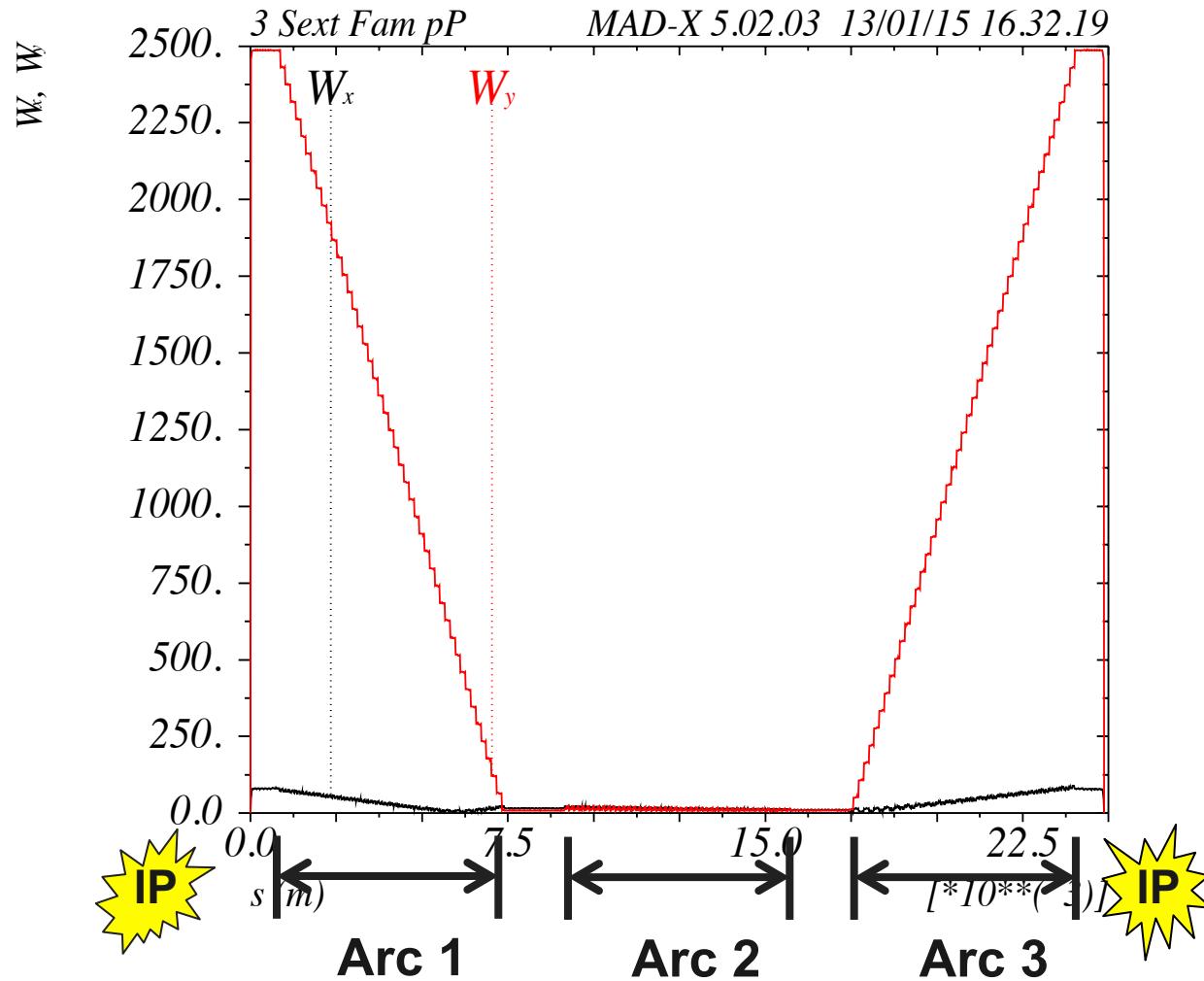
# Phase advance FD – 1<sup>st</sup> Sext.



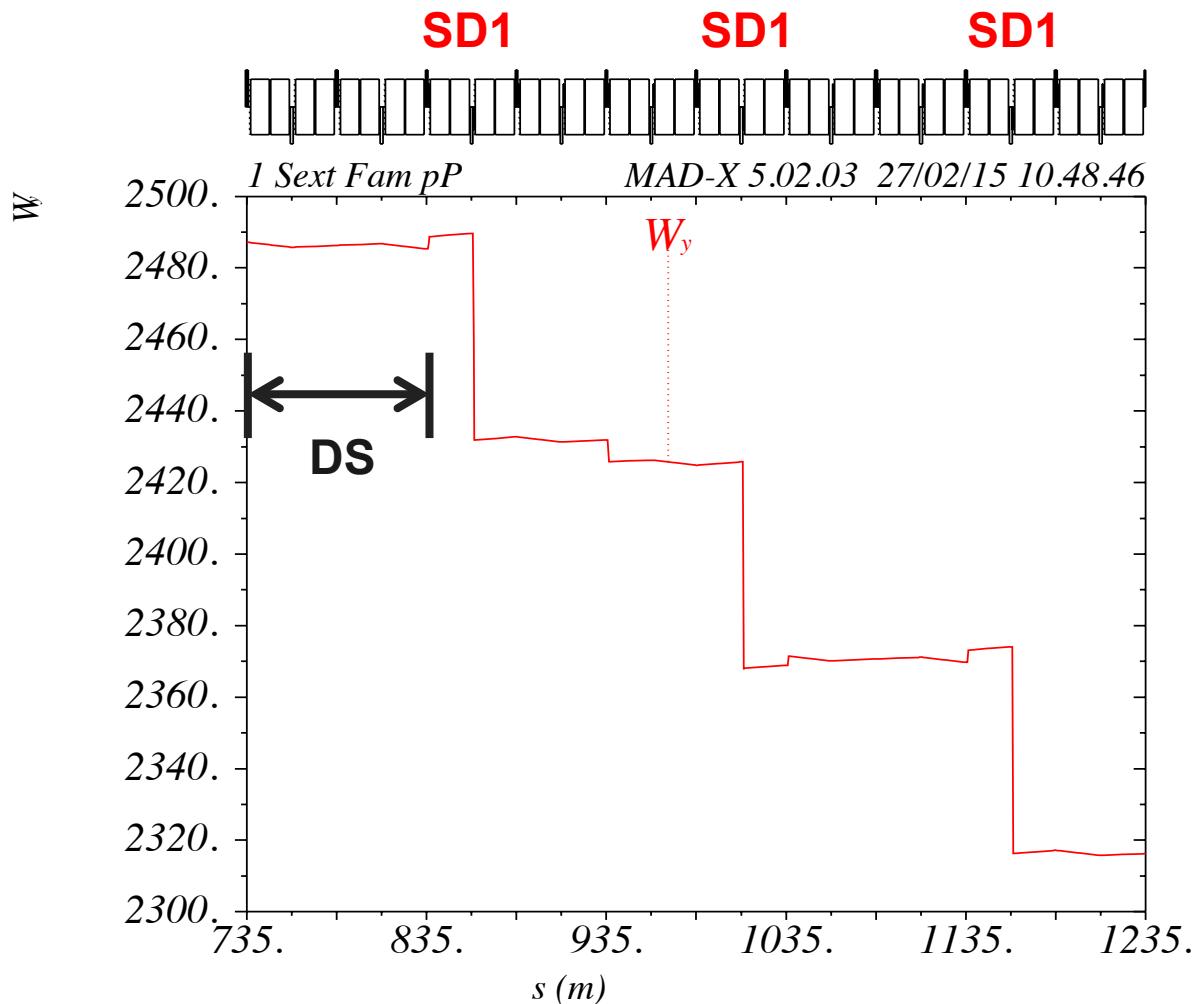
# Chromaticity correction

1. Match phase advances (FD → Sextupoles)
2. Match the tunes between IPs
3. Correct linear chromaticity (all sextupoles equal)
4. Match W functions
5. Check momentum acceptance

# W functions for 1 quarter

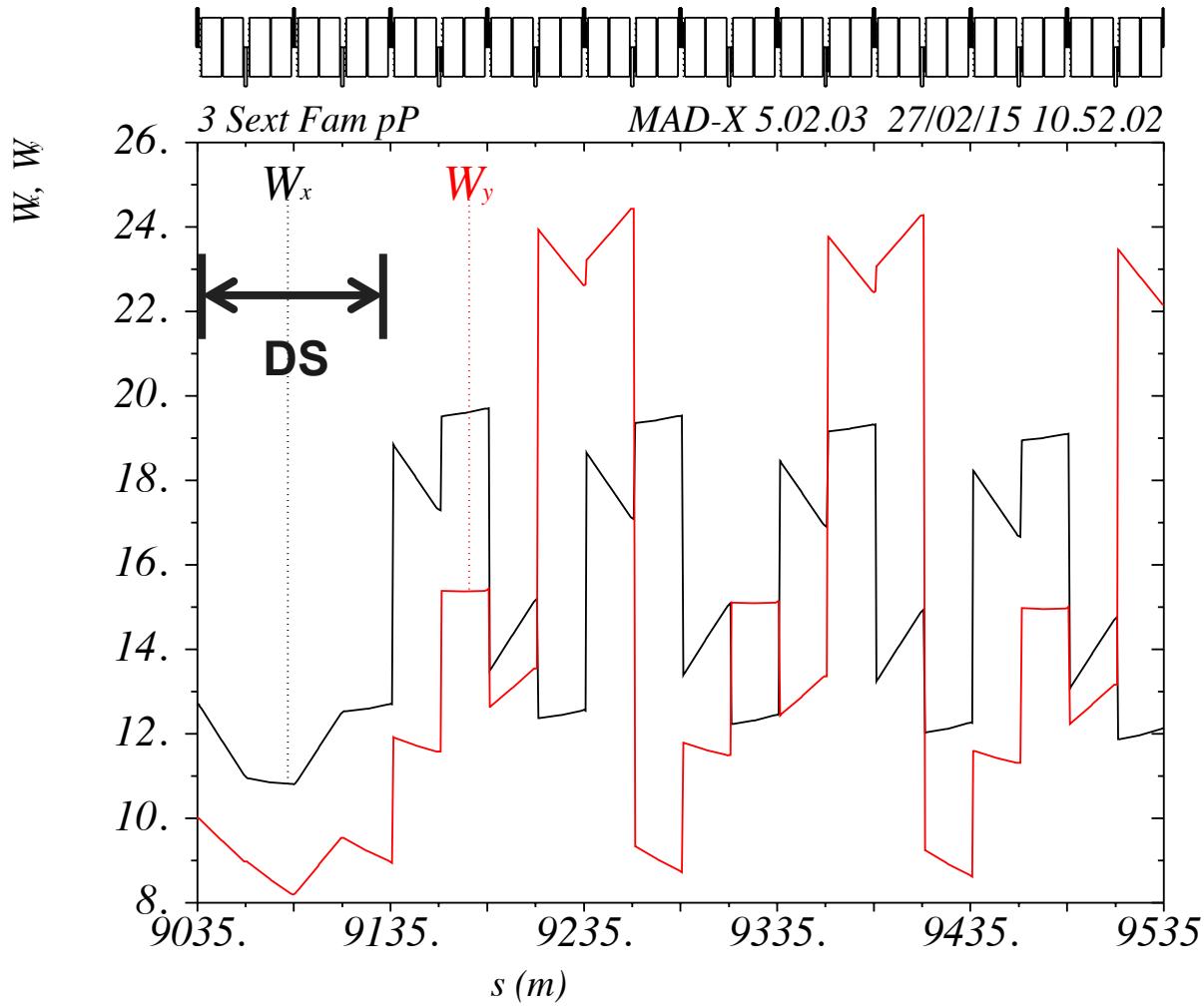


# Vertical W-function in Arc 1



$$k_{2sd1} = -18.44 \text{ } 1/\text{m}^3$$
$$k_{2sd2} = -0.11 \text{ } 1/\text{m}^3$$
$$k_{2sd3} = -0.19 \text{ } 1/\text{m}^3$$

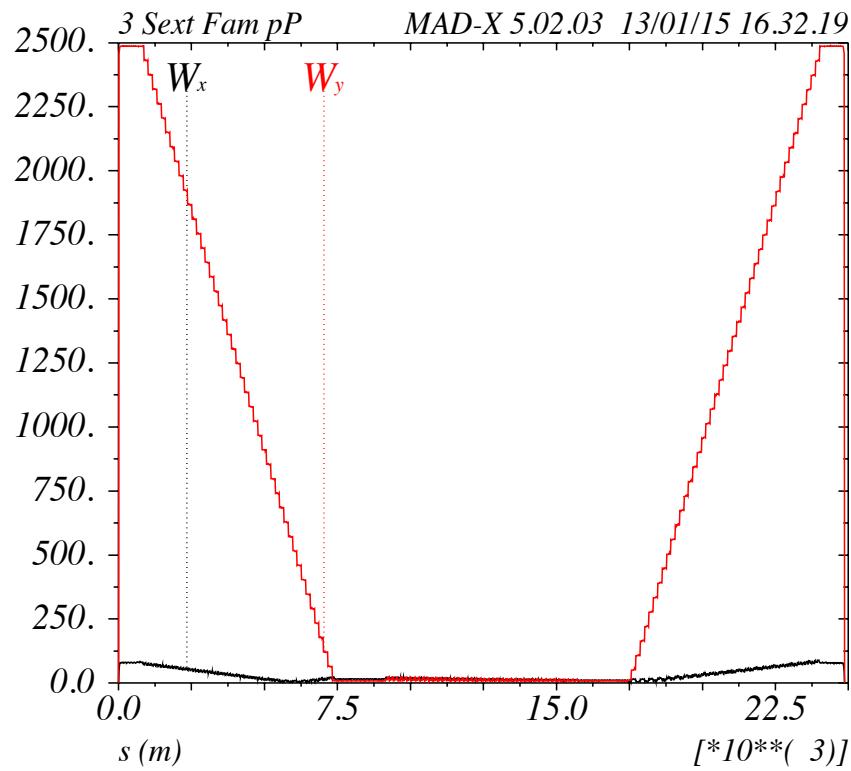
# W-functions in Arc 2



$$\begin{aligned}k_{2sd1} &= -6.22 \text{ } 1/\text{m}^3 \\k_{2sd2} &= -6.21 \text{ } 1/\text{m}^3 \\k_{2sd3} &= -6.29 \text{ } 1/\text{m}^3\end{aligned}$$

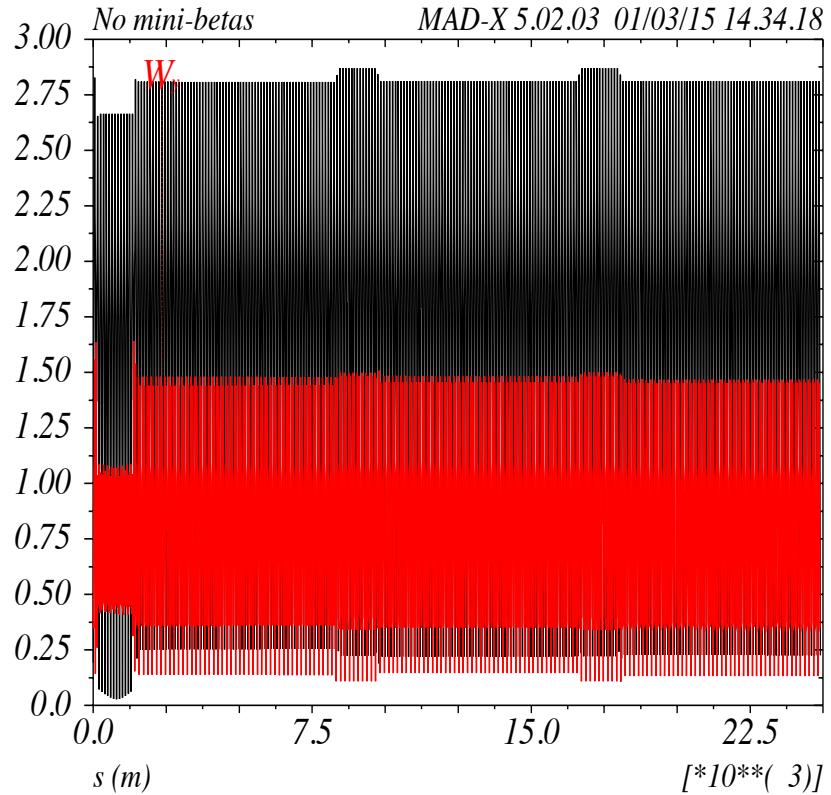
# W functions comparison

$W_x, W_y$



With IR

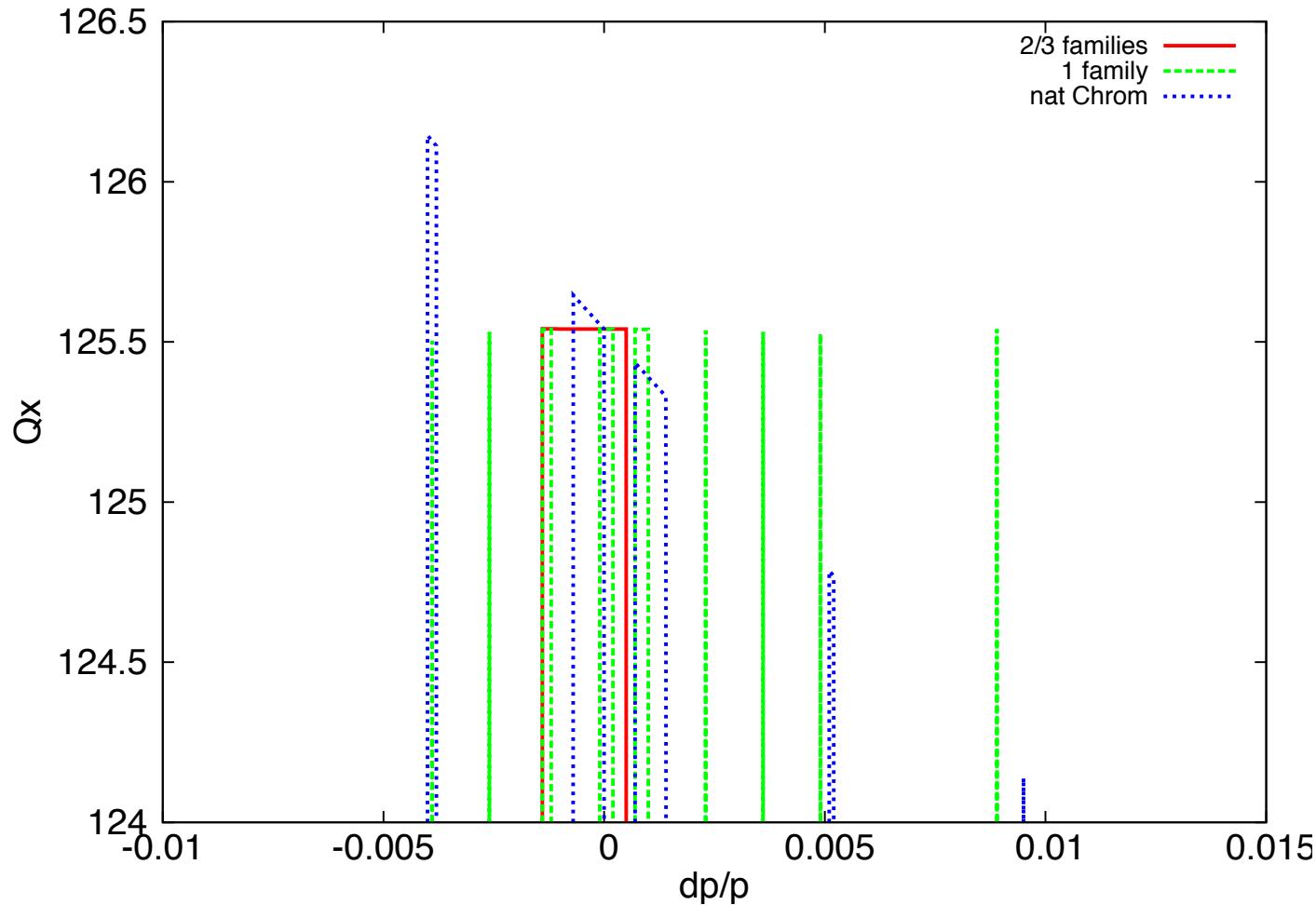
$W_x, W_y$



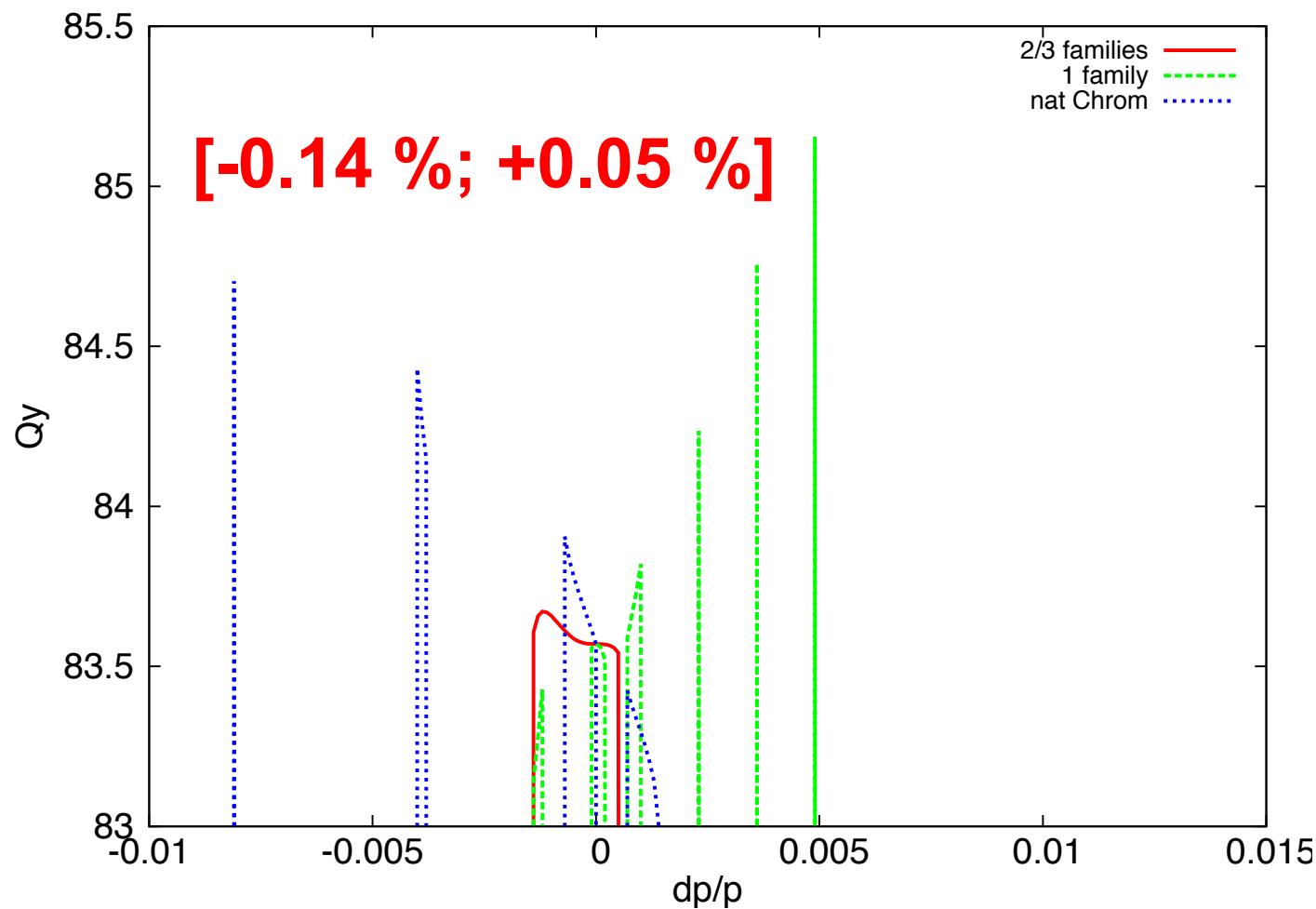
Without IR



# Momentum acceptance in x



# Momentum acceptance in y



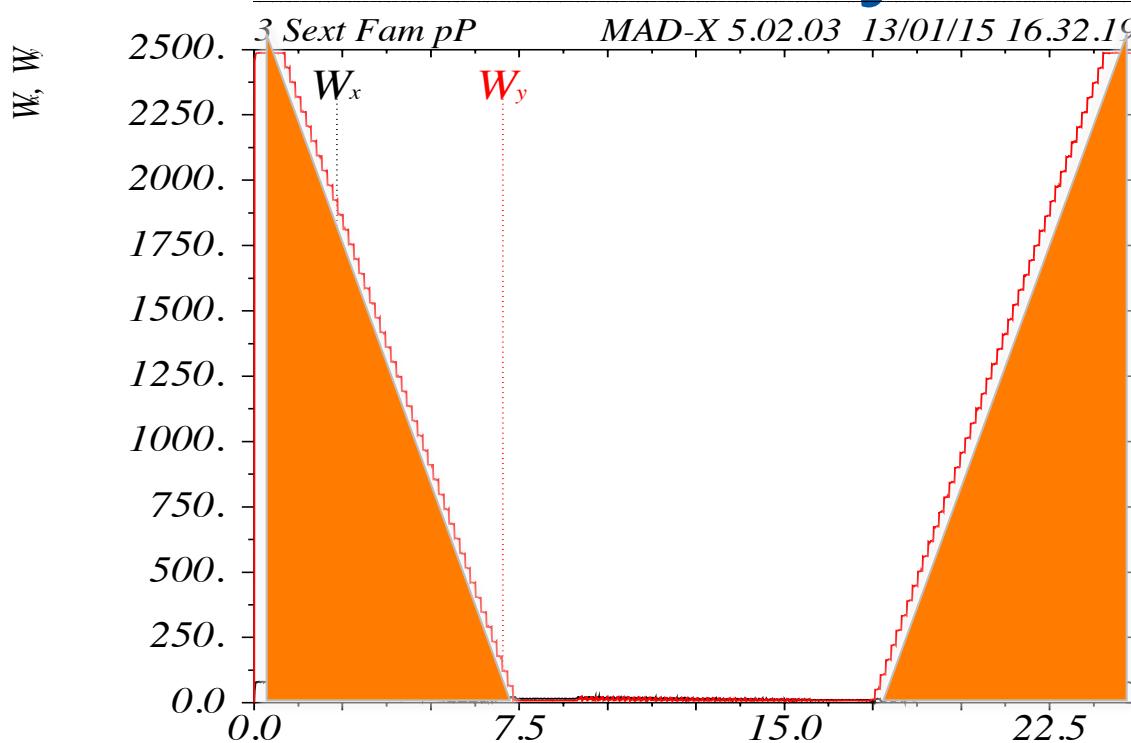
# “Corrected” Chromaticity

	Nat. Chrom.	Corr. Chrom.	$\Delta Q$ (0.05 %)
$Q_x$	502.16	502.16	
$Q_x'$	-603.80	5.7e-05	2.83e-08
$Q_x''$	-8.3e+03	3.5e+03	4.41e-04
$Q_x'''$	-1.4e+08	-5.5e+05	-1.14e-05
$Q_x''''$	-2.1e+12	-8.5e+09	-2.20e-05
$Q_y$	334.28	334.28	
$Q_y'$	-2044.43	2.8e-01	1.39e-04
$Q_y''$	-8.4e+06	-1.2e+04	-1.53e-03
$Q_y'''$	-2.0e+11	-3.4e+09	-7.00e-02
$Q_y''''$	-6.5e+15	3.6e+10	9.25e-05

(...using the whole ring.)



# 3<sup>rd</sup> order chromaticity



$$\begin{aligned} \frac{\partial^3 \varphi_y}{\partial \delta^3} = & 6 \frac{\partial \varphi_y}{\partial \delta} - \int_0^\Pi \beta_y (K_1 - K_2 \eta_0) (a_{y,1}^2 + b_{y,1}^2) ds + \\ & + 3 \int_0^\Pi \beta_y (K_2 \eta_1 - K_2 \eta_2) ds + \frac{3}{2} \int_0^\Pi \beta_y b_{y,2} (K_1 - K_2 \eta_0) ds \end{aligned}$$

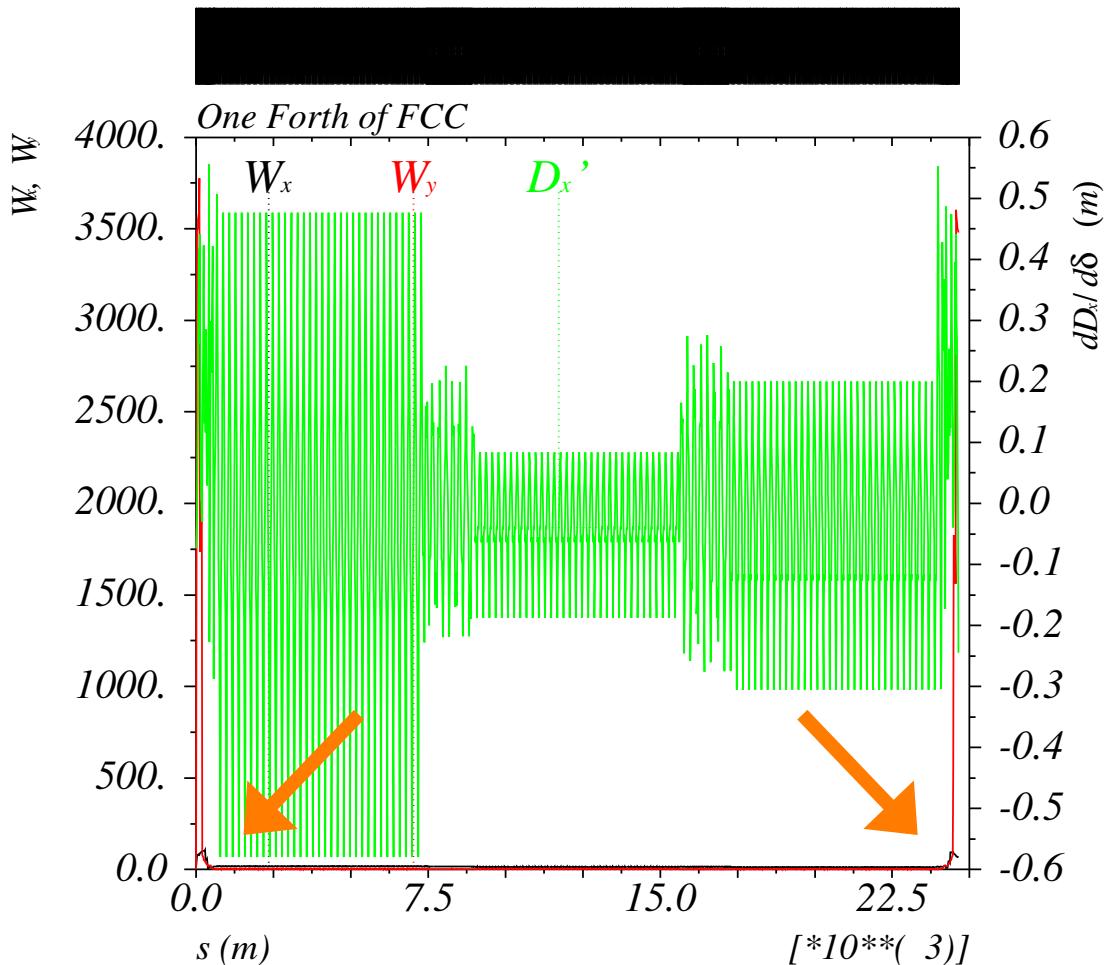
Anton Bogomyagkov



FCC-ee meeting no. 14  
2 March 2015

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Bastian Haerer (bastian.harer@cern.ch)

# Advantage of local CCS



	Value	$\Delta Q(2\%)$
$Q_x$	124.54	
$Q'_x$	0	0
$Q''_x$	170	0.034
$Q'''_x$	$-4.5 \cdot 10^4$	-0.059
$Q''''_x$	$-5.3 \cdot 10^6$	-0.035
$Q_y$	84.57	
$Q'_y$	0	0
$Q''_y$	387	0.077
$Q'''_y$	$-5.3 \cdot 10^5$	-0.7
$Q''''_y$	$-4.5 \cdot 10^6$	-0.029

3 orders of magn. smaller!!!

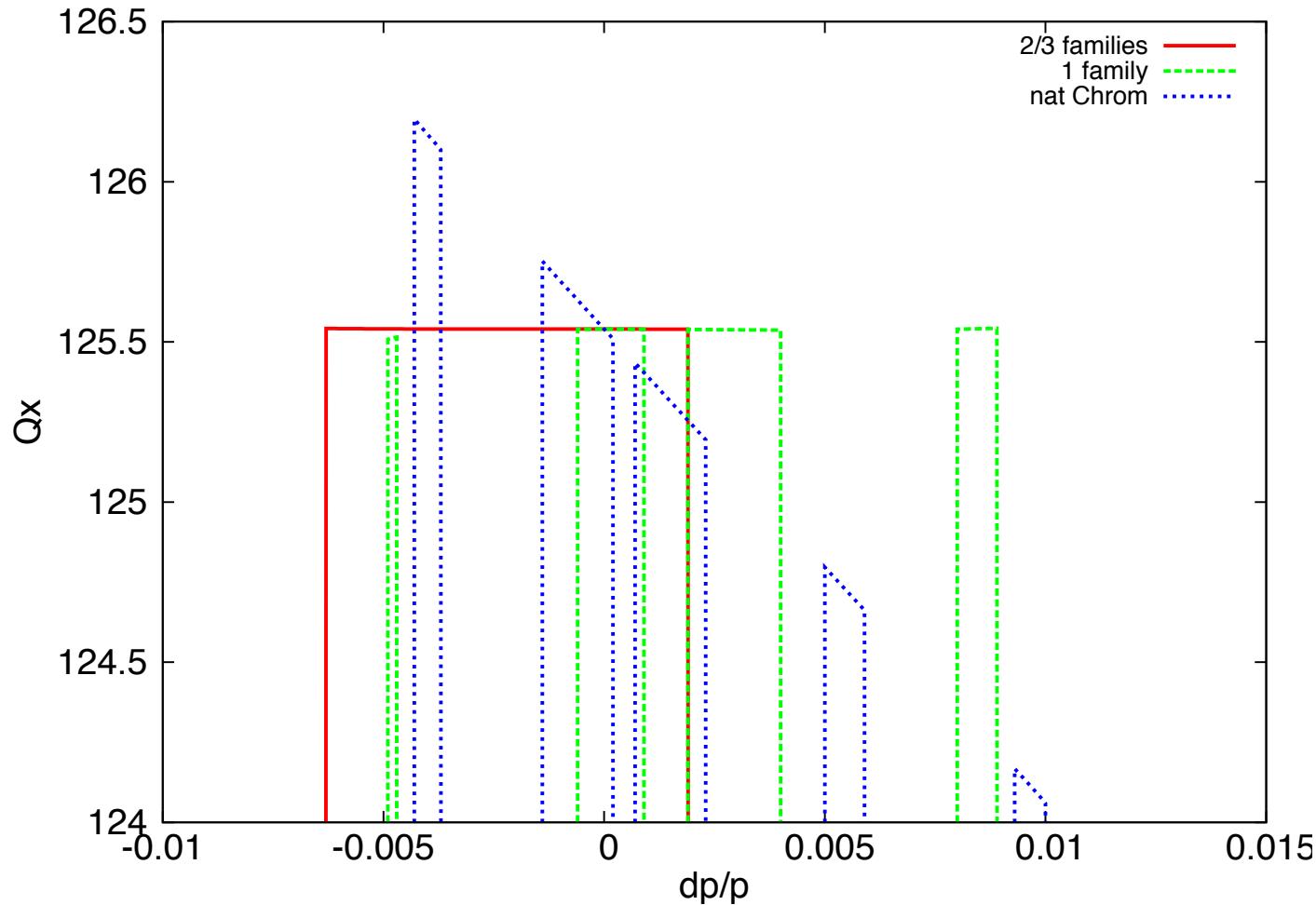
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# Next steps I

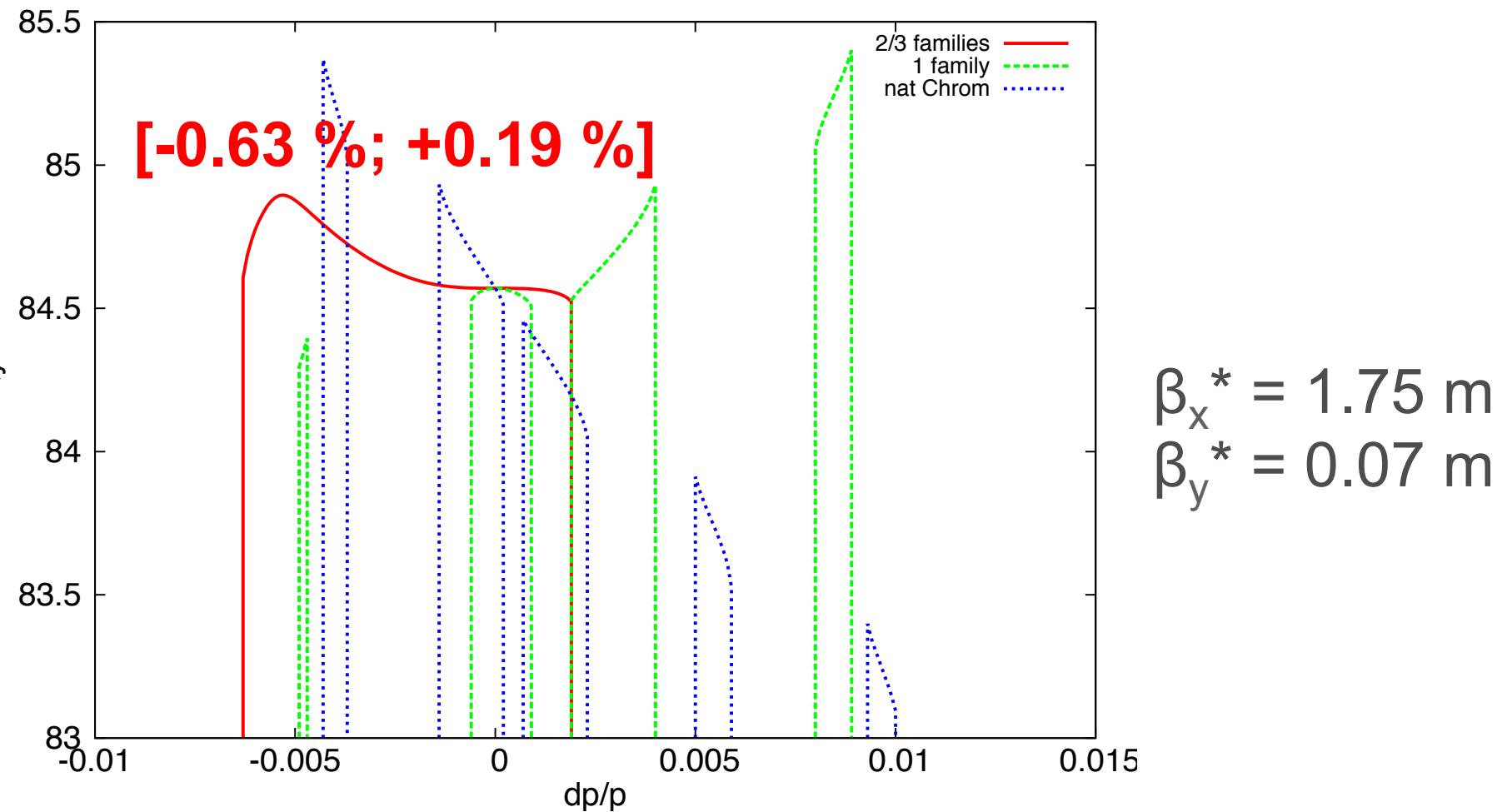
... according to the FCC-ee work plan:

- Keep the layout as ideal as possible
  - 12-fold ring with 4 equally distributed mini-betas
- Variation of  $\beta^*$  with LEP-like mini-beta module
  - How far can we get without local CCS?
  - LEP parameters: Can we achieve the same momentum acceptance?

# Momentum acceptance in x



# Mom. accept. for LEP parameters



# Next steps II

... according to the FCC-ee work plan:

- Correction of the actual chromaticities
  - ... not just the W functions
- Best possible correction of the 3<sup>rd</sup> order chromaticity
- (Anton proposed to switch to 135° phase advance
  - Scheme with 4 sextupole families might be able to correct 4<sup>th</sup> order chromaticity)





## 2) Recent lattice modifications



# Reasons for modifications

## 1) Anton found out:

“Wrong arms” in interaction region cost  
>>0.6 % momentum acceptance!!!

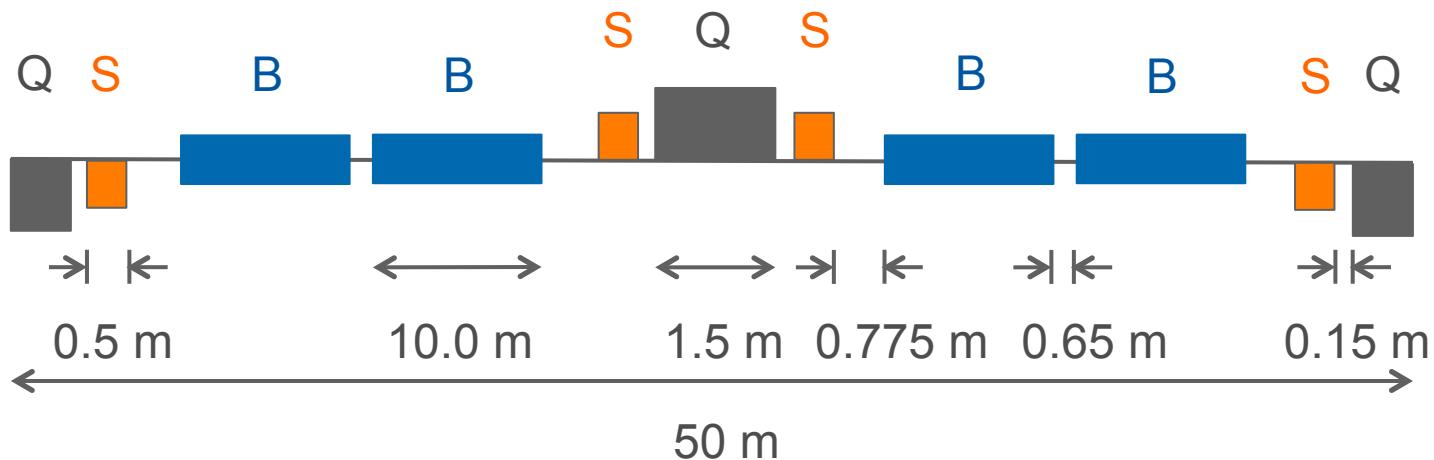
→ Symmetry of the lattice plays a larger role than expected!



# FODO cell V16

Completely symmetric!

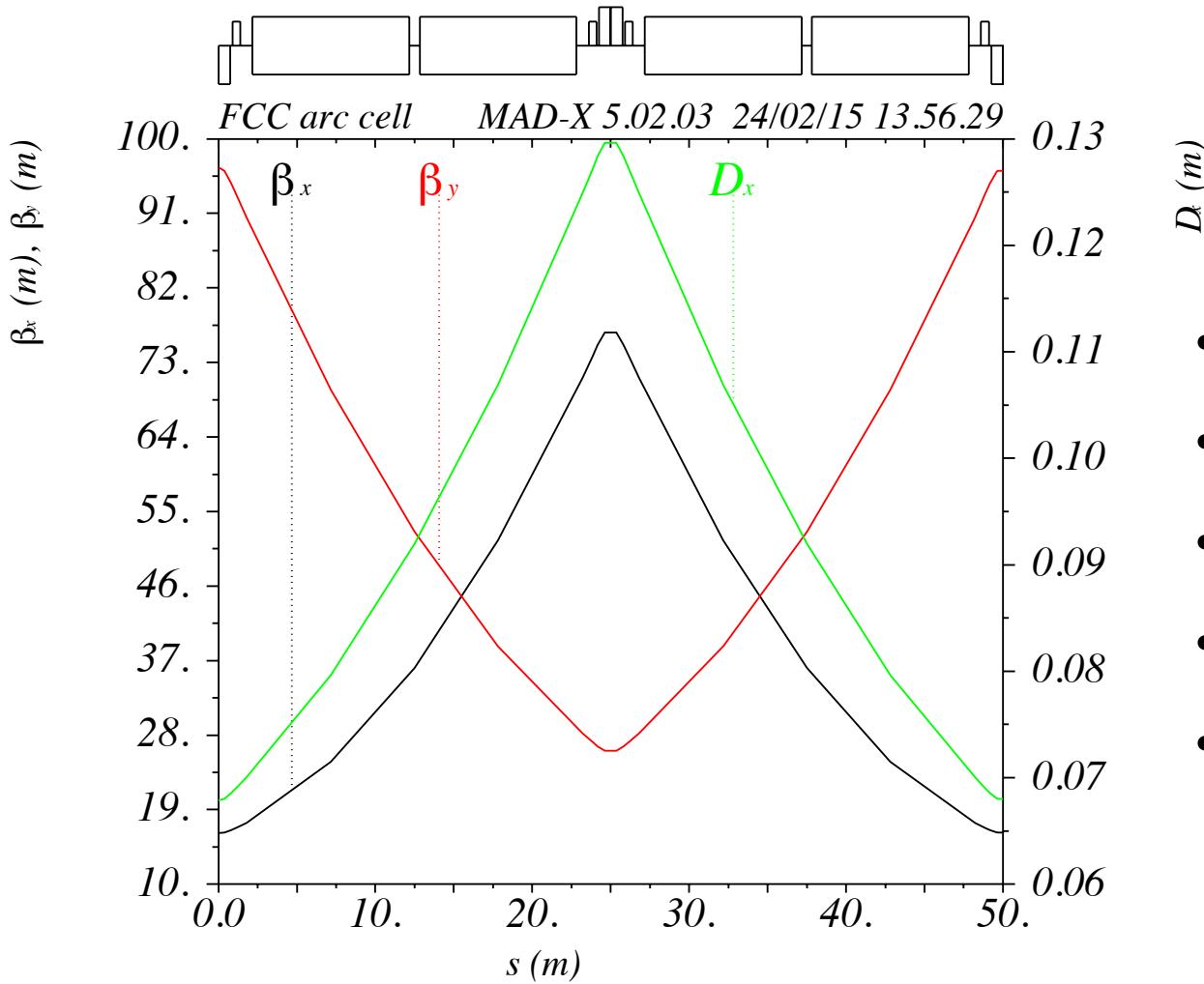
Layout already considers space for absorbers, flanges etc.



B = bending magnet, Q = quadrupole, S = sextupole

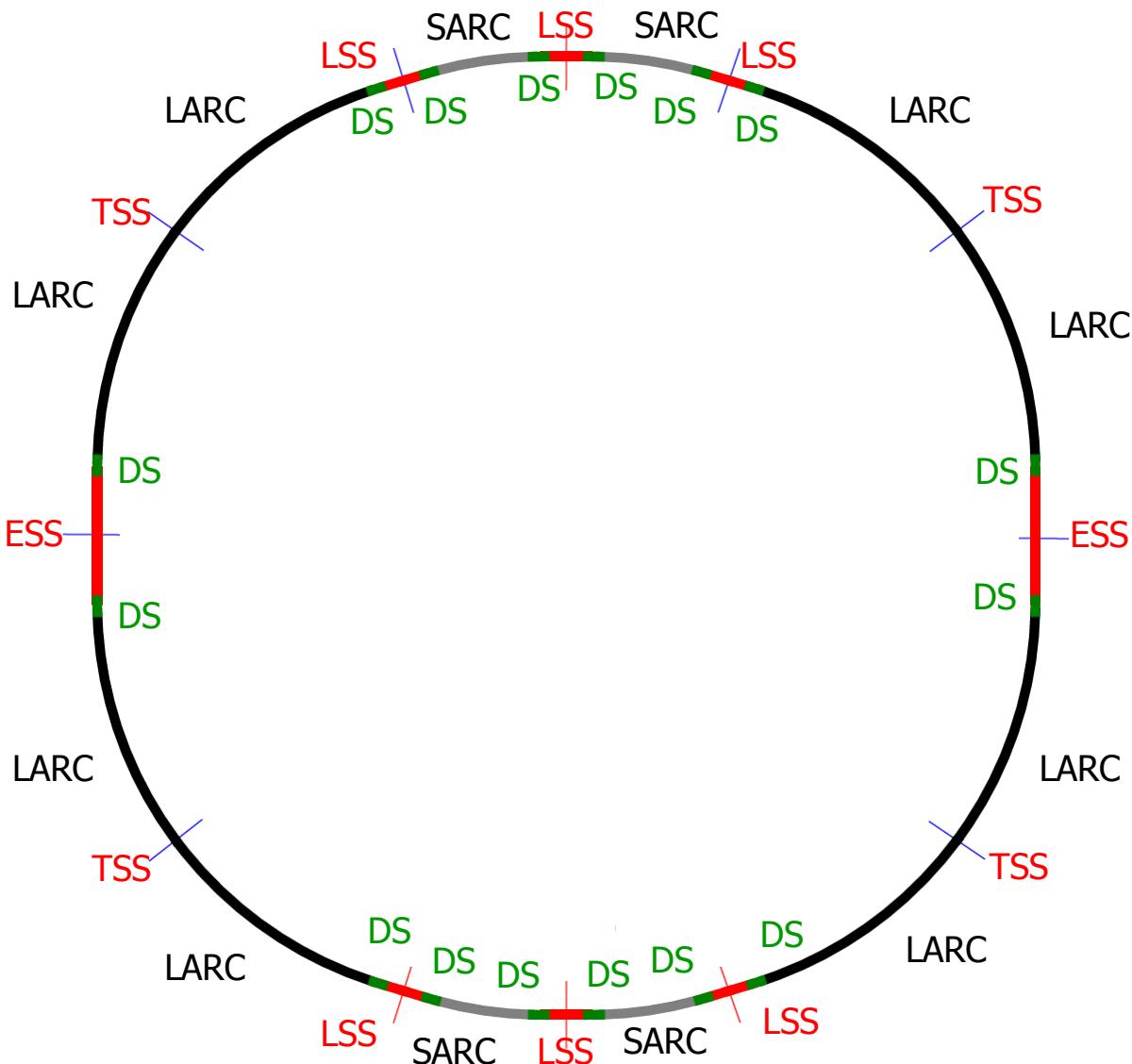
$N_{\text{dipoles}} = 6152$  (192 half bend) for Racetrack Layout  
( $\rho \approx 9.79$  km,  $\theta = 1.02$  mrad,  $B = 60$  mT)

# Arc FODO cell (V16)



- $L = 50 \text{ m}$
- $\Psi = 90^\circ/60^\circ$
- $\beta_{x,\max} = 77.0 \text{ m}$
- $\beta_{y,\max} = 96.5 \text{ m}$
- $D_{x,\max} = 13.0 \text{ cm}$

# Functional Sections of FCC-hh





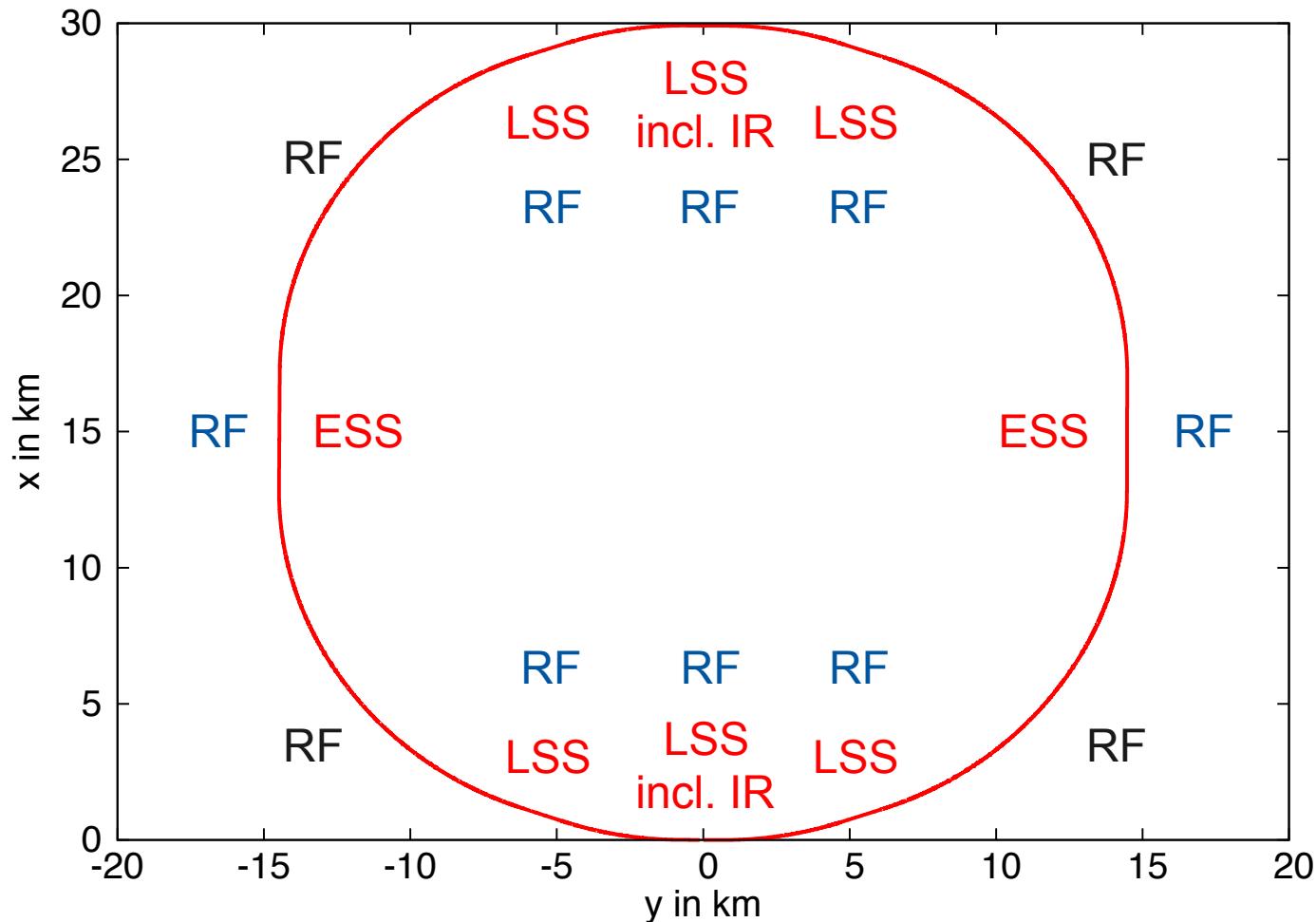
# Functional Sections



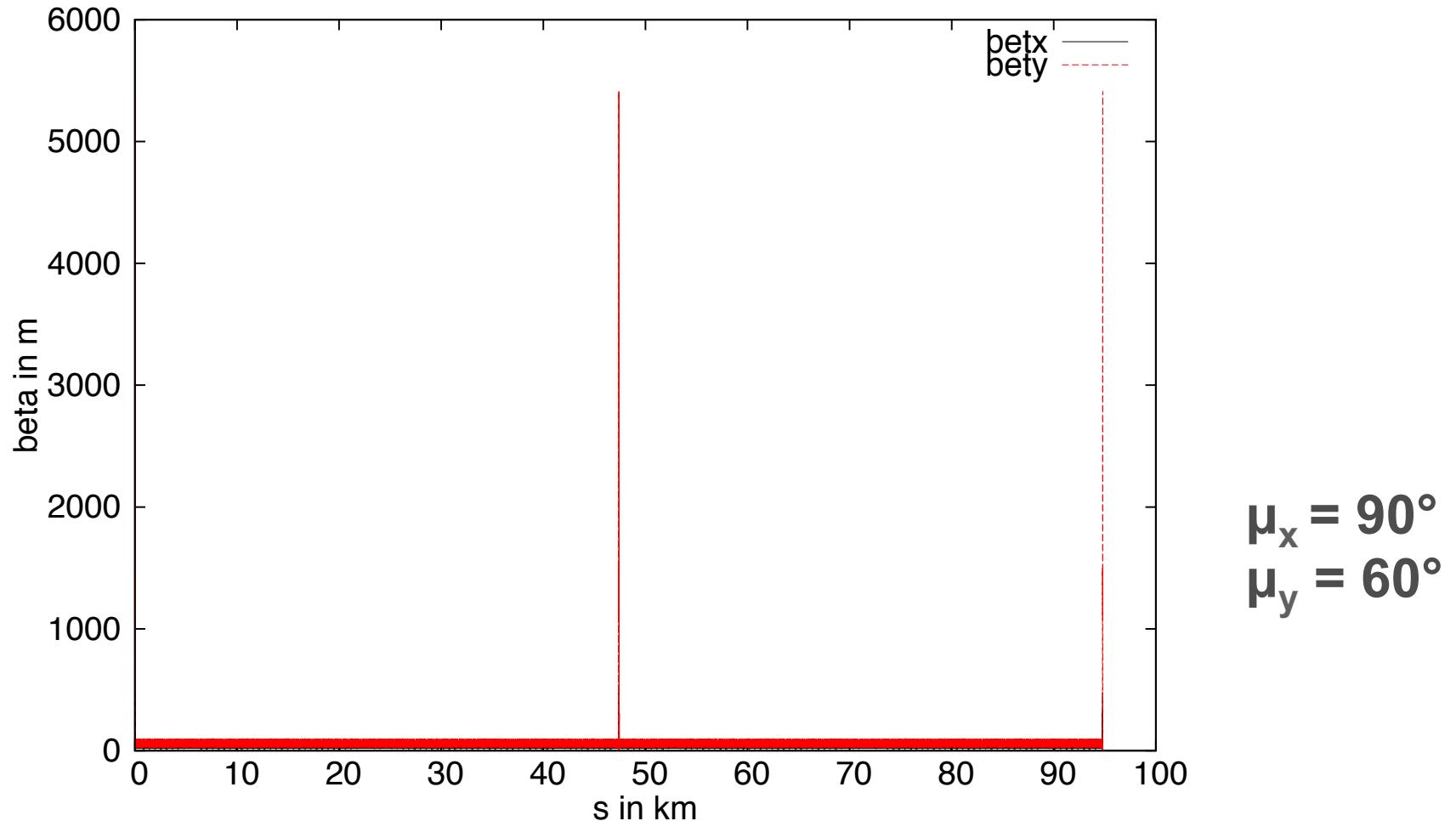
- Functional Sections
  - Functional Section: part of a sector with a given structure or function
  - Types of Functional Sections have generic names
  - A particular Functional Section has a name defined as:  
<generic abbreviation>-<Point or Sector identifier>(-<Order number>)  
*Examples: LSS-A, ESS-D, DS-AB-1, DS-CD,...*
  - Functions allocated to Functional Sections are given in following

Abbreviation	Generic name	Number	Length [km]
LSS	Long straight section	6	1.4
ESS	Extended straight section	2	4.2
TSS	Technical straight section	4	$\varepsilon$
DS	Dispersion suppressor	16	0.4
SARC	Short arc	4	3.2
LARC	Long arc	8	<i>depends on P</i>

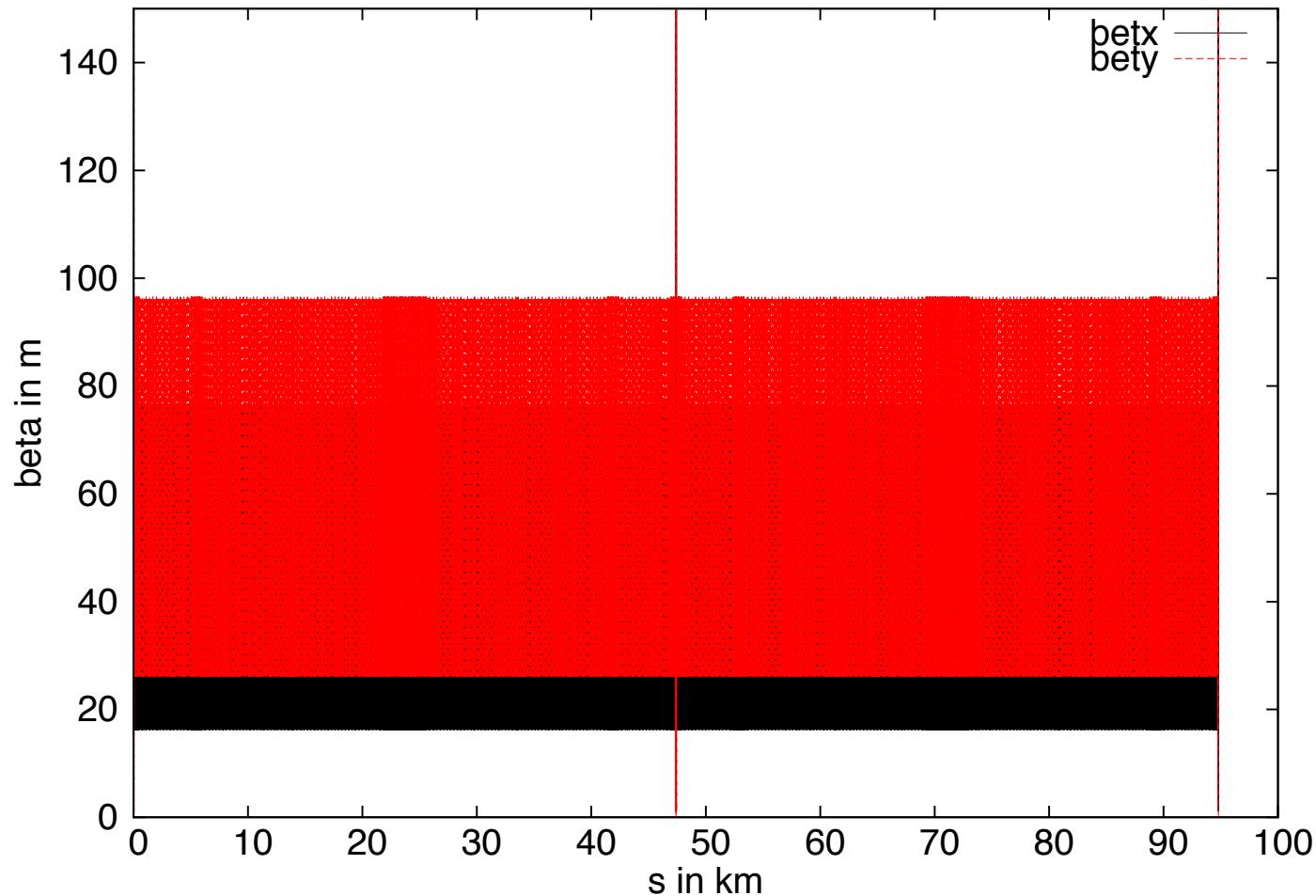
# Survey V16 Racetrack



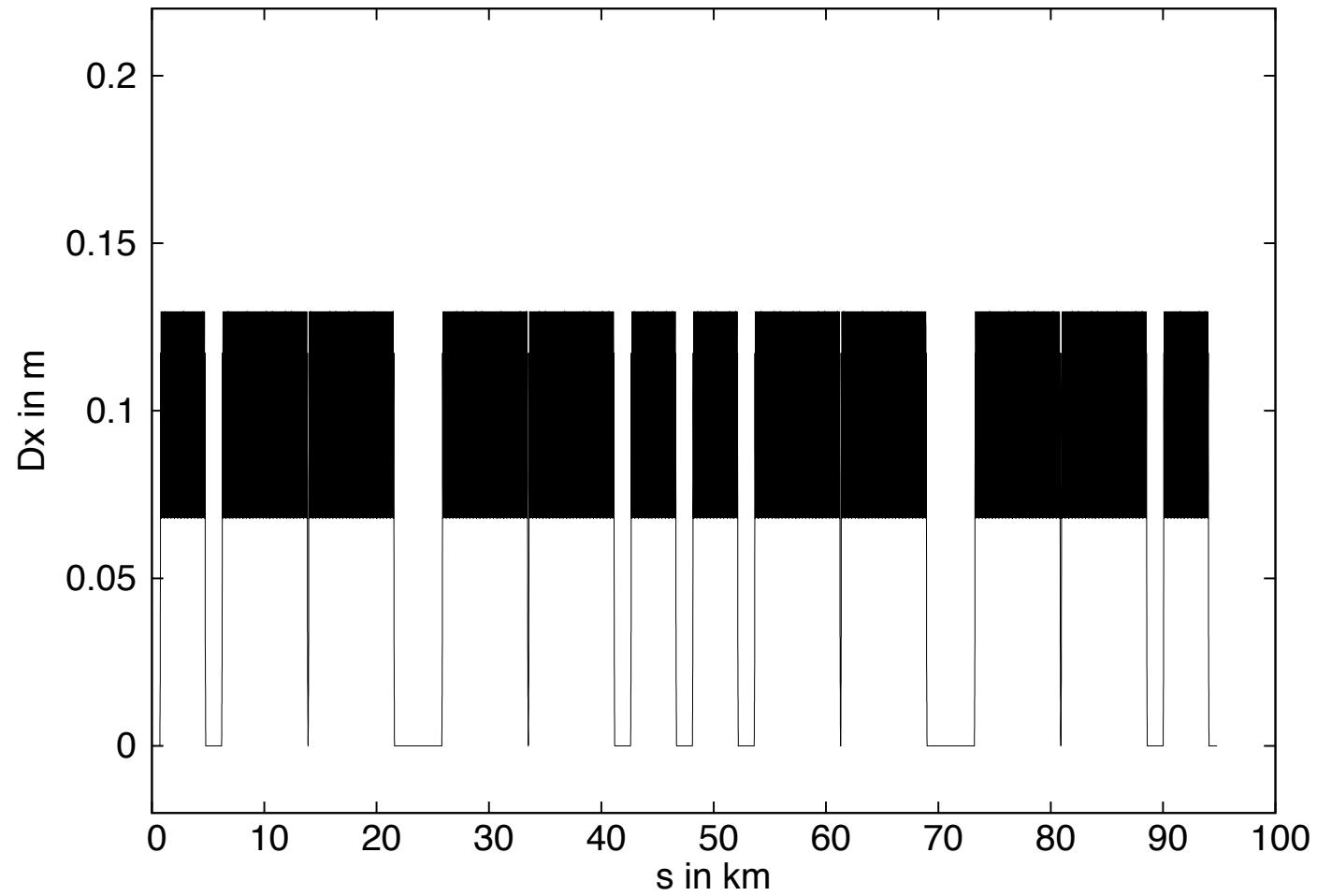
# V16 Racetrack: $\beta_x$ , $\beta_y$



# V16 Racetrack: $\beta_x$ , $\beta_y$

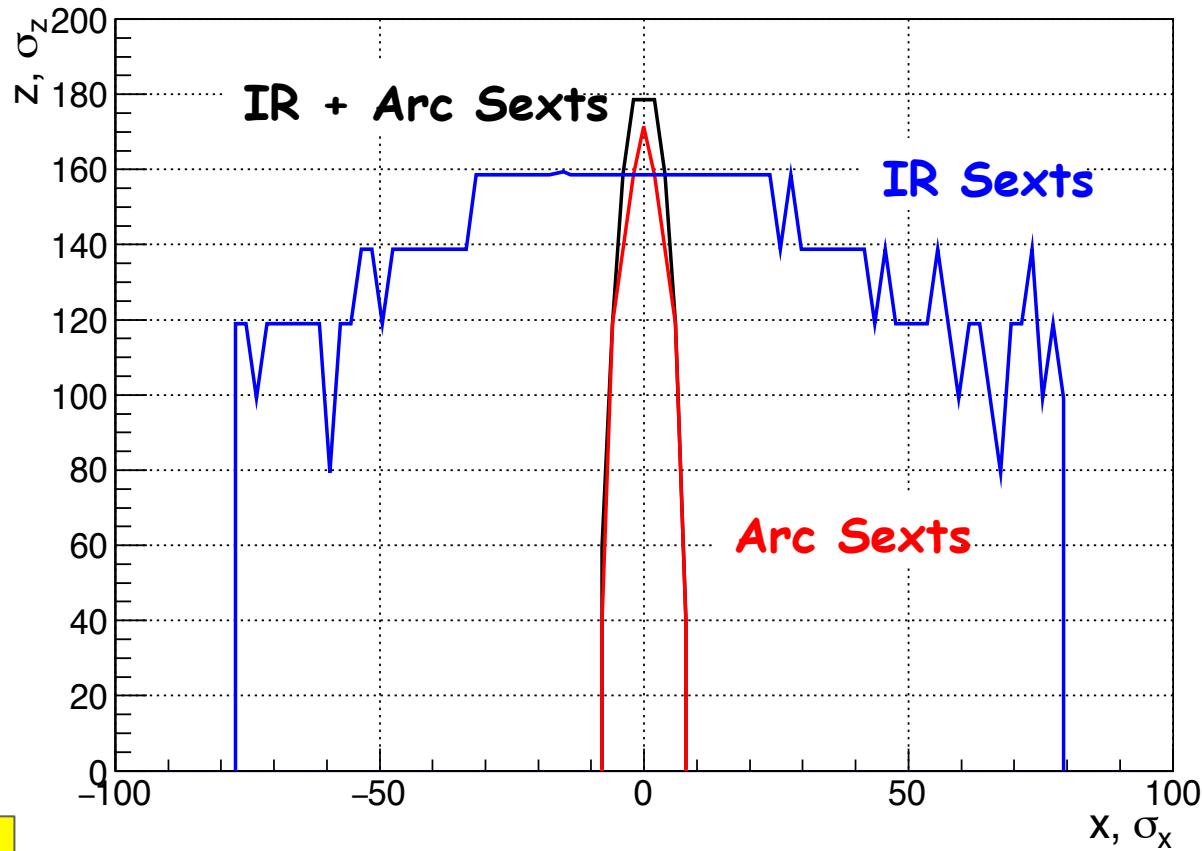


# V16 Racetrack: $D_x$



# 3) Dynamic Aperture Limitations

$E = 175 \text{ GeV}$ ,  $E_x = 1.3 \text{ nm}\cdot\text{rad}$ , 0.2% coupling



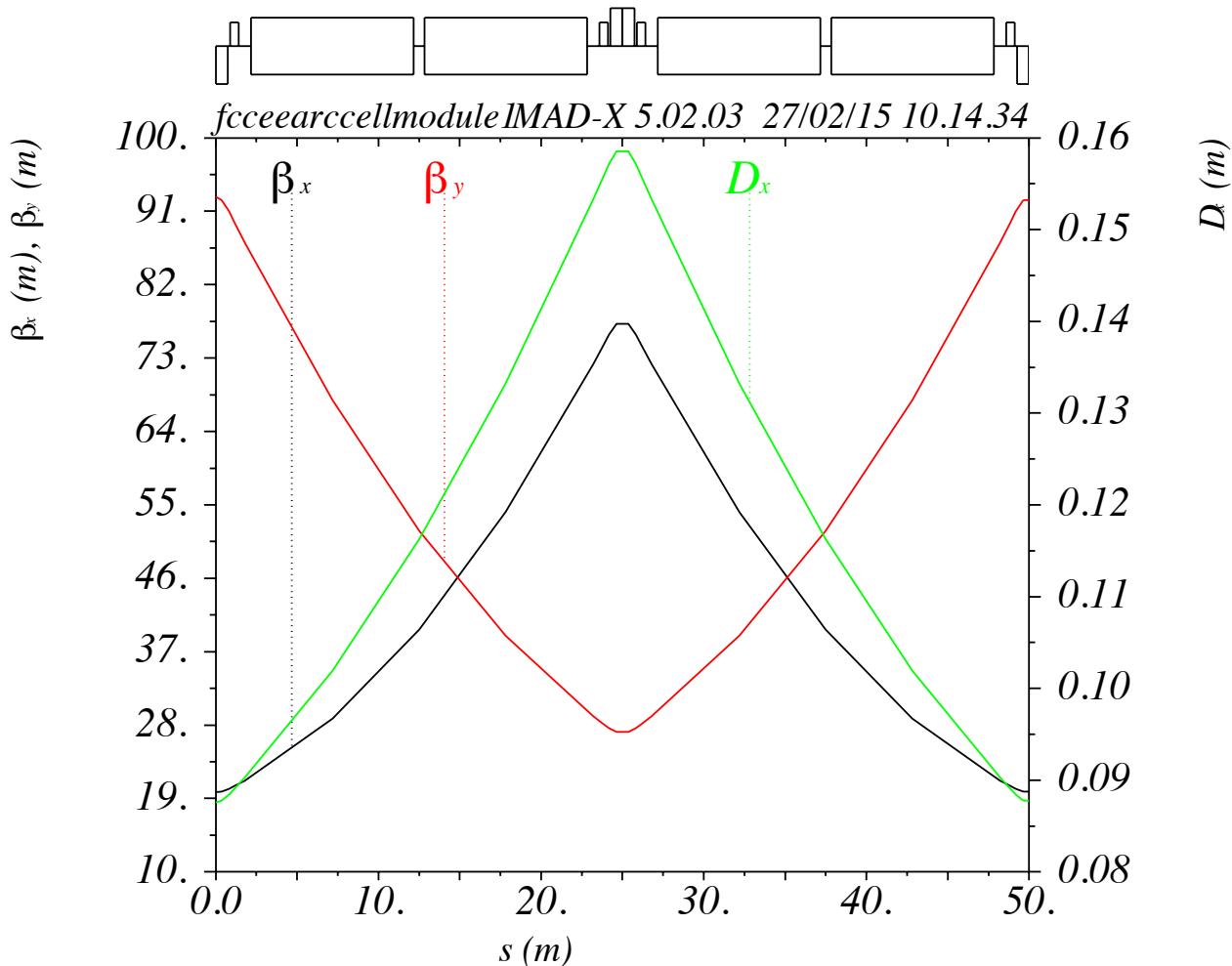
Pavel Piminov



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# 0.22 hor. phase advance



# Summary: Changes for V16

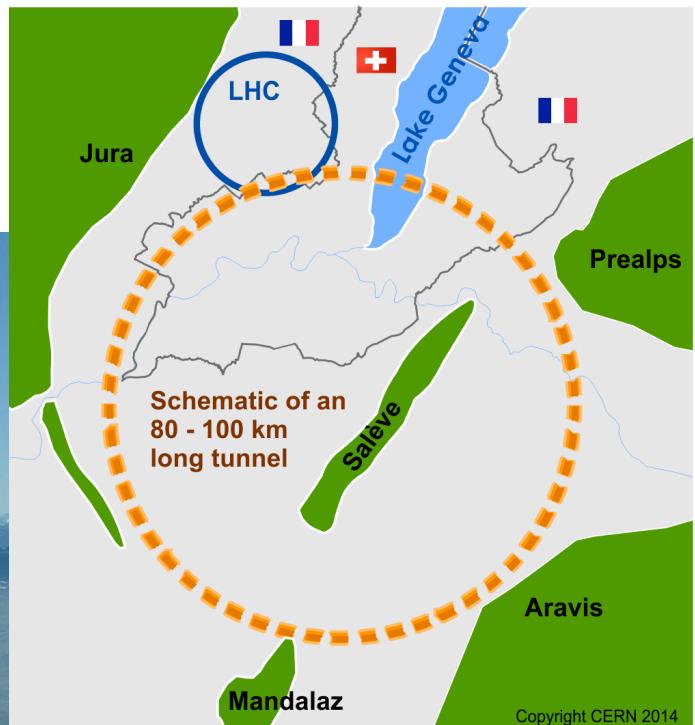
- Symmetric FODO cell with defocusing Quad at the beginning
- Semi-racetrack layout lattice is available
- Additional strength file for 0.22 horizontal phase advance is provided
- Sequence definitions are completely performed in MADX using macros

# Assignment of tasks

- Chromaticity correction scheme (Arcs)  
→ Bastian Harer
- Misalignments, coupling & vertical emittance  
→ Sandra Aumon (Fellow)
- Synchrotron light integrals: comparison of  
MADX, MAD8, (Elegant)  
→ Andreas Doblhammer (Technical student)



# Thank you for your attention!



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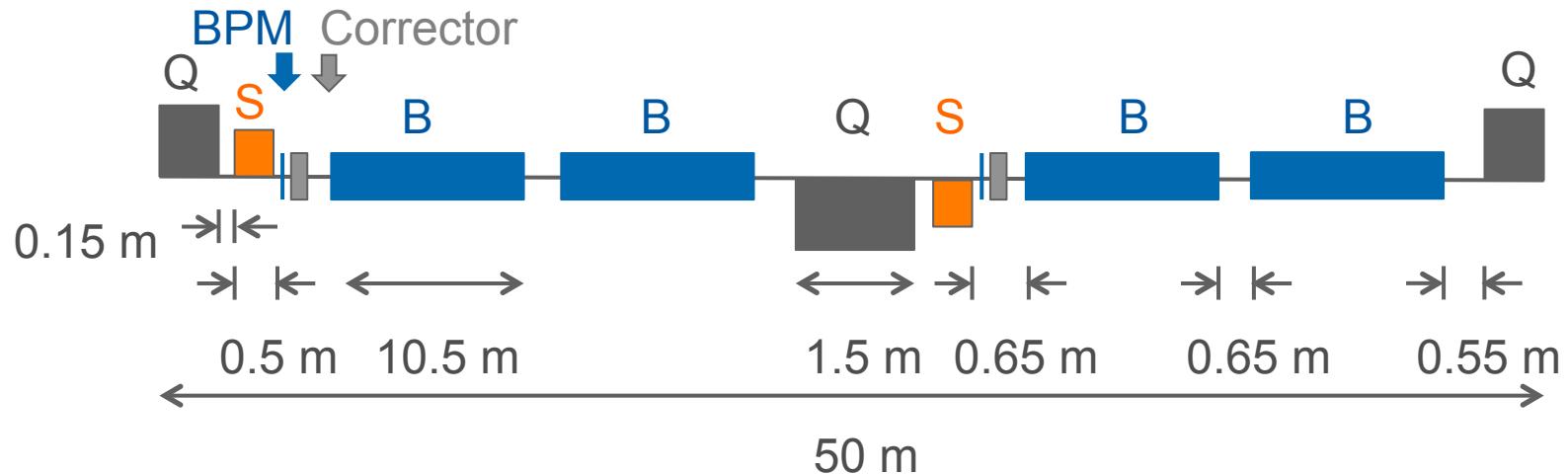


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# FODO cell V15

Layout already considers max. dipole length, drift spaces for absorbers, flanges etc.

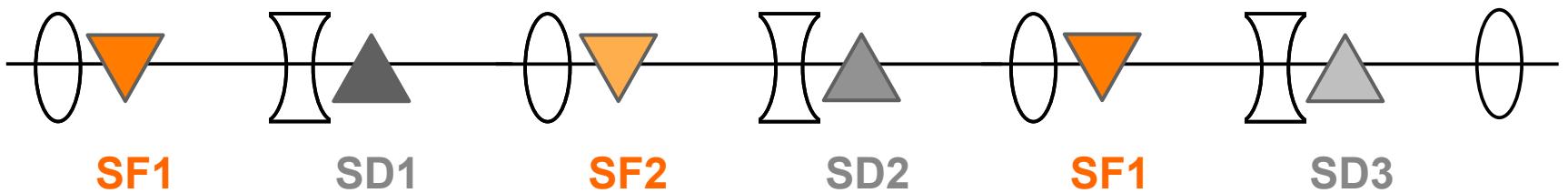


B = bending magnet, Q = quadrupole, S = sextupole

$$\begin{aligned} N_{\text{dipoles}} &= 6528 \text{ (192 half bend)} & (\text{LHC: } 1232) \\ N_{\text{quadrupoles}} &= 4704 & (\text{LHC: } 478) \end{aligned}$$

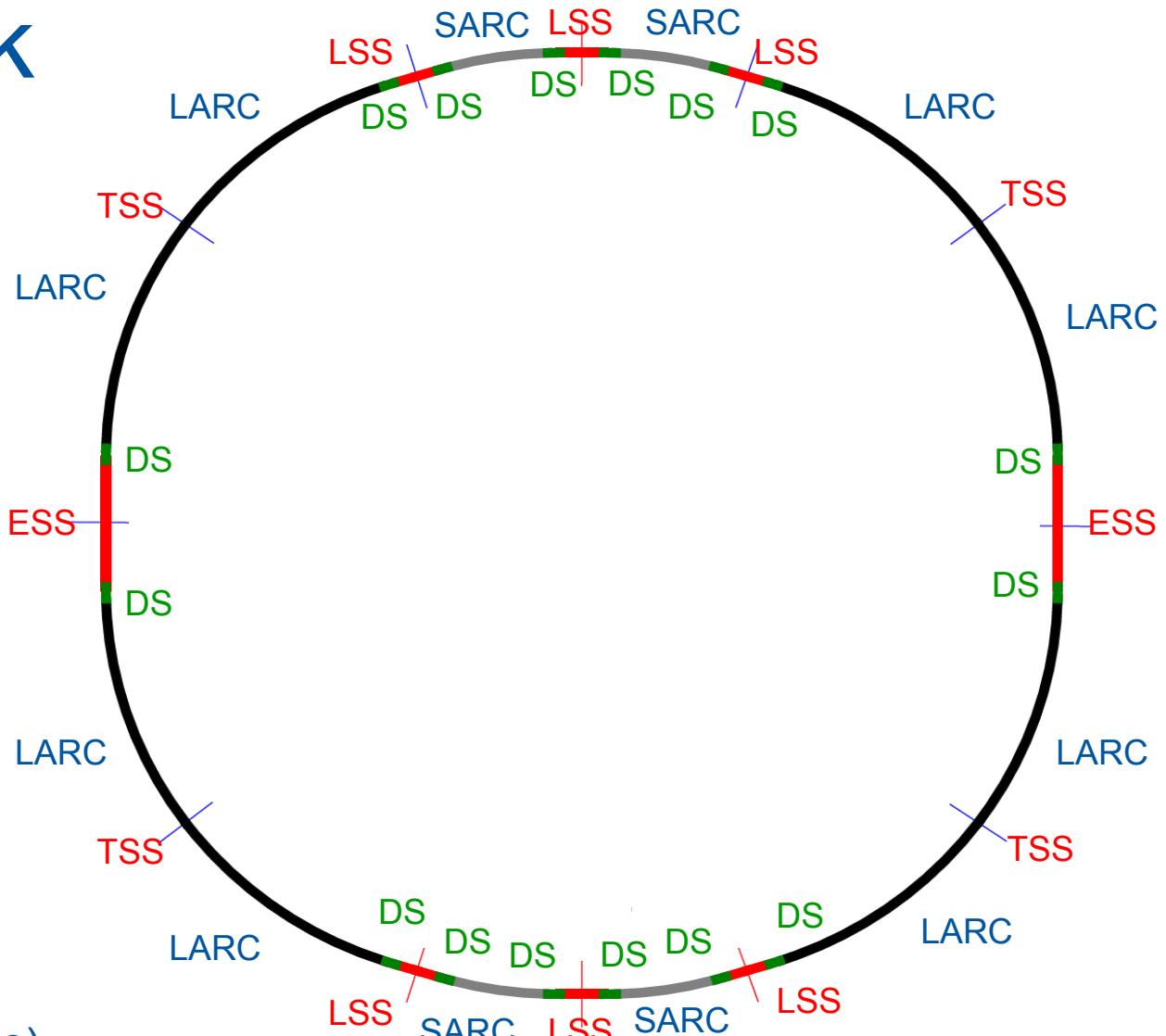
$$\begin{aligned} \rho &\approx 10.6 \text{ km} \\ \theta &= 0.99 \text{ mrad} \\ B &= 55 \text{ mT} \end{aligned}$$

# FCC-ee sextupole scheme



- 2 sextupole families in horizontal plane
- 3 sextupole families in vertical plane
- Separate sextupole families in each arc

# Racetrack



(P. Lebrun & J. Osborne)



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