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EuroCirCol
A key to New Physics

FCC
hh ee he

CEA - Saclay

First evaluation of Dynamic Aperture at injection for FCC-hh

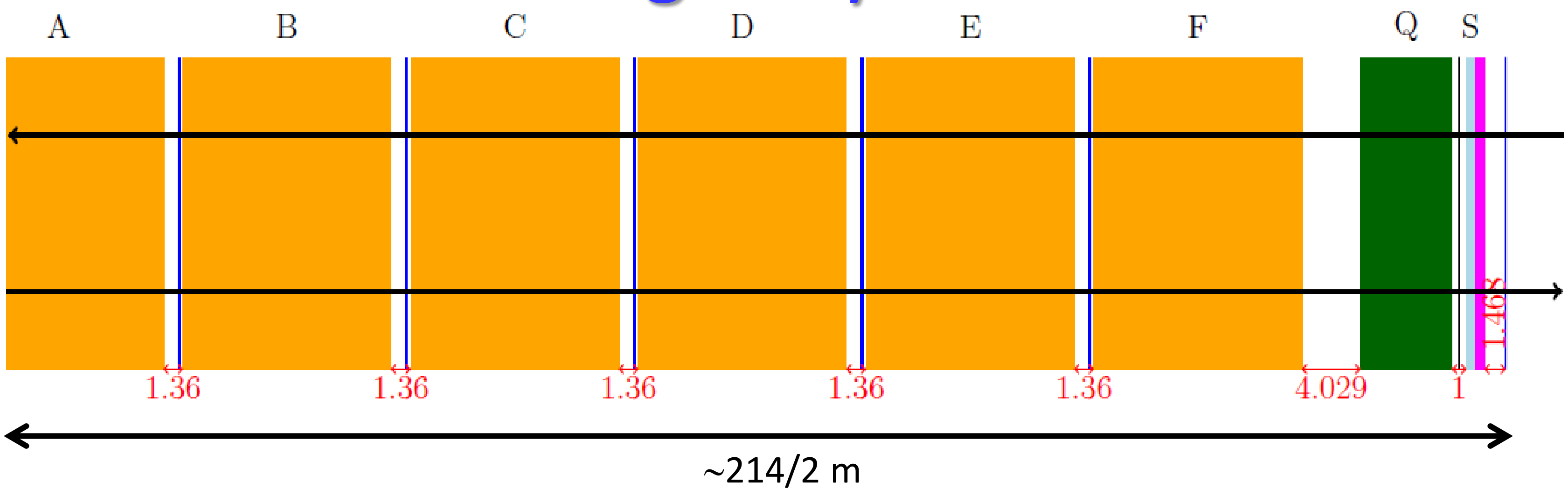
B. Dalena

Thanks to: D. Boutin, A. Chancé, R. De Maria,
S. Fartoukh, R. Martin, J. Payet, E. Todesco, K. N. Sjobaek…

Outline

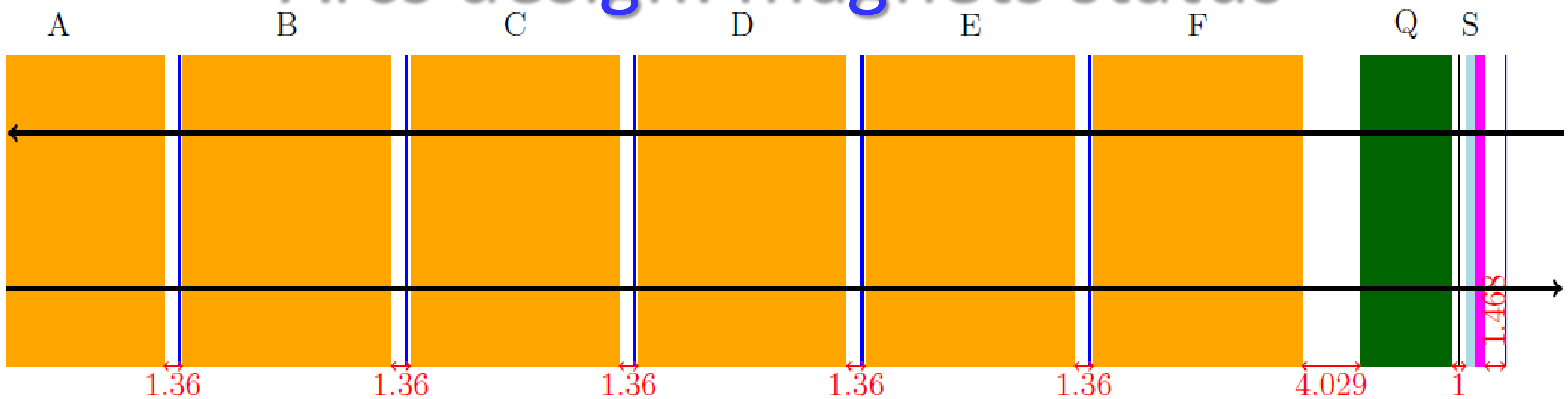
- Arcs design
  - Feedback from magnet designers
- Dipole's field errors and Dynamic Aperture
- First tolerances on systematic b_3 and correctors integrated strength
  - Feedback from magnet designers
- First consideration on systematic b_5

Arcs design: layout status



- MD and b3 correctors(MCS) have same length as LHC (12 MD and 12 MCS)
  - **minimum distance between two dipole checked (see E. Todesco talk)**
- 2 focusing and 2 defocusing sextupole families
- No octupole and decapole correctors are integrated so far
- No skew quadrupoles and skew sextupoles
- Each quad is equipped with a trim (before the quad, not showed in the sketch)
- Relative position of the BPM and the orbit corrector with respect to the MQ are different from LHC
  - see D. Boutin talk

Arcs design: magnets status



element	Length [m]	Max strength	units	comments	from Ezio Todesco talk
Main Dipole	14.3	16-ε	T		**2% less field is a non negligible gain!**
b3 corrector	0.11	0.0043	m^{-2}	2 times LHC field	**up to 3 times LHC MCS field is fine**
quadrupole	6.29	370	T/m		**with Nb_3Sn can reach 400 T/m** (6 m long magnet)
sextupole	0.5	16000.	T/m^2	$4.8\ 10^{-2}\ m^{-2}$ to have margin we wish up to $9\ 10^{-2}\ m^{-2}$ integrated strength	**$4\ 10^{-2}\ m^{-2}$ max we can reach with present technology** (1.5 m long magnet) $\Rightarrow$ $\beta^* \leq 0.3$m requires longer sextupoles or special chromaticity correction scheme
orbit corrector	0.647	3.6	Tm	90% max strengths σ_{quad}=0.35mm σ_{b1}=0.001 main field	**feasible up to 4 Tm with NbTi technology**

Dipoles errors table

First table for dipoles multipole errors provided (*E. Todesco*)

$$b_n = b_{n_S} + \frac{\xi_U}{1.5} b_{n_U} + \xi_R \sigma_{b_n}$$

ξ = random number with Gaussian distribution cut at 1.5 (U) and 3 (R)

In the following:

- the same seed for U for all dipoles of the same arc is used
- different seeds for R for each dipole are used
- random and uncertainty b2 and a2 not considered (skew correctors not inserted in the lattice yet)
- magnet misalignments not considered

Fractional part of tunes:

Q_x = .28, Q_y = .31 injection

Q_x = .31, Q_y = .32 collision

Dynamic aperture is evaluated with SixTrack adapted for FCC!

(SixTrack website, cern.ch/sixtrack-ng)

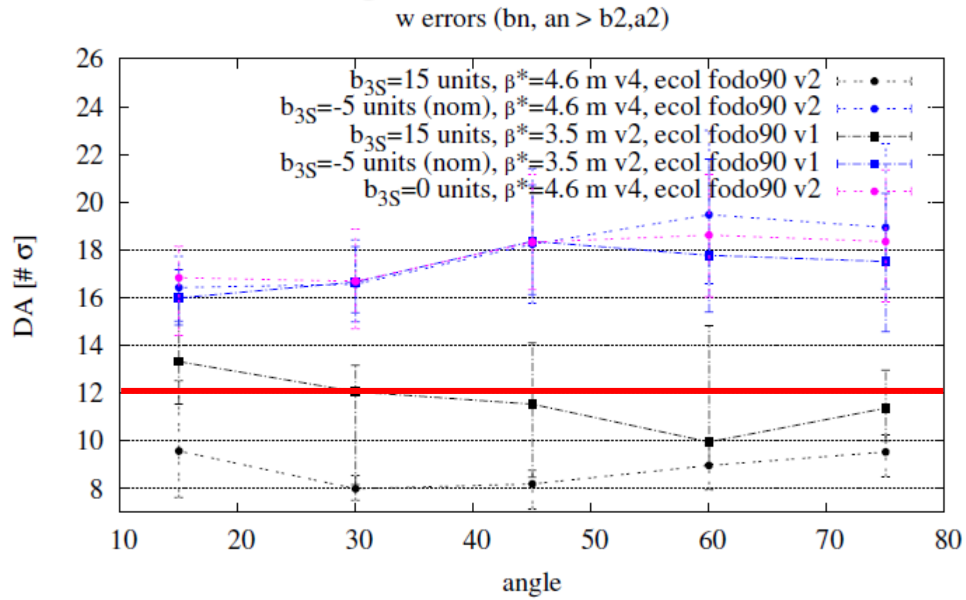
R_{ref} = 0.017 m

	Systematic		Uncertainty		Random	
Normal	Injection	High Field	Injection	High Field	Injection	High Field
2	0.000	0.000	0.484	0.484	0.484	0.484
3	-5.000	20.000	0.781	0.781	0.781	0.781
4	0.000	0.000	0.065	0.065	0.065	0.065
5	-1.000	-1.500	0.074	0.074	0.074	0.074
6	0.000	0.000	0.009	0.009	0.009	0.009
7	-0.500	1.300	0.016	0.016	0.016	0.016
8	0.000	0.000	0.001	0.001	0.001	0.001
9	-0.100	0.050	0.002	0.002	0.002	0.002
10	0.000	0.000	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000	0.000
Skew						
2	0.000	0.000	1.108	1.108	1.108	1.108
3	0.000	0.000	0.256	0.256	0.256	0.256
4	0.000	0.000	0.252	0.252	0.252	0.252
5	0.000	0.000	0.050	0.050	0.050	0.050
6	0.000	0.000	0.040	0.040	0.040	0.040
7	0.000	0.000	0.007	0.007	0.007	0.007
8	0.000	0.000	0.007	0.007	0.007	0.007
9	0.000	0.000	0.002	0.002	0.002	0.002
10	0.000	0.000	0.001	0.001	0.001	0.001
11	0.000	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000	0.000

DA with errors: injection

Inputs long-term DA study:

- 60 seeds
- 30 particle pairs
- Emit norm 2.2e-6 m.rad
- E_0 = 3.3 TeV
- Q' = 2
- dp/p = **0.00075** **(LHC)**
- dp/p max = 0.002
- σ step = 2, σ ∈ [2-40] explored
- 5 angles ∈ [0,90º]



without dipoles errors DA > 80 σ

with first dipoles errors: "systematic" b3 uncorrected (chromaticity due to b3 corrected)

MS Integrated strength	$b_3 = 0$	b_{3S} = -5 error table	b_{3S} = 15
KSF [10^{-2} m^{-2}]	0.9	2.9	**-5.2**
KSD[10^{-2} m^{-2}]	-1.8	1.4	**-11.5**

⇒ **b_{3S} =-5 units is not a problem for DA at 3.3TeV**

⇒ good compensation of b_{3S} by the ~90° phase advance, DA reduction dominated by random errors

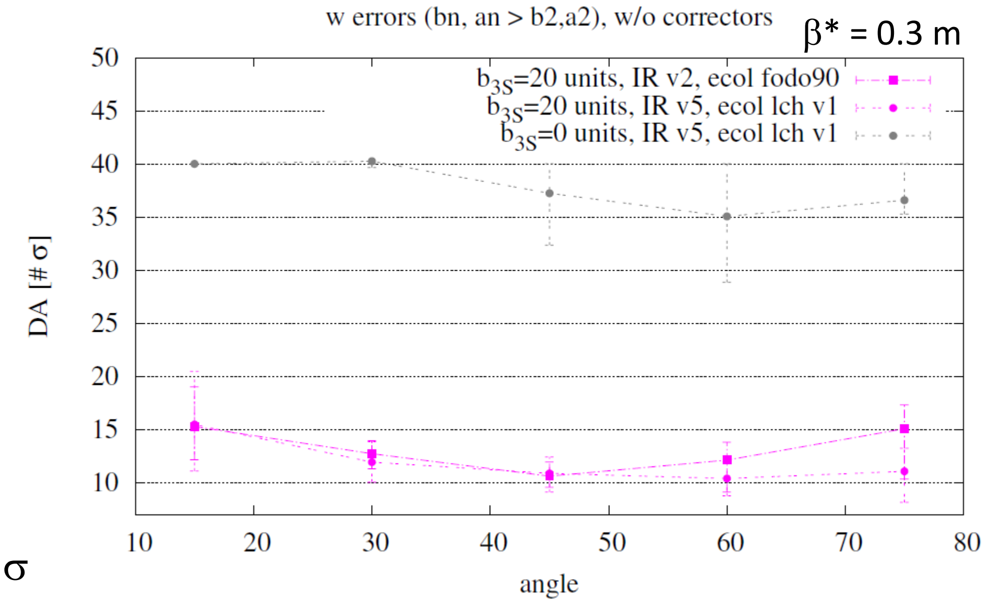
⇒ **b_{3S} = 15 units intolerable without correction** (strong sextupoles and minimum DA ~8σ)

⇒ **effect of different horizontal phase advance in the long arcs: up to 3σ of average DA** (at 15°)

DA with errors: collision

Inputs long-term DA study:

- 60 seeds
- 30 particle pairs
- Emit norm 2.2e-6 m.rad
- E_0 = 50 TeV
- Q' = 2
- dp/p = **0.00027 (LHC)**
- dp/p max = 0.002
- σ step = 2, σ ∈ [2-40] explored
- 5 angles ∈ [0,90°]



without dipoles errors minimum DA > 54 σ

with first dipoles errors: "systematic" b3 uncorrected (chromaticity due to b3 corrected)

MS integrated strength	b_3 = 0	b_{3S} = 20 error table
KSF [10^{-2} m^{-2}]	2.4	**-5.8**
KSD[10^{-2} m^{-2}]	-4.8	**-17.9**

⇒ **b_{3S}=20 units intolerable without correction** (minimum DA 8 σ and too stronger sextupoles)
⇒ **need to correct b_{3S}** (with b_{3S} = 0 units, minimum DA ~ 28 σ)
⇒ **effect of different straight sections: smaller than at injection** (different multipoles play a role)

b3 and MCS strength: collision

Based on S. Fartoukh and O. Bruning, **LHC project report 501**

MCS integrated strength for **B= 0.471 T, L_{MCS} =0.11 m**

$$(K_2^+ L)_{\mathrm{mcs}} \equiv \frac{L_{\mathrm{mcs}}}{B\rho}\frac{\partial^2 B_y}{\partial x^2} = 2 \times \frac{0.3}{p\,[\mathrm{GeV}]} \times \frac{(Bl)_{(x=R_{ref})}\,[\mathrm{Tm}]}{R_{ref}^2}$$

Coll [10-4 m-2]	Inj [10-4 m-2]	
154.	2390.	LHC
21.5	326.	FCC

Integrated strength to correct one $_3$unit of b_{3S}

$$(K_2^+ L)_{\mathrm{mb}} = 2 \times \alpha \frac{b_{3S}}{R_{ref}^2}$$

$\alpha = 2\pi/N_{dipole}$

[10-4 m-2]	
35.3 x b_{3S}	LHC
9.42 x b_{3S}	FCC

LHC MCS correct

Coll b_{3S} [10-4]	Inj b_{3S} [10-4]	
4.35	67.7	LHC
2.3	34.6	FCC

@ LHC $|b_{3S}| < 3$ [10^{-4}] equal to 70% of MCS max integrated strength

$\Rightarrow$ FCC $|b_{3S}| < 3$ [10^{-4}] equal to 70% of 2 integrated strength of LHC MCS
(to have same tolerance of LHC at FCC)

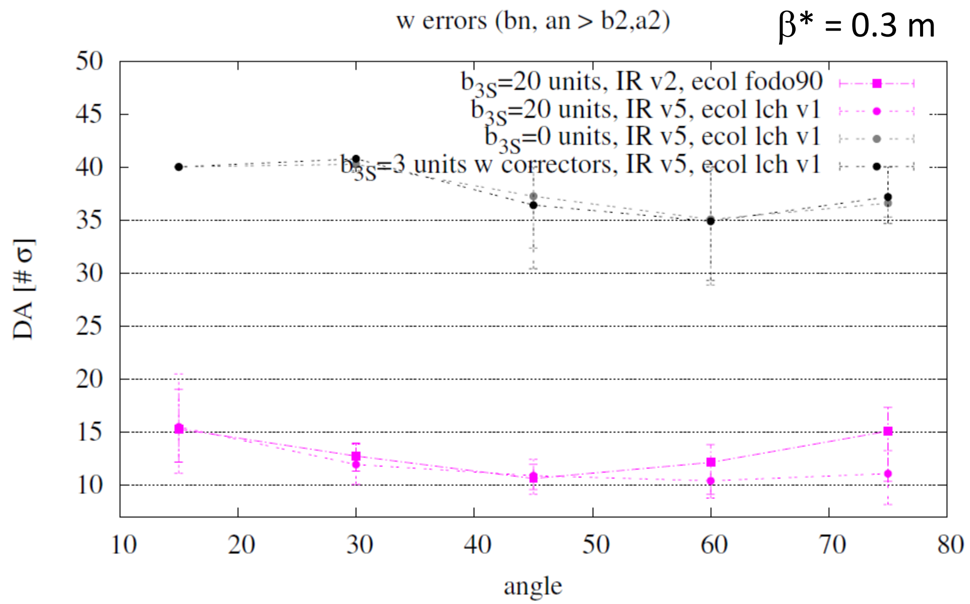
$\Rightarrow$ **3 units of b_3 are reasonable at 50 TeV if we allow 6-7 units of b_3 at injection (3.3 TeV)**

$\Rightarrow$ **3 times stronger MCS is feasible and can correct up to 6 units of b_3 at 50 TeV**

- ➢ **see E. Todesco talk**

b3 correctors: collision

Average b_{3S} for each of the 8 arcs is corrected with spool pieces MCS, one at every dipole (same scheme of HL-LHC by S. Fartoukh).



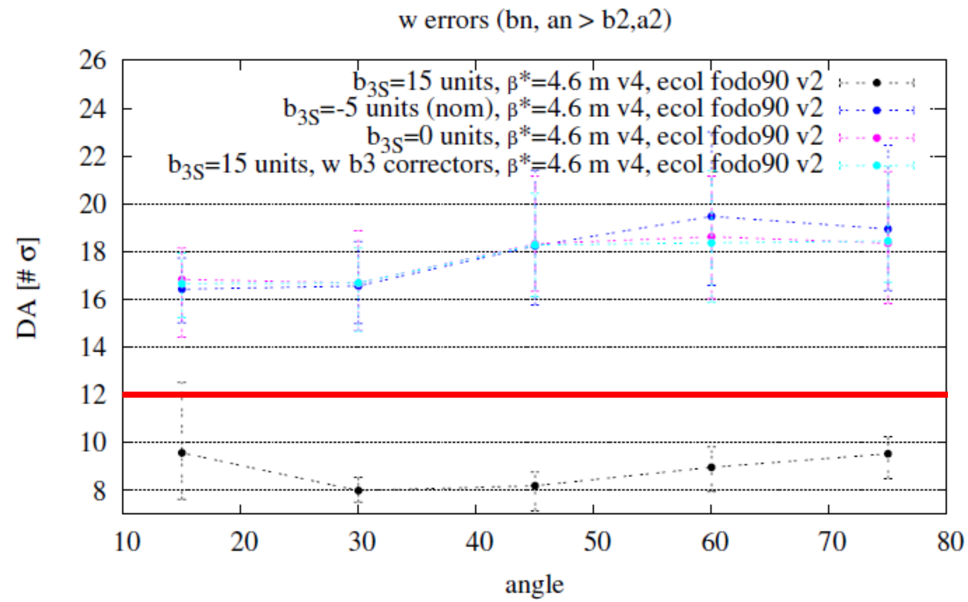
MS integrated strength	b_3 = 0	b_{3S} = 20 error table	b_{3S} = 3 + correctors
KSF [10^{-2} m^{-2}]	2.4	**-5.8**	2.4
KSD[10^{-2} m^{-2}]	-4.8	**-17.9**	-4.8

⇒ **~81% of 2 times the strength of LHC MCS fully correct b_{3S}=3 units** (minimum DA ~28 σ)

If 3 times stronger MCS are feasible and correct up to 6 units of b_3 at 50 TeV (see E. Todesco talk)
⇒ **possibility to reduce the number of MCS ?**

b3 correctors: injection

Average b_{3S} for each of the 8 arcs is corrected with spool pieces MCS, one at every dipole (as in collision).



MS Integrated strength	b_3 = 0	b_{3S} = -5 error table	b_{3S} = 15	b_{3S} = 3 + correctors
KSF [10^{-2} m^{-2}]	0.9	2.9	**-5.3**	0.9
KSD[10^{-2} m^{-2}]	-1.8	1.4	**-11.5**	-1.8

⇒ **~23% of 2 times the strength of LHC MCS fully correct b_{3S} =15 units** (minimum DA > 12 σ)

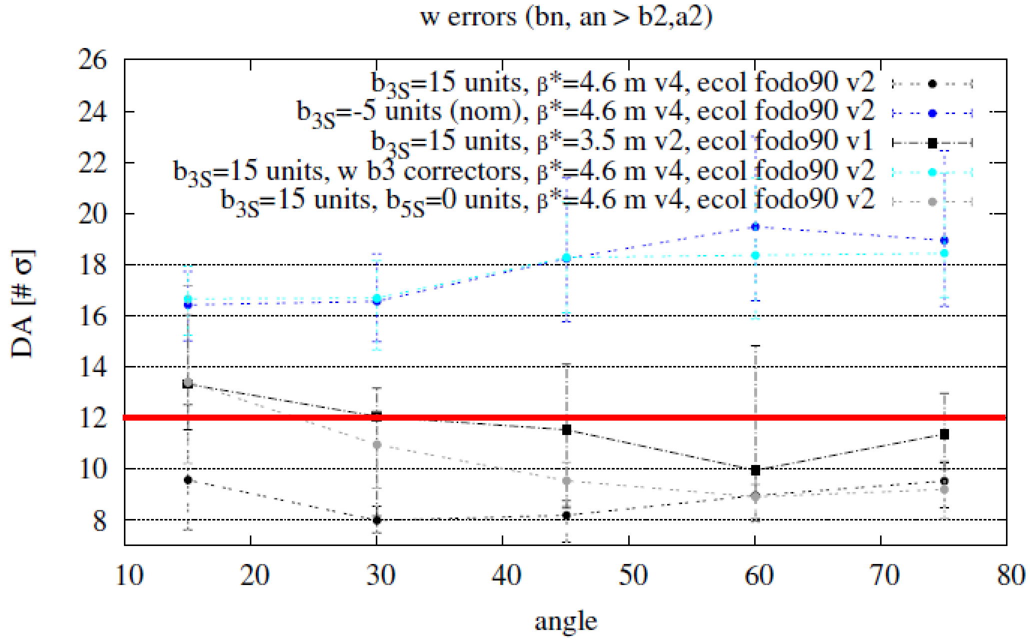
⇒ E. Todesco (see talk) proposed 6-7 units of b_{3S} at injection

⇒ as far as DA is concerned with MCS even 15 units of b_{3S} are fine, feed-down effects on random b_2 to be checked , in presence of misalignment

b5 at injection

Inputs long-term DA study:

- 60 seeds
- 30 particle pairs
- Emit norm 2.2e-6 m.rad
- E_0 = 3.3 TeV
- Q' = 2
- dp/p = **0.00075** **(LHC)**
- dp/p max = 0.002
- σ step = 2, σ ∈ [2-40] explored
- 5 angles ∈ [0,90°]



⇒ **b_{5S} = 1 unit reduces average DA of 3 σ at 15°**
⇒ **similar effect is produced by different horizontal phase advance in the long arcs**

⇒ As far as DA is the criteria (> 12 σ at injection), **we do not need the b5 correctors**

- ⇒ need to look at the impact of b_{5S} on Q''' (i.e. tune vs δp/p)
- ⇒ need to look at the feed-down effect on b4 (tune spread)

Conclusion

✓ **First dipole's errors table gives good DA (12σ) at injection**

- 5 units of systematic b_3 at 3.3 TeV are well compensated as far as DA is considered as criteria
- 15 units of systematic b_3 reduce DA to < 10 σ and too strong sextupoles required
- ~23% of 2 times the strength of LHC MCS fully correct b_{3S}=15 units at 3.3 TeV
- at present 6-7 units of b_3 at injection (3.3 TeV) are proposed (**see E. Todesco talk**)

⇒ **3.3 TeV is not the lower limit for injection energy (as far as DA is concerned)**

✓ **First dipole's errors table gives DA < 10 σ in collision**

- **3 units of systematic b3 has been fixed as target at 50 TeV**
- ~81% of 2 times the strength of LHC MCS fully correct b_3=3 units at 50 TeV
- with 3 times the strength of LHC MCS can correct up to 6 units of b_3 at 50 TeV (**see E. Todesco talk**)

⇒ **possibility to reduce spool pieces ?**

✓ As far as DA is the criteria (> 12 σ at injection), the **b5 correctors seems not to be needed**

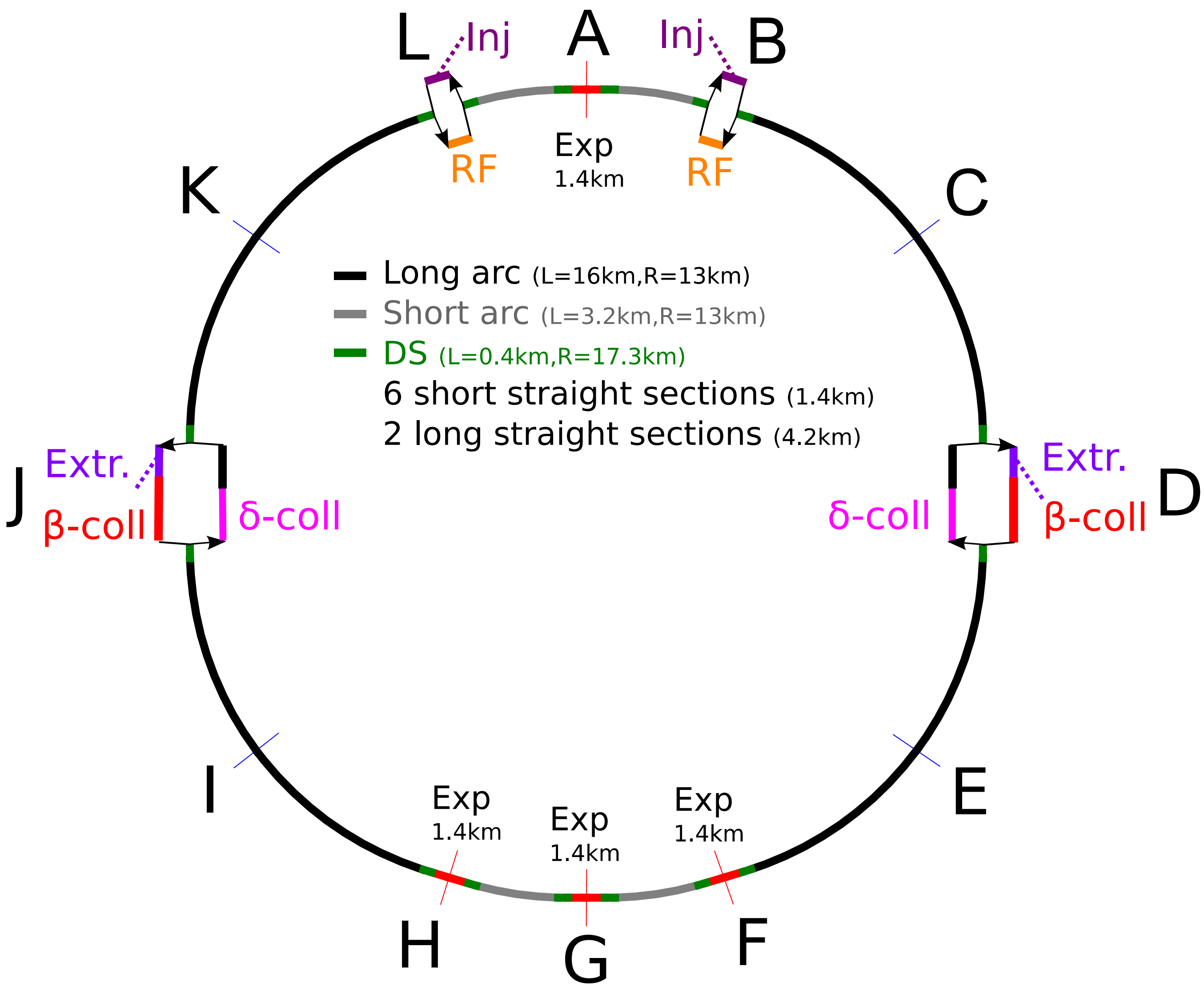
⇒ **Look at impact of systematic b_5 on Q''' and feed-down effect on b_4**

… & Outlook

- Misalignment and feed-down effects
- Tolerances on the uncertainty “U” and the random components (of higher multipoles as well)
- Effect of different optics (straight section and arcs phase advances)

SPARES

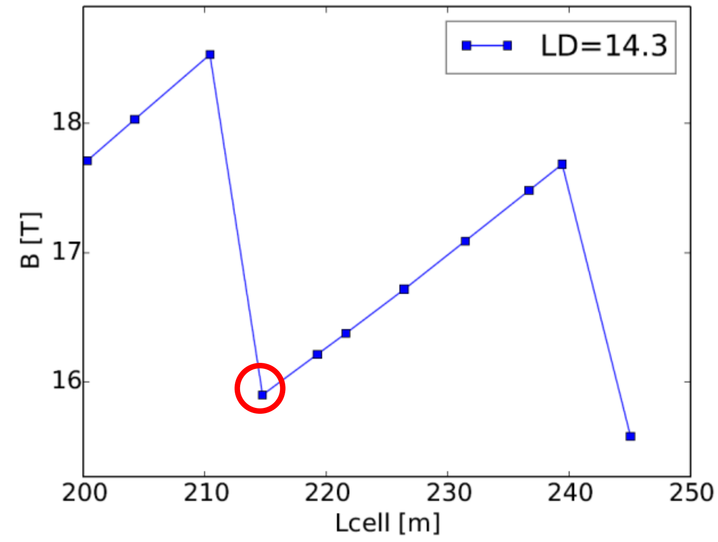
FCC-hh Layout

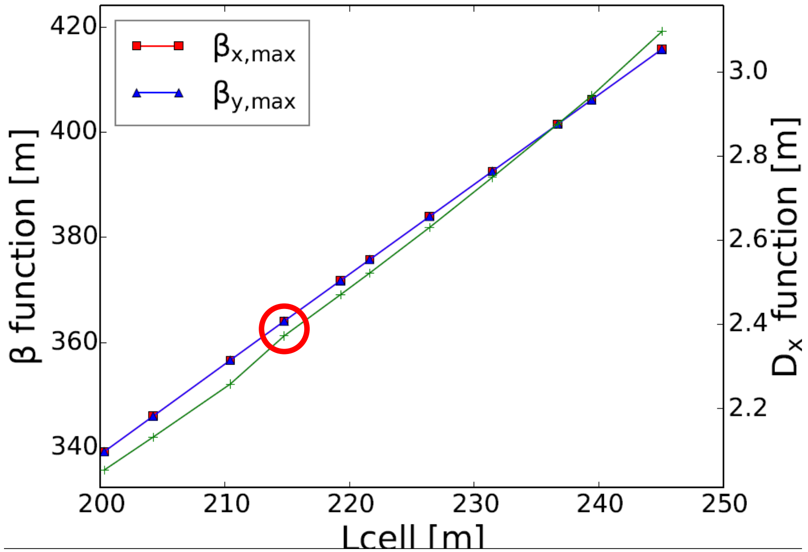


CELL PARAMETERS

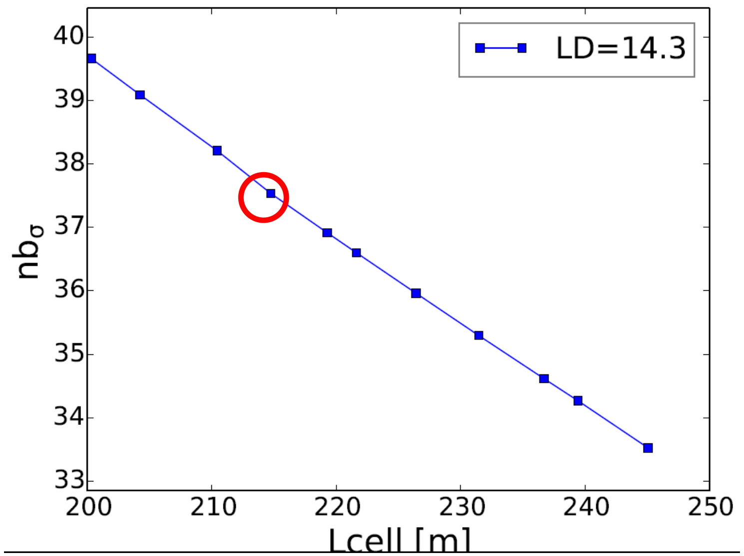
Input parameters:

- Minimum space between dipoles 1.36 m
- Dipole maximum field 16 T
- Dipole length 14.3 m
- Minimum space between quadrupole and dipoles 3.67 m
- Maximum gradient of the quadrupole 370 T/m
- ∅ = 50 mm, beam screen radius 20 mm
- Sextupole length 0.5 m
- Space between quadrupole and sextupole 1.0 m
- Phase advance per cell 90° x/y
- Circumference 3.75 × LHC ~ 100 km





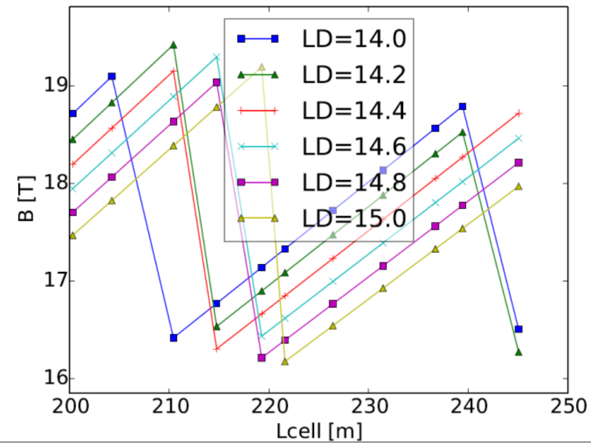
# of sigma at E_{inj}=3. 3 TeV



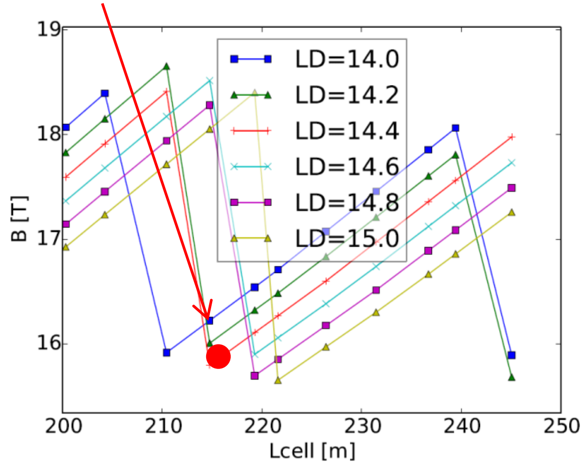
Dispersion Suppressor and dipole Field

Circumference = 100.12 km

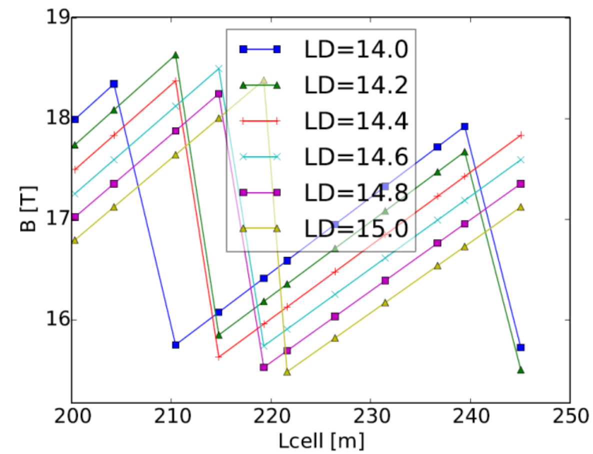
Half Bend



baseline LHC-like



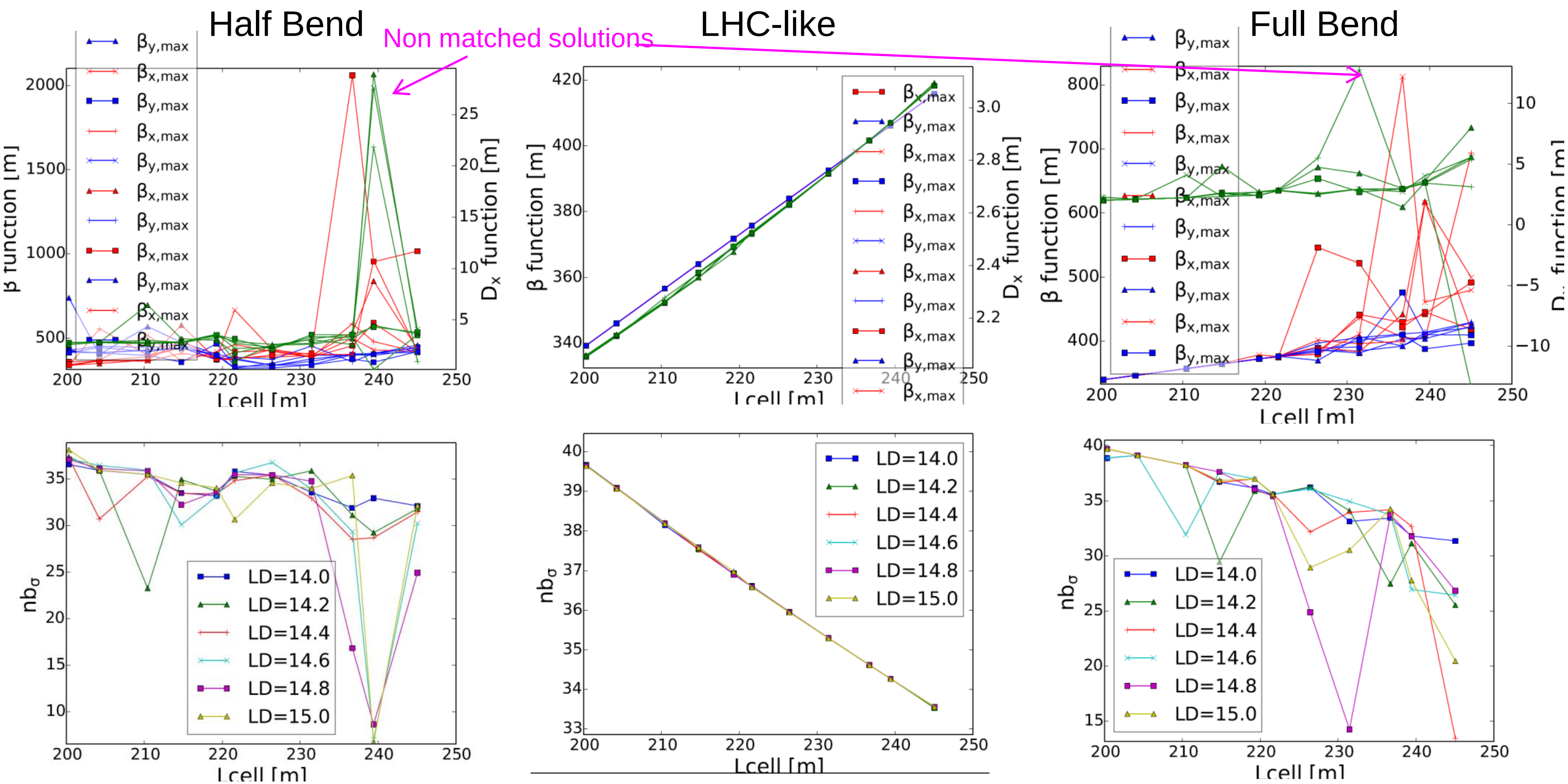
Full Bend



⇒ Full Bend DS: ~1% lower dipole field with respect to LHC-like DS
⇒ Half Bend DS: no solution below 16 T

Dispersion suppressor types & optics

Circumference = 100.12 km, beam screen radius = 20 mm

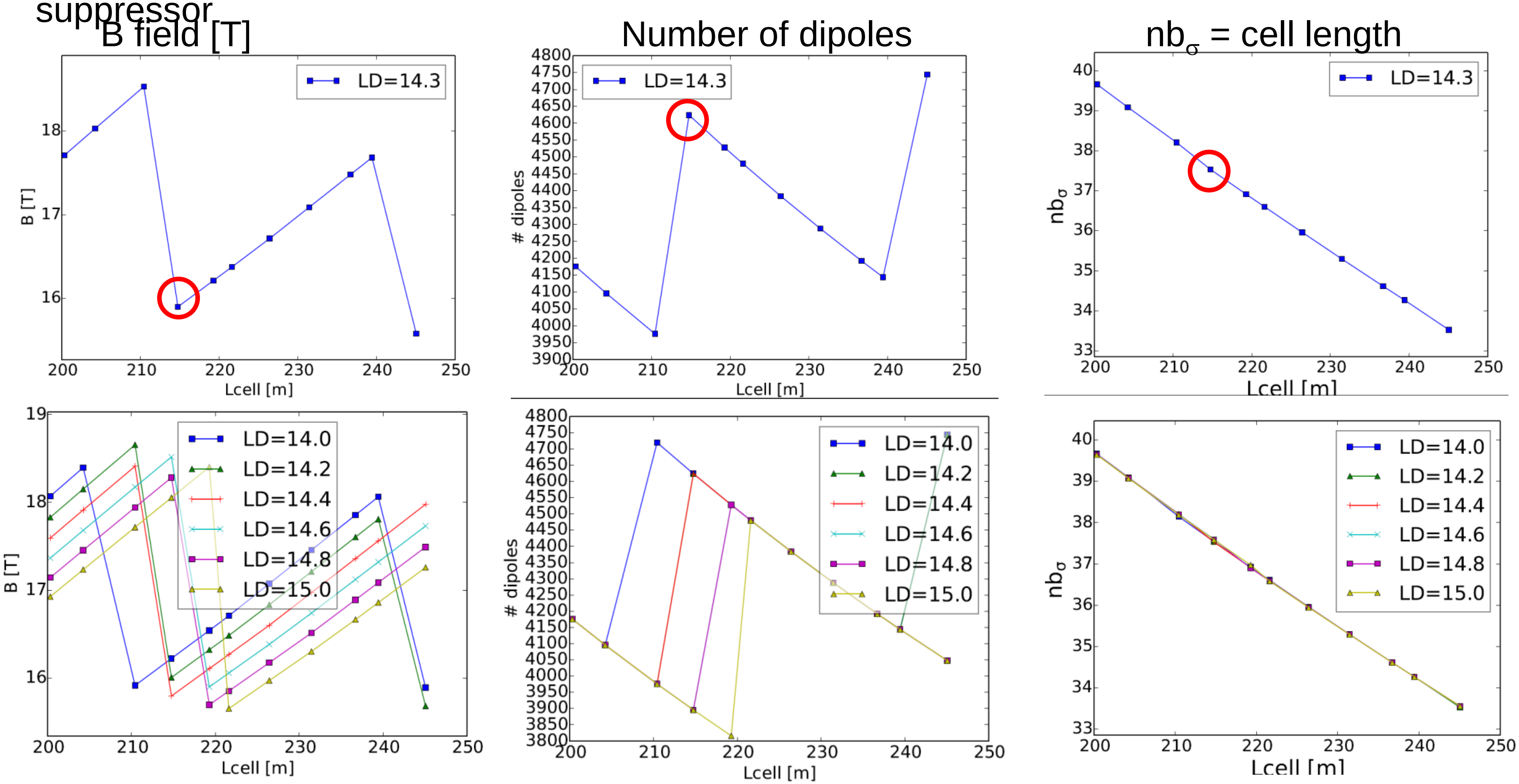


⇒ Lcell ~215 m good for optics functions and number of sigma of the beam

⇒ LHC-like DS easiest to match to the insertions

Closer look to dipoles and cells length

Circumference = 100.12 km, beam screen radius = 20 mm, LHC-like dispersion suppressor



⇒ LD =[14.0 : 14.3] m and Lcell=245 m ~2% of dipole field is saved, losing ~15% of beam sigma and having 2.5-4% more dipoles

⇒ LD =14.8 m and Lcell=219 m ~3% of dipoles and 1% of dipole field can be saved, losing ~3% of beam sigma

Some Lattice parameters

Parameter	value
Bρ [T m]	166667
γ	53289
$\gamma_{transition}$	97
α	0.0001
β^* [m]	1.1
Natural chromaticity x/y	-196./-197.
Equilibrium emittance* [m rad]	1e-12
$\varepsilon_{norm}/\beta\gamma$ [m rad]	4.1e-11
Transverse/Longitudinal Damping time** [h]	2/1

* $\varepsilon_{eq} = \dfrac{C_q \gamma^2 I_5}{\left(I_2\left(1-\dfrac{I_4}{I_2}\right)\right)}$

** $\tau_t = \dfrac{2E_0 T_0}{U_0}$ $\tau_l = \dfrac{2E_0 T_0}{U_0\left(2+\dfrac{I_4}{I_2}\right)}$