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Dynamic Aperture at injection and 3.3 TeV energy choice

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Outline

- Motivation
- Dipoles field errors and non-linear correctors in the arcs
- Impact of dipoles errors on Dynamic Aperture (DA)
- Impact of triplet and separation dipoles errors at injection
- Impact of Landau Damping Octupoles at injection
- Injection Energy considerations
- Conclusions and Perspectives

Motivation

- Define correction schemes for non-linear errors of main magnets of the arcs
- Provide tolerances for the alignment and for the main high order multipoles components of magnets of the arcs
- Key issues:
 - Reserve space for correctors in the arc cells
 - Get order of magnitude of correctors strengths to identify possible R&D needed
 - Define tolerances on magnets alignment and main fields errors
 - Define tolerances on arcs magnets field quality to ensure $DA > 12 \sigma$ at injection and much more at collision

Dipole errors tables

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v2 FCC Dipole field quality version 2 - 3 Oct 2017- $R_{ref}=16.7$ mm. 3.3 TeV Injection										v3 FCC Dipole field quality version 3 - 24 Jan 2018- $R_{ref}=16.7$ mm. 3.3 TeV Injection									
Normal	Systematic					Uncertainty		Random		Systematic					Uncertainty		Random		
	Geometric	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field	Geometric	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field	
2	-2.230	-44.610	0.000	-2.230	-46.840	0.922	0.922	0.922	0.922	-2,230	-44,610	0,000	-2,230	-46,840	0,922	0,922	0,922	0,922	
3	-18.140	17.000	-38.560	-56.700	-1.140	3.000	1.351	3.000	1.351	-18,140	17,000	-38,860	-57,000	-1,140	4,000	1,351	4,000	1,351	
4	-0.100	-0.930	0.100	0.000	-1.030	0.449	0.449	0.449	0.449	-0,100	-0,930	0,100	0,000	-1,030	0,449	0,449	0,449	0,449	
5	-0.690	-0.340	13.660	12.970	-1.030	2.000	0.541	2.000	0.541	-0,690	-0,340	9,190	8,500	-1,030	1,000	0,541	1,000	0,541	
6	0.000	-0.010	0.000	0.000	-0.010	0.176	0.176	0.176	0.176	0,000	-0,010	0,000	0,000	-0,010	0,176	0,176	0,176	0,176	
7	1.610	0.140	-1.920	-0.310	1.750	0.250	0.211	0.250	0.211	1,610	0,140	-1,010	0,600	1,750	0,211	0,211	0,211	0,211	
8	0.000	0.000	0.000	0.000	0.000	0.071	0.071	0.071	0.071	0,000	0,000	0,000	0,000	0,000	0,071	0,071	0,071	0,071	
9	1.310	0.120	3.970	5.280	1.430	1.000	0.092	1.000	0.092	1,310	0,120	2,990	4,300	1,430	0,500	0,092	0,500	0,092	
10	0.000	0.000	0.000	0.000	0.000	0.027	0.027	0.027	0.027	0,000	0,000	0,000	0,000	0,000	0,027	0,027	0,027	0,027	
11	0.960	0.090	-0.100	0.860	1.050	0.200	0.028	0.200	0.028	0,960	0,090	-0,100	0,860	1,050	0,100	0,028	0,100	0,028	
12	0.000	0.000	0.000	0.000	0.000	0.009	0.000	0.009	0.009	0,000	0,000	0,000	0,000	0,000	0,000	0,009	0,000	0,009	
13	-0.170	-0.020	0.170	0.000	-0.190	0.011	0.000	0.011	0.011	-0,170	-0,020	0,170	0,000	-0,190	0,000	0,011	0,000	0,011	
14	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.003	0.003	0,000	0,000	0,000	0,000	0,000	0,000	0,003	0,000	0,003	
15	0.010	0.000	-0.010	0.000	0.010	0.004	0.000	0.004	0.004	0,010	0,000	-0,010	0,000	0,010	0,000	0,004	0,000	0,004	
Skew																			
2	0.000	0.000	0.000	0.000	0.000	1.040	1.040	1.040	1.040	0,000	0,000	0,000	0,000	0,000	1,040	1,040	1,040	1,040	
3	0.000	0.000	0.000	0.000	0.000	0.678	0.678	0.678	0.678	0,000	0,000	0,000	0,000	0,000	0,678	0,678	0,678	0,678	
4	0.000	0.000	0.000	0.000	0.000	0.450	0.450	0.450	0.450	0,000	0,000	0,000	0,000	0,000	0,450	0,450	0,450	0,450	
5	0.000	0.000	0.000	0.000	0.000	0.317	0.317	0.317	0.317	0,000	0,000	0,000	0,000	0,000	0,317	0,317	0,317	0,317	
6	0.000	0.000	0.000	0.000	0.000	0.205	0.205	0.205	0.205	0,000	0,000	0,000	0,000	0,000	0,205	0,205	0,205	0,205	
7	0.000	0.000	0.000	0.000	0.000	0.116	0.116	0.116	0.116	0,000	0,000	0,000	0,000	0,000	0,116	0,116	0,116	0,116	
8	0.000	0.000	0.000	0.000	0.000	0.071	0.071	0.071	0.071	0,000	0,000	0,000	0,000	0,000	0,071	0,071	0,071	0,071	
9	0.000	0.000	0.000	0.000	0.000	0.041	0.041	0.041	0.041	0,000	0,000	0,000	0,000	0,000	0,041	0,041	0,041	0,041	
10	0.000	0.000	0.000	0.000	0.000	0.025	0.025	0.025	0.025	0,000	0,000	0,000	0,000	0,000	0,025	0,025	0,025	0,025	
11	0.000	0.000	0.000	0.000	0.000	0.016	0.016	0.016	0.016	0,000	0,000	0,000	0,000	0,000	0,016	0,016	0,016	0,016	
12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.009	0,000	0,000	0,000	0,000	0,000	0,000	0,009	0,009	0,009	
13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.005	0,000	0,000	0,000	0,000	0,000	0,000	0,005	0,005	0,005	
14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.003	0,000	0,000	0,000	0,000	0,000	0,000	0,003	0,003	0,003	
15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.002	0,000	0,000	0,000	0,000	0,000	0,000	0,002	0,002	0,002	

Dipoles errors model

- **b_{ns} systematic error component**
- **b_{nu} uncertainty error component:** Gaussian distributed with cut at 1.5σ , the same seed for U for all dipoles of the same arc is used (8 different sectors as in LHC)
- **σ_{bn} random error component:** different seeds for each dipole are used and Gaussian distributed with cut at 3σ

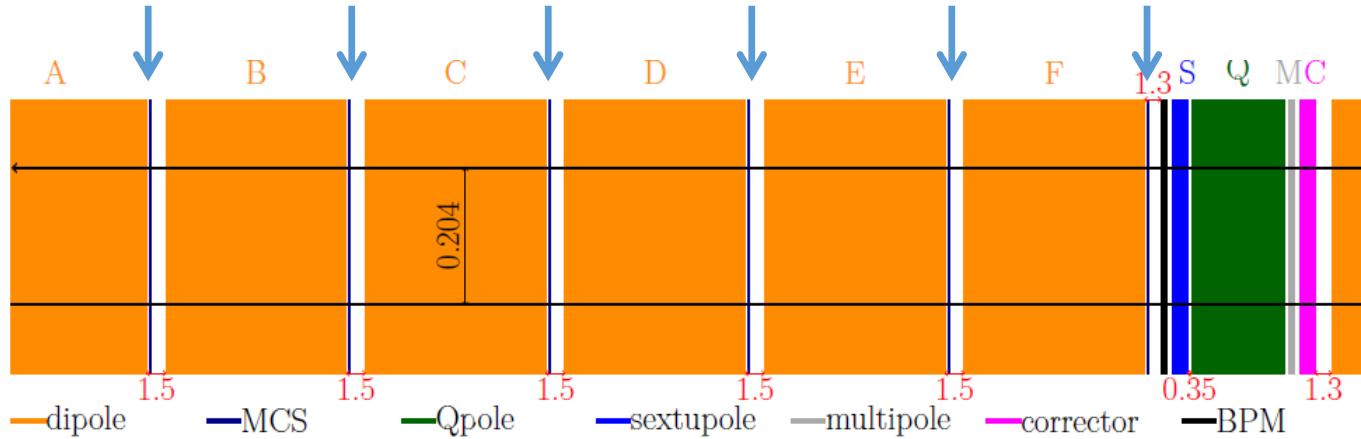
S. Fartoukh and O. Bruning LHC Project Report 501
LHC Design Report

- Even normal error components change sign between inner and outer chamber*
- Odd skew error components change sign between inner and outer chamber*
- Field quality at injection depends mainly on the sub-element diameter and critical current density: an effective filament size of $50 \mu\text{m}$ ($20 \mu\text{m}$) and $\pm 10\%$ ($\pm 5\%$) variation of critical current density to compute uncertainty are used for table v2 (v3)

S. Izquierdo Bermudez et al,
FCC-hhmagnet-beam dynamics coordination meeting 03

*NB. this is not true for the common coil design of the main dipoles...

b_3 correctors (MCS)

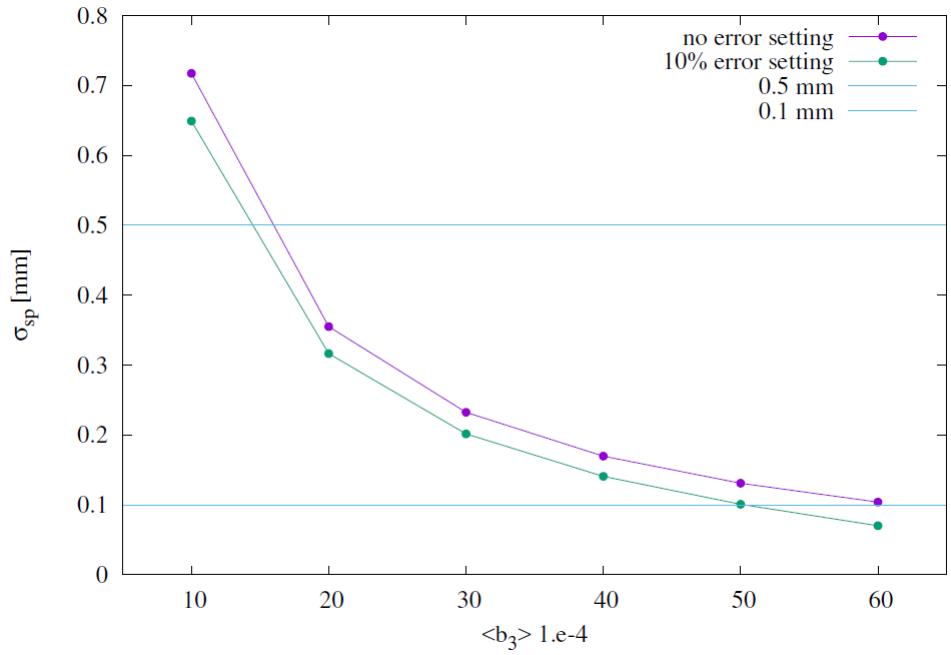


- max gradient 3000 T/m^2 , Length = 0.11 m , aperture 50 mm, one corrector at each dipole (2×4668)
- can correct a systematic component of b_3 of 4 unit at collision and up to 60 unit at injection

b_3 correctors alignment at injection

- β -beating from random b_2 components of the main dipole is $\sim 5\%$ (in LHC is $\sim 2.6\%$)^{*}
- For a **relative** misalignment of the MCS with respect to the dipole of ± 0.5 mm and a systematic b_3 of 60 unit the β -beating from feed-down of b_3 to b_2 is of $\sim 22\%$
- To align the MCS in the cryo-stat better than ± 0.5 mm seems to be difficult
- The impact of the misalignment can be reduced by adding a second MCS on the other side of the dipole
- Beta-beating correction to be studied

$$\sigma_{b_2}^{feed-down} \leq \sigma_{b_2}$$



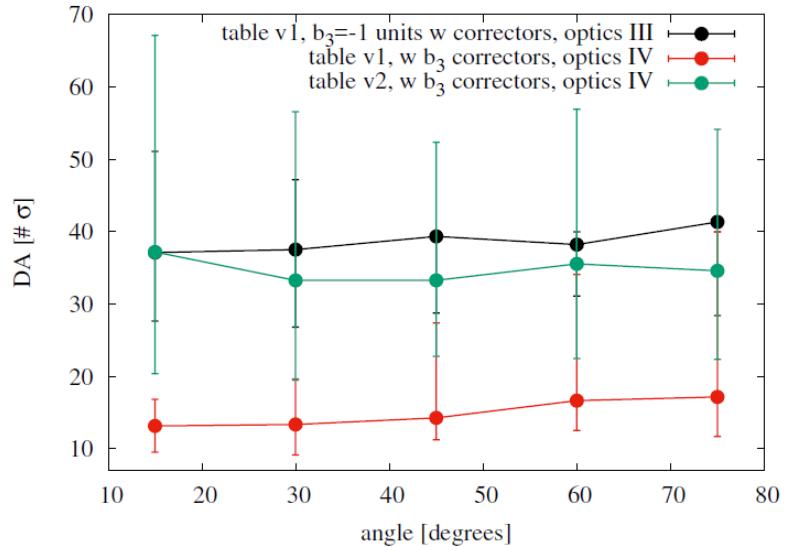
* S. Fartoukh and O. Bruning LHC Project Report 501

Dipole field quality at collision ($\beta^*=0.3\text{m}$)

- DA at collision is dominated by the random b_3 dipole error (once the systematic is corrected using spool pieces 3000 T/m^2 , Length = 0.11 m , at each dipole)
- Table v2(v3) have larger random components with respect to table v1 \Rightarrow larger uncertainty on DA value
- The systematic $b_2=50$ unit doesn't affect DA
- The new **phase between IPA-G** (.68,.14 see E. Cruz talk) gives **more than 50σ minimum DA**

\Rightarrow big impact of phases advance on DA

Optics III: 97.75 km layout, $L^*=45 \text{ m}$, $Q_x=111.31$, $Q_y=109.32$, #cell SAR/LAR=19/79
Optics IV: 97.75 km layout, $L^*=40 \text{ m}$, $Q_x=110.31$, $Q_y=108.32$, #cell SAR/LAR=20/78

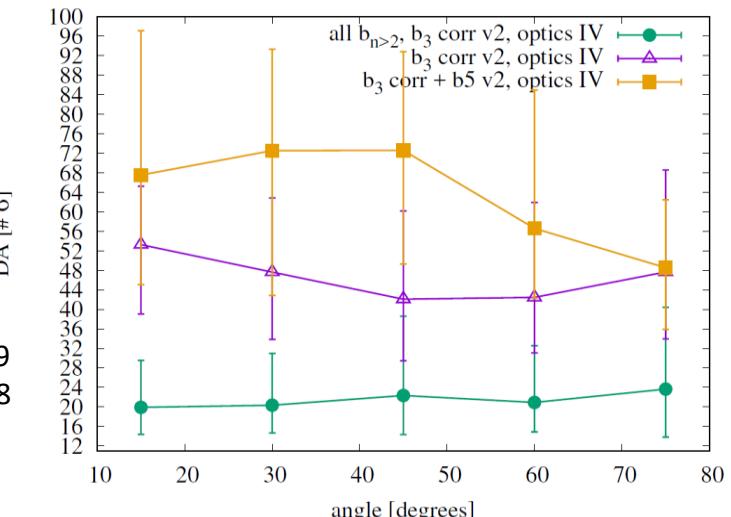
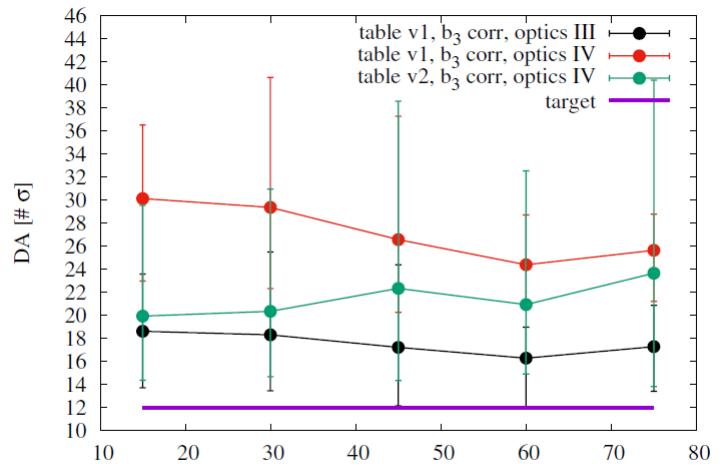


Dipole field quality at injection (3.3 TeV)

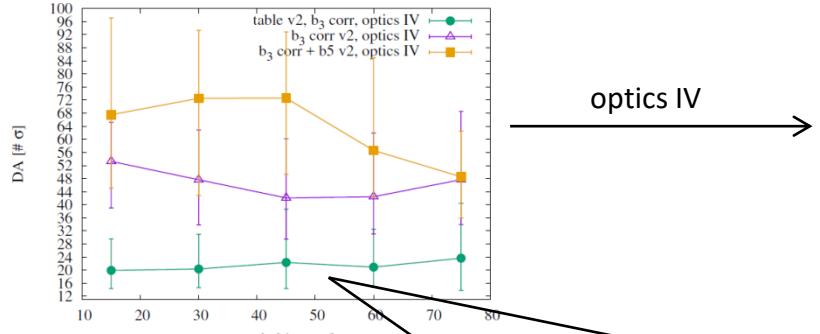
- DA at injection is dominated by the combination of random dipole errors
- ~ 60 unit of systematic b_3 , due to persistent current, can be corrected
- **Min DA 12.1σ (table v1, optics III)**
 20.2σ (table v1, optics IV)
 13.0σ (table v2, optics IV)
- Big impact of first order optics on DA
- No need of b_4 and b_5 correctors for the arcs

⇒ Difficult to define tolerances if first order optics is not frozen

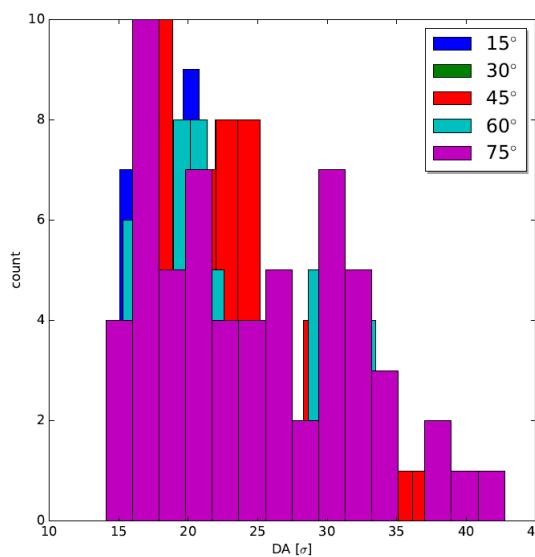
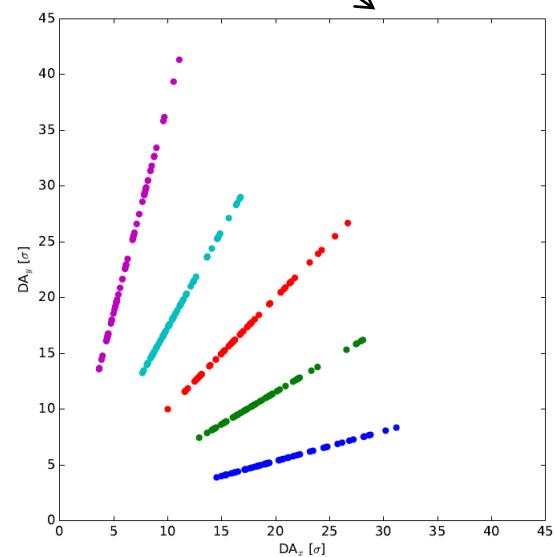
Optics III: 97.75 km layout, $L^* = 45$ m, $\beta^* = 4.6$ m, $Q_x = 111.28$, $Q_y = 109.31$, #cell SAR/LAR = 19/79
Optics IV: 97.75 km layout, $L^* = 40$ m, $\beta^* = 4.6$ m, $Q_x = 110.28$, $Q_y = 108.31$, #cell SAR/LAR = 20/78



DA seeds distributions table v2



minDA [σ]	15°	30°	45°	60°	75°	Comment
	39	33.8	29.5	31.1	33.9	b_3 only
	45.1	42.8	49.3	42.3	35.9	b_3+b_5 only
	14.4	14.7	14.3	14.9	13.8	all $b_{n \geq 3}$ errors



DA due to main dipole errors table v3 at injection

- All multipoles of order higher than 3 have been reduced with respect to table v2
- Min DA strongly dependent on phases between opposite points in the ring (compensation between arcs)
- 50 unit of systematic b_2 do not seem to have an impact on DA

Minimum DA in σ over 60 seeds

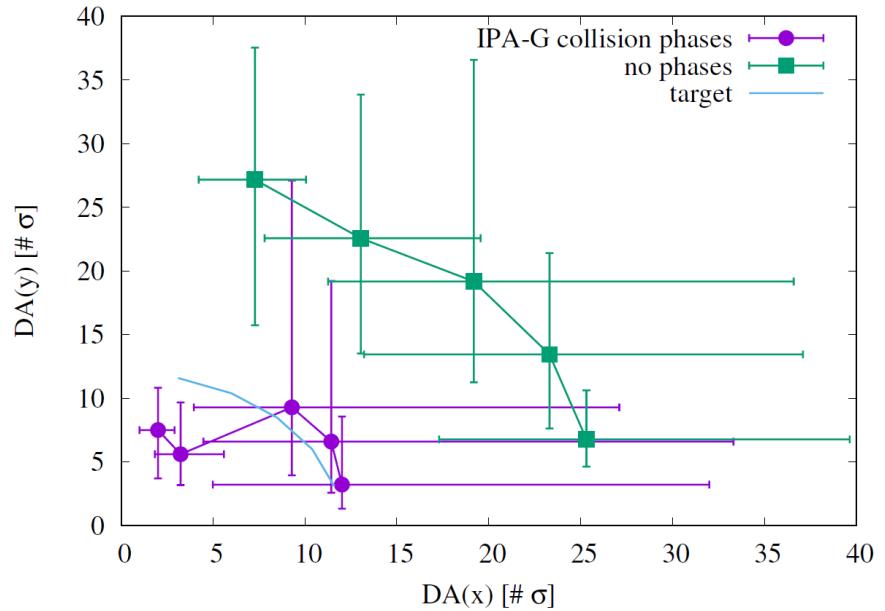
15°	30°	45°	60°	75°	comments
14.4	14.7	14.3	14.9	13.8	optics IV $b_2=0$ unit table v2
33.3	31.1	39.2	29.4	30.2	optics IV $b_2=0$ unit
34.1	36	37.2	37.1	37.5	$b_2=50$ unit IPA-G collision phases
16.8	18.4	18.7	20.3	19.9	$b_2=50$ unit no phases

Triplet and separation dipoles errors at injection

See E. Cruz talk for implementation of the triplet and separation dipole errors

- Non-linear correctors not included
crossing scheme and separation included
- Minimum DA of 28.8σ due to triplet and separation dipoles errors only
 - **Minimum DA of 3.7σ due to combination of triplet, separation dipoles and main dipoles errors with IPA-G collision phases advance**

⇒ Strong impact of first order optics on DA
⇒ Optimize phases advance between IPA-G at injection with all errors



Impact of Landau Octupoles at injection

- 480 octupoles can be installed in Long Arcs
- $G_{max} = 200000 \text{ T/m}^3$, Length = 0.5 m,
 $I_{max} = 720 \text{ A}$
- current required at injection 3.3% of max current (see C. Tambasco talk)

Minimum DA in σ					
15°	30°	45°	60°	75°	comments
5.2	5.2	5.6	3.7	3.8	$b_2=50$ unit and IPA-IPG collision phases
7.0	6.9	6.8	5.1	7.1	2.1% octupole strength

⇒ small DA increase with octupole!

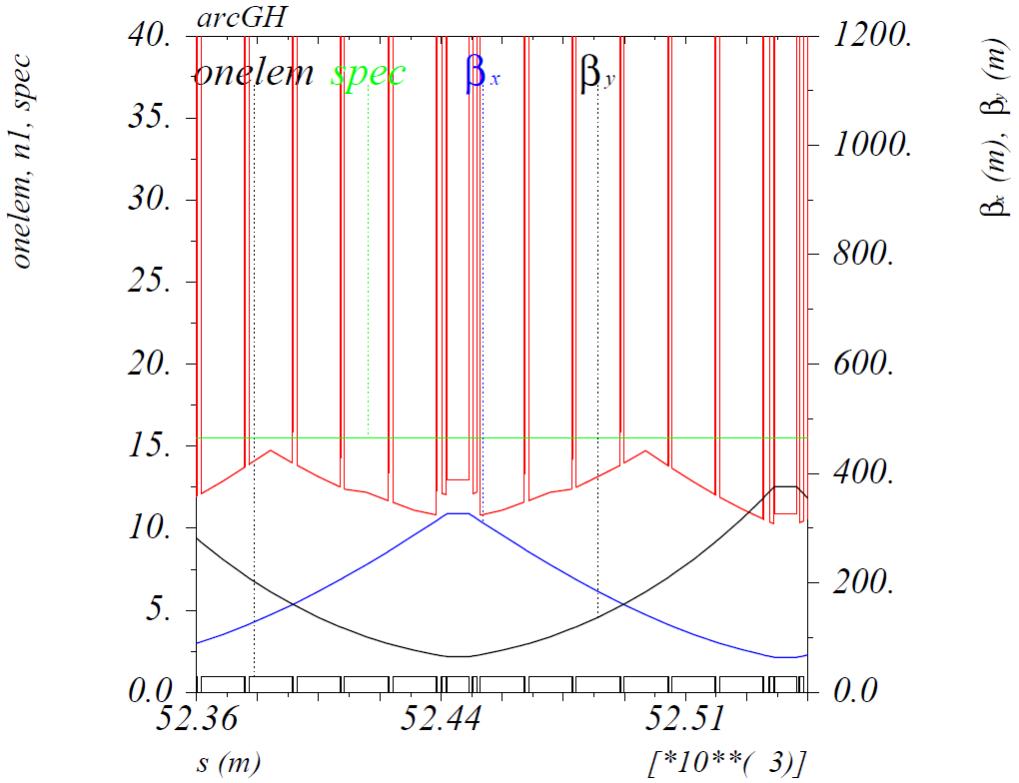
Injection Energy @ 1.3 TeV

For FCC-hh two energies are considered:

1. Baseline: 3.3 TeV (LHC or HEB as injector,
B. Goddard talk)
2. Alternative: 1.3 TeV (superconducting SPS
as injector)

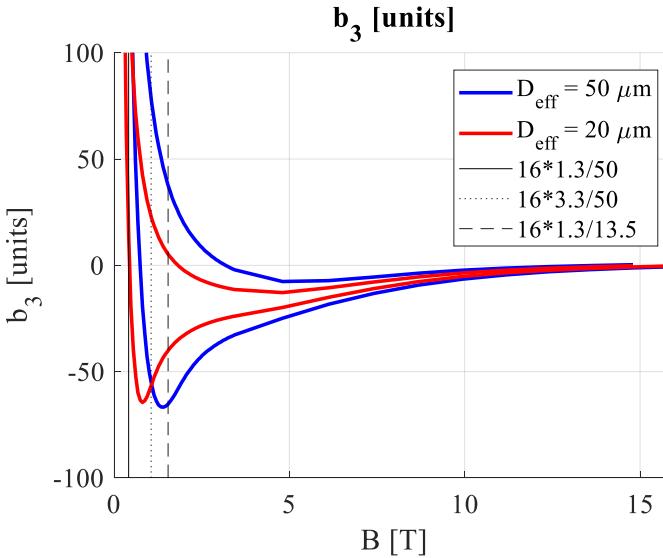
Using the latest beam screen model, and same alignment and beam tolerances of 3.3 TeV case (by R. Martin, see A. Chancé talk) the **beam stay clear** is $\sim 10.3 \sigma$ in the arcs

\Rightarrow Collimation requirements for aperture not met (15.5σ)



Dipole Field Quality @ 1.3 TeV

- minimum DA $\sim 2 \sigma$ due to dipole field quality
- N.B.** maximum persistent current contribution occurs during the ramp!



Susana Izquierdo Bermudez et al. 29/01/2018

v3 FCC Dipole field quality version 3 - 24 Jan 2018- R _{ref} =16.7 mm. 1.3 TeV Injection									
	Systematic					Uncertainty		Random	
	Geometric	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field
Normal	-2,230	-44,610	0,000	-2,230	-46,840	0,922	0,922	0,922	0,922
2	-18,140	17,000	33,140	15,000	-1,140	15,000	1,351	15,000	1,351
3	-0,100	-0,930	0,100	0,000	-1,030	0,449	0,449	0,449	0,449
4	-0,690	-0,340	-0,810	-1,500	-1,030	3,000	0,541	3,000	0,541
5	0,000	-0,010	0,000	0,000	-0,010	0,176	0,176	0,176	0,176
6	1,610	0,140	-0,410	1,200	1,750	0,500	0,211	0,500	0,211
7	0,000	0,000	0,000	0,000	0,000	0,071	0,071	0,071	0,071
8	1,310	0,120	-0,810	0,500	1,430	1,000	0,092	1,000	0,092
9	0,000	0,000	0,000	0,000	0,000	0,027	0,027	0,027	0,027
10	0,960	0,090	-0,210	0,750	1,050	0,200	0,028	0,200	0,028
11	0,000	0,000	0,000	0,000	0,000	0,000	0,009	0,000	0,009
12	-0,170	-0,020	0,170	0,000	-0,190	0,000	0,011	0,000	0,011
13	0,000	0,000	0,000	0,000	0,000	0,000	0,003	0,000	0,003
14	0,010	0,000	-0,010	0,000	0,010	0,000	0,004	0,000	0,004
15	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Skew									
2	0,000	0,000	0,000	0,000	0,000	1,040	1,040	1,040	1,040
3	0,000	0,000	0,000	0,000	0,000	0,678	0,678	0,678	0,678
4	0,000	0,000	0,000	0,000	0,000	0,450	0,450	0,450	0,450
5	0,000	0,000	0,000	0,000	0,000	0,317	0,317	0,317	0,317
6	0,000	0,000	0,000	0,000	0,000	0,205	0,205	0,205	0,205
7	0,000	0,000	0,000	0,000	0,000	0,116	0,116	0,116	0,116
8	0,000	0,000	0,000	0,000	0,000	0,071	0,071	0,071	0,071
9	0,000	0,000	0,000	0,000	0,000	0,041	0,041	0,041	0,041
10	0,000	0,000	0,000	0,000	0,000	0,025	0,025	0,025	0,025
11	0,000	0,000	0,000	0,000	0,000	0,016	0,016	0,016	0,016
12	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,009	0,009
13	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,005	0,005
14	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,003	0,003
15	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,002	0,002

Chromatic coupling (a_3 correctors): LHC

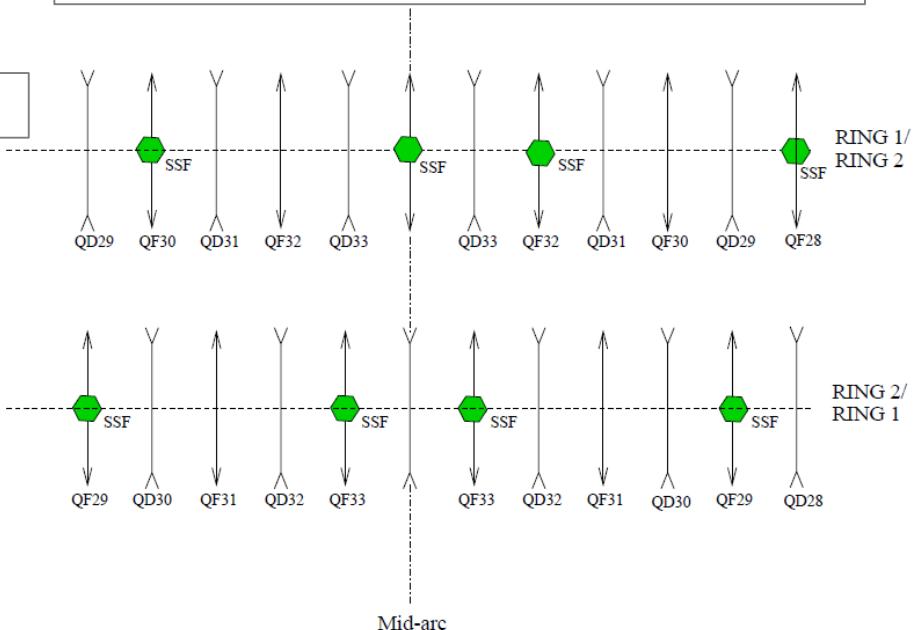
Four focusing chromaticity sextupoles tilted by 30° per arc.

The phase advance between the four skew sextupoles is $180^\circ - 90^\circ - 180^\circ \Rightarrow$ correction of the chromatic difference coupling (as for the a_2 case)

In LHC [T. Persson et al. Phys. Rev. ST Accel. Beams 16, 081003, 2013]

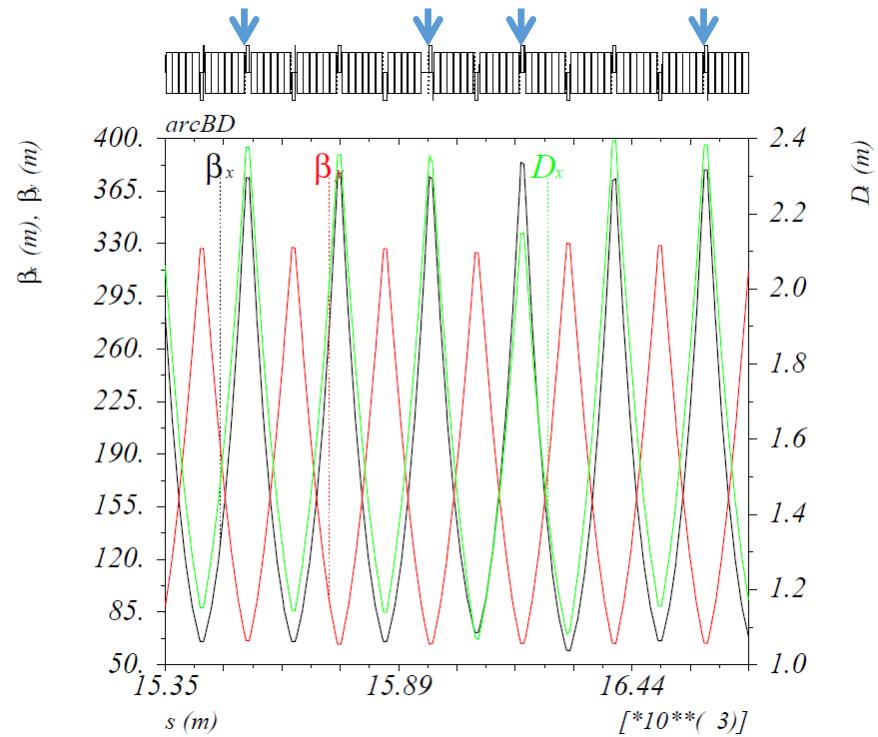
- the strength of the skew sextupoles for each arc are 4 times higher with the arc by arc calculation with respect to a global response matrix
- the chromatic coupling of one arc can be compensated by the other using the response matrix algorithm

S. Fartoukh and O. Bruning LHC Project Report 501



Chromatic coupling FCC

- Max available integrated strength for one sextupole 0.1 m^{-2}
 - 4 skew sextupoles can correct up to 3 times more chromatic coupling difference resonance of the worst long arc case (arc by arc calculation S. Fartoukh and O. Bruning LHC Project Report 501)
 - Due to missing dipoles dispersion around mid arc is not fully symmetric
- ⇒ LHC scheme provides enough strength to correct chromatic coupling but not optimized for FCC
- ⇒ From DA point of view a_3 of main dipole correction is not crucial
- ⇒ Need to understand more the impact on Q'' and tunes spread



Conclusions and Perspectives

- b_3 correctors feasible in NbTi technology
 - LHC a_3 correctors scheme is more than enough for FCC but not optimized
 - b_4 and b_5 correctors of main dipoles errors not needed
 - combination of errors from different magnets in the ring and phases advance can strongly reduce DA
 - injection energy at 1.3 TeV excluded from DA point of view or very challenging!
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- Follow up of the studies presented
 - Impact of main quadrupole field quality
 - Explore different IPA-G phases at injection
 - Impact of linear imperfections on DA

SPARES