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Status of Dynamic Aperture and alignment for FCC-hh

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Outline

- Motivation
- Dipole's field errors and alignment errors
- Linear and non-linear correctors
  alignment and field error tolerances
- Impact of linear imperfections on Dynamic Aperture (DA)
- Impact of dipole type on DA
- Impact of Landau Damping Octupoles on DA
- Conclusions and Perspective

Motivation

- Design correction schemes for linear and non-linear errors of main magnets of the arcs
- Provide tolerances for the alignment and for the main high order multipoles components of magnets or 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 σ at injection and much more at collision

Linear imperfections

Element	Error	Error Descr.	Units	FCC study	LHC	Comments
Dipole	σ(x),σ(y)		mm	0.5	0.5	no effect on observables studied
	σ(θ),δ(φ)	transv. rot.	mrad	0.07	?	est. from dipole geometry and σ(x/y)
	σ(ψ)	roll angle	mrad	0.5	n/a	effect on vertical plane
	σ(δB/B)	random b1	%	0.05	0.08	LHC value includes σ(ψ)
Quad	σ(x),σ(y)		mm	0.2	0.36	
	σ(θ),δ(φ)	transv. rot.	mrad	0.06	?	est. from quad geometry and σ(x/y)
	σ(ψ)	roll angle	mrad	1	0.5	
	σ(δB/B)	random b2	%	0.1	0.3	
BPM	σ(x),σ(y)		mm	0.30	0.24	value relative to quad
	σ(read)		mm	0.2	0.5	

Values in table correspond to 1 sigma, a Gaussian truncated to 3 sigma is used in simulations

Dipoles errors tables

v0

normal	Sys inj	Sys coll	Uncert	Ran
2	0	0	0.484	0.484
3	-5	20	0.781	0.781
4	0	0	0.065	0.065
5	-1	-1.5	0.074	0.074
6	0	0	0.009	0.009
7	-0.5	1.3	0.016	0.016
8	0	0	0.001	0.001
9	-0.100	0.05	0.002	0.002
10	0	0	0	0
skew				
2	0	0	1.108	1.108
3	0	0	0.256	0.256
4	0	0	0.252	0.252
5	0	0	0.05	0.05
6	0	0	0.04	0.04
7	0	0	0.007	0.007
8	0	0	0.007	0.007
9	0	0	0.002	0.002
10	0	0	0.001	0.001

v1

normal	Sys inj	Sys coll	Uncert	Ran
2	0	50	1.000	1.000
3	7	-1	1.600	1.600
4	0	0.5	0.100	0.100
5	1	0.5	0.100	0.100
6	0	0	0.020	0.020
7	-1.5	0.3	0.030	0.030
8	0	0	0.002	0.002
9	-0.1	0.1	0.005	0.005
10	0	0	0.001	0.001
skew				
2	0	0	2.200	2.200
3	0	0	0.500	0.500
4	0	0	0.500	0.500
5	0	0	0.100	0.100
6	0	0	0.080	0.080
7	0	0	0.010	0.010
8	0	0	0.010	0.010
9	0	0	0.003	0.003
10	0	0	0.002	0.002

Model of Dipole Field Quality

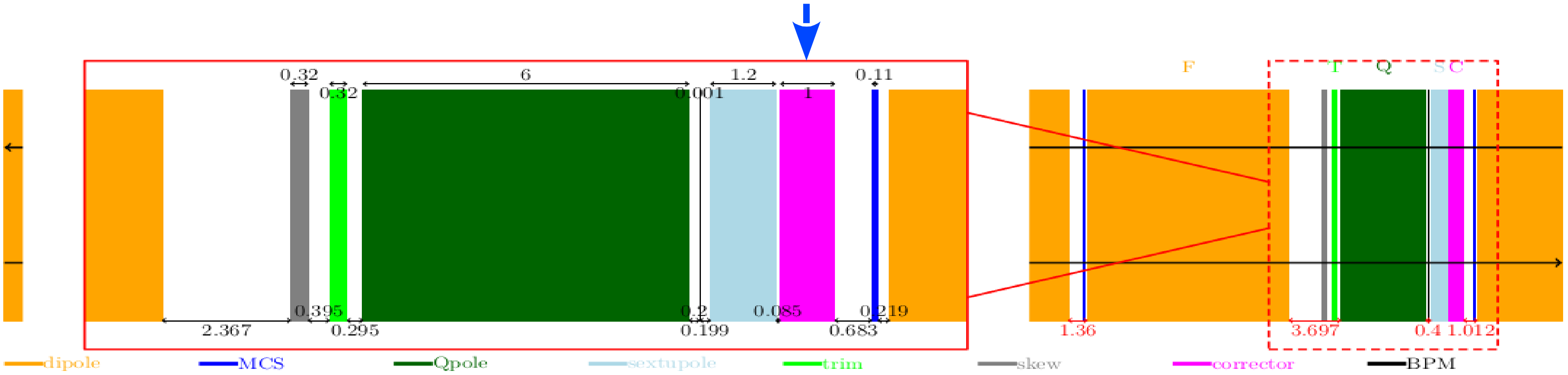
$$b_n = b_{n_s} + \frac{\xi_U}{1.5} b_{n_U} + \xi_R \sigma_{b_n}$$

- ξ = random number with Gaussian distribution cut at 1.5 (U) and 3 (R)
- the same seed for U for all dipoles of the same arc is used (8 different sectors as in LHC)
- different seeds for R for each dipole are used

Fractional part of tunes:
Q_x = .28, Q_y = .31 injection
Q_x = .31, Q_y = .32 collision

DA is evaluated with SixTrack adapted for FCC (SixTrack: cern.ch/sixtrack-ng)

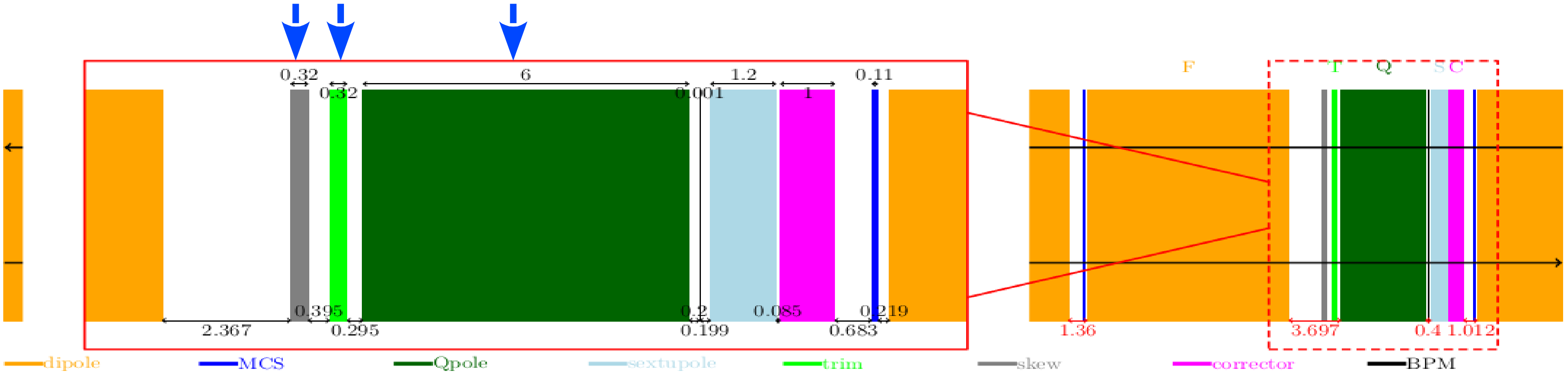
Orbit correctors and residual orbit



- max integrated strength < 4 T m (NbTi limit)
  - quadrupole alignment tolerance might be relaxed
- maximum residual orbit < 1 mm (at injection and at collision)

→ details in David Boutin presentation tomorrow

b_2 and coupling (a_2) correctors



- interference with spurious dispersion correction ⇒ coupling correctors and Trims in long arc only!
- b_2 and a_2: all main quadrupoles or 64 Trims at 90°, skew trims at 180°
  - max trims strength < 20 T/m   (R part only)
  - systematic b_2 of table v1 too high ⇒ can be corrected locally?
  - max skew gradient 250 T/m (table v0), 500 T/m (table v1), Length =0.32 m (U part)

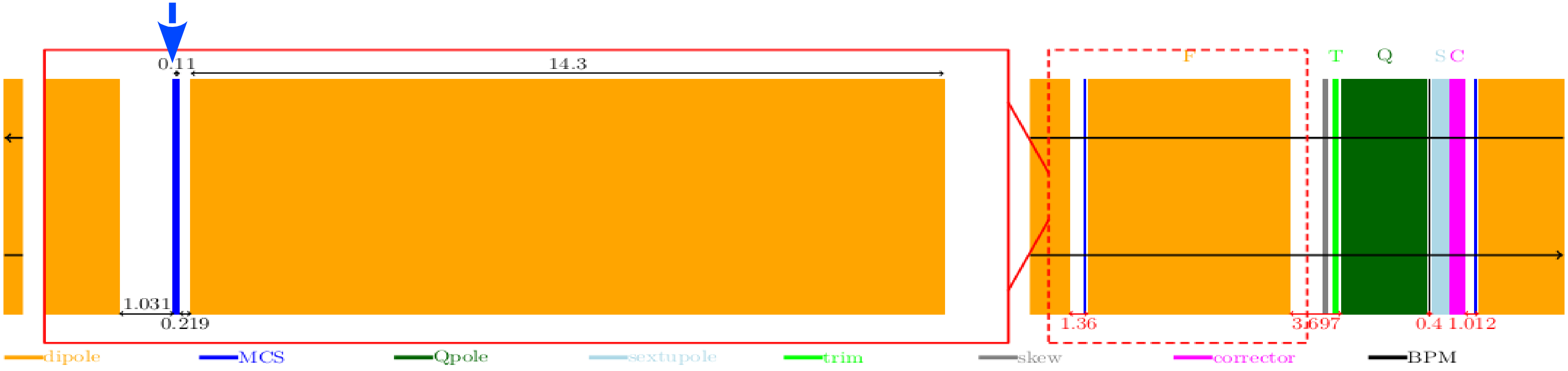
  a_2 (U) needs strong coupling correctors and gives high beta-beating

  ⇒ needs different correction schemes

  ⇒ sorting of dipoles can help

- details in David Boutin presentation tomorrow

b_3 correctors and tolerance

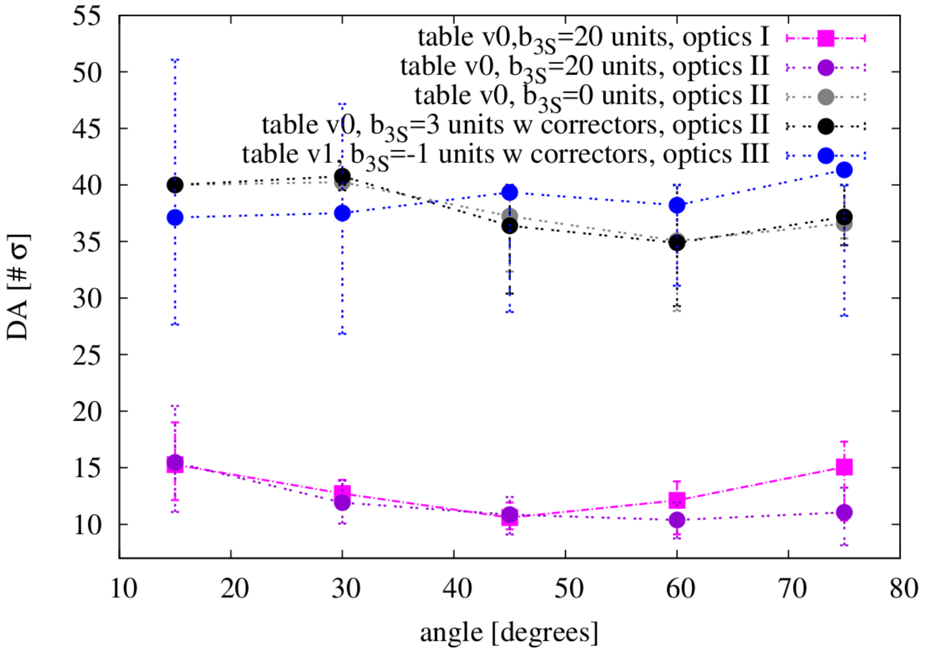


- MCS max gradient 4430 T/m^2, Length =0.11 m, one corrector at each dipole
- MCS can correct up to 6 unit of systematic b_3 at collision
- a_3 correctors/tolerance to be studied

DA at collision (β^*=0.3 m)

- DA at collision is dominated by the systematic b_3 dipole error
- tolerance of systematic component of $b_3 \leq 3$ unit at collision
- for the new layout at collision (optics III) minimum DA > 40 σ (table v0)

  ⇒ DA at collision due to dipole field quality > 26 σ

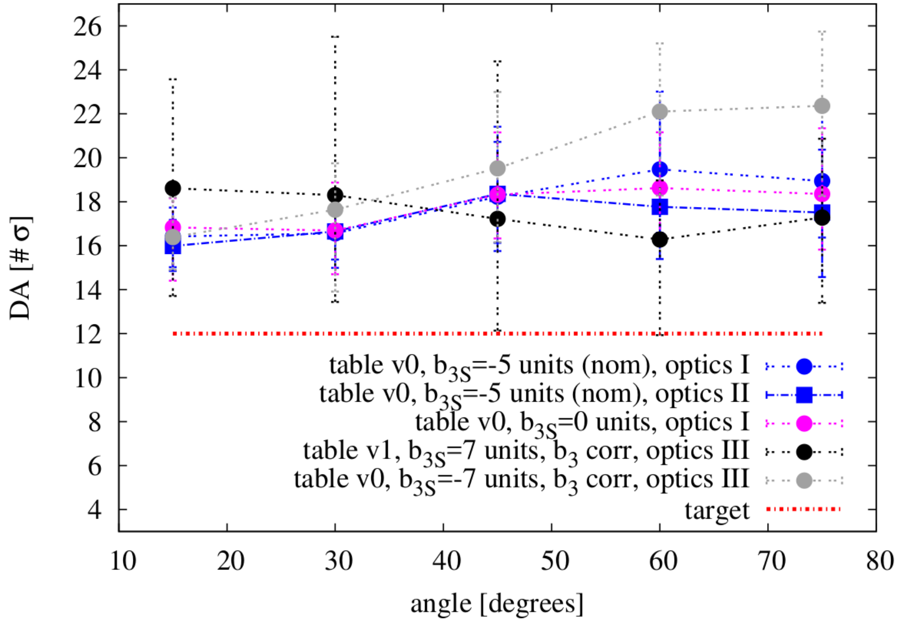


Optics I: 99.97 km layout, L*=36 m, β* =4.6 m and max momentum collimation dispersion 4 m
Optics II: 99.97 km layout, L*=36 m, β* =3.5 m and max momentum collimation dispersion 5 m
Optics III: 97.75 km layout, L*=45 m, β* =4.6 m and momentum collimation scaled from LHC

N.B. crossing scheme and final triplet errors NOT considered in these simulations (see A. Seryi & E. Cruz talks)

DA at injection

- DA at injection is dominated by the random dipole errors
- 15-20 unit of systematic b_3, due to persistent current, can be corrected
- min DA 13.9 σ (table v0)
  12.1 σ (table v1)
- no need for b_4 and b_5 correctors



Optics I: 99.97 km layout, L*=36 m, β* =4.6 m and max momentum collimation dispersion 4 m
Optics II: 99.97 km layout, L*=36 m, β* =3.5 m and max momentum collimation dispersion 5 m
Optics III: 97.75 km layout, L*=45 m, β* =4.6 m and momentum collimation scaled from LHC

b_4 tolerance

main dipole errors **table v0**:

- b_5 feed-down is not critical
- systematic $b_4 < 0.142$ at injection fine

main dipole errors **table v1**:

- same tolerance should be fine… to be checked

⇒ b_4 correctors not required

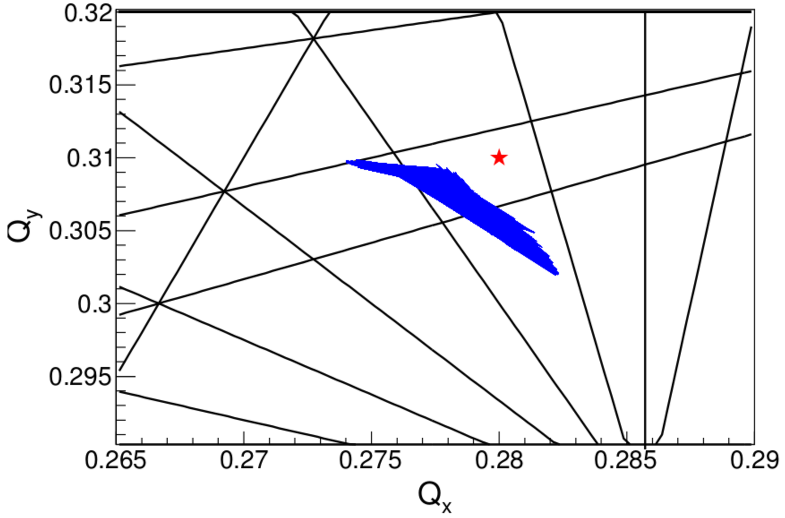


table v0

b_{4S}	b_{4R}	min DA [σ]
0 (nom)	0.065 (nom)	14.6
0.0284 (b_5 feed-down)	0.239(b_5 feed-down)	13.9
0.142 (b_5 feed-down x5)	0.239 (b_5 feed-down)	11.8
0.284 (b_5 feed-down x10)	0.239 (b_5 feed-down)	10.5

b_5 tolerance

main dipole errors **table v0**:

- detuning with amplitude and with momentum dominated by the systematic b_5 component
- systematic $b_5 < 2$ at injection fine

main dipole errors **table v1**:

- detuning with momentum dominated by a_4
- same tolerance should be fine… to be checked
  $\Rightarrow$ b_5 correctors not required

table v0

b_{5S}	min DA [σ]
-1 (nom)	14.6
-2	11.
-3	9.

table v0

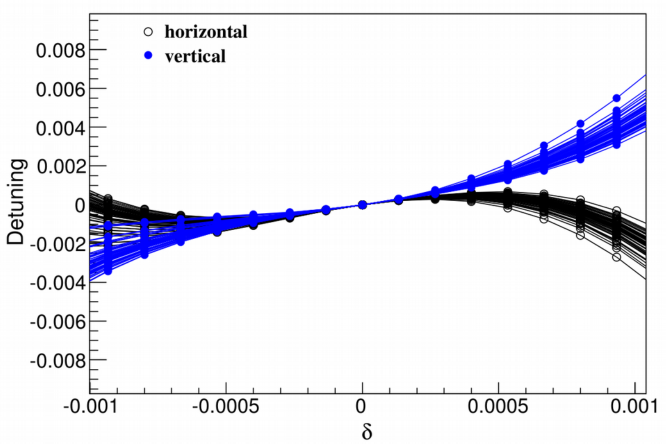
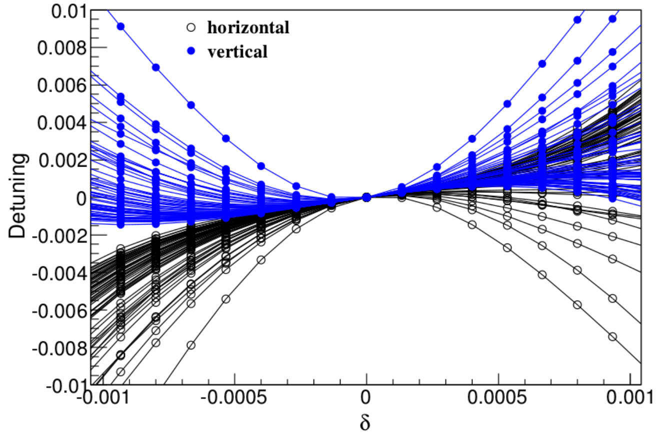
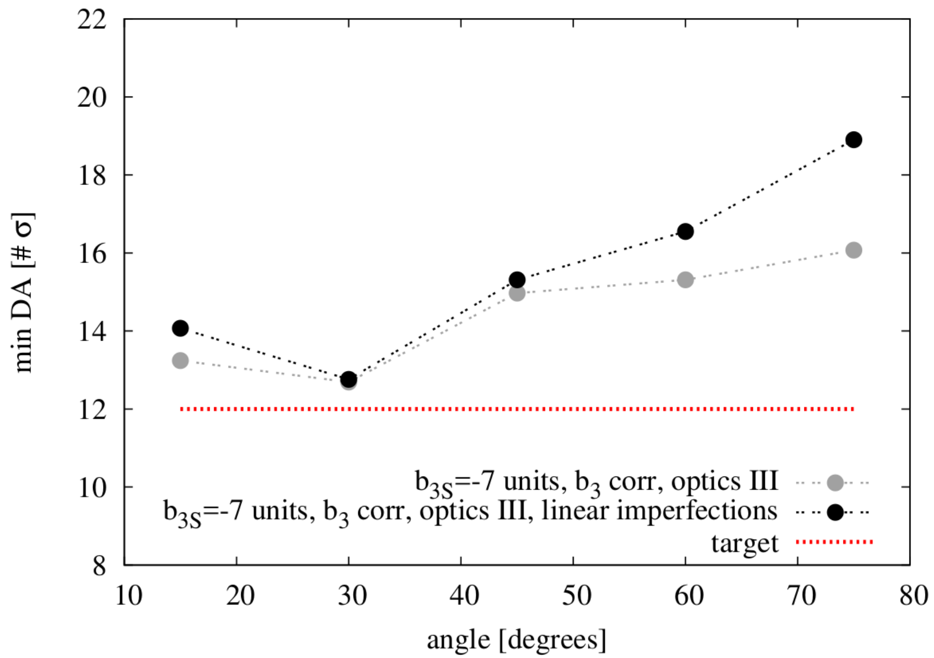


table v1

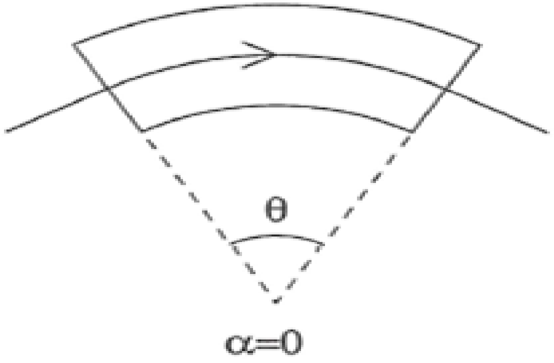


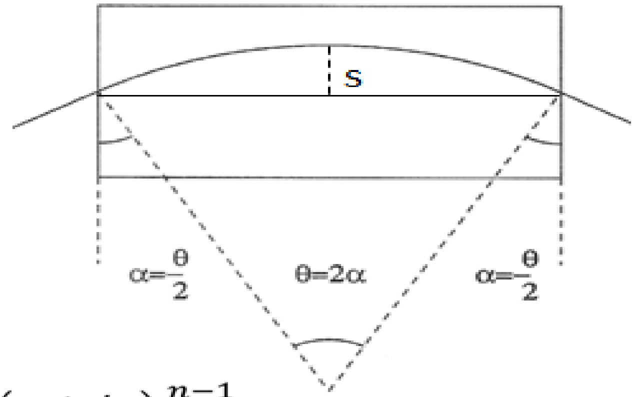
Impact of linear imperfections

- dipole field quality table v0 at injection
- linear errors and correction applied to 50 different seeds
- minimum DA unchanged or slightly better than without linear imperfections
- average DA better than without linear imperfections



Impact of dipole type





$$B_y + iB_x = B_{ref} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

$$b_{3err} = b_5 \cdot 6 \cdot \left(\frac{x_S}{R_{ref}} \right)^2 = 6 \cdot (b_{5S} + b_{5U} + b_{5R}) \cdot \left(\frac{x_S}{R_{ref}} \right)^2 \sim b_{5S} \cdot 0.13 = -0.13$$

- the value is less than the random component of b_3, that dominates the DA at injection
- the additional error is systematic for each dipole ⇒ correctable by the spool pieces

Impact of Landau Octupoles

- ~460 octupoles can be installed in Long Arcs
- G_max = 220000 T/m^3, Length = 0.32m, I_max =720 A
- K_MO = (G_max/Bρ) (I_oct/I_max) (50/energy)

⇒ important reduction of DA!

	I_oct [A]	min DA [σ]
inj	1	8.7
	10	1.2
	30	< 1
col	720	13

main dipole errors table v1 included

Conclusions

- Alignment tolerances almost defined
- Orbit correctors feasible in NbTi technology
- b_2 and a_2 (coupling) correction more difficult… need different schemes
- b_3 correctors feasible in NbTi technology
- b_4 and b_5 correctors not required and tolerances to be checked with new dipole field errors table
- Impact of linear imperfections on DA small (…to be further investigated)
- Impact of dipole type on DA small and correctable
- Impact of Landau Damping Octupoles on DA important!

Perspectives

- Follow up of the studies presented
- Define a_3 correctors and assess b_4, a_4, b_5, a_5 tolerances for new table
- Impact of main quadrupole field quality
- Impact of residual linear imperfections coming from IRs and of final triplet field quality at injection
- Tune scan

SPARES

Dipoles errors tables

v0

			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

v1

	FCC main dipole field quality targets (r = 17 mm) - version 2 - 08 May 2017								
	Systematic					Uncertainty		Random	
Normal	Geometric	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field
2	0.0	50.0	0.0	0.0	50.0	1.000	1.000	1.000	1.000
3	-8.0	7.0	15.0	7.0	-1.0	1.600	1.600	1.600	1.600
4	0.0	0.5	0.0	0.0	0.5	0.100	0.100	0.100	0.100
5	0.0	0.5	1.0	1.0	0.5	0.100	0.100	0.100	0.100
6	0.0	0.0	0.0	0.0	0.0	0.020	0.020	0.020	0.020
7	0.0	0.3	-1.5	-1.5	0.3	0.030	0.030	0.030	0.030
8	0.0	0.0	0.0	0.0	0.0	0.002	0.002	0.002	0.002
9	0.0	0.1	-0.1	-0.1	0.1	0.005	0.005	0.005	0.005
10	0.0	0.0	0.0	0.0	0.0	0.001	0.001	0.001	0.001
11	0.0	0.0	0.0	0.0	0.0	0.000	0.000	0.000	0.000
Skew									
2	0.0	0	0	0.0	0.0	2.200	2.200	2.200	2.200
3	0.0	0	0	0.0	0.0	0.500	0.500	0.500	0.500
4	0.0	0	0	0.0	0.0	0.500	0.500	0.500	0.500
5	0.0	0	0	0.0	0.0	0.100	0.100	0.100	0.100
6	0.0	0	0	0.0	0.0	0.080	0.080	0.080	0.080
7	0.0	0	0	0.0	0.0	0.010	0.010	0.010	0.010
8	0.0	0	0	0.0	0.0	0.010	0.010	0.010	0.010
9	0.0	0	0	0.0	0.0	0.003	0.003	0.003	0.003
10	0.0	0	0	0.0	0.0	0.002	0.002	0.002	0.002
11	0.0	0	0	0.0	0.0	0.000	0.000	0.000	0.000

FCC-hh Layout