FROM RESEARCH TO INDUSTRY

The European Circular Energy-Frontier Collider Study (EuroCirCol) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 654305. The information herein only reflects the views of its authors and the European Commission is not responsible for any use that may be made of the information.

EuroCirCol
A key to New Physics

ALIGNMENT AND BEAM-BASED CORRECTION

- Errors definition and correction scheme
- Evaluation of the results at injection and at collision
- Conclusions and perspectives

David Boutin, Antoine Chance, Barbara Dalena

31 MAY 2017

ERRORS DEFINITION

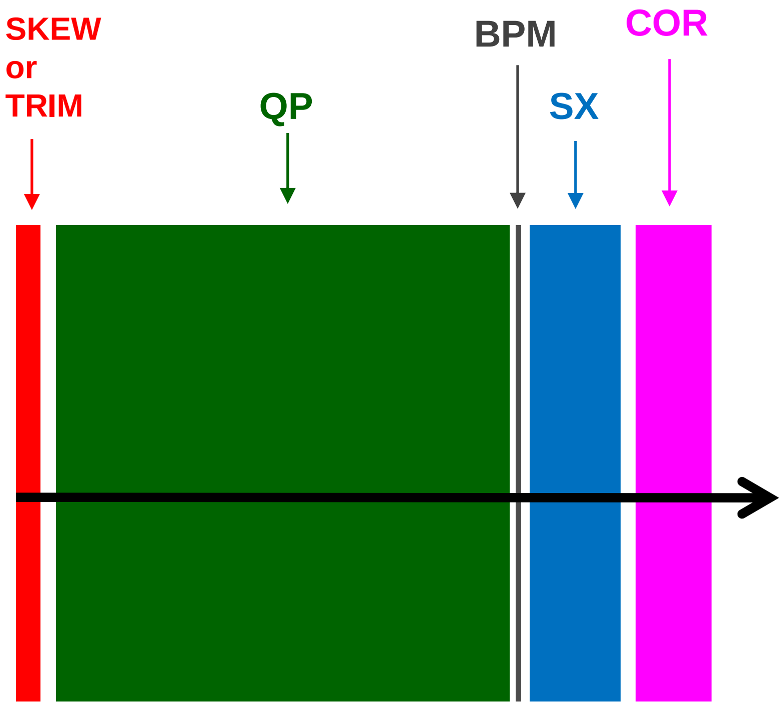
- Errors defined for all ‘MB’ dipoles (in arcs and DIS), all ‘MQ’ quadrupoles (in arcs and DIS) and for all BPMs used
- Errors are Gaussian distributed, truncated at 3-σ values, with a different seed for each run
- No errors are applied in the straight (insertion) regions unless specified
- Because of the increased computer time needed with the current correction procedure, only 100 runs were simulated for each case of this study

Element	Error	Error Descr.	Units	FCC	LHC	Comments
Dipole	σ(x),σ(y)		mm	0.5	0.5	no effect on observables studied
	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)
	σ(δB/B)	random b2	10^{-4} units	0.5	0.8	
	σ(δB/B)	random a2	10^{-4} units	1.1	1.6	
	σ(δB/B)	uncert. a2	10^{-4} units	1.1	0.5	
Quad	σ(x),σ(y)		mm	0.2	0.36	
	σ(ψ)	roll angle	mrad	1	0.5	
	σ(δB/B)	random b2	%	0.1	0.3	
BPM	σ(x),σ(y)		mm	0.3	0.24	value relative to quad
	σ(read)		mm	0.2	0.5	accuracy

LHC values are taken from LHC Project Report 501 (and 370 for BPM read error)

CORRECTION SCHEME

- Two energy regimes studied: at injection (3.3 TeV, β* = 4.6 mm) and at collision (50 TeV, no crossing scheme, β* = 0.3 mm)
- New lattice version (97.75 km), thin lenses
- All main quadrupole (MQ) units of the arc and DIS sections have a BPM and an orbit corrector (MCB), a skew (MQS) or trim (MQT) quadrupole inserted around the quadrupole.



- Each orbit corrector is coupled with a BPM shifted with a phase advance of 90°, correction of the orbit on the focusing plane of the quadrupole
- Linear coupling is corrected with skew quadrupoles
- Ring tunes are corrected with trim quadrupoles located on the outer part of the long arc sections, or main quadrupoles
- **The errors are evaluated only for the arc sections**

LINEAR COUPLING CORRECTION

- Compute the contribution of each magnet to the coupling on each arc

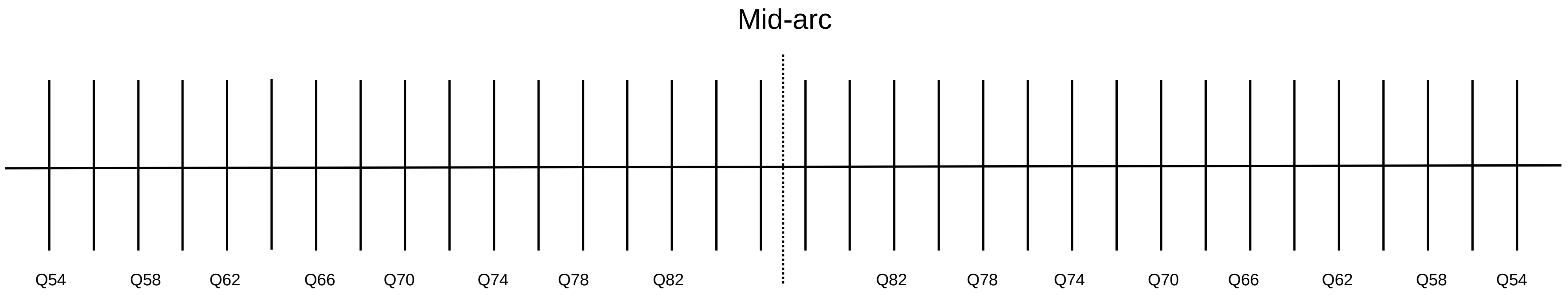
$$\triangle c_{\pm}^{i} = \frac{1}{2\pi} \cdot \int_{MB} ds \sqrt{\beta_x \beta_y} \cdot k_s \cdot e^{i(\mu_x \pm \mu_y)}$$

from LHC Project Report 399

Integrated strength per element:

Dipole	$l*k_s$ = 3.9e-6 (U), 3.9e-6 (R)
Quad	$l*k_s$ = 2.7e-5 (R)
Sext	$l*k_s$ = 1.2e-5 (R)

- Apply a correction with groups of 4 skew quadrupoles on each arc, with a phase advance of 180°
- No coupling correction in the short arcs (spurious dispersion correction)
- Coupled powering or left-right powering? More skew quads used in long arcs?



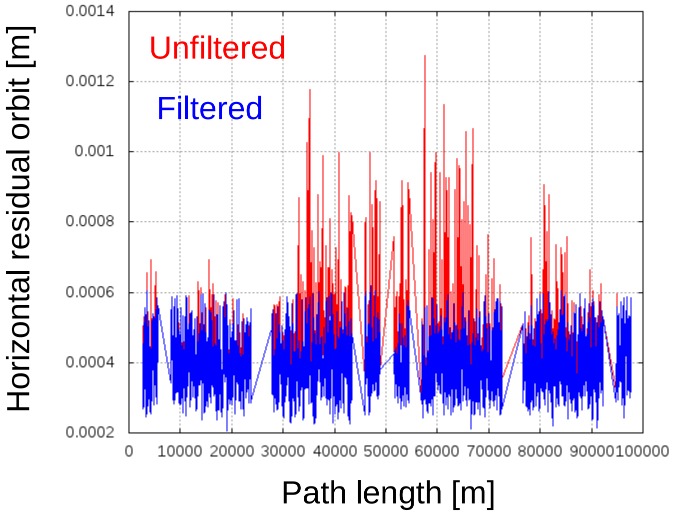
Numbered units have a skew quadrupole used for coupling correction

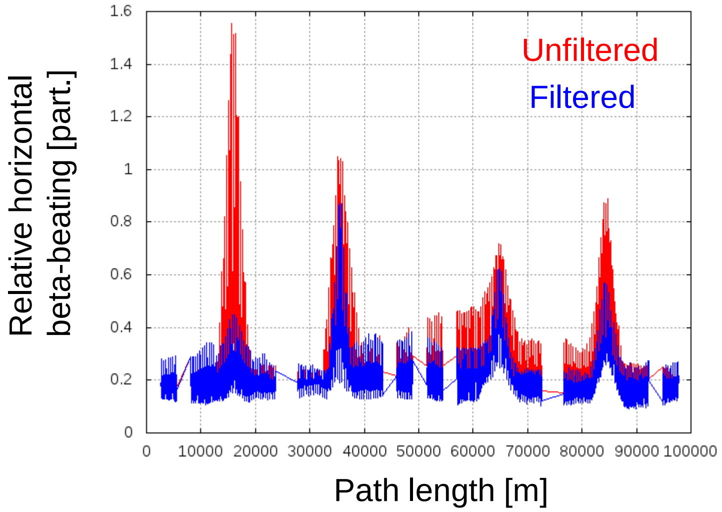
EVALUATION OF THE RESULTS

- For each run, calculation of the mean, RMS and maximum values for the following observables for all elements of the arc sections (see LHC Project Report 501 for more details):
  - Corrector strengths
  - Residual **orbit and angle**
  - Beta-beating $\boldsymbol{\Delta\beta/\beta_{ref}}$
  - Parasitic dispersion or dispersion beating $\boldsymbol{\Delta D/\sqrt{\beta_{re}}}$

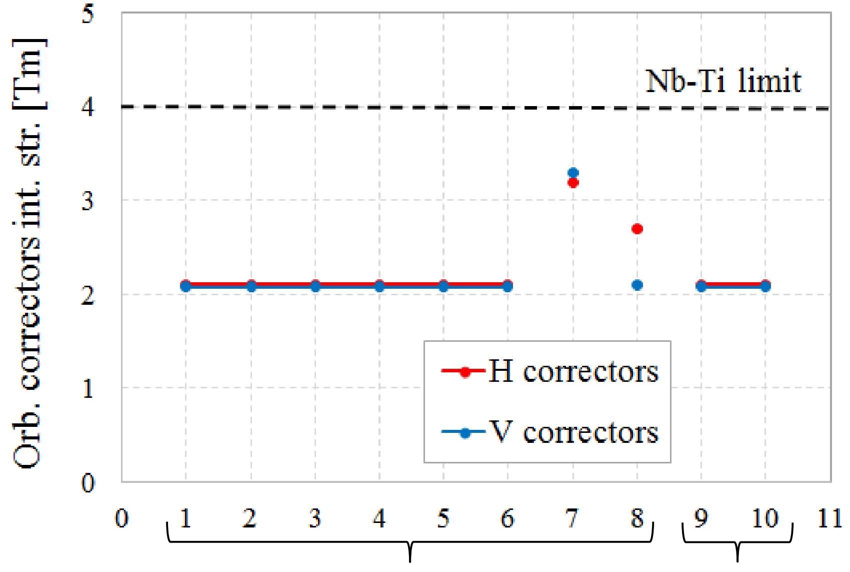
- From the distribution of the maximum values the 90-percentile (value for which 90% of the distribution is included) is calculated over all runs

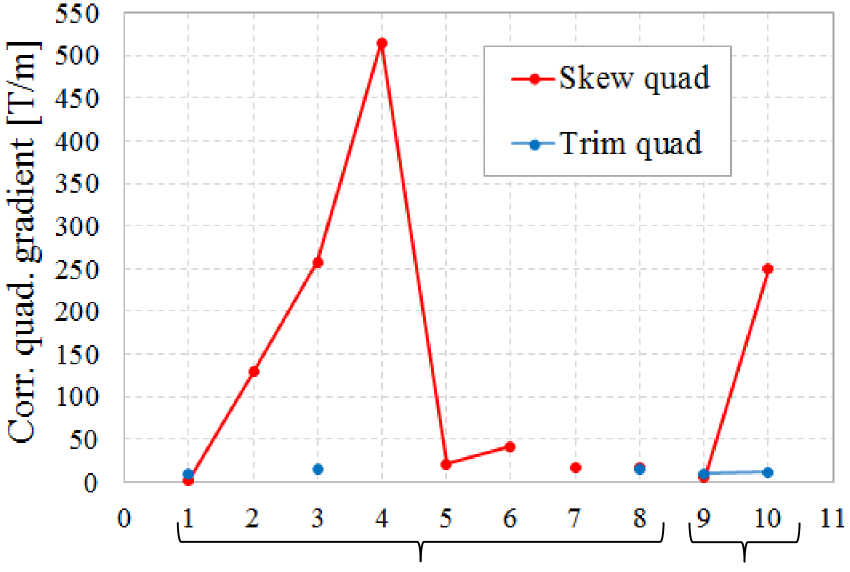
- Several runs did not have a convergence for the ring tunes and were excluded from further analysis, the errors correlation is under investigation





CORRECTOR STRENGTHS





Ranges for case 7:

Orbit correctors	0.2-3.3 Tm
Skew quadrupoles	17-249 T/m
Trim quadrupoles	0.9-12 T/m

Injection
1/ dip a2(u/r) = 0
2/ dip a2(u/r) = 0.55
3/ dip a2(u/r) = 1.1 (dipole table v0)
4/ dip a2(u/r) = 2.2 (dipole table v1)
5/ dip a2(u) = 0, a2(r) = 1.1
6/ dip a2(u) = 0, a2(r) = 2.2

Injection
7/ = case 3/ + σ(x/y) = 0.36 mm for quads (LHC value)
8/ = case 3/ + dip b1 = 0.1 %

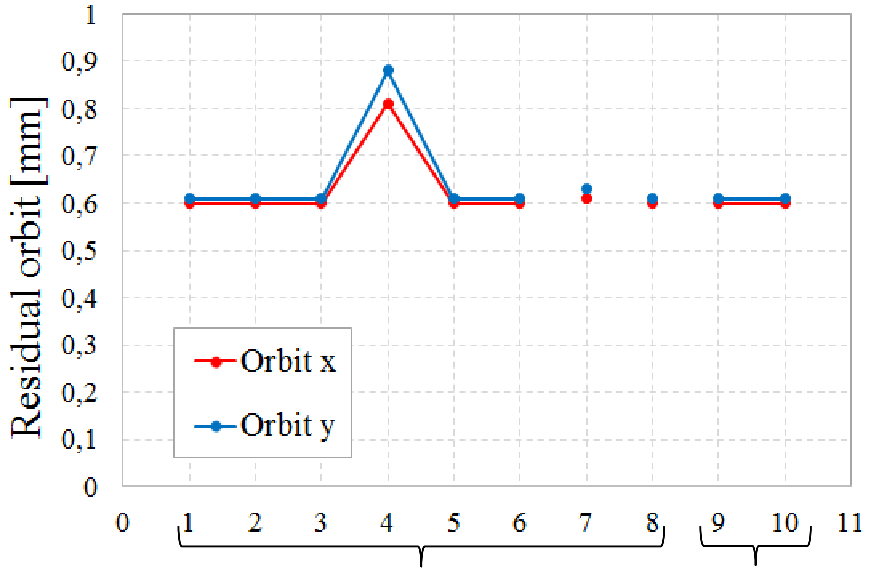
Collision
9/ dip a2(u/r) = 0
10/ dip a2(u/r) = 1.1 (dipole table v0)

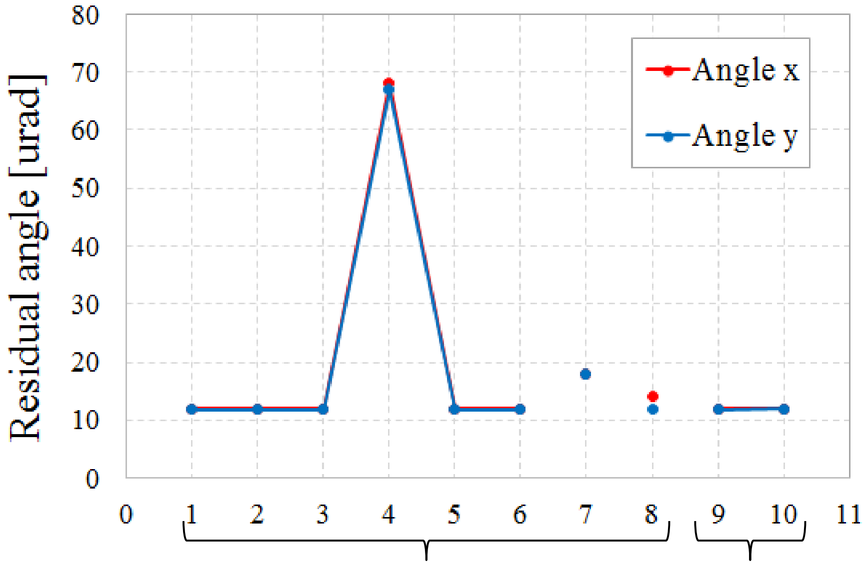
All cases compatible with the Nb-Ti technology for the orbit correctors
Combining cases 7 and 8 configurations one can expect a strength of 3.9 Tm required

Skew quadrupoles below 300 T/m except for case 4
Case 6 much weaker than case 2 => a2(u) is driving the skew quadrupole strength

Trim quadrupoles below 20 T/m

RESIDUAL ORBIT AND ANGLE





Injection
1/ dip a2(u/r) = 0
2/ dip a2(u/r) = 0.55
3/ dip a2(u/r) = 1.1 (dipole table v0)
4/ dip a2(u/r) = 2.2 (dipole table v1)
5/ dip a2(u) = 0, a2(r) = 1.1
6/ dip a2(u) = 0, a2(r) = 2.2

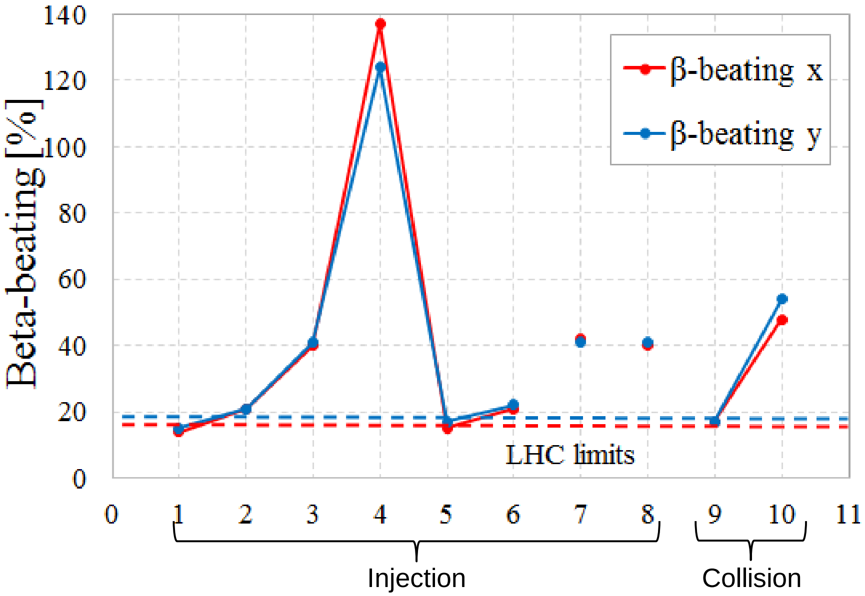
Injection
7/ = case 3/ + σ(x/y) = 0.36 mm for quads (LHC value)
8/ = case 3/ + dip b1 = 0.1 %

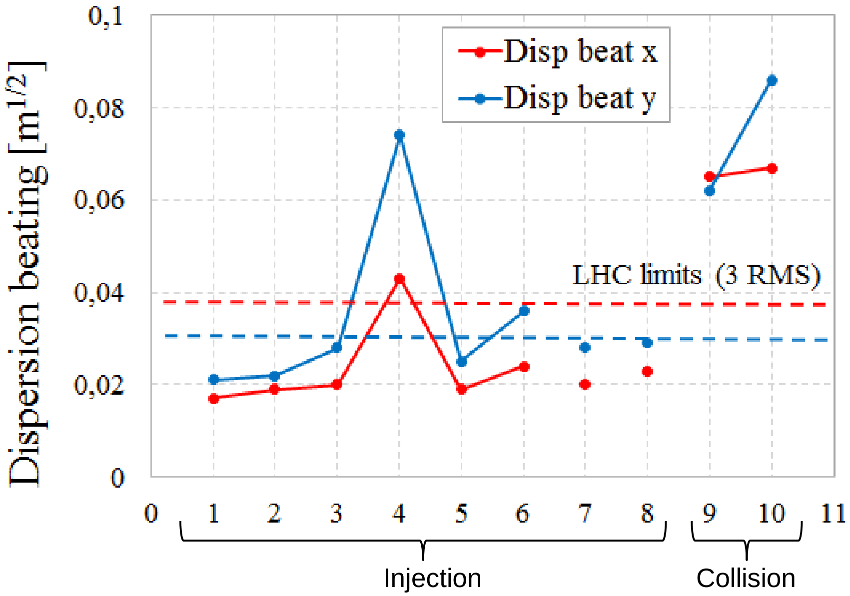
Collision
9/ dip a2(u/r) = 0
10/ dip a2(u/r) = 1.1 (dipole table v0)

All cases below 1 mm residual orbit, and compatible with the beam screen geometry (slot size increased to 5 mm => WP4 summary talk in Barcelona by F. Perez)

The combined contributions of a 20 µrad vertical residual angle and the photon emission cone (19 µrad) amount to around 0.5 mm after a drift of 11 m => total offset around 1.1 mm except for case 4
Case 4 amounts to 2 mm total vertical offset

BETA AND DISPERSION BEATING





Injection
1/ dip a2(u/r) = 0
2/ dip a2(u/r) = 0.55
3/ dip a2(u/r) = 1.1 (dipole table v0)
4/ dip a2(u/r) = 2.2 (dipole table v1)
5/ dip a2(u) = 0, a2(r) = 1.1
6/ dip a2(u) = 0, a2(r) = 2.2

Injection
7/ = case 3/ + σ(x/y) = 0.36 mm for quads (LHC value)
8/ = case 3/ + dip b1 = 0.1 %

Collision
9/ dip a2(u/r) = 0
10/ dip a2(u/r) = 1.1 (dipole table v0)

Beta-beating too strong already with a2 > 0.55
Without a2(u) much less beta-beating => a2(u) = 0.5 and a2(r) = 2.2 to be tested
Values at collision around 20% stronger than at injection (IR effect?)

Dispersion beating problematic in case 4, 6 (vertical only) and at collision

CONCLUSIONS AND PERSPECTIVES

- A correction scheme of the closed orbit, transverse coupling and ring tune has been implemented for the arc sections of the FCC ring, both at injection and collision

At injection:

- With a dipole a2 < 0.55 all desired specifications are obtained
- Dipole table v1 leads to strong values for skew quadrupoles, beta-beating (> 100% !) and dispersion beating
- a2(u) should be kept as small as possible
- Beta-beating stronger towards the middle of long arc sections => lattice issue?
- Increased tolerances on quadrupole alignment and dipole b1 lead to affordable correctors strengths

At collision:

- Beta-beating stronger by 20% than at injection
- Dispersion beating is too high even without dipole a2
- Too many convergence errors with dipole a2 included

- To be done:
  - Complete the integration of insertion regions (IR, collimation, etc)
  - Add systematic errors (b2 dipole, alignement)
  - check other linear coupling correction schemes
  - Comparison with the LHC correction scheme