FROM RESEARCH TO INDUSTRY

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EuroCirCol A key to New Physics

# CORRECTION SCHEMES

- Definition of the errors and correction scheme
- Evaluation of the results at injection and collision
- Results for the interaction region
- Conclusions and perspectives

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# ERRORS DEFINITION

- Errors defined for main dipoles, main quadrupoles and for BPMs used in arcs and DIS sections
- Errors are Gaussian distributed, truncated at 3-σ values, with a different seed for each machine
- Study of the response at injection and collision energies, with 200 machines simulated for each case of study

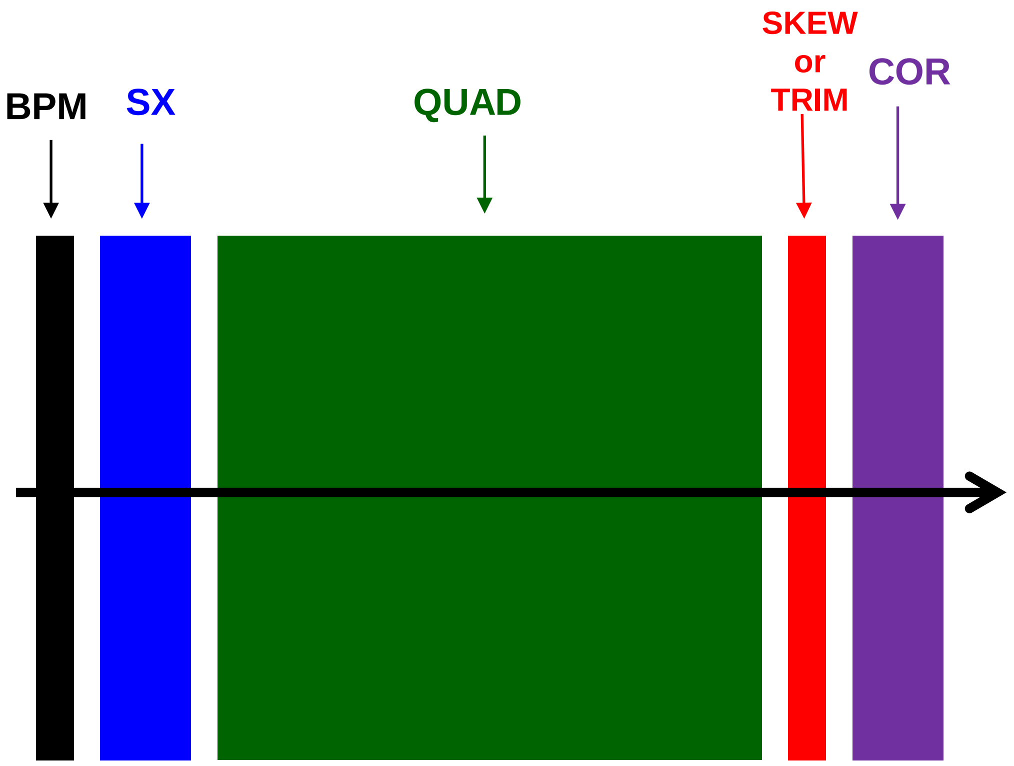
| Element | Error | Error desc. | Units | FCC | LHC | Comments |
|---|---|---|---|---|---|---|
| Dipole | σ(ψ) | roll angle | mrad | 0.5 | n/a | effect in vertical plane |
| | σ(δB/B) | random b1 | % | 0.1 | 0.08 | LHC value includes σ(ψ) |
| | σ(δB/B) | random b2 | 10-4 units | 0.92 | 0.8 | |
| | σ(δB/B) | random a2 | 10-4 units | 1.04 | 1.6 | |
| | σ(δB/B) | uncert. a2 | 10-4 units | 1.04 | 0.5 | |
| | | | | | | |
| Quad | σ(x),σ(y) | | mm | 0.5 | 0.36 | |
| | σ(ψ) | roll angle | mrad | 1 | 0.5 | |
| | σ(δB/B) | random b2 | % | 0.1 | 0.1 | |
| | | | | | | |
| 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 SCHEMES OF THE ARC SECTIONS

- Optics studied at injection (3.3 TeV, β* = 4.6 m, 'baseline injection') and at collision (50 TeV, β* = 0.3 m, 'ultimate') with crossing scheme

- All main quadrupoles units of the arc sections and DIS have a BPM and an orbit corrector included close to the quadrupole. Quadrupoles correctors ('skew' or 'trim') can also be inserted before the quadrupole unit




- The correction is performed with the MADX code, following an iterative procedure:
  - 1/ analytic correction of the linear coupling (partial tune correction)
  - 2/ global orbit correction
  - 3/ tune correction
- With collision optics two additional steps are performed:
  - 4/ global orbit correction
  - 5/ tune correction

- The results are evaluated in the following only for the arc sections and any insertion added to the global correction scheme

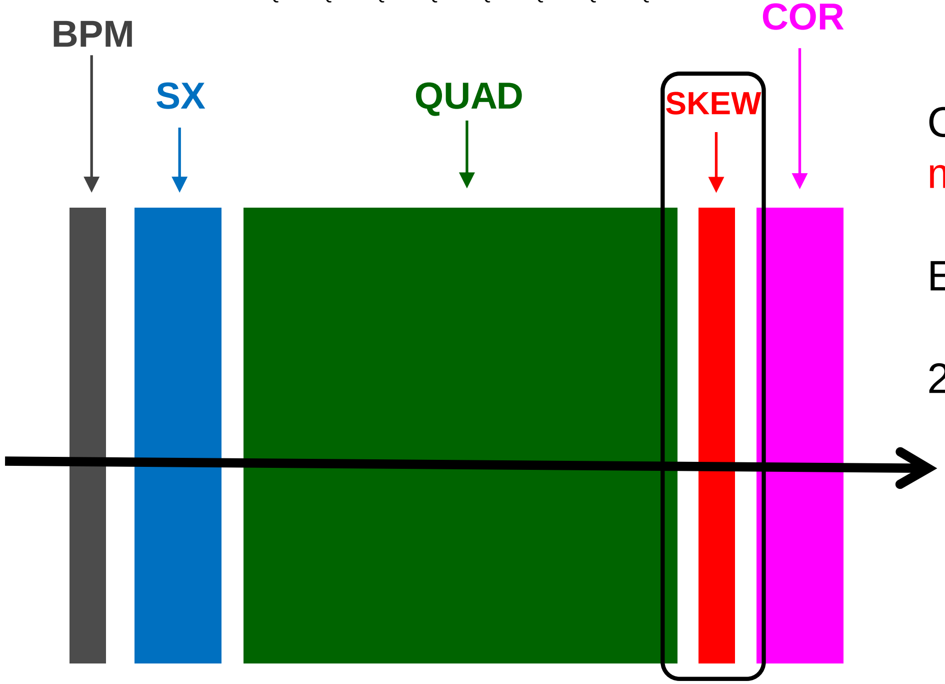
- Most of the quadrupolar correctors in the short arc sections are reserved for the spurious dispersion correction

# CORRECTION OF THE LINEAR COUPLING

- Analytic calculation of the contribution of each magnet of the arc sections to the coupling:

$$\Delta c_-^i = \frac{1}{2\pi} \cdot \int_L ds \sqrt{\beta_x \beta_y} \cdot k_s \cdot e^{i(\mu_x - \mu_y)}$$ extracted from LHC Project Report 399

- The main contribution is the a2 multipolar coefficient of the dipoles

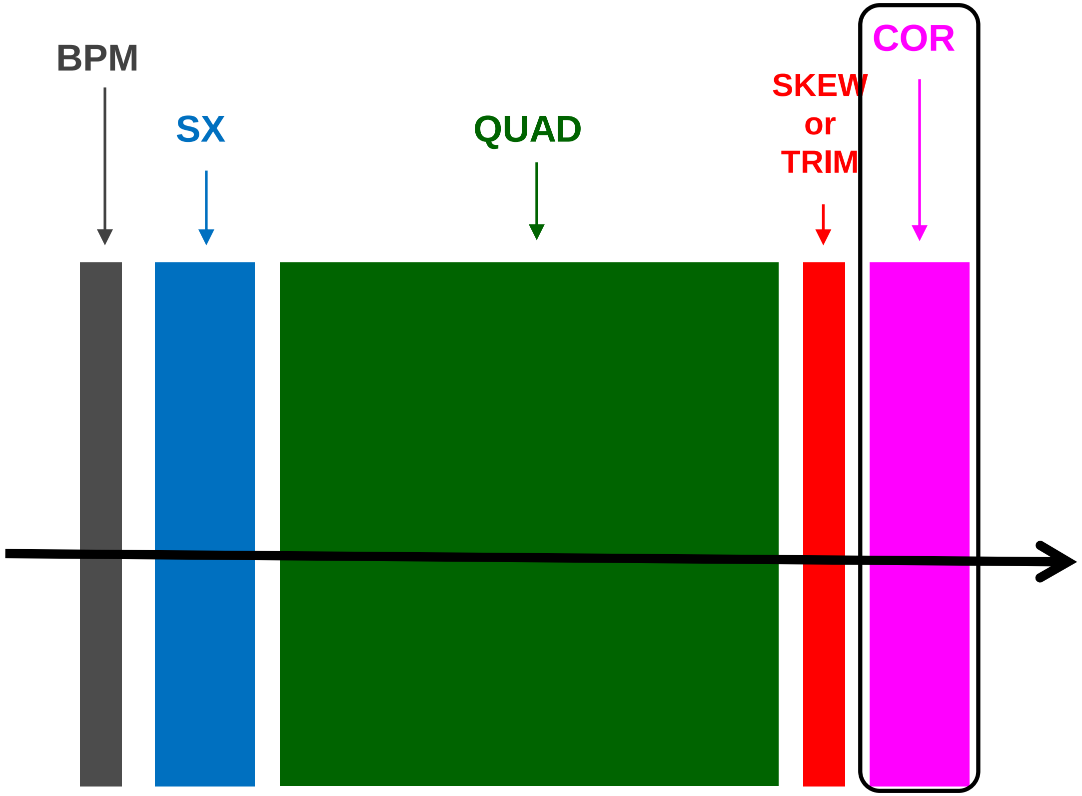

Correction applied to families of 8 skew quadrupoles (L = 0.5 m, maximum gradient 220 T/m) around the middle of each long arc

Each corrector separated by 90° phase advance

2 families per long arc => 8 families in total

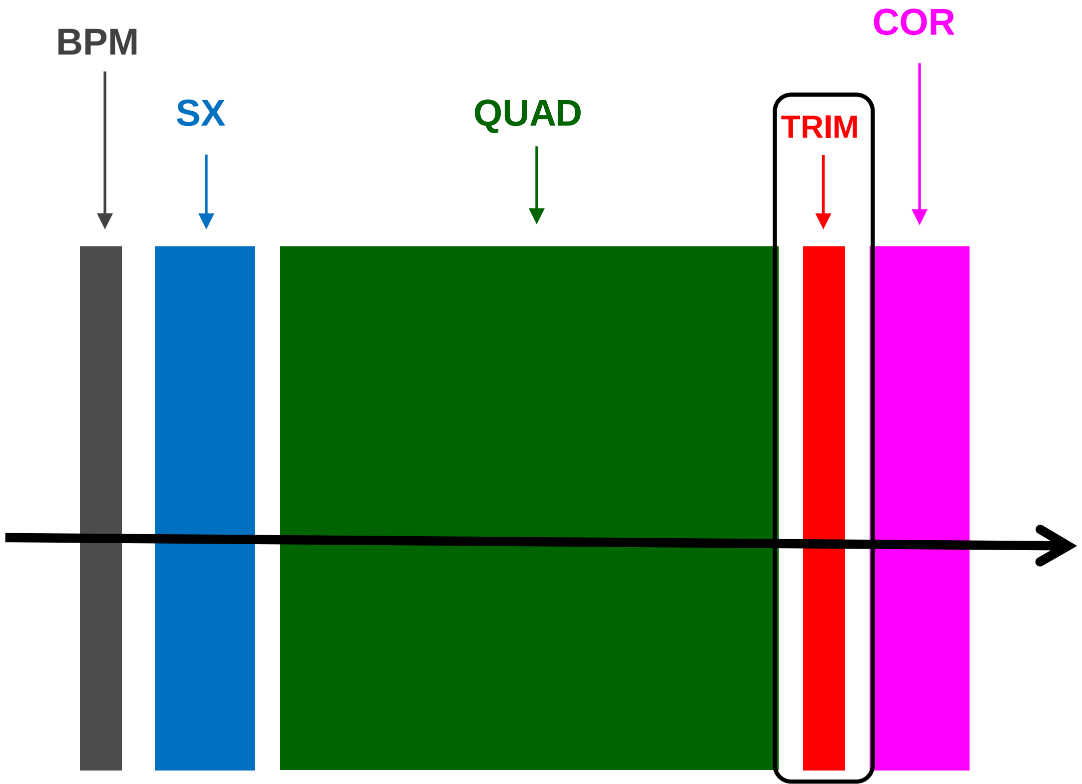
# ORBIT CORRECTION

- Performed with dipolar correctors, L = 1.2 m, max. integrated strength = 4.8 Tm, Nb-Ti technology
- Global correction of the residual orbit measured by BPMs (horizontal or vertical plane)
- Same number of BPMs (parameters) and orbit correctors (variables), over 400 independent correctors on each plane
- Within the global correction scheme, each orbit corrector is coupled with the BPM located on the 2nd next quadrupole (phase advance of 90°)



# TUNE CORRECTION

- Performed with quadrupolar correctors, L = 0.5 m, maximum gradient 220 T/m, Nb-Ti technology
- Correction of the horizontal (Q1) et vertical (Q2) tunes
- The quadrupolar correctors are inserted at the beginning and end of long arc sections
- Two families of 8 correctors on each long arc section, each family shifted by 45° phase advance => 8 families in total



# CORRECTION SCHEME OF THE INSERTION REGIONS

- Correction scheme taken from dedicated orbit correction studies of the interaction regions (courtesy of E. Cruz)

- For high-luminosity (IPA/IPG), low-luminosity (IPB/IPL) experimental sections and collimation sections (IPF/IPJ), outer regions have a similar scheme as in arcs, in inner regions each quadrupole (units 4 and triplets if present) has a corrector and BPM included in both planes, exception is IPL where all quads up to units 7 have correctors/BPMs in both planes

- Extraction (IPD) and RF (IPH) sections have the same correction schemes as in arc sections

- Tolerances are set for the IR and applied to all other insertions

- The tolerance of quadrupole units 7 have been reduced from 0.5 mm to 0.2 mm in IR sections

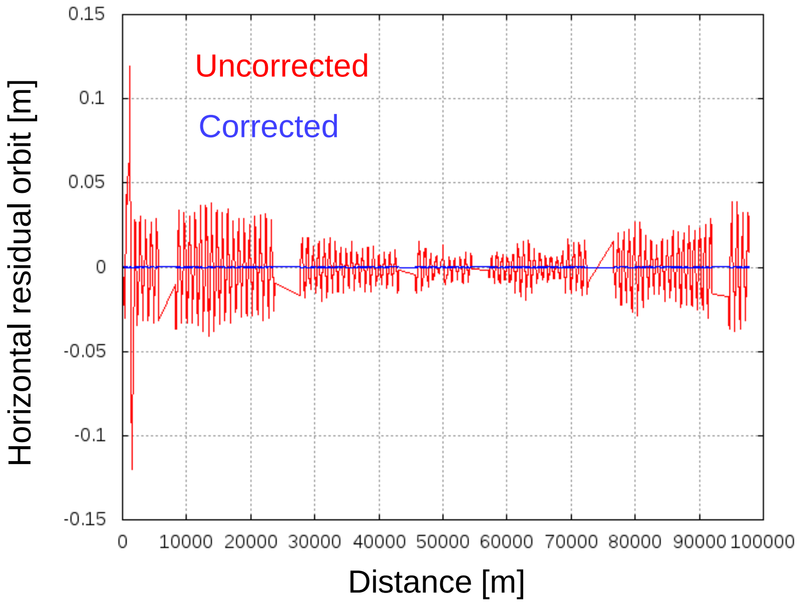
| Element | Error | Error desc. | Units | IR triplet | IR other | Comments |
|---|---|---|---|---|---|---|
| Dipole | σ(ψ) | roll angle | mrad | | 1 | Dipoles D1/D2 |
| | σ(δB/B) | random b1 | % | | 0.05 | |
| | σ(δB/B) | random b2 | 10-4 units | | 0.1/1.8 | 0.1/1.1 at collision |
| | σ(δB/B) | random a2 | 10-4 units | | 0.1/0.2 | |
| | σ(δB/B) | uncert. a2 | 10-4 units | | TBD | |
| | | | | | | |
| Quad | σ(x),σ(y) | | mm | 0.2 | 0.5 | MQ7 in IR 0.2 mm |
| | σ(ψ) | roll angle | mrad | TBD | 0.5 | 0.2/0.5 envisaged |
| | σ(δB/B) | random b2 | % | TBD | 0.05 | |
| | | | | | | |
| BPM | σ(x),σ(y) | | mm | 0.3 | 0.3 | value relative to quad |
| | σ(read) | | mm | 0.05 | 0.20 | accuracy |

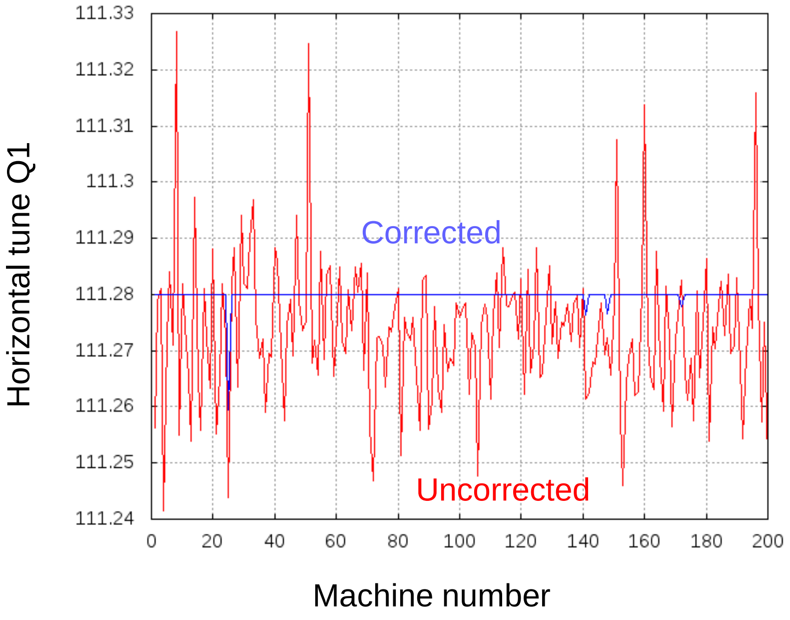
# EVALUATION OF THE RESULTS

- For each machine, calculation of the mean, RMS and maximum values of the following observables for each relevant magnet of the arc sections:
  - Residual **orbit and angle**
  - Beta-beating $\boldsymbol{\Delta\beta/\beta_{ref}}$
  - Parasitic dispersion or dispersion beating $\boldsymbol{\Delta D/\sqrt{\beta ref}}$
  - **Corrector strengths**

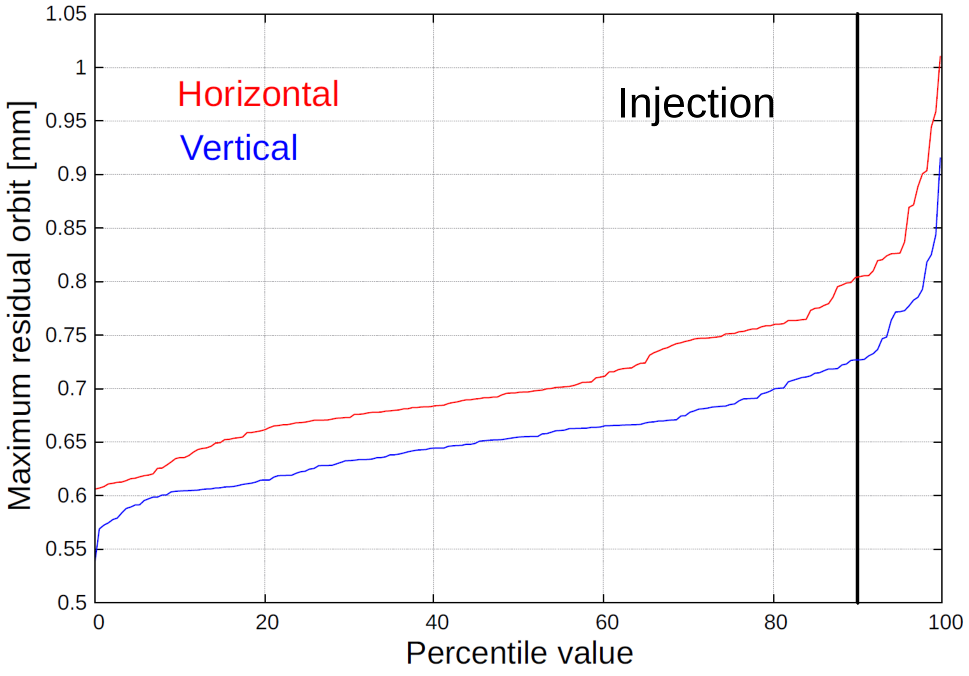
→ see LHC Project Report 501 for more details

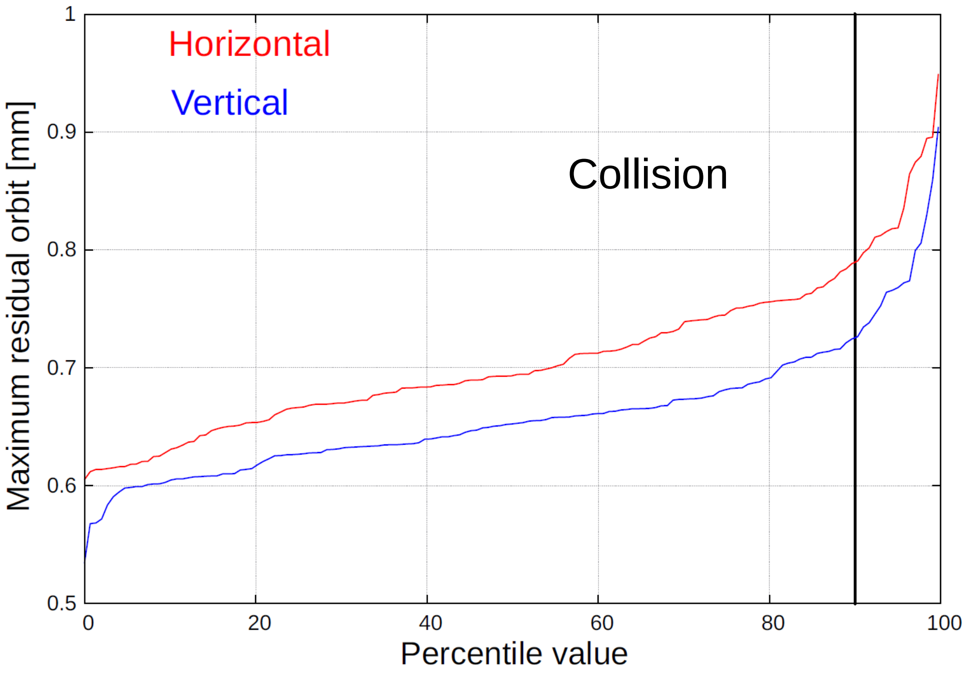
- From the maximum values distribution the 90-percentile (value for which 90% of the values of a given distribution are included) is calculated over all 200 machines



# RESIDUAL ORBIT



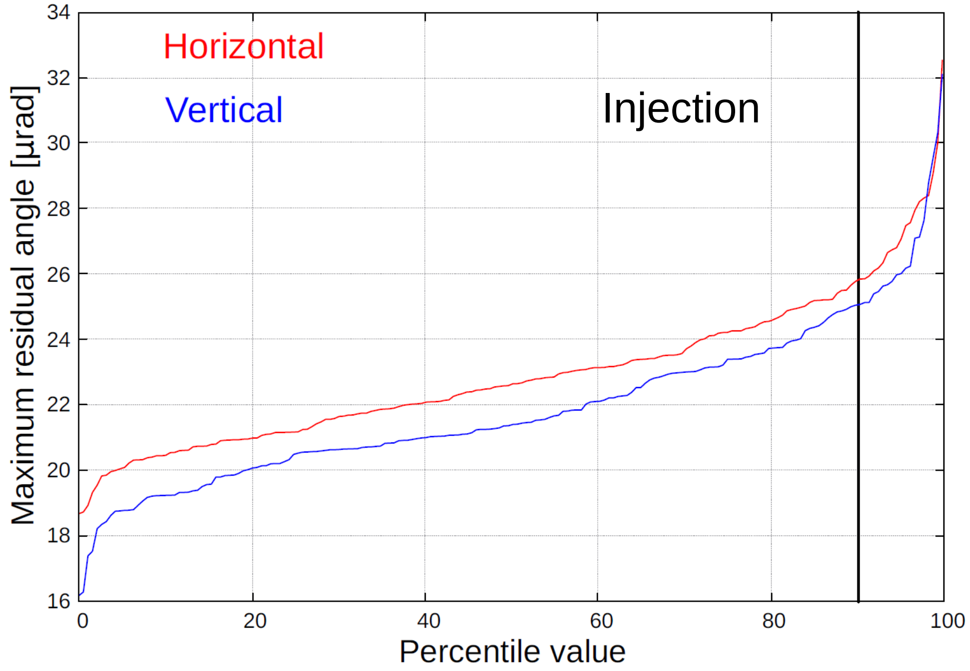



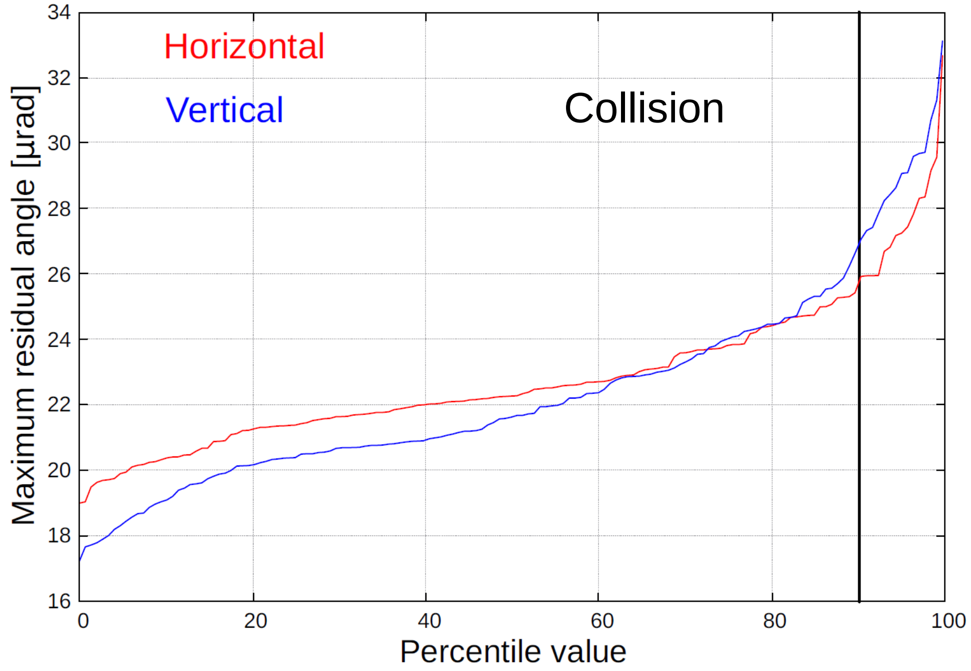

Residual orbit < 1 mm at any point of the synchrotron, in accordance with the geometry of the dipole chamber (5 mm aperture)

With an alignment error of 0.5 mm RMS for arcs and IR (non-triplet) quadrupoles, both sections contribute equally to the results

**90% values: horizontal orbit 0.80 mm, vertical orbit 0.73 mm @ injection**

# RESIDUAL ANGLE



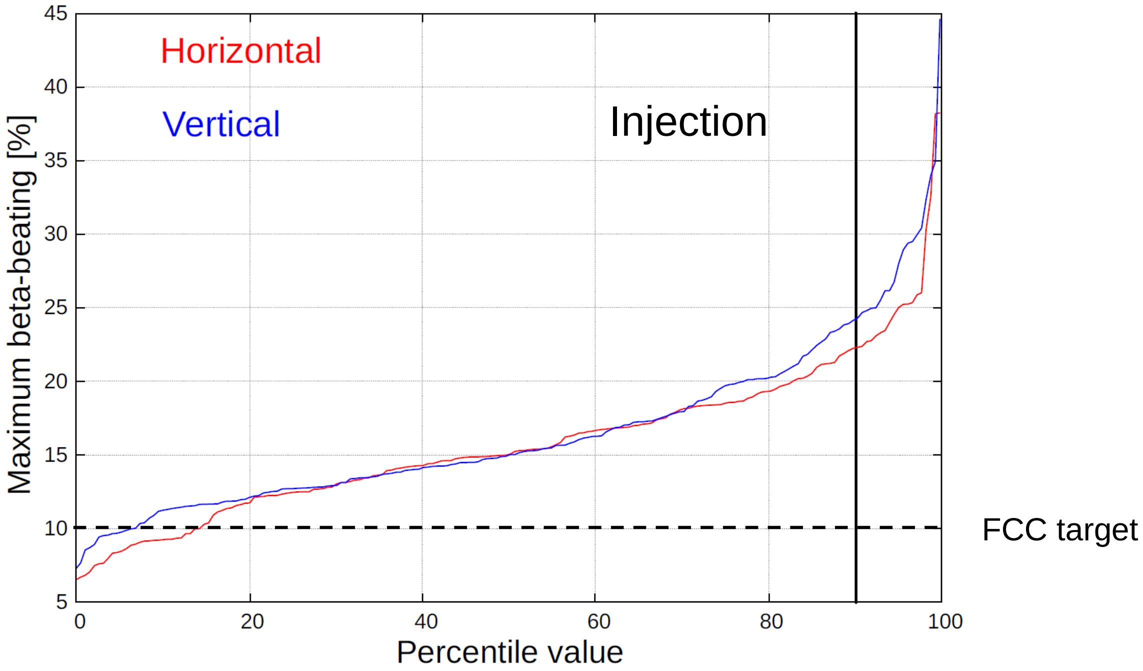

Residual angle < 35 mrad at any point of the synchrotron

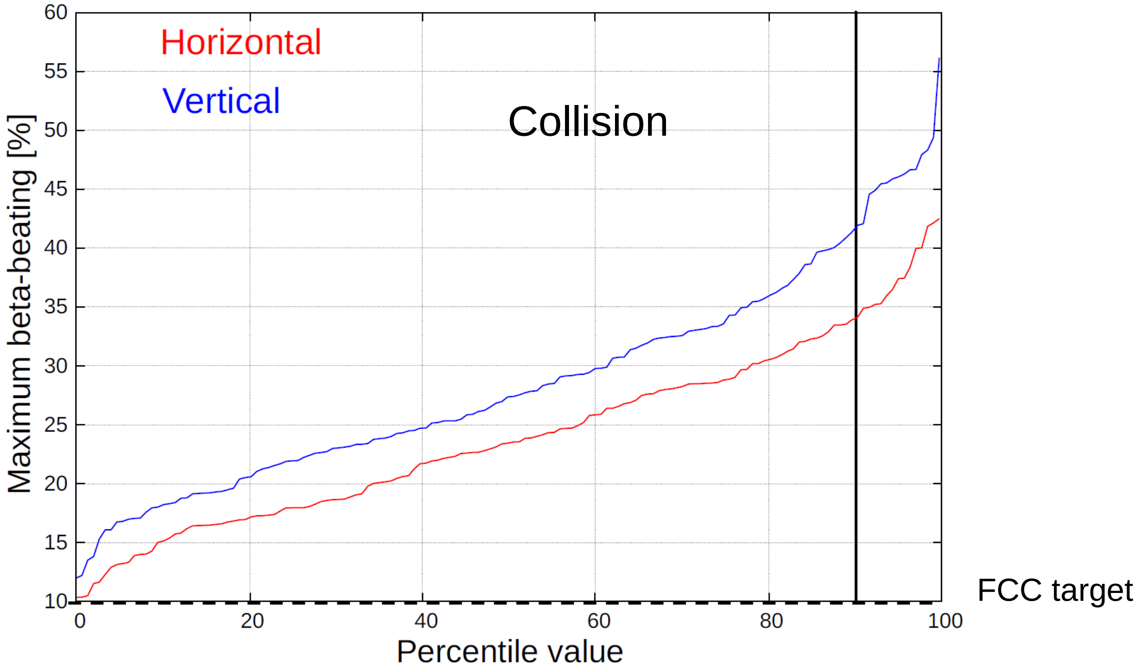
**90% values: horizontal angle 26 µrad, vertical angle 27 µrad @ injection**

At collision, the combined contributions of the vertical residual orbit of 0.73 mm, a vertical residual angle of 27 µrad and of the emission cone of photons (19 µrad) contribute to a total vertical offset of +/- 1.2 mm after a drift of 11 m

No problem to evacuate SR through beamscreen (7.5 mm total gap)

# BETA BEATING



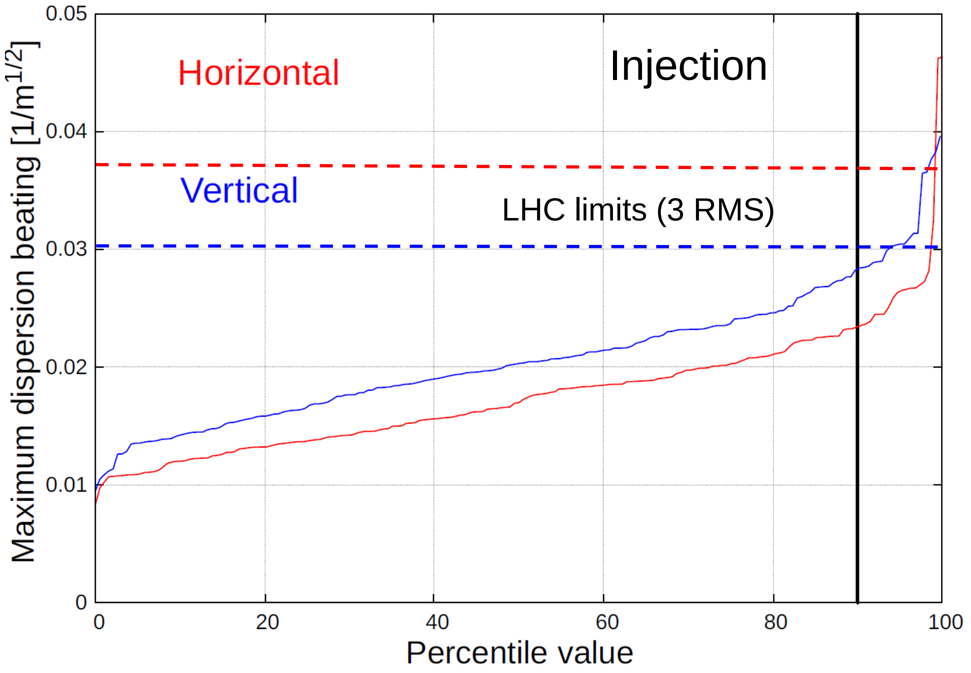

Beta-beating too strong, well above the 10% target in most machines at injection, in all machines at collision

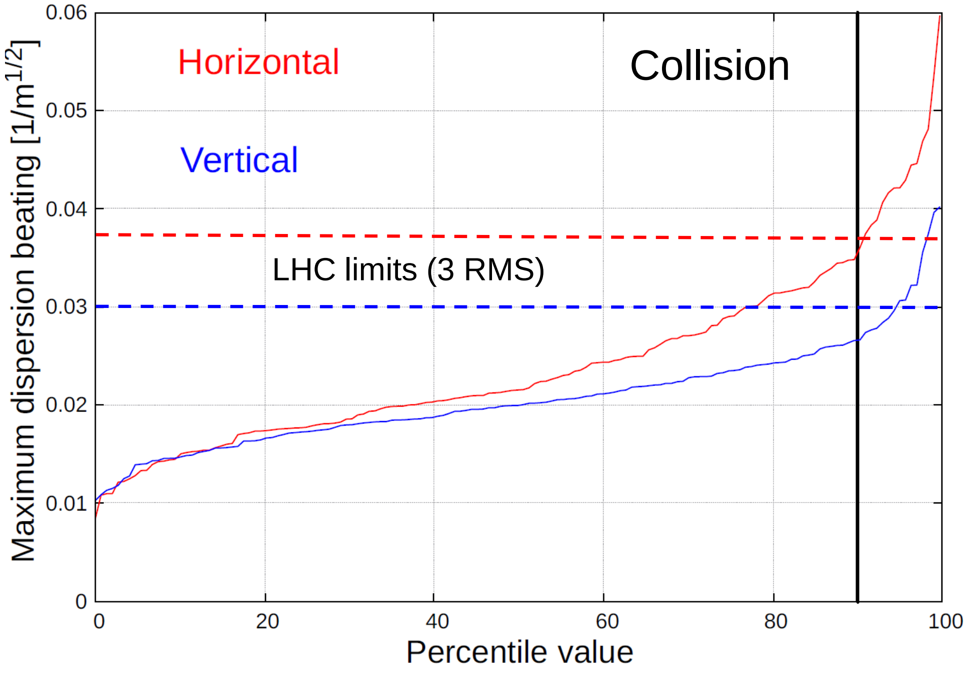
Reducing dipole a2(u) or quadrupole roll angle would help reaching the target of 10%

No dedicated correction of the beta-beating implemented yet

**90% values: hori. beta-beating 22%, vert. beta-beating 24% @ injection, hori. beta-beating 34%, vert. beta-beating 42% @ collision**

# DISPERSION BEATING



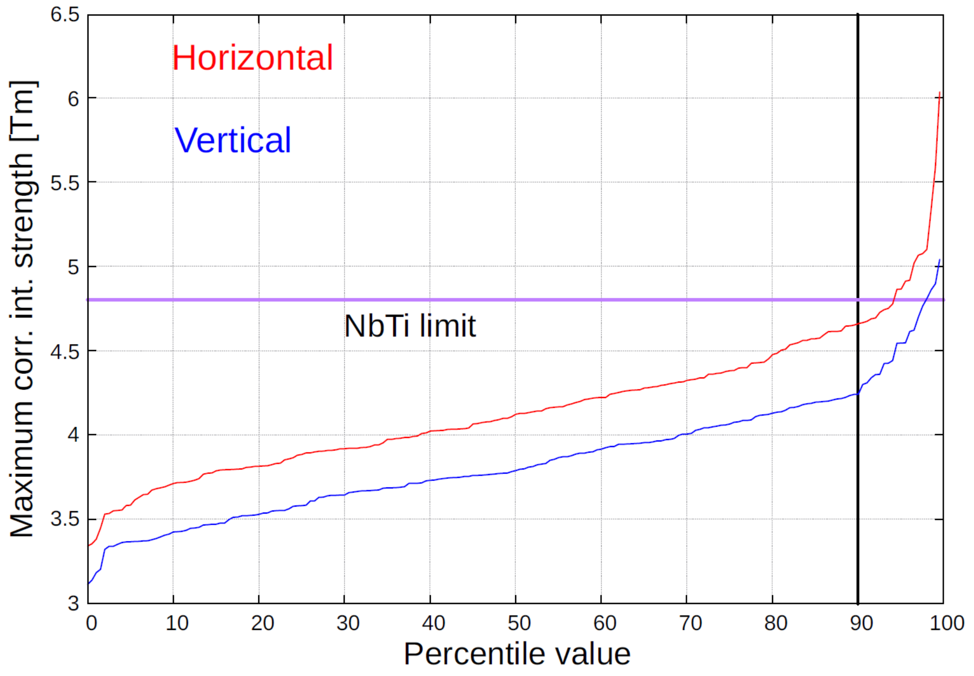



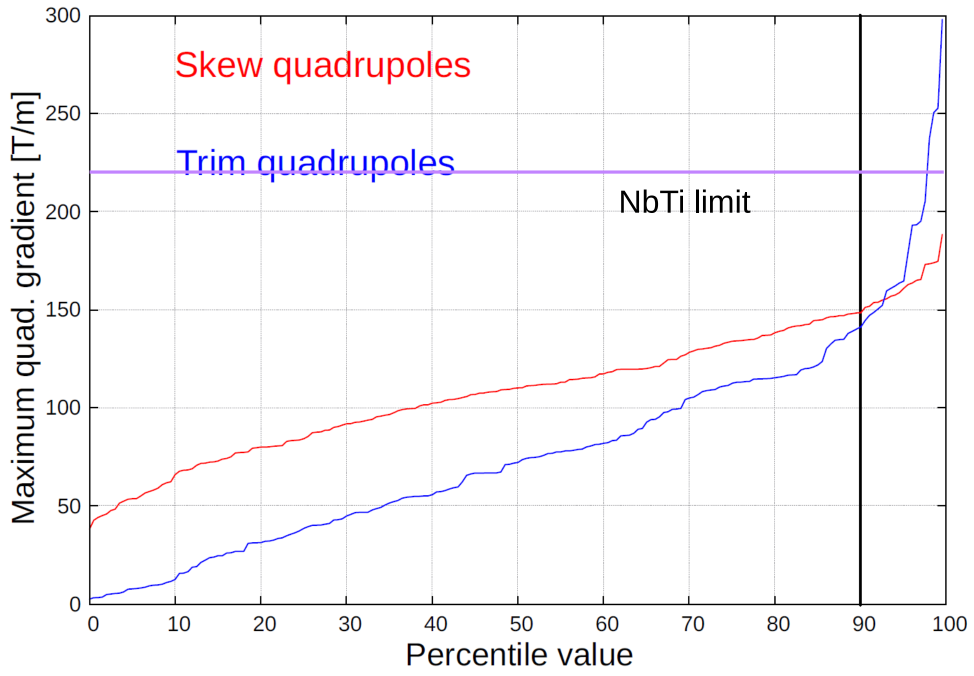

Dispersion beating satisfactory? LHC design values are not reached for > 95% of the machines at injection

**90% values: hori. disp. beating 2.3x10$^{-2}$ m$^{1/2}$, vert. disp. beating 2.8x10$^{-2}$ m$^{1/2}$ @ injection, hori. disp. beating 3.6x10$^{-2}$ m$^{1/2}$, vert. disp. beating 2.7x10$^{-2}$ m$^{1/2}$ @ collision**

No dedicated correction of the dispersion beating implemented yet

# CORRECTOR STRENGTHS AT COLLISION




Orbit corrector strengths compatible with NbTi technology at 90% level

Only the correctors inserted near arc and arc-like quadrupoles are included in the analysis

Skew quadrupoles are always below 200 T/m

Trim quadrupoles do not exceed 220 T/m at 95% level, can correct up to 0.03-0.04 tune fractions

**90% values: horizontal orb corr. 4.6 Tm, vertical orb corr. 4.3 Tm, skew quad. 156 T/m, trim quad. 133 T/m**

# OVERVIEW OF THE RESULTS

| Observable | Injection | Collision |
|---|---|---|
| Hori. orbit<br>Vert. orbit | 0.80 mm<br>0.73 mm | 0.79 mm<br>0.73 mm |
| Hori. angle<br>Vert. angle | 26 $\mu$rad<br>25 $\mu$rad | 26 $\mu$rad<br>27 $\mu$rad |
| Hori. beta-beating<br>Vert. beta-beating | 22 %<br>24 % | 34 %<br>42 % |
| Hori. disp. beating<br>Vert. disp. beating | $0.023\ \frac{1}{\sqrt{m}}$<br>$0.028\ \frac{1}{\sqrt{m}}$ | $0.036\ \frac{1}{\sqrt{m}}$<br>$0.027\ \frac{1}{\sqrt{m}}$ |
| Hori. orbit corr. str.<br>Vert. orbit corr. str. | 0.31 Tm<br>0.28 Tm | 4.7 Tm<br>4.2 Tm |
| Skew quad. str.<br>Trim quad. str. | 8.57 T/m<br>3.68 T/m | 148 T/m<br>140 T/m |

- Results satisfactory except for beta-beating
- Some DIS and all insertion correctors are not included into the results
- Beta-beating and dispersion beating need further investigation

# CONCLUSIONS AND PERSPECTIVES

- A global correction scheme of the residual orbit, linear coupling and ring tunes for FCC-hh, has been fully investigated at injection and collision energies

- All insertion regions are now implemented

- The residual orbit and angle are compatible with the aperture considered for the synchrotron radiation evacuation

- Beta-beating is too strong with the current errors => at this stage of study a global correction of the beta-beating is not performed

- A quadrupole misalignment of 0.5 mm gives reasonable orbit corrector strengths at a 90% level

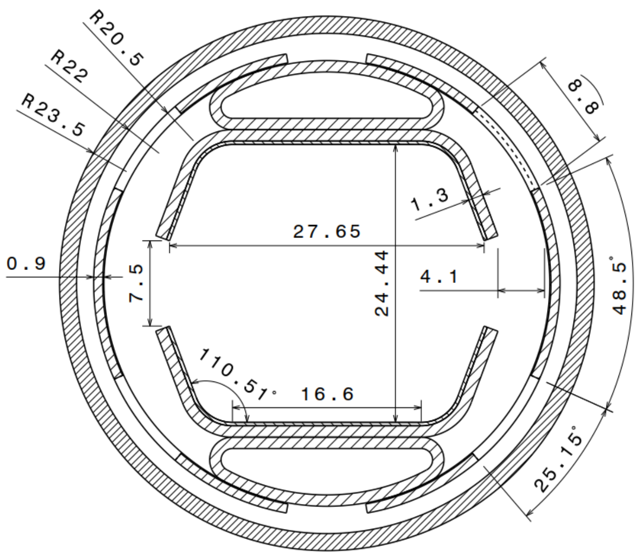
- The results at collision are similar to injection, except a stronger beta-beating and horizontal dispersion beating

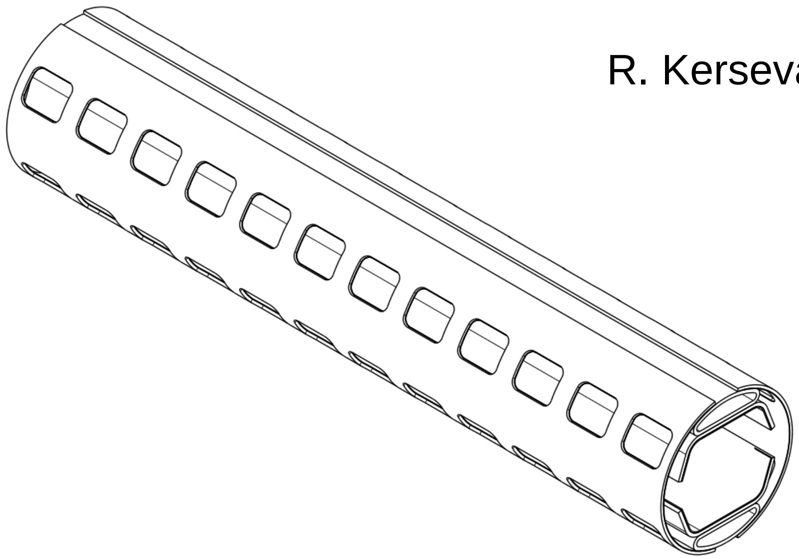
- Instabilities at collision during the optimization, 20% of the machine do not converge with the automatic procedure (coupling?)

- Perspectives (post-CDR):
    - Validate the orbit correction with corrector families in the arc sections
    - Implement a global correction scheme of the beta-beating, dispersion beating and coupling
    - Add other systematic errors (dipole b2, alignment) and use field table for quadrupoles

# BACKUP

# IMPACT OF THE ERRORS ON THE BEAMSCREEN



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- The synchrotron radiation is evacuated through an aperture in the horizontal plane of the arc dipole chamber (total gap 7.5 mm in the EuroCirCol 2017 design proposal)

- The maximum drift a photon can travel in the arc sections before hitting the chamber walls is estimated to 11 m

- Position and angle offset of the beam can affect the evacuation efficiency, leading to heating, desorption and performances losses