FROM RESEARCH TO INDUSTRY

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# ALIGNMENT

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

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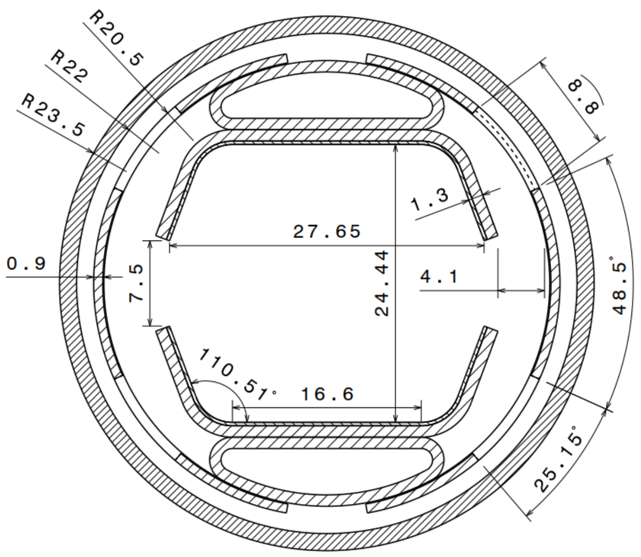
# ERRORS DEFINITION

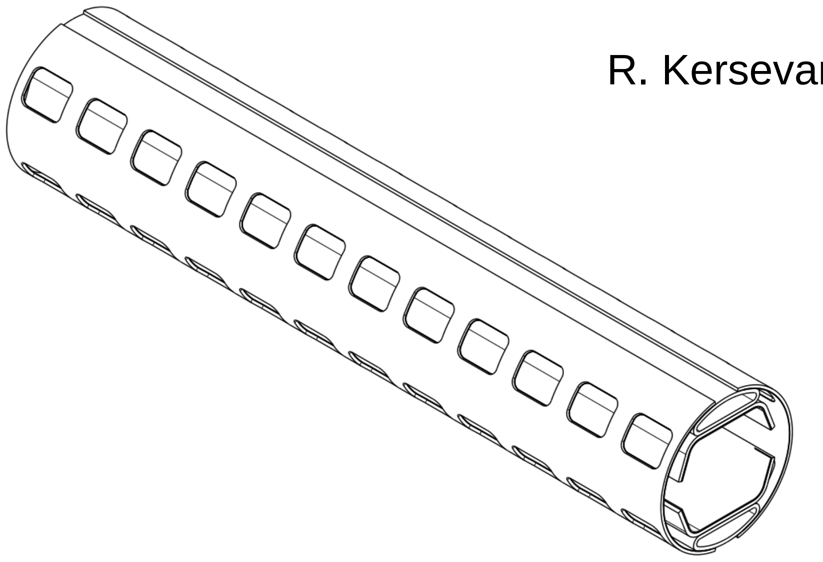
- Errors defined for main dipoles, main quadrupoles and for BPMs used in arcs and DIS sections
- Errors are Gaussian distributed, truncated at 3-σ values, with a different seed for each machine
- No errors defined in the straight sections (insertions) unless specified
- Study of the response at injection and collision energies, with 200 machines simulated for each case of study

| Element | Error | Error desc. | Units | FCC | LHC | Comments |
|---|---|---|---|---|---|---|
| Dipole | σ(x),σ(y) | | mm | 0.5 | 0.5 | no effect on observables |
| | 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 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)

# IMPACT OF THE ERRORS ON THE BEAMSCREEN



R. Kersevan, C. Garion, I .Bellafont

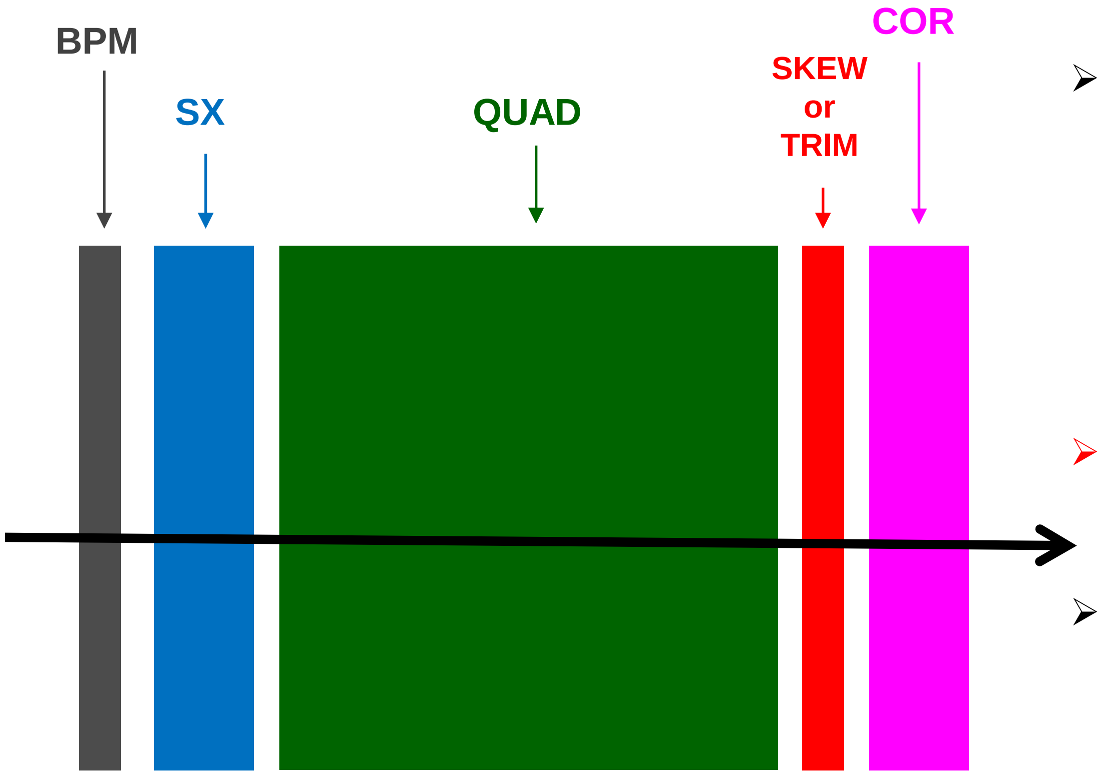
- The synchrotron radiation is evacuated through an aperture in the horizontal plane of the arc dipole chamber (total gap 7.5 mm in the latest design proposal)
- The maximum drift a photon can travel in the arc sections before hitting the chamber walls is estimated to 11 m
- Position and angle offset of the beam can affect the evacuation efficiency, leading to heating, desorption and performances losses

# 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’, no 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 elements configuration around the quadrupole has been changed in the latest lattice




- 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

- The errors 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

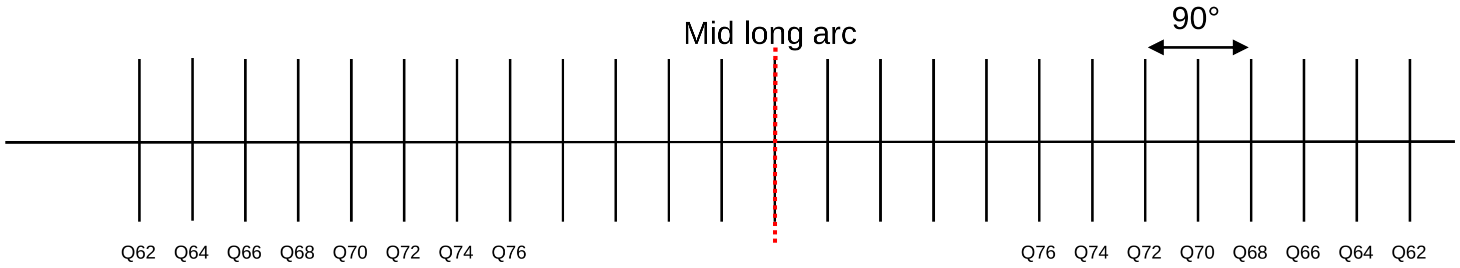
# CORRECTION OF THE LINEAR COUPLING

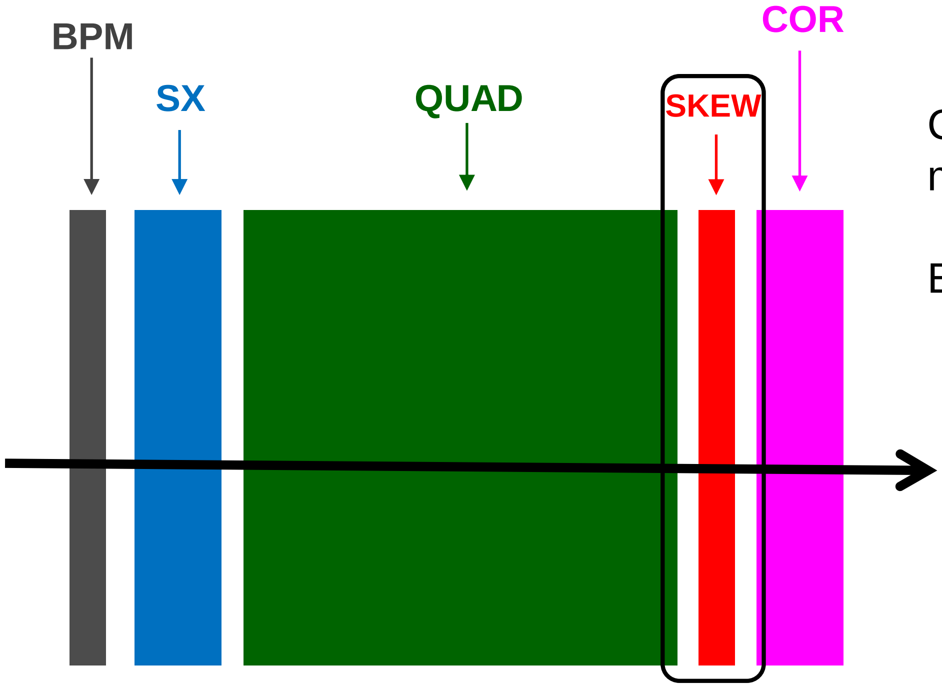
- Analytic calculation of the contribution of each magnet of the arc sections to the coupling:

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

extract of LHC Project Report 399

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



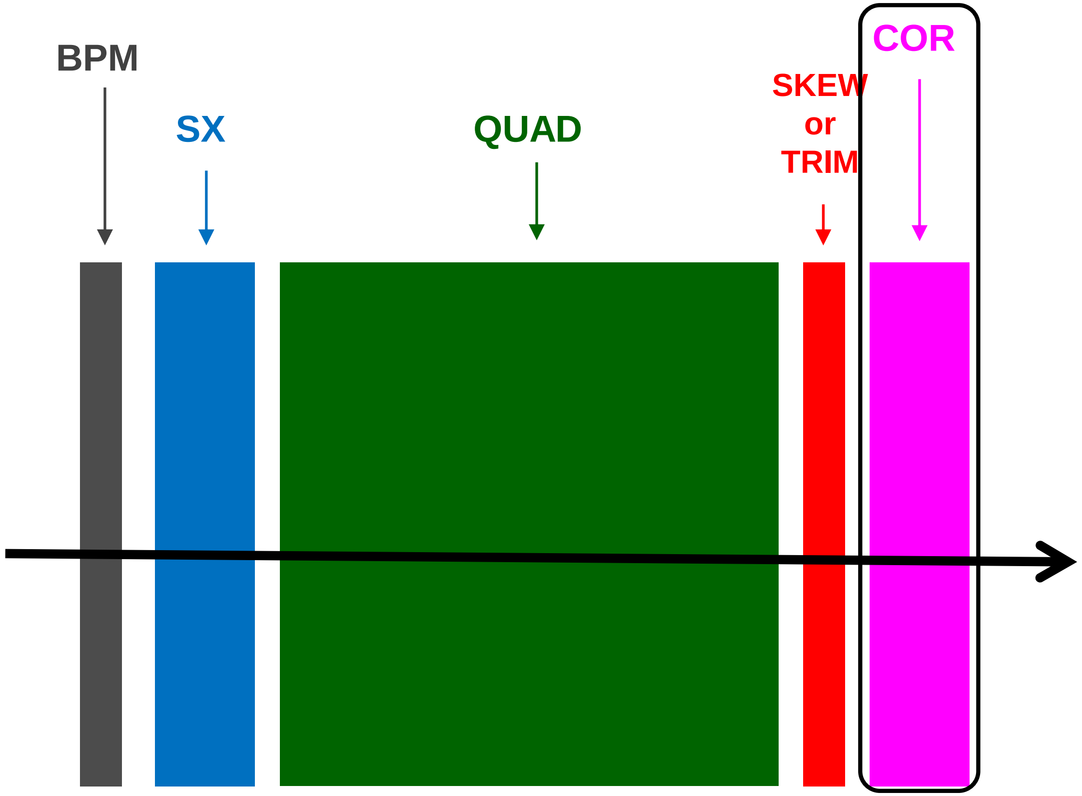




Correction applied to groups of 8 skew quadrupoles (L = 0.5 m, maximum gradient 220 T/m) around the middle of each long arc

Each corrector separated by 90° phase advance

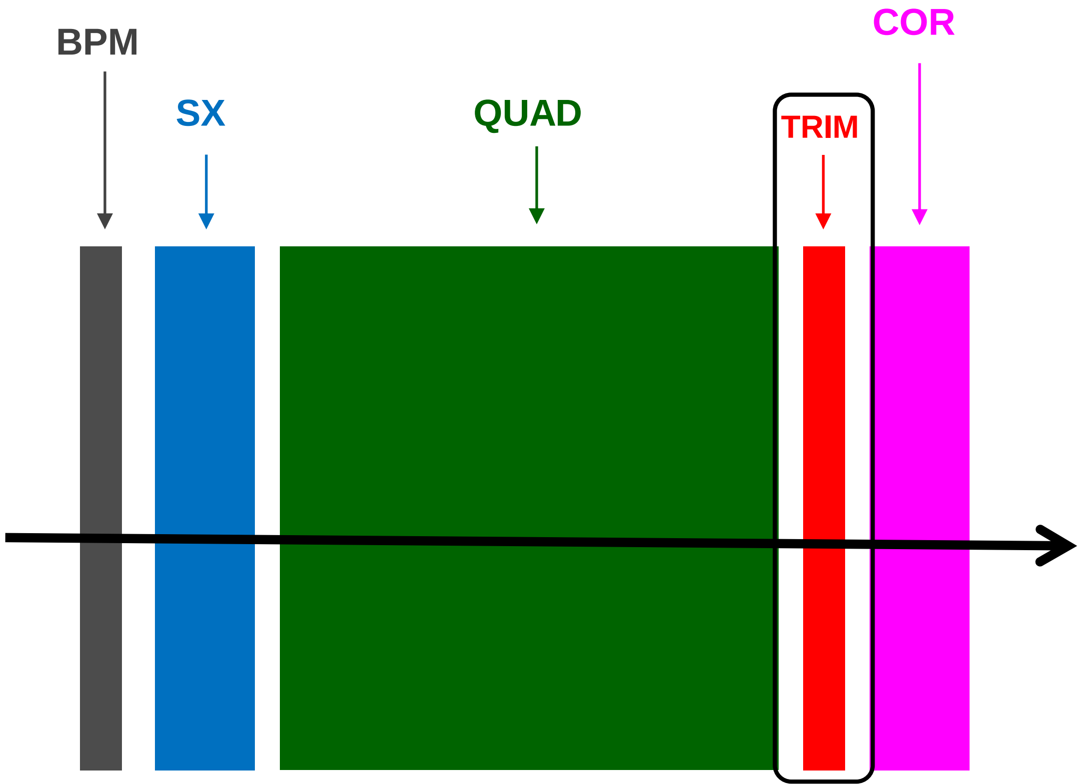
# ORBIT CORRECTION

- Performed with dipolar correctors, L = 1 -> 1.2 m, max. integrated strength = 4 -> 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) in each plane
- Within the global correction scheme, each orbit corrector is coupled with the BPM located on the 2$^{nd}$ next quadrupole (phase advance of 90°)



# TUNE CORRECTION

- Performed with quadrupolar correctors (L = 0.5 m, maximum gradient 220 T/m, Nb-Ti technology), possibility of using main quadrupoles (L = 7.2 m, maximum gradient 360 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

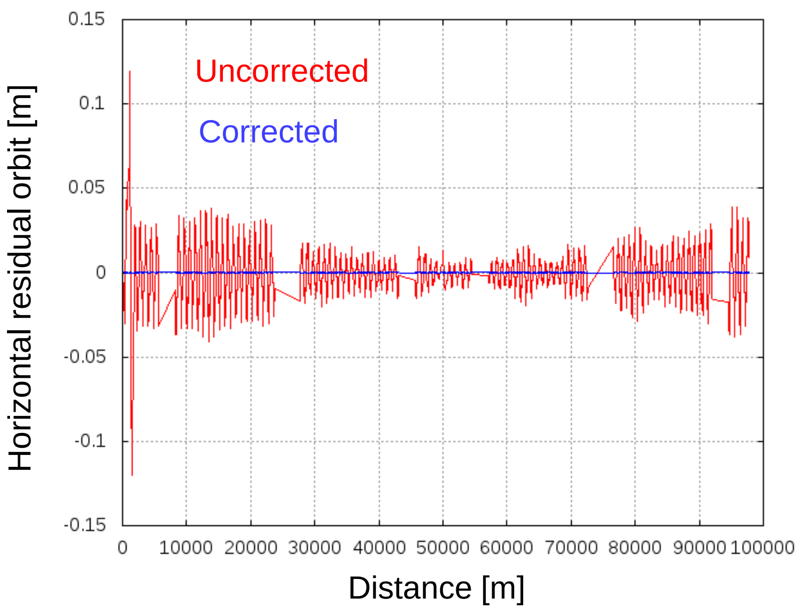


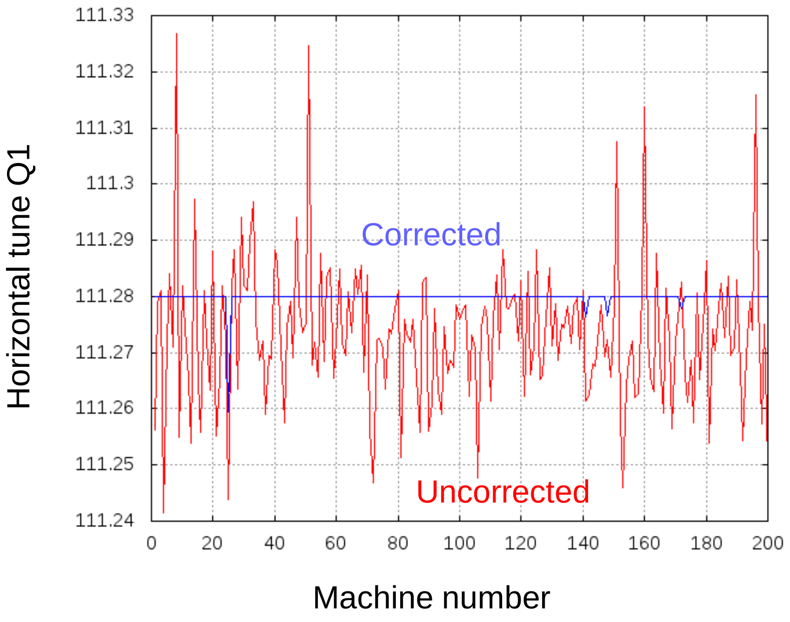
# EVALUATION OF THE RESULTS

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

→ 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

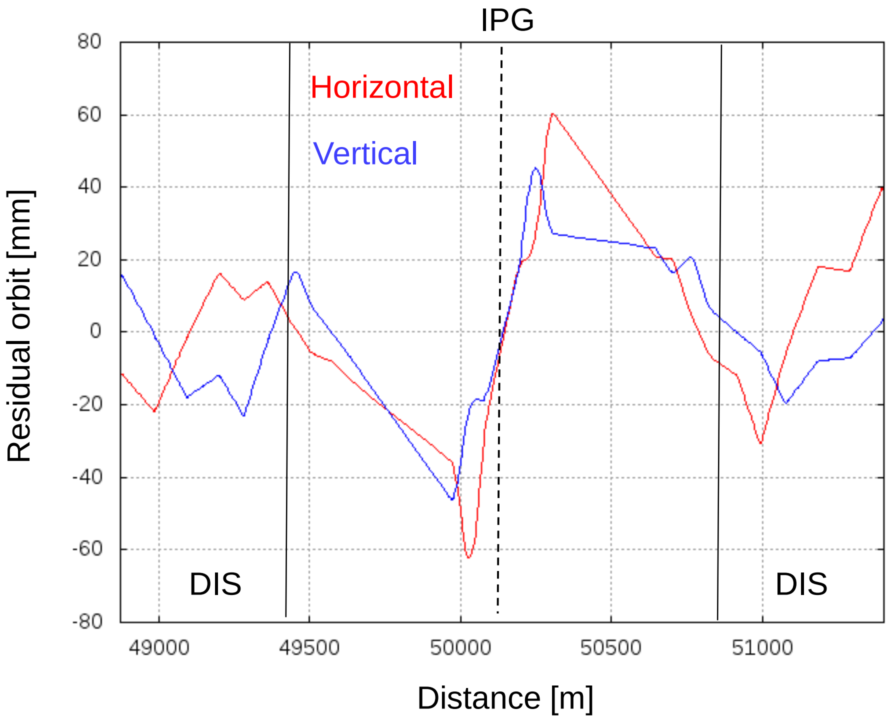


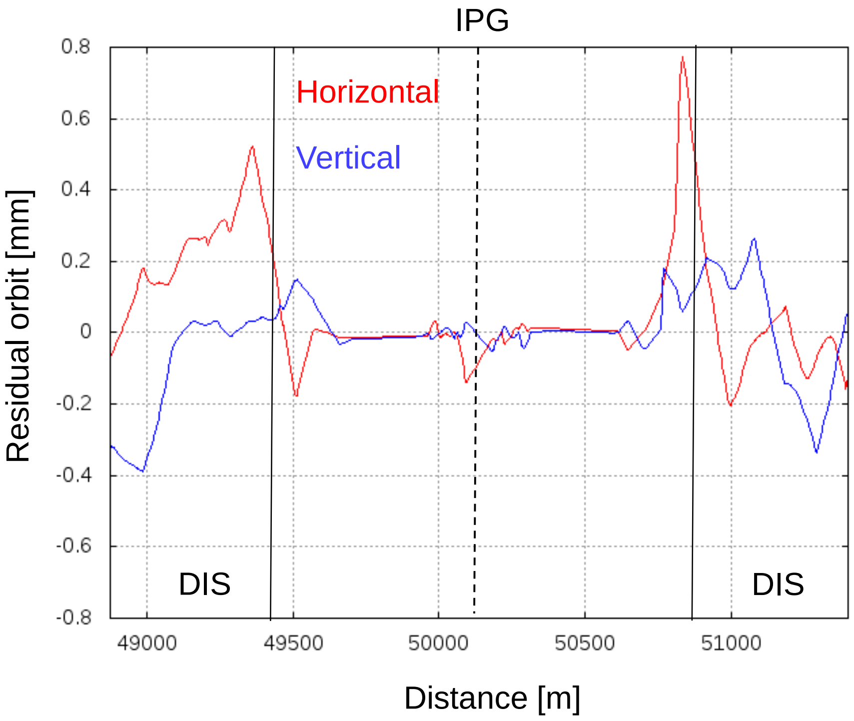
# INTEGRATION OF THE INTERACTION REGION

- The latest IR optics V7 are included
- Correction scheme taken from IR orbit correction (courtesy of E. Cruz)
- Errors implemented for the IR elements: quadrupole alignment errors (0.5 mm RMS) and dipole roll angle (2 mrad RMS)

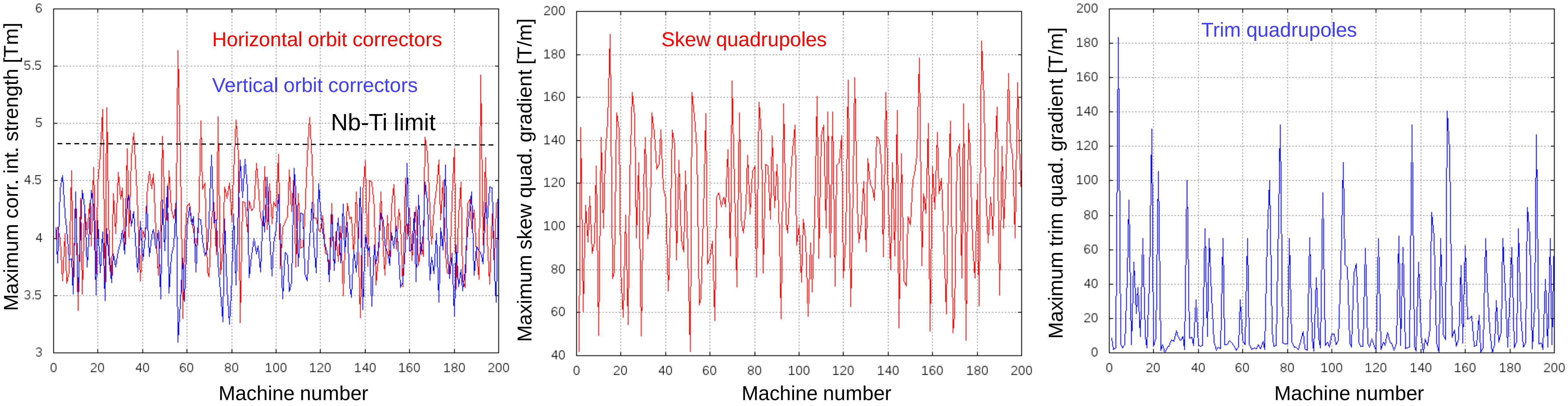
Uncorrected @ injection




Corrected @ injection



# CORRECTOR STRENGTHS




**All strengths are normalized to collision rigidity**

σ(x/y) = 0.5 mm compatible with Nb-Ti technology for 1.2 m orbit correctors at 90% level

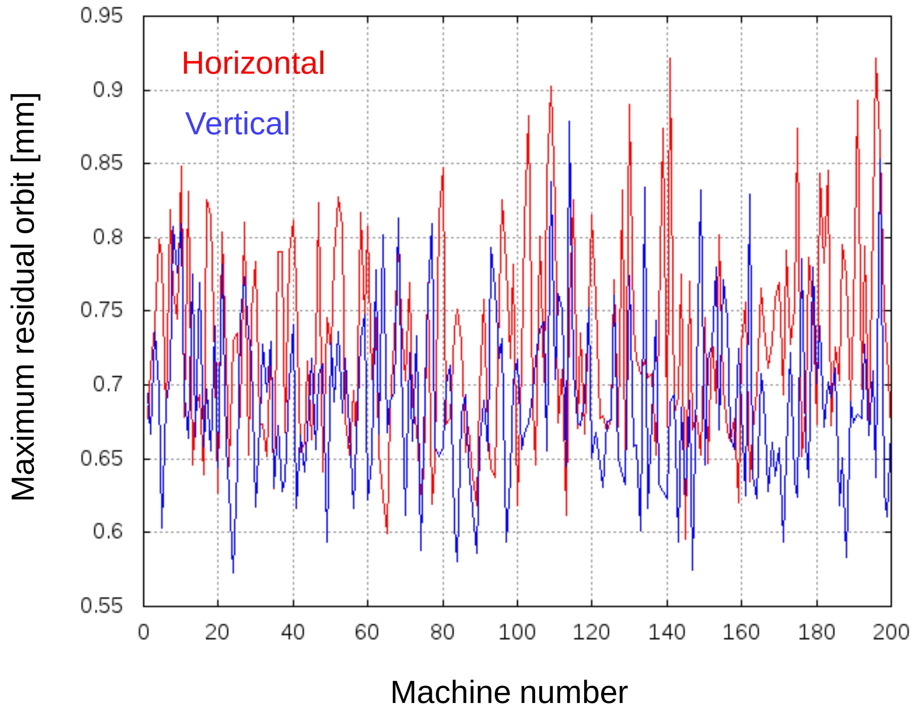
The IR orbit correctors are not included in the analysis

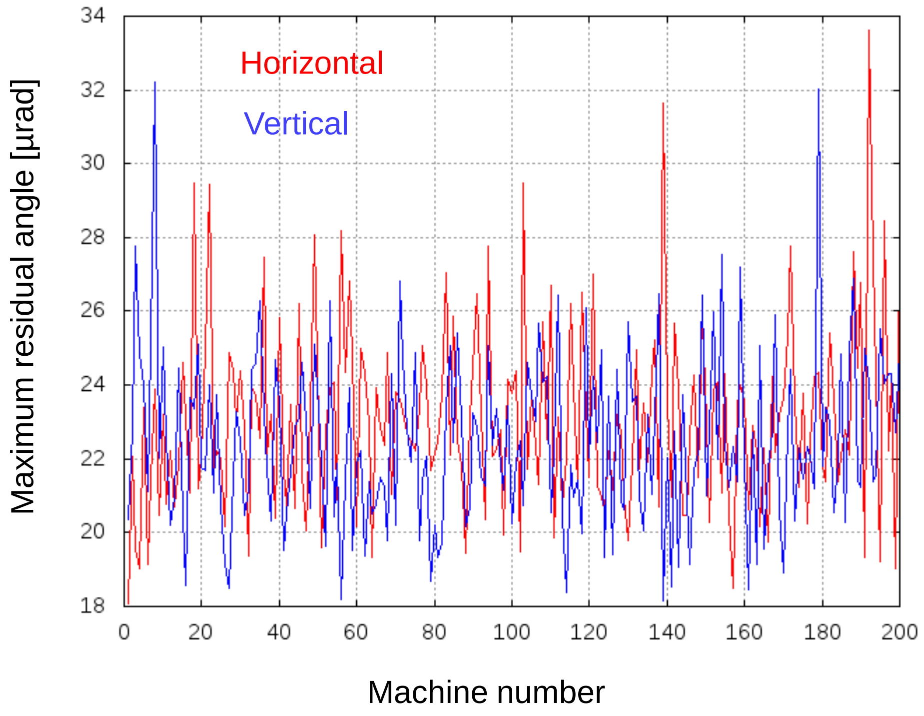
Skew quadrupoles are below 200 T/m

Trim quadrupoles do not exceed 220 T/m, strong values correlated with badly corrected tunes after coupling correction

**90% values: horizontal orb corr. 4.7 Tm, vertical orb corr. 4.4 Tm, skew quad. 153 T/m, trim quad. 68 T/m**

# RESIDUAL ORBIT AND ANGLE AT INJECTION



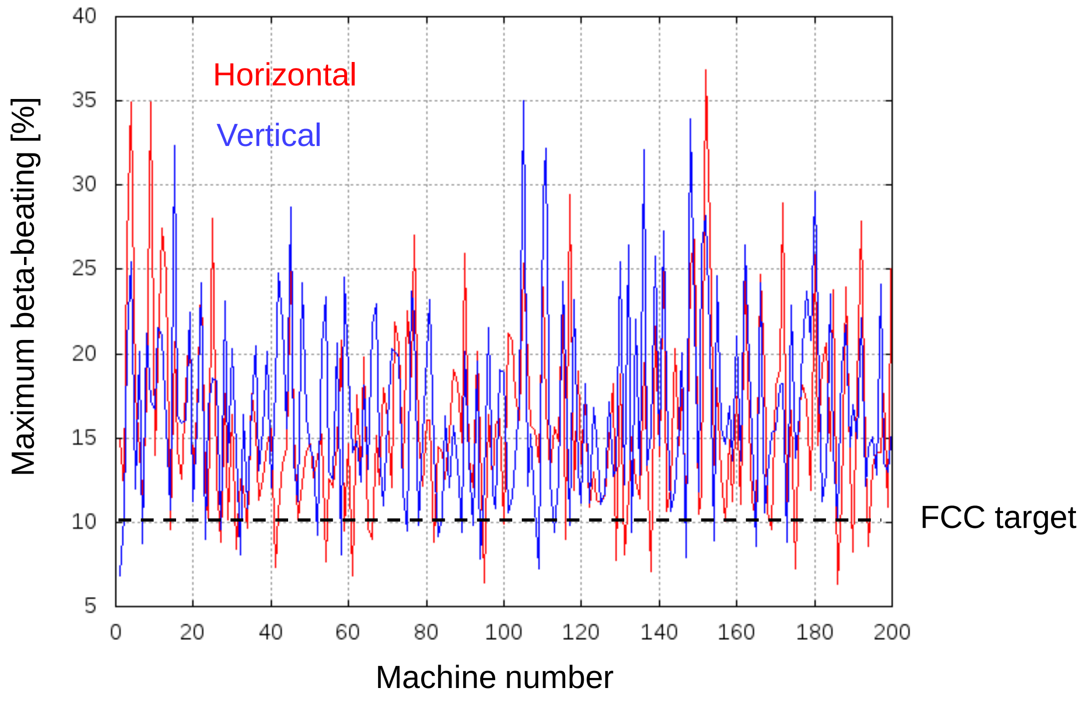

Residual orbit < 1 mm, in accordance with the geometry of the dipole chamber (5 mm aperture)

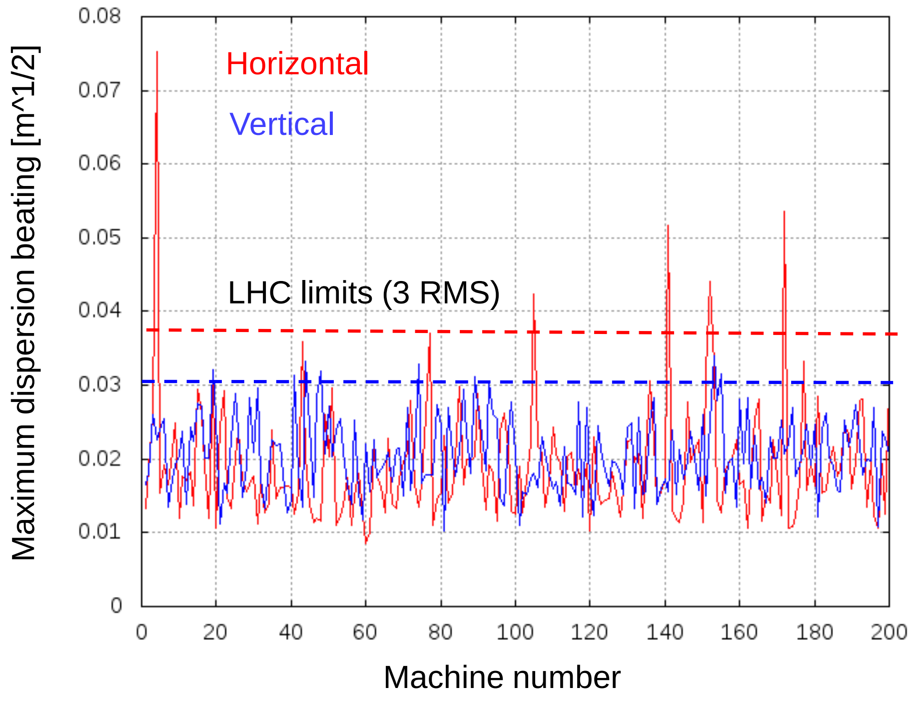
With an alignment error of 0.5 mm RMS for arcs and IR quadrupoles, both sections contribute equally to the residual orbit

**90% values: horizontal orbit 0.82 mm, vertical orbit 0.77 mm, horizontal angle 26 µrad, vertical angle 25 µrad**

The combined contributions of the residual orbit of 0.82 mm, a vertical residual angle of 25 µrad and of the emission cone of photons (19 µrad at collision) contribute to a total vertical offset of +/- 1.3 mm after a drift of 11 m

# BETA AND DISPERSION BEATING AT INJECTION




Beta-beating too strong

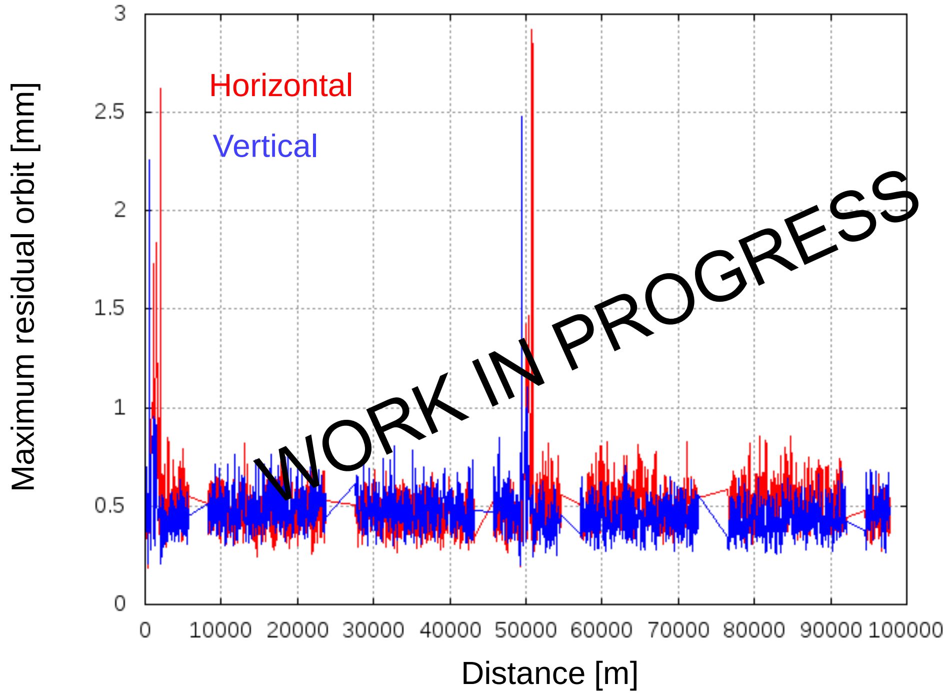
Reducing dipole a2(u) or quadrupole roll angle would lead to values closer to the target of 10%

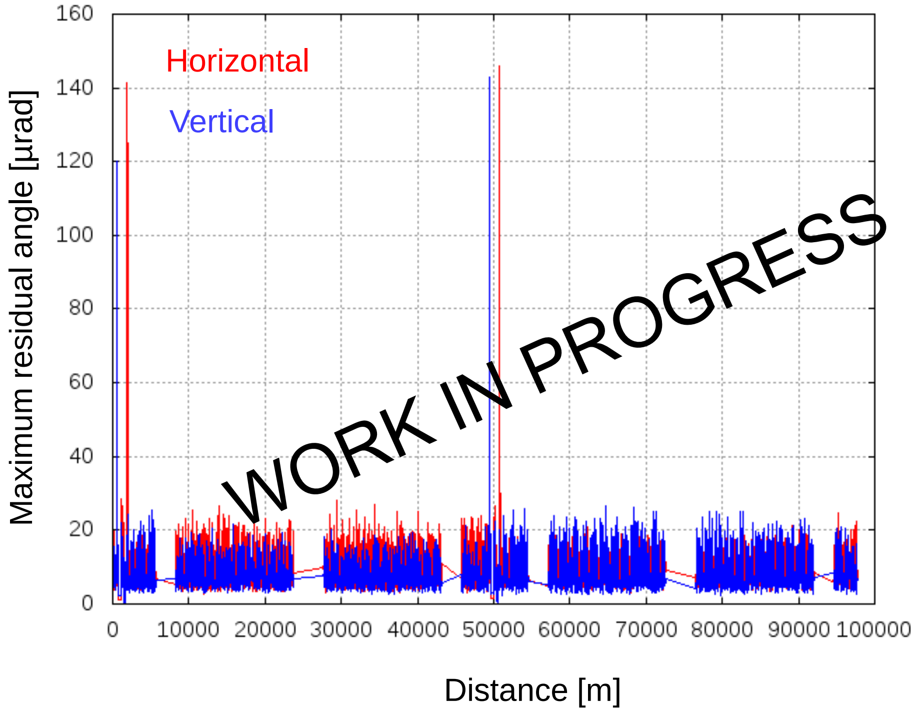
Dispersion beating satisfactory? LHC design values are not reached for > 95% of the machines

**90% values: hori. beta-beating 24%, vert. beta-beating 24%, hori. disp. beating $2.8\times10^{-2}$ $m^{1/2}$, vert. disp. beating $2.8\times10^{-2}$ $m^{1/2}$**

No dedicated correction of the beta-beating or dispersion beating implemented yet

# STATUS AT COLLISION ENERGY




Residual orbit > 2 mm in IRs
Residual angle > 100 µrad in IRs

Same orbit and angle in arc sections compared to injection case
Other variables (beta-beating, dispersion beating, corrector strengths scaled to the same rigidity) are similar to injection

many instabilities of the lattice with MADX => only 20% of the machines are converging

IR correction scheme needs a few modifications => position of BPMs and correctors to match the arcs configuration?

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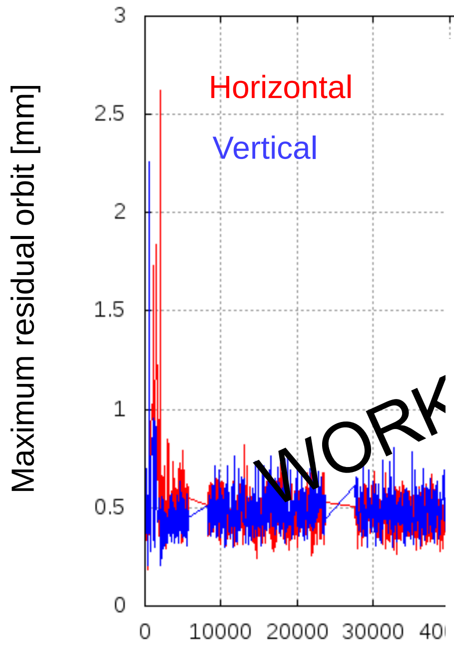


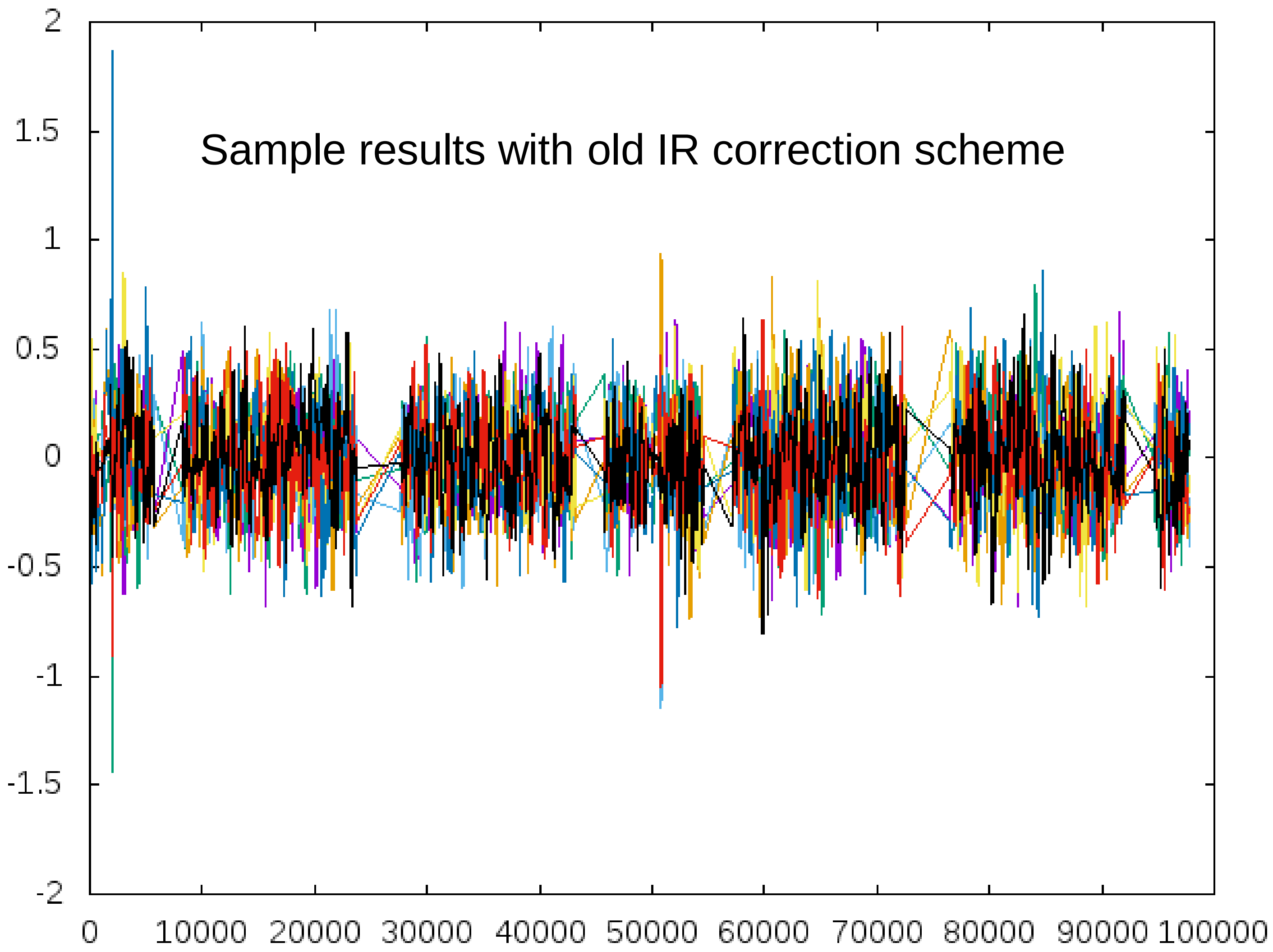


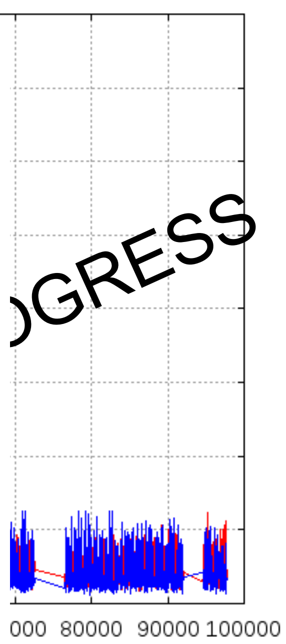


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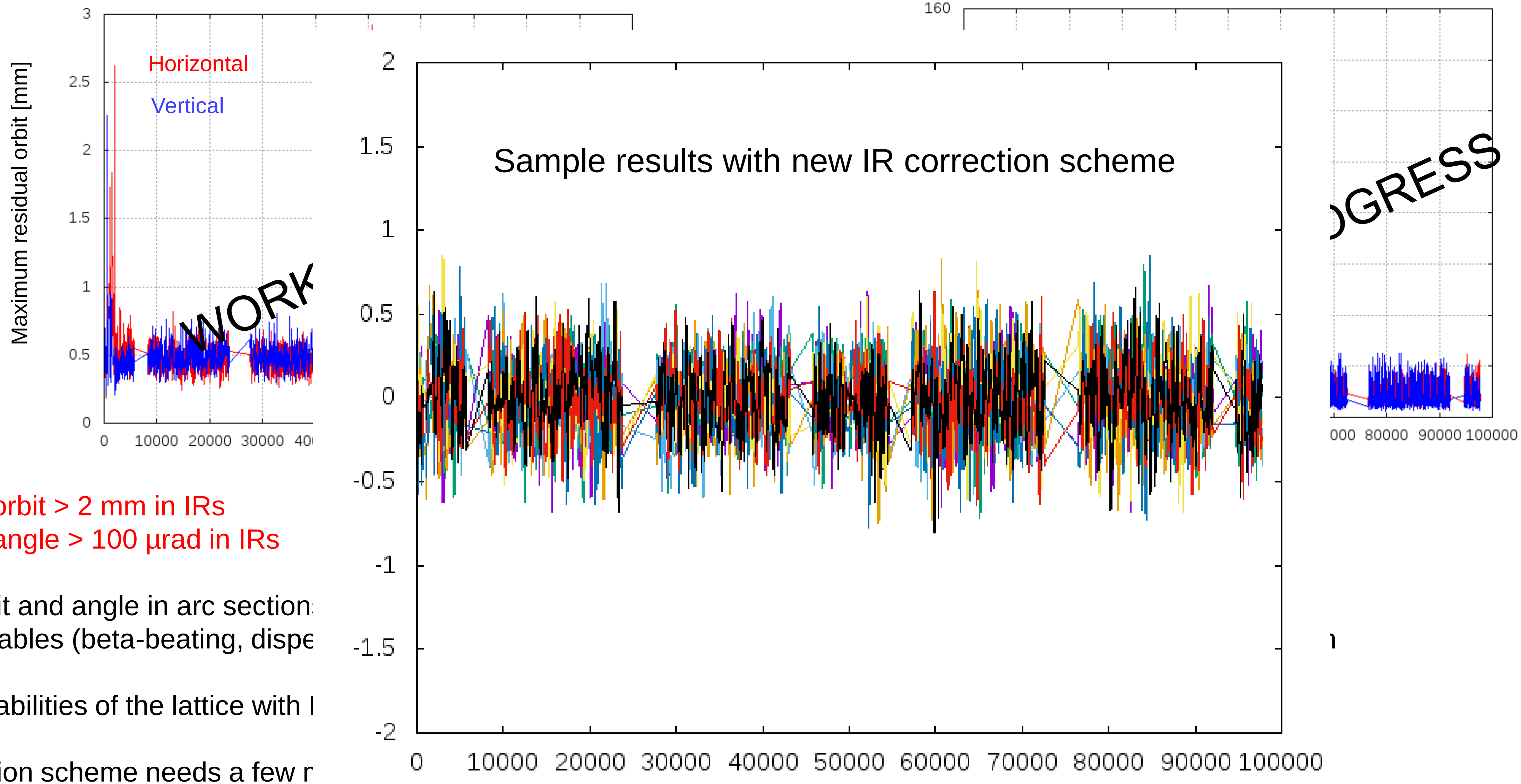


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# CONCLUSIONS AND PERSPECTIVES

- A global correction scheme of the residual orbit, the linear coupling and the ring tunes for the arc sections of FCC-hh has been updated with the newest optics, including the IR sections, fully investigated at injection

- 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 correctors strengths, but only at a 90% level (90-percentile)

- The results at collision with the new lattice need to be confirmed, but should be similar to injection

- Still many instabilities at collision (coupling)

- Perspectives (ideally for CDR):
  - Implement a global correction scheme of the beta-beating, dispersion beating and coupling
  - Validate the IR orbit correction scheme for collision
  - Continue the integration of the insertion regions (collimation, etc)
  - Add other systematic errors (dipole b2, alignment)