IR local corrections with 10 units quadrupole errors in the triplet
Local correction strategy

- In the past, just the phase advance was used to correct local errors in the IRs. The phase advance can be insensitive to waist shifts.

- K-modulation has been used in the current LHC with good success to refine the correction removing the waist shifts.

- $\beta$ from amplitude is expected to give accurate $\beta$-functions in a wider range of the IR.

- HiLumi is expected to be more challenging than the current LHC
  - 10 units of uncertainty in each of the six (per side) magnets of the triplet (per IP).
  - Lower beta-star $\rightarrow$ very high $\beta$ in the triplets, amplifying the errors.
  - Powering scheme:
• Model and BPM calibration independent.

• It is the most robust observable we have for now to measure optics errors, but it is very small in the triplet region, making errors hard to measure there.

• It does not guarantee the correction of the waist shift at the interaction point.
• The two closest Q1 magnets to the IP are modulated.

• The average $\beta$-function in the triplet is proportional to the change in tune produced by the modulation.

• Its precision depends critically on the precision on the measurement of the tune.

• It takes about 5 minutes per side per IP in the LHC.

• Close to 1% precision in the measurement of $\beta^*$ achieved in the current LHC, but worse is expected for HiLumi.
K-modulation and tune uncertainty

- The jitter in the current provided from the power supplies will produce a tune jitter of $\sim 10^{-4}$.
- This will limit the performance of k-modulation.
- Simulations show a huge error in the measurement with that uncertainty in the tune, but the modulation should improve the measurement. In the current LHC we get results compatible with $\partial Q \leq 10^{-5}$.*

K-modulation and coupling

• The precision of the measurement coming from k-modulation depends as well on how well the coupling is corrected.

• In HiLumi, simulations show that $\Delta Q_{\text{min}}$ has to be corrected down to $\sim 6 \times 10^{-4}$, to get to 1% precision.

• Depends on BPM calibration to give accurate results.

• BPM calibration can be made using data from ballistic optics, where the triplets are unpowered and we get a good $\beta$ from phase measurement.

• Thus, its precision depends on the quality of the calibration.

• At least for now, we get around 4% accuracy in the measurement of the $\beta$-beating*.

* Source: Ana García-Tabarés
Simulations parameters

- HL-LHC v1.2 sequence.
- 100 seeds, round optics 15cm.
- 10 units of B2R only in the triplet of IR1 and IR5 and correcting only with the triplet.
- Firsts local corrections just in IR1 and IR5.
- Then the correction is applied to the whole ring and a global correction is computed for refinement.
Only phase correction

- $0.7 \cdot 10^{-3}$ uncertainty in phase assumed in the arcs focusing quadrupoles, and extrapolated to the rest of the points.

- 50% of the simulations failed.
- Correcting just the phase produces huge waist shifts.

- Luminosity imbalance: $2.3 \pm 3.3$
Phase and $k$-modulation

- $0.7 \cdot 10^{-3}$ uncertainty in phase assumed in the arcs focusing quadrupoles, and extrapolated to the rest of the points.
- 1% uncertainty in $k$-modulation.

- 5% of the simulations failed.

- Luminosity imbalance: $1.12 \pm 0.18$
- Max. Corrector strength: $(1.7 \pm 0.61) \cdot 10^{-4}[m^{-2}]$
Phase, k-modulation and $\beta$ from amplitude

- $0.7 \cdot 10^{-3}$ uncertainty in phase assumed in the arcs focusing quadrupoles, and extrapolated to the rest of the points.
- 1% uncertainty in k-modulation and 2% in $\beta$ from amplitude.

- 3% of the simulations failed.

- Luminosity imbalance: $1.03 \pm 0.22$
- Max. Corrector strength: $(1.7 \pm 0.67) \cdot 10^{-4}[m^{-2}]$
Phase, k-modulation and $\beta$ from amplitude

- $0.7 \cdot 10^{-3}$ uncertainty in phase assumed in the arcs focusing quadrupoles, and extrapolated to the rest of the points.
- 1% uncertainty in k-modulation and 2% in $\beta$ from amplitude.
- 20cm $\beta^*$

• 4% of the simulations failed.

- Luminosity imbalance: $1.01 \pm 0.16$
- Max. Corrector strength: $(2 \pm 0.74) \cdot 10^{-4} [m^{-2}]$
Phase, k-modulation and \( \beta \) from amplitude

- \( 0.7 \cdot 10^{-3} \) uncertainty in phase assumed in the arcs focusing quadrupoles, and extrapolated to the rest of the points.
- 1\% uncertainty in k-modulation and 1\% in \( \beta \) from amplitude.

- No simulations failed.

- Luminosity imbalance: \( 1.023 \pm 0.078 \)
- Max. Corrector strength: \( (1.1 \pm 0.45) \cdot 10^{-4}[m^{-2}] \)
Conclusions and outlook

• The challenge is still on.

• K-modulation will be a essential tool in HiLumi as it has been for LHC.

• We have to keep the performance of K-modulation at least at its current level:
  • It will be important to improve the tune measurement precision.
  • Careful coupling control, to the $\Delta Q_{\text{min}} \sim 10^{-4}$ level.

• If $\beta$ from amplitude reaches the 1% percent level the problem almost vanishes... but we are far away.

• Need ideas in case $\beta$ from amplitude does not reach that requirement.
  • Modulate Q2, Q3 and Q4?

• The matching algorithm is quite new and can be further developed.
  • Put constraints on the correction strength.
  • Fitting different optics at the same time to break the degeneracy.

• Flat optics analysis and longitudinal misalignments still to be addressed.