Optics aspects in the accelerator complex

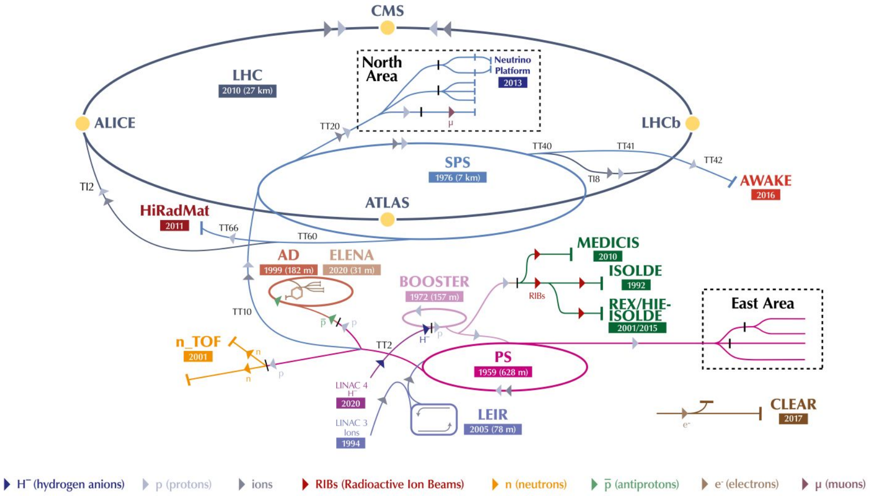
F. Carlier on behalf of many people:
Y. Angelis, F. Burkhardt, J. Cardona, R. De Maria, J. Dilly, V. Ferrentino, J. Gray, S. Horney, J. Keintzel, E. Kravishvili, P. Kruyt, M. Le Garrec, E.H. Maclean, K. Paraschou, T.H.B. Persson, K. Skoufaris, F. Soubelet, R. Tomas, K. Ujani, W. Van Goethem,

Particular thanks to:
OP, Collimation, BI, BPM, ADT, RF, and all experts that support optics studies

Moving from LHC focussed to whole complex

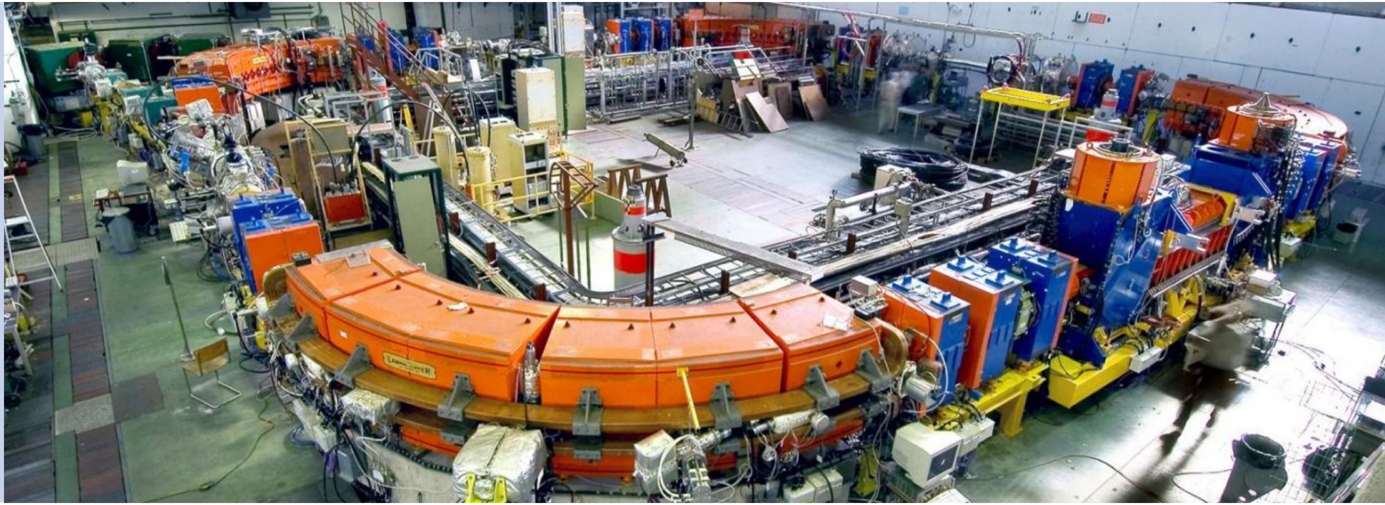
1. **LEIR**
2. **PSB & PS**
3. **LHC**
4. **Tools and ac dipole**

The CERN accelerator complex
Complexe des accélérateurs du CERN



LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

Contents



Bringing optics measurements to LEIR in Run 3

LEIR is commissioned and operated using historical settings and optimized by hand or with ML optimizers.

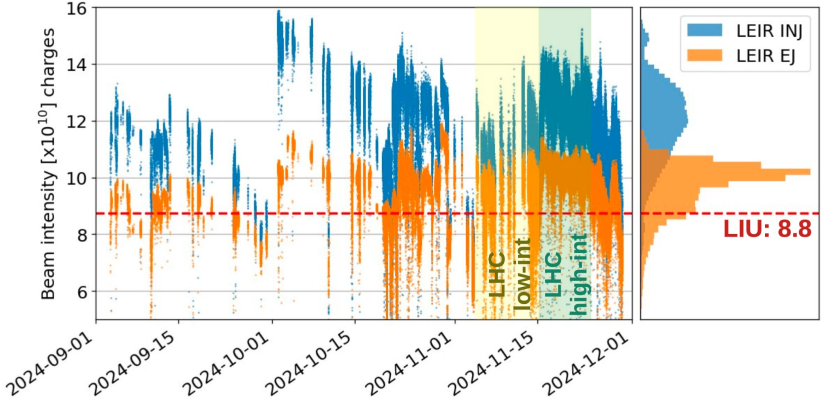
Record performance, with quasi optics agnostic operation!

- Interdependence of tuning parameters complicating tuning
- Models with limited predictive power limit studies in LEIR

Improving optics models through beam based optics measurements could help **simplify and improve** machine tuning.

Optics methods from LEIR are also applicable to ELENA as it shares same BPM systems, and many of same challenges

M. Slupecki



Orbit based measurements in LEIR

Measured orbit responses from tuning knobs at e-cooler demonstrate large orbit variations in machine

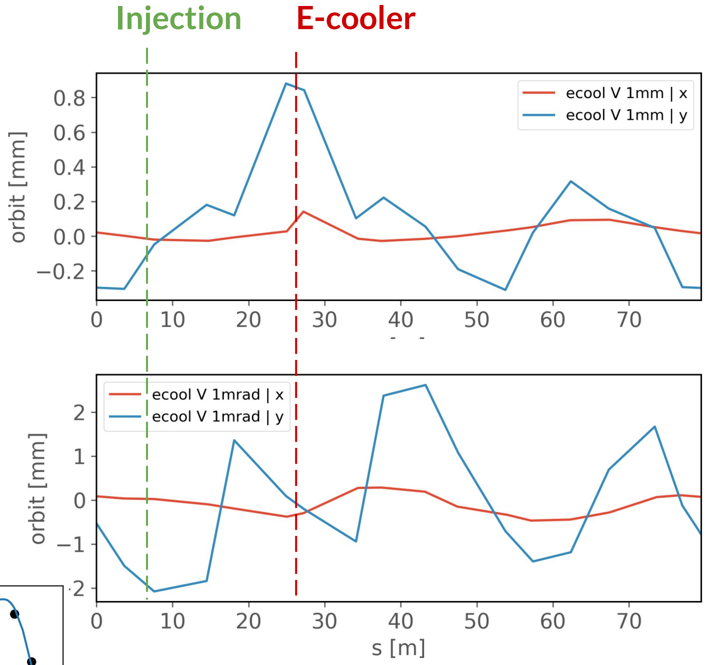
- Causes difficulty tuning machine
- E-cooler bumps affect injection orbit
  => Measurement based knob design could improve this

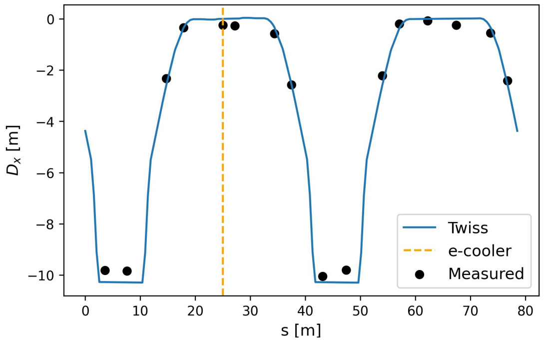
Dispersion measurements used to study effect on e-cooling

- Dispersion can cause observed instabilities during Mg run in simulation

Orbit response matrix measurements performed

- Development of LOCO ongoing
  for orbit based optics measurements





P. Kruyt

Turn-by-turn based measurements in LEIR

Explored excitation methods

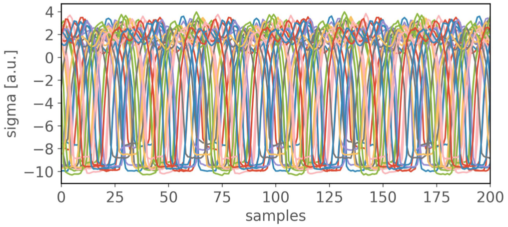
- Tune kickers, BBQ pulse, BBQ ac dipole chirp, BBQ resonant chirp, Extraction kickers (H)
- Kick methods available, **but very tedious & expert setup**

Commissioned new BPM system

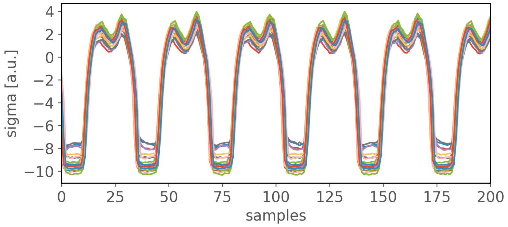
Considerable effort put in commissioning and synchronisation of new BPM systems for optics measurements in LEIR.

- Corrected delays from: cable lengths, ToF, electronics
- Simplified peak detection
- Increased number of turns

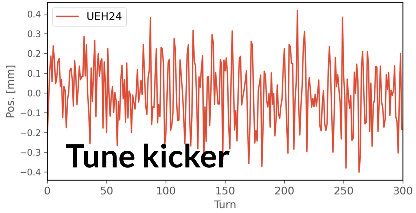
Before phasing

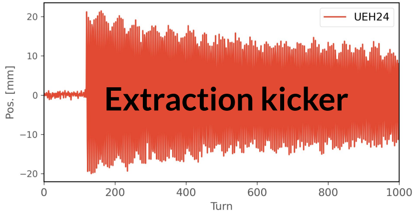


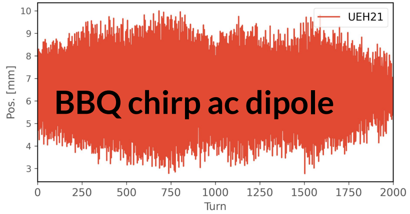
After phasing



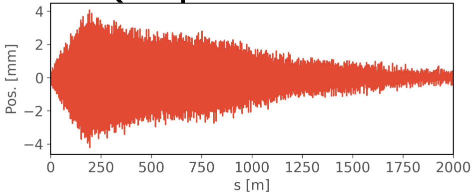
Thanks to
S. Jensen,
O. Marqversen







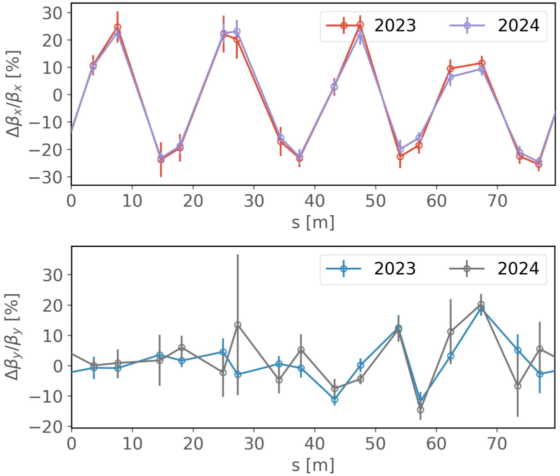
BBQ chirp - resonant kicks



Optics measurements are now available in LEIR

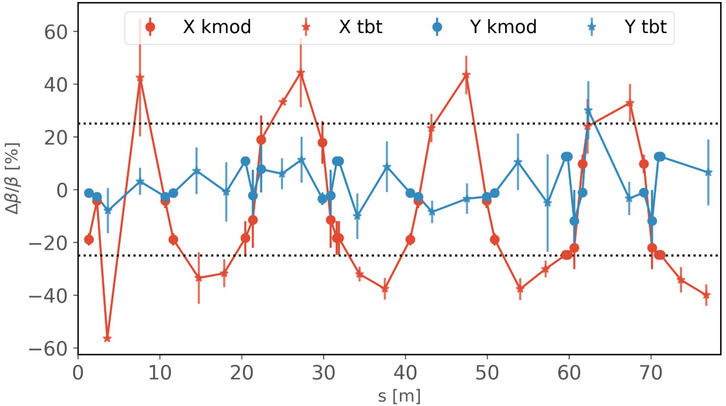
Large discrepancy with nominal models observed

- Peak beta beating:
  - Flatbottom (25%),
  - Flattop (50%)
- Good reproducibility between consecutive years



Independent K-modulation method confirms results

- Modulation of quadrupole circuits for averaged beta-functions demonstrated successfully in LEIR.

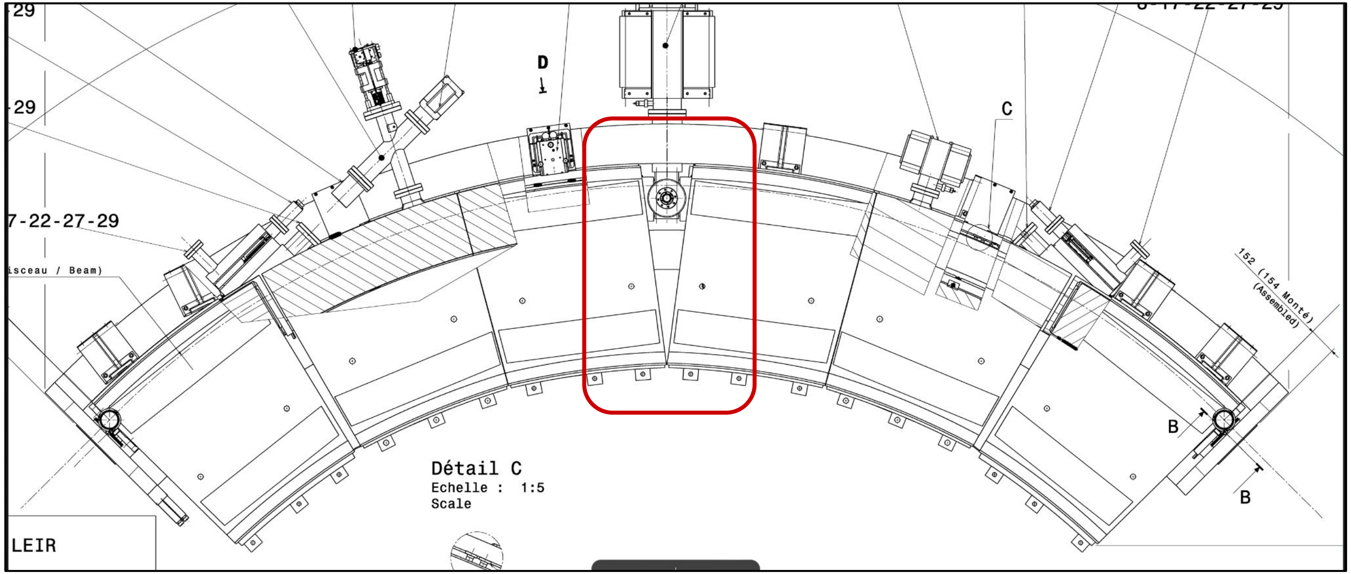


Optics measurements validated in LEIR, now starting to improve model

Will look at dipole magnetic modeling in 2025

LEIR dipoles suspected to be main source of error

- Specifically the wedge in the middle of the bend
- New project starting in 2025 on accurate modeling



Contents

Zero dispersion optics in the PS and emittance preservation

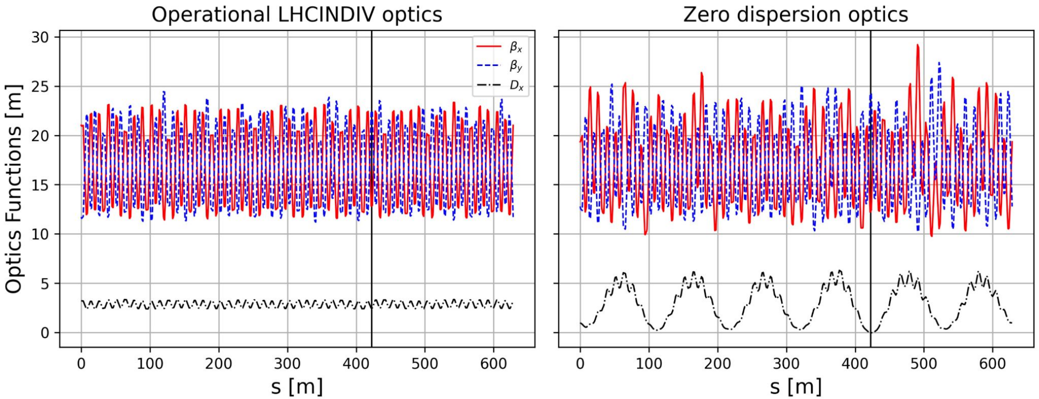
Observed horizontal emittance trend between the PSB rings

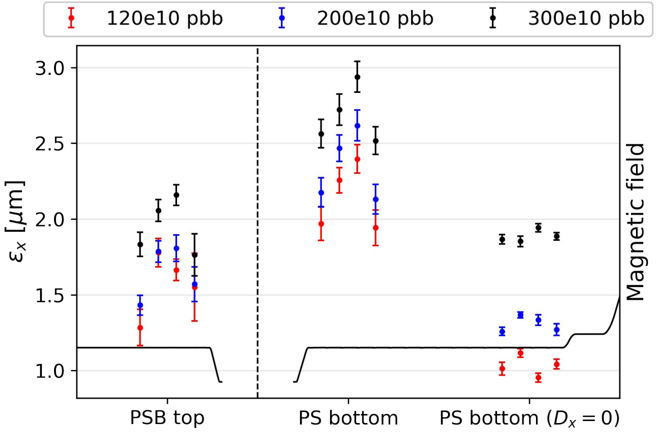
- the outer rings having a consistently lower emittance than the inner rings
- Observed since new calibration of RF voltage

New zero dispersion optics developed in PS used to deconvolute WS measurement

- PSB trend disappears in zero dispersion measurements
- Suggests a longitudinal emittance difference in the rings

W. Van Goethem

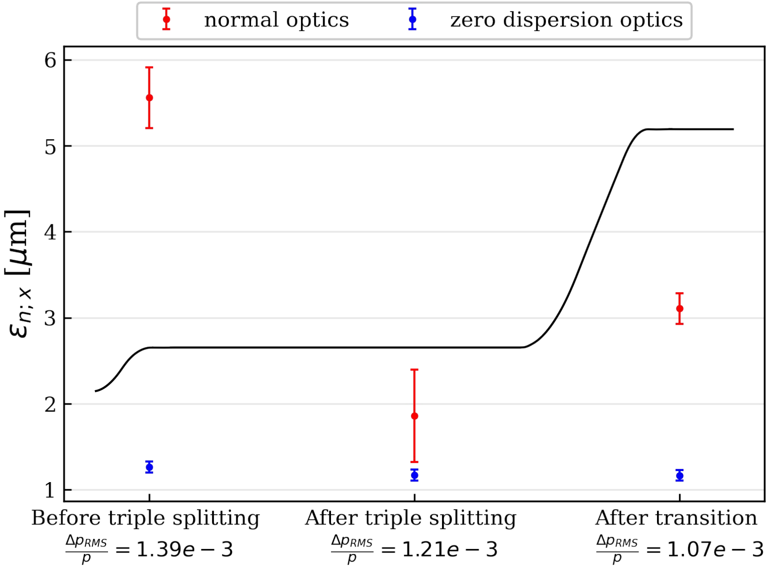




Stable horizontal emittance in PS throughout cycle

Zero dispersion optics successfully used at different moments in the PS cycle including high energy.

- Study of H-emittance over transition show good preservation across transition
- Allows new studies on tails across transition



W. Van Goethem

PS main units modeling and extraction energy

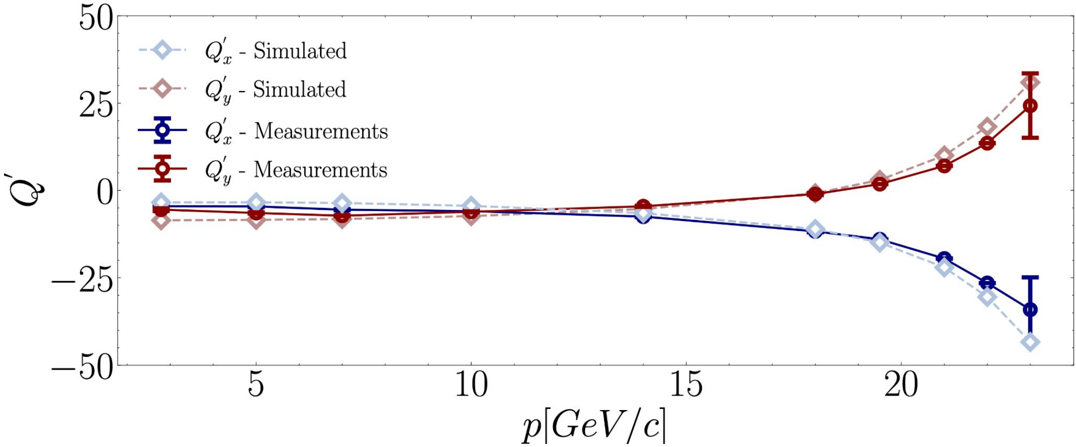
Magnetic modelling of main units shows good model reproducibility

- Saturation of Iron from around 20 GeV causing change in quadrupolar and sextupolar components
- Can be used for operational improvements to PFW compensation

Predictive modeling already inspired new operational cycle for EA

- Bare machine chromaticity measurements inspired new cycle for EA at 15 GeV
- Longer platteau for extraction added benefit

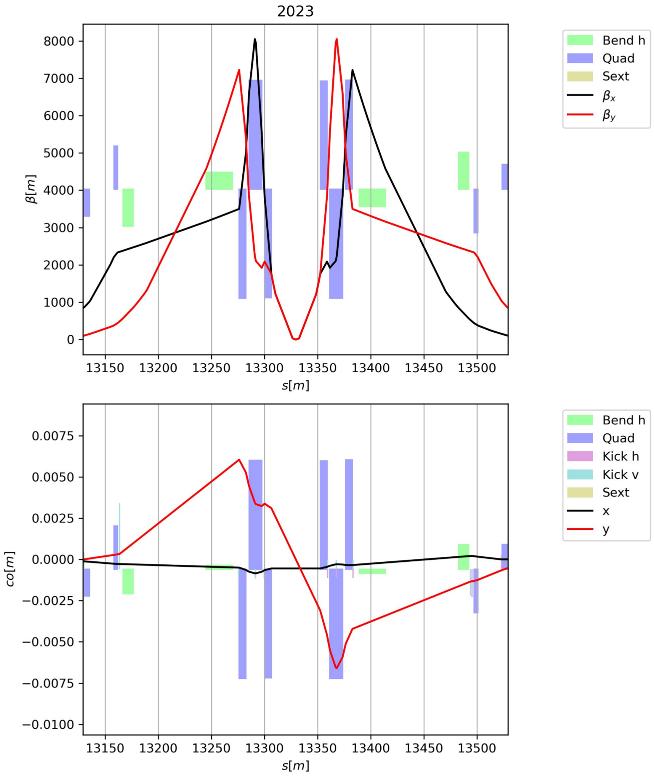
PS optics studies few years ahead of LEIR and starting to impact operation



V. Ferrentino

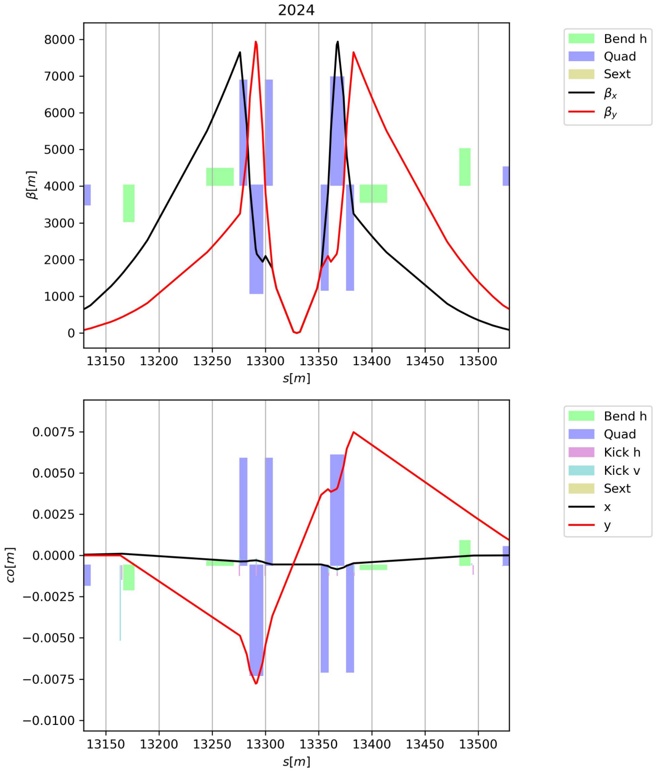
Contents

LHC optics commissioning in 2024 with RP in IP1



Two main differences in terms of settings between 2023 and 2024

1. **Inverted triplet polarity for IP1 and the Q4 turned off**
2. **Change of crossing angle in IP1 from negative to positive**

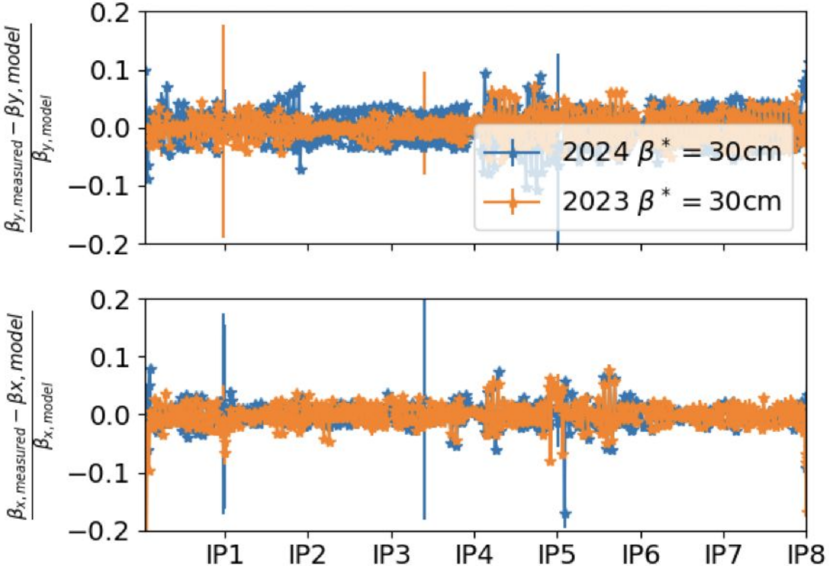


Good control of linear optics in 2024

Final linear optics corrections very similar to 2023

A slight increase of imbalance in β* between IP1 and IP5

- Mainly driven by IP1 being closer to design
- Difference in the ~2% range (favouring ATLAS)



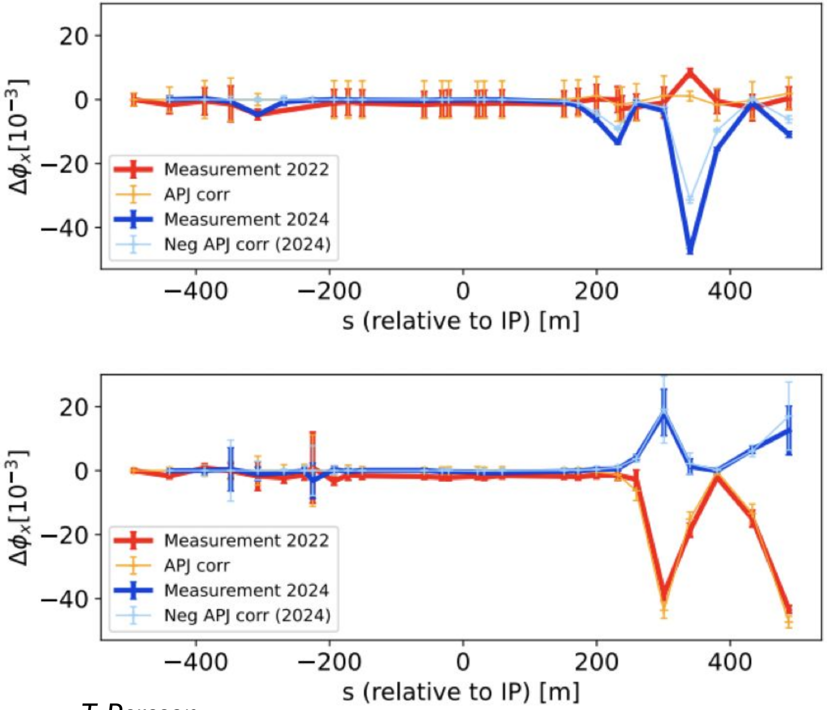
T. Persson

Successful prediction of local IP corrections

Inversion of local quadrupole corrections worked well in RP optics

- The first guess was to invert the local correction in IP1
- Coupling correction worked well too
- IP5 and IP2 (ion cycle) local corrections re-used without issue

  -> Less time than foreseen to find a correction



T. Persson

Built confidence for 2025 commissioning with foreseen polarity changes

Effective energy offsets from orbit setup

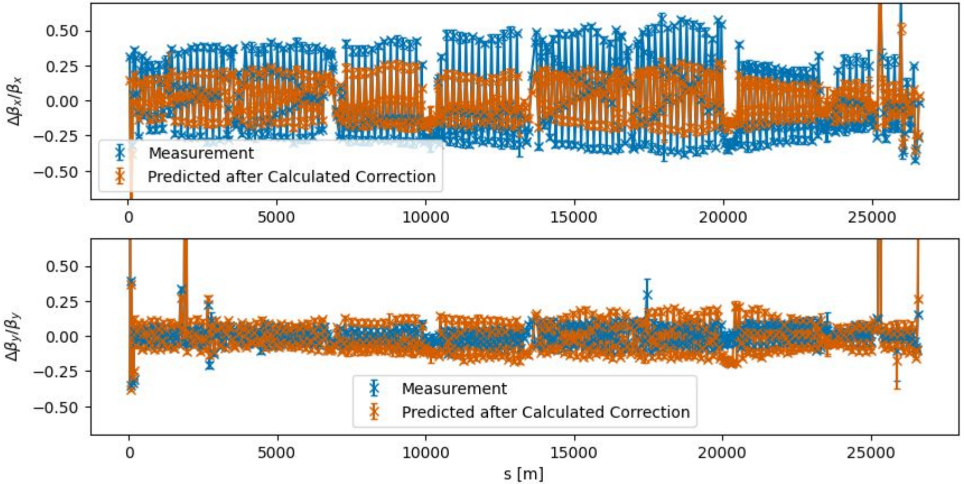
Changes in orbit setup can cause an effective energy change that significantly impacts optics corrections.

Multiple corrections required during commissioning:

09/03 : LHCB1 -2×10^{-4}
14/03 : LHCB1/B2 -2×10^{-4}
24/03 : LHCB2 1×10^{-4}

Corrections currently calculated from optics measurements.

- Can a correction be predicted directly from YASP to limit unforeseen optics correction shifts?

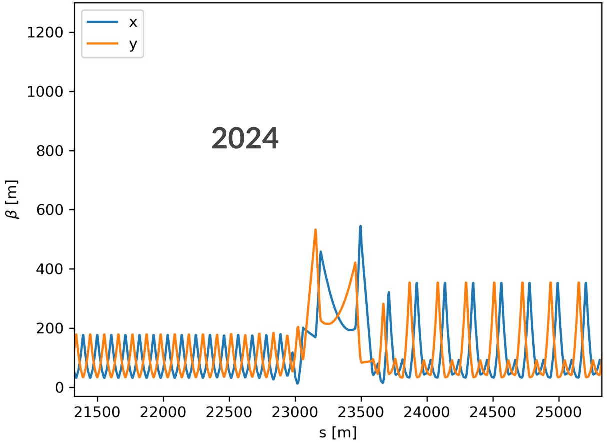


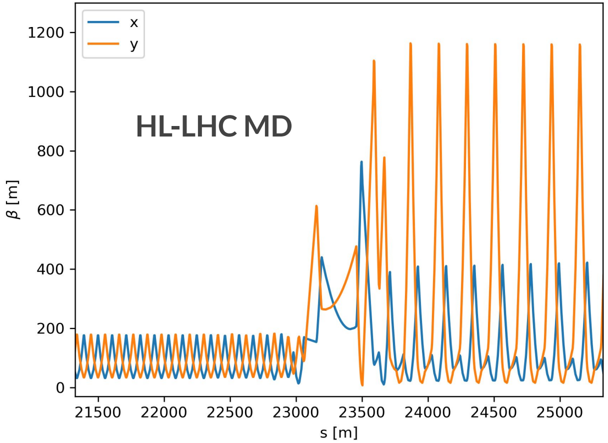
J. Gray

Linear corrections in ATS arcs

Optics with large ATS factors are more sensitive to local errors in the arcs, due to increased beta functions.

- Currently no dedicated quadrupolar correctors for local corrections in ATS arcs
- Local orbit bumps in sextupoles are used to create local quadrupolar corrections
- Used in operation in B1 since 2023

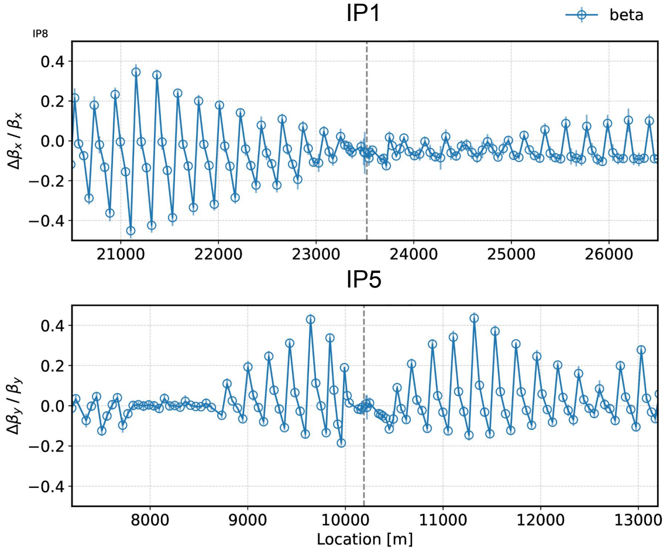


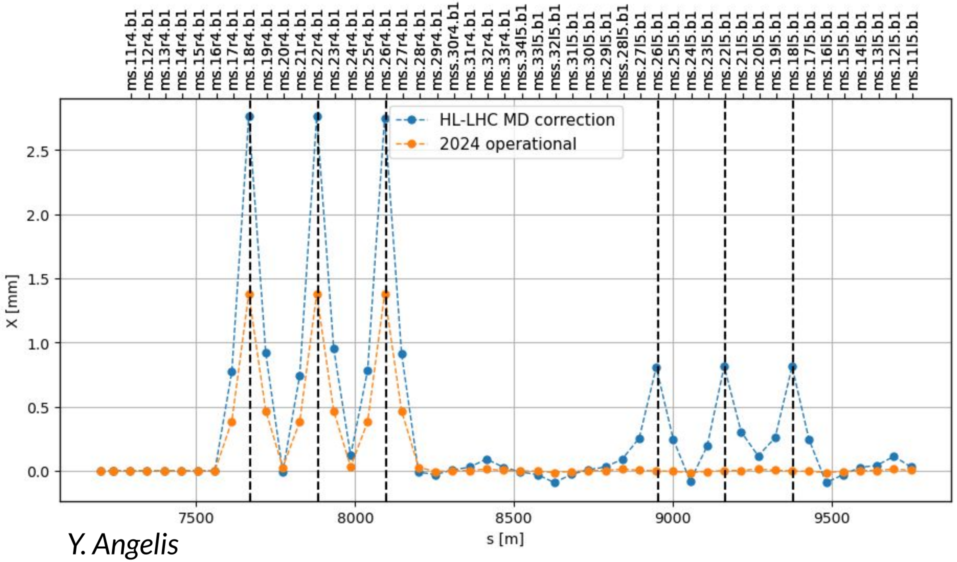


Linear corrections in ATS arcs in HL-LHC conditions

HL-LHC MD shows large optics perturbations in ATS arcs (0% → 40% beta-beat)

- Requires more and larger orbit bumps for corrections
- Ongoing effort to improve understanding and improve matching
- Could increase commissioning time in HL-LHC => **Important to address in Run 3 MDs**





Y. Angelis

Calibration optics & BPM scaling

Role of calibration optics (incl. ballistic) to improve BPM calibrations

Dedicated MD with 60 degrees phase advance in arcs was very valuable for new optics insights.

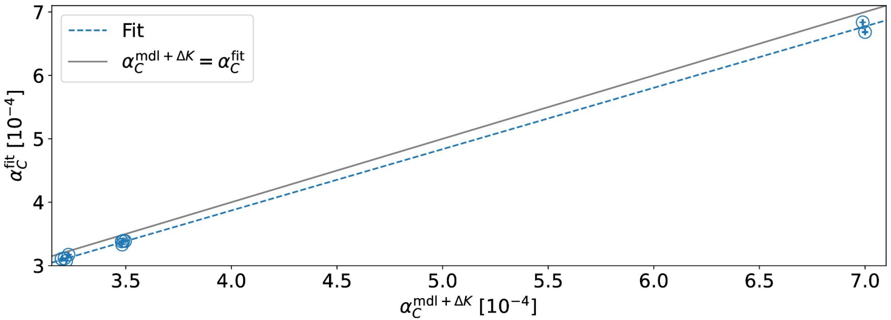
Lower momentum compaction factor for both beams measured

- strongly suggests average horizontal arc BPM calibration error off -3%

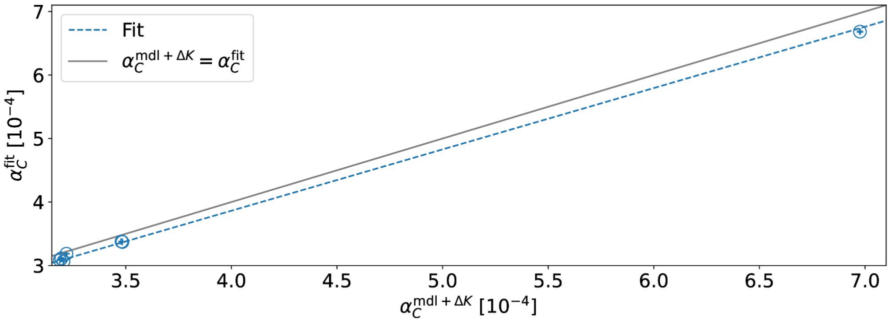
$$\delta_p = \frac{\langle D_x^{\mathrm{mdl}}\, x \rangle}{\langle (D_x^{\mathrm{mdl}})^2 \rangle}$$

$$\delta_p^{\mathrm{RF}} = -\left(\frac{1}{\gamma_{\mathrm{rel}}^{-2} + \alpha_C}\right)\frac{\Delta f}{f}$$

Beam 1



Beam 2



J. Keintzel

Nonlinear optics commissioning

Guessed corrections for nonlinear errors did not work as well as for linear case

- Required recalculation of corrections for multiple sources
- Some corrections were not successful

We have reliable methods for corrections of sextupolar and normal octupolar sources.

- Good control of b3, a3 and b4

Not all desired HL-LHC corrections have been achieved

- a4, b6, and forced DA are problematic
- Direct a5, b5, and a6 corrections remain untested due to lack of correctors in LHC

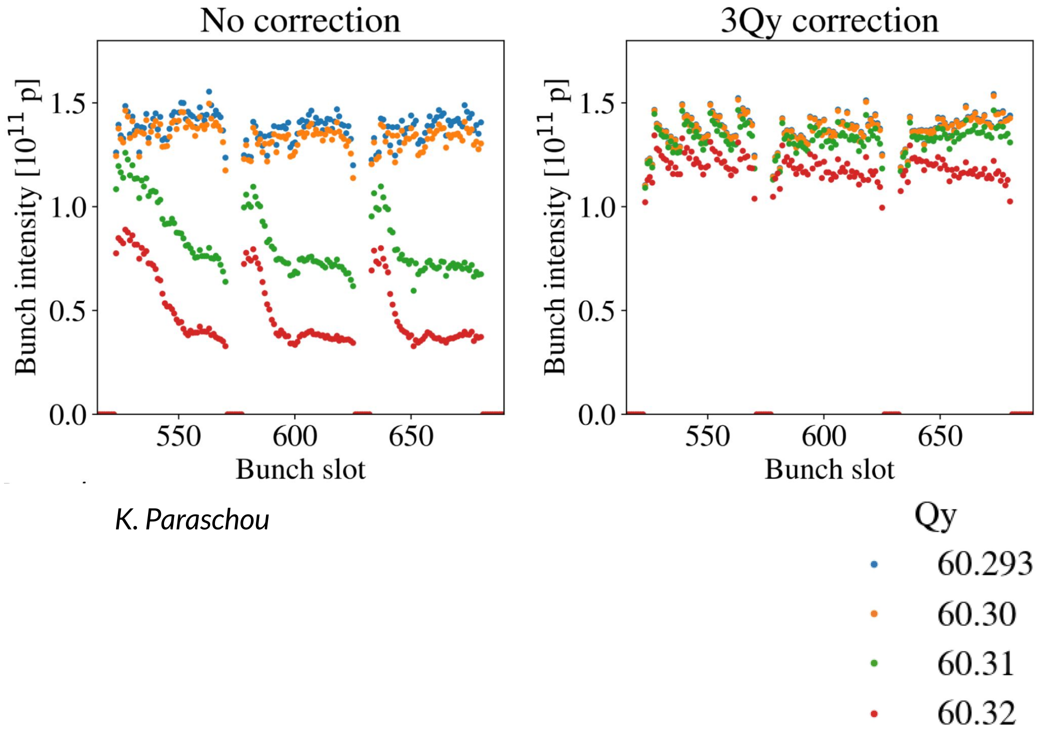
Detailed overview: (E. Maclean, LMC)

Skew sextupolar corrections with e-cloud at injection

Successfully corrected 3Qy resonance to reduce bunch intensity loss from e-cloud.

- Dual-beam correction with common MCSSX demonstrated in 2023 MD
- In operation since June 2023
- New 3Qy corrections for RP optics implemented in first few days

Valuable experience for HL-LHC operation with potential reversed MO polarities and opposite detuning direction.

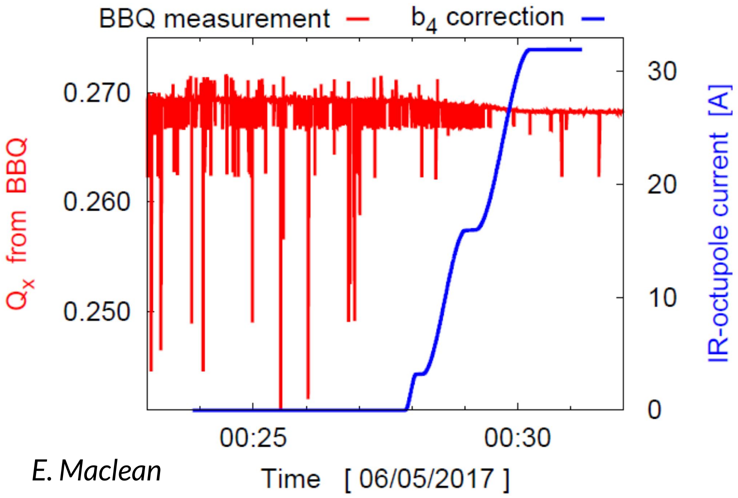


K. Paraschou

Normal and skew octupolar corrections

Normal octupolar corrections have a direct impact on optics corrections

- Improves BBQ signal for: K-modulation, chromaticity scans, crossing angle scans..
- Improves detuning -> increases available kick amp.

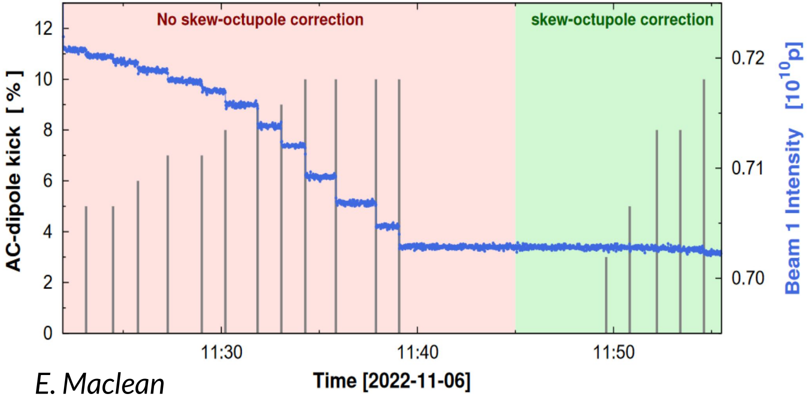


E. Maclean

Corrections of skew-octupolar errors are important to improve forced DA

- Essential for meas. and corr. of NL errors
- a4 feedown to a3 comparable to natural a3
- Chicken & egg: can't find a4 corrections because of forced DA limitations

For 2025 commissioning:
=> crossing angle scans with kicks to measure feeddown to a3



E. Maclean

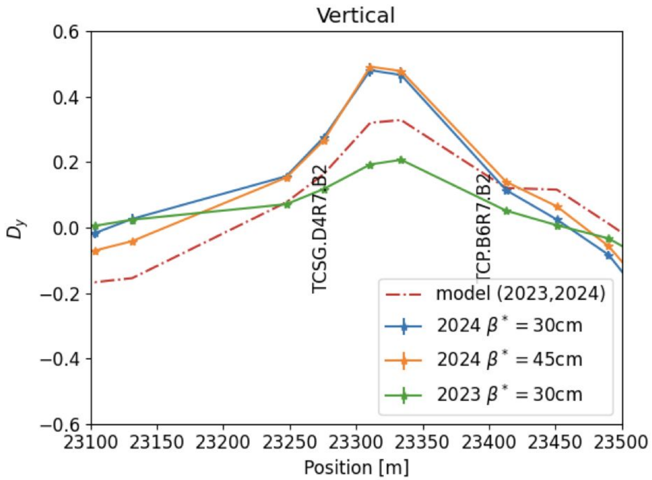
Effect of vertical dispersion on collimator hierarchy

All the linear optics parameters were controlled within same tolerance as in 2023

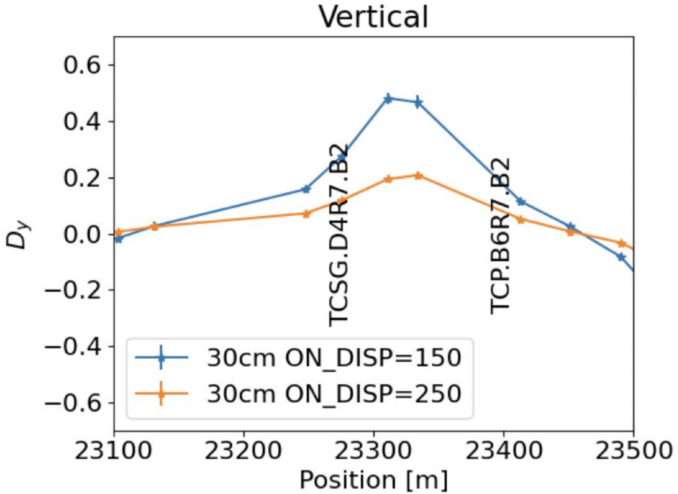
- In 2023, errors reduced the vertical dispersion
- In 2024, errors increased the vertical dispersion

Used IP1 on_disp knob from nominal (150) to 250 increased margin by 0.4 σ

- Effect not seen on loss maps or with a single beam
- Dual beam effects needed!



T. Persson



T. Persson

Effect of beam-beam on hierarchy

A clear effect is observed from the LRBB on the β-beat

- Observed beta-beating up to 10% at the collimator
- Not enough at the collimator to explain the breakage

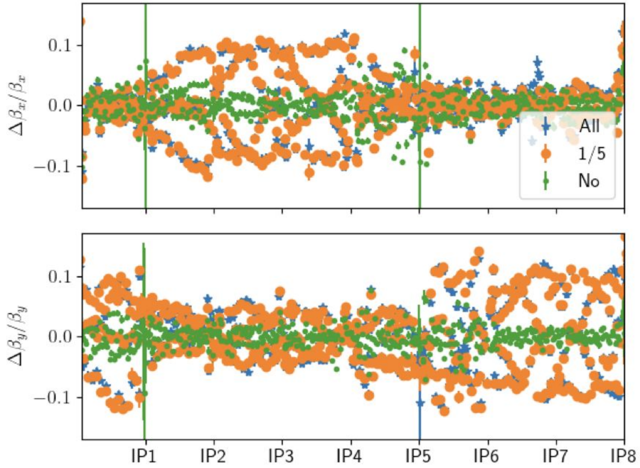
Skew sextupolar contributions to hierarchy breakage

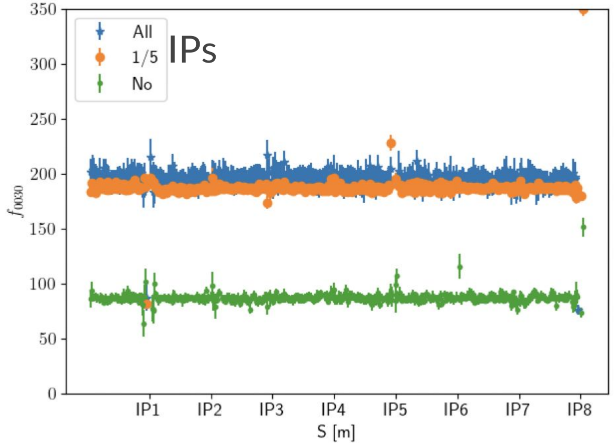
- Simulation by K. Paraschou and X. Buffat showed that the 3Qy is of importance
- When we implemented an a3 correction that also had a positive effect (~0.2 sigma)

A clear increase of the 3Qy from Long Range BB in IP1 & IP5

- Working on a correction strategy, see Ewen's talk LMC & BB workshop
- Planned test of corrections in 2025 in view of operational use

Dual beam effects on optics start to become important and can impact operation





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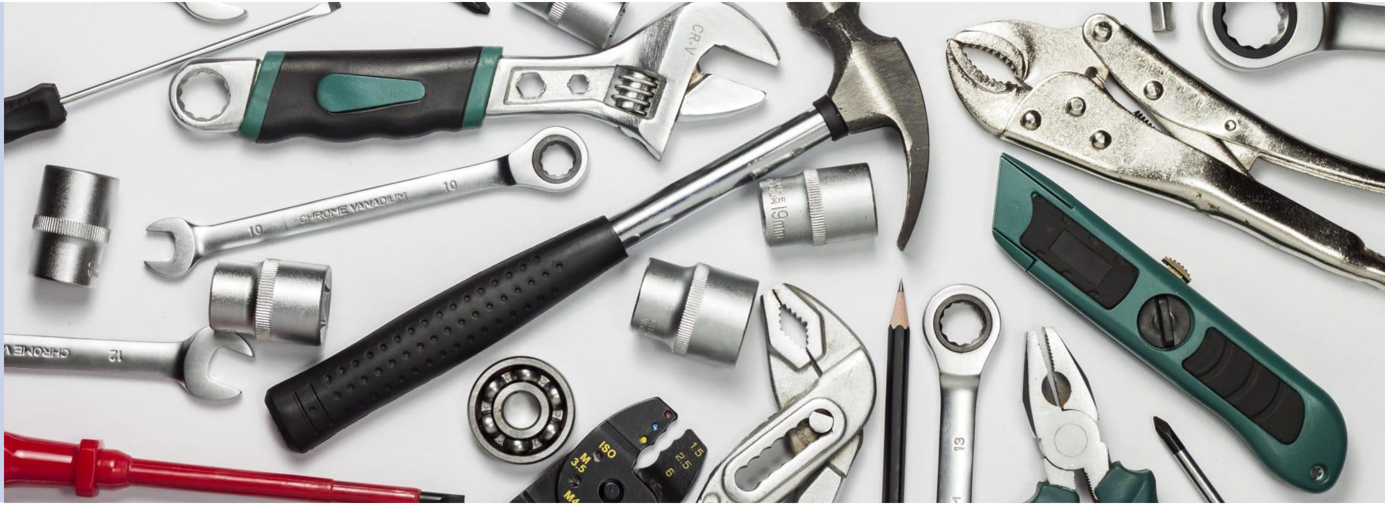
1. LEIR
2. PSB & PS
3. LHC
4. **Tools and ac dipole**



Critical situation of ac dipole for LHC operation

Single most critical device for optics measurements in the LHC.
Practically → No ac dipole = no optics measurements at top energy

2024

- Suffered from multiple ac dipole issues
- Required amplifier replacements
- **Period with 0 spares**

2025

- All FPGA will be replaced with new systems in YETS
- Amplifiers (being) repaired in Italy
- Should have 3 - 4 spares for 8 amplifiers
(G. Favia JAP'24)

Run 4

- Consolidation efforts ongoing, but no trivial solution
- Wishes in order:
    1. Higher repetition rate
    2. More turns per excitation
    3. More power

Big thanks to everyone involved for quick responses to ac dipole issues!

How much do we use the ac dipole?

2024 commissioning: ~1500 kicks

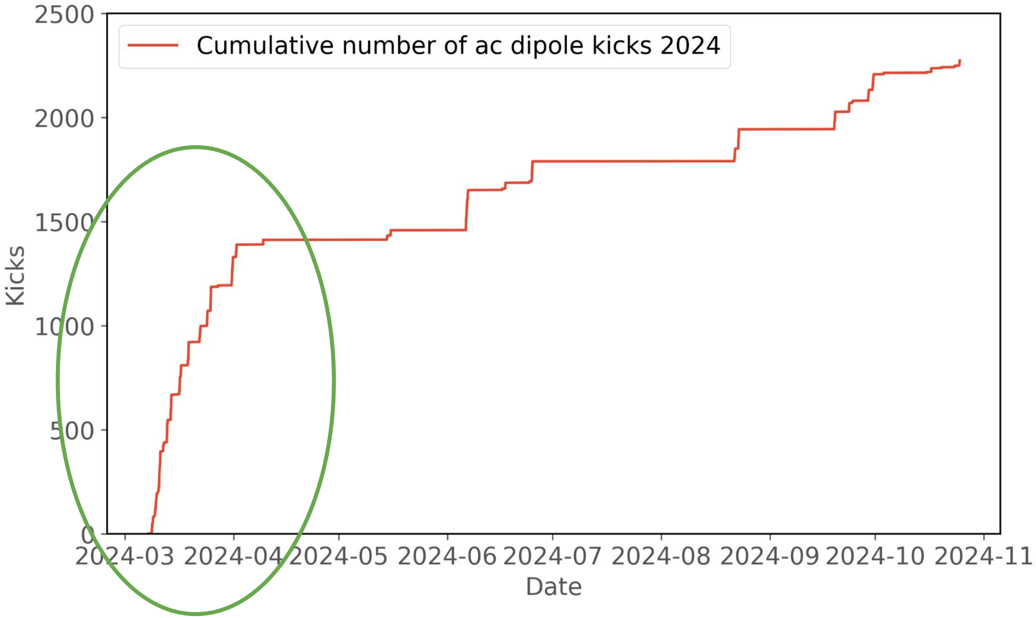
=> 25 hours of waiting

=> 3.1 shifts equivalent

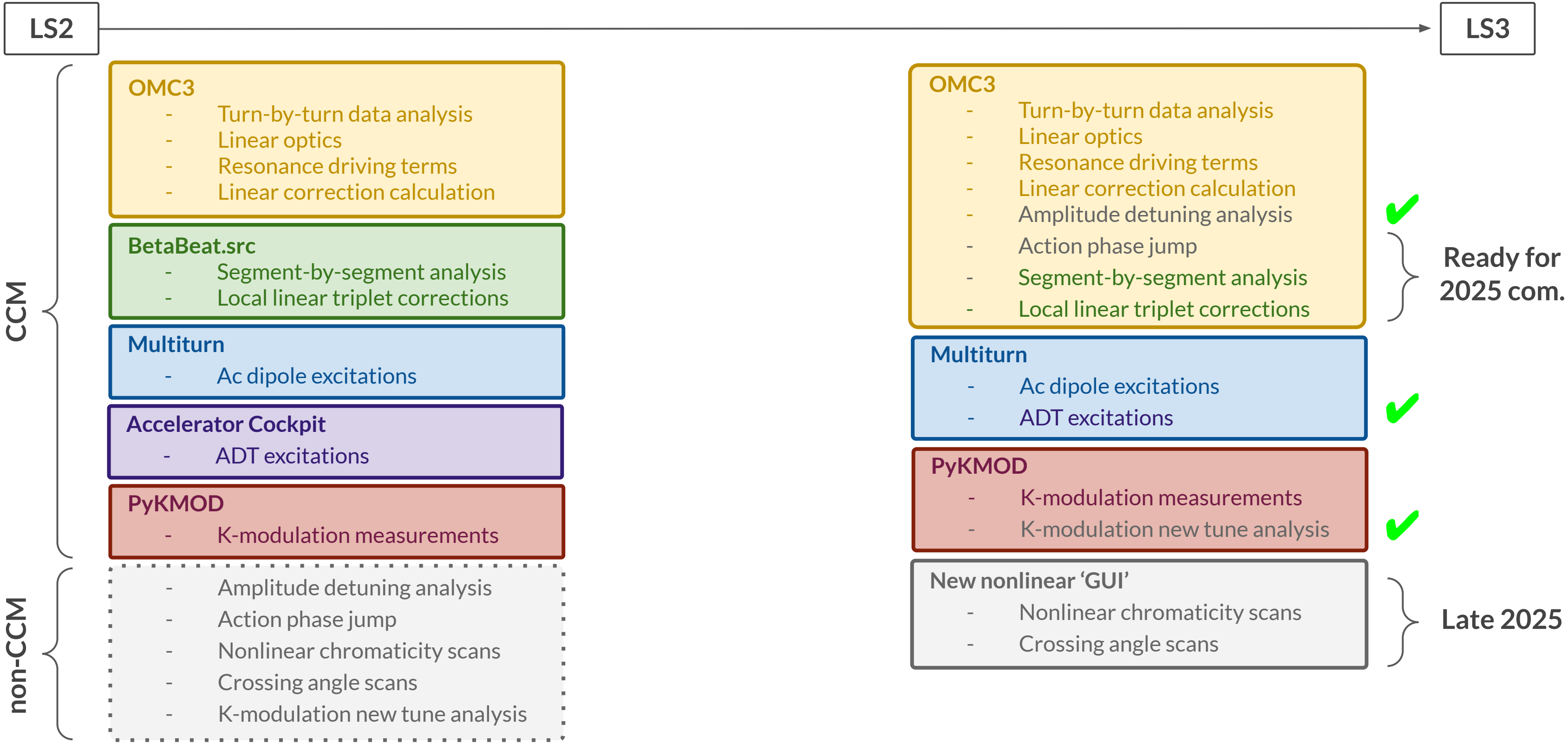
=> 25% of OMC shifts

=> 1 [1/fb]

=> … CHF



Optics measurement & correction tools



LS2 → **LS3**

CCM

OMC3
- Turn-by-turn data analysis
- Linear optics
- Resonance driving terms
- Linear correction calculation

BetaBeat.src
- Segment-by-segment analysis
- Local linear triplet corrections

Multiturn
- Ac dipole excitations

Accelerator Cockpit
- ADT excitations

PyKMOD
- K-modulation measurements

non-CCM

- Amplitude detuning analysis
- Action phase jump
- Nonlinear chromaticity scans
- Crossing angle scans
- K-modulation new tune analysis

OMC3
- Turn-by-turn data analysis
- Linear optics
- Resonance driving terms
- Linear correction calculation
- Amplitude detuning analysis ✓
- Action phase jump
- Segment-by-segment analysis
- Local linear triplet corrections

Ready for 2025 com.

Multiturn
- Ac dipole excitations
- ADT excitations ✓

PyKMOD
- K-modulation measurements
- K-modulation new tune analysis ✓

New nonlinear 'GUI'
- Nonlinear chromaticity scans
- Crossing angle scans

Late 2025

What can be standardized or automated?

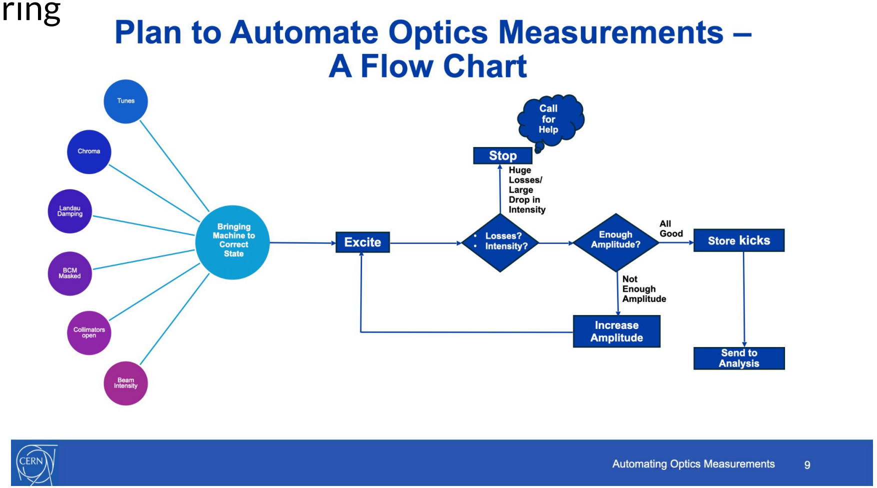
Analysis is mostly expert, but measurements could be standard

Linear optics analysis

- Analysis can be standardized, though interpretation and implementing corrections remains expert

Performing measurements

- ac dipole excitation, amplitude regulation & losses monitoring
- crossing angle scans
- chromaticity scans



Plan to Automate Optics Measurements – A Flow Chart

U. Kar

Conclusions

Good progress in optics measurements across the injector chain

- LEIR optics measurements opens road for improved control in LEIR and ELENA
- Optics measurements help create models with predictive power to simplify operation in PSB & PS

Successful optics commissioning with reversed polarity in IP1

- Successful guessed corrections gives confidence for 2025 commissioning
- Remaining challenges for HL-LHC due to large arc betas
- Important parameters identified to control collimator hierarchy

Nonlinear corrections partially successful

- Measurements limited by forced DA with ac dipole
- In 2025, skew octupole correction strategy, and plan to include LRBB measurements

Automatization of optics measurements is ongoing

- Several important milestones already reached for beam excitations
- Target to have normal optics measurements possible to be done by OP at the beginning of 2025

Contents

Single pass dispersion ions and ALICE background

Background observed in ALICE during ion run

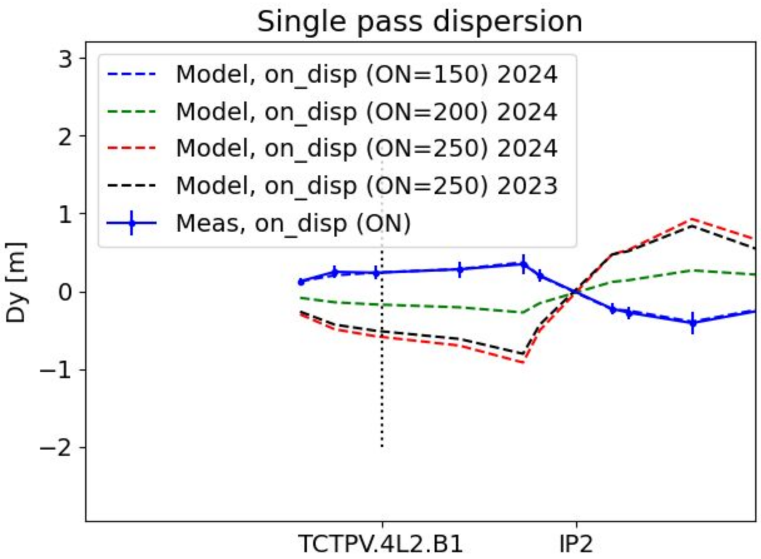
- Secondary ion species created in IR7 follow a dispersive path, hitting TCT in IP2 and creating showers (JAP'23)

Optimization with on_disp knob improves background

- On_disp knob of 150 is nominal in 2024
- 250 was best setting in 2023
- Same optimization yields setting of 200 as optimal

Method available to optimize

- However still unclear why settings are optimal
- Remaining component of background is unrelated



T. Persson