Improving optics control in the LHC with forced RDTs

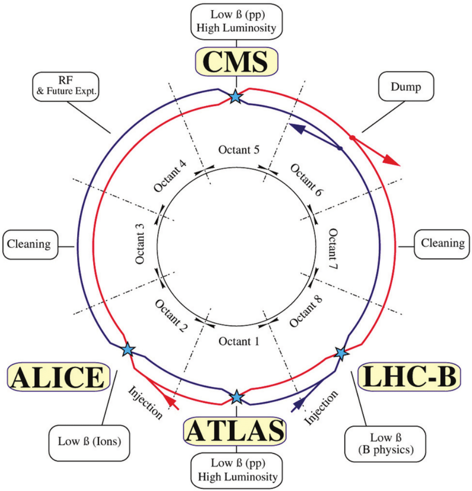
10 October 2025

Sasha Horney

Thanks to E. Maclean, R. Tomás, L. Deniau, the Optics Measurements & Corrections team and the Operations team

LHC

- **27km** twin-ring **synchrotron**



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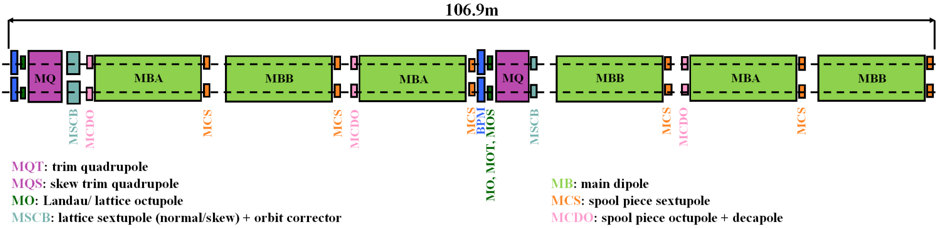

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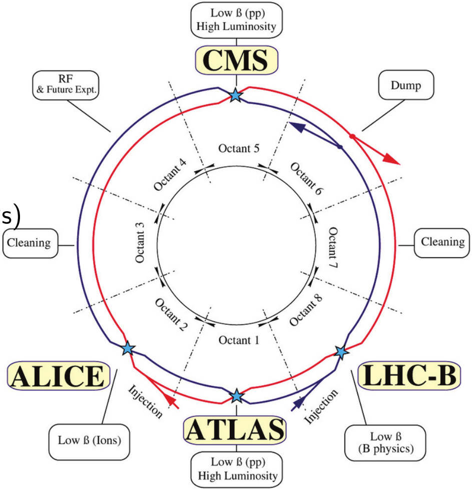
  - ⇒ 4 **low** β **interaction points** (IPs)



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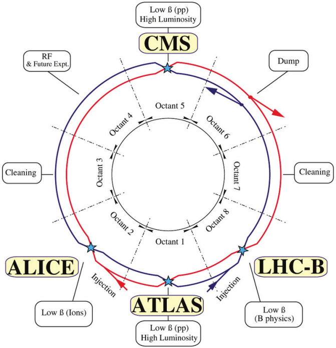

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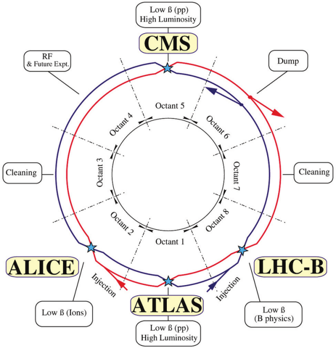

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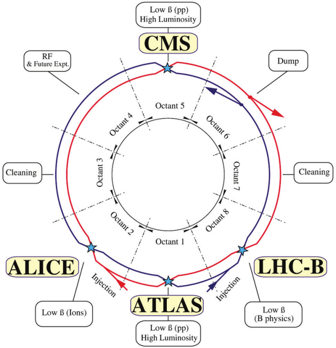

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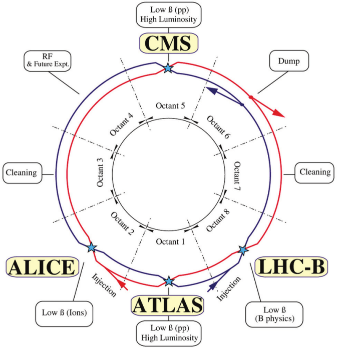

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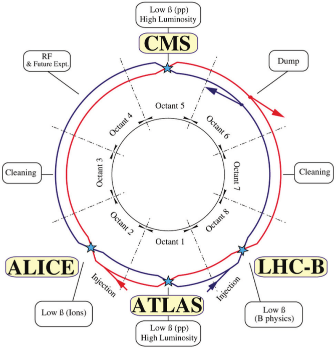

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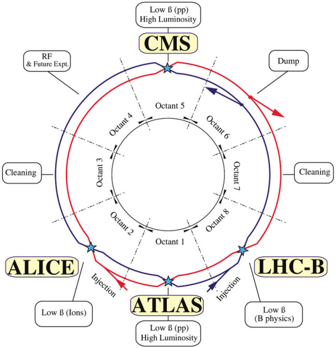

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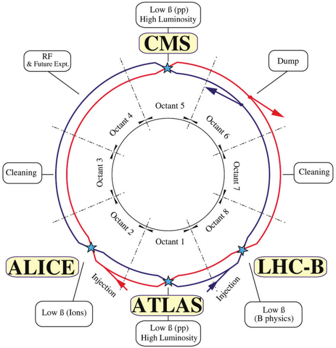
  - ⇒ Improve LHC modelling & understanding of dynamics ∴ impacting **operation** (OP) and design of **future colliders**



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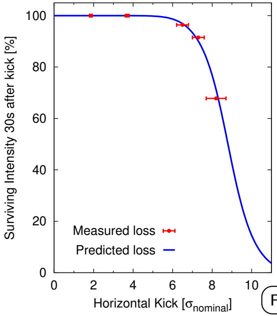
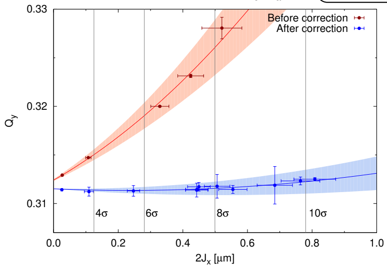
- There have been lots of studies including measurement of observables such as **dynamic aperture**, **amplitude detuning** and **non-linear chromaticity**



From: **E. Maclean**



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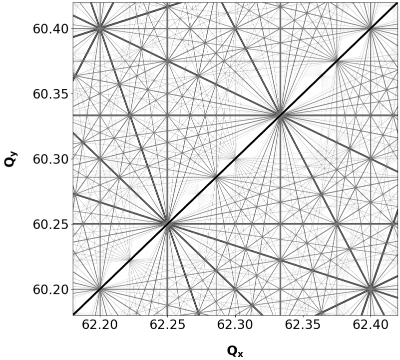

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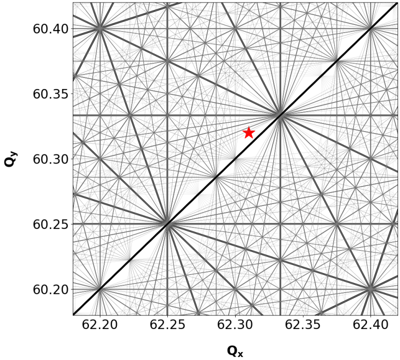

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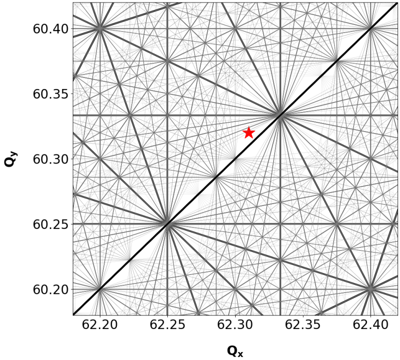
- The **strength** of a resonance can be characterised by a **resonance driving term** (RDT)



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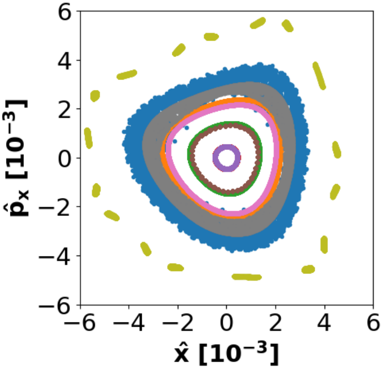

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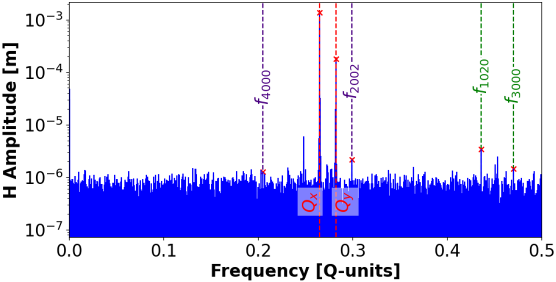

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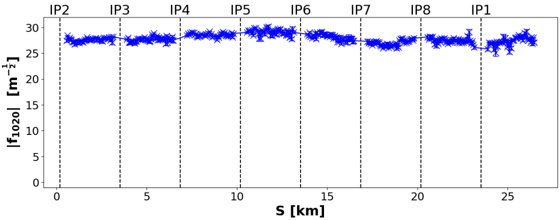
- Amplitude of peak $\propto$ how much particular resonance **perturbs** the beam $\Leftarrow$ an **RDT**



Resonances and RDTs

Resonance	RDT	Magnet type
$Q_x + 2Q_y$	f_{1020}	b_3
$3Q_y$	f_{0030}	a_3
$2Q_x - 2Q_y$	f_{2002}	b_4
$4Q_x$	f_{4000}	b_4
$4Q_y$	f_{0040}	b_4
$-Q_x + 4Q_y$	f_{0140}	b_5

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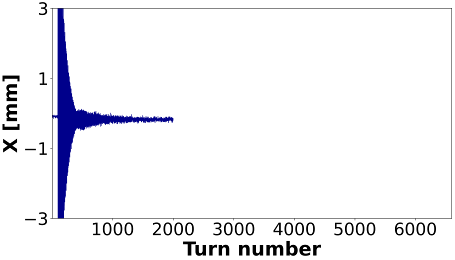

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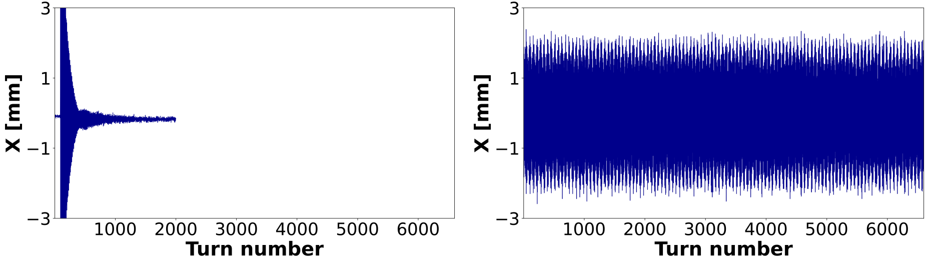

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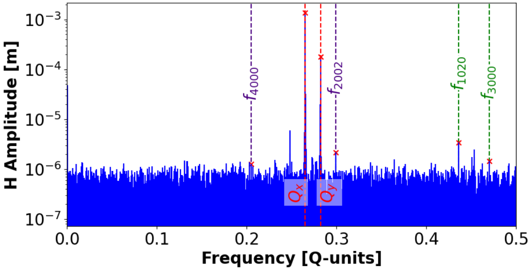

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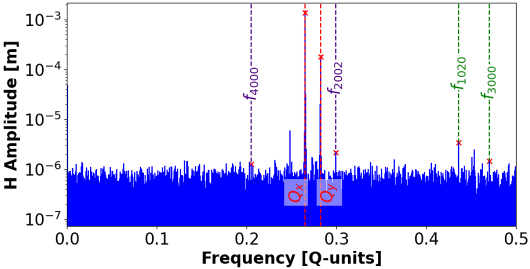

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  - ⇒ A **good spectra**
  - ⇒ **Exact frequency** of lines known
  - ⇒ Can kick **repeatedly** due to **adiabatic** excitations

How do we use RDTs in the LHC?

- E.g. 1: Benchmarking b_4 RDT
- E.g. 2: Correction of b_3 RDT
- E.g. 3: Creating new higher order RDT correction method
- E.g. 4: Long-Range Beam-Beam-driven RDT correction

E.g. 1: Benchmarking b_4 RDT

Landau Octupoles

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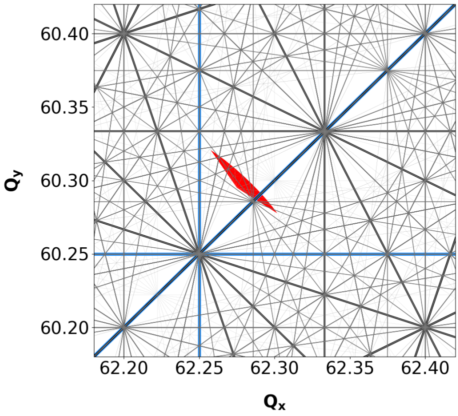
  - ⇒ This effect occurs due to **tune spread** & is in the interest of **overall stability**



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  - ⇒ Will concentrate on f_{2002} RDT since **closest to WP**

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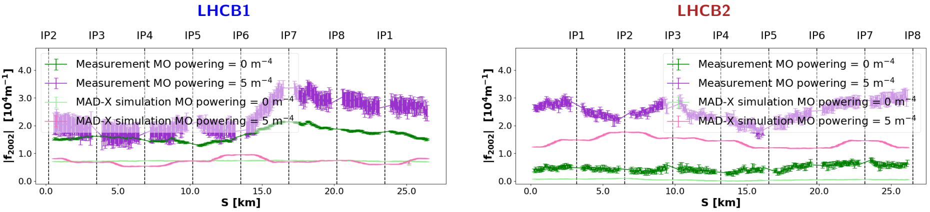
- To check this was working as expected **benchmarking** of measurements was required, looking @ f_{2002} **RDT response** to **MO powering**
  - ⇒ Found that RDT amplitude shows a **large discrepancy**, especially for **LHCB2**...



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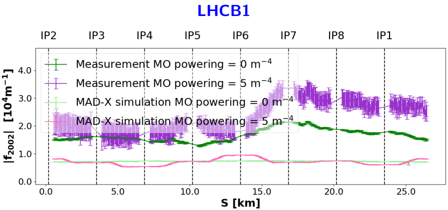
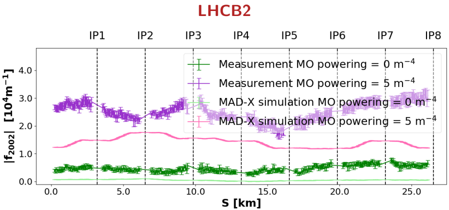
- Is it **real**? Could an MO circuit be **faulty**...?





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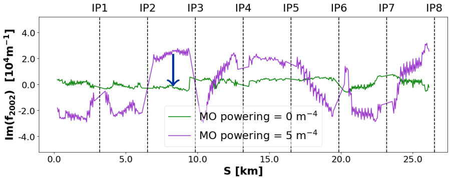

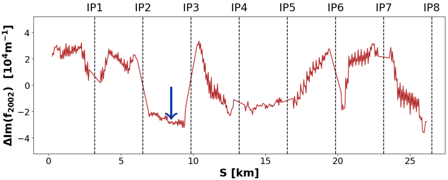

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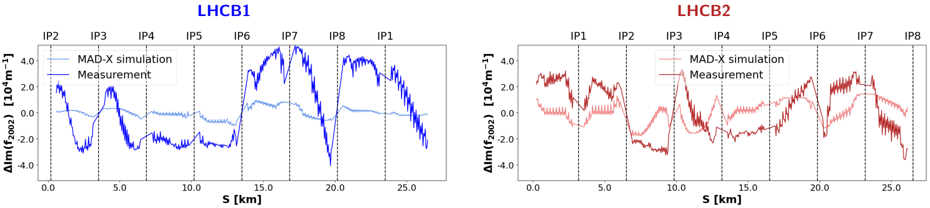

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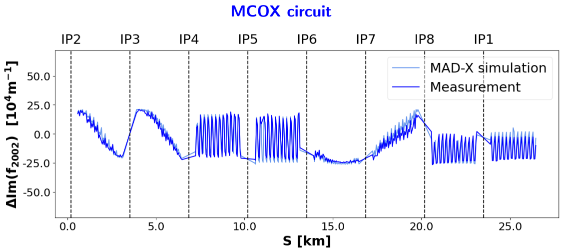
- Need to **find source** since **accurate modelling** of octupolar resonances needed for **many** different studies...

Finding the b_4 error source

- Perhaps an **analysis tools issue** ∴ tested another circuit @ top energy
  - ⇒ **Simulation matched measurement**



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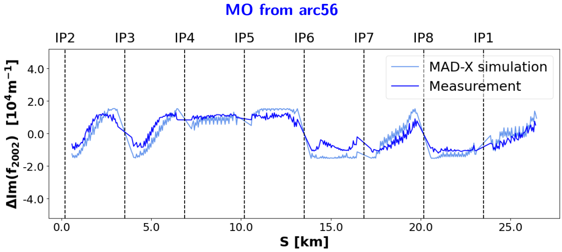

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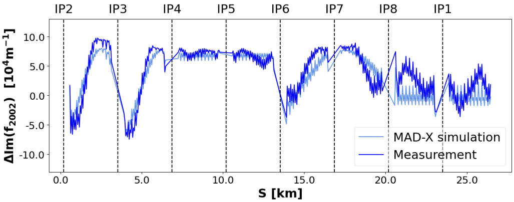

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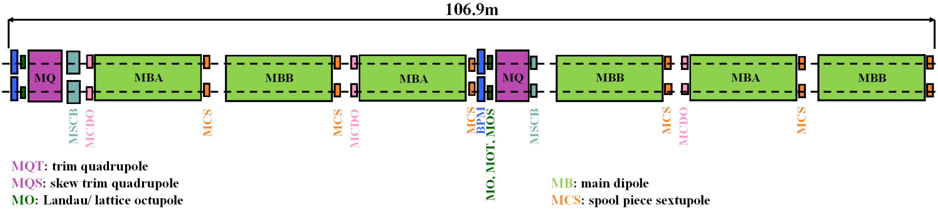
- Current hypothesis: **hysteresis issue** significant only @ injection energy for **certain** MO circuits

E.g. 2: Correction of b_3 RDT

Correction of b_3 RDT

- At **injection energy** there are **2 main sources** of b_3:



MQT: trim quadrupole
MQS: skew trim quadrupole
MO: Landau/ lattice octupole
MSCB: lattice sextupole (normal/skew) + orbit corrector

MB: main dipole
MCS: spool piece sextupole
MCDO: spool piece octupole + decapole

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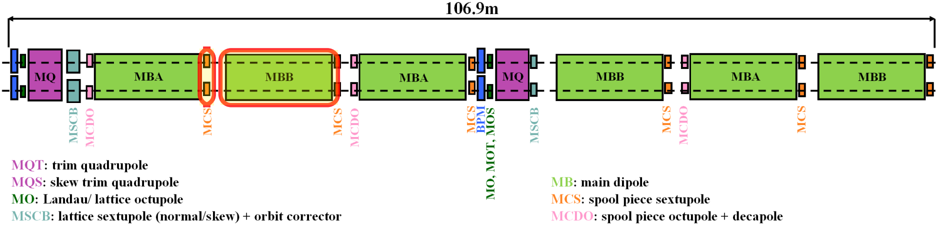

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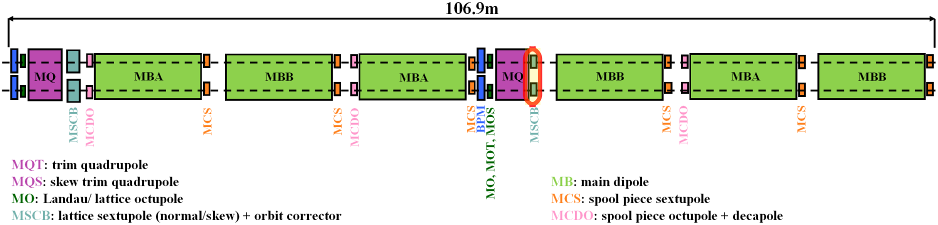
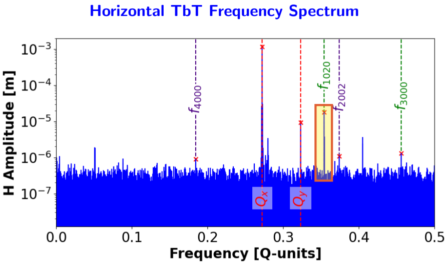
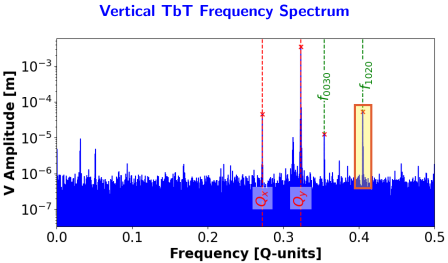
  - ⇒ One of them is errors coming from **superconducting dipoles** - these are **corrected** using **sextupole correctors** mounted on the ends of them
  - ⇒ The other is the **lattice sextupoles** (MS) - there to **modulate chromaticity**



Correction of b_3 RDT

- Interestingly, when looking @ TbT spectrums - **largest perturbation** was from **normal sextupole**.





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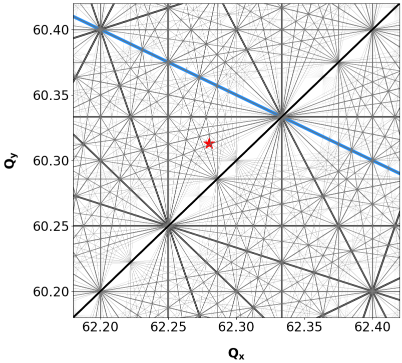

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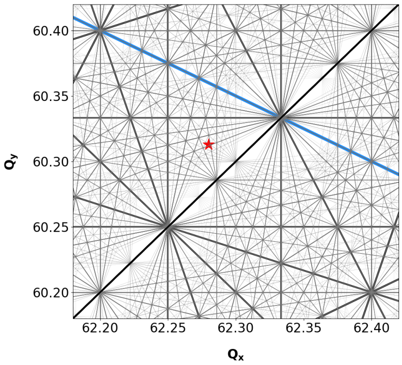
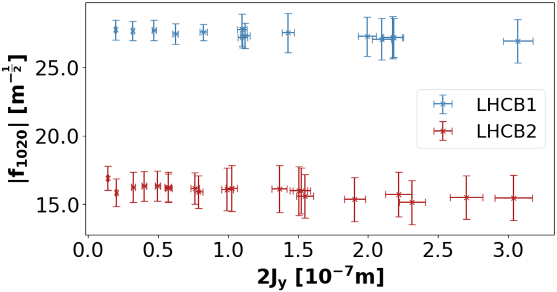


Correction of b_3 RDT

- RDT magnitude **constant** w/ kick amplitude



Correction of b_3 RDT

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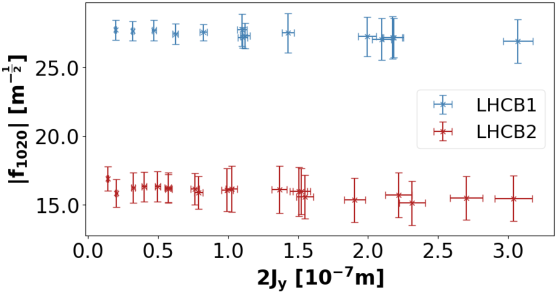
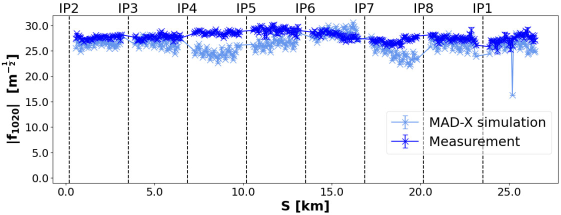
    - ⇒ LHCB1 > LHCB2 ∴ will **concentrate** on **LHCB1**



Correction of b_3 RDT

- RDT magnitude **constant** w/ kick amplitude
- Initially thought $\boldsymbol{b_3}$ **error correction** was **not working properly** $\Rightarrow$ **comparison** to **simulation** $\Rightarrow$ **good agreement** w/ simulation



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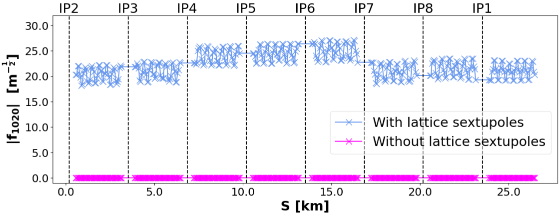
- Initially thought $\boldsymbol{b_3}$ **error correction** was **not working properly** $\Rightarrow$ **comparison** to **simulation** $\Rightarrow$ **good agreement** w/ simulation
- **Comparison** of **model w/** and **w/o** the **MS** $\Rightarrow$ they were **main drivers** of resonance



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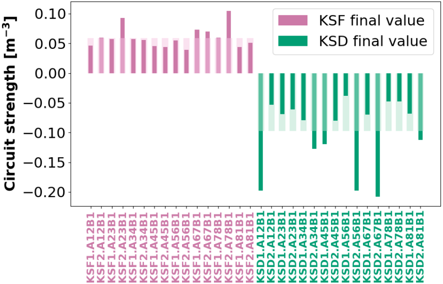

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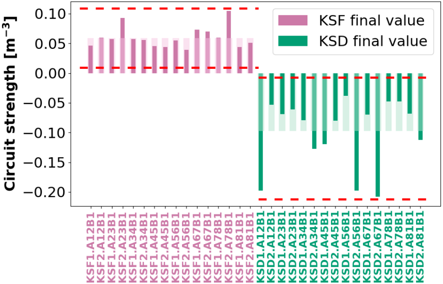

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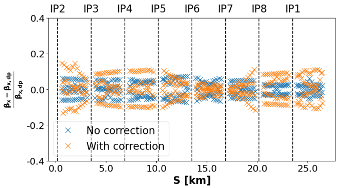
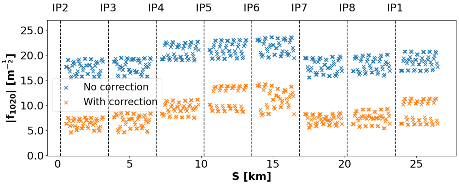
  - ⇒ Some **manual adjustments** were required to **not** induce **large chromatic β-beating**.

MAD-NG horizontal β-beating



MAD-NG f_{1020} RDT amplitude



Measuring b_3 correction

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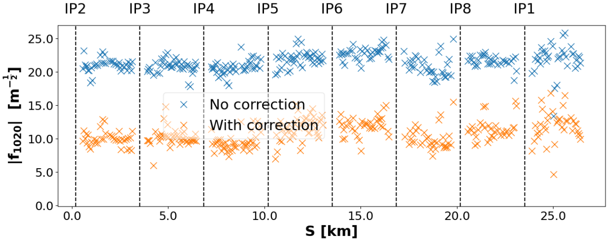

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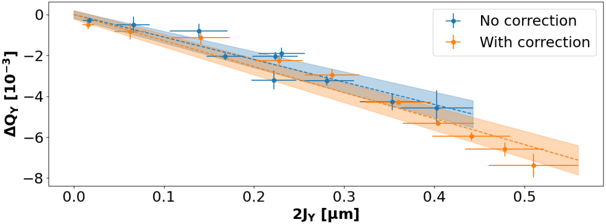

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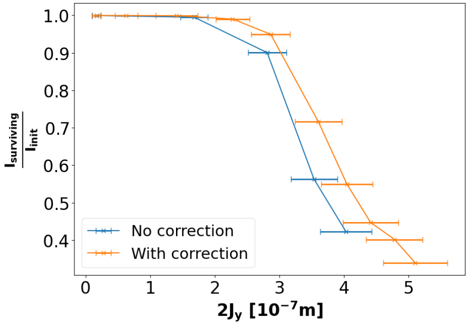

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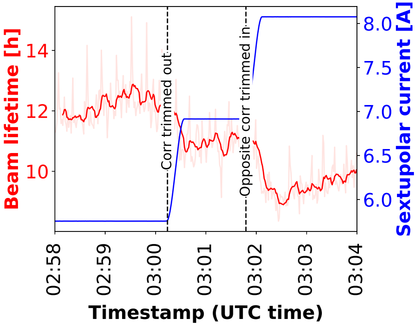

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- This was put into **operation** throughout **2024**

E.g. 3: New method to locally correct higher order errors in low-β insertion

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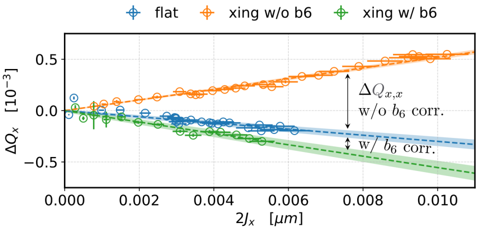

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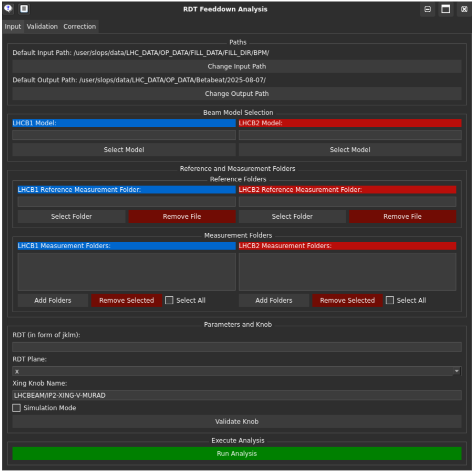
- **Feed-down** from **higher order errors** e.g. a_4, b_5 etc. can also result in **magnitude increase** of **lower order RDTs** when **crossing angles** are applied on orbit
- Due to this, an alternative, explored this year for **first time**, was to look @ **RDT feed-down** from higher order errors

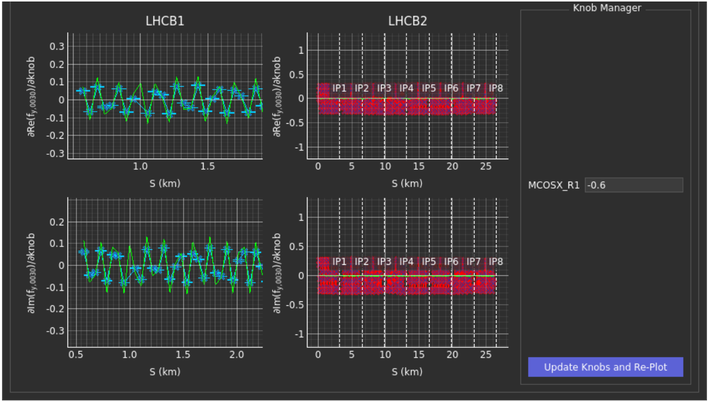
Creating the new RDT correction

- In order to carry this out a **new GUI** was created...



Creating the new RDT correction

- In order to carry this out a **new GUI** was created...
- This enabled **quick matching** of **measured RDT response** to **crossing angle** w/ RDT response to **corrector(s)** w/ **crossing angle** in **simulation**



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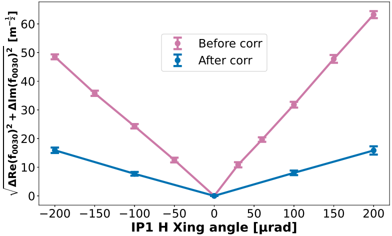
- Reduced change in $3Q_y$ as function of **crossing angle** using skew octupole corrector in **ATLAS insertion**



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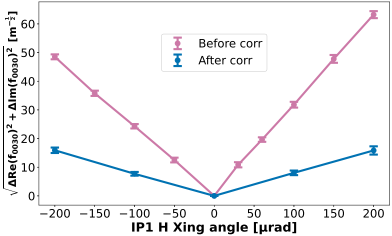

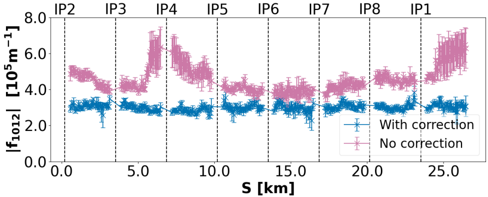

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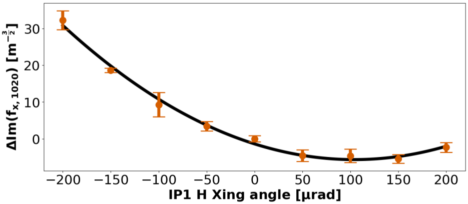

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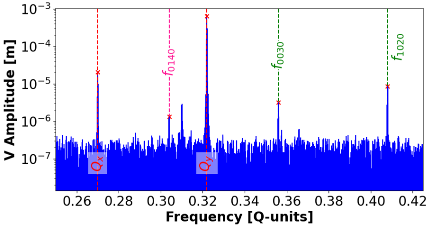
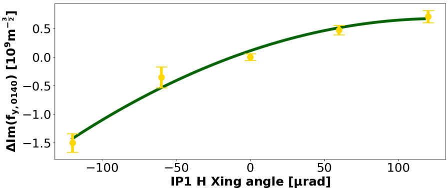
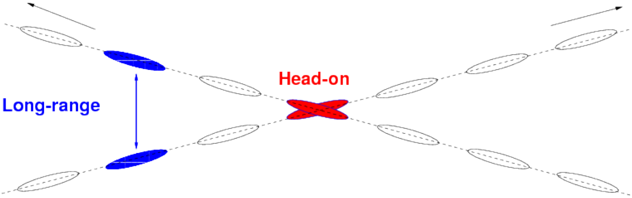
- Also, see a **linear variation** of strength coming from **1st order feed-down** from **dodecapole** error & potential $\boldsymbol{b_7}$ **or higher order** contribution feeding down to **quadratic** relation for **normal decapolar resonance** (f_{0140})





E.g. 4: Long-Range Beam-Beam-driven RDT correction



From: W. Herr

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- Therefore, **direct beam-based studies** of the impact on **optics** was of interest

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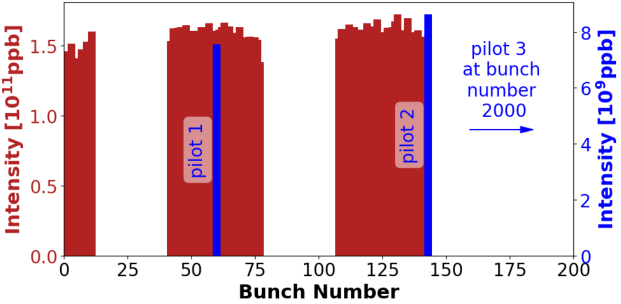

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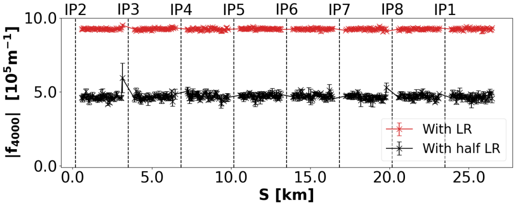
- This has also been carried out in **2025**



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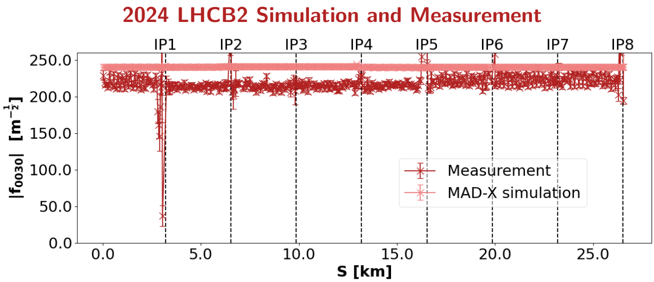
- **2024 direct measurement** showed very **good agreement** w/ simulation
  - ⇒ Model-based corrections seem **appropriate**



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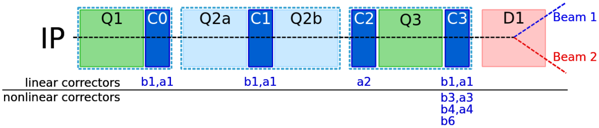

From: J. Dilly's PhD Thesis

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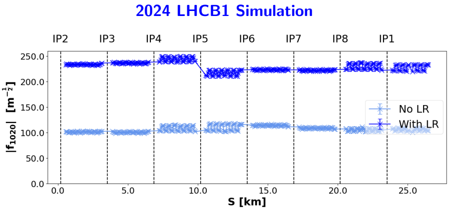

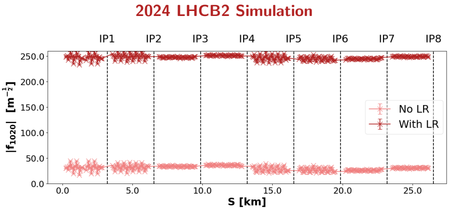

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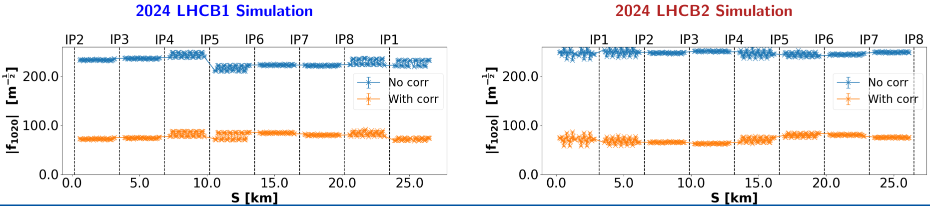

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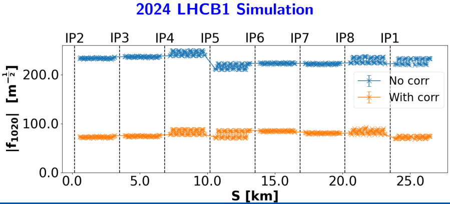

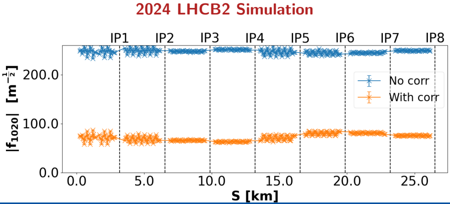

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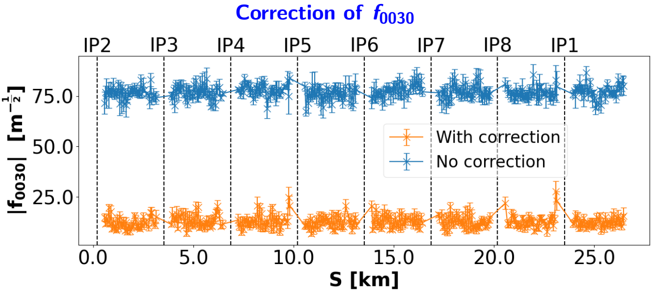

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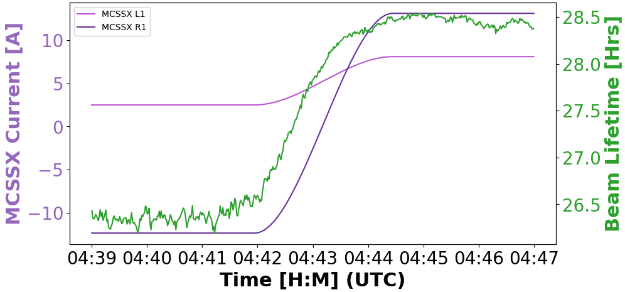
- Does reducing RDT correspond to anything? Should **increase lifetime**...



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- From this, **direct corrections** can be found for specific resonances
- Also, can be used to study & **correct high order errors** in IPs by measuring **feed-down** to lower order RDTs
- Can also go **beyond** traditional **single-particle** optics to study resonances driven by e.g. **beam-beam**

Thanks for your attention!
Any questions?

CERN