Updates on the impact of fringe fields on corrector strength

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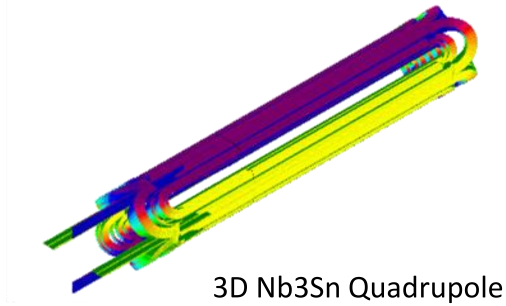
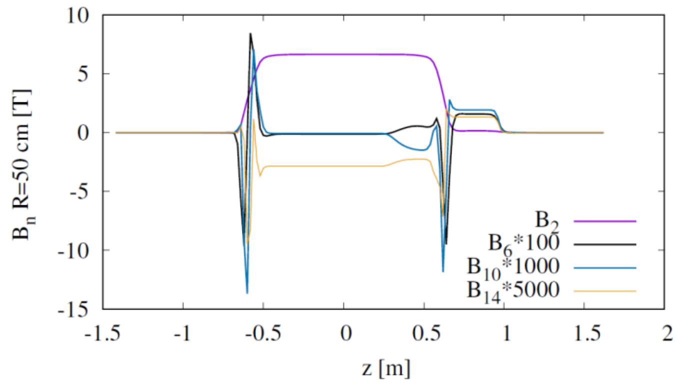
Outlook

- Recap 166th HL-LHC WP2 meeting presentation
- HL-LHC:
  - Update of impact of fringe fields on b_6 correction for optics v1.4 and new b_6 value
- LHC:
  - Update impact of fringe fields on b_4 correction in LHC
  - Impact of fringe fields on b_6 correction in LHC
- Summary and open questions

What we want to evaluate



3D Nb3Sn Quadrupole
Simulated with ROXIE
Courtesy of CERN magnets group

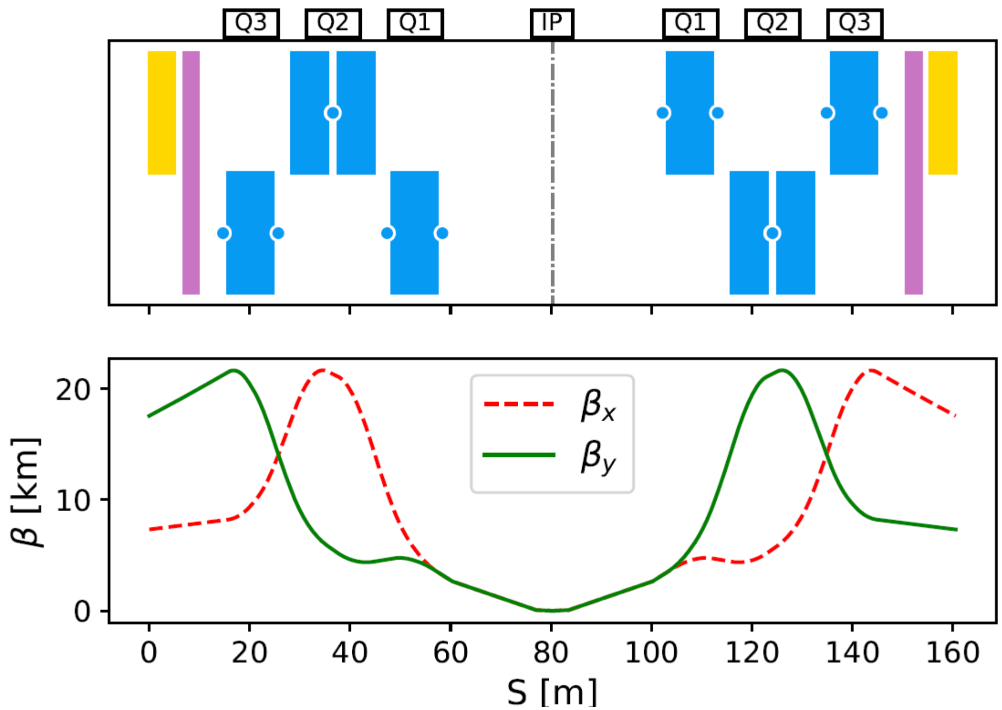


- Part of systematic non linear field is concentrated in the magnet extremities

⇒ Accurate and efficient modeling of the magnet field extremities required to see their effects on the beam

⇒ In the High Luminosity IRs the variation of the beta function along a single magnet is not small, the longitudinal distribution of field errors may impact beam based quantities

⇒ Aim: improve our capability to correct non-linear effects hence the stability of future accelerators



3D Field representation

- Field Harmonics

$$B_r(R,\phi,z) = \sum_{m=1}^{\infty} B_m(R,z)\sin(m\phi) + A_m(R,z)\cos(m\phi)$$

- Generalized Gradient for normal multipole

$$C_m^{[l]}(z) = \frac{i^l}{2^m m!\sqrt{2\pi}} \int_{-\infty}^{\infty} \frac{e^{ikz} k^{m+l-1}}{I'_m(kR)} \tilde{B}_m(R,k)\,dk$$

- 3D Vector Potential for normal multipole

$$A_x^m = \frac{x}{m}\Re[\,(x+iy)^m] \sum_{l=0}^{\infty} \frac{(-1)^l m!}{2^{2l} l!\,(l+m)!} \underline{C_m^{[2l+1]}}(z)(x^2+y^2)^l$$

$$A_y^m = \frac{y}{m}\Re[\,(x+iy)^m] \sum_{l=0}^{\infty} \frac{(-1)^l m!}{2^{2l} l!\,(l+m)!} \underline{C_m^{[2l+1]}}(z)(x^2+y^2)^l$$

$$A_z^m = -\frac{1}{m}\Re[\,(x+iy)^m] \sum_{l=0}^{\infty} \frac{(-1)^l m!\,(2l+m)}{2^{2l} l!\,(l+m)!} \underline{C_m^{[2l]}}(z)(x^2+y^2)^l$$

HE approximation for normal multipole

$$A_z^m = \frac{1}{m} B_m \Re[\,(x+iy)^m]$$

Non-linear maps

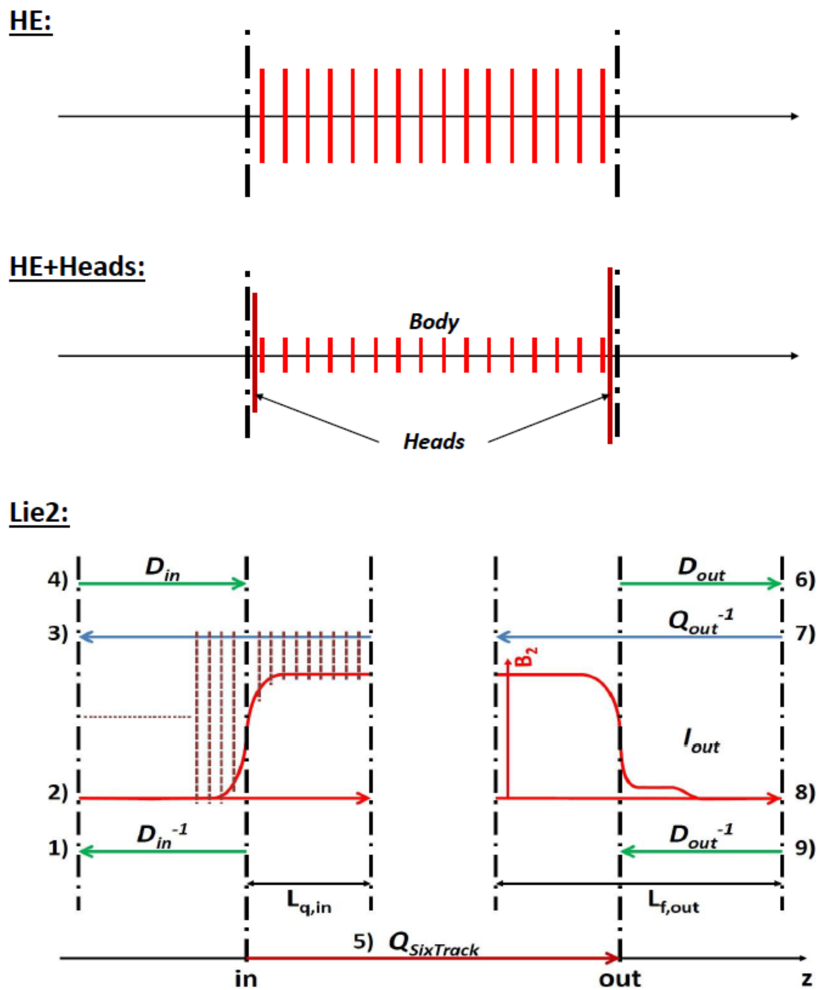
HE (Hard Edge): 16 Drifts and Kicks of equal multipolar integrated strength.

HE+Heads: Similar to HE but with a part of the total integrated strength in additional Kicks in the two extremities, respecting the connector (CS) and non connector (NC) side

Lie2: Non-linear transfer map from Lie algebra. The extremities are modeled by computing the 3D vector potential with step of 2cm:

- **ND0**: Only pure harmonics in the Quadrupole.
- **ND6**: with up to the 6^{th} derivatives of the generalized gradients.

Lie2 model has been developed at CEA and integrated in SixTrack



For details of Lie2 non-linear transfer map see T. Pugnat @ 122^{nd} HL-LHC WP2 meeting

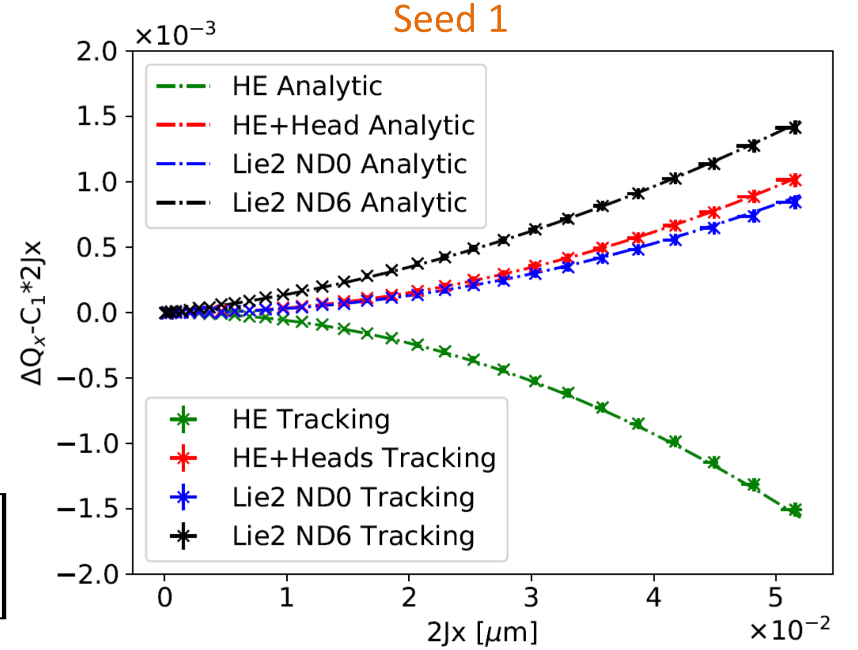
Direct amplitude detuning

Thomas Pugnat @ 166th HL-LHC WP2 meeting

HLLHC v1.0 optics
IT errors tables v5
Seed 1

$$\Delta Q_x = \frac{1}{2\pi}\sum_i \left[\frac{3}{8}\left(\beta_x^2 \overline{b_4}\right)_i (2J_x) + \frac{5}{16}\left(\beta_x^3 \overline{b_6}\right)_i (2J_x)^2\right]$$

$$\Delta Q_x = \frac{1}{2\pi}\sum_i \left[\frac{3}{8}\left(4\beta_x^2 C_4^{[0]} + 2\beta_x\alpha_x C_2^{[1]} - \frac{2}{3}\beta_x^2 C_2^{[2]}\right)_i (2J_x) + \frac{5}{16}\left(6\,\beta_x^3 C_6^0 + \frac{3}{2}\beta_x^2\alpha_x C_4^{[1]} - \frac{9}{20}\beta_x^3 C_4^{[2]}\right)_i (2J_x)^2\right]$$



In the plot: amplitude detuning with b_2 and b_6 harmonics only:

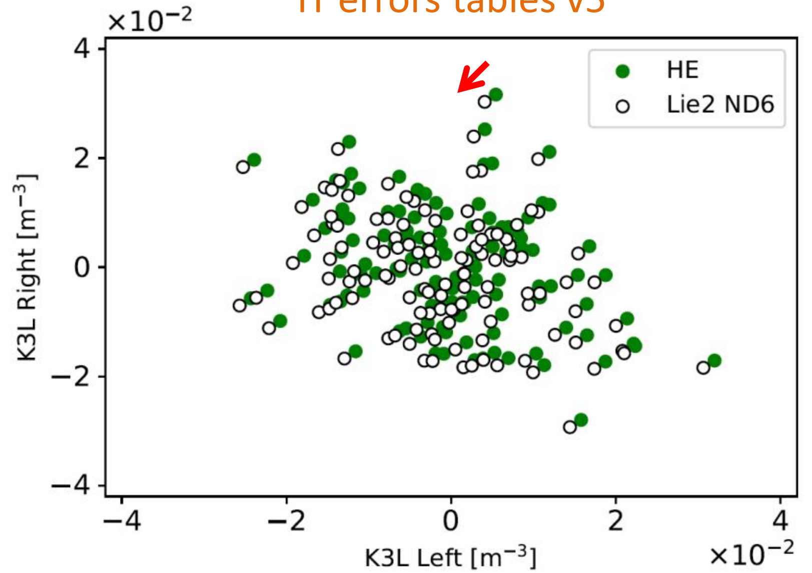
- 1st and 2nd order detuning well reproduced by analytic computation
- **HE+heads** is a good approximation of Lie2 map, but do not account for effects due to gradients derivatives

Octupole correctors strength

Thomas Pugnat @ 166th HL-LHC WP2 meeting

HLLHC v1.0 optics
IT errors tables v5

$$\Delta Q_x = \frac{1}{2\pi}\sum_i \Bigg[\frac{3}{8}\left(4\beta_x^2 C_4^{[0]} + 2\beta_x\alpha_x C_2^{[1]} - \frac{2}{3}\beta_x^2 C_2^{[2]}\right)_i (2J_x) + \frac{5}{16}\left(6\,\beta_x^3 C_6^0 + \frac{3}{2}\beta_x^2\alpha_x C_4^{[1]} - \frac{9}{20}\beta_x^3 C_4^{[2]}\right)_i (2J_x)^2 \Bigg]$$



$$\begin{pmatrix} K_{n,Left}L \\ K_{n,Right}L \end{pmatrix} = -\begin{pmatrix} \beta_{x,Left}^{n/2} & \beta_{x,Right}^{n/2} \\ \beta_{y,Left}^{n/2} & \beta_{y,Right}^{n/2} \end{pmatrix}^{-1} \sum_{s\in IR} K_{n,s}L_s \begin{pmatrix} \beta_{x,s}^{n/2} \\ \beta_{y,s}^{n/2} \end{pmatrix}$$

- First and second derivative of the main quadrupole field provide a systematic shift in the integrated octupole corrector strength (K3L)
- The shift is ~4% with respect to octupole correctors specification (IPAC13 WEPEA048)

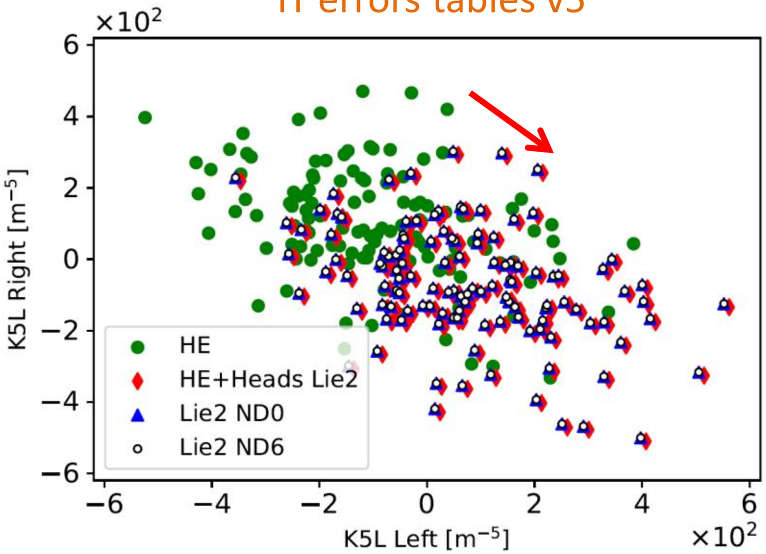
Dodecapole correctors strength (1/2)

Thomas Pugnat @ 166th HL-LHC WP2 meeting

HLLHC v1.0 optics
IT errors tables v5

$$\Delta Q_x = \frac{1}{2\pi}\sum_i \left[\frac{3}{8}\left(\beta_x^2 \overline{b_4}\right)_i (2J_x) + \frac{5}{16}\left(\beta_x^3 \overline{b_6}\right)_i (2J_x)^2\right]$$

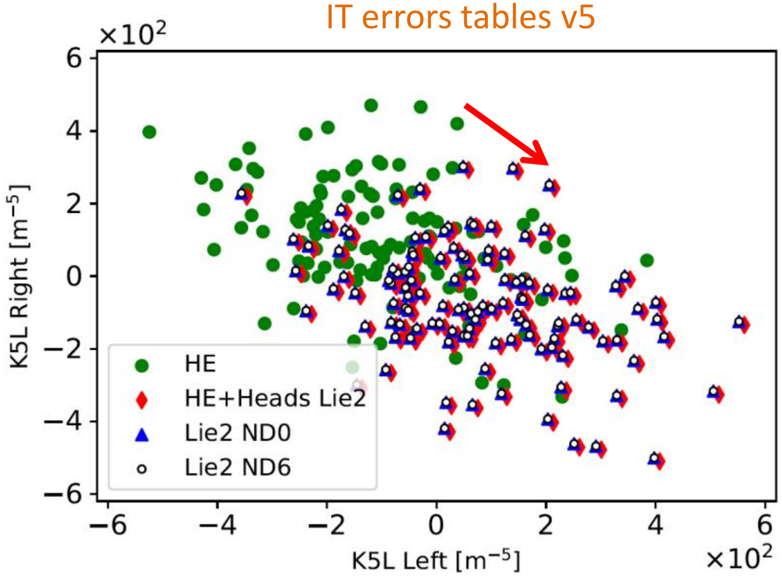
$$\Delta Q_x = \frac{1}{2\pi}\sum_i \left[\frac{3}{8}\left(4\beta_x^2 C_4^{[0]} + 2\beta_x\alpha_x C_2^{[1]} - \frac{2}{3}\beta_x^2 C_2^{[2]}\right)_i (2J_x) + \frac{5}{16}\left(6\,\beta_x^3 C_6^0 + \frac{3}{2}\beta_x^2\alpha_x C_4^{[1]} - \frac{9}{20}\beta_x^3 C_4^{[2]}\right)_i (2J_x)^2\right]$$



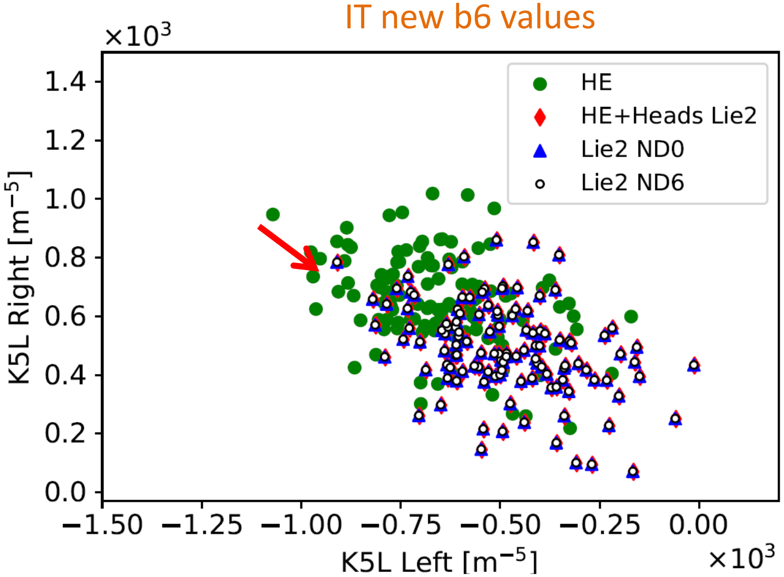
- b6 longitudinal distribution along the inner triplet quadrupoles provides a systematic shift in the integrated dodecapole corrector strength (K5L)
- The shift is ~13% with respect to correctors' specification (IPAC13 WEPEA048)
- **HE+heads** is a good approximation of the more accurate Lie2 calculation (…gradient derivatives more than 2nd have negligible impact…)

Dodecapole correctors strength (2/2)

HLLHC v1.0 optics
IT errors tables v5



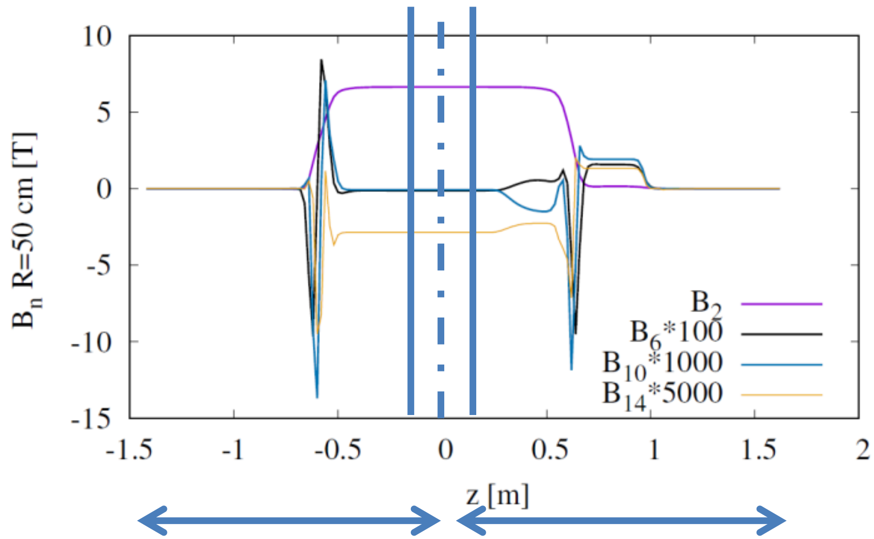
HLLHC v1.4 optics
IT new b6 values



The shift with respect to correctors' specification changes from ~13% to ~11%
The shift with respect to correctors' specification due to the optic version is ~ 1%

HE+Heads Lie2

HL-LHC MQXF prototype



Longer magnets has same Heads of prototype with longer body

Heads: Non Connector

$$L_{nc} = \int_{-1.42}^{0} \frac{B_2}{B_{2,max}} dz$$

$$L_{cs} = \int_{0}^{1.62} \frac{B_2}{B_{2,max}} dz$$

Connector Side

$$\overline{b_{6,nc}} = \int_{-1.42}^{0} \frac{B_6}{B_{2,max} L_{nc}} dz$$

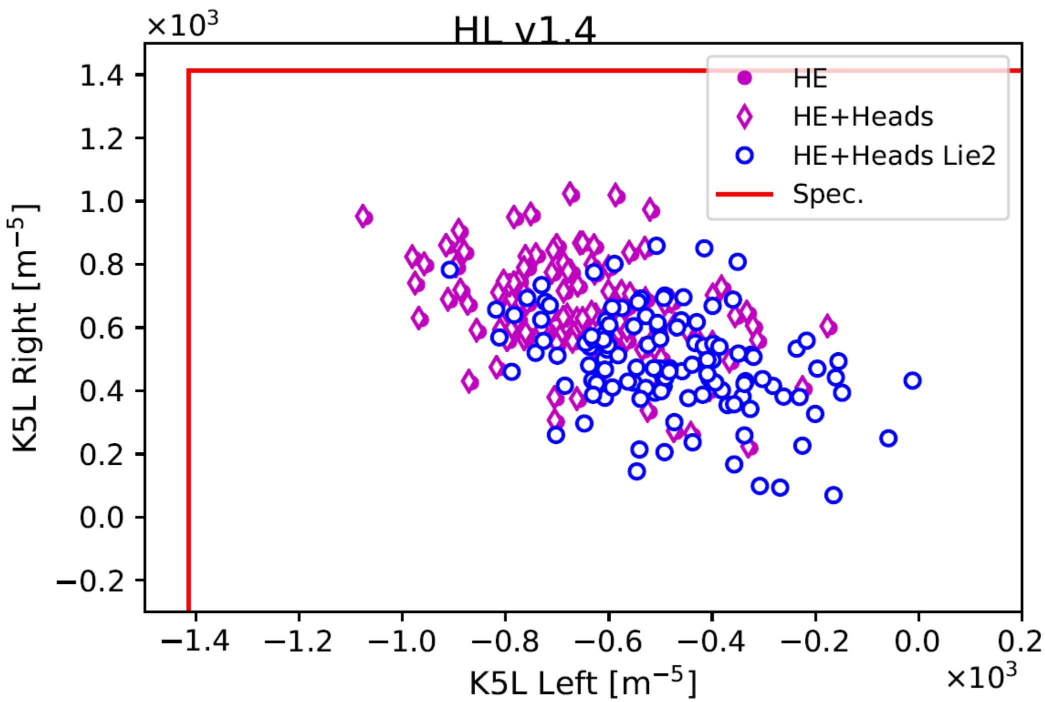
$$\overline{b_{6,cs}} = \int_{0}^{1.62} \frac{B_6}{B_{2,max} L_{cs}} dz$$

$$L_{mqxf}\overline{b_{6,mqxf}} = L_{body}\overline{b_{6,body}} + L_{cs}\overline{b_{6,cs}} + L_{nc}\overline{b_{6,nc}}$$

HE+Heads vs HE+Heads Lie2

b6	NC (0.581 m) [units]	CS (0.62 m) [units]
HE+Heads Lie2	-1.0303	4.8663

b6	NC (0.341 m) [units]	CS (0.4 m) [units]
HE+Heads	-0.0250	8.943



- HE+Heads converges to HE calculation of the correctors strength (<1% difference from HE)
- HE+Heads Lie2 converges to the calculation of the correctors strength done with 2 cm sampled harmonics in the heads (~ 11% difference from HE)

⇒ How the magnet is divided into Heads + Body change correctors strength evaluation

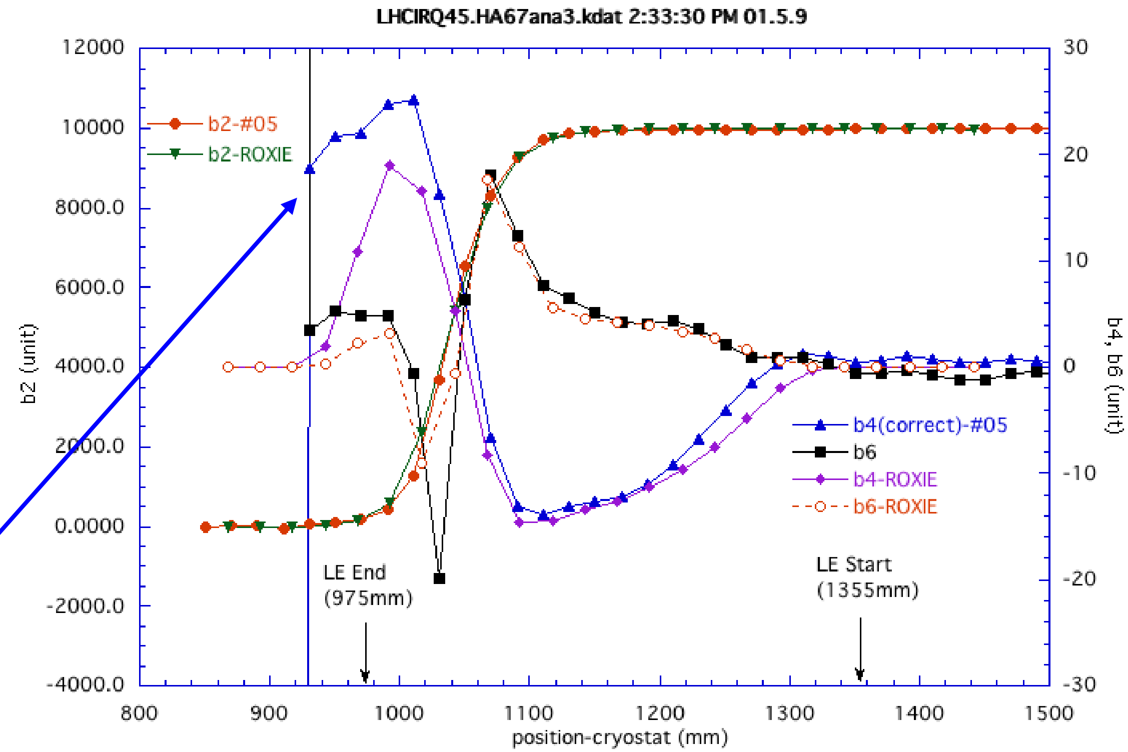
WHAT ABOUT LHC ?

MAGNETIC MEASUREMENTS: LHC

NbTi quadrupole (MQXA)

- 2 cm step for the longitudinal harmonics measurements of one head
- Systematic b_4 presents in both ROXIE model and measurements (for us, it would be better to measure until the field harmonics are zero on the axis)

No similar data or model available for the NbTi **MQXB** type of magnet



Courtesy of Tatsu Nakamoto

For difference between MQXA and MQXB design see Ezio talk WP2 172th meeting, 7th April 2020

Recap impact of Fringe Field on b_4 correction in LHC

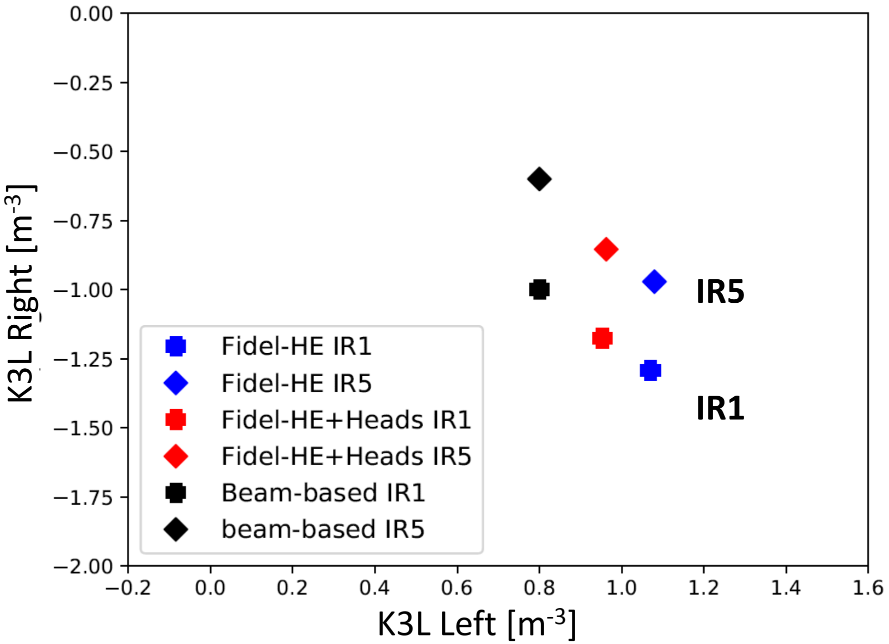
Thomas Pugnat @ 166th HL-LHC WP2 meeting

Measured Integrated b_4 [units]

	Q1	Q2a	Q2b	Q3
IR1L	1.13	0.350	0.230	1.37
IR1R	1.26	0.267	0.042	1.38
IR5L	1.27	0.168	-0.005	1.30
IR5R	1.21	0.286	0.126	1.39

Q1/Q3 (MQXA)

b4	NC (0.62 m) [units]	CS (0.34 m) [units]
HE+Heads	2.07 (0.14)	1.17 (0.14)

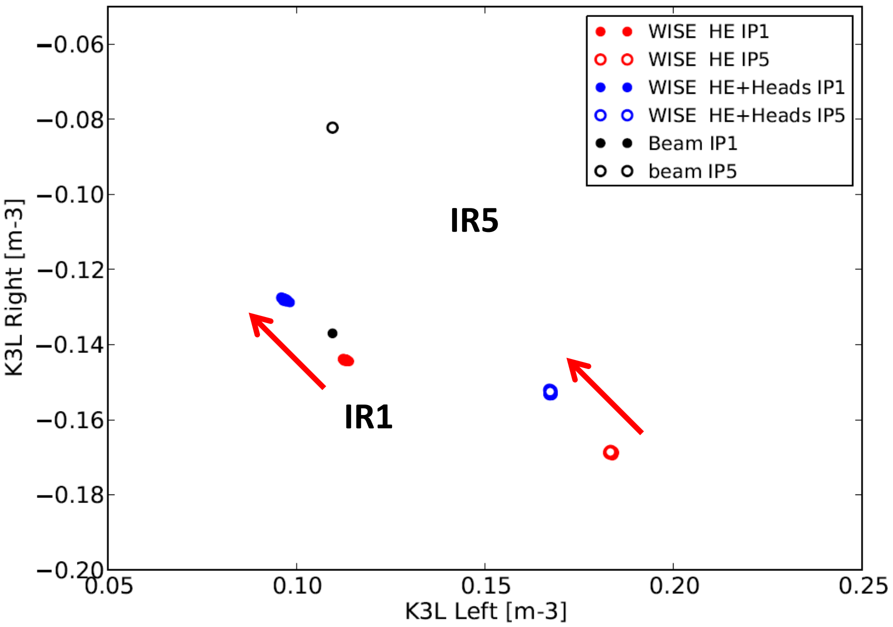


Beam-based values courtesy of E. Maclean

- Data from https://lhc-div-mms.web.cern.ch/lhc-div-mms/tests/MAG/Fidel/
- Beam Screen (BS) contribution missing (see Ezio talk @ 172nd HL-LHC WP2 meeting)!

Update impact of MQXA Heads on b_4 correction LHC

- **WISE** values for the total integrated b_4 (MQXA & MQXB), which include BS contribution
- The BS contribution of MQXA is approximately assumed to go entirely in the body



- Reduction of the discrepancy with beam based values for IR5
- Slight increase in the discrepancy with beam based values for IR1

$\Rightarrow$ It doesn't help to solve the puzzle of b_4

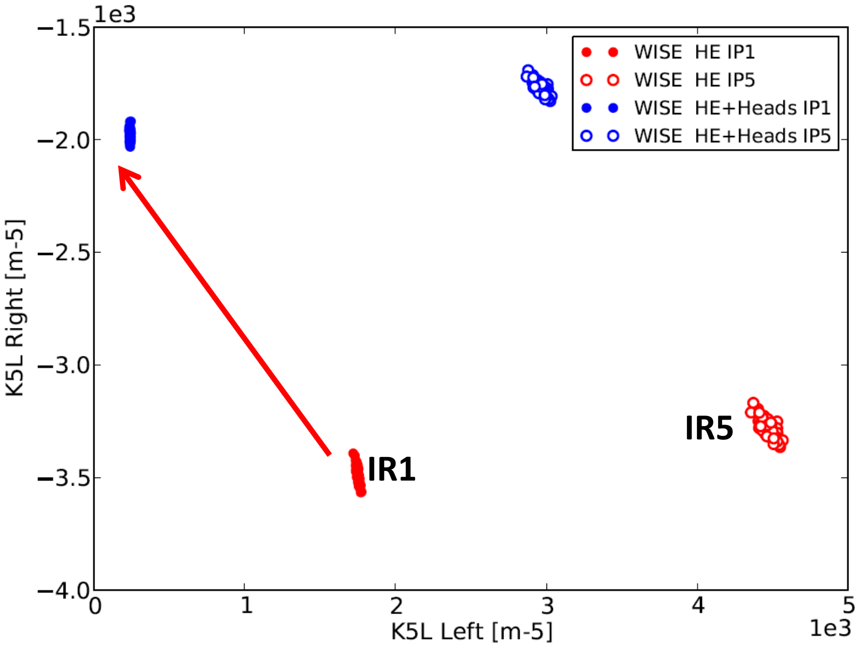
Impact of MQXA Heads on b_6 correction in LHC

- **WISE** values for the total integrated b_6 (MQXA & MQXB)

Q1/Q3 (MQXA)

b_6	NC (0.62 m) [units]	CS (0.34 m) [units]
HE+Heads	2.59 (0.10)	-0.54 (0.10)

https://lhc-div-mms.web.cern.ch/lhc-div-mms/tests/MAG/Fidel/



Big impact of longitudinal distribution of b_6 in MQXA on correctors strength calculation
$\Rightarrow$ difficult to predict a precise value

Summary and Open questions

- 3D representation of the main field and errors of the inner triplet impacts the non linear correctors strength computation
- **HL-LHC:**
  - main field derivatives have small impact on b_4 correction (~4%)
  - The impact of the longitudinal distribution of b_6 can be well approximated by splitting the magnet in 2 Heads + Body and it results in a shift of ~ 11% for HL-LHC optic 1.4 and $b_{6,body}$ =-4 units (but depends on the definition of the Body and Heads)
  - Accurate measurements of the longitudinal harmonics are important when comparing accelerators models with beam based values, in particular of the not allowed ones (b_3,b_4,b_5, etc for quad), for which no ROXIE model is available.
- **LHC:**
  - MQXA b_4 longitudinal distribution produces a small shift with respect to WISE integrated value which increases the puzzle of octupole correction in LHC
  - MQXA b_6 longitudinal distribution has a big impact on the dodecapole correctors strength, hard to predict a precise value (how much it can change with another definition of Body and Heads?)
  - Are the derivatives of the systematic b_4 in MQXA also playing a role in the second order amplitude detuning ?
  - Longitudinal profile of MQXB b_4 and b_6 are not available, any guess on them is difficult due to the strong difference between MQXA and MQXB type of magnets