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Magnetic field design of a full-scale prototype of the HL-LHC beam separation dipole with a correction of mechanical deformation

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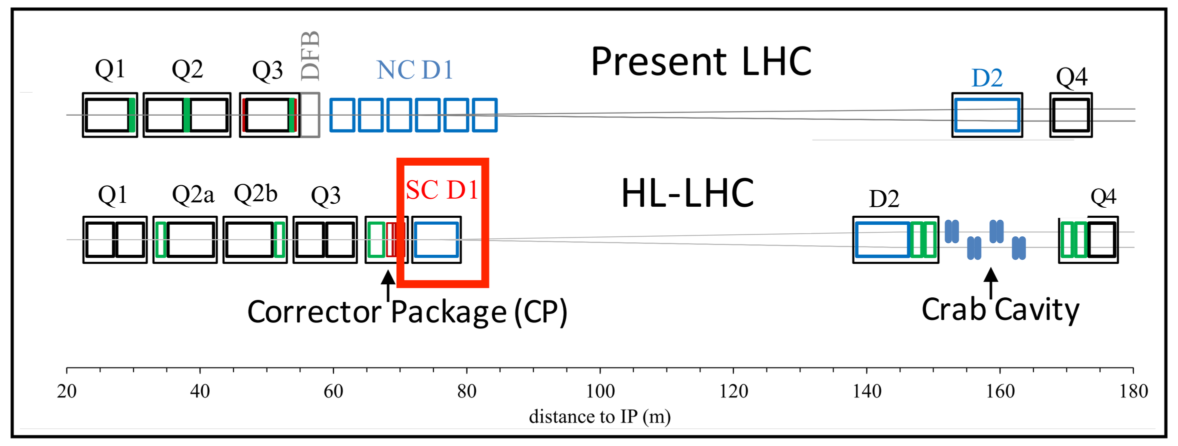
Abstract

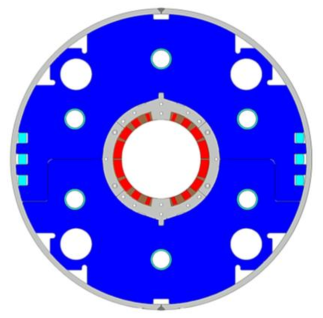
High energy accelerator research organization, KEK, have engaged in development of the beam separation dipole toward the HL-LHC project. The new cross section for the full-scale prototype is under design.
In this report we introduce strategy for designing the prototype and sensitivity to the final b_3 integral as a function of ROXIE2D inputs.

Introduction



- The HL-LHC is planned to be constructed for further exploration of the physics beyond the Standard Model (BSM)
- The following targets can be achieved by reducing β^* :
  - Peak luminosity: 5×10^{34} $cm^{-2}s^{-1}$
  - Total integrated luminosity: 3000 fb^{-1}
- **To reduce β^*:**
  - Aperture of inner triplets (Q1-Q3) : 70 mm → 150 mm,
  - Recover 10 m of the additional space for the triplet
  - New crab cavities will be installed between the recombination dipole (D2) and the two-in-one quadruple (Q4)

- KEK is in charge of the D1 (MBXF) magnet
  - NbTi technology
  - Large Aperture : 150mm
  - Field integral: 35 Tm
  - **Field quality: | b_3 (integral) | < 2.9 unit**
- So far 3 short model (2m) have been constructed
- Deliverables for HL-LHC
  - **1 full-scale prototype cold mass (MBXFP)**
  - 6 series cold masses (MBXF1-6)



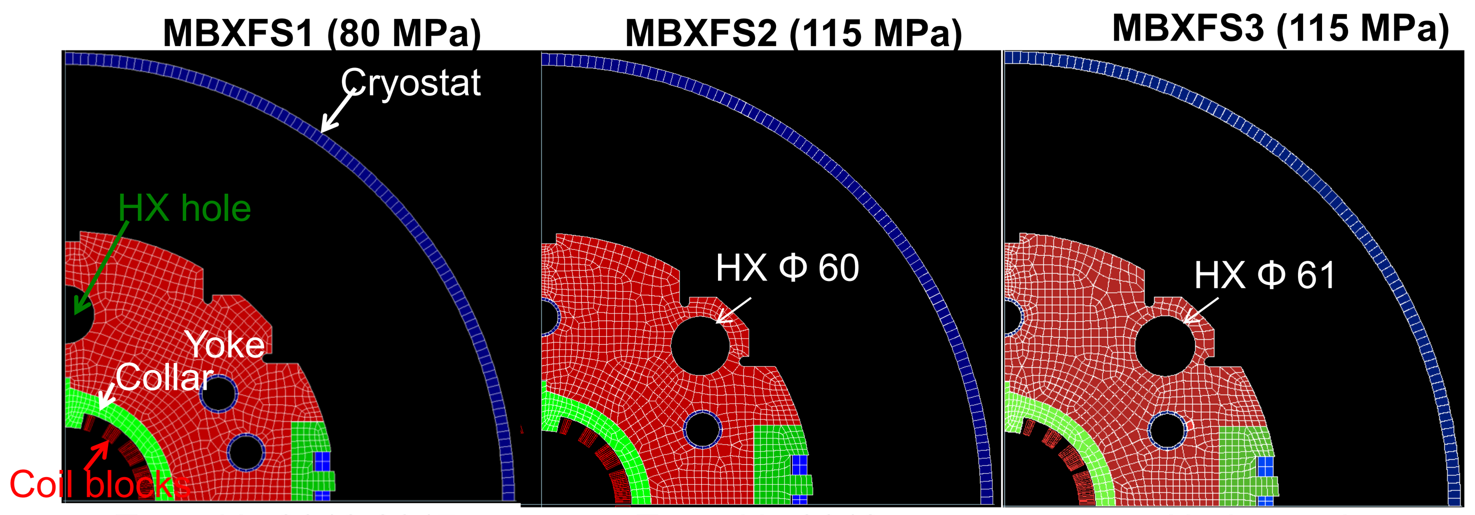
Technical challenges:
- **Large aperture : pre-stress control**
- **Iron saturation : field quality**
- **etc..**

General parameter of MBXF

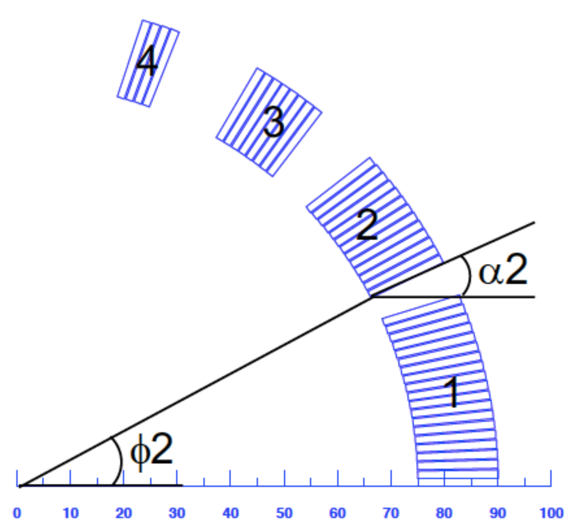
Aperture (mm)	150
Nominal field (T)	5.6
Magnetic length (m)	6.27 / 2*
Stored energy (MJ/m)	0.34
Nominal current (kA)	12
Operation temperature (K)	1.9

*For the 2m short model

Cross section of the model magnets so far

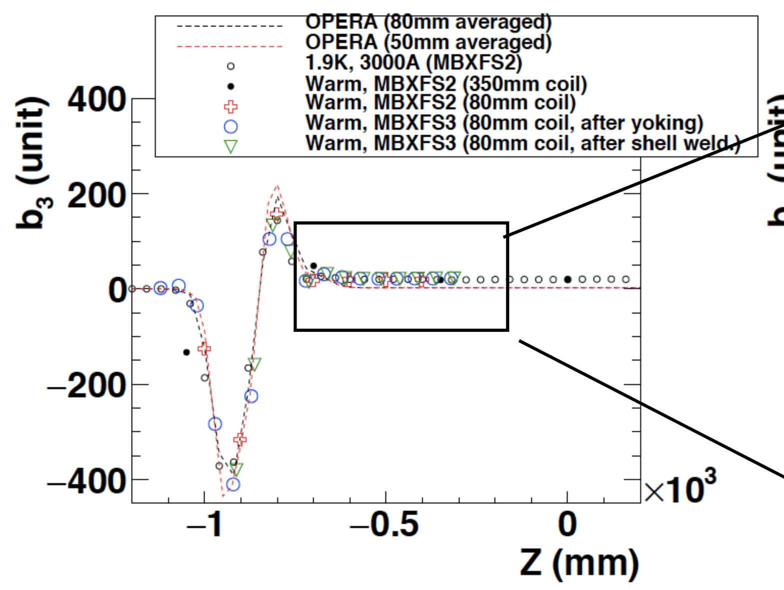


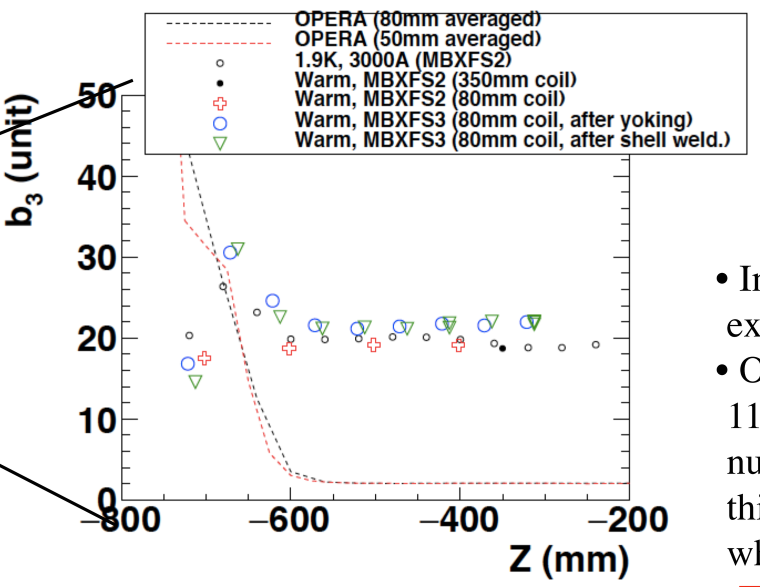
Tested in 2016-2017 | Tested in 2018 | Under testing



ROXIE 2D input	MBXFS1	MBXFS2 and 3
Φ_1 (deg)	1.026	1.135
Φ_2 (deg)	27.852	27.872
Φ_3 (deg)	50.308	50.297
Φ_4 (deg)	70.635	70.699
α_1 (deg)	0	0
α_2 (deg)	26.000	26.000
α_3 (deg)	52.351	52.421
α_4 (deg)	68.002	68.002
Azimuthal insulation thickness (mm)	0.135	0.130

Design issue in the 2nd and 3rd model (MBXFS2 and 3)





Warm field measurement

	MBXFS2	MBXFS3	
	After cold test	After yoking	After shell welding
b_3	**18.88**	**21.96**	**21.88**
b_5	-1.96	-2.31	-2.57

- In MBXFS2 and 3, b_3 is largely deviated from the expectation, which is not acceptable for production
- Oversizing wedges (GFRP) to achieve a prestress of 115 MPa was not properly performed and wrong number was used for the azimuthal cable insulation thickness (=t_{ins}) which is used as an input to ROXEI2D when designing MBXFS2 and 3.
- Thus, the final cable position differs from our expectation
  - t_{ins} should have been **0.122 mm**, not 0.130 mm

Prototype design strategy : |b_3 integral | < 2.9 unit @ 12 kA

Correction on b_3 from :
- Coil deformation
- Data-calc. difference at 12 kA
- 3D effects

Azimuthal cable insulation thickness : 0.122 mm (GFRP E=31.5 GPa)

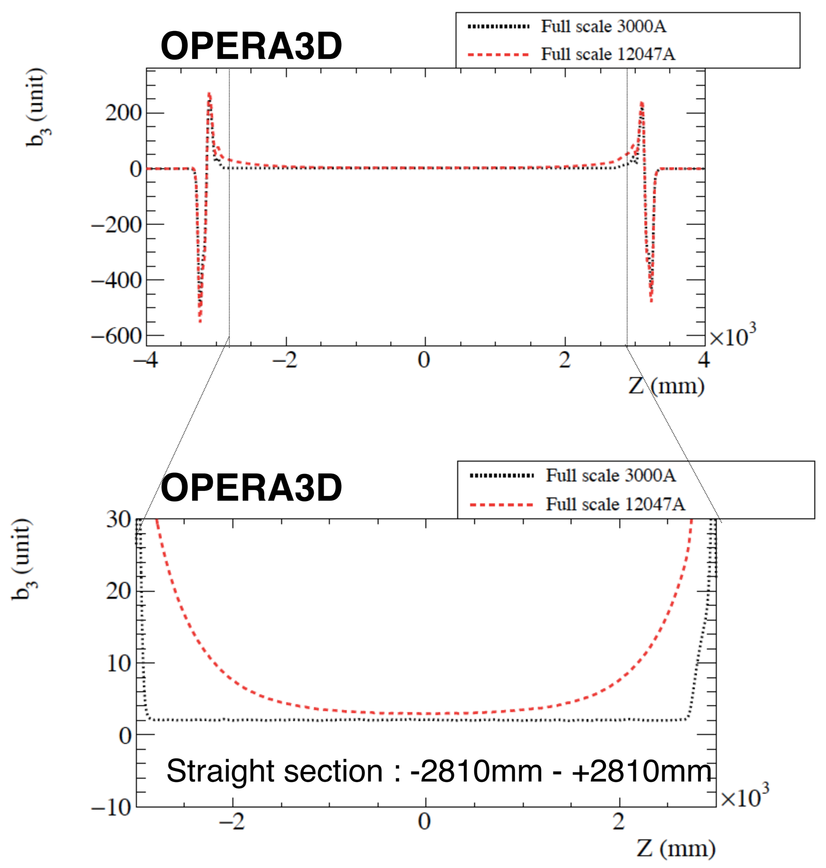
→ ROXIE2D design optimization at I=3 kA and T=1.9 K

→ OPERA3D calculation*

→ Verify integral $\bar{b}_n$ at I=12 kA

Correction to get final b_3:
- Coil deformation
- Data-calc. different at 12 kA

3D effect -saturation effect: $\Delta\bar{b}_3^{shape}$



- Comparison of the b_3 distribution in the straight section (SS) between 3 kA and 12 kA
- $b_3(z)$ at 12 kA is affected by highly saturated yoke at the coil end
- The following shape difference is assigned to the correction:

$$\Delta\bar{b}_3^{shape} = B_{ref}\times\frac{\int_{-2810}^{2810}\{b_3(z)-b_3(z=0)dz\}}{\int_{-4000}^{4000}B_1(z)dz}$$

$$= 4.10$$

→ 3D effect correction Δb_3^{shape} = 4.10 unit

Summary of b_3 correction

OPERA3D prediction | | OPERA3D prediction

$$\bar{b}_3 = \frac{\int_{z=-4000}^{z=-2810}B_3(z)dz}{\int_{z=-4000}^{z=4000}B_1(z)dz}\times10^4 + \frac{\int_{z=-2810}^{z=2810}B_3(z)dz}{\int_{z=-4000}^{z=4000}B_1(z)dz}\times10^4 + \frac{\int_{z=4000}^{z=2810}B_3(z)dz}{\int_{z=-4000}^{z=4000}B_1(z)dz}\times10^4$$

Return end (RE) | **SS** | **Lead end (LE)**

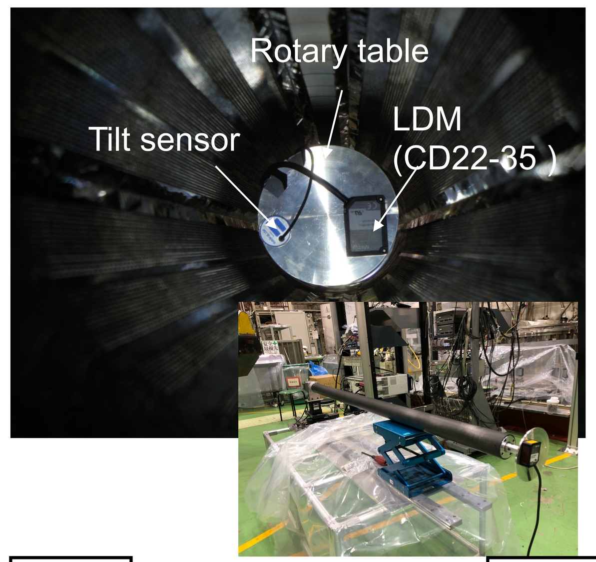
$$\int_{SS}B_3(z)dz\times10^4 = B_{ref}\int_{SS}b_3(z)dz$$

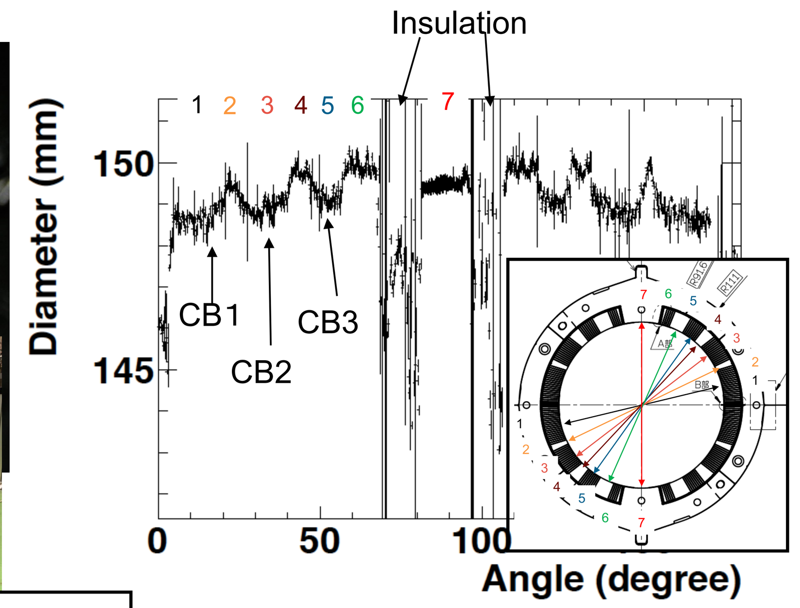
$$\simeq B_{ref}\int_{SS}b_3(z=0)dz + \Delta\bar{b}_3^{shape}$$

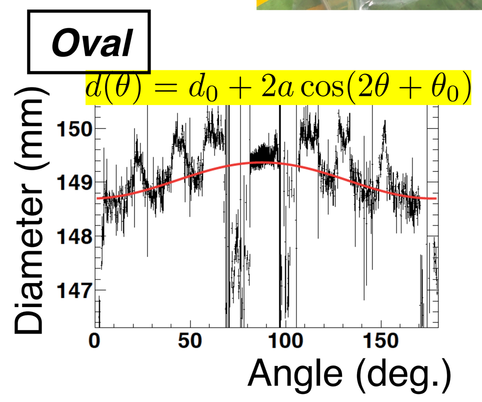
$$= B_{ref}\cdot\left(b_3^{2D} + \Delta b_3^{geom} + \Delta b_3^{3D} + \Delta b_3^{12kA}\right)\cdot\int_{SS}dz$$

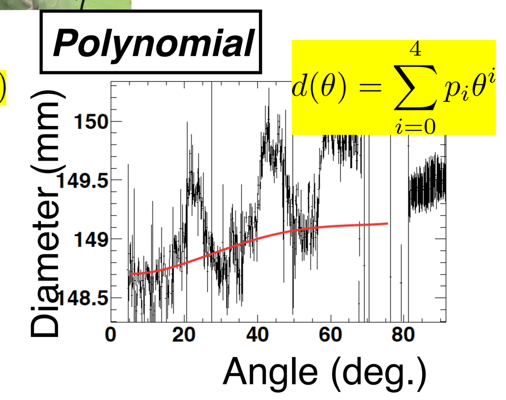
- b_3^{2D}: Input from ROXIE2D
- Δb_3^{geom}: Geometrical correction — 5.01 unit (3.51 unit + (b_3 difference between MBXFS2 and 3))
- Δb_3^{3D}: Transition from 2D to 3D — 0 unit (Confirmed by comparison of 2D and 3D)
- Δb_3^{12kA}: Correction at 12 kA — 2.02 unit
- $+\Delta\bar{b}_3^{shape}$: 3D shape — 4.10 unit

Coil deformation : Δb_3^{geom}









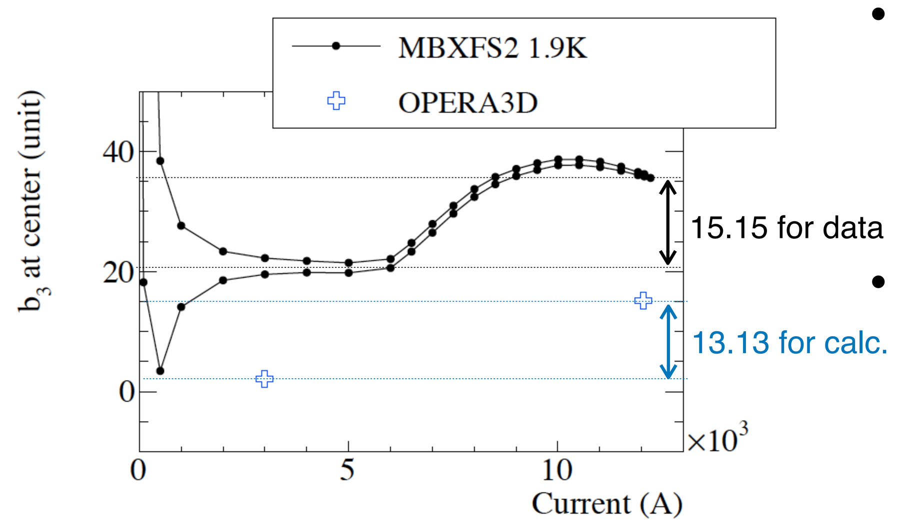
- Investigate the coil mechanical deformation using a laser displacement meter (LDM) and the influence on b_3
- Obtained diameter (=$d(\theta)$) is fitted using two models

	MBXFS2 1.9 K, I=3 kA, (ROXIE2D calc.)			MBXFS2
	No deformation	Oval deformation a=167um	Polynomial deformation	Data, I=3 kA average up/down
b_3	17.02	21.50	**20.53**	20.89
b_5	-3.12	-4.05	**-3.16**	-1.95

(+3.51)

→Geometrical correction Δb_3^{geom} = 3.51 unit

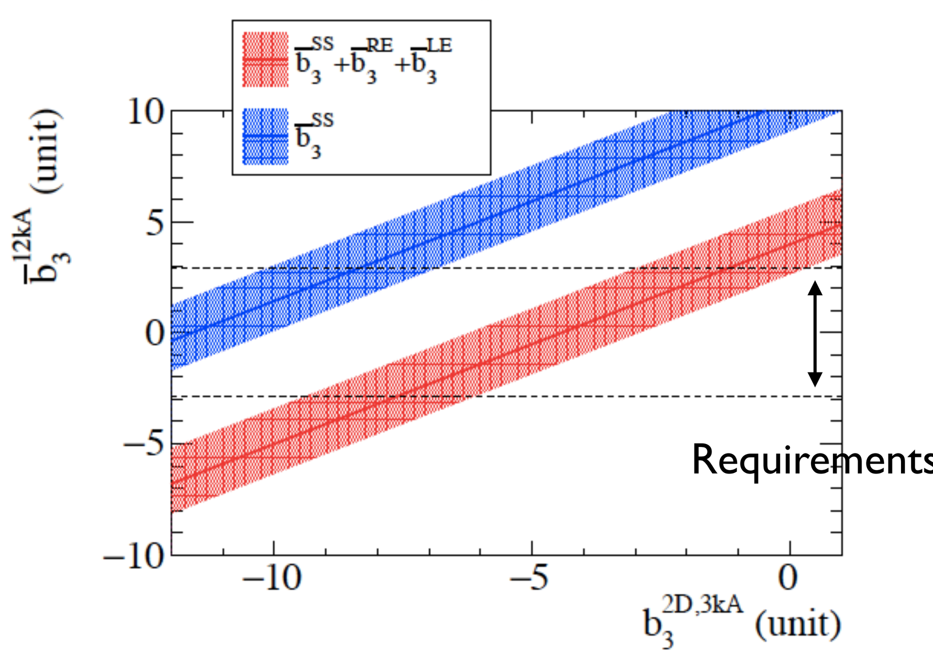
Data - calc. difference at 12 kA: Δb_3^{12kA}



- Discrepancy in b3 increase (b_3^{12kA}-b_3^{3kA}) between data and calc. (OPERA3D)
  - Iron saturation
  - cable displacement due to the Lorentz force
- The difference is simply assigned to the correction

→ Correction on data-calc. difference at 12 kA Δb_3^{12kA} = 2.02 unit

Sensitivity to the final b_3 integral



Estimation of the final b_3 integral as function of ROXIE2D inputs ($b_3^{2D,3kA}$)
- Error band represents:
  - Production uncertainty
    - ➡ b3 difference between MBXFS2 and 3
  - Model uncertainty
    - ➡ Coil deformation model (Oval or Polynomial)

Target b_3 (1.9 K, 3 kA) as input to ROXIE2D : 4 - 5 unit

Conclusion & Prospect

- Design strategy for the full-scale prototype was established
- We are now carefully checking the field quality of the prototype for different ROXIE2D inputs