Unit 20
Field models versus measurements

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With significant (ok… total!) re-use of material from the same unit lecture by Ezio Todesco, USPAS 2017

CONTENTS

Systematic components: model vs measurements (absolute) in the example of the LHC dipoles

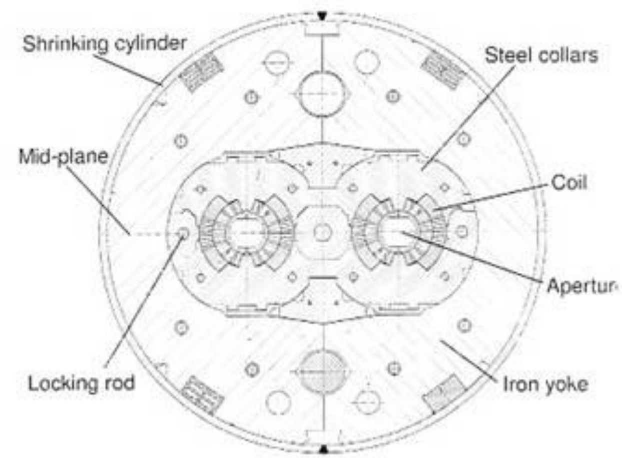
Systematic components: model vs measurements (relative), and how to perform corrections

How to estimate random component: models vs measurements

A glimpse on beam behavior vs measured field quality

2. SYSTEMATIC COMPONENT, ABSOLUTE: THE CASE OF THE LHC DIPOLE

- Special features of the LHC dipole
  - Two layers → large coil deformations
  - Thick stainless steel collars (iron gives only 20% of stress) → small collar deformations
  - Two-in-one collars → even multipoles b2, b4, … are allowed ones, but we will not discuss them
  - Thin filament and energy swing of 16 → persistent current component not so large
- Data relative to 1200 magnets
  - A good statistics …
- We will follow the sequence of the magnetic measurements
  - To have an idea of the size of the different terms
  - To see what is the agreement between model and measurements

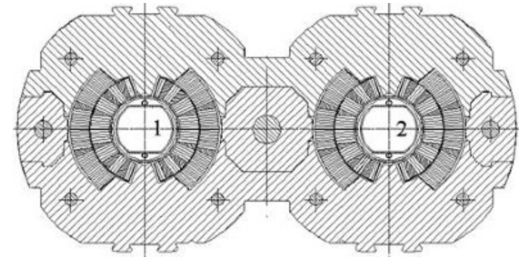


Cross-section of the LHC dipole

2. SYSTEMATIC COMPONENT, ABSOLUTE: THE CASE OF THE LHC DIPOLE

- First step: the collared coil
  - Nominal geometry
  - Coil and collar deformations
  - Collar permeability

$$b_n^{cc} = b_n^{B-S} + b_n^{ccdef} + b_n^{ccperm}$$



	b_3	b_5	b_7	b_9	b_{11}
Nominal	3.9	-1.04	0.75	0.12	0.68
Coil and collar deformations	-3.2	0.80	0.12	0.00	0.00
Collar permeability	-1.4	0.12	-0.09	0.00	0.00
Total model collared coil	-0.7	-0.12	0.78	0.12	0.68
Measured collared coil	2.2	0.94	0.64	0.31	0.74
Discrepancy	2.8	1.06	-0.14	0.19	0.06

- Remarks
  - Coil and collar deformations can have a strong effect on low order multipoles
  - Collar permeability not negligible
  - Discrepancy model-measurement must be estimated in absolute and not in relative
    - 3 units of b_3, 1 unit of b_5, ~0.1 units of higher orders
  - Higher orders usually have a much better agreement with model
    - They are less sensitive to coil displacements

2. SYSTEMATIC COMPONENT, ABSOLUTE: THE CASE OF THE LHC DIPOLE

- Second step: the cold mass – collared coil
  - Remember: we analyze the difference between cold mass and collared coil (divided by the increase of the main field due to the yoke)
  - Magnetic effect of iron
  - Mechanical effect of iron (deformation)

$$b_n^{cm} = \frac{b_n^{cc}}{k} + b_n^{iron} + b_n^{irondef}$$

	b_3	b_5	b_7	b_9	b_{11}
Iron magnetic	3.2	0.00	0.03	0.00	0.00
Iron mechanical	1.5	0.01	0.00	0.00	0.00
Total model iron	4.7	0.01	0.03	0.00	0.00
Meas. cold mass - coll. coil	4.6	0.04	-0.01	0.01	0.00
Discrepancy	-0.1	0.03	-0.04	0.01	0.00

- Remarks
  - The mechanical contribution of the iron to deformations is not negligible (1 unit of b_3, even in the LHC case)
  - Very good agreement between model and simulation
  - Higher orders are not affected by the iron (obvious from Biot-Savart)

2. SYSTEMATIC COMPONENT, ABSOLUTE: THE CASE OF THE LHC DIPOLE

- Third step: injection field
  - Remember: we analyze the difference between injection field at 1.9 K and cold mass at room temperature
  - Mechanical effect of cool-down
  - Hysteresis of persistent currents

$$b_n^{inj} = b_n^{cm} + b_n^{w-cdef} + b_n^{pers}(I) + b_n^{bs}$$

	b_3	b_5	b_7	b_9	b_{11}
Cool-down	-0.2	-0.09	0.11	0.00	0.00
Persistent currents	-8.5	0.99	-0.44	0.20	0.03
Total model injection-cold mass	-8.7	0.90	-0.33	0.20	0.03
Meas. injection - cold mass	-7.4	0.93	-0.32	0.15	0.04
Discrepancy	1.4	0.03	0.01	-0.05	0.01

- Remarks
  - Notwithstanding the small filaments, the persistent currents have a strong effect (9 units of b_3, one of b_5)
  - The agreement with model is good
  - The impact of cool-down is small

2. SYSTEMATIC COMPONENT, ABSOLUTE: THE CASE OF THE LHC DIPOLE

- Fourth step: high field
  - Remember: we analyze the difference between high field at 1.9 K and cold mass at room temperature
  - Mechanical effect of cool-down
  - Saturation of iron
  - Deformation of electromagnetic forces

$$b_n^{high} = b_n^{cm} + b_n^{w-cdef} + b_n^{sat}(I) + b_n^{Lf}(I) + b_n^{bs}$$

	b_3	b_5	b_7	b_9	b_{11}
Cool-down	-0.2	-0.09	0.11	0.00	0.00
Iron saturation	0.2	0.01	0.00	0.00	0.00
Electromagnetic forces	0.1	-0.16	0.00	0.00	0.00
Total model injection-cold mass	0.1	-0.08	0.11	0.00	0.00
Meas. injection - cold mass	-0.2	-0.25	-0.01	-0.08	0.01
Discrepancy	-0.3	-0.17	-0.12	-0.08	0.01

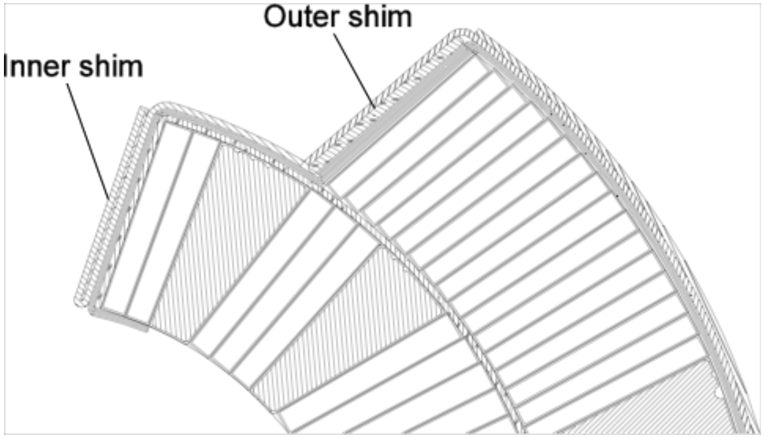
- Remarks
  - Iron saturation is small because it has been carefully optimized
  - The high field is similar to cold mass values – cool down and electromagnetic forces not so large

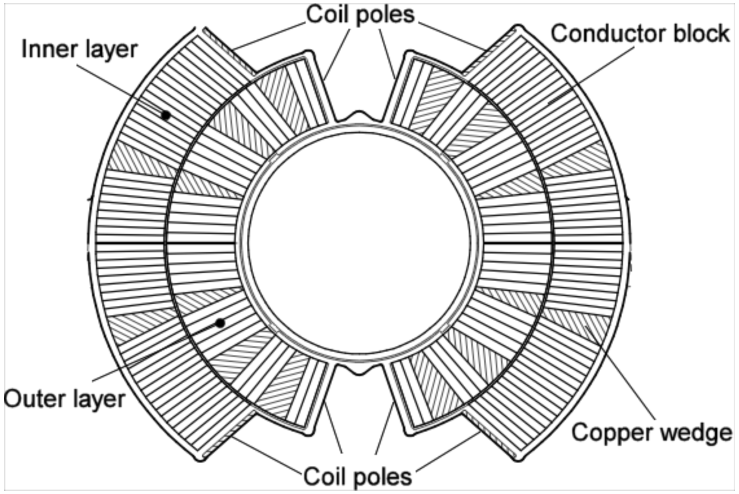
3. SYSTEMATIC COMPONENTS, RELATIVE

- Once the first models or prototypes have been built …
  - Measurements usually show a discrepancy with respect to the model
  - One or more corrective actions are necessary to bring the field quality closer to targets
- What is the capability of models to forecast changes of design?
  - We need the model in relative, not in absolute
  - Usually this task is less challenging: if the model neglects a systematic effect, it will be wrong in absolute but correct in relative
- There is no precise answer, but one can give examples and the experience of previous productions
  - We will present the case of the LHC dipole production

3. SYSTEMATIC COMPONENTS, RELATIVE

- Example 1. The impact of a variation of pole shims in the LHC dipoles
  - Shims are used to steer both field quality and stress
  - Data relative to a dedicated experiment
  - Good agreement found (model including deformations)





		Δb_3	Δb_5	Δb_7
Inner layer	Model	1.88	-0.29	0.12
	Measurement	1.85±0.26	-0.24±0.06	0.13±0.04
Outer layer	Model	1.46	-0.05	-0.02
	Measurement	1.36±0.10	-0.05±0.06	-0.01±0.04

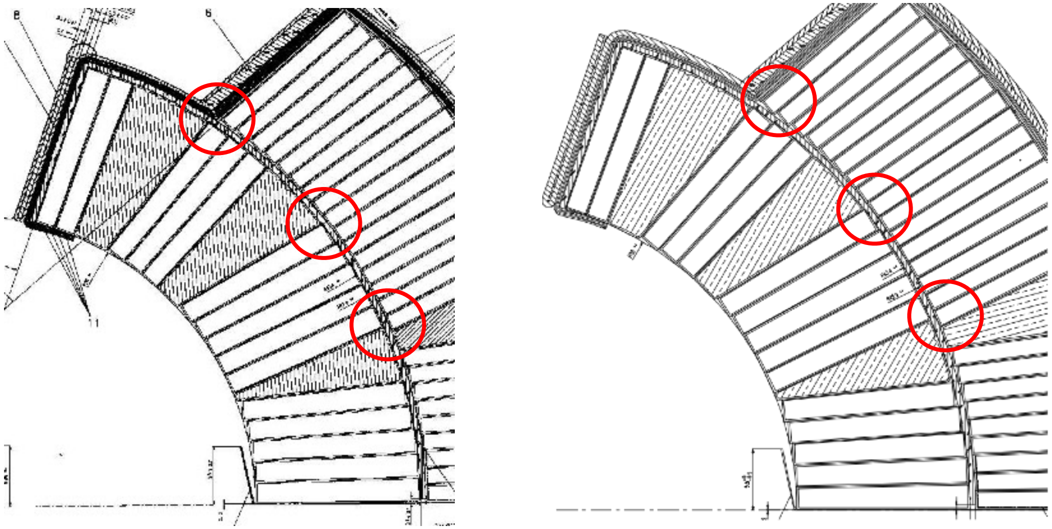
Multipole variation induced by a change of 0.1 mm of the pole shim,
From P. Ferracin, et al, *Phys. Rev. STAB* **5** (2002) 062401.

3. SYSTEMATIC COMPONENTS, RELATIVE

- Example 2. Change of cross-section in the LHC dipole to reduce b_3, b_5
  - Change decided after 9 series magnets, implemented at n. 33
  - 0.1-0.4 mm change of 3 copper wedges, keeping the same coil size
  - Data relative to 33 magnets with X-section 1 and 154 with X-section 2
  - Agreement not very good (relevant trends in production, see later)

	Δb_3	Δb_5	Δb_7
Model	-4.0±1.2	-1.35±0.35	0.17±0.12
Measurement	-1.85	-0.85	0.53

Multipole variation induced by the cross-section change from 1 to 2 (change in internal copper wedges) in the main LHC dipole

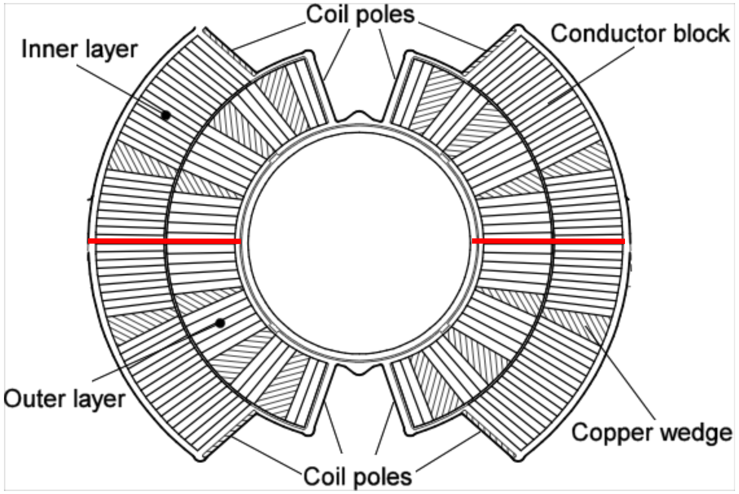


Change of the copper wedges of the inner layer in the main LHC dipole: cross-section 1 (left) and cross-section 2 (right)

- Example 3. Additional mid-plane shim in LHC dipole to reduce b_3, b_5
  - Change decided after 80 series magnets, implemented at n. 154
  - Additional mid-plane shim of 0.25 mm thickness
  - Data relative to 154 magnets with X-section 2 and ~1000 with X-section 3
  - Agreement rather good

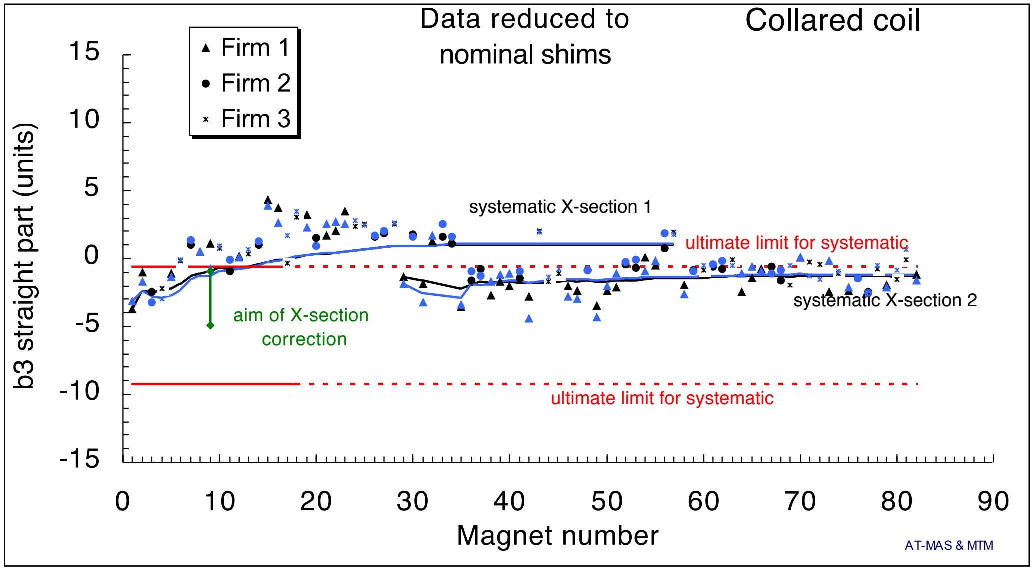
	Δb_3	Δb_5	Δb_7
Model	-2.12	-0.53	-0.14
Measurement	-2.20	-0.38	-0.09

Multipole variation induced by the cross-section change from 2 to 3 (additional mid-plane shim) in the main LHC dipole



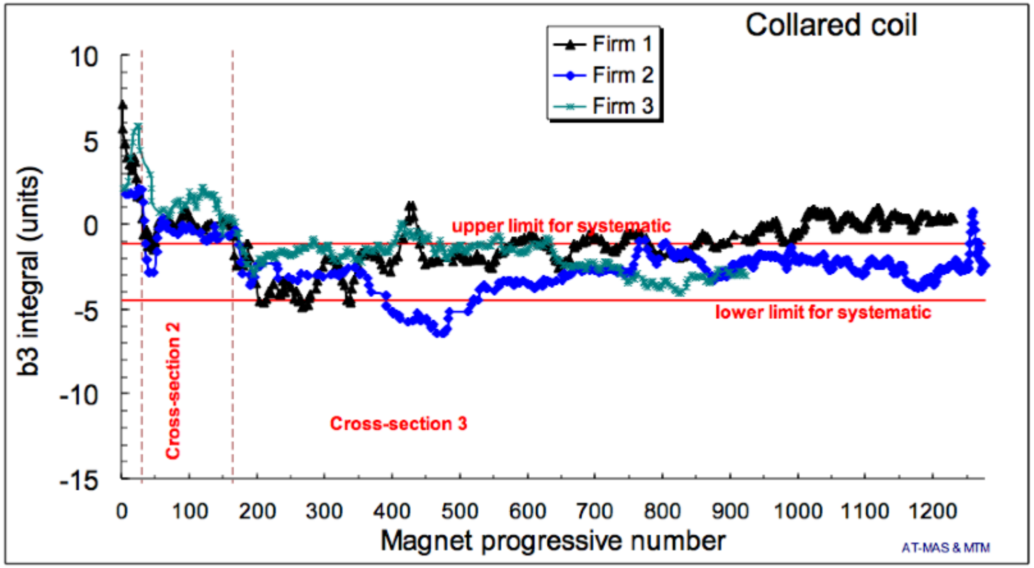
Additional mid-plane shim: cross-section 1 (left) and cross-section 2 (right)

- Conclusions – estimating the impact of a variation in the design on field harmonics
  - For dedicated experiments (the same magnet assembled with different configurations) the agreement is within the errors
  - When a correction is implemented along a production, its effect can be masked by trends, and the result can be different …



The first correction of the cross-section in the main LHC dipoles

- Conclusions – estimating the impact of a variation in the design on field harmonics
  - One has to gently insist in bringing the field quality within targets
  - It is mandatory to have a flexible design
    - Example: tuning shims in the RHIC magnets [R. Gupta, et al. …]
    - Put in the spec the possibility of changes, good contact with the Firm



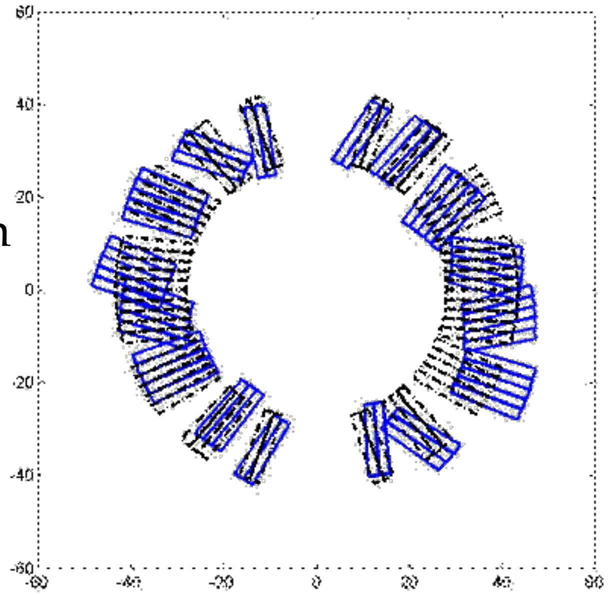
b3 along the production of 1276 LHC dipoles – red limits are for the final average

4. RANDOM COMPONENT, GEOMETRIC

- This is the component due to the limited precision in the position of the coil
  - Two components:
    - Precision of positioning with respect to the design → systematic
    - Reproducibility of the positioning → random
  - We will focus on the second component
  - The precision of reproducibility is of the order of 10-100 μm
  - In general it is dominant over all the other components, as
    - spread in magnetic properties of iron or of collars
    - spread in the persistent current
    - spread in the deformations due to electromagnetic forces
  - Moreover
    - The spread in positioning induced by cool-down is small

4. RANDOM COMPONENT, GEOMETRIC

- A simple way to estimate the geometric random component
  - Using a Monte-Carlo, coil blocks are randomly displaced with an amplitude belonging to a distribution with zero average and stdev *d*
  - In the past a thumb rule was to use *d*=0.05 mm to get a reasonable estimate of the errors
    - For each deformed coil one computes the multipoles
    - Repeating 100-1000 times, one gets a multipole distribution and can compute average (that will be close to zero) and stdev
    - The computed stdev is the guess of our random component



A random movement of coil blocks to estimate geometric random errors

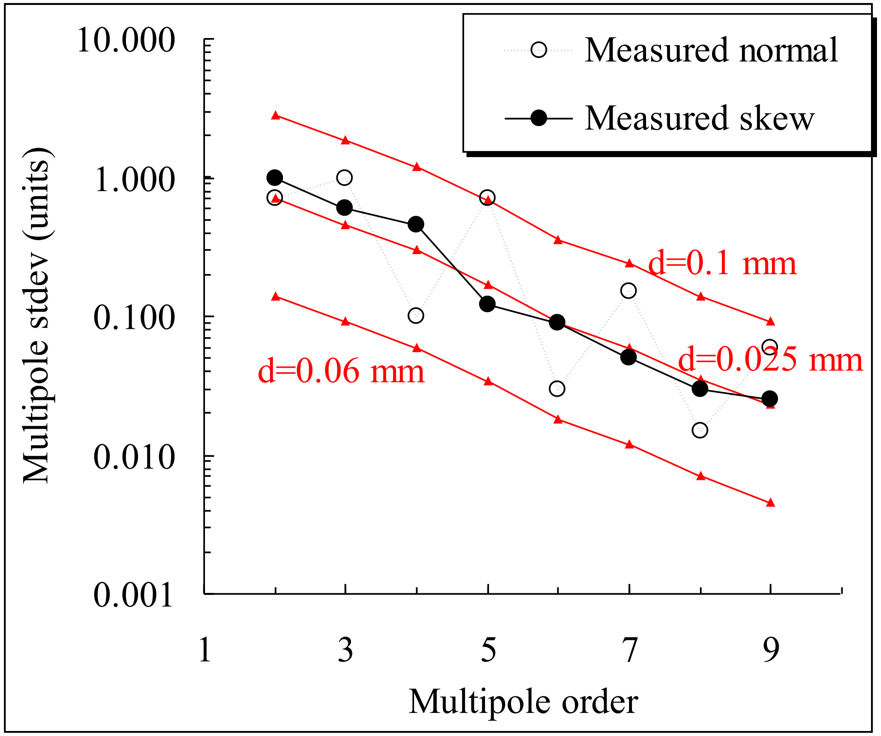
4. RANDOM COMPONENT, GEOMETRIC

- How to estimate the repeatability of coil positioning
  - The previous approach is used before starting models and prototypes
  - Once a series of homogeneous magnets is built, one can measure them, compute the stdev, and estimate the repeatability of the coil positioning by selecting the *d* that better fits data
  - In this way one can estimate (and monitor) the assembly tolerances
  - Results for different productions: repeatability of coil positioning *d* is around 0.020 mm rather than 0.050 mm
  - A considerable improvement with time !

Dipoles	d (mm)
Tevatron	0.065
HERA	0.041
RHIC	0.016
LHC	0.025

Quadrupoles	d (mm)
RHIC MQ	0.020
RHIC Q1-Q3	0.014
LHC MQ	0.031
LHC MQM	0.022
LHC MQY	0.023
LHC MQXA	0.013
LHC MQXB	0.017

- How to estimate the repeatability of coil positioning: the LHC dipoles case
  - This model gives equal estimates for random normal and skew, and a decay with multipole order
  - The decay fits well !! (this is again Biot-Savart)
  - Indeed, there is a saw-tooth, odd normal are larger than even skew and viceversa

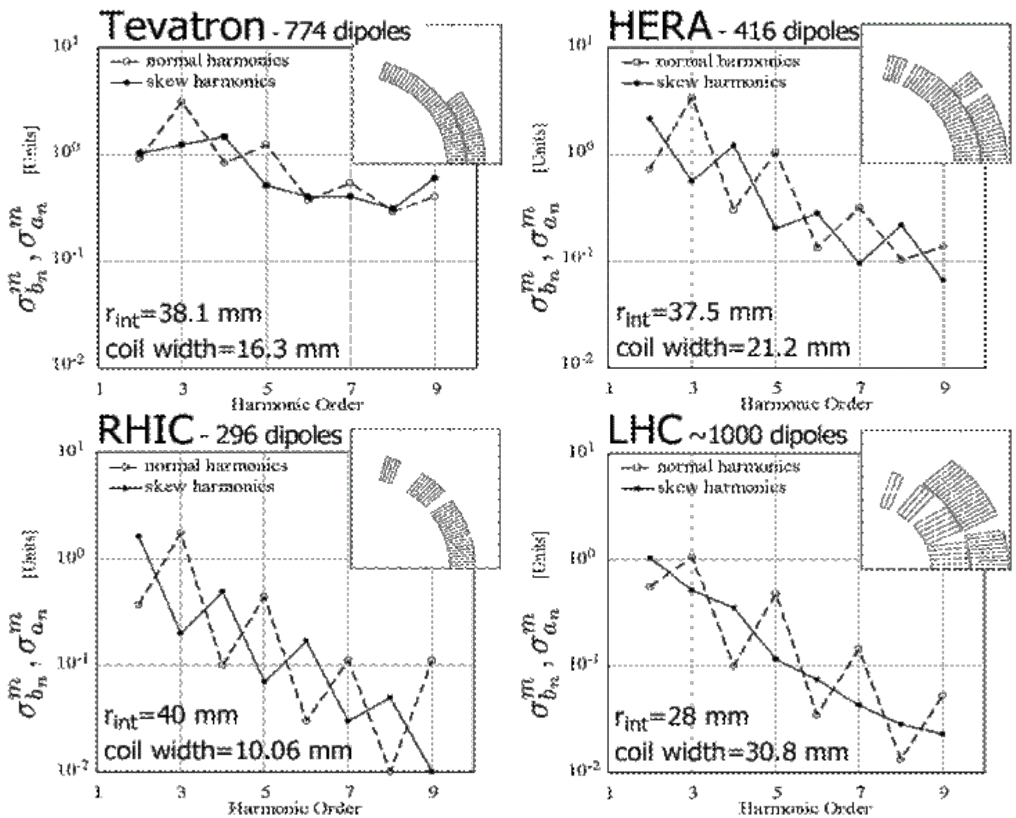


Measured random components (markers) versus model (red line) in the LHC dipoles [from B. Bellesia et al, …]

4. RANDOM COMPONENT, GEOMETRIC

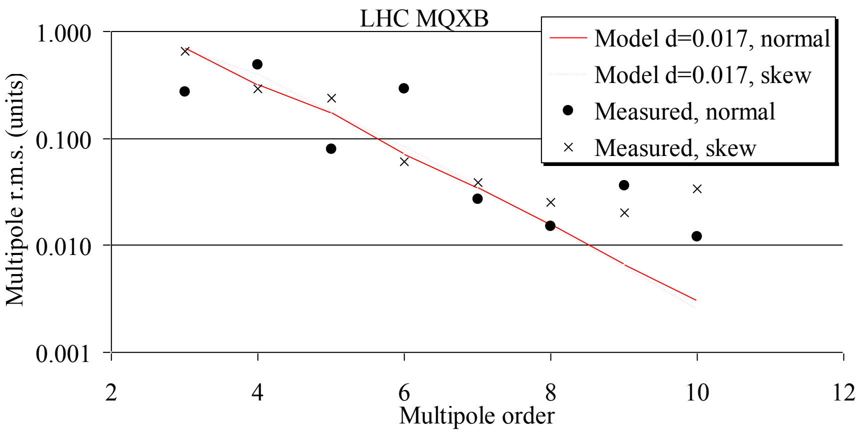
- A different behavior between normal and skew is well known in literature – it limits the prediction power of the model
  - Has been already observed in Tevatron

    [Herrera et al, PAC 1983]
  - Heuristic justification: Not all tolerances are kept in the same way, some symmetries are more preserved than others [see also R. Gupta, Part. Accel. **54** (1996) 129-140]

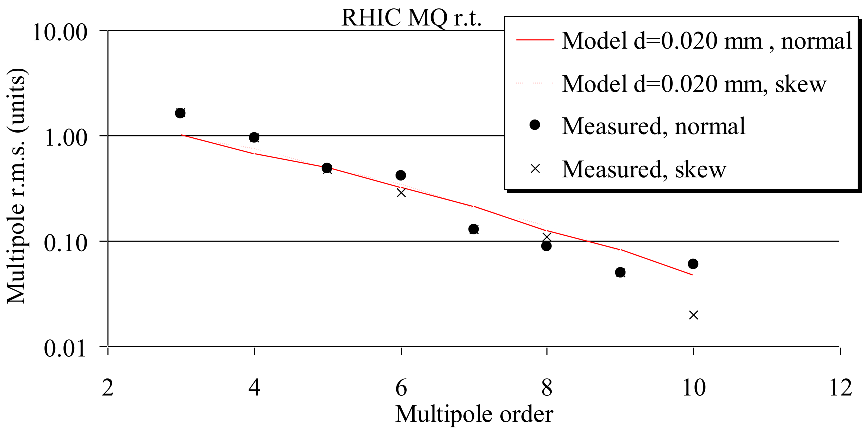


Measured random components in four dipole productions
B. Bellesia, et al. "Random errors in sc dipoles", EPAC 2006.

- Quadrupoles:
  - Also in this case the decay agrees well with the models
  - The repeatability of coil positioning is 0.015 to 0.030 mm for RHIC and LHC productions
  - In general the saw-tooth is less strong, but random allowed multipoles (b_6) are larger then estimates



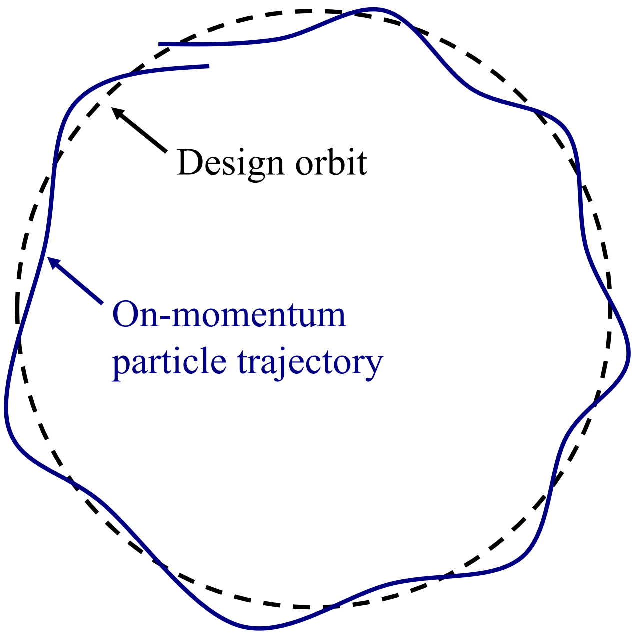
Measured random components and model fit in LHC MQXB

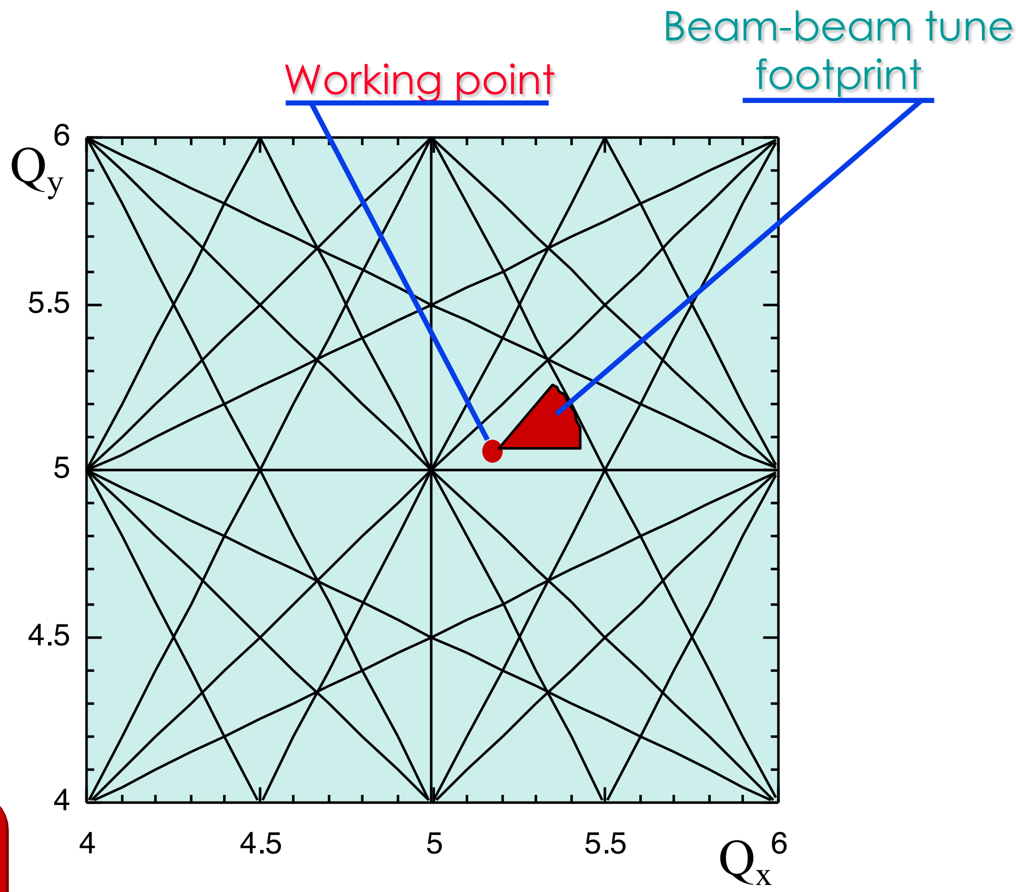


Measured random components and model fit in RHIC MQ

Quick terminology reminder

- Tune is the number of oscillations that a particle makes about the design trajectory



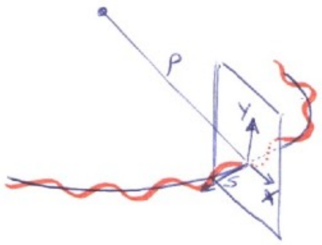


Tune resonances

$$mQ_x + nQ_y = p \qquad m, n, p \in \mathbf{N}$$

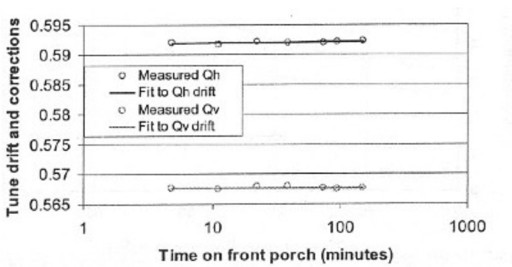
$$|m| + |n| = resonance\ order$$

- What are the main parameters that affect the beam and how are they related to field quality – the tune
  - Linear tune: Q_x ,Q_y is the number of oscillations in the transverse plane made around one turn of the ring
    - Tevatron: Q_x=20.573, Q_y=20.588
    - LHC (planned): Q_x=70.280, Q_y=70.310



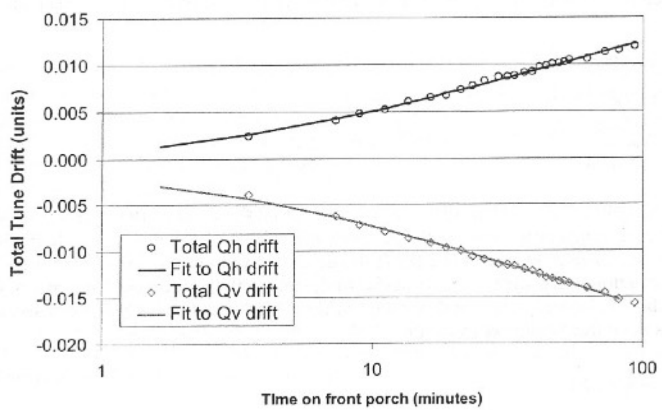
  - This number is crucial for the stability of the beam:
    - if the fractional part is zero or close to fractions with low denominators as ½ , 1/3 2/3 , ¼ … (resonances) the beam after 2, 3, 4 turns goes around the same path, seeing the same errors that can build up
    - It must be controlled within 0.003 – i.e. 2 units for Tevatron, 0.5 units for the LHC
  - The linear tune is proportional to all sources of B_2
    - Mainly quadrupoles, b_2 in the dipoles, b_3 in the dipoles plus misalignment …

- What are the main parameters that affect the beam and how are they related to field quality – the tune
  - The linear tune can be measured on-line with an absolute precision of 0.001 with several instruments
  - During the injection of Tevatron, a drift in the tune has been measured
    - Origin – decay of multipoles, rather than b_2 in quads look more probable b_2 generated by b_3 decay in dipoles and misalignment
    - It has been corrected by acting on the quad powering



Tune drift in Tevatron at injection, after correction

From J. Annala, et al., Beams-doc 1236 (2005) pg. 18



Tune drift in Tevatron at injection, without correction

From J. Annala, et al., Beams-doc 1236 (2005) pg. 18

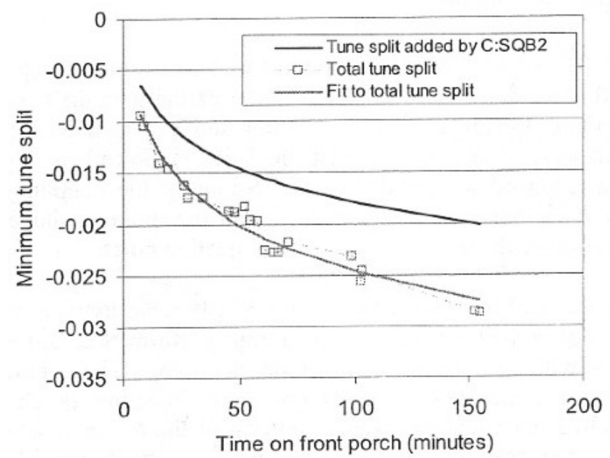
- What are the main parameters that affect the beam and how are they related to field quality – the chromaticity
  - The derivative of the tune with respect to the beam energy is called chromaticity
    - Since the beam contains particles of different energy (10^{-3}~10^{-4}), this derivative must be close to zero to avoid some particles having an unstable tune
    - It cannot be negative since it induces instability – it is usually set at 2-5, controlled within 1-2
  - The chromaticity is proportional to all sources of B_3
    - Mainly b_3 in the dipoles …
  - Chromaticity can be measured with different methods
    - Changing the energy of the beam and measuring the tune … but this takes time
    - Other parasitic methods

5. BEAM MEASUREMENTS

- What are the main parameters that affect the beam and how are they related to field quality – the chromaticity
  - The drift in b_3 at injection induced a large change of chromaticity
    - If not corrected this can kill the beam
    - In Tevatron: one unit of b_3 gives 25 of chromaticity (45 in the LHC)
    - It must be corrected
  - Tevatron experience
    - Drift of 75 of chromaticity during injection
    - Half could be explained by the measured decay of b_3 at injection
    - Using beam measurements, chromaticity has been made stable within 2 by compensating the drift with powering of the sextupole correctors

- What are the main parameters that affect the beam and how are they related to field quality – the coupling
  - Linear coupling is a mechanism that couples oscillations in the vertical and horizontal plane
    - The normal modes are not x and y any more, but a linear combination
    - Creates instabilities in certain regimes
    - All the instrumentation is on x and $y \rightarrow$ this terribly complicates all diagnostic and correction
  - Linear coupling defined as the minimal difference between the tune in the two planes
    - If there is no linear coupling, the two planes are uncoupled and the two tunes can be brought as close as we want
    - Must be controlled within ΔQ=0.003
  - Linear coupling sources
    - All skew quadrupole terms: in dipoles, misalignment of the quadrupoles (tilt), feed-down of b_3 due to misalignment, …

- What are the main parameters that affect the beam and how are they related to field quality – the coupling
  - Linear coupling must be controlled within ΔQ=0.003
    - Tevatron: ΔQ=0.03 (10 times larger than tolerance) without correction during injection
    - Probably generated by the misalignment of dipoles and b_3 decay
  - In Tevatron linear coupling has been corrected through skew quadrupoles
    - Effective to bring back linear coupling to tolerances



Tune drift in Tevatron at injection, without correction

From J. Annala, et al., Beams-doc 1236 (2005) pg. 37

CONCLUSIONS

- We analyzed the capability of the model of guessing the systematic components (absolute)
  - A few units of b3, a fraction of unit on higher order
  - The largest error is made for the collared coil at r.t.
    - When you make optimizations, do not work to get 0.00 since the model is not so precise
    - Remember that codes gives multipoles with 5 digits (or more) but that they are not meaningful is absolute
- We analyzed the capability of the model of forecasting the impact of a change in the magnet (relative)
  - The model usually works at 80%-90%, but one can have suprises
  - Once a magnet is build, the discrepancy in the absolute is corrected through one (or more) changes – fine tuning

CONCLUSIONS

- We discussed how to model the random components
  - The dominant components are the geometrical ones
  - They can be estimated through a Monte-Carlo where blocks are randomly moved of ~0.02 mm
  - This allows to estimate the reproducibility in the coil positioning in a magnet production by post-processing the magnetic measurements
- We discussed the agreement between magnetic measurements and beam measurements
  - Case of Tevatron (LHC will come soon …)

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- Beam measurements
  - Several works by Annala, Bauer, Martens, et al on Tevatron in 2000-2005.
  - Experience of RHIC and HERA

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