In-situ calibration of rotating shafts

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Outline

- *Why in-situ calibration?*
- *In-situ calibration methods for*
  - *multi-segment shafts*
  - *shafts longer than magnets*
- *Experimental results*
  - *LHC main dipoles shaft*
  - *Linac4 quadrupoles shaft*
- *Conclusions*

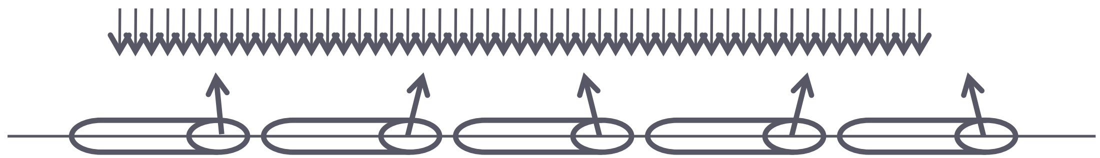
Why in-situ calibration? 1/2

- Pros
  - Better determination of precision and accuracy
  - Better correction

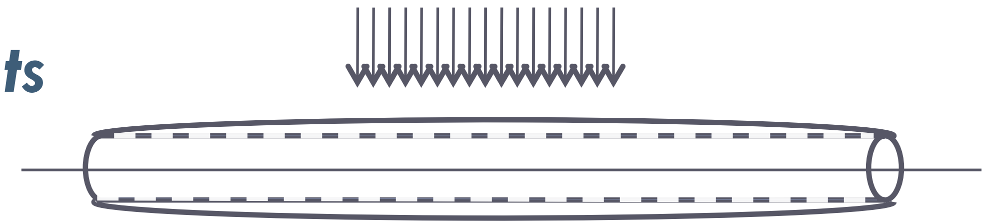
- Cons
  - Lower reproducibility
  - Lower test uncertainty ratio (U_x/U_{ref})

Why in-situ calibration? 2/2

- *Multi-segment shafts*



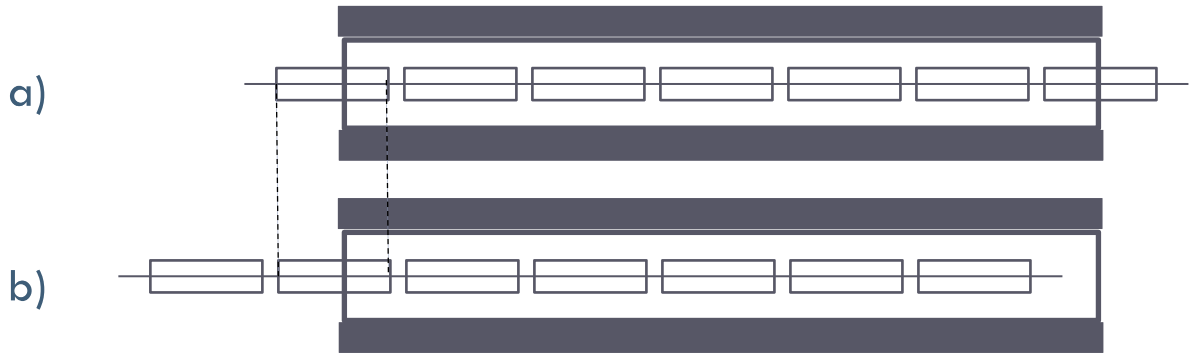
  - *angles among segments*
- *Shafts longer than magnets*



  - *longitudinal non-homogeneity*
- *Fast tests during a measurement campaign*
- *Calibration of the system as a whole*

Multi-segment dipole shaft 1/2

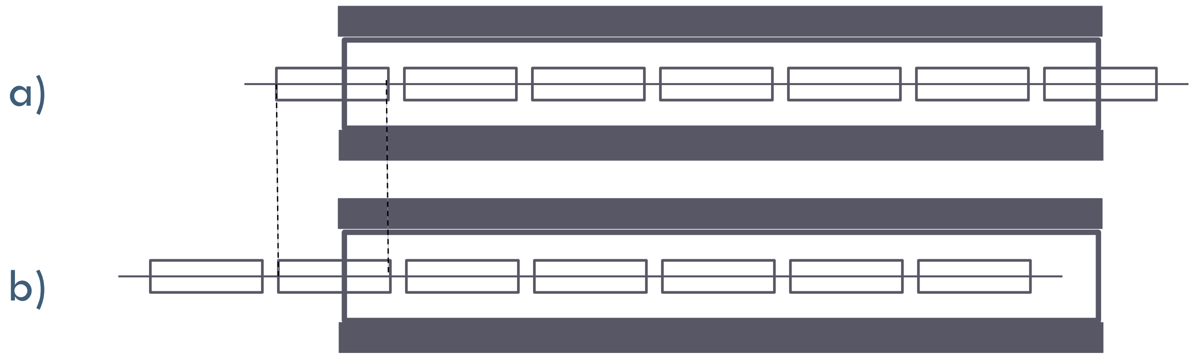
The shaft has *n* segments → *n unknown* coil surfaces



- 2 sets of measurements by displacing the shaft of one segment: 2 different coils measure the same field, → *n-1* equations from the equalities of the field seen by corresponding segments
- SSW measurement: *1* more equation obtained by imposing the equality of the integral field measured by the whole shaft and the SSW measurement

Multi-segment dipole shaft 1/2

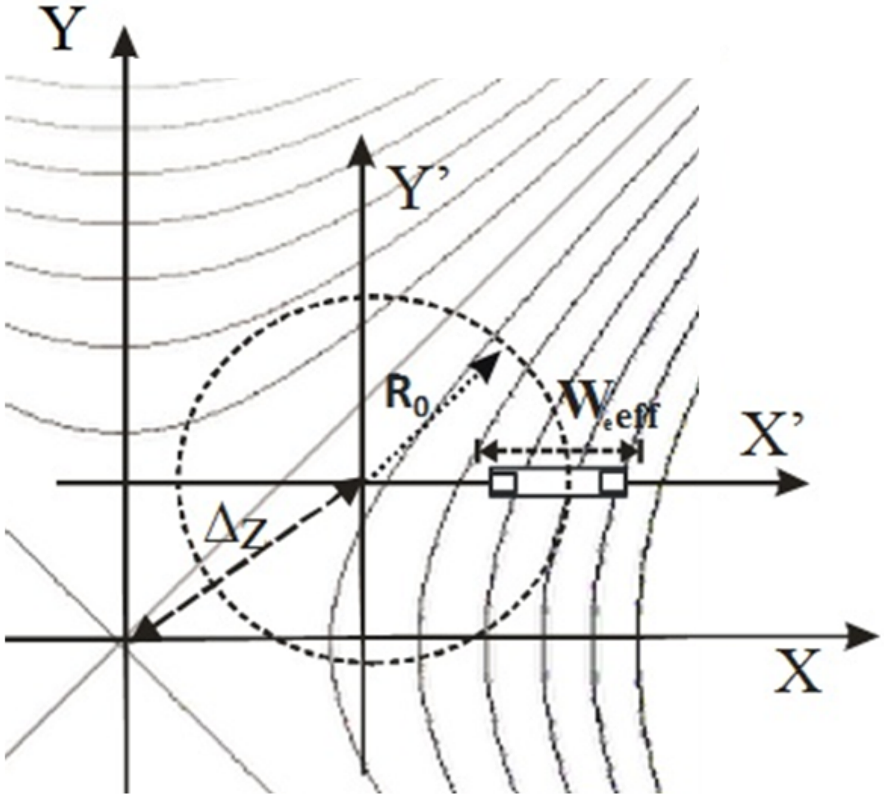
Angle of each coil mounted on the shaft → *n* unknowns



- 2 sets of measurements by displacing the shaft of one segment: 2 different coils measure the same field → *n-1* equations from the equalities of the field angle seen by corresponding segments
- *1* more equation by referring all the angles to the first segment or to the gravity

Shaft longer than magnet 1/2

Hp: Quadrupole



Radius (R_0) and surface (A_c) of the coil have to be determined: 2 unknowns

$$\begin{cases} R_0 e^{i\varphi_0} = -\dfrac{\Psi_2 \Delta z}{\Delta\Psi_1} \\ A_c e^{i\alpha} = i e^{i\varphi_0} \dfrac{\Delta\Psi_1 R_{ref}}{C_2 \Delta z} \end{cases}$$

2 measurements by moving the magnet transversally of a known distance.

By knowing the quadrupole component C_2 the problem can be solved.

Shaft longer than magnet (2)

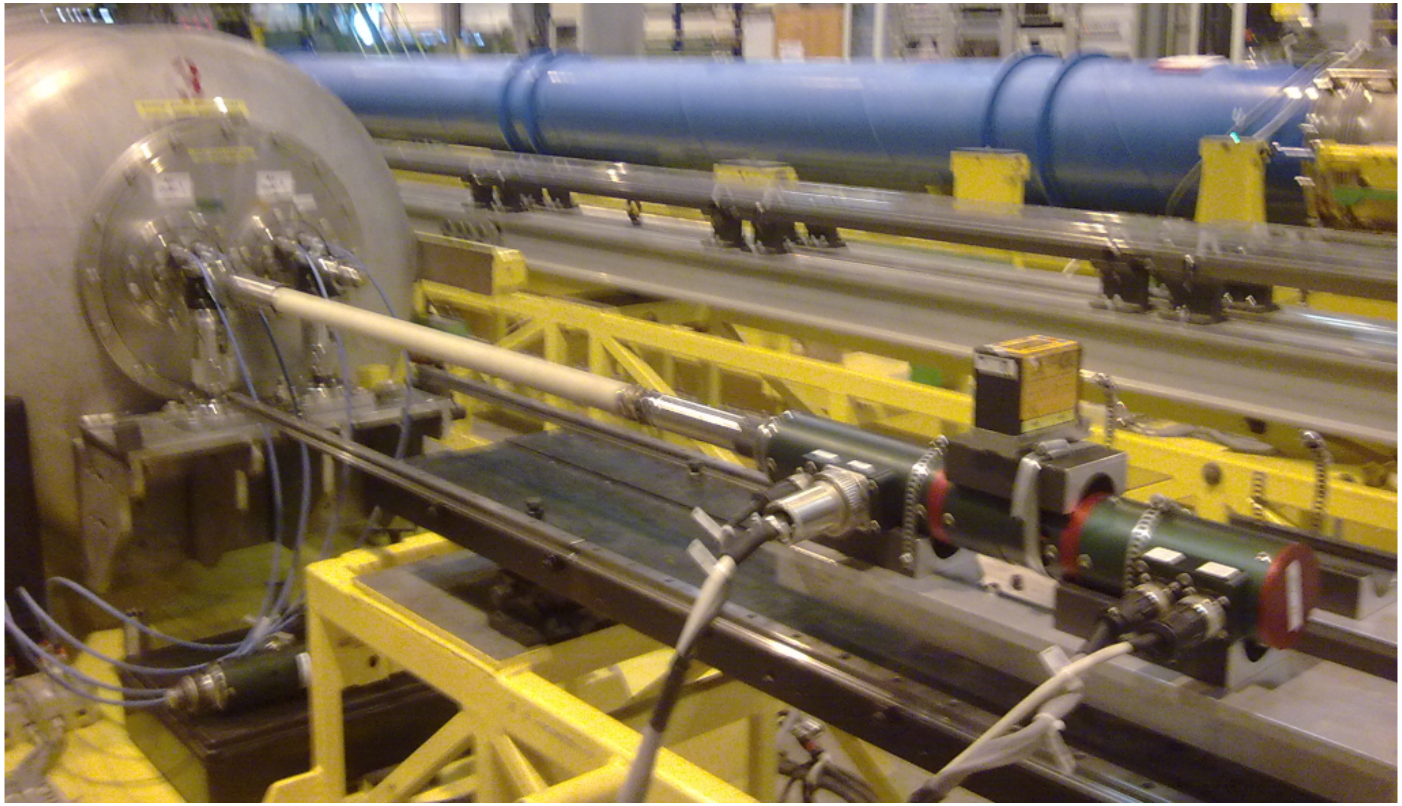
$$A_c e^{i\alpha} = i e^{i\varphi_0} \frac{\Delta\Psi_1 R_{ref}}{C_2 \Delta z}$$

This equation is valid only if the magnet has not higher multipole components. The general equation is:

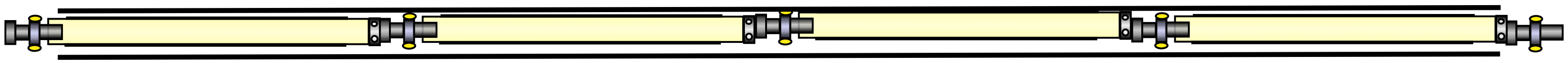
$$A_c = \left\| \frac{\Delta\Psi_1 R_{ref}}{C_2 \Delta z} \frac{1}{1 + \sum_{n=3}^{+\infty} \frac{C_n}{C_2} \left(\frac{\Delta z}{R_{ref}} \right)^{n-2}} \right\|$$

The multipoles are less than 1 % with respect to the main field C_2 for most accelerator magnets. In the worst case of a quadrupole magnet with 1 % of C_3/C_2 and a displacement of 1 mm over 8 mm radius, the systematic effect due the multipole on the surface calibration is less than 1 ‰.

Experimental results: multi-segment LHC dipole

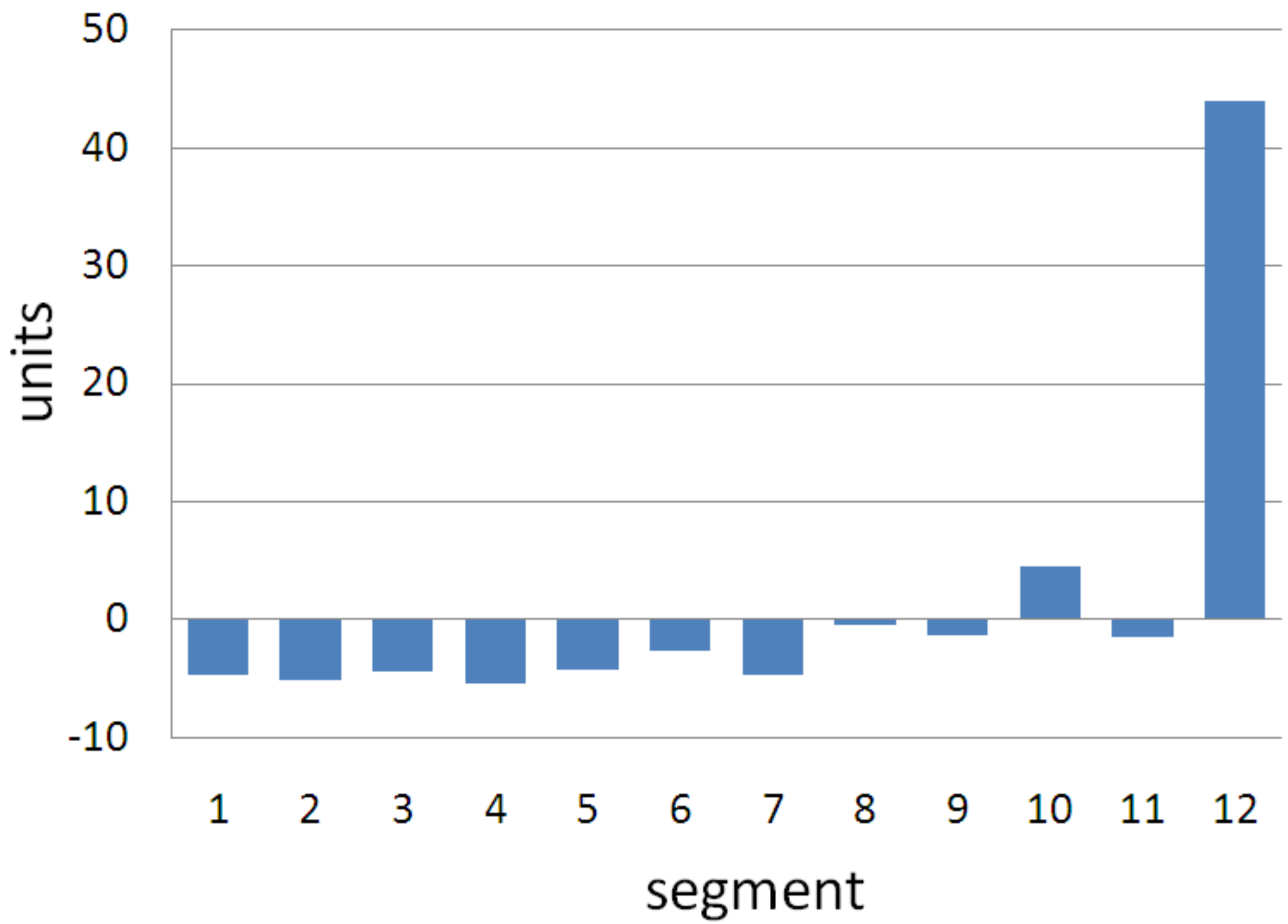


Shaft composed by 12 segments of 1150 mm mechanically connected in series



Experimental results: LHC dipole

Difference between "surface" and "in-situ " calibrations



The difference is 1 unit in average.

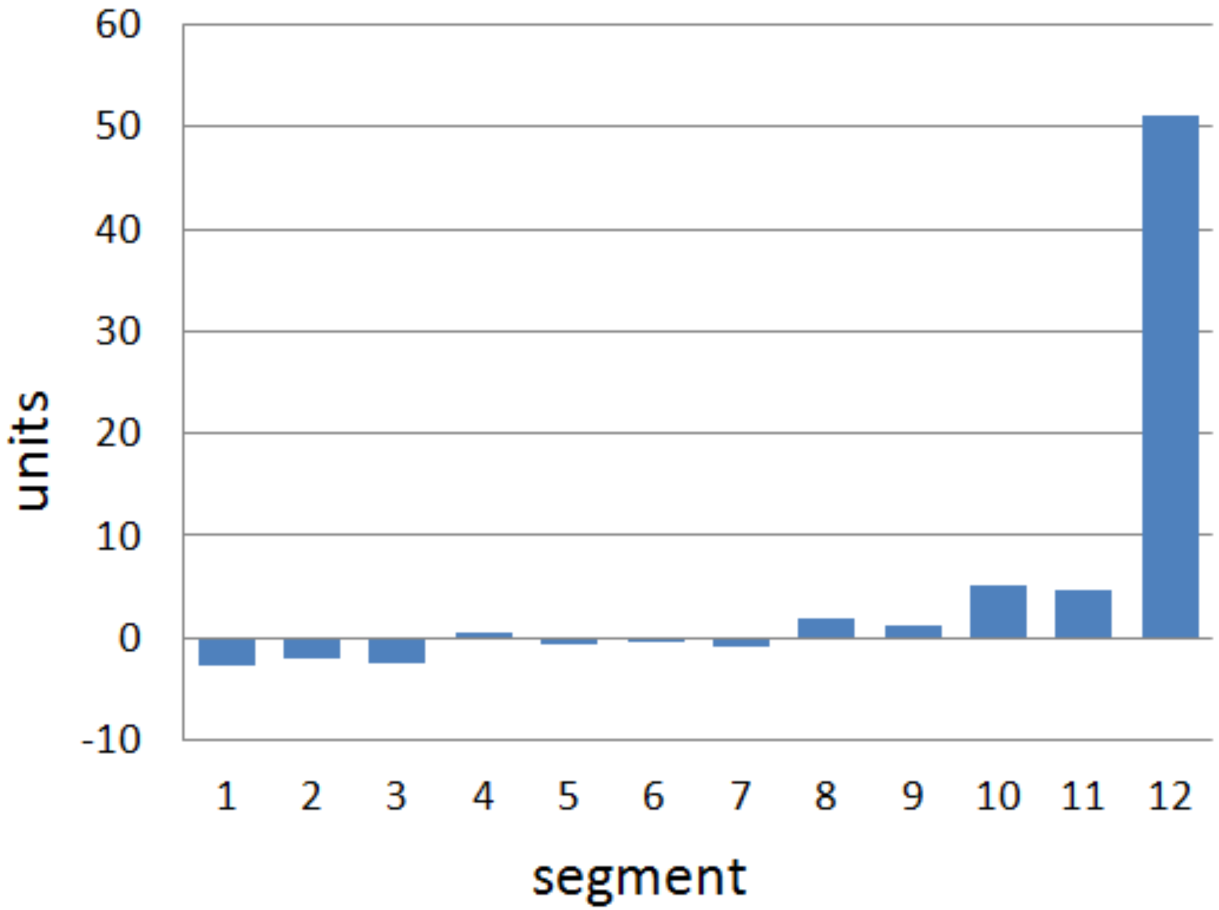
The 12th segment shows a larger error: being not fully immersed in the field, little error in the displacement gives rise to big error in the flux.

Experimental results: LHC dipole

Long shaft calibration bench

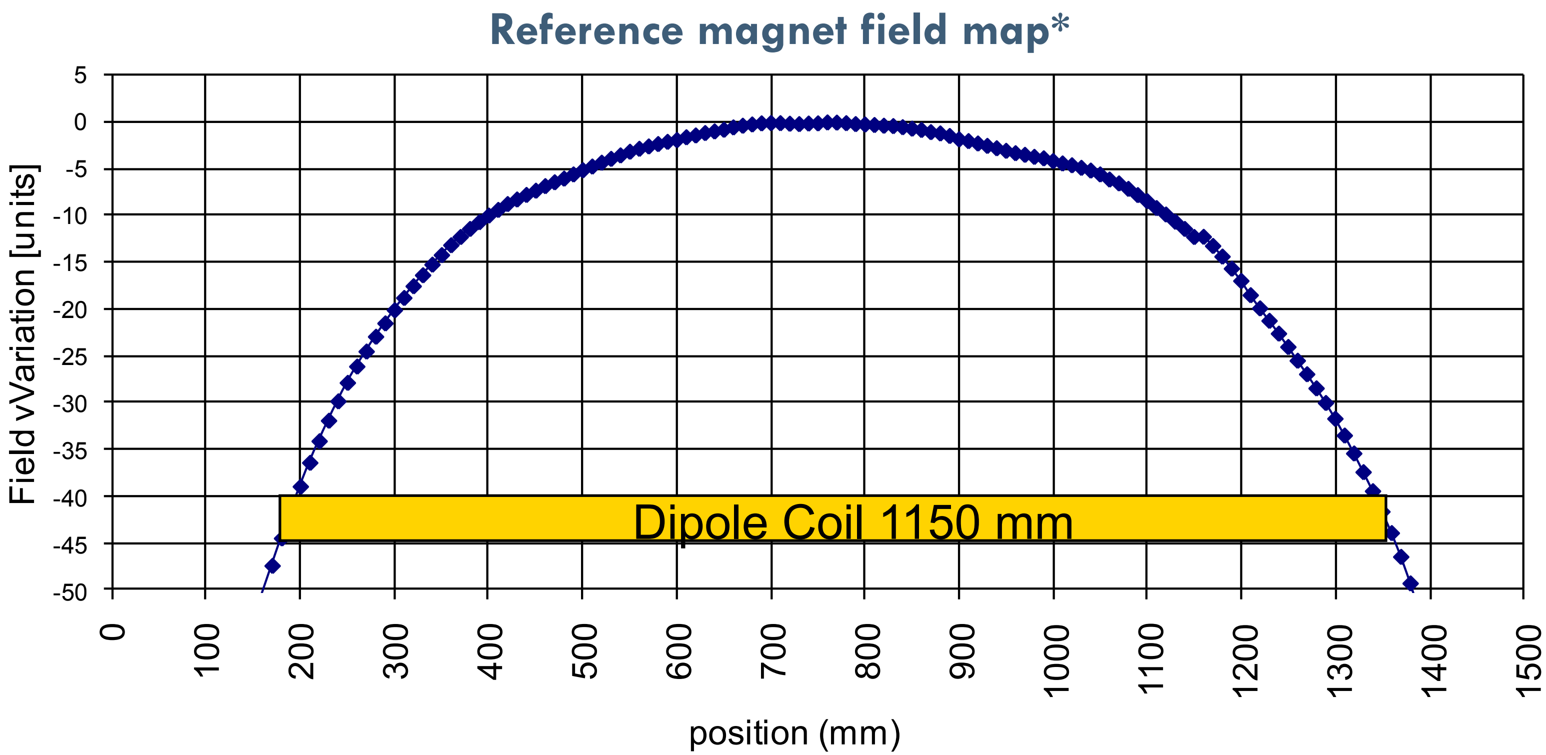
Experimental results: LHC dipole

Difference between "long shaft" and "in-situ" calibrations



The difference is -4 units in average.

Experimental results: LHC dipole



The field is not constant along the magnet.
The coil measure 14 units less the reference NMR.

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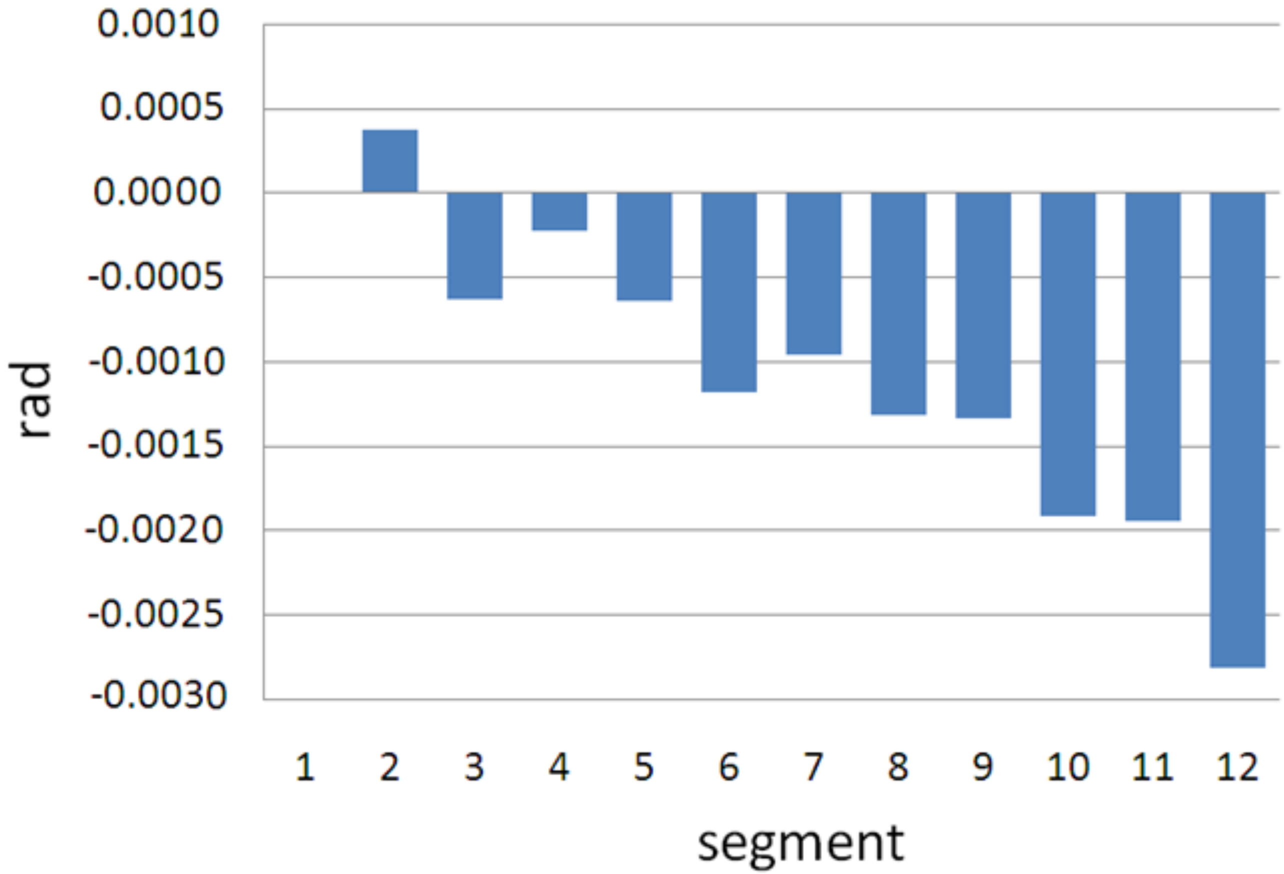
Experimental results: LHC dipole

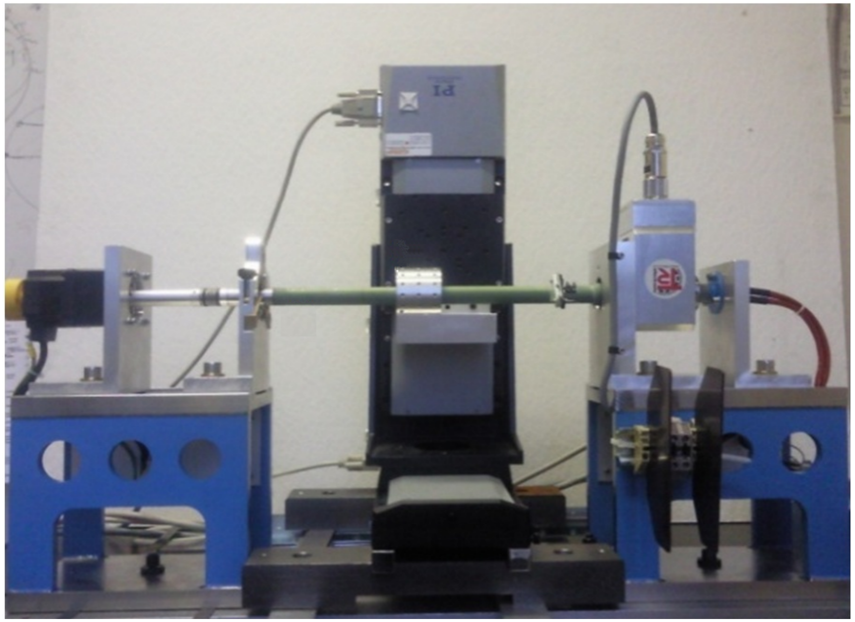
Difference between "long shaft" cal. and "in situ" cal.

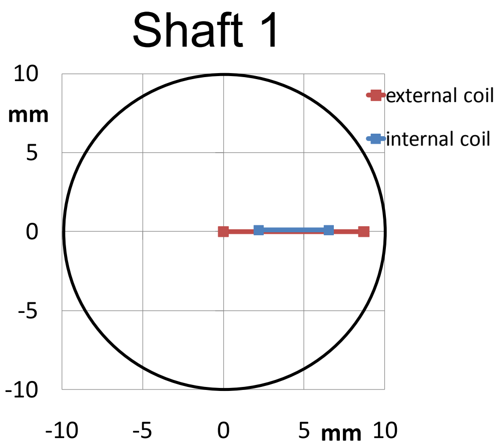


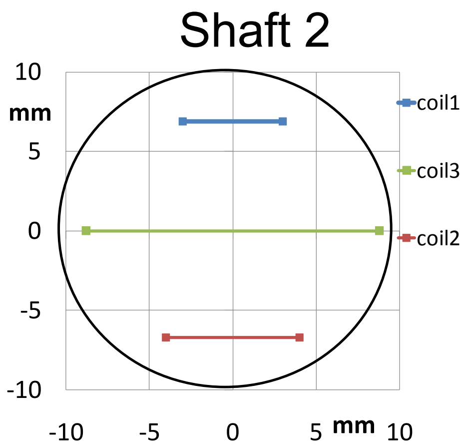
The difference is less than 2 mrad in average.

The long shaft calibration bench has been dismantled…

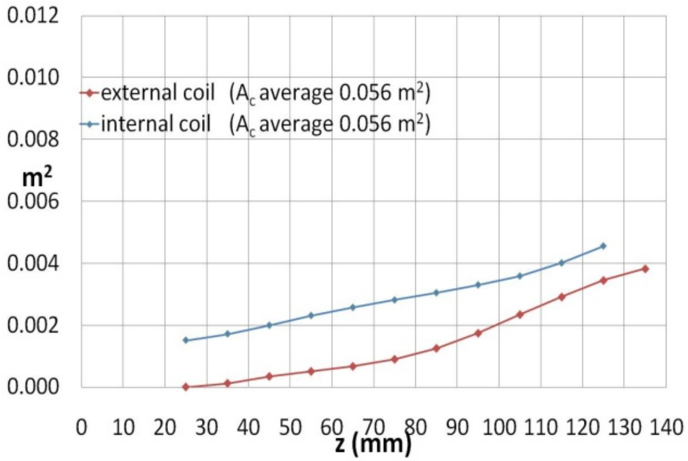
Experimental results: single segment (Linac4)

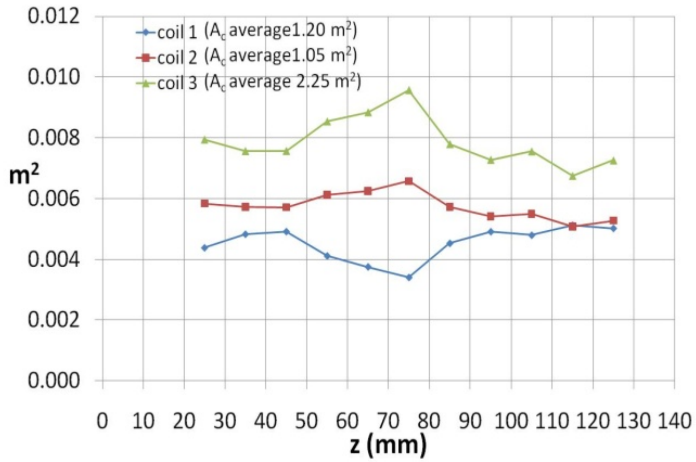






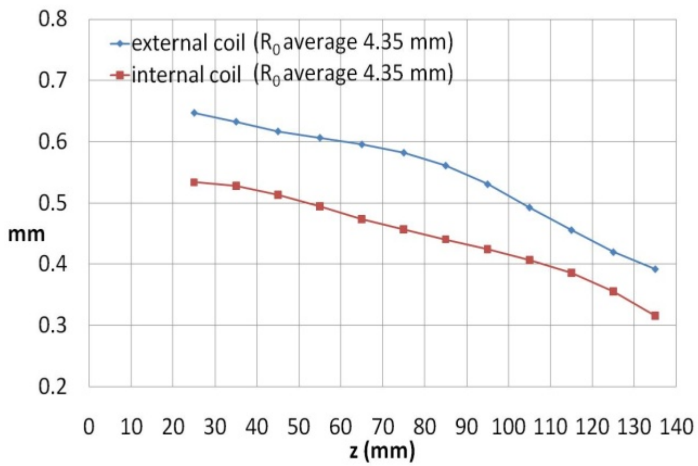
Experimental results: single segment (Linac4)

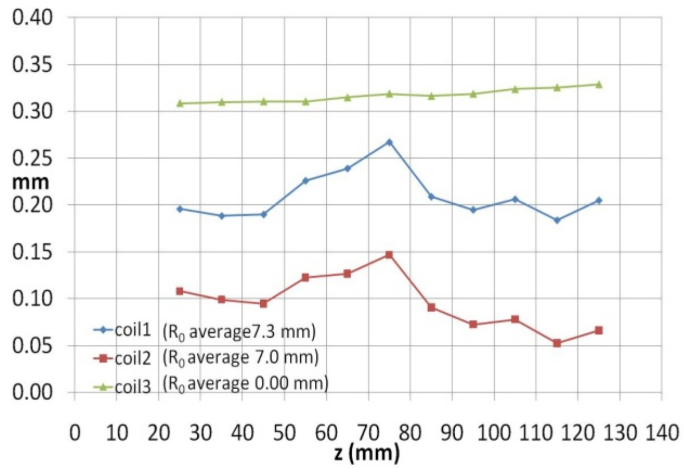




Shaft 1

Shaft 2





Experimental results: single segment (Linac4)

The new shaft was calibrated once on the R1 magnet and then the same coefficients have been used for the measurement of the other magnets.

Magnet name	Magnet length (mm)	Strength ssw (Tm/m)	ssw - coil in situ (%)	ssw - coil std cal (%)
R1	45	2.431	0.0	-6.4
R2	45	2.449	-0.2	-4.6
107	45	2.334	0.3	-5.8
108	45	2.331	0.3	-6.2
109	45	2.317	-0.2	-6.2
905	45	2.328	0.3	-5.4
1637691	80	6.861	0.3	-4.7
1637690	80	6.833	-0.1	-5.1

Conclusions

In-situ calibration:

- *for multi-segment shafts*
  - *surface errors are in the order of 1 unit in average compared to single-segment calibration*
  - *angle errors in the range of 2 mrad compared to long shaft calibration bench*
- *for shafts longer than magnets*
  - *the final difference in measured gradient with respect to SSW is in the order of 20 units*
- *for both*
  - *other deterministic errors can be corrected*

Thank you !!!

Questions?

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