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 \(\frac{U_x}{U_{ref}}\)
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**
The shaft has $n$ segments $\rightarrow$ $n$ unknown coil surfaces

- 2 sets of measurements by displacing the shaft of one segment: 2 different coils measure the same field, $\rightarrow$ $n-1$ 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 $\rightarrow n$ unknowns

- 2 sets of measurements by displacing the shaft of one segment: 2 different coils measure the same field $\rightarrow n-1$ 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

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

\[
\begin{align*}
R_0 e^{i\phi_0} &= -\frac{\Psi_2 \Delta z}{\Delta \Psi_1} \\
A_c e^{i\alpha} &= i e^{i\phi_0} \frac{\Delta \Psi_1 R_{ref}}{C_2 \Delta z}
\end{align*}
\]

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)

\[ A_c e^{i\alpha} = ie^{i\varphi_0} \frac{\Delta \Psi_1 R_{\text{ref}}}{C_2 \Delta z} \]

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

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

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 ‰.
Shaft composed by 12 segments of 1150 mm mechanically connected in series
Experimental results: LHC dipole

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

The difference between “long shaft” and “in-situ” calibrations 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.

* Olaf Dunkel, IMMW 15
Experimental results: LHC dipole

The difference between “long shaft” cal. and “in situ” cal. 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
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.

<table>
<thead>
<tr>
<th>Magnet name</th>
<th>Magnet length (mm)</th>
<th>Strength ssw (Tm/m)</th>
<th>ssw - coil in situ (%)</th>
<th>ssw - coil std cal (%)</th>
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<tbody>
<tr>
<td>R1</td>
<td>45</td>
<td>2.431</td>
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<tr>
<td>R2</td>
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</table>

*Experimental results: single segment (Linac4)*
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?