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A Transducer for Measuring the Field Quality in Superconducting Solenoids

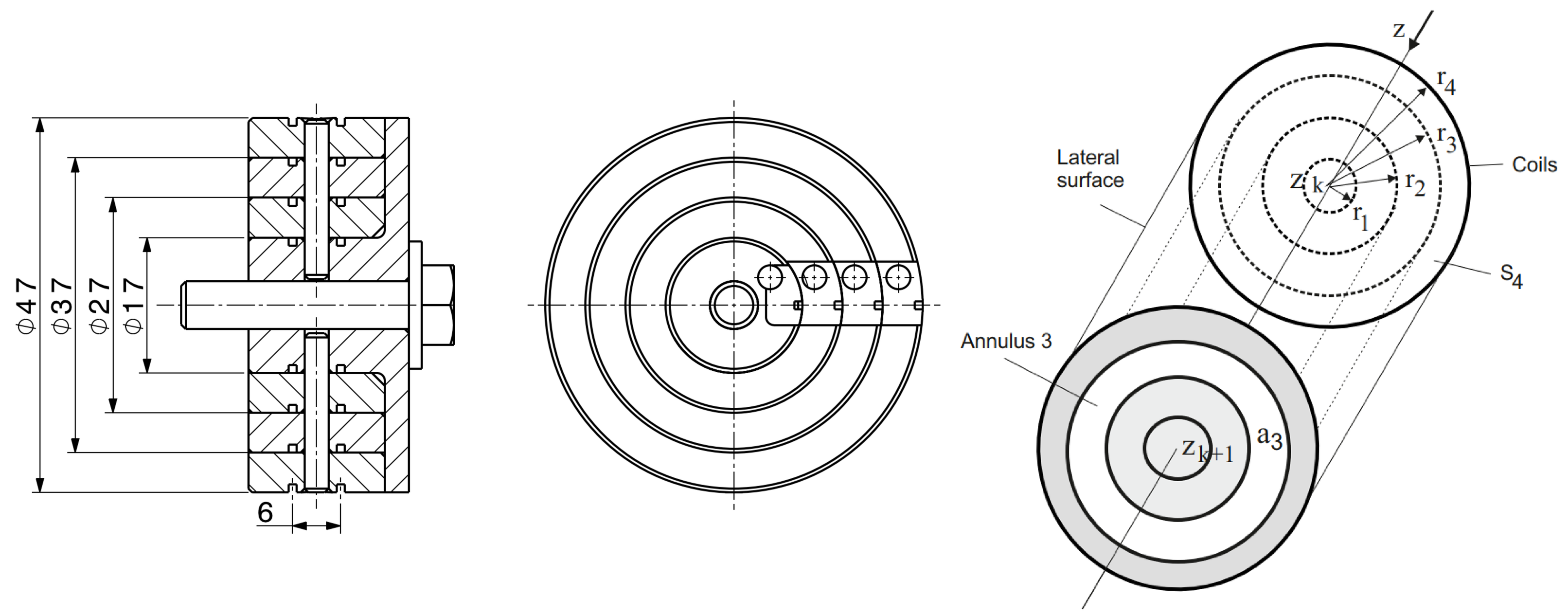
Carlo Petrone, Bernardo Bordini, Marco Buzio, and Stephan Russenschuck

Abstract

The critical current of superconducting wires is measured at CERN in four test stations that use high-field superconducting **solenoid magnets** achieving up to 15 T. The reduction of the uncertainty in the critical-current **measurements** requires the **field mapping** of the solenoids in their operating condition. This paper presents the design and application of a solenoidal-field transducer based on a pair of nested **induction coils**, which are moved along the axis of the magnet. The system allows to extract the longitudinal and transverse field components as a function of the sensor's longitudinal position. The radial dependence of the magnetic flux density can be estimated from the nested coils of different diameters in the solenoidal magnets.

Field Transducer

The field transducer comprises a pair (A and B) of **nested induction coils** (a_1 to a_4 and b_1 to b_4) mounted on a common support shaft, spaced axially by 6 mm. The coils are wound on an accurately-machined cylindrical core made from fibre-glass epoxy with the largest possible diameter to fit into the **warm bore of the cryostat**.

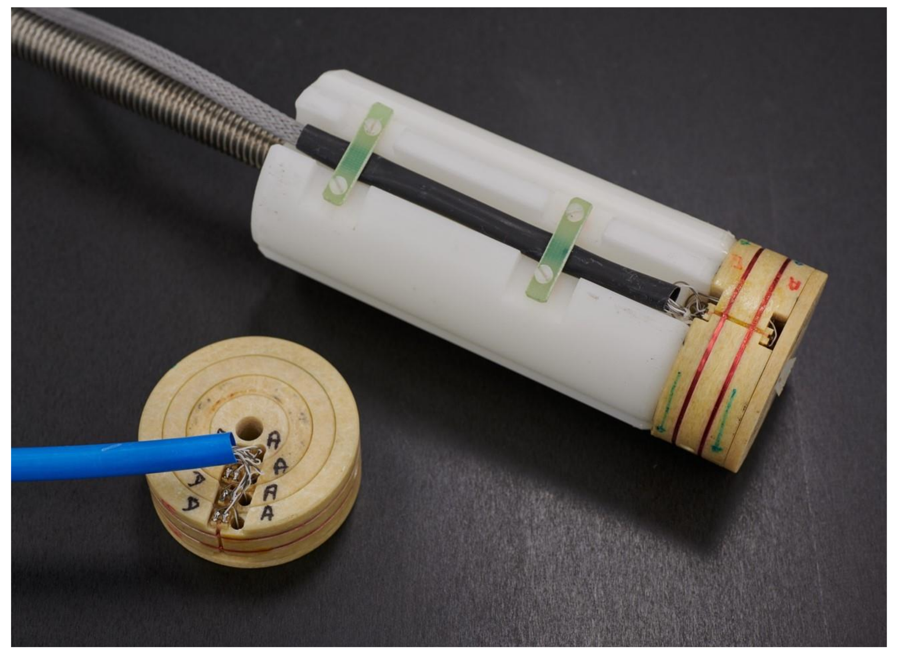


The coil surfaces S_i, are **calibrated in a reference dipole magnet**,. The coil resistances are used to correct the different attenuation on the input impedance of the integrator cards. The effective coil radii r_i are retrieved from the calibrated surfaces by $r_i = \sqrt{S_i}/(\pi N)$, where N is the number of turns in each coil ($N = 120$).

For the **field measurements**, a warm bore has been fitted in the cryogenic test station. This is motivated by avoiding feed-troughs into the helium bath, and the **coil calibration data** which is established at room-temperature.

Measurement Procedure

The **transducer** is **moved** by a **precision alignment stage** along the axis of the magnet. The induced voltages are integrated between **trigger** points from the linear encoder of the alignment stage.



Two measurement procedures are employed:

1. For measuring the **absolute field strength**, the induction coils are moved from the field-free region to a well defined longitudinal position $\boldsymbol{z_k}$. Integrating the induced voltage yields the flux linkage through the base surface S_i of the solenoidal coil. The coil measurement results are within 0.5‰ agreement respect to Nuclear Magnetic Resonance (NMR) measurements.
2. For measuring the **field homogeneity** in the magnet bore, the incremental flux linkage is integrated between two trigger points (0.058 mm).

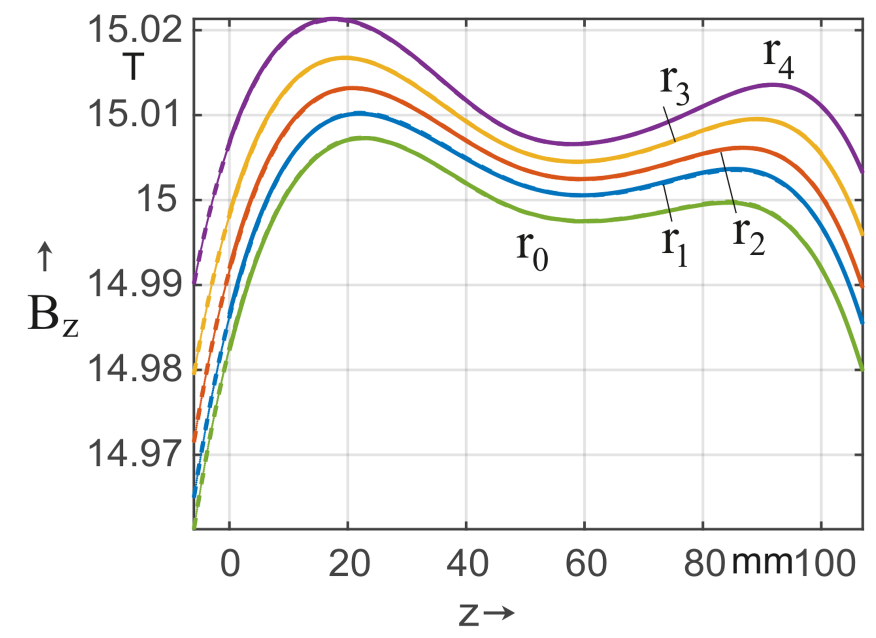
The radial dependence can be calculated by the flux linkages in the surfaces bounded by two concentric coils of area $a_i = \pi(r_{i+1}^2 - r_i^2)$. At every longitudinal position $\boldsymbol{z_k}$, where $\boldsymbol{k} = [\mathbf{1}, \boldsymbol{K}]$ is the number of the trigger point from the linear encoder stage, the flux density can be expressed by a second-order polynomial $B_z = ar^2 + br$ +c so that the flux linkages in the annuli are given by:

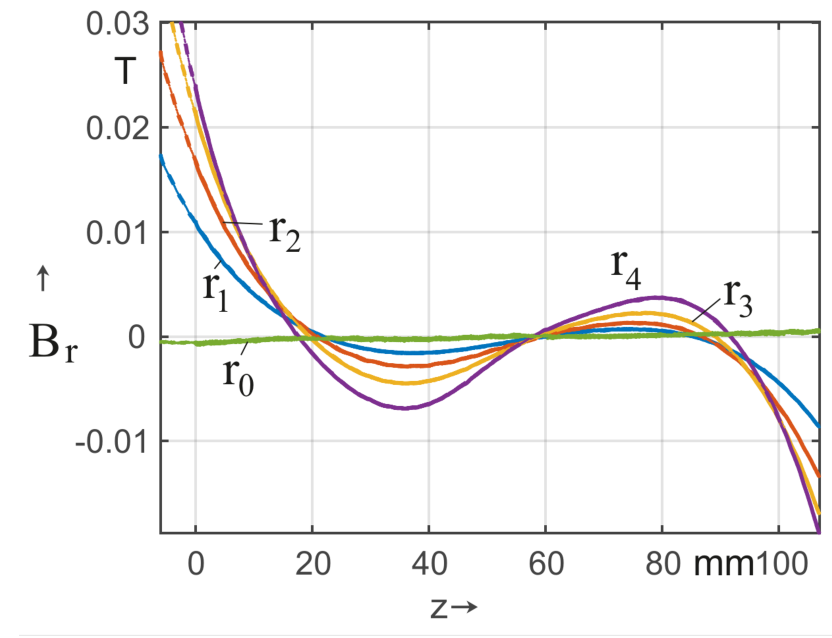
$$\Phi_i = \int_0^{2\pi} \int_{r_{i-1}}^{r_i} (ar^2 + br + c)\; r \;\mathrm{d}\phi \;\mathrm{d}r$$

The radial dependence of the longitudinal component of the magnetic flux density $B_z = (z_k, r)$ at position z_k can be fitted by solving a linear equation system.

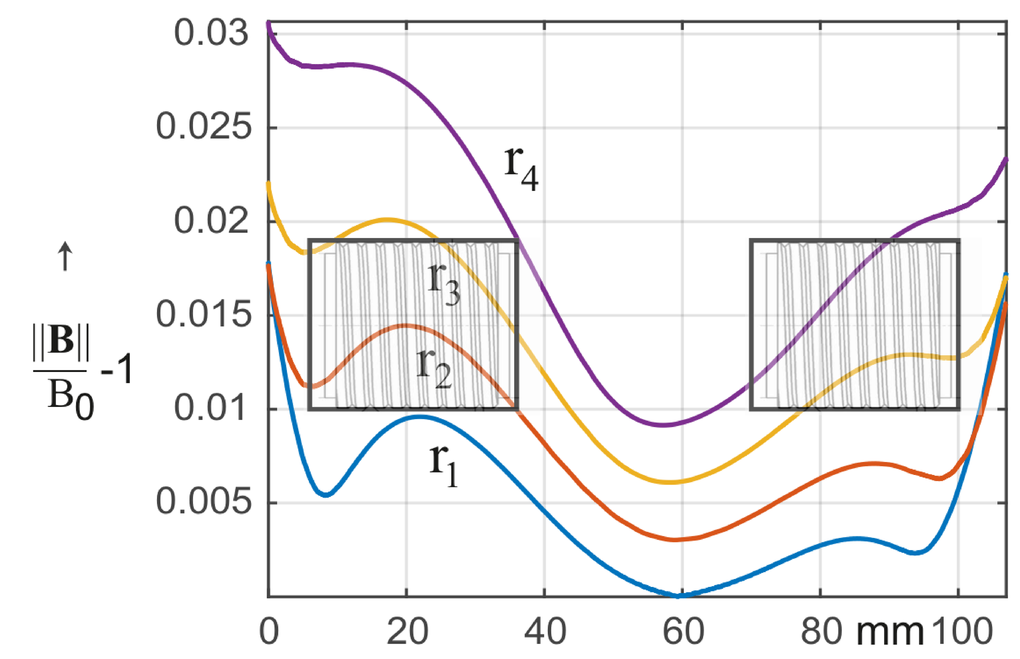
$$\begin{bmatrix}\Phi_4\\ \Phi_3\\ \Phi_2\\ \Phi_1\end{bmatrix} = 2\pi N \begin{bmatrix} \frac{1}{4}(r_4^4 - r_3^4) & \frac{1}{3}(r_4^3 - r_3^3) & \frac{1}{2}(r_4^2 - r_3^2)\\ \frac{1}{4}(r_3^4 - r_2^4) & \frac{1}{3}(r_3^3 - r_2^3) & \frac{1}{2}(r_3^2 - r_2^2)\\ \frac{1}{4}(r_2^4 - r_1^4) & \frac{1}{3}(r_2^3 - r_1^3) & \frac{1}{2}(r_2^2 - r_1^2)\\ \frac{1}{4}r_1^4 & \frac{1}{3}r_1^3 & \frac{1}{2}r_1^2 \end{bmatrix} \begin{bmatrix}a\\ b\\ c\end{bmatrix}$$

Measurement Results





- Figures shows the **longitudinal and radial field components** at the four radii.
- The green curve shows the fluxes in the annuli and fitting the radial field dependence to the second-order polynomial on-axis field.
- The field **homogeneity** of the applied on the wires is shown.
- The variation of the field levels on the order of 3‰ on the range of 107 mm at 15 T, and 1‰ within a **cylindrical domain with 28 mm inner and 32 mm outer radius**.



Conclusions

- **New transducers** for measuring the field quality in superconducting solenoids were developed. The field transducers are capable of measuring the relative field with an uncertainty below 0.1‰ and the absolute field of 1‰.
- The field measurements of the test **solenoids** were performed to evaluate the uncertainty in the measurements of the **critical current** density of the superconducting wire.
- Within the mapped domain, the field homogeneity in the solenoidal test magnet is on the order of 1‰, as required for the critical-current measurements of the HL-LHC wires.

www.CERN.ch - carlo.petrone@cern.ch

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