Extraction of 3D field maps of magnetic multipoles from 2D surface measurements†

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In large-aperture, short-length magnets with strong magnetic fields, such as superconducting triplet quadrupole (STQ)[1)] magnets in the BigRIPS[2)], the fringing field region is generally very large, and the shape and effective length of the magnetic field distribution change with the excitation current due to saturation of the iron core. Further, higher-order pseudo terms become relatively large in these magnets compared to those in small-aperture, long-length magnets because they originate from the changes of the magnetic field in the direction along the beam axis. It is indispensable to correctly extract pseudo quadrupole components as well as first-order quadrupole components from measured 3D field maps even for first-order ion-optical simulations.

Pseudo terms have the same azimuthal angle dependence as that for the leading term, such as $\cos 2\theta$ for a quadrupole, but have a higher-order radial dependence, such as r^3 rather than r for a quadrupole. At first glance, it appears that field map data measured at different radii are required to solve the r dependence. However, we present a practical numerical method that eliminates the need for this data. In this method, the measurement data for one radius of one component in the cylindrical coordinates, i.e., 2D field measurements on the surface of a cylinder, are sufficient to determine the full 3D magnetic multipole field in the cylinder. Using this novel method, we can extract the distributions along the beam axis for the coefficient of the first-order $2n$-pole component $b_{n,0}(z)$, which is the leading term of the $2n$-pole components in the multipole expansion of magnetic fields. Higher-order pseudo components $b_{n,m>0}(z)$ can be deduced from the leading term via recursion relations. The full 3D field map of $2n$-pole is completely described by these components. See the original paper† for details about the formalism and procedure of the method. Steps of the process of extraction of full 3D field maps of magnetic multipoles from 2D surface measurements are summarized in Fig. 1.

The proposed method was applied to large-aperture STQ magnets in the BigRIPS fragment separator at the RIKEN Nishina Center RI Beam Factory. Figure 2 shows the leading term $b_{2,0}(z)$ together with the pseudo terms $b_{2,1\cdots4}(z)$, which were obtained from the measurement result of $B_{\theta,2}$ at 100 A. Here $b_{2,1}$ is relatively large, showing that the pseudo terms cannot be ignored.

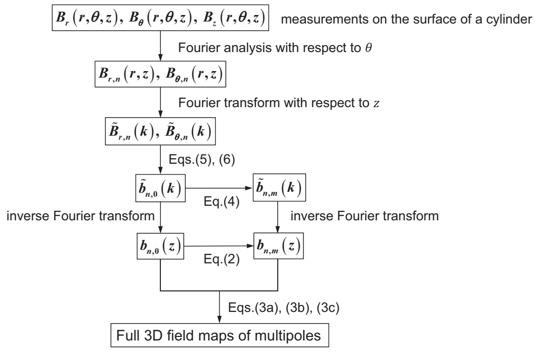

Fig. 1. Diagram of full 3D field map extraction from 2D surface measurements. The process of extracting the leading term $b_{n,0}(z)$ and the pseudo terms $b_{n,m}(z)$ from the 2D measurements of the surface of a cylinder are shown step-by-step. The equation numbers shown by the arrows indicate those used for the corresponding processes described in the original paper†.

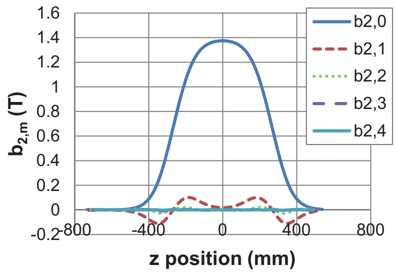

Fig. 2. Examples of $b_{2,0\cdots4}(z)$. $b_{2,0}$ was extracted from $B_{\theta,2}$, which was measured at a radius of 107 mm and at an excitation current of 100 A for a Q500 quadrupole magnet in STQ24. Pseudo terms $b_{2,1\cdots4}$ were calculated from $b_{2,0}$ with the differential recursion relation (2) in the original paper†.

The obtained $b_{2,0}(z)$ distributions were parametrized using the Enge functions to fit the fringe field shapes at all excitation current values, so that unmeasured values are interpolated. We implemented these parameters in the ion-optical calculation code COSY INFINITY[3)] and realized a first-order calculation that incorporates the effect of large and varying fringe fields more accurately.

References
1) K. Kusaka et al.: IEEE Trans. Appl. Supercond. **14**, 310 (2004).
2) T. Kubo: Nucl. Instr. Meth. **B204**, 97 (2003).
3) K. Makino, M. Berz: Nucl. Instr. Meth. **A558**, 346 (2006).

† Condensed from the article in Nucl. Instr. Meth. **B317**, 798-809 (2013)
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