

Establishing C^3 , the Coherence between Accelerator Physics Requirements, Magnet Manufacture, and Magnetic Measurements

Stephan Russenschuck¹ and Oliver Boine-Frankenheim²

¹*CERN, 1211 Geneva 23, Switzerland, stephan.russenschuck@cern.ch*

²*GSI and Technical University Darmstadt, Germany*

Abstract – In mathematics, C^3 denotes a 3-times continuous differentiable function. We use this as shorthand for establishing the coherence between beam physics simulations and machine requirement, magnet design and manufacture, and magnetic measurements.

Magnetic field measurements primarily serve for the quality assurance of the magnet production, both at an early stage in the production process and after the reception of the magnets in the laboratory. Measurements are also performed for validating numerical field simulation (FEM) tools and magnet design techniques.

In order to study the performance of the accelerator and to allocate a budget for magnet misalignment in the tunnel, the beam physicists require the field maps and multipole field errors of the magnet system, either from validated numerical models or from magnetic measurements. Field measurements are also done for on-line monitoring of the magnet behavior and thus providing direct feedback to the accelerator control room for adjusting the magnet current cycles, and to tune the high-frequency accelerator cavities.

This paper describes the approaches and techniques in magnetic field measurements, discusses their limitations and attempts to put them in coherence with the requirements from beam physics and magnet design.

I. INTRODUCTION

For the LHC magnet system, the coherence in the approach for beam physics simulations, magnet design and manufacture, and magnetic measurements was well established [1]. The aperture of the superconducting magnets is round and the beam is pencil shaped with respect to the dimensions of the magnet aperture. The LHC beam is ultra-relativistic and stiff, that is, the dipole magnets give only a small kick to the particle trajectory even though their magnetic lengths is 14.3 meters. Moreover, the betatron phase amplitude changes only very slightly within the arc magnets (the beam is paraxial with the magnetic axis of the magnets), so that they can be represented as a thin lenses in the beam tracking codes. The small sagitta of 9.14 mm of the LHC main dipole magnets can be neglected in the

measurements and field description.

A classical method for describing the magnetic flux density in accelerator magnets is to develop the eigenfunctions of the 2D Laplace equation (expressed in cylindrical coordinates) into the Fourier components of the field solution (calculated or measured) at a given reference radius; usually $2/3$ of the aperture, or 17 mm in case of the LHC [2]. This method works well for long, straight magnets and is perfectly in line with magnetic field measurements using rotating search coils. The Fourier coefficients of the field solution, known in the accelerator community as field harmonics, serve for the integrated field reconstruction and are the direct interface between the magnet "owners" and the beam physicists.

Extensive beam tracking studies during the LHC design and construction phase, have yielded a good knowledge on the effect of multipole field errors and the role (and limitations) of the correction system. The magnetic measurements were therefore based on rotating search coils assembled in long shafts and driven by a motor unit [3]. An angular encoder and a digital integrator were used to re-parametrize the measured voltage (over time) into flux increments measured as a function of the coil's angular position. In this way the requirements on the uniform motion of the drive unit could be relaxed.

The magnet system of the LHC could also be based on the experience with the Tevatron and HERA machines [4]. In particular, the dynamic effects in superconducting magnets were intensively studied and brought under tight control during the magnet construction period. A strategy could therefore be developed to monitor the production process with field measurements at ambient temperature. Using a well established cold-warm relationship, the magnetic measurements at cryogenic conditions could be reduced to about 10% [5].

Recently, a large number of magnetic measurement requests have arisen from new accelerator projects, which include SESAME, HIE-ISOLDE, ELENA, and Linac4, at CERN, as well as the magnet system for MedAustron and the magnets for the FAIR superFRS magnets. Limited resources and a narrow time slots impose optimized procedures and instrumentations. Standardization of measure-

ment equipment becomes essential in order to increase efficiency in terms of installation time and workflow. Large efforts have been undertaken to optimize CERN measurement resources while keeping a stringent measurement quality. This resulted in a flexible control and acquisition software, a standard drive system, rotating-coil systems with standard assembly of tangential search coils, and multipurpose measurement benches. Moreover, an increasing number of measurement have been based on the stretched wire techniques, as these techniques are very universal and do not require magnet-specific probes and instrumentation.

However, the most important savings on material and resources are made on a different level: it is important to establish a coherence between the beam physics requirements, the magnet system, and the magnetic measurements in order limit the development of dedicated instrumentation and reduce the measurement time, while providing exactly the feedback needed. In this respect, the new projects are very challenging. Magnets with small bending radii and large aspect ratios of the air gap will be built. A brute force method consists of mapping the field with a 3D Hall probe, which is relatively inaccurate (compared to the rotating search coils) and very time consuming. For fast-cycling magnets the field is often measured only on the mid-plane using a stationary fluxmeter which is (because of its size) very expensive to fabricate in PCB technology. While fluxmeter measurements yield a relatively fast feedback on the magnet-to-magnet reproducibility, the measurements are of limited relevance for beam simulations. Fluxmeters are moreover limited to fast ramping magnets to avoid too small signals and integrator drifts. When the magnet is operated in steady state condition, the only meaningful measurement using a flux meter can be done by moving the entire fluxmeter from a field-free region into a final position within the magnet and integrating the induced voltage. This yields the total flux intercepted by the conductor.

Components of a more coherent approach towards C^3 include the expansion of the field solution into bipolar and elliptic coordinates, the local description of field errors in the magnet ends, and the post-processing of measurement data using numerical field computation methods. For example, 3D hall probes can be calibrated by imposing that the measured magnetic flux density must be divergence free. The raw data (fluxes or fields) can be used as Dirichlet and Neumann data of the boundary element technique, and the positioning errors of the mapper can be corrected on FEM mesh of the boundary [6]. Taylor maps can then be obtained with higher precision by differentiating into the Greens kernels of these boundary data.

II. MAGNETIC MEASUREMENT TECHNIQUES

When magnets must be measured in fast-ramping conditions a flux meter at fixed position delivers a voltage signal

in a pulsed field. Modern integrators with large bandwidth and time resolution connected to such a coil can give the full $B(t)$ curve and measure saturation effects of the iron yoke. Hysteresis and eddy current effects can be separated by measurements at different ramp rates. One precaution must be taken for the remanent field of the magnet, i.e., the field at zero current value. The possible measures are to use a bipolar power supply and perform symmetric sweeps from negative to positive maximum current. Other methods are to demagnetize the magnet with a bipolar supply or measure the remanent field, for instance with a flip coils or Hall probes.

Search coils are the standard method for measuring multiple field errors in accelerator magnets [7]. However, the measurement of magnets with small apertures of less than 20 mm in diameter is a challenging task [8]. Consider a rotating coil inside a bore of radius r , then the maximum number of coil turns that can be wound with a conductor of given diameter is proportional to r^2 and, consequently, the coil sensitivity factor scales with r^{-2} . The impact of mechanical tolerances and calibration errors increases drastically and the measurement uncertainty can be expected to be one to two orders of magnitude higher than in typical synchrotron magnets with an aperture radius of 50 to 100 mm. Moreover, the coils are affected by longitudinal non-uniformity of the width and radius of about 0.6%. When measuring a magnet that is shorter than the search coil, such variations imply that standard calibration of the average geometry becomes meaningless.

A method to circumvent these problems is based on displaced or moving wires [9], [10], [11]. A conducting wire is moved inside the magnetic field by precision displacement stages at which the two end-points of the wire are fixed. Copper-Beryllium (CuBe) wires, 0.1 mm thick, are commonly used because of their high tensile strength and low martensitic contaminations. The return wire must be routed through a field-free region. The integrated voltage at the connection terminals of the wire is a measure for the flux linked with the surface that is traced out by the moving wire.

This so-called single stretched wire method is commonly used to measure the magnetic field strength and magnetic axis. It can also be used in a vibrating mode when it is excited with an alternating current at resonance frequencies. This operation mode is very sensitive to determine the magnetic axis in solenoidal magnets [13]. This method has recently been extended to measure multipole field errors in accelerator magnets by exciting the wire with an alternating current well below the natural resonance frequency to make use of the linear relationship between wire oscillation amplitude, integrated field, and current amplitude. We therefore distinguish between magnetic measurement methods based on vibrating (resonant) and oscillating (non-resonant) wire motions although these terms are often

used synonymously [12], [14].

A brute force method for measuring magnetic fields is the mapping with hall probes. The challenges here are the calibration of the probes, which are very sensitive to temperature variations. The accuracy of the measurement strongly depends on the mechanical stability of the displacement stage, as often a long shaft is required to enter into the aperture of the magnet. Typical specifications for such systems require ranges of about a meter in the transversal directions and up to 10 meters in longitudinal directions with an accuracy on the order of 0.1 mm. Mapping of fields, even if the data acquisition can be done "on the fly" is a very time consuming method and delivers discrete measurements on a grid only.

III. ISSUES IN ESTABLISHING C^3

To establish the coherence between accelerator physics requirements, magnet manufacture, and magnetic measurements is not an easy task. We present, therefore, a list of open issues rather than an established path. All parties involved must be aware about the risk of over-specification: Assumptions that must be made of beam tracking results in specifications of the field homogeneity on the order of 1 unit in 10000. This yields tight (and costly) tolerances on the material selection, punching of laminations and assembly of the magnet, which in turn leads to even higher demands on measurement probe calibration and data acquisition techniques for magnetic measurements.

A classification of coherence issues can be done according to who will be the main "user" of magnetic measurements. Measurements driven by beam physics requirements must deal with the appropriate definition of the good-field region and the field homogeneity. This will depend on the specific application of an optical element. For example, a curved, normal-conducting dipole magnet may be used as a bending magnet in a synchrotron, as a spectrometer, or as bending magnet in a beam transfer line. Will it therefore be sufficient to measure the longitudinally integrated field errors or will a more local field measurement be needed? What are the systems variables of the beam tracking codes (multipole field errors, field maps, Taylor approximations, integrated strength values) and how can they be derived from the magnetic measurement raw data?

A. *Beam physics requirements*

A large number of software packages have been developed to study the dynamics of charged particles in accelerators. For many applications it is sufficient to track an ensemble of single particles through the magnetic elements of the machine. Such codes include MADX [15], SixTrack [16], and PTC [17], among others. Self interactions between the particles in the beam (space charge) can

cause emittance growth and beam loss. Special purpose codes to simulate space charge effects in linear and circular accelerators are pyORBIT [20] and Synergia [21], for example. In contrast to single particle codes, the numerical accuracy in space charge codes is limited by finite particle and grid effects [22].

MADX consists of different routines for (single) particle tracking, beam optics (twiss parameters and beam envelopes) as well as symplectic integrators. For tracking the elementary magnetic elements are thin and thick lens descriptions of dipoles and quadrupoles. PTC has been added to MADX in order to enable thick element tracking with arbitrary order [18]. MADX allows straight and curved trajectories of the particles (which is known as the design orbit) requiring the field and gradients in the transversal plane to this orbit.

For the study of the beam envelope and long term stability in synchrotrons and storage rings as well as light sources employing wigglers and undulators, the description of the magnet elements must be symplectic, that is, the integral operators acting on these elements must preserve the volume form of the phase space (of all possible values of position and momentum variables). This is automatically the case as long as the magnetic field in a magnet can be described by a series of thin lenses with an equivalent kick.

Only a few codes, such as PTC and COSY INFINITY, among others, can accurately handle a displacement of the design orbit in the magnet element itself.

The field and its derivatives are required around the design orbit. The order is defined by the specific beam physics requirements, for example by the storage time or the maximum emittance of the beam. As long as the design orbit is not deviating too much from the central orbit, and the multipole field expansion is valid, the calculation of these gradients is straightforward. This is, however, less than trivial in the magnet extremities, in strongly curved magnets, wigglers, and solenoids.

Measured or calculated fields on a grid are only appropriate to first and second order in the grid spacing because of the discretization errors.

Often, the field description relies on measurements on the midplane of the magnetic element. Out-of-plane field expansions therefore depend strongly on the quality of the field derivatives in the midplane. This is not a problem for computed but for measured fields. In this case it is advantageous to measure the field on a closed volumetric domain and to represent the field by integrals based on the Kirchhoff theorem. For this reason, the magnetic measurement section at CERN is developing field transducers based on a longitudinal displacement mechanism, which because of its resemblance, is nicknamed "toy train".

B. Magnet design and production

When measurements are driven by modeling capabilities of the employed magnet design codes (usually based on structural and electro-magnetic finite-element FEM packages) it is important to check the necessary model reduction and measure the effect of shims, chamfers, welding seams, material parameter etc. [2]. An iterative process is often required to distinguish manufacturing or modeling errors from measurement artifacts and to decide on corrective actions for the magnet design. It is here where a strong link between the magnet designer and the magnetic measurement engineer can yield improvements on both the measurement techniques and the modeling capabilities of the design codes. If the coherence is established, beam simulations can often be based on computed rather than measured data. It will then also be possible to simulate the effects of tolerances and in this way arrive at a technical specification for the manufacturing of the magnets.

When measurements are driven by (series) magnet manufacturing, the aim is to check the magnet-to-magnet reproducibility and to arrive at acceptance criteria for the delivered magnets. Often inverse field computation are needed in order to relate the measured field errors to manufacturing errors. During the series production of the magnets, a reduced set of magnetic measurements will be sufficient as long as there are no unforeseen effects or sudden changes in the quality of the delivered magnets.

C. Accelerator operation

When magnetic measurements are driven by the accelerator operation, the demands are much more challenging. In some cases the magnets exceed the model capabilities of the FEM codes, or not sufficient information is available to set up such a precise model. Different machine cycles may result in a coupling of dynamic and hysteretic effects which are difficult to predict. Magnetic measurements employing search coils as well as NMR and ferromagnetic resonance probes are therefore required for on-line monitoring of the magnetic field in reference magnets that are excited at the same current as the magnets in the machine [23].

IV. CONCLUSION

The coherence between accelerator physics requirements, magnet manufacture, and magnetic measurements was very well established for the LHC. This is much less so for the latest projects requiring fast-ramping, small, short, and curved magnets.

In an ideal world, a magnet is built without tolerances, without any systematic manufacturing error, and without variations in the material parameters. The numerical field computation model is able to predict all static and dynamic phenomena, and the magnetic measurements, without sys-

tematic errors from calibration or any random errors, confirm the prediction of the magnet designer.

In the real world, however, an iterative process is often required to distinguish manufacturing or modeling errors from measurement artifacts and to decide on corrective actions for the magnet design. In some cases, hysteresis effects in the magnets require on-line monitoring of the field strength for the optimization of the accelerator performance.

In an accelerator project, the field measurements are often on the critical path, because delays in the performance or interpretation of these measurements lead to a late release of the series production or a late installation of the components in the accelerator tunnel. For the LHC, magnetic measurements at ambient temperatures were performed at the magnet manufacturers' promises in order to intercept manufacturing errors at an early stage. A good knowledge on the correlation between measurements at ambient and cryogenic temperatures made it possible to limit the number of time-consuming measurements after the electrical tests at CERN.

For smaller projects, such an approach is not feasible; either because there is a considerably shorter R&D phase or because of the low number of magnet units. In these cases, the magnetic measurements must be well chosen and limited to the methods that yield the required feedback to the magnet designers and beam physicists at minimum cost of time and resources.

REFERENCES

- [1] L. Evans, "The Large Hadron Collider: a Marvel of Technology", EPFL Press, Lausanne, Switzerland, 2009
- [2] S. Russenschuck, "Field Computation for Accelerator Magnets: Analytical and Numerical Methods for Electromagnetic Design and Optimization", Wiley, 2011.
- [3] L. Walckiers, "Magnetic measurement with coils and wires" in CERN Accelerator School CAS 2009: Specialized Course on Magnets, Bruges, 16-25 June, CERN, Bruges, 2009.
- [4] B. H. Wiik, "Progress with HERA", IEEE Transactions on Nuclear Science, 32, 1985
- [5] L. Bottura, "Standard Analysis Procedures for Field Quality Measurements Part I: Harmonics", Document LHC-M-ES-0007 rev 1.0, CERN, Geneva, Switzerland 2001
- [6] M. B. Giles, N. Pierce, E. Süli, "Progress in adjoint error correction for integral functionals", Computing and Visualization in Science, 2004
- [7] A. K. Jain, "Harmonic Coils", CERN Accelerator School on Measurement and Alignment of Accelerator and Detector Magnets, Anacapri, Italy, April 11-17, 1997; CERN Report 98-05, .

- [8] J. DiMarco, G. Chlachidze, A. Makulski, D. Oris, M. Tartaglia, J. C. Tompkins, G.V. Velev and X.Wang, "Application of PCB and FDM Technologies to Magnetic Measurement Probe System Development", IEEE Transactions on Applied Superconductivity, Vol. 23, No.3, June 2013.
- [9] A. Temnykh, "Vibrating wire field-measuring technique", Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Vol. 399, 1997.
- [10] T. Lei, X Wang, M. Wang, "Pulsed wire magnetic field measurement on the permanent magnet focusing device of millimeter-wave traveling wave tube", Journal of Applied Physics, 2008
- [11] Z. Wolf, "A Vibrating Wire System For Quadrupole Fiducialization", SLAC National Accelerator Laboratory, Menlo Park, 2005
- [12] P.Arpaia, M.Buzio, J.Garcia Perez, C.Petrone, S.Russenschuck and L.Walckiers, "Measuring field multipoles in accelerator magnets with small-apertures by an oscillating wire moved on a circular trajectory", Jinst May 8, 2012.
- [13] P. Arpaia, M. Buzio, J. Garcia Perez, C. Petrone, S. Russenschuck, L. Walckiers, "Measuring field multipoles in accelerator magnets with small-apertures by an oscillating wire moved on a circular trajectory", Journal of Instrumentation, 2012
- [14] P. Arpaia, C. Petrone, S. Russenschuck, L. Walckiers, "Vibrating-wire measurement method for centering and alignment of solenoids", Journal of Instrumentation, 2013
- [15] <http://madx.web.cern.ch/madx/>
- [16] F.Schmidt, CERN/SL/94 56 (2012)
- [17] E. Forest and F. Schmidt, Proc. ICAP, p.17 (2006)
- [18] P. K. Skowronski, F. Schmidt, R. de Maria, Proc. ICAP, p. 209 (2006)
- [19] K. Makino and M. Berz, Nucl. Instr. Methods A 427, 338 (1999)
- [20] <http://code.google.com/p/py-orbit/>
- [21] <http://web.fnal.gov/sites/Synergia>
- [22] I. Hofmann, O. Boine-Frankenheim, <http://arxiv.org/abs/1405.4153> (2014)
- [23] M. Buzio, R. Chritin, D. Cornuet, P. Galbraith, D. Giloteaux, "Status and outlook of B-train systems for magnetic field control", private communication, CERN, ATC/ABOC days, 2008