3D FIELD SIMULATIONS FOR CYCLOTRON MAGNET SYSTEMS

Abstract

Numerical modelling of cyclotron fields with the use of the software package KOMPOT is presented. KOMPOT 3D calculation models enable precision calculations of the “influence functions” for different components in order to adjust magnet system geometry and provide a desired field distribution. The models are developed with regard to fabrication/maintenance/cost saving requirements. KOMPOT enables modelling of non-linear magnetic properties and complex geometry of ferromagnetic and conducting elements. Simulated field maps are applicable for the trajectory analysis. Calculated EM loads are presented in a format suitable for the stress analysis. Solving the tripled problem makes it possible to form a closed iterative adjustment of the required field distribution

One of the central problems for isochronous cyclotrons is to form a desired radial field distribution at a constant period of ion revolution [1,3]. The cyclotron field has an intricate configuration. On the basis of the trajectory analysis, the isochronous field should be formed with an acceptable error as low as $10^{-3} \div 10^{-4}$. The demand for high-quality field indicates the importance of field formation in the cyclotrons.

The cyclotron magnet system may implement a radial-sectored or spiral-sectored configuration [1,3]. The radial-sectored configuration is easier in design and fabrication and is commonly used for low-energy cyclotrons (below 100MeV for protons) [1].

The promising method of field formation in cyclotrons is to combine simulations of 3D field distribution and sector profiles with magnetic measurements in the median plane. The simulated and measured data are then used for sector shimming to adjust the field [2].

An important aspect to provide a desired field distribution in the cyclotron is shimming [3]. The basic shimming methods are

- axial shimming by adjusting the sector thickness near the median plane;
- axial shimming by adjusting the sector thickness near the pole;
- azimuthal shimming by varying the azimuthal sector length with the radius.

As a criterion to choose the shimming method, radial variations of an averaged magnetic field in relation to the field in the magnet centre are studied. The goal is to provide a desired radial field distribution in the magnet median plane at different current levels taking advantage of field flattering as the magnet is saturated [3]. Based on the results of the study, the most effective shimming method is chosen. For example, the axial shimming near the median plane was utilised in the isochronous cyclotron DC-72 [2,4].

To provide a required isochronous curve for nominal operating points, field simulations are performed with the use of the program package KOMPOT [5,6]. Due to its open architecture, the package is flexible and easily adaptable to a specific problem. Special pre-and postprocessing tools can be added to expand KOMPOT capabilities.

In particular, a set of application programs have been developed specifically for cyclotron modelling:

– a mesh generator based on a parametric calculation of the cyclotron magnet system implemented in a specialised programming language;
– additional modules for the mesh generator to enable parametric calculations of complex curved surfaces, such as profiled sector surfaces;

– an interpolator for field calculations at any given point, specifically useful for field mapping with given angular, radial, and vertical steps;
– tools for a calculation of integral field parameters, such as radial distributions of an azimuthally averaged field, flatter and harmonics.

The additional tools allow effective synthesis of the cyclotron magnet systems.

For DC-72, the magnet system synthesis implied a choice of the magnet system geometry so that the radial distribution of an azimuthally averaged field in the median plane

$$\overline{B(r)} = \frac{1}{2\pi}\int_0^{2\pi} B_z(r,\varphi,0)\,d\varphi$$

gave isochronous acceleration at an operating point.

To account for the main features of a spatial field distribution, $B_{iz}(r)$ is found by solving a self-consistent problem for field behaviour and particle dynamics [7,8,9]. Additional constrains are taken as follows:

1) field at any point of the median plane should be below the maximum allowed level $B < B_{\max}$;
2) flatter $F = \overline{B^2}/\overline{B}^2 - 1$ should be below the upper limit $F < F_{\max}$ at any radius r,
3) free room available, particularly, in the central area, to install other DC-72 subsystems.

Synthesis of the DC-72 magnet system has been performed in 2 phases. The first phase comprised the computation of an influence of variable parameters on the radial distribution of the averaged field in the median plane. 3 sets of parameters were varied:

1) the main coil current;
2) the shape of the median-facing surface of the sector described via a spline function in terms of a set of parameters (this set of parameters could be supplemented during the synthesis to improve the field formation);
3) the shape of the central plug median-facing surface described with two parameters to comply with the plug taper.

Also the impact of the central shim shape and outer end radial facet of the sector has been studied. The influence of the central shim shape is found to be very weak comparing to other factors. This allows us to exclude it from the set of variable parameters for further calculations. The presence of the radial facet on the sector outer end leads to considerable improvement of the field quality, resulting in a field build-up in the working area, a high field at the external radius, more sharp field decrease in the extraction region, a low saturation in the sector edges at the external radius.

For all magnet systems the sizes of facets have been optimised.

Influence functions of the variable parameters are obtained as a difference between the initial and changed field distributions. To simulate the changed field, one of the parameters is varied slightly to observe the linear component of its influence function without losing calculation accuracy. To form the field with a required accuracy, 17 influence functions were calculated for DC-72, 19 influence functions — for U400 and CC18/, 15 influence functions — for CC12, 14 influence functions — for DC60. It should be noted that in a preliminary stage the number of influence function was approximately twice higher, but many influence functions were rejected in further computations.

The influence functions obtained are used as inputs for the second phase. The second phase is devoted to adjustment of the varied parameters so as to provide a field distribution best fitted (in terms of mean-square error) to the requirements. Since the influence functions are actually non-linear, the simulated field will differ from the expected distribution. This necessitates an iterative procedure to adjust the simulated field. Usually, it takes up to 20 iterations to form a cyclotron field with a required accuracy. The required field in the DC-72 prototype was generated in 4 iterations. For accelerators, the KOMPOT-simulated field maps match a required field distribution within tens of Gauss.

The simulation accuracy is governed by a range of computational and manufacturing factors. The computational accuracy depends essentially on the fineness of a calculation mesh. However, a large number of mesh nodes requires extensive computational resources. Typically, a calculation mesh has 10^5 to 10^6 nodes, that gives an error as low as ~10 G for a field level in the working zone. Another reason for error is a possible mismatch between standard $\mu(H)$ curves used in the model and properties of real magnets. Displacements and misalignments occurred during fabrication of magnets can also produce field distortions.

An analysis of the influence functions made it possible to assess influence of manufacture/assembly tolerances on a field distribution in the working zone of a cyclotron.

A comparison between the magnetic measurements and simulated results suggests that numerical simulations of magnet systems is a promising alternative for building a prototype cyclotron, offering much more cost- and time-effective, yet accurate, results in any cyclotron design. A successful experience of field formation in DC-72 has been applied to improvement of the basic cyclotron U-400 in the JINR (Dubna, Russia) and design and fabrication of a number of cyclotrons including CC12 (Russia), CC18/9 (Finland, Russia), DC-60 (Kazakhstan).

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