EFFECT OF ACTUAL MAGNETIC PROPERTIES OF STEEL ON FIELD QUALITY IN DC60

Abstract

An effect of actual magnetic properties on magnet system field quality was analysed for the steel used in fabrication of the cyclotron DC60 (Kazakhstan). Precision 3D simulations of a field in the working zone demonstrate the necessity of taking into account the actual non-linear magnetic properties (B-H curves). The ferromagnetic saturation effect occurred in magnet systems necessitates magnetic measurements in a field range expanded up to 2.5-3.5 T. An original measurement technique is proposed which enhances the standard procedure for B-H measurements. Field calculations with the use of a finite-element model enable simultaneous consideration of several B-H curves to analyse behaviour of different materials used in the fabrication.

One of the key stages in the design of modern complex electrophysic and electric devices. such as cyclotrons, is numerical simulation of spatial field distribution in order to ensure desired field quality.

Advanced software tools enable detailed 3D modelling of magnet systems and simulation of their magnetic field with a desired accuracy to perform the analysis and optimisation of the magnet system design. The use of magnetic properties of real magnets would lead to higher precision and reliability of simulations.

Magnetic properties of materials are characterised by dependence between induction B and field strength H, known as the B-H curve [1]. A relation between the vectors $\vec{B}$ an $\vec{H}$ given in terms of a magnetic permeability μ as $B=\mu H$ is one of the basic Maxwell's equations [2]. For ferromagnetics, which are the key materials in the magnet fabrication, the B-H curves exhibit the following behaviour: 1) marked non-linearity, 2) hysteresis, i.e. magnetic history effect and ambiguous relation between vectors B and H; 3) magnetic anisotropy. Usually, a known B-H curve gives sufficient information for solving magnetostatic problems. Such curve is formed by a set of peak points of symmetrical hysteresis loops obtained when ferromagnetics are repeatedly magnetised.

Numerical simulations of magnetic fields in electrophysic devices involve the use of some additional parameters derived from the B-H curve ($\frac{\partial \mu}{\partial H}$ and saturation intensity) and are rather sensitive to the curve smoothness.

Due to technological and cost reasons, a cyclotron magnet system comprises components made of different ferromagnetic materials. This necessitates development of software tools capable of processing magnet data bases [3,4] and updating them via an input file describing B-H curves.

Efremov Institute has developed a measurement system that constitutes a combination of soft- and hardware intended for magnetic measurements, primarily B-H curves. The measurement procedure implements conventional measurement techniques, which comply with Russian standard 8.377-80, enriched with original engineering solutions to improve measurement uncertainty and extend applicability [5]. Magnetic measurements are performed within two overlapping field range covering, in combination, typical operating fields for magnet systems. A comparison of measured data within the overlapping ranges gives additional assessment of measurement uncertainty.

Magnetic measurements over the low and middle field range (0.05 kA/m to 15 kA/m, B<1.9 T) are performed on ring samples according to the Russian standard for magnetic measurements of non-retentive materials.

For measurements in high fields (1kA/m<H<600 kA/m, B>1.5 T), an original technique is proposed. The measurements are performed on barrel samples with the use of a computer-based permeameter [1,5]. A sample is placed between the poles of an E-shaped laboratory dipole magnet, which generates a longitudinal field inside the sample. The sample and the dipole magnet form a closed magnetic circuit.

Magnetic properties are determined by the induction method [5]. Both for the ring and barrel samples, induction is determined by measuring emf generated in a measuring coil. A variable field is produced by current pulses in an exciting coil. The shape and frequency of the current pulses are taken so that to avoid eddy current and noise effects.

Readings from measuring devices (control current, measuring coil voltage, Hall voltage) are transferred via the data acquisition system to the processor, which also continuously controls measurements. This enables automated measurement at 10-20 points over each field range to generate a set of symmetric hysteresis loops with different field amplitudes. The peaks of the hysteresis loops form a B-H curve. It takes 2 to 20 min depending on the field level in the sample to obtain one point on a B-H curve. The full measurement period in both field ranges, including device testing and sample pre-magnetization, is 0.5 to 1.5 hr for one B-H curve.

The computerised measurement system and measurement procedure were tested and validated during magnetic measurements on ferromagnetic steel for the magnet system of the cyclotron DC-72 developed and built at the Flerov Laboratory (JINR, Dubna, Russia) [5] for the Center of Nuclear Physics and Medicine (Metrology Institute, Bratislave, Slovakia). The measured data were used to simulate DC-72 field maps and optimise the magnet system design so as to provide required field distribution [6].

This study shows results of field simulations for the cyclotron DC-60, which is under construction for Gumilev Eurasian National University in Astana, Kazakhstan. The analysis and optimisation of the spatial field distribution in DC60 were carried out with the use of the program package KOMPOT [3]. The results are reported in details in Ref.[7]

The presented study is devoted to the effect of actual magnetic properties of the steel used in fabrication of DC60 on field quality and possibility to adjust the field distribution by varying coil currents. Fig.1 shows a typical field map in the central cross section of the DC-60 magnet system at a current of 248.05A in the main coil. At the first design stage (before steel casting), the B-H curve for the cyclotron DC-72 [6,7] was used as reference. Fig.2 presents a comparison between B-H curves for DC-72 and DC-60. Fig.3 illustrates average field variations calculated for two B-H curves (reference and actual) to analyse behaviour of different materials used in the DC60 magnet system. In the simulation, magnetic properties were taken identical for different magnet components, such as beams, supports, poles, sectors, shims, plugs.

The simulated curves of average field were compared with the desired isochronous curve obtained from the trajectory analysis on the basis of simulated field maps [7]. Finally, a good match between the simulated and desired isochronous curves should be achieved. As evident from Fig.3, the average field varies along the magnet radius in a similar manner for the reference and actual materials, with a 140 G difference in the field level. The average field difference is practically constant along the radius, a local discrepancy being estimated as low as 5 G (see Fig.4). The data obtained suggest that the non-linearity effect of materials on the field distribution in DC-60can be effectively compensated by changing the main coil current only. An increase in the main coil current from 248.05 A to 253.68 A gives a near-isochronous field distribution as shown in Fig.3. Fig.5 illustrates an average field difference between the simulated and required fields for the two considered materials.

References

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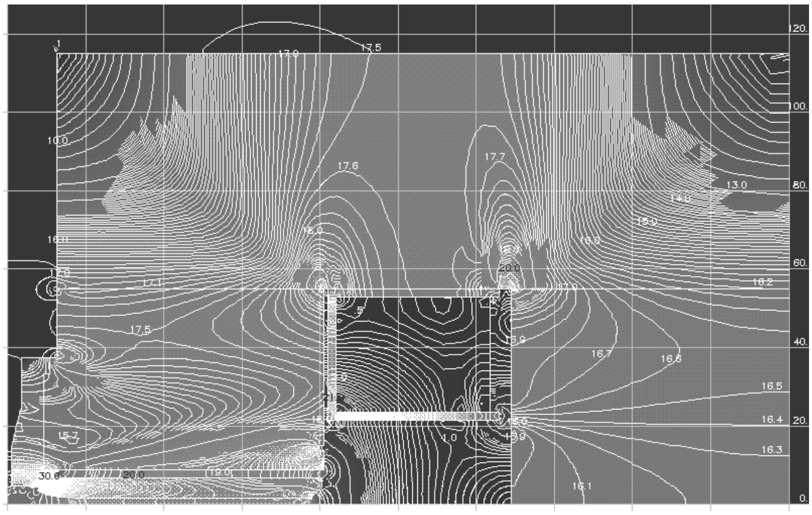

Fig.1 Simulated DC60 field in vertical cross section, kG.

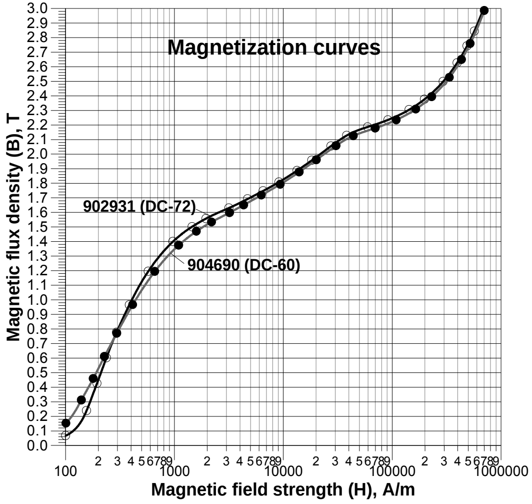

Fig.2 B-H curves used in simulations

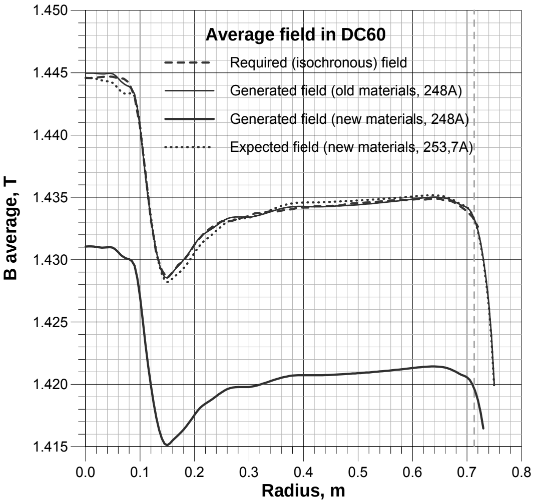

Fig.3 Average field vs magnet radius

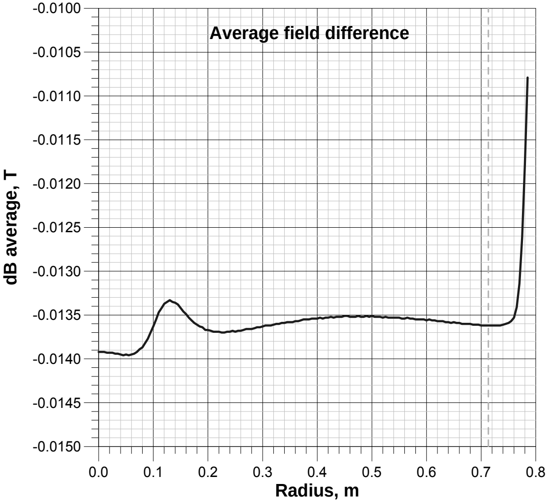

Fig.4 Field difference for reference and actual materials

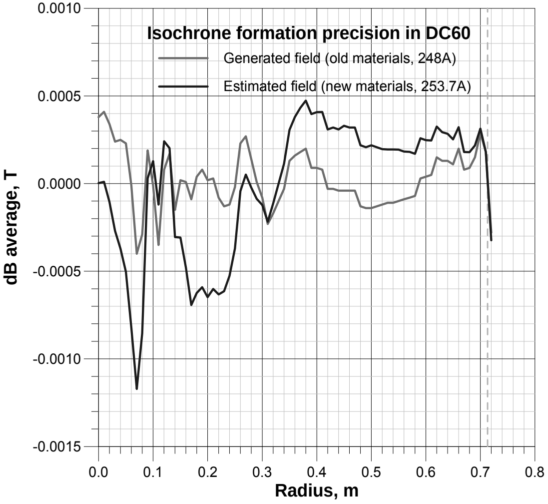

Fig.5 Difference between simulated and required field.