POLE PROFILE OPTIMIZATION OF VLHC TRANSMISSION LINE MAGNET

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Abstract

A pole profile optimization method has been developed for accelerator magnets. It is based on the analytical solution of reverse Cauchy's problem combined with the numerical solution of nonlinear Poisson's equation. This method was used for the pole profile optimization of VLHC transmission line magnet [1]. It was achieved, using crenelation technique the good field quality $2 \cdot 10^{-4}$ in magnet aperture for the fields up to 2 Tesla.

1 INTRODUCTION

One of the more complicated problem in design of magnets for accelerators is to form needed magnetic fields with very high accuracy at low pole width and correspondingly weights of magnets. In common case, it is the nonlinear reverse problem of magnetostatic and can not be solved by analytic methods. There were suggested various methods [2 – 4] of solution this problem but, in practice, usually use numerical solution of Poisson's equation with step by step correction of pole profile. It is labor intensive procedure, based mostly on the experience of designer. For linear problem, when the saturation effects of iron core do not influence on the field distribution, were designed a number of analytic methods [4-6]. In this work described the method, which combine the accuracy of analytic approach for the reverse problem solution with efficiency of numerical methods. The optimization process was used for the pole profile design of the Very Large Hardron Collider (VLHC) prototype magnet [1]. At the first step with help to the analytic transformations of Taylor's series, using field harmonics as initial data, was received the pole profile, which was optimized during next analytic-numeric iterative solutions. «Crenelation» technique [1] gave possibility to receive magnetic field in range from 0.1 Tesla up to 2 Tesla with quality $2 \cdot 10^{-4}$.

2 ANALYTIC SOLUTION OF THE REVERSE MAGNETOSTATIC PROBLEM

Usually for accelerator magnets the demands to the field harmonic content and the aperture dimensions are known from the beam dynamics analysis. Magnetic field in the middle plane of magnet may be expressed

$$B_{y0} = \sum_{m=0}^{\infty} a_m \left(\frac{x}{x_0}\right)^m , \qquad (1)$$

where a_m -field harmonics, x_0 - normalization parameter. If the magnetic permeability of ferromagnetic poles is infinite and the areas with currents are far away, the field in magnet air gap is defined by the form of pole profiles. Scalar potential of this field satisfies Laplace's equation

$$\Delta U_m = 0$$

and in middle plane is known the field distribution or the scalar potential derivative. It is well-known Cauchy's problem for the upper half plane. Solution may be received on the base of the scalar potential analytic continuation by Taylor's series:

$$\wp(z) = \sum_{k=0}^{\infty} \frac{\wp(x)^{(k)}}{k!} (z-x)^k , \quad z - x = jy , \text{ then}$$

$$U_m = \sum_{k=1}^{\infty} \frac{(-1)^{k+1} B_{y0}{}^{(2k-2)}}{(2k-1)!} y^{2k-1} \qquad (2)$$

Pole surface in this case coincides with equipotential on which $U(x,y) = const$. For magnet with the symmetry relatively y – axis the scalar potential on the pole surface may be defined trough the field in the center $U_p = -B_y(0,0) \cdot \delta$, where δ is the magnet air gap. So, for the defining pole profile coordinates, at known U_p and B_{y0}, it is need to solve equation (2) relatively unknown y_p – coordinates of the pole profile. It seems rational to use for it the method of analytic transformations of Taylor's series, widely used in a high precision calculations of astronomy. Extracting from (2) the first term of y_p, have

$$y_p = \frac{U_m - \sum_{k=2}^{\infty} \frac{(-1)^{k+1} B_{y0}{}^{(2k-2)}}{(2k-1)!} y_p{}^{2k-1}}{B_{y0}}$$

This method was proposed and successfully tested in [6] for the dipole magnet with 5 cm air gap.

3 POLE PROFILES OPTIMIZER

The pole profiles optimizer is created as the additional modules for the base software package POISSON and consists of the following parts: mesh regenerator, processor, harmonic analysis module, restoration pole module, postprocessor, controlling module. For the entering of input data is used original POISSON preprocessor. Harmonic analysis module is based on the algorithm of field interpolation on the dipole magnet axis by polynomial

(1), with using Newton's interpolation algorithm. Polynomial coefficients $a_0 ... a_n$ are used with restoration of pole profile. The used algorithm ensures an exact evaluation of polynomial coefficients up to 15^{th} harmonics (practically were used 6 first harmonics).
Regeneration pole profile module is based on the analytical approach previously described. On each iteration is produced the improvement of the polynomial coefficients and the new pole profile synthesis. On the convergence of iterative process highly influence the amount of taken into account harmonics. Synthesis of a minimal pole width (with artificially cut off corners) and the convergence of process is limited by 5-6 harmonics taken into account during optimization process. High harmonics defines the form of the pole ends and their influence extremely connected with the corners saturation effects. For the saturated poles ends, which close to straight angle the convergence is worse. Number of harmonics also influence on the convergence velocity. Most optimal is the algorithm to allow the first harmonic vary until it reach required value, then to allow first and second vary until each of them become the required value and so on, adding each cycle one harmonic until all harmonics will satisfy the needed accuracy.

4 POLE PROFILE OPTIMIZATION OF VLHC TRANSMISSION LINE MAGNET

The optimizer was successfully used for the VLHC transmission line magnet pole profile optimization. It was need to generate the pole of minimal width which provide the following parameters: field gradient -4%/cm in circular good-field aperture with the diameter 2cm at B ~ 0.1T and 1cm at B ~ 2T. Required field quality $\left|\Delta B_y / B_0\right| \le 10^{-4}$. Upper right quadrant of magnet cross-section is shown on Fig.1.

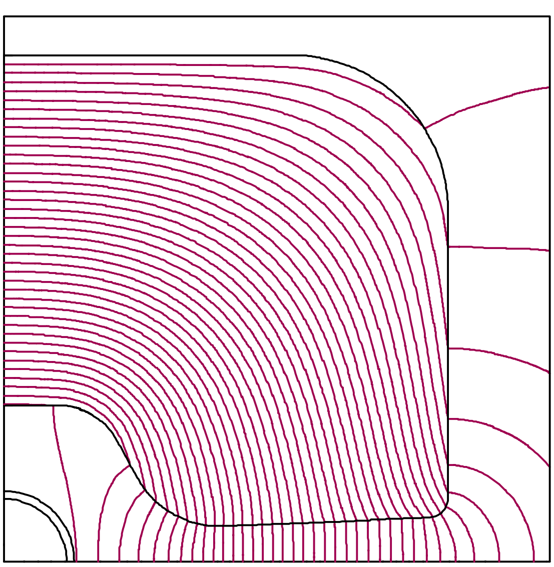

Fig.1 Quadrant of magnet cross-section

During the first calculations was generated the pole profile of a minimal width, which ensures required field quality at 0.1T in 2cm diameter area. The good field aperture at high fields decreased up to 0.6 cm. It is explained by the large saturation of inner pole corner in relation to outer corner. This effect causes the gradient change up to -3.98%/cm. After optimization were found more optimal parameters of inner and outer pole corners: inner corner radius 2.38cm; outer corner radius 0.52cm.
Due to this the gradient at high field was stabilized at -4.006%/cm. Good field apertures are shown on Fig.2 - low field and Fig.3 - high field (because of different scale in vertical and horizontal directions circular apertures look as elliptical).

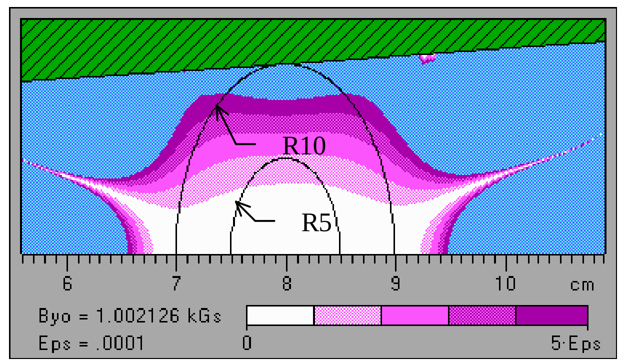

Fig.2 Good-field aperture for high field level (non - crenelated pole)

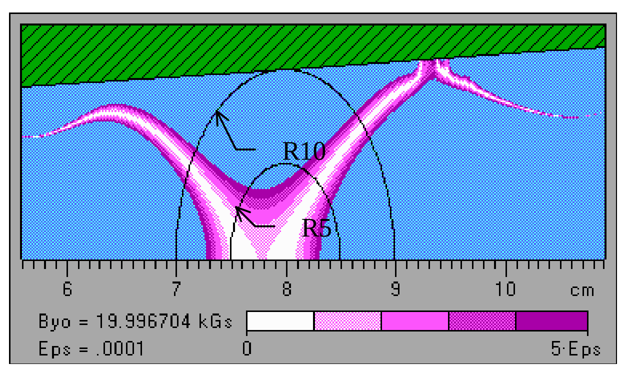

Fig.3 Good-field aperture for high field level (non – crenelated pole)

However the good-field aperture less than required value at high field. The reason of it was too large value sextupole at high field (at low field sextupole equals zero). Such large sextupole is connected with larger saturation of the pole corners on a comparison with the pole center. Usual solution of this problem is to increase the pole width to get 1cm of good-field aperture at high field. But that however disagrees with the accepted concept of minimization pole width in the whole range of field variations, since low field good aperture correspondingly increases more than required value.

5 CRENELATION TECHNIQUE FOR FIELD QUALITY IMPROVING

One of the ways to receive the good field quality in all range of field variations is the crenelation technique. This technique was proposed in [7]. Since the magnet pole is assembled from laminated steel there is a possibility to reduce common steel «density» by removing a part of material each N-th lamination - to crenelate it. The steel packing factor in crenelated area will be correspondingly decreased: $k_p = 1 - n/N$, where N - number of laminations in package; n - number of crenelated laminations.

For described dipole magnet it is necessary to crenelate central area of the pole tip to increase saturation in this part of the pole up to the level of pole corners saturation. Such pole of equal saturation will ensure more stable field distribution in the whole range of fields, because each point of steel will lie on about the same point of curve. During realization this optimizing technique was found strong influence of crenelation profile at high field levels. Accordingly for the crenelated surface optimization was used the algorithm similar used for the pole tip generation. Also a large importance has the right choice of packing factor for crenelated area. At high field for compensation of pole corners saturation it is necessary to increase height of crenelation surface. But it hampers smoothing of field distribution in magnet gap as the influence of pole surface $\sim 1/h^2$, where h is a distance between gap axes and pole surface. At low packing factor crenelation surface may has small height and influences almost as basic pole surface, but in such strong compensated system is probably deterioration of field quality at middle field levels because of «bad» flux redistribution between crenelated and non-crenelated areas. For ARMCO type steel used in tentative calculations most optimal were $k_p = 0.8$ and crenelation height $0.0215 \cdot \delta$ in the center of pole. During optimization was generated the basic pole profile at field 1.1T, where the effects of saturation begin to influence on the field quality. Then was generated the crenelated area at high field and checked field quality in the range 0-2T. The best results were obtained for the generation of the crenelated surface at 1.7T field. Figures 4 and 5 show the good field aperture at various field levels.

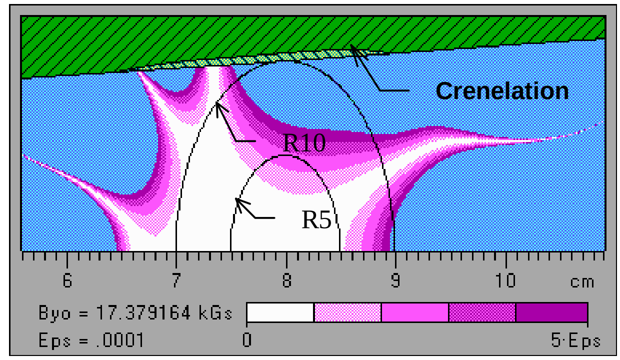

Fig.4 Good-field aperture for high field level (crenelated pole)

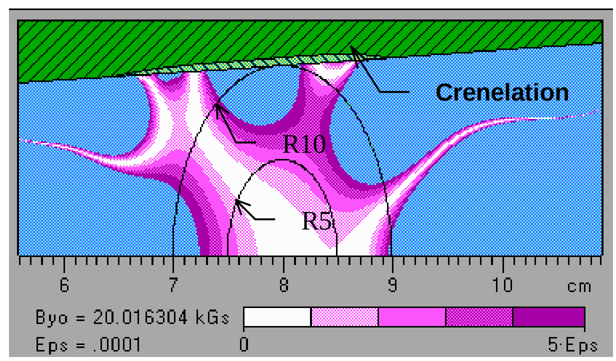

Fig.5 Good-field aperture for high field level (crenelated pole)

CONCLUSION

The proposed method of a pole profile generation may be used for the other type of magnets, when the field formed by iron surfaces. Combination with crenelation technique will allow the design of magnets with the good field quality up to 2 Tesla. Soon the crenelation technique will be tested at the resistive model in Fermilab.

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