Smooth Shimming of Pole Profiles

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***Abstract*—A fast and reliable 2D optimisation technique for smooth shimming of magnet pole faces is presented. It has a physical basis and always yields a solution with shims that provide high field matching over a wide range of excitation. The OPTIMA code has been developed to automate the optimisation process. It is easily modified to different types of magnets for a variety of applications. It has been proved as a very valuable tool in the process of designing dipole, quadrupole, sextupole and combined function magnets for the Swiss Light Source (SLS) at the Paul Scherrer Institute (PSI).**

***Index Terms*—inverse problems, optimisation, shimming, 2D, pole profile, smooth, spline, PSI, SLS magnets**

I. Introduction

We describe a novel approach to the age-old problem of 2D shimming of finite magnet poles in the region between the central pole face, described by a line of constant scalar potential and the pole sides, which can be defined as straight, tapered or curved (Rogowski-tapered).

In most practical cases, a smooth positive-negative shim combination will ensure good field matching over a wide excitation range. This approach avoids many of the problems associated with the use of the MIRT programme [4] and provides better results.

II. Optimisation Method

A. Constraints

If the pole face width is not given by space limitations and for a field matching in the order of 10^{-4} over a specified good field region *GFR*, a pole overhang of $0.65 \cdot gap$ is sufficient. The half pole face width *w* is then given by the sum of the GFR width and the pole overhang. The shim width *s* is typically one half gap wide, which gives the anchor points C and E on the pole profile as shown in Fig. 1.

For quadrupole, sextupole or higher multipoles, these points should be determined by conformal mapping into dipole space.

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B. Geometric Modeller

The central pole region, from the middle point M to the point C, is set equal to the perfect pole contour and this remains unchanged during the optimisation process. The perfect pole contour for a dipole magnet is a line parallel to the mid-plane, for a quadrupole it is a hyperbola but for higher multipoles and especially for multiharmonic magnets it becomes more complex. Nevertheless, it can be calculated easily by taking the scalar potential line that passes through the middle point M (r_0,φ_0) of the pole. The equations in polar coordinates are

$$V = -\sum_{i=1}^{n} \frac{B_i}{i} \cdot r^i \cdot \sin(i\varphi) = V_0 \ ,$$

$$V_0 = V(r_0, \varphi_0) \qquad (1)$$

where B_i are the desired harmonics.

The shim region is defined by a cubic spline function through 4 points C, P_1, P_2 and E. Two intermediate points P_1 and P_2 are sufficient in order to model smooth positive-negative shims between points C and E.

The spline is tangential to the central region at point C, assuring a smooth transition between the regions. The other transition at point E depends on the given pole side. The spline is tangential only to a Rogowski-tapered pole side or

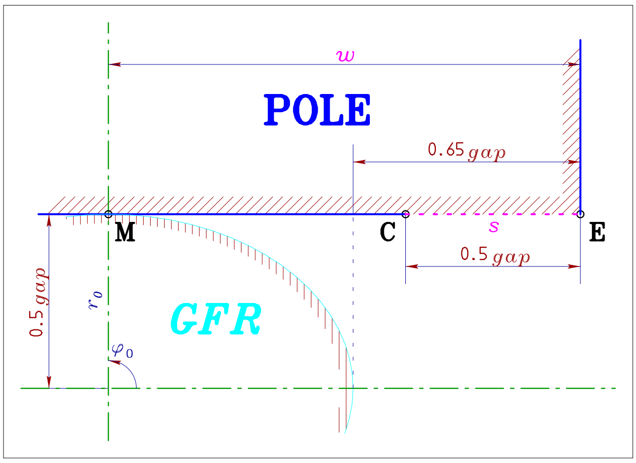

Fig. 1. Defining the pole cross section width and the shim region.

to a strongly tapered pole. Otherwise, the spline angle (its first derivative) should be set. Our best results were obtained by enlarging the angle (by 10° to 15°) of the extended central pole contour at the end point E in order to eliminate the creation of sharp pole corners.

C. Parameter Definition

1) Search: During the optimisation, the points P_1 and P_2 are allowed to move in both (X and Y) space directions, while point E is constrained to follow the given pole side form. This requires optimisation of 5 parameters for the symmetrical poles, as in the quadrupole shown in Fig. 2, or 10 parameters for asymmetric poles. Earlier versions which also allowed the point C to move along the perfect pole contour were unsatisfactory.

A direct search method must be used for the optimisation in order to handle this number of parameters in a reasonable computation time. The system is well defined, it does not contain erroneous local extrema, and therefore the method cannot stray or get trapped, so the *downhill simplex method* can be used [2].

2) Initialisation: The initial set of parameters (coordinates of points P_1, P_2 and E) is provided by user. We usually place the points P_1, P_2 and E on the extended central pole contour. The next N sets (N is the number of parameters) required to form the *simplex* are then scattered automatically around the initial set by randomly altering the initial parameters up to about 0.5 mm.

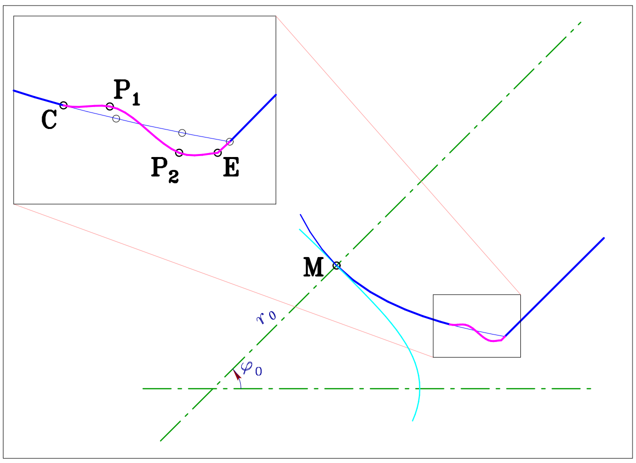

Fig. 2. Pole cross section of a symmetrical quadrupole during optimisation.

D. Quality Check

1) Field Analysis: Each parameter set is a candidate to be evaluated using any 2D electro-magnetic (EM) code. The interpretation of the field calculation is done by analysing the vector potential along the good field region boundary (GFRb). This ensures that all of the *GFR* area is included and not just points on the mid-plane. The equation for the vector potential of an ideal magnet with the desired B_i harmonics in polar coordinates is

$$A_{id} = -\sum_{i=1}^{n} \frac{B_i}{i} \cdot r^i \cdot \cos(i\varphi) \qquad (2)$$

The deviation of the calculated vector potential A from the ideal A_{id} is a direct measure for the quality of a solution

$$\sigma = \sqrt{\frac{\sum_{GFRb}^{n} \left[A(r,\varphi) - A_{id}(r,\varphi)\right]^2}{n}} \qquad (3)$$

In order to take saturation effects into account and to avoid solutions that are good for one excitation only, the evaluation is done at several excitation levels. We found that normally two cases suffice, one at the operational excitation level and the other at low excitation, which can be simulated with a very fast linear computation. The quality of a solution is then taken as a weighted RMS average of σ.

2) Convergence Check: The optimisation is terminated when either the change in geometry becomes negligibly small (a few microns) or when the field quality insignificantly improves (10^{-5}, order of magnitude less than specified).

III. Software

For this task we have developed a group of FORTRAN codes that form the optimisation programme OPTIMA.

While the search part of OPTIMA is universal for all optimisation problems, the other two parts, the evaluation part and the geometric modeller must be tailored to each problem separately. In practice, the evaluation part may be the same for a group of magnets with similar specifications.

The field calculations have been done with the POISSON/PANDIRA [4] programmes on a VMS Alpha computer. The outputs from the geometric modeller are meshed by AUTOMESH and LATTICE. All the programmes are managed and controlled by a single VMS command file.

A typical optimisation of 10 parameters requires some hundreds of calculations before it converges. The time needed

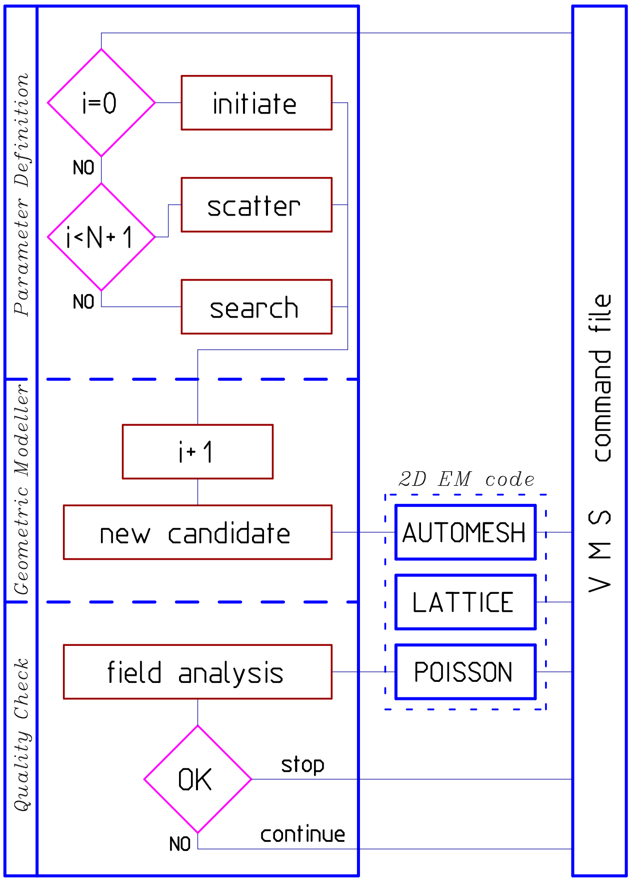

Fig. 3. OPTIMA flow chart.

for OPTIMA to find a solution depends strongly on the model involved and our experience is that it can take anything from 10 minutes to 10 hours on an Alphaserver 8400. In most cases we were able to obtain a solution within a working day.

IV. Examples

The smooth shimming method has been developed for designing of Swiss Synchrotron Light Source (SLS) magnets at PSI [1,3]. The magnets have to be compact due to space limitations and therefore smooth pole shimming is required to attain good field matching ($\sim 10^{-4}$) over the whole excitation range.

The next few contour plots show field errors of some of SLS magnets that were optimised with OPTIMA. The field error at any point is a vector defined by

$$\vec{B}_{err} = \vec{B} - \vec{B}_{id} \tag{4}$$

where B_{id} is the ideal or required field at the point. Additionally a sign is given to the magnitude of the field error

$$\left|B_{err}\right| \begin{cases} + & \text{for} \quad |B| > |B_{id}| \\ - & \text{for} \quad |B| < |B_{id}| \end{cases} \tag{5}$$

thus providing extra information on the plots.

A. Elliptical Quadrupole

The quadrupoles for the SLS storage ring have an aperture diameter of 60 mm and a nominal field gradient of 20 T/m. The quadrupoles are DC powered but laminated.

In the early stages of the SLS design and for stability reasons, quadrupoles made out of two halves have been studied [1]. The consequence of such a solution is that the coil size is limited by the distance between neighbouring poles. Since the *GFR* is specified inside an ellipse of 60 mm by 40 mm it is possible to cut back the pole on one side without any loss of field quality, thus allowing larger coils.

The central part of the pole is a fixed hyperbola. Since the quadrupole is not symmetric, both pole ends have to be optimised. The pole end points are constrained to follow the tapered pole side. The field error of the solution is shown on Fig. 4.

B. Dipole

Dipoles BE and BX for the SLS storage ring have a gap of 41 mm. The nominal field is 1.4 Tesla for the electron beam

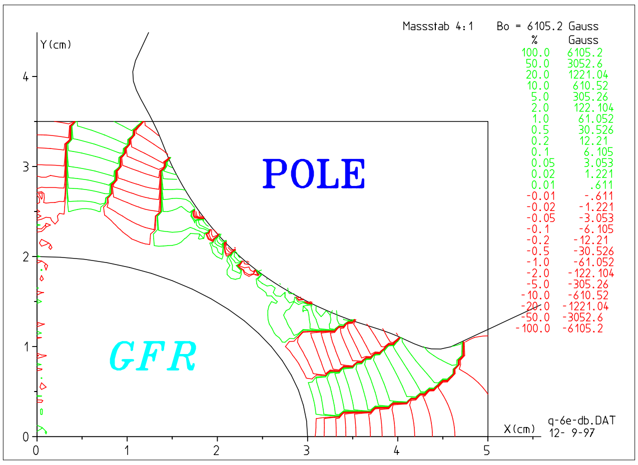

Fig. 4. Field error of an elliptical version of the quadrupoles for the SLS storage ring.

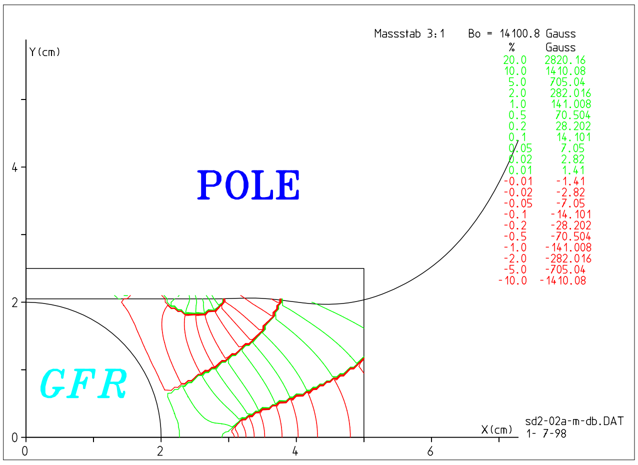

Fig. 5. Field error of BE and BX magnets for the SLS storage ring.

energy of 2.4 GeV but the magnets may also operate at 1.2 Tesla for the lower beam energy of 2.1 GeV and at 1.6 Tesla for the higher beam energy of 2.7 GeV. Rogowski-tapered pole sides were necessary to avoid saturation.

The *GFR* region is specified inside a circle of 40 mm diameter. The central pole part is flat and the end point is constrained to follow the Rogowski profile. The shim is symmetric on both sides so that only 5 parameters were needed to optimise. The field error for the nominal excitation level is shown on Fig. 5.

C. Multiharmonic Magnets

The SLS booster ring magnets BD and BF [3] have dipole, quadrupole and sextupole harmonics built into their profile.

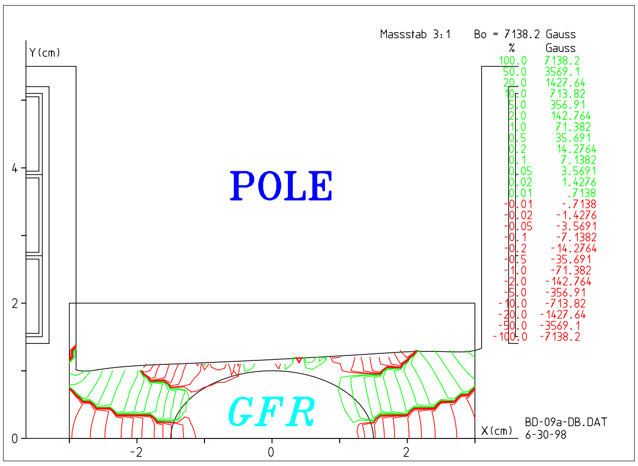

Fig. 6. Field error of the combined function magnet BD for the SLS booster ring.

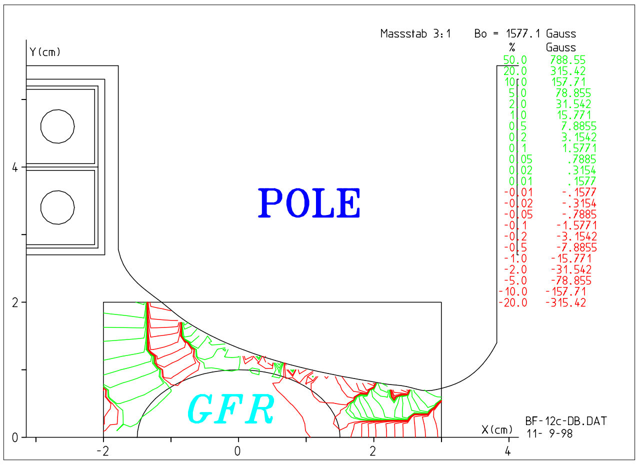

Fig. 7. Field error of the combined function magnet BF for the SLS booster ring.

BD is basically an indexed magnet with a gap of 23.3 mm, while BF is very close to a half quadrupole with an aperture diameter of around 60 mm.

The central pole regions are neither straight nor part of a hyperbola due to the multiharmonic field content. The specified *GFR* is inside an ellipse of 30 mm by 20 mm. Both magnets are asymmetric and 10 parameters were optimised. The field errors are shown on Fig. 6. and 7.

V. CONCLUSION

The smooth shimming method is simple, robust and always converges to a reasonable solution. It is fast and easily adaptable to a wide range of pole profile optimisations.

The programme OPTIMA has been successfully used for designing magnets of PSI's SLS synchrotron. Prototype measurements proved the quality of the achieved field matching [3].

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