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DESIGN OF THE COMBINED FUNCTION DIPOLE-QUADRUPOLES(DQS) WITH HIGH GRADIENTS*

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Abstract

Normally, combined function dipole-quadrupoles can be obtained with the design of tapered dipole or offset quadrupole. However, the tapered dipole design cannot achieve a high gradient field, as it will lead to poor field quality in the low field area of the magnet bore, and the design of offset quadrupole will increase the magnet size and power consumption. Finally, the dipole-quadrupole design developed is in between the offset quadrupole and septum quadrupole types. The dimensions of the poles and the coils of the low field side have been reduced. The 2D pole profile is simulated and optimized by using POSSION and Radia, while the 3D model using Radia and OPERA-3D. The end shimming and chamfer are modelled to meet the field uniformity requirement.

INTRODUCTION

Space and cost reduction in the design of system components is one of the main topic in accelerator technologies. Combined function magnets present a feasible solution to achieve the compact design. A reduction in a very large number of magnets is facilitated by combining of dipole, quadrupole (and/or sextupole) fields in a fewer number of components. Compared to the separated-function magnet (i.e., without gradient field), the combined function magnet has the advantage in that it reduces the lattice perimeter by combining a vertically focusing quadrupole with a bending magnet. It also helps separate β-functions at sextupoles and reduces the natural emittance of the circulating beam by introducing additional radiation damping due to the field gradient [1].

The Hefei Advanced Light Source (HALS) is proposed as a future soft X-ray diffraction-limited storage ring at NSRL. At present, the electron beam energy is chosen to be about 2.0 GeV, and the beam emittance is aimed at below 50 pm·rad [2]. High gradient dipole-quadrupole is one of the key components for the HALS. Several types of DQs are installed at the HALS. The central field is $B_0 = 0.5$ T, while the gradient field is from 11 T/m to 25 T/m. The magnet aperture is 26 mm with a 7 mm Good Field Region (GFR).

This paper present a general design methodology and parameter optimization for the DQ design, namely, the ferromagnetic structure and the pole profile shapes are sought. To optimize the pole shape, a Gauss-Newton algorithm has been used, and the optimization problem was linearized by computing the Jacobi matrix, and iterating a few times [3]. The pole shape is designed to reach the required field quality of 5×10^{-4}. The 2D pole profile is simulated by using POSSION and Radia, while the 3D model by using Radia and OPERA-3D.

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MAGNET DESIGN

In a conventional approach, the gradient field of DQ can be generated by varying the gap along the transverse direction, which also called tapered dipole design. As it is shown in Fig. 1, the pole of DQ magnet can be regarded as part of the ideal hyperbola. The ideal hyperbola with asymptotes at Y = 0 and X = $-B_0/G$ is the pole of a very large quadrupole.

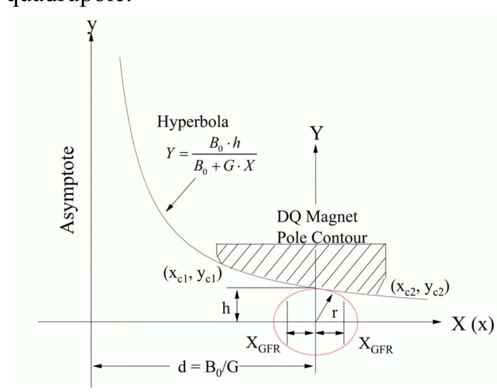

Figure 1: The pole of DQ magnet with a tapered dipole design.

The central field of DQ magnet is B_0, and the gradient field is G. So the offset distance from quadrupole center to vacuum chamber center is $d = B_0/G$. The radius of vacuum chamber is r. It's not difficult to determine the vertical half gap h at the magnet center:

$$h \geq \frac{3d + \sqrt{d^2 + 8r^2}}{4d} \cdot \sqrt{\frac{4r^2 - d^2 + d\sqrt{d^2 + 8r^2}}{8}} \quad (1)$$

One can obtain the equation of the ideal hyperbola as:

$$xy = \frac{H^2}{2} = d \cdot h = \frac{B_0 \cdot h}{G} \quad (2)$$

Where H is the normalized to the quadrupole radius.

To determine the location of the pole cutoff point (x_c, y_c), the conformal maps has been used. The function describing the conformal map from the quadrupole to dipole space is:

$$w = \frac{z^2}{H} \quad (3)$$

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Using this expression, the quadrupole good field radius, $|r_0|$, maps into the dipole good field radius $|w_0| = r_0^2/H$. The u coordinates of the left edge u_1 and right edge u_2 of the mapped dipole are [4]:

$$\begin{cases} u_1 = \dfrac{x_{1GFR}^2}{H} = \dfrac{(-x_{GFR} + B_0/G)^2}{H}, \quad v_1 = H \\ u_2 = \dfrac{x_{2GFR}^2}{H} = \dfrac{(x_{GFR} + B_0/G)^2}{H}, \quad v_2 = H \end{cases} \tag{4}$$

For the dipole, the field uniformity in the required good field region can be improved by adding excess pole beyond the edge of the good field region, which is called the pole overhang. And the coordinates of the mapped dipole pole edges with the pole overhang are:

$$\begin{cases} u_{c1} = \dfrac{x_{1GFR}^2}{H} - a = \dfrac{(-x_{GFR} + B_0/G)^2}{H} - a \\ u_{c2} = \dfrac{x_{2GFR}^2}{H} + a = \dfrac{(x_{GFR} + B_0/G)^2}{H} + a \end{cases} \tag{5}$$

Where $a = H \cdot x_{ov}$ is the pole overhang.

The expression for the potential field quality and the pole overhang required to achieve a specified field quality for an optimized pole is [4]:

$$x_{ov} = \frac{a}{h} = -0.14 \ln \frac{\Delta B}{B} - 0.25 \tag{6}$$

And for an unoptimized pole is [4]:

$$x_{ov} = \frac{a}{h} = -0.36 \ln \frac{\Delta B}{B} - 0.90 \tag{7}$$

In general, the DQ magnet with a tapered dipole design requires the left edge of the mapped dipole $u_{c1} > 0$. It means that the good field region is located at the right side of the hyperbolic center. The low gradient field can be obtained with two tapered poles. One obtains:

$$u_{c1} = \frac{x_{1GFR}^2}{H} - a = \frac{(-x_{GFR} - B_0/G)^2}{H} - a \geq 0 \tag{8}$$

$$\frac{B_0}{G} \geq x_{GFR} + x_{ov} \cdot h + \sqrt{x_{ov}^2 \cdot h^2 + 2hx_{ov} \cdot x_{GFR}} \tag{9}$$

This expression is not strict. As h contains the offset distance B_0/G, and the Eq. (6) and Eq. (7) are used to estimate the required dipole pole width to satisfy field uniformity requirements.

The DQ magnet with a high gradient field cannot be obtained with a tapered dipole design, it will lead to poor field quality in the low field area of the magnet bore [5]. For the high gradient DQ magnet, the offset distance B_0/G is small, it may lead to $u_{c1} < 0$. The left side of the good field region is very close to the hyperbolic center or located at the left side the hyperbolic center. It means that the auxiliary pole is needed for ensuring a linear increase of the field.

The offset quadrupole design is a safe solution to obtain the high gradient field in DQ magnets. The offset quadrupole magnet design resembles a curved quadrupole magnet with a very large aperture. The offset distance from quadrupole center to vacuum chamber center is $d = B_0/G$ (Fig. 2). The beam runs horizontally displaced relative to the geometric center of the magnet. The core and coils are straight, and the pole tips are curved [6].

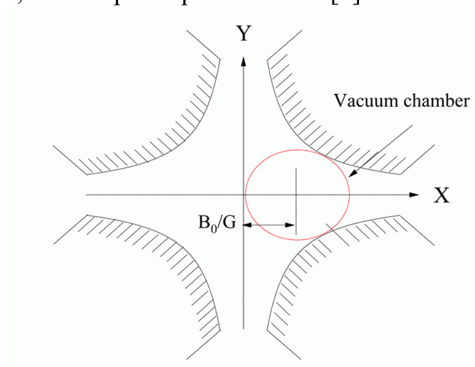

Figure 2: DQ magnet with offset quadrupole design.

As it is shown in Fig. 3, only a part of quadrupole field region has been used in the offset quadrupole magnet. This design will increase the magnet size and power consumption and lead to a lot of power waste.

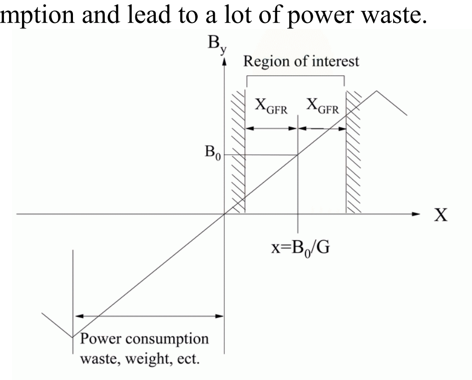

Figure 3: The field of offset quadrupole.

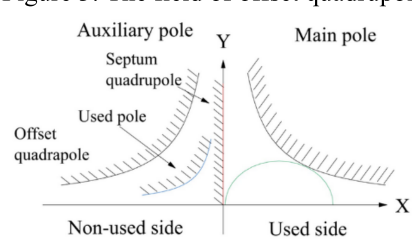

Figure 4: Magnet pole with different design.

The DQ design finally developed is in between the offset quadrupole and septum quadrupole types (Fig. 4). The dimensions of the poles and the coils of the low field side have been reduced, meanwhile the power consumption can be low down. This design can lighten the magnet weight and simplify the vacuum chamber design.

The auxiliary pole is also a part of the ideal hyperbola, but the radius is smaller than main pole. The location of the pole cut-off point can also be calculated with the conformal map.

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OPTIMIZATION AND RESULT

The HALS lattice includes several types of DQ magnets, and the maximum gradient field will reach 25 T/m or higher. The magnet aperture is 26 mm with a 7 mm Good Field Region (GFR). The 2D pole profile is simulated and optimized by using Radia and POSSION, while the 3D model by using Radia and OPERA-3D (Fig. 5). The end chamfer is modelled to meet the field uniformity requirement.

The pole shape can be simply parametrized by deviations from a reference hyperbolic profile. A Gauss-Newton algorithm was used. The optimization problem is linearized by computing the Jacobi matrix, and iterating a few times [3].

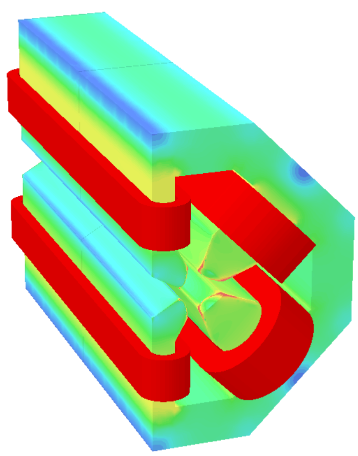

Figure 5: 3D model of DQ1.

The main parameters of the DQ1 magnet are shown in Table 1. The radius of auxiliary pole is about a half of the main pole, and the power of auxiliary pole is reduced to 19% of the main pole.

Table 1: Main Parameters of the Combined Function Dipole-quadrupole (DQ1)

Magnetic material	DT-4
Aperture radius[mm]	26
Magnetic effective length[mm]	600
Central field [T]	0.5
Gradient field[T/m]	25
Main pole power[kW]	2.027
Auxiliary pole power[kW]	0.391

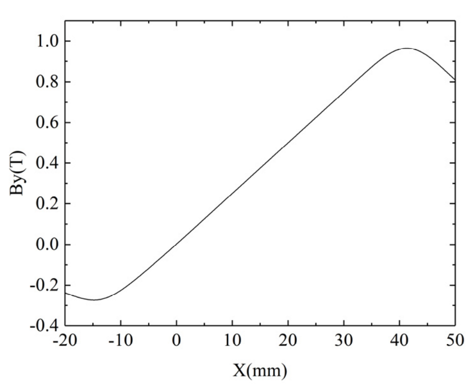

Figure 6: Magnet field of the DQ1.

Figure 6 shows the field and the gradient of the DQ1 magnet. The vacuum chamber center is located at x = 20 mm, and the central field of DQ1 is 0.5 T.The maximum field on the non-used side is reduced to less than one third of the used side.

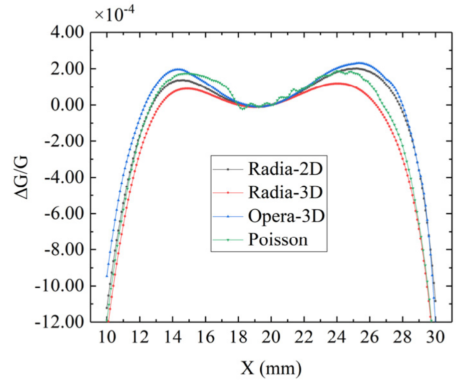

Figure 7: Relative gradient error of the DQ1 magnet.

The relative gradient error of the DQ1 magnet presents in Fig. 7. The inhomogeneities of the gradient are in the range of 5×10^{-4} for 12 mm $\leq$ x $\leq$ 28 mm, one order of magnitude below the specifications.

CONCLUSION

The physical design of the high gradient DQ magnets were finished. It was designed with a quadrupolar field on one side and a low field on the other side which enables easier installation of vacuum chambers, lower power consumption and facilitates magnetic measurements. It is was simulated in POSSION, Radia and OPERA-3D, and the poles shape has been optimized to meet the field uniformity requirement.

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