SHORT MULTIPOLE MAGNET DESIGNS FOR JLAB FEL UPGRADE

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Abstract

Novel designs for octupole and sextupole magnet families for the JLab 10kW IR FEL upgrade were developed and characterized. The designs were made with 3D simulations, and provided very short effective length that nearly equals the aperture radius, along with 1% accuracy of the field integral over 70% of a large aperture. The main feature is shaping of the cylindrical pole tips to provide high field quality dominated by fringe fields. Other features include magnetically isolated field clamps, usage of non-tapered coils of standard racetrack shape, and non-linear saturation effects (for sextupole magnets).

1 INTRODUCTION

Thomas Jefferson National Accelerator Facility (JLab) is upgrading a CW infrared FEL [1] to extend the IR power output to 10 kW and allow generation of UV radiation for industrial, defense, and scientific applications. The main requirement for the FEL beam optics is to avoid phase space dilution and to provide matched beam transport with high precision and brightness. This dilution is usually caused by beam lattice imperfections causing chromaticity and aberrations. Additional constraints on the beam lattice design result from the energy recovering system of the FEL, with an increased 6D phase space volume, and from an octupole component of the undulator field.

To meet the physics, performance and operational requirements [2], the octupoles and sextupoles should have specific parameters: field integral accuracy $\Delta IB_\perp/IB_\perp$ over 70-80% of the magnetic aperture radius to be better than 1%; and the aspect ratio $A= R/L_{eff,}$ to be close to unity, where R is the magnetic aperture radius, and L_{eff} is the effective length.

Along with high variable magnet strength, power consumption limited by heating, and manufacturing cost, these requirements present challenging issues for both magnetic design and construction.

2 DESIGN APPROACH

Unlike traditional magnets having A<<1 it is impossible to provide comparable field quality with the same pole shaping when A~1. As the magnet length reduces, the fringe field effect grows because of contribution of parasitic azimuthal harmonics. In the first order, magnetic flux leakage at the magnet end faces reduces the effective magnetic strength. This fringe flux near the pole is higher for bigger azumuthal angles ϑ (ϑ=0 at the minimal radial coordinate of the pole) and radii because of higher partial side area of the pole and shorter magnetic path between adjacent poles. In the second order, it sharpens the field integral profile across the aperture, i.e. there is an effective increase of the equivalent parameter, $n_{equiv}= n(A\neq 0) > n$ =*integer,* which describes the pole shaping in a real magnet having a higher aspect ratio A, in terms of an equivalent long magnet with $A_0 \rightarrow 0$ (see (1)). To correct the field profile, we need to change the shape of the pole in such a way, that

$r(\theta) = R\Big/\sqrt[m]{\cos(m\theta)}$, where $2n\text{-}n_{equiv}\approx m<n$. (1)

In most cases we have n-1≤m<n. The value n_{equiv} can be calculated using a standard procedure of parametric fitting of the given function (1) to approximate data for the field integral simulated (or measured) initially for a given value of A. An iterative procedure can be applied, i.e. for a calculated m from (2) we can find a new value n_{equiv} and so on (two iterations usually is enough). Another way to find m is direct optimization of the design over the generalized non-integer parameter m.

To implement this approach in magnetic design simulations, we used the 3D code Radia [3], a flexible tool enabling analytical programming of pre- and post-processing.

3 OCTUPOLE COMPACT MAGNET

The specifications for the family of octupole magnets [4] are given in the Table 1.

Table 1. Octupole magnet specification

Transverse field integral IB_r at r_g=12.5cm	5 T·mm
Field integral inaccuracy $\Delta IB_r/IB_r$ (r_g)	< 1%
Magnetic aperture radius R	15cm
Effective length L_{eff} at r_g=12.5cm	≤ 15cm
Geometric length	<25cm

In Fig. 2 we characterize several variants of the pole tip shaping with the following set of parameters:

- $\Delta IB_r/IB_r(\theta=0)$ is the maximum relative deviation of the transverse field integral with respect to an ideal octupole with the same field integral and for fixed angle (θ is angular position of the pole) in the "good field region" r< r_g;
- $\Delta IB_r/IB_r(r=r_g)$ is the maximum relative deviation of the transverse field integral with respect to an ideal octupole having the same field integral and for fixed radius over the circumference of good area at r=r_g;
- $|C_3|/|C_1|$ is the first unwanted harmonic C_3 related to the fundamental one (n=1) for the Fourier transform of

the field integral at fixed radius $r = r_g$;

- $\sum|C_k|/|C_1|$ is the sum of spurious harmonics (25 or more odd harmonics) related to the fundamental one at fixed radius $r = r_g$.
- P is the total power consumption by the coils (copper wire with cooling channel) required to achieve the specified magnet strength.

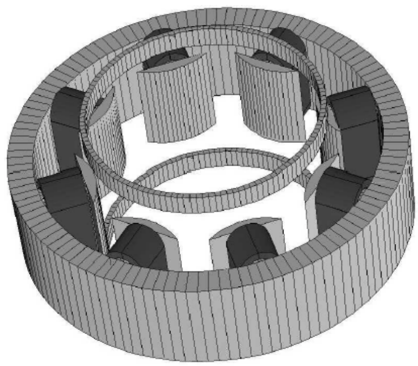

Figure 1. Magnetic design of a short octupole with ring field clamps, cylindrically shaped pole tip and standard racetrack coils.

Index n=1 corresponds here to octupole field component, n=3 corresponds to 24 -pole field component and so on. The main goal of the design under consideration (Fig. 1) is to satisfy field quality requirements: $max\{\Delta IB_r/IB_r(\theta=0), \Delta IB_r/IB_r(r=r_g), |C_3|/|C_1|\}<1\%$ for the given integrated magnet strength (which is 2.56T/m^2 in our example). Fig. 2 shows the explicit optimum achieved simultaneously for different field and field integral parameters in the vicinity of "sextupole-like" shaping (for fixed angular size and without field clamps). The optimal values found for this configuration (without clamps) are m=3.12 and $\Delta\theta$=32°. The corresponding parameters of this final variant #2 are given in Table 2.

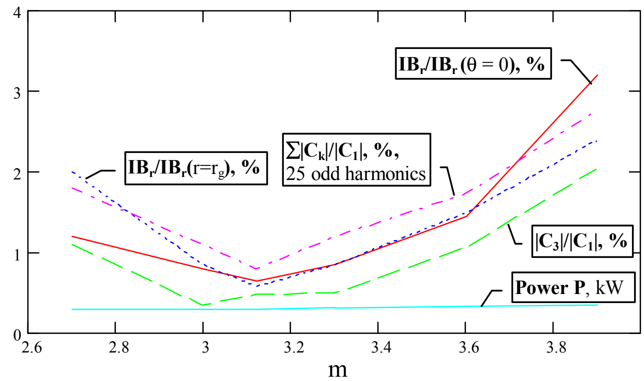

Figure 2. Octupole magnet parameters versus the order of tip shape m at fixed magnet strength 2.56T/m^2, $\Delta\theta$=38.6° (no clamps), r_g=12.5cm, and magnetic aperture radius r_{ap}=150mm.

One can see that the most dangerous first parasitic harmonic of the field integral is effectively suppressed by almost two orders compared to the initial design (without clamps). Introduction of field clamps (steel rings) to decrease the effective length, L_{eff}, adversely affects the field. To restore the field integral quality, a new optimization over the parameter m was undertaken with simple 3-point-parabola method. It resulted in further reduction of the key parameter m (see variant #3 in Table 2).

Thus the non-integer key parameter m in the extended formula (1) makes it possible to provide high quality field integral for multipole magnets with cylindrical pole tips of different lengths with/without field clamps. In addition, it gives enhancement of the magnet strength (or efficiency – *e.g.*, the power consumption is reduced by 33%, variant #2 vs. #1 in Table 2).

Table 2. Simulation results for octupole magnet with aperture r_{ap}=150mm and fixed magnet strength 2.56T/m^2: conventional (#1, n=4=m) and advanced designs (m<4).

#	Clamps	Tip Δθ (opt)	m	J, $\frac{A}{mm^2}$	ΣI, kA	P, W	L_{eff} mm	$\frac{\Delta IB_r}{IB_r}(0,r)$	$\frac{\Delta IB_r}{IB_r}(\vartheta,r_g)$	$\frac{C_3}{C_1}$, %	$\frac{\sum C_k}{C_1}$, %
1	no	36°	4	3.6	2.1	388	173	0.7, %	1.8 %	1.4	2.6
2	no	32°	3.12	2.93	1.71	261	173	0.58, %	0.42 %	0.018	0.75
3	yes	32°	2.9	3.49	2.04	370	146	0.64, %	0.79 %	0.31	1.6

4 SEXTUPOLE COMPACT MAGNET

Magnetic design of the sextupole magnet family for TJNAF Upgrade[5] is depicted in Fig. 3. Careful optimization of the pole shape was done to provide the highest field integral quality at nominal magnet strength. It led to the following value of the key parameter: m=2.67 (instead of standard value m=n=3 for a conventionally designed sextupole). The entire magnet operates far from saturation. However, unlike the octupole design above, high magnetization of some regions causes local non-linearities that can affect the field quality at different currents. We found such critical "hot spots" near the edge of the pole tip and in the vicinity of connection of the yoke and core. The magnet was optimized for a nominal strength ~2.15T/m. As a result the field quality is noticeably different for much smaller fields (see Fig. 4). Nevertheless, the magnetic design indicates high quality of the field integral for a wide range of coil currents: (0.4-1.4) with respect to nominal current.

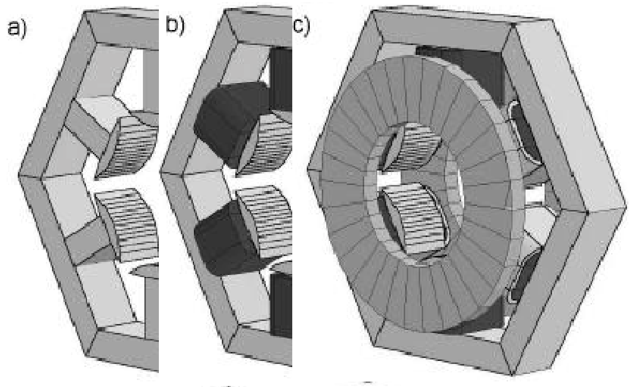

Fig. 3. Sextupole magnet design with conventional racetrack coils and circular disk clamp.

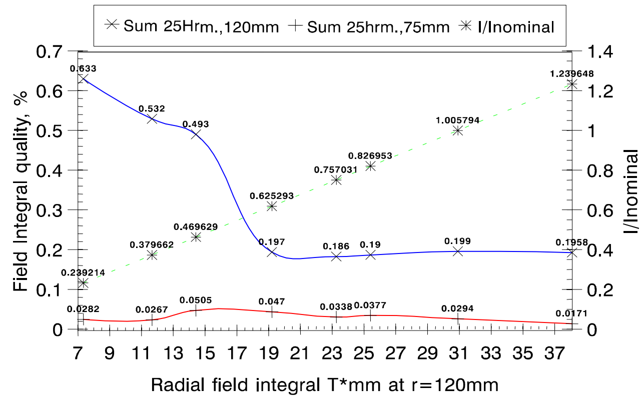

Fig. 4. Normalized sextupole field integral $I/I_{nominal}$ (right ordinate axis) and its quality $\sum|C_k|/|C_1|$ for 25 unwanted harmonics (on the left axis) vs field integral at r_g=120mm and r_g=75mm. Parameters: P_{max}=2.8kW, m=2.671, r_{ap}=150mm, pole tip angle $\Delta\theta$=44.9°.

Table 3. Sextupole design performance at different materials for the pole (tip+core) and constant (nominal) current

Material	Maximum magneti-zation M, T	Field strength $H\mu_o$, T at I·n=11668 A	Field quality at r=120mm, %	Estimated Power required, kW
RadMatXc06: Low Carbon Steel C<0.06% [AFNOR]	2.11	0.299	0.6 %	2.21
RadMatSteel37: Steel C<0.13%	2.052	0.286	0.7 %	2.065
RadMatSteel42: Steel C<0.19%.	2.06	0.282	0.67 %	2.092
RadMatAFK1: FeCo Alloy from MetalImphy (Fe : 74.2%, Co: 25%, Cr: 0.3%, Mn: 0.5%	2.35	0.297	0.87 %	1.85
RadMatAFK502: Vanadium Permendur from MetalImphy; (Fe : 49%, Co: 49%, V: 2%; similar to Vacoflux50)	2.34	0.318	0.92 %	1.72

Different geometries and materials were included in the study of saturation effects in local areas with maximum fields (see Table 3).

5 CONCLUSION

The design approach described here is applicable for any multipole magnet (i.e. quadrupole and higher). This type of shaping can be easily produced with programmable machinery tools. It simplifies the process of magnetic design of short multipole magnets and enhances its integrated moment. This is done by reducing the multi-parametrical, non-linear, complicated problem of 3D field optimization to a problem dominated by a main physical parameter variable in a well-defined range. One can also reduce the cost of the design with wider usage of simplified or standard elements like racetrack coils and disk clamps.

6 REFERENCES

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[4] R. Wines, Engineering Services Task Order #D2, FEL Upgrade, TJNAF 7/16/01.
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