AN ADJUSTABLE PERMANENT MAGNET QUADRUPOLE (PMQ) FINAL FOCUS SYSTEM FOR LOW ENERGY EXPERIMENTS

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Abstract

The final focus system for the Thomson X-ray scattering experiment termed PLEIADES (Picosecond Laser-Electron InterAction for Dynamic Evaluation of Structures) at LLNL demands ultra-high field gradient quadrupoles in order to focus initially small beams to 10-20μm spot sizes. The scheme present here circumvents limitations due to chromatic aberrations and space-charge effects in this relatively low energy (<100MeV) system. The final focus scheme is based on an ultra-high gradient (≥300T/m) quadrupole which employs the Halbach 16-piece, permanent magnet design. Use of this optimized geometry, NdFeB material, and a small (5mm) bore allows the desired field gradient, and a few cm focal length, to be achieved. The adjustability of the focusing system is obtained by changing the relative longitudinal positions of sub-component focusing and defocusing magnets on precision movers. We present the results of RADIA 3D design simulations, and also discuss the results of beam dynamics simulations of the PLEIADES system using the tracking code.

INTRODUCTION

PLEIADES (Picosecond Laser Electron InterAction for Dynamic Evaluation of Structure) is a next generation Thomson x-ray source facility at LLNL (Lawrence Livermore National Laboratory) which expected to produce x-ray flux between 10^7–10^8 photons at pulse durations of 100fs to 5ps long[1]. The maximum production of x-rays depends on short duration electron bunch generated by a photo-injector, and the new installation of high performance beam optics for a tightly focused small transverse beam size at the Thomson interaction zone. The standard UCLA electromagnetic quad triplet (≤15T/m) currently installed at the facility gives a final beta function of 13.5mm; this corresponds to a rms spot size of about 67μm. Achieving a spot size of even smaller scale at the interaction point is done with a strongly magnetized permanent magnet based quadrupole magnets. An immediate advantage of permanent magnet quadrupole over the standard quadrupole is in miniaturization of design without reduction of magnetic field strength. On the other hand standard quad's field strength has a linear proportionality dependence on physical size, or (current density)$^{-1}$.

We have devised a quad which is an asymmetric triplet configuration. TRACE 3D code is used to simulate beam transport of 30-60MeV, normalized emittance of 10mm-mrad, and beta function of 7mm/mrad. The lattice configuration is proved to be working well as shown later in the simulation results.

16-PIECE HALBACH PMQ MODEL

Magnet Design

We adopted a design initially proposed by Halbach[2]. The design of a PMQ consists of 16-piece magnet blocks put together to form a cylinder of 10mm in length, 2.5mm in bore radius and 7.5mm in outer radius. A slanted side view of a complete assembly of a PMQ is illustrated in Fig. 1. Also shown in the figure on the right-hand side is the magnetic easy-axis direction in each magnet block piece which rotates by 22.5° angle from one magnet block to the next. The remnant magnetic field of each Neodymium Iron Boride (NdFeB) magnet is set to B_r=1.2T. These final magnet physical parameters are chosen to obtain a desired high field gradient B'≥300T/m in the 3D magnetostatics modeling.

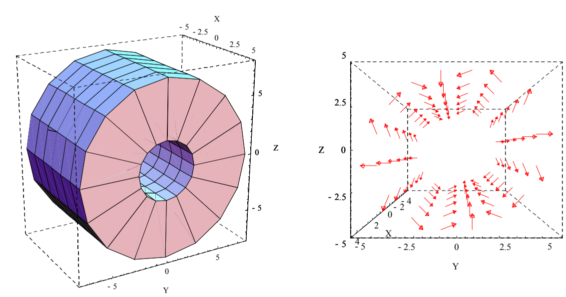

Fig 1: 16-piece Halbach PMQ illustrated on left. Magnetic easy-axis directions illustrated (red arrows) on right.

3D Modeling: Radia

A freely available magnetostatics computation software code termed Radia[3] was used in 3D modeling and numerical analysis of a 16-piece Halbach PMQ. Radia provides easy-to-define functions to easily create a sophisticated virtual model, and its capability to interface with Mathematica® allows one to easily do post-numeric analyses.

The desired field strength of B'=318.3T/m is obtained after a series of trial-and-error computations are carried out. The magnetic field gradient plotted in the bore region exhibited a linear behavior as shown in Fig. 2. Near the bore surface we encounter non-linear fields, and we suspect this is because magnetic field symmetry is broken

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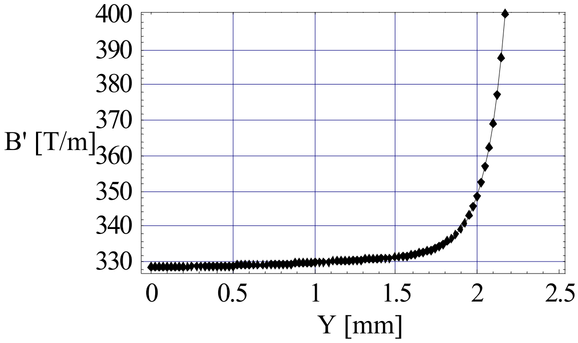

Fig 2: Magnetic field gradient B' plotted in the bore region.

as one moves close to the magnet bore surface where higher magnetic multipole moments are no longer small perturbations. As can be seen from Radia results, significantly large integrated sextupole and dodecapole fields are found at a reference radius of 2mm.

Generally the fringe field is simply neglected by assuming B_Z field to be a step function with a constant nonzero field within and zero outside of PMQ. This is to be replaced when one considers a short fringe field extending away from two ends of a PMQ. Fortunately, Radia can automatically define the fringe field components into our PMQ model. For our chosen physical input parameters, we obtained an effective magnetic length (l_{eff}) of 10.23mm. The magnetic field plotted in axial direction is shown in Fig. 3. An deviation in focal length of PMQ due to magnetic length difference, $\delta l = l_{eff} - l$, is defined by

$$|\delta f| = \frac{1}{K \cdot l^2} \delta l \qquad (1)$$

where K is the quadrupole focusing strength. For K= $1.9\times10^3 m^{-2}$ (50MeV, 318.3T/m), l=10mm and δl=0.23mm, a focal length deviation of ±1.2mm is expected.

Design Tolerance

So far we have described an ideal PMQ model where design imperfection is not factored into our modeling. However, we need to find out the performance of our magnet design in the presence of fabrication and assembly errors.

Possible mechanical and magnetic imperfections are easily defined into the Radia 3D modeling of PMQ and showed the robustness of our PMQ. Allowing tolerances of ±1% and ±0.1° in mechanical and magnetic values, we obtained the new magnetic field gradient 320.9T/m and the magnetic effective length 10.07mm, or respectively ±0.8% and ±1.2% in deviations from the ideal model.

When 16 magnets are pieced together to form a PMQ, these magnets will mutually try to influen ce magnetization characterizations. Such mutual magnetic influence can in fact change the over all ma gnetic properties of a PMQ. In Radia, magnetic relaxation of the PMQ due to inter-magnetic field interactions among 16 magnet block is shown to be almost negligible: the

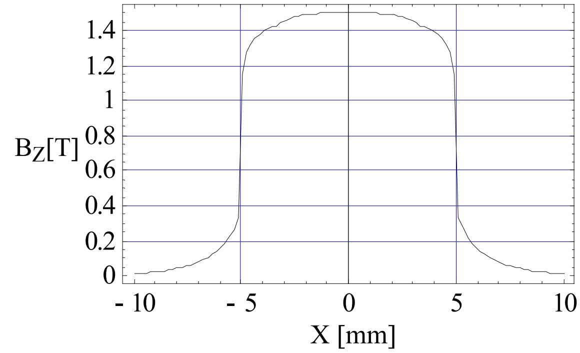

Fig 3: Magnetic field is plotted in the PMQ axis direction.

absolute average in change of magnetizations in 16 magnet blocks is 3×10^{-3}%.

Magnet Material Properties

High performance permanent magnet materials are known to be available in current market in large quantities such as Neodymium Iron Boride (NdFeB), Samarium Cobalt (SmCo) and Ferrite (Fe_2O_3). Particularly NdFeB is suitable for our application for its high-performance magnetic properties, machineability, strong material characteristic and availability of low-cost high-grade magnet material. In contrast, SmCo is generally known to be weaker in B_r by 25%, extremely brittle and more expensive than NdFeB. Key magnetic properties of NdFeB (grade 35SH) are listed in Table 1[4].

Radiation hardness of NdFeB magnet compound seems to exhibit a moderate level of resistant against magnetic degradation[5]. At PLEIDEAS facility, magnets will be operated at constant room temperature which is significantly below our maximum operation temperature of 160°C, and B_r loss to due temperature fluctuation is expected to be below a loss rate of 0.10%/°C. The summary of remanence loss due to irradiation sources are as follow: the exposure of 69Mrad of ^{60}Co γ-ray irradiation doses resulted in no remanence loss, 1.5% remanence loss is observed after direct hit by a total of 25 pulses of 82MeV electron beams, and the most remanence loss is observed in NdFeB by Bremsstrahlung source at a dose of 0.45Grad induced 2% minimum up to 14% maximum in loss[5]. We expect to minimize a remanence loss by placing lead based collimators before and after the PMQ final focus system. Also, a high internal coercivity of NdFeB material helps to reduced remanence loss. A further detail study of radiation induced remanence of our NdFeB PMQ system is warranted in the future.

Table 1: NdFeB Grade 35SH Properties

B_r (Gauss)	12,200
H_c (Oersteds)	11,700
H_{ci} (Oersteds)	26,000
Max. Energy (MGOe)	36
Temp. Coeff. Of B_r (%/°C)	-0.10
Max. Op. Temp. (°C)	160
Density (lb/in^3)	0.271

Fig. 4: TRACE3D simulation of 30MeV (Top) and 60MeV (Bottom) beam bunches transporting through PMQ final focus system.

FINAL FOCUS BEAM TRANSPORT SIMULATIONS

PMQ Triplet Final Focus System Layout

Our PMQ asymmetric final focus system consists of three permanent magnets arranged in Focus-Defocus-Focus (FODO) lattice configuration. The first PMQ is 1cm long and the second and third PMQs are 2cm long. Increase in physical length of PMQ effectively changes magnetic field gradient and effective magnetic length of a longer PMQ: 326.5T/m and 20.07mm.

TRACE 3D Simulation

TRACE 3D simulation results showed the tunability of focusing strength of PMQ final focus system. In practice tunability is achieved through varying drift space lengths with linear translators. The initial electron beam parameters entering the first PMQ are shown in Table 2. For 60MeV beam energy, the optimum focusing is achieved for drift space lengths of 36.52mm, 21.50mm and 41.84mm. The final transverse β functions obtained from the simulation are both 1.41mm. The adjustability of PMQ system for a different beam energy setting is also demonstrated in the simulation. For 30MeV, beam parameters are assumed to be the same as before for 60MeV. The optimum focusing is achieved for drift space lengths of 7.79mm, 1.40mm and 12.92mm. The transverse final β functions are 0.50mm and 0.49mm. The TRACE3D simulation plots of 30 and 60MeV beams are shown in Fig. 4.

Conclusion

3D modeling of the PMQ with Radia demonstrated a high magnetic performance based on 16-piece Halbach permanent magnet quadrupole (PMQ) of ≥300T/m and $B'l_{eff}\approx 3$T integrated magnetic field. And the beam transport simulation of PMQ final focus triplet system with TRACE 3D demonstrated a viability of linear translator mechanical device scheme to control effectively the focusing strength of PMQ final focus system: control of individual PMQ position with linear translator device. We have also shown in Radia that our PMQ had a

Table 2: Initial electron beam parameters

Beam energy	59.2MeV
σ_E	0.2%
σ_t	4ps
ε_{xn}, ε_{yn}	10mm-mrad
α_x	0.124
α_y	0.146
β_x	6.56mm/mrad
β_y	6.48mm/mrad
Beam charge	250pC

minimum error in its magnetic characteristics under presences of mechanical and magnetic tolerances of ±1% and ±0.1°. Remanence loss due to radiation bombardment is moderately low as detail experimental results showed[5]. We also expect a temperature fluctuation to incur no remanence loss. But we will need a future plan to study systematically both of these factors in our PMQs.

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