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HIGH RESOLUTION IMAGING DESIGN USING PERMANENT MAGNET QUADRUPOLES AT BNL UEM

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Abstract

Ultrafast electron microscopy techniques have demonstrated the potential to reach very high combined spatio-temporal resolution. In order to achieve high resolution, strong focusing magnets must be used as the objective and projector lenses. In this paper, we discuss the design and development of a high-resolution objective lens for use in the BNL UEM. The objective lens is a quintuplet array of permanent magnet quadrupoles, which in sum, provide symmetric focusing, high magnification, and control of higher order aberration terms. The application and design for a proof-of-concept experiment using a calibrated slit for imaging are presented. The image resolution is monitored as a function of beam parameters (energy, energy spread, charge, bunch length, spot size), and quintuplet lens parameters (drifts between lenses).

INTRODUCTION

Ultrafast electron microscopy (UEM) is a technique that uses RF photo-injector technology [1] at ~3 MeV, increasing beam energy from a nominal 300 keV in conventional transmission electron microscopes, and thereby mitigating space charge effects. However, operating at higher energy poses additional challenges for the focusing magnets required to achieve high imaging resolution. Permanent magnet quadrupoles (PMQs), with high field gradients, are useful as focusing elements due to compactness, magnetic strength, and field quality [2]. In addition, the focal length of PMQs is inversely proportional to the electron momentum, whereas the focal length of solenoid magnets is inversely proportional to the square of the electron momentum [3]. PMQs also display good harmonic control when arranged in highly segmented configurations and offer suppression of higher-order modes [2].

In this project, the objective lens of a UEM system will be replaced with a high-resolution version consisting of PMQs. The fields provided by PMQs are focusing only in one dimension, while defocusing in the other. Therefore, in order to construct a lens with overall focusing, or a round lens, a multiplet configuration of PMQs must be used. In [4], a description of a quintuplet array of PMQs for use as an objective lens is described. The main advantages of using five (or more) PMQs is that the extra degrees of freedom allow for optimization of both the overall magnification as well as correction of higher-order aberration terms.

A quintuplet lens using PMQs was designed and simulated for application at the BNL ultrafast electron microscopy facility [5]. The design was performed using a custom, multi-objective genetic algorithm for optimization of the lens magnification while minimizing aberration coefficients [6]. The results of the optimization routine accounted for manufacturing tolerances and typical discrepancies involved in the procurement, manufacturing, and assembly of permanent magnet material, especially in quadrupole applications. The end design consisted of small aperture PMQs, arranged in the “Halbach-style”configuration. The PMQ quintuplet is designed to be symmetric (about the center plane of the middle PMQ), and constrained by the location of the sample holder chamber, and other physical restrictions at the facility. The entire PMQ array was fabricated and bench measured [7] in anticipation of employ at the BNL UEM system.

EXPERIMENT DESCRIPTION

In preparation for use, and as a replacement for the objective lens in the upcoming UEM system, an experiment has been conjured to test the characteristics of the developed lens within existing framework at the BNL UED facility [8]. In this reduced scale experiment, the quintuplet array is isolated from other contributing factors of the microscope, and simplified to directly characterize the performance parameters as an objective lens. A sketch of the experiment is shown in Fig. 1, which consists of a focusing solenoid (used as the condenser lens in typical TEMs), a sample target for imaging resolution analysis, the PMQ lens array, and a detector.

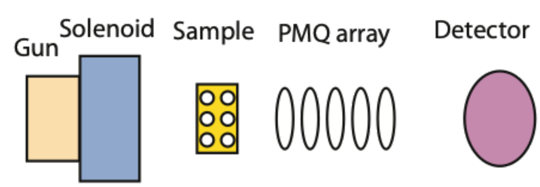

Figure 1: Sketch of experimental configuration to test characteristics of quintuplet lens within existing beamline layout.

Simulations were conducted to determine if the single solenoid was sufficient for imaging the sample target. Figure 2 shows a trade-off plot using a cost function that depends on the beam emittance and energy spread. There is an optimal region of parameter space in terms of solenoid current and photoinjector RF phase, where the beam has optimized emittance at the interaction point (i.e. the sam-

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ple). Such configurations are routinely used at BNL UED for diffraction experiments [8].

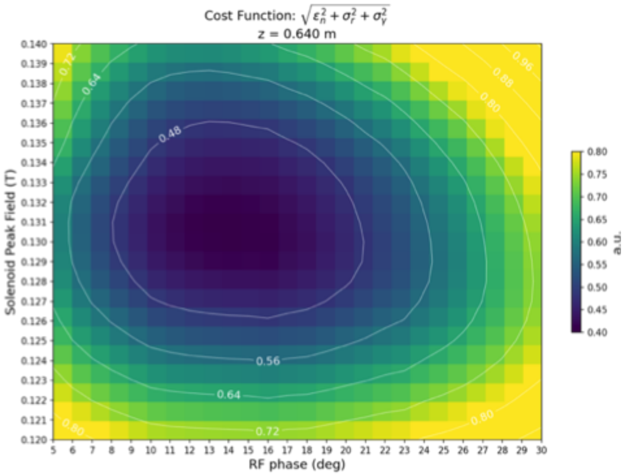

Figure 2: Simulation of cost function to optimize beam emittance and energy spread at interaction point using BNL UED parameters.

In preparation for the experimental measurements, the beam of Fig. 2 was propagated through the entire beamline at the BNL UED facility in simulations. Using the typical beam parameters of 10 pC, and 1 mm-mrad normalized emitttance. The beam spot size at the interaction point is <60 μm rms. The entire transport is shown in Fig. 3. The blue lines show the ideal beam size evolution for detection on a scintillator screen ~1 m downstream of the photocathode. The shaded area shows the extent of the PMQ quintuplet. During optimization of the lens, the beampipe diameter was an enforced constraint, and the beam size was not allowed exceed this value otherwise it would clip the chamber walls. The effects of the lens show a near symmetric focus of both horizontal and vertical components. The beam is then allowed to drift (magnet free region) to the detection plane. The yellow lines in the graph show the same beam size evolution, however with the inclusion of space charge forces, which has nonlinear effect on image aberration coefficients [9]. It is evident that the effects of space charge play a role in this reduced beamline model, and should be mitigated by operating at lower charge than nominal.

The target for the experiment consists of an array of slits, that are 1 μm wide and spaced at 10 μm center-to-center increments. For the first experiment, the target is only a 1-D array of slits, however options for more complex targets are also considered. The beam distribution just after the sample is pictured in Fig. 4 (left column), with the corresponding histogram. After transport, the same distribution is imaged on the detector (right column) with respective histogram. The test case will also be used to optimize the PMQ positions (relative to one another) on the assembly to determine the resolution limits of the system.

In follow on experiments, different targets will be used including TEM grids, and "V-shaped"slits that are translatable

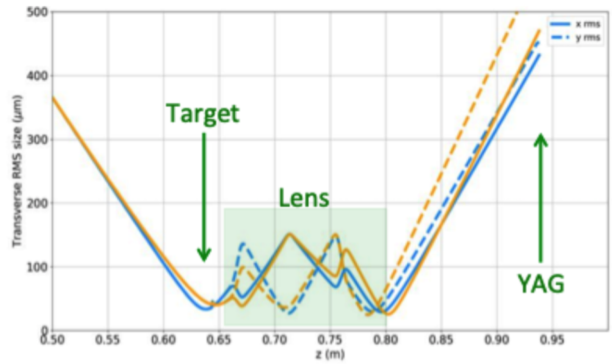

Figure 3: Transverse beam spot size (solid- x, dashed -y) for BNL UED transport with target and quintuplet lens identified in graph. The detector is a YAG scintillator. Blue lines are ideal, and yellow lines include space charge effects.

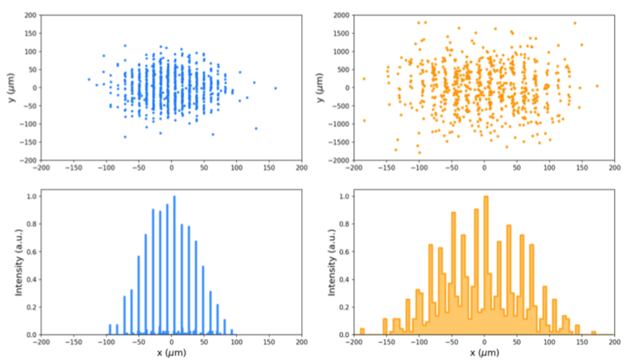

Figure 4: Top row: Simulation of 1-D imaging target with 1 μm slitted array at interaction point (left column), and imaged distribution at screen (right column). Bottom row: histograms of respective beam distributions.

in order to determine the limits of the lens imaging. Using gridlines (2-D array) will also yield information on geomteric aberrations of the imaging system. The experiment is designed to be minimally invasive to the existing BNL UED configuration.

ENGINEERING CONSIDERATIONS

The design and engineering of the entire assembly consisted of procurement of magnet material and assembly in Halbach geometry. The assembly of the quintuplet array requires the precision motion of each quadrupole with respect to a common reference axis. This is accomplished with an aluminum strongback and precision rails (Fig. 5). Each PMQ is mounted in an aluminum frame, that is subsequently attached to a stack of translation and rotation stages with the ability to move in multiple degrees of freedoms. Only translation along the longitudinal coordinate (i.e. relative to each other) is remote controllable for the prototype tests, whereas the other axes are manual and used for fine tuning of the magnetic field on benchtop tests. The entire footprint of the PMQ lattice is approximately 15 cm, from the first PMQ to the last.

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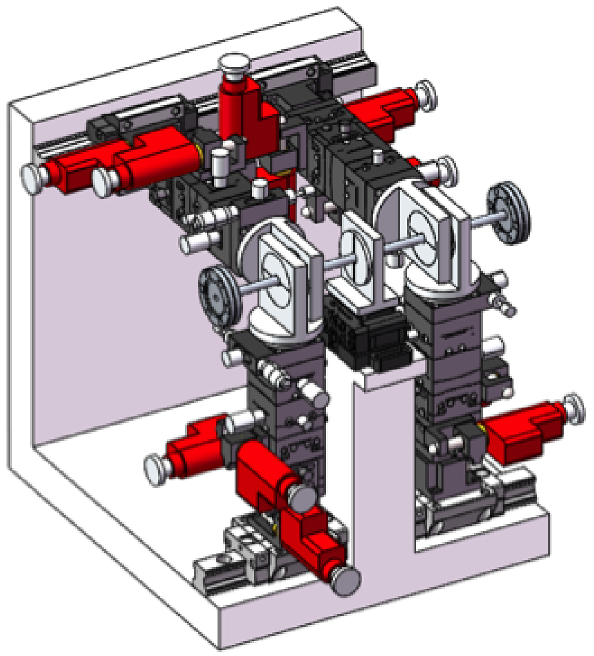

Figure 5: Model of complete assembly using multiple rotation and translation stages to accommodate multiple degrees of freedom for PMQ quintuplet.

In addition to the engineering of the complete assembly, the PMQs are designed to operate outside of the vacuum environment, in order to accommodate the focal length to the sample chamber in the UEM system. This required the use of a small (< 4 mm) diameter beam pipe in order to maintain the fields of the PMQs. The beampipe is welded onto flanges that are compatible with the rest of the beamline.

The small diameter beampipe is not threaded through the PMQ bores. Rather, a novel system was developed for eventual replacement of PMQs. In this configuration, four of the magnetic wedges in the Halbach array are replaced with steel wedges of the same dimensions. The steel wedges reduce to overall field available at the center of the quadrupole, however simulations, and subsequent measurements, show that the field is still sufficient for the intended lensing applications. A photograph of the complete PMQ is shown in Fig. 6. The steel wedges allow machining across the center-line of the PMQ, which is not manageable with brittle permanent magnet materials. The PMQ is then splittable into two parts, with precision dowels for reattachment, and able to be fit around the small beampipe.

The quintuplet lens is symmetric, i.e. the first and last PMQ have the same fields, as do the second and fourth ones. The middle PMQ, which has lower fields, consists of fewer wedges. In preparation for the BNL UED experiment, and future uses, many PMQs were assembled, and tested. The values of the tests were re-inputted in the optimization algorithm to determine whether an ideal configuration from available sets was desirable. This study is ongoing and would assist in delivering the optimal quintuplet lens for the initial experimental runs.

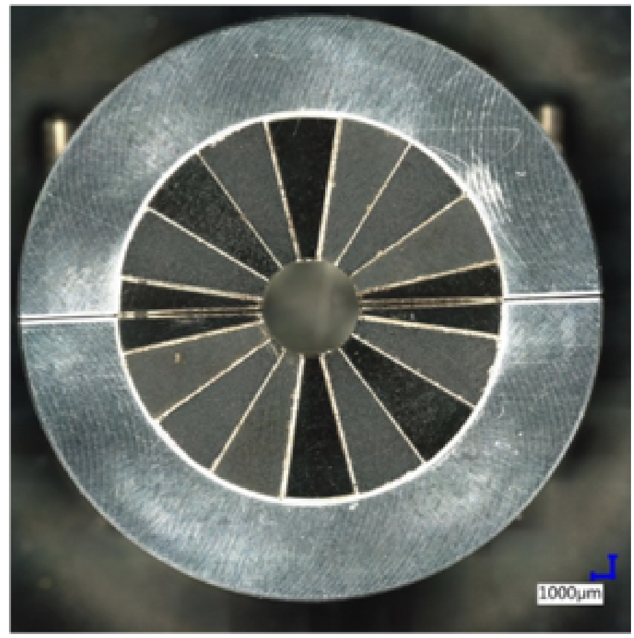

Figure 6: High resolution photograph of hybrid-PMQ with steel wedges for split design. Aperture is 4 mm.

SUMMARY

A PMQ quintuplet array was designed and fabricated for use in high-resolution imaging in UEM applications. The specific design is intended for the BNL UEM program. In the first tests, the quintuplet lens is isolated in a reduced experiment at the existing BNL UED facility. The experiment is similar to "device-under-test"runs where the PMQ lens is the device being tested. The goals of the experiment are to determine the imaging resolutions of the quintuplet array scaled to the UED facility parameters. The information gleaned from this study will inform further modification to lens system, as well as engineering the complete assembly,

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