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A SIMPLE VARIABLE FOCUS LENS FOR FIELD-EMITTER CATHODES*

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Abstract

We present the design and initial test results for a simple, variable-focus solenoidal lens with integrated emittance filtering. The design was developed as a first-iteration injection optics solution for transport of a beam from a field-emitter cathode into a dielectric laser accelerator structure. The design is easy to fabricate and, while based on permanent magnets, can readily be modified to allow for remote control of the focal length. The emittance is controlled via selection of collimating irises. The focal length can be changed by altering the spacing between two permanent ring magnets.

INTRODUCTION

Los Alamos National Laboratory is currently investigating the use of Diamond Field-Emitter Arrays (DFEAs) as cathodes for a Dielectric Laser Accelerator (DLA) [1, 2]. These DFEAs have the advantage of providing outstanding emittance, but at the cost of also producing a very divergent beam, with divergence measured at around 5 – 10 degrees [3]. This divergence presents a focusing challenge, as the beam must be very tightly focused in order to be accepted into the DLA structure [1].

We have developed a simple variable focus lens, which uses permanent-magnets in a solenoid like configuration to provide initial focusing of our beam. This approach allows for easy fabrication using commercially available components in order to provide a first-iteration solution for transporting our beam from the cathode to the DLA structure. The lens is also intended for use with an electrostatic fixed-slit emittance measurement system [4].

DESIGN CONCEPT

Several requirements guided our design process. First, our focusing system needed to be easy to fabricate and implement, while still being robust enough to expand upon in the future. Second, it would need to be able to produce a field strong enough to focus our divergent beam. The overall concept of our lens is very simple, and is solenoid-like in its result; it bears some similarity to conventional permanent-magnet solenoid designs [5] but is considerably simplified. We utilize two readily available, opposed permanent ring magnets in place of an actual solenoid. In practice this allows us to assemble a very portable structure, which can still be adjusted with relative ease and has the potential for future remote adjustment capabilities for 'on the fly' focusing adjustments. The magnet design itself is illustrated in Fig. 1.

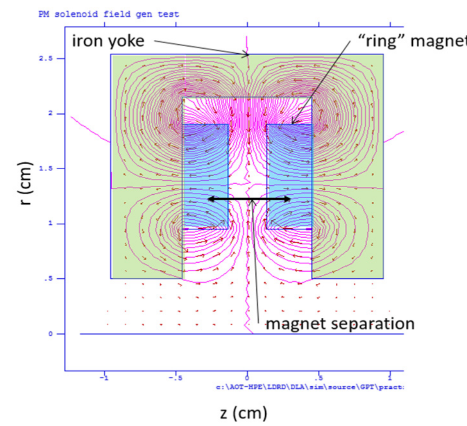

Figure 1: Poisson calculation of magnetic field of the lens. The lens consists of an outer iron yoke, and two inner 'ring' magnets which oppose each other.

The focal length of lens is varied by adjusting the separation between the ring magnets. Analytically, the focal length of an axisymmetric magnetic lens may be expressed as

$$f_{lens} := \left[\frac{q_e^2}{4\cdot(\beta\gamma\cdot c)^2\cdot m_e^2}\cdot\int_{\min(z)}^{\max(z)} B_s(s)^2\, ds\right]^{-1}. \quad (1)$$

We used GPT [6] to simulate transport of an initially parallel beam through the lens, using a 2-d field map generated by POISSON, for comparison with the analytically calculated focal length using only the on-axis field. Simulations were performed at our operating voltage of 40 kV.

Figure 2 shows a comparison between calculated and simulated focal length for our lens using the above interpolation function while Fig 3 shows the peak on-axis field as a function of the magnet separation.

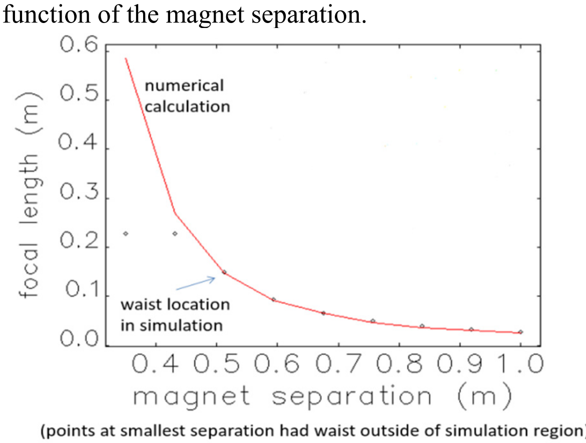

Figure 2: Comparison between on-axis predicted focal length, and particle tracking through a z-r field map.

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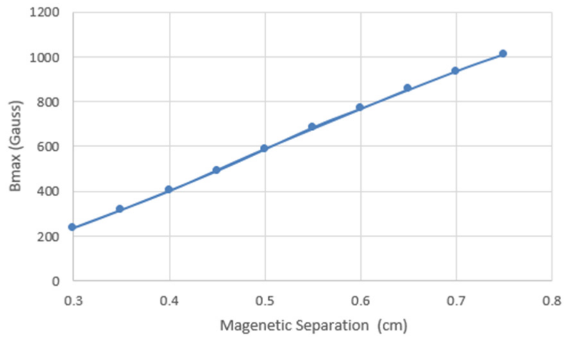


Figure 3: The relation between magnet separation and the peak on-axis field.

The next step in designing our lens was addressing the spherical abberation present in all axisymmetric magnetostatic focusing systems. Adding copper collimator disks into the system proved to be a simple and highly effective solution, providing two benefits to the lens as a whole. First, it reduces the effective spherical abberation in our lens (albeit by filtering, and thereby reducing the beam current), and second it acts as a basic emittance filter, required to meet DLA requirements in any event.

Further simulations indicated that with the additional collimators our lens system should be able to get down to a 3 micron RMS beam size, approximately 6 cm from the cathode as shown in Fig. 4. The spot size can be reduced even further by adding an additional collimator plate after the lens assembly, albeit at the cost of reduced beam current. More lenses can be added to extend our beam transport line, but at the cost of beam quality degradation and required filtering.

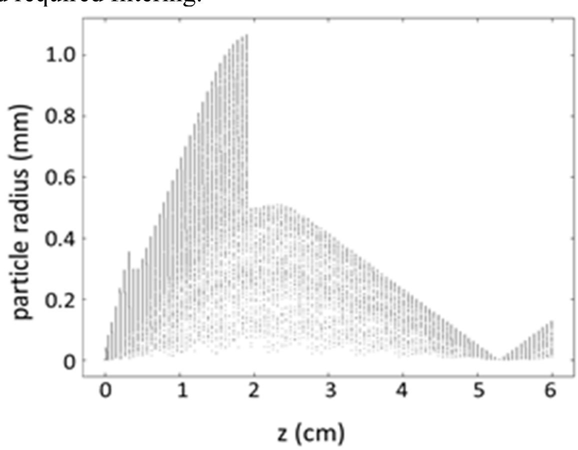


Figure 4: GPT Simulation of the beam propagation through the lens and two collimators

FABRICATION

The lens system needed to be implemented in such a way as to be easy to procure, assemble, and adjust. In order to do this, we decided to use commercially available parts wherever possible. Using a lens tube from Thorlabs [7] as the basic support framework also ensured that the entire lens could be mounted with ease on standard optics equipment.

All lens components are available commercially with the exception of the copper collimator plates and iron yokes. These pieces are simple and relatively easy to manufacture by any local machinist.

The magnet separation, and therefore focal length, simply is adjusted by using a spanner wrench to adjust a retaining ring holding one magnet in position within the lens tube. As the magnets repel each other, their alignment is maintained as their separation is adjusted.

The lens will be modified in the future to allow the retaining ring to be motorized. This adjustment would be controlled via python and would allow remote adjustment of the focal length.

INITIAL TESTING AND RESULTS

The lens was assembled and initially tested by using a hall probe on axis. We then compared the simulation result with the measured result. The comparison was done using Mathcad [8], and is shown in Fig. 5.

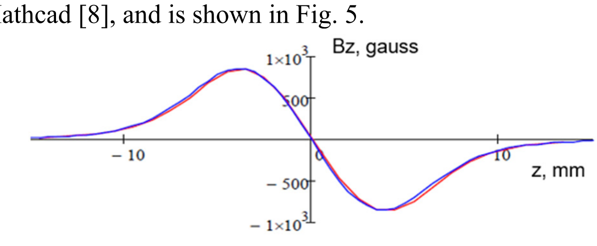
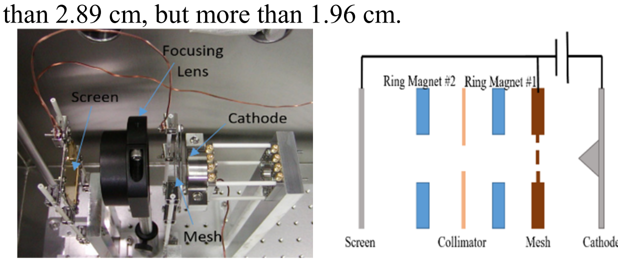


Figure 5: Simulated field vs measured field at various distances from the magnetic center.

The simulation and measurements match as well as we expected and encouraged us to proceed with testing the lens and assembling it in the beamline for further measurements. A photograph of the experimental setup is shown in Fig. 6(a), with a simple schematic alongside it 6(b). The spacing between the cathode and mesh, as well as the lens and mesh is fixed. The spacing between the lens and the screen is variable, allowing us to move the screen through the focal point of the lens. This movement allows us to verify that the lens is focusing as we expect and that moving out of our focal point will produce an unfocused beam.

For the initial test conditions for the lens we set the magnets at a separation of 0.65 cm with a measured peak field of 950 gauss. We expected our lens focal length to be less than 2.89 cm, but more than 1.96 cm.



(a) (b)

Figure 6: Photograph of current experimental setup (a) alongside a simple schematic of the setup (b).

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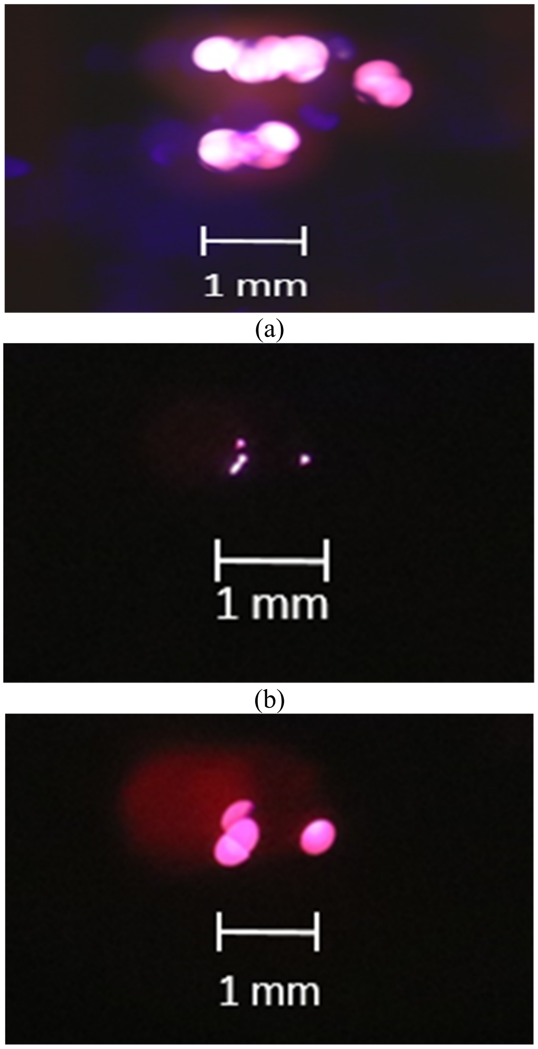

Figure 7: Comparison between an unfocused beam without a lens (a), our focused beam (b) at 23.5 mm, and our unfocused beam (c) at a distance of 30.5 mm. The focused beam has a spot size of 75 µm while the unfocused beam measured at 197 µm

We moved the stage from a distance of 4.14 cm to 1.55 cm from the magnetic center of our lens, covering our expected range of focal length.

Figure 7(a) shows the results of our unfocused beam, without the lens installed; Fig. 7(b) shows the beam focusing at a distance of 2.35 cm. The spot size was measured by counting the pixels per millimeter of our image and resulted in a diameter of 75 µm when the lens screen was at our focal point of 2.35 cm. We measured a beam current of 8.3 µA from screen to cathode. The measured focal point agrees with the predicted focal point given the peak on-axis magnetic field and beam voltage. For comparison, at a distance of 3.05 cm from the lens, our beam is 197 µm across and has a transmitted current of 6.5 µA as shown in Fig. 7(c). The number of beam spots is reduced in Fig 7 (b) and (c), compared to (a), due to the use of a collimator.

These tests indicate that the design and concept of the lens are effective and that with further fine tuning we should be able to come very close to our simulation results. In turn, this prepares us for emittance measurement to be conducted using a 2-slit scanner [4]. With a spot size of 75 µm we have yet to achieve the parameters required for our dielectric laser accelerating structure [1] design, however, we shall continue to refine our lens system, measurement techniques, and overall system calibration as we work towards meeting those goals.

CONCLUSION

We have designed, simulated, fabricated, and tested a variable focusing lens for field emitter cathodes. The lens is simple and easy to implement, yet provides considerable flexibility in our experimental setup. At present, we can achieve a beam spot size of 75 µm. We will further refine the physical implementation of our overall system as we move towards our goal of approximately 3 micron RMS beam size. Our intended steps include: improving the overall alignment of the lens to the cathode/anode plane; centering specific emitting pyramids on the axis; and centering the anode mesh openings on-axis also. We will also explore refining the magnetic and collimator designs. These steps will improve the accuracy of our emittance measurements and divergence studies, as well as move us one step closer to our goal of utilizing a dielectric laser accelerating structure [1].

ACKNOWLEDGEMENTS

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