ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR77

DEVELOPMENT OF A FLUX-CONCENTRATOR-BASED 2-TESLA SOLENOID AS A ROUND LENS FOR ULTRAFAST MICROSCOPY *

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Abstract

Ultrafast Microscopy using MeV beam has made considerable progress in the past 10 years. However, in order to push to atomic level resolution, other than the requirements of beam source, there are also high demands in high strength focusing elements. In comparison of commercial 100s KeV level electron microscopes, an MeV imaging beamline requires Tesla level lenses, preferably round solenoid lens. Tesla class DC solenoids are prohibitively bulky and heavy, and superconducting solenoids are not cost effective. We have developed a novel miniature flux concentrator-based solenoid lens system for MeV UED/UEM applications. It can reach 2-Tesla with 1e-5 level stability (depending on the pulsed current source). Here we present detailed development process and experimental results.

MOTIVATION

Thanks to its unparalleled temporal resolution and less restrictive sample requirements, MeV Ultrafast Electron Diffraction (MeV UED) has emerged as a powerful tool for investigating ultrafast dynamics in materials, gaining even more attention in the past decade. MeV electrons from a normal conducting photoemission cavity are capable of providing <100 fs bunches for ultrafast probing. With the aid of bunch compression techniques, the bunch can be < 10 fs. However, MeV Ultrafast Electron Microscopy (MeV UEM) still faces challenges in achieving spatial resolution comparable to that of conventional Transmission Electron Microscopy (TEM). Two major limiting factors are the presently poor energy spread of the ultrashort MeV beam produced in the RF photogun and the absence of suitable electron optics for the MeV beam. Specifically, a set of high-field solenoids (up to 2 Tesla) acting as condenser, objective, and projection lenses are needed. While superconducting solenoids are expensive and require cryogenics, normal conducting solenoids are remarkably bulky, weighing approximately 2 tons each. As of now, there are no compact solenoid-based UEM optics available that can facilitate the creation of a commercially viable machine. Lens consisting of a set of permanent magnet quadrupoles is being explored as a potential solution [1]. However, its complexity and lack of tunability may eventually restrict its application to compact MeV UEM systems.

On the other hand, because most MeV UED and UEM facilities are pulsed machines, naturally we may consider using a pulsed solenoid for the beam optical lens which is much compact and lighter than the DC solenoid. However, ensuring the stability of the high current pulser used to drive the solenoid remains a significant concern for the application of pulsed solenoids in MeV UEM. To address the requirement for a stable pulsed current source, this article presents the development of a Flux Concentrator (FC)-based solenoid lens, which is a pulsed technology previously adopted for the design of high-energy positron target collection solenoids [2]. Relying on the strong eddy currents, the FC offers an additional enhancement factor for the magnetic field generated by the pulsed solenoid. As a result, it is possible to achieve a Tesla-level field strength with a relatively lower current, thus significantly reducing the technical challenges associated with obtaining a stable pulsed current source.

PRINCIPLE OF FLUX CONCENTRATOR

The flux-concentrator first appeared in the context of inductive heating. It was also introduced for the positron production. Figure 1 shows cross-sectional views of a typical FC. It consists of a primary excitation coil, carrying an azimuthal current, surrounding a solid conducting core with a radial slot running from the inner bore of the core to its outer surface. A time dependent current in the primary coil will induce a magnetic flux in the core. Since there is a slot in the core, an induced current on the outer surface will be directed to flow along the radial direction when it reaches the slot. The direction of the current around the inner contour of the bore will be opposite to that on the outer surface. The induced current generated in the core tends to shift the flux of the primary coil into the smaller region inside the central bore and relieves the mechanical stress arising from the Lorentz force on the primary coil. In addition, a benefit of the FC structure is that the field profile can be changed by the shape of the FC inner channel.

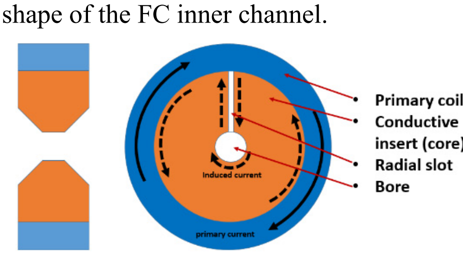

Figure 1: The typical geometry of an FC: primary coil, conductive insert, radial slot and bore.

* Work supported by DoE SBIR Grant # DE-SC0018622.
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& now with PALM Scientific.

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The enhancement of the magnetic field in an FC primarily depends on the rise time of the pulsed drive currents in the primary coil. It defines the magnetic flux gauged by Faraday's law of electromagnetic induction. For this reason, the primary coil in general has less turns in order to reduce the coil inductance thus ensure a fast rise time. On the other hand, less turns indicates a large in-pulse current is needed for Telsa level of field in the concentrator. Several other factors also contribute to the field enhancement, including the design and material properties of the concentrator, the geometry of the system, and the characteristics of the applied magnetic field. To maximize magnetic field enhancement, it's essential to consider these factors and carefully design the FC to suit the specific application and requirements. The trade-offs between various parameters are needed to achieve the desired performance.

Figure 2 shows an example of FC design. We define the coil with an external current density corresponding to 200 Ampere-turn current. Two versions of the FC have been studied (we use COMSOL, a commercial finite element method software package, for the simulation). One has the field length of the coil with a FC is 10 cm, and the other has the same coil but a tapered in FC (equivalently a shorter FC in around the bore). We considered the typical time structure of a current pulse, choosing ~ 2ms pulse length for this simulation. For a 200A pulse we obtain ~ 0.12 Tesla field in the case of coil only and ~0.29 Tesla of standard FC. By reducing the effective length of the FC, the magnetic field on axis can reach 0.6 T. This illustrates another benefit of using a FC: the same coil can be reused with alternate FC geometries which pursue different design purposes.

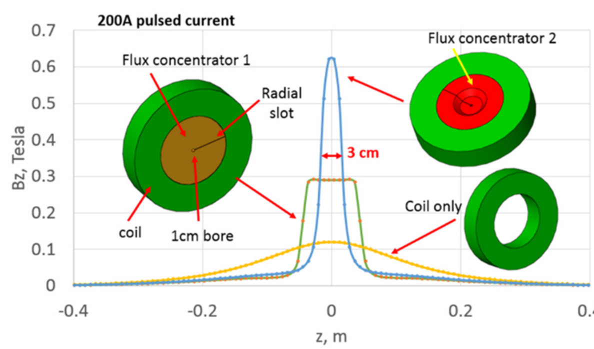

Figure 2: Longitudinal distribution of the magnetic field for two FC designs compared to the coil alone for a 200A pulsed current. Coil is rated for 200A DC operation.

DESIGN OF A 2-TESLA FC LENS

Inevitably the asymmetricity of the single-slit FC as shown in Fig. 1 will result in a small transverse gradient across the center region, which is undesirable as a round lens. Symmetrical slits would solve the issue, but the cost to pay is the field strength reduction at the same drive current. Practically, the beam into a lens is less than 1mm over the full length in general (depending on the aperture, focal strength of the upstream lens, and electron scattering after the sample). In order not to compromise the field strength too much, we choose to use the dual slits FC design as a good trade-off. After the optimization, the transverse field has been minimized to insignificant value in 1mm of diameter of good field region. The simulated field profile of an optimized 2-Tesla dual slits FC is shown in Fig.3, where the plot indicates no difference for Bz (2T) across X and Y direction in the same region.

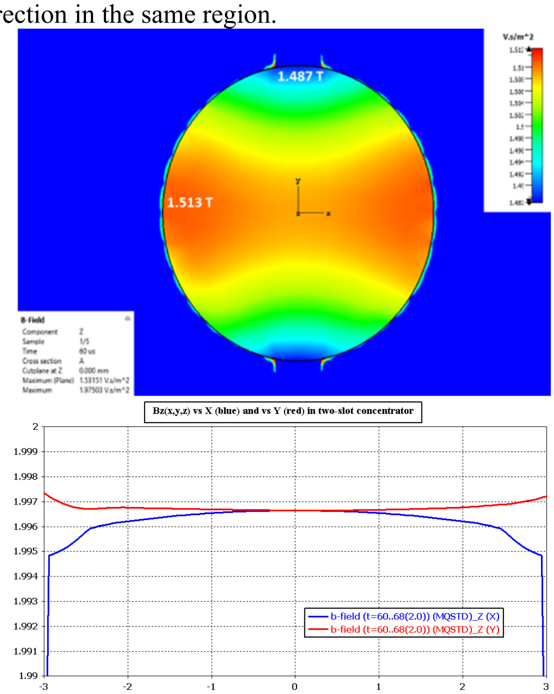

Figure 3: The simulated magnetic field map of Bz (a) and plot of Bz over X and Y axes (b) in a dual slits FC. Note, the field strength in (a) was scaled to 2T for a single slit FC. Under the same current the field drops to 1.5T for the dual slits FC.

Figure 4 illustrates the final design of 2-Tesla FC. In order to further minimize the fringe field, we introduced the ferrite at both ends of the FC. It also helps reduce the requirement of drive current from 2.1kA to 1.7kA for 2-T Bz field on the beam path.

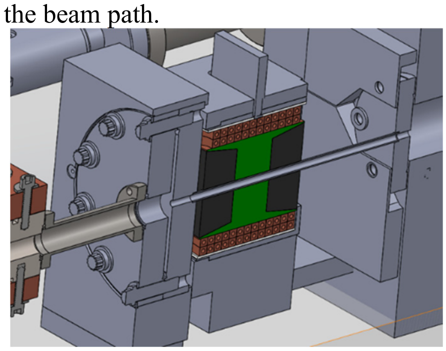

Figure 4: 3D cut-away view of the 2-Tesla FC with a ceramic beam pipe. Green: copper FC; Black: ferrite; Brown: copper coil.

FABRICATION AND MEASUREMENT

The final FC lens was fabricated with water cooled coil and ceramic beam pipe (Fig. 5). The total coil inductance was measured to be 24.2uH which is matched well with the simulation, 25uH without Ferrite. Its time dependent field

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map with a pulsed current source was measured. The result is shown in Fig. 6 with maximum Bz field set to 1-Tesla.

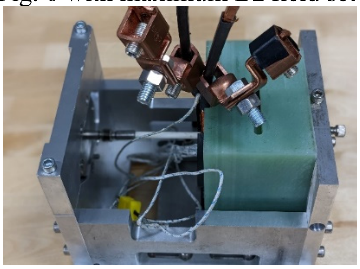

Figure 5: Picture of the 2-Tesla FC with mounting fixture and beam pipe.

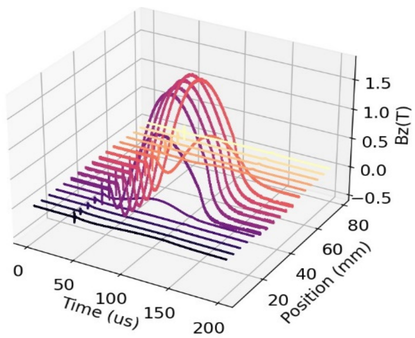

Figure 6: The measured Bz profile and their time response.

To test Bz symmetry, Bz at the time (64.72us after the current pulse starts) when Bz reaches maximum was measured. The result is plotted in Fig. 7. The maximum value is 1.82T due to the voltage limit of the pulse current source. One hour test was performed at 5 Hz of repetition rate. After 30 minutes a stable operating point was reached, shown in Fig.8. Bz is stabilized at 1.824T with stability at ±0.0015T (±0.08%) and temperature is stabilized at 31.05C with stability at ±0.15C (±0.48%). The current source has the stabilization in 0.01%.

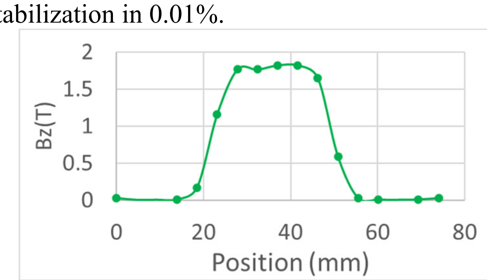

Figure 7: The snapshot of Bz field at the moment that Bz is maximum at the center of FC.

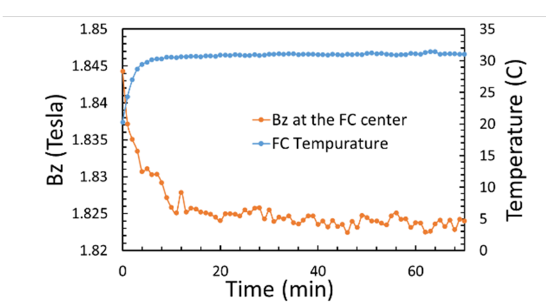

Figure 8: Evolution of temperature (at the concentrator body) and field (Bz) over 70-minutes at 5Hz repetition rate.

BEAM TEST

The final beam experiment was carried out at BNL-ATF-UED beamline. The 1.7MeV photoemission beam was injected to the FC lens. Three retractable Beam Profile Monitor (BPM) screens and associated cameras are the primary diagnostic tools. The upstream beam was focused using the RF photogun solenoid. Two upstream correctors were used to align the beam going through the FC lens. The current and voltage signals to drive the FC lens were recorded in a remotely controlled oscilloscope. The trigger signal was provided from a digital delay box (DG535), which set the precise timing delay from the machine master trigger to synchronize the beam with the pulsed FC lens. It ensures each electron bunch will experience the maximum focusing strength from the FC lens. The statistic from the recorded current profile also indicates 10^-4 level stability of the drive current. It should be pointed out that the 10^-4 stability is mainly attributed to the Heinzinger precision voltage source that we used for the current pulse forming circuit. 10^-5 level stability can be achieved with their a high end product line. During the experiment, images at three BPMs were recorded different FC drive currents. At each value, hundreds of images were recorded to check the strength jitter. There was no observable position jitter in BPMs after the FC lens. The Bz values of the FC lens are converted using the measured current and the bench measurement results prior to the beam test. Around 2.6kG of field can make the crossover, the smallest beam size, at the distance of BPM-B (~0.33m from the FC center. The Zoom-in images near the crossover strength (Fig. 9) reveals the occurrence of astigmatism. The beam injection alignment (position and angle) may attribute it, which can be easily corrected with help from upstream steering coils or downstream stigmator.

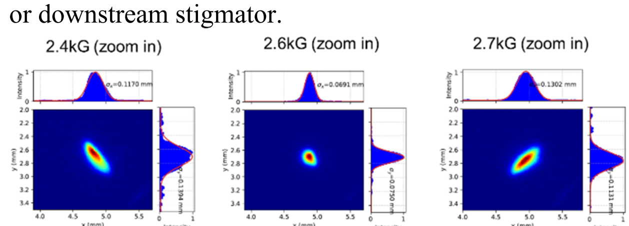

Figure 9: The measured beam profiles at BMP-B indicates the astigmatism.

CONCLUSION

In conclusion, this project has validated the use of FC-based lenses as a viable technical approach for constructing a table-top MeV UEM beamline.

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