Beam Manipulation via Superconducting Magnets for Ultrafast Electron Diffraction and Electron Beam-Ultrafast High Power Laser Interaction experiments

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Abstract

Particle accelerators drive advances in medicine, technology, and fundamental science. This study explores three core components of accelerator systems from superconducting magnets (SCM) to ultra-fast electron diffraction (UED), and to ultra-fast high-power (UFHP) lasers. At the Superconducting Magnet Division (SMD), dipole and quadrupole window magnets were designed using SIMULIA OPERA and RAT-GUI, with a canted-cosine theta (CCT) quadrupole coil directly wound using Nb-Ti wire and tested for field quality. These magnets align electron beams in the UED beamline, where General Particle Tracer (GPT) simulations modeled beam dynamics, including beam emittance and space charge effects, which are confirmed through solenoid and quadrupole scans. At the Accelerator Test Facility (ATF), 3DOptix software was used to design and optimize mirror geometries, beam paths, and focal spots. By combining superconducting magnet, ultrafast electron diffraction beam diagnostics, and laser and optical alignment, this work lays the foundation for accelerator science performance.

Background

Instrumentation and Results

Superconducting Magnets (SMD)

Superconducting magnets are the heart of particle accelerators, they create intense magnetic fields that focus, bend, and steer particle beams. They are made from special materials of Nb-Ti that carry electric current with zero resistance once cooled down to cryogenic temperatures [1]. Understanding the operation of the magnets is essential as the magnetic forces are dictated by the following laws:

Ampères Law explains current production.

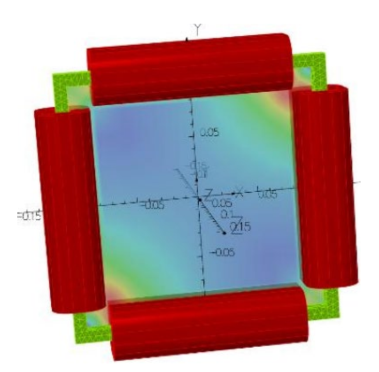
$$\nabla \vec{B} = \mu_0 \vec{J}$$

Lorentz force demonstrates how fields act on moving charged

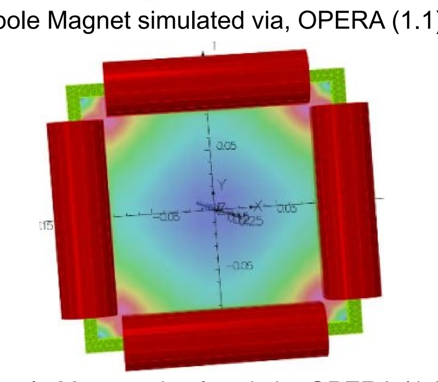
$$F = qv \, x \, B$$

Gauss' Law ensures the magnetic field remains uniform and precise for stable beam transport.

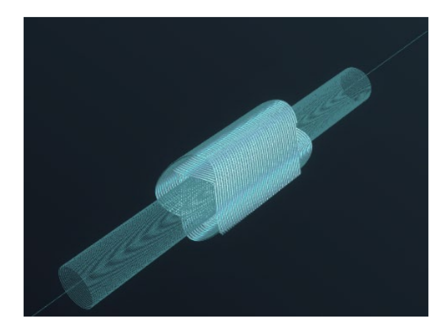
$$\nabla \vec{B} = 0$$



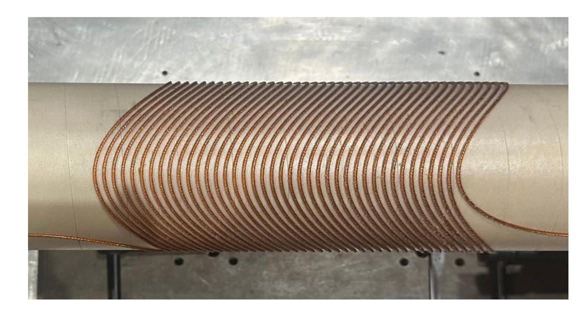
Dipole Magnet simulated via, OPERA (1.1)



Quadrupole Magnet simulated via, OPERA (1.2)

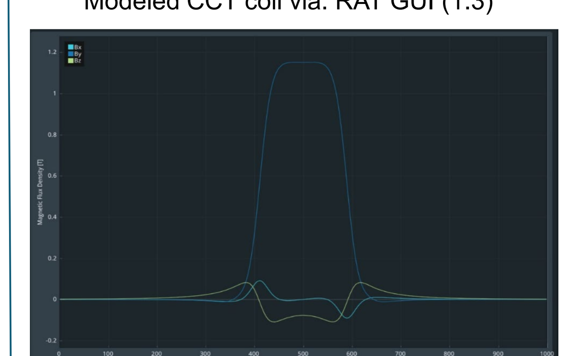


Modeled CCT coil via. RAT GUI (1.3)



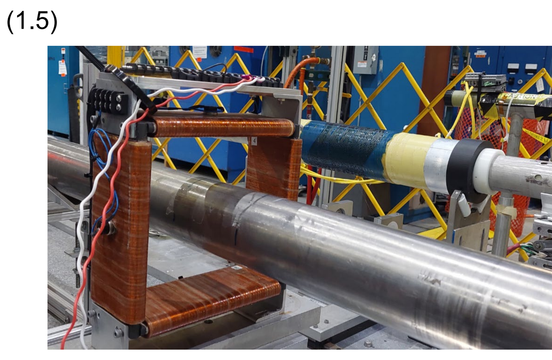
CCT coil wound through BNLS's direct wind method (1.5)

CCT coil with serpentine patterns built using BNL's Direct Wind Machine.



Line Calculation via RAT GUI (1.4)

Line calculation of magnetic field components along the center of a CCT magnet, used to evaluate field strength and uniformity.



Window magnet and CCT magnet tested at Superconducting Magnet Division (1.6)

Ultrafast Electron Diffraction (UED)

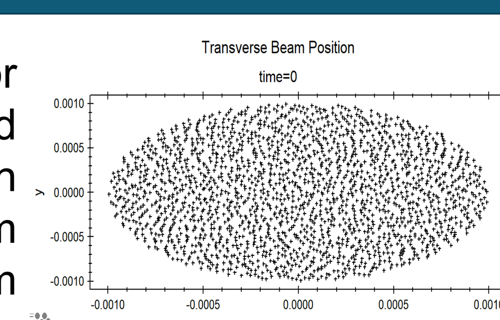
Ultrafast Electron Diffraction plays a key role in particle accelerator research by probing lattice vibrations, phase transitions, and chemical reactions by sending short electron bursts through materials [2]. The resulting diffraction patterns are shaped by beam dynamics, emittance, space charge, and beam spread [3]. Beam behavior is shaped by the following core equations:

Emittance measures beam spread & quality

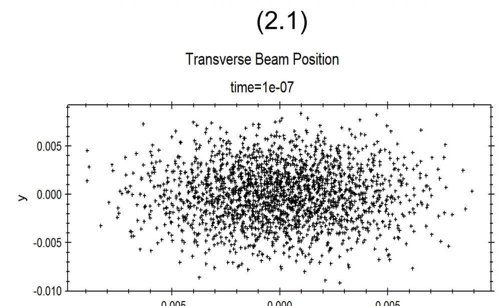
$$\varepsilon_g = \sqrt{<x^2><x'^2> - <xx'>^2}$$

Space Charge captures beam self-repulsion

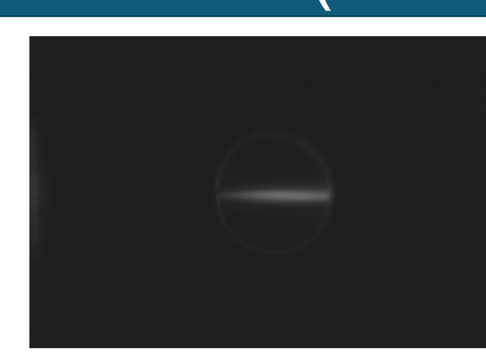
$$\epsilon_n = \beta\gamma\epsilon_g$$



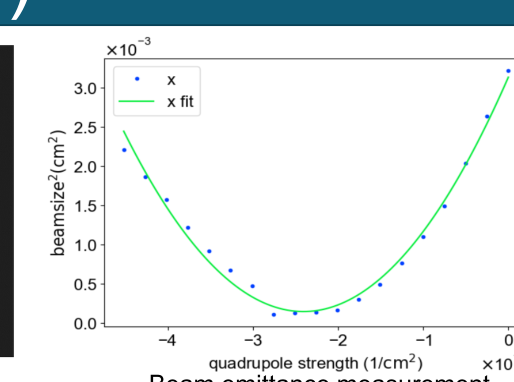
Beam emittance at t = 0 via. GPT (2.1)



Beam emittance at t =1E-07 via. GPT (2.2)

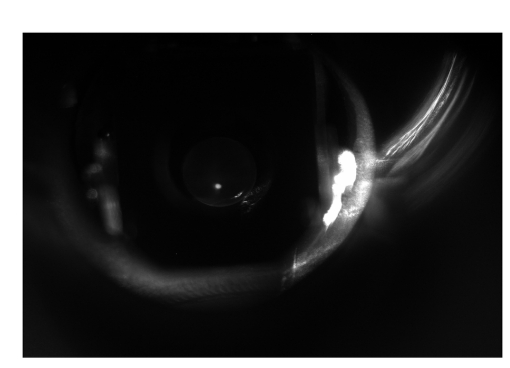


Quadrupole Scan at .700 A (2.3)

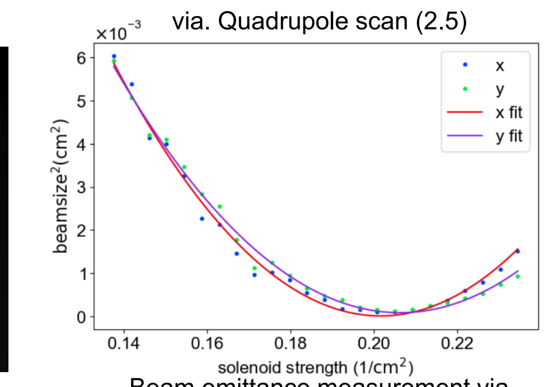


Beam emittance measurement via. Quadrupole scan (2.5)

The quadrupole scan focuses the beam in one plane, creating a parabolic curve plotting beam size squared versus quadrupole strength. The lowest point of the curve shows where the beam is tightly focused.



Solenoid Scan at 167 A (2.4)



Beam emittance measurement via. Solenoid scan (2.6)

The solenoid scan focuses the beam evenly in both the x and y directions. Plotting separate parabolas for x and y, and their lowest points show the tightest focus in each plane. As current increase so does the field strength.

Optics and Lasers

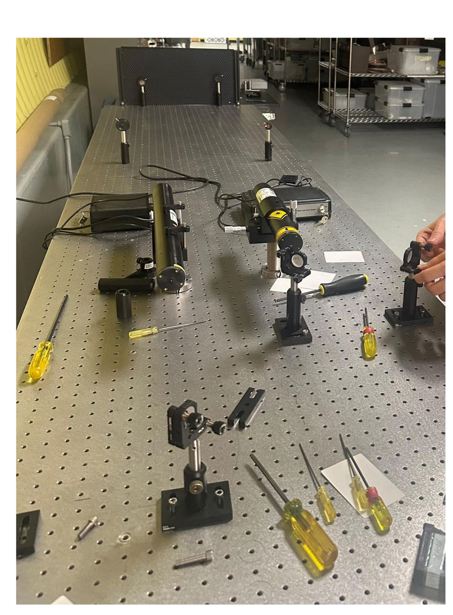
Optical systems were designed to support ultrafast high power laser into particle accelerators. 3D-Optix optimized mirror geometries and beam paths. Parabolic mirrors and lenses focused beams for precise interaction with electron bunches. Magnification setups and fiber alignment maintained beam delivery and diagnostics. These optical designs were guided though optical equations:

Lens equation determines image position

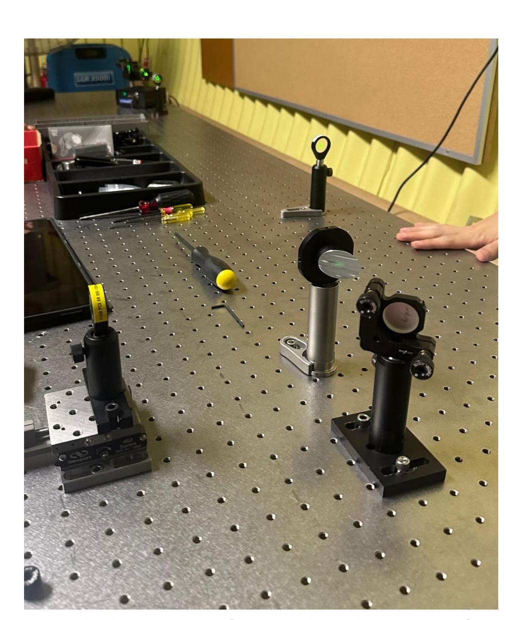
$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

Thins lens equation describes the image size based on object and image distances.

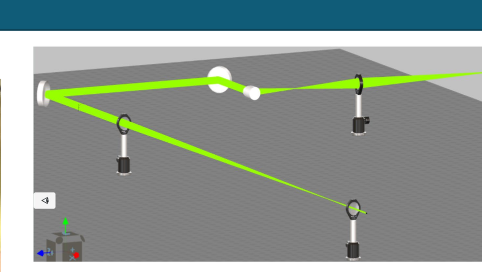
$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$



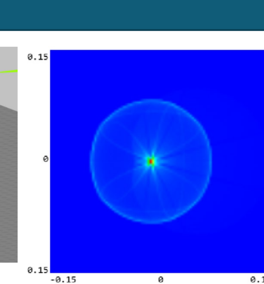
Laser Alignment of mirrors on optical table (3.1)



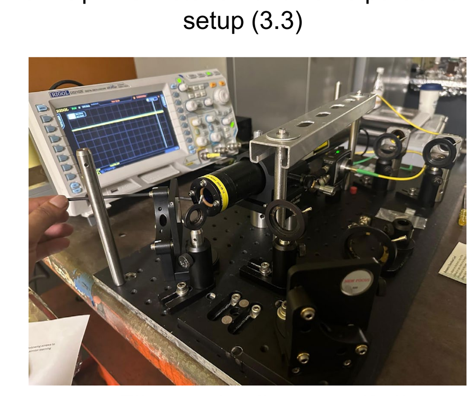
Real alignment of optical table setup of off axis parabola (3.2)



3D Optix Simulation of off axis parabola setup (3.3)



Photon beam of off axis via. 3D Optix (3.5)



Fiber optic alignment (3.4)

In figure 3.4 632 nm laser passes through an optical fiber to a photodetector, generating a signal shown on an oscilloscope.

Fiber optic alignment (3.6)

Conclusion

This study brings together superconducting magnets, ultrafast electron diffraction, and laser optics to advance particle accelerator technology. Superconducting magnet design, beam simulations and measurements, and laser and optical system optimization each contributed to precise beam control and system performance. Experimental results closely matched theoretical models and simulations, reinforcing core concepts and supporting continued progress in particle accelerator science technology. This presentation includes "No export controlled" work.

Acknowledgements

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Cited Work

[1] Xu, Hantao, et al. "Development and Testing of the First Quadrupole Magnet Prototype for the Electron-Ion Collider." arXiv, 10 June 2024, https://arxiv.org/abs/2506.05004.

[2] Brookhaven National Laboratory. Ultrafast Electron Diffraction. U.S. Department of Energy, www.bnl.gov/cmpmsd/xray/highlights/ultrafast_electron_diffraction.php.

[3] Carbone, Fabrizio. Ultrafast Electron Diffraction and the Visualization of Matter Structural Dynamics: Principles and Applications. arXiv, 1 July 2022, arXiv:2207.00080

[4] Ma, Y., T. Doner, P. Musumeci, and J. Duris. "Relativistic Electrons from Vacuum Laser Acceleration Using Tightly Focused Radially Polarized Beams." arXiv, 21 Feb. 2024, https://arxiv.org/abs/2402.08009.

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