An Integrated Study of Particle Accelerator Technologies: Magnet Fabrication, Electron Beam Dynamics, and Lasers Optics

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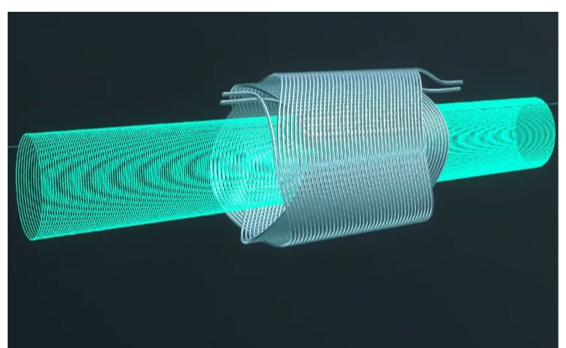
Abstract

Particle accelerators consist of complex systems including advanced magnets, precision beam diagnostics, and ultrafast lasers. This work outlines scientific and technical progress from three training modules at Brookhaven National Laboratory (BNL). In the superconducting magnets module, we collaborated with BNL's Superconducting Magnets Division to design a Canted Cosine Theta (CCT) magnet using RAT GUI and direct wind technology. OPERA software simulated dipole and quadrupole magnets, validating their role in guiding charged particles. The electron beam diagnostics module focused on measurements and simulations at the Ultrafast Electron Diffraction (UED) facility, using emittance and spectrometry techniques. General Particle Tracer (GPT) simulations matched experimental results. The laser module at the Accelerator Test Facility (ATF) involved aligning and characterizing beams using 3DOptix. Ultrafast laser systems are crucial to modern accelerator research, as they enable advanced beam manipulation, diagnostics, and acceleration schemes like Laser Wakefield Acceleration (LWFA). Understanding the framework empowers us to become key contributors to scientific progress, advancing both our careers and the field of science.

Methods

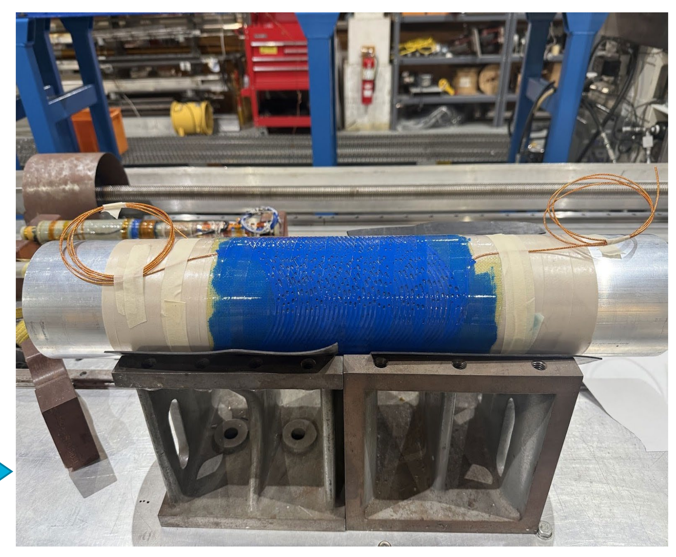
Superconducting Magnet Design

Collaborated with BNL's **Superconducting Magnet Division**



Simulated CCT magnet

RAT GUI exports XYZ files for direct transfer of magnet designs to BNL's fabrication system, avoiding translation errors.

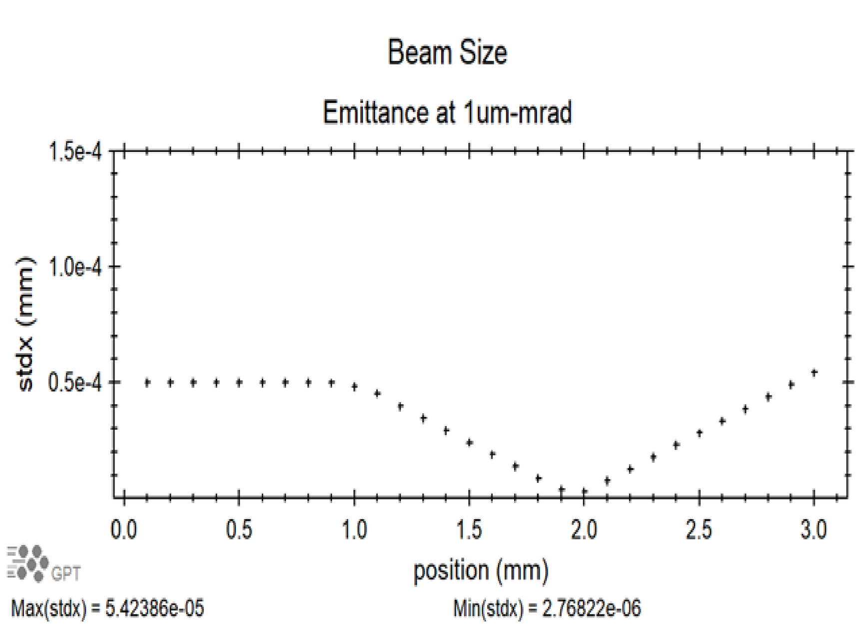


Completed CCT magnet

Electron Beam Diagnostics

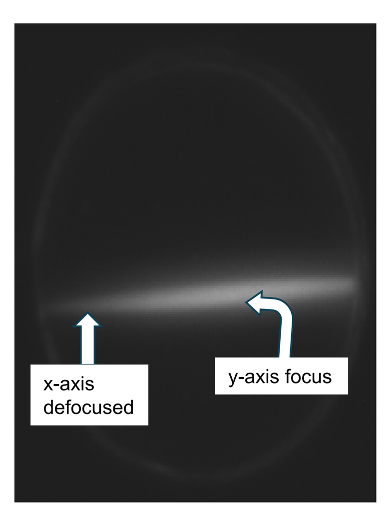
Conducted at the **Ultrafast Electron Diffraction (UED)** facility

Performed **emittance measurements** and simulated beam dynamics using **General Particle Tracer (GPT)**



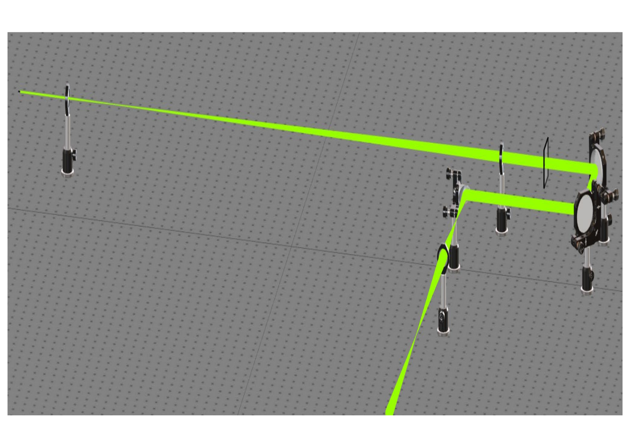
•**GPT(left)** modeled electron beam behavior under various field settings.

•**Emittance scan (Right)** measured beam emittance using quadrupole scan



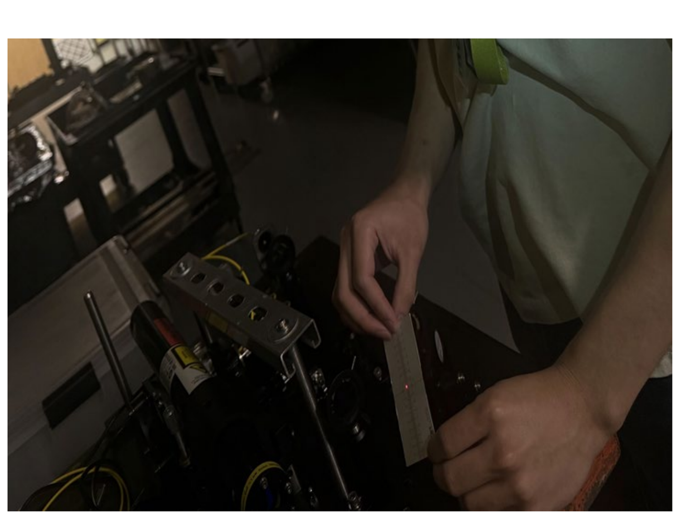
Laser Optics

•Aligned, characterized, and simulated laser beams on breadboards at the **Accelerator Test Facility (ATF)**

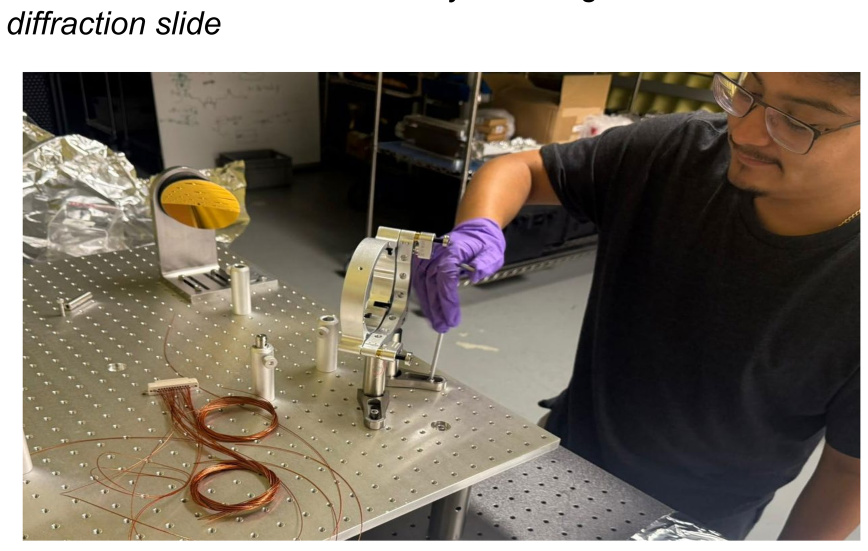


3DOptix simulation of a parabolic mirror

Precise alignment of optical components on an optical table for accurate laser beam delivery and magnification of a diffraction slide



Alignment of a laser beam into a fiber optic cable



Alignment of vacuum compatible optical table used in the beamline of ATF

Background

Particle accelerators depend on precise magnets, beam diagnostics, and optical systems[1]. Canted Cosine Theta (CCT) superconducting magnets guide charged particles using strong fields, described by the Biot–Savart law:

$$B = \frac{\mu_0 I}{2R}$$

where B is the field strength, I is current, and R is the coil radius.

Electron beam quality is measured by the root-mean-square (rms) emittance:

$$\epsilon_{rms} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

where x is the transverse position, and x′ is the angular divergence. This equation reflects the statistical properties of the beam and is fundamental for characterizing and optimizing accelerator performance.[2]

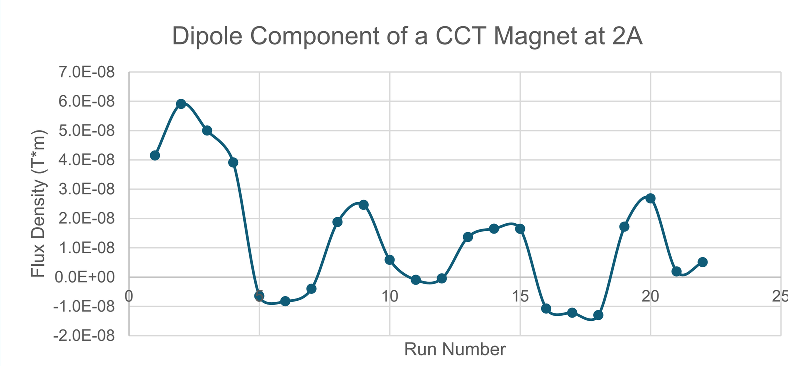
Laser-driven and optical systems play a crucial role in particle generation, diagnostics, and manipulation[3]. The focusing of beams, whether laser or particle, follows the lens equation:

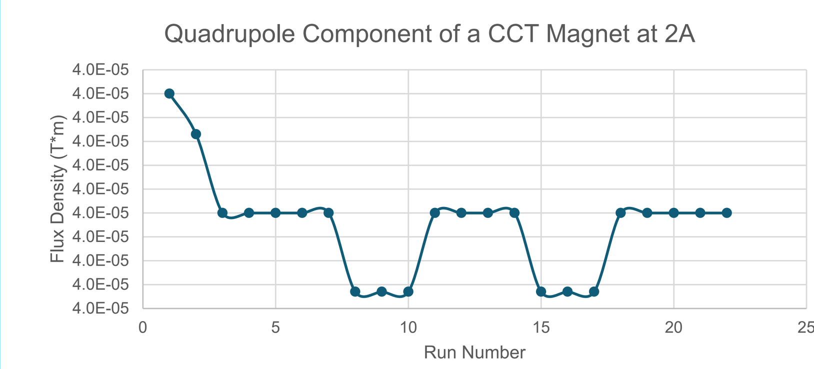
$$\frac{1}{f} = \frac{1}{d_0} + \frac{1}{d_1}$$

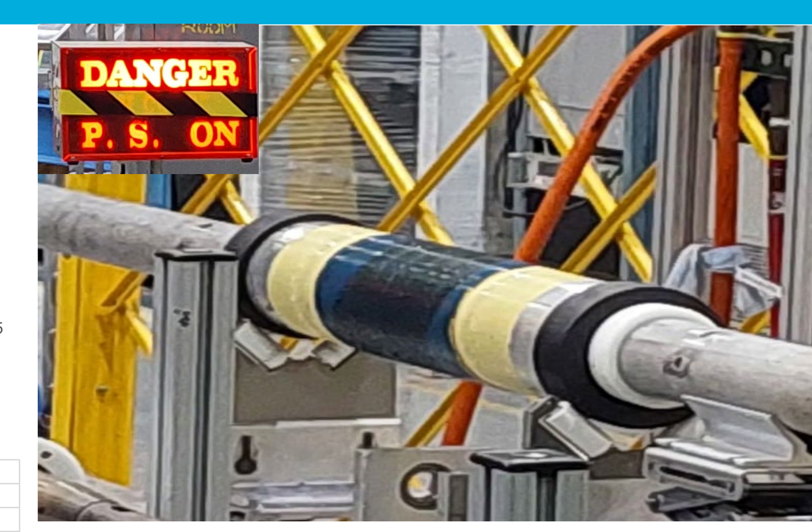
where f is the focal length, and d_0, d_1 are object and image distances.

Outcomes

Superconducting Magnets



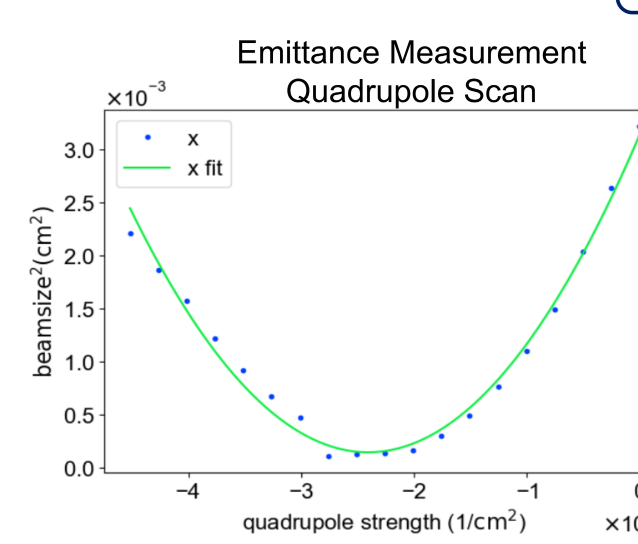




- The CCT magnet was measured with a mole, results shown on the graph
- B1–B4 are magnetic field components from dipole to octupole
- B2 (quadrupole) is strongest, indicating a strong quadrupolar field.

Electron Beam Diagnostics

$$x^2_{rms}(s) = \epsilon\beta(s) = As^2 - 2ABs + (C + AB^2)$$

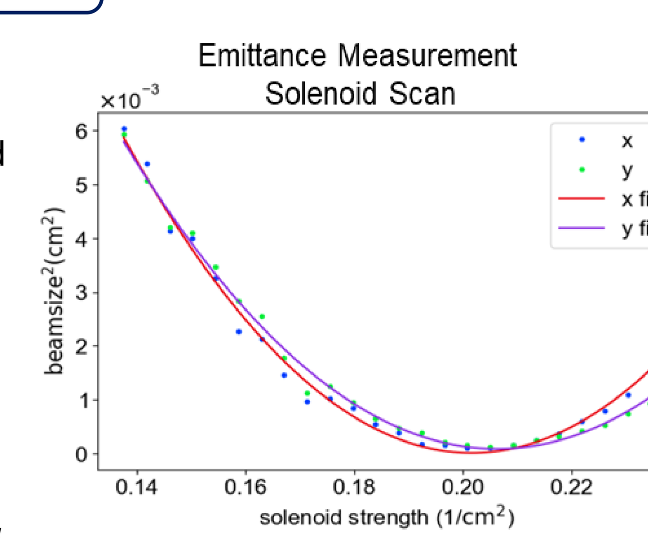


$$\epsilon = \sqrt{AC}$$

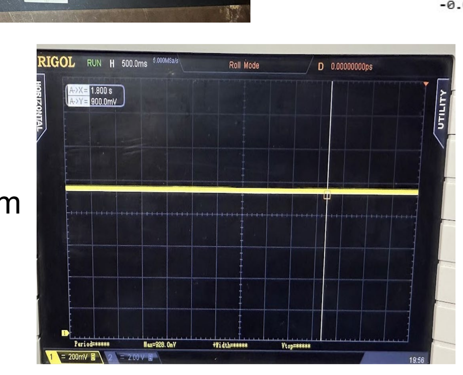
Emittance found using from a quadratic fit

Controlling emittance ensures stable, focused beams

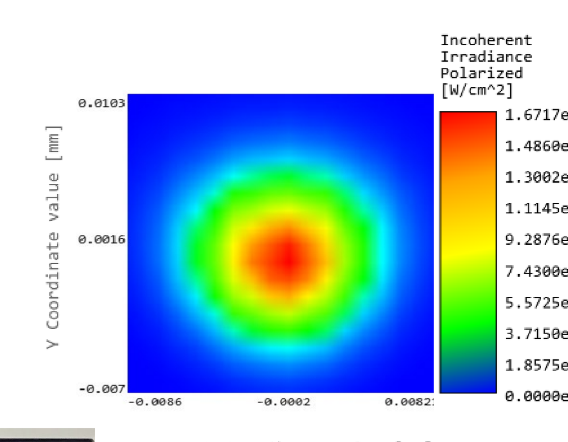
$\epsilon = 100nm\text{-}rad$

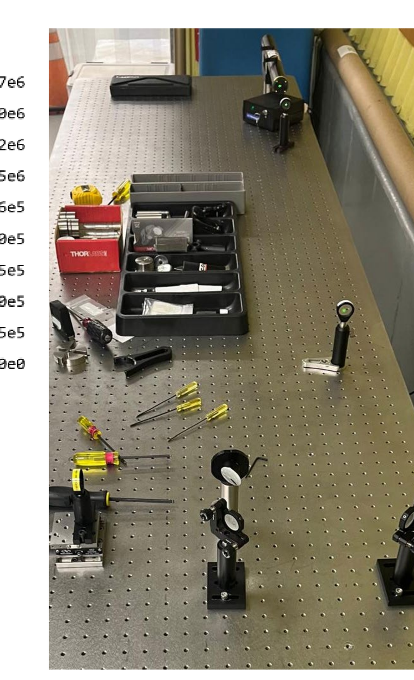


Laser Optics



Output voltage, converted from current using a photodetector, from the Fiber Optic alignment test





Intensity of the simulated laser beam in 3DOptix. On the right we have the actual optical setup.

Conclusion

This work provides an integrated overview of particle accelerators by focusing on CCT magnet design, emittance measurement, and laser optics These techniques show how magnets, beam diagnostics, and laser systems combine to achieve precise beam control and reliable performance. Building expertise in these areas prepares the next generation of scientists and engineers for future work in accelerator technology. The many applications of accelerators in medicine, industry, and research highlight the importance of mastering these fundamental concepts and techniques. Future research would focus on of these many applications. *This presentation includes "No export controlled work"*

Acknowledgments

This work was supported by the Department of Energy RENEW Grant, "Science and Engineering Student Apprenticeship Program in Accelerator Science and Technology" (DE-SC0025742), and by the Office of Workforce Development for Teachers and Scientists (WDTS). We also thank the scientists, engineers, technicians, and leadership at Brookhaven National Laboratory, especially those in the Accelerator Science and Technology Department, Magnet Division, and Instrumentation Division, for their valuable support and guidance throughout this project.

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