# Integrated Magnet, Electron Beam, and Ultrafast Laser Studies for Accelerator Applications

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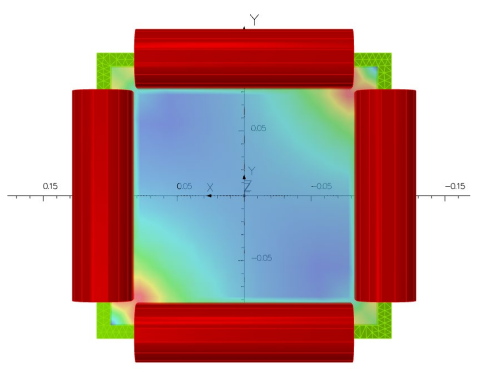
## Abstract

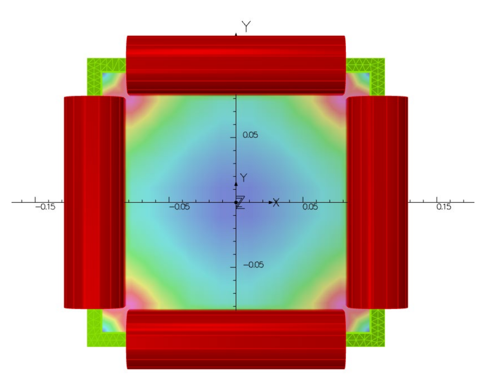
This study provides an integrated overview of key accelerator technologies explored at Brookhaven National Laboratory: superconducting magnets, ultrafast electron diffraction, and ultrafast high-power lasers. At the Superconducting Magnets Division, dipole and quadrupole magnets were designed using Simulia OPERA and Rat-GUI, with simulations validated through 3D-printed coil testing. These magnets were later applied in the Ultrafast Electron Diffraction facility, where General Particle Tracer (GPT) simulations and real experiments with solenoids, dipoles, and quadrupoles revealed consistent particle beam behavior. At the Accelerator Test Facility, ultrafast lasers were used to generate and manipulate electron pulses. Laser setups were simulated in 3DOptix, then assembled and tested using instruments like oscilloscopes and beam profilers. Across all modules, experimental results closely aligned with simulations, confirming model accuracy.

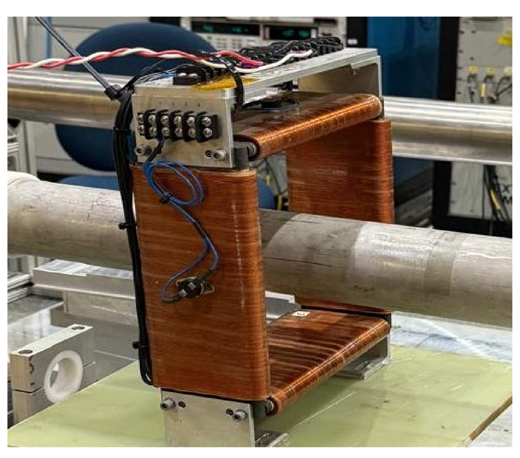
## Methodology

### Superconducting Magnets

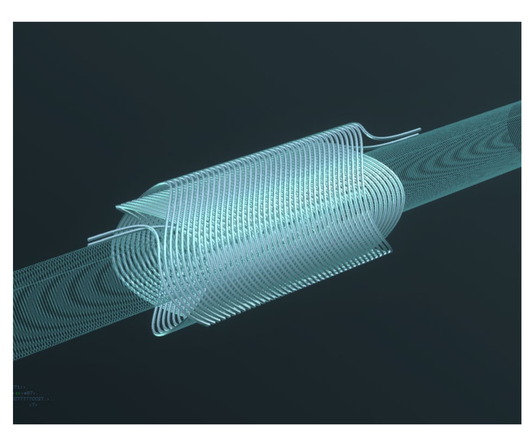
Using Opera, 3D models of dipole and quadrupole magnets were simulated through parametric studies varying yoke materials and current densities to assess magnetic field strength and uniformity.

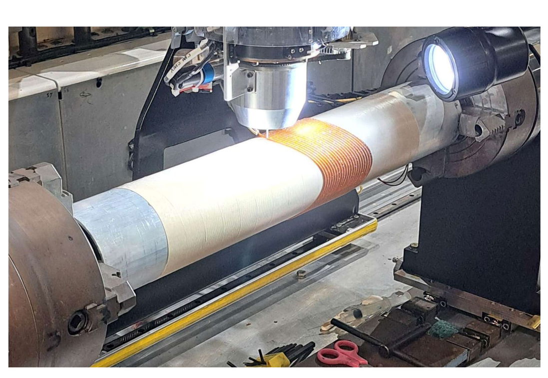






Using RAT-GUI, a canted cosine theta (CCT) quadrupole coil was modeled and analyzed for harmonic content and flux distribution. The finalized design was processed in MATLAB and 3D-printed as a physical prototype.



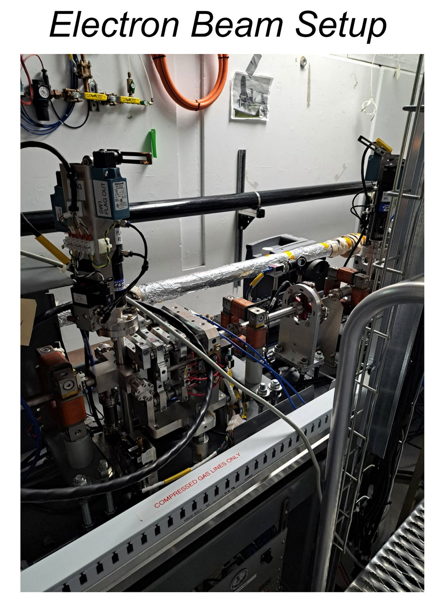


$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{\text{enc}}$$

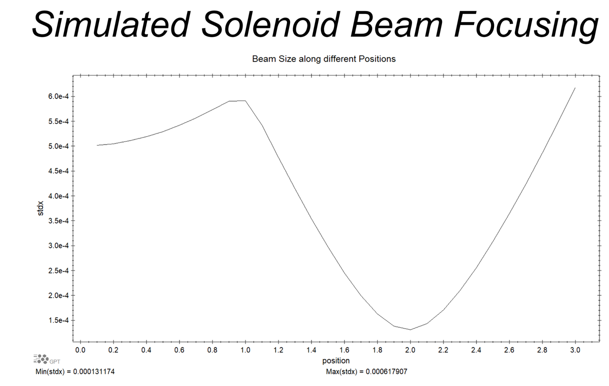
### Electron Beam

GPT was used to simulate electron beam generation, propagation, and focusing. Exercises included creating beams with varying properties, analyzing space charge effects, and using solenoids for focusing. Further simulations modeled beam dispersion in dipole-based spectrometers to study energy and energy spread, with key concepts like emittance and phase space visualized through Python analysis.

*Electron Beam Setup*

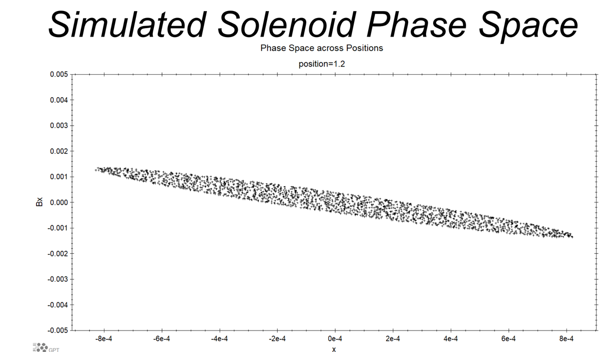


*Simulated Solenoid Beam Focusing*



Beam size along different positions, in three different setups. A solenoid is present 1m away from the source and a space charge of 100 pC is used. The beam has an initial radius of 1mm.

*Simulated Solenoid Phase Space*



Geometric:

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

Normalized:

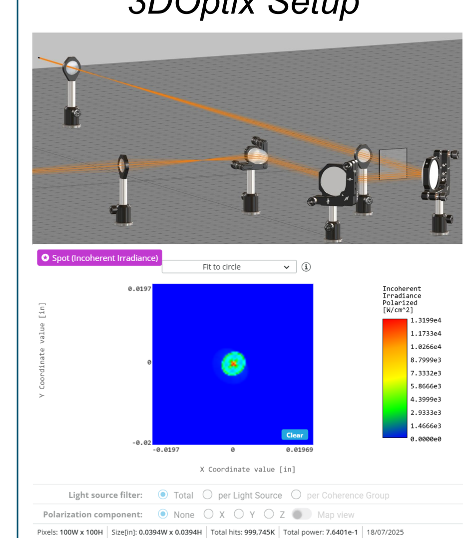
$$\epsilon_n = \beta\gamma\epsilon_g$$

Phase space is a way to describe both the position and momentum of particles in the beam at the same time. Each particle is represented as a point in this space. The overall area of the distribution gives information about the beam's size, focus, and quality, and is directly related to emittance.

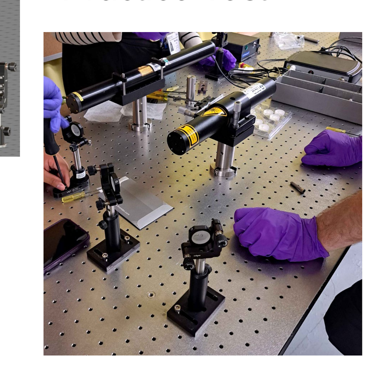
### Optics and Lasers

Experimental optical setup and laser propagation through various nonlinear crystals and optical components (3DOptix). Using 3DOptix, we modeled beam propagation through lenses, mirrors, and mounts to guide real-world alignment. SNLO was used to simulate nonlinear effects like second-harmonic generation and optimize crystal configurations. These tools helped design efficient, high-power laser systems for experimental use.

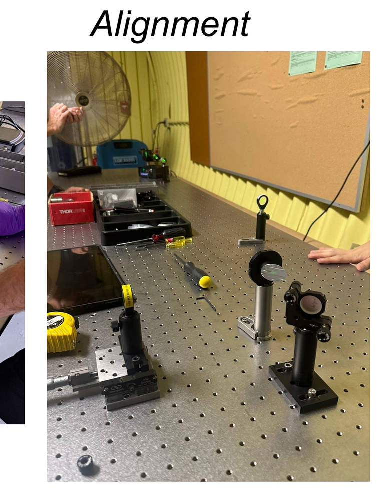
*3DOptix Setup*



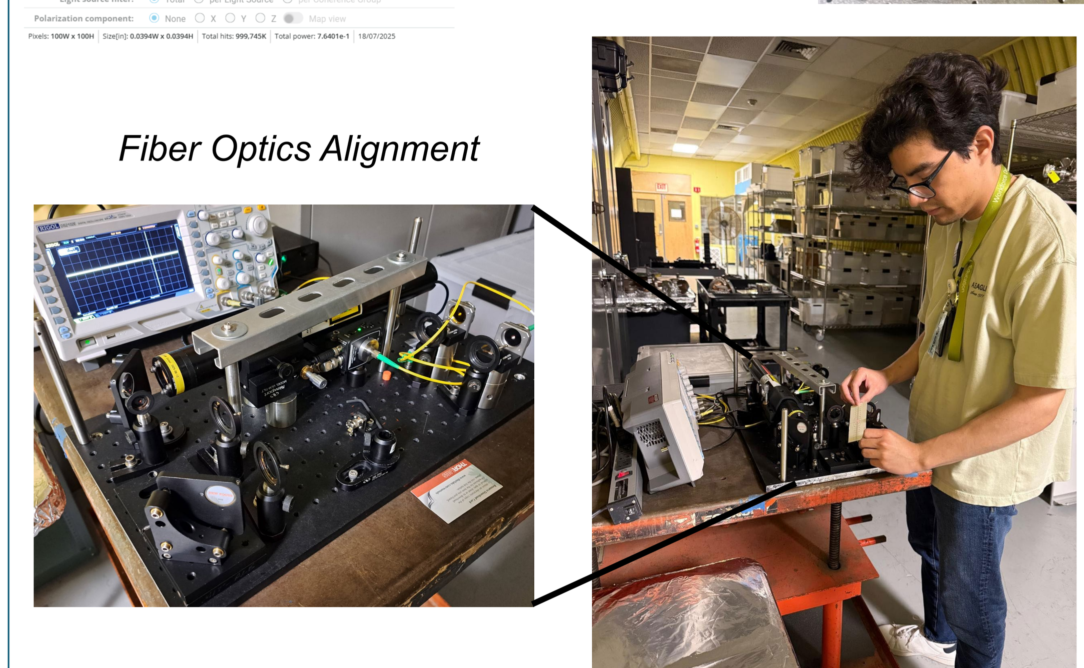
*Optics Alignment Practice Test*



*Parabolic Mirror Alignment*

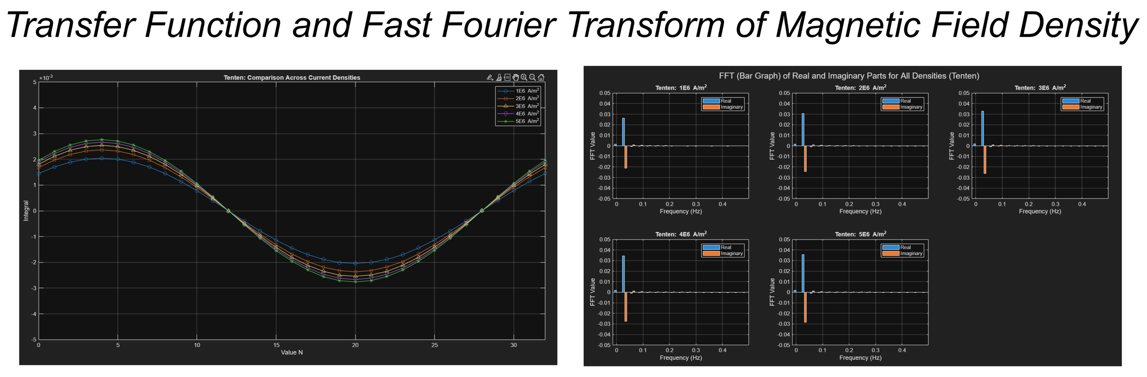


*Fiber Optics Alignment*



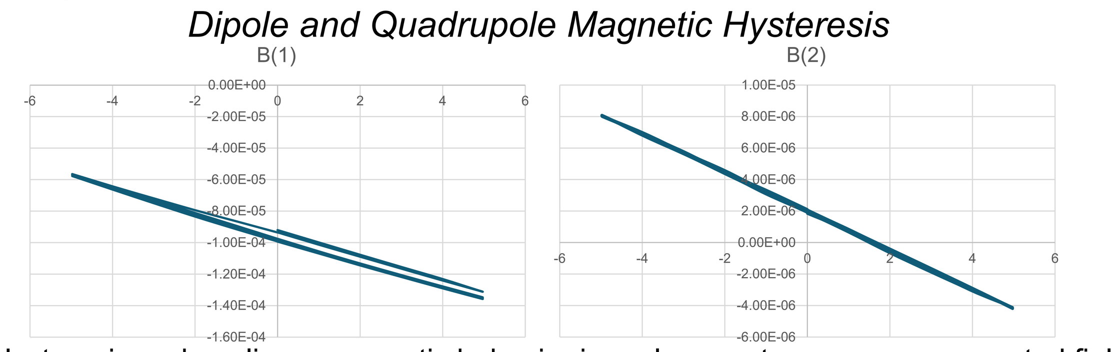
## Results & Analysis

*Transfer Function and Fast Fourier Transform of Magnetic Field Density*



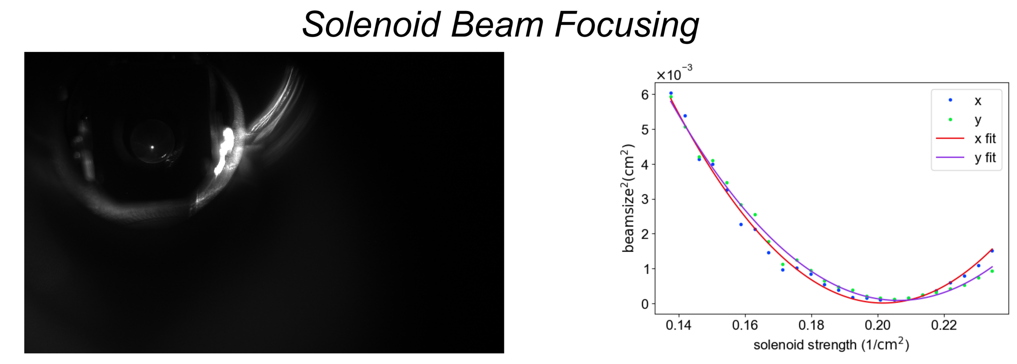
To assess magnetic field quality, we compared transfer functions across different current densities, revealing slight shape changes. Fast Fourier Transform analysis helped identify dominant field components and unwanted harmonics. This approach allowed us to detect magnetic "noise" and evaluate the precision of our magnet designs.

*Dipole and Quadrupole Magnetic Hysteresis*



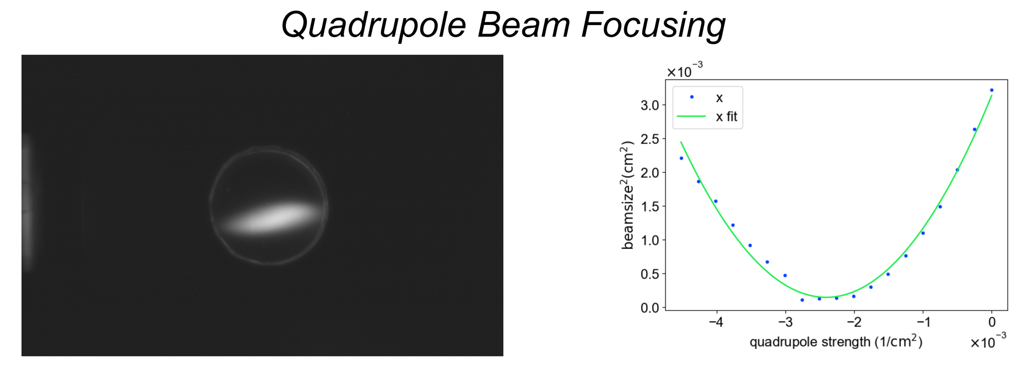

Hysteresis and nonlinear magnetic behavior in real magnets can cause unwanted field components to appear. As a result, a dipole magnet may also exhibit quadrupole-like fields, and vice versa, leading to alignment errors or beam distortion. This is often referred to as "magnetic noise" and is a key reason for careful calibration and harmonic analysis in accelerator magnet design.

*Solenoid Beam Focusing*




Solenoid scans were made to show the behavior of the electron beam at its focal point, using different solenoid currents. As expected, the width of the beam decreased as the current increased, until a certain value, past which the beam began to defocus again, due to beam divergence.

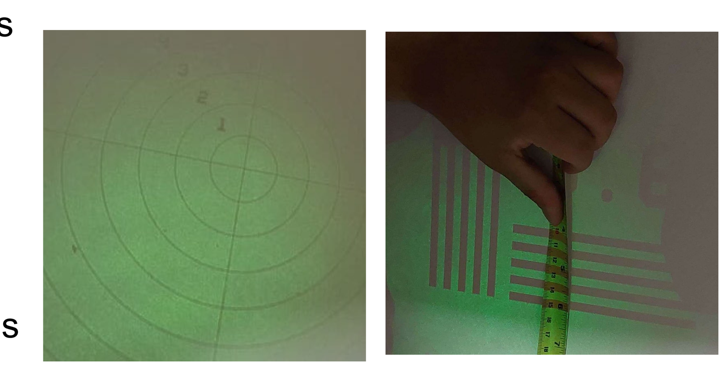
*Quadrupole Beam Focusing*



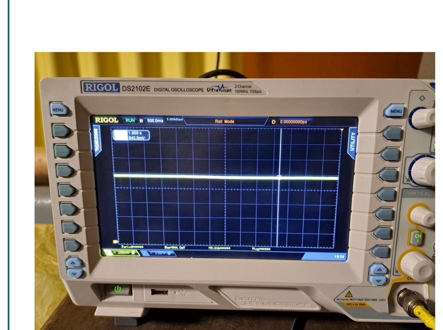

A quadrupole can focus a beam like a solenoid, but only in one direction, like the horizontal direction, and can also defocus it in the direction perpendicular to the focusing direction. By changing the current of the quadrupole, the beam's focus is changed, just like with the solenoid.

*Laser Light Diffraction*

In this module, we used a green laser and lenses to project and analyze beam behavior through optical systems. A circular reticle helped verify alignment and collimation, while a resolution test target was used to measure magnification and system resolution.



*Fiber Optics Max Alignment Signal*



To understand the importance of laser alignment, we worked with a fiber optics alignment optimization setup. The goal was to direct a laser beam precisely through a series of mirrors and lenses into an optical fiber. A photodetector converted the transmitted light into an electrical signal, which was then displayed on an oscilloscope.

## Conclusions & Future Work

Across all three modules, we explored key technologies used in particle accelerators through both simulation and hands-on experimentation. In the Superconducting Magnets module, FFT analysis of magnetic field harmonics revealed that our coil designs achieved strong field purity with minimal unwanted components, while also highlighting minor imperfections typical in real-world systems. The Ultrafast Electron Diffraction module showed how beam dynamics are affected by parameters like emittance, charge, and energy, with simulations and experiments confirming the importance of space charge effects and magnetic focusing for maintaining beam quality. Finally, in the Optics and Lasers module, we designed and simulated laser setups using 3DOptix and SNLO to study beam propagation and nonlinear optical processes. Together, these experiences deepened our understanding of how magnetics, beam physics, and laser systems work in tandem to advance accelerator science.
This presentation includes "No export controlled work".

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