Comprehensive Design and Testing of Particle Accelerator Technology

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Abstract

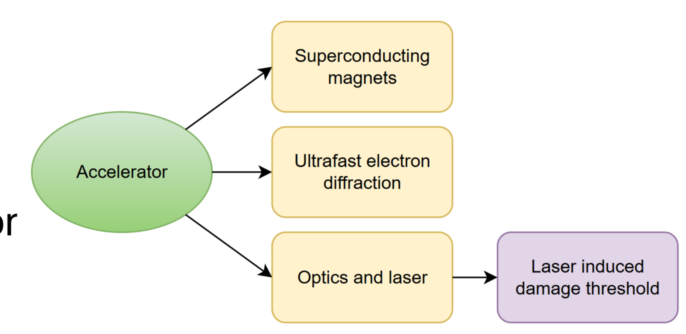
Electron diffraction converts atomic motion into directly measurable patterns and is widely used in solid-state physics and chemistry for phase identification and atomic-position determination. At Brookhaven's Ultrafast Electron Diffraction facility, laser-driven electrons are RF (Radio Frequency)-accelerated and magnetically focused onto a crystal to record femtosecond-resolved diffraction. Beyond the solenoids on the beamline, we designed and built a quadrupole magnet to refine the focus of these electron beams. Using SIMULIA Opera and the RAT GUI, we modeled the quadrupole and optimized the coil layout for integration into the experiment to analyze electron-bunch energy. Ultrafast High Power (UFHP) lasers are at the forefront of these accelerators, providing energy to the photoinjector, the main source of the e-beam. These femtosecond lasers need optical components of superior quality that must survive the same ultrashort-pulse fluence that drives the experiment. In this regard, we measured laser-induced damage thresholds (LIDTs) for fused-silica wedges and BBO crystals under 800 nm, 80 fs pulses by ramping fluence until the first pits or haze appeared, then set conservative safety margins for all NIR optics. Through the RENEW Accelerator Science and Technology program, we gained substantial technical skills and insight into accelerator physics, components, experiments, and operations.

Keywords: Accelerator, UED, superconducting magnet, laser, LIDT.

Introduction

We are studying, simulating, and testing the subsystems of particle accelerators by breaking the system into focused subtopics: accelerators steer and focus charged e-beams with strong magnetic fields provided by stable superconducting magnets needed without excessive power loss.

An important subsystem of accelerators is the UFHP laser which generates electron bunches (via photocathodes) and provide femtosecond timing for pump–probe experiments. Ultrafast Electron Diffraction (UED) then exploits these laser-synchronized, magnet-focused electron packets to capture transient structural changes in materials, tying the core accelerator physics to a concrete ultrafast application.



Relationship between accelerator and subtopics

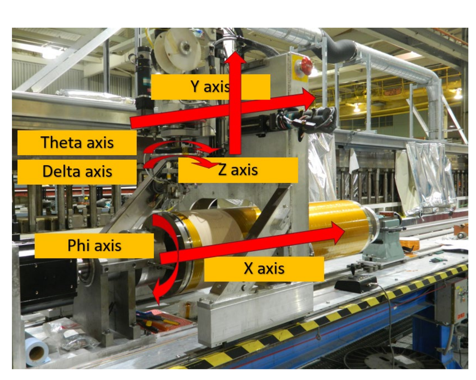
Instrumentation & Procedure

Superconductive magnets:
1. Opera simulation
2. Rat GUI 3D coil model construction
3. Direct winding machine
4. Window & Quadrupole magnet testing

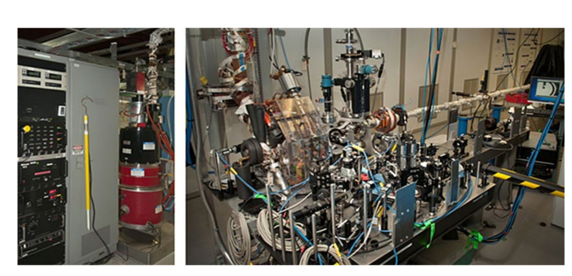
Electron beam (UED):
1. General particle tracer simulation
2. Low energy electron beam experiment
3. Electron beam measurement

Optic and Lasers:
1. 3D Optix simulation
2. Experimental optical alignment
3. SNLO simulation

Laser induced damage threshold:
1. Ti:sapphire laser beam alignment
2. Laser beam diagnosis
3. LIDT experiment on different samples.
4. Results analysis

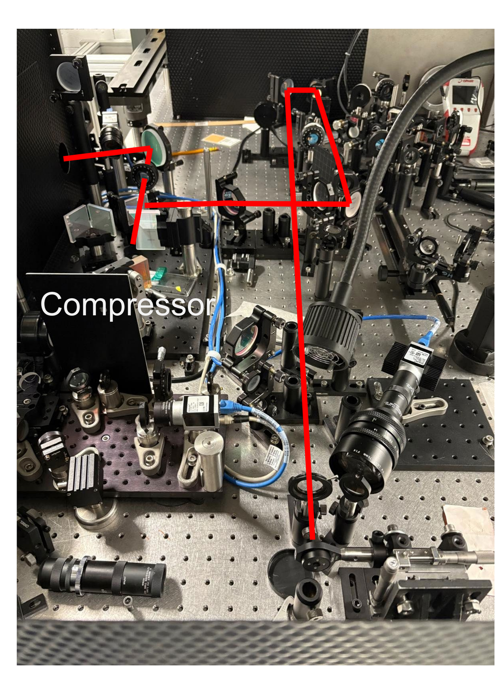


Direct winding machine in Superconductive magnet division.



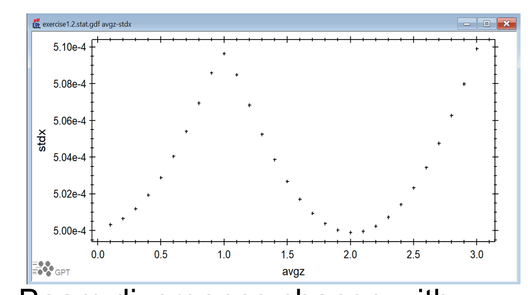
UED experiment setup

Experimental laser alignment

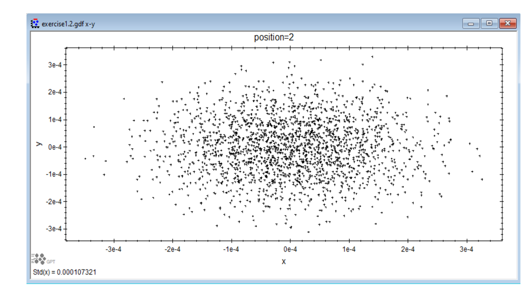


LIDT laser beam path

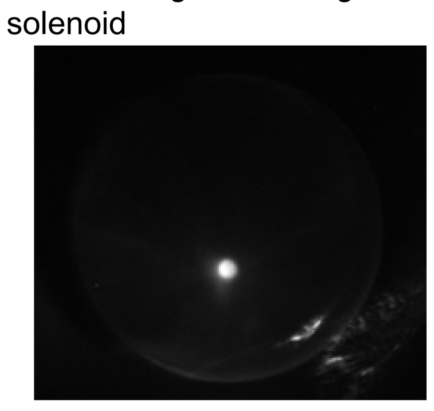
Electron beam module



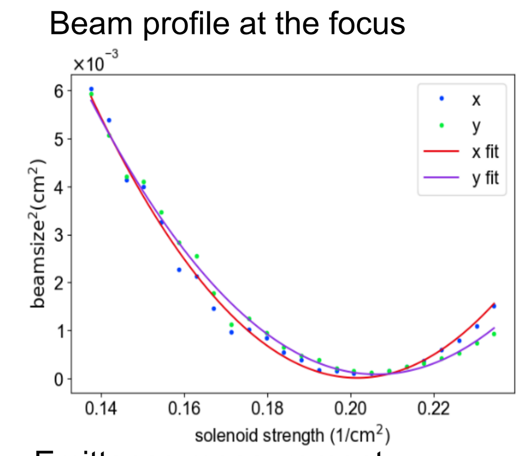
Beam divergence change with solenoid



Beam profile at the focus



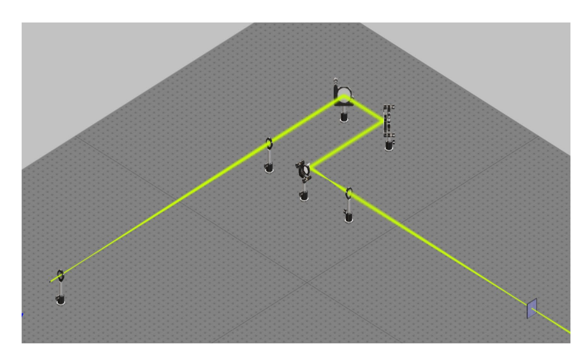
Electron beam observation through CCT camera



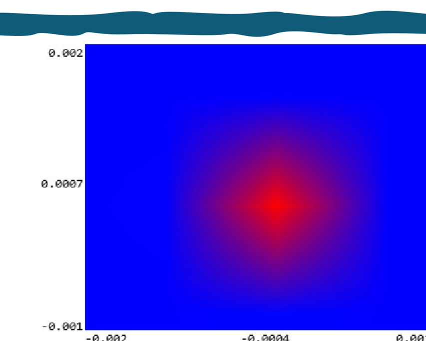
Emittance measurement solenoid scan

- GPT simulations included a solenoid in the electron beam path.
- Beam observations and solenoid current measurements (98–167 kA) were used for validation.
- The solenoid provided focusing in both X and Y directions.
- The two data sets agree closely, confirming strong, reliable beam focusing performance.

Optic and lasers module



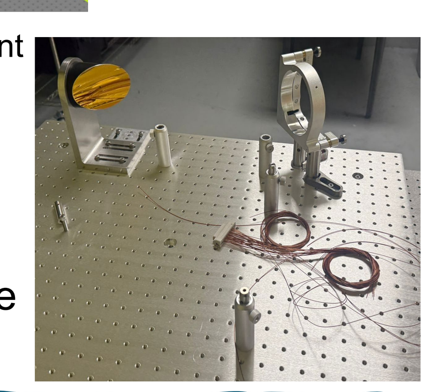
Vacuum chamber laser alignment simulation

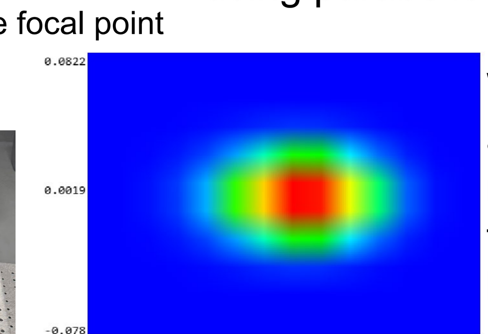


Beam profile at the focal point

3DOptix simulates optical setup of in-vacuum Laser-wakefield acceleration (LWFA) alignment using parabolic mirror

Actual build setup with Pico motor controlled Parabolic mirror for alignment of LWFA in the vacuum chamber

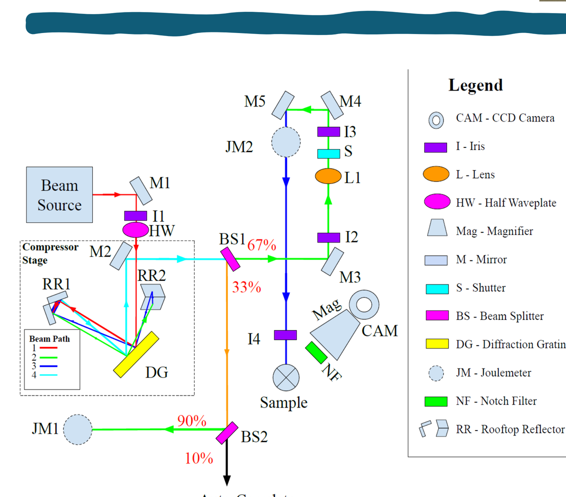




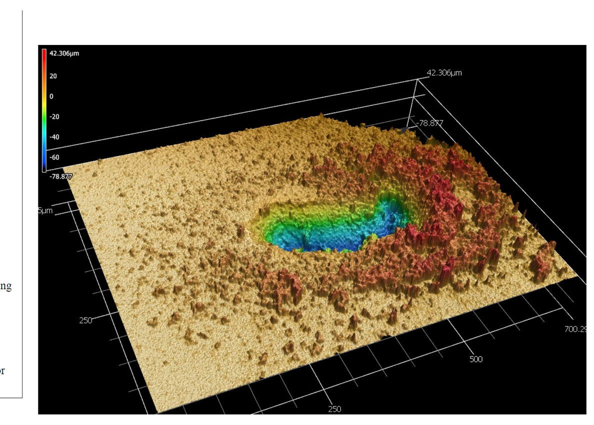
Beam profile with tilted light source

We modeled how angular misalignments affect the final focus and beam path.

Laser induced damage threshold



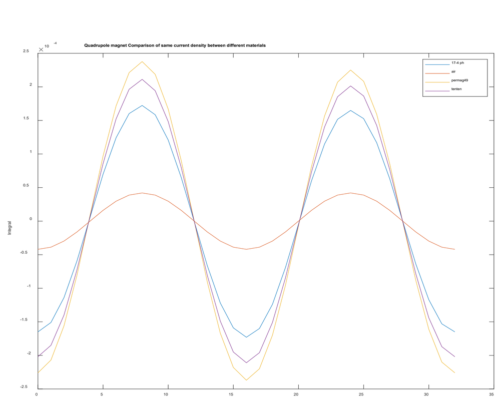
LIDT laser alignment



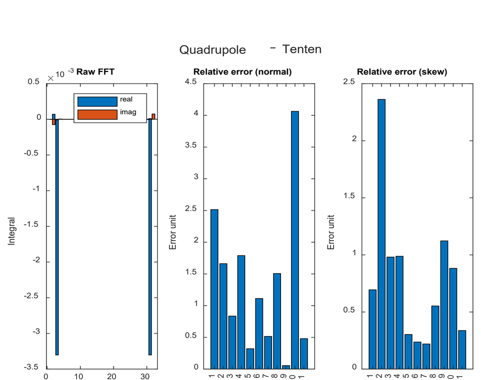
Damage analysis on BBO Crystal

- Using the 800nm 80 fs laser to damage different materials of optic components.
- Beta-Barium Borate crystal (BBO).
- Titanium sapphire (Ti:Sa).
- Fused silica.

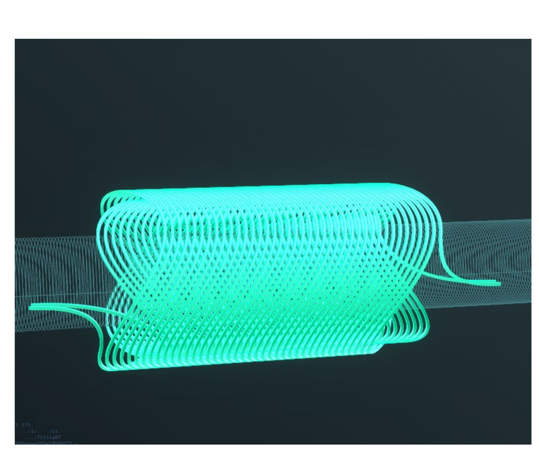
Result & Analysis



MATLAB analysis of the magnet strength



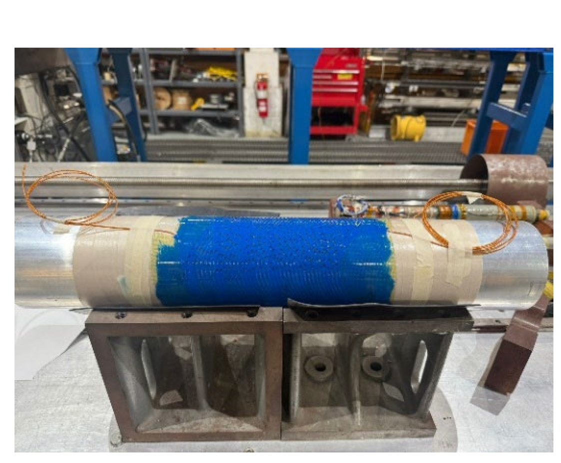
Relative error from the harmonics



Rat GUI magnet coil simulation

Superconducting magnet module

- The integrated field, ∫B, changes only with the material; it reflects the magnet's strength and quality.
- We evaluated the relative error of the magnet harmonics (error = Emax/10,000). A maximum value of 4 indicates very good performance.
- Outcome: a fully completed quadrupole magnet.
- Nb-Ti material: ductile, twistable, low cost.



CCT quadrupole magnet

Discussion & Conclusion

The four indispensable parts of a particle accelerator jointly deepen my understanding of accelerator science and technology. The performance of the electron beam depends on the precision of the magnets used in e-beam alignment and the e-beam source, the photoinjector, which depends on the ultrafast high power laser performance. Small inaccuracies in the performance of the independent subsystems can lead to system failure, therefore accurate characterization of the different parameters in the system is paramount.

Reference

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