

Automated Laser Alignment, Electromagnet Design and Simulation, Ultrafast Electron Diffraction Simulation, IQ Modulator Repair

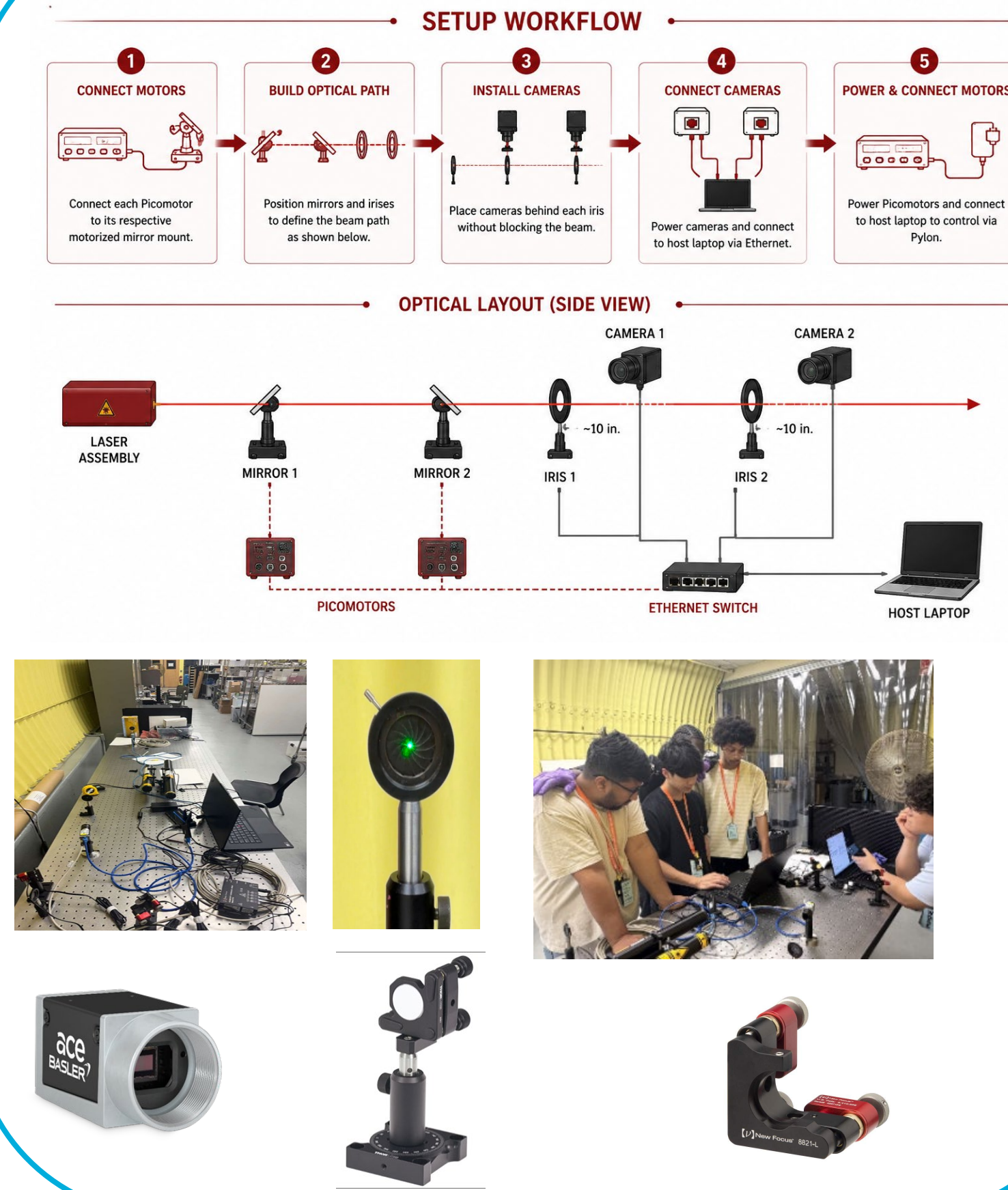
Avanti Williston¹, Viviana Vladutescu¹, Mikhail Polyanskiy², Li Geng¹, Marcus Babzien², Vikas Teotia², Lufeng Leng¹, William Li², Giovanni Ossola³, Jhair Alzamora², Sheikh Tusher¹, Tianyi Zhao¹, Henry Ye¹, Efrain Luna¹, Raul Barajas Vargas¹, Aldane Duncan¹, Anita Nam³, Christopher Chow¹, Spencer Diamond², Sheikh Tusher¹

¹New York City College of Technology/CUNY; ²Accelerator Science & Technology Dept. at Brookhaven National Laboratory; ³City College/CUNY

Abstract

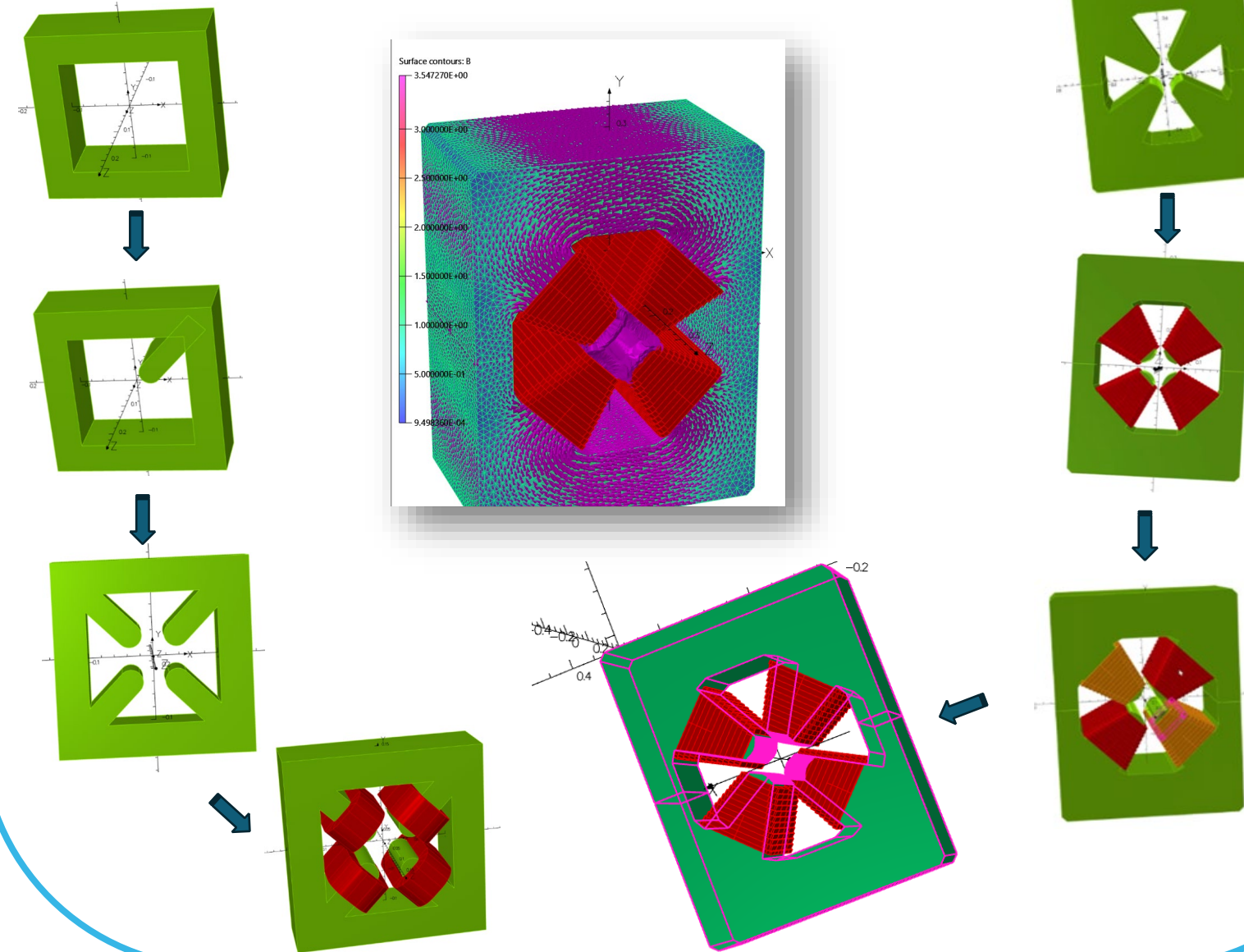
The U.S. Department of Energy's Brookhaven National Laboratory is home to the Accelerator Test Facility (ATF), which supports accelerator science research for facilities including the National Synchrotron Light Source II (NSLS-II) and the Electron-Ion Collider (EIC). During this summer internship, participants completed four technical projects spanning optics, magnet design, beam physics, and RF systems. These included developing an automated laser alignment system with a graphical user interface (GUI), designing and simulating quadrupole magnets using Opera 3D, performing Ultrafast Electron Diffraction (UED) beam simulations with ImpactX, and characterizing an IQ modulation system to support development of a replacement klystron drive chain. Together, these projects provided hands-on experience in the interdisciplinary engineering and physics that enable modern particle accelerator research.

Automated Laser Alignment Module



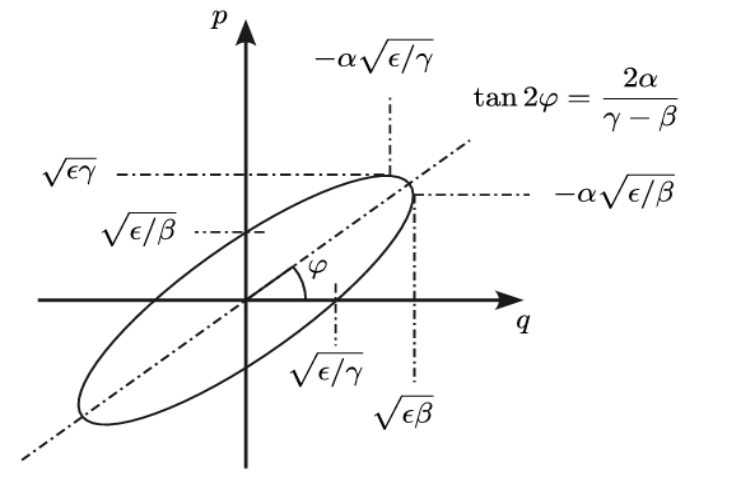
Electromagnetic Design and Simulation

1) A symmetric quadrupole magnet with racetrack coils was designed from specifications provided by Dr. Vikas Teotia. Simulations evaluated the effects of coil current density on magnetic field, field gradient, and core saturation to assess quadrupole performance. 2) Using a predesigned magnetic core and Opera-modeled racetrack coils, COMSOL scripts evaluated the magnetic field gradient, integrated gradient, and B-H characteristics to assess quadrupole performance.

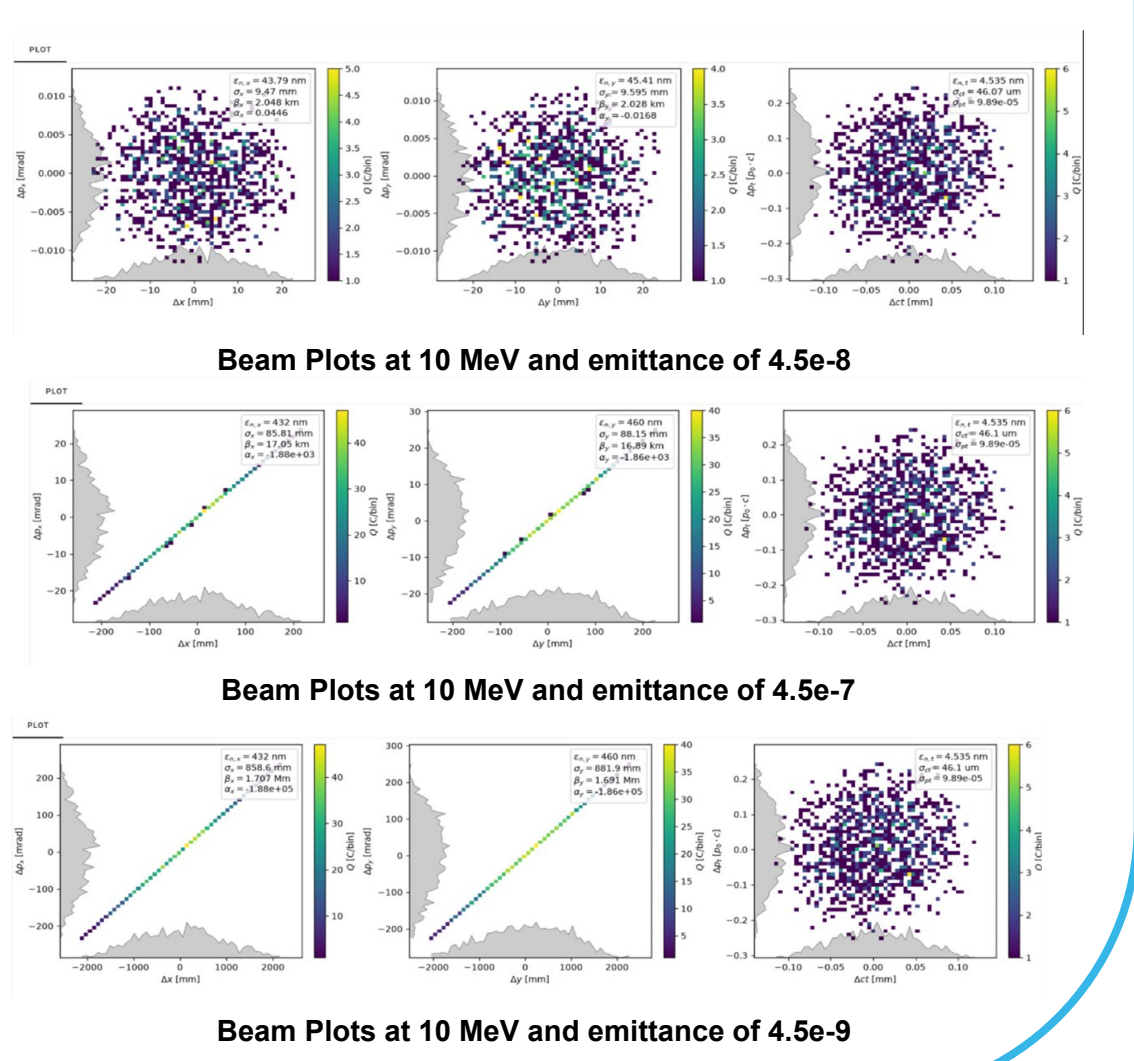


Ultrafast Electron Diffraction

ATF's Ultrafast Electron Diffraction is a pump-probe technique that uses a femtosecond laser to pump the sample. Synchronization of the laser pulse to the electron pulses is vital to produce diffraction patterns that reveal structural dynamics.



The β (Beta) parameter describes the beam envelope or beam size. The α (alpha) parameter tells you whether that radius is increasing or decreasing. The γ (gamma) parameter describes the beam divergence (angular spread).

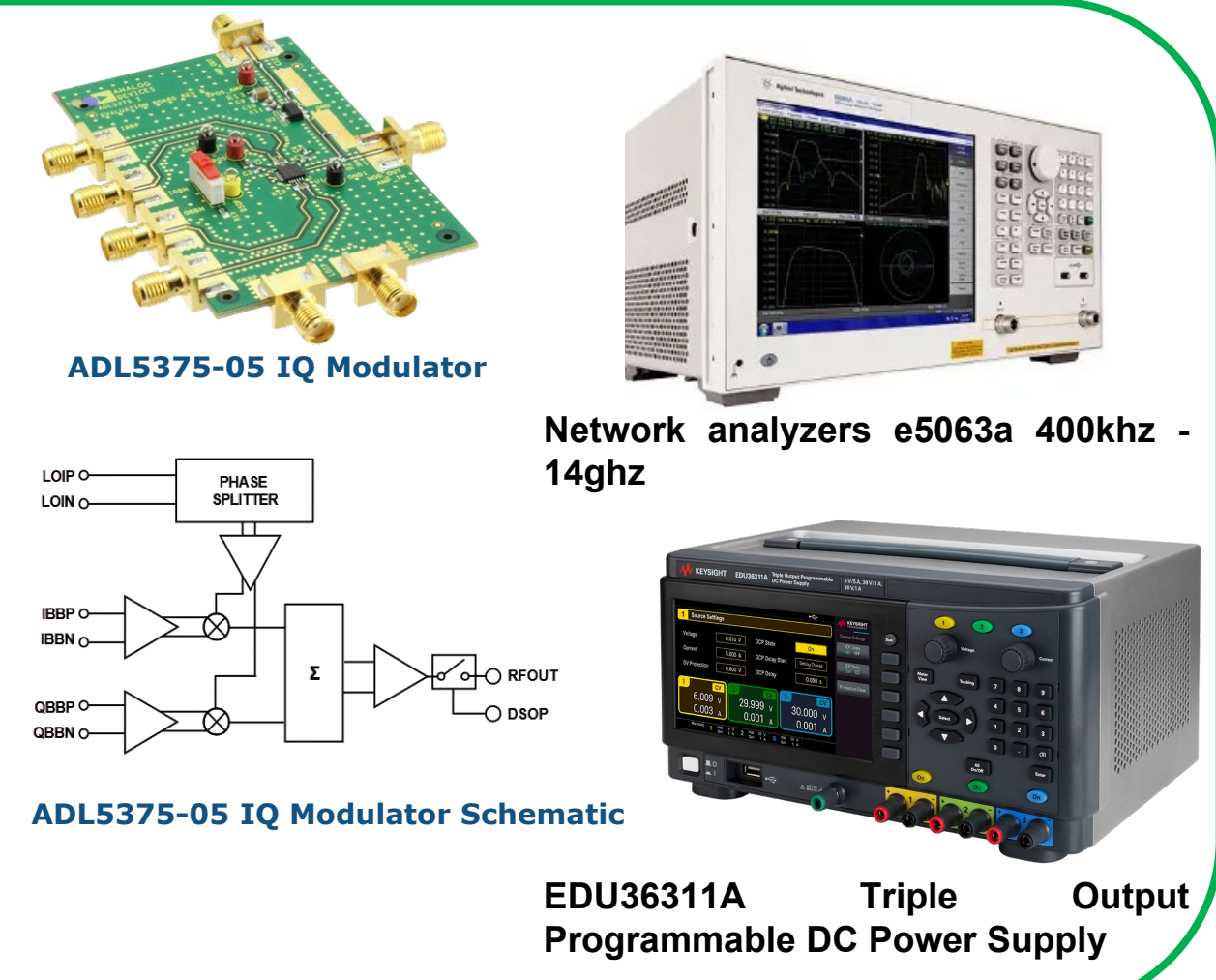
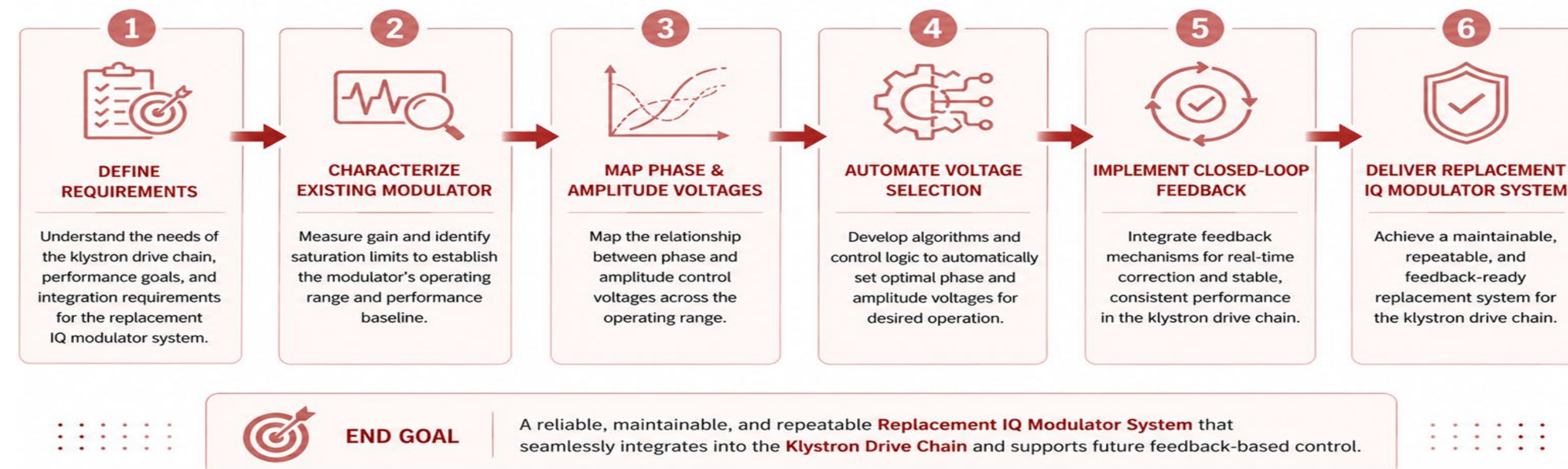


PROJECT ROADMAP

REPLACEMENT IQ MODULATOR SYSTEM FOR THE KLYSTRON DRIVE CHAIN

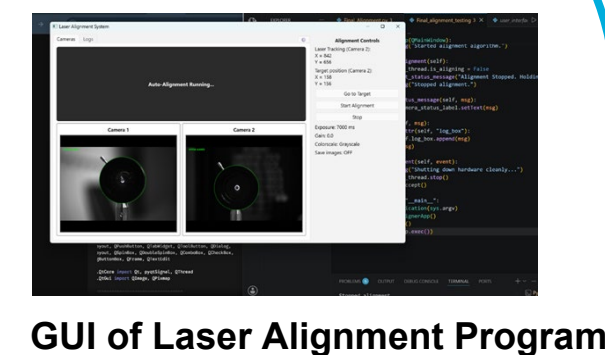
IQ Modulator Repair and Characterization

This project aims to replace the aging IQ modulation unit in the klystron drive system. The existing modulator is characterized by measuring gain, identifying saturation limits, and mapping phase and amplitude control voltages. These results are used to automate voltage selection and implement closed-loop feedback. The goal is to develop a reliable, maintainable, and repeatable replacement IQ modulator system for the klystron drive chain.



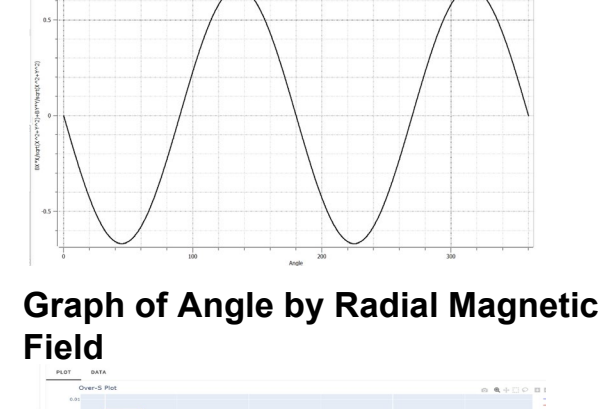
Results and Analysis

A Python-based graphical user interface (GUI) was developed to integrate beam-monitoring cameras with motorized mirror mounts, enabling remote control of the laser alignment process. The system provided real-time beam position feedback, reducing the need for manual adjustments and improving the efficiency, accuracy, and repeatability of laser alignment.



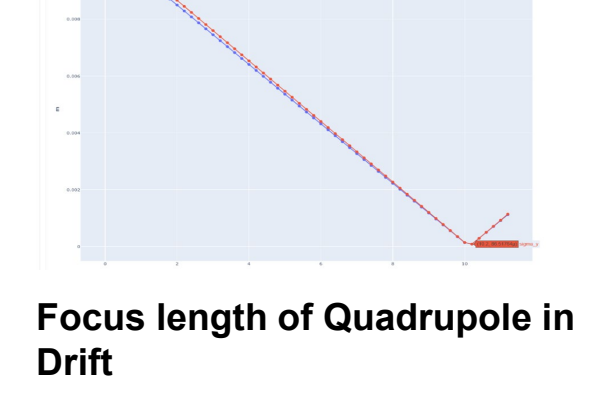
GUI of Laser Alignment Program

Quadrupole magnet models were designed using Opera 3D finite-element software to evaluate their magnetic performance. COMSOL scripts were used to analyze magnetic field gradients, integrated gradients, and B-H characteristics, verifying that the simulated field distributions were consistent with expected accelerator magnet performance.



Graph of Angle by Radial Magnetic Field

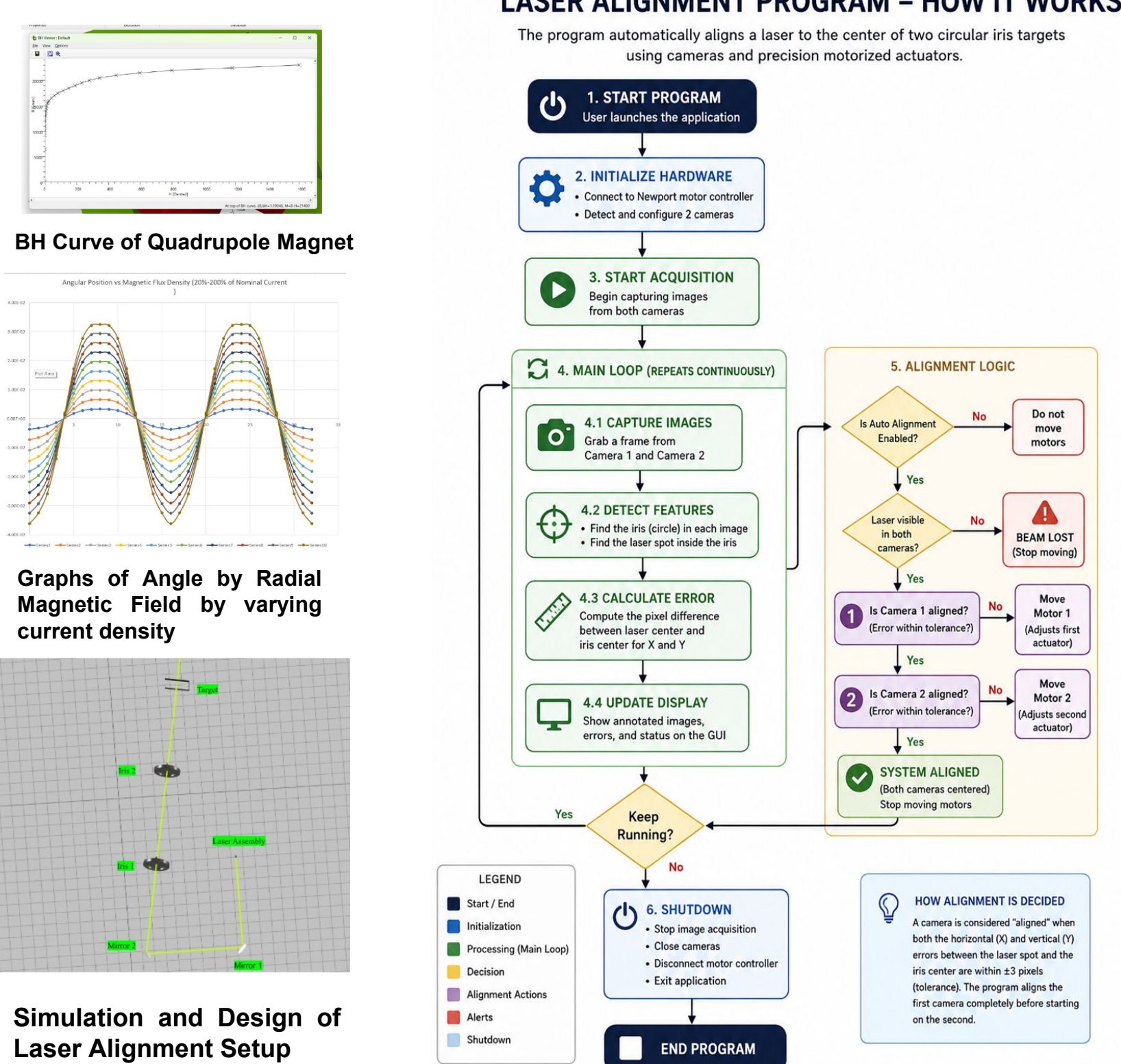
Electron beam simulations were performed using ImpactX to investigate the effects of Courant-Snyder beam parameters on beam size, emittance, and energy evolution. The simulations demonstrated how optimizing these parameters improves electron beam quality, providing insight into beam dynamics for ultrafast electron diffraction (UED) applications.



Focus length of Quadrupole in Drift

The IQ modulator was characterized by varying the voltage difference between the positive and negative I/Q inputs and analyzing the resulting output response. This analysis improved understanding of the modulator's performance and operating characteristics, providing the data needed for system calibration and the development of a reliable replacement IQ modulation system for accelerator instrumentation.

Significant Figures



Conclusion and Future Works

The projects presented demonstrate the interdisciplinary engineering principles that underpin modern accelerator science, integrating optics, electromagnet design, beam dynamics simulation, and RF instrumentation. By combining computational modeling, automation, and experimental techniques, this work addressed key engineering challenges that improve the performance, reliability, and maintainability of particle accelerator systems. These contributions support the development of advanced research infrastructure, enabling more precise accelerator operation and expanding the capabilities of scientific facilities such as Brookhaven National Laboratory for future discoveries.

References

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