

Abstract

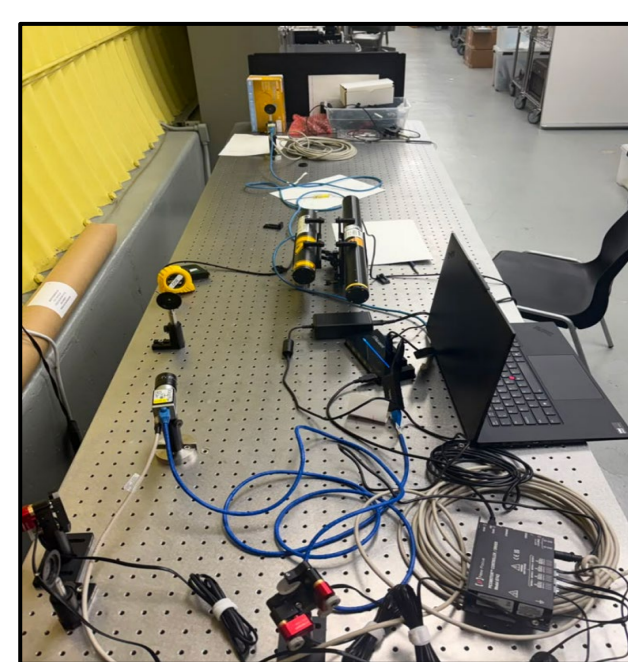
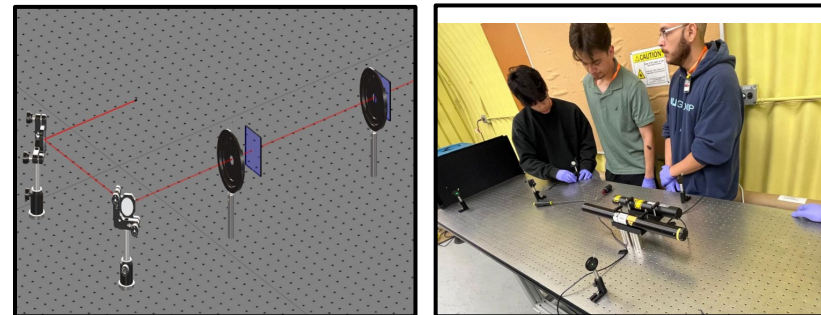
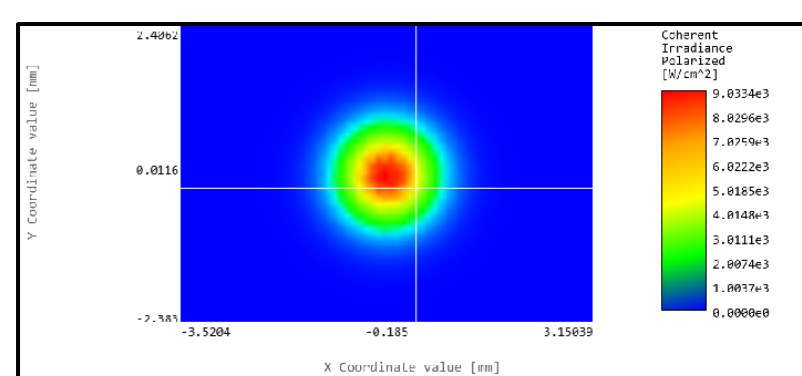
Through the SESAPARD/RENEW program at Brookhaven National Laboratory, this project explored accelerator research through three modules: laser optics, superconducting magnets, and ultrafast electron diffraction (UED). An automated laser alignment prototype was developed using computer vision and motorized optics, while superconducting quadrupole magnets and electron beam dynamics were investigated using OPERA, MATLAB, and ImpactX simulations. Together, these activities provided practical experience in optical systems, computational modeling, beam dynamics, and accelerator technologies while strengthening technical communication and research skills relevant to modern accelerator science.

Methodology

Lasers Optics

Alignment simulation and experimental set up.

- 3DOptix modeling
- Beam path visualization

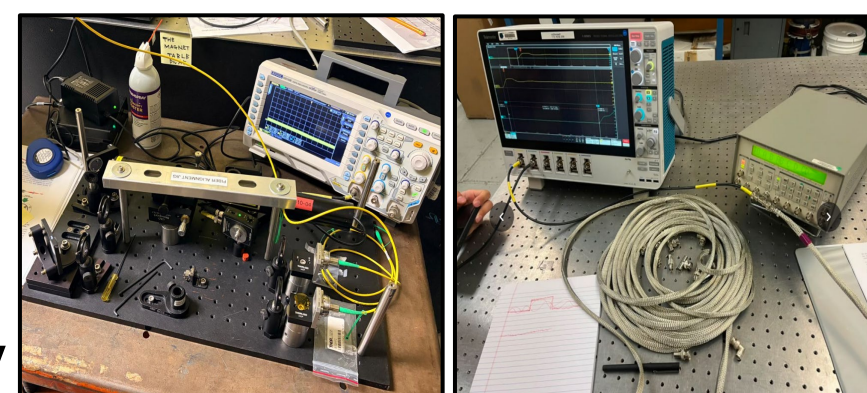


Main Project

- Automated Laser alignment
- Uses computer vision
- Operates on a closed-loop feedback system for mirror control

Supporting exercises

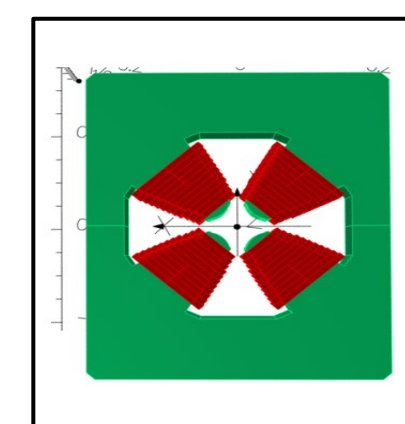
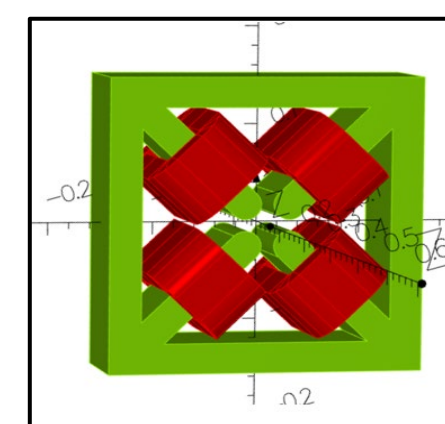
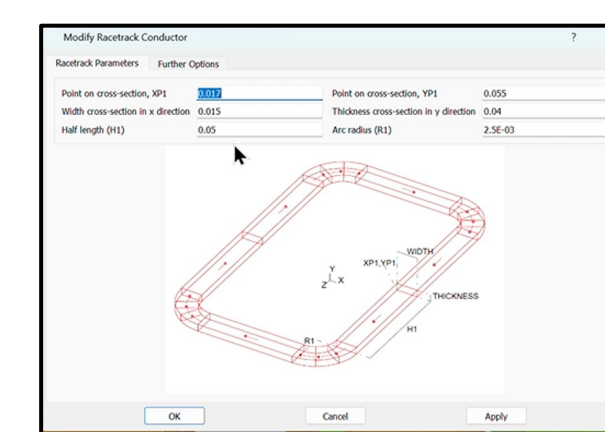
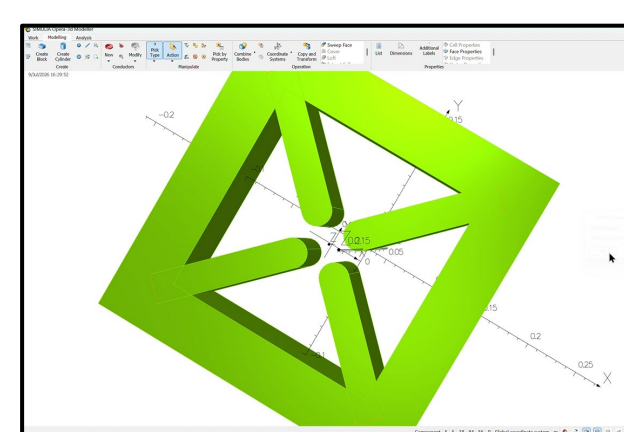
- Fiber optic alignment
- OAP mirror focusing
- Signal propagation delay



Superconducting Magnets

Magnet Design & Analysis

- Developed accelerator quadrupole magnet models using SIMULIA OPERA.
- Simulated two quadrupole magnet geometries of under varying excitation currents.
- Exported simulation data (COMI files) to MATLAB to process magnetic field distributions and evaluate field gradients and harmonic content.



Quadrupole Magnet 1

Quadrupole Magnet 2

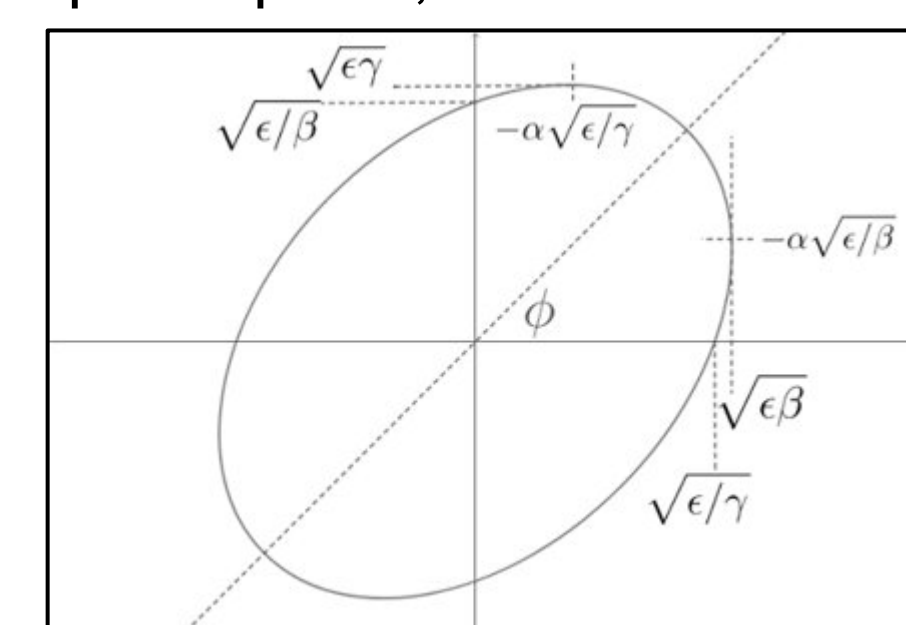
Ultrafast Electron Diffraction (UED)

Beam Optics

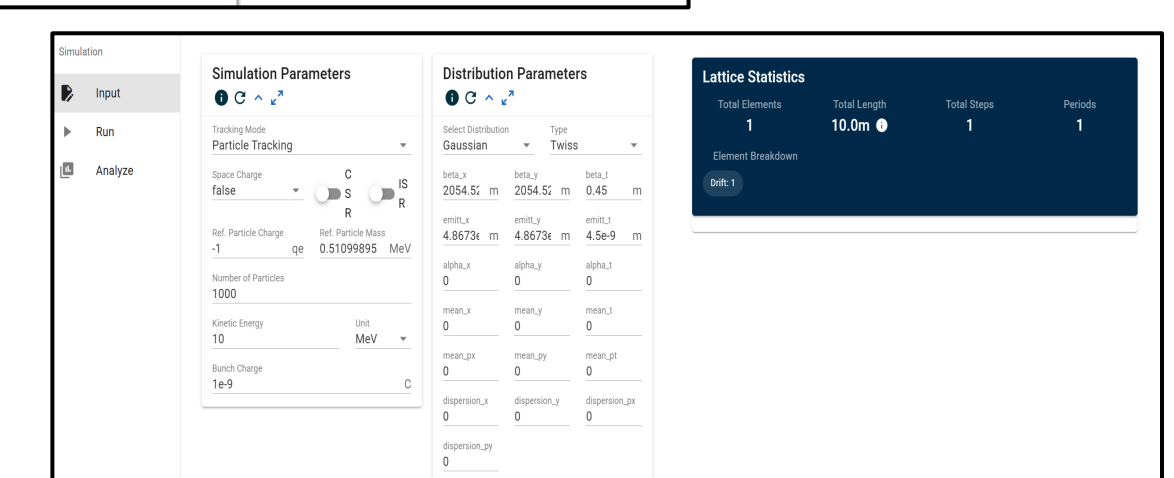
- Explored Courant-Snyder parameters to observe electron beam characteristics using ImpactX.

Beamline Modeling

- Modeled beam transport through drifts, solenoids, quadrupoles, and RF cavities.

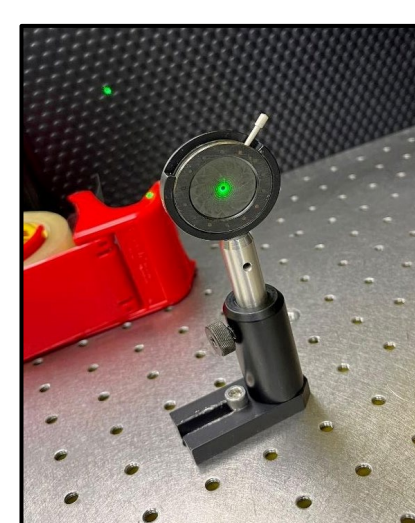
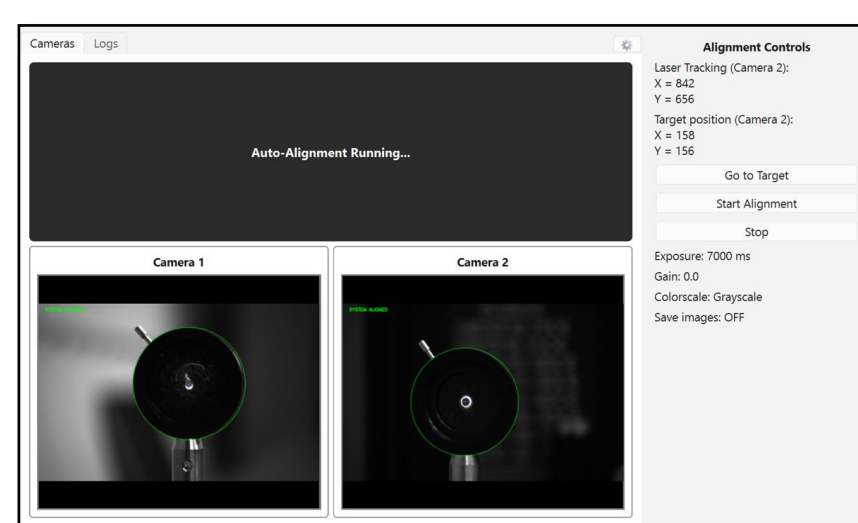


The ellipse describes the beam's position and angular divergence, with its shape determined by the Courant-Snyder parameters

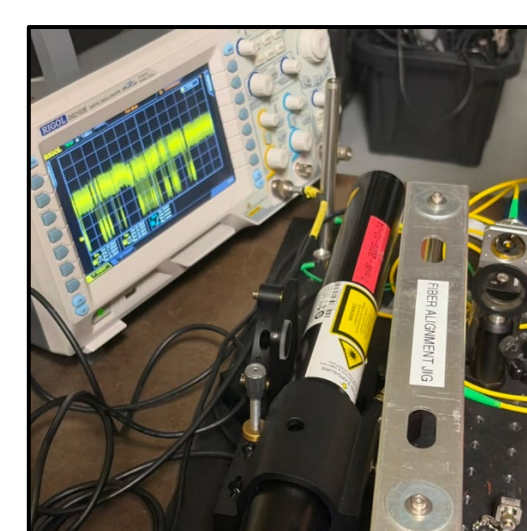
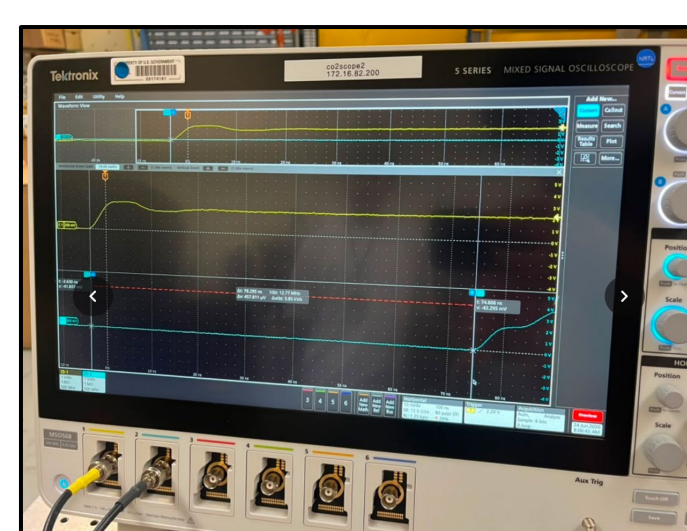


ImpactX UI

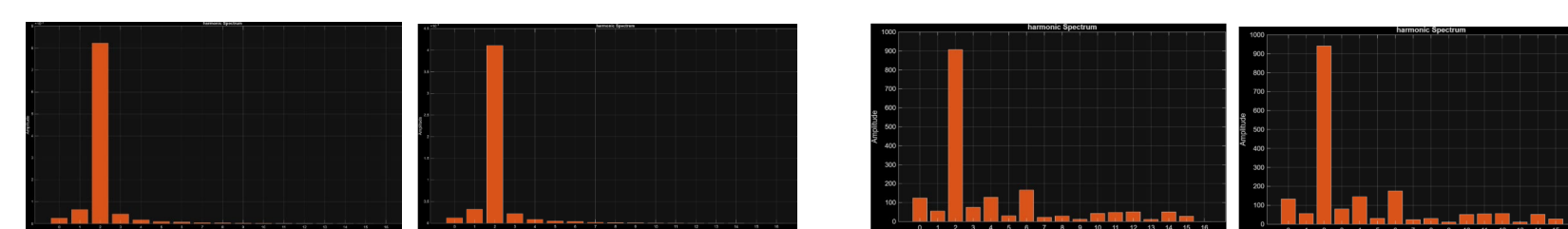
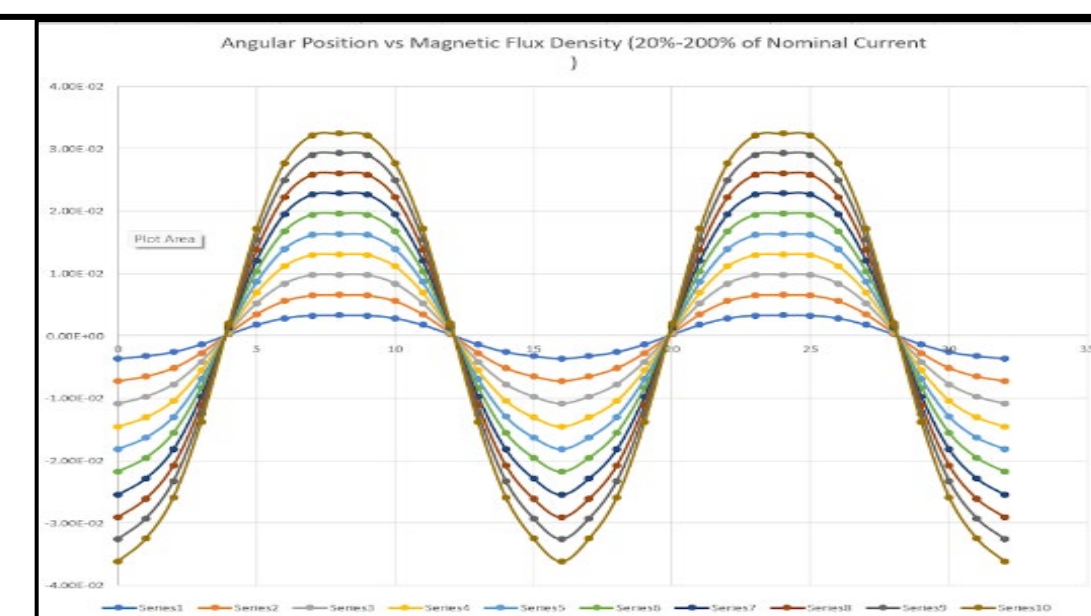
Results & Analysis



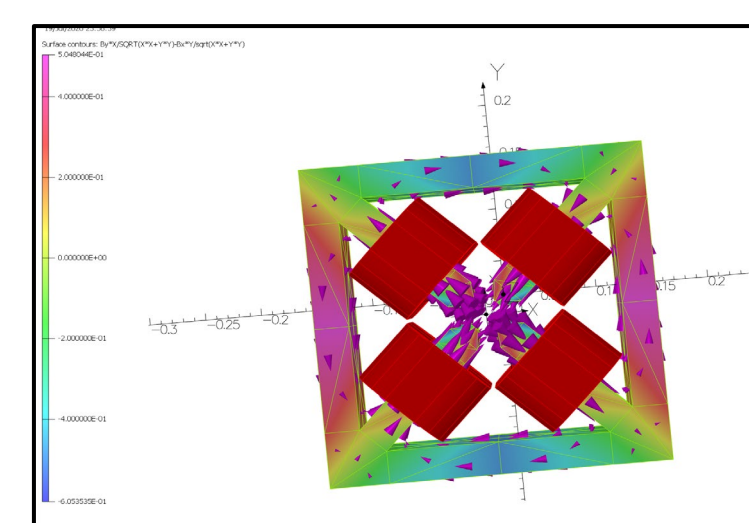
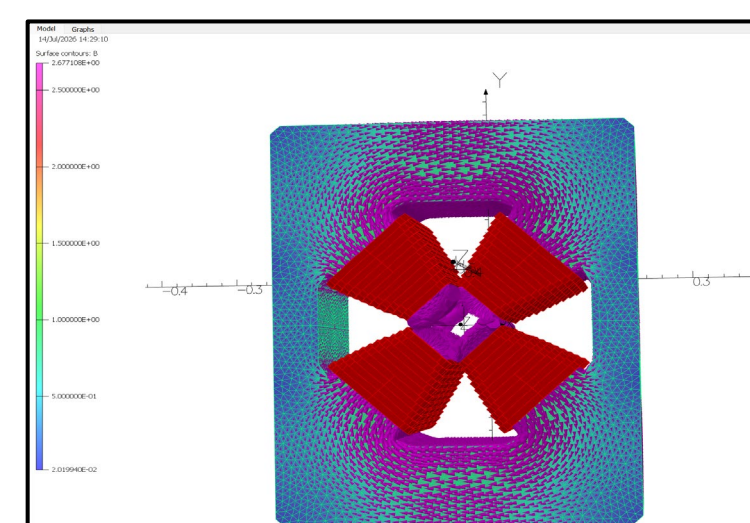
The automated laser alignment prototype successfully reproduced a conventional two-mirror alignment procedure using computer vision and closed-loop feedback. The system iteratively corrected beam position until the laser was centered on both irises.



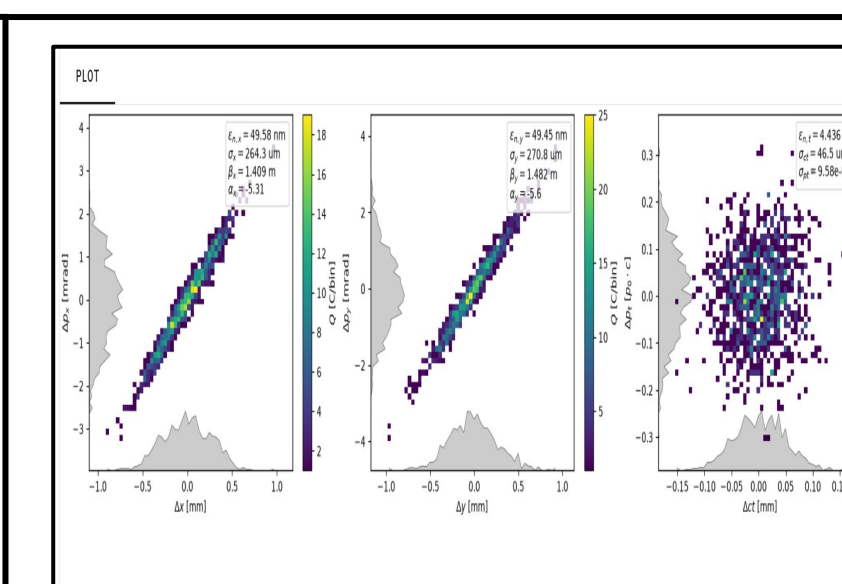
The three supporting exercises strengthened the understanding of beam propagation, optical focusing, fiber coupling, and signal timing, providing hands-on experience with optical diagnostics and alignment techniques used in accelerator laboratories.



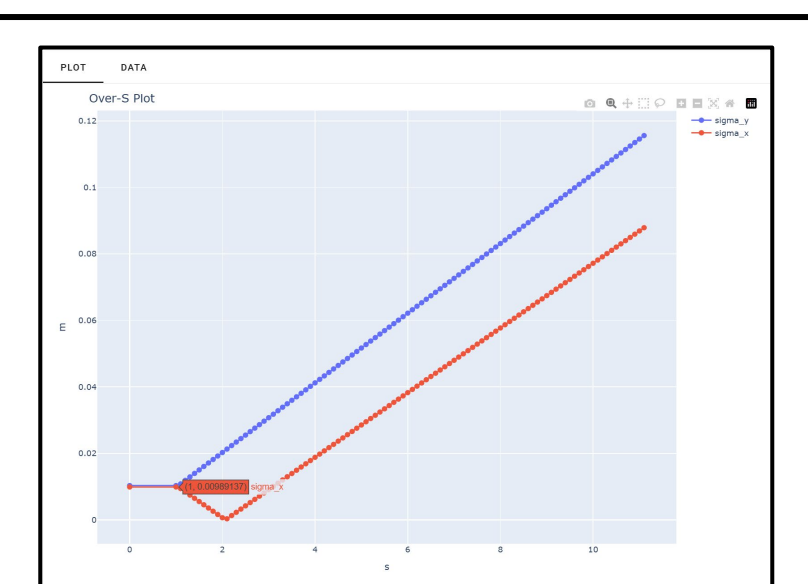
Harmonic analysis performed in MATLAB using Fast Fourier Transform (FFT). The FFT confirms that the second harmonic is dominant, indicating successful quadrupole field generation.



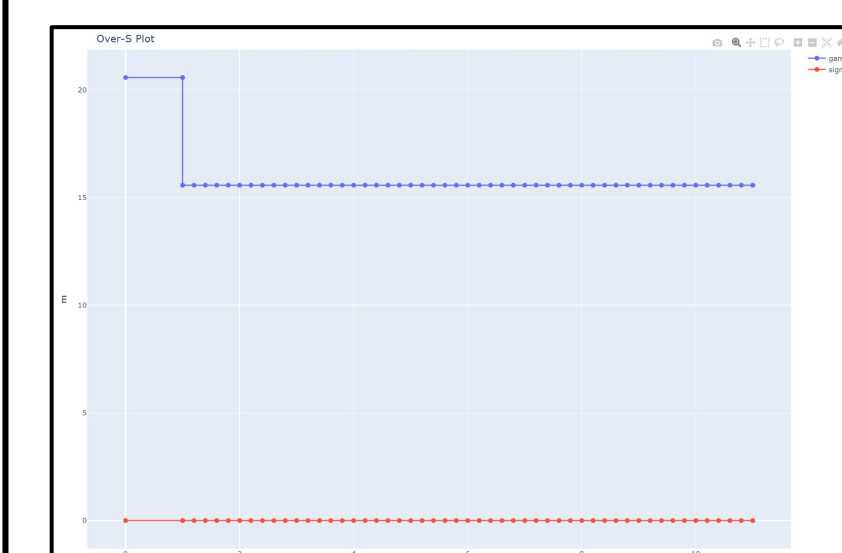
In SIMULIA OPERA, magnetic field results were evaluated by comparing field strength, and field quality across both magnet configurations.



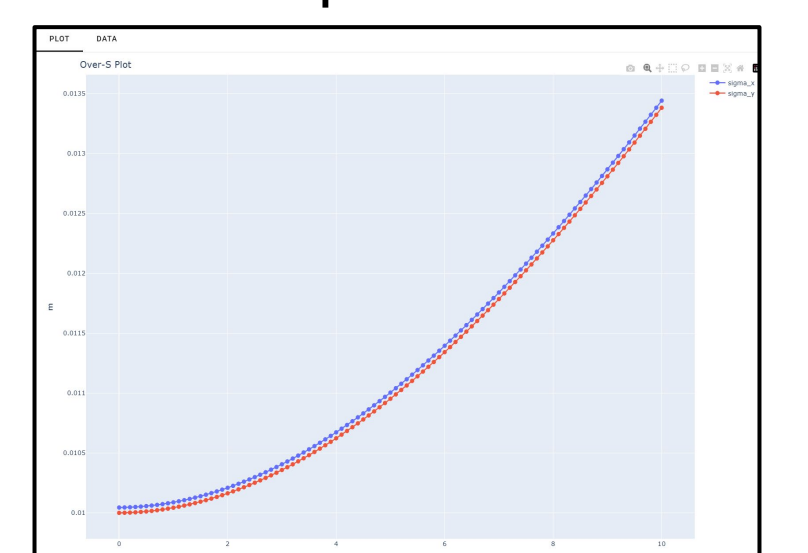
Initial phase-space distributions of the electron beam



Quadrupole focusing the electron beam in one transverse plane.



ShortRF phase at 180° where the electron beam is decelerated.



Space charge effects showing increased beam size due to collective electron repulsion.

Conclusion

All of the research done provided a comprehensive introduction to accelerator science by combining experimental and computational studies in laser optics, superconducting magnets, and ultrafast electron diffraction. An automated laser alignment prototype was developed, quadrupole magnets were modeled and analyzed, as well as phase space beam profiles for UED. Together, these projects provided practical experience with the software and equipment used to support accelerator research at Brookhaven National Laboratory.

Acknowledgements

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