



Applications and Modeling in Accelerator Sciences

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Abstract

Accelerator science combines experimental physics, engineering, and computational modeling to develop technologies for modern particle accelerators. Through the SESAPARD/RENEW program at Brookhaven National Laboratory, students completed research modules in laser optics, superconducting magnets, and ultrafast electron diffraction. The laser optics module developed an automated two-mirror beam-alignment prototype using cameras, motorized mirror mounts, precision irises, and Python-based image processing. The superconducting magnets module used SIMULIA Opera and MATLAB to evaluate quadrupole magnet geometries, magnetic-field distributions, and harmonic content under varying excitation currents. The ultrafast electron diffraction module used ImpactX to model electron-beam transport through accelerator components and examine the effects of emittance, energy, RF phase, and space charge on beam size, energy gain, and bunch evolution. Together, these modules provided practical experience in experimental methods, simulation, data analysis, technical communication, and collaborative accelerator research.

Methodology

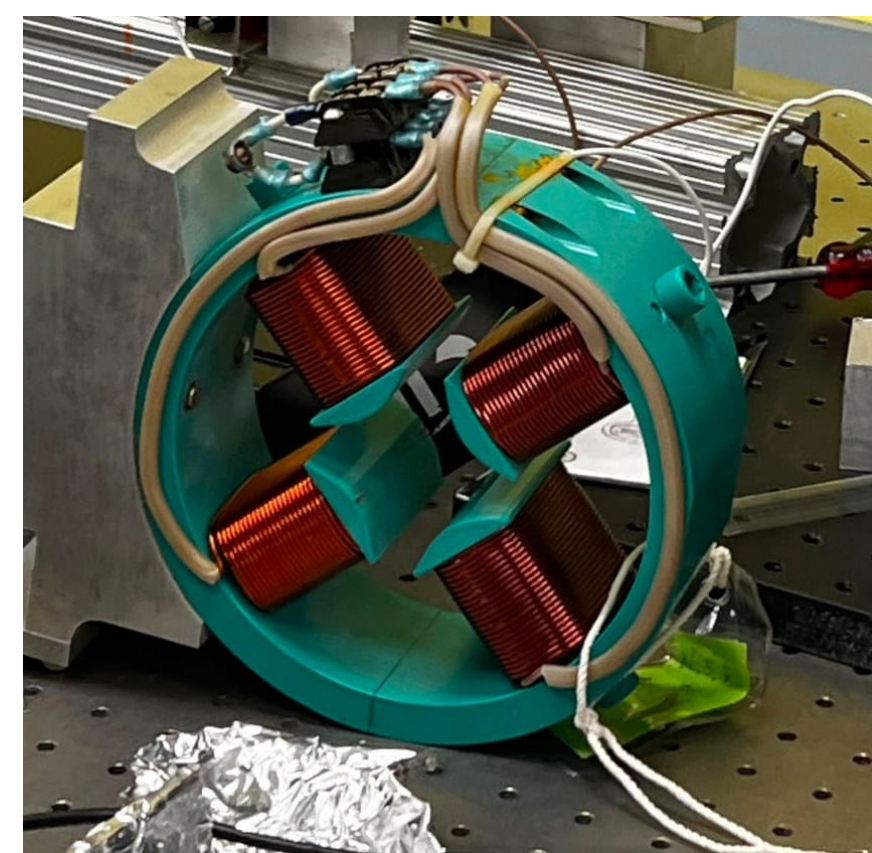
Optics

- Processed camera images in Python to identify the beam position and calculate its displacement from the target center.
- Created a user-friendly GUI to allow for control over camera settings and manual or automatic alignment.
- Applied feedback-based mirror adjustments to reduce alignment error and reproduce the conventional manual alignment procedure.



Magnets

- Developed and compared two accelerator quadrupole magnet geometries using SIMULIA Opera.
- Performed finite-element simulations at multiple excitation currents to calculate magnetic-field distributions.
- Exported simulation data to MATLAB to evaluate field gradients, harmonic content, and magnet performance.



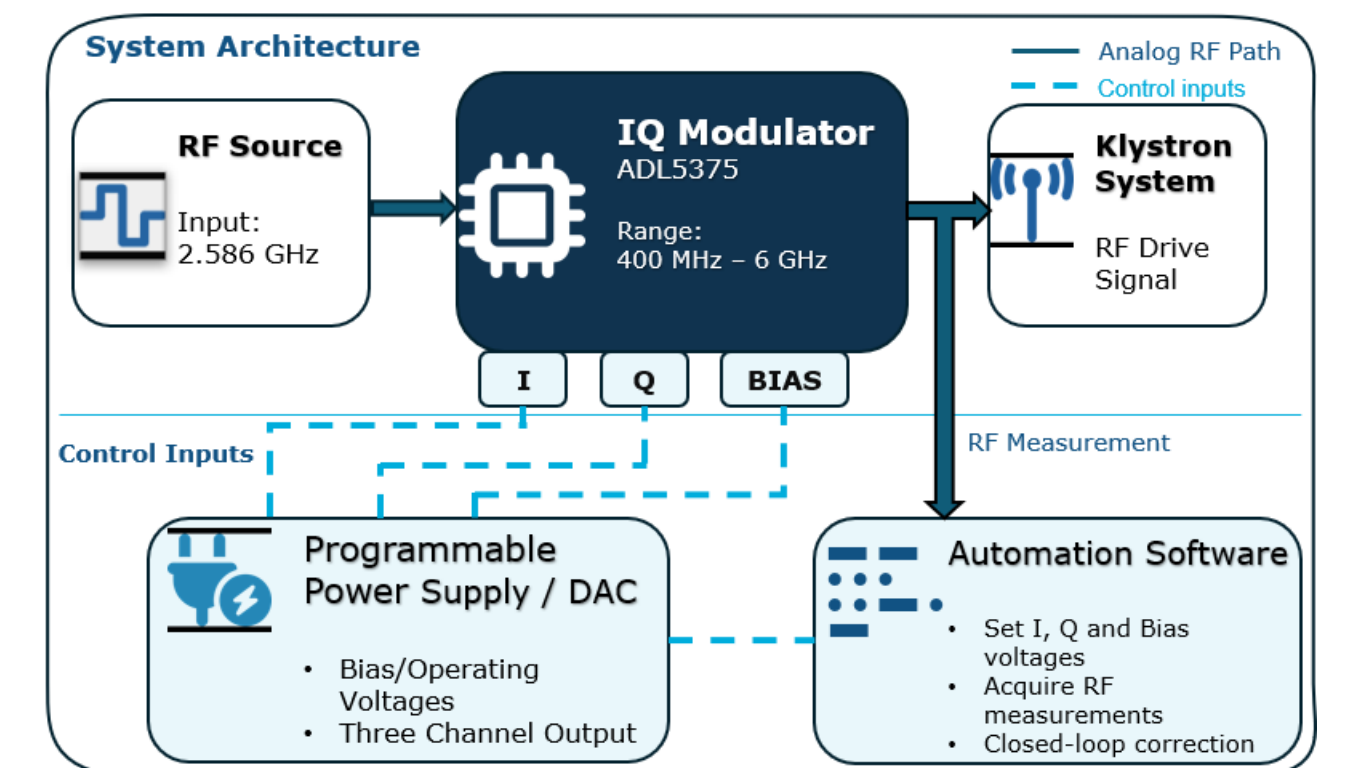
UED

- Created an electron-beam transport model in ImpactX using drifts, solenoids, quadrupoles, and radio-frequency cavities.
- Tracked Courant-Snyder parameters, transverse beam size, energy gain, and longitudinal bunch evolution.
- Varied beam emittance, initial energy, RF phase, and space-charge settings to evaluate their effects on beam quality.

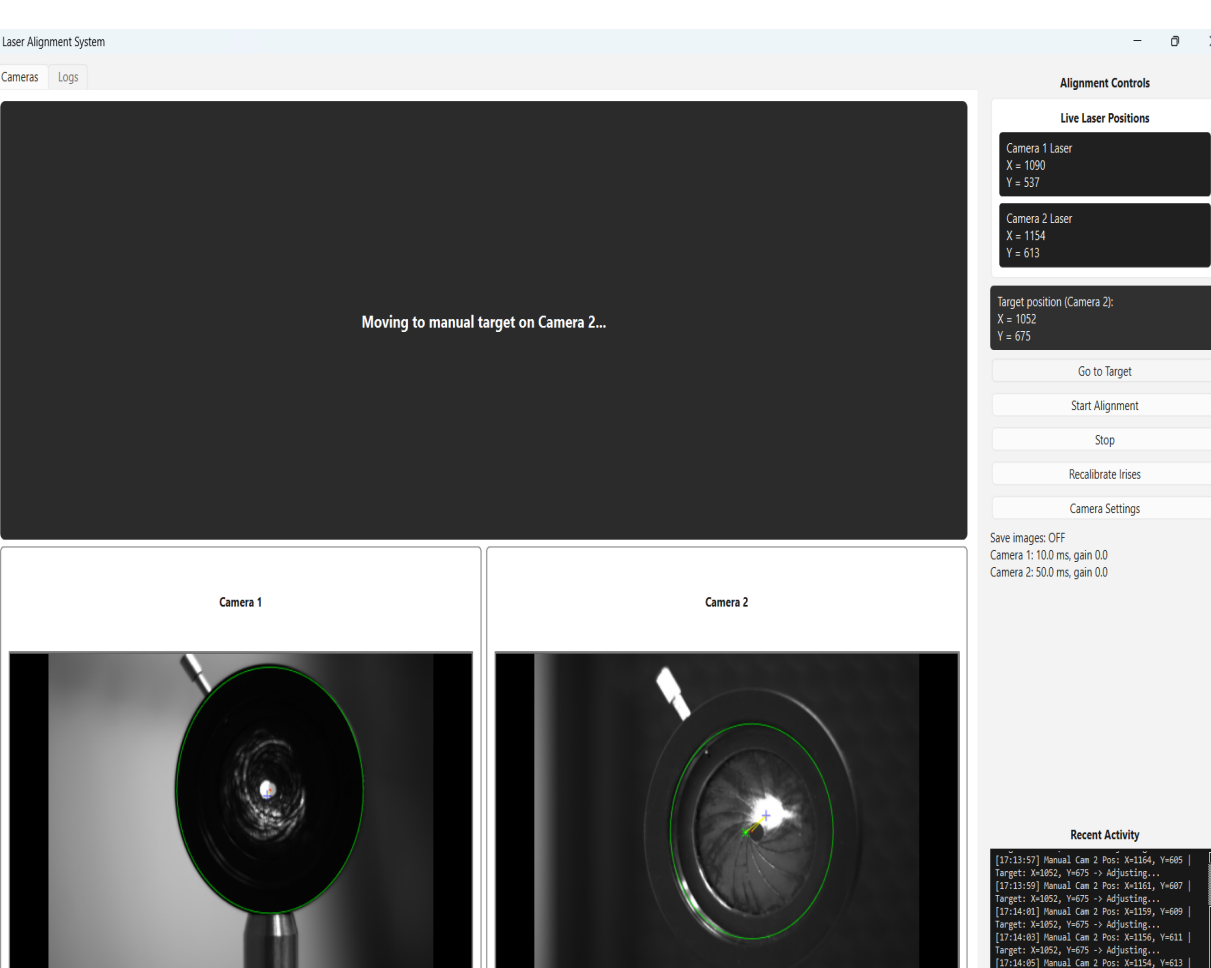
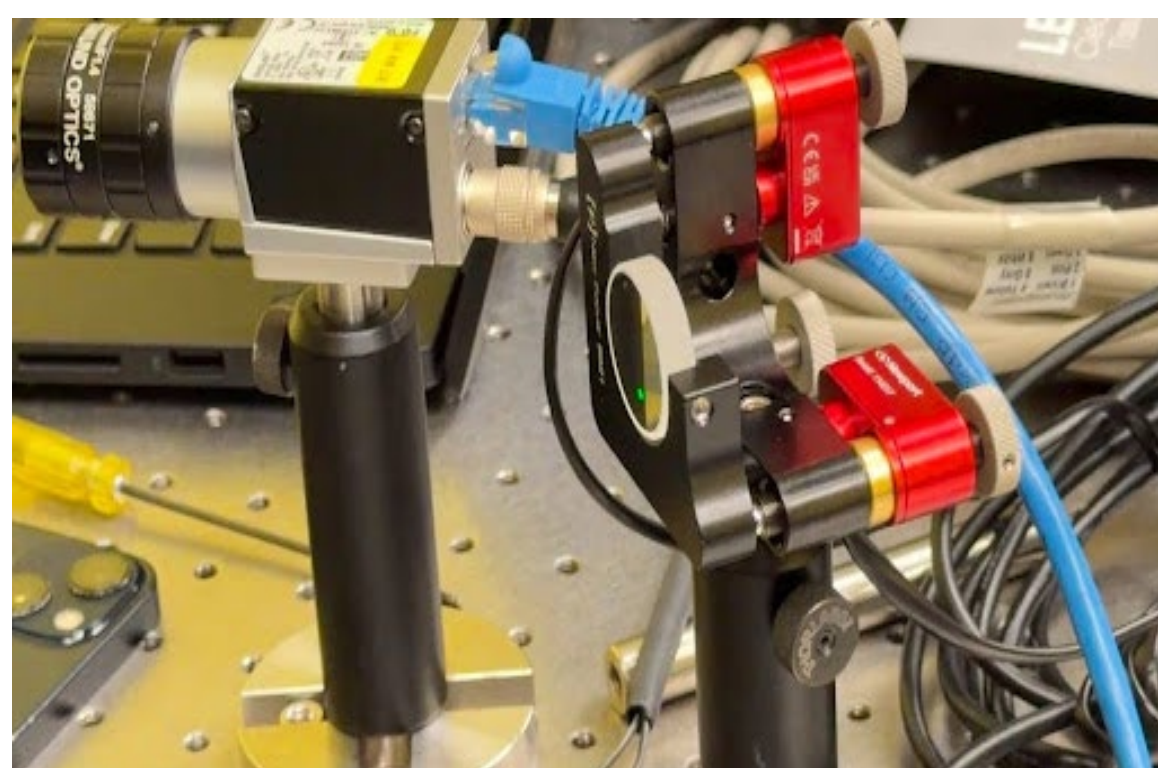


IQ Modulation

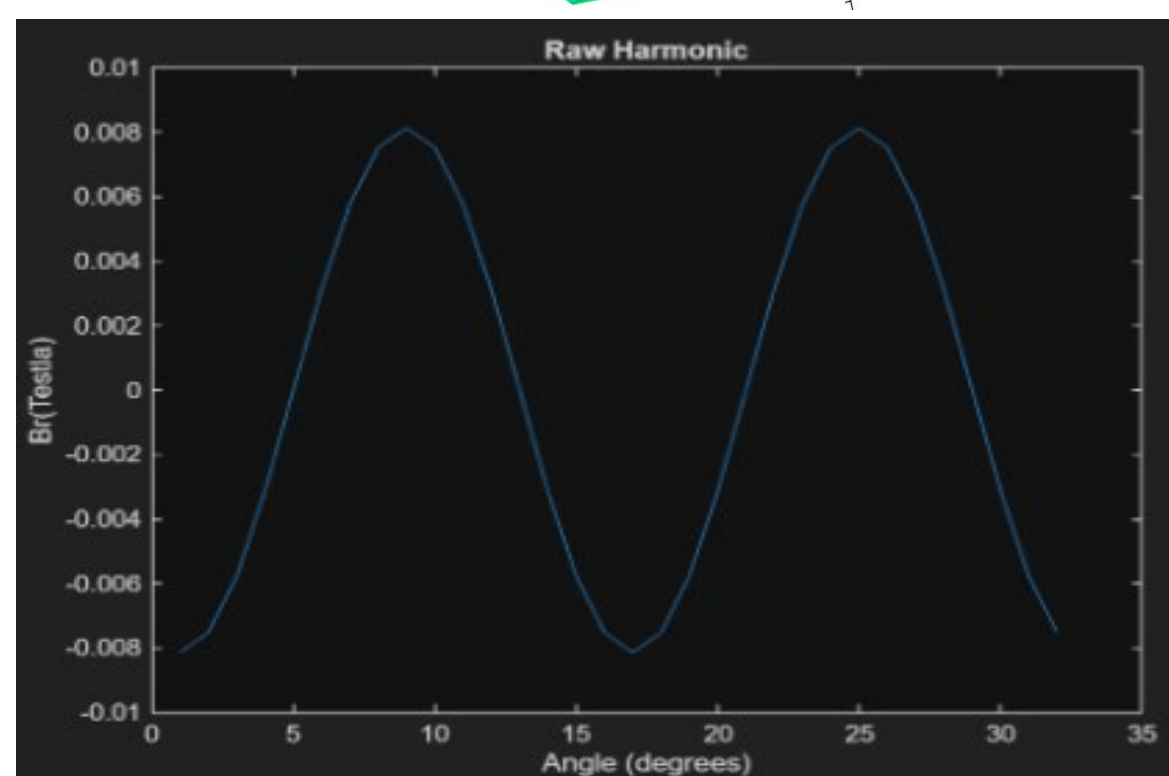
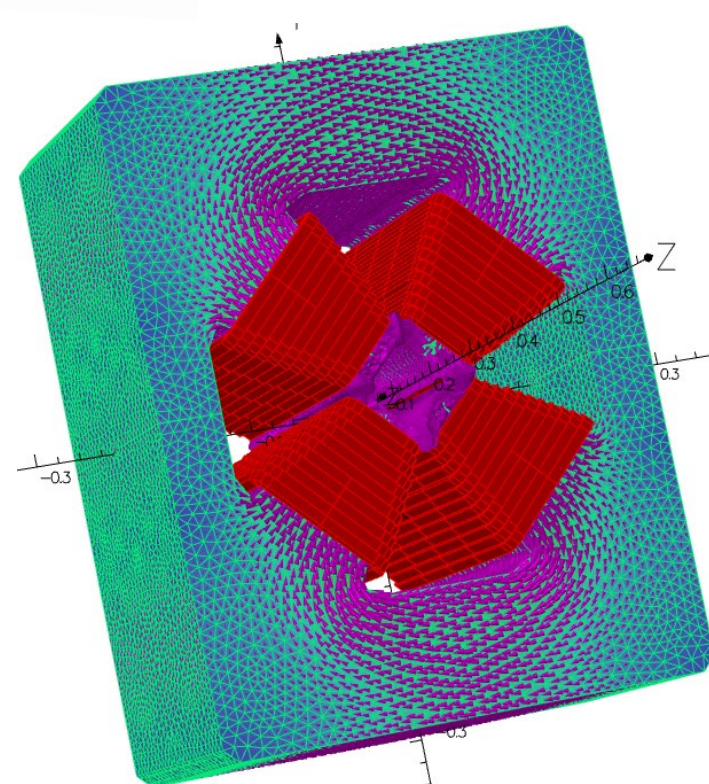
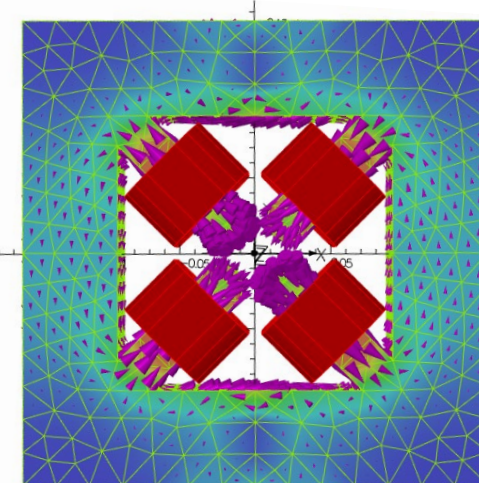
- Connected the IQ modulator to a vector network analyzer and programmable voltage sources to measure RF output under controlled I, Q, and bias voltages.
- Swept the control voltages over the operating range while recording transmission magnitude and phase to identify the linear region, gain behavior, and saturation limits.
- Organized the measured data into an I/Q-to-RF response map for software-based voltage selection and future closed-loop correction.



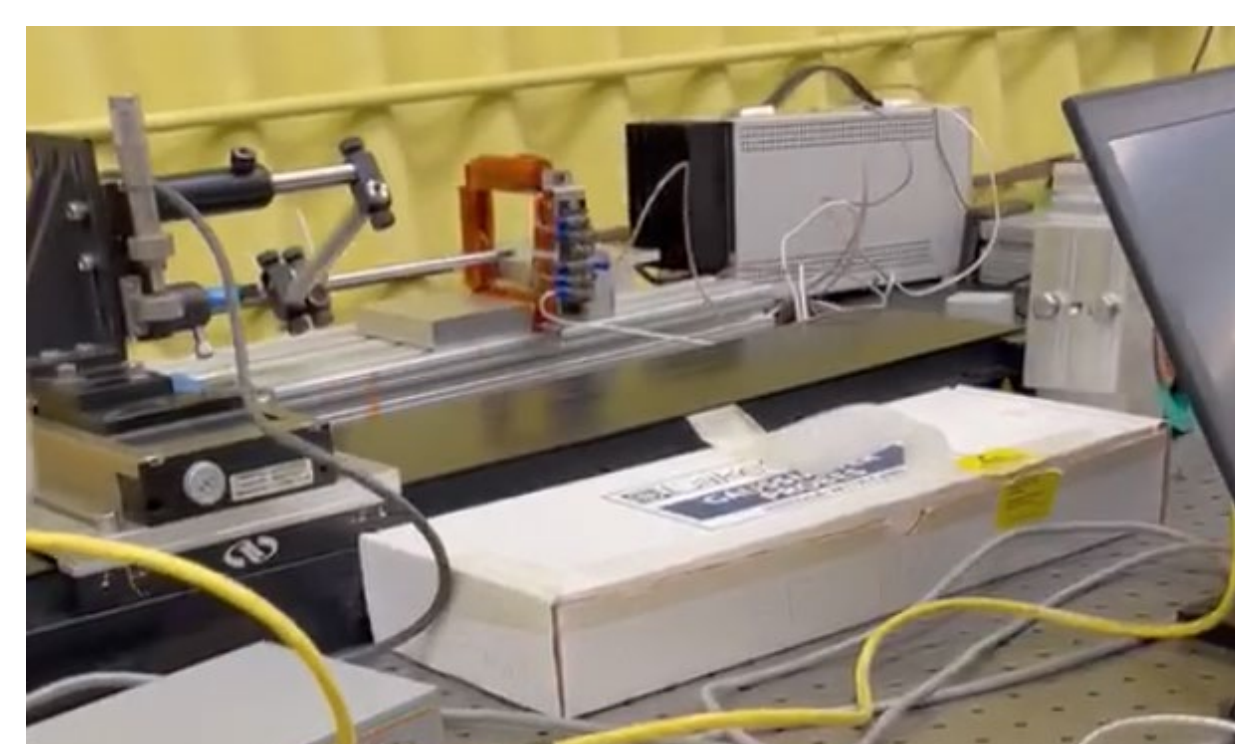
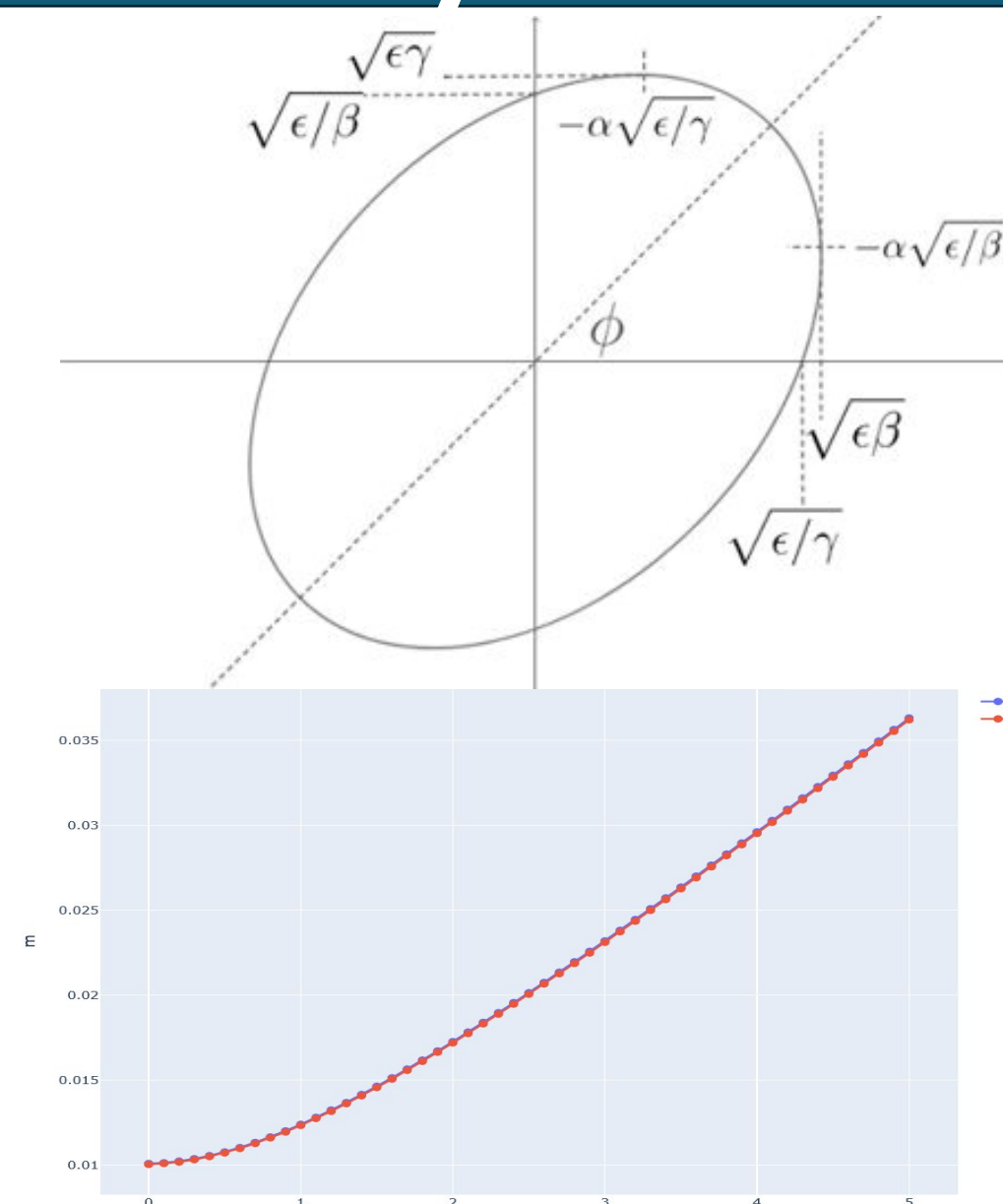
Results & Analysis



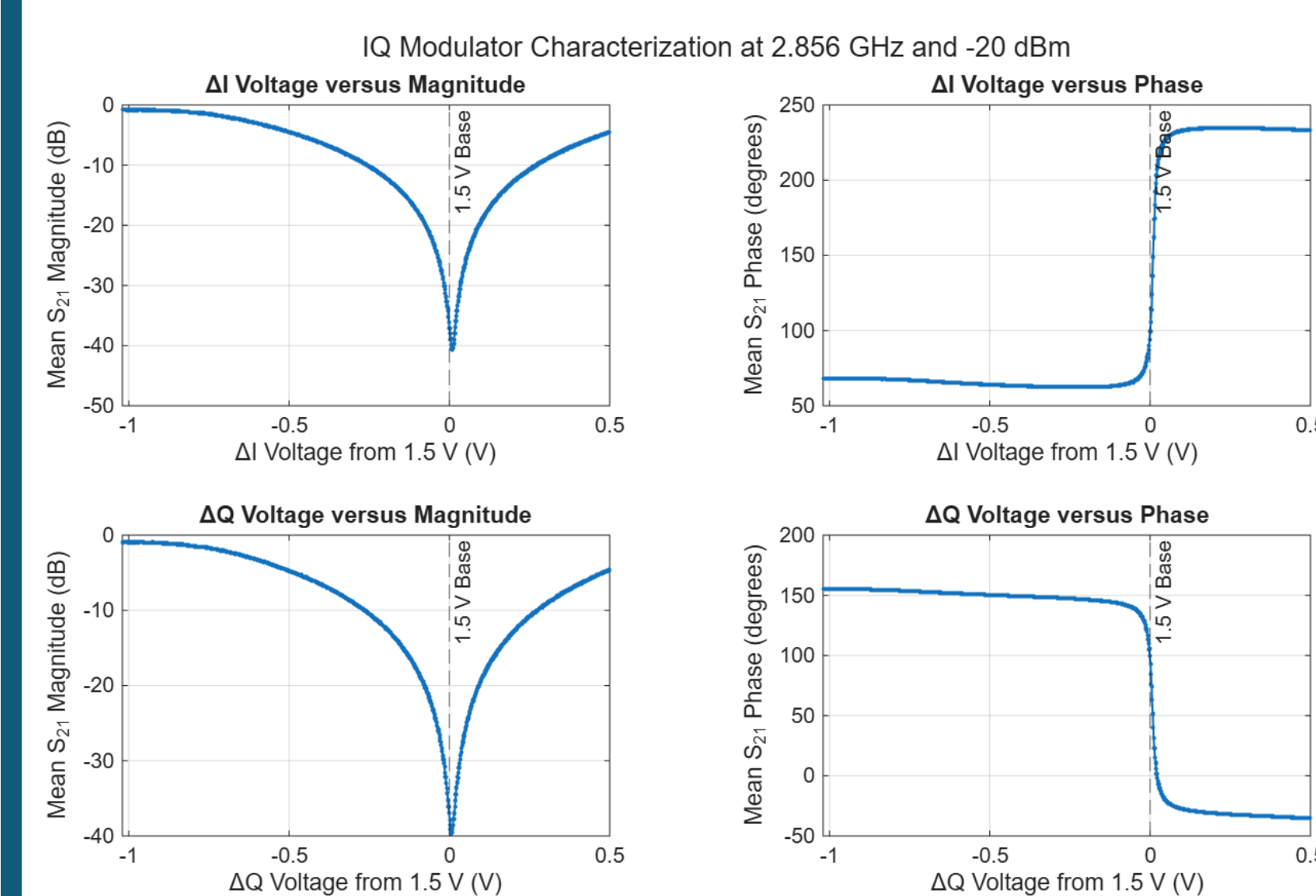
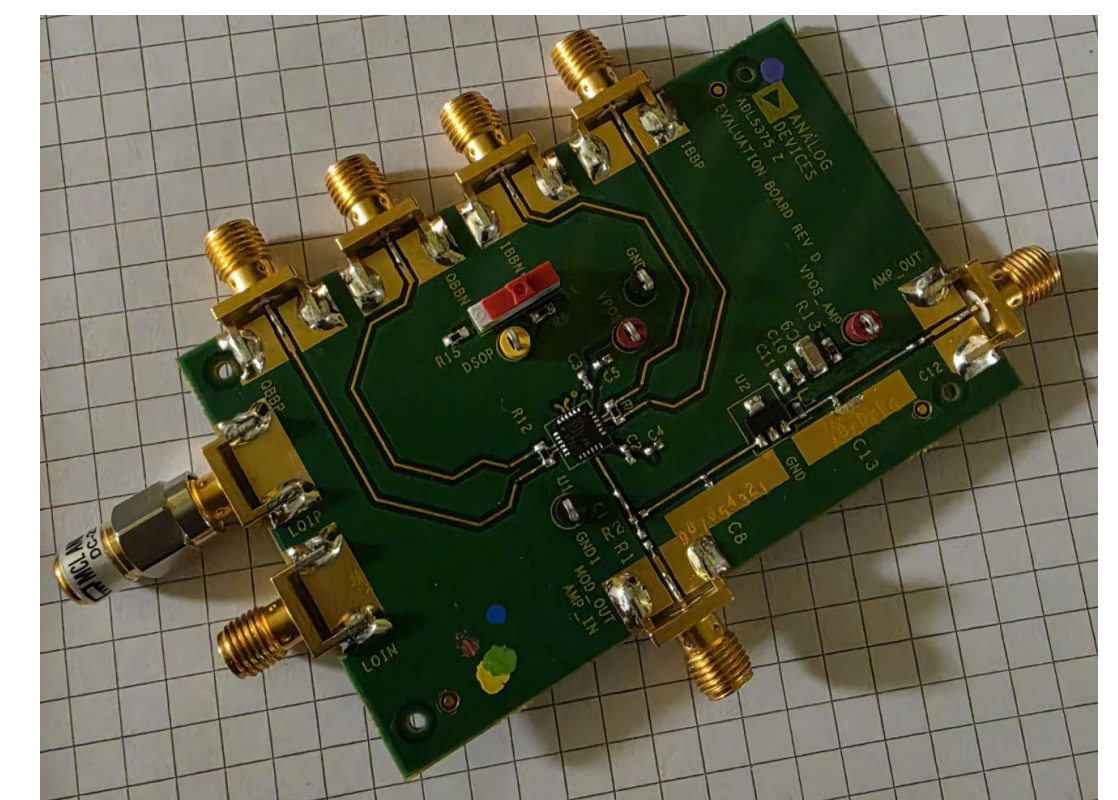
Camera-based beam detection successfully identified beam position and provided the feedback needed for automated mirror alignment.



Opera and MATLAB analysis quantified the quadrupole field distribution, gradient, and harmonic response for the modeled geometry.



ImpactX simulations showed predictable beam evolution through the modeled beamline, including transverse phase-space and bunch-size growth.



Measured I, Q, and bias responses established the relationship between control voltage and RF magnitude and phase.

Conclusions & Future Work

These research modules demonstrated how experimental methods, computational modeling, and automated control can be combined to address challenges in accelerator science and engineering. The laser optics project explored automated beam alignment using camera-based image processing and motorized mirror control, while the magnetism module used finite-element simulations to evaluate quadrupole field distributions and harmonic behavior. ImpactX simulations provided insight into how accelerator components and operating parameters influence electron-beam transport, and the IQ modulation project established an automated method for measuring RF magnitude and phase as control voltages were varied. Future work will focus on improving the reliability of the laser-alignment system, refining magnet geometries, expanding the UED beamline models, and completing the IQ modulator response map. The IQ characterization data can then be used to implement automated voltage selection and closed-loop correction of RF magnitude and phase.

Acknowledgements

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Code Repositories:
Github.com/AxelWattl

