



Applications and Computational Modeling in Accelerator Science

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Abstract

The SESAPARD partnership between New York City College of Technology and Brookhaven National Laboratory, supported by the DOE RENEW initiative, examined how laser optics, accelerator magnets, and electron-beam physics work together at the Accelerator Test Facility. The project included laser alignment and Python-based automation, quadrupole-magnet modeling with Opera-3D, TOSCA, and MATLAB, and ImpactX studies of 10 MeV and 100 MeV electron beams for ultrafast electron diffraction. Together, the modules showed that precise optical alignment, high-quality magnetic fields, and controlled beam properties are essential for reliable accelerator operation while strengthening skills in simulation, programming, instrumentation, data analysis, safety, teamwork, and scientific communication.

Motivation

A major objective of research at Brookhaven National Laboratory's Accelerator Test Facility is to improve the precision, reliability, and efficiency of laser-driven accelerator experiments. The work focused on laser alignment, magnetic focusing, electron-beam transport, and optical-material durability. An automated alignment system using cameras, Python image processing, motorized mirrors, and real-time feedback was developed to improve beam stability and reduce setup time. Quadrupole magnets were designed and simulated in SIMULIA Opera, TOSCA, and MATLAB to evaluate field distribution, gradient, integrated strength, and harmonic quality. ImpactX was used to study 10 MeV and 100 MeV electron beams for ultrafast electron diffraction, including emittance, magnetic rigidity, focusing, beam-waist formation, RF bunching, and space-charge effects. Laser-induced damage testing of BaF₂ with an 800 nm, 100 fs laser was also performed to determine safe fluence limits and investigate surface damage, internal modification, self-focusing, and filamentation. Together, these studies show that precise alignment, strong magnetic-field quality, stable beam transport, and durable optical materials are essential for advanced accelerator operation.

Methodology

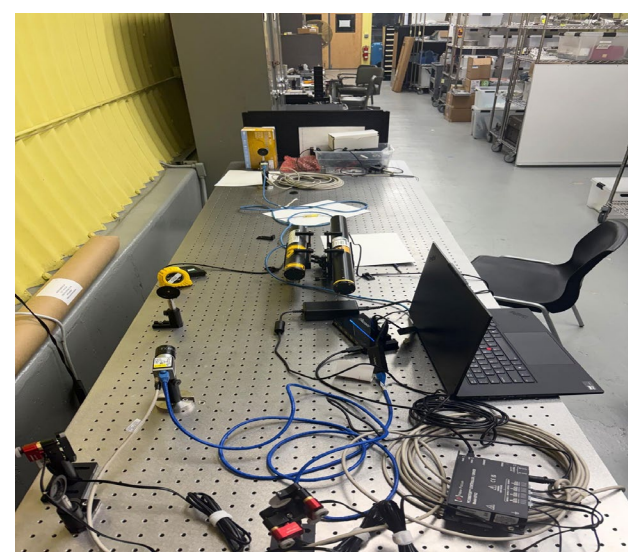
Automated Laser Alignment System

Brookhaven's ATF develops laser-driven acceleration, supported by our automated system for faster, more accurate, and stable laser alignment.

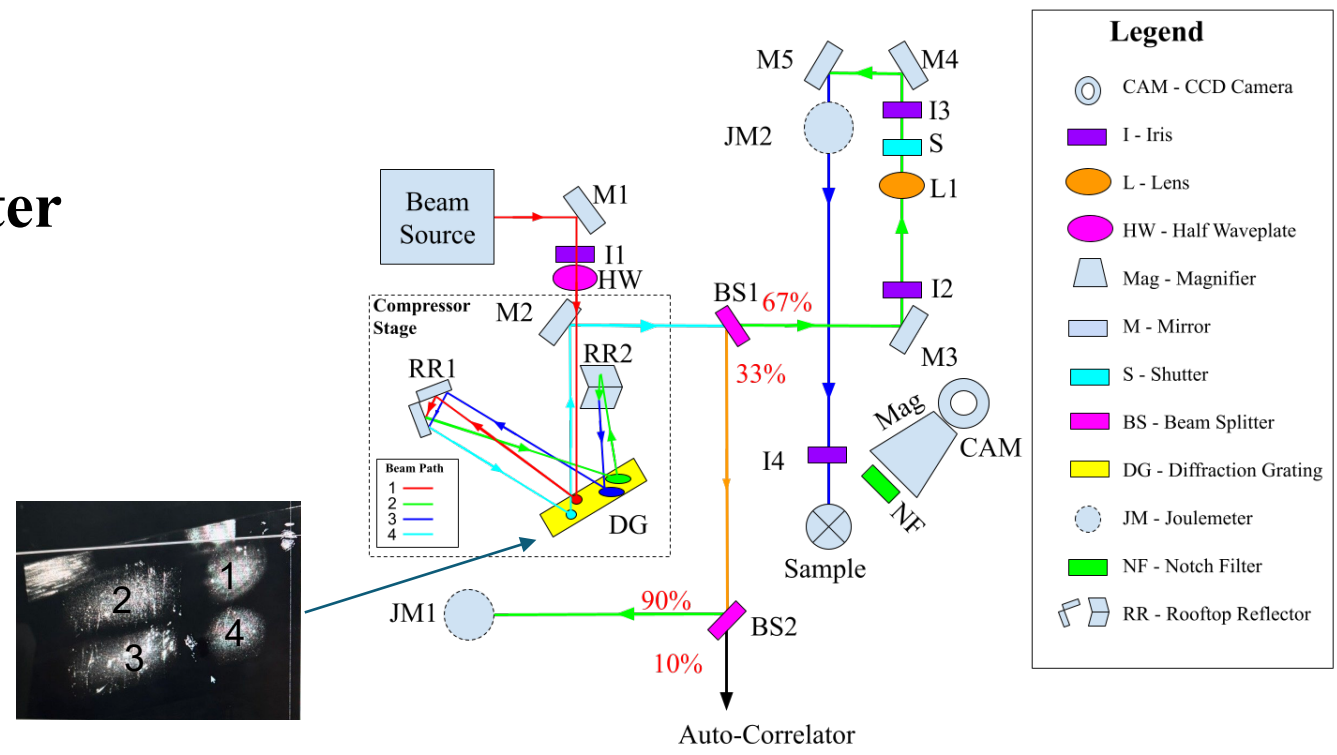
Off Axis Parabolic Mirror Alignment

Fiber Optics: Alignment

Automated-alignment arrangement on the optical table



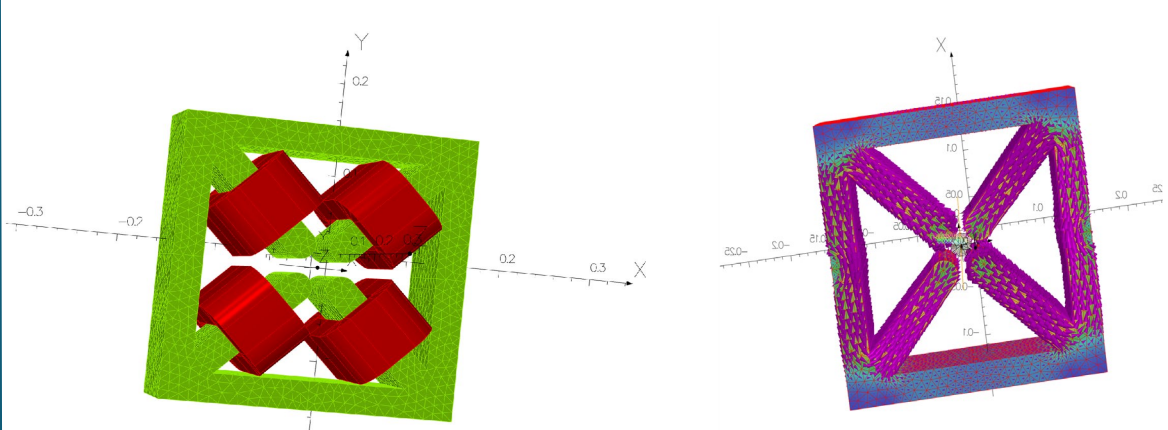
LIDT setup



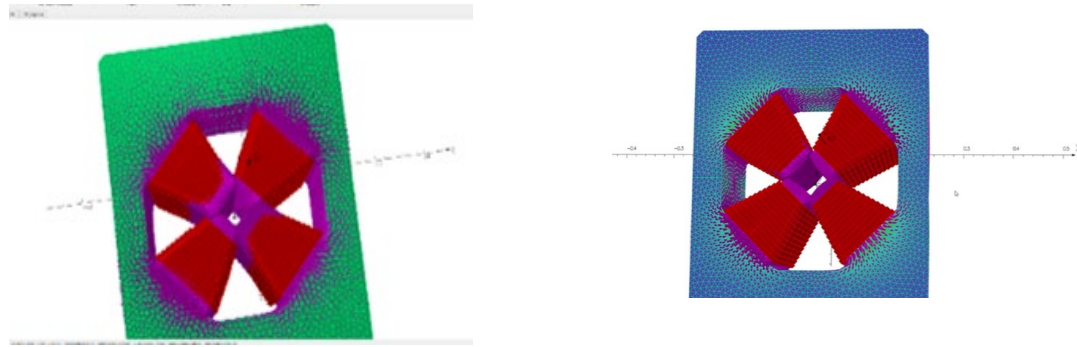
Quadrupole Design with OPERA 3D

Two quadrupole magnets were simulated in Opera and MATLAB to evaluate their magnetic fields and focusing performance.

Quadrupole Magnet 1



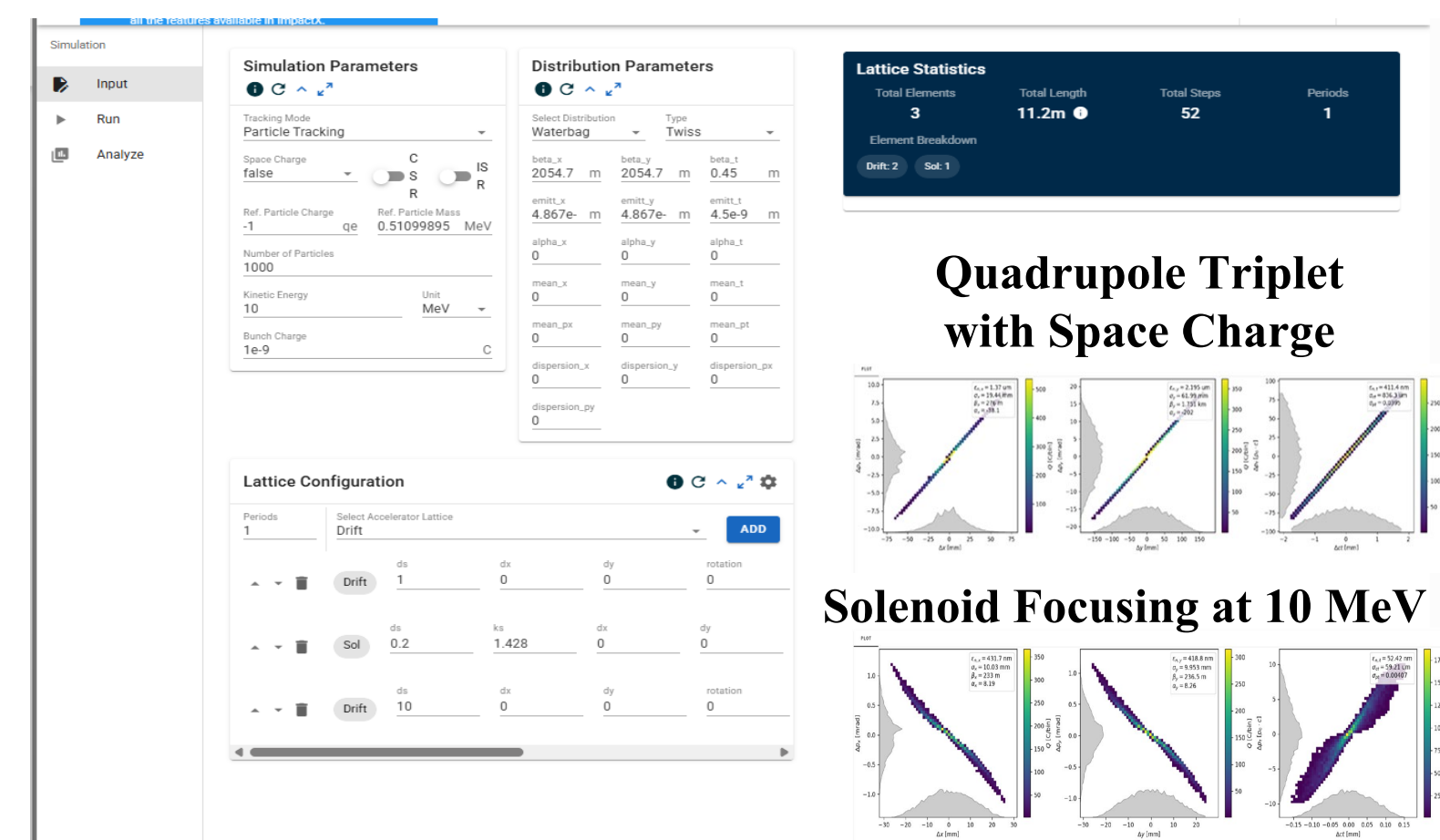
Quadrupole Magnet 2



Electron Beam Simulation Via ImpactX

Ultrafast Electron Diffraction observes rapid atomic changes, while ImpactX optimizes electron-beam transport and timing.

ImpactX Setup for 10 MeV Solenoid Focusing with Space Charge

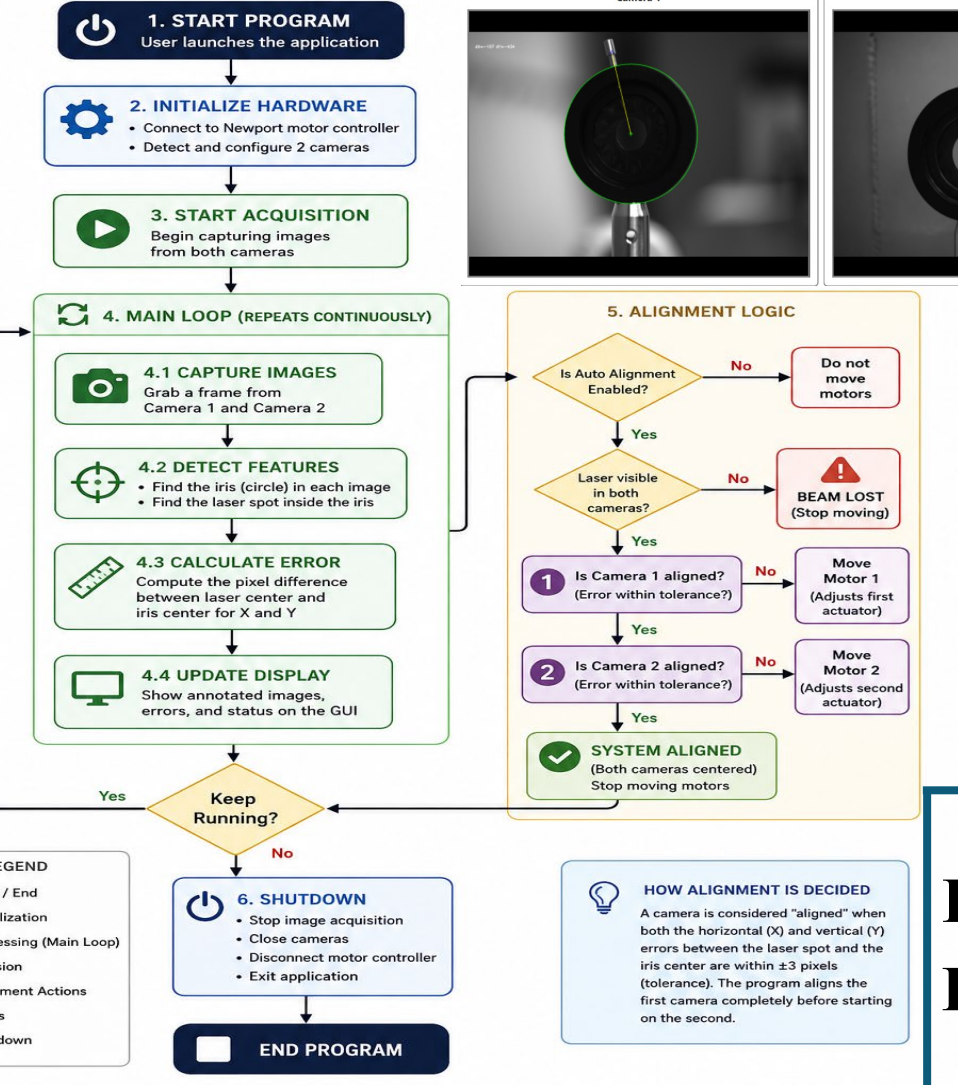


The solenoid focuses both planes to about 10 mm, while the quadrupole triplet and space charge produce unequal beam sizes of 19.4 mm in x and 62.0 mm in y, indicating that further tuning is required.

Results & Analysis

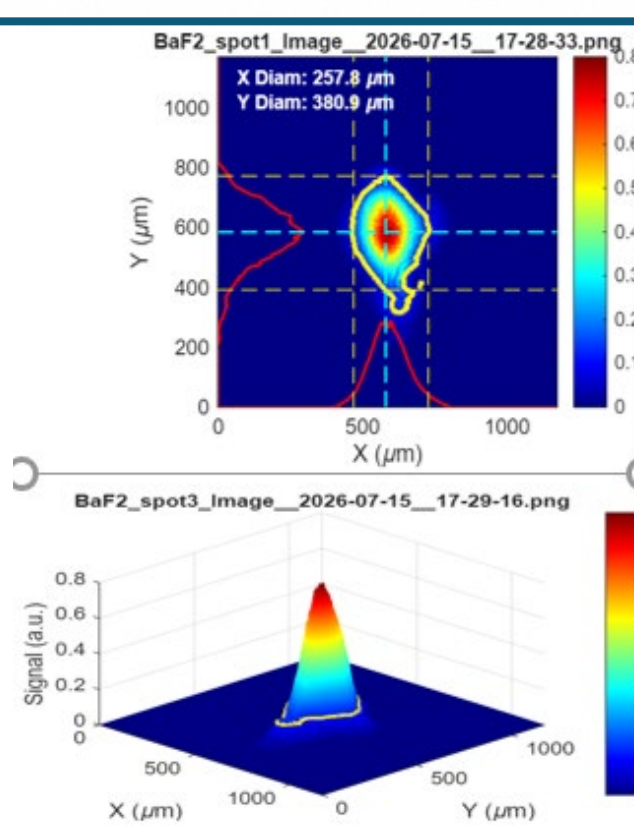
LASER ALIGNMENT PROGRAM – HOW IT WORKS

The program automatically aligns a laser to the center of two circular iris targets using cameras and precision motorized actuators.



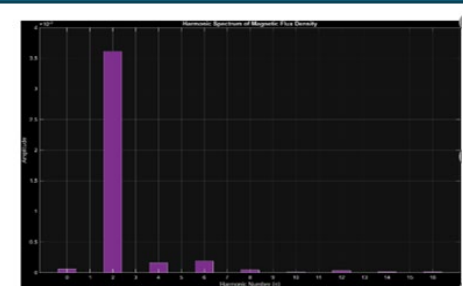
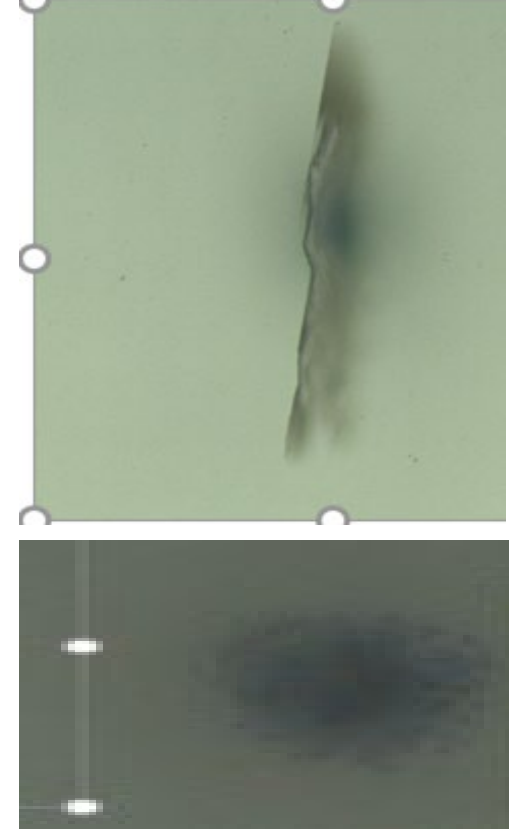
The 3DOptix simulation shows interference fringes formed by two coherent beams with different optical path lengths. A real-time GUI automated alignment to the target coordinates.

LASER INDUCED DAMAGE THRESHOLD

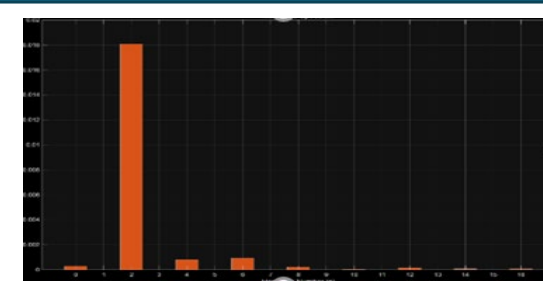


The top image shows the laser's 2D and 3D speckle pattern

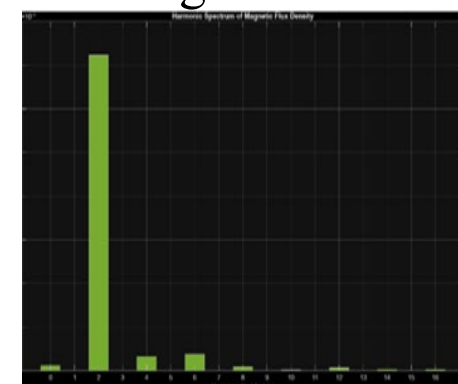
The image shows internal BaF₂ damage



100% Current Density Scaling Factor



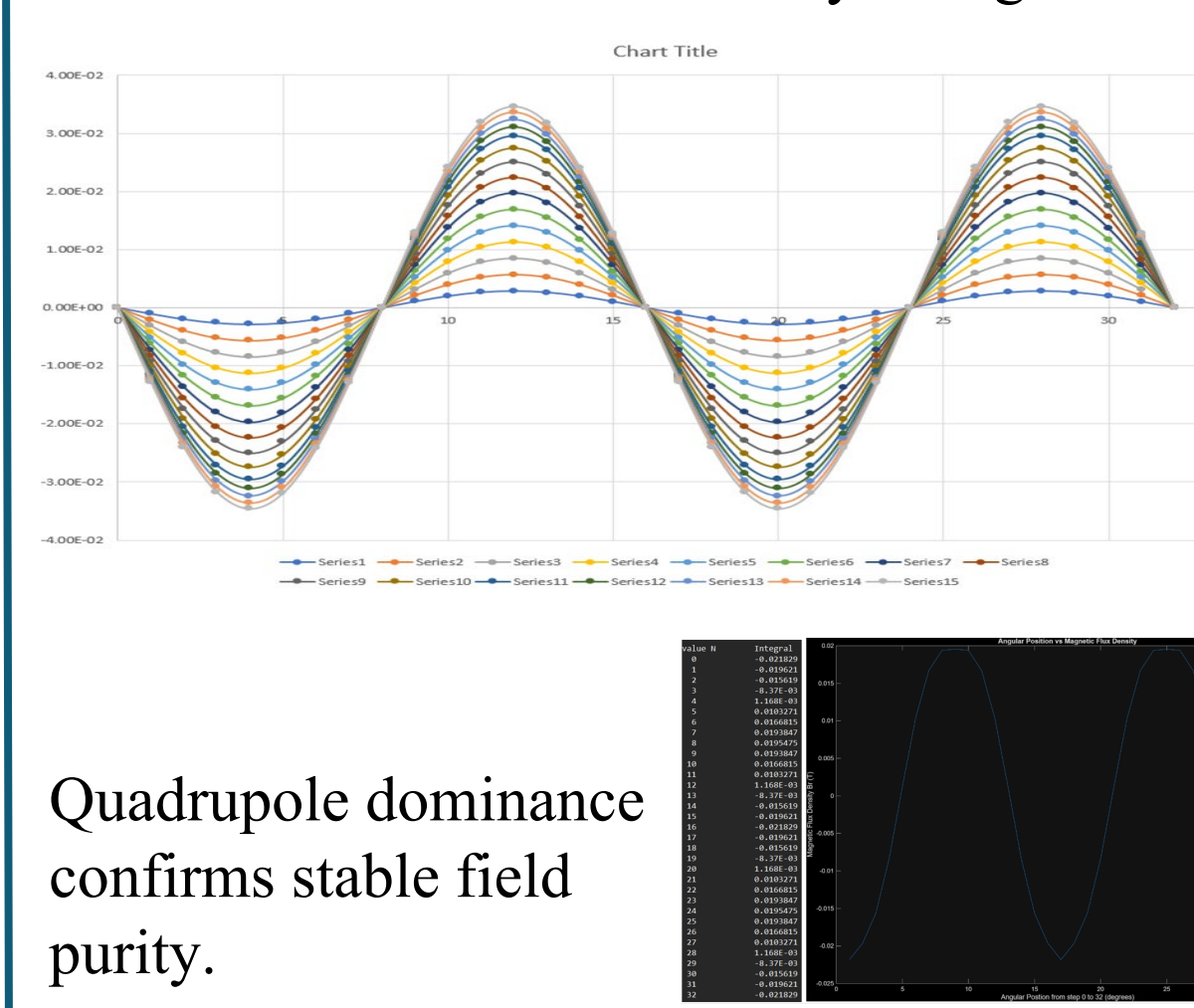
20% Current Density Scaling Factor



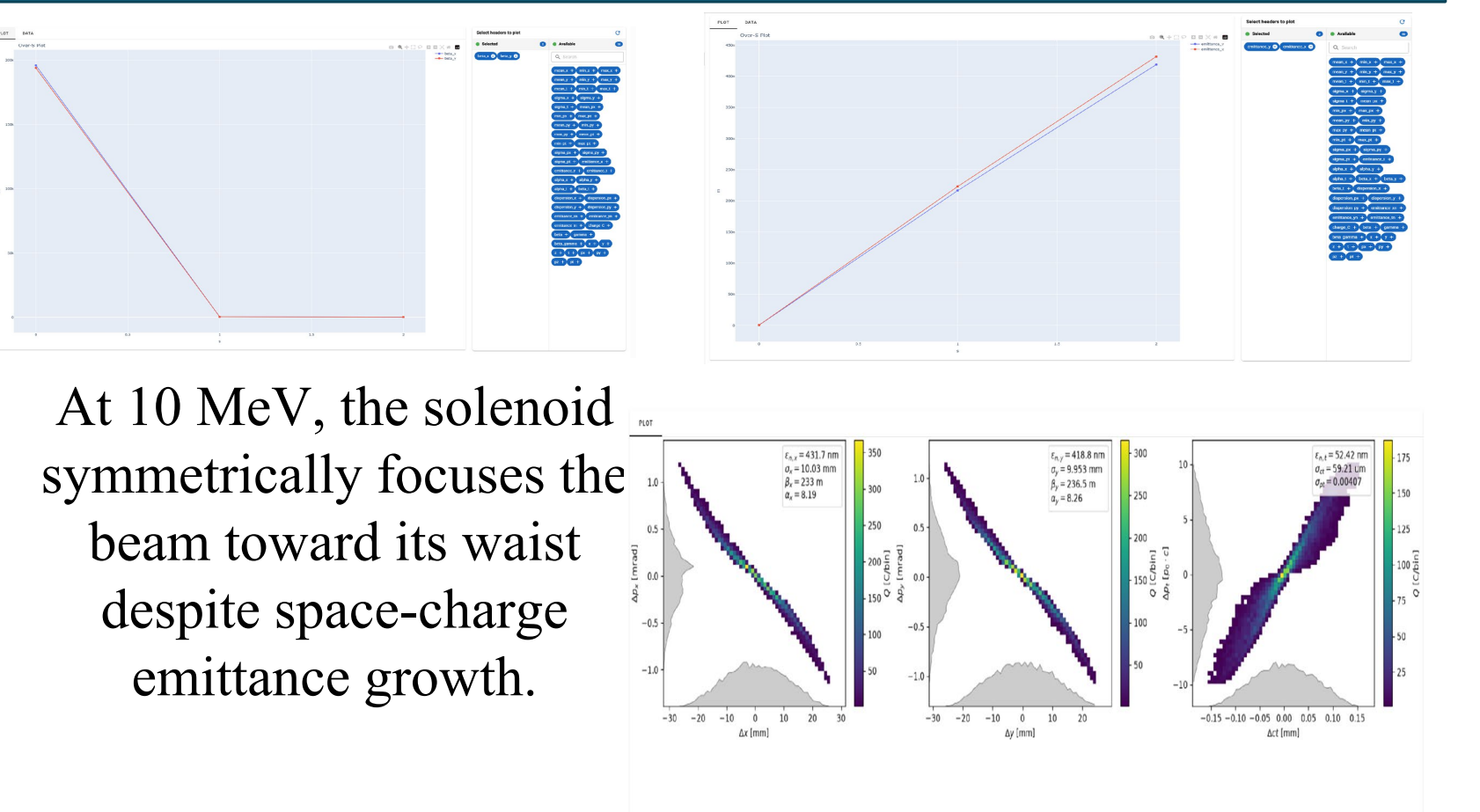
60% Current Density Scaling Factor

Quadrupole dominance confirms strong, stable field quality.

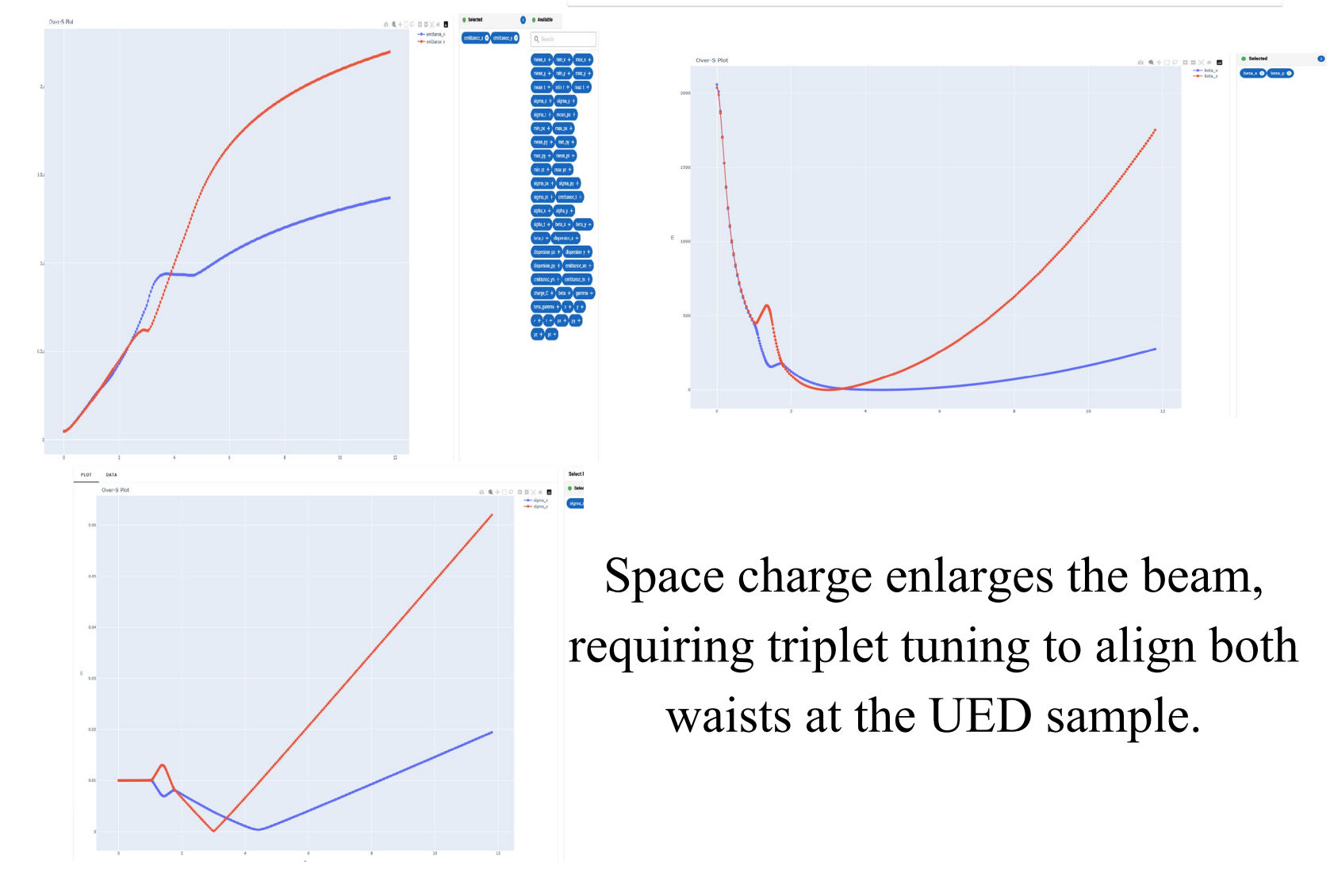
Two cycles represent the four poles, while 32 measurements track flux-density changes.



Quadrupole dominance confirms stable field purity.



At 10 MeV, the solenoid symmetrically focuses the beam toward its waist despite space-charge emittance growth.



Space charge enlarges the beam, requiring triplet tuning to align both waists at the UED sample.

Conclusion

This research demonstrated how experimental measurements and computational modeling can be combined to improve accelerator-system performance. The results from quadrupole-magnet analysis, UED beam simulations, automated laser alignment, and BaF₂ damage testing highlight the importance of magnetic-field quality, precise beam control, optical stability, and material response in developing reliable and safe accelerator technologies.

Acknowledgements

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