



Integrating Optics, Magnetics, and Beam Dynamics in Accelerator Research

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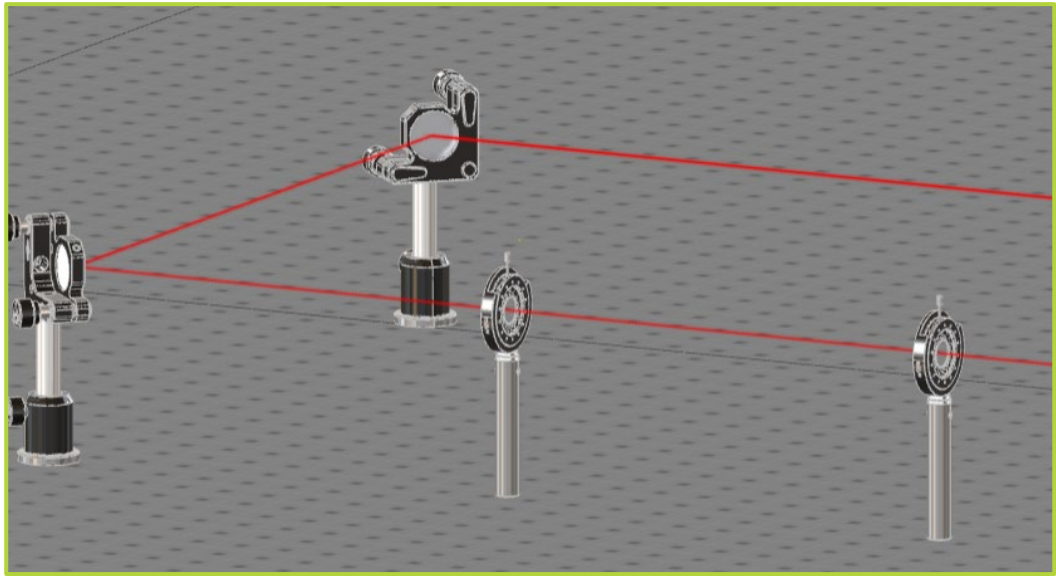
Abstract

This work summarizes research conducted at Brookhaven National Laboratory’s Accelerator Test Facility across three areas of accelerator science: optical laser systems, superconducting magnets(SCM), and ultrafast electron diffraction(UED). In the laser systems module, an automated beam-alignment system was developed using digital cameras, Python-controlled motorized actuators, and real-time spatial error calculations. The closed-loop system steered the laser through target irises, improving alignment accuracy and beam stability compared with manual methods. For superconducting magnets, quadrupole geometries were evaluated using finite-element simulations in SIMULIA Opera and MATLAB analysis. Results confirmed that magnetic flux density increased linearly with excitation current without core saturation. In the ultrafast electron diffraction module, ImpactX simulations modeled electron-beam transport and phase-space dynamics to optimize transverse focusing and longitudinal bunching under space-charge effects. Together, these projects demonstrate how lasers, magnetic focusing, computational modeling, and optoelectronics support next-generation light sources and accelerator infrastructure.

Methodology

Automated Laser Alignment

Developed a closed-loop system that automatically detects and corrects laser-beam misalignment, reducing the need for slow manual mirror adjustments.



• 3DOptix simulation of laser setup.

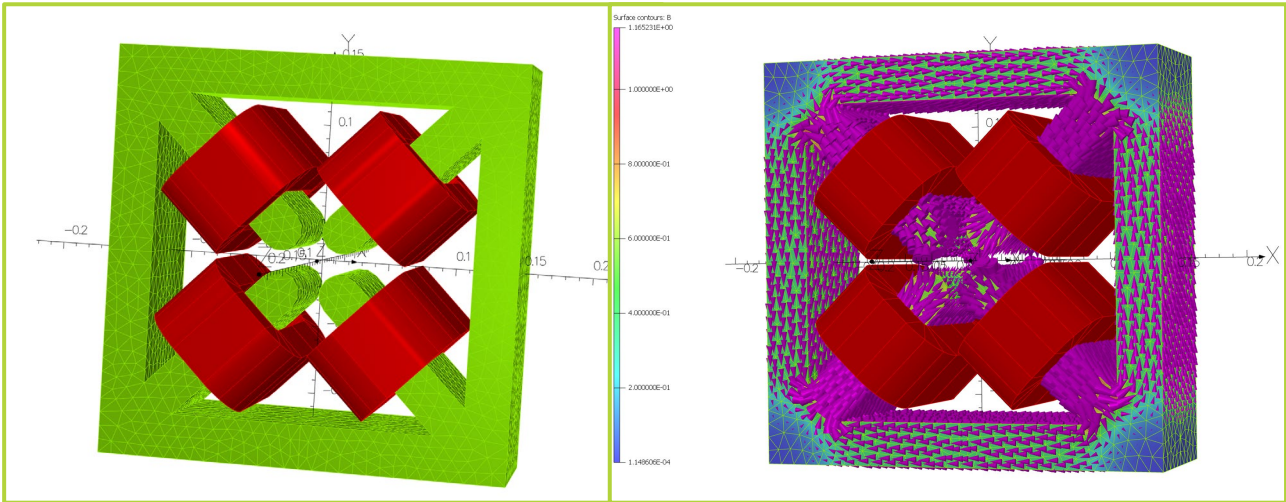


• Physical setup of the automated laser alignment setup.

Superconducting Magnets (SCM)

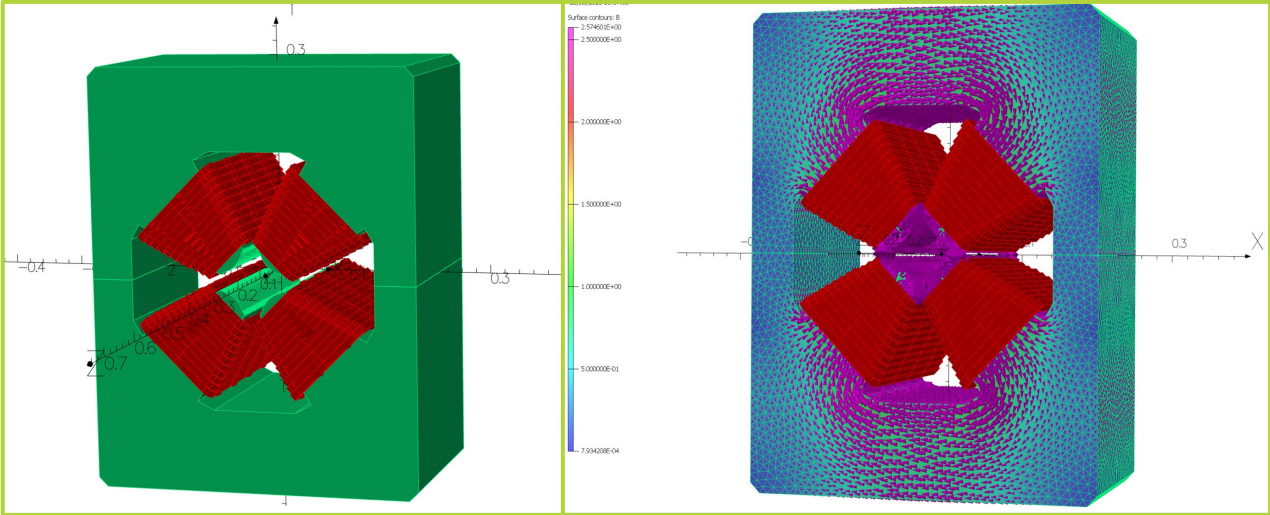
Two superconducting quadrupole magnets for Ultrafast Electron Diffraction was modeled in SIMULIA Opera and analyzed in MATLAB to evaluate field strength, harmonics, and material response across multiple excitation currents.

Quadrupole Magnet #1



• Single racetrack coil quadrupole with yoke radius 15.3 mm. • Single racetrack coil showing magnetic field.

Quadrupole Magnet #2

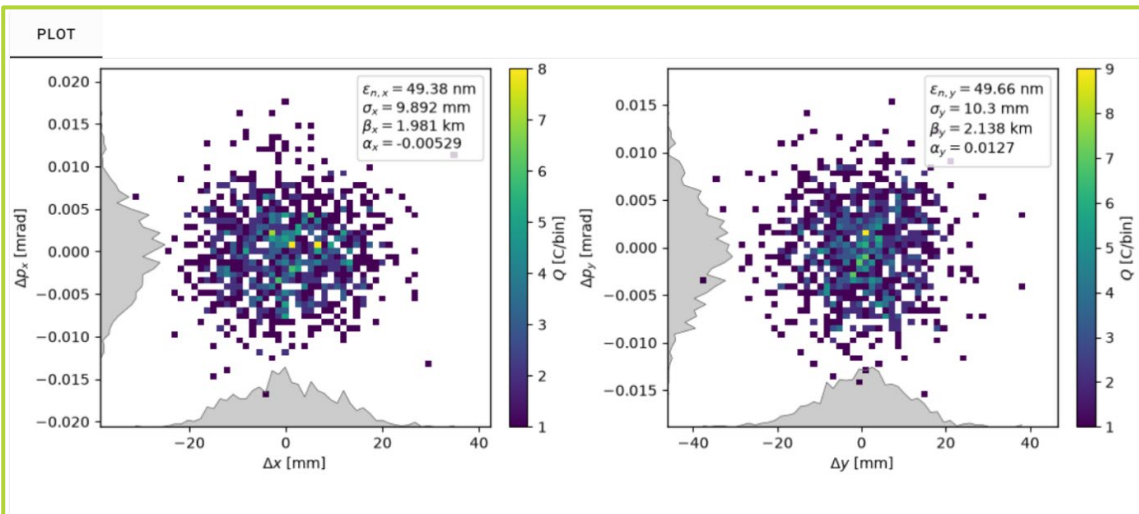


• Eleven coil/pole magnet design with 7552A/pole. • Eleven coil/pole magnet showing magnetic field.

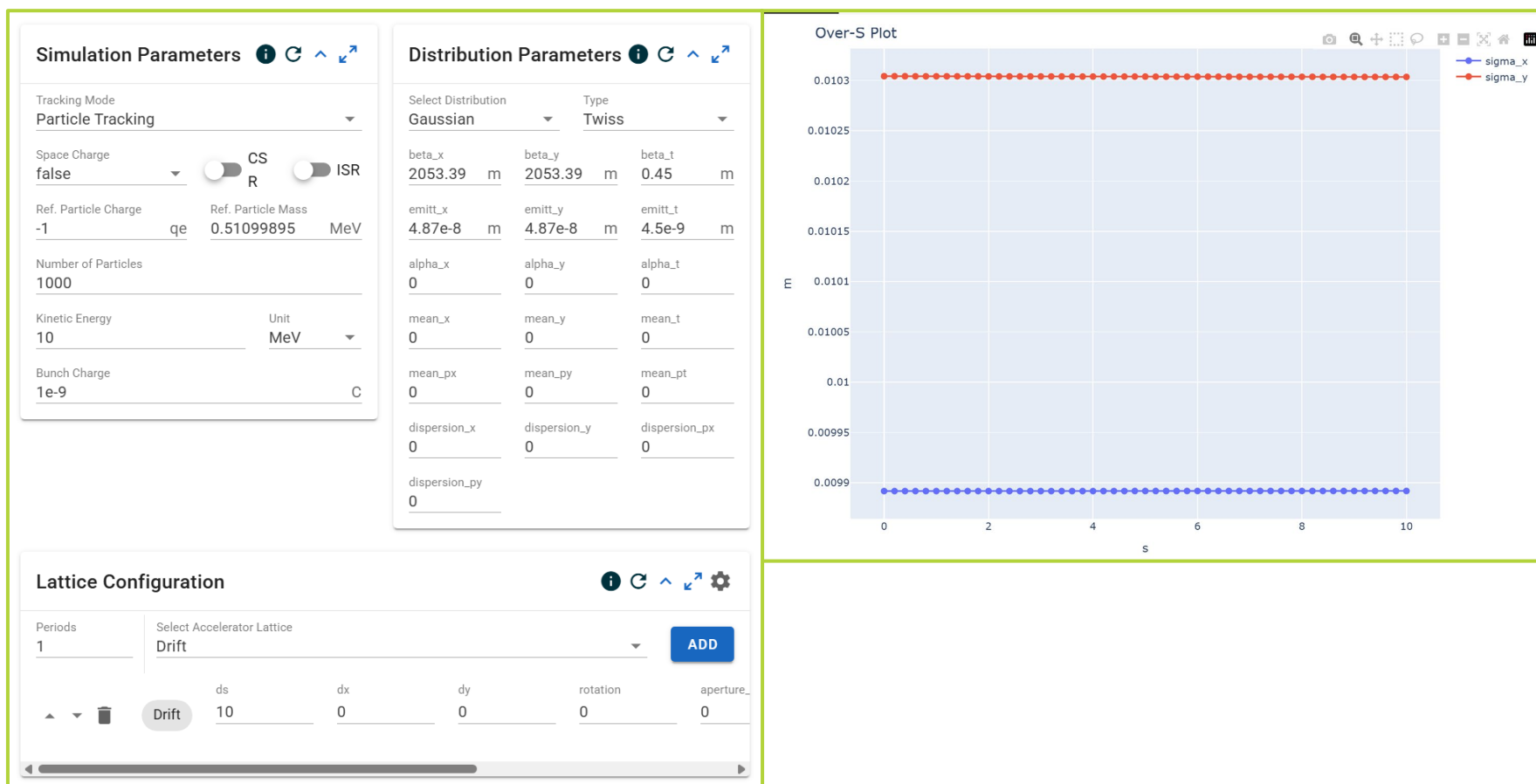
Electron beam (UED)

Simulating the electron beam in ImpactX under varied conditions helps optimize beam transport and maintain the stability needed for reliable UED experiments.

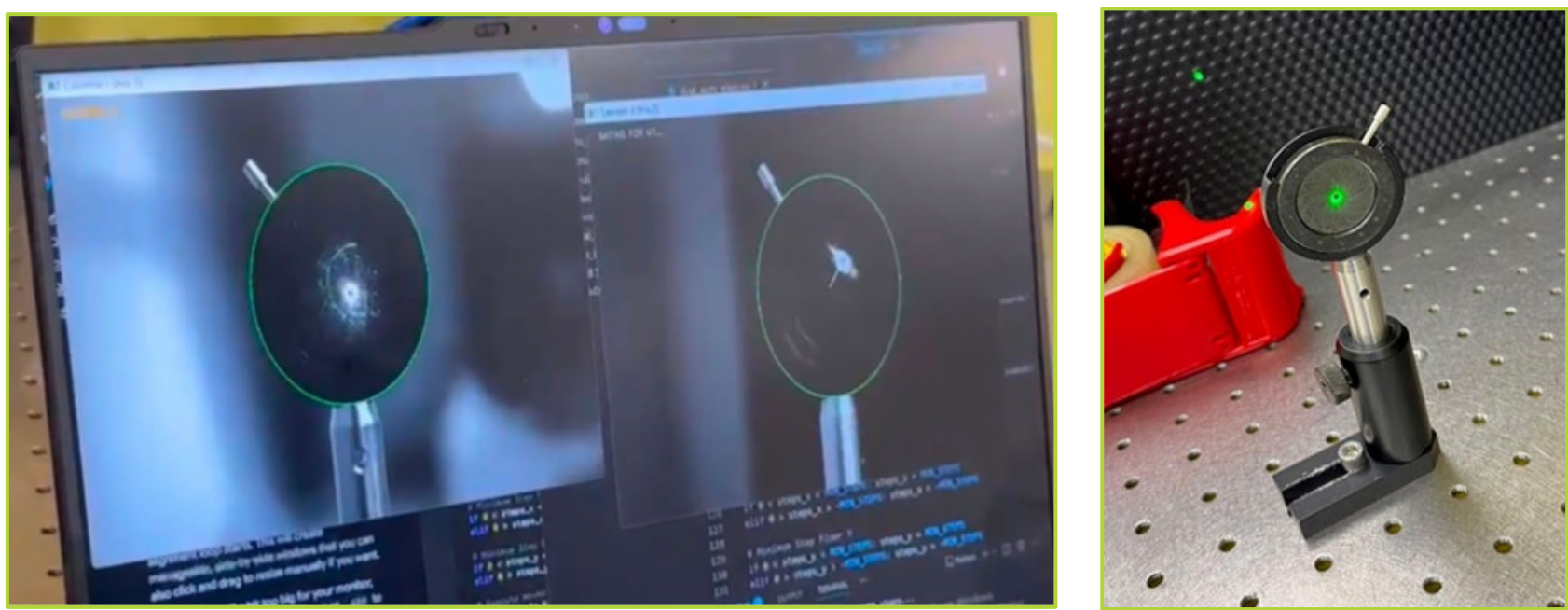
Initial Electron beam



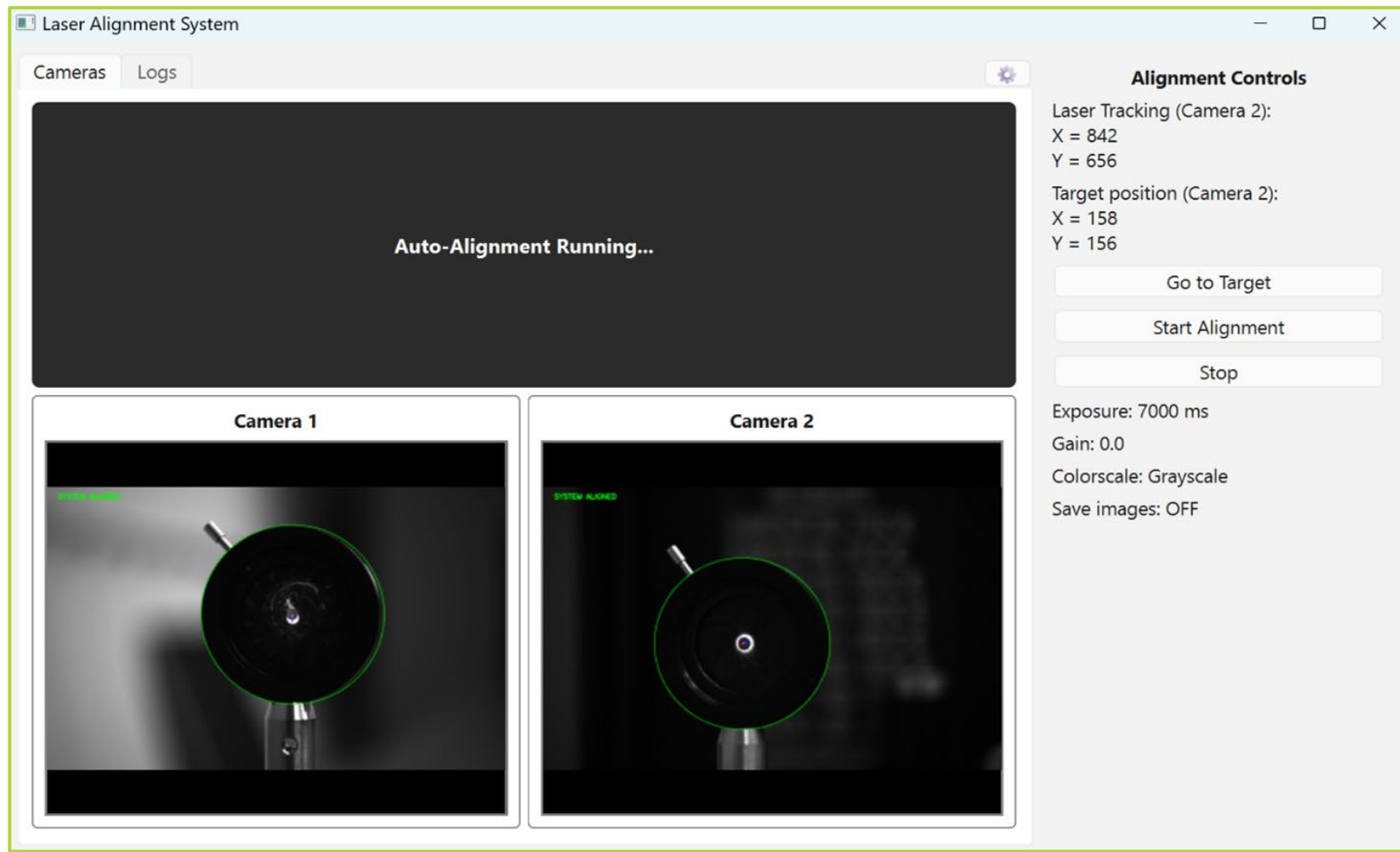
Baseline ImpactX simulation of the initial Gaussian electron beam distribution, displaying no position-momentum correlation



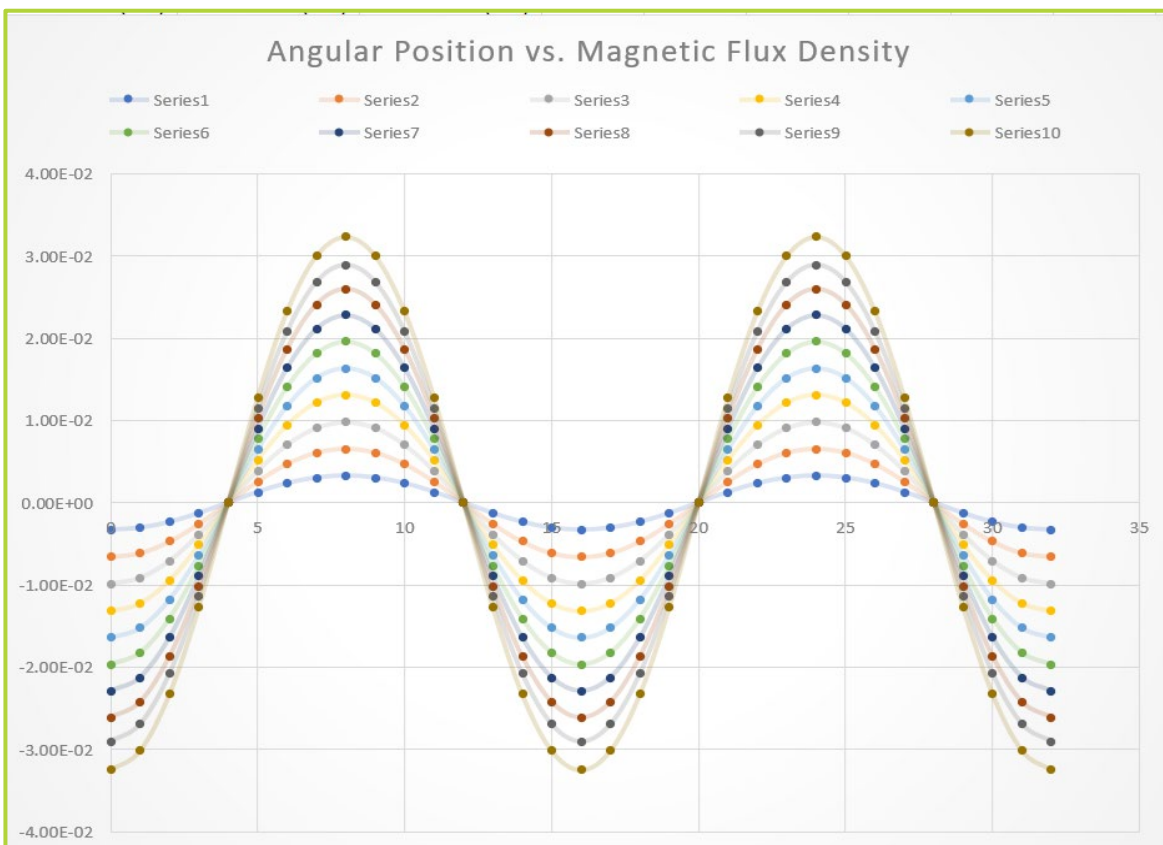
Results



• A user interface was created to provide real-time visualization of the system status. The software alternates automatically between the two motorized camera pairs and iteratively reduces the alignment error until the specified target pixel coordinates are achieved.

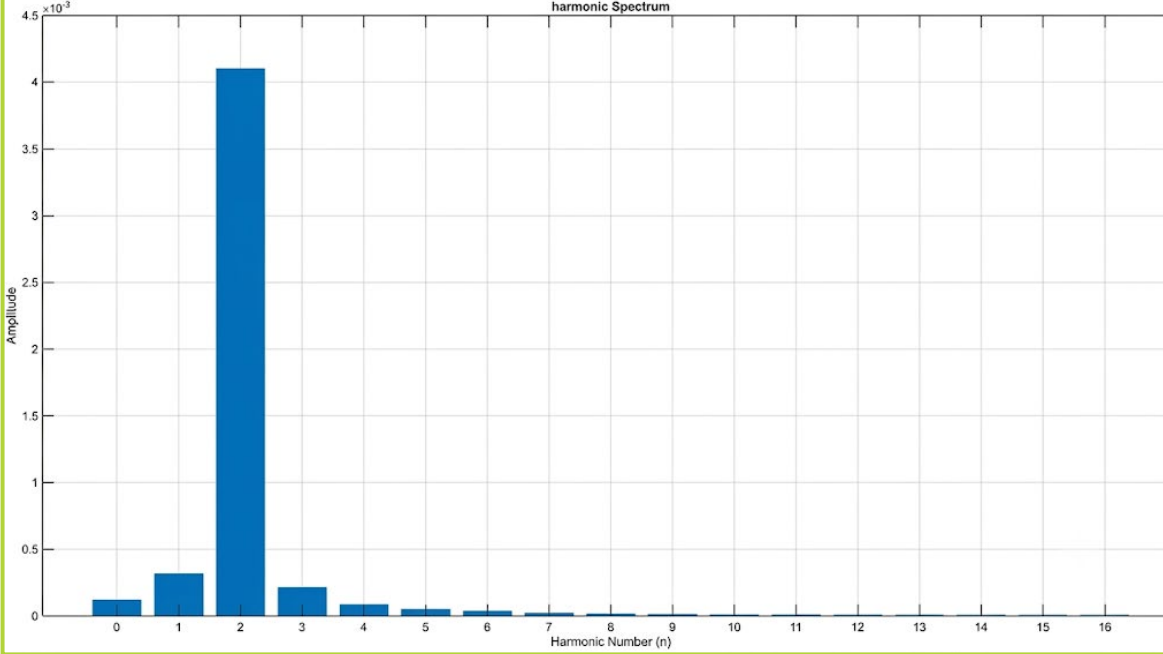


• Custom auto-alignment GUI, showing the laser beam centered and fixed in center position.



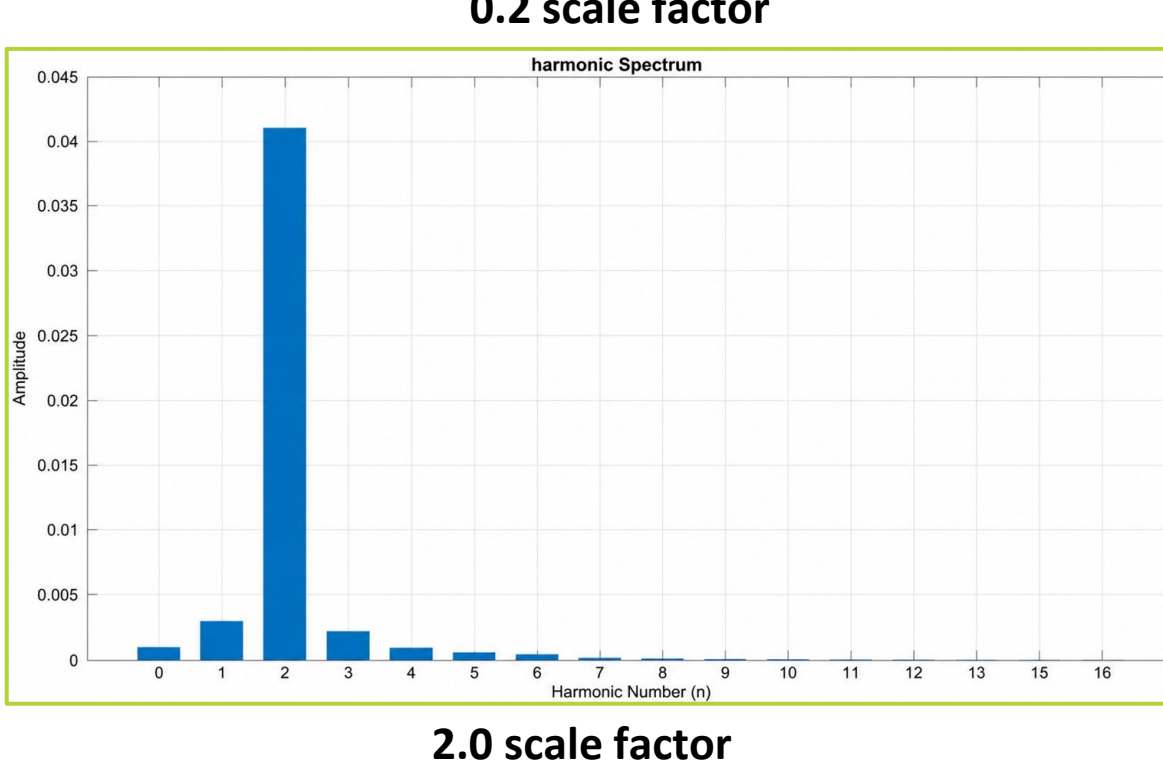
Quadrupole Magnet #1

• **Current Scaling:** Simulated quadrupole performance by scaling the nominal operating current from 0.2 to 2.0 scale factor.
• Angular field distributions successfully exhibited the characteristic two-cycle spatial waveform expected of a quadrupole magnet.



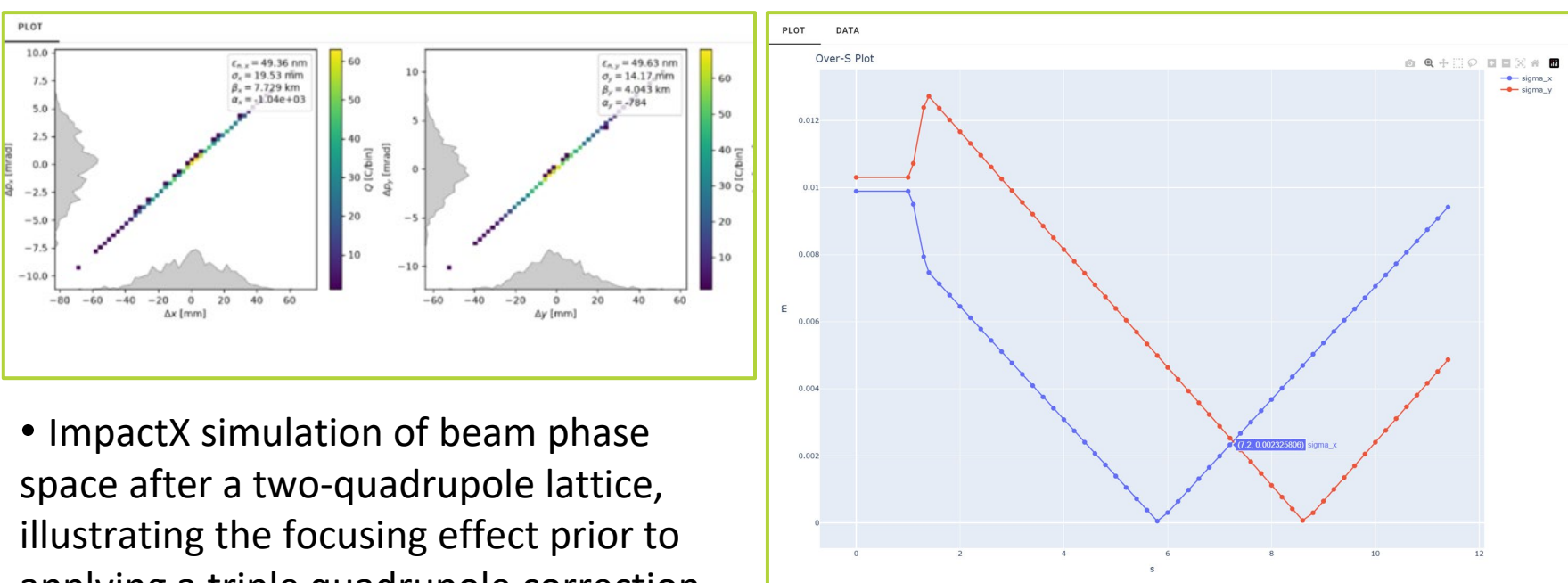
Quadrupole Magnet #2

• Harmonic spectrum of the magnet at a current-density scale factor of 0.2. The second harmonic is dominant, with an amplitude of approximately 4.1×10^{-3} while all other harmonic components are substantially smaller.



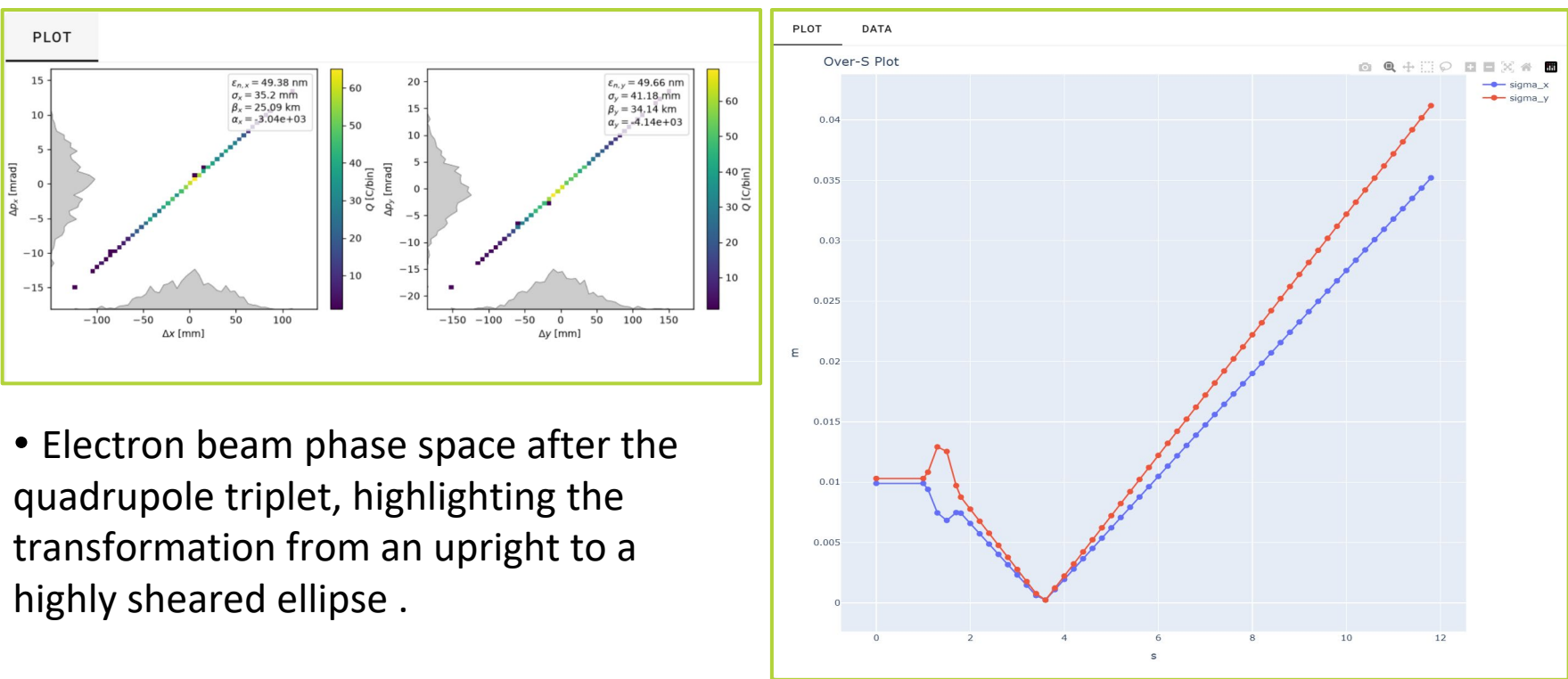
• Compared with the 0.2 scale-factor case, the dominant second-harmonic amplitude increases from approximately 4.1×10^{-3} to 4.1×10^{-2} , a tenfold increase. The overall relative harmonic distribution remains essentially unchanged, indicating approximately linear scaling with current density.

Quadrupoles act as the primary optical lenses for the electron beam. By utilizing alternating focus-defocus configurations, we can strategically manipulate transverse beam dynamics, correct for inherent astigmatism, and ultimately squeeze the beam down to a highly concentrated focal point.



• ImpactX simulation of beam phase space after a two-quadrupole lattice, illustrating the focusing effect prior to applying a triple quadrupole correction.

• Focusing of a quadrupole doublet, demonstrating the offset focal points for the horizontal and vertical beam planes



• Electron beam phase space after the quadrupole triplet, highlighting the transformation from an upright to a highly sheared ellipse.

• Transverse beam size profile after a quadrupole triplet, illustrating simultaneous focusing of both the horizontal and vertical planes.

Conclusion

This research advanced three interconnected areas of accelerator science: quadrupole magnet design and operation, particle acceleration and phase-space characterization for ultrafast electron diffraction, and automated alignment for precision accelerator experiments. The results demonstrate the combined importance of magnetic-field control, beam-dynamics analysis, and high-accuracy component alignment work in coordination across Brookhaven National Laboratory to support reliable accelerator operation and experimental performance.

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