



Integrated Accelerator Research at BNL:



Automatic Laser Alignment, Quadrupole Magnet Design, and UED Beam Dynamics

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Abstract

This poster summarizes three connected accelerator research projects completed at Brookhaven National Laboratory. The first project developed a camera-based automated laser-alignment system using Basler cameras, Python/OpenCV, and a Newport 8742 controller. The system detected the laser and iris centers, calculated alignment errors, and automatically corrected beam drift. A custom user interface displayed live camera images, beam position, alignment status, and manual motor controls. A separate fiber-optics experiment also demonstrated the importance of precise beam coupling and alignment.

The second project focused on quadrupole magnet design and magnetic-field analysis using SIMULIA Opera. A three-dimensional quadrupole model was created using iron poles, a magnetic yoke, and racetrack coils. Finite element analysis was used to study magnetic flux density, field distribution, field vectors, and beam-focusing behavior. MATLAB and Microsoft Excel were also used to examine angular field variations and magnetic-field harmonics.

The third project investigated Ultrafast Electron Diffraction beam dynamics using ImpactX in Anaconda. Simulations were performed with drift sections, solenoids, single quadrupoles, doublets, triplets, and RF elements. Beam size, emittance, phase-space evolution, bunch compression, and space-charge effects were studied. Together, these projects connected optical alignment, magnet design, and particle-beam control while providing practical experience in automation, programming, electromagnetic simulation, numerical analysis, and accelerator physics.

Project 1 Automatic Laser Alignment

Cameras + Coding + UI + Pico motor feedback

Project 2 Quadrupole Magnet Design

Opera 3D field modeling and harmonics

Project 3 UED Beam Dynamics

ImpactX lattices: drift, solenoid, quadrupoles, RF

One research workflow: align the laser → design focusing magnets → simulate beam transport.

Methodology

AI-Assisted Laser Alignment

Two Basler cameras, Python/OpenCV, and a Newport 8742 controller were used to automatically detect and correct laser misalignment through a custom live interface.

A separate fiber-optics experiment showed why precise beam coupling is important for automatic alignment.

Quadrupole Magnet Design

The quadrupole magnet geometry was created in SIMULIA Opera using four pole pieces, racetrack coils, and an iron yoke. Material properties, coil currents, and mesh settings were assigned before running the finite element simulation. MATLAB was then used to organize and visualize the magnetic-field data.

UED Beam-Dynamics Simulation

Anaconda launched ImpactX to simulate a Gaussian electron beam through drifts, solenoids, quadrupoles, and RF elements. Beam size, emittance, energy, and bunch compression were analyzed.

Results & Analysis

1. Laser Alignment

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

Laser and iris centers were detected from the camera images, while motor feedback reduced the beam-position error and guided the laser toward the iris center. Coarse, fine, and micro step control improved stability near the target and helped prevent overshoot.

2. Quadrupole Magnet

The quadrupole design focused the beam in one plane while defocusing the other, with completed work optimizing the pole profile, mesh quality, current density, field harmonics and here Magnetic Flux Density is 100%.

3. UED Simulation

Drift sections increased beam size, while solenoids focused both transverse planes. Quadrupoles controlled horizontal and vertical focusing, and RF phase affected beam energy and bunch compression. Space charge caused additional beam expansion.

Key physics connections

To measure how far the beam is from the correct position, we use 1. Position Error Formula
Error=X beam-X center and Error=Y beam-Y center 2.Total Distance Error (Euclidean Error)

$$\text{Total Error} = \sqrt{(X_{\text{beam}} - X_{\text{center}})^2 + (Y_{\text{beam}} - Y_{\text{center}})^2}$$

$$\text{Magnetic focusing: } k_s = \frac{B_z}{B_p}$$
$$\text{Magnetic focusing } B\rho = \frac{p}{q}$$

$$\text{Solenoid: } k_s = \frac{B_z}{B_p}$$

$$\text{Quadrupole: } k_q = (1/B_p)(dB_z/d_x)$$

$B\rho$: Magnetic rigidity
 p : Momentum
 q : Charge
 k_s : Solenoid strength
 B : Solenoid field
 k_q : Quadrupole strength
 $\frac{dB_z}{dx}$: Field gradient
 B_z : Vertical field
 x : Horizontal position
 f : Focal length
 L : Magnet length

1. Beam Quality

$$\sigma_x^2 = \epsilon_x \beta_x$$
$$\epsilon_n = \beta_{\text{rel}} \gamma_{\text{rel}} \epsilon$$

Low $\epsilon \rightarrow$ smaller spot

3. RF Bunching

$$\Delta K = V m_e c^2 \cos \phi$$

Negative $\phi \rightarrow$ chirp $\rightarrow$ compression

2. Magnetic Focusing

$$k_s = \frac{B_z}{B_p} \quad \frac{1}{f} = \frac{1}{4} k_s^2 L$$
$$k_q = \frac{1}{B_p} \frac{dB_z}{dx} \quad \frac{1}{f} = k_q L$$

4. Space Charge

e^- repulsion $\rightarrow$ beam expansion
Strongest at low energy, high density

Conclusions & future Work

The three projects showed that accelerator performance depends on accurate laser alignment, magnetic focusing, and electron-beam control. Camera feedback improved alignment, quadrupole modeling demonstrated beam focusing, and ImpactX simulated drift, solenoid and quadrupole focusing, RF acceleration, and bunch compression.

Future work will improve laser detection and motor calibration, optimize quadrupole geometry and field harmonics, and expand ImpactX simulations with stronger space-charge effects and experimental comparisons.

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