Magnetic Spectrometry of Electron Beams for Ultrafast Electron Diffraction Applications

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Abstract

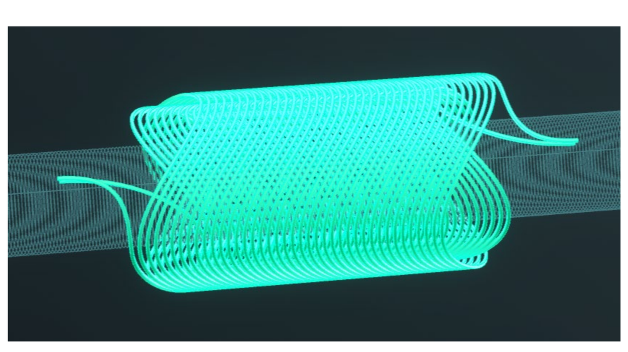
Electron beams (e-beam) are used for a variety of applications including particle accelerators, microscopes, as well as medical treatments. These e-beams must be precisely tuned to match the energy levels required for these applications. This study leveraged the deflection of electron beams within a magnetic field to measure the energy spread of these electron beams, called a spectrometer. To model how the spectrometer will behave, General Particle Tracer (GPT) was utilized to simulate electron beams and their deflections in various magnetic fields. The deflected beams were struck onto a scintillator which illuminates and is captured by a CCD camera. The camera captured the footprint of the electron bunch, which will look like a small point or a vertical or horizontal smear depending on the energy bandwidth. E-beams are steered, focused, and corrected using magnets. These magnets were modeled using software packages such as Simulia OPERA and Rat-GUI to ensure proper magnetic field properties for the purpose of such measurements. The designed magnet was built in a Canted-Cosine Theta (CCT) configuration and featured superconducting wire windings for minimal losses and to support higher currents of a few hundred amperes. One major component of the UED is the laser source necessary for the means of which electrons are produced in the photoinjector, where a 266nm laser pulse strikes the photocathode, causing electrons to be emitted. Lasers are at the forefront of future particle accelerators, for example, the Laser Wake Field Acceleration (LWFA) and Particle Acceleration by Stimulated Emission of Radiation (PASER) methods. This project directly challenges student's knowledge, and provides a systematic gateway for the transition from an academic environment to a scientific workplace.

Introduction

The objective of this project was to prepare for the next generation particle accelerators. Unlike conventional particle accelerators that use RF, electric, or magnetic fields, the next generation particle accelerators use lasers to generate a laser wake field in its path, known as Laser Wake Field Acceleration (**LWFA**). This method of acceleration leads to higher acceleration gradients, reducing the overall size of particle accelerators.
This project focused on 3 different areas related for the next generation particle accelerators **Superconducting Magnets, Electron Beam, LASERs and Optics**

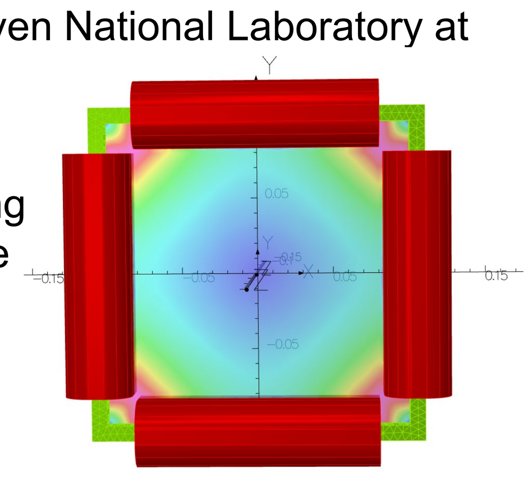
Superconducting Magnets

Using Simulia OPERA and Rat-GUI, various dipole and quadrupole magnets were simulated using parameters related to particle accelerators. A quadrupole magnet was designed and built using the Direct winding machine at Brookhaven National Laboratory at the Superconducting Magnet Division (SMD).



Dual Layer Quadrupole Canted Cosine-Theta (CCT) Magnet Design in Rat-GUI

Magnetic simulations in Simulia OPERA were ran using practical conditions to observe the affects of materials and current densities on magnetic field quality, shown in the model on the right.

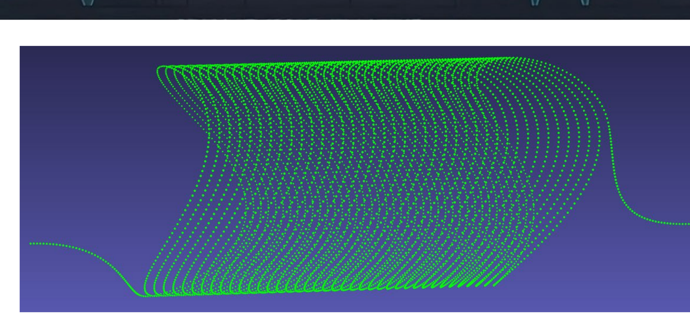


Quadrupole Window-Frame Magnet simulated in Simulia OPERA

Rat-GUI simulations were ran to model a two layer Canted Cosine-Theta (CCT) superconducting quadrupole magnet to be mounted on two aluminum tubes. Figure 2 shows the final design of the CCT magnet in Rat-GUI, which utilizes 1.6mm diameter Niobium-Titanium (Nb:Ti) superconducting wire.

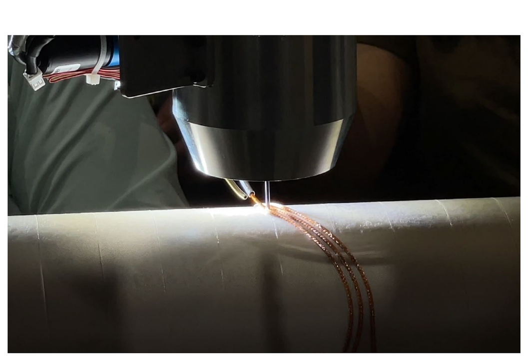
Harmonic Calculations of the CCT Magnet on Rat-GUI

To ensure that the modeled magnets was pure quadrupole, harmonics calculations were performed within the Rat-GUI software, which yielded a high accuracy quadrupole field with subordinate higher order harmonics.

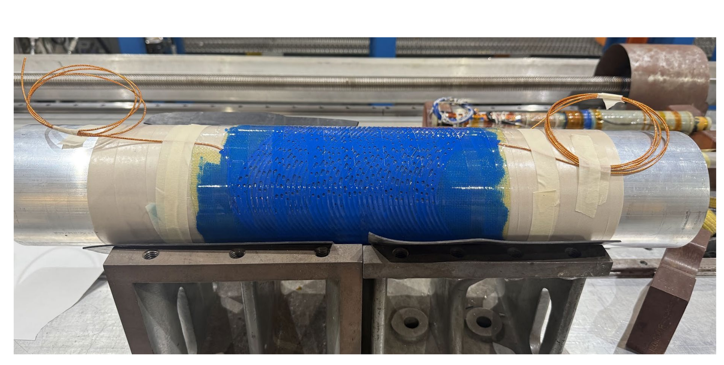


Point Cloud Conversion of the CCT Magnet

The direct winding machine at the Superconducting Magnet Division (SMD) uses discrete 3D point cloud data, which was converted from Rat-GUI using MATLAB, as shown in the model.



Direct Winding Machine During Operation



CCT Magnet After Stycast Epoxy Application

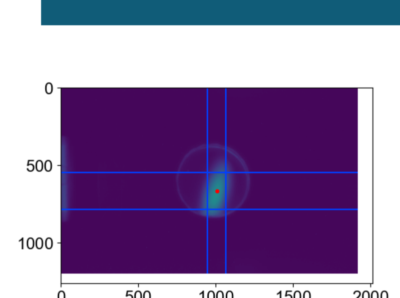
Finalized CCT Prototype Magnet

3D Model of CCT Endcaps

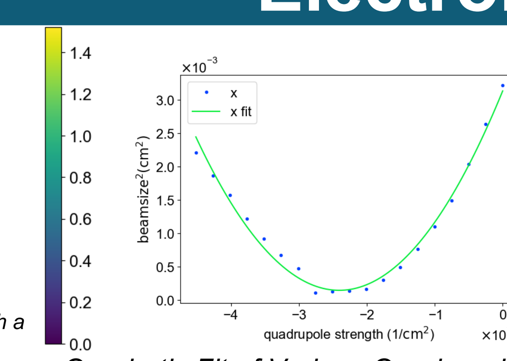
The direct winding machine at BNL, where superconducting wire is ultrasonically placed onto a fiberglass/resin substrate. This method yields high accuracy coil dominated magnets with little harmonics. To prevent the superconducting coils from unwinding during testing and operation, additional fiberglass and STYCAST epoxy was applied to the magnet.

Prototype endcaps were engineered and fabricated to fixate the two aluminum tubes with the windings using Autodesk Fusion, and a 3D printer.

Electron Beam



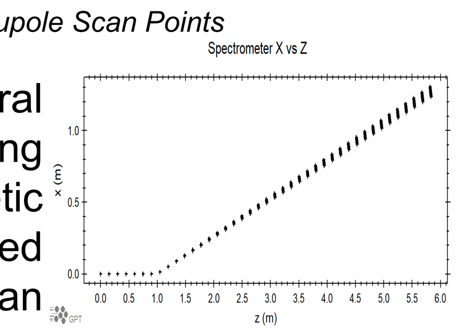
Electron Beam Cross Section with a Gaussian Fit



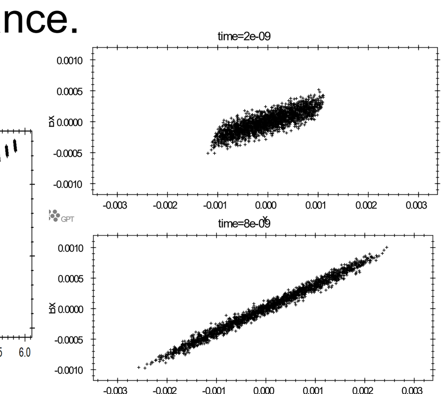
Quadratic Fit of Various Quadrupole Scan Points

A quadrupole magnet was used for beam diagnostics in the beamline. Emittance was measured by scanning the quadrupole strengths, focusing the beam, and fitting a gaussian distribution to extract the emittance.

Using General Particle Tracer, several simulations were performed, including emittance calculations and a magnetic spectrometer. This spectrometer was modeled and designed to measure energy spread of an electron beam as shown on the plot here.

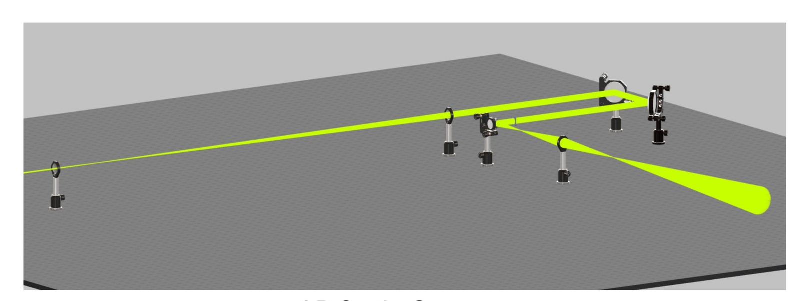


Magnetic Spectrometer



GPT Phase Space Simulation

Optics and Lasers

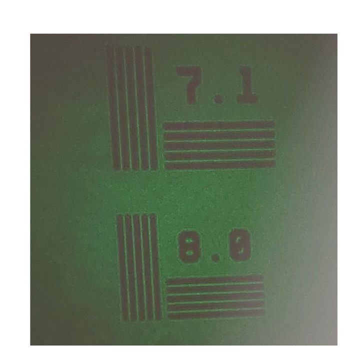


3DOptix Setup

In order to support the future accelerators, the Lasers & Optics module focused on designing high power laser systems in 3DOptix and building them according to the design made within the software.

Optical Exercise Setup

To better understand optics, exercises involving aligning lasers were performed. One of the exercises included utilizing a parabolic mirror to focus a visible laser beam and imaging a set of microscopic lines. The optical setup partially displayed is used to collimate the beam. The actual projected image is shown on the left, resulted in about 37.5x magnification with adequate separation between lines, showing that the setup has good resolution



Laser Imaging Projection

Conclusion

In favor of the advancement of the future particle accelerators, it is important to understand the principles and technologies involved. Applications of electron beams are vast, and utilizing various beam qualities and properties enables beam focusing, emittance measurements, as well as measuring energy spread using electromagnet spectrometers. The measurements incorporated magnets and solenoids highlighting the importance of understanding and experimenting with magnets. Lasers are at the heart of the future accelerators, as they are responsible for providing the wake field used for LWFA. Interdisciplinary knowledge in all these different aspects are crucial for the operation, maintenance, and the development of these accelerators. Future work involves using the designed in the measurement of the energy of the e-beams in the Ultrafast Electron Diffraction (UED) facility at Brookhaven National Laboratory.

Acknowledgements

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