Pulsed-Wire Method for an Undulator Magnet

Summer 2013 Internship Report

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We want to test and calibrate an undulator; a periodic structure of alternating polarity dipole magnets. As an electron bunch from a linear accelerator travels through the undulator magnetic field it periodically changes directions due to the Lorentz force. This traverse acceleration results in electromagnetic radiation being produced and if this light is guided and interacts correctly with the electron beam it will culminate in an operational free-electron laser. The pulsed-wire system will be used to measure and rectify magnetic fields in the undulator. The quality of the magnetic field must be high and so the fields must be measured and tuned correctly. By use of the pulsed-wire system we can readily measure the important first and second field integrals and corrections can be made accordingly using magnetic shims.

This semester the mechanical system that holds the wire will be built and the undulator will be tested and attuned. This will consist of optical setup processed through computer software, wire positioning, weight/pulley/damper system, known reference magnet alignment, and pulse circuit connection with oscilloscope.

The wire must be precisely positioned inside the undulator so that exact measurements can be achieved. During pulse vibration the wire must not touch any part of the undulator. The wire must also not experience any outside vibrations from the physical setup.

Abstract

Construction has begun on a state-of-the-art accelerator facility at Colorado State University's (CSU's) foothills campus and should be completed by the fall of 2013. Due to the magnitude of the venture and the research to be performed there, collaboration with scientists and engineers from all over the world has been required. The primary focus of this project is to design and implement a pulsed-wire system for an undulator magnet. Thankfully, CSU has expertise in the safety and operation of particle accelerators, as one is operational for oncology and related research at the School of Veterinary Medicine.

The pulsed-wire system will be used to measure magnetic fields in the undulator, a periodic structure of alternating polarity dipole magnets. As the electron bunch, from the linear accelerator, travels through the undulator magnetic field it periodically changes directions due to the Lorentz force. This traverse acceleration results in electromagnetic radiation being produced and if this light is guided and interacts correctly with the electron beam could culminate in an operational free-electron laser. But the quality of the magnetic field must be high and so the fields must be measured and tuned correctly. By use of the pulsed-wire system one can readily measure the important first and second field integrals and corrections can be made accordingly using magnetic shims.

Introduction

In 2009, The Department of Energy's Office of High Energy Physics commissioned a report, Accelerators for America's Future, compiled by professionals from major areas of accelerator technology. The six areas focused on were Energy and the Environment, Security and Defense, Discovery Science, Accelerator Science and Education, Medicine, and Industry. The most important findings were to create more compact, efficient, and lower cost accelerators. Colorado State University is committed to creating an accelerator laboratory for research and training in accelerator technology. The facility will initially focus on generating long-wavelength free-electron lasers (FEL), electron beam components, and peripherals for FELs and other light sources. The goals of the laboratory are to perform world-class research in beam physics, attract excellent researchers, collaborators, and users to CSU, and to train the next generation of scientists, engineers, and technologists. This is a multimillion dollar endeavor and everything must be built from the ground level as there is no existing accelerator vault at CSU for this new device. The result is an ever-changing task list and schedule, driven by the arrival of components. Coursework in accelerating engineering and beam instrumentation have been important, as well as understanding the function and normal operation of accelerator components has been very helpful in this project. These ideas and teachings are now being applied to a real world challenge – building up an accelerator facility.

The performance of FELs depends on the integrity of the magnetic field in the undulator. A pulsed-wire system can give accurate measurements on the first and second field integrals. The magnetic field on the axis of the undulator is transverse and sinusoidally varying due to the periodic sequence of dipoles. The ideal trajectory of a relativistic electron bunch, inserted along the axis, is sinusoidal in the plane of oscillation. Phase errors are produced when the path of the electron is not the ideal sinusoid trajectory. The result of the phase error is a reduction of laser gain, which reduces performance. Therefore, it is crucial to characterize the magnetic field of the undulator.

Issues with pulsed-wire measurements in the past include dispersion, sag and impurities in the wire. By taking into account the dispersion, distortions in the field measurements will be greatly reduced and more precise measurements can be achieved. Tactics that have been utilized previously include; increasing the tension in the wire and making the wire's radius larger. Once the field profile is determined, the undulator will then be tuned such that the electron bunch is on the correct trajectory. The device can then be used for creating light in the accelerator system.

In the pulsed wire method, a copper beryllium wire is held at constant tension between two points. A fraction of the wire is positioned within an external reference magnet, with known field properties. A current pulse is then applied to the wire. Due to the Lorentz force

$$\vec{\mathbf{F}} = \mathbf{q}[\vec{\mathbf{E}} + (\vec{\mathbf{v}}\,\mathbf{x}\,\vec{\mathbf{B}})]$$

displacement in the wire (proportional to the magnetic field and current amplitude) is induced. The wire motion then propagates with characteristics of a traveling wave, simulating an electron bunch. Depending on the length of the pulse, the first or

magnetic field integrals can be determined. The displacement is then measured by the optical detector, mounted at a specific location, which includes a photodiode, laser and a thin slit.The undulator for the experiment is a hybrid type of NdFeB magnets. The undulator has a period of 25mm, with 50 periods; the total length is 1.25m.

Once the apparatus has been build and aligned properly, a pulse from a function generator is discharged through the wire with the desired length and amplitude. The force exerted on the wire becomes a wave traveling in both directions along the length of the wire. The vibration in the wire is detected by the optical detector. The detector is positioned at one end of the wire beyond the bounds of the undulator to measure the profile of the acoustic wave. In order to measure wire displacements in micrometer range, the photodiode must be extremely sensitive.

Data taken from the detector determines the field integrals. Short pulse (~µs) excitation is used,

simulating a delta-function, to generate a signal that is proportional to the first integral of the

magnetic field. A longer pulse (~ms), step-function, is discharged through the wire to generate

a signal that is proportional to the second field integral. By numerically differentiating the integrals, one can determine the velocity of electrons, 1st, or the trajectory profile of electrons traveling through the undulator, 2nd integral. Once the fields in the undulator are tuned, it may be available for use in the linac system for FEL creation.

A common technique used to characterize permanent magnets is by use of a Hall probe and Gauss meter. This method has proven very reliable, but it cannot be used to measure the the CSU undulator magnets due to a large stabilizing frame surrounding it and the spacers between the jaws. A new method needed to be developed to get the magnetic field profile. Research into past undulator measurement methods is beneficial. One method of particular interest to us is the one used at Lawrence Berkeley National Laboratory (LBNL) by Diego Arbelaez. Here is developed a very sensitive and accurate undulator measurement system based on the pulsed-wire technique. Our project involves the construction and implementation of a similar pulsed-wire system, and collaboration with Diego has resulted in a strong initial design. The undulator being analyzed is different than the one at LBL, so the measurement system of and the results are specific to CSU's magnet. An aspect making this project unique is that it will take into account dispersion of the resulting frequency components within the wire thereby making the measurement much more accurate. The undulator will eventually be a key part of the accelerator system in creating light. The goal is to get smooth magnetic field transitions between the dipoles throughout the undulator.

Pulse Circuit

The completed physical circuit was applied to a two meter long section of CuBe wire (similar to what will be needed for the final design) and was measured on an oscilloscope. It was necessary to achieve a parallel output using the wire in place of the resistor with the same applied pulse. The final circuit was implemented on a solderable board and mounted in a secure aluminum housing. Three female banana clips were applied to the outer side of the box for easy connection to the power supply. Two female SMA ports were then mounted directly below the three banana clips; these are used for an input from the BG535 pulser for an output to the oscilloscope. On the back side of the housing, two more female banana clips were placed for easy connection of the CuBe wire. One challenge was attempting to connect the 50μm wire to the circuit. The fragility of the wire made it very difficult to solder or place connectors on it. The solution was to use a connection block, shown right, to secure the wire. This was then mounted on the spool holding the CuBe wire and was able to connect to an insulated wire without fear of breakage. Two male banana clips were then soldered on the other end of insulated wires.

Summer Work

For my summer internship I continued work on the project for Pulsed-Wire Method for an Undulator Magnet with Alex. We worked together to complete the casing and testing of the pulser circuit. We started by testing the pulser box we created in the previous semester. Our test circuit was functional; however, we found that the pulser box we created was defective.

In order to fix the pulser box we started by comparing the tester circuit with the pulser circuit itself. There seemed to be no errors found when comparing elements of the circuits. We then started to test the connections of the pulser. After setting up the pulser circuit with the oscilloscope, power source and the

BG535 we found that we were not getting the desired results on the oscilloscope.

After consulting with John Harris he suggested that we resolder the entire pulser circuit. He provided us with helpful documents on how to solder properly. Alex and I spent the next few days effectively resoldering the entire circuit. The noticeable difference between the two soldered circuits showed in the connections of the elements of the circuit to the board. After setting up the pulser to the complete system we were still not getting the necessary results. We then removed the circuit from the box and used direct connections instead to set up the system. Connecting the circuit directly to the system without the use of the pulser box provided the results we were looking for. The oscilloscope confirmed that our circuit was functional. These outcomes confirmed that the pulser box was not functioning because of internal connections.

To test the internal connections of the pulser box we used a voltammeter. The voltammeter was used to test the continuity of the circuit. The continuity of the circuit tested satisfactory; however, our circuit was still not working.

Lastly, we checked the connections on the box to the power source, BG535, and the oscilloscope. The connections of the oscilloscope on the box looked like they required grounding. In order to ground the connections we had to drill more holes into the pulser box. Grounding the connections of the box solved the problem of why it was not operational. With an operational pulser box we can now move forward with the next phase of the project.

Safety issues

This experiment uses large capacitors to create currents over an amp, which is a major safety issue. The pulsed wire circuit must always be supervised and only knowledgeable personnel may operate the equipment.

The other major safety issue associated with this project is the high levels of current that are present in our circuit. By first building a test circuit, we are able to make mistakes and optimize without fear of major setbacks.

We made sure that we were the only people around the circuit when it was hooked up to the power supply. There was some damage to capacitors and resistors at this stage in the design. There was even an arcing occurrence at one point. Stephen was also supervising when the major capacitors were installed.

The safety of and other people in the lab has been a top priority for us while working on this project. We also allow for ample time to let the capacitors discharge before removing or replacing them. This is the first time we have been around high voltages and currents so many precautions have been taken.

Project Phases

Phase 1- Build complete setup without the undulator; Complete by Sept 30(All Members)

Build setup completely without the undulator. This allows for testing of the system using a known magnetic field. It will consist of optical setup processed through computer software, wire positioning, weight/pulley/damper system, known reference magnet alignment, and pulse circuit connection with oscilloscope.

Phase 2-Test Setup-Complete by Oct 11(All Members)

Make sure all components of the system are ideal. Test for vibrations in all components including stands, table, screws, air, anything that may disrupt procedures.

Phase 3- Build setup with undulator- Complete by Nov 1(All Members)

Place wire within the undulator being careful not to have any defects along the entire wire. The wire must be precisely positioned inside the undulator so that exact measurements can be achieved. During pulse vibration the wire must not touch any part of the undulator. The positioning will be done with two sets of XY translation stages. The pulley and weight will be keep required tension on the wire. The damper will remove vibrations in between pulses.

A reference magnet with known magnetic properties will be placed outside of the undulator along the wire. This will be used to determine where the pulse is at a given time or place in the undulator.

The completed pulse circuit will be connected to this apparatus to provide the needed signal through the wire. The pulse lengths can change dynamicly using the DG535 to get first or second field integrals. What pulse is being produced by the circuit can be measured using the connected oscilloscope.

Phase 4- Test and Calibrate undulator- Complete by Nov 22(All Members)

The data measured will be processed and analyzed through the Labview software. Any problems associated with the magnets can then be seen and corrected. The corrections will be done using magnetic shims that will damper the fields of specific dipoles. The magnetic fields between each dipole pair must be adjusted to desired specifications.

Phase 5- Complete Findings- Complete by end of Semester(All Members)

Review entire setup and data findings. Report on findings, achievements, problems, and other relevant data.

Timeline

Sept 30- Build complete setup without the undulator (All Members)

Oct 11-Test Setup (All Members)

Nov 1- Build setup with undulator (All Members)

Nov 22- Test and Calibrate undulator (All Members)

Dec 9- Complete Findings (All Members)