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Delta undulator model: Magnetic field and beam test results

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ABSTRACT

A novel type of in-vacuum Elliptical Polarization Undulator (EPU) magnet optimized for linac beam (Delta undulator) was developed at the Laboratory for Elementary-Particle Physics (LEPP) at Cornell University as part of insertion device development for the future Cornell 5 GeV Energy Recovery Source of coherent hard X-rays [1,7]. To evaluate mechanical, vacuum and magnetic properties of the magnet, a short 30 cm model with a 5 mm diameter round gap and a 2.4 cm period was built and tested in LEPP. The beam test of the Delta undulator model was conducted at Accelerator Test Facility (ATF) in BNL with $\sim$60 MeV linac beam. The beam testing results confirmed basic properties of the undulator magnet obtained through the magnetic field measurement. In the paper we describe the magnet design, techniques and setups used for the magnetic field measurement and the beam testing results.

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1. Introduction

The Delta undulator consists of four magnet arrays symmetrically arranged around the beam axis as shown on the computer generated view shown in Fig. 1.

These arrays formed with "Delta" shaped permanent magnet blocks are mounted on miniature rails inside of a strong box-like frame. The rails allow independent displacement of each magnet array along the beam axis. This displacement is used to control magnetic field strength and radiation polarization. The undulator has a round gap which naturally matches to a linac type beam. Four slits between the magnet arrays provide residual gas escape from the on-axis region. Compared to conventional undulators, the Delta undulator is more compact, has stronger magnetic field, and because of its high symmetry, is easy to tune.

To verify the basic principles of the design, a 30 cm model was built. We used NdFeB permanent magnet material of 40 SH grade. After magnetic field mapping the model was enclosed in a vacuum vessel, vacuum-baked, pumped down and transferred to BNL for beam testing. The beam test results confirmed properties of the magnetic field obtained in characterization.

Details of the model design and construction can be found in Refs. [1,2]. The present report describes the procedure and results of the magnetic field measurement and beam testing.

Original work for insertion devices with variable polarization, tilted magnetization configuration and recent similar project are described in Refs. [3–5].

2. Magnetic field characterization

Prior to model final assembly, the field of each of magnet arrays was tuned to the level corresponding to an optical phase errors of 2° or less. The field was measured with Hall probe; local field strength was adjusted by small vertical displacement of the magnet blocks. For the field mapping of the assembled model a special setup was developed. A miniature Hall sensor, HGT-2101, was attached to the tip of a piece of thin ceramic tubing which was guided through the undulator by another tube of a larger diameter. The guiding tube was fitted tightly into the undulator bore. The sensor offset from the beam axes was less than 0.1 mm. This offset gives a 2e−4 of the normalized field errors for the field roll-off calculated in Ref. [1], which is satisfactory.

Magnetic field components measured in two helical and two planar modes are shown in Figs. 2 and 3.

In helical-left mode, Fig. 2 (left), the magnet arrays generating the vertical field are displaced by 1/4 of a period relative to the horizontal field arrays in positive "z" direction. This creates a 90° shift in phase between vertical and horizontal field components, resulting in a helical-left beam trajectory, and, subsequently, in left circular polarized X-rays. In helical-right mode, vertical magnet arrays were displaced by 1/4 of period in the opposite direction. This creates a helical-right beam trajectory and right circular polarized X-rays. An accurate fit of the field with sine waves gave an amplitude of 0.92 T for a horizontal field and 0.88 T for the vertical. The small difference ($\sim$4%) between these amplitudes is due to mechanical imperfections.

In "+45°" and "−45°" planar modes, pairs of magnet arrays are in phase and shifted relative to each other by 1/2 of a period correspondently. In the first case, the resulting magnetic field is in the plane tilted by 45° relative to horizontal, and in the second is in the plane tilted by −45°. Two orthogonal field components, B1 and B2,

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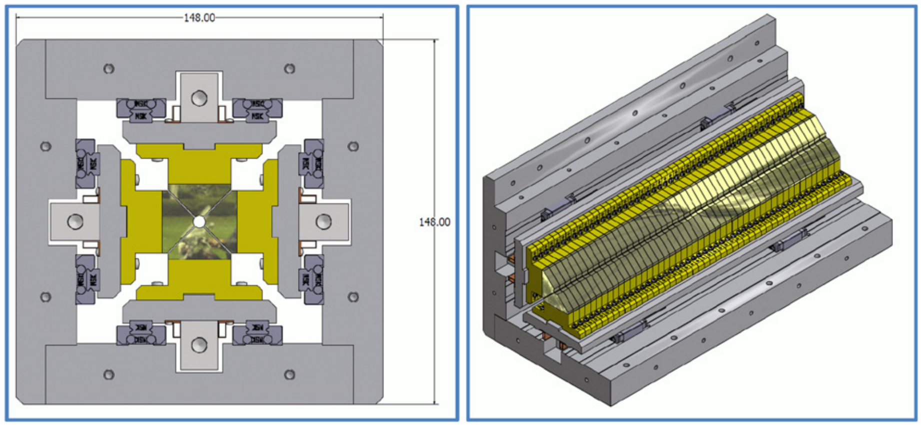

Fig. 1. Delta undulator cross-section (left) and internal view (right).

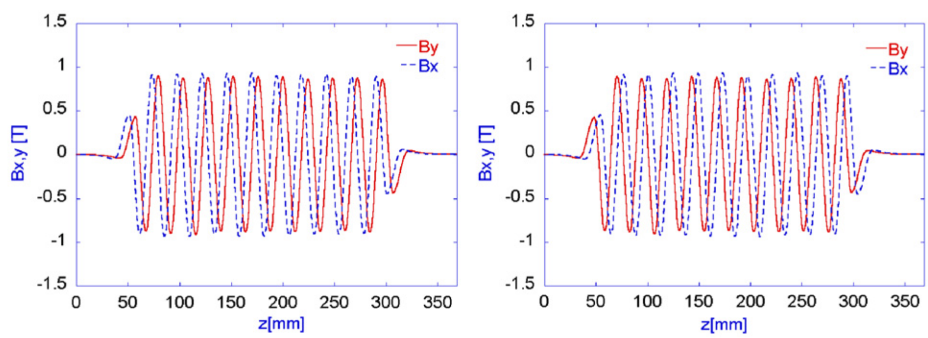

Fig. 2. Vertical (By) and horizontal (Bx) magnetic field components measured in helical-left (left plot) and helical-right (right plot) modes.

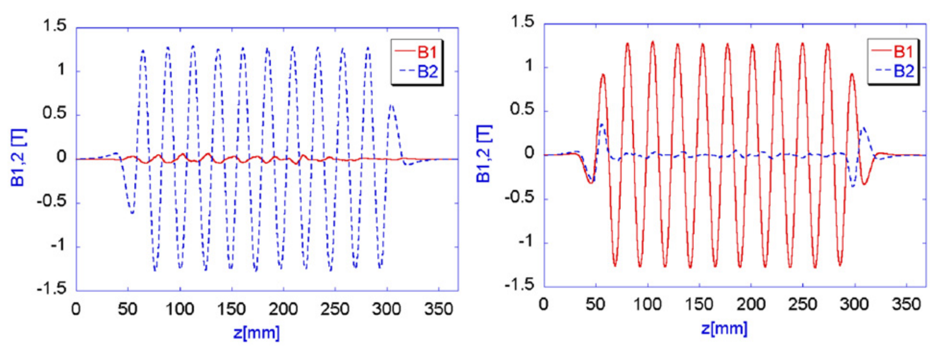

Fig. 3. Two orthogonal field components, B1 and B2, measured in planar "+45°" (left plot) and planar "−45°" (right plot) modes.

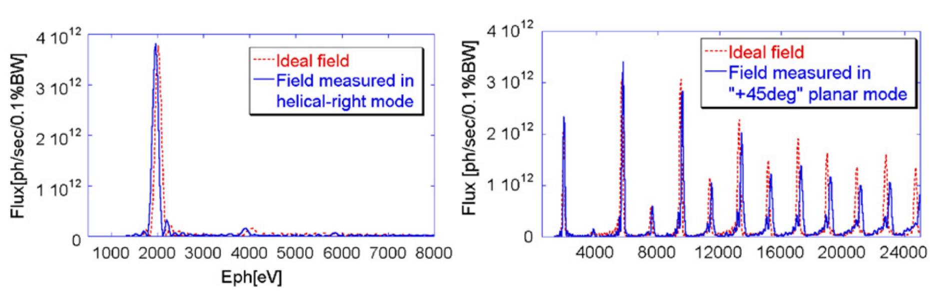

Fig. 4. Spectra of the X-ray flux through the 1 mm diameter slit, calculated for ERL electron beam and for ideal and measured magnetic fields. Left plot is for helical-left mode, right plot is for "+45°" planar mode.

measured by a Hall probe tilted by +45° and −45° in the both planar modes are shown in Fig. 3. With all magnet arrays in phase, the measured B1 component is close to "zero" and amplitude of B2 is 1.28 T, see left plot in Fig. 3. This field will generate X-rays with linear polarization in the −45° plane. With a 1/2 period shift between vertical and horizontal magnet arrays, see Fig. 3 right, B1 amplitude is

1.29 T and B2 is close to "zero". In this case, X-rays will be linear polarized in +45° plane.

To evaluate the field quality, we calculated (using program SPECTRA [6]) the spectrum of X-rays flux through a 1 mm diameter slit located on beam axis 30 m away from the source for Cornell ERL high coherence mode operation [7]. As a source magnetic field we used the fields measured in helical-left and planar "+45°" undulator modes and an ideal field. As expected, see Fig. 4, the spectrum in helical mode revealed a single peak representing a fundamental mode of radiation. In planar mode the spectrum consisted of a series of peaks corresponding to higher orders of undulator radiation. The small difference between spectra calculated for measured and ideal fields suggests satisfactory quality of the undulator field.

To estimate the effect of vacuum baking on magnetic field quality, prior to final assembly, all magnet arrays were baked for 48 h at 90 °C. The field measurements, before and after the heating, indicated a small, ~0.5%, reduction in the field amplitude. The field uniformity distortion corresponded to approximately 1° of the optical phase error.

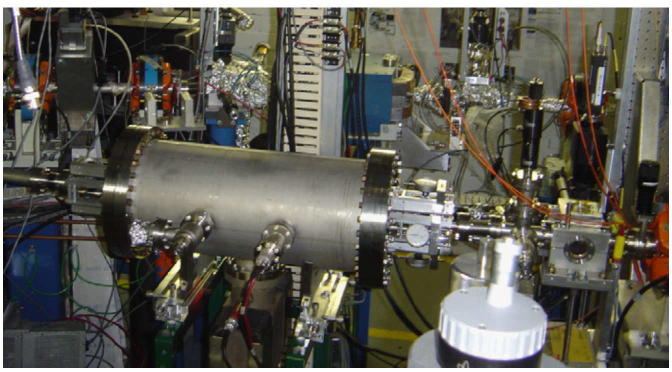

Fig. 5. Delta Undulator model in vacuum vessel installed in ATF beam line #2.

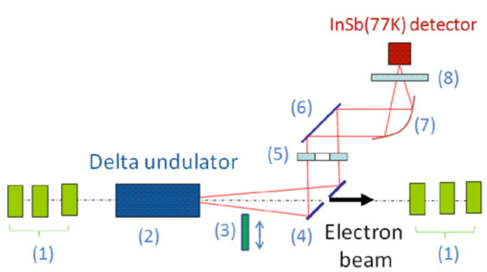

Fig. 6. Beam test setup schematic view. Here are: (1)—beam line magnetic elements; (2)—Delta undulator model; (3)—removable flag; (4)—cooper mirror with hole for electron beam passage; (5)—round collimator; (6)—flat mirror; (7)—parabolic mirror; (8)—narrowband pass filter.

3. Beam test

Beam testing of the Delta undulator model was conducted at the Accelerator Test Facility at BNL. On December 15, 2009 the model was transported from Cornell to BNL and installed in ATF beam line #2, see Fig. 5.

The following day, the vacuum pressure recovered to acceptable level and beam testing was started.

3.1. Beam testing setup

A schematic view of the setup is given in Fig. 6. Here, the electron beam of ~1 mm diameter with a 1.5 Hz repetition rate, ~0.8 nC per bunch charge and energy in the range between 50 and 70 MeV passes through the undulator. Downstream of undulator, a removable flag (3) was used to monitor electron beam size and position.

A cooper mirror (4) with a 5 mm diameter hole in the center deflected undulator radiation to the outside of the beam pipe. Outside, radiation was first collimated with variable aperture (5), and then reflected by a flat mirror (6) onto the parabolic mirror (7). The latter focused radiation onto the InSb(77 K) detector. To study spectral characteristics of the undulator radiation, we placed various NBP filters in front of the detector (8) and scanned the electron beam energy.

3.2. Beam test results

The left plot in Fig. 7 shows the experimental result of a beam energy scan with undulator in *planar* "+45°" mode and the model prediction (dashed line). In the experiment, collimator (5) was fully open, providing ~60 mm aperture. A 5300 nm optical filter with 200 nm BW was placed in front of detector. In the model calculation we used this geometry and magnetic field measured in the undulator in planar mode, see Fig. 3 (left). The sharp rise of the radiation intensity observed in the experiment and predicted by calculation at 55 MeV electron beam energy was caused by fundamental mode of undulator radiation. Good agreement between experimental data and the calculation confirmed properties of the magnetic field obtained with a Hall probe.

Results of the beam energy scan with undulator in *helical-left* mode are shown on the right part of Fig. 7. Here, the collimator aperture was reduced to 12.6 and a 4520 nm filter with 180 nm BW was placed in front of the detector. Because of the smaller collimator aperture, we were able to measure the location and width of the fundamental radiation harmonics more precisely.

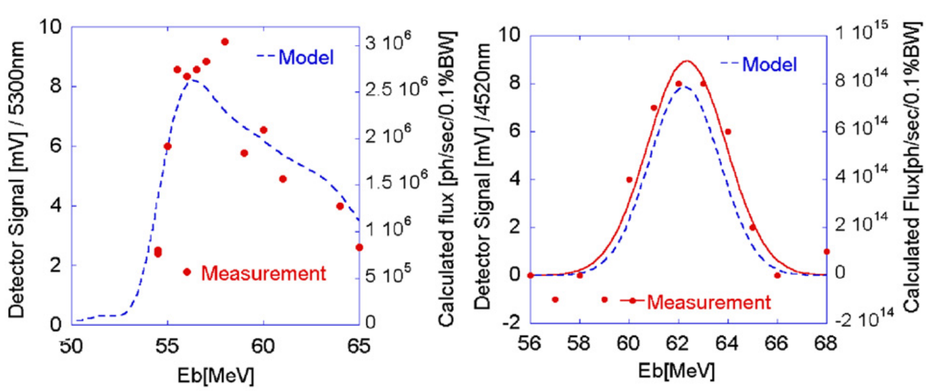

Fig. 7. 5300 nm wavelength radiation from undulator in planar mode (left plot) and 4520 nm radiation from undulator in helical mode (right plot) as function of electron beam energy. Dashed lines show the model calculation.

In the calculations, as in a previous case, we used the experimental geometry and measured magnetic field presented in Fig. 2 (left). Both data were fitted with Gaussian curve. For the measured data, the fit gave a peak location at 62.33 ± 0.15 MeV, for a calculation at 62.24 MeV. The fitted width (sigma) is 1.60 ± 0.15 MeV for experimental data and 1.43 MeV for modeled. The good agreement between observed and calculated locations and widths of the fundamental radiation harmonic again confirmed the properties of the Delta undulator magnetic field obtained with the Hall probe.

4. Conclusion

We built, characterized and beam tested a short undulator magnet model of novel type optimized for linac beams. The test results confirmed the magnetic field properties as measured with a Hall probe and proved the principles of the design. Experience and data obtained in the course of the model design, construction and testing will be used in the construction of a longer insertion device.

Acknowledgments

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