UNDULATOR-BASED LASER WAKEFIELD ACCELERATOR ELECTRON BEAM DIAGNOSTIC*

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Abstract

The design and current status of experiments to couple the Tapered Hybrid Undulator (THUNDER) to the Lawrence Berkeley National Laboratory (LBNL) laser plasma accelerator (LPA) to measure electron beam energy spread and emittance are presented.

INTRODUCTION

The design and current status of experiments to couple the Tapered Hybrid Undulator (THUNDER) [1] undulator to the Lawrence Berkeley National Laboratory (LBNL) laser plasma accelerator (LPA) are discussed. Currently the LPA has achieved quasi-monoenergetic electron beams with energies up to 1 GeV [2]. In principle, these ultrashort, high-peak-current, electron beams are ideal for driving a compact XUV free electron laser (FEL) [3], [4]. Understanding the electron beam properties such as the energy spread and emittance is critical for achieving high quality light sources with high brightness. By using an insertion device such as an undulator and observing changes in the spontaneous emission spectrum, the electron beam energy spread and emittance can be measured with high precision [5]. A high resolution XUV spectrometer allowing for better than 0.1% (rms) energy spread measurements has been built and characterized at the Advanced Light Source(ALS) [6] and is currently being installed on the LOASIS beam line. A pair of quadrupole magnets with three axis independent alignment have been installed on the beam line in order to collimate the electron beam and insert it into the undulator [7]. The initial experiments will use spontaneous emission from 1.5 m of undulator. Later experiments will use up to 5 m of undulator with a goal of the demonstration of a high gain, LPA driven extreme ultraviolet (XUV) FEL.

ELECTRON BEAM ENERGY SPREAD AND EMITTANCE

The wavelength of the optical radiation emitted by a relativistic electron beam on-axis in a linearly polarized undulator is

$$\lambda = \frac{\lambda_u}{2\gamma^2 N_h}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) \quad (1)$$

where λ_u is the magnetic undulator period, γ is the electron beam energy in units of mc^2, θ is the observation angle, N_h is the undulator harmonic number, and K is the dimensionless wiggler parameter. For the THUNDER undulator at minimum gap, K=1.25. One can see from Eqn. (1) that the wavelength spread of the optical spectra is directly related to the electron beam energy spread. The optical spectra of the undulator radiation have been modeled numerically using the synchrotron radiation code SPECTRA [8] showing that the optical harmonic width of the spontaneous emission can be used to measure the electron beam energy spread, while the beam emittance can be measured by the on-axis flux ratio of the even optical harmonics to the odd optical harmonics (being ideally zero for a zero emittance electron beam). The dependence of the line width on beam energy spread is shown in Fig. 1.

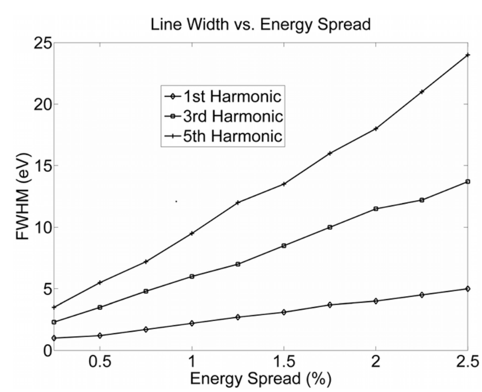

Figure 1: Wavelength spread of the optical spectra versus relative rms electron beam energy spread for the first three odd harmonics. The simulations were carried out using 500 MeV electrons with 100 pC of charge, a normalized transverse emittance of 1.0 mm-mrad and a wiggler parameter of 1.85.

THUNDER UNDULATOR

The THUNDER undulator is a rare earth permanent magnet undulator, comprised of 10 sections of 0.5 m each, containing magnets made of SmCo5 and vanadium permendur poles. The undulator sections have been magnetically tuned and characterized at LBNL using a Fanamation Coordinate Measuring Machine (CMM). The probe

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on the CMM has been fitted with a magnetic Hall probe, so that mechanical as well as magnetic measurements can be automated with micron resolution. The undulator sections are magnetically aligned using a mechanical separation structure with differential screws allowing for micron scale physical adjustments of the undulator sections. After magnetic tuning the undulator has a total length of 1.5 m, a magnetic period of 2.18 cm with 66 total periods, a magnetic gap of 7 mm, and a wiggler parameter of 1.25.

Magnetic Tuning

Magnetic tuning was accomplished through magnetic sorting and shimming. Course tuning was done by magnetic sorting where individual magnets that were producing large errors in the electron trajectory and optical phase are replaced by more suitable magnets. Fine tuning was done by magnetic shimming where, 100 micron thick steel shims were cut by water jet and placed onto the magnets on both sides of a vanadium permendur pole. In this way the magnetic flux from each individual pole piece could be reduced in order to optimize the electron trajectory and optical phase error. The maximum trajectory deviation from the undulator axis has been reduced to 8 microns and the maximum optical phase error has been reduced to 35 degrees. With the magnetic tuning completed, gap blocks were machined to set the final magnetic gap distance, with final alignment being surveyed using the CMM touch probe. The final alignment of the undulator sections will be re-established and validated to micron precision in the LOASIS laboratory using a portable coordinate measuring machine.

Optical Spectra with Undulator Field Errors

Magnet sorting and shimming has significantly reduced the magnetic errors in the undulator. To asses the quality of the actual field and the impact of the errors on the photon flux from the undulator, numerical simulations of the undulator flux using the SPECTRA code have been carried out using the magnetic field data measured with the Hall probe. From Fig. 2 it can be seen that relative to the other harmonics, the fundamental harmonic at 40 eV has been attenuated the most due to magnetic field errors. As evidence for near optimum tuning, the overall attenuation of the first harmonic is less than 16% of the flux at 0.1% of the bandwidth compared to a perfect undulator. Fluxes of this order are sufficient for our initial experiments. In addition a micro channel plate based spectrometer will be used to measure the spectra allowing improved signal to noise in our initial experiments.

XUV GRAZING INCIDENT SPECTROMETER

A high resolution XUV spectrometer has been designed and built to measure the optical spectra emitted from the THUNDER undulator. The spectrometer uses an

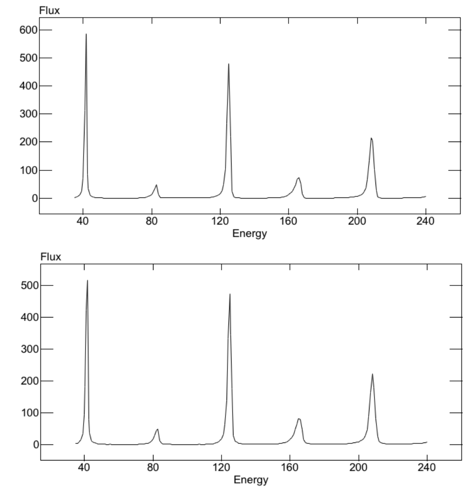

Figure 2: Photon flux (per 0.1% bandwidth) from a perfect undulator with no magnetic errors (top figure) and from the THUNDER undulator with measured magnetic errors (bottom figure). Both simulations were carried out using 500 MeV electronswith 10 pC of charge, an energy spread of 0.25% and a normalized transverse emittance of 1.0 mm-mrad.

aberration-corrected concave grating with 1200 l/mm covering 11-62 nm and a grazing incidence geometry with an imput angle of 4.7 degrees and a spectral plane of 110 mm wide. The grating angle is controlled by a motorized linear actuator and can be positioned to view the zeroth order reflection. The detector is a microchannel plate with 10 micron channel diameter, a 40:1 length to diameter ratio, a bias angle of 12 degrees and a CsI photocathode coating for enhanced quantum efficiency in the XUV. The microchannel plate has a 2:1 fiber optic image reducer and a flexible fiber optic cable which relays the image to a CCD. The spectrometer is equipped with an entrance slit that is comprised of four jaws, each controlled by a linear actuator with the ability to overlap all the jaws closing the slit completely. Nominally the slit is set with the vertical jaws completely opened to 12.5 mm and the horizontal jaws set to a width of 100 microns. Calibration of the XUV spectrometer was done on the Advanced Light Source (ALS) of LBNL beamline 6.3.2. From Eqn. (1) and assuming a negligible emittance it can be derived that the relative spectral bandwidth of the fundamental harmonic emitted from the undulator is proportional to the electron beam energy spread and the divergence θ as:

$$\frac{\Delta\lambda}{\lambda} = \frac{2\Delta E}{E} + \gamma^2\theta^2 \qquad (2)$$

In order to measure the spectrometer resolving power, a 200 pixel binning of the CCD image over the measured beam size in the non-spectrally dispersive plane was performed. A Gaussian distribution was fit to this data and the square root of the variance was used as the minimum resolvable wavelength $\Delta\lambda$. Fig. 3 shows the resolvable electron beam energy spread as a function of wavelength of the emitted fundamental radiation. The spectrometer can resolve energy spreads less than 0.1% rms.

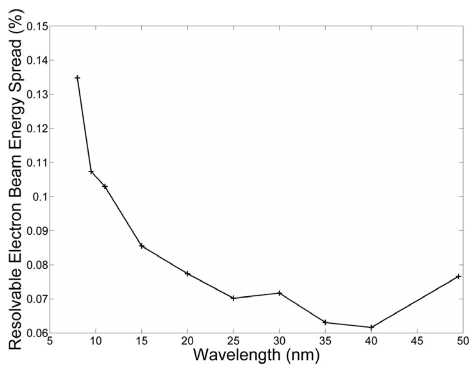

Figure 3: The minimum spectrally resolvable electron beam energy spread (assuming negligible emittance) as a function of wavelength from 8-49 nm. The spectrometer can resolve energy spreads less than 0.1% rms.

The spectral responsivity of the XUV spectrometer was determined through a comparison of the signal acquired by the ALS photodiode. The photodiode signal was converted to photon flux using the photodiode response function which has been accurately measured [9]. The respective spectrometer signal for this photodiode signal was found by exposing the spectrometer to light at each wavelength, for an exposure time of 300 ms, with the aperture jaws completely opened. The relative calibration for the 1200 l/mm grating is shown in Fig. 4.

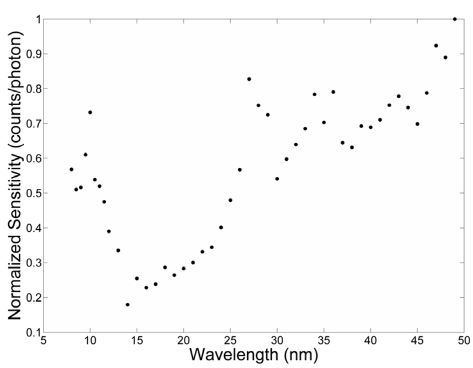

Figure 4: The normalized spectrometer sensitivity in counts per photon as a function of wavelength from 8-49 nm.

QUADRUPOLE MAGNETS

A pair of quadrupole magnets 50 mm and 25 mm long have been installed on the beam line in order to collimate the electron beam and insert it into the undulator [7]. The magnets are each controlled by three motorized stages with micron resolution allowing for three axis independent alignment of each magnet with respect to the electron beam. The magnets are nominally placed 84 mm from the electron source and 3.9 m away from the undulator. When placed in this configuration and assuming a beam divergence of 1 mrad the quadrupoles collimate the beam in the center of the undulator into a 300 micron waist in the wiggle plane and a 2.0 mm waist in the vertical plane. Simulations using the SPECTRA code and assuming an electron beam energy of 500 MeV, 1% energy spread and a normalized emittance of 1 mm mrad show that the photon flux, in the first harmonic, is increased by more than a factor of 53 when collimating the beam using the quadrupoles.

SUMMARY

In summary, the design of an undulator-based electron beam diagnostic to be used in conjunction with the LOASIS LPA 500 MeV electron beam and a pair of quadrupole magnets has been presented. Details of the THUNDER undulator and its magnetic characterization and tuning have been provided. An XUV spectrometer has been built and characterized at the ALS yielding a spectral resolution of 0.1 nm at 30 nm, thus capable of resolving electron beam energy spreads of less than 0.1% rms. Initial experiments will use the observed changes in spontaneous emission from 1.5 m of undulator to measure the energy spread and the emittance of the electron beam. Later experiments will use up to 5 m of undulator with a goal of a compact, high gain, XUV FEL.

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