Non-invasive Detection and Characterization of Beams

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For a free-electron laser (FEL) to work effectively the electron beam quality must meet exceptional standards. In the case of an FEL operating at infrared wavelengths in an amplifier configuration the critical phase space tends to be in the longitudinal direction. Achieving high enough longitudinal phase space density directly from the electron injector system of such an FEL is difficult due to space charge effects, thus one needs to manipulate the longitudinal phase space once the beam energy reaches a sufficiently high value. However, this is fraught with problems. Longitudinal space charge and coherent synchrotron radiation can both disrupt the overall phase space, furthermore, the phase space disruption is exacerbated by the longitudinal phase space manipulation process required to achieve high peak current. To achieve and maintain good FEL performance one needs to investigate the longitudinal emittance and be able to measure it during operation preferably in a non-invasive manner. Using the electro-optical sampling (EOS) method, we plan to measure the bunch longitudinal profile of a high-energy (~120-MeV), high-power (~10kW or more FEL output power) beam. Such a diagnostic could be critical to efforts to diagnose and mitigate deleterious beam effects for high output power FELs.

I. Introduction

The electro-optical (EO) effect is a powerful diagnostic tool for determining the time profile of ultrashort relativistic electron bunches [1]. When a relativistic bunch passes within a few mm of an electro-optical crystal, such as zinc telluride (ZnTe) and gallium phosphide (GaP), its transient electric field modifies the birefringence of the crystal. This modification can be detected with polarized femtosecond laser pulses and thus can be used to accurately map the electron bunch longitudinal profile.

II. EOS Techniques

Several different techniques for measuring the temporal profile of a relativistic electron beam have been developed and tested. Based on results from previous work we have chosen two methods to evaluate, Electro Optical Temporal Decoding (EOTD) and Electro Optical Spatial Decoding (EOSD). We also explored the utility of the Spectral Upconversion method.

A. Electro Optical Temporal Decoding (EOTD)

In EOTD, the optical beam is split into two beams, a probe and a gate. The probe is passed through a grating pair to stretch the pulse to a length that is longer than the electron bunch duration. This probe pulse samples the electron beam induced birefringence in the electro-optic crystal. The gate beam serves as a short pulse reference in the cross-correlation performed in a nonlinear crystal. In detail, the stretched probe pulse passes through a half-wave plate and a linear polarizer and is focused onto a ZnTe electro-optic crystal. This 0.2 mm thick <110> ZnTe crystal is placed inside the accelerator beam pipe so that the electron bunch can pass near to it [1]. The phase retardation induced in the crystal by the bunch field induced birefringence is translated into an intensity modulation on the stretched pulse by passing through an arrangement of polarizers. This encoded intensity is then cross-correlated with the short pulse in a BBO crystal. The non-collinear nature of the cross correlation geometry provides a mapping of time onto spatial position in the BBO crystal and the CCD [3].

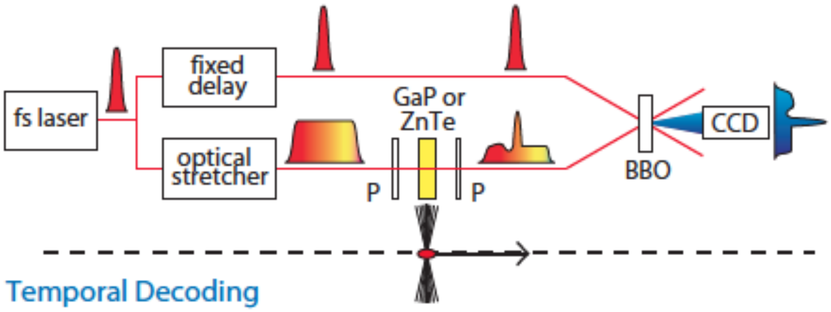

Figure 1: Diagram of Electro Optical Sampling by the Temporal Decoding Method [2]

This technique requires a pulse of sufficiently high power for the nonlinear crystal to operate efficiently and makes it costly to implement. However, literature suggests it is capable of very short temporal resolution and is less distorted by noise from proximity to the beam line compared to other methods [2]. These characteristics will be examined in the CSU lab experiment. The EOTD technique could support multiple locations using a single laser with sufficient energy by splitting the pulse and sending it to each location. Pulse broadening and dispersion effects would need to be evaluated for this case.

This method would provide high power pulses better suited to a noisy beam line environment, as would be expected in the case of higher beam power, but at a much lower repetition rate than that of EOSD.

Implementing a control system to vary the proximity of the EO crystal to the beam line could prove more difficult with this technique due to the need to adjust multiple optical components simultaneously. Initial implementation for each measurement location would also be complicated by the likelihood that each would require the full suite of optical components; furthermore, the delay time and optical stretching needs may be different for different locations.

B. Electro Optical Spatial Decoding (EOSD)

In EOSD, a Ti:Sapph oscillator or fiber laser may be used, drastically reducing the system implementation cost [4]. Additionally, an EOSD system would likely be much simpler to implement and operate. The method works by sampling the Coulomb field with an optical pulse obliquely incident to the EO crystal and the Coulomb field propagation direction. With such a geometry, a spatial to temporal mapping is introduced for the relative delay of the laser arrival time at the crystal. Field-induced birefringence is thus encoded spatially and may be detected by a suitable arrangement of polarizers and imaging of the crystal. An important requirement for spatial encoding is spatially uniform EO materials. The tolerances of this requirement can be difficult to satisfy, as even stress induced birefringence can potentially add significant experiential difficultly [2].

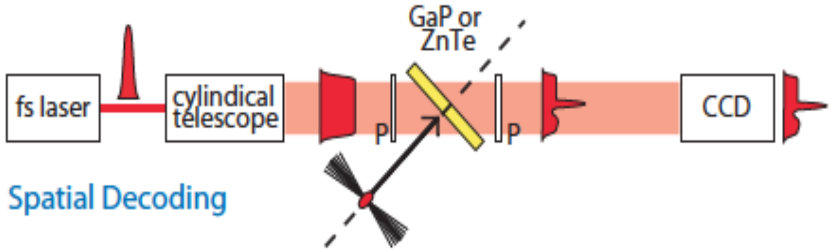

Figure 2: Diagram of Electro Optical Sampling by the Spatial Decoding Method [2]

The EOSD technique may be capable of similar temporal resolution as EOTD if a probe laser with a sufficiently short pulse duration is used. However, due to the significantly lower probe laser pulse energy it may be necessary for the entire system to be located in close proximity to the beam line, occupying more space and increasing noise distortion vulnerability. The tradeoff in cost may be worth the potential temporal resolution sacrifice and potential occupation of beam line space. A detailed experiment will test these characteristics. We will evaluate probe laser beam transport options for this system. Using a fiber laser, optical fibers may be able to transport a single probe laser beam to multiple measurement locations if pulse energy requirements can be maintained.

The crystal control system may not be as difficult to implement for EOSD due to fewer optical components in the system. The reduced optical component requirement also greatly simplifies the overall measurement process.

C. Spectral Upconversion

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Comment [1]: I thought this was worth mentioning, since considerable time was spent evaluating it. Why we ruled it out is relevant.

A third technique was evaluated for implementation. The spectral upconversion method of electro-optical sampling would allow monitoring the bunch using a picosecond laser, and a greatly simplified measurement system, thereby reducing the system cost considerably. However, it fails to provide phase information adding ambiguity to the reconstruction of the distribution. We considered using Kramers-Kronig relations to recover phase information based on a sequence of shots, but shot to shot phase jitter is typically on the same order as the measurement technique so no consistent data would be available to evaluate.

III. CSU Accelerator Laboratory Experiment

At CSU we are developing an experimental setup to test a variety of characteristics of the different EOS techniques. Since we have ambitions of operating at low electron beam energies, (< 10-MeV), we must be cognizant of the $1/\gamma$ Coulomb field opening angle impacting our temporal resolution. The temporal resolution of an EOS system for a single electron at normalized energy $1/\gamma$ is simply a function of the distance between the EO crystal and the Coulomb field source, $\Delta t = d \tan(1/\gamma)/c$ where d is the relative distance between the electron and the crystal. Thus an EOS diagnostic would not be useful on a very low energy beam if the beam is very short. Based on this relation, the temporal resolution of a 120-MeV bunch at a distance of 5 mm is limited to approximately 70 fs. This is within the range of the capability of a GaP crystal [1]. This level of resolution would not be needed for routine operation, but would be useful in diagnosing longitudinal space charge induced microbunching or longitudinal distortions on a bunch caused by coherent synchrotron radiation.

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Comment [2]: Move to top, after EO theory?

In our lab experiment we will employ an amplified Ti:Sapph laser to generate THz pulses in a plasma [5] to simulate electron bunches, and measure those pulses with each technique. Our measurements will be compared with measurements detected by a balanced diode configuration. The balanced diodes have been found to be unsuitable for use on an electron beam line due to severe noise susceptibility, but this technique has been shown to provide accurate measurements for comparison testing in a laboratory environment [4].

For testing with actual electron beams, a system will be developed to vary the proximity of the EO crystal relative to the beam or remotely switch crystals, and so allow for variation in the temporal resolution to the limits of crystal response, probe laser pulse width, CCD detection rate or crystal damage threshold. This may allow for the capability of magnifying beam instabilities as needed and allow for fine-tuning of beam parameters to minimize them.

Proximity to high current beam lines may be detrimental to the EO crystals. The effects of beam halo on the crystal are yet unknown. Exploring issues such as this in a laboratory environment and on an accelerator is important to reduce the diagnostic to practice. When the best EOS system for the accelerator genre of interest has been determined, we hope to test it on the Jefferson Lab FEL.

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Comment [3]: Not sure what else to say about this, but I'm sure there is much more that could be added. Maybe Carmen could contribute?

IV. Conclusion

Development of high-output power FELs requires mitigation of beam effects that reduce or distort the beam quality. The ability to effectively diagnose these effects is necessary and a non-invasive diagnostic such as EOS could meet this need. EOS systems have been successfully deployed in the past; however, not at low energies or with very high average current beams. Several challenges must be investigated prior to implementation of an EOS system on a machine such as the JLAB FEL. The CSU accelerator laboratory will explore these challenges and develop an optimized EOS system that considers practical concerns as well as performance characteristics. We have recently received funding and will commence physical research soon.

V. Acknowledgements

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