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Compact Laser-Driven Dielectric Accelerator for Future X-Ray Lasers

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14. ABSTRACT
We propose to develop a compact laser-driven dielectric electron accelerator system over the course of three years that could be used for driving future x-ray free-electron lasers. This compact accelerator system will incorporate a high brightness laser-triggered photocathode source integrated with an on-chip laser accelerator network, as well as the associated fiber drive laser system. Thorough simulation and modeling of the accelerator structures will be used to build upon the foundation we have already established to improve the accelerating gradient and efficiency at both non-relativistic and relativistic energies. These designs will be prototyped and tested using a modular electron-optic column custom designed for these experiments that will allow the testing of accelerator, focusing, and beam steering structures as well as high brightness electron sources. Over the course of the project, these components will be integrated together to form the basis for the compact laser driven source of attosecond bunched, relativistic electrons for future x-ray free electron lasers and high energy physics experiments.

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FINAL REPORT
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Proposal to develop a

Compact Laser-Driven Dielectric Accelerator for Future X-Ray Lasers

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Original Proposal Submitted to

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Development of a compact laser-driven dielectric accelerator for future x-ray lasers

Abstract

We propose to develop a compact laser-driven dielectric electron accelerator system over the course of three years that could be used for driving future x-ray free-electron lasers. This compact accelerator system will incorporate a high brightness laser-triggered photocathode source integrated with an on-chip laser accelerator network, as well as the associated fiber drive laser system. Thorough simulation and modeling of the accelerator structures will be used to build upon the foundation we have already established to improve the accelerating gradient and efficiency at both non-relativistic and relativistic energies. These designs will be prototyped and tested using a modular electron-optic column custom designed for these experiments that will allow the testing of accelerator, focusing, and beam steering structures as well as high brightness electron sources. Over the course of the project, these components will be integrated together to form the basis for the compact laser driven source of attosecond bunched, relativistic electrons for future x-ray free electron lasers and high energy physics experiments.

FINAL REPORT

The AFOSR grant FA9550-14-1-0190 led to the first laser driven accelerator fabricated from silicon. This work was the PhD thesis of Ken Leedle who authored two papers supported by AFOSR.

The Silicon accelerator is now the mainstay approach and is supported by a silicon electron photo cathode based on a emission tip of silicon. The tip provides a source of electrons from a sub nanometer size and driven by multi photon absorption of 300fsec laser light near two microns wavelength that yields up to 1000 electrons per laser pulse. Silicon also provides unprecedented fabrication opportunities that has led to demonstration of focusing of electrons, accelerator alternating phase focusing along the accelerator channel, and recently bunching of electrons to 250attosecond duration at 100kHz repetition rate.

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The Silicon Integrated Photonics has enabled a fully integrated accelerator on a chip with inverse design used for designing the accelerator. This is a major breakthrough in accelerator design and will enable scaling of laser driven accelerators from MeV energies to GeVscale energies which can drive table top coherent x-ray sources by FEL emission.

Our success over the first four years of the accelerator on a chip (ACHIP.Stanford.edu) science program, supported initially by AFOSR followed by Moore Foundation, has been recognized by our Advisory Board and by the Moore Foundation. This very successful high risk with very high payoff potential research program has been extended an additional two years at an additional $6 million in funding. The goal is to demonstrate prototype accelerators that fit in a shoe box and operate at up to 1MeV energy. A second goal is to conduct attosecond electron diffraction and electron microscopy experiments. A third goal is to demonstrate the generation of attosecond UV and X-ray light sources based on the Dielectric Laser Accelerator (DLA).

This work was initiated under a DARPA grant that was cancelled abruptly. AFOSR, under Howie Schlossberg, recognized the potential for DLA accelerators and provided funding for the first three years which led directly to the DLA based on silicon. Professor Fabian Pease, Electrical Engineering at Stanford University, loaned us space in his laboratory and gave us access to the 100keV electron beam column which was used in the first experiments. Fabian Pease also introduced us to streak cameras. I promised him that we would build an atto-second high speed streak camera thus extending his favorite research topic to new performance levels. We have submitted a paper to Phys Rev Letters (accepted) that describes the first attosecond electron bunches and describes the measurement of the pulse duration by using a laser driven streak camera with 250 attosecond resolution.

The AFOSR has often taken calculated risk in funding research projects in the past. Often these highly risky research programs have been successful and have made an impact on capabilities of interest to the Air Force. The AFOSR support in this case led directly to an accelerator on a chip that in turn offers the possibility to open whole new approaches to attoscond measurements and to ultrahigh speed electronics. A stretch goal is a laser accelerator on a table- top driving a dielectric undulator to convert attosecond electrons to coherent attosecond x-rays for science. We have taken significant steps in this direction over the past four years. We plan to continue to make progress over the remaining three years.

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The Project Timetable for the AFOSR funded three year program is shown here.

Project Objectives and Timetable

Year 1
1. Measurement of energy modulation in a low-beta (80keV) structure from Si or SiC
2. Design and initial fabrication and testing of optically robust on-chip waveguides
3. Development of phase-stable, multi-output master oscillator power amplifier for driving multiple accelerator stages.

Year 2
1. Demonstrate a two-stage buncher-accelerator for net laser acceleration of electrons
2. Demonstrate energy modulation using on-chip waveguide coupled accelerators structures
3. Begin development of an ultrafast laser triggered photocathode source

Year 3
1. Demonstrate high gradient net acceleration of a bunched electron beam from a laser triggered photocathode source.
2. Demonstrate beam deflection structures for use in a dielectric laser undulator

We have met the Objectives by the end of Calendar Year 2019.

Year 1 Objectives of a Silicon based accelerator is described in the Thesis of Dr. Ken Leedle and published in References 1 and 2. The Phase stable waveguide operation work has been submitted to Science and is accepted for publication (reference 8). The phase stable table-top laser is a commercial product that provides outputs at 2microns, 1.5microns and 1.0microns wavelengths based on a OPO tunable source operating at 100kHz, 300fsec, and 10Watts of average power.

Year 2 Objectives have been met by the demonstration of a two stage buncher (Reference 9) and the demonstration of a multiphoton silicon tip electron source) (Reference 10). The highest acceleration gradient to date in 650 MeV/m in a fused silica structure (Reference 7) The programmatic goal is 1GeV/m gradient and 1.0MeV net energy gain. Experiments to achieve these goals are in progress at UCLA as part of the ACHIP program.

Year 3 Objectives have been met by the demonstration of an accelerator in a show box size apparatus the use of a laser triggered silicon photocathode as the source of electrons. The demonstration of focusing and beam deflection was published in Phys Rev Letters in Spring 2019 (Reference 5).

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AFOSR future interests in accelerator on a chip technology

The rapid progress in dielectric laser driven accelerators on a chip has caught the attention of the broader community. We have held three workshops on the applications of the DLA accelerator and intend to invite scientists to join the ACHIP Collaboration to explore attosecond electron diffraction and attosecond electron microscopy. Further, we are working toward the demonstration of X-ray generation with attosecond electron bunches for future table top light sources.

The Moore Foundation has extended the ACHIP program for two additional years with a funding level of $3 million per year. We are seeking additional funding to help move the technology from a science of accelerators effort to an engineering of accelerators for specific and well identified applications. We would like to explore with the AFOSR possible applications and programs for accelerators on a chip.

Robert L. Byer
Principal Investigator, AFOSR "Compact Laser-Driven Dielectric Accelerator for Future X-ray Lasers"
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9. Dylan S. Black et al "Net Acceleration and Direct Measurement of Attosecond Electron Pulses in Silicon Dielctric Laser Accelerator" (accepted for publication in Phys Rev Letters)

10. Andrew Charles Ceballos PhD Thesis EE Department Stanford University November 2019 "Silicon Photocathodes for Dielectric Laser Accelerators"

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