ZEUS: A National Science Foundation mid-scale facility for laser-driven science in the QED regime

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Abstract: Building on past support, NSF has funded the Zetawatt Equivalent Ultrashort pulse laser System (ZEUS), a mid-scale 3PW multi-beam user facility, to explore nonlinear quantum electrodynamics, relativistic plasmas, and other phenomena in High-Field Science.© 2020 The Author(s)

1. Introduction

The Zetawatt-Equivalent Ultrashort pulse laser System (ZEUS) is being developed as a National Science Foundation Mid-Scale RI-1 Implementation Project in the research area encompassed by the NSF Physics Division of the Mathematical and Physical Sciences Directorate. ZEUS will be a user facility and will be located in newly renovated space in the Gerstacker Building at the University of Michigan, Ann Arbor (UM). It will be a significant upgrade of the existing NSF funded HERCULES 500 Terawatt (TW) laser system, consisting of multiple beamlines that are designed to operate simultaneously and in perfect synchronization. One beam will be 2.5 PW and the other will operate at 500 TW. In this configuration, when pulses of several hundred TW are used to drive wakefield electron acceleration to GeV energies and multi-Petawatt pulses are tightly focused onto the electron beam, the apparent power of the focused laser pulse is boosted by a little more than the square of the Lorentz factor (by more than a million-fold) from the Petawatt range to the Zetawatt range. Thus, the wakefield electrons see a Zetawatt Equivalent Ultrashort pulsed laser System–ZEUS [1]. Additionally, a 3 PW single-beam mode will be available.

The Gérard Mourou Center for Ultrafast Optical Science (CUOS) is an interdisciplinary research center focused on the use of ultra-short laser pulses in science and technology and was established by Prof. Gérard Mourou (Nobel Prize in Physics 2018) who was Director until 2005 and remains an emeritus Professor at UM. The high field science group at CUOS is developing this unique high power laser facility which will be used to uncover the physics of non-linear quantum electro-dynamic effects, laser wakefield acceleration, relativistic positron generation and radiation reaction in ultra-high power laser plasma interactions. The majority of the facility to be constructed uses commercial components and the preliminary design of the system will result in a reliable laser facility – yet one which enables experiments at the frontier of relativistic plasma physics. After construction and commissioning, the facility will be open to users across the US and be capable of performing a wide range of experiments including those related to scientific applications such as particle acceleration, laboratory astrophysics and energy research. Note that the laser facilities at CUOS are already open access partial-user facilities under the DOE/Fusion Energy Sciences sponsored “LaserNetUS” program (lasernetus.org).

This will be a new high power laser facility for the US scientific community, which will have an open and transparent external review panel for facility access and at least 30 weeks per year dedicated to external user experiments. The facility leverages a recent NSF-funded upgrade to the HERCULES laser at UM as well as laboratory renovations funded by the university. The development of this facility is in direct response to recommendations from the recently published National Academy Report on “Opportunities in Intense Ultrafast Lasers: Reaching the Brightest Light (2018)” [2] which advocates for the construction of mid-scale university based intense laser facilities in the US

2. Science anticipated for ZEUS

Table 1 illustrates the diversity of science that will be accessible at ZEUS—discussed in reading order below.

Laser wakefield accelerators may be able to miniaturize high-energy-physics particle accelerators to the tabletop scale, and enable new sources of ultrafast, extreme brightness and precise x-rays for applications from life-sciences to physics and engineering to industry. Based on 3D particle-in-cell calculations and this scaling, acceleration to 30 GeV in a single stage is possible for the 3 PW ZEUS beam if parameters are optimized. This astonishing 30 GeV/m accelerating gradient is equivalent to the 2 mile SLAC accelerator being reduced to a meter in length.
Table 1. Science on ZEUS

<table>
<thead>
<tr>
<th>Laser wakefield acceleration</th>
<th>Production of ions &amp; other particles</th>
<th>QED-strong fields &amp; relativistic plasmas</th>
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</thead>
<tbody>
<tr>
<td>Extreme laboratory astrophysics</td>
<td>Basic laser-plasma physics</td>
<td>Nuclear photonics</td>
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High-intensity laser pulses couple energy predominantly to electrons, but laser-plasma interactions may also produce a variety of other particle sources through secondary processes. These interactions can generate particle sources with short temporal duration and small source size which may find applications from medicine (proton therapy) and security (neutron/gamma scanning) to advanced radiography with positrons and muons. ZEUS will allow for a larger focal spot and therefore should achieve the theoretical scaling to be investigated, to produce ion energies per nucleon beyond a GeV through “light sail” acceleration.

Present understanding of the physics of laser matter interactions at irradiation conditions above $10^{22}$ W/cm$^2$ is at the frontier of physics. This coupling of quantum processes and relativistic collective particle dynamics can result in dramatically new plasma physics phenomena such as the generation of dense e$^+$e$^-$ pair plasma from near vacuum, complete laser absorption or using a femtosecond pulse of light to stop an ultrarelativistic electron beam that would otherwise penetrate centimeters of lead. At higher intensities still, beyond $10^{24}$ W/cm$^2$, one of the most exciting phenomena that is predicted to arise from supercritical electromagnetic fields is the development of showers or cascades of prolific amounts of electrons and positrons.

Astrophysical flows have shown indirect evidence of turbulence in accretion phenomena, magnetic dynamos, and stellar interiors. The dynamics of magnetic fields in reconnection and in generating relativistic plasma jets emerging from extreme objects is a frontier research area, with the recent observation of plasma emission from a supermassive black hole [Event Horizon Telescope Collaboration 2019]. With a laser system such as ZEUS capable of driving relativistic shocks it might soon be possible to create a “gamma ray burst in a lab,” i.e., to produce shocks with nearly astrophysical-plasma conditions in lab experiments.

Plasma is a highly nonlinear and complex medium, and the fundamental physics of plasma under extreme conditions, the behavior of strong magnetic fields, laser-plasma interactions including scattering and streaming instabilities and absorption, the relativistic optics of plasma and dense plasma physics are all crucial for understanding the environments of fusion plasma, astrophysical scenarios and high-power laser plasma particle sources. Complex plasma dynamics at the surface of dense plasmas results in the generation of extremely strong magnetic fields, exceeding $10^5$ Tesla, which is comparable to that of neutron stars.

Laser-driven Compton sources hold the promise to advance the field of nuclear spectroscopy in the manner similar to the revolution in atomic spectroscopy. Nuclear photonics is complementary to the area of laser-driven energetic particle source generation. In common with high-energy X rays, energetic particles can probe nuclear physics and address a broad spectrum of applications. High-intensity laser-driven sources may allow improved studies of photofission barriers, cross sections, and rare fission modes and will enable studies of nuclear isomers by inducing photoexcitation of nuclear isomeric states, which is important for understanding stellar conditions and nuclear isomers in high-density energy storage.

We will discuss the laser design in connection with these types of experiments.