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Laser-Wakefield driven compact Compton scattering gamma-ray source

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Disclaimer

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LLNL Postdoc

1. Introduction

We propose to demonstrate a novel x-ray and gamma-ray light source based on laser-plasma electron acceleration and Compton scattering at the Jupiter Laser Facility at LLNL. This will provide a new versatile and compact light source capability at the laboratory with very broad scientific applications that are of interest to many disciplines. The source's synchronization with the seed laser system at a femtosecond time scale (i-e, at which chemical reactions occur) will allow scientists to perform pump-probe experiments with x-ray and gamma-ray beams. Across the laboratory, this will be a new tool for nuclear science, high energy density physics, chemistry, biology, or weapons studies.

Compton scattering sources, where laser photons are scattered off a relativistic electron beam to produce x-ray and gamma-ray light pulses, have been extensively studied in the past decade. This is mainly due to the fact that their potential applications are very broad. At photon energies below 100 keV (x-rays), applications include x-ray protein crystallography [1], K-edge imaging [2], and phase-contrast imaging [3] for medical applications. At MeV photon energies (gamma-rays), they are interesting for photo-fission, positron beams generation, and nuclear resonance fluorescence (NRF), a useful technique for special nuclear materials detection in homeland security. Until now, all the major Compton scattering source projects have utilized electron beams from radiofrequency (rf) accelerators, because the later are currently more reliable and controllable than beams from a laser-plasma accelerator (LPA). LLNL has been at the forefront of this research in the past decade, with successful projects such as PLEIADES [4] and T-REX [5].

On the other hand, LPAs, since their first theoretical proposal in 1979 [6], have constantly aimed toward higher quality and higher energy electron beams, mostly due to the advent of ultrafast high intensity laser systems based on chirped pulse amplification (CPA) [7]. In this scheme, electrons are accelerated by a plasma wake excited at the back of an intense laser pulse. Unlike rf structures, plasmas can sustain very large acceleration gradients of more than 100 GV/m (typical rf accelerators run at <100 MV/m). In 2004, three groups reported the generation of monoenergetic electron beams in a LPA [8-10]; however, the schemes presented relied on very nonlinear laser-plasma interaction effects that made the electron beam production quite unpredictable.

Methods to increase the energy and control of the electron beams have been recently investigated and successful, such as guiding in a capillary structure [11], controlled injection with counter propagating laser beams [12], self guiding of the laser at low plasma density [13] and ionization induced trapping [14].

We propose to merge those two exciting technologies by doing the first experimental demonstration of a Compton scattering light source based on electrons from a LPA at LLNL. This will be the first gamma-ray class laser-based Compton scattering source demonstrated. This will provide scientists with a new light source capability at LLNL with photons of up to several MeV, and a very broad scientific community will benefit from this project.

2. Project plan

2.1. Previous work and background

Previous work achieved by the team members, both on Compton-scattering source development and LPA schemes will provide a solid working basis for the success of this proposal.

2.1.1. Laser-plasma accelerator

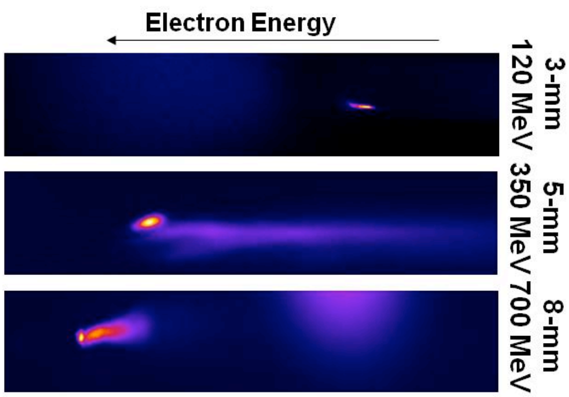

Fig. 1: measured electron spectrum for three plasma lengths (3 mm, 5 mm, 8 mm) where the corresponding beam energy increases from 120 to 700 MeV.

Successful LPA experiments led by D.H. Froula have been achieved at the Jupiter Laser Facility at LLNL, in collaboration with C. Joshi's group at UCLA. We led and participated in several experimental campaigns on the Callisto laser (60 fs, 10 J). The electron beams were produced as follows: the laser was focused by an off-axis parabola (OAP) onto the edge of a supersonic helium gas get. When this happens, the ponderomotive force, proportional to the light intensity gradient, plows the electrons away from the high intensity regions, leaving an ionic bubble in the wake of the light pulse. Electrons trapped at the back of this bubble experience a longitudinal accelerating force due to space-charge separation. With proper laser and plasma parameters that have been well defined, the laser can be efficiently self-guided over several millimeters to accelerate electrons up to 720 MeV in a 8 mm He gas jet [13]. We plan to use this scheme as our electron beam source for our experiments, since it is well implemented at JLF (see Fig. 1). In FY09 and FY10, several additional experiments have been achieved to increase the energy and enhance the trapping and self-guiding mechanisms.

2.1.2. Compton scattering sources

Compton scattering sources are produced when laser photons are scattered off a high-energy electron beam. Their properties rely on energy-momentum conservation before and after scattering. With this feature, one can derive the on-axis relativistic Doppler-shifted energy E_x: for the case of a head-on (180 degrees) collision between the laser and the electron beams, $E_x \approx 4\gamma^2 E_L$, where $\gamma = 1/\sqrt{1-v^2/c^2}$ is the relativistic factor of an electron with velocity v and E_L the laser photon energy. This makes Compton scattering sources very attractive because one can obtain high-energy (MeV) scattered photons with relatively modest electron beam energies, making the source rather compact compared to machines like 3rd generation synchrotrons. For example, with a 200 MeV ($\gamma \approx 400$) electron beam and an infrared laser (800 nm or 1.5 eV), one can obtain a 1 MeV gamma-ray beam.

T-REX, the brightest MeV-class Compton scattering source ever reported has been developed using the 100 MeV LLNL linac facility. By colliding a 116 MeV electron beam with a custom frequency doubled Nd: YAG laser, a bright 0.5 MeV photon beam was generated. It was successfully utilized to perform NRF experiments in 7Li, a proof-of-principle demonstration of the capability of such a source [5].

2.2. Modeling efforts

In a first collaborative work, we plan to merge the modeling efforts already done at LLNL for Compton scattering source development with UCLA's expertise on particle-in-cell (PIC) simulations. PIC simulations will be used to estimate the electron trajectories in the plasma, a key point to model the properties of the gamma-ray beam. Then, an interface with the PIC simulation results will be realized with the Mathematica software to model the laser-electron interactions and predict the properties of the gamma-ray beam, such as spectral width, energy and flux. Optimum electron and laser parameters will be determined for a thoughtful planning of the experiment.

2.3. Proposed experiment at LLNL

2.3.1. Gamma-ray production

Once the theoretical properties of the gamma-ray beam will be theoretically well established, we will plan an experimental campaign (6-10 weeks) at the Jupiter laser facility, using the Callisto laser. The first part of the campaign (2-3 weeks) will be dedicated to electron beam generation. The 10 J, 60 fs laser will be focused onto the edge of a helium gas jet, in a scheme similar as in [13], ensuring us a low-risk way of successfully producing the required electron beam for this experiment. We expect to produce several 100 MeV electrons. Then, for the remaining part of the campaign we will use a second OAP to focus the laser beam on the electron beam at the exit of the LPA, as depicted in Fig. 2. For this, we plan to use either a little fraction (10-20%) of the 532 nm green Janus laser beam or of the 800 nm Callisto beam. According to the Compton scattering scaling law in section 2.1.2, this will potentially yield 18 MeV gamma-rays.

2.3.2. Gamma-ray detection

Detecting the high-energy gamma-rays and proving their origin will be the other challenging key point of this experiment. For this, we plan to have the detection system developed and calibrated for the T-REX project [15], in which we detected high-energy photons on a scintillator coupled to an intensified CCD camera. Systematic studies (such as turning the scattering laser on and off) will be made to ensure the reliable origin of the gamma-rays.

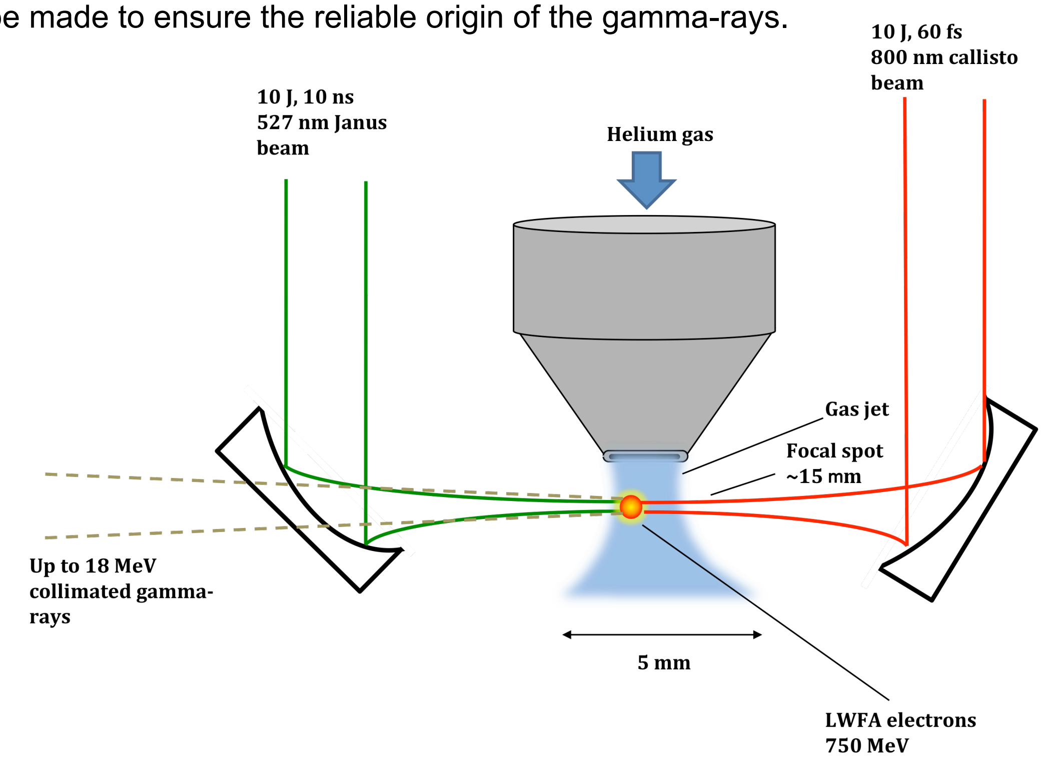

Fig. 1: Schematic of the proposed experiment

3. Management plan

The project will be coordinated by the principle investigator F. Albert. The PI, physicist in NIF's PS&A program, has more than five years of experience with LPAs (developed at LLNL and at the terawatt laser facility at LOA, France) as well as with Compton scattering x-ray and gamma-ray experiments (T-REX project) and will thus lead the experimental campaigns. The Co-PI D.H. Froula, a group leader in the NIF laser plasma interactions division, has established a LPA capability funded by LDRD at LLNL that led to several high impact publications and presentations, and he will bring his expertise and support in that field. The theoretical modeling will be done in collaboration with the group of Prof. C. Joshi at UCLA. Prof. Joshi is an early developer and now a world expert in LPAs; he has trained several distinguished experts in the field. Prof. Joshi's group will provide us with PIC simulations to develop our codes. F.V. Hartemann, a lead scientist in NIF's PS&A who has more than 15 years of experience in Compton scattering source design and modeling, with a reference book published on the subject [16], will have an advisory role in the project, especially on the modeling aspect. This project enables the continuation of collaborations between LLNL and UCLA that will continue to provide critical training for future scientists interested in pursuing careers at LLNL. We thus expect to support one full-time graduate student from UCLA who will participate in planning and realizing the experiments, which will combine academic and LLNL's efforts to develop novel light sources.

Communication will be handled in regular meetings, emails and calls. The experiments will also be planned with the JLF technical and administrative people in order to assess the potential risks, hazards and issues.

4. Dissemination

We expect to rapidly publish a design paper on our light source (Physical Review or Physics of plasmas), with detailed theoretical results and predictions. Then, a successful demonstration of a high-energy LPA-based Compton scattering light source will lead to a high impact publication in Physical Review Letters. The results will be also presented at international conferences and meetings.

5. Summary

We proposed to realize the first experimental demonstration of a Compton Scattering source with electrons from a laser plasma accelerator. After a detailed theoretical design of this source, we plan to demonstrate it at the Jupiter Laser Facility. Because our Team has a strong expertise on both laser-plasma acceleration and Compton scattering sources, and because at this time LLNL possesses the highest intensity (200 TW) ultrafast operating laser system in the world, we have the key elements for the success of this proposal. The acceptance of this proposal will allow our strong scientific team to develop the next generation table-top ultrafast gamma-ray light source, bringing a unique capability to LLNL that will be used across the laboratory. This will provide scientists with a new versatile light source capability for nuclear photo science or ultrafast dynamics, among other applications. Funding through internal (ER) or external agencies (NA-22, NA-42, NSF or DOE's Office of Science) is envisioned after this LDRD.

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(a) Professional Preparation

Ecole Nationale Superieure de Physique de Marseille Marseille, France	Engineering	B.S. 2003
CREOL University of Central Florida Orlando, FL	Optics	M.S. 2004
Ecole Polytechnique-Laboratoire d'Optique Appliquee Palaiseau, France	Plasma Physics	PhD 2007
Lawrence Livermore National Laboratory Livermore, CA	Laser-based X-ray sources, Laser plasma acceleration	2008-present

(b) Appointments

Lawrence Livermore National Laboratory	NIF and PS&A Staff Member <u>Projects:</u> MEGa-Ray (gamma-ray source), Laser-plasma acceleration.	2010-present
Lawrence Livermore National Laboratory	Post-doctoral Staff Member <u>Project:</u> Ultra-bright Laser based gamma-ray source (T-REX)	2008-2010
Ecole Polytechnique-LOA	Graduate research assistant <u>Project:</u> Production and characterization of a polychromatic x-ray source from laser-plasma interaction	2004-2007
Ecole Polytechnique	Teaching assistant <u>Class:</u> Lasers and Plasmas	2004-2007
CREOL-University of Central Florida	Graduate research assistant <u>Project:</u> Design and realization of an ultrafast Titanium-Sapphire oscillator	2002-2004
CREOL-University of Central Florida	Teaching assistant <u>Class:</u> Laser engineering	2004

(c) Awards

- 2003: CREOL/School of optics graduate Fellowship
- 2004-2007: French ministry of research and education Graduate Fellowship
- 2006: SPIE scholarship
- 2006: Incubic-Milton Chang Travel Grant for CLEO 2006 in Long Beach, CA

(d) Publications

F. Albert, S.G. Anderson, D.J. Gibson, C.A. Hagmann, M.S. Johnson, M.J. Messerly, V.A. Semenov, M.Y. Shverdin, A.M. Tremaine, F.V. Hartemann, C.W. Siders, D.P. McNabb and C.P.J. Barty, "Characterization and applications of a tunable, laser-based, MeV-Class Compton scattering gamma-ray source", *Phys. Rev. ST Acc. Beams*, in press (2010).

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(a) Professional Preparation

University of California at Davis	Plasma Physics	Ph.D. (2003)
California Polytechnic State University, San Luis Obispo	Physics	B.S. (1998)

(b) Appointments

2002–present	LLNL, Experimental Physicist (Indefinite Staff Position)
2009 – 2010	UCLA, Sabbatical with C. Joshi and W. Mori's Groups
2000 - 2002	LLNL, Student Employee Graduate Research Fellow
1999-2000	Corrales Applied Physics Company, Santa Barbara, Research Scientist/Partner
1999	Mission Research Corporation, Santa Barbara, Consultant
1997 - 1998	LLNL, Acoustic Research Scientist

(c) Awards/Invited Talks

2010	Plenary Talk, Advanced Accelerator Conference
2010	Invited Talk, APS-DPP
2008	Invited Talk, Advanced Accelerator Conference
2007	D.O.E. Outstanding Mentor Award
2006	Invited Talk, APS-DPP
2006	Invited Talk, HTPD
2005	Science and Technology Award 2005
2003	NIF Directorate Performance Award
2003	Invited Talk, APS-DPP
2002	Student Employee Graduate Research Fellowship
1998	Invited Talk, Congressional Committee

(d) Selected Publications (D. H. Froula)

Measurements of the Critical Power for Self-Injection of Electrons in a Laser Wakefield Accelerator, **D. H. Froula**, C. E. Clayton, T. Döppner, K. A. Marsh, C. P. J. Barty, L. Divol, R. A. Fonseca, S. H. Glenzer, C. Joshi, W. Lu, S. F. Martins, P. Michel, W. B. Mori, *J. P. Palastro*, B. B. Pollock, A. Pak, *J. E. Ralph*, J. S. Ross, C. W. Siders, L. O. Silva, and T. Wang, *Phys. Rev. Lett.,* **102** 024009 (2009), http://link.aps.org/doi/10.1103/PhysRevLett.103.215006

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(a) Professional Preparation

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MIT	FELs	1987

(b) Appointments

LLNL	2001 -
University of California	1993-2001
MIT – Visiting Scientist	1988-1991
Thomson Electron Tubes	1987-2001

(d) Publications

High-field electrodynamics, CRC Press (2000)

Phys. Rev. Lett. 59, 1177 (1987)

Phys. Rev. Lett. 72, 1192 (1994)

Phys. Rev. Lett. 72, 2391 (1994)

Phys. Rev. Lett. 74, 1107 (1995)

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Phys. Rev. STAB 8, 100702 (2005)

Phys. Rev. STAB 10, 011301 (2007)

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(a) Professional Preparation

London University, England	B.S. Nuclear Engineering	1974
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(b) Appointments

UCLA, Los Angeles	Distinguished Professor of Electrical Engineering	2006-Present
UCLA, Los Angeles	Professor of Electrical Engineering	1988-2006
Center for High Frequency Electronics , UCLA	Director	1992-Present
Neptune Laboratory for Advanced Accelerator Research , UCLA	Director	1998-Present

(c) Honors and Awards

APS James Clerk Maxwell Prize, 2006
Physics News 2003, 2001, 1993
2001-02 APS Distinguished Lecturer in Plasma Physics
1999 APS Centennial Speaker
1997 USPAS Prize for Achievement in Accelerator Physics and Technology
1997 Best Paper Award, Gordon Conference on Nonlinear
Optics and Lasers
Excellence in Plasma Physics Research Award, APS (1996)
Fellow, American Physical Society (1990)
Fellow, IEEE (1993)
Fellow, Institute of Physics, U.K. (1998)
Queen Mary Prize of Institute of Nuclear Engineers (1974)

(d) Recent Publications:

1. Chan Joshi, “Harnessing the power of the plasma wakefield,” CERN Courier, June 2007,

pp. 28-31.
2. C. Joshi, “The development of laser- and beam-driven plasma accelerators as an experimental field,” Review Paper, Physics of Plasmas 14, 055301 (2007).
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