Lecture Notes: Radioactive ions (and x-rays!) from laser pulses

David R. Schultz
Physics Division, ORNL

Recent very rapid developments in both high-power laser technology and the science of particle acceleration via laser-produced plasma wakefields has spurred investigation of how the next generation of radioactive ion beam facilities might benefit from these newly developed capabilities. For example, a very compact device using an ultrafast, ultraintense laser can efficiently accelerate electrons to over 100 MeV enabling a compact, laser-driven photofission source to be created. The same basic methods also provide novel and potentially advantageous means for generating x-rays either for RIB diagnostics via fluorescence or for applications in chemical and material science.

To provide more detailed information about the pioneering radioactive ion production experiments that are ongoing, references to a number of publications are given below in a very brief excerpt from a forthcoming paper, "Efficient initiation of photonuclear reactions suing quasi-monoenergetic electron beams from laser wakefield acceleration," by S. Reed, C.R. Vane, A. Maksimchuk, V. Yarnosky, V. Chvykov, G. Kalintchenko, D. Stracener, J.R. Beene, and D.R. Schultz that has been submitted to Nuclear Instruments and Methods in Physics Research, Section A (2006).

"Introduction

Recent interest in using high-intensity laser-plasma interactions to generate energetic charged particles and γ-rays has increased considerably due to the broad array of applications in radiography, radioisotope production, nuclear physics and nuclear medicine that can be explored at university laboratories [1,2] Previous experiments studying electron acceleration with high-intensity ultrafast laser pulses focused on gas and solid targets have demonstrated that very energetic, highly directional, pulsed electron beams can be produced utilizing contemporary "table-top" laser systems [2-8]. The energies of these electron bunches have exhibited Maxwellian distributions, typically peaked at low-MeV energy, with approximately exponentially decaying numbers of particles reaching energies of hundreds of MeV. Development of such compact, ultrafast electron acceleration schemes would be beneficial for many applications. They would be especially useful if the outputs were monoenergetic and tunable, as would be necessary, for example, in generatation of tunable ultra-short pulses of x-rays in all-laser Thomson scattering schemes [9]. Nevertheless, many applications do not require monoenergetic electron beams. For example, several groups have reported achieving significant yields of photonuclear reactions driven by bremsstrahlung radiation arising from laser accelerated hot electrons striking converters placed just before a photonuclear target sample [1,7,8,10]. Activation of nuclei by γ-induced reactions requires γ-ray energies corresponding to the giant resonances of the nuclei, which typically lie in the 10-20 MeV energy range for (γ,n) reactions and 5-10 MeV for (γ,fission) reactions. For example, the threshold γ–energy for one of the reactions studied here (^{63}Cu(γ,n)^{62}Cu) amounts to ~13 MeV. Such multi-MeV γ-rays can be efficiently generated through bremsstrahlung only if most of the accelerated electrons acquire energies above ~ 50 MeV.

Recent experimental advancements in laser wakefield studies [11-13] have demonstrated methods for generation of quasi-monoenergetic electron beams that satisfy the above conditions. For example, experiments by Faure et. al. [13] reported production of highly directional electron beams with energy up to 170 MeV and a spread of ~12% containing 0.5 ± 0.2 nC of charge per Joule of laser energy. Similar experiments have been performed using the Hercules laser at the University of Michigan where quasi-monoenergetic electron beams in the energy range of 100-300 MeV have been observed [14]. We report here on the application of quasi-monoenergetic electron beams generated with the Hercules laser for the efficient initiation of photonuclear reactions of $^{12}C(\gamma,n)^{11}C$, $^{63}Cu(\gamma,n)^{62}Cu$, and $^{238}U(\gamma,fission)^{134}I$ and ^{92}Sr. From our results and comparison with Monte Carlo modeling of the electromagnetic cascades produced, we infer characteristics of the accelerated electrons striking the targets, including their total number per laser pulse. As described further below, we have obtained between 10 and 100 times the photonuclear yields per Joule of laser energy compared to earlier similar experiments, signifying progress towards making this technique a practical tool for nuclear applications.

…

Results and Discussion

…

While the present table-top terawatt laser experiments, as well as those referred to here, have been aimed at demonstrating nuclear reaction rates that can be obtained with compact, relatively inexpensive, high repetition rate laser systems, laser driven photofission in uranium has also been produced previously by very high power, ps pulse lasers, namely RAL's Vulcan laser [19,20] and LLNL's Nova Petawatt laser [21,22]. Even with much greater energy per pulse, those single-shot experiments induced only somewhat greater rates of fission than the present experiment. For completeness, we summarize in the accompanying table the characteristics of the laser systems and uranium photofission rates for this full range of experiments.

Laser	Type	Rep. rate for fission exp. (Hz)	Peak intensity (W/cm^2)	Pulse energy (Joules)	Pulse duration (fs)	Fissions per Joule	Fissions per pulse
LLNL PW	Glass	10^{-4}	10^{20}	260	450	7×10^4	1.82×10^7
Vulcan	Glass	10^{-3}	10^{19}	50	1000	2×10^4	10^6
LOA	Ti:Sa	10	4×10^{19}	2	30	10^4	2×10^4
Jena	Ti:Sa	10	10^{20}	0.5	80	10^4	5×10^3
Hercules	Ti:Sa	0.017	10^{19}	1.2	30	3×10^5	3×10^5

Table II. Comparison of the laser systems and ^{238}U photofission rates achieved. The laser systems are the LLNL Nova Petawatt [21,22], the RAL Vulcan [20], the LOA "Salle Jaune" [5], the Jena 15 TW laser [18], and the University of Michigan Hercules (present work). The first two of these employ doped glass amplifiers and therefore operate in

essentially single shot mode, whereas the others use Ti:Sa and operate at up to 10 Hz repetition rate. The present Hercules repetition rate was limited primarily by the ability to pump the residual gas from the target vacuum chamber. Also listed here are the approximate peak laser intensities, pulse energies and durations, and the number of fissions inferred per Joule of laser energy and per laser pulse.

…

References

[1] W.P. Leemans, D. Rodgers, P.E. Catravas, C.G.R. Geddes, G. Fubiani, E. Esarey, B.A. Shadwick, R. Donahue, and A. Smith, Phys. Plasmas 8, 2510 (2001).

[2] W. P. Leemans, P. Catravas, E. Esarey, C. G. R. Geddes, C. Toth, R. Trines, C. B. Schroeder, B. A. Shadwick, J. van Tilborg, and J. Faure, Phys. Rev. Lett. 89, 174802 (2002).

[3] A. Modena, Z. Najmudin, A. E. Dangor, C. E. Clayton, K. A. Marsh, C. Joshi, V. Malka, C. B. Darrow, C. Danson, D. Neely, F. N. Walsh, Nature 377, 606 (1995).

[4] D. Umstadter, S.-Y. Chen, A. Maksimchuk, G. Mourou, and G. Wagner, Science 273, 472 (1996).

[5] V. Malka, S. Fritzler, E. Lefebvre, M.-M. Aleonard, F. Burgy, J.-P. Chambaret, J.-F. Chemin, K. Krushelnick, G. Malka, S. P. D. Mangles, Z. Najmudin, M. Pittman, J.-P. Rousseau, J.-N. Scheurer, B. Walton, and A. E. Dangor, Science 298, 1596 (2002).

[6] H. Schwoerer, P. Gibbon, S. Duesterer, R. Brehens, C. Ziener, C. Reich, and R. Sauerbrey, Phys. Rev. Lett. 86, 2317 (2001).

[7] G. Malka, M.M. Aleonard, J.F. Chemin, G. Claverie, M.R. Harston, V. Tikhonchuk, J.N. Scheurer, S. Fritzler, V. Malka, P. Balcou, G. Grillon, S. Moustaizis, L. Notebaert, M. Pittman, and E. Lefebvre, Proc. SPIE 4510, 47 (2001).

[8] B. Liesfeld, K.-U. Amthor, F. Ewald, H. Schwoerer, J. Magill, J. Galy, G. Lander, and R. Sauerbrey, Appl. Phys. B 79, 1047 (2004).

[9] Szu-Yuan Chen, A. Maksimchuk, and D. Umstadter, Nature 396, 653 (1998).

[10] H. Schwoerer, F. Ewald, R. Sauerbrey, J. Galy, J. Magill, V. Rondinella, R. Schenkel, and T. Butz, Europhys. Lett. 61, 47 (2003).

[11] S.P.D. Mangles, C.D. Murphy, Z. Najmudin, A.G.R. Thomas, J.L. Collier, A.E. Dangor, E.J. Divall, P.S. Foster, J.G. Gallacher, C.J. Hooker, D.A. Jaroszynski, A.J. Langley, W.B. Mori, P.A. Norreys, F.S. Tsung, R. Viskup, B.R. Walton, and K. Krushelnick, Nature 431, 535 (2004).

[12] C.G.R. Geddes, Cs. Toth, J. van Tilborg, E. Esarey, C.B. Schroeder, D. Bruhwiller, C. Nieter, J. Cary, and W.P. Leemans, Nature 431, 538 (2004).

[13] J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J.-P. Rousseau, F. Burgy, and V. Malka, Nature 431, 541 (2004).

[14] A. Maksimchuk, S. Reed, N. Naumova, V. Chvykov, B. Hou, G. Kalintchenko, T. Matsuoka, J. Nees, P. Rousseau, G. Mourou and V. Yanovsky, submitted to Phys. Rev. Lett. (2006).

…

[18] H. Schwoerer, F. Ewald, R. Sauerbrey, J. Galy, J. Magill, V. Rondinella, R. Schenkel, and T. Butz, Europhys. Lett. 61, 1 (2003).

[19] P. A. Norreys, M. Santala, E. Clark, M. Zepf, I. Watts, F. N. Beg, K. Krushelnick, M. Tatarakis, A. E. Dangor, X. Fang, P. Graham, T. McCanny, R. P. Singhal, and K. W. D. Ledingham, A. Creswell and D. C. W. Sanderson, J. Magill, A. Machacek, J. S. Wark, R. Allott, B. Kennedy, and D. Neely, Phys. Plasmas 6, 2150 (1999).

[20] K. W. D. Ledingham, I. Spencer, T. McCanny, R. P. Singhal, M. I. K. Santala, E. Clark, I. Watts, F. N. Beg, M. Zepf, K. Krushelnick, M. Tatarakis, A. E. Dangor, P. A. Norreys, R. Allott, D. Neely, R. J. Clark, A. C. Machacek, J. S. Wark, A. J. Cresswell, D. C. W. Sanderson, and J. Magill, Phys. Rev. Lett. 84, 899 (2000).

[21] T. E. Cowan, M. Roth, J. Johnson C. Brown, M. Christl, W.Fountain, S. Hatchett, E. A. Henry, A. W. Hunt, M. H. Key, A. MacKinnon, T. Parnell, D. M. Pennington, M. D. Perry, T. W. Phillips, T. C. Sangster, M. Singh, R. Snavely, M. Stoyer, Y. Takahashi, S. C. Wilks, and K. Yasuike, NIM A 455, 130 (2000).

[22] T. E. Cowan, A. W. Hunt, T. W. Phillips, S. C. Wilks, M. D. Perry, C. Brown, W. Fountain, S. Hatchett, J. Johnson, M. H. Key, T. Parnell, D. M. Pennington, R. A. Snavely, and Y. Takahashi, Phys. Rev. Lett. 84, 903 (2000).”