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Compact quasi-monoenergetic photon sources from laser-plasma accelerators for nuclear detection and characterization ☆

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ABSTRACT

Near-monoenergetic photon sources at MeV energies offer improved sensitivity at greatly reduced dose for active interrogation, and new capabilities in treaty verification, nondestructive assay of spent nuclear fuel and emergency response. Thomson (also referred to as Compton) scattering sources are an established method to produce appropriate photon beams. Applications are however restricted by the size of the required high-energy electron linac, scattering (photon production) system, and shielding for disposal of the high energy electron beam. Laser-plasma accelerators (LPAs) produce GeV electron beams in centimeters, using the plasma wave driven by the radiation pressure of an intense laser. Recent LPA experiments are presented which have greatly improved beam quality and efficiency, rendering them appropriate for compact high-quality photon sources based on Thomson scattering. Designs for MeV photon sources utilizing the unique properties of LPAs are presented. It is shown that control of the scattering laser, including plasma guiding, can increase photon production efficiency. This reduces scattering laser size and/or electron beam current requirements to scale compatible with the LPA. Lastly, the plasma structure can decelerate the electron beam after photon production, reducing the size of shielding required for beam disposal. Together, these techniques provide a path to a compact photon source system.

1. Introduction

Near-monoenergetic photon sources (MPSs) at 1–10 MeV energies offer improved sensitivity at greatly reduced dose for detection and characterization of nuclear materials. Many of the issues with current broad-band photon sources, including unnecessary dose that can interfere with the signatures to be detected and/or restrict operations [1], can be resolved using MPS capabilities to select energy, energy spread, flux, and pulse structure to deliver only the photons needed. MPS applications have however been limited by the sizes of the required high-energy electron accelerator, scattering laser, and electron beam dump. While nuclear transitions can be a source of very narrow line width photons, they are limited in selection of energies, intensity and portability. To enable new applications outside of fixed facilities, compact tunable MPSs are desired with narrow divergence to allow high spatial resolution and dose control, and to reduce need for collimation.

Thomson scattering of a laser from an electron beam is a well-established, tunable and narrow divergence MPS (also referred to as a Compton-Scattering or Inverse Compton-Scattering source) whose application is currently limited by the need for high energy electron linacs, which are large fixed facilities using conventional technology. Current MeV sources include HIGS at Duke [2] and TREX/MEGA-Ray at LLNL [3]. A new generation of sources is under construction including the Extreme Light Infrastructure project in Romania [4], a project at the Japan Atomic Energy Agency [5], and proposed facilities including those at FNAL [6], SLAC [7], and BNL [8]. More compact accelerators at electron energies of 200–600 MeV, suitable for application needs of 1–9 MeV photons (and to >15 MeV if desired), are now possible using cm-scale laser-plasma accelerators (LPAs). Initial experiments have demonstrated Thomson scattering photon production from LPAs [9] by placing a foil to back-reflect the drive laser onto the electron beam [10], or a femtosecond laser split from the LPA driver [11,12], but so far have resulted in broad bandwidth photon beams. LPA electron beam quality and scattering laser control must be improved to generate narrow bandwidth sources.

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Heavy shielding is conventionally required due to the high electron beam energy in Thomson MPSs. The low photon production cross section of Thomson scattering has also hitherto required either high electron current (and thus heavier shielding) or very large scattering lasers. Techniques to reduce shielding needs and scattering laser size, which can dominate overall system size and weight as the electron accelerator is made smaller, are hence important.

In this proceedings we show how a compact high flux Thomson scattering based MPS can be achieved by integrating a high quality LPA with techniques for scattering efficiency and for reduced shielding needs. MPS flux and bandwidth parameter ranges suitable for applications are reviewed in Section 2, and the implications of these for Thomson source design in Section 3. Development of high quality LPAs to provide the required electron source is described in Section 4. Techniques to achieve high photon flux with low bandwidth while reducing electron current and scattering laser size are presented in Section 5. Using the LPA to decelerate the electron beam to low energy after photon production can greatly reduce shielding requirements, as discussed in Section 6.

2. Monoenergetic photon applications

Experiments on existing fixed-facility sources, as well as simulations, have characterized the MPS beam photon flux, bandwidth, and repetition rates required to improve detection and/or characterization of nuclear material, as well as for nuclear physics studies. Modalities of interest for nuclear studies include radiography, photofission, and Nuclear Resonance Fluorescence (NRF). Photon energy, bandwidth, flux, and pulse structure are primary criteria.

For Radiography, selecting the energy of the photon beam can minimize dose, while using two or more energies can improve Z discrimination [13]. Because radiography cross sections vary gradually at MeV energies, relatively broad bandwidth at the 10–25% level is sufficient. For example scanning a 2.4 m high container at 80 cm/s with 1 cm resolution and penetrating 20 cm of steel (cf. ANSI N42.46) would indicate use of order 10^6 photons/shot at rates $\geqslant$20 kHz, while penetration of areas 40 cm thick would require of order 10^8 photons/shot. In this case, the repetition rate lower limit is set by the number of pixels which must be resolved. Milliradian beam divergence would allow the desired 1 cm resolution. To penetrate a given target thicknesses using doses approaching the lowest obtainable values, a first shot at each position can be taken with low flux, and the measured transmission used to determine attenuation for further shots at higher flux. Narrow bandwidth sources at the 10% level near 9 MeV, and at similar fluxes, also improve photofission-based interrogation and characterization by suppressing extraneous signals that can be generated with broader bandwidth or higher energy sources [14]. NRF methods, at isotope specific energies near 2 MeV, offer powerful isotope-specific identification for verification of absence of a substance [15], NDA of fuel [5], and the full range of applications. While the resonance line bandwidth is very narrow ($\sim 10^{-6}$ at room temperature), numerous studies (e.g., [5,15]) show that MPS bandwidth at the percent level FWHM (full width at half maximum) combined with control of photon energy allows isolation of the NRF line. Typical fluxes are in the range of 10^7ph/shot at $\geqslant$kHz repetition rates. In this case, the repetition rate lower limit is set by detector considerations. Sub-percent bandwidths improve resolution and can allow use of simple calorimetric detectors.

3. Compact monoenergetic photon system requirements

The parameters of a MPS in the required range of 10^6–10^8 photons/shot can be derived from the Thomson scattering equations for energy spreads of 10–25% at energies of 2–9 MeV (radiography/photofission) or energy spreads of a few percent at energies near 2 MeV (NRF). These are well understood and verified, to the level that scattering is used as an accelerator diagnostic on conventional machines such as the ALS linac at LBNL [16], HIGS at Duke [2], and Helmholtz-Zentrum Dresden-Rossendorf [17]. LPA-specific designs presented in detail in [18] are summarized here. Scattering near 180° between the electron and photon beams (backscatter) is chosen for peak photon energy. MeV photons are produced by upshifting of the scattering laser due to the relativistic motion of the electron beam. Available high power scattering lasers typically have $E_L \sim 1.5$ eV (0.8–1 μm) requiring a high-energy electron accelerator to produce MeV photons. Electrons near 200 MeV produce $\sim$1 MeV photons, and electrons near 600 MeV produce $\sim$9 MeV photons. Using conventional technology, such accelerators and the associated beam manipulation lines are large fixed facilities. Frequency up-conversion can double scattered energy to 2–18 MeV for the same electron energies, but use of very high frequency lasers is limited by the scattering cross section issues below. Scattered photons are emitted into an angular range $\sim 1/\gamma \sim 1/(2 * E_e[\mathrm{MeV}])$ around the electron beam direction and within that angular range display an energy-angle correlation resulting in a bow-like spectral intensity distribution (Fig. 1) which must be collimated to produce narrow bandwidth (limited by the on-axis bandwidth). The on-axis source bandwidth convolves electron beam energy and angular spread. The scattering laser can also contribute to this bandwidth via nonlinear broadening at high intensity, via its laser bandwidth or via multiple scattering. Limiting these effects typically requires operation of the scattering laser at low intensity ($\leqslant 10^{17}$ W/cm^2) and with long pulse lengths ($\geqslant$0.5 ps).

Due to the low scattering cross section and the need to keep scattering laser intensity low, very few (typically $<10^{-10}$) of the laser photons are scattered, and even scattering one photon from each electron is challenging. Lengthening the scattering laser pulse to increase yield is conventionally inefficient because it also requires increasing the laser spot size so that the laser remains focused over its pulse length. This results in wasted scattering laser energy since the laser diameter then greatly exceeds that of the electron bunch. The scattered photon yield then scales only as the square root of the laser energy. Fixed facility MPSs for this reason typically use modest laser energies and recirculate the (mostly unused) scattering laser to intersect with many electron bunches, from each of which much less than one photon is scattered per electron. This however increases the required electron current to produce a given number of photons, and hence increases both accelerator power and shielding, which is problematic in weight for transportable or small laboratory applications. In these cases, scattering efficiently at $\gtrsim$ 1 photon/electron can be important.

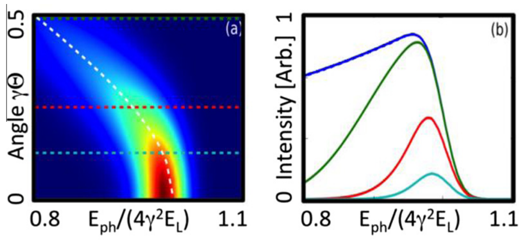

Fig. 1. A typical Thomson scattering photon spectrum, showing (a) intensity (colorscale) as a function of normalized energy and scattering angle; (b) spectra integrated over different collimator angles. The colors correspond to the collimations shown by the respective dashed lines in (a), illustrating that narrow collimation is required to achieve low bandwidth, down to the limit of the on axis bandwidth beyond which tighter collimation affects only intensity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)