Compact source of narrowband and tunable x-rays for radiography

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Abstract

We discuss the development of a compact x-ray source based on inverse-Compton scattering with a laser-driven electron beam. This source produces a beam of high-energy x-rays in a narrow cone angle (5-10 mrad), at a rate of 10^8 photons-s⁻¹. Tunable operation of the source over a large energy range, with energy spread of ~50%, has also been demonstrated. Photon energies > 10 MeV have been obtained. The narrowband nature of the source is advantageous for radiography with low dose, low noise, and minimal shielding.

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Selection and peer-review under responsibility of the Organizing Committee of CAARI 2014.

Keywords: Wakefield acceleration, Thomson scattering, X-rays, Photonuclear physics

1. Introduction

X-ray sources with MeV energy are critical for radiography and photonuclear applications. Currently, such sources are either based on bremsstrahlung or Compton scattering. The former are compact but have a broadband energy spectrum, while the latter produce narrowband x-ray beams but require facility-size devices [1,2]. Recent breakthroughs in the generation of high-quality electron beams from laser-driven wakefield accelerators have made it possible to develop a device that possesses both these attributes: narrowband, collimated MeV x-ray beams generated by a table-top device [3]. This novel x-ray source at the University of Nebraska-Lincoln (UNL) uses the process of inverse Compton scattering—in which a high-energy electron beam scatters off an intense laser pulse—to produce a forward directed beam of energetic x-rays [4]. The all-optical architecture comprises two high-intensity laser pulses. One laser pulse is focused to relativistic intensity (electrons oscillate in the laser field with a velocity close to the speed of light) and interacts with a supersonic gas jet to generate quasi-monoenergetic electron beams by the process of laser wakefield acceleration [5,6]. The second laser pulse, also focused to high-intensity, scatters off the laser-driven electron beam. The double Doppler shift associated with this process leads to a boost in the energy of the incident near-infrared light photons to x-ray wavelengths.

The UNL compact high-energy x-ray source is promising for a number of applications. The ability to generate photons with MeV energy makes it possible to use this device for radiography of dense objects [7,8], or trigger photonuclear reactions in order to detect the presence of actinides [9,10]. Small source size enables high-resolution

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imaging [11]. Moreover, narrow x-ray bandwidth can enable both radiography and photonuclear activation with low dose [12]. Collimated x-ray beams, with an angular spread of a few mrad, are useful for long standoff studies [13]. Finally, tunability over a large range of x-ray photon energy (from 10's of keV to MeV) makes it possible to study a range of phenomena, such as x-ray absorption [14], x-ray fluorescence, photodisintegration, photofission as well as high-resolution studies of embedded voids and cracks.

In this paper, we describe the development of the UNL all-laser-driven x-ray source. Detailed measurements of the source parameters are presented. Current efforts to extend the operational characteristics of the source, as well as improvements to the spectral characteristics, in particular reduction of the energy spread, will also be discussed. Finally, we consider some examples of specific applications that exploit the unique characteristics of the UNL source.

2. Laser-driven x-ray source

The x-ray source described in this work is driven by the 100-TW DIOCLES laser system at the University of Nebraska, Lincoln [15]. This laser operates on the principle of chirped pulse amplification [16]. A low-energy (nJ), ultrashort laser pulse (12 fs) is first stretched to 400 ps, then amplified to 5 J, and lastly recompressed to a final pulse duration of ~ 30 fs. At the output, the laser system produces 3 J per pulse (10-Hz repetition rate) at a central wavelength of 805 nm with a 40 nm bandwidth. The x-ray source based on inverse Compton scattering [17] requires two high-intensity laser pulses. In the first implementation of the source, the laser pulse is split after it is compressed using a beamsplitter (80% reflecting, 20% transmitting). The general layout for the device is shown in Fig. 1.

Figure 1: Layout of the all-optically-driven inverse-Compton x-ray source. Two laser pulses from the same laser system are used in this device to drive an energetic electron beam (drive pulse) and to scatter off the laser-driven electron beam (scattering pulse). The electron beam is imaged using a magnetic spectrometer and the x-ray beam by a fluorescent screen.

The wavefront of the high-power pulse is corrected using an adaptive feedback loop that is implemented using a deformable mirror and wavefront sensor. The reflected beam (drive pulse) is 1.9 J, 35 fs, and is focused onto the front edge of a supersonic gas jet using a 1-m parabolic reflector. As a result of the wavefront correction, a near-diffraction limited focal spot is obtained on target with a Gaussian full width at half maximum (FWHM) focal spot size of $20\ \mu\text{m}$. Thirty-three percent of the laser energy is enclosed in the FWHM width, corresponding to a peak intensity of $\sim 10^{19}\ \text{W cm}^{-2}$ (normalized vector potential of $a_0 \sim 2$). The choice of target is determined by the characteristics of the electron that are required to be generated. The scattering pulse was focused using a lens or a

parabolic reflector with 1-m focal length and intersects the drive pulse at an angle of $\sim 170^\circ$. A feedback loop is also used to optimize the spectral phase of the drive laser pulse such that the laser pulse at the interaction point is transform limited. Complete spectral characterization of the laser pulse is performed on target and in vacuum, and optimization of the spectral and spatial characteristics is performed under these conditions [18].

For the experimental results reported below, mixed gas targets (99% He + 1% N₂) are used for the generation of high-energy electron beams [19]. In the simplest implementation, a 2-mm supersonic nozzle is used to produce a high density gas flow ($n_e = 10^{19} \text{ cm}^{-3}$) and the drive pulse is focused onto the front edge of the flow. At the intensities used, the medium is fully ionized by the foot of the laser pulse. The peak of the pulse is self-guided in the medium, drives a wake in the underdense plasma, and electron beams are produced by the ionization injection mechanism (Pak et al. (2010)). The energy and charge of the electron beam are measured using a magnetic spectrometer with a fluorescent screen (LANEX) as the electron detector. The latter is imaged by a 12-bit CCD and the response of the detection system was calibrated independently. Under optimal conditions, beams with cutoff energy $< 300 \text{ MeV}$ are produced with charge $\sim 100 \text{ pC}$ for energy $> 50 \text{ MeV}$. A sequence of 20 shots for this accelerator is shown in Fig. 2 and illustrates that the accelerator operates in a stable regime with reproducible shot-to-shot characteristics.

Figure 2: Spectra of electron beam from the laser wakefield accelerator. The data shown is for 20 consecutive shots. The energy spectra are polychromatic with a cutoff energy $\sim 250 \text{ MeV}$ and total charge of 0.1 nC ($> 50 \text{ MeV}$).

The scattering laser pulse with 0.5 J is focused by a 1-m focusing lens. On account of dispersion in the beamsplitter, the pulse duration is 120 fs and b-integral effects lead to a focal spot with $22 \mu\text{m}$ diameter (FWHM) and 16% enclosed energy in the central spot. This measurement is performed under vacuum and at high power. The latter is accomplished by the use of wedges to attenuate the beam energy and permit measurements of the focal spot using a high-dynamic range CCD. Under these conditions the intensity at the focus of the scattering pulse is $\sim 3 \times 10^{17} \text{ W cm}^{-2}$, and the associated normalized vector potential a_0 is 0.4. Thus, the interaction is therefore in the linear regime. Spatio-temporal overlap of the beams is accomplished in several steps. First, the wakefield accelerator is optimized to ensure that the laser and electron beam are co-propagating. Optical techniques are then utilized to spatially overlap the two foci at the exit of the jet. For these experiments, the interaction point is chosen to be 1-mm downstream of the nozzle to ensure that focusing of the scattering pulse is not affected by the target. At this location, the transverse size of the electron beam and the focused scattering pulse are nearly matched. The pointing fluctuation of the high-power laser pulse on target is $5 \mu\text{rad}$, and the angular jitter of the electron beam is $5\text{--}10 \text{ mrad}$. Temporal overlap is obtained by means of spectral interference between the drive and scattering pulses.

The generated x-rays are detected by a CsI detector imaged with a 14-bit EMCCD operated in high-gain mode. The CsI array consists of 1-mm diameter, 10-mm long voxels, which are separated by epoxy [20]. Forty voxels are arranged in a two-dimensional $50 \text{ mm} \times 50 \text{ mm}$ grid. This arrangement ensures efficient energy deposition from MeV x-rays as well as reasonable spatial resolution limited by the pitch of the array (1 mm). The absolute response of the detection system was measured using standard radioactive source (^{137}Cs and ^{60}Co) and also modelled using the code MCNPX [21]. The latter was used to compute both the energy deposited in the array and the number of visible photons that are emitted. The results of the computation are validated by an absolute calibration of the detection system. Suitable shielding composed of lead blocks is used at appropriate locations to suppress the background signal on the CsI array from scattered electrons and bremsstrahlung x-rays. The shielding geometry is optimized by the use of MCNPX simulations that computes the background on the detection system as a result of scattering of high-energy electrons from the chambers walls and the walls of the room.

Figure 3: Layout of detection system for MeV x-rays: a voxelated CsI array is placed on the beam axis. The incident high-energy photons are absorbed in the array and result in the emission of visible photons which are imaged by a 14-bit EMCCD.

Under these experimental conditions, the interaction of the high-power laser pulse with the laser-driven electron beam results in generation of a forward directed beam of high-energy x-rays. These are imaged by the voxelated detector; a typical profile of the beam is shown in Fig. 4(a). Based on this measurement and the detection geometry, it is inferred that the angular divergence of the beam is 12 mrad. A simple attenuation measurement is then performed to determine the spectrum of the high-energy x-ray beam. Three different thicknesses of lead are used in a quadrant geometry to cover different sections of the beam as shown in Fig. 4(b).

Figure 4: Spatial and spectral characteristics of the x-ray beam measured using the CsI array. The angular profile of the beam is shown in (a) with angular divergence of 12 mrad. (b) The energy of the x-ray beam is inferred by the use of attenuating filters and measurement of the net transmission through each quadrant. (c) The expected spectrum of the x-rays is computed using a numerical model and the measured and computed transmissions are in excellent agreement.

A detailed numerical model that takes into account the spatial profile of the focused scattering pulse is used to compute the spectrum of the scattered x-rays [22]. The distribution of electrons in phase space is constructed using the measured angular profile and the energy spectrum of the electron beam. Based on these calculations, the angle-dependent spectrum of the x-rays is determined. The spectral distribution as a function of laboratory observation

angle is shown in Fig. 4(c). Using the computed spectrum at different angles, the transmission through each quadrant can then be computed and they are in excellent agreement with the measured transmission. Based on the absolute response, it is determined that 10^8 photons s^{-1} are produced at 10 Hz repetition rate. The size of the x-ray source is measured using a cross-correlation technique in which the scattering pulse is scanned along the vertical direction and samples different parts of the electron beam. The size of the x-ray source using this technique is found to be 5 μm . Based on prior studies measuring the temporal duration of the electron beam under the same conditions as this experiment, the peak spectral brightness is 2×10^{19} photons $s^{-1} mm^{-2} mrad^{-2}$ (0.1% BW). This brightness is nearly four orders of magnitude higher than from inverse Compton sources based on the scattering of a high-intensity laser pulse off an electron beam produced by a conventional accelerator [23].

3. Generation of narrowband x-rays

A modified design for the gas target was implemented to generate quasi-monoenergetic x-ray beams. Many schemes have been developed over the past few years to produce narrowband electron beams using the process of laser-wakefield acceleration. We have developed a method that produces energy-tunable electrons over a large energy range, while maintaining electron beam parameters such as energy spread and charge constant, as well as operates in a robust and reproducible manner. This was accomplished by the use of a structured gas target consisting of two jets. Mixed gas (99%He+1%N₂) was used in the first jet which functioned as the electron injector. Pure helium was used in the second jet and the electrons injected into the wake were accelerated in this section. This design enabled the generation of quasi-monoenergetic electron beams spanning 50-300 MeV. The scattering of these electrons with a high-intensity laser pulse produces quasi-monoenergetic x-ray beams, representing a significant advance over prior work using betatron emission as well as Compton scattering that produced broadband x-ray spectrum [3,11,24].

Figure 5: Measurement of the spectrum of narrowband x-rays using the Ross filter technique (a) checkerboard pattern of Ross filters on the CsI array (b) spatial profile of x-ray beam after transmission through the Ross filters (c)-(e) spectrum of x-rays measured using the Ross filters (black squares), measured electron beam spectrum (red curves) and computed x-ray spectrum (blue curves). The measured data points are in excellent agreement with the numerical model. Data shown in panel (c) is in absolute units: 10^7 photons $MeV^{-1} Sr^{-1}$ for the x-ray beam and $pC MeV^{-1}$ for electron beam.

Several methods can be used to precisely measure the energy spread of the x-ray beam, such as Compton scattering, single photon spectroscopy, or x-ray transmission. We implemented the Ross-filter technique that relies on measurement of transmission through materials near the k-edge, as shown in Fig. 5. Since the highest k-edge available is 116 keV for uranium, the electron energy was tuned such that the peak photon energy would be <100 keV. A set of k-edges were chosen to correspond to the relevant energy for this measurement. The detection system was the voxelated CsI detector described previously. The filters were attached to the detector in a checkerboard pattern to yield multiple data points per shot as shown in Fig. 5(a). The thicknesses were carefully adjusted so that each filter pair would provide the precise photon number between the corresponding k-edges and no signal outside this band. The x-ray beam transmitted through the filters is shown in Fig. 5(b), and the profile of the filters can be seen imprinted on the beam. The results of this measurement are shown in Fig. 5(c). They show the results from three different conditions for the electron beam spectrum ranging from narrowband to polychromatic (red curves). The measured spectrum is shown by the black squares and the blue curves show the fit to the data using the model with the electron spectrum as input. The measurement and the predicted spectrum are in excellent agreement. These results show that a monoenergetic x-ray beam can be produced in this all-optical architecture, and the beam characteristics can be controlled by variation of the electron beam parameters.

Measurements of the x-rays were performed using the entire tunability range of the electron accelerator from 50-250 MeV. For energies beyond 100 keV, spectral data was measured using transmission through known thicknesses of filters. These measurements indicated the mean x-ray energy was consistent with the electron spectrum. The bandwidth of the x-rays was inferred based on the measured electron spectrum and modeling. The results indicate that tunable narrowband x-rays spanning 0.05 – 2 MeV were generated for this configuration. Using the absolute response of the detection system, it was inferred that $\sim 2 \times 10^7$ photons s^{-1} were produced with 10 Hz operation for the laser system. The average energy spread is 40-50%, consistent with the 20% spread in the energy of the electron beam; the fluctuation in the photon number was $\sim 50\%$ on a shot-to-shot basis [25].

4. Narrowband x-rays above the photonuclear threshold

Following the demonstration of narrowband MeV x-ray beams, the next step was to extend the photon energy above the threshold for nuclear processes. The photofission threshold of actinides is ~ 6 MeV while the threshold for (γ, n) reactions is ~ 8 MeV. Two approaches are possible in order to increase the scattered photon energy which depends on the electron beam energy and the photon energy as $E_s = 4\gamma^2 E_L$, where γ is the Lorentz factor for the electron beam, E_L is the energy of the incident photons, and E_s is the scattered photon energy. While both approaches are possible, increasing the photon energy of the scattering beam is advantageous, since up-converting laser light by the process of harmonic generation is relatively straightforward. This would avoid the problems associated with the use of large magnets and the substantial shielding required when higher energy electron beams are used. Two further improvements were made to the system used for prior work. The beam was split before the pulse compression system in order to mitigate the effects of b-integral [26]. Two pulse compressors were used to independently compress and optimize the temporal characteristics of the scattering pulse. A KDP crystal was used in the scattering beamline to convert the incident 800 nm light to 400 nm by the process of second harmonic generation.

The lens used previously for focusing the scattering pulse was replaced with an off-axis paraboloid. Aberration in the crystal and the incident beam as well as nonlinear effects during the harmonic conversion process led to degradation of the 400 nm focus. A trade-off was found between the pulse duration and focusability, and it was empirically determined that for a pulse duration of 300 fs, the focusability of the 400 nm was acceptable. The detection system was further improved and the scattered x-rays were imaged using two CsI arrays. The x-ray beam was incident on the 1-cm thick CsI array, and the transmitted x-rays were then propagated through a custom filter and incident on a second CsI array with 2-cm thickness. The first array measured the spatial profile and pointing of the beam while the second array was used for measurement of the x-ray photon energy. The transmission of the x-ray beam through a specially designed filter was used to infer the energy of the x-rays. This measurement was

validated by computing the scattered photon spectrum and comparing the predicted transmission to the measurement.

X-ray beams were produced by the scattering of the 400-nm pulse off a high-energy electron beam. For these experiments, a 4-mm Laval nozzle was used. In this case, the energy spread of the electron beam is larger than the previous case where a dual nozzle was used. However, much higher energy x-rays were obtained. By tuning the plasma density, and using the highest laser power available, electron beams with energy up to 600 MeV were generated. Using again the process of inverse Compton scattering, extremely high energy x-ray photons were produced. The results of this experiment are shown in Fig. 6. The transmitted profile of the x-ray beam is shown in Fig. 6(a), and the reconstructed profile of the beam with the transmission through the filter is shown in Fig. 6(b). The transmission factor is obtained using the computed spectrum of the x-ray beam based on the electron spectrum shown in Fig. 6(c). The beam has an angular spread of < 5 mrad and maximum photon energy extending to 14 MeV with a quasi-monoenergetic feature at 13 MeV. The total photon number for this shot is estimated to be 10^6 . Under optimal conditions, we have measured $> 10^7$ photons per laser shot. By tuning the electron energy, it was possible to obtain x-ray beams with a quasi-monoenergetic spectral distribution with peak spanning the range 3–13 MeV. The angular spread decreased for higher energy x-rays, which is consistent with the fact that the angular width depends on the electron energy as $\sim 1/\gamma$.

Figure 6: Spatial profile of the high-energy x-ray beam (a) x-ray beam profile on second CsI array after transmission through the filters (b) reconstructed x-ray profile on second CsI array (c) electron spectrum (black curve) and corresponding photon spectrum (red curve).

5. Applications of narrowband Compton source

The UNL x-ray source represents a significant breakthrough for applications that require MeV photons, by virtue of its table-top size combined with its tunable, narrowband, high-brightness and well-collimated x-rays. The fact that it is laser-driven makes it relatively compact as compared with conventional Compton sources. Its narrow bandwidth can lead to lower dose on target relative to standard bremsstrahlung sources. Thus, it can potentially lead to detection with lower noise, on account of the absence of background from the scattering of low-energy photons. The absence of a strong flux at lower energies also minimizes the need for shielding. The low-divergence of the source is useful for long stand-off studies. Moreover, the linear dependence of the x-ray flux on scattering laser intensity implies that the dose delivered by the source is easily controllable by adjusting the laser power. Finally, by operating near the threshold for photonuclear reactions, the tunability of the photon energy enables element-sensitive detection in particular actinides. The source characteristics are being further improved in the following ways: (i) increase of x-ray photon flux by the use of higher energy in the scattering beam (ii) lower bandwidth x-rays by tuning the electron accelerator to reduce the energy spread to $< 10\%$ (iii) stable and reliable operation of the source by improvements to the pointing of the laser and electron beams as well as minimization of fluctuations. Experiments in which the source is used for radiography and activation are currently in progress.

Acknowledgements

This material is based on work supported by the US Department of Energy (DOE), Office of Science, Basic Energy Sciences (BES), under Award # DE-FG02-05ER15663 (ultrafast x-ray science); the Air Force Office for Scientific Research, FA9550-11-1-0157 (high-field laser-electron scattering); the Department of Homeland Security Domestic Nuclear Detection Office, under competitively awarded contract HSHQDC-13-C-B0036 (low-dose x-ray radiography); and National Strategic Research Institute, FA4600-12-D-9000 (selective photo-activation analysis). This support does not constitute an express or implied endorsement on the part of the Government.

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