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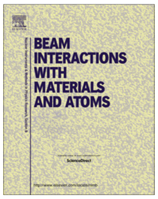

Compact source of narrowband and tunable X-rays for radiography

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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.

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 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

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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.

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 μm. Thirty-three percent of the laser energy is enclosed in the FWHM width, corresponding to a peak intensity of $\sim 10^{19}$ 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 ~170°. 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% N_2) 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 ($n_e = 10^{19}$ 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. 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 MeV are produced with charge ~100 pC for energy >50 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.

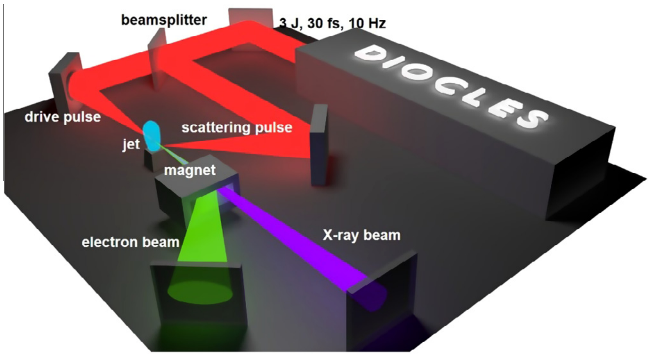

Fig. 1. Layout of the all-optically-driven inverse-Compton X-ray source. Two laser pulses from the same laser system are used in this device to drive an energetic electron beam (drive pulse) and to scatter off the laser-driven electron beam (scattering pulse). The electron beam is imaged using a magnetic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

The 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 μm 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 $\sim 3 \times 1017$ 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 μrad, and the angular jitter of the electron beam is 5–10 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 (Fig. 3). 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 mm × 50-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 modeled 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.

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).

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