All-laser-driven, MeV-energy X-ray source for detection of SNM

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A quasi-monoenergetic MeV x-ray source based on laser-driven electron acceleration and Thomson scattering is under development at the Extreme Light Laboratory at the University of Nebraska, Lincoln. Reported are experimental results on the generation of high-brightness, nearly monoenergetic 300-MeV energy electron beams with the high power, short-pulse DIOCLES laser system. The laser system produces > 100 TW of maximum peak power per pulse. The maximum pulse energy is 3.5 J with a temporal duration of 30 fs. Energetic electron beams are produced by focusing a laser pulse with 40-50-TW peak-power on a supersonic helium nozzle to drive a relativistic plasma wave (laser wakefield). Electron beams with energies of $320 \pm 20 MeV$ are accelerated over a distance of 3 mm. The beam has an angular spread of 5 mrad with a charge of 100 pC. The use of a stable and well-characterized laser system----in conjunction with high temporal contrast and adaptive optics correction on the amplified beam (to obtain ideal focal spots) ---has enabled generation of very reproducible electron beams, both in terms of energy and pointing stability. It is found that electron acceleration is most efficient, beam brightness is highest and reproducibility is best in the resonant regime, where the temporal duration of the laser pulse equals the plasma period. A beamsplitter is used after compression to generate two pulses in the ratio of 80% to 20%. The higher power pulse drives the laser wakefield to produce the energetic electron beams while the lower power pulse is transported through an independent line and focused on the electron beam to generate x-rays. Experiments are currently in progress to observe and characterize the x-ray beam. Theoretical predictions indicate that 1--2±10% --MeV x-ray photons can be produced in a well-collimated beam. The expected photon flux is 10^9 photons per laser shot. Characterization of such a high-flux high energy x-ray beam is in progress. Quasi-monoenergetic x-rays offer significant advantages for the detection of sensitive nuclear materials using techniques such as nuclear resonance fluorescence. A systematic effort is also in progress to further improve the characteristics of laser produced electron beams with regard to monochromaticity, divergence and stability and also permit easy tunability of the x-ray source. The design of a compact system capable of being deployed in the field will also be discussed as part of a long-term solution to the critical requirement for an efficient cargo-scanning system.

I. Introduction

Laser systems based on chirped pulse amplification [1], like the DIOCLES system at UNL, are extremely compact devices capable of producing simultaneously ultra-high peak power, >100 TW [2, 3], ultra-short duration pulses, <30 fs [4], at 10-Hz repetition rate. The recent development of robust high-power laser systems has been accompanied by similar progress in laser-based particle accelerators [5,6]. Early breakthroughs in laser-based electron acceleration resulted in the generation of MeV energy electron beams with mm-sized accelerators [7,8]. While these beams had extremely low transverse emittance, the acceleration mechanism led to a Boltzmann-like distribution in energy that resulted in poor longitudinal emittance which would severely limit the brightness of any radiation source constructed with these electron sources. However, beginning in 2004, this problem has been partially overcome by the discovery of a new mechanism, the so-called "bubble regime," and quasi-monoenergetic beams have been produced [9, 10, 11]. The energy of these beams is also significantly larger than that obtained with most experiments using longer laser pulses, and opens up the possibility of generating hard x-rays using table-top accelerators.

At the same time, it is possible to envision control and manipulation of the plasma itself to tailor the characteristics of electron beams for specific applications via the use of well-defined density distributions to promote self injection or the use of multiple laser beams to directly inject electrons into the plasma. Matching of the laser and plasma parameters has been proposed as a simple yet effective way to increase the beam energy as well as achieve lower energy spread, improved transverse emittance and more reliable operation. Guiding of the laser beam over many Rayleigh lengths by the use of suitable media is of considerable interest as a way to achieve ultra-high (»1 GeV) energy gains.

Additional significant considerations to enable for real-world applications of such accelerators rest on their reliability, reproducibility, robustness and compactness. Over the past decade a large body of evidence has indicated that laser driven electron accelerators suffer from significant fluctuations on a shot-to-shot basis. It was generally assumed that such instabilities were from the laser system itself. However, it raises the question as to the extent to which laser driven accelerators can be controlled and stabilized. Is controllability just engineering or are there fundamental physical limitations based on the fact that the process rests on nonlinear effects in

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a plasma. To this end a stable and well characterized laser system is required in order to establish the limits on the performance of laser accelerators. If successful, such an accelerator producing high-quality, > 100 MeV electrons beams in a reliable way would open up a plethora of applications of relevance to homeland security applications, in particular scanning of cargo containers for detection of shielded sensitive nuclear materials.

In this paper we describe the program currently underway at the University of Nebraska, Lincoln (UNL) to develop high-brightness x-ray sources using a state-of-the-art 100 TW laser system and a compact wakefield accelerator. In section II we describe the high-power laser system and the characteristics which make it unique for applications. Section III summarizes the results obtained with regard to generating high-brightness electron beams. In section IV we discuss the current status of experiments to generate x-rays using a counterpropagating geometry. The expected photon yield from such a device is detailed. Section V discusses the applications of such sources to problems of relevance to homeland security and the path forward in particular the next generation of ultracompact laser systems and mobile detection.

II. 100 TW LASER SYSTEM

The 100 TW DIOCLES laser system at UNL was built by Thales laser and is a table-top short-pulse laser system producing > 5 J per pulse at 10 Hz. The laser system built to extremely stringent standards and housed in a temperature and humidity controlled class-10000 clean room attains unprecedented levels of reproducibility and reliability. A schematic of the laser system is shown in Fig. 1. The system consists of an oscillator producing nanojoule level pulses at 76 MHz with a pulse duration of 12 fs. An acousto-optic modulator (DAZZLER) steps down the frequency to 1 kHz which is then stretched to ~300 ps. These stretched pulses at 1 kHz are then amplified in a multi-pass amplifier to 1 mJ. The choice of a multipass amplifier was made to avoid the poor contrast typically associated with regenerative amplifiers. Typical nanosecond contrast attained after this amplification stage and an electro-optic pulse cleaner is better than 10^{-9}. The pulses (at 10 Hz) after the pulse cleaner undergo three more stages of amplification in flashlamp pumped titanium:sapphire amplifiers which boosts the energy of the pulse from 1 mJ to 60 mJ, then 2 J and finally 5 J. The laser system is extremely compact and the upto 2 J per pulse can be obtained using a system which occupies a single optical table 15'x5'. Most applications described here require the power associated with this level of energy. The beam exiting the final power amplifier is expanded in size to 3" and then compressed using a pair of large diffraction gratings to a final duration of 30 fs and ~3.5 J per pulse. The use of the DAZZLER permits precise control of the spectral characteristics of the pulse to compensate for gain narrowing and red-shifting in the amplifier as well as compensation of second and higher order phases to obtain the shortest possible pulse. Precise tuning of the various multipass amplifiers, in particular the delay between the pump and amplified enables us to attain a nanosecond contrast of 10^{-8} for the amplified pulse which is amongst the best ever attained for such systems without additional pulse cleaning techniques.

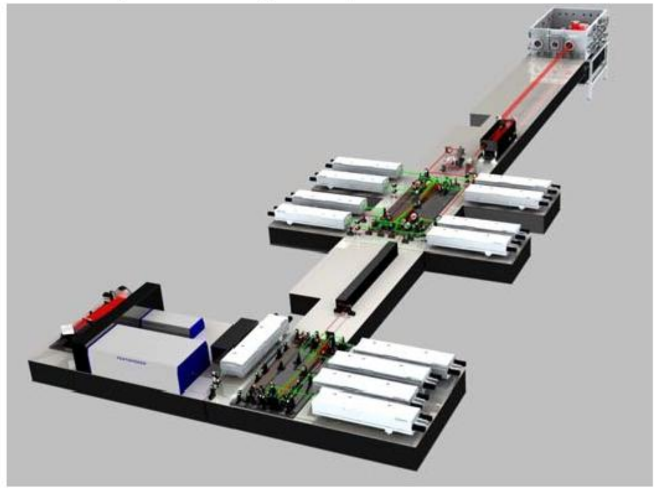

Fig. 1: Layout of the 100 TW laser system. Chirped pulse amplification is used to amplify a seed pulse to 5 J and finally compressed to 30 fs. The highest peak power attained is 140 TW.

Peakpower:		**140 TW.**
Repetition rate:		**10 Hz (0.1 Hz)**
Central wavelength:		**805 nm**
Pulse duration:		**< 30 fs**
Pulse energy:		**3.5 J (compressed)**
Energy Stability:		
	•Short-term (1 min): 1.5%	
	•Medium (1 hour): 0.5% rms	
	•Long(8 hours): 0.8% rms	
Pointing stability:		**(1 min): 3.5mrad**
Strehl ratio:		**0.95**
Focusability:		**Diffraction-limited**

Table 1: Characteristics of the DIOCLES laser system at full power operation. The unprecedented levels of stability made possible by a robust design and an optimal environment lead to reliable and reproducible daily operation.

The characterization of high-power laser pulses presents significant challenges. In particular extrapolation of results obtained at low power, are invalid, since significant changes occur in the wavefront as power amplifiers are turned on. In order to perform measurements with laser pulses at the Joule level, sampling of the beam is required to obtain the level of attenuation required for performing these measurements. DIOCLES has been equipped with a multi-stage sampling unit to permit the use of diagnostics on the beam. An optical shutter system is also used to permit modification of the repetition rate of the laser from single-shot to 10 Hz. The laser system is fully characterized with regard to characteristics and reliability. All measurements below were done with the laser operating at full output and the beam sampled with a wedge, a beam attenuation system comprising of a waveplate and polarizers and a final sampling wedge after compression.

Initially, the focal spot obtained with a 1 m focal length paraboloid without any correction of the phase-front of the laser pulse had a size of 25-30 microns containing 30-40% of the incident energy. The resulting electron, beam had a large divergence, low-energy and with poor-reproducibility. A large aperture dielectric deformable mirror integrated with a wavefront sensor was implemented to improve the spatial quality of the laser beam. The use of adaptive optics to correct the beam led to a dramatic improvement in the focusability of the laser and a corresponding improvement of the electron beam. The strehl ratio of the pulse could be improved to 0.95, which indicates a nearly perfect beam in terms of the spatial intensity and phase. In practical terms, this implies a beam which can be focused to the diffraction limit. Direct measurement of the focus with a 1-m focal length paraboloid leads to a focal spot with a diameter of 16 microns was obtained for an incident beam of 2.7 inches diameter with a top-hat profile containing 75-80% of the incident energy. The experimental measurements performed with a high-dynamic range, 12 –bit CCD camera are show in Fig. 3.

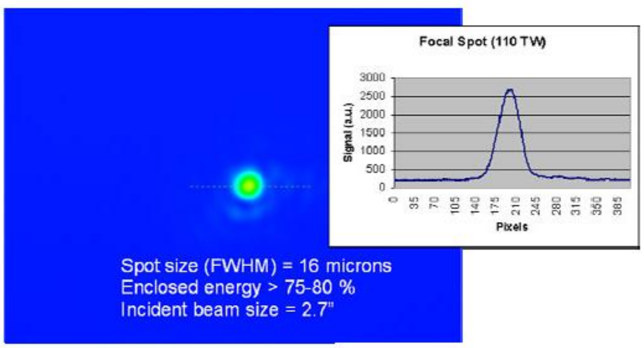

Fig. 3: Focal spot obtained with a 1 m focal length paraboloid. The incident wavefront of the laser has been corrected with a deformable mirror.

III. GENERATION OF ENERGETIC ELECTRON BEAMS

We have carried out a detailed study of the generation of energetic electron beams from the interaction of ultraintense and ultrashort laser pulses with underdense plasmas. A high-intensity laser pulse is focused onto the supersonic nozzle using a 1 meter focal length paraboloid. The resulting vacuum intensity is 5×10^{18} W cm^{-2}. In order to obtain the best electron beam it is necessary to position the nozzle precisely with respect to the focus. This requires accurate three-dimensional positioning of the nozzle. Experiments indicate that the best electron beams are obtained when the focal spot is placed at the gas-vacuum interface, the beam propagates along the middle of the nozzle and the focal spot is 300-400 μm above the nozzle. The experimental setup permits a large number of parameters to be varied independently. In particular we have studied the dependence of the electron beam on the following: (i) laser energy (ii) pulse duration (iii) gas pressure (iv) focal spot and have optimized the beam with respect to these parameters.

In order to optimize the electron beam we have studied in detail the characteristics of the electron beam produced under different laser and plasma conditions. This is accomplished by varying the corresponding parameters and measuring the electron beam parameters. Typically, in these experiments the laser pulse duration and the focal spot are optimized. During actual experiments, most commonly the laser intensity is scanned. We have also studied the stability of the electron beam with respect to the laser contrast. It can be concluded on the basis of our investigation that the best electron beams are produced for pulse duration of < 30 fs, Strehl ratio of 0.9 or better and laser power > 30 TW. Additionally the nanosecond contrast of the beam needs to be 10^{-8} of the main pulse. Any degradation of laser parameters from these values results in electron beams with low charge, large divergence angle and large energy spread. Under optimal laser conditions we have also studied the dependence of electron beam parameters on the plasma condition. This is varied by varying the backing pressure which results in a change of the plasma density, or by using supersonic nozzles with different lengths which effectively alters the acceleration length. We have studied the process of electron beam generation for electron densities in the range 2×10^{18}-2×10^{19} cm^{-3} and for acceleration lengths in the range 1-3 mm. As a result of the optimization process we have obtained very high quality electron beams. The best electron beams are obtained for laser power of 40-45 TW, with 3 mm nozzles and resonant density. The resonant density corresponds to the case where the plasma period equals the temporal duration of the laser pulse. For these scans, it is necessary to vary the position of the jet along the propagation direction since the self-focusing of the beam changes as the intensity or density is varied and the new optimal point has to be located for each setting. At high-density (self-modulated regime), the electron beam has large divergence and Maxwellian energy distribution. As the density is lowered, the energy distribution becomes more monochromatic. At resonance, the best beams are obtained with extremely small divergence and energy spread. The results of these experiments are depicted in Figs. 4. If the density is lowered even further, the energy spread increases and the beam brightness is decreased on account of a reduction of charge in the beam.

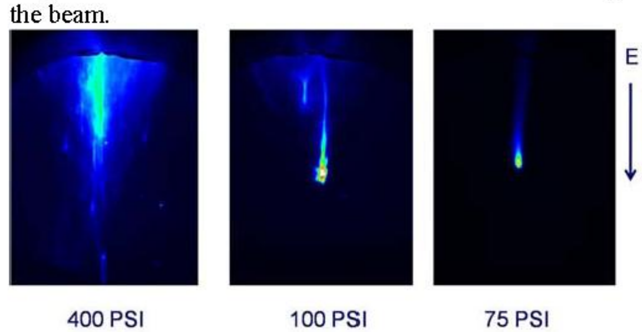

Fig. 4: Dependence of electron beam characteristics on plasma density. Horizontal axis depicts angular divergence and vertical axis is electron energy. As resonance density is approached the beam divergence decreases and becomes more monochromatic.

At resonant density (corresponding to a backing pressure of 50 PSI) we obtain high monoenergetic beams with extremely low divergence. With the laser operating in the high-contrast mode, the beam is very reproducible in terms of pointing and energy. For the results, depicted in Fig. 5 we have calculated the characteristics of the electron beam produced in our experiments. Under best conditions the electron beam can be produced on every shot with an angular profile whose width is nearly constant but the beam pointing varies shot-to-shot. Typical results show that the electron beam has an angular divergence of 10 mrad (full beam) and the pointing stability is approximately the size of the beam.

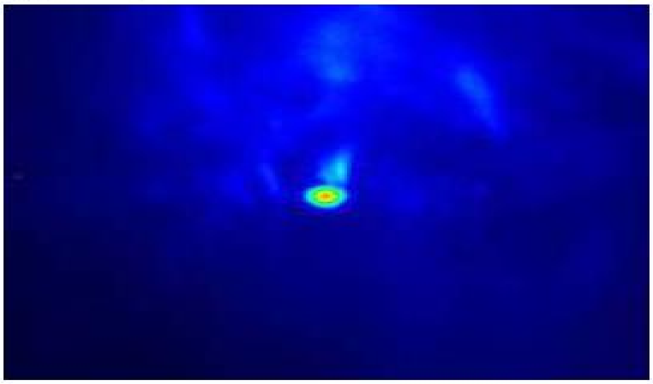

Fig. 5. Electron beam produced with 45 TW of laser power at 1.2 times resonant density.

The energy spectrum and the corresponding angular divergence of the electron beam is obtained by dispersion through a 0.5 T permanent magnet spectrometer with pole faces of 2" length which is placed inside the vacuum chamber ~ 3" from the interaction region. The results are depicted in Fig. 6. It is clear from the spectrum that the electron beam has a strong quasi-monoenergetic component at high energy. Based on the calibration of the spectrometer using standard formulae, the monoenergetic peak is found to be located at ~ 220 MeV with an energy spread of ±7.5%.

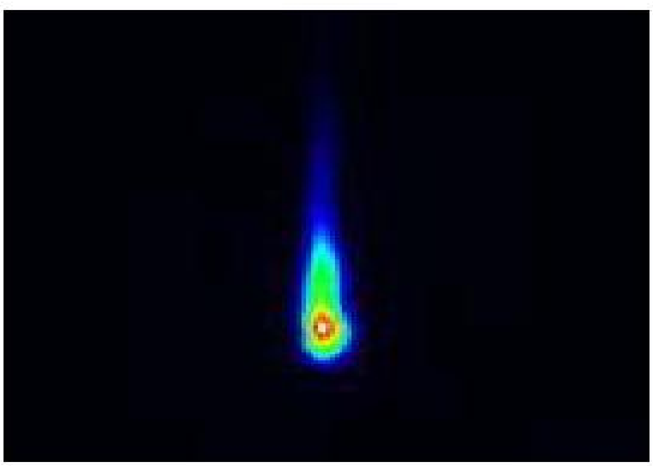

Fig. 6. Energy spectrum of electron obtained for the conditions of Fig. 4. The peak energy is 220 MeV and the spread is ~15%.

Based on the above results it is possible to estimate the transverse emittance of the beam. For the entire beam, assuming a spot size of 10 μm, corresponding to the focal spot, and a beam divergence of 10 mrad, the emittance, $\varepsilon = 5\times10\times10^{-3} = 0.1$ mm mrad. However, the emittance strongly depends on the electron energy. For the monoenergetic peak at 320 MeV (γ=650), the angular spread is ~ 2.5 mrad. The normalized emittance, $\varepsilon_N = \gamma\times2.5\times10^{-2} = 17$ mm mrad, which compares favorably with standard rf guns at these energies. It is to be noted that other groups have assumed the electron beam to have a spot size of 3-4 μm for a laser spot of 20 μm. A similar assumption for our case would result in a transverse emittance of only 10 mm mrad which is amongst the best ever reported for an electron beam at these energies.

Detailed measurements of the beam charge have also been carried out with a fast transformer. It is found that the total beam charge is 10-12 nC for the whole beam. However, much of the charge is located in the lower energy tail. The charge of the quasi-monoenergetic component can be estimated by one of two ways (i) integrating the area under the spectrum and comparing to the total area. This leads to a charge of 0.5 nC in the quasi-monoenergetic component. However, since the spectrometer does not extend to energies <10 MeV, this overestimates the charge in the monoenergetic bunch. A more accurate measure is obtained by comparing the output for shots where a monoenergetic beam is present and comparing to those where there is no such component. This leads to a beam charge of ~0.1 nC in the monoenergetic component.

One of the major issues associated with a wakefield accelerator is the shot-to-shot instability. Our experiments show a dramatic improvement in the quality of the electron beam when a deformable mirror is used. However, even with diffraction limited focusing it is found that the angular position and energy spectrum of the electron beam varies shot-to-shot. This has been verified by monitoring the laser focal spot via equivalent plane imaging. Thus, the observed instability cannot be entirely eliminated using an extremely stable laser system. A significant component of the instability arises from the nonlinear interactions in the plasma; specifically strong modulations of the laser pulse as it propagates in helium from ionization induced defocusing as well as self-phase modulation. These nonlinear interactions can be greatly suppressed by the use of a high-contrast laser pulse. Our experiments indicate that there is dramatic improvement in the shot-to-shot stability both for the beam energy and pointing when the laser contrast is better than 10^{-7}. The latest results indicate that the pointing improves to < 1 mrad (rms) shot-to-shot in this regime. Further improvement can be attained with the use of a discharge to eliminate the effects of ionization induced defocusing.

IV. X-RAY GENERATION FROM THOMSON SCATTERING

High-brightness gamma-ray beams can be generated by the scattering of energetic electrons off ultraintense laser pulses. The approach we have proposed and are implementing is based on the recent demonstration that high-energy quasi-monoenergetic electron beams can be obtained from laser-produced plasmas. When such an electron beam scatters off an ultraintense laser pulse, a collimated γ-ray beam results (akin to a synchrotron, but with a device ten-thousand times smaller). This is in contradistinction to un-collimated radiation from bremsstrahlung or radioactive sources. As an example, a 400- MeV electron beam scattering off an ultraintense laser pulse (~10^{18} W cm^{-2}) in the counterpropagating geometry would produce x-ray photons with energy 2.6 MeV.

We have implemented a setup to study the generation of x-ray from the Thomson scattering of an intense laser pulse off a laser-generated electron beam. The pulses have been aligned, focused and spatio-temporally overlapped. The stringent requirements on the overlap require the use of multiple motor drives to permit precise movements in vacuum. We have observed, channels from both pulses in the interaction region and current efforts are focused on obtaining signatures of the interaction of the two pulses using shadowgraphy. It is possible to use external injection to produce stable monoenergetic beams. However, Thomson scattering experiments at this time will rely on self-injection which we have already demonstrated produces electron beams adequate for the generation of MeV x-rays.

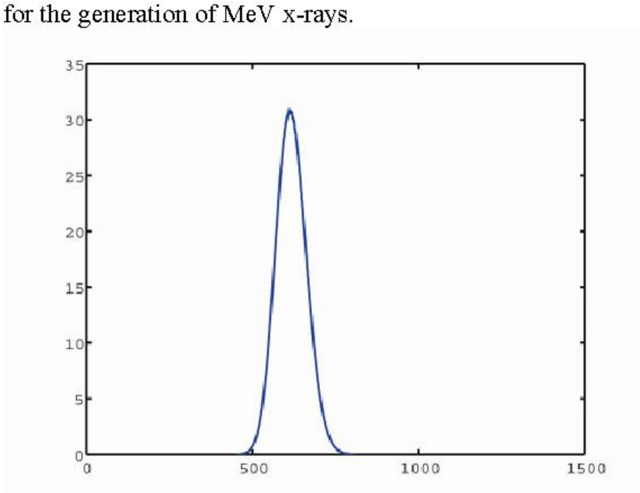

Fig. 7. Calculated x-ray characteristics shows a strongly peaked forward directed beam results when a 200 MeV electron beam interacts with a moderately intense laser pulse. The peak contains 10^9 photon per pulse.

The performance of the Compton source has been theoretically simulated for the regime it is expected to operate in. detailed calculations have been performed which enabled us to obtain preliminary predictions on the x-ray yield as well as associated beam characteristics. With experimental data expected to be obtained shortly with the Compton device now being tested at UNL, it will become possible to benchmark these predictions which will enable refinement of the code to improve accuracy for future predictions. The laser pulse is taken to have linear polarization and to be much broader than the diameter of the electron beam. The effect of electron beam energy spread is included by taking an incoherent sum of the mono-energetic cross-section over a distribution of beam energies. The strength of the laser field is described in terms of the normalized vector potential a_0. For the values of a_0 considered, the frequency of the scattered radiation is only weakly dependent on it. Thus the temporal envelope of the laser pulse will not result in additional bandwidth and can be ignored. The divergence of the electron beam will broaden the cone of the scattered radiation. We have conservatively estimated that the overall divergence of the scattered radiation will be the sum of the natural cone width plus the electron beam divergence. Additionally it is assumed that this electron beam divergence will not, to lowest order, increase the bandwidth. The spectral characteristics of the scattered radiation is shown in Fig. 7.

V. Applications of Laser produced sources to problems of relevance to homeland security

Nuclear excited states can be accessed by the absorption of high-energy photons. Typical excited states of nuclei lie in the MeV range and have linewidths of <1 eV. When, excited nuclear states decay, γ-photons with characteristic energies are emitted isotropically, and these lines, which can be resolved by high-resolution detectors (e.g. Ge) form unique signatures for every isotope. Thus a combination of a suitable γ-source to cause excitation in matter and detection of the scattered photons can be used to uniquely identify the isotopic composition of bulk matter; its application in cargo inspection was first proposed by Bertozzi. The use of NRF as a sensitive tool to detect SNM can be enabled by the use of a suitable γ-source and associated detection system, constituting a compact device capable of scanning large objects in the shortest possible time. An all-laser driven γ-source is expected to have all of the desired characteristics - (1) high spectral intensity, $I = N\gamma/eV\ s$ (number of photons per energy bin and second), (2) good monochromaticity 3 $\Delta E\gamma/E\gamma<<1$, (3) tunable in a broad energy range, and (4) a high degree of linear polarization $P\gamma\sim100\%$.

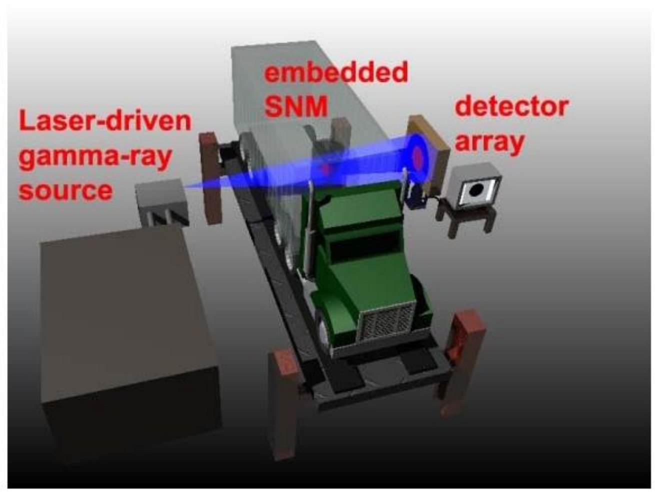

Fig. 8: Schematic of mobile cargo-scanning device based on an all-optical system producing MeV x-ray beams.

Generation of hard x-rays from laser electron scattering is being actively pursued by several groups worldwide. The PLEIADES group at LLNL has been at the forefront of activity in this field and other groups, notably at Vanderbilt and INEEL have also reported the generation of keV x-rays using such a configuration. All of these groups have used a combination of a linear accelerator and a high power laser system to generate energetic photon beams. An all-laser device is now possible, based on previous theoretical studies and the ability to generate 0.1−1-GeV electron beams from laser accelerators. Laser accelerators have a degree of tunability with respect to the electron energy, making possible a tunable γ-source, unlike most standard RF-accelerators, which operate at a fixed energy. The simplicity and compactness of laser-electron accelerators can also be exploited to obtain a tunable source by varying the angle between the laser and electron beams. Isotopic specificity will be obtained via nuclear resonance fluorescence (NRF), made possible by the quasimonoenergetic and tunable characteristics of the source, while ballistic photon discrimination will lead to improved contrast. LLNL predicts that Compton scattering-based sources of x-rays can be 10^{12} times more effective than bremsstrahlung for NRF. More reliable detection of true positives, and near-elimination of false-positives, will enable the use of this system as an early warning device. Additionally, the quasi-monoenergetic nature of the laser-produced γ-source, and its current shot-to-shot fluctuation with-respect-to the central energy, is advantageous in as much as it permits excitation of NRF lines, for a wide-range of actinides without the need for tuning. In terms of portability, an all-optically driven source has a significant advantage over the standard configuration of a linear accelerator used in conjunction with a high-power laser. In order to generate $2 - 3$ MeV or higher energy γ-rays, the corresponding electron energy would have to be in the range of $350 - 430$ MeV, requiring extremely large accelerators, which would require a large and dedicated facility to operate. A laser based accelerator and scattering device would have a footprint of a $100 - 200$ sq. ft., which would fit in a freight vehicle, and could be moved from one location to another, significantly enhancing the capability of DNDO to look for SNM at various locations, and permitting spot inspections. Active detection of shielded SNM by means of NRF has significant advantages over competing approaches based on radiography, or the passive detection of radiation from fissile material. In order to effectively image the interior of cargo containers, extremely bright x-ray sources are required. Prototype devices can only deliver keV x-rays, which have limited penetration depth, and do not provide specific isotopic signatures, leading to the possibility of a high-rate of false-positives, a feature, which is not desirable in an early warning system. Passive detection schemes, *e.g. neutron emission* while simple to implement, can be defeated by the use of suitable radiation shields. Another, possibility is the use of high energy neutrons, and detection of the resulting γ-rays. This however has the drawback of activating most common materials, a feature shared by techniques that have proposed the use of >6 MeV γ-rays. It is also possible to perform radiography using γ-emission from isotopes like 137Cs or 60Co; besides the lack of tunability and low brightness this approach uses large quantities of radioactive material, which — by itself — constitutes a dirty-bomb type security hazard.

ACKNOWLEDGMENT

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