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Next-Generation X-Ray Lightsource and First Applications

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Final Report

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14. ABSTRACT
During the period of this grant we have investigated and developed two sources for generating highly brilliant X-ray radiation from a comparably compact setup. The sources are based on the emission of synchrotron radiation from ultrashort relativistic electron bunches that are generated through high-intensity laser-plasma interactions, namely laser-wakefield acceleration.
The developed sources include (i) a setup, where the radiation is generated by an external permanent magnet undulator and (ii) a source, where the radiation is generated by transverse (betatron) oscillations of the electron beam during the plasma acceleration process itself. The undulator-based source is capable of generating narrow-band radiation, which for current parameters of laser-wakefield accelerated electron beams emit at soft X-ray wavelengths. In particular, we have observed radiation at a photon energy around 300 eV from electron beams with an energy of 350 MeV. To this end, we have developed an ultrafast X-ray beamline that includes a compact electron transport system based on miniature quadrupole magnets, a home-built undulator with one the shortest periods of only 5 mm for permanent magnet undulator published to date, and electron beam and X-ray diagnostics.
Our betatron-based source generates polychromatic radiation that extends from the soft X-ray (< 2 keV) into the hard X-ray range (>30 keV). In particular, within this grant period, we have demonstrated a novel method of enhancing and controlling laser-driven betatron radiation that has led to an increase of more than one order of magnitude in the number of generated photons compared to previous methods using the same laser parameters. We expect that the method has the potential to lead to further significant enhancements. We also showed that the method allows us to control the X-ray beam parameters. This part of the research has led

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Grant #: FA9550-15-1-0125
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Accomplishments

The overall goal of the proposed research was the development of a compact laser-driven next-generation X-ray source. The source is based on the emission of synchrotron radiation from ultrashort relativistic electron bunches that are generated through high-intensity laser-plasma interactions from a comparably compact setup. It is driven by the Diocles PetaWatt laser at the Univeristy of Nebraska – Lincoln. The developed sources include (i) a setup, where the radiation is generated by an external permanent magnet undulator and (ii) a source, where the radiation is generated by transverse (betatron) oscillations of the electron beam during the plasma acceleration process itself.

Part of the grant involved the design and fabrication of an ultrafast X-ray beamline endstation, that includes the electron beam transport from the source through the undulator that is specifically designed for laser-wakefield accelerated and various electron beam and X-ray diagnostics. To house the endstation, we have designed and built a versatile vacuum chamber compatible with the existing hardware at the Diocles laser.
For the electron beam transport, we have simulated and designed an extremely compact electron beam transport system. The setup is based on miniature permanent magnet quadrupole lenses with field gradients of 500 T/m (see figure 1). We have successfully tested the setup and were able to focus electron beams with energies around 350 – 400 MeV at various positions inside the chamber. This was an extremely important milestone as the gap of our undulator is only 1.5 mm wide, which requires a well-collimated electron beam. The typical energy spread of laser-wakefield accelerated electron beams of 5 -10% makes is a challenge for the focus and collimation of the electron beam. We have also demonstrated that we can angularly steer the electron beam with our lenses.
An undulator is a device that generates a sinusoidal magnetic field, which is used to transversally accelerate electrons that propagate through the device and force them to emit radiation. As undulators with the required properties are commercially not available, we have developed an undulator with the shortest period reported in the literature for a permanent magnet device. The undulator has been assembled and the magnetic field tuned and characterized. The undulator has a period of only 5 mm, but despite the small period, the undulator has still a moderate K parameter of 0.5.

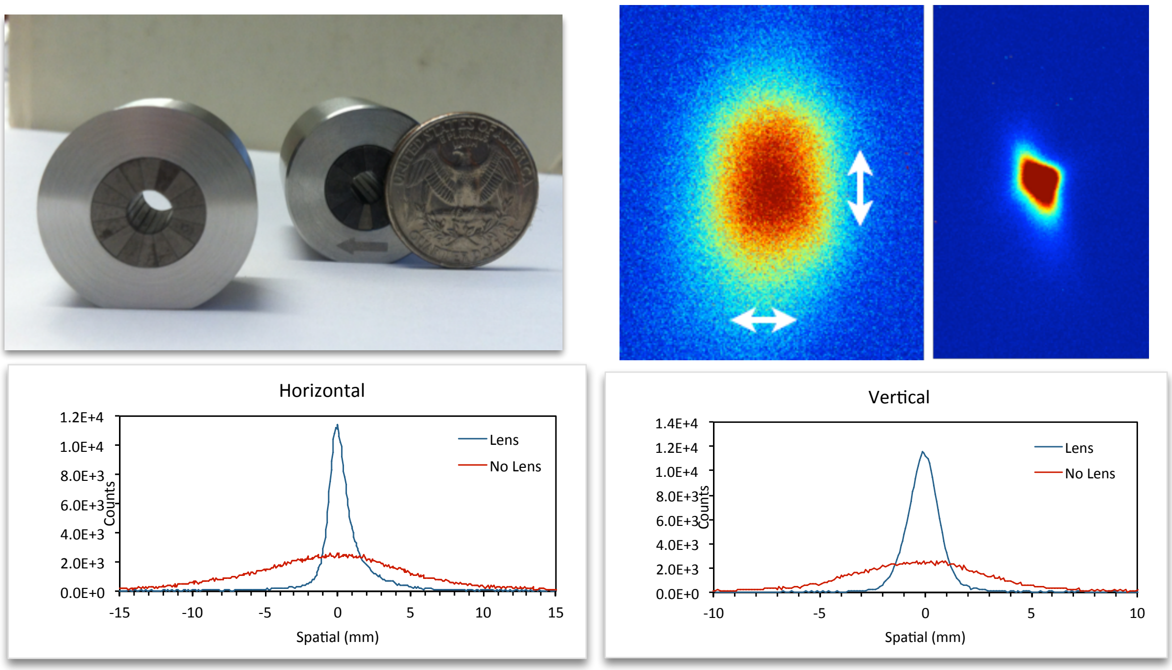

Figure 1: Electron beam transport. *Left shows the compact permanent-magnet quadrupole lenses. The unfocused electron beam is shown in the middle and the collimated beam on the right. The white arrows indicate a 5 mm size corresponding to a solid angle of 2.9 mrad. Horizontal and vertical line-outs of the unfocused (collimated) electron beam are shown on the bottom.*

In a subsequent step we introduced the undulator, which was set to a gap distance between the magnets of only 1.5 mm. The setup of the beamline includes an X-ray spectrometer for characterization of the generated radiation (see figure 2). The energy of the electron beam was tuned to around 350 – 400 MeV, from which we expect to generate radiation with a photon energy of ~300 eV. Figure 3 shows the X-ray signal recorded with a transmission grating based spectrometer. Unfortunately, we observed a significant background that presumably is due to betatron radiation generated in the plasma electron accelerator. Through modifications in the setup, we were able to mitigate most of the background but only by significantly decreasing the acceptance angle into the spectrometer. This also significantly decreased the undulator signal reaching the detector. We were able to observe the 0.th (non-diffracted beam) of the transmission grating.

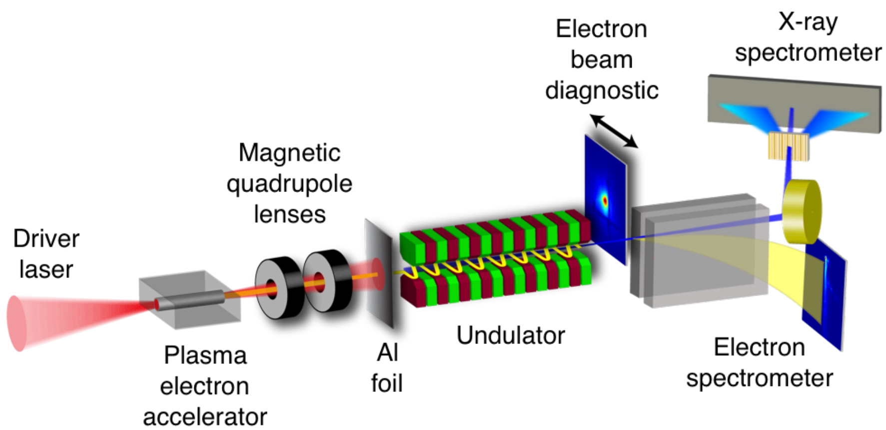

Figure 2: Experimental undulator setup. *The laser-wakefield accelerated electron beam (yellow) is collimated by a doublet of permanent magnetic lenses. The laser is filtered by a thin Al foil, while the electrons propagate through the undulator, where they generate X-ray radiation (blue). The electron spot size, divergence and energy are characterized by various diagnostics. The X-rays are spatially and spectrally characterized by a transmission-grating based spectrometer and an X-ray CCD detector.*

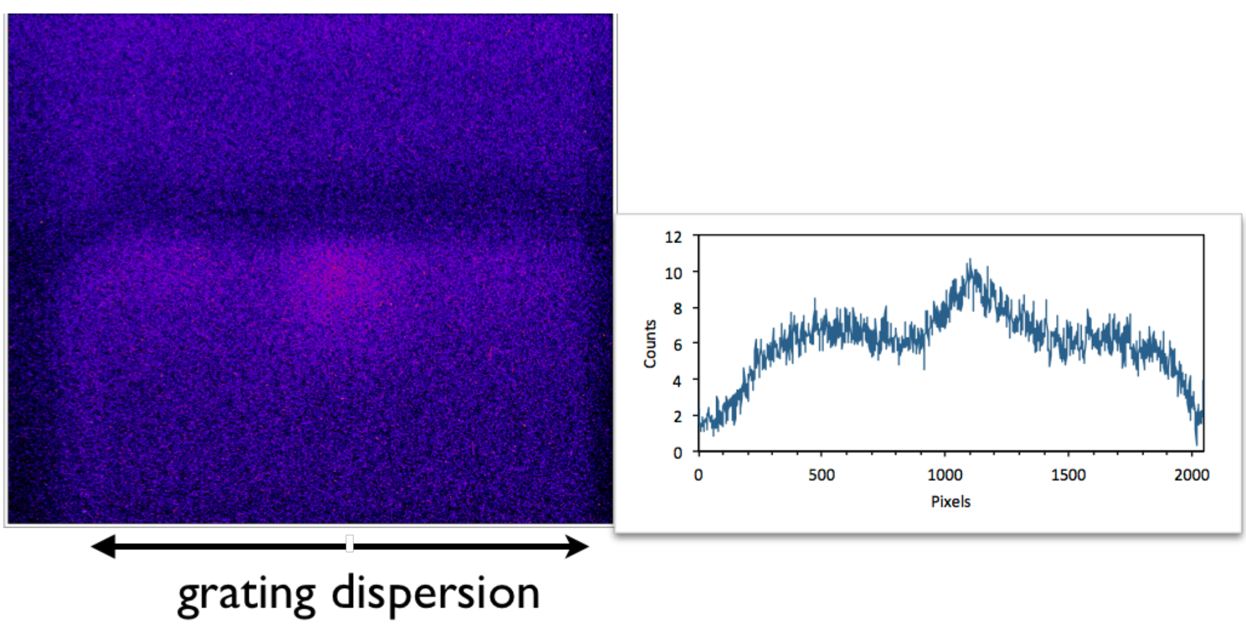

Figure 3: Observed undulator spectrum*. Left shows the observed undulator radiation signal measured with the transmission grating-based X-ray spectrometer. The bright spot is the zeroth diffraction order (transmitted beam). The lineout on the right shows the signal of the +- 1st diffraction orders.*

In a subsequent campaign, we have investigated a novel method of generating highly-brilliant laser-driven betatron X-ray radiation that allows a significant enhancement and control of the radiation parameters (manuscript in submission). In this method, the radiation is produced by electrons that are transversally oscillating in the plasma accelerating structure during the acceleration process. The photons are emitted in a wiggler-like spectrum with a high number of closely spaced harmonics. The number of generated photons and the energy of the emitted photons can be enhanced, among others by increasing the oscillation amplitude. In particular, in a recent proof-of-principle experiment we have used a specifically tailored plasma density profile, namely a double-peaked "M"-shaped profile with a density depression (see fig. 4). Compared to a non-structured gas jet, the data shows an increase of more than one order of magnitude in generated photons per pulse. The photons are emitted into a wiggler-like spectrum with an estimated total number of $5x10^9$ photons per pulse in the energy range of 3-30 keV. The spectral observation range was limited by the experimental setup. The method also showed significantly more stable operation compared to a non-structured jet. The generated radiation has an extremely high brilliance due to a source size of only a few micrometers and an expected pulse duration of only a few tens of femtoseconds. We have also demonstrated that by using this novel technique we were able to change and control the radiation parameters.

In a betatron source, the radiation is generated by the transverse (betatron) oscillation of the electron beam during the acceleration process. In laser-wakefield accelerators, the oscillation is due to the non-zero initial transverse momentum of the electrons acquired during the injection process and to strong transverse focusing forces. In our experiment, we have used a specifically tailored density profile to enhance and control the amplitude and period of the transverse oscillations and thus control properties of the X-ray radiation as they are strongly correlated to those of the electron trajectories. More specifically, we have focused the laser into our novel gas target. In the first density peak of the plasma profile (see fig. 4), the laser undergoes significant evolution due to the laser-plasma interaction. This results in a periodic transverse modulation of the electron self-injection region and the injection of copious amounts of charge during the density downramp. This leads to a large-amplitude coherent transverse betatron motion of the injected electrons and a strong X-ray emission that is significantly enhanced in comparison to the non-structured, round gas jets.

In the experiment, we have compared the radiation generated from a double-peaked "M"-shaped density profile to round 4 and 6 mm diameter gas jets, having a Gaussian radial profile. The peaks of the tailored gas jet each have a width of ~2.2 mm and are interrupted by a density depression of 2.3 mm (see Fig. 4). Note that the effective plasma length in this target is only ~4.4 mm. We have measured an increase of more than an order of magnitude in the number of generated photons and an extension in the emitted photon energy as compared to a non-structured jet.

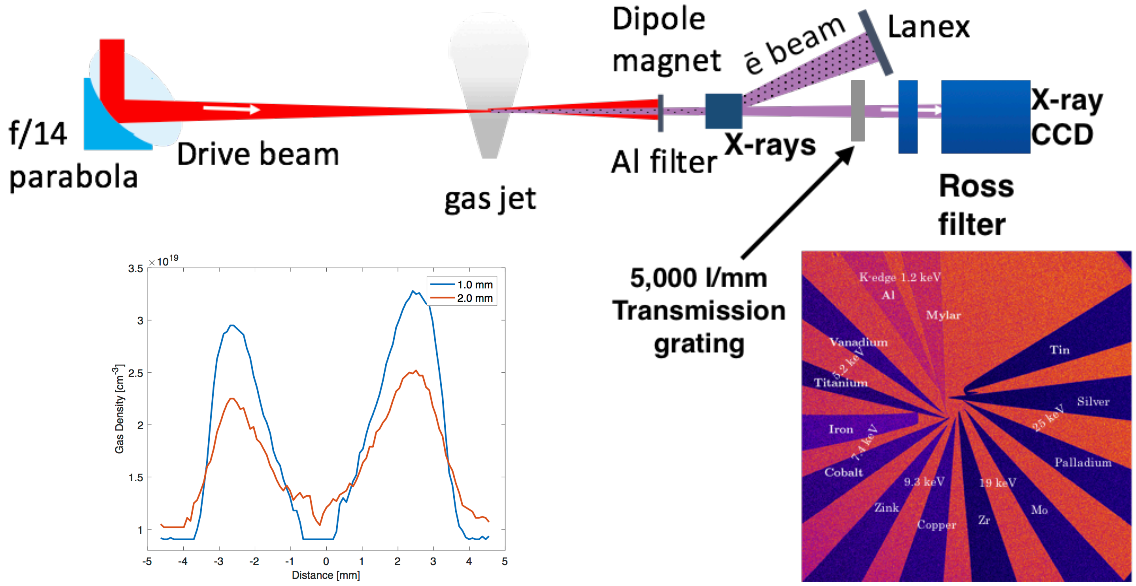

Figure 4 | Experimental betatron setup*. A high-power laser (red) is focused into a gas jet (blue), where generates a relativistic electron beam (yellow). Because of the nonzero transverse momentum, electron transversely oscillation during the acceleration. This leads to an emission of betatron radiation (purple). The laser is filtered out using a thin Al foil, while the X-rays are largely transmitted. The electron beam is deflected by a dipole magnet and its spectrum is recorded. The X-ray radiation is characterized using a set of Ross filters or a 5000 lines/mm transmission grating and is recorded using an X-ray CCD camera. The transmission through the different filters used for the Ross measurements is shown in the inset. A gas jet with a double-peaked density profile (measurement shown in lower left for different heights above the jet) was used to demonstrate an enhancement of the betatron emission.*

We only compare the tailored jet to the round 6 mm diameter jet, because that jet generated significantly brighter X-rays than the 4 mm jet. In the experiment (see Fig. 4), we were able to simultaneously measure the electron beam and the X-ray pulse properties. We have used multiple methods to spectrally characterize the X-ray beam. The results based on differential transmission filter measurements are shown in Fig. 5 and the results using a 5000 l/mm Au transmission grating in Fig. 6. It can be clearly seen that both, the number of emitted photons and the critical energy of the betatron radiation are significantly enhanced using the tailored gas density profile. Note that due to a finite detector size, we were only able to observe part of the emitted betatron radiation. We can use the observed electron beams (see Fig. 6) to get an estimate of the emission angle of the X-ray pulse and from that obtain the number of photons in the entire X-ray beam. Since the observed electron beam divergence of the double-peaked jet is clipped by the aperture of the dipole magnet, we use a conservative low value of 50 mrad. The observed number of photons using the transmission grating agree well with the Ross filter pair measurement. In case of the 6mm non-structured jet, we observe ~1×10^8 photons/pulse using the grating and ~2×10^8 photons/pulse using the filters. For the density-tailored jet, we observe more than 5×10^9 photons/pulse with the grating and 4×10^9 photons/pulse for the filters. For the structured jet, not only the total number of photons were increased but also the on-

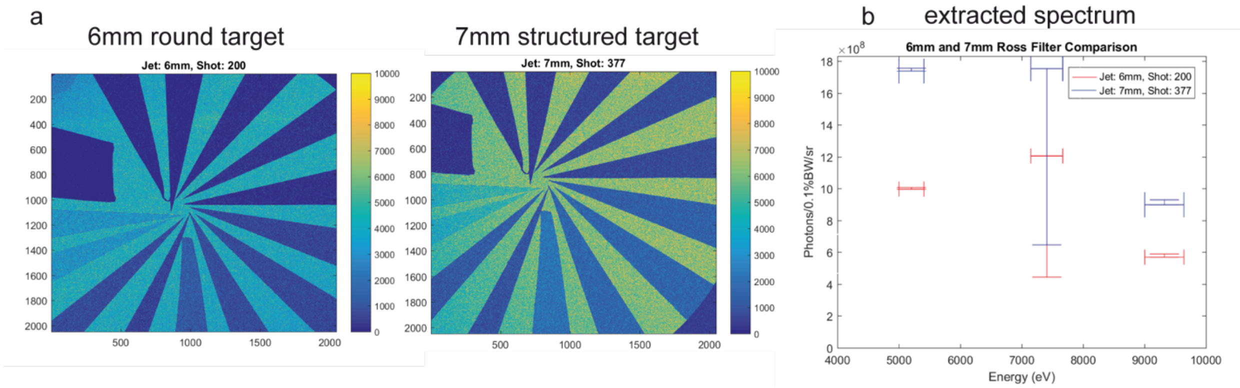

***Figure 5 | Ross Filter Spectral Measurement**. The betatron spectra for a 6mm round jet and a 7 mm structured gas target were measured using 6 pairs of Ross transmission filters. An enhancement of the on-axis flux can be observed for the structured jet. Due to the finite size of the X-ray camera, only part of the whole beam was detected. **b** shows the spectral flux extracted for 3 Ross pairs. The error bars are due to counting statistics and the mismatch in the filter transmission. The pressure of the 6 mm jet was optimized for maximum emission. The number of photons were extracted at 5.25 keV to be for the 6 mm jet: 10 x10^8 ph/0.1%b.w./sr. For a 100% b.w. and an angular divergence of 15 mrad (estimated from the electron beam divergence), the number of photons in the whole beam is 2x10^8 photons/pulse. In case of the 7 mm jet, 17.5x10^8 ph/0.1%b.w./sr lead to 4x10^9 photons/pulse for a divergence of 50 mrad.*

axis flux. With the same laser parameters, the radiation generated by the jet with the density depression was also significantly more reproducible.

The angularly-resolved spectra of the electron beams shown in figure 7 generated by the double-peaked jet agree with the kinematics of the model described above. The broad energy spectrum from the 6 mm jet is due to continuous injection into the bubble caused by the comparably high plasma density. The spectrum of the electron beam generated by the "M"- jet extends to significantly higher energies and shows a spectrally relatively narrow peak at the highest energies. However, the divergence of the high-energy feature is significantly larger than that of any spectra observed from the round jet and is even clipped by the aperture of the spectrometer magnet. This is consistent with a coherent betatron oscillation with an significantly increased amplitude. In order to investigate the validity of the model, we have performed extensive particle in cell (PIC) simulation. The simulation results agree well with the observed data.

We have also modified the gas density profile by lowering the gas jet with respect to the laser focus position, while increasing the backing pressure to obtain similar peak densities. As can be seen from the density measurement in Fig. 4, the gas density profile diverges with increasing distance from the nozzle, which effectively decreases the density gradients of the peaks. By decreasing the density gradients, both the number of generated photons and the emitted photon energy can be decreased. This allows us to effectively control the properties of the generated radiation.

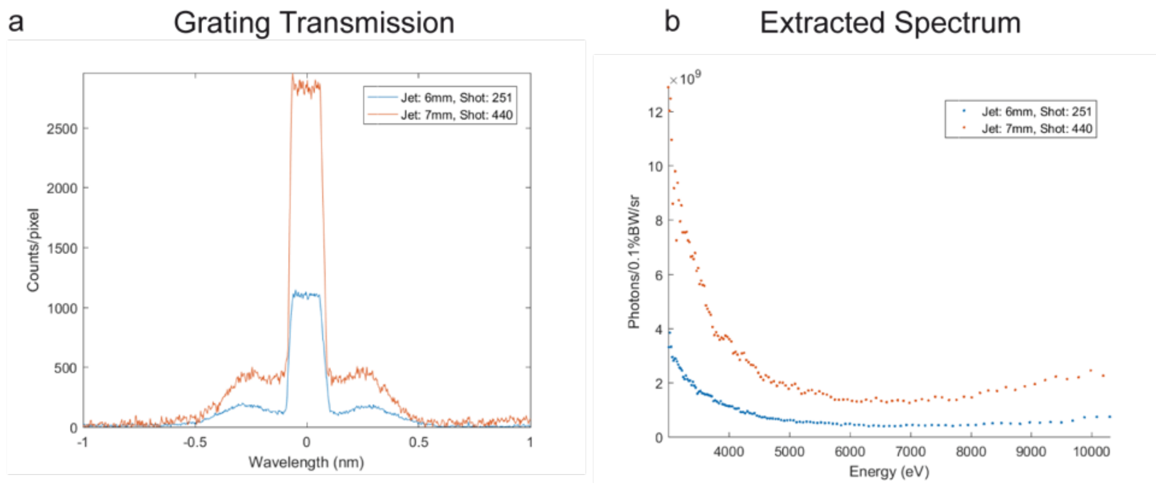

***Figure 6 | Transmission Grating Spectral Measurement**. **a)** shows the transmitted radiation through a 5000 lines/mm grating for a 6 mm round jet (blue) and a 7 mm structured jet (red). **b)** shows the extracted spectra. The spectrally integrated photon number for the 6 mm leads 0.5x10^{12} photons/sr and for an estimated 15 mrad divergence to an estimated number of 1x10^{8} photons/pulse. For the 7 mm jet, 2x10^{12} photons/sr and 5x10^{9} photons/pulse (assuming a 50 mrad divergence).*

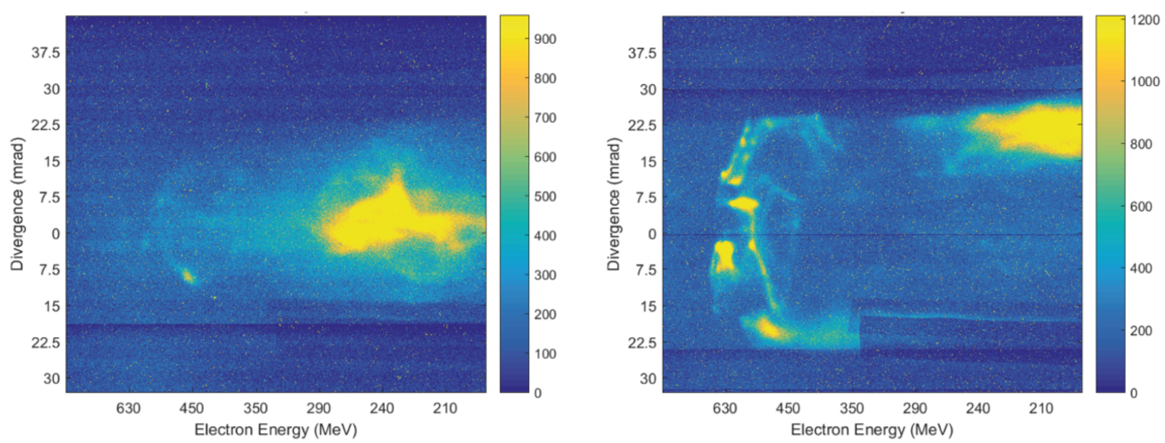

***Figure 7 | Angular-resolved Electron Beam Spectra**. Left shows the electron beam generated by the 6 mm round gas jet. The broad spectrum is typical for continuous injection in LWFAs operated at high plasma density. Right shows the spectrum generated by the structured gas jet. It shows a comparably narrow feature at higher energies than the 6 mm jet with a significantly larger divergence. This is consistent with a beam that is injected in the first peak and then performs oscillations with a larger amplitude in the 2nd peak. The lower-energy broad feature is most likely due to self-injection in the 2nd peak.*