Progress toward a laser-driven x-ray free-electron laser

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Measurements of the beam quality of electrons from the ALPHA-X laser-plasma accelerator show it is close to what is required to drive a compact short-wavelength synchrotron source.

The use of x-ray radiation has driven the development of synchrotron sources and, more recently, x-ray free-electron lasers (FELs). These microwave-based facilities are huge and expensive, yet governments are prepared to support them (usually one per nation) because of their great value to industry, academia, and society. However, laser-wakefield accelerators (LWFAs) are now advancing to the point where compact radiation sources could be developed into a new, complementary, or even disruptive technology. In addition to reductions in scale and cost—by a factor of up to 1000—x-ray pulse durations are significantly shorter than those of conventional lasers, which could facilitate probing of ultrafast dynamic processes.

The Advanced Laser-Plasma High-Energy Accelerators towards X-rays (ALPHA-X) project, based at the University of Strathclyde, is developing laser-plasma accelerators as drivers of radiation sources.¹ The first demonstration of a compact synchrotron source based on an LWFA was recently demonstrated using a conventional undulator and a diverging electron beam.² Our challenge is to develop a compact x-ray FEL. Here we focus on developments to improve the electron-beam properties and discuss the suitability of LWFAs as drivers of FELs. Our work shows that the once-distant prospect of a compact x-ray FEL is now within reach.

On the ALPHA-X accelerator beam line (see Figure 1), electrons are accelerated in a relativistically self-guiding plasma channel formed in a hydrogen-gas jet by a 35fs titanium-sapphire laser pulse with a power of 1J. Electrons are self-injected from the background plasma into the density wake that trails behind the laser pulse (through the combined action

Figure 1. The ALPHA-X compact wakefield accelerator, beam-transport system, and undulator.

of the laser's ponderomotive force and the plasma's restoring force). Measurements of the electron-energy spectra are carried out using a magnetic-dipole spectrometer with a wide energy range (up to 700MeV) and excellent energy resolution ($<0.5\%$).

To date, laser-plasma accelerators have produced electron beams with rms energy spreads typically in the 2–10% range that are usually instrument-resolution limited.^{2–5} Our initial results show that monoenergetic electron beams of up to 100MeV can be produced with an rms relative energy spread $\sigma_\gamma/\gamma < 0.8\%$ (see Figure 2), where γ is the Lorentz factor. We also demonstrate effective beam transport using dipole and quadrupole magnets. We know from simulations that the electron bunches are a fraction of a relativistic plasma wavelength (i.e., $\ll \lambda_p \approx 6\mu\text{m}$ for our gas-jet parameters), which implies that electrons see a large variation in potential across their length. However, the Coulomb force of the electron bunch produces its own wake, which has the effect of partially cancelling out the laser-generated wake and thus of reducing the variation in the potential. This results in a

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Figure 2. Electron-energy spectrum measured using a magnetic-dipole spectrometer, in arbitrary units (a.u.). σ_γ/γ : rms relative energy spread.

marked reduction in the energy spread (see Figure 3).

We explore the implications for FEL operation using our 15mm period-magnetic undulator. CCD images of the transverse electron-beam profile show that the divergence is of order 2mrad. Assuming a beam size at the accelerator exit (on the basis of simulations) on the order of a few microns, we can estimate the beam's normalized emittance $\varepsilon_n < 1\pi\text{mm mrad}$. This satisfies one condition for FEL gain, which requires the geometric emittance to be less than the wavelength, i.e., $\varepsilon_n < \lambda\gamma/4\pi$, where λ is the radiation's wavelength ($\lambda \approx 250\text{nm}$ for our setup).⁶

A more stringent condition exists for the energy spread. For net FEL gain, σ_γ/γ should be less than the FEL gain parameter ρ .⁶ For a 10pC electron bunch in our beam line, we estimate $\rho \approx 0.011$ and 0.002 for $\lambda = 250$ and 8nm, respectively. Comparing this to the measured energy spread (upper limit: $\sigma_\gamma/\gamma = 0.008$), the beam quality is close to (or may already satisfy) the requirement for net FEL gain.

We showed that the quality of the electron beams produced by our laser-plasma accelerator approaches that required for an FEL, which would substantially increase the photon yield. The next step is to pass the matched electron beam through an undulator to realize a compact vacuum-UV FEL. Our current setup should also be able to demonstrate FEL gain in the soft x-ray regime ($\lambda < 10\text{nm}$).

Figure 3. Simulations showing energy-spectrum compression due to beam loading. ξ is an axial coordinate parameter showing that the electron bunch length is about 1 micron. γ is the Lorentz factor.

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