Coherent radiation sources based on laser driven plasma waves

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Abstract— **In this talk we will explore ways of converting laser radiation to coherent electromagnetic radiation using laser-driven plasma waves. Several schemes will be explored, including colliding laser pulses in magnetized plasma and utilizing ultra-short electron bunches from laser wakefield accelerators to produce intense single-cycle pulses through coherent transition radiation and few-cycle coherent synchrotron radiation in undulators and plasma channels. These sources rely on high current electron bunches with femtosecond durations, which result in radiation over a broad range of frequencies from 1 to 10^5 THz.**

I. INTRODUCTION

PLASMA is an extremely flexible medium for producing electromagnetic radiation. In this talk we will focus on several methods for generating coherent radiation using plasma waves. A plasma density wake can be produced by the ponderomotive force of intense laser pulses travelling at speeds close to that of light in vacuum, which set in motion electron oscillations at the plasma frequency, thus creating a bubble-shaped accelerating structure (Fig. 1) with field gradients that can exceed 1 TV/m. We will discuss how the ultra-short duration bunches of charged particles in laser wakefield accelerators (LWFAs) can be injected from the background plasma into the ion bubble and accelerate to 100's MeV in millimetres [1-3].

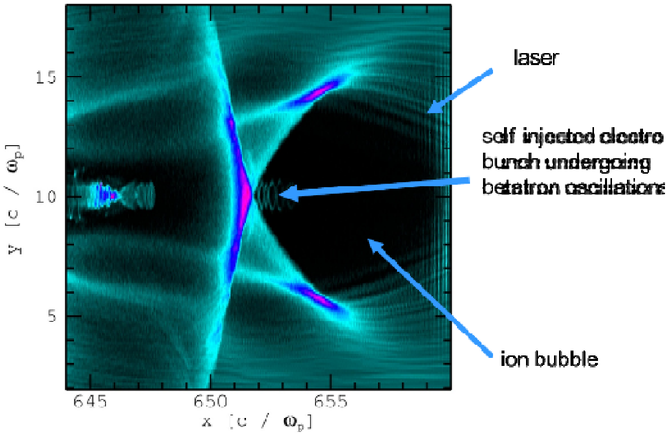

Fig. 1. LWFA bubble created by the ponderomotive force of the laser pulse. All lengths are normalized to $1/\omega_p$, where ω_p is the plasma frequency.

These femtosecond duration bunches can lead to the emission of coherent radiation with high efficiency over a broad spectral range stretching from 1 THz to 10^5 THz. Transverse acceleration of the ultra-short duration electron bunches in the bubble or an external undulator can produce intense coherent synchrotron radiation. Intense single-cycle coherent transition radiation can also be produced when the femtosecond bunches pass through a thin metal foil. A strong, localized, long-lasting electron oscillation in plasma can also act as a radiating antenna and emit continuous THz waves [4]. In this case the current is due to the ponderomotive force of two ultra-short duration, counter-propagating laser pulses in magnetized plasma. The field grows as its energy is fed by the driving current and both electric and magnetic components of the field diffuse strongly and eventually propagate across the plasma-vacuum boundary, where they are converted to a propagating electromagnetic wave (Fig. 2).

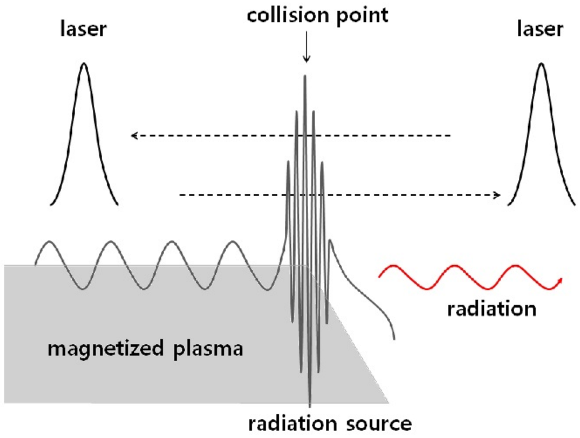

Fig. 2. THZ generation using colliding laser pulses in magnetised plasma [4].

Coherence of all beam-driven sources is governed by the spectral density of the electron bunch, $f(k)=\left|\int_{-\infty}^{\infty} e^{ikr}S(r)dr\right|^2$, where $S(r)$ is the density distribution and k is the wavenumber of the radiation. Coherent radiation results when an ultra-short bunch is shorter than the wavelength of the emitted radiation, or the electron beam has a periodic density modulation, as in the free-electron laser (FEL) [5-7]. The power radiated coherently from N bunched electrons is $P(k)=N(N-1)P_1(k)f(k)$, where P_1(k) is the power radiated by a single electron [8]. For fully bunched beams $(f(k) \approx 1)$ the emission, $P(k) \approx N^2P_1$, is coherent [9]. This is the basis of the FEL, where the ponderomotive force of the radiation and undulator fields results in periodic bunching and $f(k)\rightarrow 1$. The coherent enhancement occurs at the resonant wavelength for the FEL and leads to efficient emission of radiation.

The laser wakefield accelerator (LWFA) accelerates electrons to high energies [1-3] using fields of evacuated plasma "bubbles" [10] created by the ponderomotive force of an intense laser pulse in plasma and the restoring Coulomb force of the ions [11]. In the "bubble regime" plasma electrons form a high-density sheath around the bubble, from which electrons are injected when their axial velocity exceeds that of the bubble [12] (Fig. 1). When the laser power exceeds the critical power for relativistic self-focussing the pulse compresses and increases the normalised vector potential a_0 of the laser field, which leads to injection of plasma electrons into the bubble. The injected electrons then accelerate until their Lorentz factor increases to $\gamma = \gamma_d \approx 2\gamma_g^2 a_0 / 3$, at the dephasing length $L_d = 4c\gamma_g^2 a_0^{1/2} / 3\omega_p$, where $\gamma_g = \omega_0 / \omega_p$, and ω_p and ω_0 are the plasma and laser frequencies, respectively. The shortest bunches are injected close to threshold for self-injection, where injection is governed by charge build-up in the sheath crossing region at the back of the bubble [13]. The brief persistence of the charge build-up leads to femtosecond duration bunches.

II. RESULTS

The experiments describe below have been carried out on the ALPHA-X [2, 14] beamline (Fig. 3), where 0.9 J, 40 fs, 800 nm laser pulses are focused to a 25 μm ($1/e^2$ radius) spot to give an initial intensity of 1.3×10^{18} W/cm^2 ($a_0 \approx 0.8$) on a He gas jet (Fig. 4), which ionises the gas to produce plasma with densities of 1-3 × 10^{19} cm^{-3}. Relativistic self-focussing results in a plasma bubble and a LWFA that produces 80-300 MeV electron beams that can be very stable. The bunch charge is measured on Lanex screens placed 0.6 m from the gas jet.

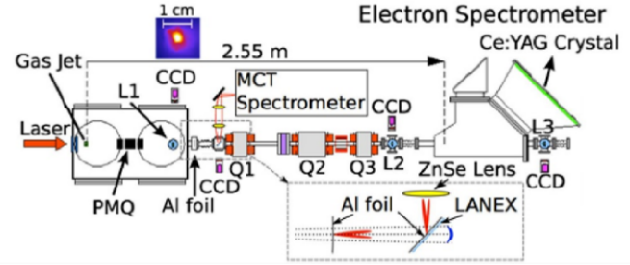

Fig. 3. ALPHA-X beamline used in the experiments.

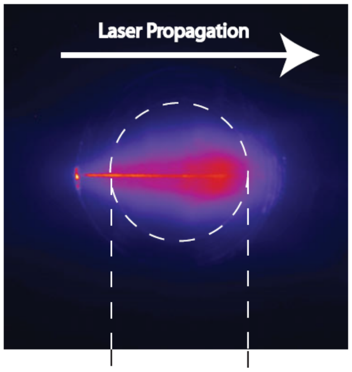

Fig. 4. Thomson scattered laser radiation from the plasma channel. The 2 mm diameter He gas jet is indicated by the dashed lines.

The LWFA is optimised for stable electron beam production (Figs. 5 – 7) close to threshold for injection. Electron beam energy spectra are measured using an imaging dipole magnet spectrometer placed 2.6 m from the gas jet. Two sets of triplet quadrupoles (PMQ and Q1, Q2, Q3) collimate the beam to optimise the resolution of the spectrometer (Fig. 3 and Fig. 5) and for transporting the beam through an undulator.

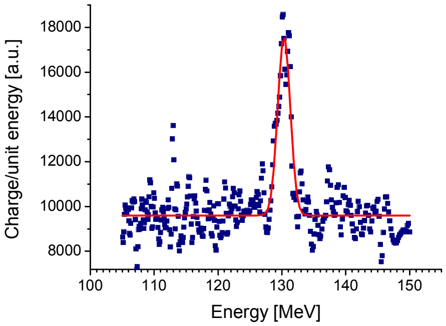

Fig. 5. Electron spectra for an electron beam for near threshold injection.

Electron beams with an emittance of 1 π mm mrad [15], energies in the range of 80-300 MeV, and percent level energy spreads [16] (Fig. 5), divergences of 1-2 mrad, peak currents >1 kA at the LWFA and femtosecond bunch durations [13] (Fig. 8), propagate through two coherent transition radiation (CTR) foils and then on to an undulator. Beam transport and CTR emission is modelled using GEANT4 for the experimental parameters.

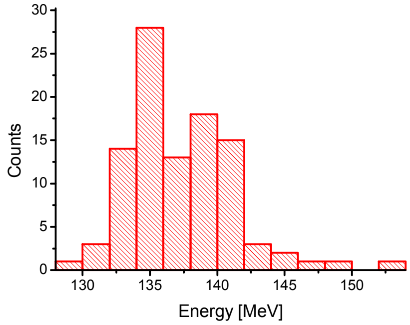

Fig. 6. Statistical distribution of the mean energy from the LWFA.

The pointing stability of the LWFA is excellent when the laser performance is optimised (Fig. 7), which allows comparison of simulated and measured CTR spectra. The CTR spectrum in Fig. 8, for electron energies of 90 MeV, has a peak around 4 μm, a dip around 7 μm and a continuous rise to longer wavelengths.

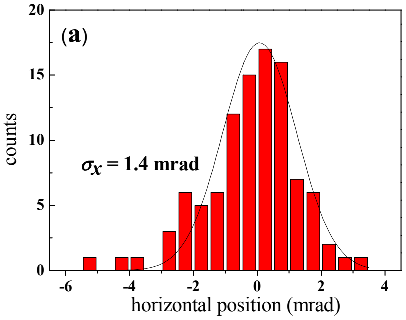

Fig. 7. Statistical distribution of LWFA pointing angle in the x-direction. A similar distribution is measured in the y-direction.

CTR spectra of smooth bunch shapes would show no structure. However, a train of two or more bunches can accurately reproduce the observed features: the dip at 7 μm is consistent with two bunches separated by 11.5 fs after 1 m propagation from the accelerator. The peak at 4 μm requires at least one bunch to have a bunch duration at the source of 1 fs for 2 mrad r.m.s. divergence. The ratio of the amplitudes of the two peaks and the depth of the dip is reproduced when one bunch contains about 70% of a total charge of 10 pC. The short wavelength part of the spectrum is generated by the most energetic electron beams. The simulations shown in Fig. 9 have been obtained by setting the energy of two bunches to 100 MeV, close to the measured values.

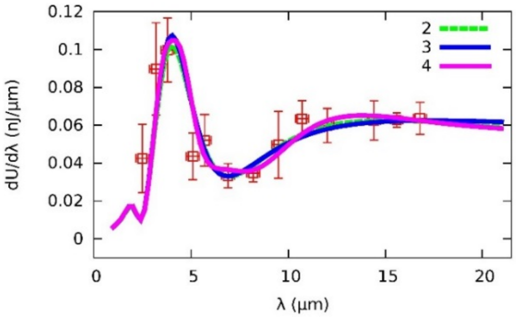

Fig. 8. Measured CTR spectra for 1 fs bunches (at source) separated by 2 fs, but which then drift to 11.5 fs at the CTR foils.

The measured spectra are consistent with the presence of additional 0.5 pC ultra-short bunches with short inter-bunch delays. Fig. 9 shows the CTR spectra calculated from OSIRIS [17] PIC simulations, which indicate a strong peak around 4.5 μm due to multiple electron bunches with temporal separation of 2 fs and PIC Simulation-2 where there is no peak, which indicates the presence of a solitary bunch.

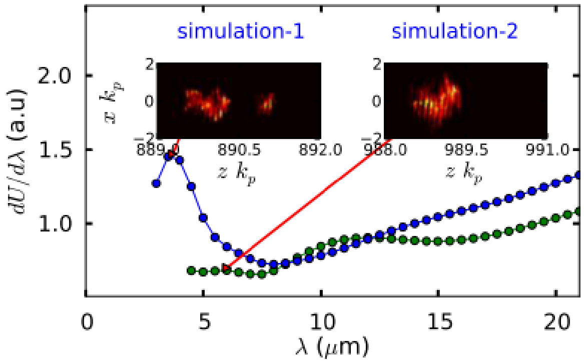

Fig. 9. Simulated spectra corresponding to Fig.2. Insets show bunch distributions of particle-in-cell (PIC) simulations using the OSIRIS PIC code [17] with experimental parameters.

To demonstrate the LWFA as a source of synchrotron radiation the LWFA electron beam has been focussed through an undulator by matching the transport beta function with the undulator length using the quadrupole magnets. Initial experiments have been carried out in the visible using a 2 cm periodicity undulator [18] using 100 MeV beams (using a laser at Jena). This has been replaced by a 100 period, 1.5 cm periodicity undulator with a slotted pole planar design and adjustable pole gap (at Strathclyde). The LWFA energy has also been increased to 130 MeV (Fig. 10) to obtain XUV radiation (Fig. 11) [19] to explore the feasibility of a compact tuneable ultra-short pulse XUV synchrotron source. The distance from accelerator exit to undulator entrance is 3.5 m and undulator radiation spectra are measured using a calibrated VUV spectrometer and 16-bit CCD camera. The quadrupole lenses act as energy bandpass filters for electrons.

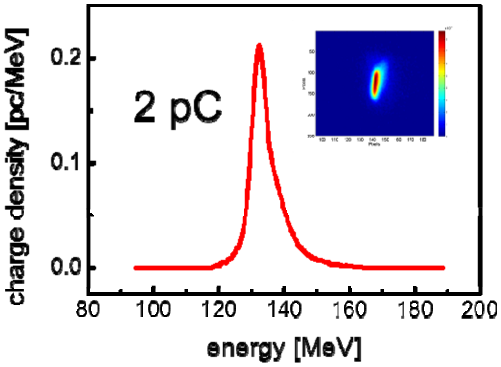

Fig. 10. Energy spectrum of LWFA beam used to produce undulator synchrotron radiation

The next stage in these investigations will be to optimise the beam transport to preserve the ultra-short bunch duration in the undulator so that $f(k) \approx 1$ for the resonant wavelength. This will ensure that the undulator radiation is coherent and will dispense with the need for FEL amplification, at least for lower frequencies, between 1-200 THz [9].

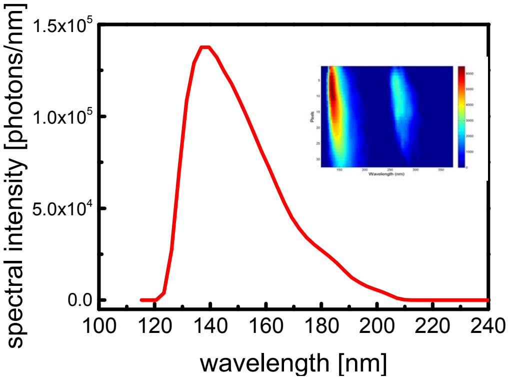

Fig. 11. VUV spectrum of radiation for 100 period, 1.5 cm period undulator for beam with energy spectrum in Fig. 10. A total of 10^7 photons are measured.

The ion-channel laser (ICL) [20] is an ultra-compact alternative to the FEL. The ion channel, which acts as a compact undulator, can be formed by an ultra-short laser pulse or a relativistic charged particle bunch in plasma. ICL amplification can be described using a modified FEL formalism [20], which results in scaled equations for radiation and electron beam.

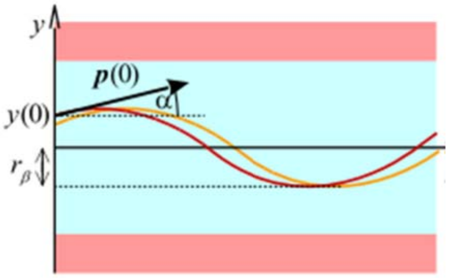

Fig. 12 Schematic of electron motion in an ion channel laser.

These equations suggest the feasibility of a compact coherent radiation source for wavelengths down to the XUV, with a gain parameter ρ as high as 0.03, which would give amplification for LWFA electron bunches with realistic energies and emittances.

In the ICL the undulation period depends on the ion density, electron energy and oscillation amplitude, in contrast with the FEL, where it is fixed by magnet spacing and periodicity. Similar to the FEL, the gain parameter is given by $\rho \approx 0.13[(\eta_m \eta_f / \gamma)(n_b / 10^{18}\ \mathrm{cm}^{-3})(R_\beta / \mu\mathrm{m})^2]^{1/3}$, where the electron bunch density, n_b = 10^{16} - 10^{20} cm^{-3}, the betatron amplitude, $R_\beta = \left\langle \gamma_0^{1/2} r_\beta^2 \right\rangle^{1/2} \gamma_0^{-1/4}$ = 1 – 10 μm, for an electron beam Lorentz factor, γ = 10^2 – 10^3, with coupling parameters η_m = 0.01-0.1, η_f = 10^{-6}-0.1, and r_β, the betatron amplitude [20]. With 100-200 MeV low energy spread electron beams from a LWFA (Fig. 5) [16] and low emittances [15], and high density bunches, n_b = 10^{20} cm^{-3}, with the betatron amplitude R_β = 10 μm and γ = 300, the gain parameter $\rho = 0.02$ for $\lambda > 5$ μm. [20]. For these parameters the betatron wavelength (which is the analogue of the undulator wavelength) $\lambda_\beta = \lambda_p \sqrt{2\gamma}$ for a background plasma density of 1.8×10^{19} cm^{-3} is $\approx$200 μm, which gives a gain length of 0.5 mm, and a total length to saturation of the order of 1 cm.

III. CONCLUSION

We have explored several unique coherent radiation sources based on laser-plasma interactions, some operational and some suggested. These can be quite intense and efficient sources and can produce very short duration pulses, down to a single cycle. Furthermore, they can be built around the same laser, which suggests that one could produce a very useful compendium of radiation sources for applications that require tunable ultra-short pulses for pump-probe time resolved studies.

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