Few-femtosecond laser-accelerated electron bunches

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Abstract: The ultra-short duration of laser-accelerated electron pulses is diagnosed by wide-band measurements of coherent optical transition radiation (CTR). High quality electron beams are produced by controlled optical injection into the plasma wave trailing behind an intense laser pulse. The shape and intensity of the measured CTR spectrum agrees with analytical modeling of electron bunches with 3-4 fs duration [full width at half maximum (fwhm)]. The measurements are supported by three-dimensional particle-in-cell simulations.

In a laser-wakefield accelerator [1], the ponderomotive force of an intense laser pulse drives a longitudinal plasma wave as it propagates through an underdense plasma. The electric field (wake field) associated with the plasma wave exceeds several hundred GV/m and can accelerate injected electrons to hundreds of MeVs in only millimeters.

The accelerating cavity that forms behind the driving laser pulse has a characteristic length, the plasma wavelength, which, in a typical experiment, is of the order of 10-15 um. The electric field changes across the plasma wave so, in order to generate an electron beam with low energy spread, injected electrons can only occupy a fraction of a plasma wavelength. These heuristic arguments indicate that, when the accelerated electron bunch is quasi-monoenergetic, one would expect its duration to be ultrashort [2, 3].

Traditional techniques to measure the electron bunch duration, such as streak cameras and rf sweeping cavities do not have the temporal resolution required for femtosecond bunches. Therefore, we have employed a method in the frequency domain and measured the coherent transition radiation (CTR) that is emitted by the electron bunch as it passes a thin metallic foil. If the electron bunch length is comparable to- or less than the observed radiation wavelength, the electrons radiate in phase and the radiation adds up coherently.

CTR in the THz frequency domain was used for temporal characterization of laser-accelerated electron bunches with 50-fs duration [4, 5]. Here we employ near- to mid-infrared (IR) CTR spectroscopy for measurement of bunches with durations of only a few femtoseconds.

The experiment is performed using the multi-terawatt laser in "salle jaune" at Laboratoire d'Optique Appliquée. The colliding pulse injection scheme [6] is employed and two 30 fs (fwhm) laser pulses are delivered to the interaction chamber. The pump pulse, driving the plasma wave, is focused onto the sharp edge of a 3 mm-diameter supersonic helium gas jet and collides with the injection pulse in the middle of the jet. During the collision, interference leads to stochastic heating and injection of background plasma electrons into the plasma wave. In difference to previous experiments [6, 7], the injection pulse collides at an angle of 135^{O}. This geometry facilitates a 100 um aluminum foil, used as CTR radiator, to be placed 15 mm from the exit of the gas jet without obstructing the injection beam.

The CTR spectrum is diagnosed using two instruments. A scanning monochromator is used to measure the spectrum in a wide infrared wavelength range, 1.4-5.5 um. The CTR, within a half angle of collection of 2.5 mrad, is dispersed by a ZnSe prism and focused onto an absolutely calibrated InSb photovoltaic detector. Data from up to 15 laser shots are acquired for each wavelength position. The instrumental response of the monochromator, the collection optics and the InSb detector have all been absolutely calibrated in order to give absolute measurements of the emitted CTR.

On each laser shot, an imaging spectrometer (of type Czerny-Turner) measures the CTR spectrum in the wavelength range 0.55-1.0 um. The spectrometer collects light within a half angle of 15 mrad and the spectrum is recorded using an absolutely calibrated 16-bit CCD camera. On some shots, the spectrum display high frequency modulations. Such modulation could arise from interference of CTR generated by multiple electron bunches [8]. Here, we wish to determine the duration of one single bunch, and consequently shots for which spectral modulations are observed on this diagnostic are rejected from the dataset.

The measured CTR spectrum, shown in Fig. 1, has a distinct peak around 3 um. The radiation is up to seven orders of magnitude brighter than the incoherent level (gray area in the inset). The inset shows data from both the spectrometer and the monochromator, normalized to the solid angle covered by each instrument. Using the measured mean values for electron peak energy, bunch charge and divergence, the CTR spectrum is calculated for Gaussian temporal bunch shapes, with different root-mean-square (rms) durations. A good agreement is found for a bunch duration of 1.5 fs (rms), corresponding to 3.5 fs (fwhm). For an average bunch charge of 15 pC, this leads to an inferred peak current of 4 kA.

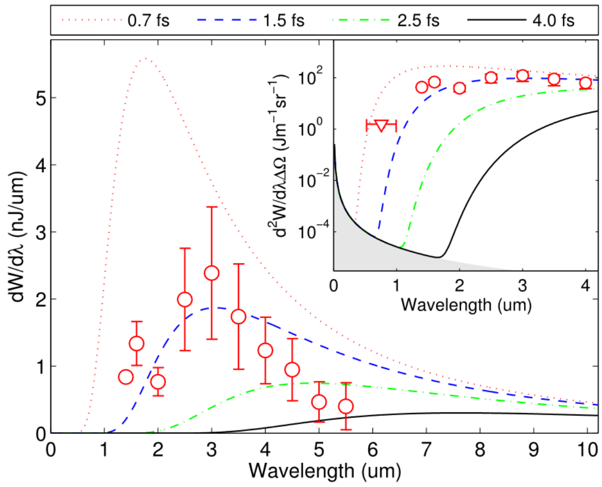

Fig. 1. Measured CTR spectrum (symbols), using an IR monochromator (circles) and a visible spectrometer (triangles), and analytical CTR spectra for different root-mean-square (rms) bunch durations (solid lines). Error bars indicate rms shot fluctuations (vertical) and spectral range of the measurement (horizontal). Electron bunch shape is taken to be gaussian with duration (rms) as indicated by the legend. Other bunch characteristics used for this calculations are the measured values for peak energy, charge and divergence, that are registered on the same laser shots by the electron beam diagnostics. Data in the inset has been divided by the solid angle of respective instruments.

To model the experiment, 3D particle in cell (PIC) simulations have been performed using the code CALDER [9] for parameters similar to the experiment. Figure 2 shows the phase space of electrons in the first plasma wave period, 300 um beyond the injection point. At this point, the electron peak energy is 65 MeV and, since the electrons are highly relativistic, the length of the bunch is not expected to change dramatically during further acceleration. Figure 2 also shows the temporal profile of the bunch. In this simulation, the pulse shape is slightly asymmetric with rise- and fall times of 2 and 3 fs respectively. The bunch duration is 1.7 fs (rms) or 4.4 fs (fwhm), in good agreement with the conclusions from the measurement of the CTR spectrum.

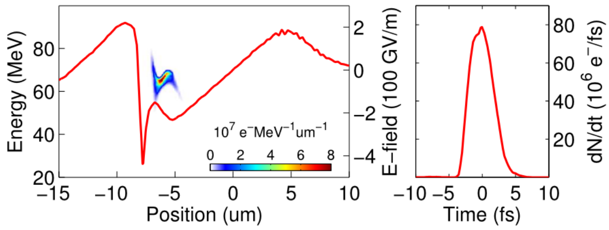

Fig. 2. Simulation results. (Left) Phase space of trapped electrons and longitudinal electric field. (Right) Temporal profile of the trapped bunch.

In summary, we have used wide-band spectral measurements of coherent transition radiation to estimate the duration of few-femtosecond highly relativistic electron bunches, optically injected and accelerated in a laser-wakefield. In a detailed analysis, we found the electron bunch duration to be equivalent to a Gaussian bunch with 1.5 fs (rms) or 3.5 fs (fwhm) duration, leading to an inferred peak current of 4 kA. These results were further found to be in agreement with three-dimensional particle in cell simulations of the experiment.

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