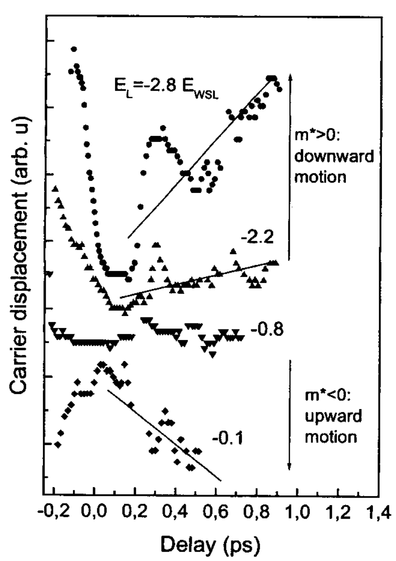
Shapiro steps [1]) which appear at voltages which are multiples of the photon energy of the AC field. Similar resonances for the incoherent (phase-independent) current in a semiconductor SL have been observed in a SL under THz illumination.[2]

We here observe a novel *coherent Shapiro current* in semiconductor superlattices:[3] the oscillatory motion of electrons in a biased semiconductor superlattice is superimposed by a linear (quasi-DC) transport effect which is induced by the interaction of the carriers with the oscillating field generated by themselves. The motion can be *coherently controlled* via the amplitude and phase of the wave packet oscillations by changing the spectral position of the laser pulse: It is possible to drive the carriers *both downwards and upwards in energy*, depending on whether the carriers are created at the lower or upper edge of the miniband: This difference can be understood by the sign of the effective mass: the carriers with lower energy have positive effective mass (and thus screen partially the external DC field) while the carriers excited with higher energy have *negative effective mass carriers and thus antiscreen* the external field. A second proof that the motion is due to vertical quantum transport is given by the density dependence of the current: Standard carrier drift velocity should in first order be independent on the carrier density. The data however, clearly show that the coherent quasi-DC current is proportional to the carrier density.

The observation of downward coherent motion due to stimulated emission is also the *first proof for THz gain in such a system*, which is of key importance for the realization of an electrically pumped Bloch emitter.




**QFB6 Fig. 1.** Carrier motion as a function of the delay time. The parameter for the different curves is the relative spectral position of the laser pulse given in units of the Wannier Stark ladder splitting. For excitation of positive mass carriers (upper two curves), the carriers move with the static field; for excitation with negative mass (lowest curve), the carrier move upward in energy against the static field. The central curve corresponds to carriers close to the inflexion point of the band, i.e. with infinite mass.

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2. K. Unterrainer et al., Phys. Rev. Lett. 76, 2973 (1996).
3. F. Löser et al., Phys. Rev. Lett., November 27, 2000 issue.

## QFC 8:00 am–9:45 am Room 341/342

### Femtosecond Generation and Propagation

Alexander Luis Gaeta, *Cornell Univ., USA*, *Presider*

**QFC1 8:00 am**

### Nonlinear relativistic optics in the single-cycle, single-wavelength regime with kilohertz repetition rate

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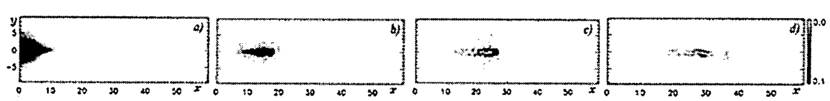
Laser intensity in the relativistic regime, i.e. $>10^{18}$ W/cm$^2$ for near-IR light,[1] has opened new frontiers in physics. At this intensity, electrons acquire quiver energy greater than, 0.5 MeV, corresponding to the mass-energy of the electron. Their relativistic behavior is dominated by a mass increase and a large ponderomotive force ($v \times B$) where v is the quiver velocity of the electrons and $B$ the light magnetic field. The laser-matter interaction in this regime is characterized by the generation of high-energy photons (x-rays and γ-rays) and energetic electrons and ion. The latter are accelerated to tens of MeVs by the large forces associated with the $v \times B$ term. Until recently this regime could only be attained by large low-repetition-rate Ti:Sapphire and Nd:glass CPA systems. Recently, we have shown[2] that single milijoule pulses in the 10-fs regime (single cycle), focused to 1-µm (single wavelength), can produce intensities greater than $10^{19}$ W/cm$^2$ at kilohertz repetition rates. Because of their very short Rayleigh range (~1 µm) one might think that these pulses would have only limited applications. They would not be useful in electron acceleration, where longer interaction distances are necessary. If the laser numerical aperture (NA) is matched to the NA of a relativistic waveguide (determined by the laser power and the plasma frequency), *single-mode propagation* of the relativistic pulse over many Rayleigh ranges can be obtained, as in conventional waveguide optics. This is demonstrated by the following 2D PIC simulation[3] of laser pulse matching with a plasma slab.

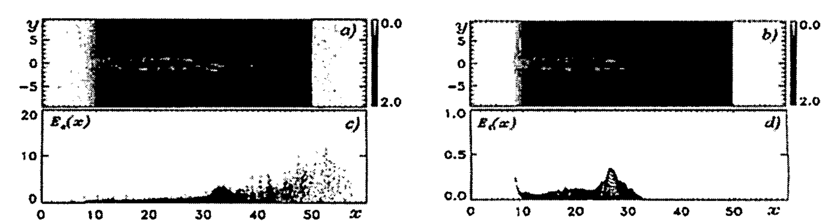
The simulation box size is 60λ × 20λ. An under-dense hydrogen plasma slab with density n = $0.5n_{cr}$ is localized in the region 10λ < x <5 0λ. A linearly polarized, 20-fs, ~800-nm laser pulse is initiated in the left-hand side vacuum region with magnetic field vector parallel to z and electric field in the x,y-plane It is focused at the plasma-vacuum interface which is localized at x = 10λ. The width of the focal spot is about 1λ. Here the laser intensity is equal to I = 5 × $10^{19}$ W/cm$^2$. In this case we have the optimal conditions for the laser plasma matching. Just after focus the laser pulse becomes guided due to relativistic self-focusing, as seen in Fig. 1. By t = 50 (cycles) the laser pulse has lost nearly all of its energy.

The ponderomotive pressure of the light forms a channel, which can be seen in the electron and ion density distributions in Fig. 2(a and b). The laser pulse accelerates electrons predominantly in the forward direction and ions in the transverse direction. The maximum energy of electron is ~12 MeV (Fig. 2c) and ions ~0.5 MeV (Fig. 2d). Fast electrons propagate forward and backward through the plasma and create an electric field that accelerates ions to energies of 0.4 and 0.7 MeV, respectively.

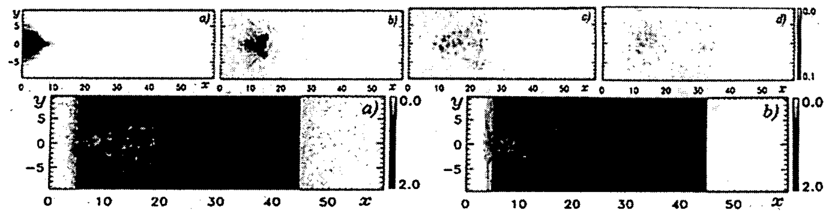
In Fig. 3 we show the same calculation as in Figs. 1 and. 2 a and b, but for non-optimal laser-plasma coupling. In this case, the laser focus is shifted 5λ into the plasma. Just after focus, filamentation appears, resulting in energy depletion



**QFC1 Fig. 1.** Electromagnetic energy density in the x, y-plane at t = 15 (a), 30 (b), 45 (c) and 60 (2π/ω) (d).




**QFC1 Fig. 2.** Electron (a) and ion (b) density in the x, y-plane, electron (c) and ion (d) kinetic energy inside the channel at t = 70 (2π/ω).



**QFC1 Fig. 3.** The same as in Fig. 1 and Fig. 2 a and b for not optimal laser-plasma matching.

by t = 40. Instead of a single well-pronounced channel, we see several relatively short and wide channels.

This ability to create and couple to single-mode relativistic channels opens the door to the following prospects: (i) the possibility to produce few femtosecond duration tens of MeV electron bursts with kHz repetition rate; (ii) the study of strong-field phenomena with high accuracy due to the enhanced signal-to-noise ratio, (iii) potential production of positronium by the trident process from accelerated electrons,[4] (iv) a new source of incoherent or coherent x-ray pulses by Thomson scattering, (v) accessibility of relativistic nonlinear optics to a larger number of laboratories.

### References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**QFC2** **8:15 am**

## Nonlinear optics with phase-controlled pulses in the sub-two-cycle regime


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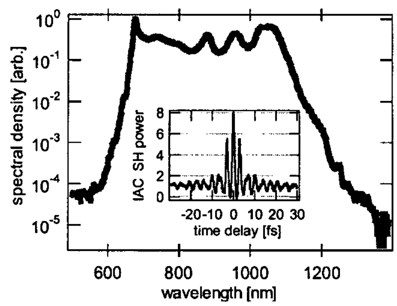
Very recently, two groups have observed and stabilized the pulse-to-pulse carrier-envelope phase slip $\Delta\phi$ by spectrally broadening femtosecond laser pulses in an external optical fiber.[1,2] In this paper we report the determination and stabilization of $\Delta\phi$ using pulses obtained directly from a mode-locked laser itself. We have done this both by monitoring the coherent interference of the fundamental pulse with its second harmonic and by observing a similar interference between the second and third harmonic.

The bandwidth requirement for the overlap of adjacent harmonics decreases with their order. Effects of the carrier-envelope-phase can become relevant even with relatively narrow bandwidth pulses in a nonlinear system of high order. Therefore phase-controlled pulses may have a large impact on high harmonic generation, where the generation efficiency can be undermined by the destructive interference between harmonics due to an unfavorable carrier-envelope phase[3,4]

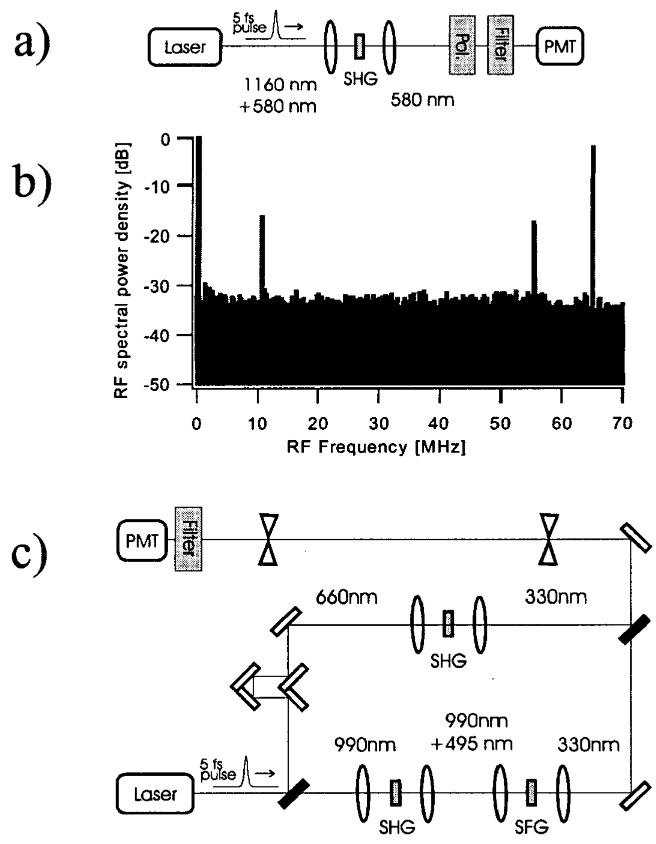



**QFC2 Fig. 1.** Octave spanning power spectrum directly from the two-foci-laser-oscillator on a logarithmic scale. Inset: Interferometric autocorrelation; a phase retrieval algorithm reveals a pulse FWHM of 5.0 fs.

Until recently, spectra obtained directly from a laser have been significantly narrower than one octave.[5,6] Now, however, octave spanning spectra are made possible by the invention of double-chirped mirror pairs and their use in a strongly dispersion managed Kerr-lens mode-locked Ti:sapphire laser (Spectrum and interferometric autocorrelation see Fig. 1).

For the measurement of the pulse-to-pulse carrier-envelope phase slip frequency, two experiments have been performed (see Fig. 2). First, the long wavelength end of the laser output light at 1160 nm is doubled and interferes with the short wavelength end of the fundamental at a polarizer. The beat frequency is detected after an optical filter. The RF-spectrum of the detected signal is displayed in Fig. 2b. The peak at 65 MHz corresponds to the fundamental repetition rate. The two peaks in the center are due to the carrier-envelope phase evolution frequency of 12 MHz and its mixing product with the repetition rate.

We obtained the same result by beating the second and the third harmonics of the pulse. The pulse train from the laser is launched into a Mach-Zehnder type interferometer, see Fig. 2c. The short wavelength part of the spectrum at 660 nm is coupled into one arm where the second harmonic is produced, the long wavelength part




**QFC2 Fig. 2.** a) Interference between fundamental and second harmonic in a compact detector. Second harmonic light interferes with the other end of the fundamental spectrum in a polarizer. A PMT detects the beat frequency. b) The resulting RF-spectrum. c) Interference between the second and the third harmonics in a Mach-Zehnder type interferometer