Ultracold Electron Source

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We propose a technique for producing electron bunches that has the potential for advancing the state-of-the-art in brightness of pulsed electron sources by orders of magnitude. In addition, this method leads to femtosecond bunch lengths without the use of ultrafast lasers or magnetic compression. The electron source we propose is an ultracold plasma with electron temperatures down to 10 K, which can be fashioned from a cloud of laser-cooled atoms by photoionization just above threshold. Here we present results of simulations in a realistic setting, showing that an ultracold plasma has an enormous potential as a bright electron source.

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Ultrashort, high-brightness electron bunches find application in many areas of science and technology. For instance, they are used as time-resolved probes for the solid-liquid phase transition of surfaces heated by ultrafast lasers [1] and for observing transient structure in femtosecond chemistry [2]. Such electron bunches are furthermore a sine qua non for the realization of high-brightness x-ray sources [3], in particular, the hard x-ray free-electron laser [4], enabling time-resolved studies in new parameter regimes in physics, chemistry, and biology [5,6]. An extremely exciting prospect is single-shot, subpicosecond time-resolved electron microscopy [7], which may become possible with continuing advances in pulsed electron sources with ever higher brightness.

The brightness B, i.e., the current density per unit solid angle and per unit energy spread, is a comprehensive figure of merit for particle beam quality. It is proportional to the six-dimensional (6D) phase space density of an accelerated particle bunch. The highest brightness measured at present is produced by carbon nanotube (CNT) field emitters, recently developed for electron microscopy [8]. CNTs can produce up to 1 μA of continuous current from a few nm^2 source area. The more established, pulsed, picosecond photo-emission-based guns [9], on the other hand, produce peak currents up to a few 100 A from a few mm^2 source area, and are typically 2–3 orders of magnitude less bright. In a recent hybrid approach, 10 ns electron pulses of 0.1 A current are extracted by pulsed photo emission from micron-sized needle cathodes, suggesting a brightness comparable to continuous CNT emitters [10].

The strategy for improving the brightness that both photo- and field-emission-based sources have in common up to now is to increase the current density at the source. In all cases the angular spread, which is determined by the effective electron temperature of the source T (typically 10^3–10^4 K), is kept constant. In this Letter we discuss a completely different approach, which aims instead at reducing the electron temperature T. This new source concept is based on pulsed extraction of electrons from an ultracold plasma (UCP), which is created from a laser-cooled cloud of neutral atoms by photoionization just above threshold [11]. Such plasmas are characterized by electron temperatures down to 10 K [12], i.e., 2–3 orders of magnitude lower than photo- or field-emission-based sources, implying a potentially enormous gain in brightness. Here we present results of numerical simulations based on realistic and well-established experimental conditions which show that ultracold, high-current, subpicosecond electron bunches can be produced orders of magnitude brighter than the best ultrashort pulsed electron sources today.

In practice, the quality of pulsed electron beams is usually expressed in terms of the transverse brightness $B_\perp$, which is a measure for the current density per unit solid angle. The full 6D brightness B is proportional to the ratio of $B_\perp$ and the energy spread. For a beam traveling in the z direction [13]

$$B_\perp = \frac{I}{4\pi^2 \epsilon_x \epsilon_y}, \tag{1}$$

where I is the peak current and ϵ_x and ϵ_y the normalized root-mean-squared (rms) emittance in, respectively, the x and y direction,

$$\epsilon_x = \frac{1}{mc}\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle x p_x\rangle^2}. \tag{2}$$

Here $\langle\rangle$ indicates averaging over the distribution, m is the electron mass, c the speed of light, and $p_x = \gamma m v_x$, with v_x the x velocity and $\gamma = [1 - (v/c)^2]^{-1/2}$. The emittance ϵ is a Lorentz-invariant measure for the focusability of the beam. For a beam with a Gaussian distribution in transverse (x, p_x, y, p_y) phase space, $(\gamma^2 - 1)B_\perp$ is equal to the peak value of the current density per unit solid angle. In the field of electron microscopy the beam quality is usually expressed in terms of the reduced brightness $B_r = eB_\perp/mc^2$, with e the elementary charge [14]. For a thermal electron source with peak current density J one may show that [14]

$$B_\perp = mc^2 J/\pi kT, \tag{3}$$

which clearly illustrates the advantage of reduced electron temperatures.

The best performing pulsed picosecond sources are radio-frequency (rf) photoguns, in which electron bunches are created by pulsed-laser photo emission and subsequently accelerated in rf fields of, typically, 100 MV/m. The rf photogun of the Accelerator Test Facility at Brookhaven National Lab can produce 0.5 nC electron bunches with $I \approx 120$ A and $\epsilon_x \approx 0.8$ μm, corresponding to a beam brightness $B_\perp = 5 \times 10^{12}$ A/(rad^2 m^2), $B_r = 1 \times 10^7$ A/(rad^2 m^2 V) [9], about an order of magnitude smaller than the thermal brightness limit given by Eq. (3). The emittance achieved is limited by nonlinear space charge forces. Recently, it was shown that the detrimental effect of space charge forces can be virtually eliminated by proper shaping of the radial intensity profile of a femtosecond photo-excitation laser [15]. This would make it possible to reach the thermal brightness limit corresponding to $T = 10^3$–10^4 K.

Our proposed pulsed UCP source is similar to an rf photogun in the sense that it produces (sub)ps bunches with a comparable bunch charge from a comparable source area. The much lower temperature of the source, however, implies a potential increase of the brightness by up to 3 orders of magnitude.

To realize a UCP source in practice we propose a four-step procedure, illustrated schematically in Fig. 1:

(I) A cold ($T < 1$ mK) cloud of atoms is trapped in a magneto-optical trap (MOT) in a volume of a few mm^3 with densities up to 10^{18} m^{-3} [16].

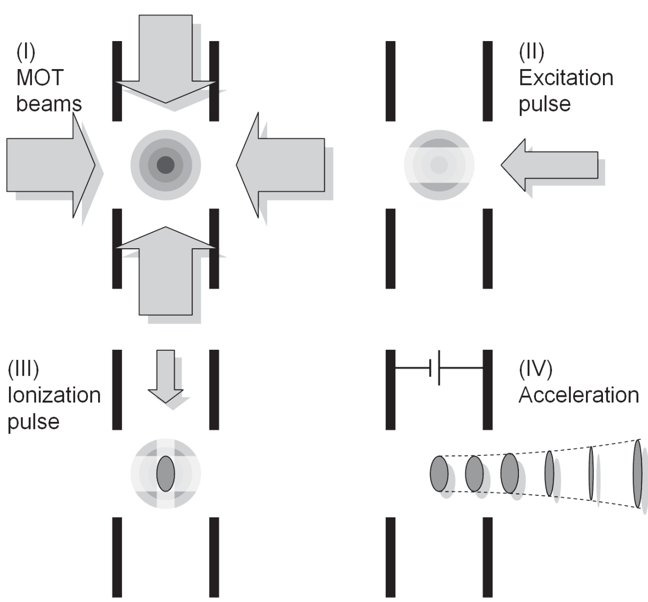

FIG. 1. Schematic of the four-step procedure to realize a pulsed UCP electron source.

(II) Part of the cold atom cloud is excited to an intermediate state with a quasicontinuous, μs laser pulse.

(III) Then, a pulsed-laser beam propagating at right angles to the excitation laser ionizes the excited atoms only within the volume irradiated by both lasers. Here a UCP is formed [11]. In this way electron bunches of up to 100 pC can be created in a volume of $\sim$1 mm^3. By exciting the atoms to just above the ionization limit with a ns laser pulse, the electrons are created at $T \approx 1$ mK. Ponderomotive heating of the free electrons in the optical field is negligible. Subsequently, ns time scale heating processes inside the plasma increase the temperature to $T \approx 10$ K [12].

(IV) The bunches are extracted by an electric field at least an order of magnitude stronger than what is minimally required for pulling the electrons and ions apart. For a 1 mm-sized 100 pC bunch this typically means applying a voltage of 1 MV across a 1 cm gap, which should be switched on extremely rapidly (< 1 ns) to prevent space-charge-induced emittance growth during acceleration. Such rapid switching of high voltages is possible by using, for example, laser-triggered spark gap technology [17]. For a MOT a loading rate of over 1×10^{11} atoms/s is possible [16], so a total charge of up to 10 nC may be extracted per second.

The extracted bunches are automatically compressed in the drift space after acceleration because the electrons in the back of the bunch experience a larger acceleration potential difference than those in the front. This "velocity bunching" leads to sub-ps bunch lengths.

The fact that the initial electron density is proportional to the product of the intensities of the excitation and the ionization laser beams in the region of overlap offers an excellent opportunity for control over the initial charge distribution. As we showed recently [15], the detrimental effects of space charge forces may be virtually eliminated by the combination of lowering the dimensionality of the bunch and proper shaping. A highly desirable initial charge distribution, for example, is a *pancake* bunch (bunch length much smaller than radius R) with a *half-circle* radial charge density distribution [15]

$$\rho(r) \propto \sqrt{1 - (r/R)^2}. \tag{4}$$

Such a distribution automatically evolves into a uniform, ellipsoidal bunch, which is characterized by perfectly linear space charge fields and thus zero space-charge-induced emittance growth. A second initial distribution is a *cigar* bunch (radius R much smaller than bunch length) with a *parabolic* longitudinal charge density distribution, which will also evolve into a uniform, ellipsoidal bunch. Using Eq. (2) one may show that the normalized rms emittance of such objects is given by

$$\epsilon = R\sqrt{kT/5mc^2}. \tag{5}$$

Because of the two-step ionization scheme it is possible to create the UCP in either the ''half-circle-profile pancake'' or the ''parabolic-profile cigar'' configuration, each with its own specific advantages: as we will show, the pancake bunches are characterized by a high charge, a small energy spread, and robust, stable behavior, while the cigar bunches offer a low emittance and high compressibility. Note that, in spite of the ideal initial distribution, rapid acceleration is still necessary, because initially the electron bunch is still subjected to nonlinear forces due to the ion cloud. The time it takes to separate the electrons from the ions should be kept as short as possible.

To investigate the feasibility of the proposed source, we performed an extensive set of simulations with the general particle tracer (GPT) code [18]. The starting point is a MOT containing rubidium atoms in a spherically symmetric Gaussian density distribution with an rms radius of 2 mm and a density in the center of 1×10^{18} m^{-3}.

To create a pancake bunch, a fraction of the atoms is excited with a radial distribution given by Eq. (4), with $R = 2$ mm. The ionization laser beam then cuts out a longitudinal slice of 15 μm thickness. Assuming an overall ionization efficiency of 50%, this results in 10 pC charge. To create a cigar bunch, the atoms are excited within a radius of 80 μm from the axis. Subsequently, the ionization laser cuts out a parabolic longitudinal density profile with a total length of 1 mm, resulting in 1 pC of charge. The initial electron temperature of both bunches is set at 10 K.

For the accelerating stage, a cylindrically symmetric field geometry is assumed in which both the cathode and the anode are thin conducting plates with a circular hole of 5 mm radius, separated by a distance $d = 20$ mm, as is shown in Fig. 2(a). The hole in the cathode enables optical access for both the trapping and excitation laser beams.

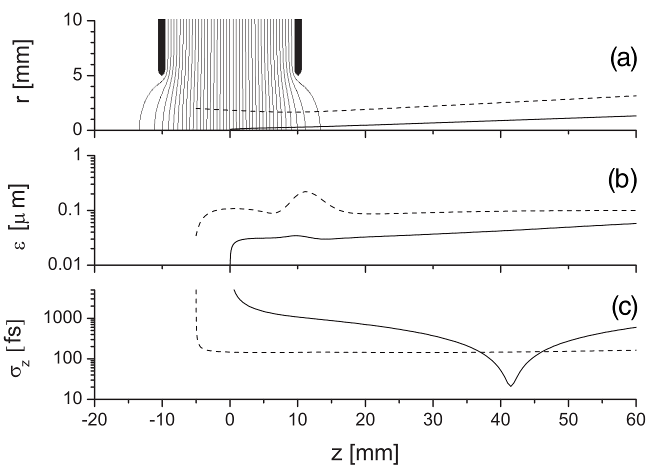

FIG. 2. (a) Field geometry and radial bunch envelope as a function of z; (b) rms normalized emittance as a function of z; (c) rms bunch length as a function of z. Solid lines: cigar bunch; dashed lines: pancake bunch.

The electric field is modeled by the product of an electrostatic field due to a voltage $V_0 = 1$ MV across the diode, calculated with SUPERFISH [19], and a linearly increasing time factor t/τ_r, with $\tau_r = 150$ ps. The time dependent electric field gives rise to an azimuthal magnetic field B_ϕ, which is calculated on the basis of the SUPERFISH field map. Near the axis $B_\phi \approx -V_0 r/(2c^2\tau_r d)$, acting as a positive lens. The validity of this approach has been verified with the 3D time domain code MW-STUDIO [20]. In the GPT simulations space charge forces are calculated with a 3D anisotropic Poisson solver, tailor made for bunches with extreme aspect ratios [21]. The effect of the ions on the electron bunch during extraction has also been included, but turns out to be negligible.

In Fig. 2(a) the acceleration electric field geometry is shown, indicated by equipotential lines, as well as the radial bunch envelope as a function of z. In Figs. 2(b) and 2(c), respectively, the rms normalized emittance ϵ and the rms bunch length σ_z (in fs) are plotted as a function of z. The pancake bunch is started upstream at $z = -5$ mm. As a result the bunch is initially focused by the nonuniform electric field, as can be seen in Fig. 2(a), thus partially compensating for the radial space charge forces and the defocusing ''exit kick'' of the diode. The final energy of the pancake bunch is 470 keV. The cigar bunch is started at $z = 0$, as its small initial radius does not require any additional focusing. The final energy of the cigar bunch is 270 keV.

As is shown in Fig. 2(b), ultralow normalized emittances are achieved of the order of $\epsilon \approx 0.1$ μm for the pancake bunch and even lower for the cigar bunch. The behavior of ϵ as a function of z is similar for both configurations. Initially $\epsilon \approx 0.04$ μm for the pancake bunch and $\epsilon \approx 0.0015$ μm for the cigar bunch, in agreement with Eq. (5). After initiation, ϵ first rises sharply due to space charge forces and then levels off to slow monotonic growth, only briefly interrupted by a temporary rise while passing through the nonuniform field in the hole of the anode.

Figure 2(c) shows that in the proposed setup sub-ps bunch lengths can be realized indeed, without the use of ultrafast lasers or magnetic compression. Compression is solely due to velocity bunching, which is particularly efficient for the cigar bunch: at $z = 42$ mm an rms bunch length $\sigma_z = 20$ fs is achieved, resulting in a peak current $I > 25$ A. The position of the bunch length minimum can be conveniently adjusted over a range of several cm by shifting the initial position by a few mm.

The pancake bunch, on the other hand, almost immediately reaches a respectable bunch length value of $\sigma_z = 150$ fs, corresponding to $I = 25$ A, which is maintained over many cm of its trajectory. This steady behavior reflects a balance between space charge force repulsion and velocity bunching, which is relatively weak due to the small acceleration potential difference experienced by pancake bunches.

The combination of ultralow emittances and ultrashort bunch lengths results in extremely high brightness values: after leaving the diode, the pancake bunch attains a constant value $B_\perp = 5 \times 10^{13}\mathrm{A/(rad^2\,m^2)}$, $B_r = 1 \times 10^8\mathrm{A/(rad^2\,m^2\,V)}$. This value is an order of magnitude higher than state-of-the-art rf photogun performance [9]. The cigar bunch performs even better: at the bunch length minimum, $z = 42$ mm, $B_\perp \geq 5 \times 10^{14}\mathrm{A/(rad^2\,m^2)}$, $B_r \geq 1 \times 10^9\mathrm{A/(rad^2\,m^2\,V)}$, comparable to CNT performance [8]. The cigar bunch configuration clearly offers the highest peak brightness and the shortest bunch lengths, but only at specific positions and with a relatively large energy spread. The pancake bunch is typically less bright, but exhibits robust, stable behavior with a relatively small energy spread.

We therefore conclude that UCP-based electron sources have enormous potential for advancing the state-of-the-art in ultrashort electron bunch brightness. This potential gain in brightness is due to the combination of a low initial thermal emittance and a short bunch length that results from velocity bunching. The brightness values resulting from the simulations are impressive, but still 1–2 orders of magnitude removed from the thermal limit. In principle, therefore, even higher brightness values may be attained, for example, by optimizing the accelerating diode structure.

Interestingly, UCP sources do not require any conditioning and do not suffer from aging, in contrast with most solid state (photo and field) emitters [cf., e.g., [8]]. Essentially, for each shot a new, fresh source is used, which may be beneficial in terms of reproducibility and lifetime. Furthermore, a pulsed UCP source is equally suitable for producing ultrabright ion beams, which may be of interest for focused ion beam (FIB) applications.

Finally, we speculate that even lower electron temperatures may be realized, for example, when the atoms are not photoionized but excited to a high level. From there they can be ionized by a high-voltage pulse, which simultaneously extracts the electrons from the plasma. If the excited level is chosen such that in a field of $\approx 10^7$ V/m only its highest Stark-shifted sublevel is ionized, then a pancake slice of electrons is extracted from the plasma within a few ps. Since this is much faster than the time scale (100 ps) at which plasma heating occurs, mK electron temperatures may be retained.

It is intriguing to note that at $T = 1$ mK, the electron thermal De Broglie wavelength $\lambda_{\mathrm{th}} = h/\sqrt{2\pi mkT}$ is 2.4 μm, comparable to the interparticle distance $n^{-1/3}$ at densities $n \approx 10^{18}$ m^{-3}. This would imply the production of Fermi degenerate electron bunches, and thus the ultimate, fundamental quantum limit in electron beam brightness.

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