SLAC-PUB-12160

PROPOSAL FOR A HIGH-BRIGHTNESS PULSED ELECTRON SOURCE*

M. ZOLOTOREV[1], E. D. COMMINS[2], S. HEIFETS[3] AND F. SANNIBALE[1]

[1]*Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[2]*Physics Dept., University of California Berkeley, Berkeley CA 94720, USA*
[3] *Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA*

We propose a novel scheme for a high-brightness pulsed electron source, which has the potential for many useful applications in electron microscopy, inverse photo-emission, low energy electron scattering experiments, and electron holography. A description of the proposed scheme is presented.

1. Introduction

We propose a novel scheme for a high-brightness pulsed electron source, which has the potential for many useful applications in electron microscopy, inverse photo-emission, low energy electron scattering experiments, and electron holography. The source makes use of Cs atoms in an atomic beam. Each cycle of the device begins with a laser pulse that excites a single Cs atom on average to a band of high-lying Rydberg nP states. The resulting valence electron Rydberg wave packet evolves in a nearly classical Kepler orbit. When the electron reaches apogee, an electric field pulse is applied that ionizes the atom and accelerates the electron away from its parent ion. The collection of electron wave packets thus generated in a train of cycles can occupy a phase volume near the quantum limit and it can possess very high brightness. Each wave packet can exhibit a considerable degree of coherence.

A proof of principle experiment is underway at the Lawrence Berkeley National Laboratory to demonstrate the essential features of the source.

* Work supported by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Contributed to Workshop on the Physics and Applications of High Brightness Electron Beams (PAHBEB 2005), 9-14 October 2005, Erice, Sicily, Italy

Work supported in part by Department of Energy contract DE-AC02-76SF00515

2. Source Scheme Description

To explain the essential features of the source, we recall several basic quantities. In the rest-frame of a beam of electrons propagating in the z direction, the dimensionless differential phase volume dΓ is:

$$d\Gamma = \frac{1}{h^3} dx dp_x dy dp_y dz dp_z = \frac{dx d\beta_x dy d\beta_y dz d\beta_z}{(2\pi)^3 \lambda\!\!\!^{-3}_C} \tag{1}$$

where $\beta_{x,y,z} = v_{x,y,z}/c$ and c is the velocity of light, and $\lambda\!\!\!^{-}_C = \hbar/m_e c = 3.86 \times 10^{-11}$ cm is the electron Compton wavelength. Assuming that the electron beam is described by a six-dimensional Gaussian distribution in phase space, the total dimensionless phase volume Γ occupied by the electron beam may be expressed in terms of the transverse emittances $\varepsilon_{x,y}$ and longitudinal emittance ε_z as follows:

$$\Gamma = \frac{\varepsilon_x \varepsilon_y \varepsilon_z}{\lambda\!\!\!^{-3}_C} \tag{2}$$

where

$$\varepsilon_x = \sqrt{\left(\langle x^2 \rangle - \langle x \rangle^2\right)\left(\langle \beta_x^2 \rangle - \langle x\beta_x \rangle^2\right)} \tag{3}$$

with similar definitions for ε_y and ε_z [1]. Let N_e be the actual number of electrons, and consider the ratio:

$$\delta_F = \frac{N_e}{\Gamma} = \lambda\!\!\!^{-3}_C \frac{N_e}{\varepsilon_x \varepsilon_y \varepsilon_z} = \lambda\!\!\!^{-3}_C B \tag{4}$$

where $B = N_e/\varepsilon_x \varepsilon_y \varepsilon_z$ is the "brightness". The Pauli exclusion principle requires $\delta_F \leq 1$ for electrons of a given spin polarization; hence $\varepsilon_x \varepsilon_y \varepsilon_z \geq \lambda\!\!\!^{-3}_C$. Typically, field emission electron guns of modern design achieve δ_F up to 5×10^{-6}, [2]. For the present electron source it appears possible to reach $\delta_F \approx 2 \times 10^{-2}$.

In our electron source (see Fig. 1) an atomic beam effusing from an oven at temperature ≈ 500 K is collimated to reduce the transverse beam temperature to ≈ 5 K. Also, laser excitation along the beam axis selects a narrow band of longitudinal velocities. Thus excited atoms have a thermal energy spread $\Delta E \approx 4 \times 10^{-4}$. If the valence electrons were then optically excited to

ionization threshold and we could ignore subsequent space-charge heating, the electron energy spread would be $\delta E = (m_e / M_{Cs})\Delta E \approx 1.6 \times 10^{-9}$ eV. However space-charge interactions result in an electron temperature given by $kT \approx e^2 n_e^{1/3}$ where n_e is the electron density. For $n_e \approx 10^9$ cm^{-3} this would yield $\delta E \approx 10^{-4}$ eV. In the present proposal this undesirable heating is avoided by exciting one atom at a time on average (see Fig. 1) to a very high lying band of nP Rydberg states (for example $\bar{n} \approx 800$, $\Delta n \approx 50$), with 3 mutually perpendicular laser beams: [L1: CW, 852 nm ($6S_{1/2}$-$6P_{3/2}$)]; [L2: CW, 1.47 μm ($6P_{3/2}$-$7S_{1/2}$)]; [L3: pulsed, 777 nm ($7S_{1/2}$-nP)]. These intersect in a small interaction region [volume ≈ (10 μm)^3] midway between two plane parallel electrodes E1, E2 with separation ≈ 1 cm. The laser intensities and atom number density are chosen to give a single atom excitation probability per pulse ≈ 1.

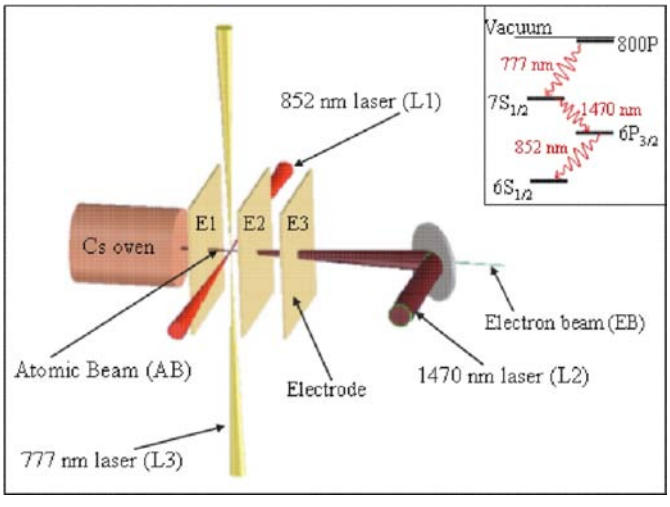

Figure 1. Schematic diagram of pulsed electron source, with insert showing relevant Cs energy levels (not to scale).

Each resulting valence-electron Rydberg wave packet describes a pendulum-like orbit that is very nearly classical, with a half-period $T = (\pi \hbar^3 \bar{n}^3)/(m_e e^4)$ ($T \approx 39$ ns for $\bar{n} \approx 800$). The frequency of the 777 nm laser pulse can be chirped so that the classical Kepler orbits for various n values in the vicinity of $n = 800$ all reach apogee simultaneously. The most favorable chirping parameters are found by optimizing a quantum mechanical calculation of laser excitation and subsequent time evolution of the Rydberg wave-packet. At

apogee this wave packet fills a spherical shell centered on the remaining Cs ion, with mean shell radius $\langle R \rangle \approx 67$ μm and shell half-thickness $\Delta R \approx 6$ μm (see Fig.2), while $\Delta\beta_R$ reaches a minimum value such that $\Delta R \bullet \Delta\beta_R$ is very close to the uncertainty principle limit. (Note that $\Delta\beta_\theta$ is negligible compared to $\Delta\beta_R$).

The "intrinsic" transverse emittance at apogee is $\varepsilon_{x,y} \cong \left\langle \sin^2\theta \begin{pmatrix} \cos^2\phi \\ \sin^2\phi \end{pmatrix} \right\rangle \langle R \rangle \Delta\beta_R$. Here θ, ϕ are the usual angles in polar coordinates between the electron position vector **R** and the z axis. Spectroscopic observations show that for Cs the oscillator strengths for 7S-n$P_{3/2}$ transitions are much larger than for 7S-n$P_{1/2}$. Taking into account this spin-orbit effect [3, 4] and assuming that the 777 nm photons are linearly polarized along z, one finds that the probability density of the Rydberg wave packet is proportional to $1+3\cos^2\theta$. Thus $\left\langle \sin^2\theta \begin{pmatrix} \cos^2\phi \\ \sin^2\phi \end{pmatrix} \right\rangle = \frac{4}{15}$ and for optimum chirp conditions at $\overline{n} \approx 800$, $\varepsilon_{x,y} \cong 2.5\lambda\!\!\!^{-}_C$.

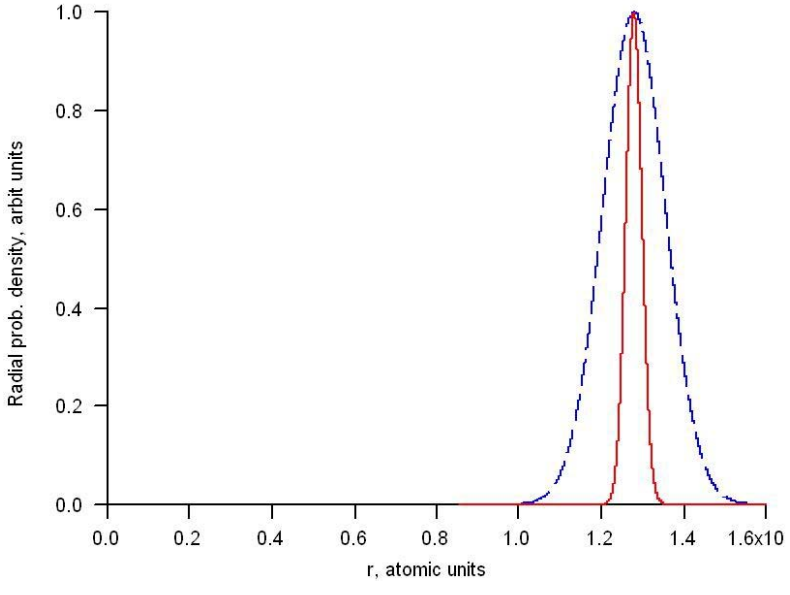

Figure 2. Radial probability distributions for Rydberg wave packet at apogee. Red solid curve: 777 nm laser pulse FWHM=2.35 ns, no chirp. Blue dashed curve: 777 nm laser pulse FWHM=8.2 ns, optimum chirp.

In addition appreciable phase coherence in each electron wave packet can be achieved. Thus in principle the proposed source could be employed for electron holography and other interferometric experiments.

At apogee, an electric field pulse is applied in the –z direction; it ionizes the atom and accelerates the electron in the +z direction. For a pulse peak = 100 V/cm and FWHM = 0.5 ns, the final electron energy is $E \approx 2$ eV, with $\Delta E \approx 10^{-4}$ eV. Several ns after the accelerating pulse, the electron reaches electrode E2 (Fig.1) and passes through a circular aperture A. The diameter of A is chosen to minimize aberrations and simultaneously to maintain reasonable field uniformity in the excitation region. To analyze the emittances of the electron bunch downstream from A we employ a Monte Carlo calculation to integrate the electron classical equations of motion in the acceleration pulse field and the Coulomb field of the parent ion, taking into account the apogee values for $<R>$, ΔR, and $\Delta\beta_R$, the random value of θ at apogee, smearing effects due to the finite size of the interaction region, and the velocity distribution of the cesium atoms and the resulting transverse and longitudinal Doppler effects. We estimate that one can achieve emittances $\varepsilon_{x,y} \cong 3.0\lambda\!\!\!^{-}_C$, $\varepsilon_z = 4.8\lambda\!\!\!^{-}_C$, and a fractional energy spread $\Delta E/E \approx 4 \times 10^{-5}$.

For a Rydberg atom with principal quantum number n, the electric field required for spontaneous ionization is $E_I = e/\left(16\, a_0^2 n^4\right) \approx 8 \times 10^{-4}$ V/cm for $n = 800$. Such a field is generated by an electronic charge at a distance $s = 0.014$ cm. Therefore we require that when the next laser pulse occurs, the residual ion from the present pulse is at a distance $s' >> s$ from the interaction region. To achieve this, after the acceleration pulse another "ion clearing" electric field pulse in the –z direction is applied to remove the remaining Cs ion from the interaction region. Because the ion is massive, the duration of the clearing pulse and its amplitude must be quite large. After termination of the ion clearing pulse, another laser pulse is applied which begins the next cycle. For realistic ion clearing pulses, a cycle repetition rate ≈ 3MHz can be achieved.

If we are to achieve the emittances described above, it will be necessary to reduce stray electric fields in the interaction region to a level $E_S \leq 10^{-4}$ V/cm. This is a difficult but not impossible task, as has been demonstrated by the results of earlier experiments on Rydberg states [5]. Stray magnetic fields B can also cause undesirable perturbations that degrade brightness unless the electron radius of curvature is much greater than R. To achieve this, one must reduce the ambient magnetic field to a level ≤ 0.001 Gauss. This can be done readily by enclosing the interaction region in an appropriate magnetic shield. Care must

also be taken to avoid generation of photo-electrons by absorption of stray laser photons on electrode surfaces.

Collisions between the Rydberg atoms of interest and ground state atoms as well as molecules are unlikely to cause serious difficulties, even though the volume of an $\bar{n} \approx 800$ Rydberg atom is so large at apogee that for an atomic beam number density $n_0 \approx 10^{10}\,\mathrm{cm}^{-3}$, approximately 10^4 ground state atoms are contained within that volume. The cross-sections for collisions of the Rydberg atom with Cs_2 and with background gas molecules are undoubtedly large, but the number densities of these molecules will be so small (with proper design of the atomic beam source and in ultra-high vacuum) that they should not present serious problems. We are encouraged by the results of previous alkali Rydberg atom experiments done in rather rudimentary vacuum conditions, which achieved principal quantum numbers $n \approx 1000$ [6].

3. Conclusions

The proposed source would be a first step toward a novel scanning electron microscope with current density on the sample of several kA/cm^2 and Angstrom resolution. Such resolution for a low energy microscope would be achieved for two main reasons: the requirements on chromatic aberration are minimized by extremely small energy spread, and spherical aberration can be compensated by axial symmetric lenses. In fact, the well defined time structure of the electron beam allows use of time- dependent fields that can be either focusing or defocusing, which implies the possibility of positive or negative spherical aberration. The source would also extend applications for electron beams to energy exchange with μeV accuracy in inelastic atomic and molecular scattering, and new ways of investigating chemical reactions and dynamics on a picosecond time scale using pump-probe techniques. Finally, the feasibility of phase coherence between successive electron wave packets opens the possibility of electron holography and other interferometric experiments.

A proof of principle experiment is underway at the Lawrence Berkeley National Laboratory to demonstrate the essential features of the source.

Acknowledgments

We thank J. Byrd, S. Chu, D. Colomb, P. Denes, G. Huang, Z. Hussain, J. Krupnik, G. Lebedev, S. Lidia, J. Oneill, D. Robin, K. Robinson, R. Schoenlein, R. Vogel, and W. Wan, who have provided very valuable discussions as well as scientific and technical support.

References

1. C. Lejeune, J. Aubert, Applied Charged Particle Optic, Advances in Electronics and Electron Physics, A. Septier Editor, Supp. 13 A (1980).
2. J. C. H. Spence, M. R. Howells, Ultramicroscopy **93** (2002) 213.
3. D. Norcross, Phys. Rev. A **7**, 606, 1973.
4. V H. Kaminski, J. Kessler, and K.J. Kollrath Phys. Rev. Lett. **45**, 1161, 1980.
5. J. Neukammer, et al., Phys. Rev. Lett. **59**, 2947, 1987.
6. M. T. Frey, S. B. Hill, K. A. Smith, and F. B. Dunning Phys. Rev. Lett. **75**, 810, 1995