AN ULTRA-BRIGHT PULSED ELECTRON BEAM
WITH LOW LONGITUDINAL EMITTANCE*

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Abstract

Most existing electron sources extract electrons from conductors. Since the actual temperature inside the conductor is much less than the Fermi temperature of the conduction electrons, the electron degeneracy δ_f is close to 1, the maximum allowed by the Pauli exclusion principle. However, during extraction several factors conspire together to reduce δ_f many orders of magnitude, limiting the achieved values to $\approx 10^{-5}$.

A new concept is described for building a novel electron source designed to produce a pulsed beam with $\delta_f \approx 2\ 10^{-3}$ and longitudinal emittance four orders of magnitude smaller than currently achieved values. This high brightness, low longitudinal emittance regime enables a wide range of novel applications that utilize angstrom-scale spatial resolution and eV-scale energy resolution.

The current state of a proof-of-principle experiment conducted at LBNL is also described.

INTRODUCTION

This article uses the terms degeneracy and brightness interchangeably. It uses the usual definition of brightness for a pulsed beam

$$B = \frac{N}{\epsilon_x \epsilon_y \epsilon_z}$$

where N is the average number of electrons per pulse. However, emittances are expressed as dimensionless quantities in Compton wavelength units:

$$\lambda_c^2 \epsilon_x^2 = \overline{(x - \bar{x})^2 (\beta_x - \bar{\beta}_x)^2} - \overline{(x - \bar{x})(\beta_x - \bar{\beta}_x)}^2$$

Using this definition of emittance, brightness and degeneracy are equal.

Existing electron sources produce beams whose brightness is far less than 1, the maximum allowed by the Pauli exclusion principle. For example, a state of the art room-temperature field-emitter can produce a DC beam with $\delta_f \approx 10^{-5}$ [1], while high-current pulsed RF photoinjector sources for high-energy accelerators strive to produce a beam with $\delta_f = 2.5\ 10^{-12}$ [2].

Several factors limit the brightness of these sources. The Fermi temperature of the emitted electrons is significantly lower than the electrons remaining in the source, while interactions with the collective electric field (space charge) and with randomly positioned electrons in the beam further decrease the beam brightness. In the case of field emitters, large inhomogeneities in the electric field near the tip also degrade brightness considerably.

We describe a new concept for a pulsed electron source designed to produce a beam with $\delta_f \approx 2\ 10^{-3}$, average current up to 1 pA, and emittances $\epsilon_x \approx \epsilon_y \approx \epsilon_z \approx 5$. Instead of using a solid metal or semiconductor, our electron source consists of an atomic beam of Cesium atoms. A laser with pulse duration FWHM 2.5 ns excites, on average, one atom per pulse in the atomic beam to a very high Rydberg state. After 40 ns, as the electron reaches the 'apogee' of its orbit, a pulsed electric field ionizes the nearly stationary electron. This ionized electron forms one pulse in the beam; afterward the remaining ion is removed with a cleaning pulsed electric field. This process can have repetition rate up to 10^7 per second, producing an average current up to 1 pA.

Since each ion is cleaned before the next electron is produced, Coulomb interactions between the electron and previously produced ions are eliminated. Because the electrons are produced one by one, the space charge problem is eliminated. Since the electrons are nearly stationary when ionized by the homogeneous ionizing field, they emerge from the atom with very small temperature ($\approx 10^{-9}$eV). This more than compensates for the relatively large volume within which the electron is extracted. All these factors work together to yield a beam with $\delta_f \approx 2\ 10^{-3}$.

An electron source with these parameters can open a wide range of novel applications that utilize angstrom-scale spatial resolution and meV-scale energy resolution. Possible applications for this electron source include angstrom-scale resolution electron microscopy, electron holography, and investigations of dynamics on a picosecond time scale using pump-probe techniques. By accelerating or decelerating the beam, one can adjust the energy and time uncertainties according to the requirements of the target application, subject to the constraint $\Delta E \Delta T / \hbar = \epsilon_z \approx 5$. For example, in our test beam we plan to have an energy spread 10^{-4}eV which corresponds to 30 ps jitter relative to the ionization pulse.

APPROACH/METHODS

An effusive source generates a beam of neutral Cesium atoms, some of which pass through an interaction volume about $10 \times 10 \times 10 \mu m^3$ defined by three overlapping laser beams. The first two CW lasers excite about 1/4 of these atoms through two transitions to the $7S_{1/2}$ state, while the third pulsed laser excites about one atom per pulse up to an

extreme Rydberg state within 25 μeV of ionization.

After each pulse, the excited electron takes about 40 ns to travel from its initial position a few atomic radii from the Cs nucleus to approximately 65 μm. At this 'apogee', the almost ionized electron is nearly stationary with minimal momentum spread, and distributed within a 10 μm thick spherical shell with angular distribution $1 + 3\cos(\theta)^2$ about the polarization axis of the pulsed laser

At this point, the atom is ionized with a 1 ns pulse of a 30 V/cm electric field. Because the electron is so far from the Cs ion, Coulomb interactions with the ion introduce minimal increase in emittance and decrease in brightness.

The electron then exits through an aperture into a DC accelerating field, and then on to electron optics which will manipulate the distribution of the beam in 6-D phase space to match the target application. Once the electron has finished its flight, the cleaning pulse removes the ion from the interaction volume.

BRIGHTNESS CALCULATION

The brightness has been calculated two ways, both yielding identical results.

The first calculation assumes from quantum mechanics that the ionizing photon has energy uncertainty $\Delta E = \hbar/\Delta t$. Also, we know that the electron has angular distribution $1 + 3\cos(\theta)^2$ from experiment[3]. The remainder of the calculation follows a classical Kepler orbit.

The second calculation uses the angular distribution from experiment, but treats the motion of the electron up to the turning point quantum mechanically, starting in the $7S_{1/2}$ state.

Both calculations show the emittances $\epsilon_x \approx \epsilon_y \approx \epsilon_z \approx 5$ and $N \approx .25$. This justifies the use of simple analytical expressions from the classical calculation to optimize experimental parameters.

OPTIMIZING BRIGHTNESS

Several parameters need to be optimized to create a beam with maximal brightness. The most important parameters and justifications for their optimal values are briefly described here.

Choice of Atomic Species

Cesium was chosen because it has high vapor pressure at room temperature and appropriate lasers that are commercially available. The high atomic weight and low temperature required for significant vapor pressure minimizes the effective temperature of the electron due to the thermal motion of the atom.

Interaction Region Size

The region defined by the intersection of the lasers was chosen as small as possible, to minimize the contribution of the spread in ion position to the total transverse emittance.

Given the laser wavelengths and geometric limits on the laser beam angle of convergence, the minimum volume is $\approx$ 10x10x10 μm^3.

Excitation Level

Given the interaction region above, the Rydberg state which yields the smallest emittance corresponds to a principle quantum number about $n = 800$.

Larger n corresponds to electron momentum spread at apogee smaller than that of the atomic beam, while smaller n corresponds with smaller position uncertainty at apogee than that of the interaction region. Thus, a deviation in either direction from 800 slightly increases the emittances.

$n = 800$ corresponds to a time to apogee about 40 ns.

Laser Pulse Duration

Given 40 ns to apogee, the optimal FWHM is approximately 2.5 ns. This optimum is a compromise between two processes. The longer the laser pulse duration, the larger the uncertainty in the time at which the electron reaches apogee, thus, the larger the spread in momentum at ionization time. The shorter the laser pulse, the larger the energy uncertainty, thus a larger spread in momentum.

Laser Intensity

The saturation intensity at resonance is approximately 10mW/cm^2. To minimize the required atomic beam density, the intensity is increased by an order of magnitude. Power broadening will thus ensure that all atoms in the interaction region will participate in the transitions. At these intensities, the 852 nm CW laser populates half of the atoms in the $6P_{3/2}$ state, and of those, the 1470 nm CW laser populates half in the $7S_{1/2}$ state.

The saturation intensity for excitation into the Rydberg state is approximately 10^{8}W/cm^2. This is determined by the cross section for excitation into the Rydberg state - about 10^{-18}cm^2 and the laser pulse length, 2.5 ns. A 100 W 777nm laser with 10MHz repetition rate, pulse width 2.5 ns and Fourier limited bandwidth is commercially available.

Atomic Beam Density

The atomic beam density is determined by the fact that one atom is to be ionized in a volume of 10^{-9}cm^3. Taking into account the fraction of atoms available to interact with the lasers, a minimum density of few 10^{10} atoms per cm^3 is required. To keep things simple, the atomic beam should come from an effusive source; this restricts the maximum density to approximately the same value.

Stray Electrons

Given that the beam is a fraction of a pA, photoionization of electrons from metal surfaces near the source must be excluded. This places limitations on the composition of

the metal and surface layers of Cs. We are currently experimenting with different metals and methods of controlling surface contaminants in an ultra-high vacuum to minimize the photoionization rate.

Stray Magnetic Fields

A few 10^{-3} Gauss will degrade brightness - and the source needs to be contained within suitable magnetic shielding and isolated from currents.

Stray Electric Fields

Estimation shows that stray electric fields need to be constrained within 10^{-4} V/cm.

CURRENT STATUS AND CONCLUSION

We currently have three lasers operational, and are conducting an experiment to measure stray electrons and electric fields as a function of geometry, timing, composition of metal surfaces and other factors.

Assuming known and unknown technical challenges can be overcome, the electron source will improve brightness by two orders of magnitude and longitudinal emittance four orders over existing sources.

An electron source with these parameters will open up new applications, e.g., in electron microscopy, sub-meV energy resolution, inverse photoemission spectroscopy, precise measurement of electric fields in orbital laboratories, energy exchange with tens of μeV accuracy in inelastic atomic and molecular scattering, and opening new ways of investigating chemical reactions and dynamics on a picosecond time scale using pump-probe techniques.

ACKNOWLEDGEMENTS

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