ULTRACOLD AND HIGH BRIGHTNESS ELECTRON SOURCE FOR NEXT GENERATION PARTICLE ACCELERATORS

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Abstract

The ultracold plasma-based electron source has recently been proposed as an alternative to conventional photo-injectors or thermionic electron guns, which are widely used in today's particle accelerators. The advantages of the ultracold plasma-based electron source lie in the fact that the electrons extracted from the cold plasma (from near threshold ionization of ultracold atoms) has very low temperature, e.g. down to 10 K, and has the potential for producing very low emittance and therefore high brightness electron bunches. These features are crucial for the next generation particle accelerators, e.g., free electron lasers, plasma-based accelerators and the future linear colliders. In this paper, we discuss the basic mechanism of ultracold electron beam production and introduce our new facility for an ultracold, high brightness electron source based at the University of Manchester's Photon Science Institute (PSI).

INTRODUCTION

Ultracold plasma-based electron sources have recently been proposed as an alternative to the existing photo-emitters and thermionic electron guns used in current particle accelerators [1, 2]. The advantages of this new generation of electron sources arise since the electron beam temperature is many orders of magnitude lower than that of conventional electron sources. The resultant beam emittance (which defines the beam focusing properties) is hence around a few orders of magnitude lower. In addition, cold electron sources have the potential to produce pulses with ultra-short bunch lengths (e.g. sub picosecond or femtosecond), making them ideal electron sources for the next generation of particle accelerators. These include high luminosity colliders, plasma wakefield accelerators, injectors for free electron lasers and Compton backscattering for the production of femtosecond x-rays. Further, since these new sources have much higher energy resolution, their coherence is correspondingly greater. This makes them ideal for the development of a new generation of electron diffraction experiments, with potential use in structure studies ranging from materials science through to cell biology [3].

ULTRACOLD PLASMA

Ultracold plasmas (UCP) can be produced through near threshold photoionization of an ultracold atom cloud. The advent of cheap and reliable laser light has enabled rapid development of methods to cool and trap atoms. Rb atoms are typically studied because they have convenient transitions that are readily accessible with 780 nm laser radiation, as is available from diode lasers. A commonly used technique employs a magneto-optical trap (MOT) [4], which consists of a near resonant laser field in the presence of an inhomogeneous magnetic field (provide by a pair of anti-Helmholtz coils) to cool and spatially confine a cloud of ~10^9 atoms at temperatures as low as ~100 μK. The low temperature of the atom cloud means the atoms are virtually stationary, which allows almost Doppler-free photoionization to take place. The photoionizing laser can then be tuned to near threshold to produce cold electrons and ions with very little excess energy. By carefully shaping the intensity distributions of the laser beams involved in the ionization process, it is possible to produce cold electrons with a uniform density distribution. This will allow any expansion of the electron cloud due to space charge to be countered with the use of standard linear electron lensing [3, 5].

Due to the large mass difference between ions and electrons, the excess energy produced in the photoionization process, i.e., the laser energy above the ionization limit, is mainly taken away by the electrons. Finely tuning the ionization laser frequency can produce electrons with a very well-defined temperature on the order of 10 K (with corresponding energy spread of several meV). In contrast, the ions receive only a small fraction of excess energy and stay in the mK regime [6]. To get a full understanding of the physical processes of formation of ultracold plasmas, a simple model can be employed [4]. When the cold atoms are photoionized, the charge distribution is neutral everywhere, i.e., the numbers of electrons and ions are basically equal and with a quasi-uniform distribution. As the hotter electron cloud expands faster than the ion cloud, the charge in the center of the plasma becomes imbalanced with a positive charge. The resulting local ions create a Coulomb potential well for trapping electrons. The Coulomb potential energy, *U*, is given by

$$U = \sqrt{\frac{2}{\pi}} \frac{Ne^2}{4\pi\varepsilon_0 r} \qquad (1)$$

Where e and ε_0 are the electron charge and permittivity of free space respectively, N is the number of positive ions that has a Gaussian density distribution with a characteristic radius r. Electrons with energy greater than U escape from the ions' potential well. The more the electrons that escape, the deeper the Coulomb potential becomes, until the remaining electrons' kinetic energy is less than or equal to U, so that they remain trapped in the potential well. As electrons in the potential well thermalize, the average kinetic energy of some electrons can be greater than the well depth. These electrons then escape the well and evaporation occurs. Finally, the potential well becomes deep enough to trap all remaining electrons. Free electrons and positive ions exist independently in the trap well and an ultracold plasma is then formed. The cold electrons can then be extracted by applying a strong electric field across the ultracold plasma.

In summary, a four-step procedure can explain how to generate the cold electrons from an UCP. (I) Rb atoms are cooled and trapped in a MOT; (II) The cold atoms are then laser excited to an intermediate state; (III) A second laser beam ionizes the excited atoms only within the volume irradiated by both lasers. In this way, the shape and density of the initial electron cloud can be carefully controlled; (IV) Finally, the cold electrons in the UCP are extracted by an externally applied electric field.

BRIGHTNESS OF ELECTRON BEAM

In order to compare the ultracold electron source with conventional photo-injector and thermionic electron sources, here we examine how particle beam quality can be defined. In accelerator physics, the quality of electron beams can be expressed in terms of the transverse brightness, $B_\perp$, which can be written as

$$B_\perp = \frac{I}{4\pi \varepsilon_x \varepsilon_y} \tag{2}$$

where I is the peak beam current, ε_x and ε_y are the normalized transverse beam emittances given by

$$\varepsilon_x = \frac{1}{mc}\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle xp_x\rangle^2} \tag{3}$$

where < > denotes the averaging over the ensemble of electrons in the bunch, m is the electron mass, c is the speed of light and $p_x = \gamma m v_x$ the transverse momentum, in which $\gamma = \left[1-(v/c)^2\right]^{-1/2}$ the relativistic gamma factor and v_x the horizontal velocity the beam. For a beam with a Gaussian distribution in transverse phase space (x, p_x, y, p_y), $(\gamma^2 - 1)B_\perp$ is equal to the peak value of the current density per unit solid angle.

At the beam waist, Eq. (3) can be simplified to

$$\varepsilon_x = \frac{1}{mc}\sigma_x \sigma_{p_x} \tag{4}$$

where σ_x is the rms bunch radius and $\sigma_{p_x} = \sqrt{mkT}$ is the temperature dependent rms transverse momentum of the electrons with respect to the average momentum (k is Boltzmann's constant). For an electron source with electron temperature T, the transverse emittance is given by [6]

$$\varepsilon_{source} = \sigma_{source}\sqrt{\frac{kT}{mc^2}} \tag{5}$$

here σ_{source} is the rms source size.

For a thermal electron source with a peak current density J one can define the transverse brightness as follows

$$B_\perp = \frac{mc^2 J}{\pi k T} \tag{6}$$

From Eq. (6), one can clearly see the advantage of lower electron temperature.

For the conventional electron sources, the best performing pulsed picosecond sources are RF photo injectors, in which electrons are created by pulsed laser photoemission, subsequent acceleration and bunch compression in RF fields, e.g. the RF photo-injector electron guns used at LCLS at SLAC [7] and the one used at Accelerator Test Facility (ATF) at BNL [8]. As a typical example the ATF electron photo-gun at BNL can produce 0.5 nC electron bunch with $I \approx 120\,\text{A}$ and $\varepsilon_x \approx 0.8\,\mu m$, corresponding to a beam brightness $B_\perp = 5\times10^{12}\,\text{A/(rad}^2\text{m}^2)$, about an order of magnitude smaller than the thermal brightness limit given by Eq. (6) [1]. The emittance coming out of the gun is usually dominated by emittance growth stemming from nonlinear space-charge forces and RF effects. This study has shown that the space-charge force could be eliminated by a proper shaping of the radial intensity profile of a femtosecond photo-excitation laser [9]. This would make it possible to reach the thermal brightness limit corresponding to $T = 10^3$-10^4 K. Table 1 below shows the comparison of the specifications of beam quality between the ultracold electron source based on a MOT, and the conventional electron sources based on RF photo-injectors or thermionic guns. One can see that the electron temperature for the ultracold electron source is about two to three orders of magnitude lower than the conventional electron source. This means a small emittance and high brightness for the ultracold electron source. It might be worth noting that it is difficult to get very high bunch charge, e.g. 1 nC and maintain the low temperature/emittance at the same time. Concerning the bunch length, in principle, a femtosecond electron bunch can be achieved by firing a femtosecond laser pulse to ionize the cold atom cloud. As far as the lifetime of the electron source is concerned, the experiments conducted at Eindhoven University of Technology has shown that there is almost no age limit for a MOT based cold electron source if one continues to provide the Rb vapor to the ionization chamber, and the quantum efficiency is also comparable to the metallic-based photocathode materials, e.g. copper or magnesium [10].

Table 1: Comparison between ultracold electron source and conventional electron source

	Ultracold Electron Source	Conventional electron source
Electron temperature [K]	<10	1000-10000
Beam charge (pC)	1000	100-3000
Emittance[mm.mrad]	0.04	~1
Brightness [A/m^2 sr]	10^{16}	10^{12}-10^{13}
Bunch length [ps]	0.1-1	~10
Lifetime [hours]	no age limit	< few hundred

AC-MOT AT MANCHESTER PSI

A novel MOT has been invented in Manchester, which uses alternating current to generate the magnetic trapping field together with high speed polarization switching of the damping laser field. This new type of trap, the ac-MOT, allows the magnetic fields within the trapping region to be switched off over 300 times faster than for a conventional MOT [11]. This trap has the advantage that the cold electrons produced by the photoionization process will not experience additional heating due to the magnetic field present in conventional MOTs.

COLD ELECTRON SOURCE AT PSI

We are currently designing and constructing a cold electron source based on the ac-MOT. Atoms cooled and trapping in the ac-MOT will be selectively photoionized with a laser pulse. Cold electrons will then be extracted by applying an electrostatic field. After extraction, the electron beam will be allowed to drift a short distance (up to several meters) followed by characterization, by using a microchannel plate (MCP). A pepper pot, together with YAG screen measurement system will be set up to characterize the beam emittance. The beam emittance information will then be used to derive the effective electron temperature and to understand the dynamics of the cold beam formation and to compare it with the conventional electron source. Figure 1 shows the layout of the cold electron source at the PSI. In this configuration, we use a rubidium oven together with a Zeeman slower to provide a high flux of atoms to rapidly load a storage MOT [12]. Atoms are then guided on demand to the interaction chamber where they are retrapped in the ac-MOT. Here they will be photoionized and a cold electron beam extracted before being focused and characterized.

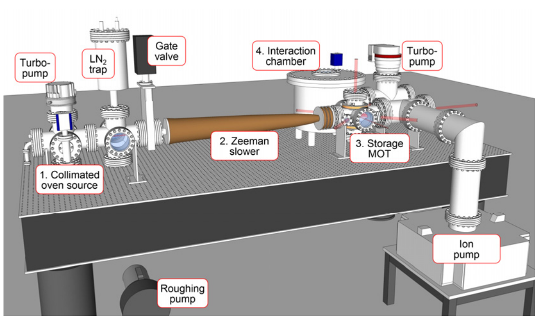

Figure 1: The layout of the PSI cold electron source.

Figure 2 shows a schematic of the PSI cold electron source with the beam extraction and characterization system. Initially a two or three electrode system will be used to extract cold electrons from photoionized trapped atoms. This simple system allows optical access for all the necessary trapping and ionization laser beams. A three-electrode system (similar to the extraction system of a Pierce electron gun) divides the extraction and acceleration parts and has the advantage due to its smaller electric effect on the heating of cold electrons created at the center of the ac-MOT. The main acceleration section will have a strong electric field, e.g. 1 MV/m for fast acceleration of the cold electrons. This system will be used as a test-bed to design a high brightness, cold electron source for future applications, e.g. an electron diffraction facility, injectors for free electron lasers, linear collider and plasma wakefield accelerators.

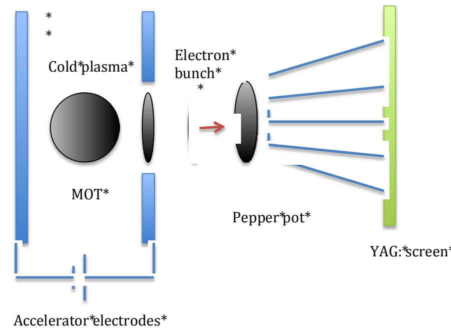

Figure 2: Schematic of the PSI cold electron source with beam extraction and the characterization system.

As an important example for application, we plan to build an ultracold electron diffraction facility. Immediately after extraction, the cold electrons will be accelerated and compressed by an RF cavity so as to avoid beam emittance expansion (due to space charge related heating processes).

CONCLUSION

Ultracold electron sources have the advantage of low beam emittance and high brightness compared to the conventional electron sources used in current particle accelerators. The ultracold electron source project in Manchester will study details of cold electron beam production, extraction and characterization. Ultracold electron sources are a new worldwide initiative, which are expected to revolutionize electron source technology and eventually will find many applications in the future.

REFERENCES

[1] B. J. Claessens et al., Phys. Rev. Lett. 95, 164801 (2005).
[2] G. Taban et al., EPL 91, 46004 (2010).
[3] S. B. van der Geer et al., Microsc. Microanal. 15, 282 (2009).
[4] T. C. Killian et al., Phys. Rev. Lett. 83 (1999) 4776.
[5] T. F. Gallagher et al., J. Opt. Soc. Am. B 20, 1091 (2003).
[6] O. J. Luiten et al., Int. J. Mod. Phys. A 22, 3882 (2007).
[7] D.H.Dowell et al., Proceedings of FEL07, 276(2007).
[8] J. Rosenzweig et al., The Physics and Applications of High Brightness Electron Beams, World Scientific, Singapore, 2003, p. 127.
[9] A. J. McCulloch et al., Nature Physics 7, 785 (2011).
[10] E.J.D. Vredenbregt, private communications, (2013).
[11] M. Harvey et al., Phys. Rev. Lett.101, 173201(2008).
[12] W. D. Phillips et al., Phys. Rev. Lett. 48, 596 (1982).