Arbitrarily Shaped High-Coherence Electron and Ion Bunches from Laser-Cooled Atoms

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Ultrafast electron diffractive imaging of biological molecules and defects in solid state devices can provide valuable information on dynamic processes at the nanoscale. The effective brightness of electron sources has been limited by non-linear divergence caused by repulsive interactions between the electrons, known as the Coulomb explosion. It has been shown that electron bunches with ellipsoidal shape and uniform density distribution have linear internal Coulomb fields,[1] which allows for reversal of the Coulomb explosion using conventional optics. Charged particle sources based on photoionisation of laser cooled atoms can in principle create bunches shaped in three dimensions and hence achieve the transverse spatial coherence and brightness needed for picosecond diffractive imaging with nanometre resolution.

We have recently demonstrated[2] such arbitrary shaping of the cold atom cloud (Fig. 1), and hence of the extracted electron bunches (Fig. 2a), and used the shaping capability to allow detailed measurement of the spatial coherence properties of the cold electron source.[3] We also show remarkable ion bunch shape formation and evolution, with direct visualisation made possible by the very low (milli-Kelvin) temperature of the ions (see Fig. 2b). Using two-step coherent excitation with a femtosecond laser from ground to excited state, and a nanosecond laser from excited state to the continuum, we have produced sub-nanosecond (or less) electron pulses. Diffraction experiments of simple crystalline materials are currently in progress, to demonstrate application of the high coherence of the novel source.

In separate work,[4] we have demonstrated coherent diffractive imaging with electrons in scanning transmission electron microscopy. Future development of the cold atom electron source will increase the bunch charge and charge density, demonstrate reversal of Coulomb explosion and picosecond pulse durations, and ultimately, ultrafast coherent electron diffractive imaging.

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[2] A. J. McCulloch, D. V. Sheludko, M. Junker, S. C. Bell, S. D. Saliba, K. A. Nugent, and R. E. Scholten, Nature Physics **7,** 785 (2011).
[3] S. D. Saliba, C. T. Putkunz, D. V. Sheludko, A. J. McCulloch, K. A. Nugent, and R. E. Scholten, (submitted).
[4] C. T. Putkunz *et al.*, Phys. Rev. Lett. (in press).

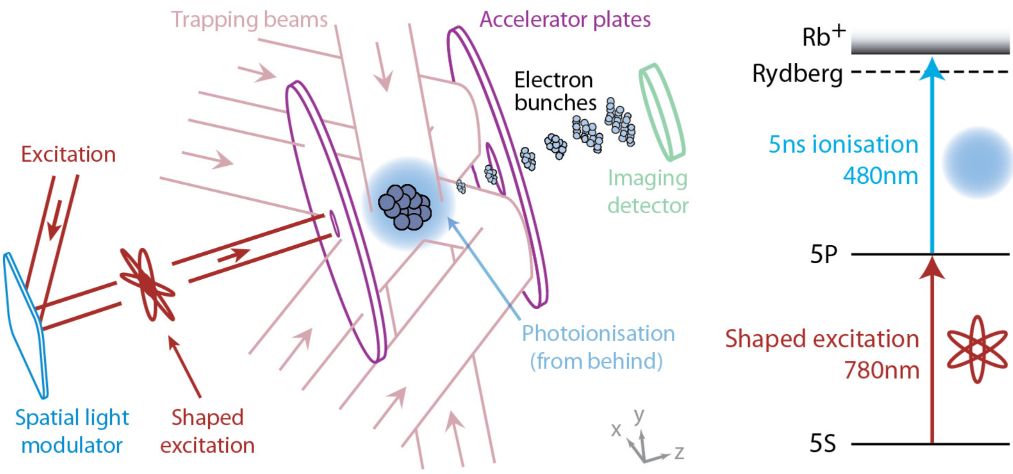

Figure 1 Experimental Schematic: Laser cooled and trapped atoms are photoionized with a combination of a 780 nm laser beam shaped by a spatial light modulator, and a 480 nm laser pulse with uniform intensity or shaped profile. Electrons and ions produced in the region of overlap between atoms, excitation, and photoionisation beams propagate to an imaging detector.

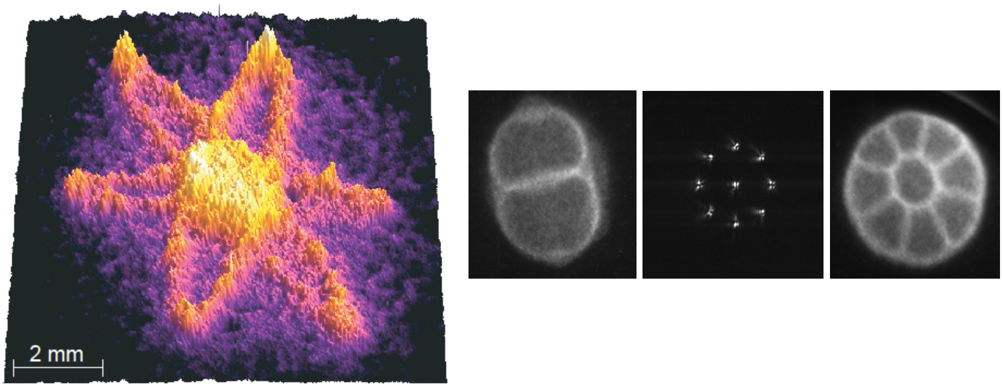

Figure 2 Cold Bunches: (a) A bunch of electrons (left) has been produced with a complex spatial distribution, and because of the low electron temperature (about 10 K) the bunch has retained its shape after propagating 24cm. (b) Images of propagated ion bunches (right) show two adjacent expanding ion bunches; excitation laser beam intensity profile for an array of mini-ion-bunches, and far right, the array of mini-bunches after propagation.