



Ion microscopy based on laser-cooled cesium atoms[☆]



M. Viteau^a, M. Reveillard^a, L. Kime^a, B. Rasser^a, P. Sudraud^a, Y. Bruneau^b, G. Khalili^b,
P. Pillet^b, D. Comparat^b, I. Guerri^c, A. Fioretti^{d,e,*}, D. Ciampini^{c,d,e}, M. Allegrini^{c,d,e},
F. Fuso^{c,d,e}

^a Orsay Physics, TESCAN Orsay, 95 Avenue des Monts Auréliens – ZA Saint-Charles – 13710 Fuveau, France

^b Laboratoire Aimé Cotton, CNRS, Université Paris-Sud, ENS Cachan, Bât. 505, 91405 Orsay, France

^c Dipartimento di Fisica, Università di Pisa, Largo Pontecorvo 3, 56127 Pisa, Italy

^d Istituto Nazionale di Ottica, INO-CNR, U.O.S. "Adriano Gozzini", via Moruzzi 1, 56124 Pisa, Italy

^e Consorzio Nazionale Interuniversitario per le Scienze Fisiche della Materia, CNISM, Sezione di Pisa, 56127 Pisa, Italy

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ABSTRACT

We demonstrate a prototype of a Focused Ion Beam machine based on the ionization of a laser-cooled cesium beam and adapted for imaging and modifying different surfaces in the few-tens nanometer range. Efficient atomic ionization is obtained by laser promoting ground-state atoms into a target excited Rydberg state, then field-ionizing them in an electric field gradient. The method allows obtaining ion currents up to 130 pA. Comparison with the standard direct photo-ionization of the atomic beam shows, in our conditions, a 40-times larger ion yield. Preliminary imaging results at ion energies in the 1–5 keV range are obtained with a resolution around 40 nm, in the present version of the prototype. Our ion beam is expected to be extremely monochromatic, with an energy spread of the order of the eV, offering great prospects for lithography, imaging and surface analysis.

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1. Introduction

Charged particle beams of controlled energy and strong focusing are widely used tools in industry and science [1]. State-of-the-art machines provide the possibility of modifying, analysing and imaging different objects and materials from the micro to the nanoscale. As an example, a Focused Ion Beam (FIB) column can be combined with a Scanning Electron Microscope (SEM) to provide full control of nanofabrication or nanolithographic processes. Ion energy can be varied typically in the 1–30 keV range, with an energy-dependent resolution attaining the nanometer range. State-of-the-art FIBs are commercially available (see for example: [2–5]), based mainly on plasma, liquid metal tip or helium ion sources for large, intermediate, and low currents, respectively. Despite the very high technological level of the available machines, research of new ion sources allowing even higher resolution and a wider choice of atomic or molecular ions for new and demanding application is very active [6].

[☆]This paper is in memory of Pierre Sudraud, outstanding inventor and entrepreneur.

* Corresponding author at: Istituto Nazionale di Ottica, INO-CNR, U.O.S. "Adriano Gozzini", via Moruzzi 1, 56124 Pisa, Italy.

E-mail address: andrea.fioretti@ino.it (A. Fioretti).

In the last decade, proposals [7–9] and experimental realizations [10,11] of novel ion or electron sources based on the ionization of laser-cooled atoms have been reported and have shown potential improvements with respect to standard sources, in particular a low energy-spread and a high resolution in the low-energy regime. Due to the low temperatures associated with laser cooling, the ion (or electron) beam originating from the cold sample has an extremely narrow angular spread, i.e. a very low emittance. This means that ion or electron sources based on cold atom ionization would be able to create at low acceleration energy very small focal spots with relatively strong currents. Focused ion beams have been generated starting from both a magneto-optical trap (MOT) [10,11] and a slow and cold atomic beam [12]. Their properties as nanoprobe have been demonstrated first with chromium [13] and then with lithium [14] ions, the latter reaching a 27 nm resolution at 2 keV energy and 1 pA current. Very recently the lithium source has evolved into a complete system of scanning ion microscope able to work in the 500 eV–5 keV low energy range [15]. On the electron side, high-coherence electron bunches, obtained by ultrafast photo-ionization of cold atoms, have been demonstrated for single-shot electron diffraction studies [16,17]. It is worth mentioning that, in the 0.1–5 fA current range, a laser-cooled atomic beam is being tested as a candidate for the controlled production of low-density ion beams [18]. This could be of

interest for ion implantation onto surfaces with nanometric precision aimed at engineering few atom devices [19].

Here we present the prototypal realization of a complete low-energy Focused Ion Beam system based on laser-cooled cesium atoms. The system represents the practical implementation of our original proposal [20]. Atomic ionization is obtained either by laser promoting the neutral atoms into highly excited Rydberg states that are subsequently field-ionized, or by direct laser photo-ionization. The produced ions are coupled to a standard FIB column from Orsay Physics. Once accelerated to energies in the range 1–5 keV, ions are used for imaging and surface modifications of different substrates. A current up to 130 pA is available, and a typical spatial resolution on the order of 40 nm at lower currents, largely independent of the ion acceleration in the explored range, is achieved in the produced images. Our results are a first step towards the realization of an industrial prototype of laser-cooled atom based FIB machines.

2. Experimental setup

The experimental setup has been detailed in Ref. [20]. Briefly, it consists of a recirculating Cs oven outsourcing an effusive flux of cesium atoms, a laser-cooling region, an atomic excitation/ionization region, and finally a FIB column. A picture of part of the setup is shown in Fig. 1. The oven delivers a typical flux of

$1\text{--}2 \times 10^{13}$ atoms/s, with an average velocity of 200 m/s, for an oven temperature of 160 °C. After the oven, these atoms are transversally laser-cooled by the interaction with a quasi-resonant laser light until their transverse temperature drops in the few hundreds microKelvin range [21]. At this stage the atomic beam diameter is 4 mm and the estimated atom density is around 10^{10} cm^{-3} . A few cm downstream atoms enter a constant electric field region, where they are laser promoted to a highly-excited (Rydberg) state by interaction with two laser beams, and then a region of a few mm with of rapidly increasing electric field, where they are ionized at a specific field value. The ions are extracted and accelerated by the electric field towards the FIB column. At the end of the column they can be either focused on a sample mounted on a translation stage, or deflected onto a Faraday cup connected to a picoammeter to measure the current.

Differently from most similar experiments [10–13] where photo-ionization is used, atomic ionization is obtained through Rydberg excitation. As detailed in Ref. [20], the use of Rydberg atoms has two potential advantages compared to photo-ionization: a very large excitation efficiency and a low energy spread. The former quality is especially true for low principal quantum numbers n , and leads to a more efficient ionization of the atomic beam. The latter quality is largely independent of the excitation volume. Conversely, in the photo-ionization case, the energy spread is proportional to the product of the longitudinal length of the ionization region with the extraction electric field [11]. As a

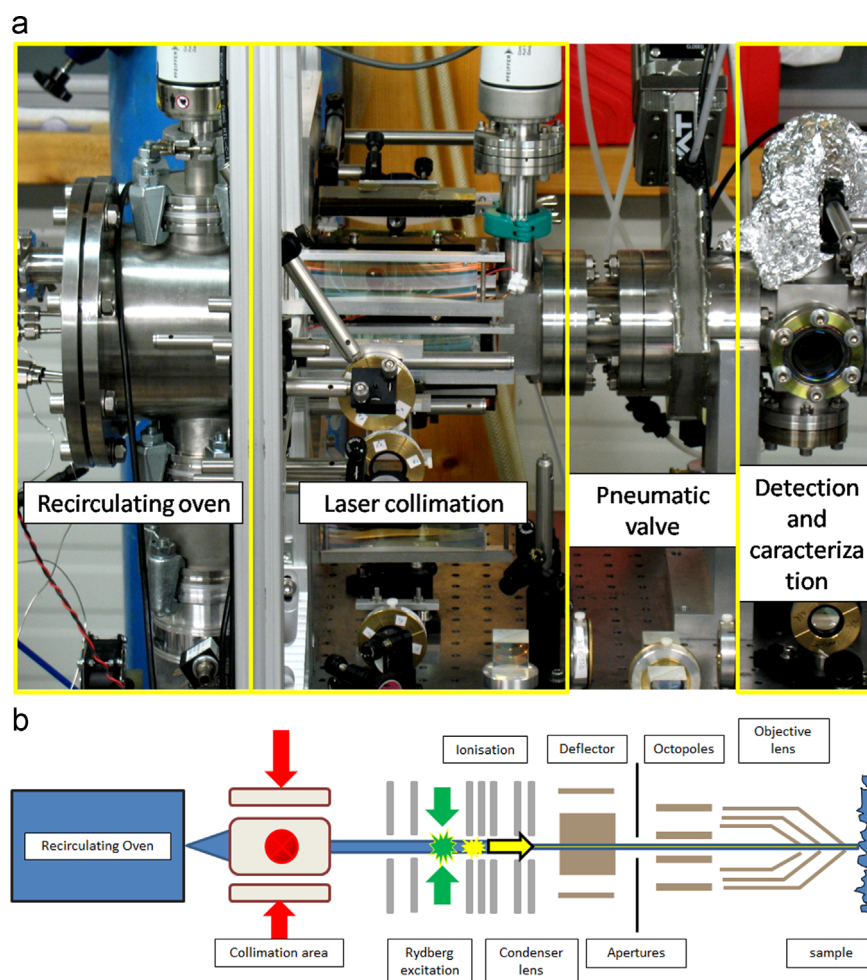


Fig. 1. (a) Picture and (b) sketch of the ultra-cold electron/ion source. An intense effusive atomic beam is transversally cooled using laser cooling techniques. Electrons or ions (depending on electrode polarities) are produced either by laser excitation to Rydberg states that are then field-ionized or by photo-ionization. The laser apparatus, the optical setup and the FIB column are not shown in the picture.

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