# FIRST EXPERIMENTAL RESULTS FROM DEGAS, THE QUANTUM LIMITED BRIGHTNESS ELECTRON SOURCE*

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*Abstract*

The construction of DEGAS (DEGenerate Advanced Source), a proof of principle for a quantum limited brightness electron source, has been completed at the Lawrence Berkeley National Laboratory. The commissioning and the characterization of this source, designed to generate coherent single electron "bunches" with brightness approaching the quantum limit at a repetition rate of few MHz, has been started. In this paper the first experimental results are described.

## INTRODUCTION

Electron sources find application in a number of fields, ranging from electron microscopy to high energy physics accelerators. The characteristics of the source strongly depends on the specific application, but for all of them the main parameter to be optimized is the brightness:

$$B = N/\varepsilon_x \varepsilon_y \varepsilon_z \qquad (1)$$

where $N$ is the number of particles in the beam and $\varepsilon_w$ are the normalized emittances in the three planes ($w = x, y, z$). A larger brightness is desirable for all applications and source designers play their game in trying to maximize this important quantity. Nevertheless, there is a fundamental limit to account for: quantum mechanics sets a minimum phase space volume that a particle can occupy:

$$V_E = (\lambda_C/2\pi)^3 \qquad (2)$$

where $\lambda_C = h/m_0c$ is the Compton wavelength with $h$ the Planck constant, $m_0$ the particle rest mass and $c$ the speed of light. Particles inside this volume are indistinguishable or in other words are in the same coherent state. In the case of polarized fermions, the Pauli exclusion principle states also that not more than one particle can occupy the volume $V_E$.

If we now measure the product of emittances in Eq. (1) in $V_E$ units, we obtain a dimensionless expression for the brigthness usually referred as the degeneracy parameter $\delta$:

$$\delta = BV_E \qquad (3)$$

This is a convenient quantity when comparing different sources and for what we said before, the degeneracy parameter in the case of polarized electrons cannot be larger than 1. At the present time, the highest brightness electron source in operation is a field emission gun where a carbon nanotube is used as the emitting tip [1]. The degeneracy parameter for such a source is ~ $10^{-5}$. In the high current photo-injectors typically used in accelerators the value for $\delta$ is only ~ $10^{-11}$. Electrons inside a metal cathode before the extraction occupies almost all available states and thus have degeneracy parameter ~ 1. Scattering with phonons during the extraction and electron-electron scattering after extraction are among the main phenomena that quickly degrades $\delta$ down to many orders of magnitude lower values.

A scheme for a pulsed electron gun approaching the degenerary parameter quantum limit have been proposed in [2]. Such a source would allow for revolutionary applications in fields such electron microscopy and holography for example. At the Lawrence Berkeley National Laboratory we are completing the construction and initiating the test of DEGAS (DEGenerate Advanced Source), a proof of principle source based on the scheme described in [2]. In this paper we present the first experimental results obtained during the tune-up of the source subsystems.

## SCHEME DESCRIPTION

The complete description of the source scheme and operation principles can be found elsewhere [2], here we only summarize the fundamental concepts. Figure 1 shows the main parts of the source. The neutral Cs atom source is composed by an oven with a pinhole aperture (50 µm radius). The oven is heated at ~ 500 °K to generate a continuous flux of neutral Cs atoms through the pinhole into the ionization chamber. In the center of the ionization chamber, three lasers (852 nm CW; 1470 nm CW; 777 nm pulsed, 2.5 ns FWHM, 3 MHz rep-rate) mutually overlap to create an interaction region (IR) of about (10 µm)$^3$ volume where the Cs atoms can be excited from the ground level $6S_{1/2}$ to a very high lying Rydberg state nP (with <n> = 800 at ~ $10^{-5}$ eV below ionization). The intensity of the lasers and the density of the Cs beam are tuned to have on average one single atom excited per cycle. The electron in the Rydberg level is represented by a wavefunction with radial evolution described by a Kepler-like orbit. After the laser excitation a waiting period of ~ 40 ns allows for the electron to arrive at the apogee of its orbit at ~70 µm from the parent nucleus where its kinetic energy is almost zero. At this

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point a short pulsed voltage is applied to finally ionize the atom and to give to the electron some kinetic energy (~ 1-100 eV) for leaving the ionization chamber and entering the acceleration chamber where it is finally accelerated up to the energy required by the application. After the electron leaves the gun, a "clearing" pulse is applied to the ionization chamber in order to remove the residual ion before of the following laser pulse. The full cycle can be repeated with a 3 MHz repetition rate generating an average current of ~0.5 pA.

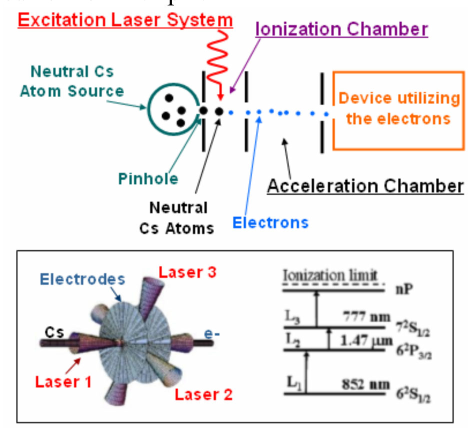


Fig. 1. Source layout and Cs atom excitation scheme.

The described scheme allows to eliminate the Coulomb interaction between electrons (a single electron per cycle is produced) and to properly control the interaction between the electron and the ions (parent and residual ones). Calculations [2] showed that a degeneracy parameter of ~0.002 can be obtained with the described scheme, and of ~0.6 if the 777 nm is properly "chirped" in frequency and transverse laser cooling of the neutral Cs beam is performed.

In order to achieve such a result, all "environmental" variables need to be carefully controlled. In particular, residual magnetic and electric fields must be smaller than ~1 mG and ~0.1 mV/cm respectively and UHV vacuum pressures must be achieved in the gun chamber. Additionally, the laser frequencies need to be stably controlled by means of active feedback systems.

In order to develop the techniques necessary to achieve such results DEGAS a proof of principle source has been built at the Lawrence Berkeley National Laboratory.

## DEGAS DESCRIPTION

In the present configuration, DEGAS includes the complete set of subsystems required for the source described in the previous section, with the exception of the frequency chirp in the 777 nm laser pulse and of the transverse laser cooling for the Cs atoms. In addition DEGAS is equipped with two time of flight (TOF) systems based on micro-channel plates (MCP) detectors for the measurement of the residual electric field and for the characterization of the electron beam energy spread. Fig. 2, shows 3D CAD views and a picture of the source.

The core of the source is included inside a double magnetic shield and includes coils for the compensation of the residual magnetic field, photodiodes for measuring the fluorescence from the excited Cs atoms and heaters and thermocouples for controlling the temperature of the various parts of the source during vacuum baking.

Contacts between different metals in the parts inside the magnetic shield have been carefully avoided in order to not generate local voltages and/or currents and thus undesired stray fields.

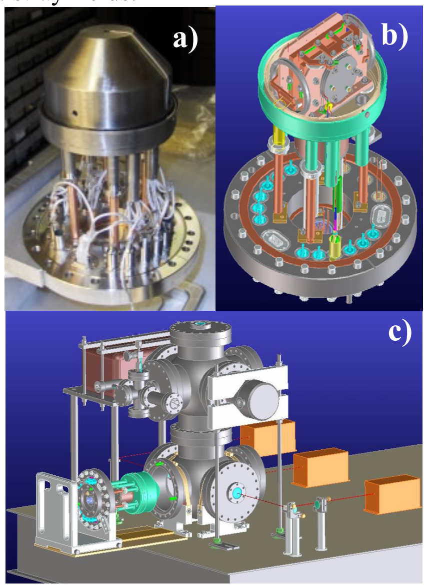


Fig. 2. 3D CAD views and picture of DEGAS. a) The source fully assembled on the main flange (8" conflat) with the magnetic shield on. b) A view without the magnetic shield. c) The main flange with the source being inserted into the main vacuum chamber. The 3 laser boxes in orange are also visible.

The Cs inside the oven is contained in dispensers that can be electrically heated to evaporate the Cs that then condenses on the internal walls of the oven. This is a few minutes operation that needs to be performed every once in a while in order to have on the oven walls the amount of Cs required for few days of operation. The total amount of Cs contained in the dispensers is sufficient for many days of operation. The Cs oven is outside the magnetic shield and its walls are heated by means of filaments arranged in a way that creates a temperature gradient along the oven keeping the pinhole area warmer for avoiding Cs condensation on that area. Three thermocouples allow monitoring the temperature in the different parts of the oven in order to control the oven pressure and thus the density of the neutral Cs beam released through the pinhole.

By supporting and connecting the MCPs body to the source support using AlN ceramics, electrical insulation and thermal conductivity were simultaneously obtained. This configuration sets a high conductivity path for the heat during the baking and avoids temperature damage of the detectors. Connections to the MCP detectors have been done by using home-made in vacuum high temperature coaxial cables to preserve the bandwidth required to transports the ~ 1 ns pulses from the detectors to the reading electronics. The arrival time of the electrons on the MCP with respect to the pulsed laser trigger is measured and digitised by time to digital converter boards and finally acquired by a computer through a digital PCI I/O board (National Instruments). The overall time resolution of the TOF system is ~ 130 ps FWHM.

All signals from the thermocouples are also digitised and read by the same computer through a LabView application that also implements the two frequency feedbacks for the 852 nm and 1470 nm lasers that will be described in the next section.

## FIRST EXPERIMENTAL RESULTS

Figure 3 shows the schematics of the feedback system used for stabilizing the frequency of the 852 nm CW laser. A similar system is used for the stabilization of the 1470 nm laser. The frequency for the pulsed 777 nm laser will is set according to the results from the TOF system.

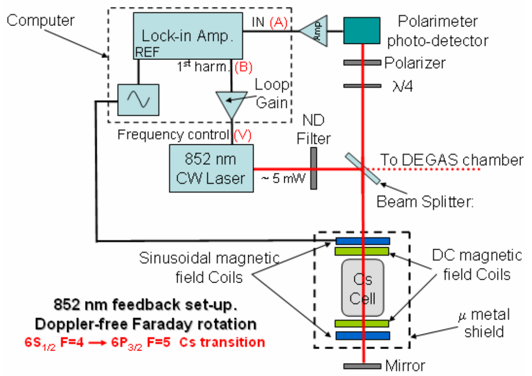


Fig. 3. Frequency feedback scheme for the 852 nm laser.

The linearly polarized 852 nm beam generated by a diode laser (Sacher) is split in two parts, one goes to the DEGAS chamber while the other is sent through a Cs cell and is reflected back through the same cell by a mirror. The cell is enclosed in a magnetic shield that contains two couples of coils that generates a magnetic field parallel to the photon beam path. A sinusoidal signal is applied to one of the coil sets to generate a magnetic field of few tens of mG and ~ 100 Hz frequency. The other set of coils can be powered with a DC current and used to nullify residual fields in the cell. After the cell, the reflected beam is sent to a polarimeter system composed by a quarter wave plate, a polarizer and a photodiode. The signal from the photodiode is then amplified, digitised and analysed by a lock-in amplifier developed in LabView and running on a PC computer. The signal component at the modulating magnetic field frequency is then extracted, sent to a DAC and to the frequency control of the laser (a piezo-actuator that controls the position of one the laser cavity mirrors). If no magnetic field is applied and the laser frequency is scanned around the $6S_{1/2}$ to $6P_{3/2}$ transition, part of the photons are absorbed by the Cs atoms in the cell and the photodiode signal will show a depletion with width determined by the Doppler shift due to the thermal velocity distribution of the Cs atoms in the cell, see Fig. 4. The interaction between the electron and the magnetic field of the nucleus generates a hyperfine structure on the Cs levels that shows in Fig. 4 as a set of local peaks in the transmission curve (some of the peaks are also due to the excitation of atoms with different group velocity). For the DEGAS operation, the laser must be tuned on the peak indicated by the arrow in Fig. 4. By tuning the frequency on that line and switching on the sinusoidal magnetic field on the Cs cell, the laser beam experiences a polarization rotation induced by the nonlinear Faraday rotation due to the Cs transition resonance.

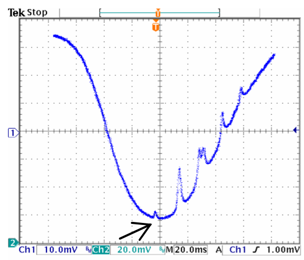

Fig. 4. Cs transition from $6S_{1/2}$ to $6P_{3/2}$ Doppler free spectroscopy. the horizontal axis is proportional to the laser frequency while the vertical one shows the transmission through the Cs cell.

Such a rotation is modulated with the same frequency of the magnetic field and can be detected in the polarimeter. The addition of the quarter wave plate allows measuring the effect in terms of polarization ellipticity.

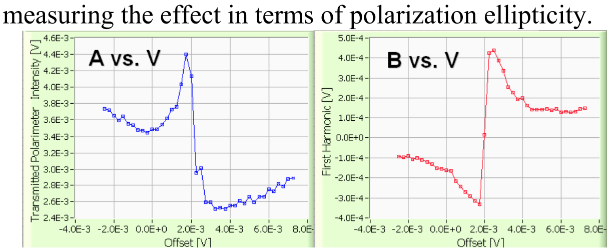


Fig. 5. Signal at the polarimeter exit (point A in Fig. 3) and its first harmonic (point B in Fig. 3). Quarter wave plate in.

The ellipticity signal (right portion of Fig. 5) shows a sharp derivative at the atom resonance. This signal can be efficiently used for driving the frequency control of the laser. A frequency stability of ~$10^{-8}$ has been routinely achieved. It is worth to point out that no laser frequency modulation is required in this scheme.

Both the TOF systems have been fully tested and calibrated by means of cosmic rays and by a thermionic electron source placed at the DEGAS IR temporarily..

In summary all DEGAS subsystems are now in operation and are starting to work together. Near future plans include the characterization of stray electric fields and of the electron energy spread.

## REFERENCES

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