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

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A Team Work

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- **Degeneracy parameter for current high brightness electron sources.**
- **A scheme for a quantum limited brightness source.**
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Brightness and Quantum Limitations

- **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 maximized is the brightness.**

$$\boxed{B = \frac{N}{\varepsilon_{nx}\varepsilon_{ny}\varepsilon_{nz}}}$$

$N \equiv \#\ of\ \ particles$

$\varepsilon_{nw} \equiv norm.\ emittances$

- **Quantum mechanics sets a minimum phase space volume that a particle can occupy:**

$$\boxed{V_E = \left(\lambda_C / 2\pi\right)^3}$$

$\lambda_C = h / m_0\, c$

Compton wavelength

- **Particles inside this elementary 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.

The Degeneracy Parameter

- By measuring the product of emittances in V_E units, we obtain a dimensionless expression for the brightness usually referred as the degeneracy parameter δ:

$$\boxed{\delta = BV_E}$$

- The degeneracy parameters tells you how many particles are in the elementary phase space volume, or how efficiently the available phase space is filled.

- In the case of bosons, δ is not limited and can be very large. For example, in the case of a 1 J visible lasers δ~10^{18}

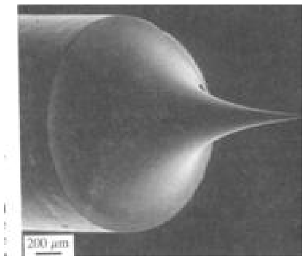
- For what said before, in the case of polarized electrons :

$$\boxed{\delta \le 1}$$

δ is a convenient quantity for comparing different sources.

Degeneracy Parameter in Existing Electron Sources

- In the case of low emittance RF photoinjectors for FEL and ERL applications (~ 1 nC, 10^{-6} m emittance): $\delta \approx 10^{-11}$



- The highest brightness source presently in operation is a field emission source for electron microscope applications, where the tip is a carbon nanowire. For this source: $\delta \approx 10^{-5}$

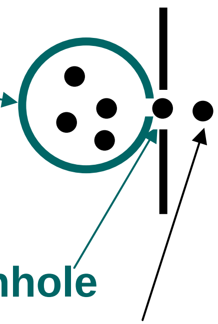
- Electrons inside a metal cathode before the extraction occupies almost all available states and thus have degeneracy parameter ~ 1 **!!!**

How do we loose all of that ?

Extraction Mechanism
Phonon scattering during extraction, ...

Coulomb interaction
e^--e^- scattering after extraction

A Quantum Limited Brightness Electron Source

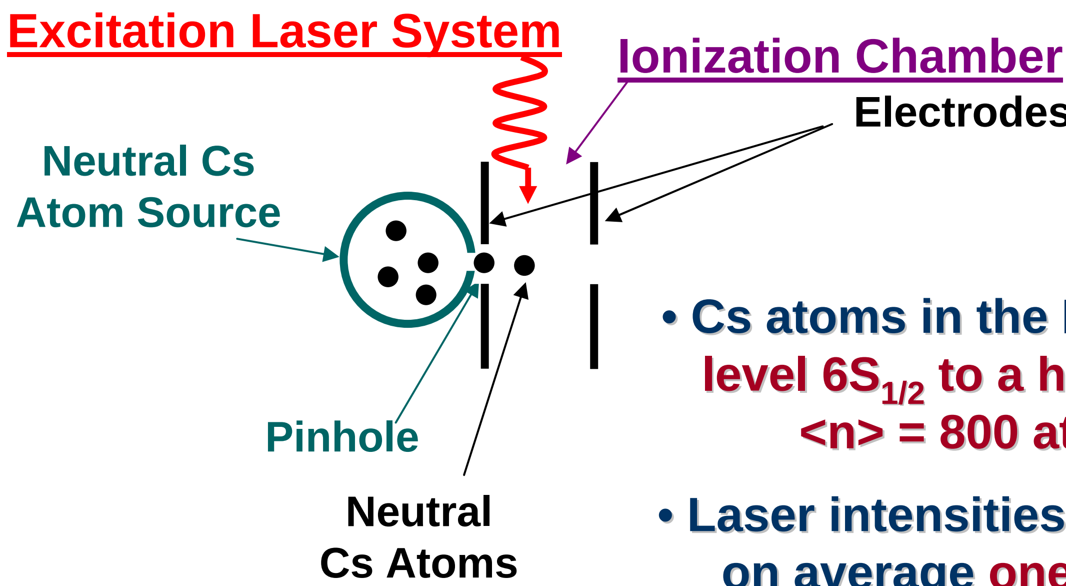


• A **neutral Cs atom source** composed by an oven with a pinhole aperture (50 μm radius).

• The oven is heated at ~ 500 ºK to generate a continuous flux of neutral Cs atoms through the pinhole.

• Why Cs?
Well known atomic structure, laser availability, one electron in the outer shell, easy to obtain the required pressure in the oven, ...
• K could be used as well

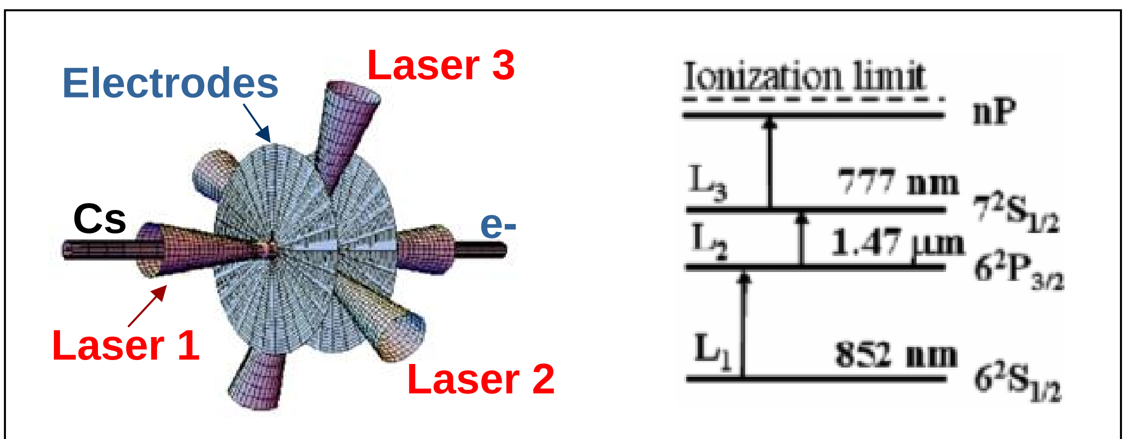
A Quantum Limited Brightness Electron Source



- Two CW lasers 852 and 1470 nm and one pulsed 777 nm, 2.5 ns FWHM, 3 MHz rep-rate mutually overlap in an interaction region (IR) of ~ (10 μm)^3.

- Cs atoms in the IR can be excited from the ground level $6S_{1/2}$ to a high lying Rydberg state nP (with <n> = 800 at ~ 10^{-5} eV below ionization).

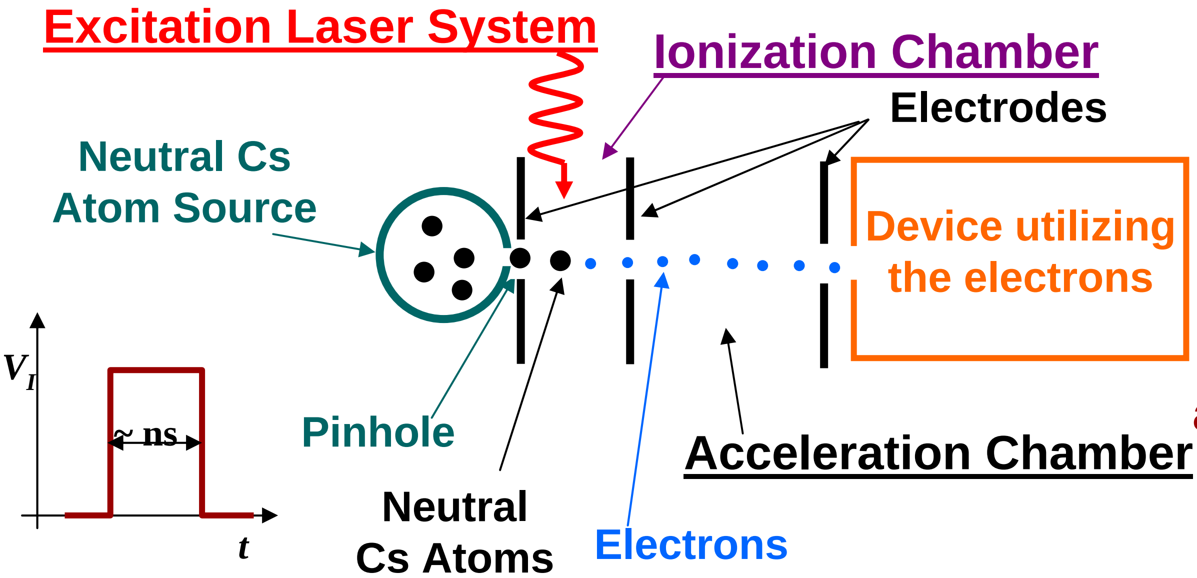
- Laser intensities and Cs density are tuned to have on average one single atom excited per cycle.



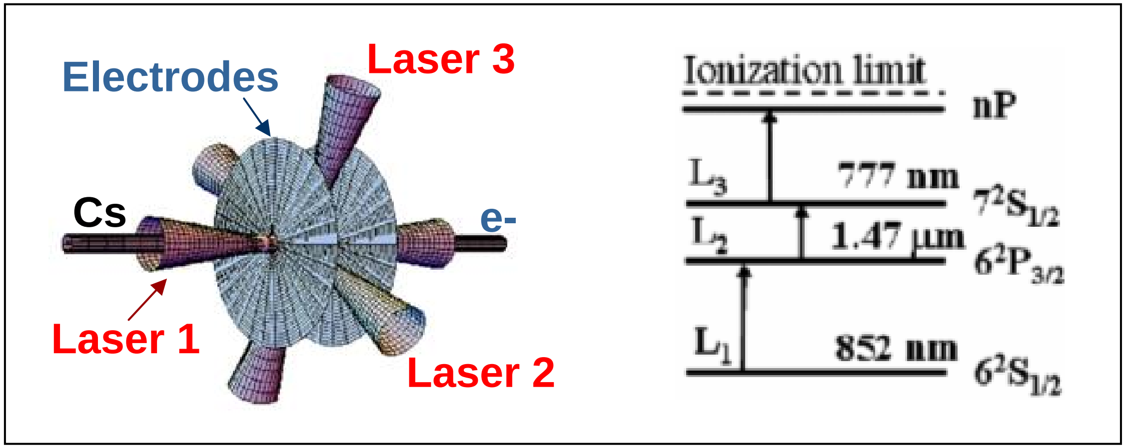
- The electron in the Rydberg level has a wavefunction with radial evolution described by a Kepler-like orbit.

- After excitation a waiting period of ~ 40 ns allows the e^- to arrive at the apogee of its orbit (~ 70 μm from the nucleus) with a kinetic energy ~ 0.

A Quantum Limited Brightness Electron Source

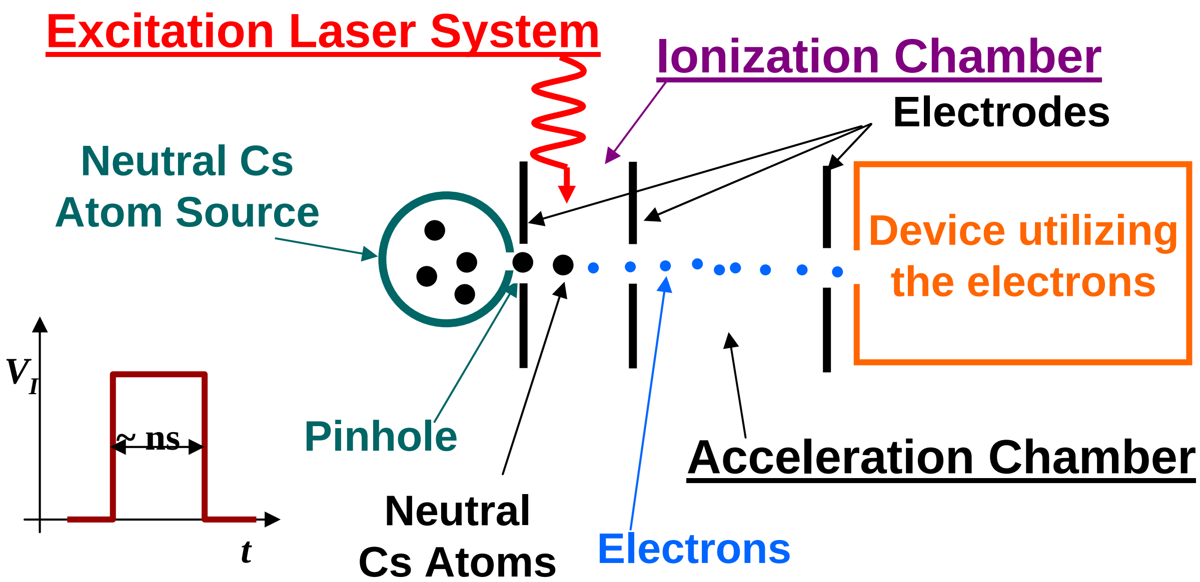


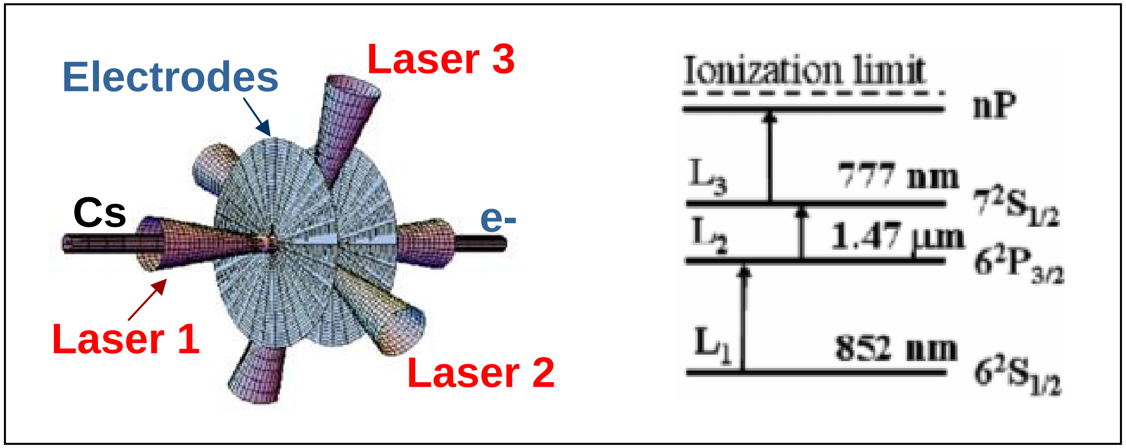
- After the 40 ns a short pulse is applied to ionize the atom and gives to the e$^-$ a kinetic energy of 1-100 eV.
- The e$^-$ leaves the ionization chamber and enters the acceleration chamber where it is accelerated up to the energy required by the application.



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.

A Quantum Limited Brightness Electron Source





M. Zolotorev, *et al.*, Phys. Rev. Letters **98, 184801, (2007).**

- **The cycle can be repeated with a 3 MHz rep-rate generating an average current of ~0.5 pA.**

- **The scheme allows to eliminate the interaction between electrons (a single electron per cycle is produced) and to control the interaction between the electron and the ions (parent and residual ones)**

- **Calculations showed that $\delta \sim 0.002$ can be obtained and $\delta \sim 0.6$ if the 777 nm is "chirped" in frequency and transverse laser cooling of the Cs beam is performed.**

Critical R&D Required

• In order to achieve the degeneracy parameter performance, all "environmental" variables of the source need to be carefully controlled.

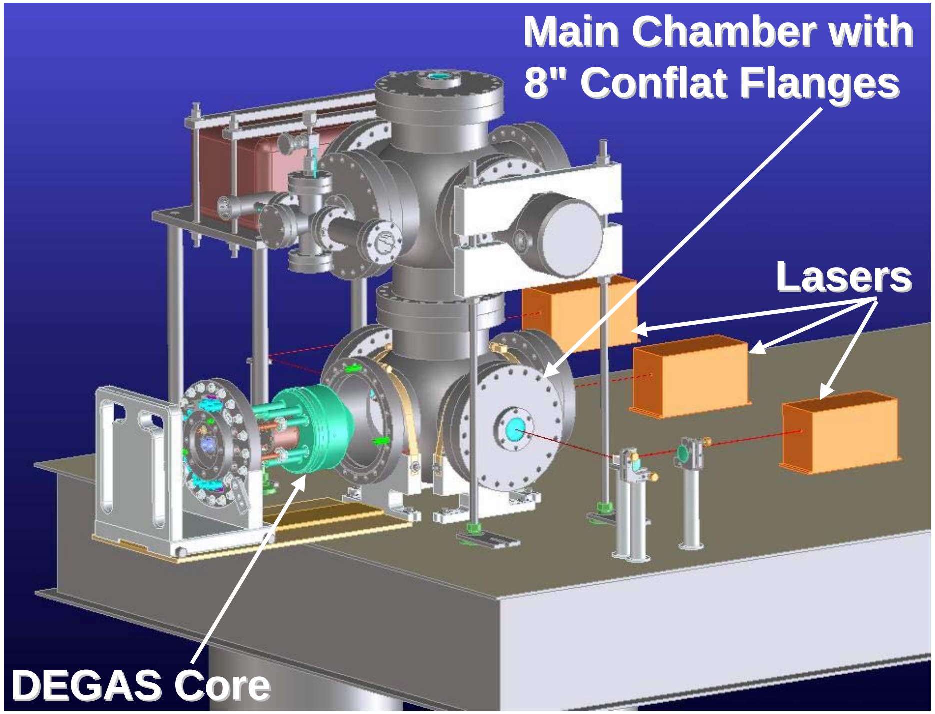
• For example, residual magnetic and electric fields must be smaller than ~1 mG and ~0.1 mV/cm respectively and UHV vacuum pressures must be achieved in the gun chamber.

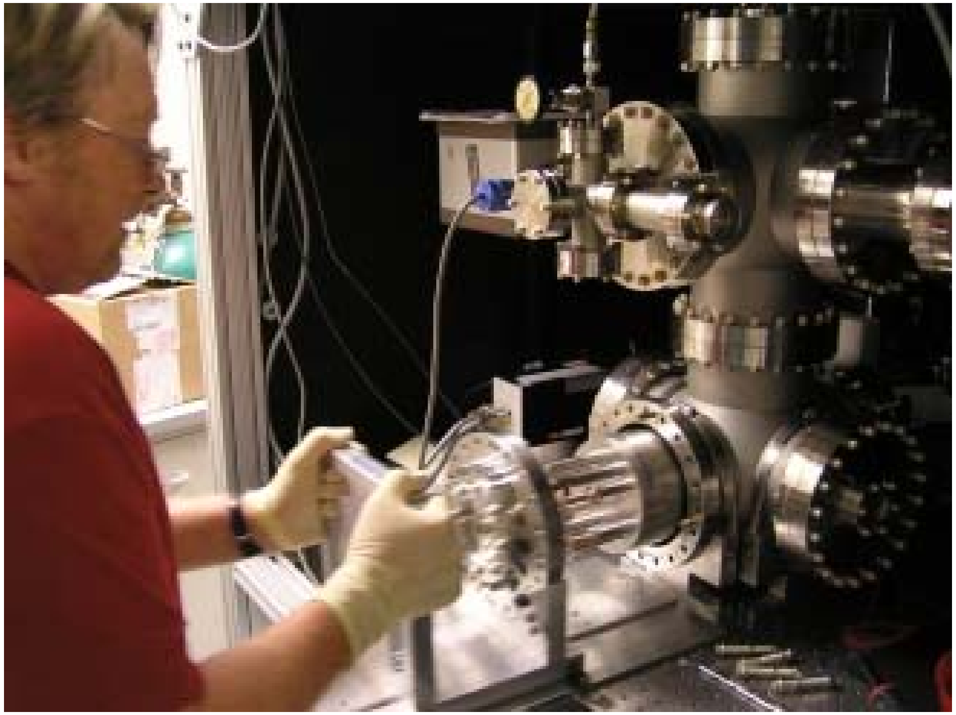
• Additionally, the laser frequencies need to be stably controlled by means of active feedback systems.

• In order to develop the techniques necessary to achieve such results DEGAS (DEGenarate Advanced Source) a proof of principle source has been built at the Lawrence Berkeley National Laboratory

The DEGAS Proof of Principle Source

• **DEGAS includes the complete set of subsystems required for the described source, does not include the frequency chirp of the 777 nm laser pulse and the transverse laser cooling for the Cs atoms.**

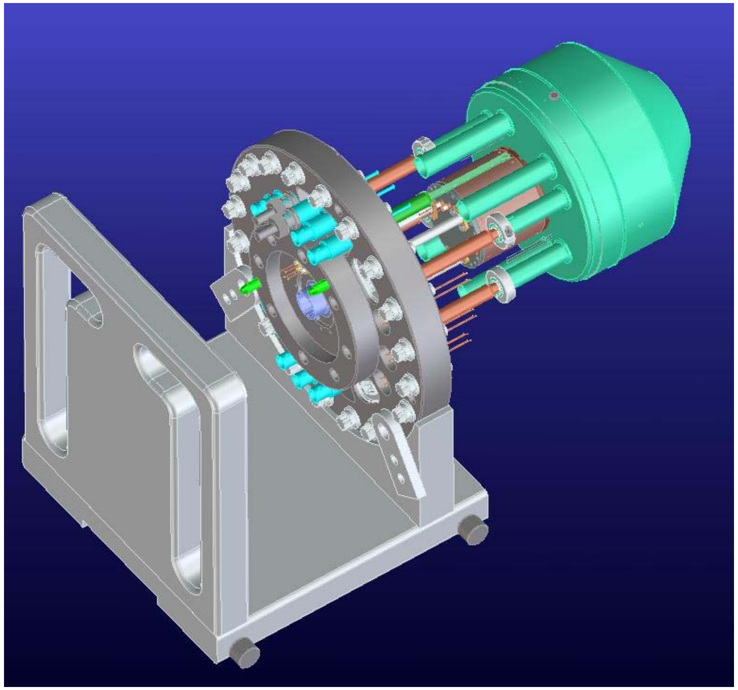




The DEGAS Core

• **The DEGAS core is inside a double magnetic shield and includes:**
- coils for the compensation of the residual magnetic field,
- photodiodes for measuring the excited Cs atom fluorescence,
- heaters and thermocouples for controlling the temperature of the various parts of the source during vacuum baking.

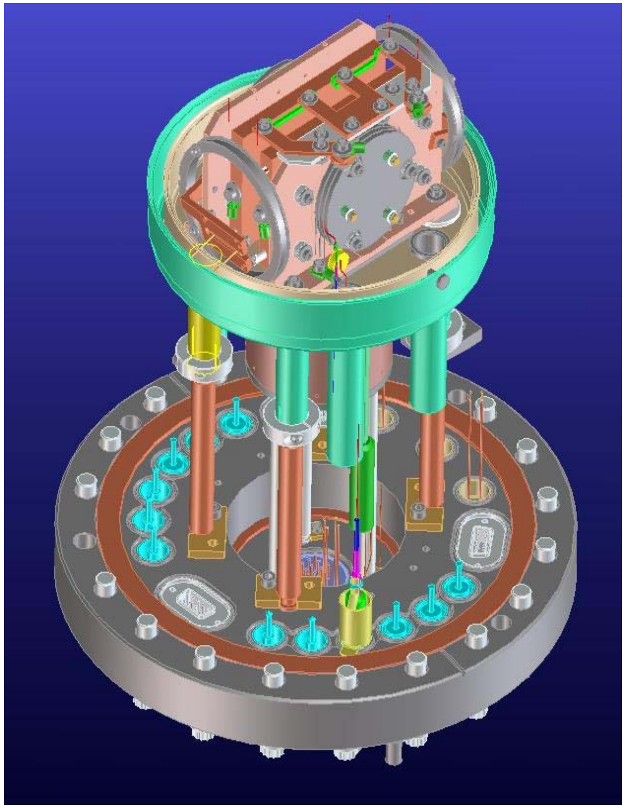
Contacts between different metals in the parts inside the magnetic shield have been carefully avoided in order to not generate local voltages and/or currents and thus undesired stray fields.



The Time of Flight System (TOF)

• The two TOF systems are based on micro-channel plates (MCP) from Photonis.

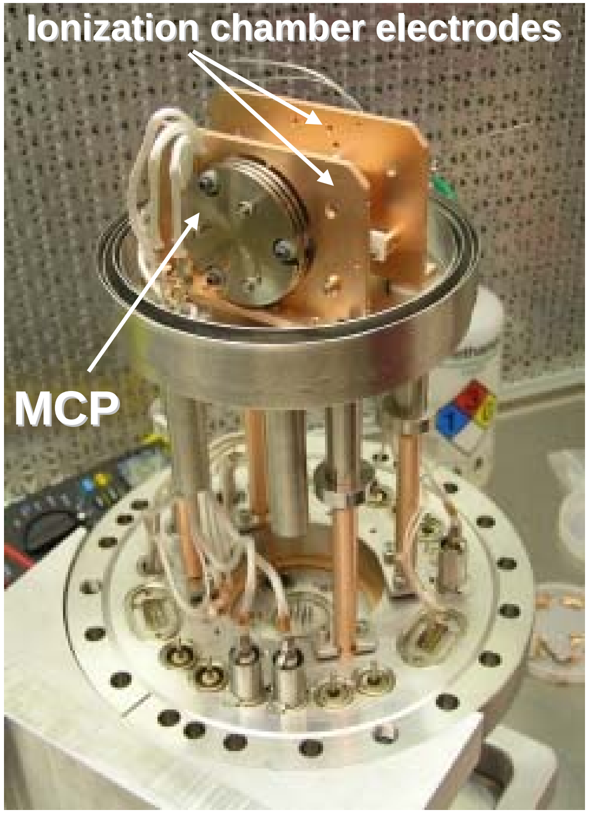
• The systems allow the **measurement of the residual electric field** and of the **electron beam energy spread**.



• The e^- arrival time at the MCPs measured respect to the pulsed laser trigger is measured and digitised by time to digital converter boards.

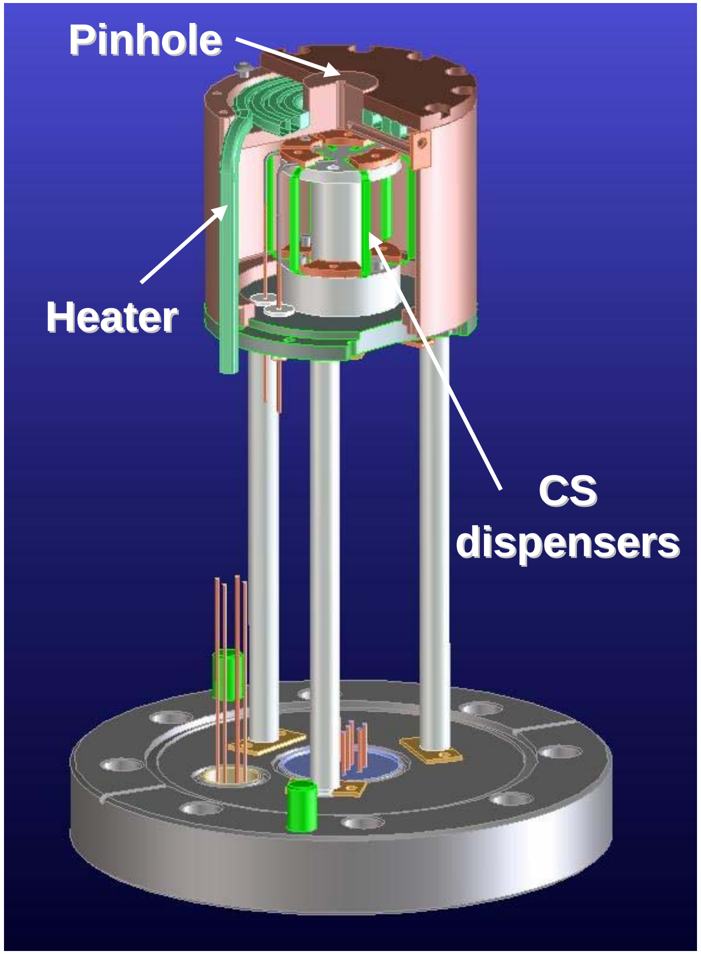
• The result is acquired by a computer through a digital PCI I/O board (National Instruments).

• The overall **time resolution of the TOF system is ~ 130 ps FWHM**.



The Cs Source

• 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.



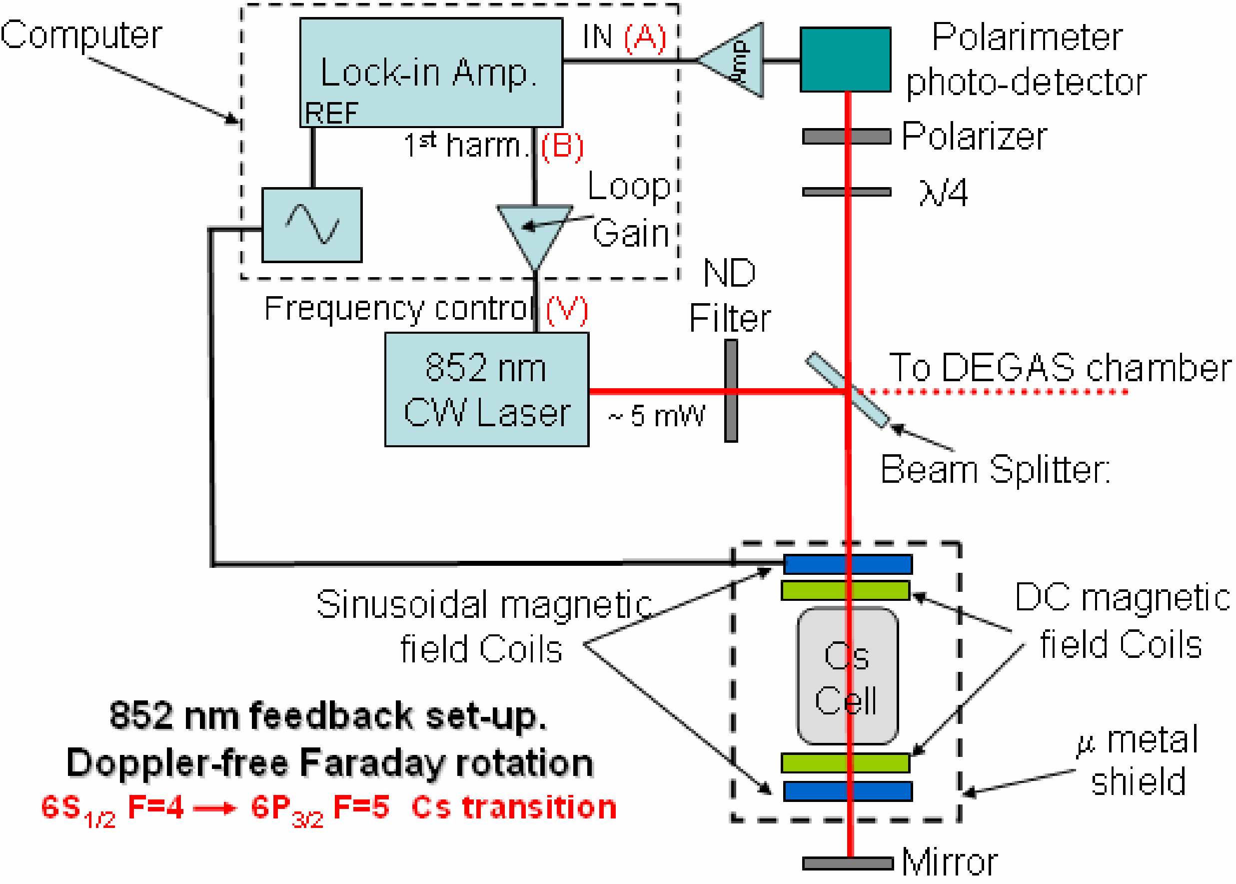
• The total amount of Cs contained in the dispensers is sufficient for many days of operation.

• The oven is placed 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 Cs pressure in the oven and thus the density of the neutral Cs beam released through the pinhole.

Laser Frequency Feedbacks

- **The figure shows the schematics of the 852 nm laser frequency feedback.**
- **A similar system is used for the stabilization of the 1470 nm laser.**
- **The frequency for the pulsed 777 nm laser is set using the TOF results.**



852 nm feedback set-up.
Doppler-free Faraday rotation
$6S_{1/2}$ F=4 → $6P_{3/2}$ F=5 Cs transition

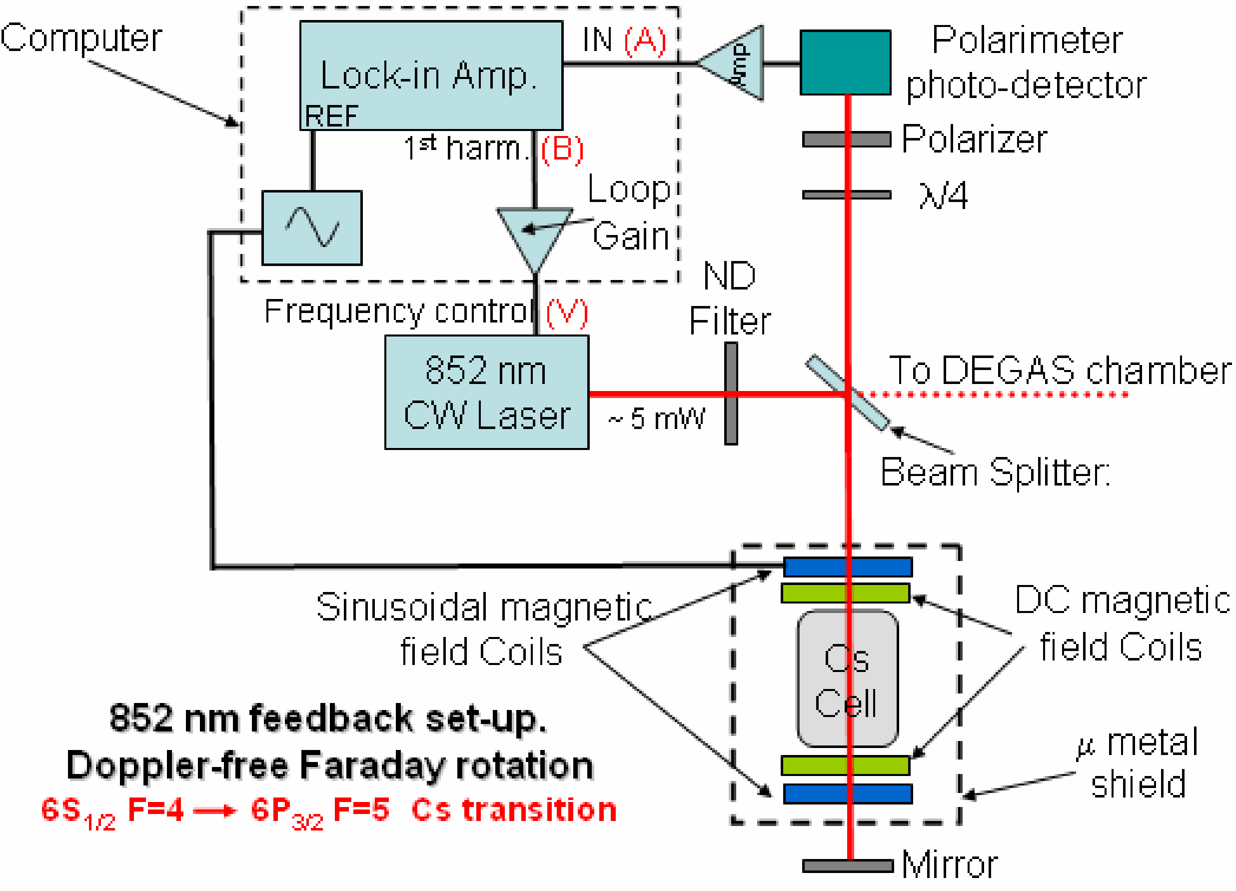
- **The linearly polarized 852 nm beam from a diode laser (Sacher) is split in two parts:**

- one goes to the DEGAS chamber

- the other is sent through a Cs cell and is reflected back through the same cell by a mirror.

A Team Work

• 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.



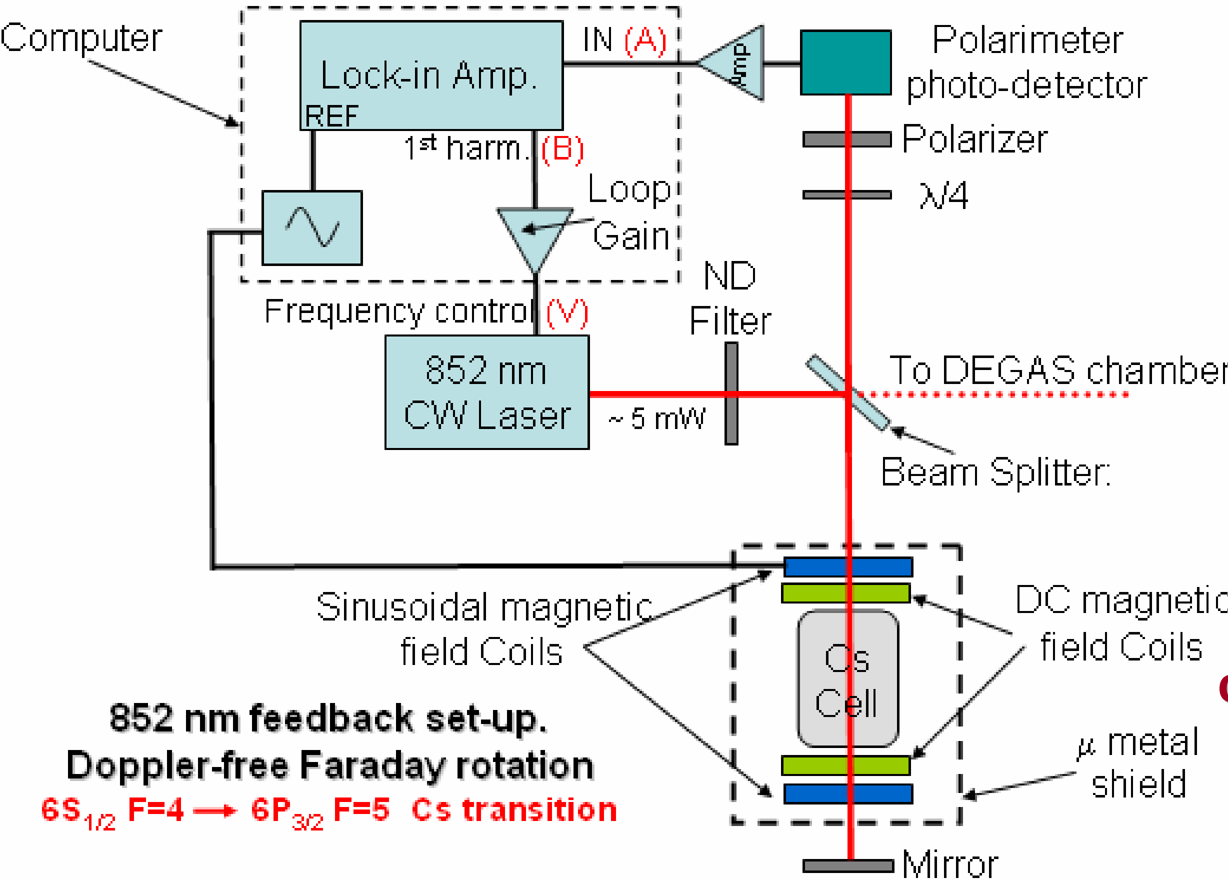
852 nm feedback set-up.
Doppler-free Faraday rotation
$6S_{1/2}$ F=4 ⟶ $6P_{3/2}$ F=5 Cs transition

• 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.

A Team Work

- **After the cell, the reflected beam is sent to a polarimeter system composed by a quarter wave plate, a polarizer and a photodiode.**



852 nm feedback set-up.
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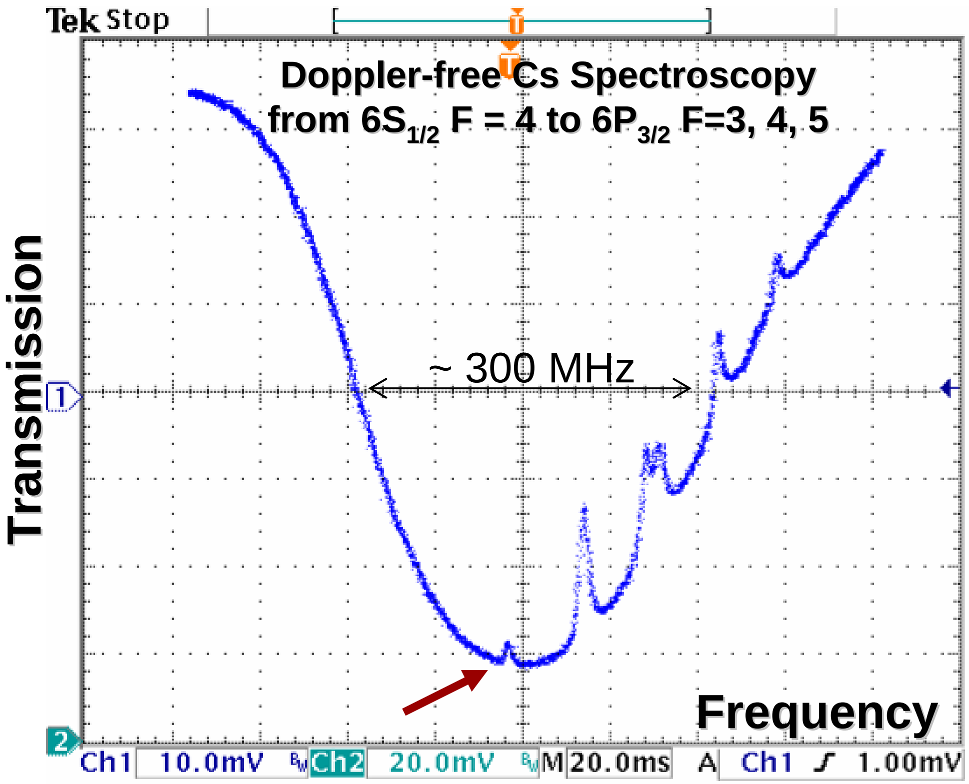
- **The signal from the photodiode is then amplified, digitised and analysed by a lock-in amplifier developed in LabView and running on a PC computer.**
- **The signal component at the modulating magnetic field frequency is then extracted, sent to a DAC and to the frequency control of the laser (a piezo-actuator that controls the position of one the laser cavity mirrors).**

Cs Doppler-Free Spectroscopy

• If no magnetic field is applied to the cell 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.



• The interaction between the electron and the magnetic field of the nucleus generates a hyperfine structure on the Cs levels that shows 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
(6S1/2 F=4 to 6P3/2 F=5, 0 group velocity)

Non Linear Faraday Rotation

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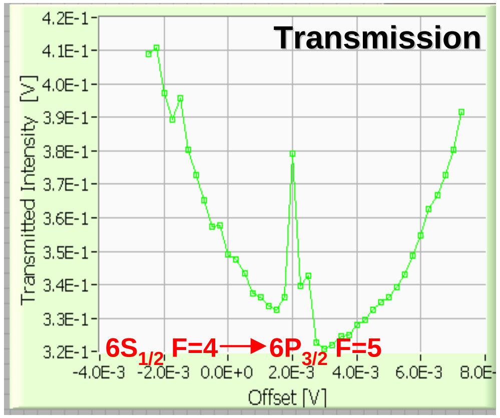
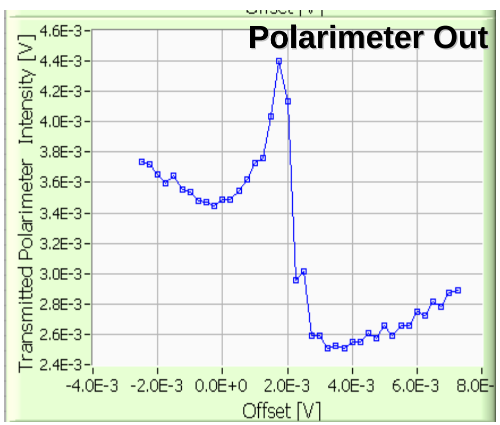
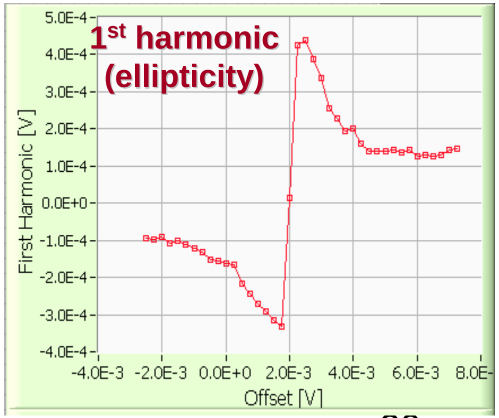
- **Tuning the frequency on the resonance with the sinusoidal magnetic field on, the laser beam experiences a polarization rotation induced by the nonlinear Faraday rotation due to the Cs resonance.**



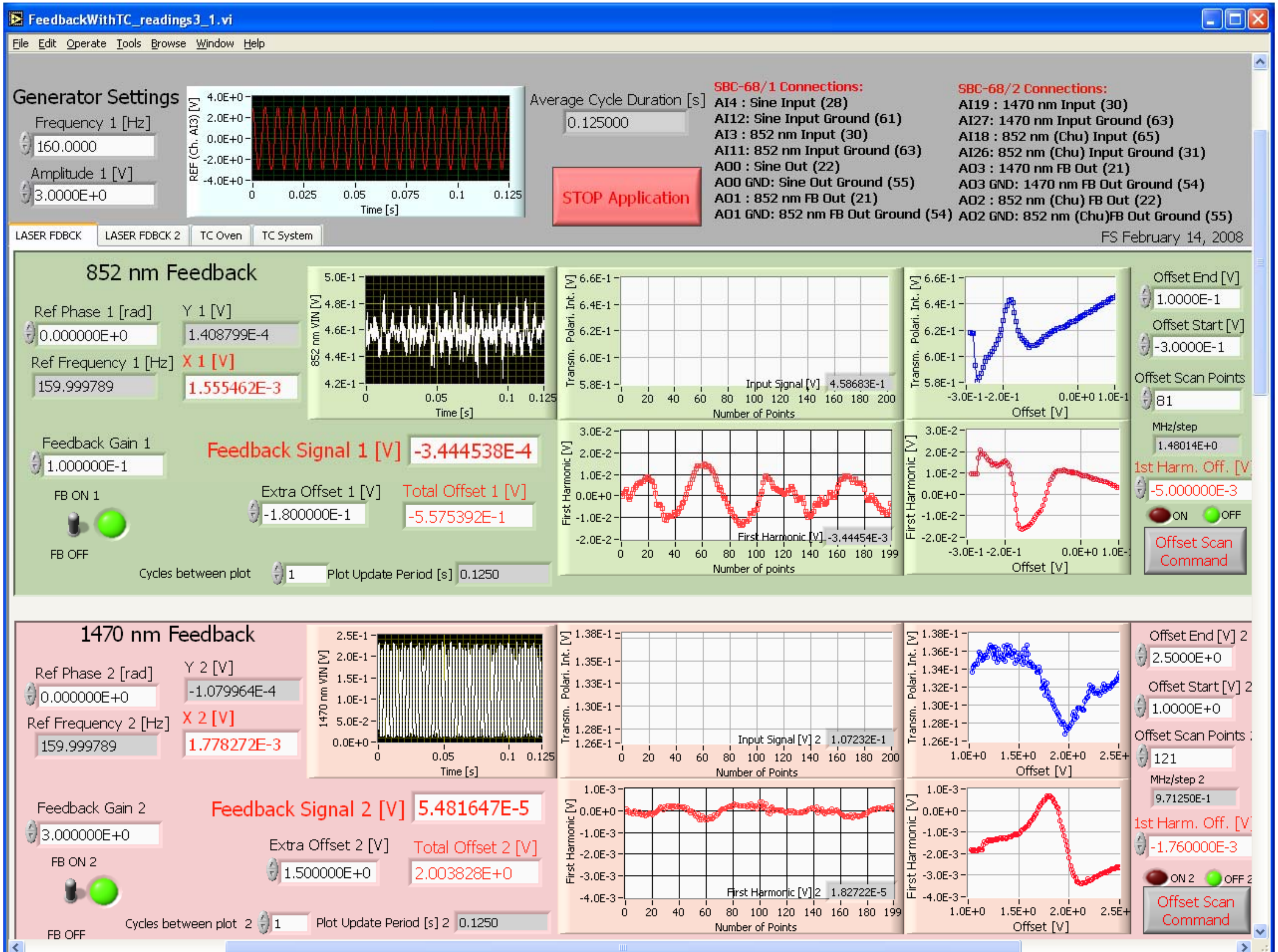
- **The rotation, modulated at the same frequency of the magnetic field, is detected in the polarimeter and its first harmonics is extracted by the numerical lock-in.**
- **The $\lambda/4$ plate allows measuring the effect in terms of polarization ellipticity.**



- **The ellipticity signal shows a sharp derivative at the atom resonance. This signal is used for driving the frequency control of the laser.**
  - **A frequency stability of ~10^{-8} is routinely achieved.**
  - **No laser frequency modulation is required in this scheme.**

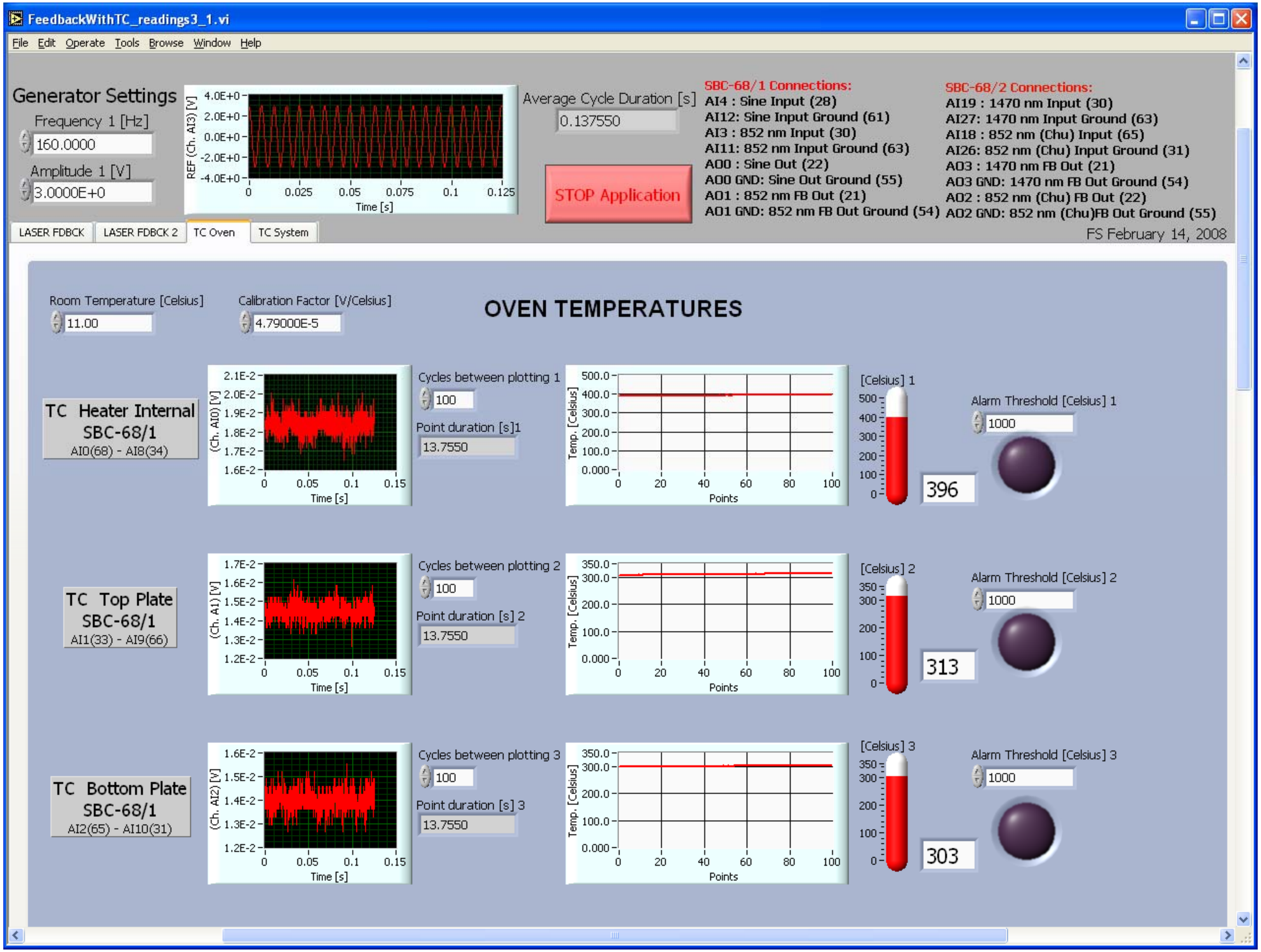


The Main Control Application



LabView on a PC platform

The Main Control Application



- Cs oven fully tested.
- Observed Cs fluorescence with the internal photodiodes due to the 852 and 1470 nm combined excitation

Time Of Flight Control Operation and Calibration

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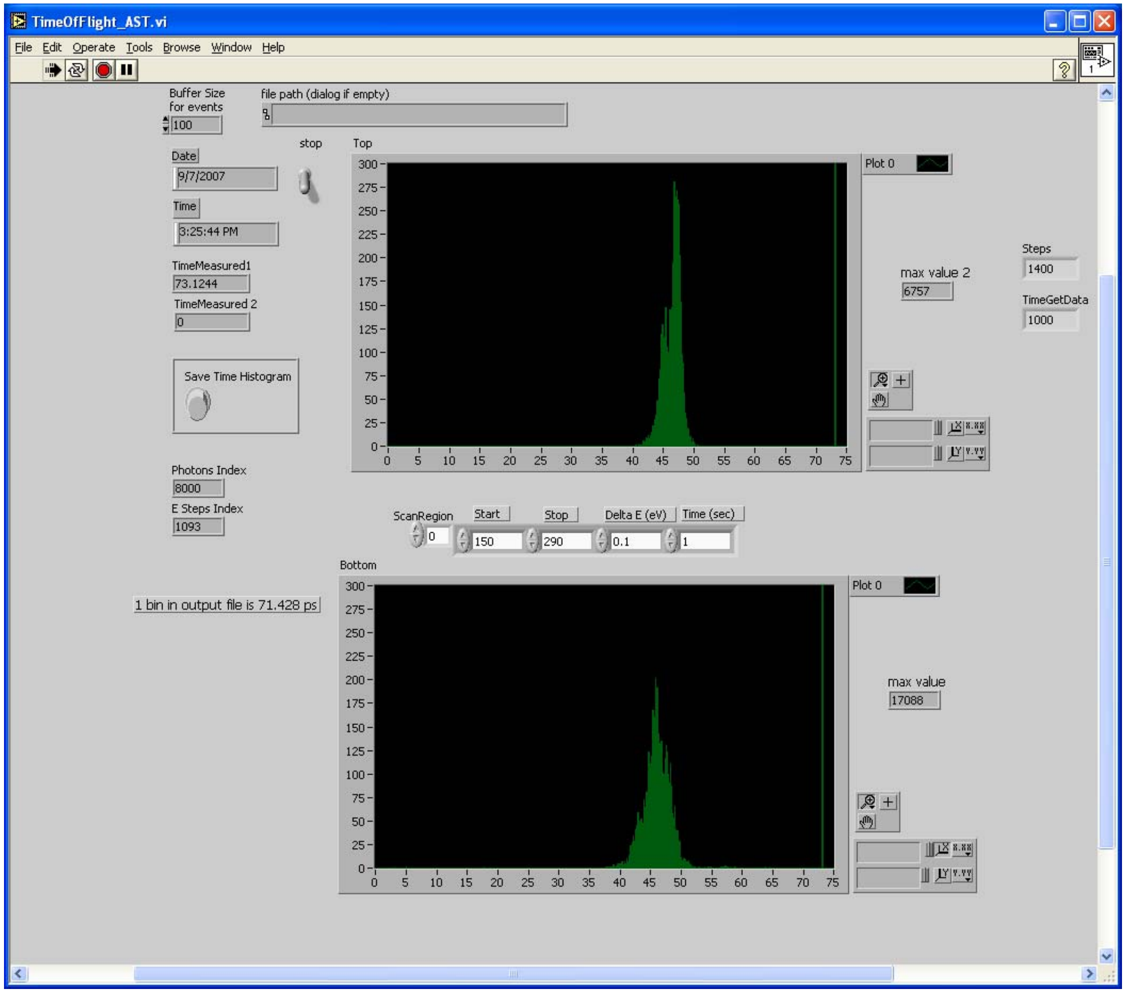

The TOF systems have been fully tested and calibrated by means of cosmic rays and by a thermionic electron source placed at the DEGAS IR temporarily

Concluding Remarks

• 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, of the electron energy spread, (extraction of the beam and interference experiments).

• What to do with a quantum limited brightness pulsed e^- source with ~ pA average current and energy tunable from few tens of eV to few keV ?

• The successful construction of such a source would allow for revolutionary applications in fields such electron microscopy, inverse photo-emission, precision low-energy electron scattering experiments, and because of the full coherence in electron holography.

• It could be the injector for scanning electron microscope with current density on target of ~1 pA/Angstrom^2 (comparable with existing ones) but with Angstrom resolution at low energy (achievable nowadays only at many hundreds keV). (negligible chromatic aberration; spherical aberration correction in axial symmetry using pulsed electromagnetic optics).

• The full coherence would allow for diffraction experiments similar with the ones done using x-rays (lens less imaging) but benefiting of the many order of magnitude higher electron cross section.