Modified laser-induced fluorescence-dip spectroscopy in Xenon for measuring a weak space electric field distribution

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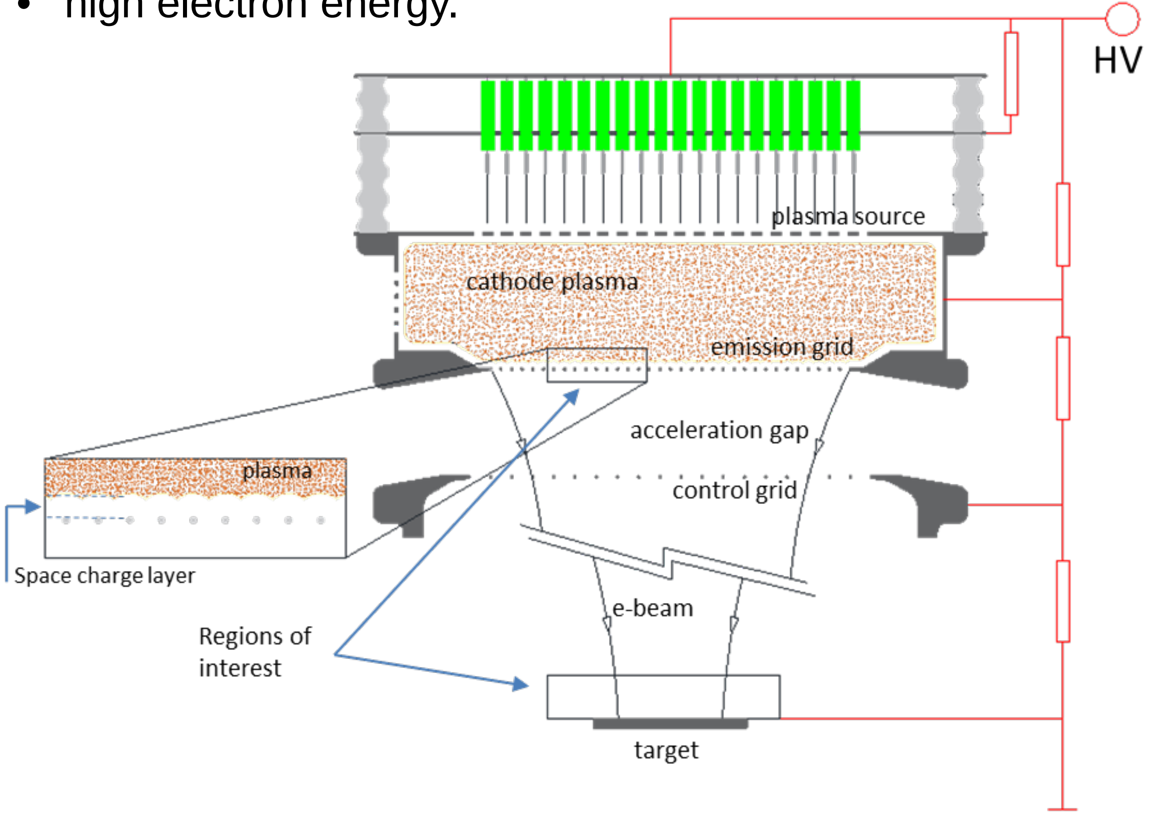
Object of the measurements

High power electron beam facilities Gesa with the plasma cathode:

- sub millisecond pulse duration;
- large beam aperture;
- high electron energy.



Schematic of GESA-SOFIE

Decisive influence on the stability of the Gesa-operation and the beam quality – plasma forming areas: cathode and target.

Requirements for the plasma cathode: high electron emissivity; long time scale stability.

Target plasma: suppression of the negative influence on the cathode function due to of the ion beam and avoid of the breakdown between the control grid and the anode.

Regions of interest for measurements

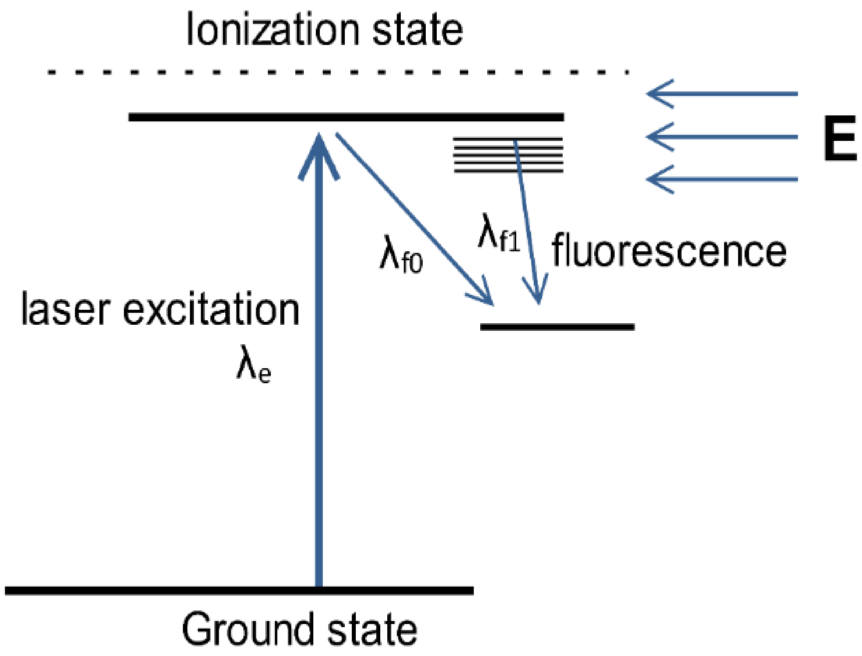
- Emission edge of cathode plasma – electric field distribution, width of space charge layer.
- Target plasma – formation, time evolution, acceleration voltage for ion beam

Expected electric field strength

- Emission edge of the cathode plasma – about 1 kV/cm
- At the front of target plasma – about 10 kV/cm

The width of Langmuir layer – several hundred micrometers

Classical LIF diagnostic method



LIF principle

The measured signal corresponds to a transition directly from the disturbed level

Sufficient sensitivity to the electric fields around 1kV/cm can be achieved by selecting Rydberg levels with relatively high n-number which are close to the continuum.

Property	n-scaling
Binding Energy W	n^{-2}
Orbital Radius	n^2
Energy difference of adjacent n states Δ	n^{-3}
Radiative Lifetime τ	n^{-3}

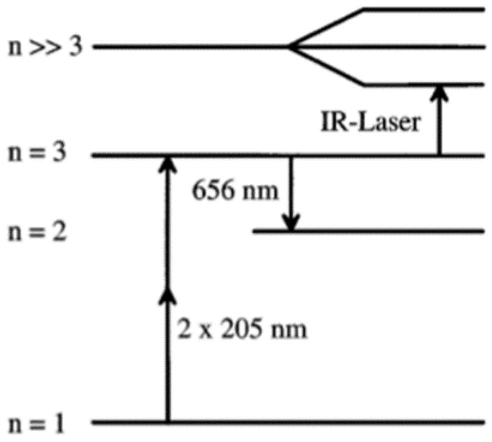
Scaling laws for properties of the Rydberg states

Limitation:

- Measurement by scanning the excitation wavelength – high accuracy, acceptable sensitivity, requires high reproducibility of the event.
- Measurement of the shift of the fluorescence wavelength – low accuracy and sensitivity, requires high quality of signal and excellent performance of spectroscopic devices
- Loss of population of the excited level by high rate of ionization

LIF-dip method

In 1998, U. Czarnetzki et al. introduced a **laser-induced fluorescence-dip** (LIF-dip) spectroscopy based on the double resonance of hydrogen atoms.



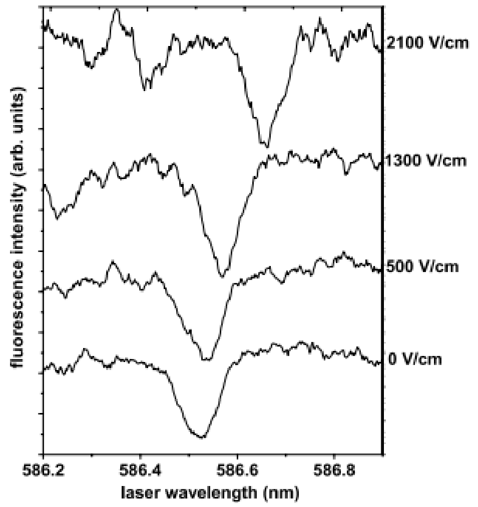
LIF-dip measurement

Benefits:

- Fluorescence signal itself is not affected by external electric field nor by ionization from excited level.
- Spectral position and profile of the dip reflect the splitted structure of the Rydberg level.

In 2006, E Wagenaars etc gathered dips through LIF

- The xenon pressure 50 Pa.
- The electric field measured: 500-2100 V/cm.

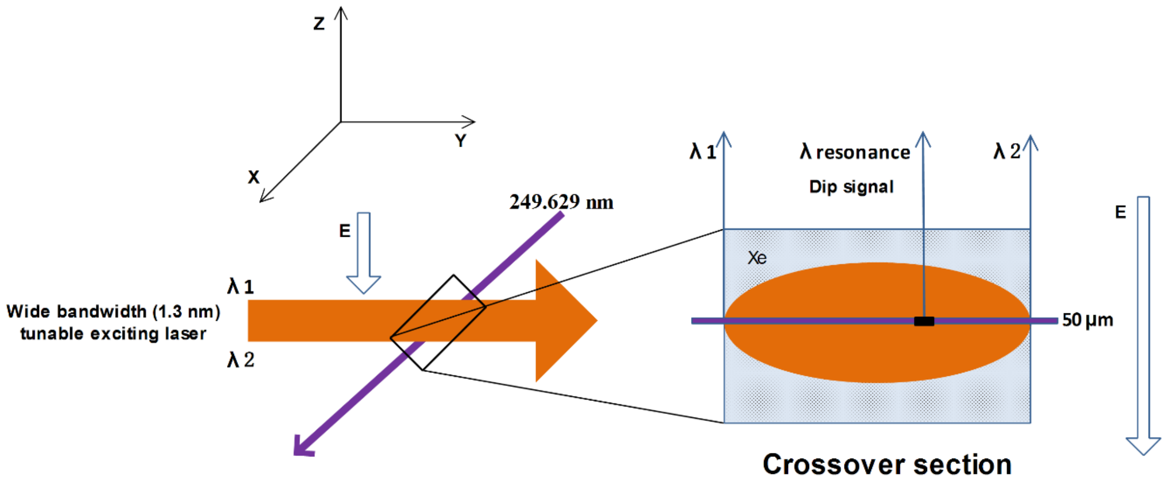


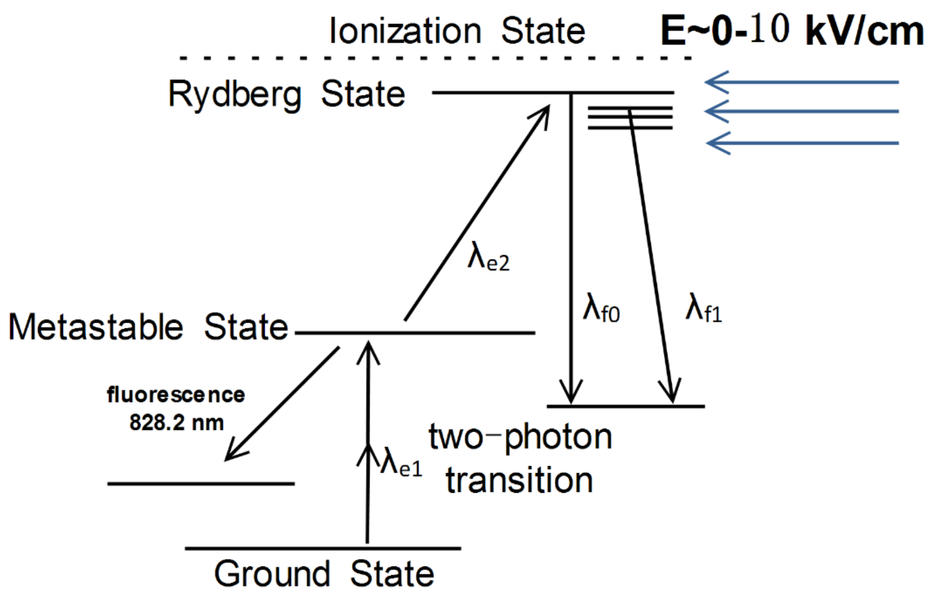
Limitation:

For the measurement of the electric field in one point it is necessary to make several measurements under the same conditions to form the profile of the dip.

LIF-dip measurement is not suitable for the low pulse-to pulse reproducibility system.

Modified LIF-dip method





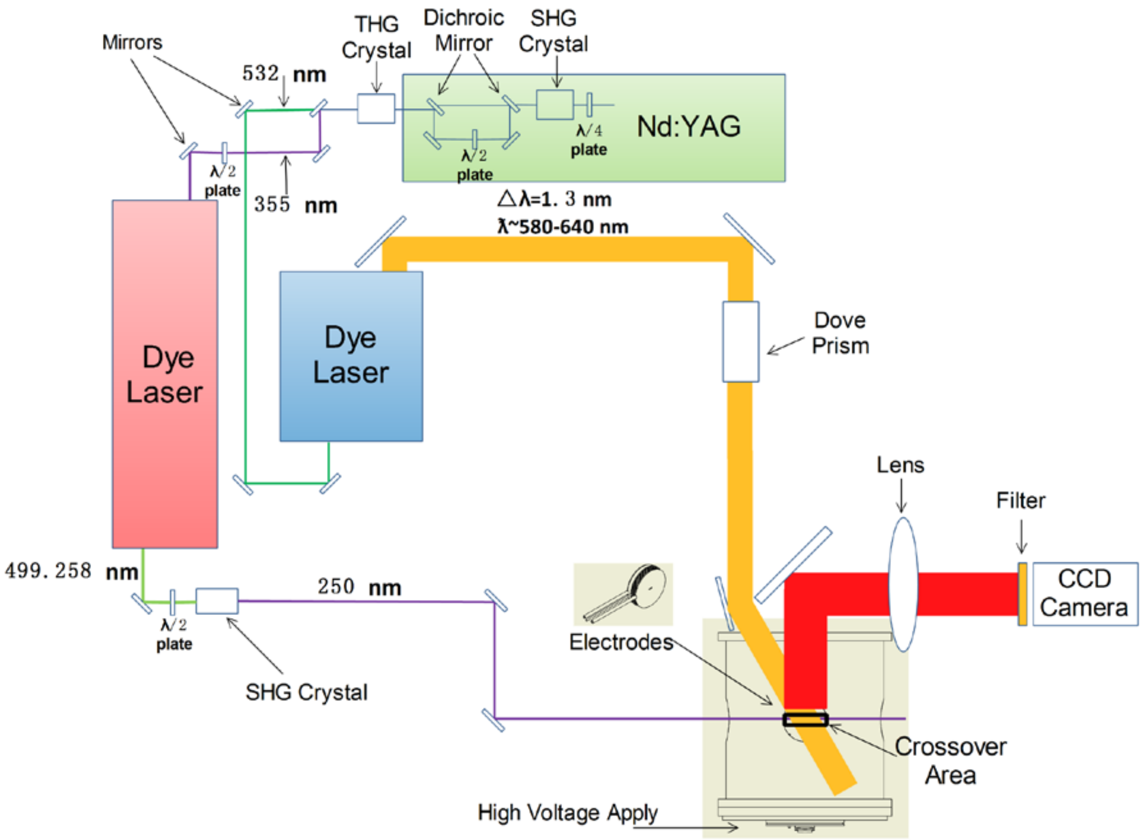
Excitation scheme for LIF-dip spectroscopy in xenon

- The core of the measurement technique is a tunable dye laser with a bandwidth of about 1.3 nm, which is used for resonant excitation of the Rydberg level.
- The spectral width of the laser covers the variation of the electric field from a few hundred V/cm up to a few kV/cm.

- Xenon as a trace gas
- Three-photon resonant excitation.

In one shot, the electric field can be got through the dip position shift

Measurement setup



Laser System:

- Nd:YAG – Continuum Powerlite 7000, 650mJ 8ns
- Dye laser 1 – Radiant Dye Laser. Dye solution: Coumarin 307, wavelength: 499.258 nm, linewidth: 5 pm , accuracy of wavelength: 50 pm, energy: 1 mJ, SHG: BBO crystal.
- Dye laser 2 – Cobra Dye Laser. Dye solution: Pyrromethene 597, wavelength: 580-640 nm, linewidth: 1.3 nm, accuracy of wavelength: 18 pm, energy: 1 mJ.

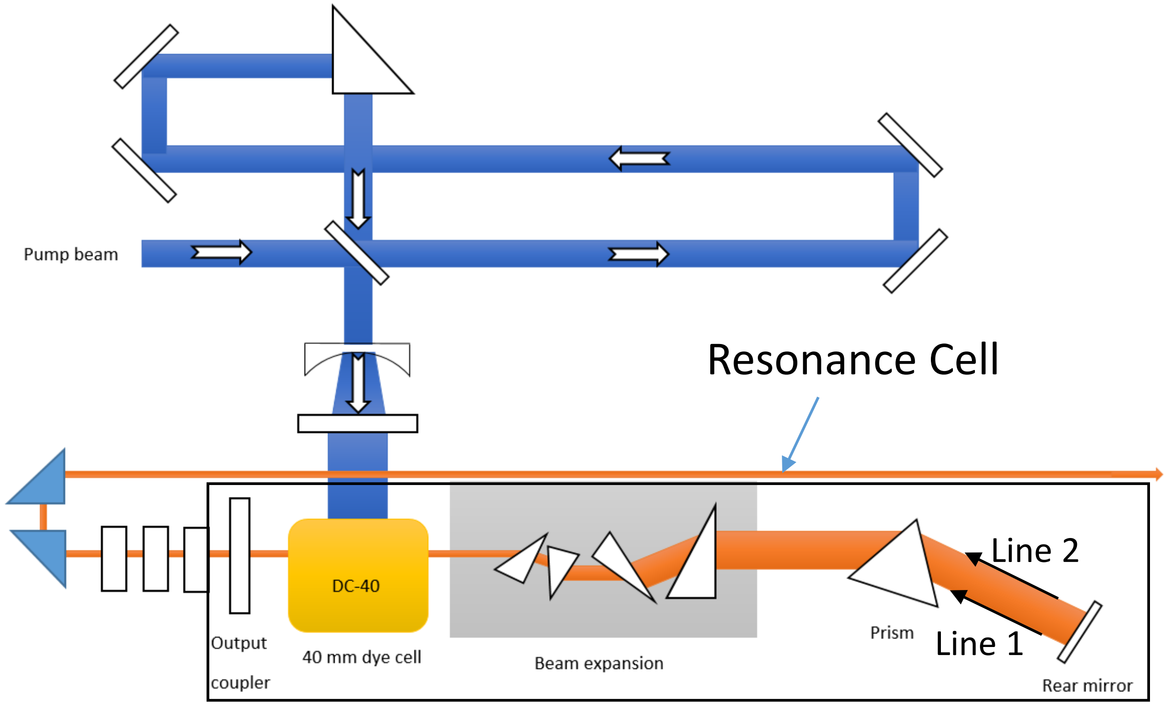
Test cell:

- distance between cathode and anode: 2 cm.
- position of electrodes: two exciting beams parallel to the electrode surface, a crossover between cathode and anode.
- applied voltage on electrodes: 0~15 kV.

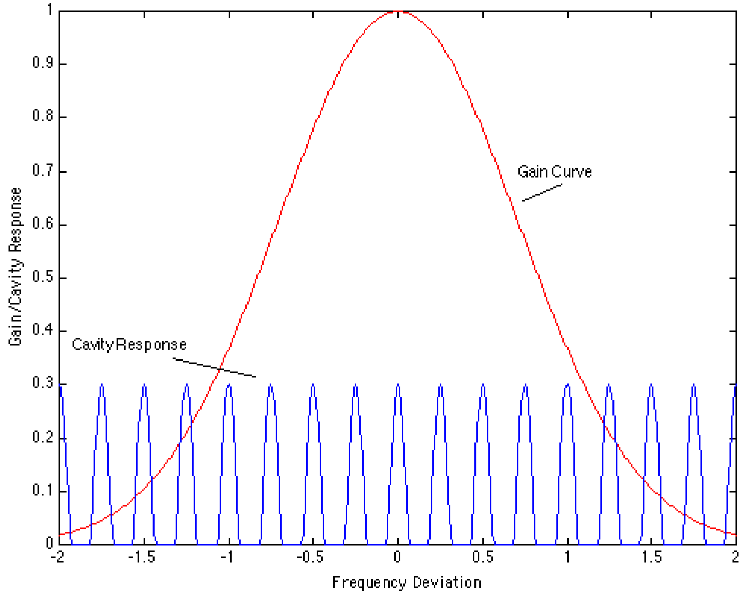
Detection system:

ICCD Camera PCO Dicam Pro. A interference filter for 828.8 nm with bandwidth 1.0 nm

Cobra-Sirah: Special broad band dye laser



sketch of the dye laser system



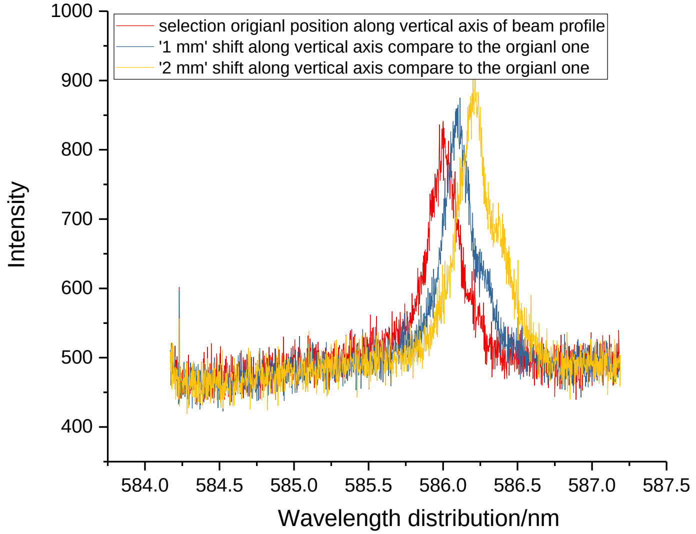
Changing the angle of prism, the resonance frequency changes.

- Line 1 and Line 2 has different resonance cell length 'L'.
- Between the two lines, the L changes in order.
- The output beam has a bandwidth of 1.3 nm.
- The distance between two modes is a constant of 0.018 nm, the output beam contains about 70 modes.

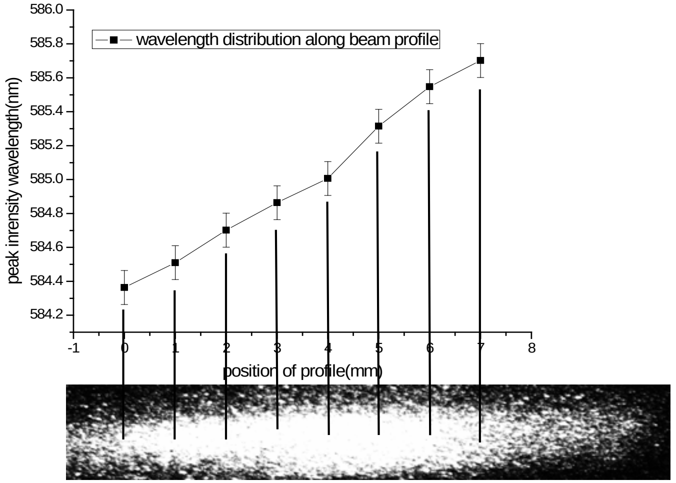
From the gain curve, in certain resonance cell length 'L'.

- There exists one mode with maximum gain, whose intensity of this frequency is maximum.
- There exist other modes mixed in the same position of output beam with lower intensity.

Cobra-Sirah: Spectral and spacial profile



Wavelength distribution along the vertical axis of the beam profile



Relationship between peak intensity wavelength and beam profile

A spectrometer with a 1200 l/mm grating, 1000mm focus lenght is used to measure the spectral distribution of the dye laser along the beam profile.

- Selection position along axis of profile 1 mm step by step.
- Each position has the bandwidth of 0.5 nm.
- Each position has one wavelength with maximum intensity. Corresponding to the mode which has the maximum gain.

Calibration of peak intensity wavelength and beam profile.

- Resonance wavelength with different intensity cover 3-4 mm along the vertical axis of beam profile.
- Peak intensity wavelength along beam profile changes in order.

Benefits:

- Dip signal because of resonance wavelength covers a 3-4 mm region, is easy to observe.
- By finding the darkest dip signal among dark region, the peak intensity wavelength can be got.

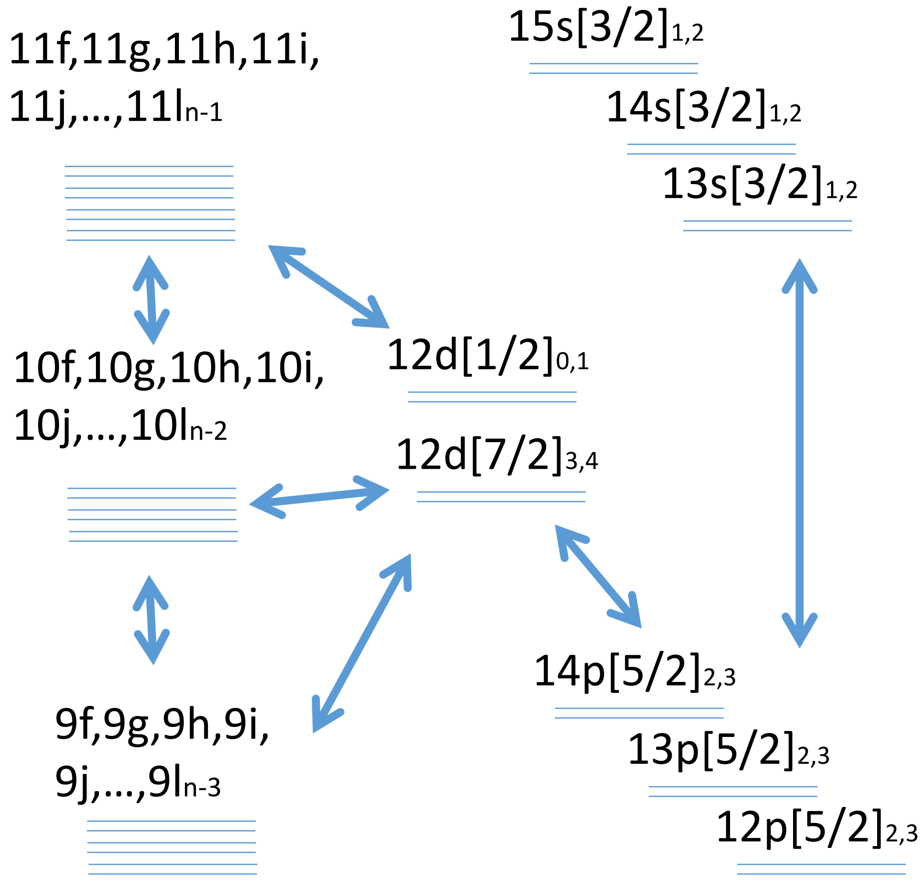
Stark effect: calculation method

- Schrödinger equation: $H\psi=E\psi$ $H=H_0+H_{stark}$
- Construct H

  zero-field energies are diagonal elements of H_0

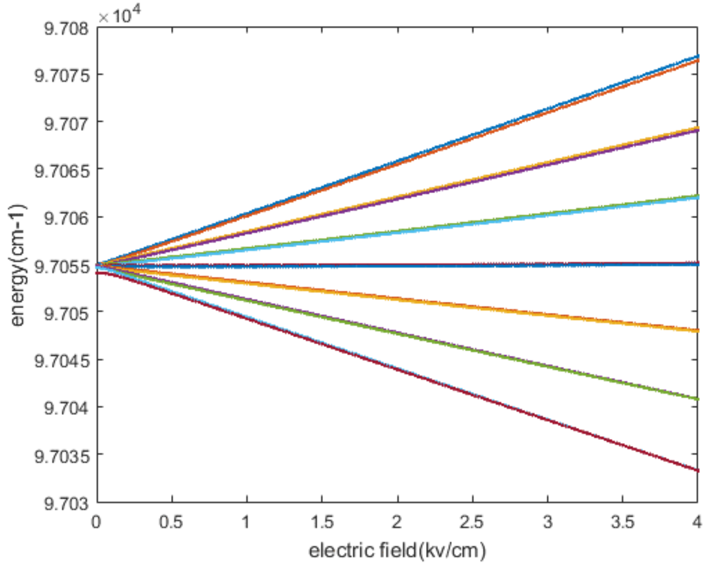
  H_{stark} is off-diagonal matrix, j-k coupling theory
- Diagonalise H for each electric field F and total magnetic quantum number M
- Eigenvalues of H are energies of the perturbed states

A 41*41 matrix is constructed for calculation

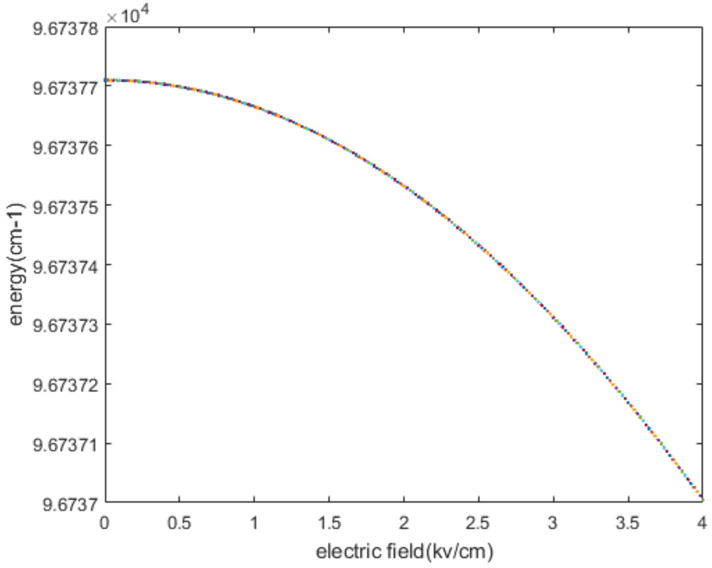


Set of states used in the calculation

Rydberg level of Xenon: results of calculation



Shifts of 11f,11g,11h levels under electric field



Shifts of $14s[3/2]_1$ levels under electric field

From these curves, the shifts of energy level under electric field can be got.
The state $14s[3/2]_1$: the energy level change from 96737.7 cm-1 to 96737.0 cm-1 under the electric field of 4 kV/cm.

‘Cold’ measurements on the test facility.

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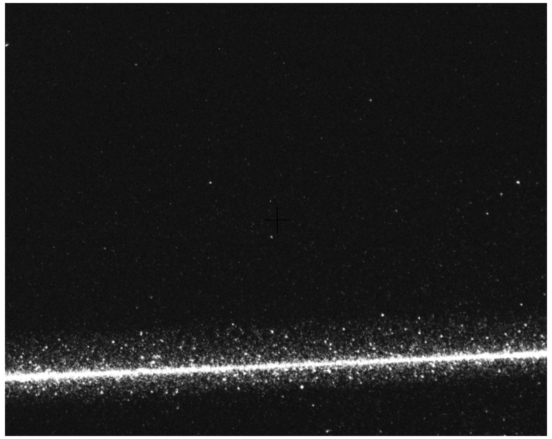
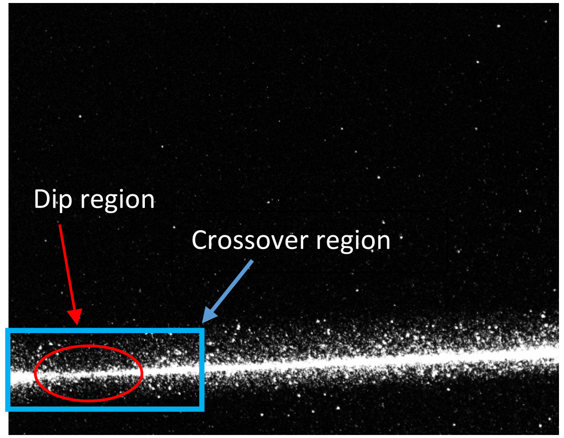
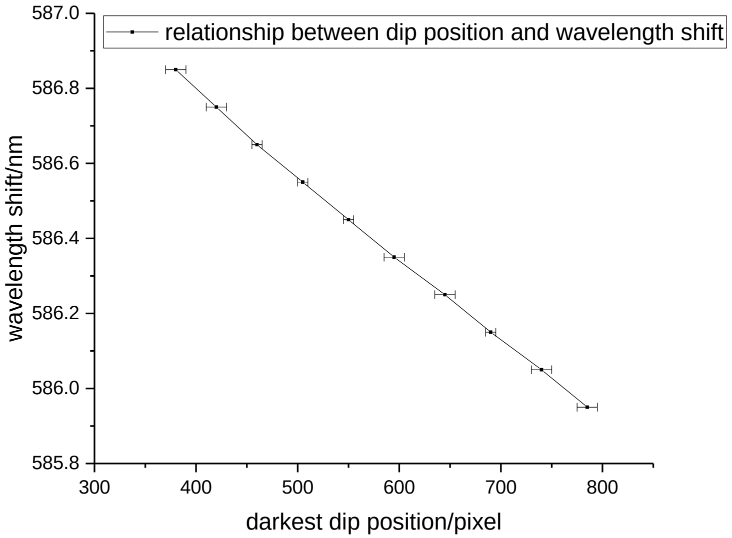


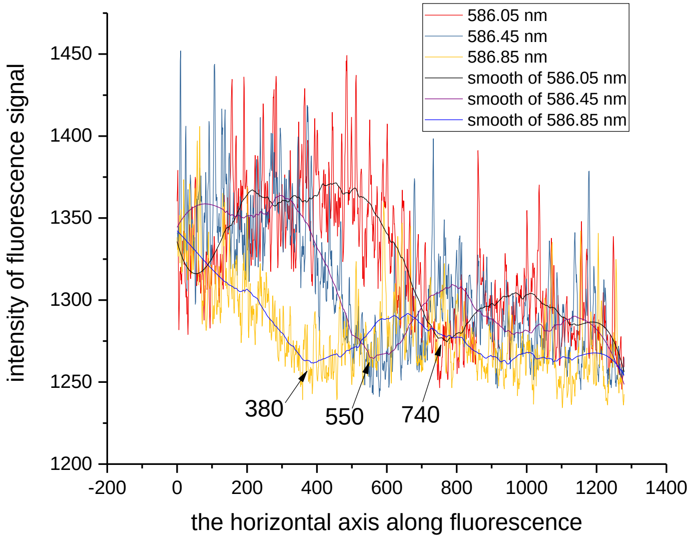
Fluorescence light without dip



Fluorescence light with dip area



Calibration between Position along beam profile and wavelength shift.



The cold measurement without electric field is carried out.

- Dip region occurs after tunable laser applied.
- Dip region has the darkest point where peak intensity wavelength exists.
- When change the resonance wavelength of dye laser, dip region also shifts logicality.

Changing the wavelength of dye laser from 585.95 nm to 586.85 nm by step 0.1 nm, the shifts of dip positions can be got.

- 0.1 nm corresponding to 45 pixel. If the resonance wavelength of dye laser is fixed. After apply electric field, the dip position shift 45 pixel in monitor, the resonance wavelength shift of 0.1 nm can be got.
- Dip position shift error of 10 pixel (22 pm) can be measured. The reason can be mode jump of laser. Since one mode jump can produce 18 pm error. This lower our accuracy of our measurement.

Measurements with electric field on the test facility.

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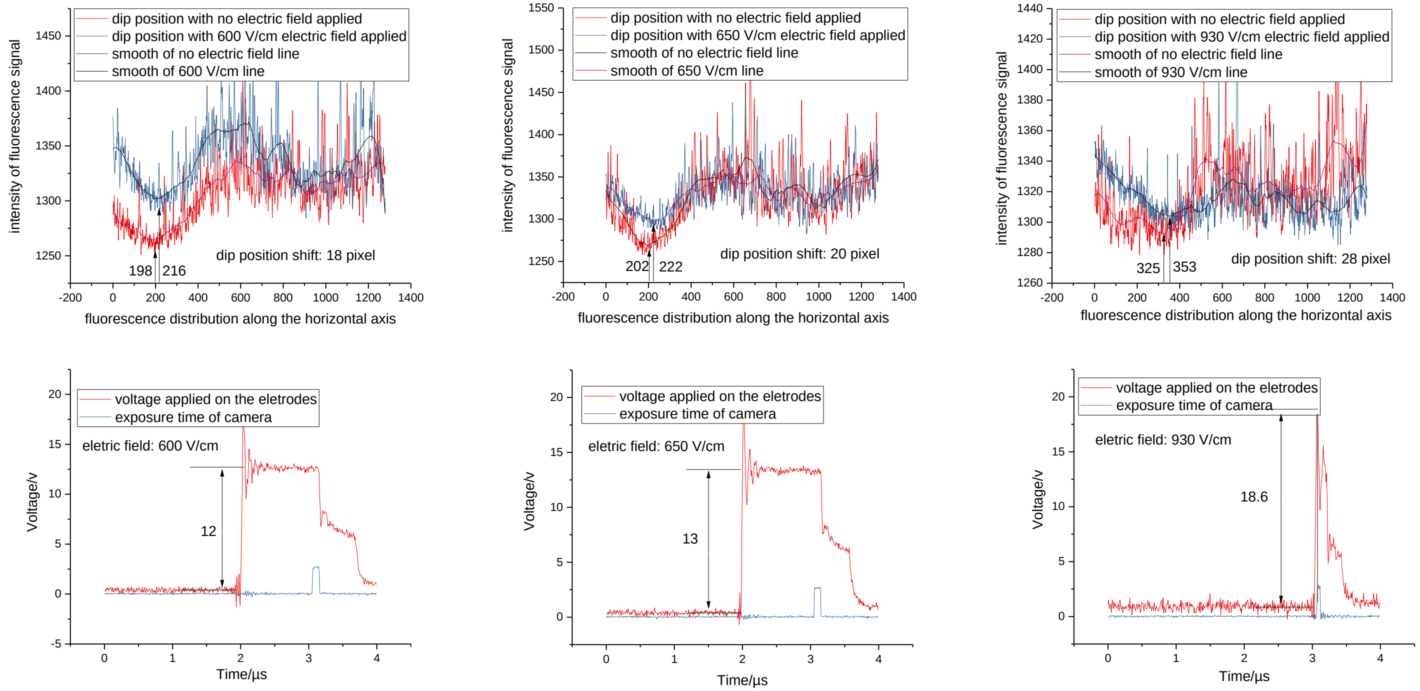

- 600 V/cm, 650 V/cm and 930 V/cm electric fields are applied.
- The dip position shifts can be got in the monitor.
- Through calibration of position and wavelength, the wavelength shifts can be obtained.

Electric field (V/cm)	Dip position shift (pixel)	Resonance wavelength shift (pm)
600	18	40
650	20	44
930	28	62

Error analyze:

- One Mode jump error makes around 18 pm error.
- Measurement error.

Mode jump error dominate!

External electric field (v/cm)	Theory wavelength shift (pm)	Experimental wavelength shift (pm)
600	17	22
650	18	26
930	37	44

Data after one mode jump error modified

After one mode jump error modified, the experimental data compare to theory data is reasonable.

As the electric field increase, the wavelength shift exponential increase, the mode jump error influence will be lower.

Measurements with electric field on the test facility.

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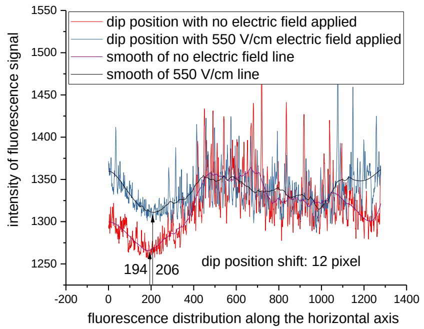

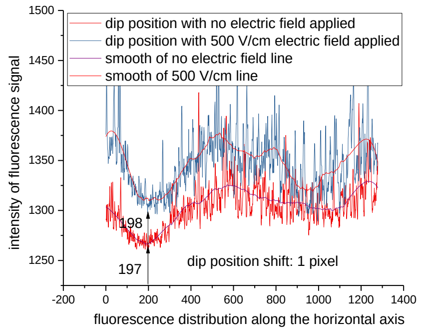

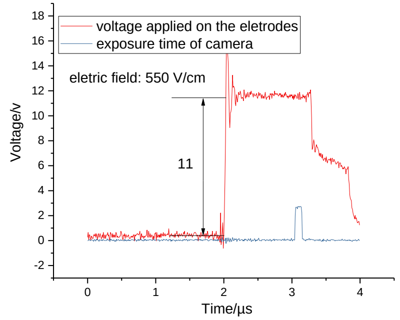

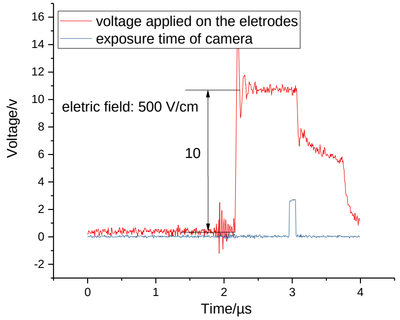

- 550 V/cm and 500 V/cm electric fields are applied.
- The dip position shifts can be got in the monitor.
- Through calibration of position and wavelength, the wavelength shifts can be obtained.

Electric field (V/cm)	Dip position shift (pixel)	Resonance wavelength shift (pm)
550	12	1
500	26	0

Error analyze:

- Mode jump error makes around 18 pm error.
- Measurement error.

Mode jump error dominate!

Data analyze:

- Under 550 v/cm, the theory wavelength shift is 15 pm.
- One Mode jump error is 18 pm.
- It can not be distinguish from real shift and one mode jump error.

The minimum electric field can be measured is 600 V/cm.

Benefits of modified LIF-dip diagnostic

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We propose a modified LIF-dip measurement, the electric field strength can be obtained in one measurement.

	LIF-dip diagnostic	Gesa facility
Sensitivity	Minimum electric field: 600 v/cm.	• Emission edge of the cathode plasma – about 1 kV/cm • At the front of target plasma – about 10 kV/cm
Accuracy	Electric field resolution: 50 V/cm (ranged from 2000-5000 v/cm).	
Space resolution	Space resolution along the electric field: 50 µm.	The width of Langmuir layer – several hundreds micrometers.
Time Resolution	Time resolution : 5 ns.	Sub millisecond pulse duration.

Next Steps:

- Reduce mode jump error.
- Transfer this modified LIF-dip diagnostic from test cell to Gesa facility.