Laser-aided diagnostics for Electric Propulsion

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Outline

- Needs for LAPD
- LAPD at ICARE
- 3 techniques: LIF, CTS and LPD
- Development of new LAPD
- Conclusion

Need for diagnostic tools

Unresolved problems and remaining challenges in EP:

- Measuring fundamental quantities
- Understanding the physics of complex systems,
- Validating physical models and computer simulation outcomes,
- Improving current technologies,
- Confirming technological solutions,
- Developing advanced and new concepts

Need for **Plasma diagnostic techniques**, combined with data analysis, treatment methods and uncertainty budget assessment

Example of variables

neutral and charged-particle velocity,
charge-state, particle flux and current
potential, electric field, magnetic field
electron density and temperature, ion and neutral density,
EEDF, ion VDF, atom VDF
surface temperature, SEE yield, sputtering yield
mobility, diffusion coefficient
radiation
…

Plasma diagnostics at ICARE

Diagnostic technique	Quantity to be measured/analyzed	Special features
Electrical		
Emissive probe	V_p, T_e	Temporal resolution (MHz), reciprocating system
Langmuir probe	V_p, T_e, N_e, EEDF	Temporal resolution, reciprocating system
RPA	Ion energy	
E×B probe	Ion velocity, charge-state	compact
Planar probe, Farady cup	Ion current density	
Optical		
CCD imaging	Discharge and beam dynamics	
Calibrated IR thermal imaging	Surface temperature, energy flux	Temporal resolution (500 Hz)
Emission spectroscopy	Plasma composition, excited states	
Fabry-Pérot interferometry	Atom/ion temperature, velocity	
LASER		
Laser Induced Fluorescence	Ion VDF, atom VDF, electric field	Photon counting (temporal resolution = 100 ns)
Doppler-free LIF	HFS, magnetic field	
Coherent Thomson scattering	Microturbulence	Temporal resolution, HF, high spatial resolution (< 1 mm), low density medium
Laser Photodetachment	Electronegativity, negative ion density	UV range

Laser-based diagnostics

Laser-aided diagnosics are necessary to access to critical variables

Comparison with other electrical/optical techniques

Advantages

Non intrusive (used in hostile environments and regions of high B field)

High spatial resolution (< mm)

High temporal resolution (< ns)

Vast family of lasers(wavelenghts), optical components and detectors

Drawbacks

Complex and cumbersome techniques

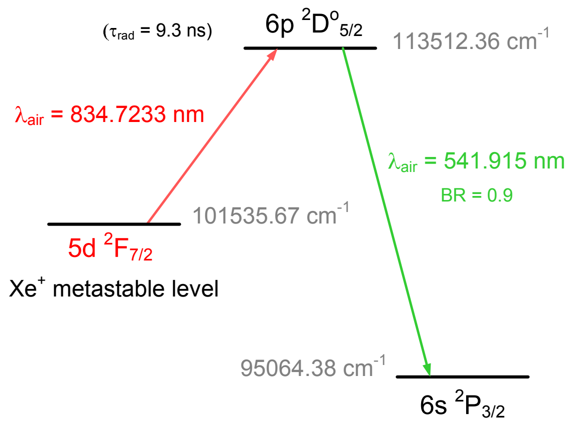
Need expertise as well as experience

Expensive

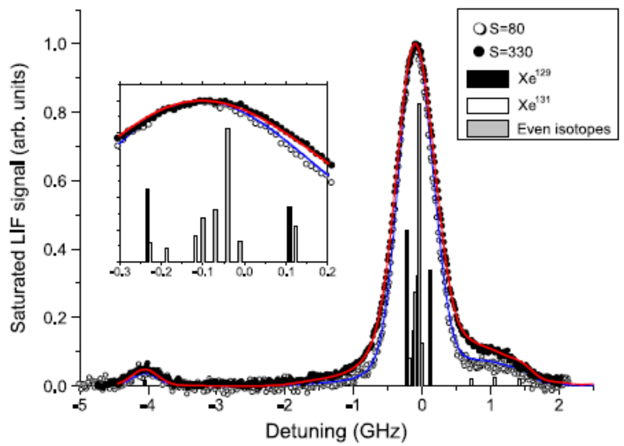
LIF spectroscopy with DL

Use of tunable single-mode diode lasers (high spectral purity)
Measurement of VDF for Xe, Kr and Ar atoms and Xe^+, Kr^+ and Ar^+ ions

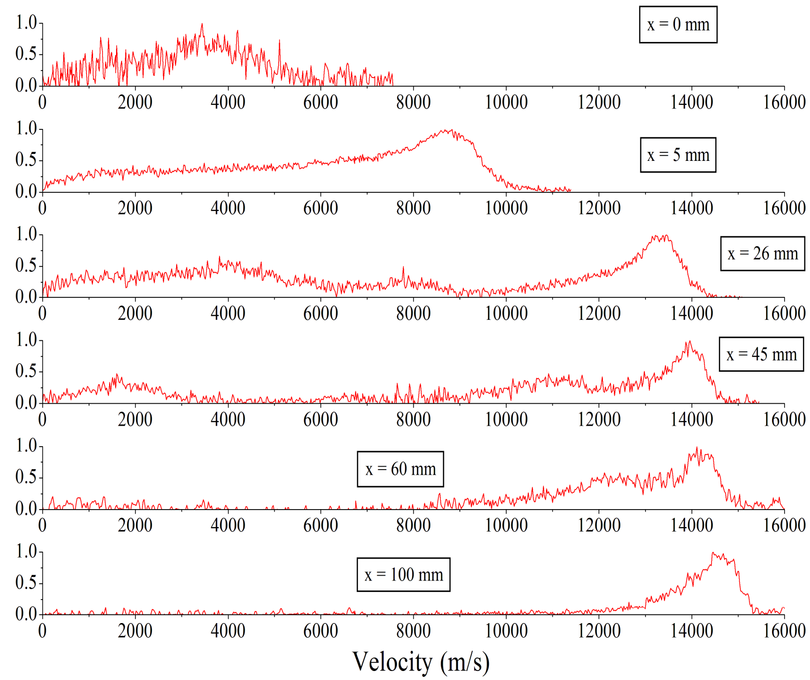
Energy diagram: Xe^+ line at 834.7 nm



HFS: Xe+ line at 834.7 nm



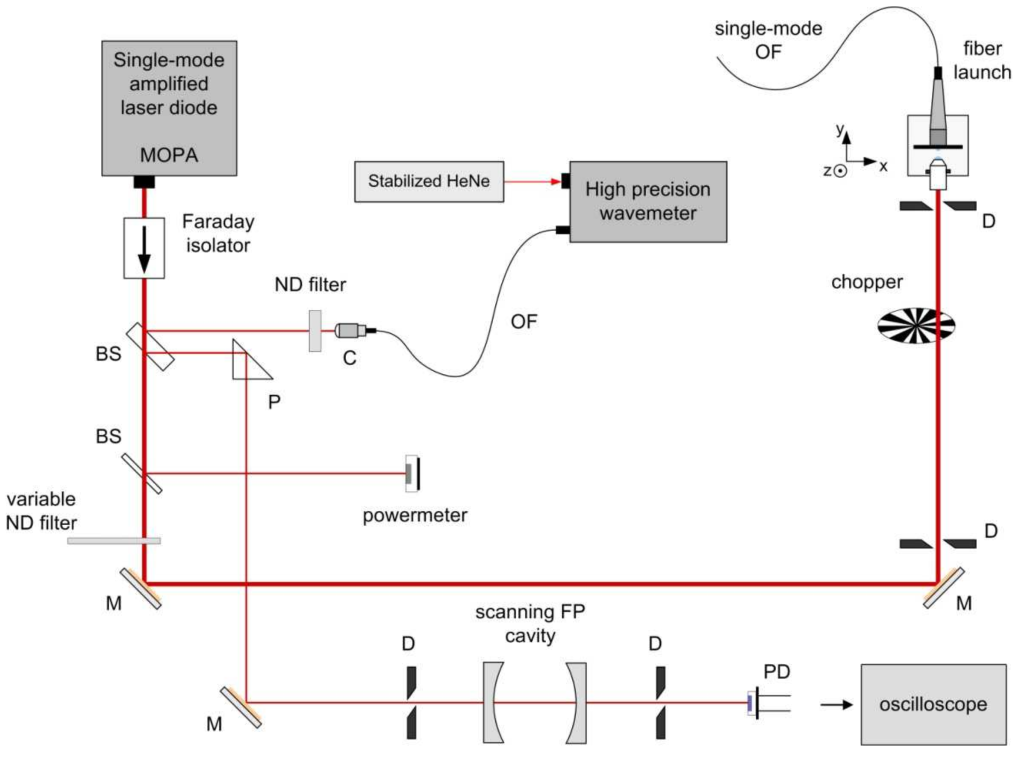
Xe^+ ion VDF
200 W PPI Hall thruster



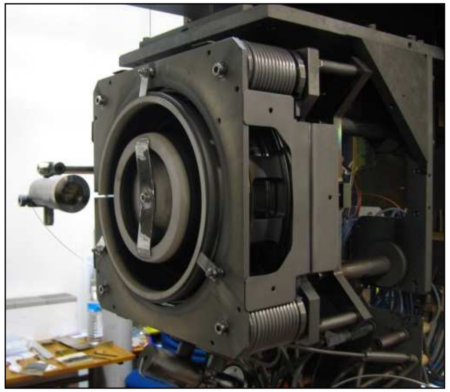
LIF spectroscopy with DL

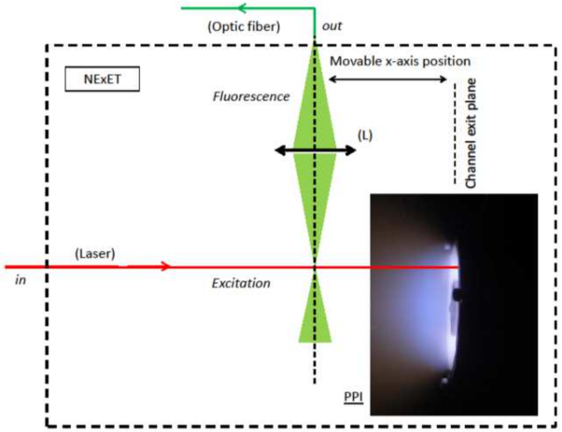
Optical train

Laser bench with amplified DL, wavemeter and FP



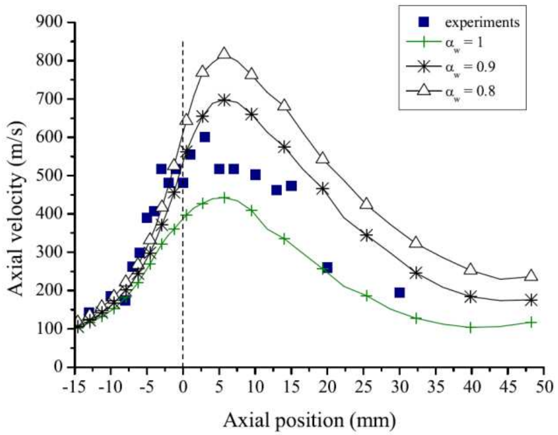
Collection optics



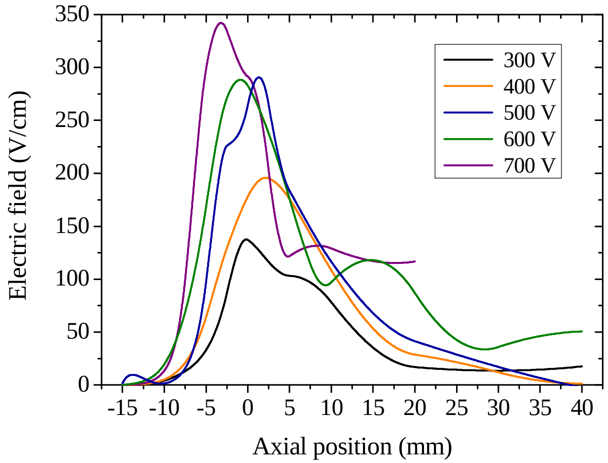


LIF spectroscopy with DL

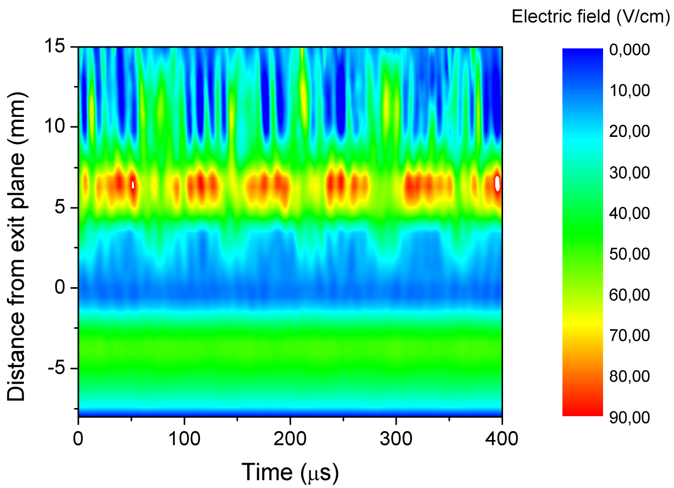
Xe atom velocity (SPT100)



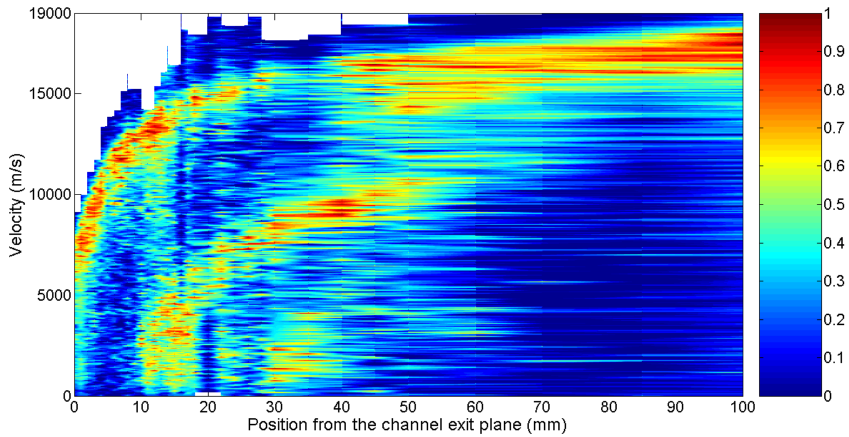
Electric field profile (PPSX000)



Electric field oscillations (PPI)



Kr+ ion VDF (PPI)



Coherent Thomson scattering

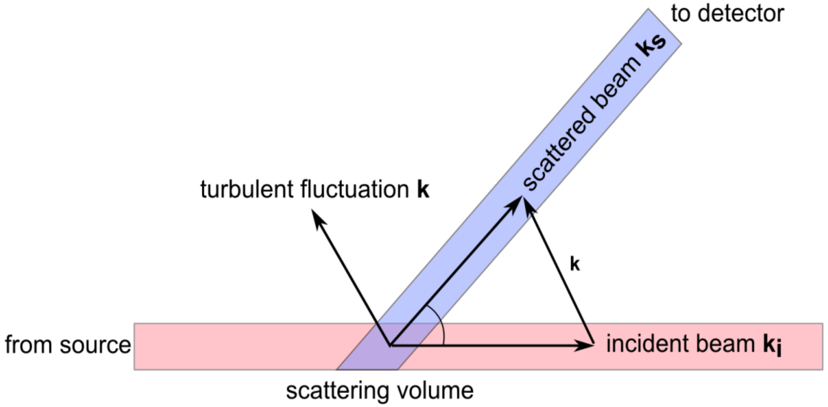
Principle - Measurements

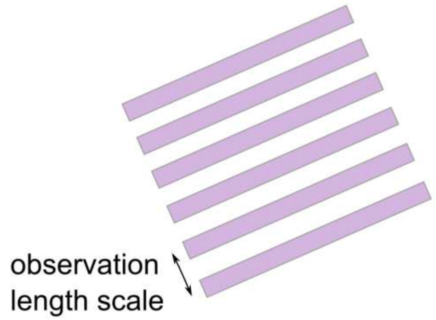
- scattering of incident electromagnetic field supplied by a laser

- observation length scales → electron Debye length

  - access to <u>correlated</u> plasma fluctuations at these scales
  - a means of identifying instabilities
  - access to new information <u>inaccessible via conventional diagnostics</u>

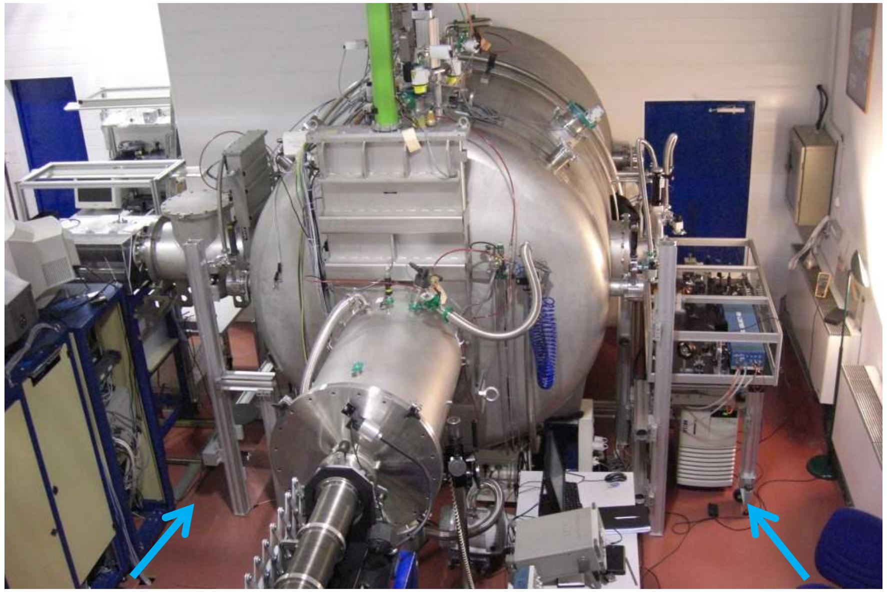
- recently adapted for low density environments such as the Hall thruster plasma





Coherent Thomson scattering

Diagnostic **PRAXIS** (**PR**opulsion **A**nalysis e**X**periments via **I**nfrared **S**cattering)
- an innovation for electric propulsion

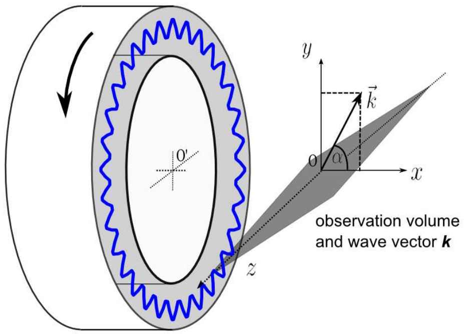


Diagnostic setup at the PIVOINE test-bench

Cryopumps: 250000 l/s Xe
Chamber: 4m × 2.2 m
Pressure < 10^{-5} mbar-Xe
Operation range
1 – 50 mg/s
100 W - 25 kW
Xe, Kr, Ar

- 50 W single-mode cw laser at 10.6 mm
- Heterodyne technique (2 beams)
- High sensitivity LN_2-cooled HgCdTe detector
- High acquisition frequency: 100 MHz
- High sample depth: several Ms/channel
- Detection of density fluctuation levels as low as 1% of mean density

Measurement geometry for (k_x, k_y)



length scales probed: **0.5 – 2 mm**

→ **anomalous transport**

Coherent Thomson scattering

Some key results

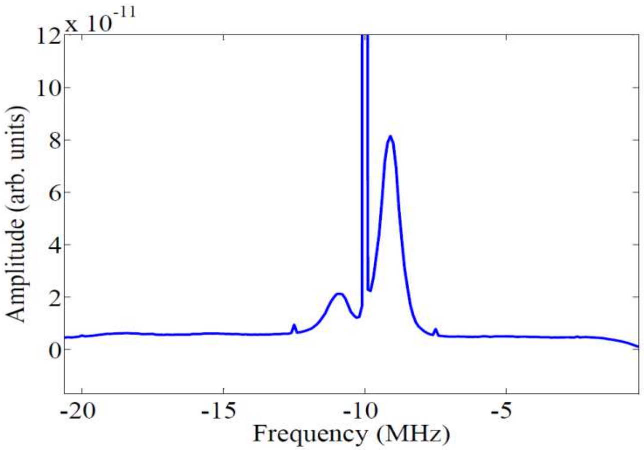
- first <u>detection</u> and <u>characterization</u> of a mm-scale, MHz-frequency wave implicated in anomalous electron transport

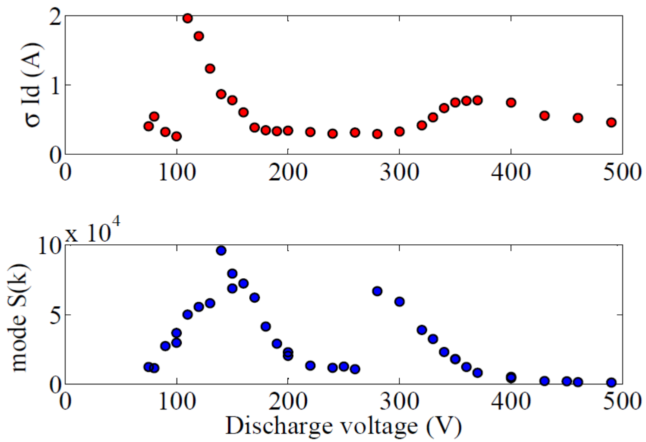
→ validation and advancement of numerical PIC simulations of the plasma
→ improvement of theoretical models for thruster drift instabilities

- establishment of universality of the instability, regardless of thruster size

- evidence of wall material influence on microturbulence

- evidence of likely link between microturbulence and discharge current fluctuations





Laser photodetachment

Information about negative ion density and dynamics

Two step process:

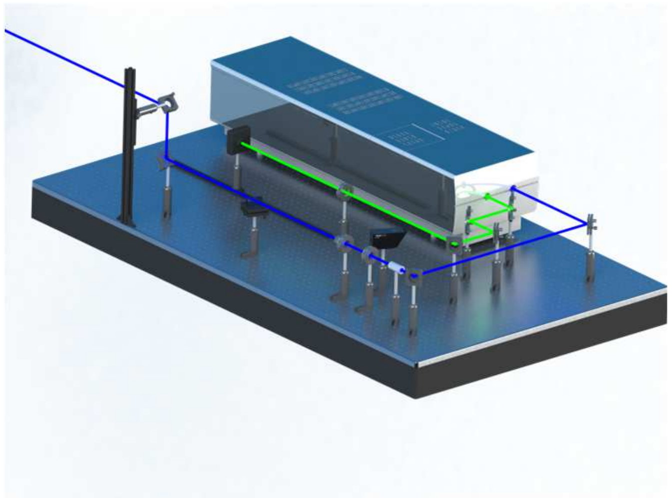
1) detachment of the electron with a photon: $A^- + \gamma \rightarrow A + e$
2) measurement of the associated electron current with an electrostatic probe

Electronegativity: $\alpha = \frac{\Delta I_e}{I_e} = \frac{n^-}{n_e}$

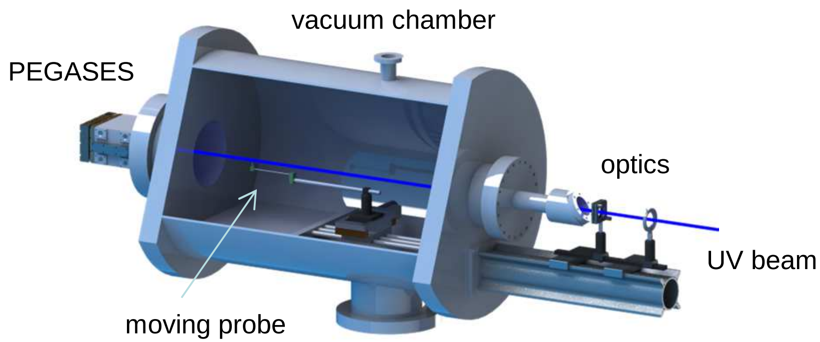
LPD bench at ICARE

Investigation of the ion-ion plasma **PEGASES** thruster (SF_6 discharge)

Pulsed Nd:YAG laser
10 ns, 266 nm, 30 mJ



Collimated UV laser beam
Positively biased Pt probe
On-axis measurements with Cu screen



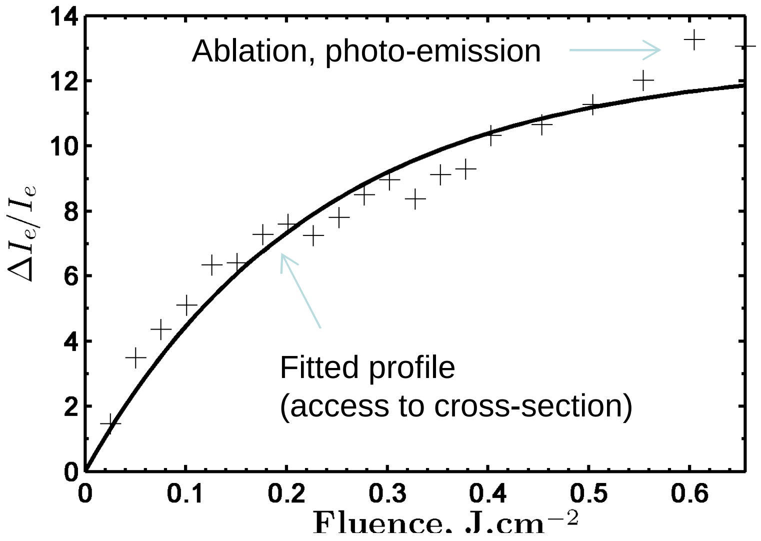
Laser photodetachment

First results with PEGASES
Inductively-coupled RF discharge (4 MHz) in SF_6

LPD → optimisation of the magnetic filter

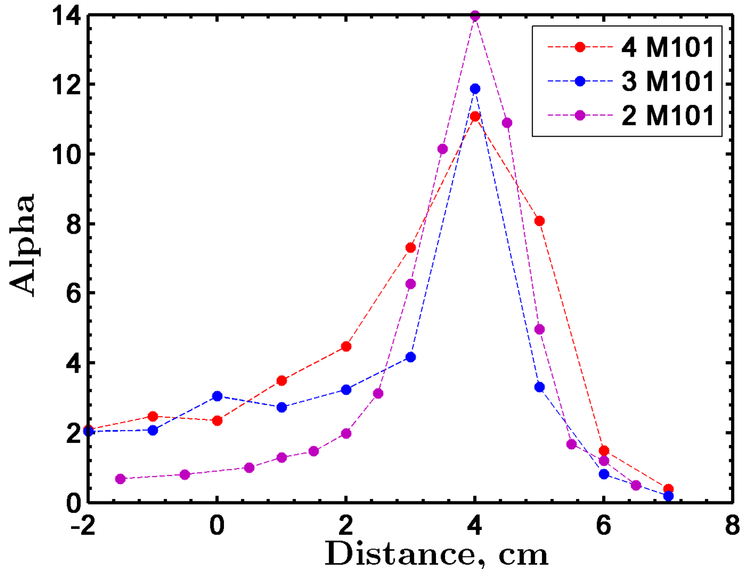
Saturation curve

λ low enough to photodetach all ion types
Influence of the laser beam power density



On-axis distribution of α

Effect of the magnetic field strength on the axial profile of the electronegativity



New laser-aided diagnostics

The EP community would benefit from new laser diagnostic tools:

(i) **Incoherent Thomson scattering**
- vital for analysis of basic transport processes, ionization and acceleration
- realistic EEDFs needed in numerical code development
- a tool for validating new thruster concepts (wall-less HT, ECR, helicon…)

(ii) **Stark spectroscopy**
- provide a direct access to the electric field
- fundamental quantity in plasma physics

(ii) **Two-photon Absorption LIF**
- for probing electronic ground-state of atoms and ions
- Measurement of density, velocity and temperature

Incoherent Thomson scattering

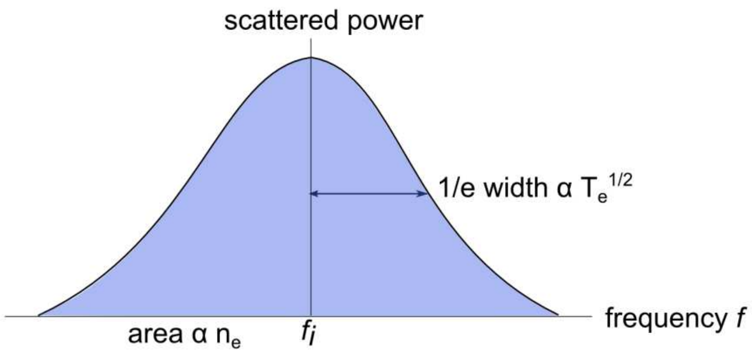
Principle:

- scattering of incident electromagnetic field supplied by a laser

- observation length scales **<<** electron Debye length

• a means of determining the electron energy distribution function (**EEDF**)

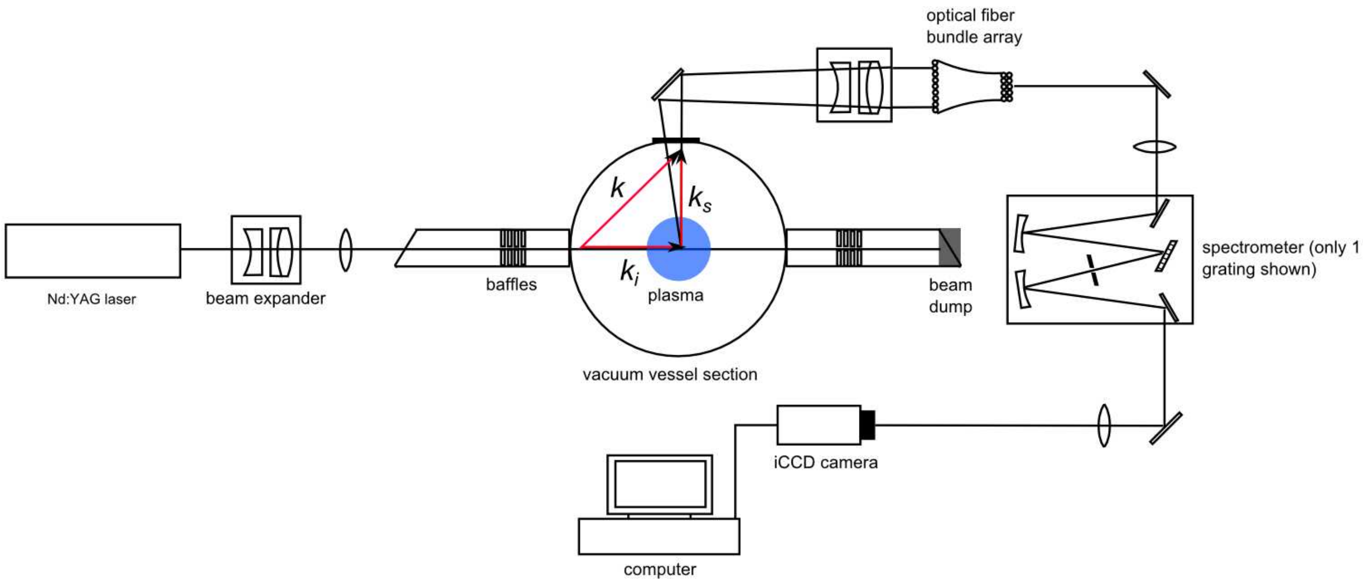
• Doppler broadening for T_e, scattered intensity for n_e



With such a diagnostic, we would bypass some of the limitations of invasive probes

Incoherent Thomson scattering

An incoherent Thomson scattering bench would be unique in electric propulsion!



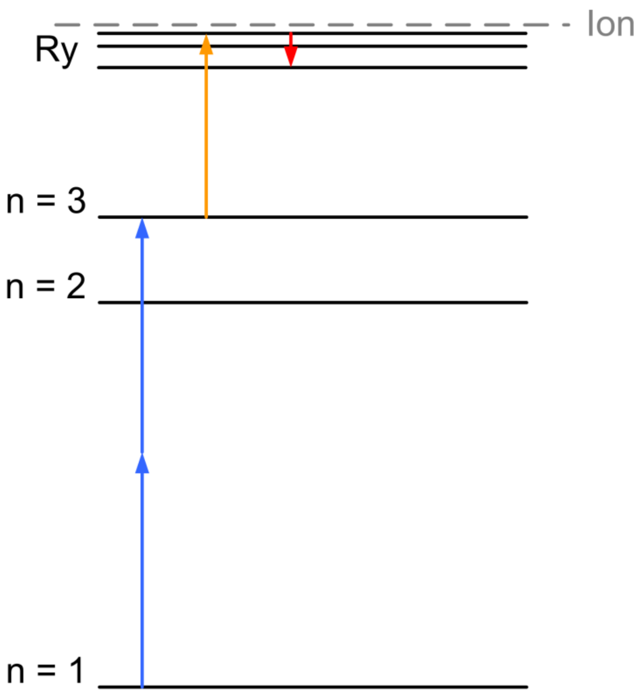
Diagnostic goals:

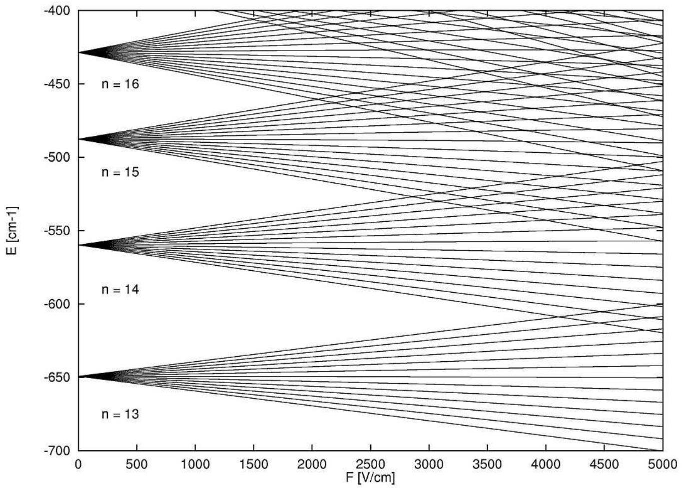
- measurements inside thruster discharge, in near-field region and far-field plume
- axial, radial and azimuthal orientations for observation wave vector
- T_e up to 50 eV
- n_e as low as 10^{16} m^{-3}

Stark spectroscopy

The **Stark effect** is the shifting and splitting of energy levels of atoms due to presence of an external electric field.

The effect of the electric field is greater for outer electron shells
→ Rydberg states





Computed energy level spectra of hydrogen in an electric field (Rydberg state)

Multi-color multi-photon LIF on highly-excited state

Dip spectroscopy

Sensitivity < 5 V / cm

Two-photon Absorption LIF

TALIF allows to probe the electronic ground state of atoms and ions

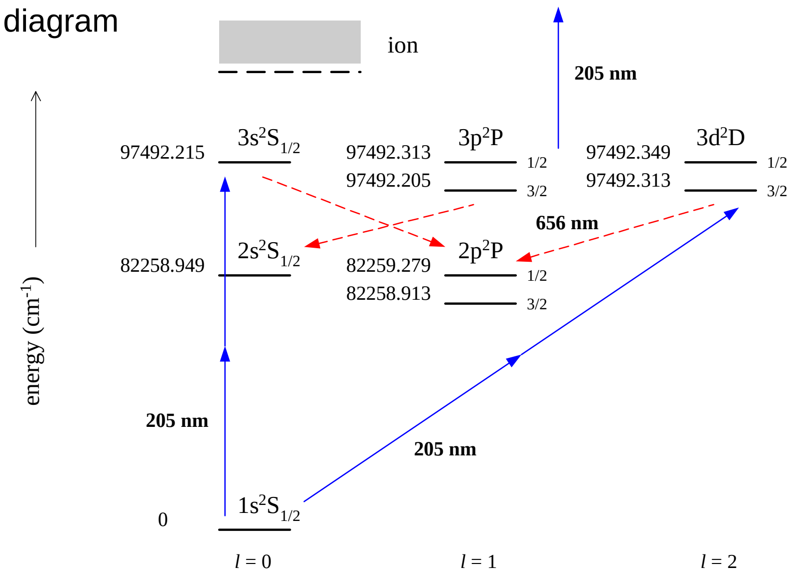
principle: Use of 2 UV photons (200 nm) instead of 1 XUV-VUX photon (< 100 nm)

Direct access to

- density
- temperature (line broadening mechanism)
- velocity

But calibration is needed for absolute number density (Rayleigh, titration…)

H Atom diagram



Conclusion

LAPD	Property to be measured/analyzed	Special features
Available		
Laser Induced Fluorescence	Ion VDF, atom VDF, electric field	Photon counting (temporal resolution = 100 ns)
Doppler-free LIF	HFS, magnetic field	
Coherent Thomson scattering	Microturbulence	Temporal resolution, HF, high spatial resolution, low density medium
Laser Photodetachment	Electronegativity, negative ion density	UV range
To be developed for EP		
Incoherent Thomson scattering	EEDF n_e, T_e	High sensitivity ($n_e \approx 10^{16}$ m^{-3}) for large T_e
Stark spectroscopy (LIF)	Electric field	High sensitivity (~V/cm)
Two-photon Absorption LIF	Density Temperature Velocity	Temporal resolution (ns)