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"Scattering" spectroscopy in thermal plasmas

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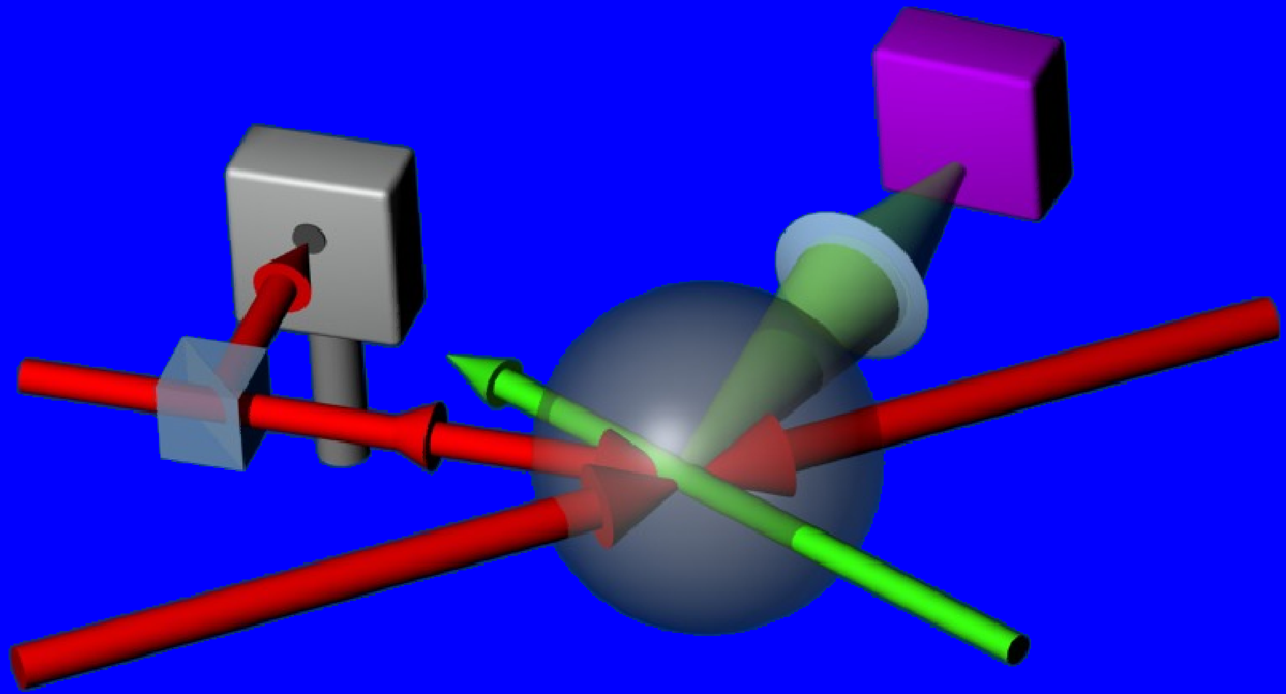
Plan of the Presentation

1. Background: Spatially and Temporally resolved thermal plasma diagnostics
    a. Thermal plasma
    b. Methods of plasma diagnostics
2. A brief theoretical description
    a. Scattering of waves in plasma: Rayleigh, Thomson
    b. Thomson scattering in different plasmas
3. Thomson scattering in thermal arc plasma
    a. Experimental procedure and data interpretation
    b. Plasma disturbance by laser pulse
    c. Spatial and Temporal averaging over laser pulse
4. Thomson scattering in laser induced plasma (LIB)
    a. What is LIB ?
    b. Laser induced sparks in gases: Ar, Air, He
        - Experimental procedure: Imaging, emission spectrum, data treatment
        - Plasma disturbance by laser pulse and Determination of initial Te
        - Ion feature of TS spectrum: Determination of ion temperature
        - Rayleigh scattering: evolution of , shock wave
    c. LIP generated on Al target
5. Summary and Conclusions

Background:

Spatially and Temporally resolved thermal plasma diagnostics



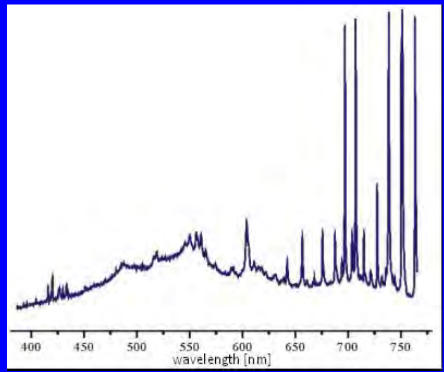
Thermal plasma

Isothermal balance close to the equilibrium $\Rightarrow T_e \approx T_h$

$\Downarrow$

High electron density, pressure, temperature and ionization degree

For argon arc plasma at $p = 10^5$ Pa LIE is achieved for $N_e \sim 10^{22}$ m^{-3} $T_e \sim 10^4$ K

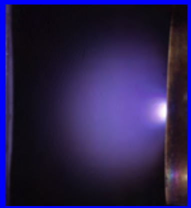


Spectrum

- intense continuous radiation
- lines appreciably broadened due to Stark broadening
- important contribution of Doppler broadening

Examples analyzed in this talk:

Arc plasma at atmospheric pressure – Stationary plasma



Plasma induced by pulsed laser – Transient plasma

Plasma diagnostics requirements

Main goal:

Plasma parameters:	N_e, T_e, T_h
Plasma composition	(Quantitative analysis)

Ideal method:

- Temporal resolution adequate to a time scale of the plasma evolution
- Spatially resolved - good spatial resolution necessary to map plasma parameters
- Non-intrusive $\rightarrow$ plasma state not disturbed
- No assumptions about the plasma state

There is no such method which meets all of these requirements

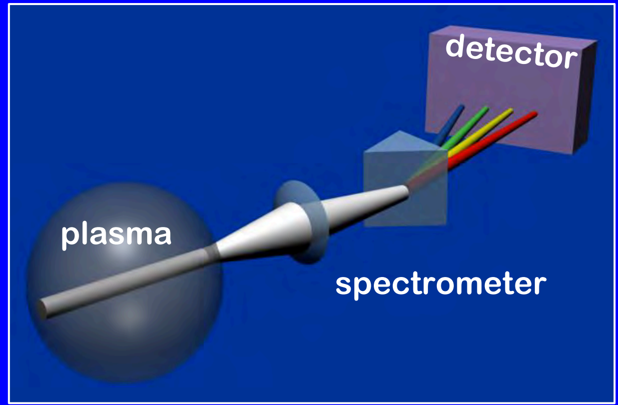
Inhomogeneous plasma $\Rightarrow$ Spatial resolution is crucial factor affecting quality of diagnostics

Methods of plasma diagnostics

Optical emission spectroscopy (passive)

☹ **only <u>spatially integrated</u> intensity along the line of sight can be directly measured** (local values need Abel transformation)

- possible reabsorption
- *only excited particles can be probed*
- *required assumptions about the plasma equilibrium state*



Methods of plasma diagnostics

Optical emission spectroscopy (passive)

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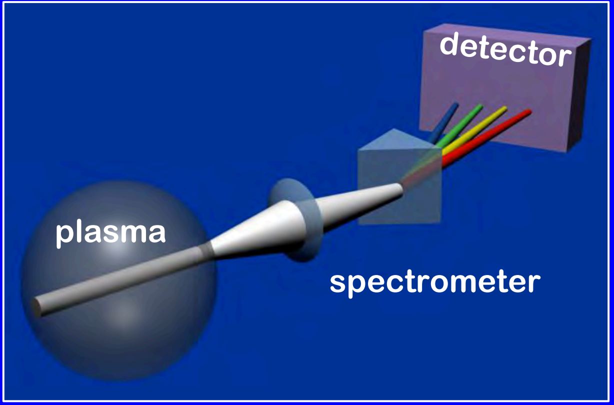
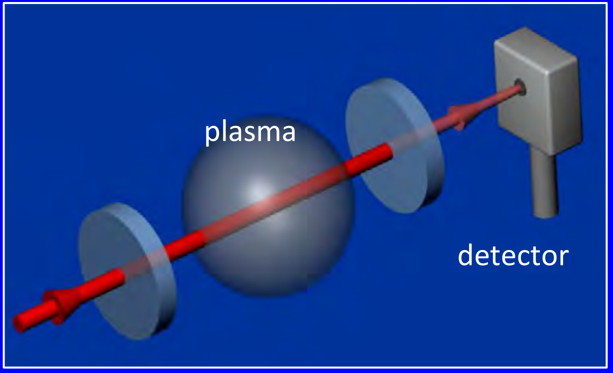


- possible reabsorption
- *only excited particles can be probed*
- *required assumptions about the plasma equilibrium state*

Methods based on transmitted light analysis (active)

- ✓ Laser absorption spectroscopy
- ✓ Polarization spectroscopy
- ✓ Cavity ring-down absorption
- ✓ Interferometry



☹ **Non-local methods!**

Spatially resolved laser based techniques

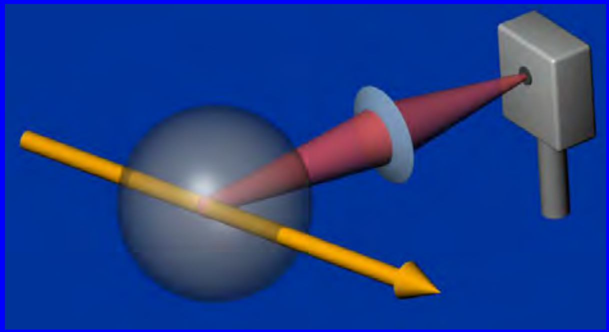
Laser based, local methods

✓ **Laser induced fluorescence (LIF, TALIF)**

Not useful at high electron density

- Signal diminished by non-radiative decay
- Masked in strong plasma radiation background

Pump – probe technique



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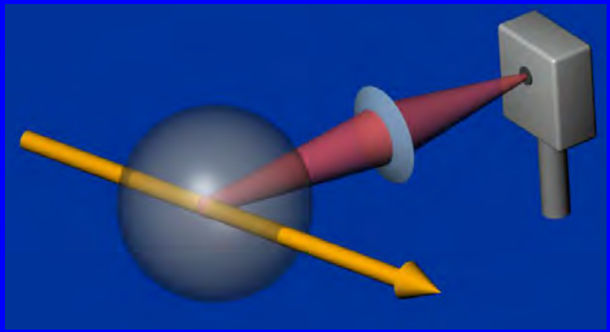


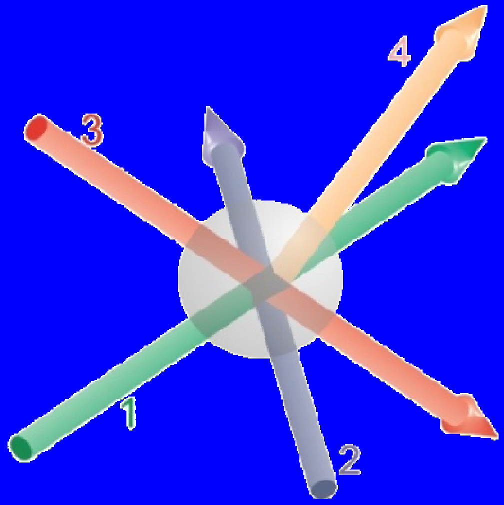
✓ Non-linear spectroscopy

FWM: Coherent third order non-linear process

$$\omega_4 + \omega_3 = \omega_1 + \omega_2 \qquad \omega_4 = \omega_1 + \omega_2 - \omega_3$$

$$\vec{k}_1 + \vec{k}_2 = \vec{k}_3 + \vec{k}_4$$

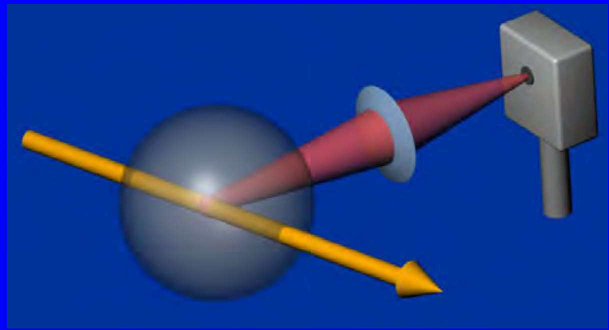
Phase matching condition



Spatially resolved laser based techniques

Laser based, local methods

Pump – probe technique



✓ **Laser induced fluorescence (LIF, TALIF)**

Not useful at high electron density

- **Signal diminished by non-radiative decay**
- **Masked in strong plasma radiation background**

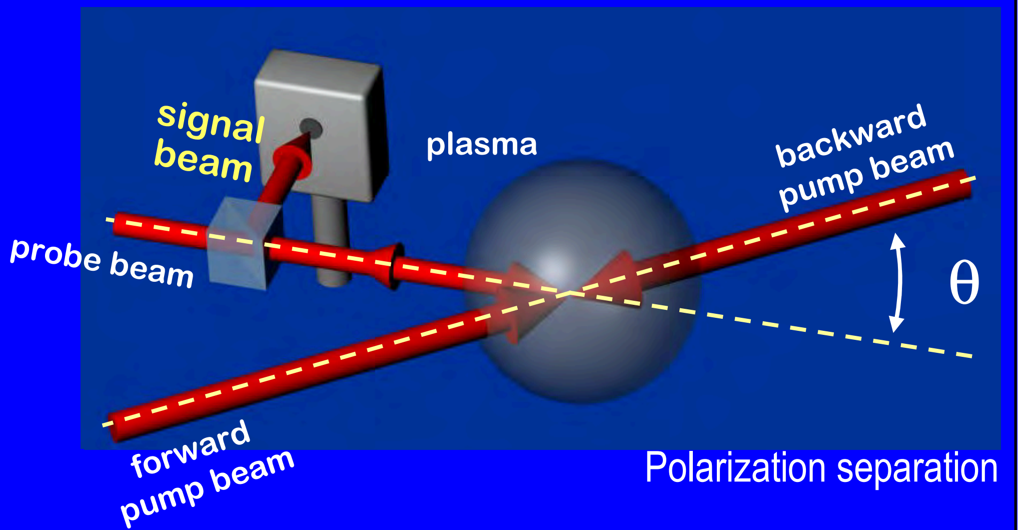
✓ **Non-linear spectroscopy** → **PC-Degenerate Four Waves Mixing**

$$\omega_1 = \omega_2 = \omega_3 = \omega_0 \Rightarrow \omega_4 = \omega_0$$

Degenerate mixing

$$\vec{k}_1 = -\vec{k}_2 \Rightarrow \vec{k}_4 = -\vec{k}_3$$

Phase-conjugate

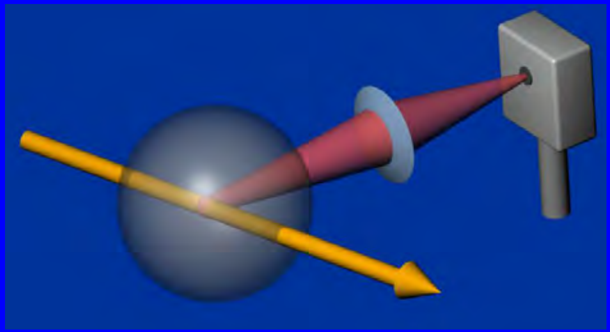


Polarization separation

Spatially resolved laser based techniques

Laser based, local methods

Pump – probe technique



✓ Laser induced fluorescence (LIF, TALIF)

Not useful at high electron density

- Signal diminished by non-radiative decay
- Masked in strong plasma radiation background

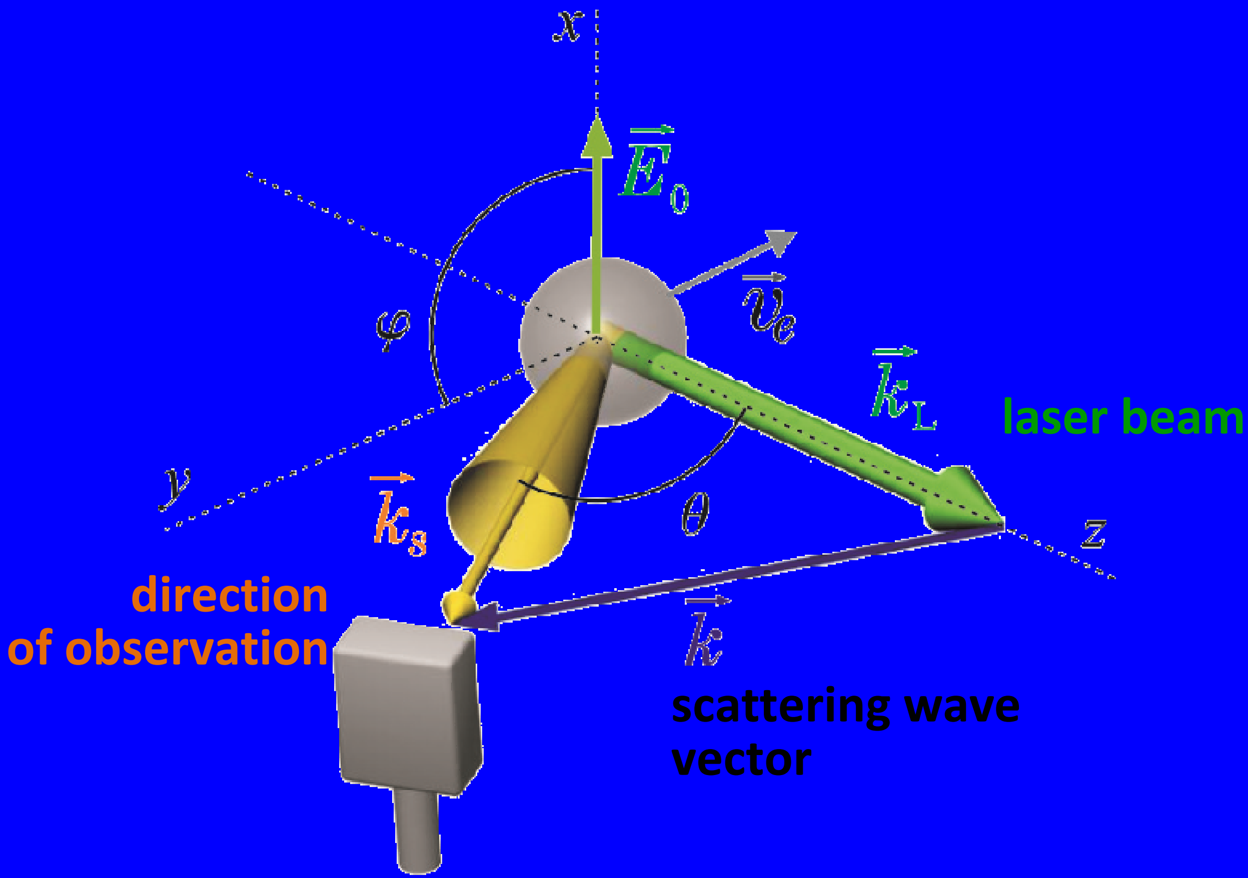
✓ Non-linear spectroscopy

✓ Scattering of laser radiation

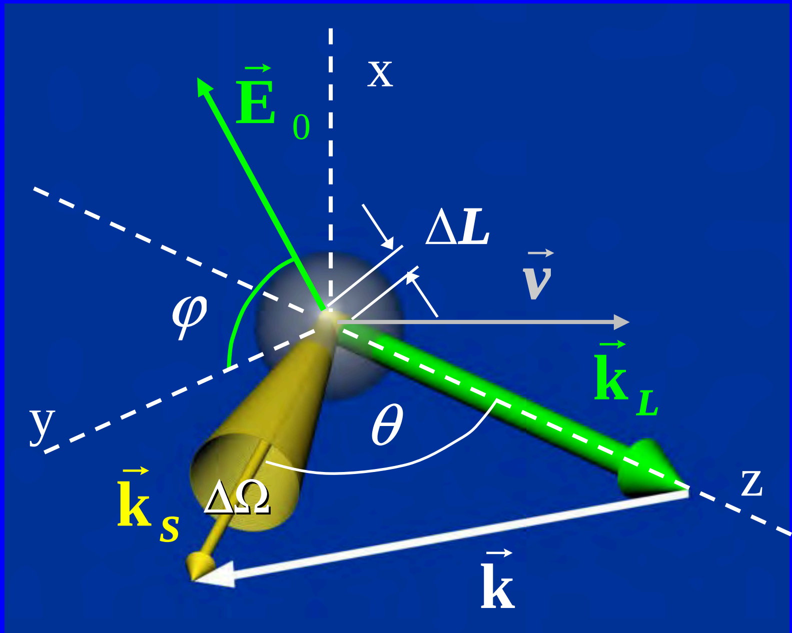
Remains to consider:

Thomson scattering

Scattering of laser radiation:
A brief theoretical description



Non-relavistic scattering of laser radiation



$$\Delta P_S = P_L \, \Delta L \Delta\Omega \; N \frac{d\sigma}{d\Omega} \; \underline{S(\mathbf{k}, \Delta\omega)} \, \Delta\omega_S$$

spectral density function

$$\frac{d\sigma}{d\Omega} = \frac{3}{8\pi} \sigma \left(1 - \sin^2\theta \cos^2\varphi\right)$$

$$\left|\vec{\mathbf{k}}\right| = \left|\vec{\mathbf{k}}_S - \vec{\mathbf{k}}_L\right| \cong \frac{4\pi}{\lambda_L} \sin(\theta/2)$$

scattering vector

Motion of scattering centers

$$\Delta\omega \equiv \omega_L - \omega_S = \left(\vec{k}_S - \vec{k}_L\right) \cdot \vec{v} = \vec{k} \cdot \vec{v}$$

Elastic scattering

- **Rayleigh scattering**
- **Thomson scattering**

Inelastic scattering

- **Raman scattering**

Non coherent scattering on an ensemble

$$S_k(\Delta\omega)\, d\omega_s = F_k(v_k)\, dv_k = k^{-1} F_k(\Delta\omega / k) d\omega_s$$

Spectral density function reproduces velocity distribution of moving scattering centers

From Rayleigh, Thomson and Raman scattering we have information on electron and heavy particles density and their temperatures → PLASMA DIAGNOSTICS

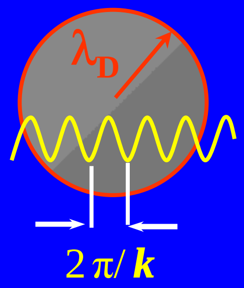
Incoherent and coherent Thomson scattering

$$\alpha \equiv \frac{1}{k\lambda_D} \approx \frac{1}{4\pi\sin(\theta/2)}\frac{\lambda_L}{\lambda_D}$$

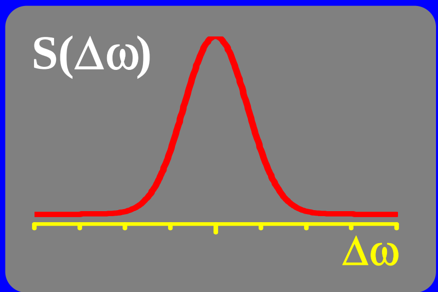
$$\lambda_D = \left(\frac{\varepsilon_0 k_B T_e}{e^2 N_e}\right)^{1/2}$$

$$\hat{\omega}_{pl} = \sqrt{e^2 n_e/(\varepsilon_0 m_e)}$$

$\alpha \ll 1 \rightarrow$ Non-collective scattering

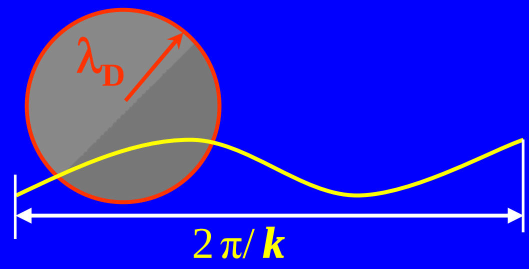


Spectral distribution gives EEDF



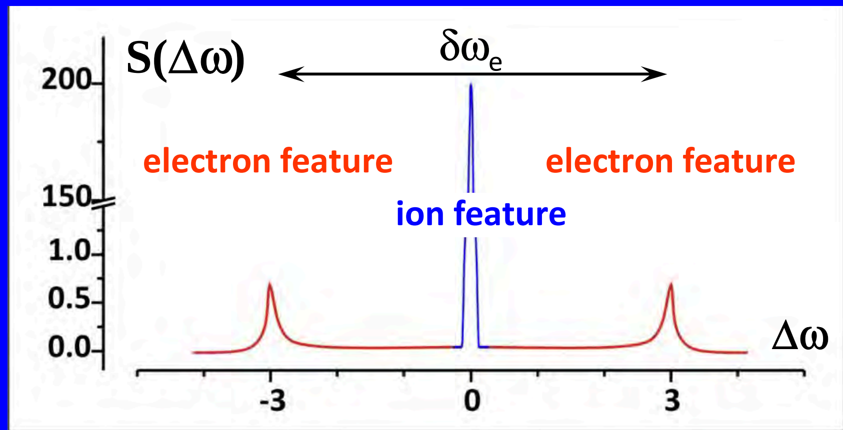
At optical wavelength and thermal plasma $\alpha \sim 1$

$\alpha \gg 1 \rightarrow$ Collective / Coherent scattering



- ✓ Coupling with Langumir plasma waves
- ✓ Coupling with ion acoustic waves

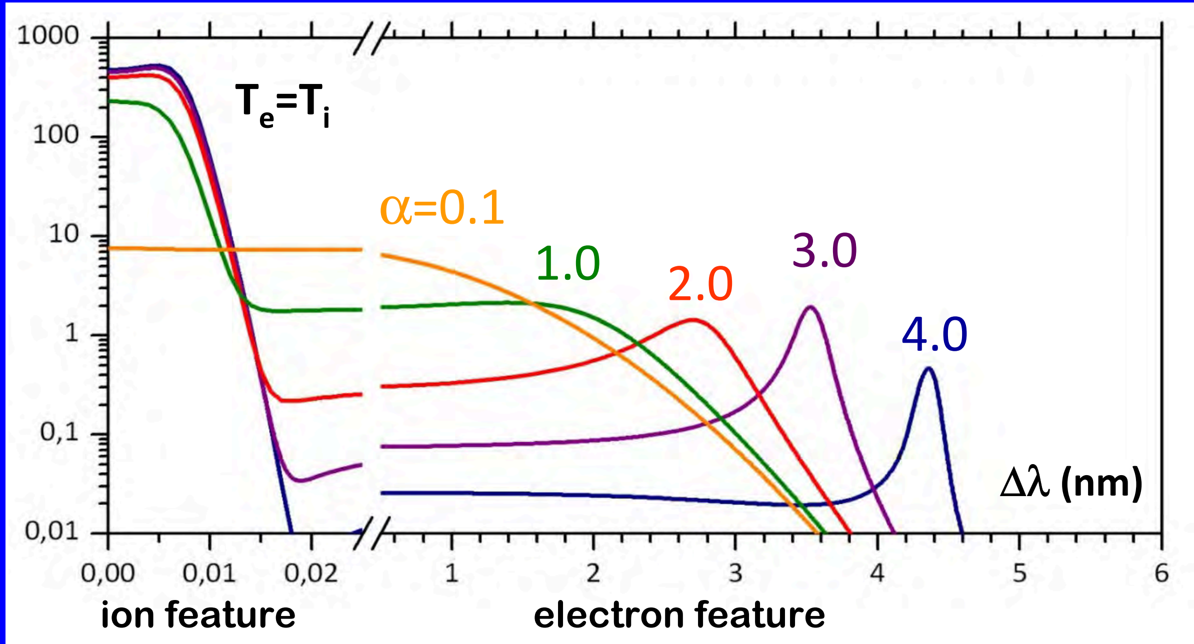
$$\delta\omega_e = \sqrt{\hat{\omega}_{pl}^2 + 3k^2 k_B T_e / m_e} \qquad \delta\omega_i = k\sqrt{2k_B T_i / M_i}$$

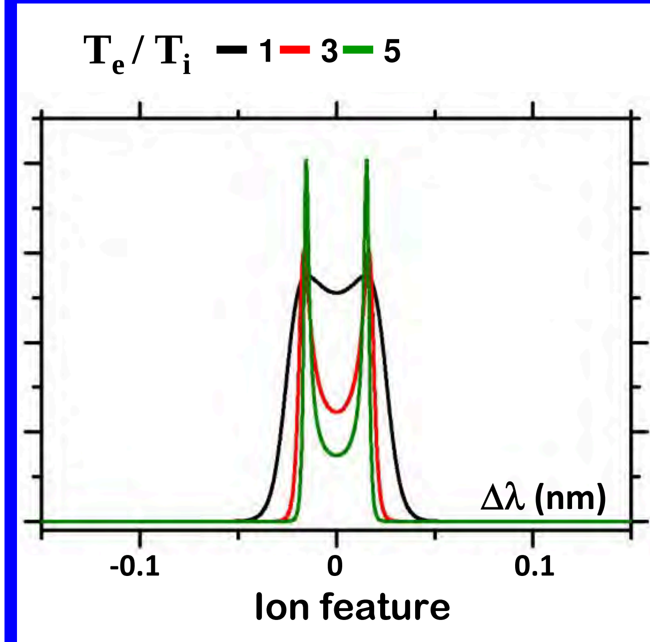


Thomson scattering – Partially collective case (α≈1)

$$S(k,\Delta\omega) = \frac{1}{k\,v_e}\Gamma_\alpha(\Delta\omega/k\,v_e) + \frac{1}{\sqrt{\pi}\,k\,v_i}\frac{\alpha^2}{1+\alpha^2}\Gamma_\beta(\Delta\omega/k\,v_i)$$

electron feature — ion feature

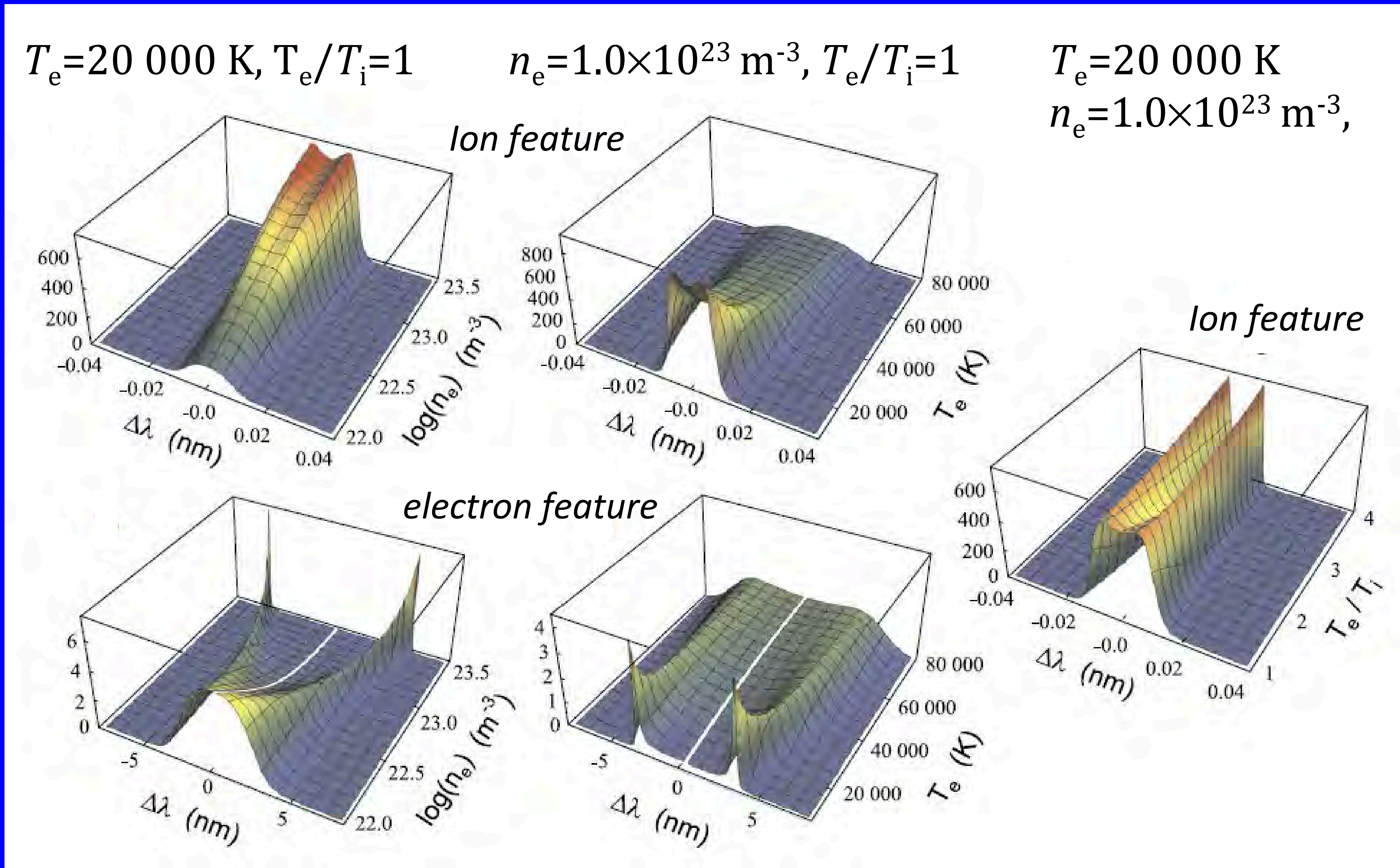




- Electron feature contains information about electron density and electron temperature.
- Ion feature contains information about ratio of electron temperature and heavy species temperature.
- Straightforward interpretation, no LTE assumption required

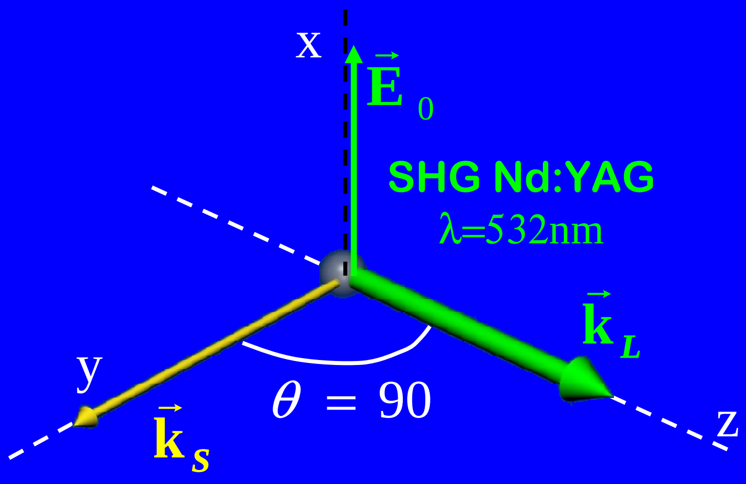
Thomson scattering – Partially collective case (α≈1)

↳ The spectral form factor



λ_L = 532 nm, φ = θ = π/2 , Z = 1

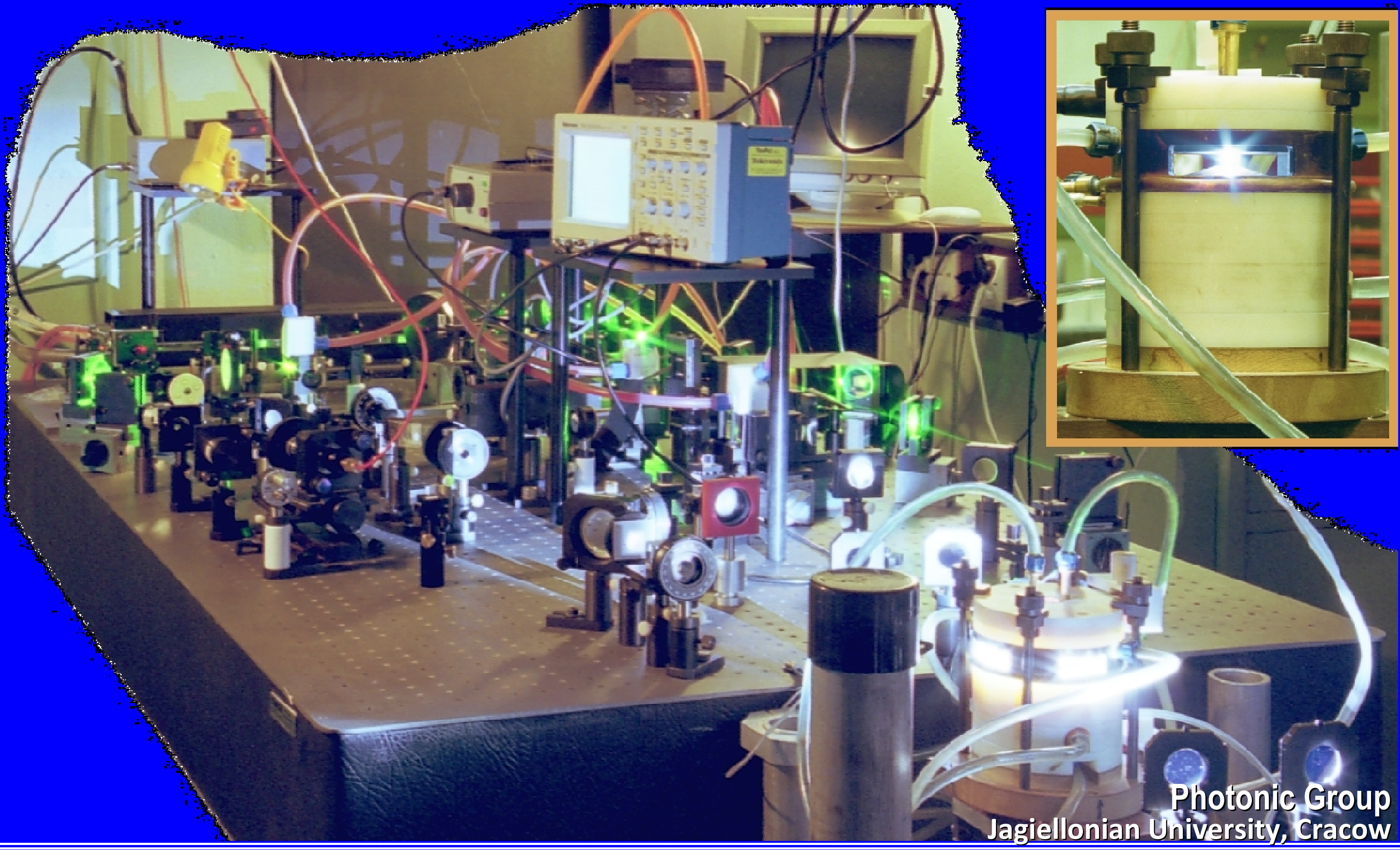
Thomson scattering in different plasmas



Plasma source	N_e [m^{-3}]	T_e [K]	α
Tokamak	10^{20}	10^{7}	0.006
Glow discharge	10^{18}	10^{4}	0.02
Argon arc at atmospheric pressure	10^{23}	10^{4}	3.0
Laser induced plasma	10^{25}	10^{5}	6.0

- Always collective scattering dominates !
- N_e, T_e can be determined based on the single Thomson scattered spectrum

Thomson scattering in thermal arc plasma

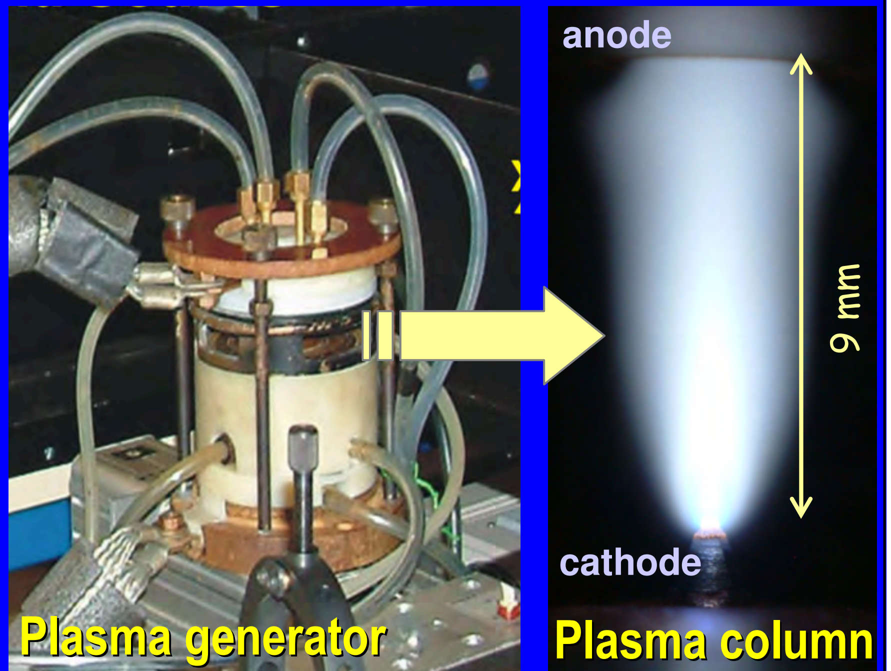


Thomson scattering in thermal arc plasma

Plasma generated in a transferred arc,
burning in pure (99.995%) argon
at atmospheric pressure
with 40 - 160A arc curent

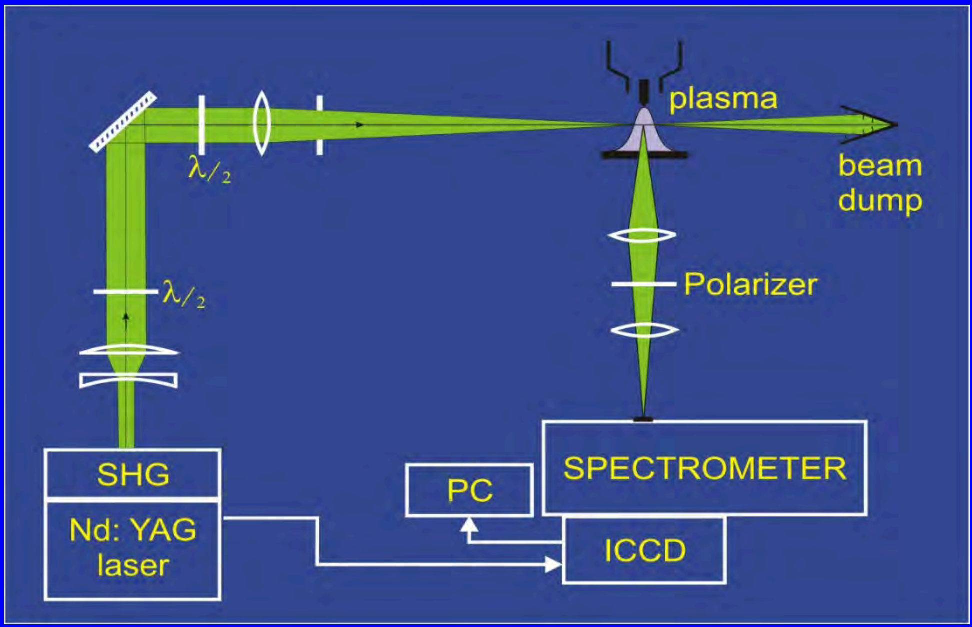
- Electron temperature T_e : 10000 – 24000 K
- Electron concentration N_e : $10^{22} – 10^{23}$ m^{-3}
- Stark broadening dominates
- Long term stability

- Large gradients of plasma parameters
- Strong continous emission
$$\propto N_e^2 / \sqrt{T_e}$$
- Domination of non-radiative processes



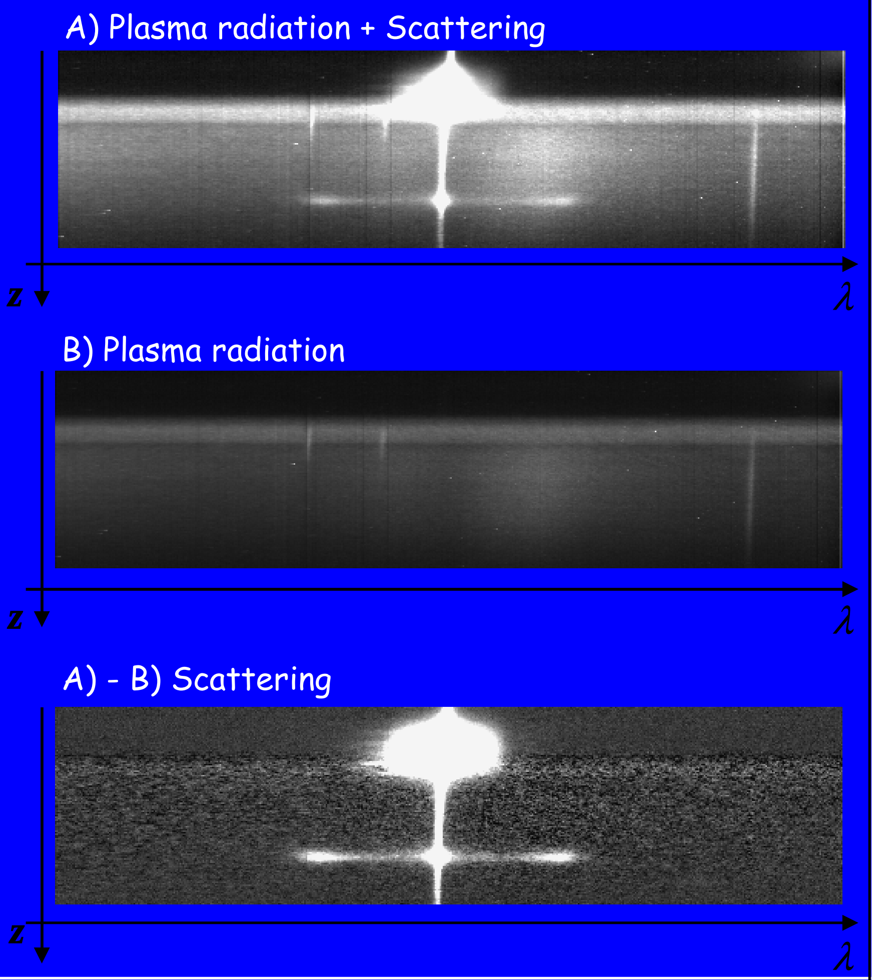
Thomson scattering in thermal arc plasma

Experimental set-up

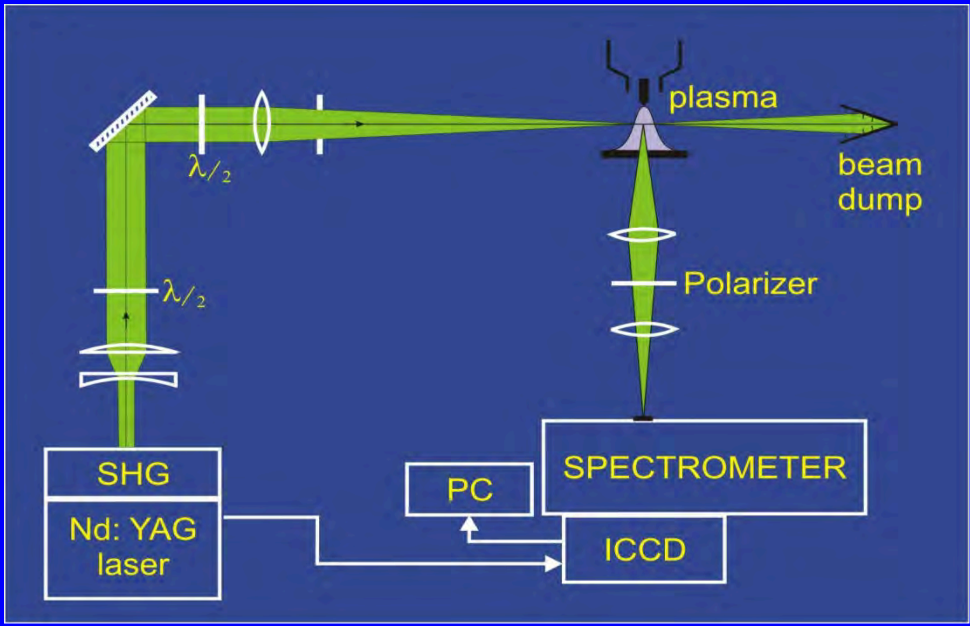


Arc plasma, pure argon at p=10^{5}Pa , I=200A

Measurement procedure

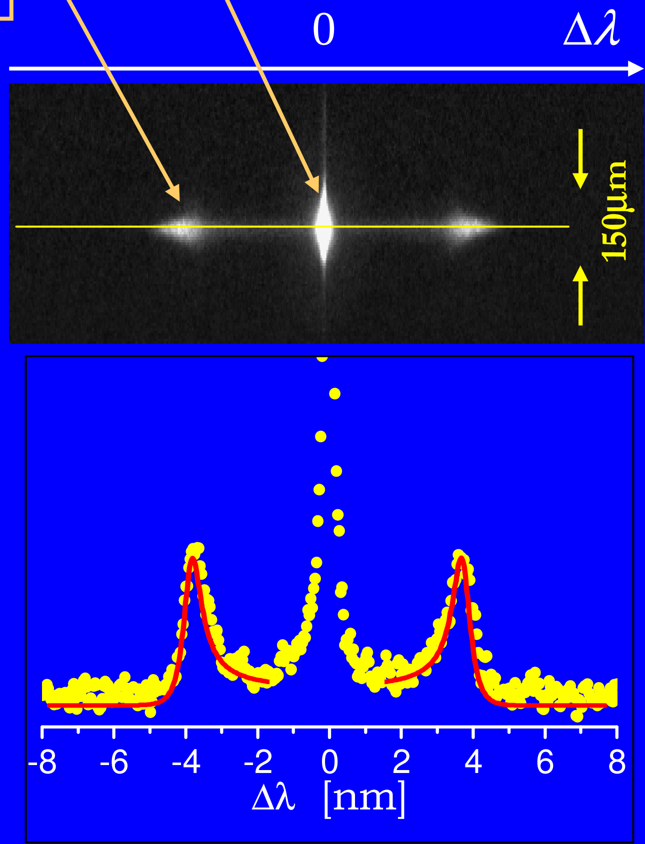


Thomson scattering in thermal arc plasma



Thomson scattering – electron feature

Ion feature + Rayleigh scattering + stray light



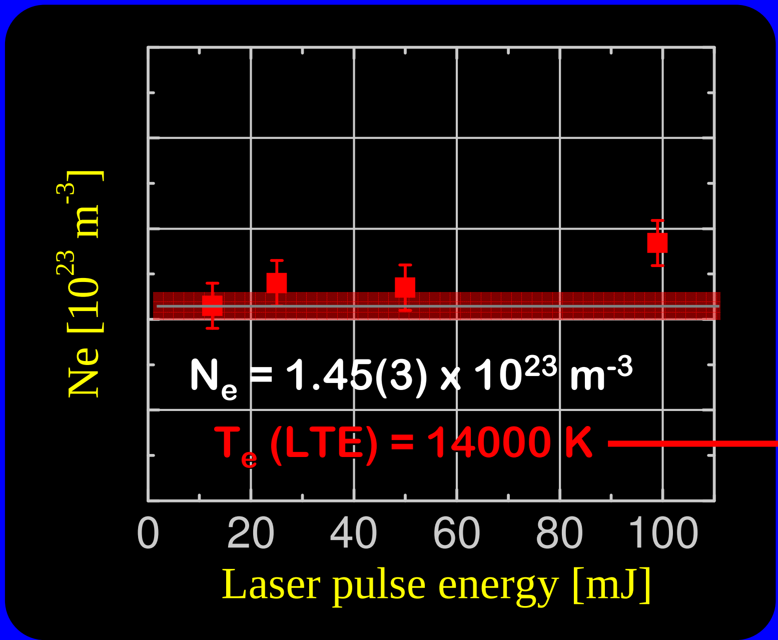
Arc plasma, pure argon at p=10^5Pa , I=200A

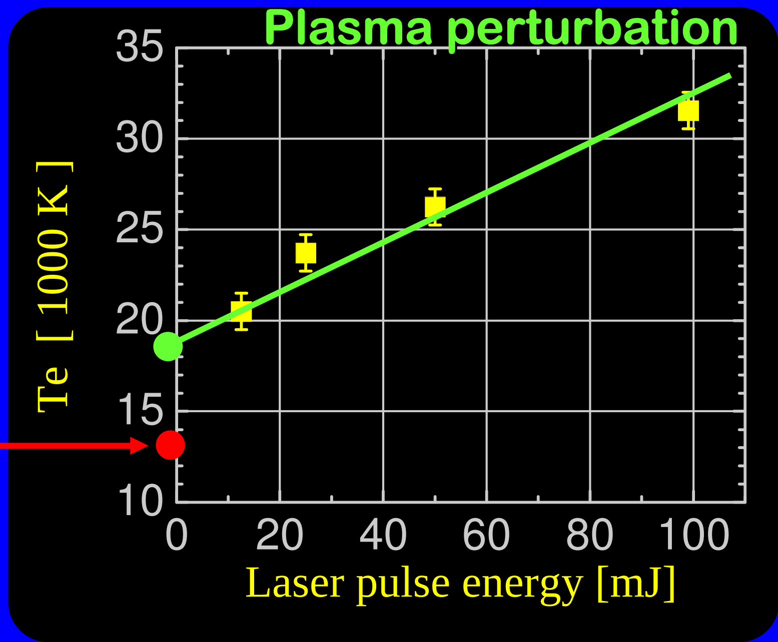
$S(k,\Delta\omega)$ ⇒ $N_e = 1.1 \times 10^{23}\ m^{-3}$

$T_e = 21000\ K$

Thomson scattering in thermal arc plasma

N_e and T_e versus energy of the laser pulse





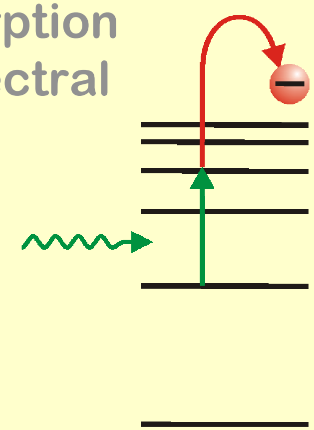
- T_e is higher than T_{LTE} obtained form N_e, by few thousands kelvins, which contradicts the LTE plasma model
- Either most of theoretical and experimental studies are false ..
  OR interpretation of TS results is incorrect ???

Thomson scattering in thermal arc plasma

↳ Plasma disturbance by laser pulse

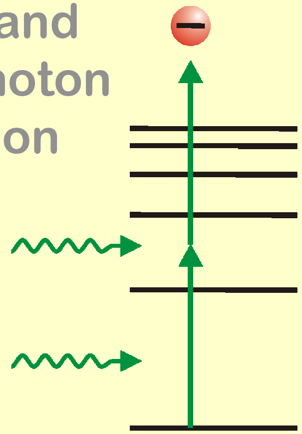
Possible absorption processes

Absorption at spectral lines



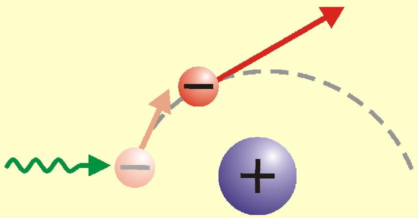
Increase of n_e

Single and multiphoton ionization



Electron heating, Increase of T_e

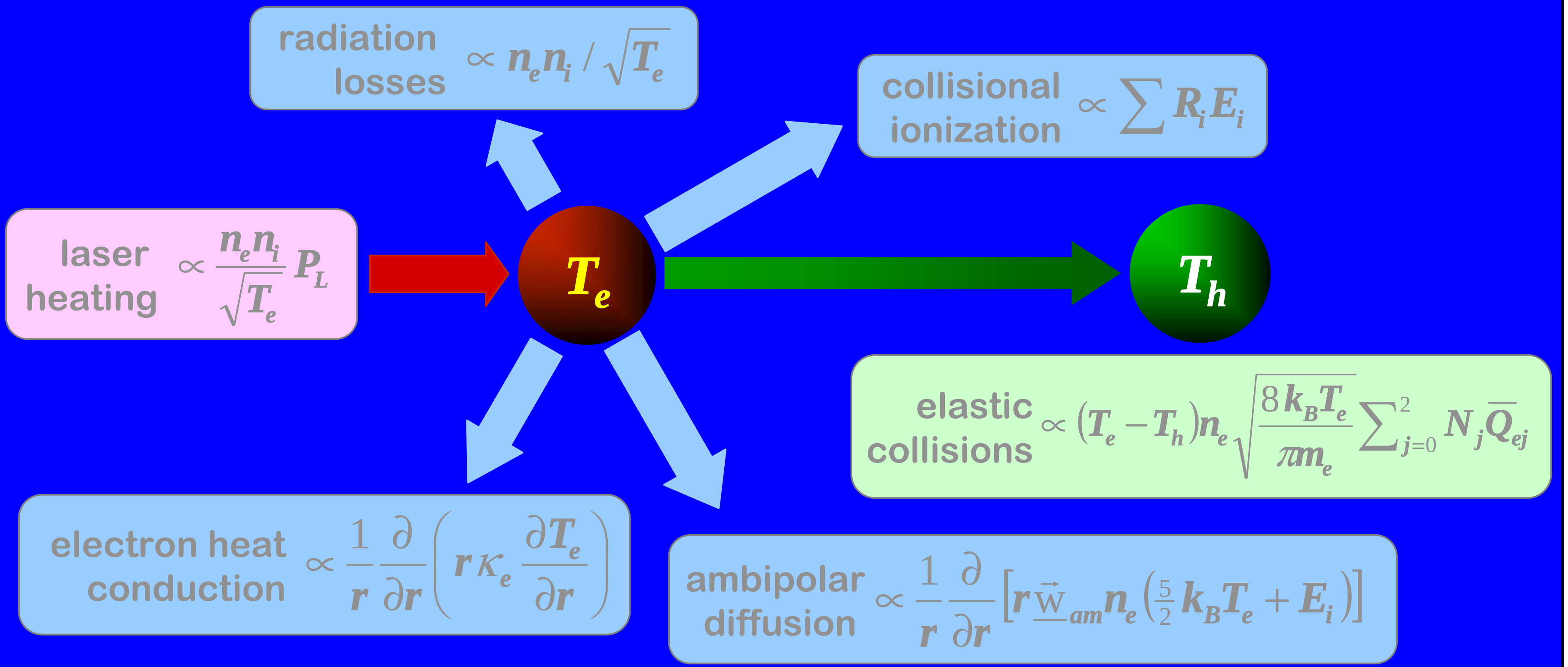
Inverse bremsstrahlung



Thomson scattering in thermal arc plasma

Electron heating by laser pulse

- Plasma perturbated (heated) in the inverse bremsstrahlung process !!



A.B. Murphy; PRL 89, 025002 (2002); Phys Rev E 69, 016408 (2004)

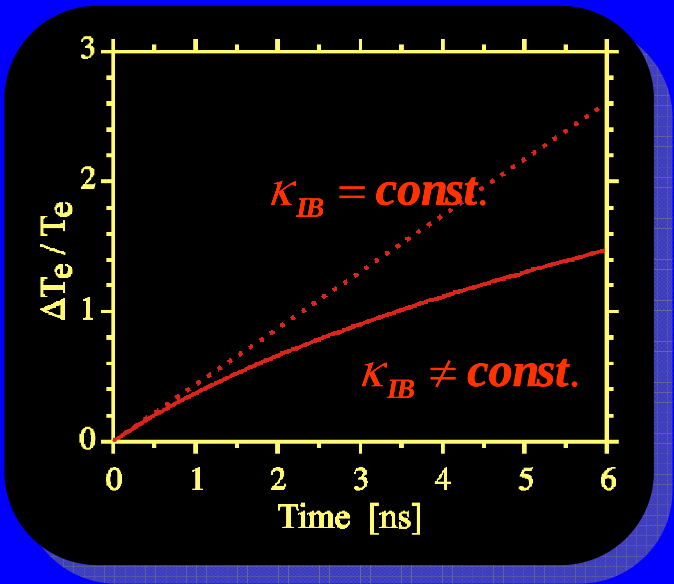
Thomson scattering in thermal arc plasma

Electron heating by laser pulse

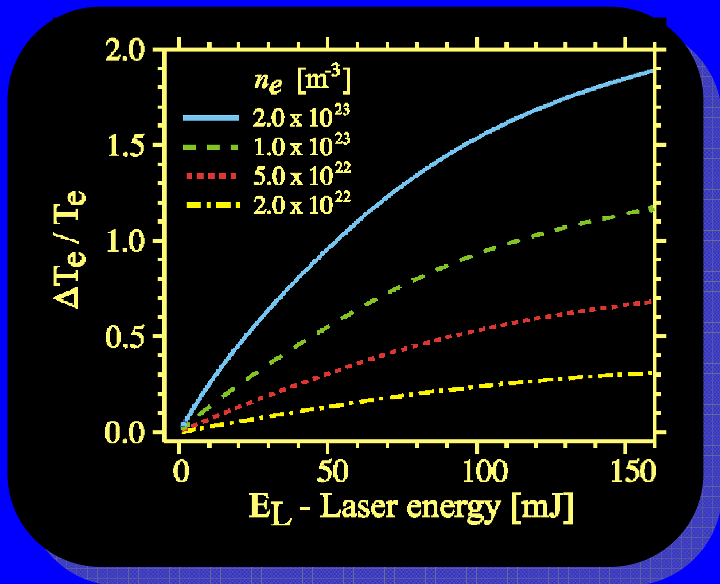
- **Plasma perturbated (heated) in the inverse bremsstrahlung process !!**

$$\frac{\Delta T_e}{T_e} = \frac{2}{3}\frac{\kappa_{IB} E_L}{k_B T_e\, n_e\, \pi r_0^2}$$

$$\frac{\Delta T_e}{T_e} = 6.6\times10^{-5}\frac{\sum_Z Z^2 n_{i,Z}}{T_e^{3/2}}\frac{E_L}{\pi r_0^2}\times \bar{g}_{ff}(\lambda_L)\,\lambda_L^3\left(1-\exp(-hc/k_B T_e \lambda_L)\right)$$



E_L = 100mJ, T_e = 17400 K, n_e = 2 x10 ^{23} m^{-3}



Initial temperature : T_e = 11600 K

A.B. Murphy; PRL 89, 025002 (2002); Phys Rev E 69, 016408 (2004)

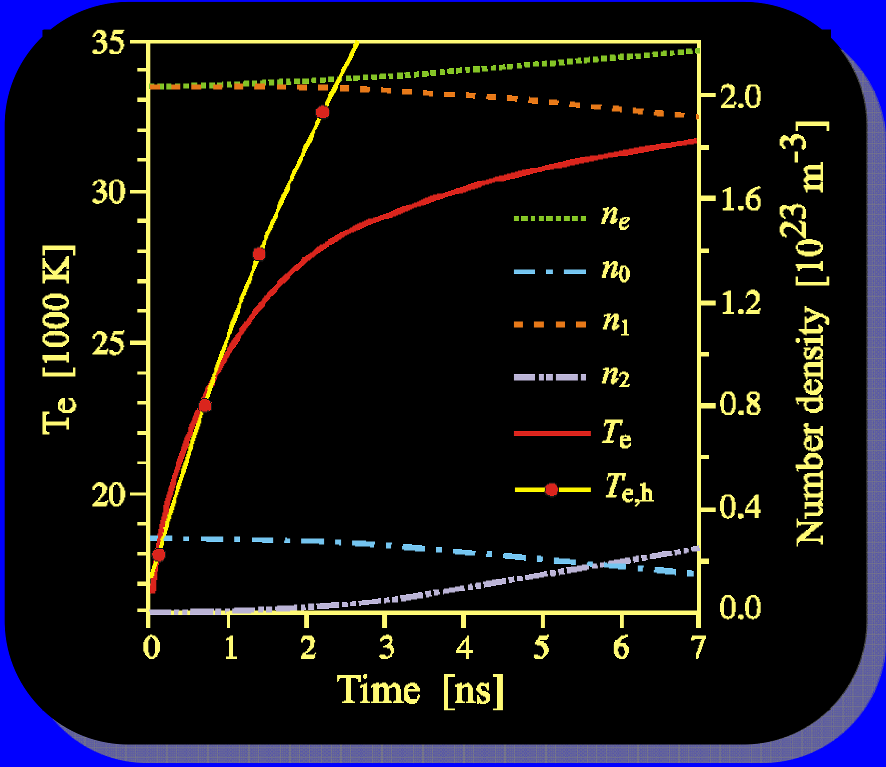
Thomson scattering in thermal arc plasma

Electron heating by laser pulse

MHD model, argon thermal plasma heated by the square, 7ns long laser pulse

- *Electron heating is a strongly nonlinear function of the laser power*

  so the linear extrapolation to zero pulse energy is invalid !



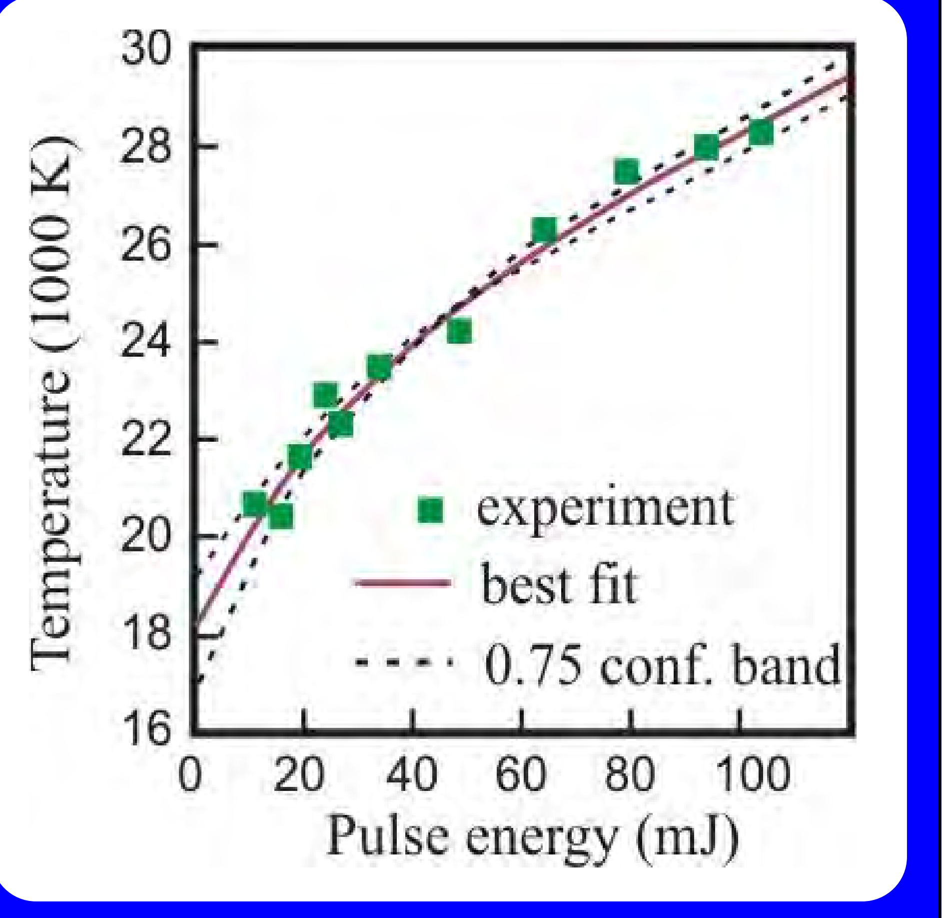
$T_{e,h}$ – assuming no cooling channels

A.B. Murphy; PRL 89, 025002 (2002); Phys Rev E 69, 016408 (2004)

Thomson scattering in thermal arc plasma

↳ Electron heating by laser pulse

MHD model, argon thermal plasma heated by the square, 7ns long laser pulse



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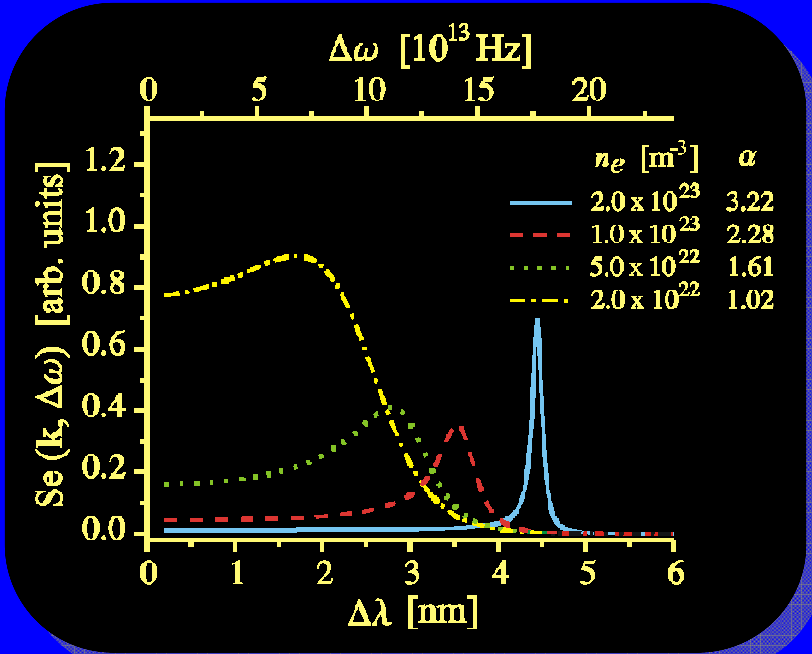
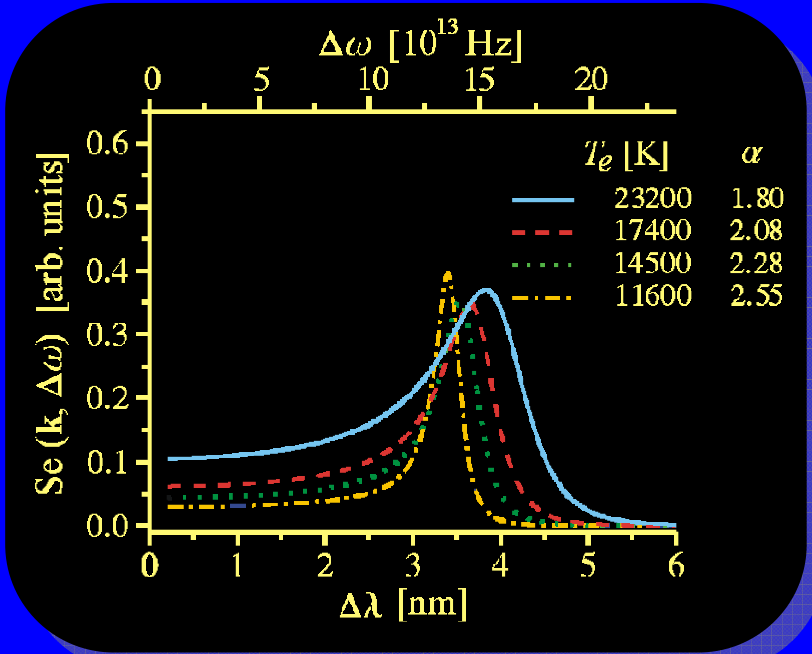
A.B. Murphy; PRL 89, 025002 (2002); Phys Rev E 69, 016408 (2004)

Thomson scattering in thermal arc plasma

↳ **Averaging over laser beam cross section and over duration of laser pulse**

TS spectra for different n_e and T_e values

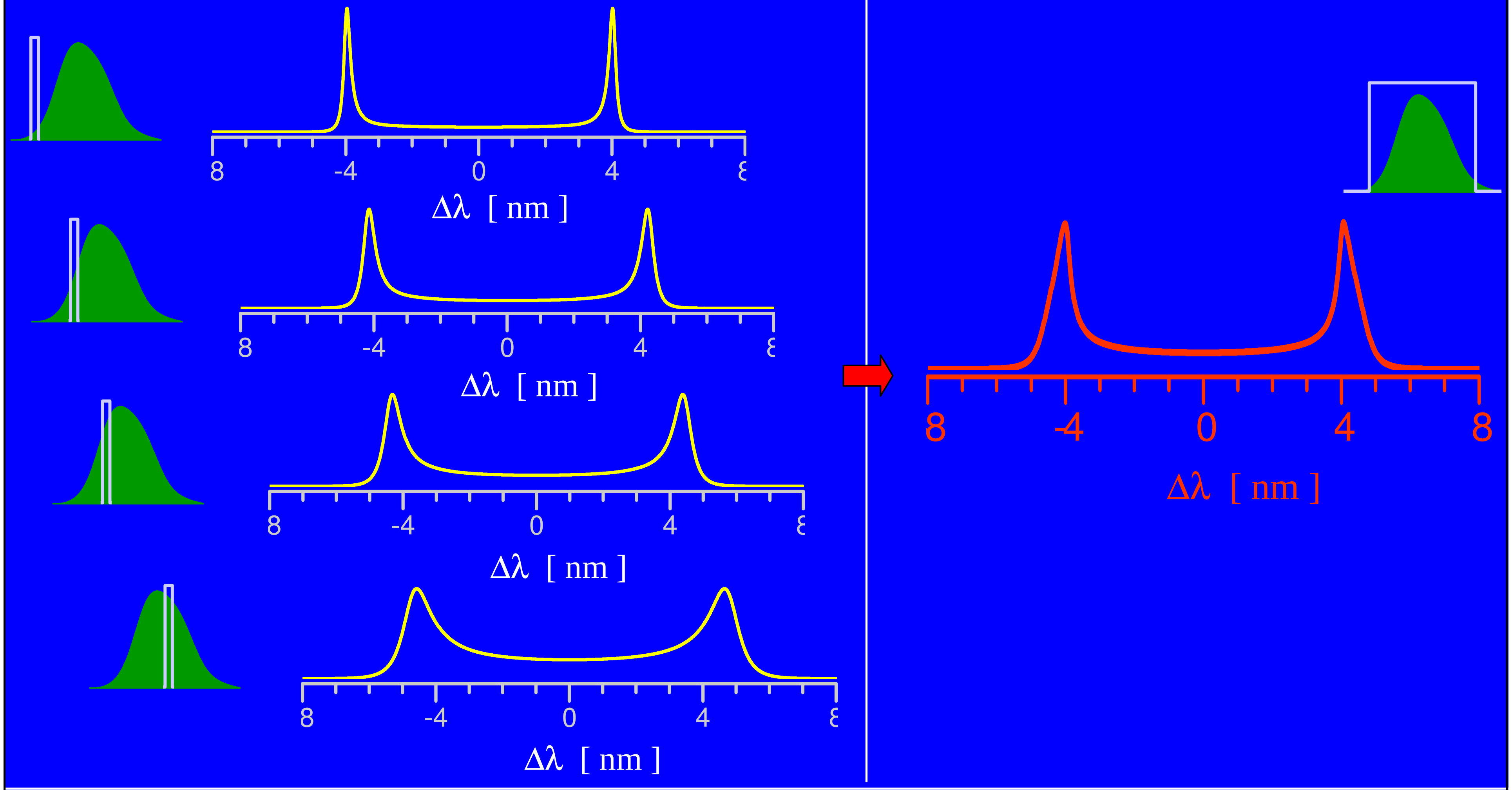




Thomson scattering in thermal arc plasma

↳ **Averaging over laser beam cross section and over duration of laser pulse**

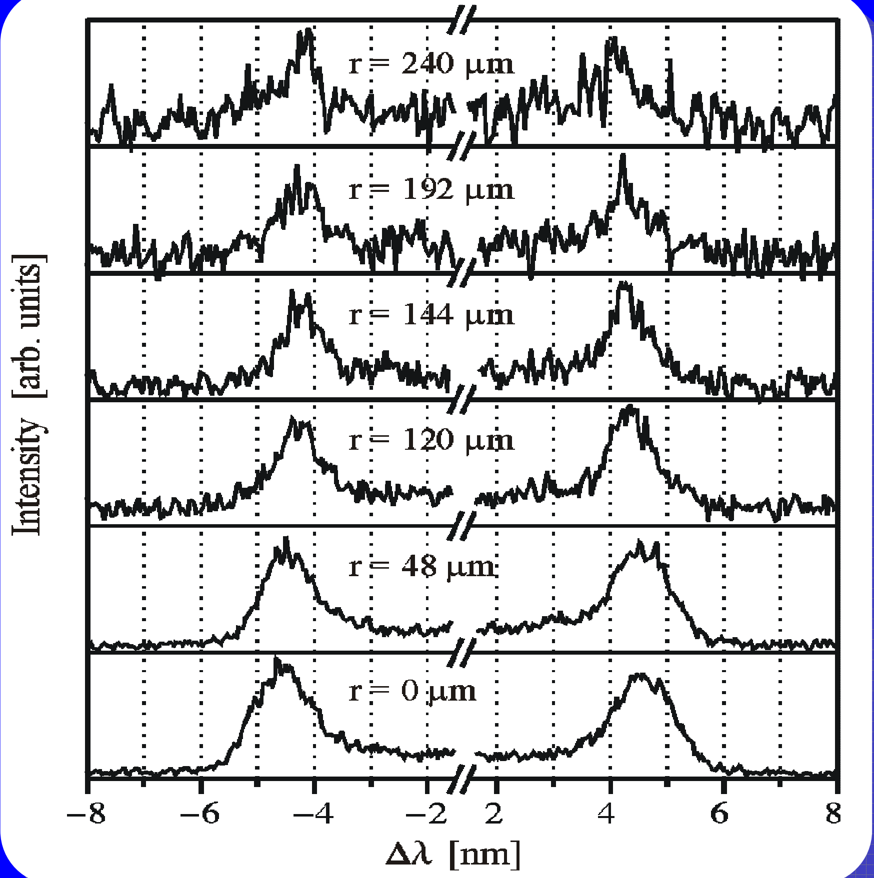
Effect of electron heating by laser pulse

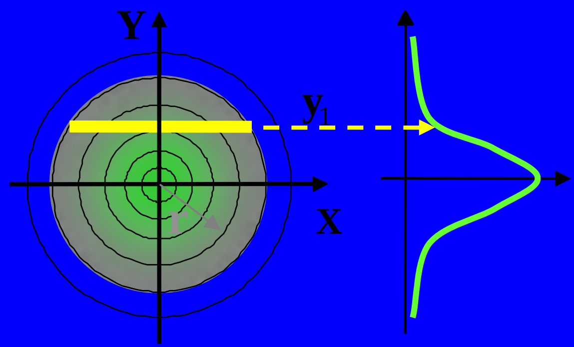


Thomson scattering in thermal arc plasma

Averaging over laser beam cross section
(Experimental results: spatially resolved results)

TS spectra (electron terms) across the laser beam





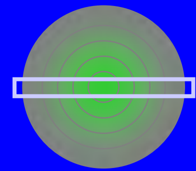
$$I(\lambda, y_1) = \int I(\lambda, y_1, x)\, dx$$

Abel transformation

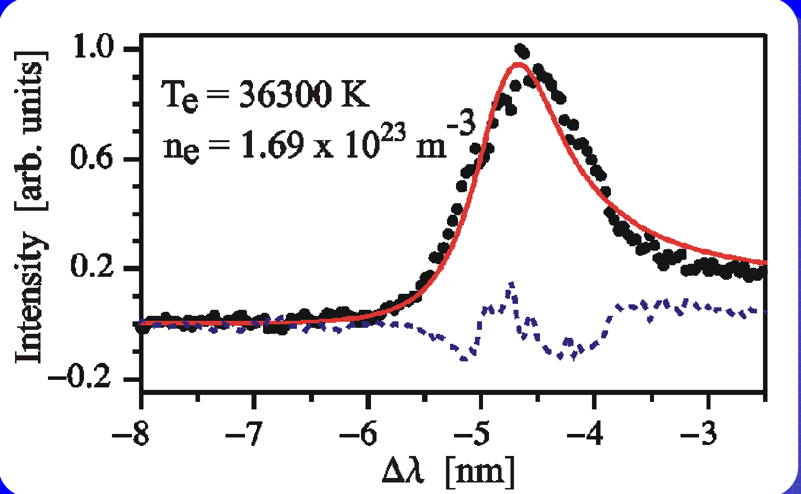
$$I(\lambda, r) = \int_r^R \frac{dI(\lambda, y)/dy}{\sqrt{y^2 - r^2}}\, dy$$

Thomson scattering in thermal arc plasma

Averaging over laser beam cross section
(Experimental results: spatially resolved results)

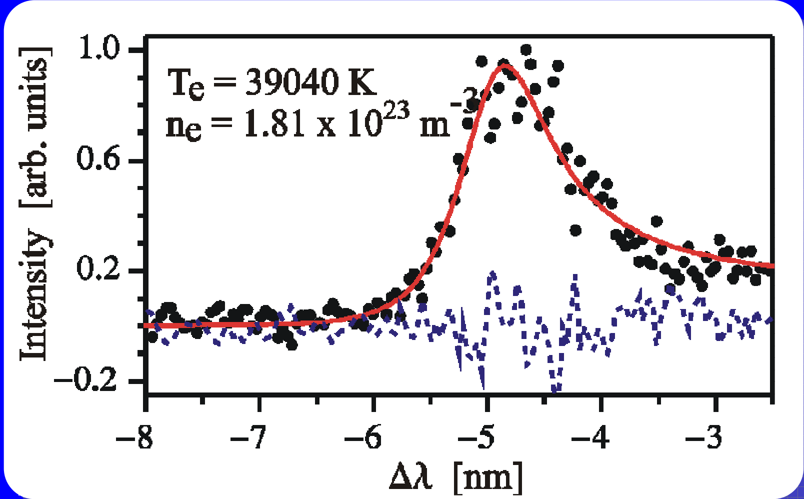


Before Abel transformation
TS @ y=0



systematic errors dominate

After Abel transformation
TS @ r=0

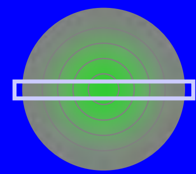


statistical errors dominate

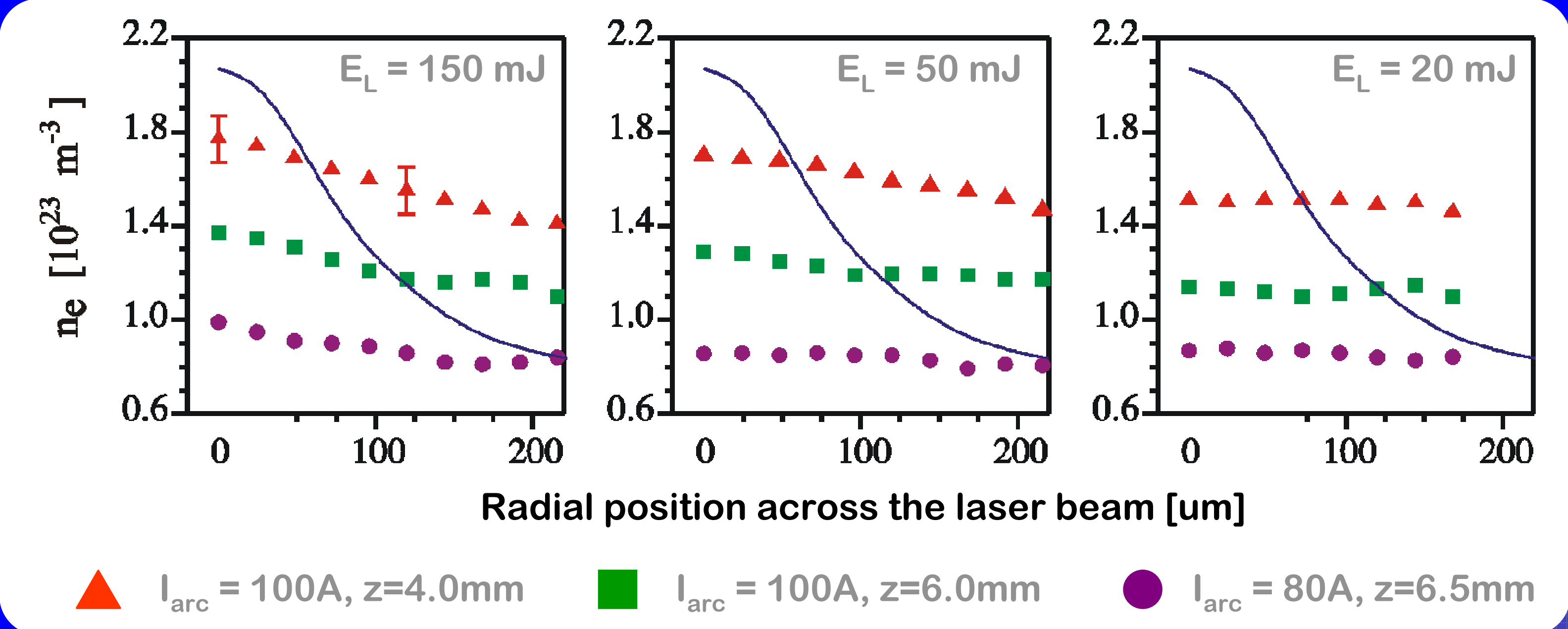
Thomson scattering in thermal arc plasma

Averaging over laser beam cross section

(Experimental results: spatially resolved results)



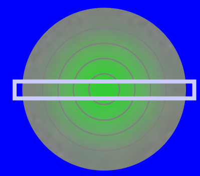
Local values (across the laser beam) of n_e



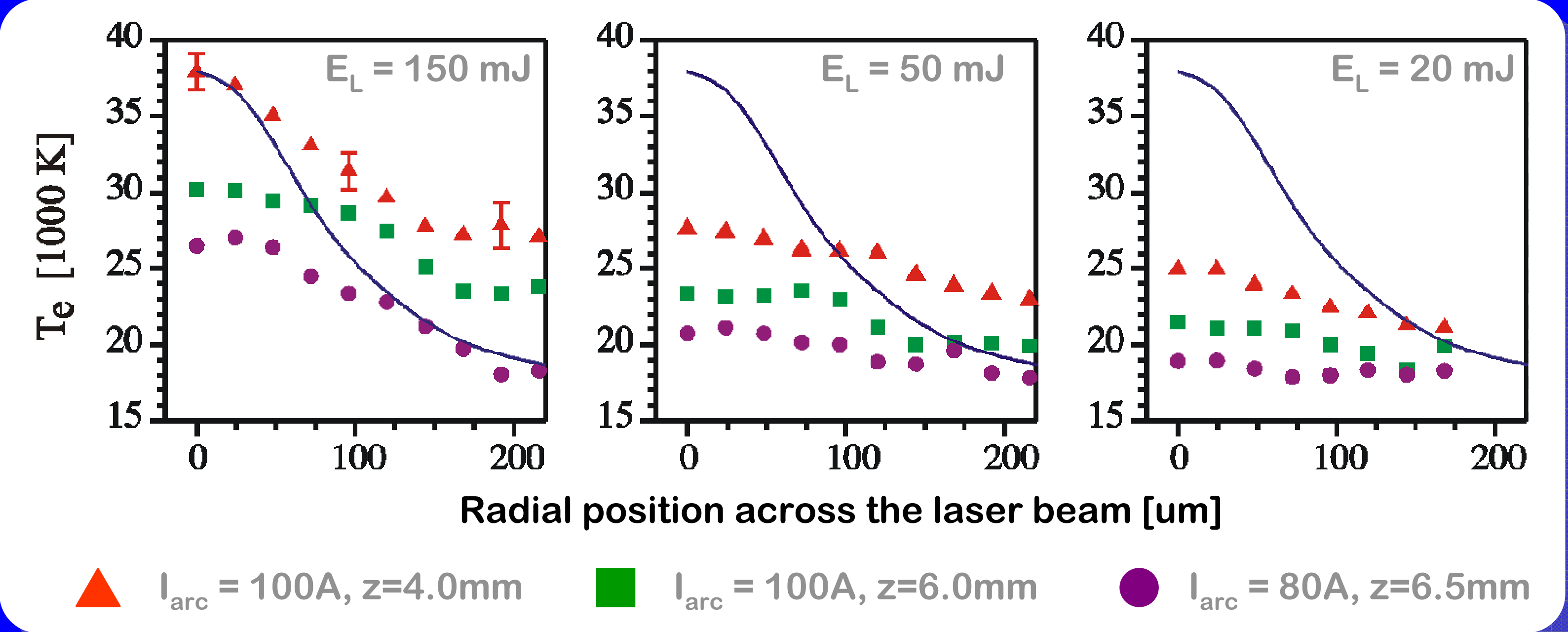
No variations of n_e at lower laser energies
and at the edges of the laser beam

Thomson scattering in thermal arc plasma

Averaging over laser beam cross section
(Experimental results: spatially resolved results)



Local values (across the laser beam) of T_e

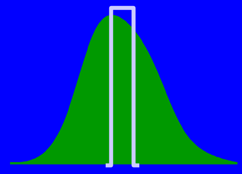


Increase of T_e depends on laser power and initial plasma conditions, i.e. the electron number density and temperature

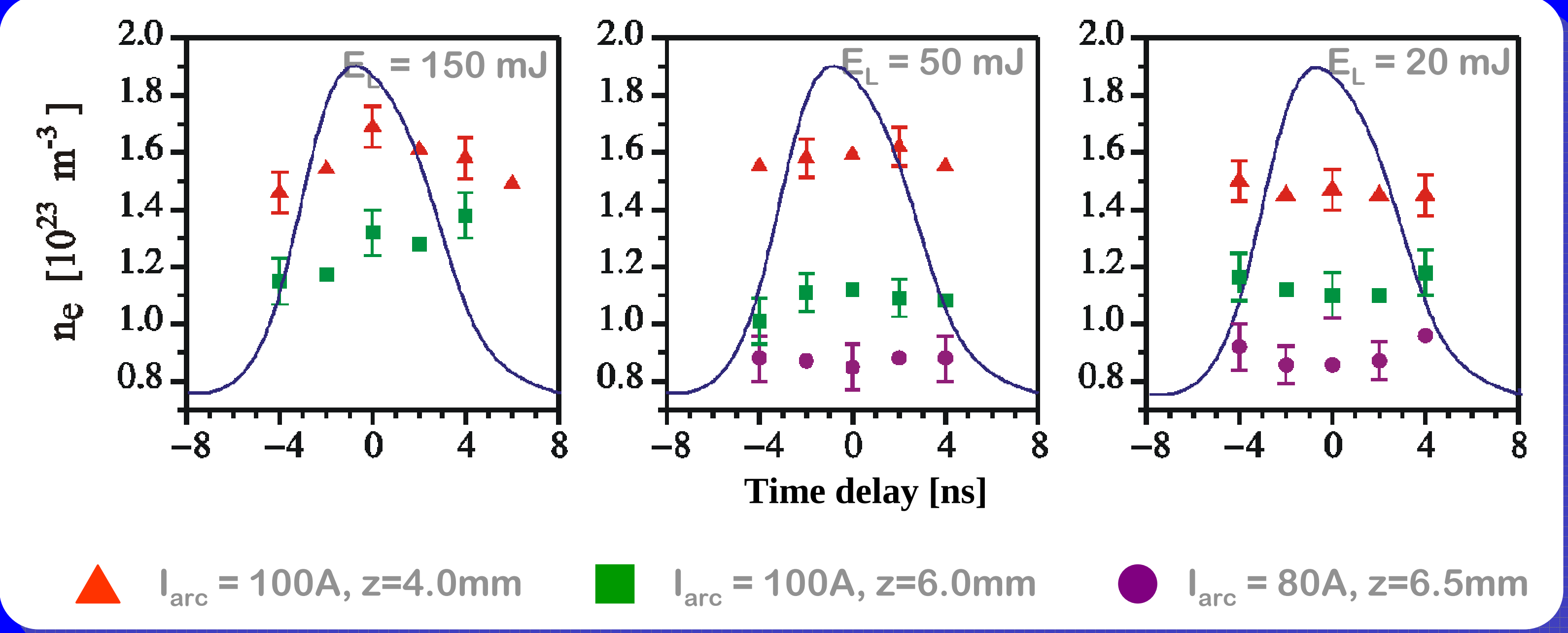
Thomson scattering in thermal arc plasma

Averaging over laser beam cross section

(Experimental results: <u>temporally resolved results</u>)

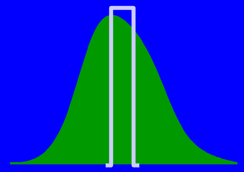


Temporal evolution of n_e during the laser pulse

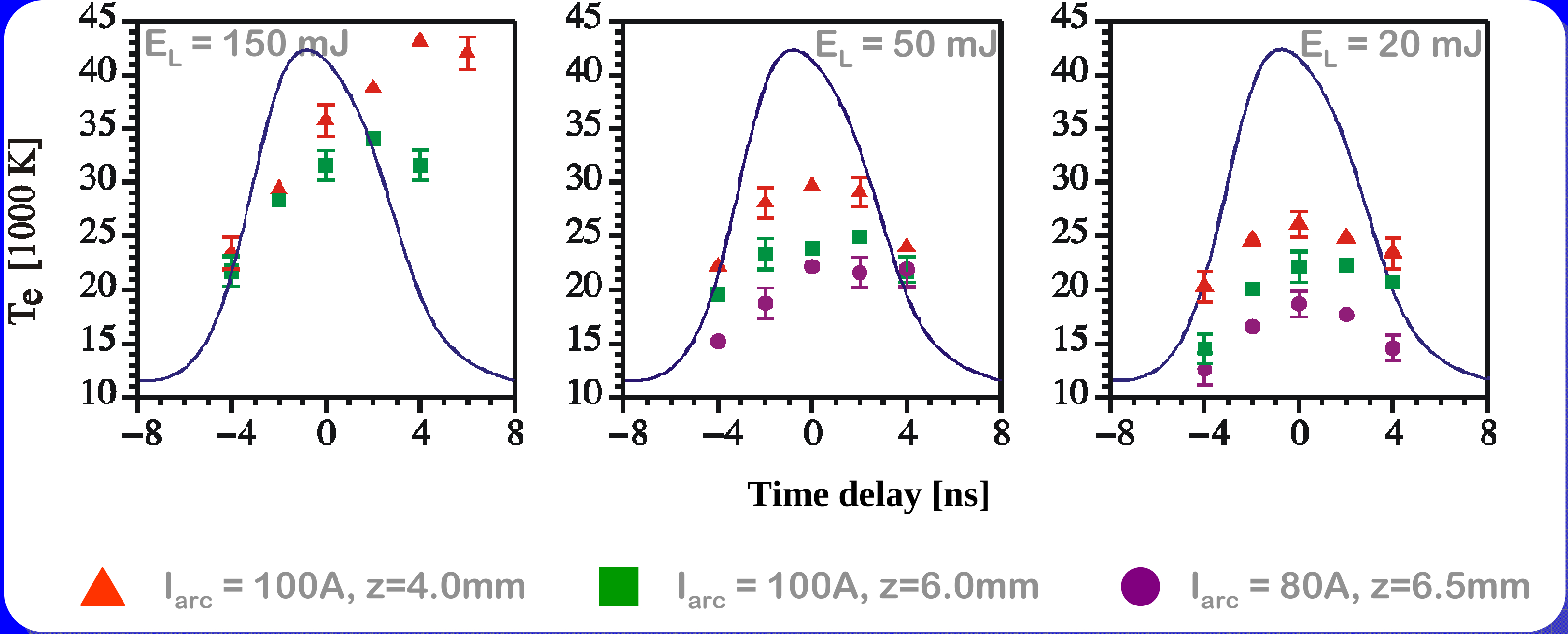


Thomson scattering in thermal arc plasma

↳ **Averaging over laser beam cross section**
(Experimental results: temporally resolved results)

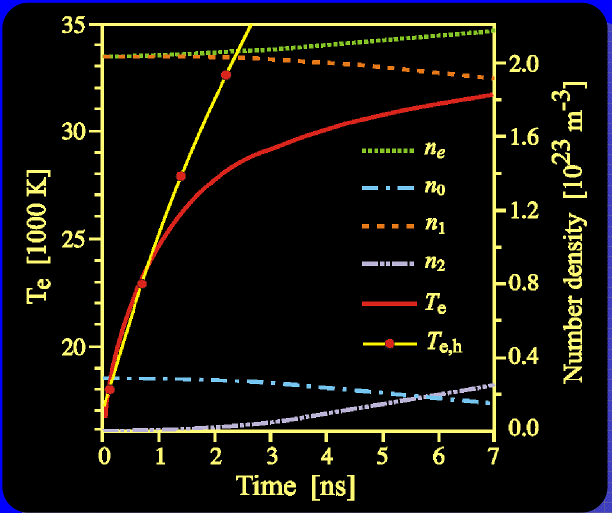


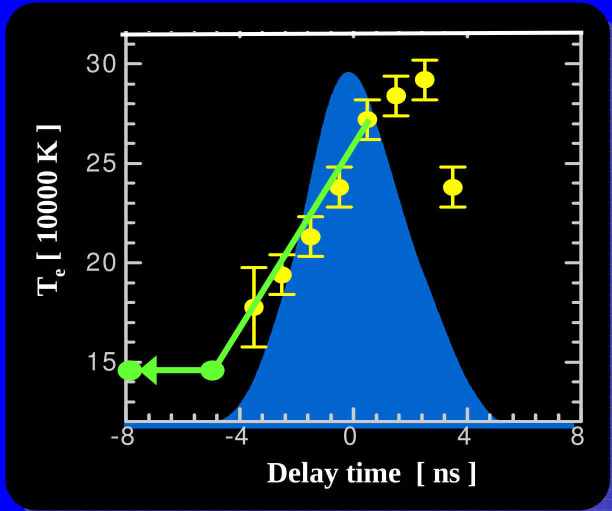
Temporal evolution of T_e during the laser pulse

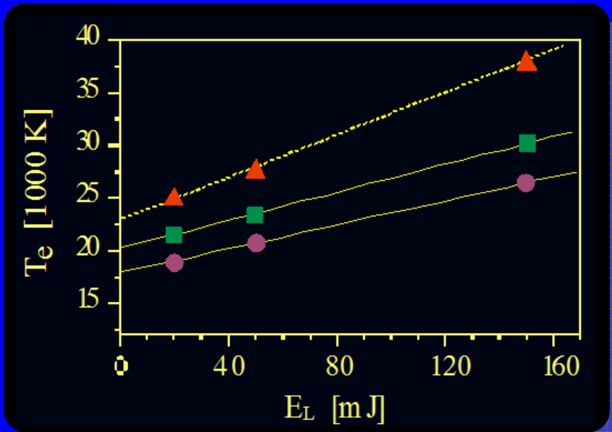


Thomson scattering in thermal arc plasma

Determination of initial T_e



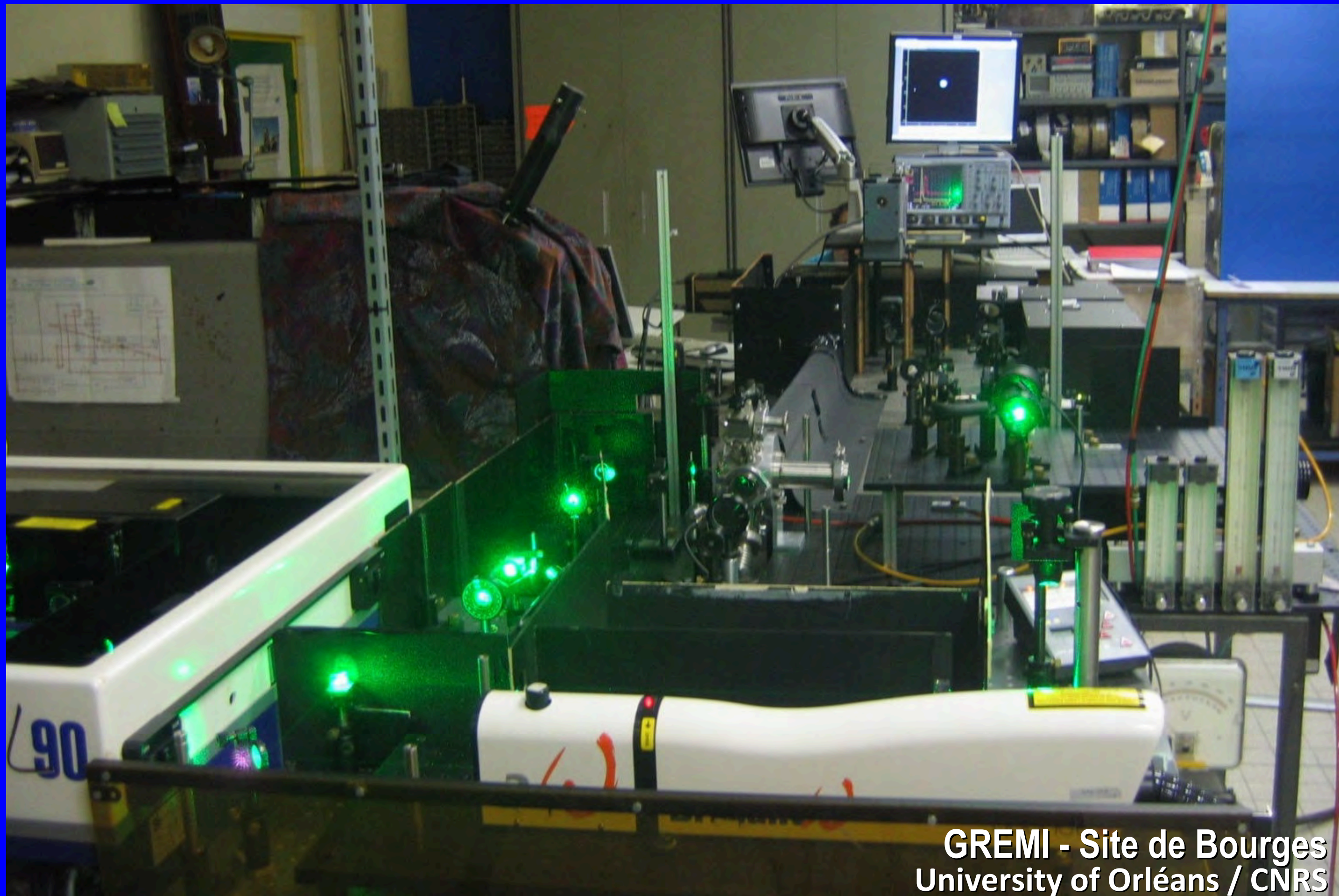




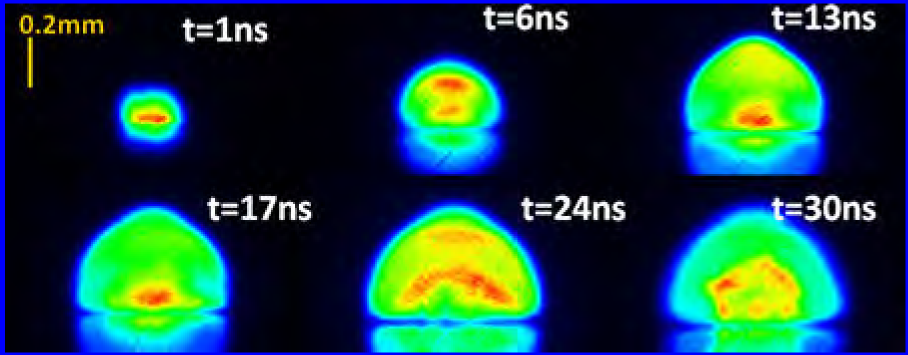
N_e [10^{23} m^{-3}]	T_e [LTE]	T_e [lin.extr.]	T_e [origin]
▲ 1.46	13900	22780	14000
■ 1.14	13050	20090	12200
● 0.89	12500	17760	10000

Measurement of the temporal evolution of T_e
and then extrapolation to the origin of the pulse
is more adequate method than extrapolation to the zero laser energy

Thomson scattering in laser induced plasma

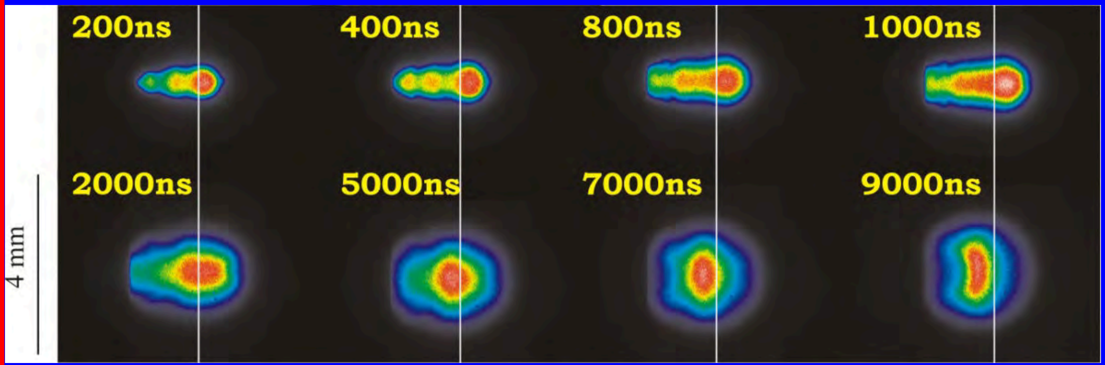


Laser induced plasmas: two main types

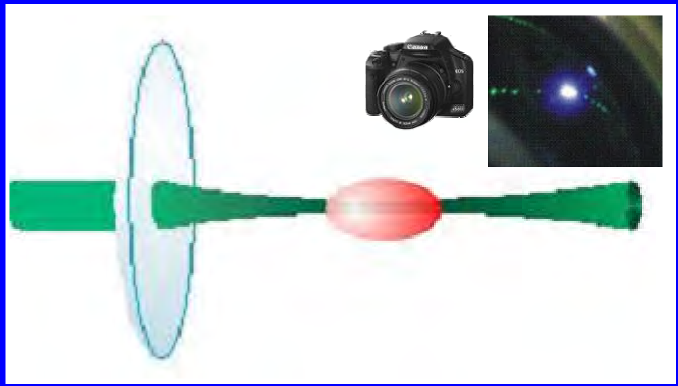


A. Mendys et al. / Spectrochimica Acta Part B 96 (2014) 61–68

Solid target (ablation)
Application: film deposition, analysis…



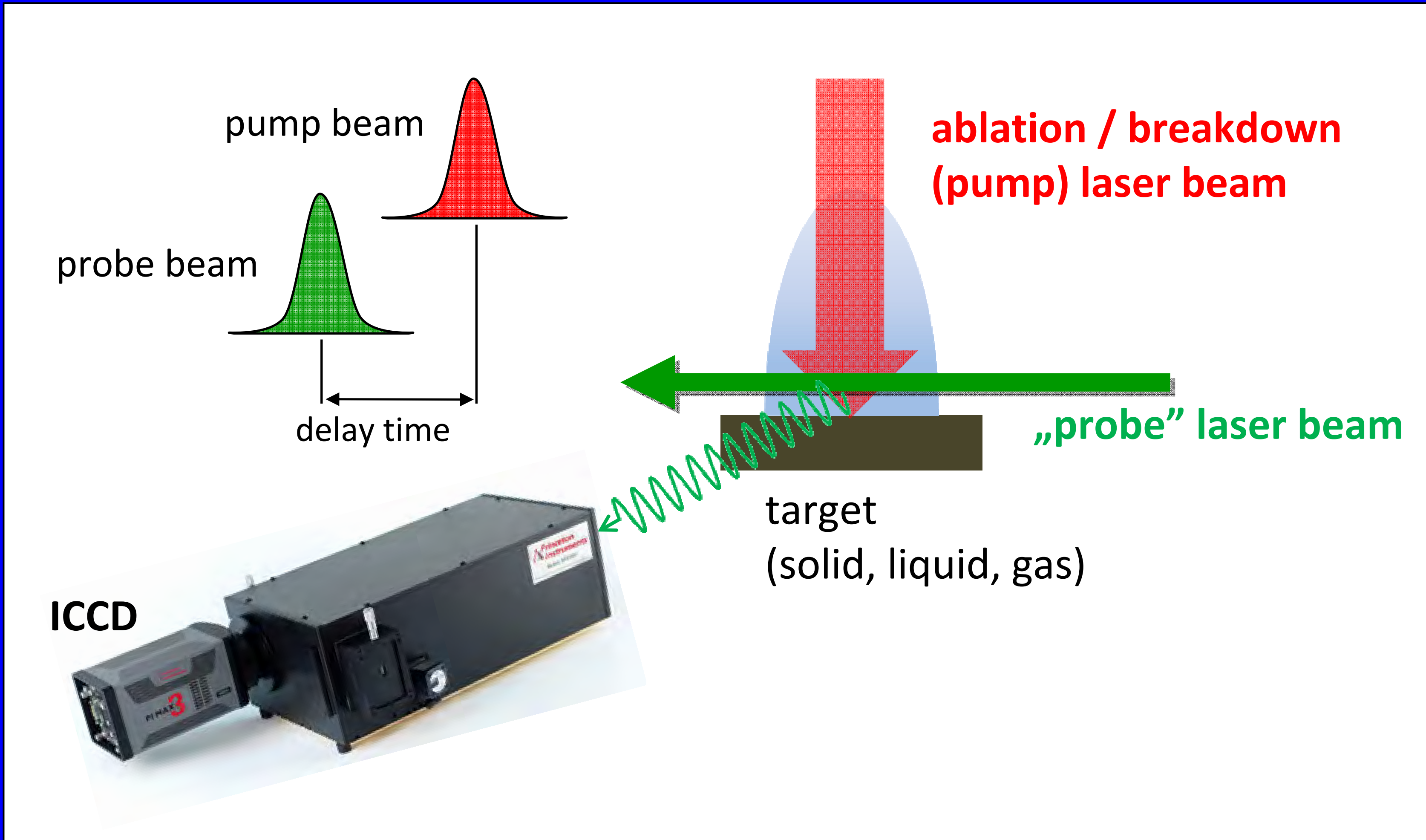
A. Mendys, at al., Spectrochim. Acta B (2011) ***66****, 691*



Gaseous target (breakdown)
Application: plasma igniters…

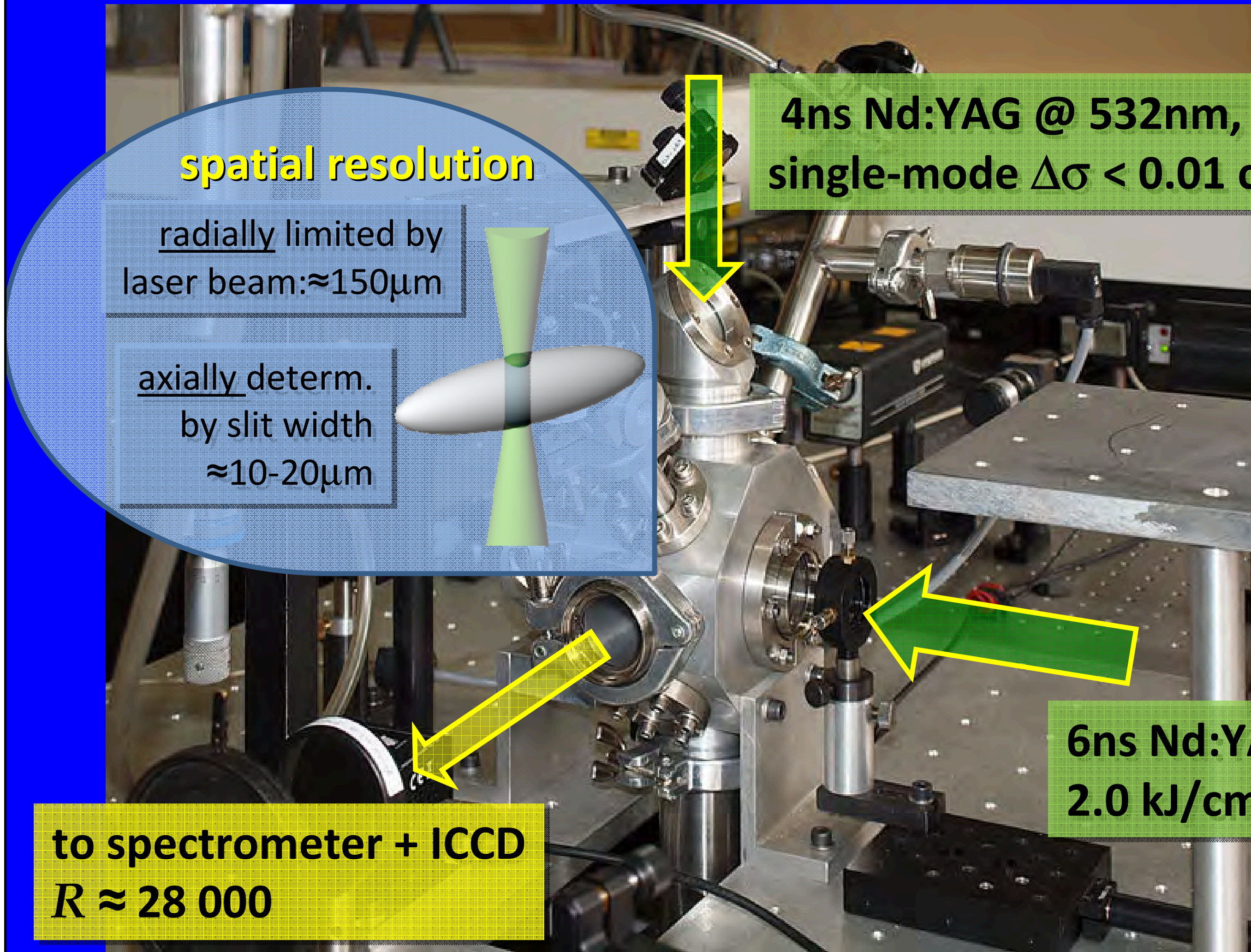
Laser induced plasmas

↳ „Pump – probe" experiments



Laser induced sparks in gases

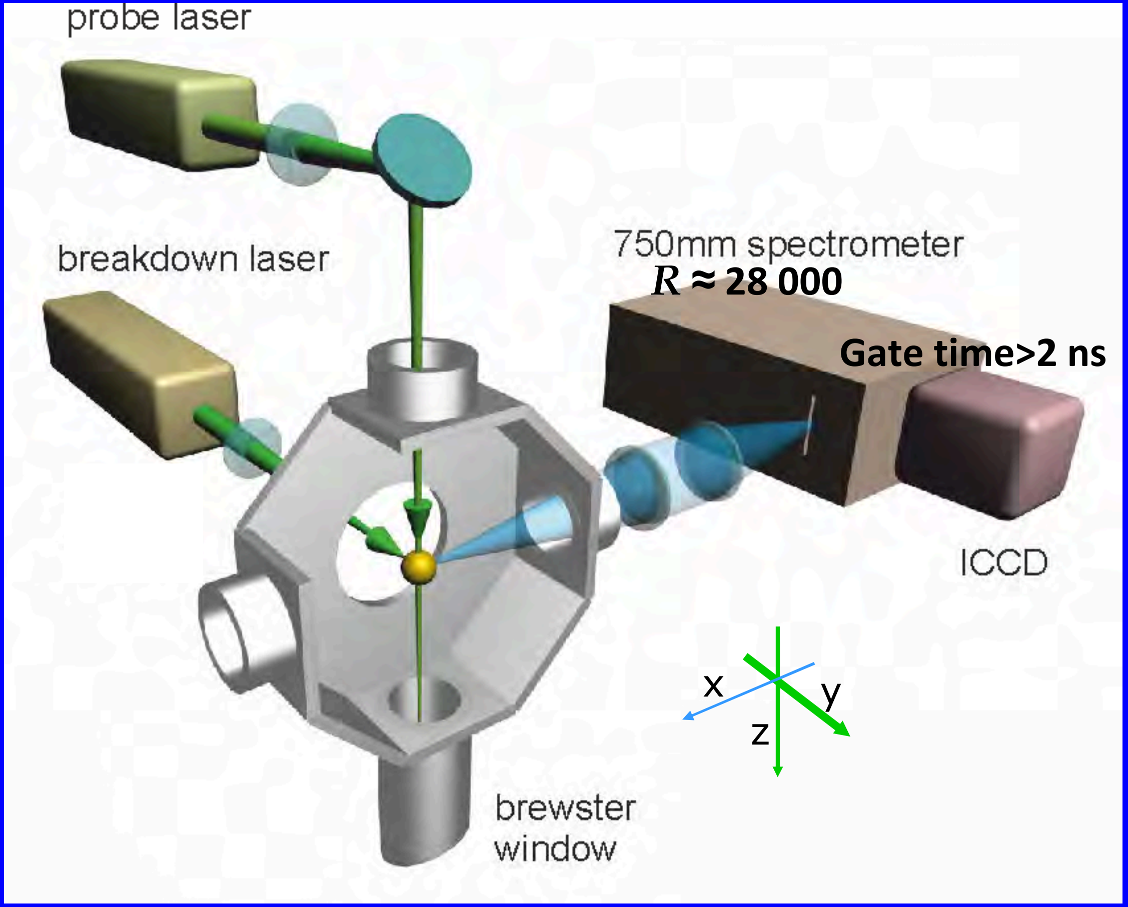
Experimental setup to study laser induced spark created and probed by ns Nd:YAG lasers



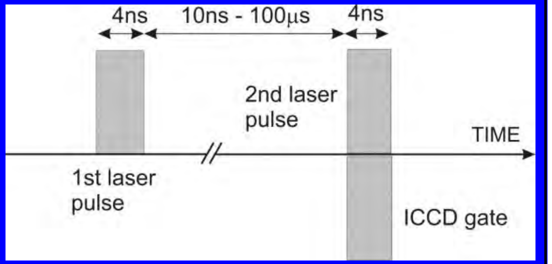
Laser induced sparks in gases

↳ **Experimental setup** to study laser induced spark created and probed by ns Nd:YAG lasers

Breakdown laser Nd:YAG @ 532nm, 2.0 kJ/cm², $\Delta\tau = 6$ns, single-mode $\Delta\sigma < 1.0$ cm^{-1}
Probe laser Nd:YAG @ 532nm, up to 40 J/cm², $\Delta\tau = 4$ns, single-mode $\Delta\sigma < 0.01$ cm^{-1}



ICCD:
delay → 5ns – 100µs
gate → 2ns – 500ns



Laser induced sparks in gases

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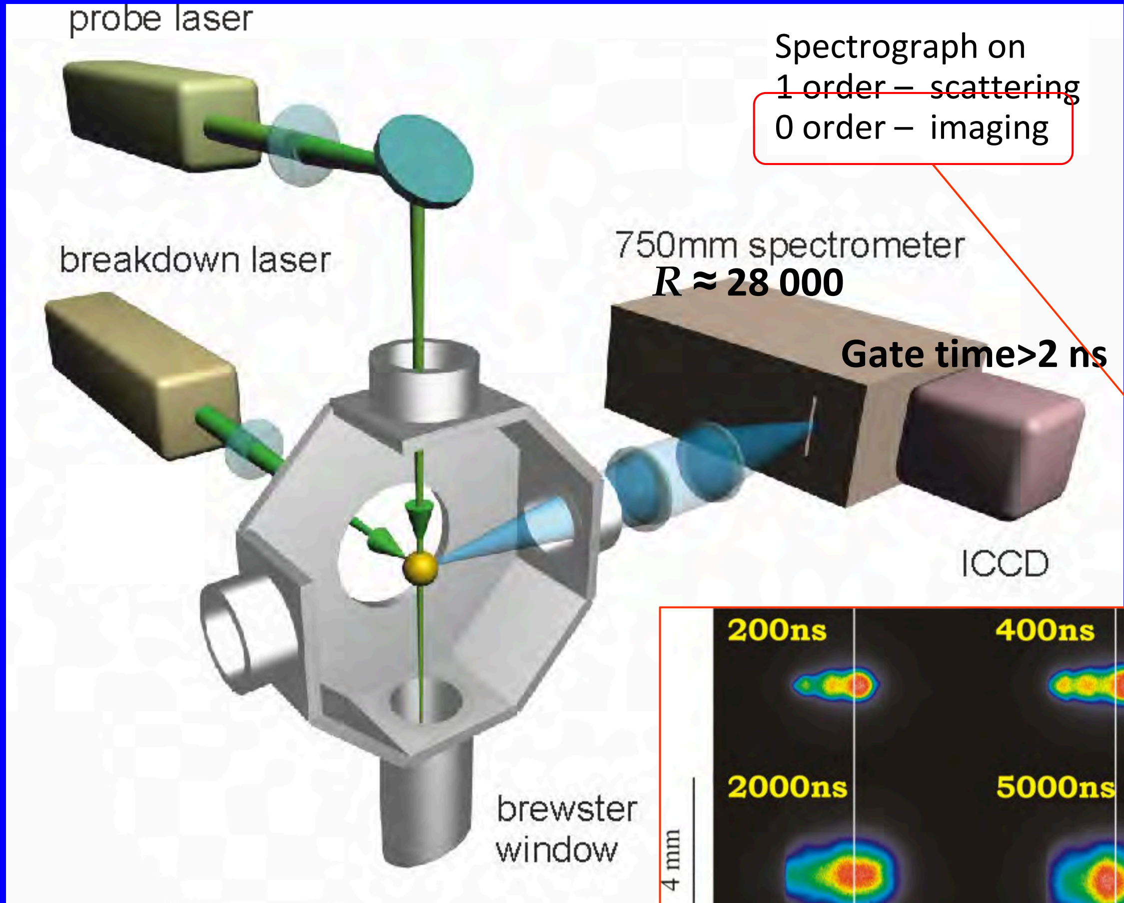
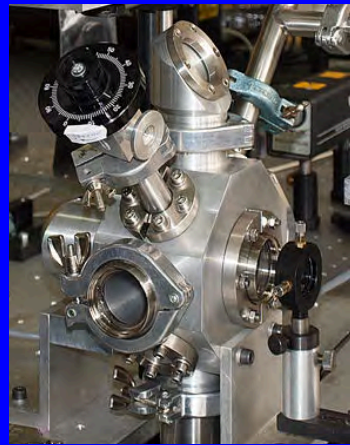
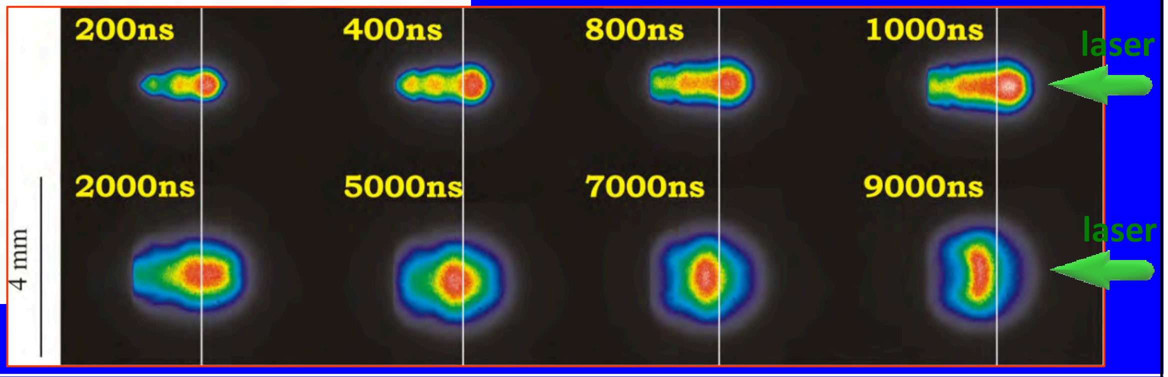
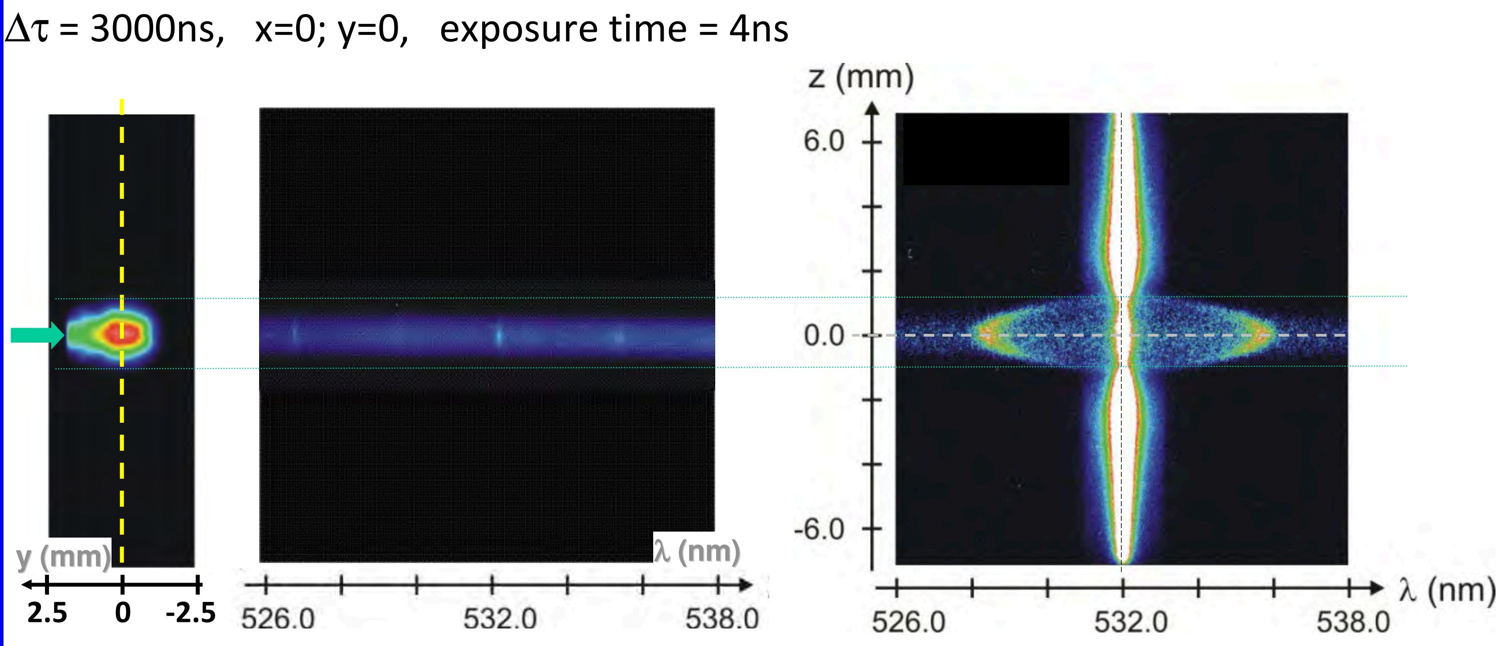


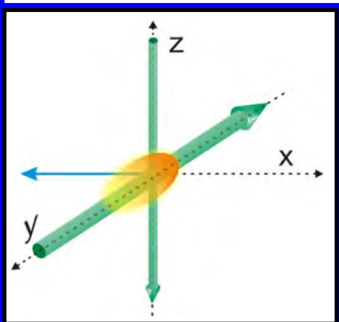




Laser scattering from laser spark in Ar at P_{atm}

plasma image plasma emission scattered probe laser light



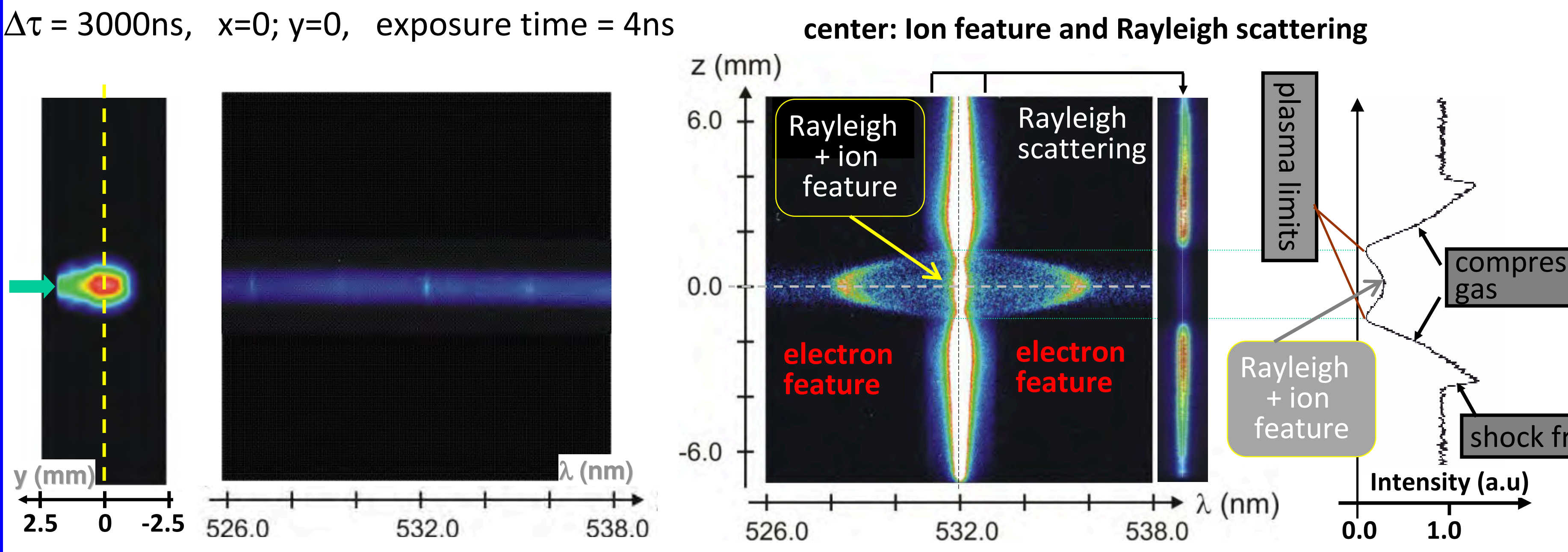


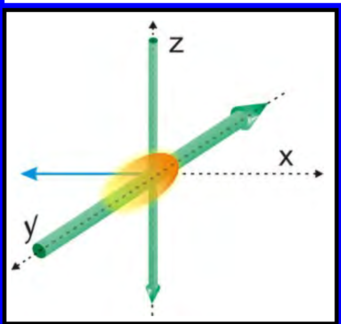
Pump fluence – 2kJ/cm²

Probe fluence – 18 J/cm²

θ = 90°

Laser scattering from laser spark in Ar at P_{atm}

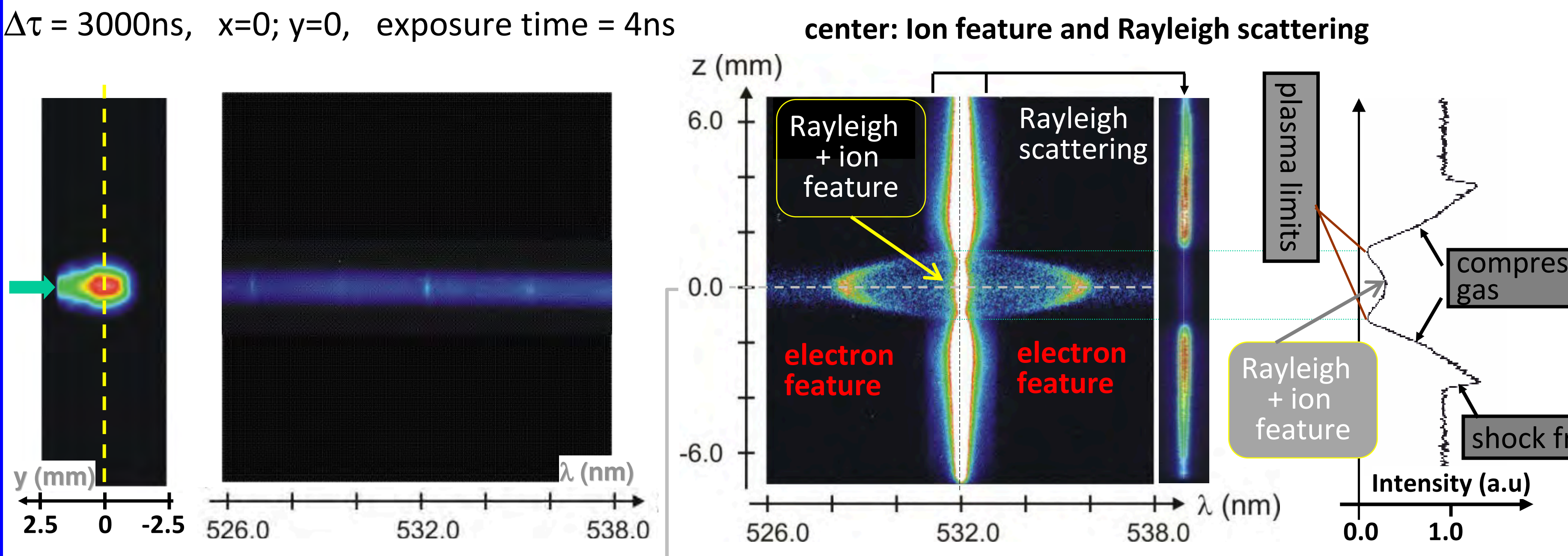


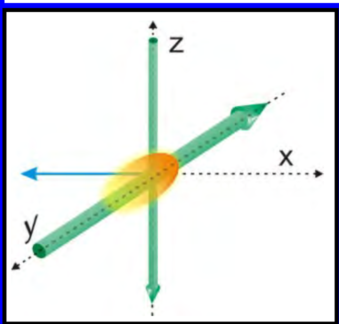


Pump fluence – 2kJ/cm²
Probe fluence – 18 J/cm²
ICCD gate – 10 ns

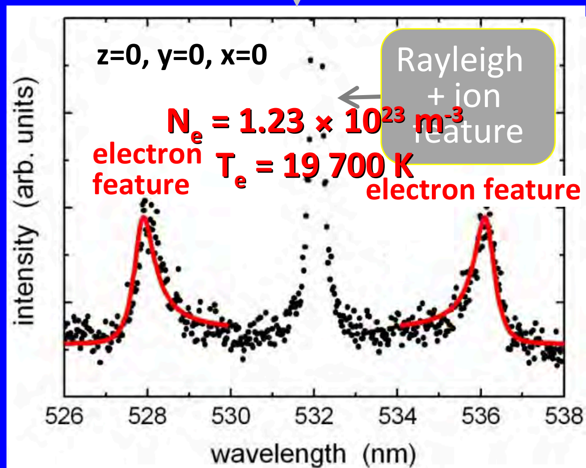
Laser scattering from laser spark in Ar at P_{atm}

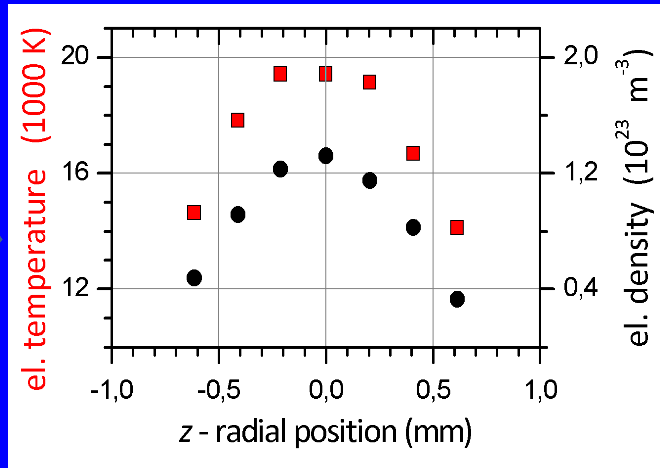
plasma image plasma emission scattered probe laser light





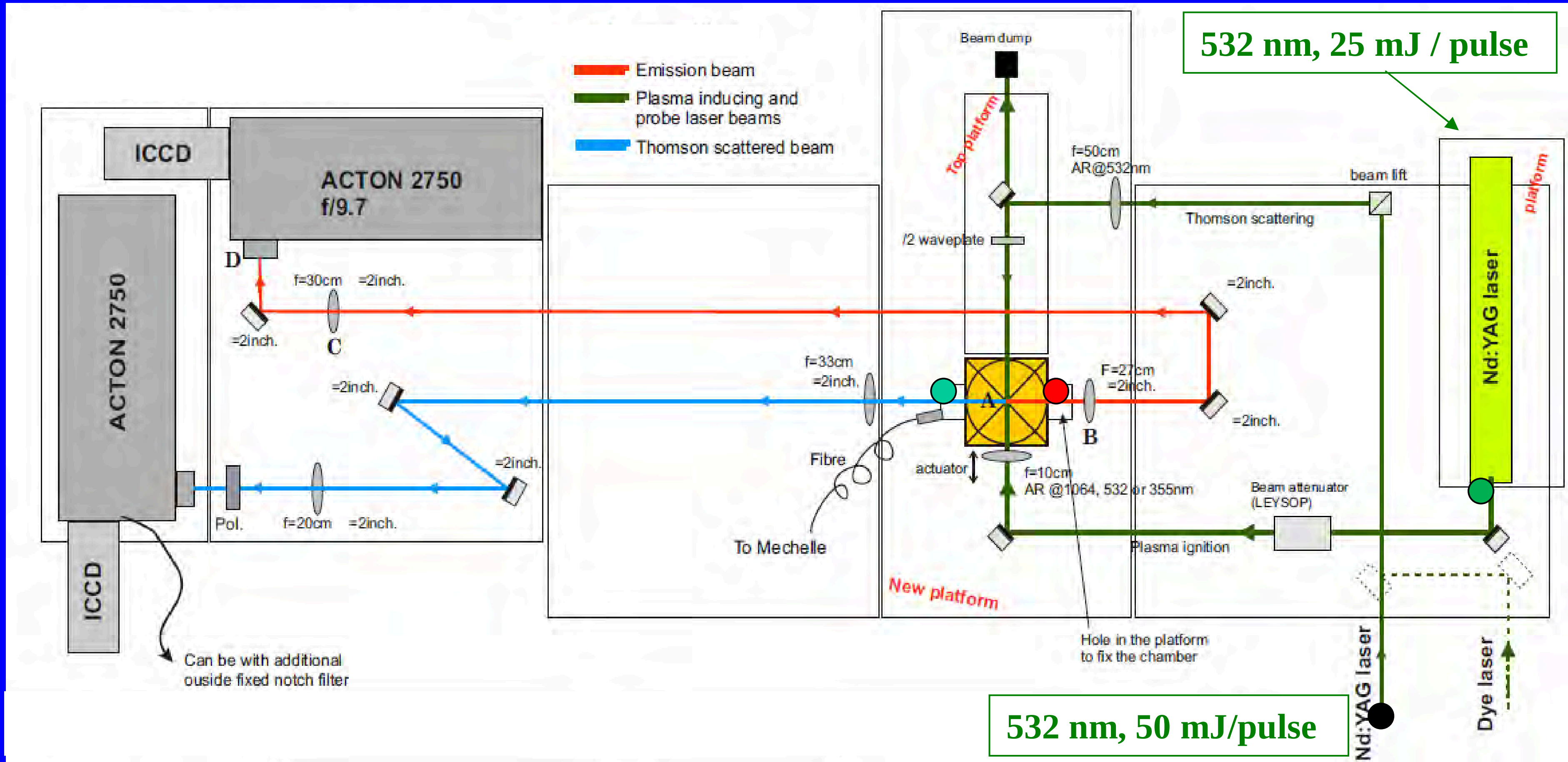
Pump fluence – 2kJ/cm²
Probe fluence – 18 J/cm²
ICCD gate – 10 ns





Laser scattering from laser spark in Ar at P_{atm}

↳ Comparison with OES

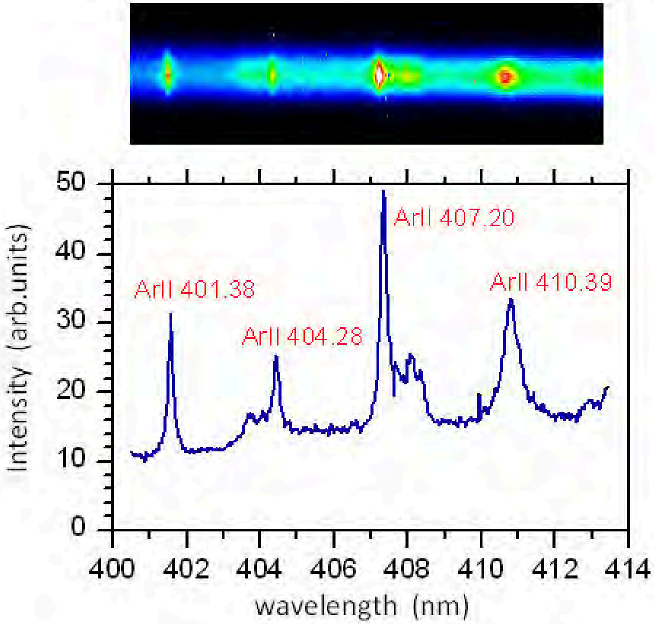


• Imaging of the plume • Optical Emission Spectroscopy (OES) • Thomson Scattering (TS)

Laser scattering from laser spark in Ar at P_{atm}

↳ Comparison with OES

emission from LIP in Argon
at 400ns after breakdown pulse

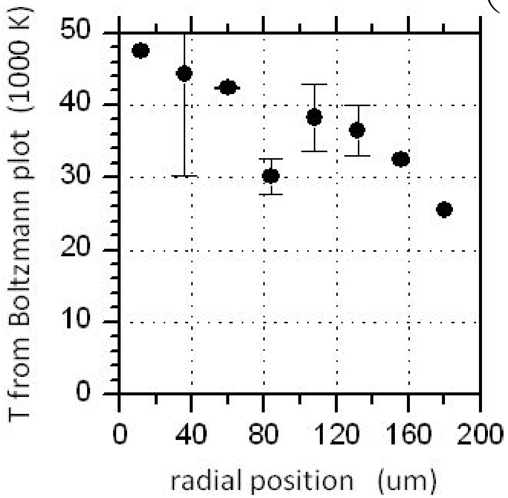


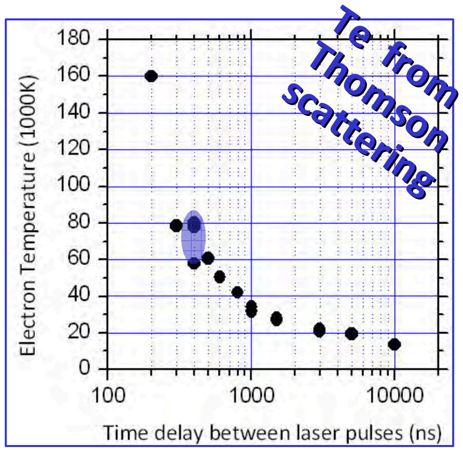
☞ **Boltzmann plot**

$$\varepsilon_{ij} = A_{ij}\frac{h\nu}{4\pi}n_i \quad \Rightarrow \quad I_{ij} \propto n_i$$ ***if plasma optically thin***

$$n_i = n\frac{g_i}{Q(T)}\exp(-E_i / k_B T)$$ ***if excitation equilibrium***

$$\Rightarrow Y = \ln\left(\frac{\lambda_{ij} I_{ij}}{A_{ij} g_i}\right) = -E_i / k_B T + C$$





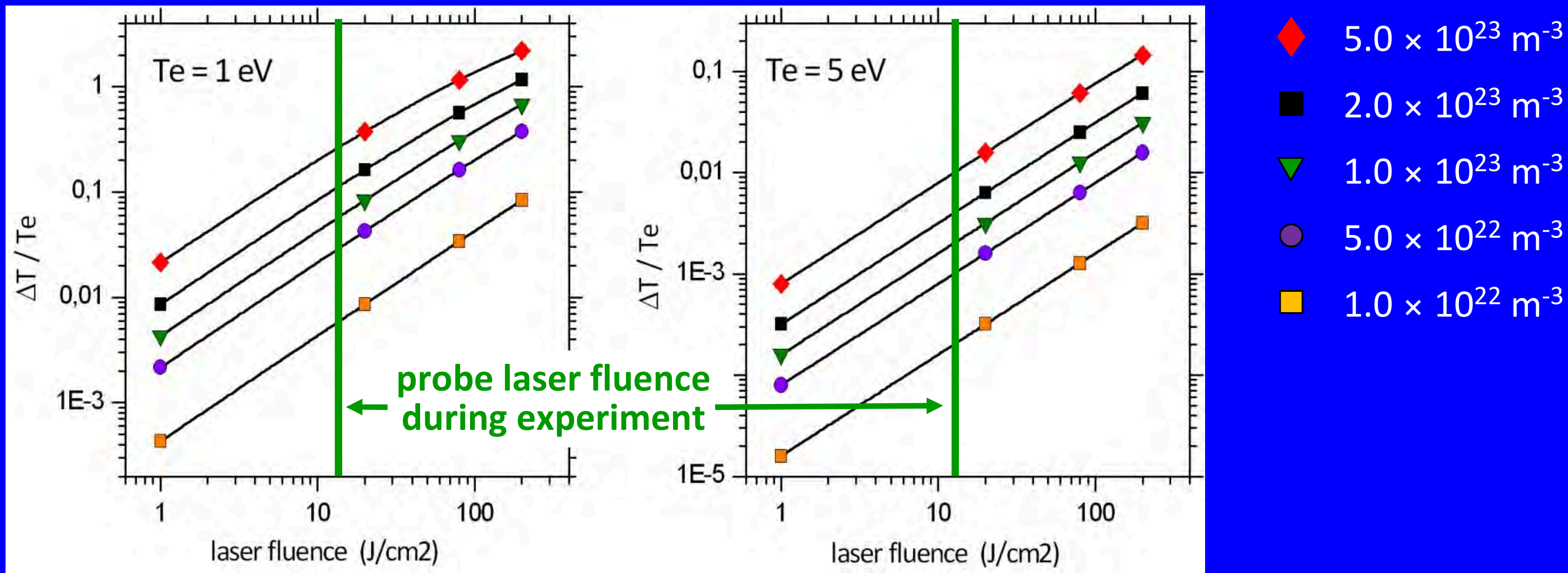
! Excitation temperature defined under assumptions of LTE plasma !

Laser scattering from laser spark in Ar at P_{atm}

➥ Electron temperature perturbation

due to electron heating by the probe pulse in the process of inverse bremsstrahlung ?

LIBS = thermal plasmas: low Te and high Ne ⇨ very susceptible to el. heating

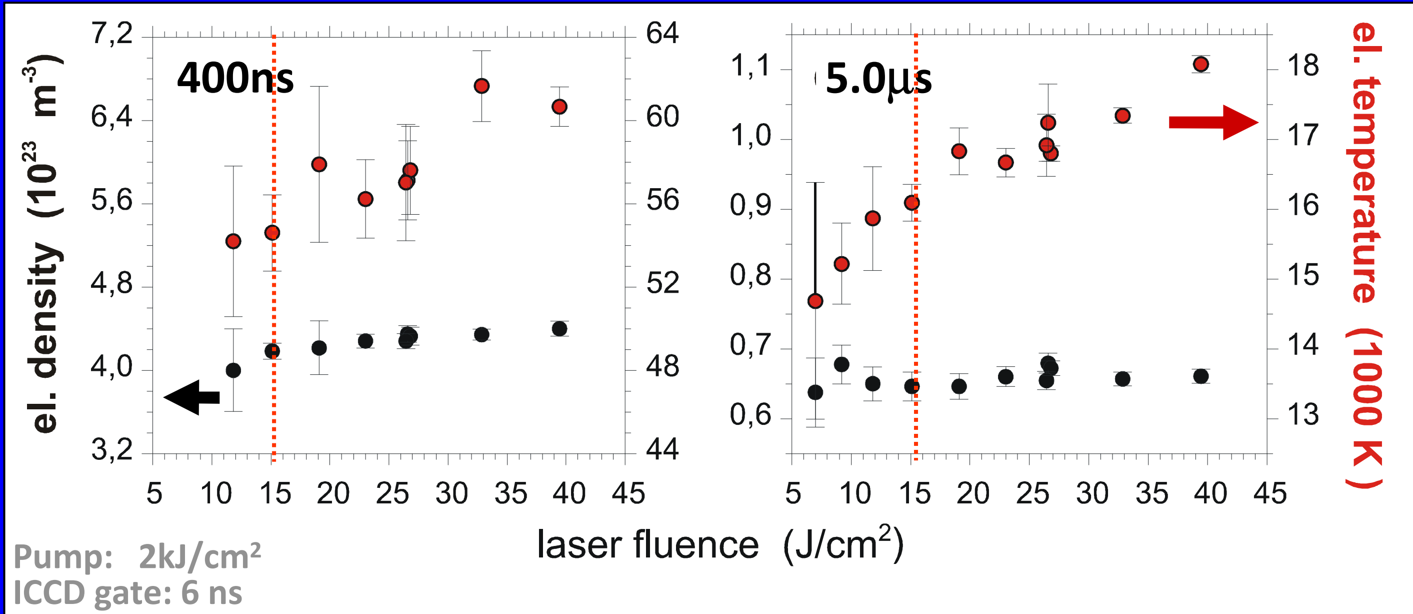


Heating LIP plasma by probe laser strongly depends on its initial conditions

Laser scattering from laser spark in Ar at P_{atm}

↳ Electron temperature perturbation:
Influence on probe laser fluence on T_e

LIP in argon at 1atm

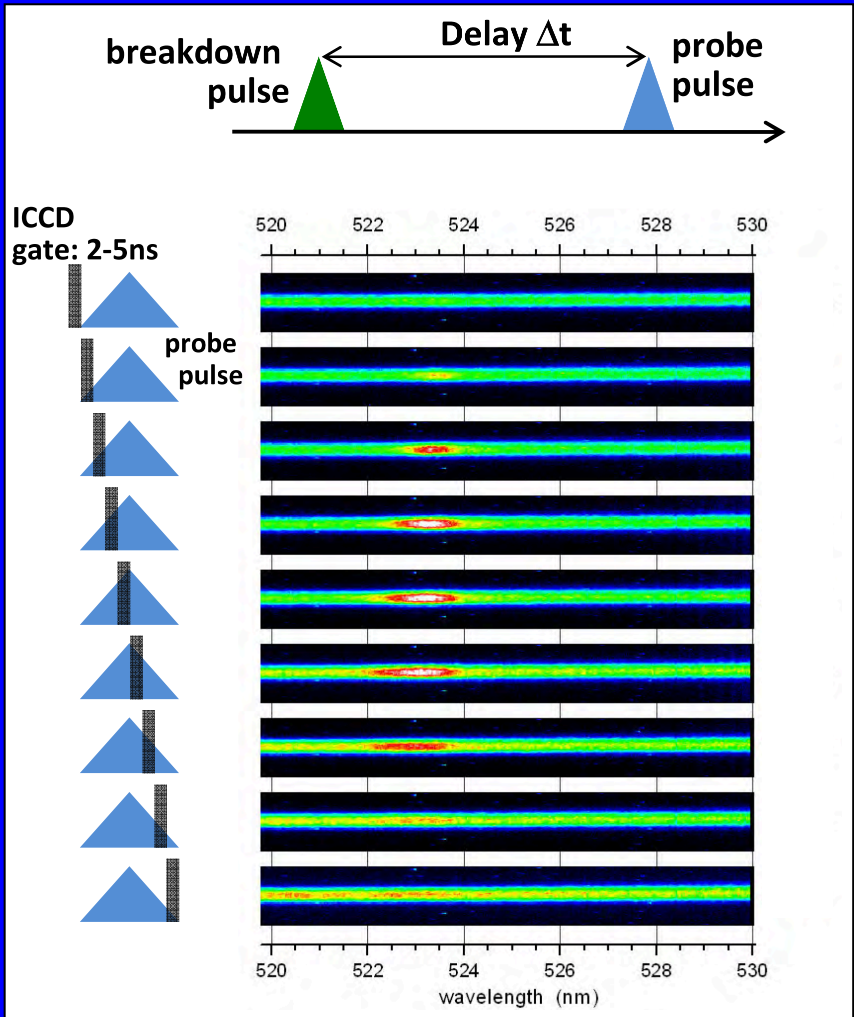


- Below some value of laser fluence no significant change of T_e is observed but only **uncertainties are rapidly growing**
- For high values of laser fluence, **Electron temperature can be significantly elevated by the probe laser pulse**

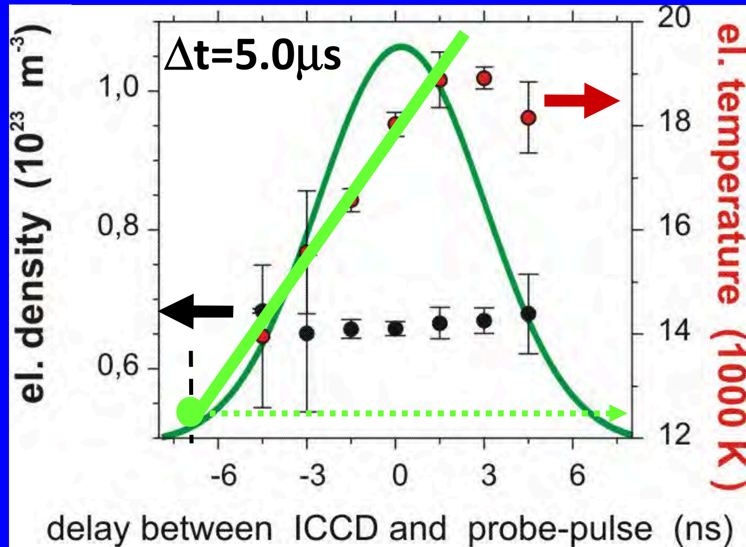
A. Mendys, at al., Spectrochim. Acta B (2011) 66, 691; doi:10.1016/j.sab.2011.08.002

Laser scattering from laser spark in Ar at P_{atm}

↳ Electron temperature perturbation:
T_e evolution during the probe laser pulse



Probe laser fluence: 50J/cm², ICCD gate width: 3ns

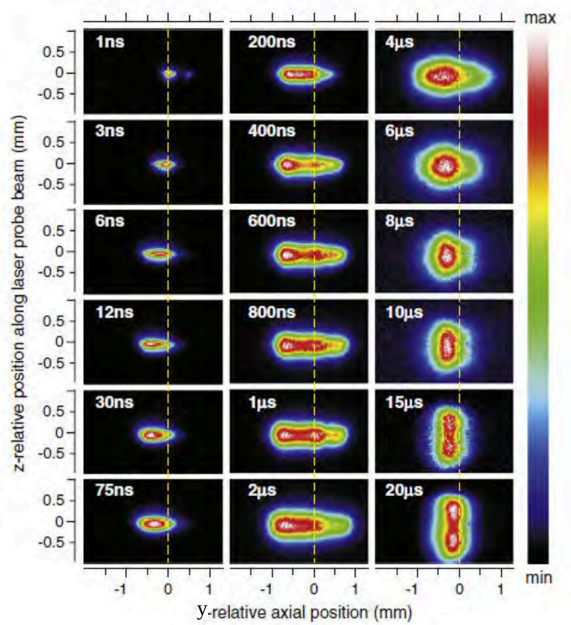


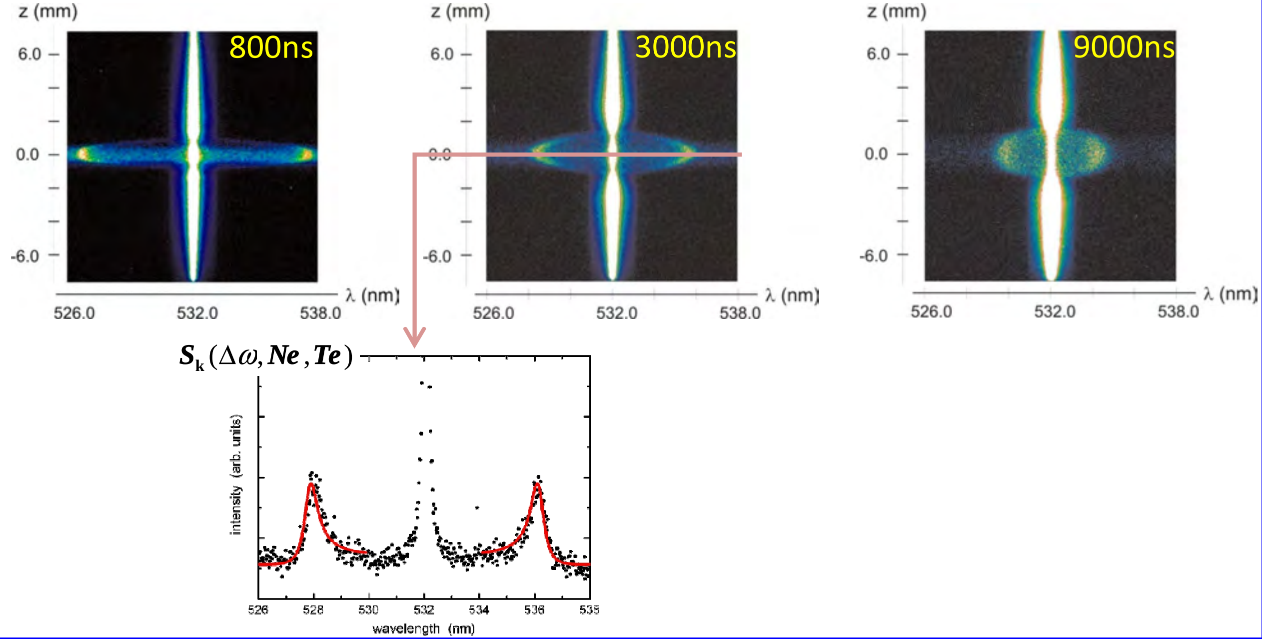
Unlike N_e, T_e is significantly disturbed as the result of much shorter time scale of inverse bremsstrahlung process

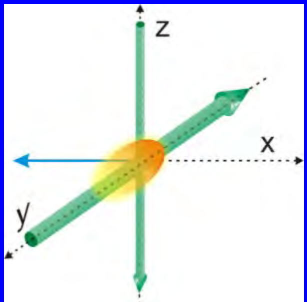
A. Mendys, at al., Spectrochim. Acta B (2011) **66**, 691; doi:10.1016/j.sab.2011.08.002

Laser scattering from laser spark in Ar at P_{atm}

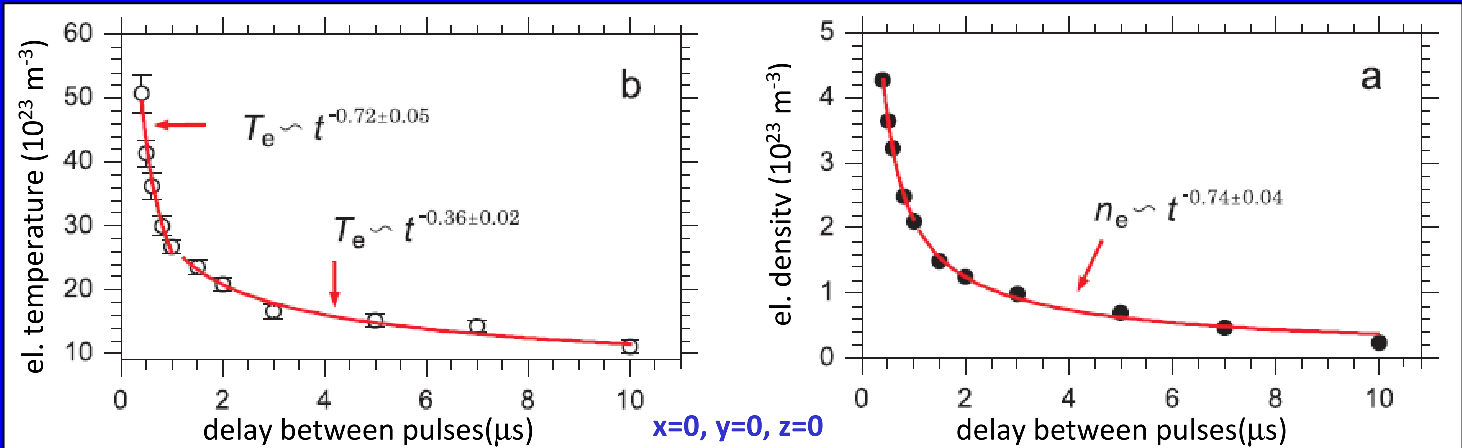
N_e and T_e evolution on axis of LIP generated in argon by 6ns pulse of 2kJ/cm² fluence







Pump : 2kJ/cm²
Probe : 16J/cm²
ICCD gate – 6 ns

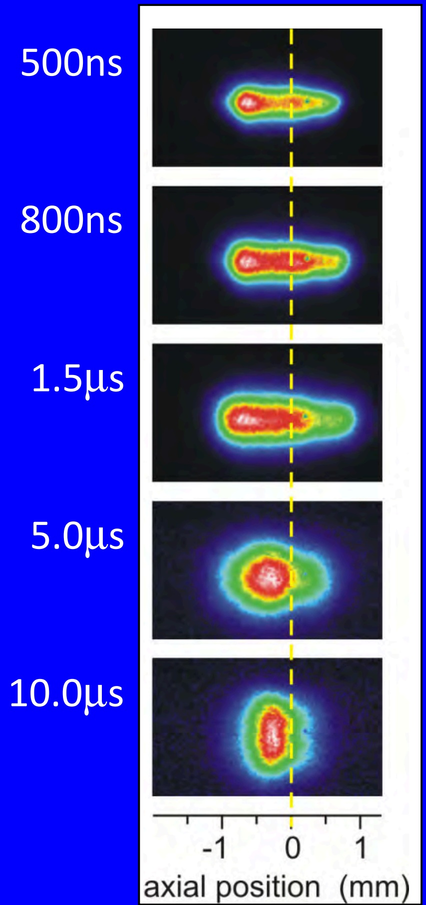


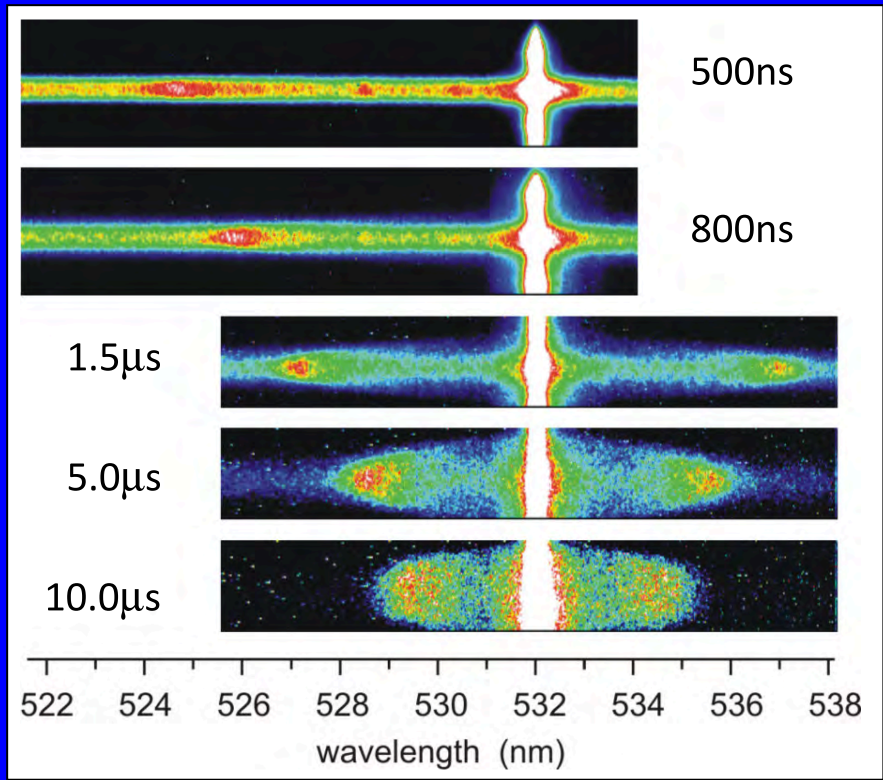
*A. Mendys, at al., Spectrochim. Acta B (2011) **66**, 691; doi:10.1016/j.sab.2011.08.002*

Laser scattering from laser spark in Ar at P_{atm}

N_e and T_e evolution on axis of LIP generated in argon by 6ns pulse of 2kJ/cm² fluence

↳ **Electron feature of TS diminishes at short delays**
due to high continuum plasma radiation

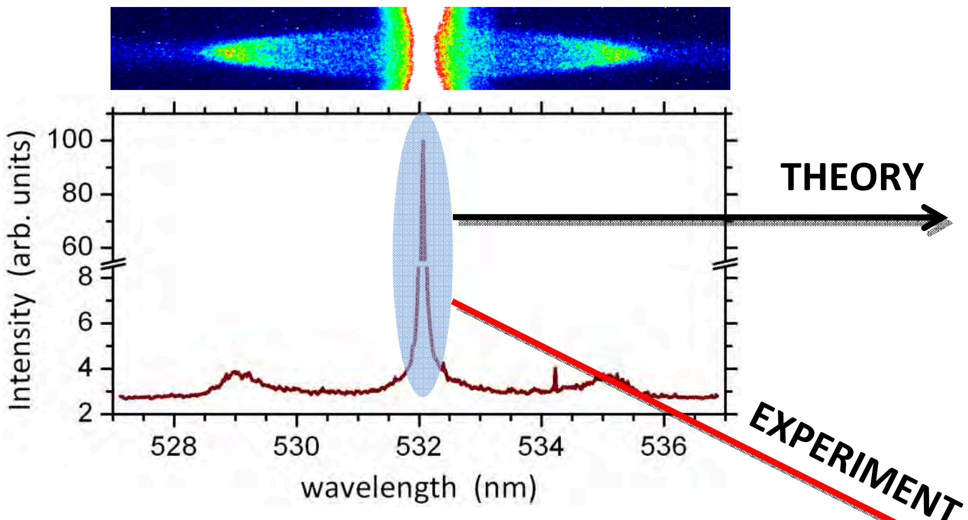


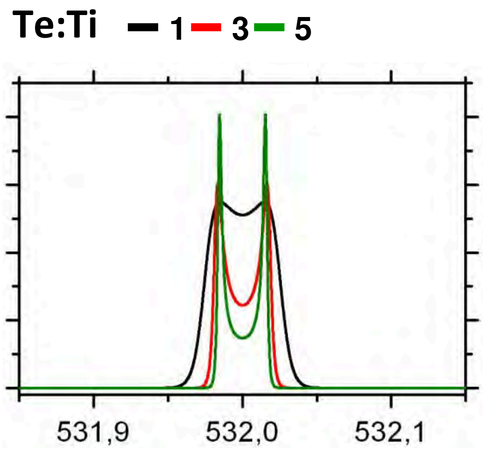


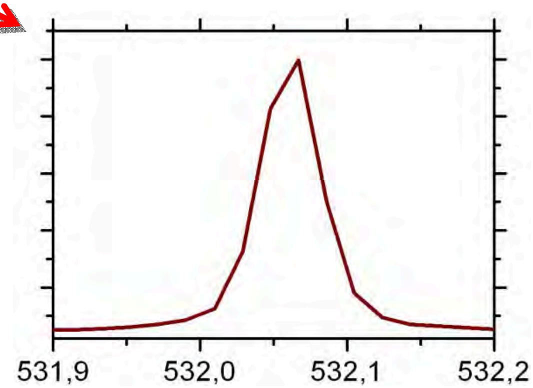
High continuum radiation of plasma significantly reduces S/N of electron feature of TS signal, only ion feature can be considered

Ion feature of TS spectrum: Determination of the ion temp.

↳ **indispensable to verify the thermodynamic equilibrium of LIP**





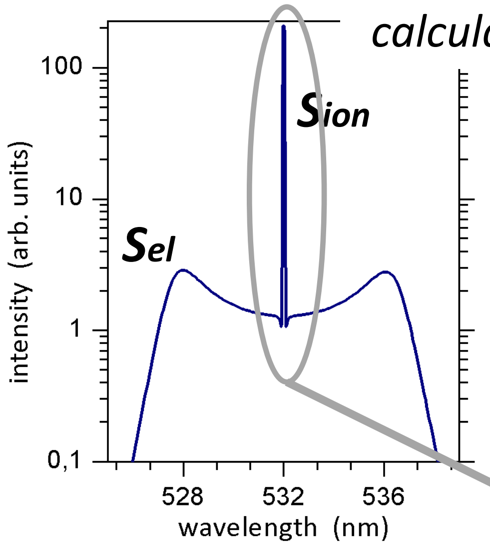


- *Ionic feature of TS spectrum contains information about T_e:T_i which is a direct measure of plasma departure from LTE*
- *The measurements need relatively high spectral resolution, better than 0.1cm^{-1} .*
  Pulsed ns laser with narrow linewidth and spectrometer of spectral resolution higher than 100 000 are indispensable

Ion feature of TS spectrum: Determination of the ion temp.

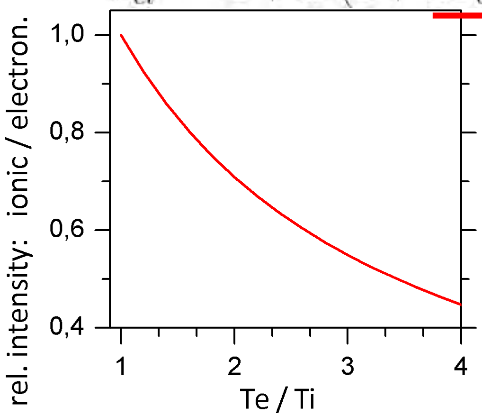
↳ **indispensable to verify the thermodynamic equilibrium of LIP**

calculations for LIP in He, α*=1.51,* N_e=1.04 × 10^23^ m^-3^, T_e*=34300 K*



- from the intensity ratio of the ion to electron part

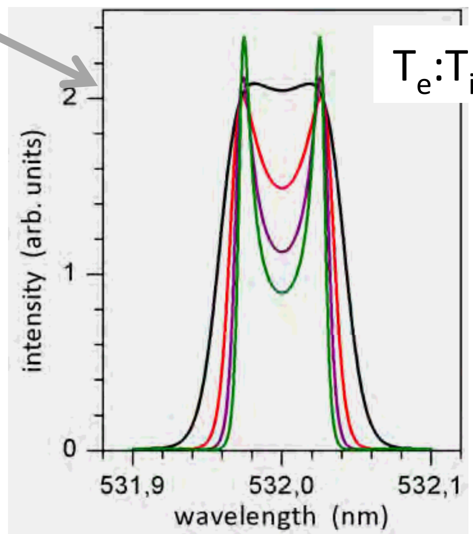
$$\frac{S_{ion}}{S_{el}} = \frac{Z\alpha^4}{1+\alpha^2(1+ZT_e/T_i)}$$

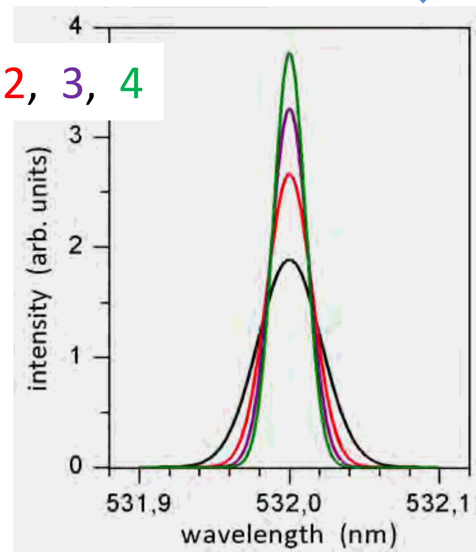


- from the spectral profile of the TS ionic feature

- … or from the Doppler profile of the **Rayleigh scattered light**

T_e:T_i = 1, 2, 3, 4

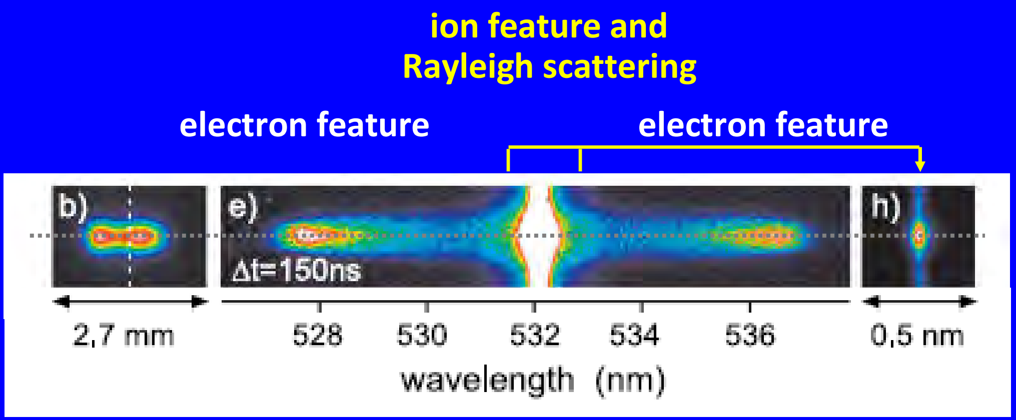


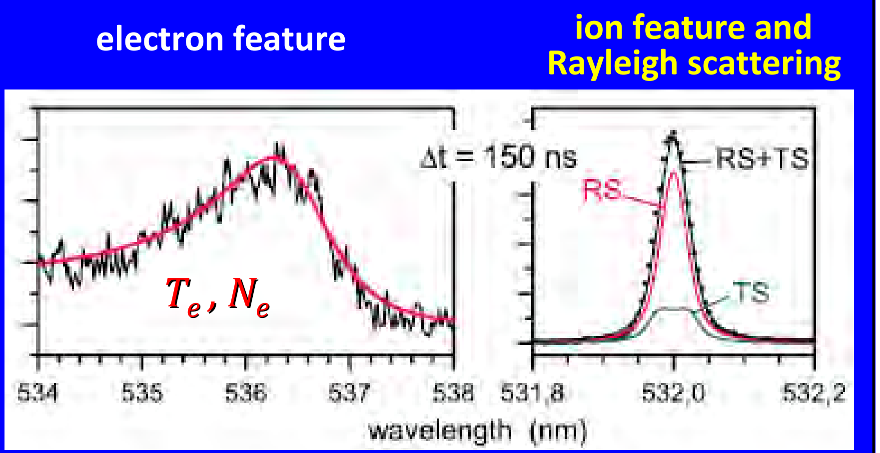


Ion feature of TS spectrum: Determination of the ion temp.

Example: Helium

pump fluence – 1.2 kJ/cm^2; probe fluence – 9.5 J/cm^2.





Data treatment

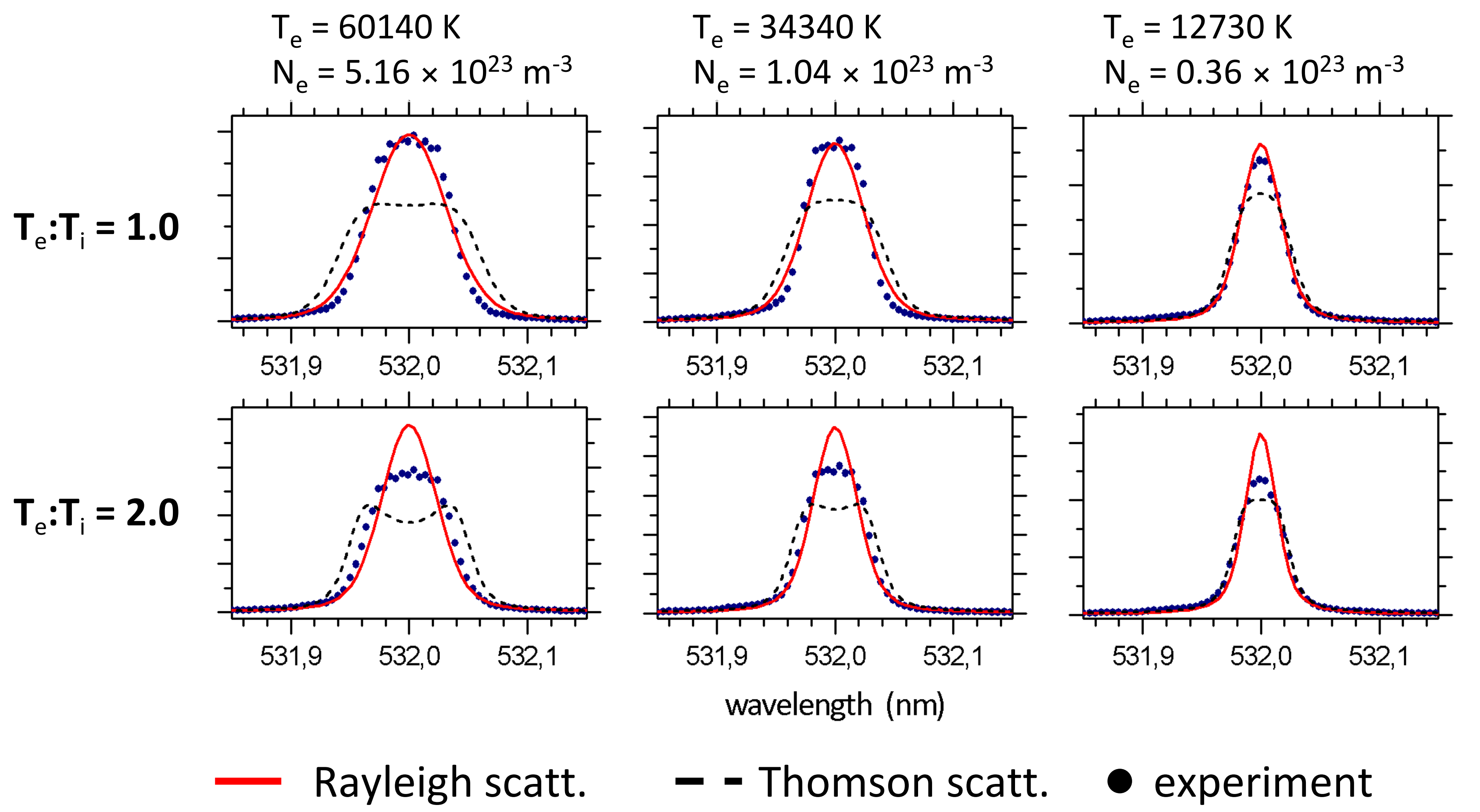
1. Determination of T_e and N_e from electronic feature
2. Deconvolution of the apparatus profile (FWHM = 0.028 nm) from central peak (h)
3. Fitting ion feature of TS and Rayleigh spectra with T_i as a parameter

K.Dzierzega et al. Appl. Phys. Lett. ***102****, 134108 (2013)*

Ion feature of TS spectrum: Determination of the ion temp.

Example: Helium

pump fluence – 1.2 kJ/cm²; probe fluence – 9.5 J/cm².



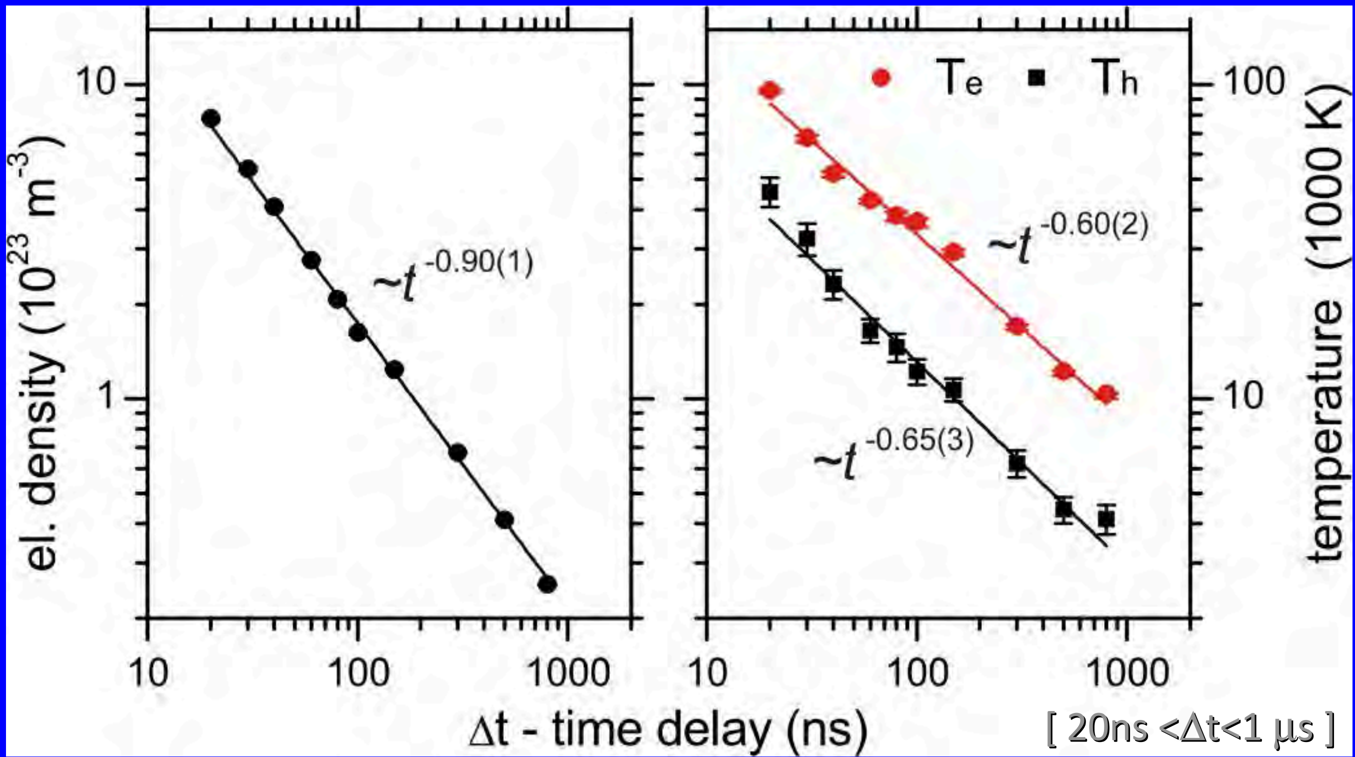
☞ **Ion temperature measurement: difficult to discriminate Thomson from Rayleigh contribution**

K.Dzierzega et al. Appl. Phys. Lett. ***102****, 134108 (2013)*

Ion feature of TS spectrum: Determination of the ion temp.

Example: Helium

pump fluence – 1.2 kJ/cm²; probe fluence – 9.5 J/cm².



10^{24} m^{-3} > N_e > 10^{22} m^{-3}

$100\cdot 10^3$ K > T_e > $10\cdot 10^3$ K

$50\cdot 10^3$ K > T_h > $2\cdot 10^3$ K

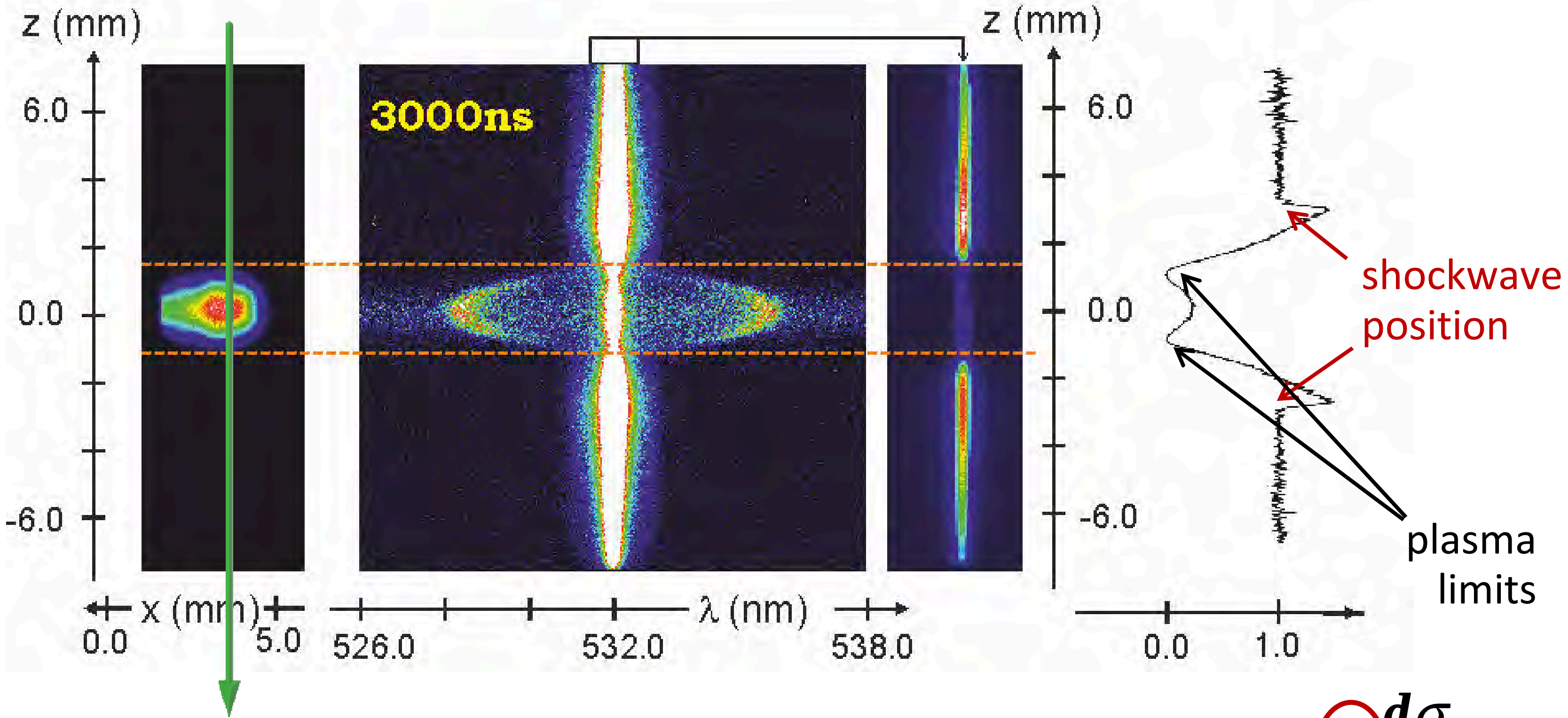
→ **Deviation from isothermal equilibrium**

Large discrepancy between electron and heavy particle temperatures which indicates two-temperature plasma out of the local isothermal equilibrium.

Results do not rely on assumptions about the equilibrium state of the plasma!

K.Dzierzega et al. Appl. Phys. Lett. ***102****, 134108 (2013)*

Rayleigh scattering from laser induced plasma



probe laser beam @532nm

$$I_{scat} = I_{las} \, L \, n \, \frac{d\sigma}{d\Omega} \Delta\Omega$$

atom density

B.Pokrzywka et al.,Spectrochim. Acta B (2012) ***74–75,*** *24*

Rayleigh scattering from laser induced plasma

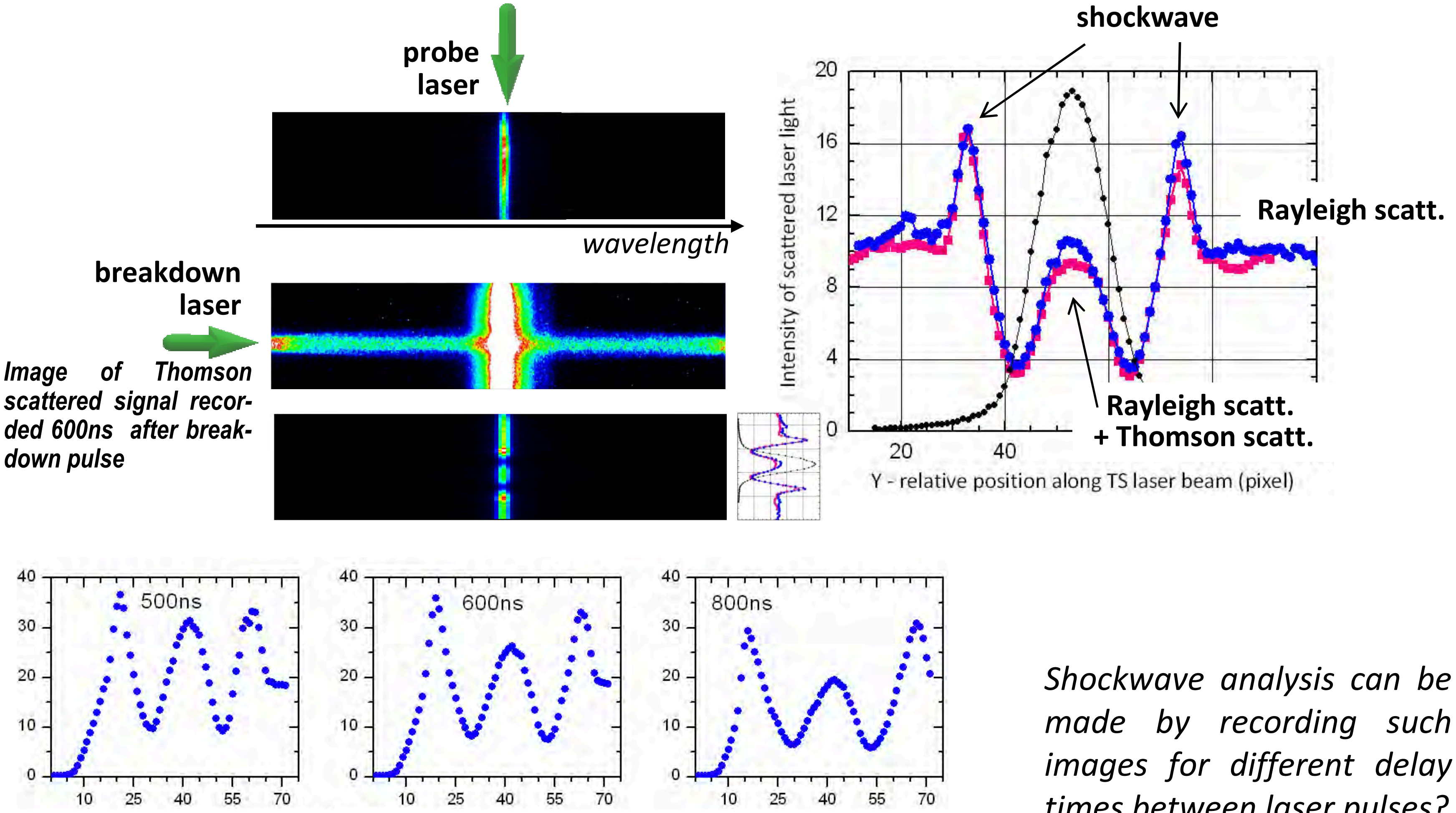


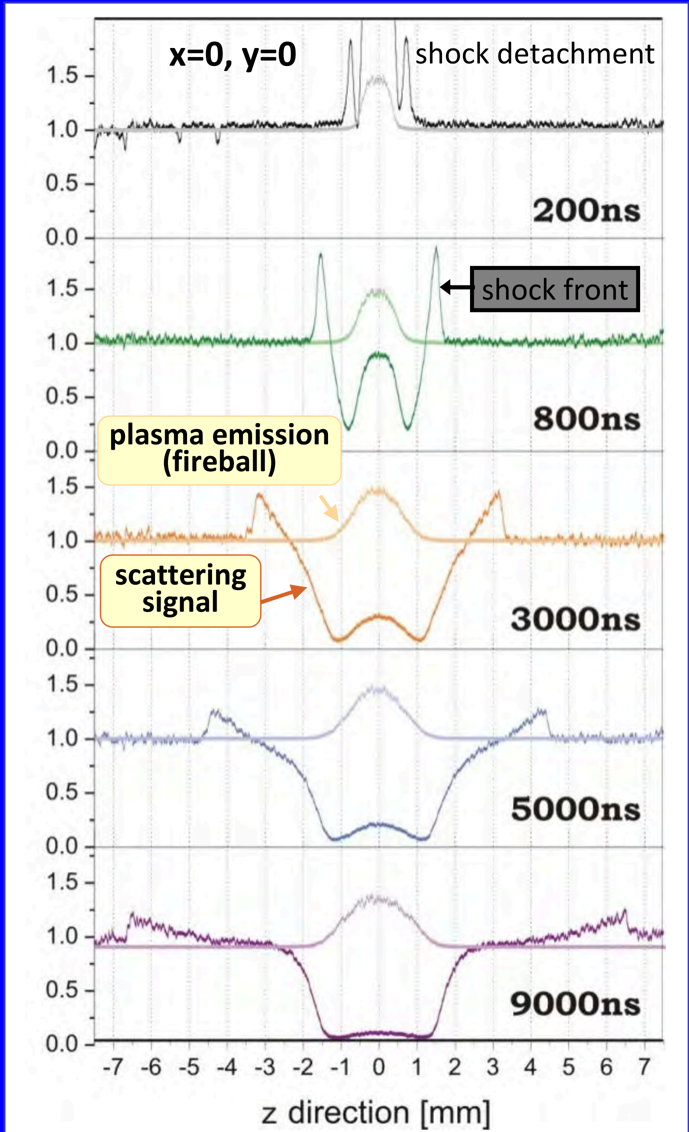
Image of Thomson scattered signal recorded 600ns after breakdown pulse

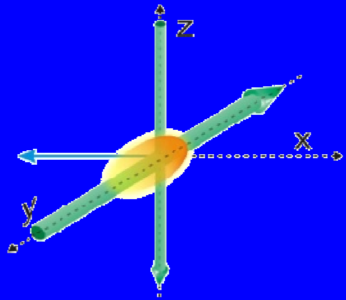
Shockwave analysis can be made by recording such images for different delay times between laser pulses?

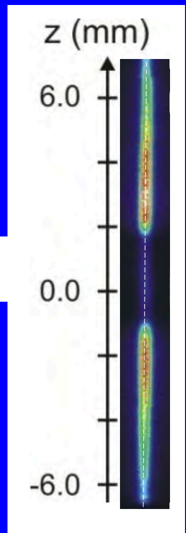
B.Pokrzywka et al.,Spectrochim. Acta B (2012) ***74–75,*** *24*

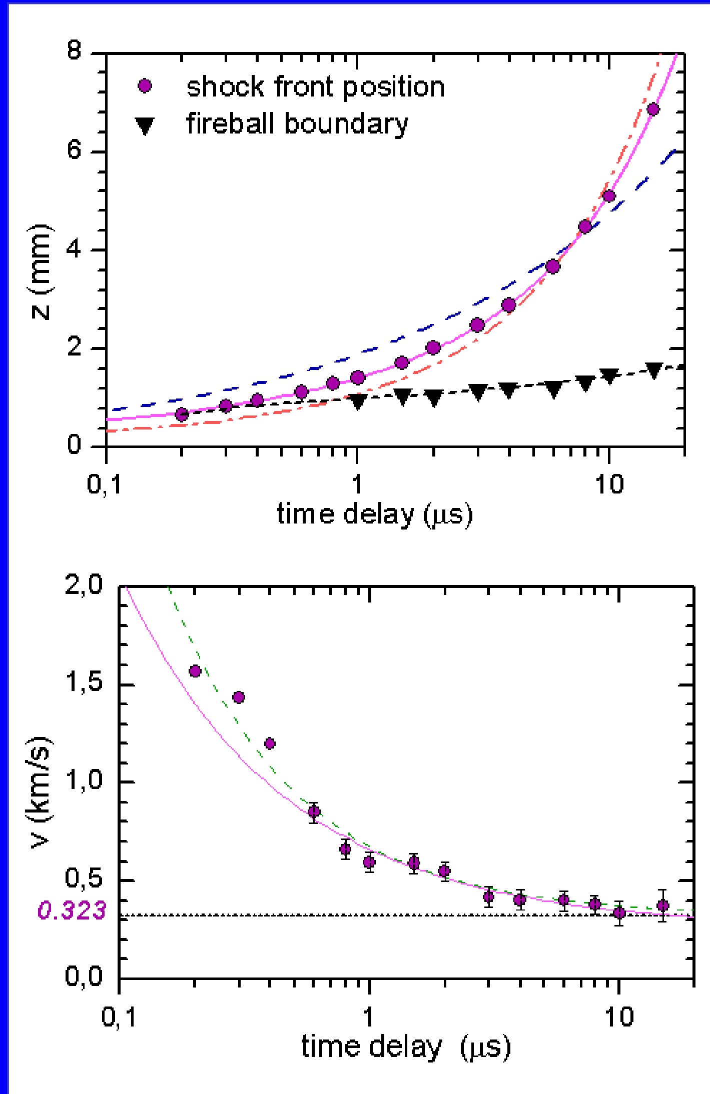
Rayleigh scattering from laser induced plasma

Shockwave evolution on axis of LIP generated in argon by 6ns pulse of 2kJ/cm² fluence





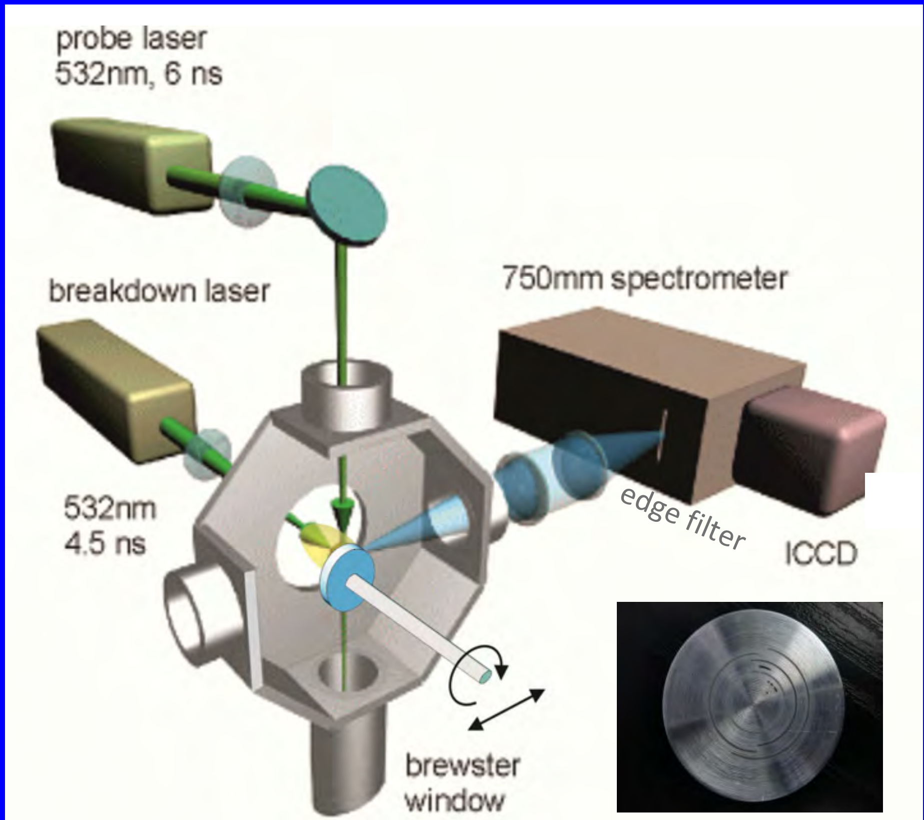


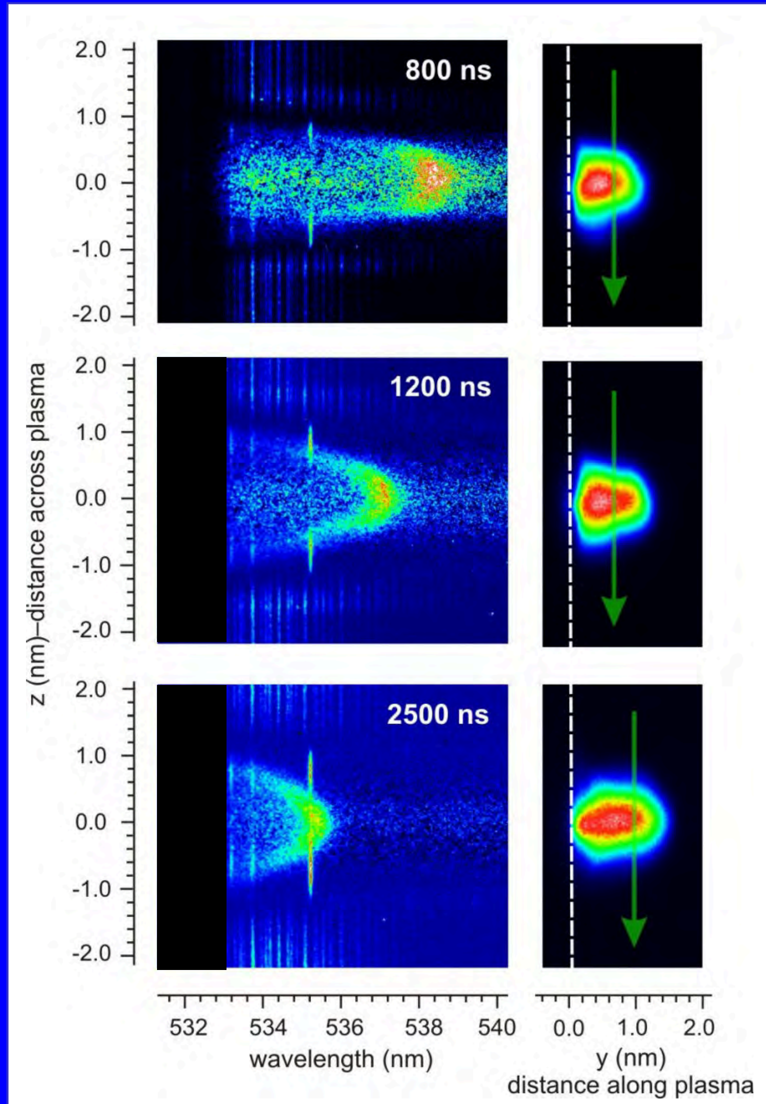


B.Pokrzywka et al.,Spectrochim. Acta B (2012) ***74–75****, 24*

LIP generated on Al target in air

↳ Set-up and Optical scattering





ablating laser: fluence 30 J/cm^2 (6.7 × 10^9 W/cm^2)
probe beam: fluence 100 J/cm^2 (16.6 × 10^9 W/cm^2)
Spatial resolution: 200μm (radial) x 30μm (axial)
iCCD gate: 8 ns - 2000 laser shots

A. Mendys, et al. Spectrochim. Acta B ***96****, 61–68, (2014) doi:10.1016/j.sab.2014.03.009*

LIP generated on Al target in air

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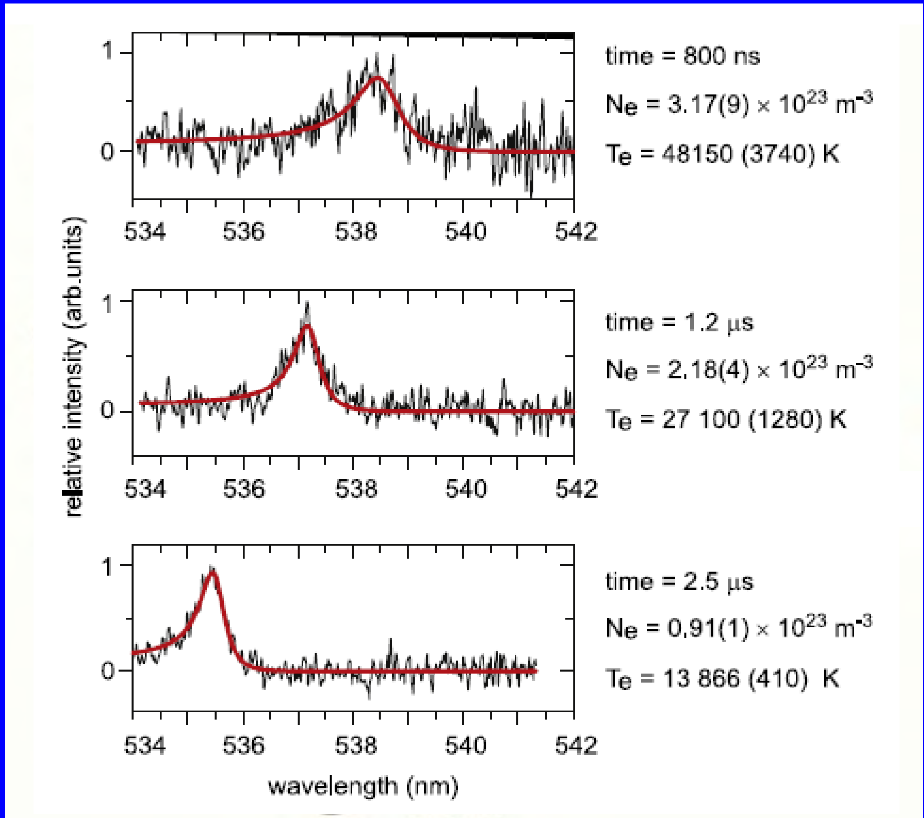

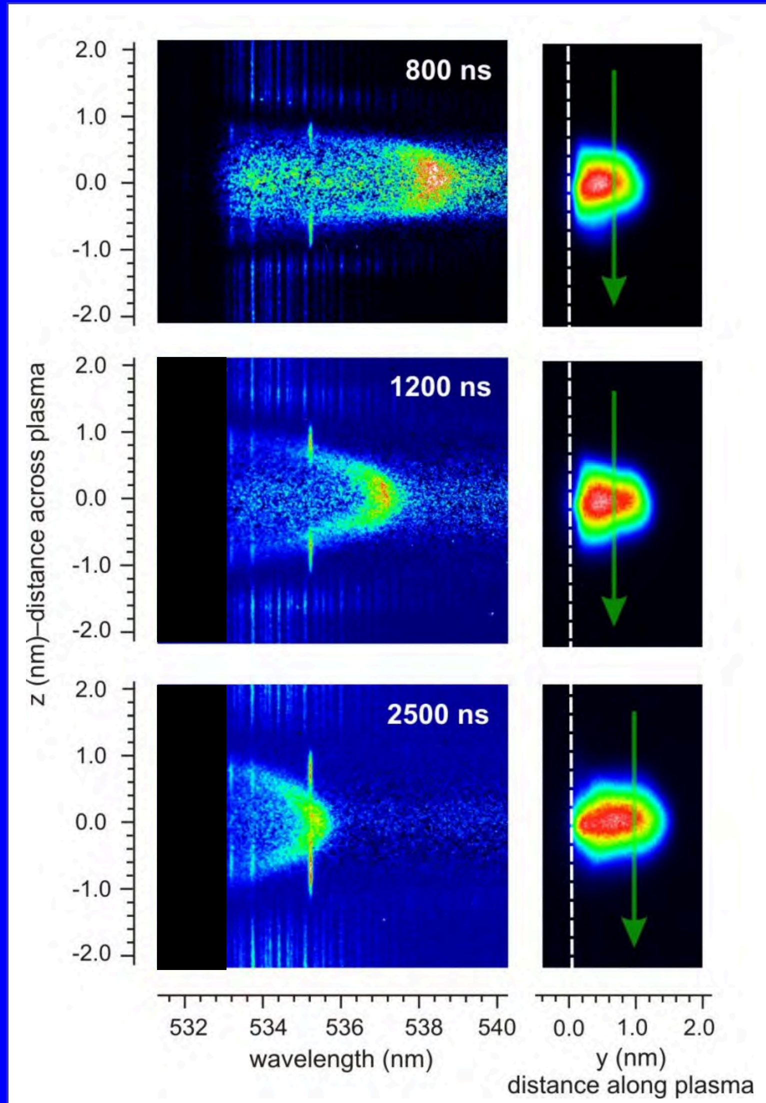

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LIP generated on Al target in air

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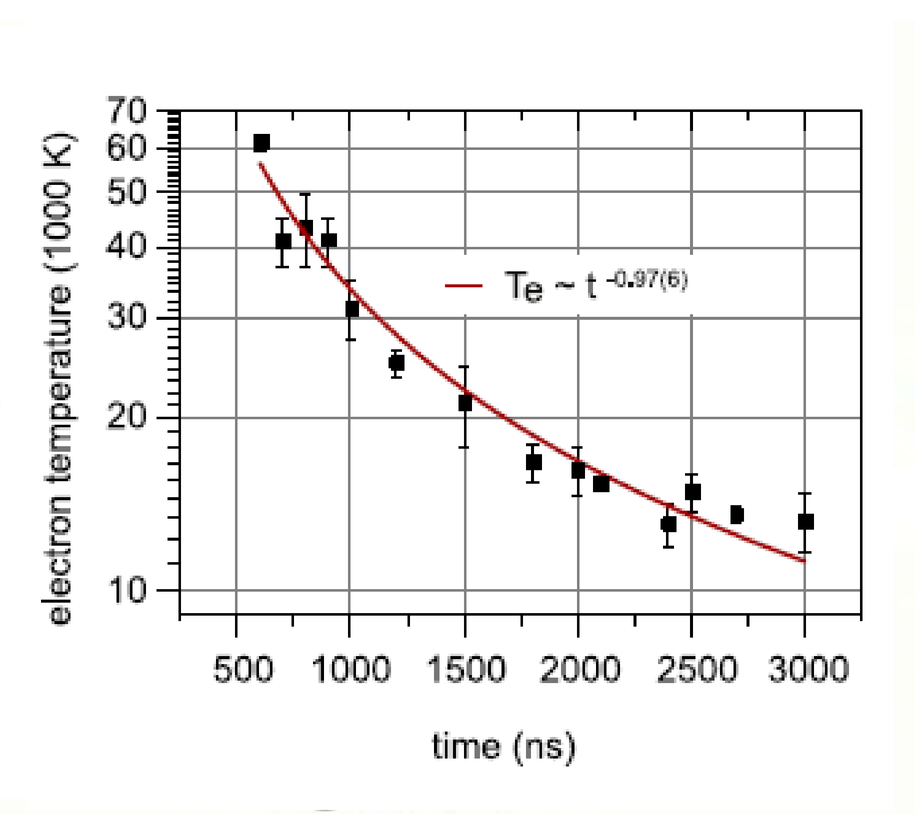

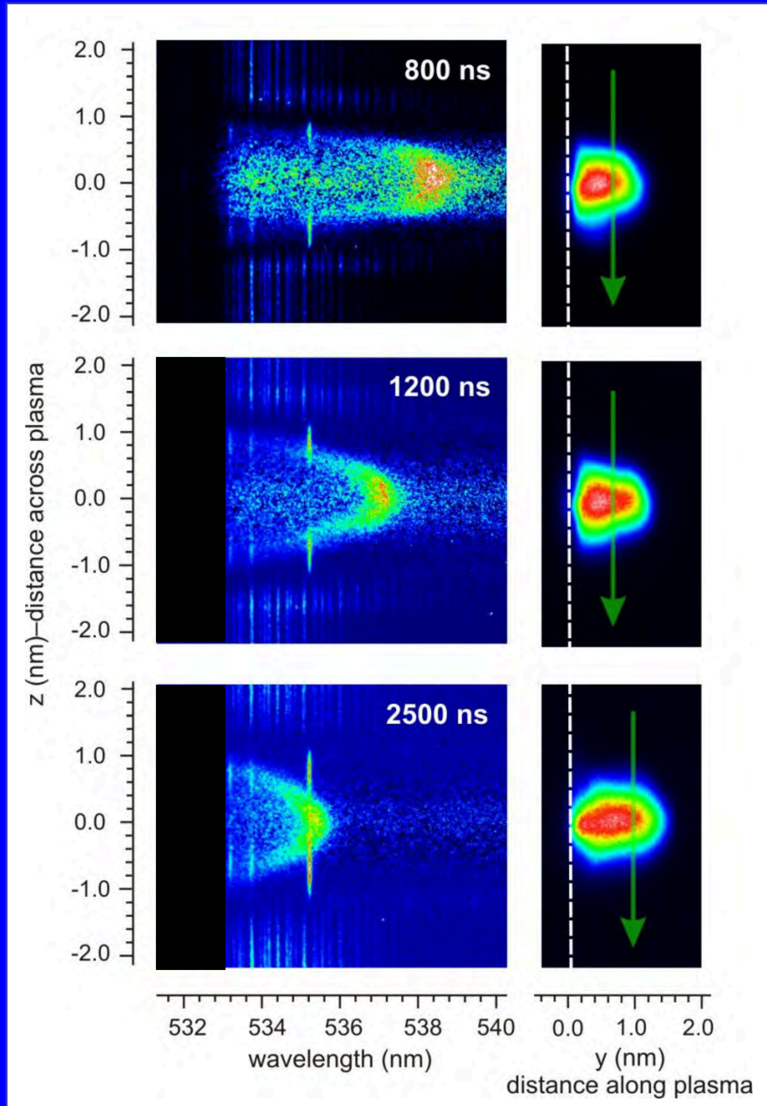

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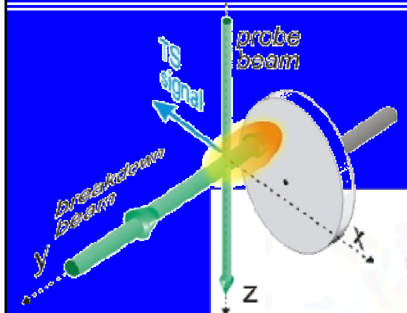
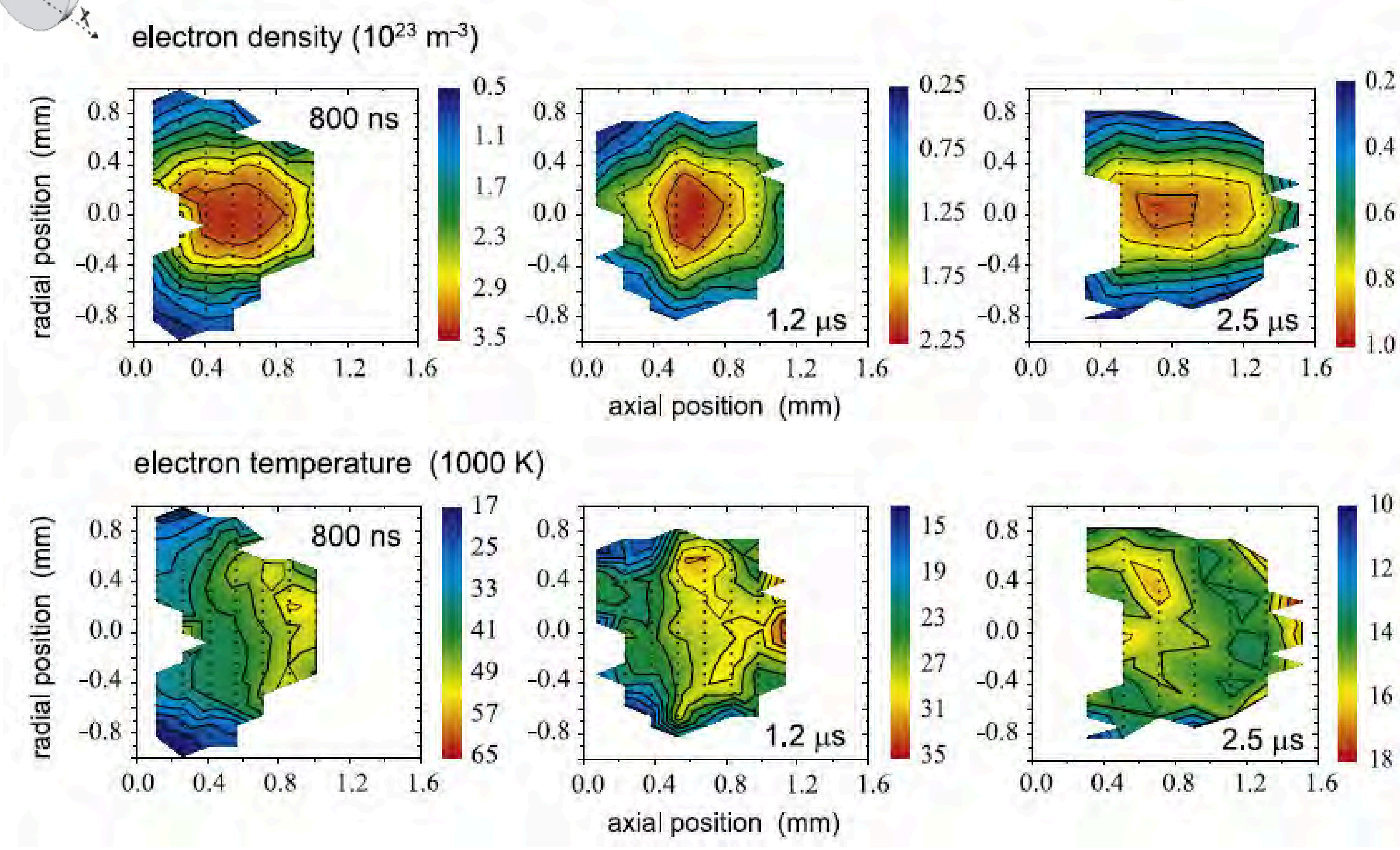
LIP generated on Al target in air

➯ N_e, T_e distribution in the plume

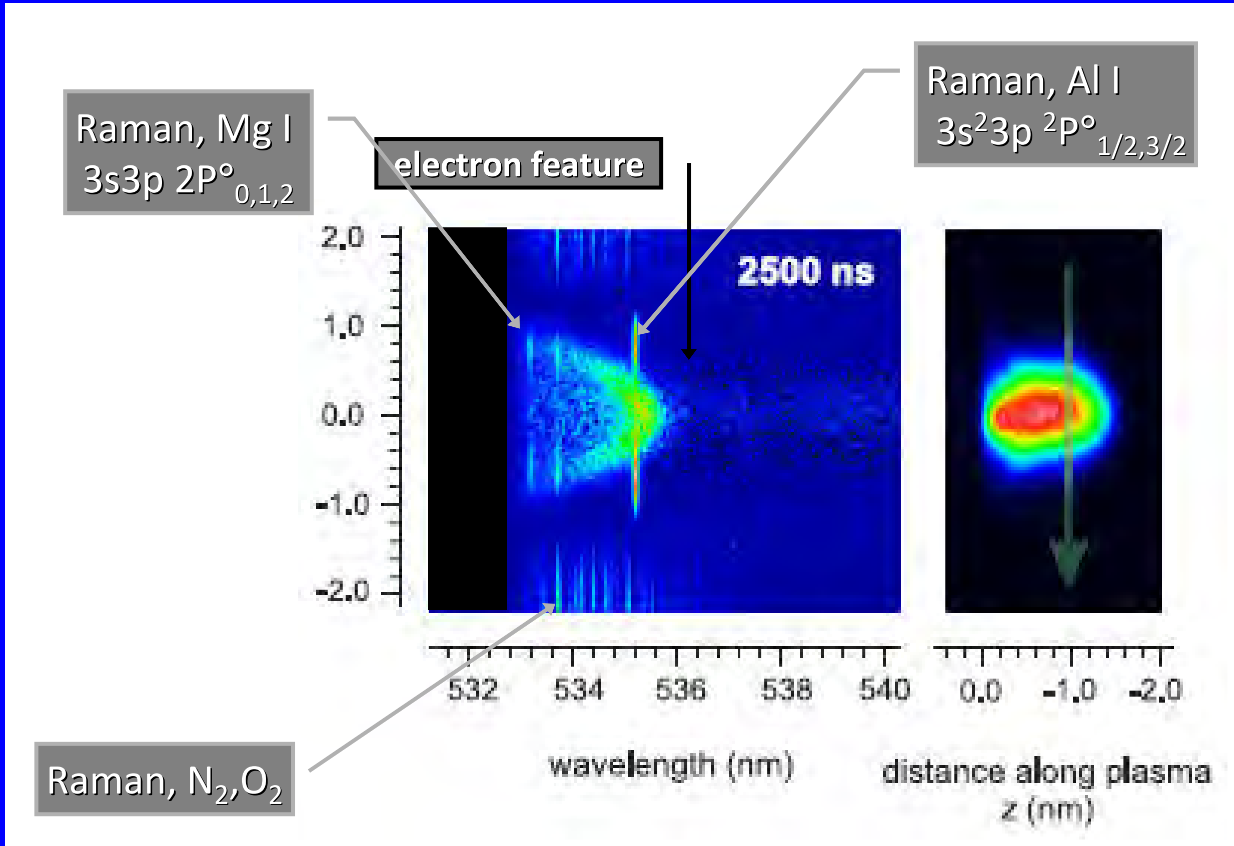




A. Mendys, et al. Spectrochim. Acta B **96**, 61–68, (2014) doi:10.1016/j.sab.2014.03.009

LIP generated on Al target in air

↳ Perspective: Raman scattering



*Ref: A.Delserieys, F.Y.Khattak, S.Sahoo, G.F.Gribakin, C.L.S.Lewis, and D.Riley , **Raman satellites in optical scattering from a laser-ablated Mg plume;** Physical Revies A **78** (2008) 055404*

➡ **Raman scattering could be used for diagnosing the relative populations of excited levels in a partially ionized plasma.**

Summary and Conclusions

- Laser scattered light from LIBS plasma gives a **lot of information on plasma, especially on transient one.**
- **Simultaneous measurement** of plasma parameters
  - Scattering of laser radiation is **local method – high spatial resolution**
- Direct prediction of plasma parameters **without assumption of thermodynamic equilibrium**
  - Derivation of the most important plasma parameters like N_e and T_e from TS spectra is straightforward and usually does not need further **calibration**
- **BUT Elevation of the electron temperature (heating)** in Thomson scattering experiment, fortunately this effect can be corrected

↳ *"What can we learn about laser-induced plasmas from Thomson scattering experiments" (Review), K. Dzierzega, A.Mendys B.Pokrzywka, Spectrochimica Acta Part B 98 (2014) 76–86*

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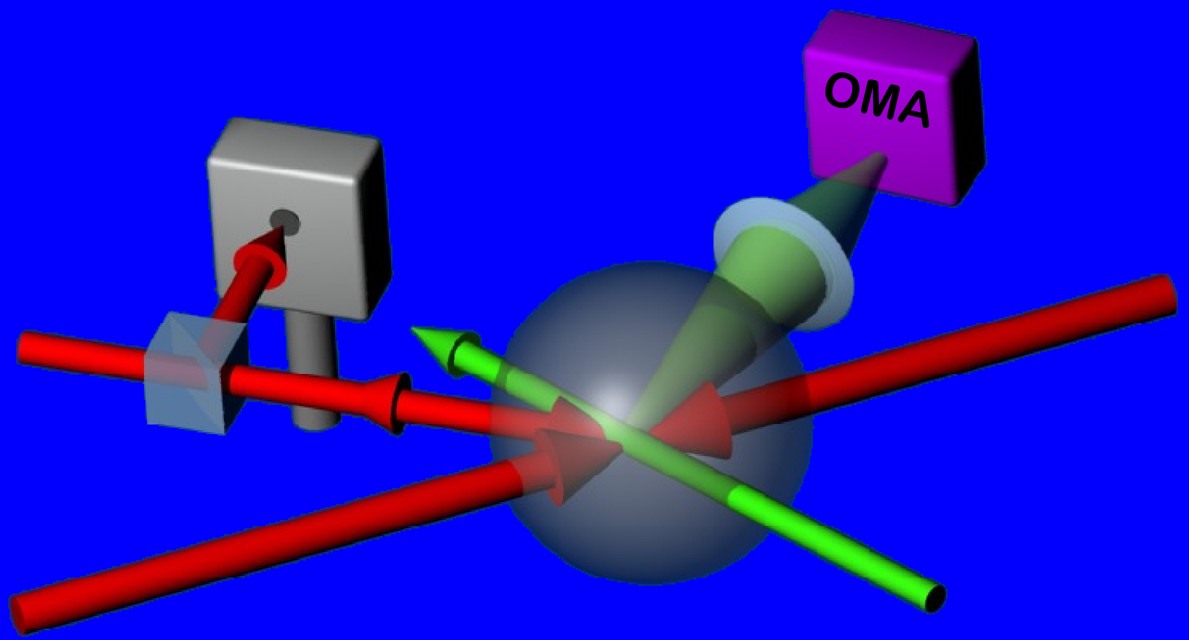
Thank you for your attention



Questions ?