Producing ion waves from acoustic pressure waves in pulsed ICP plasmas

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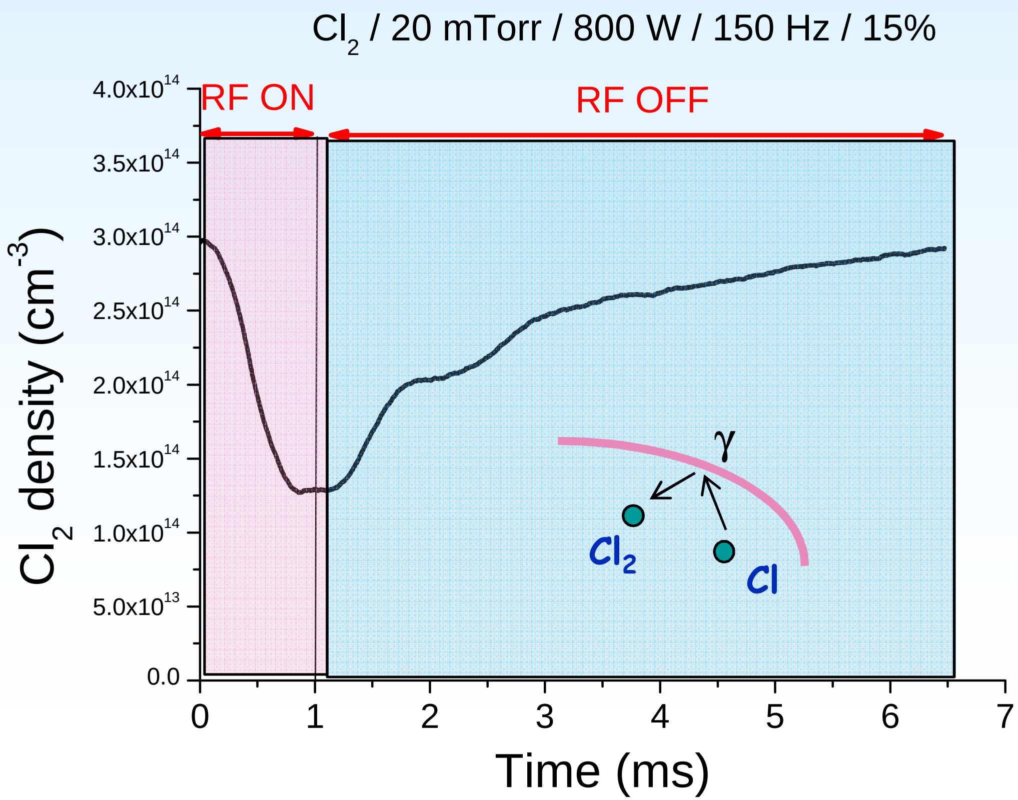
Background/motivation

- *Pulsed discharges* are promising for advanced etching applications

⇒ necessity to understand the basic plasma phenomena involved when rf power is time-modulated

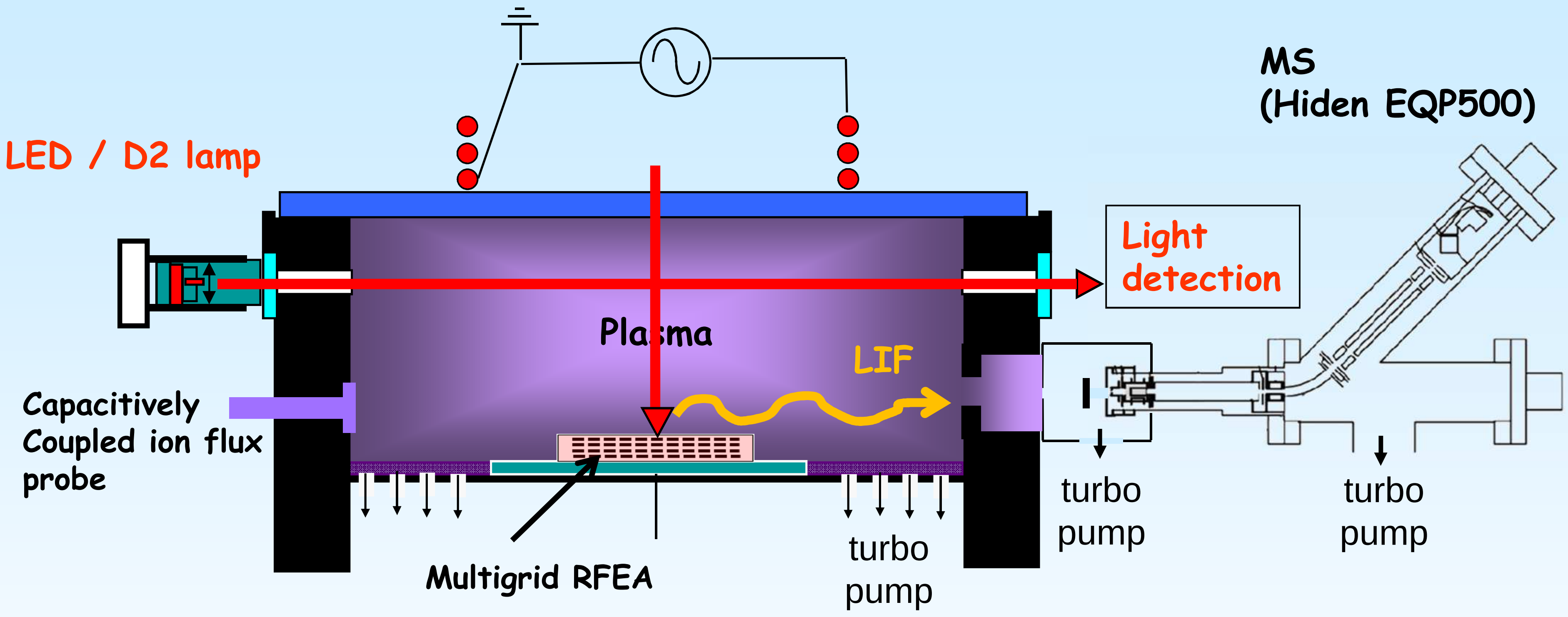
- Pulsed discharges are also used to probe radicals' kinetics: by measuring the rise/decay rate of the radical's density in the afterglow ⇒ surface reactivity



In afterglow: Cl_2 density rises due to Cl atoms recombination on reactor walls…

but why is density oscillating ?

Experimental set-up: details of DPS 300 mm ICP reactor



- Radicals detection by BBAS: in the hot/dense region of the ICP plasma

For details see:
APL 94, p 21504 (2009), APL 91, p.231503 (2007), PSST 19, p34017, (2010), APL 96, p131501 (2010)

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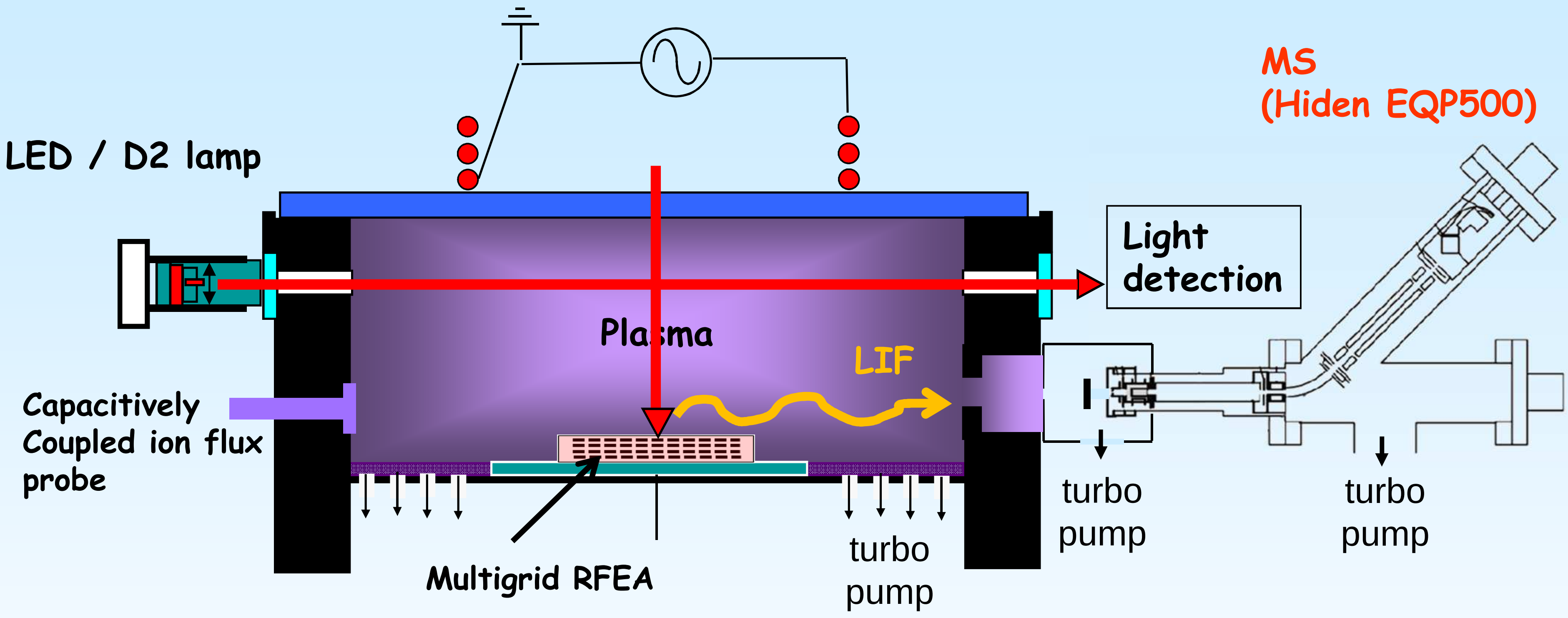

- Radicals detection by BBAS: in the hot/dense region of the ICP plasma
- Radical detection + pressure variations by MS: "downstream" and near the reactor walls

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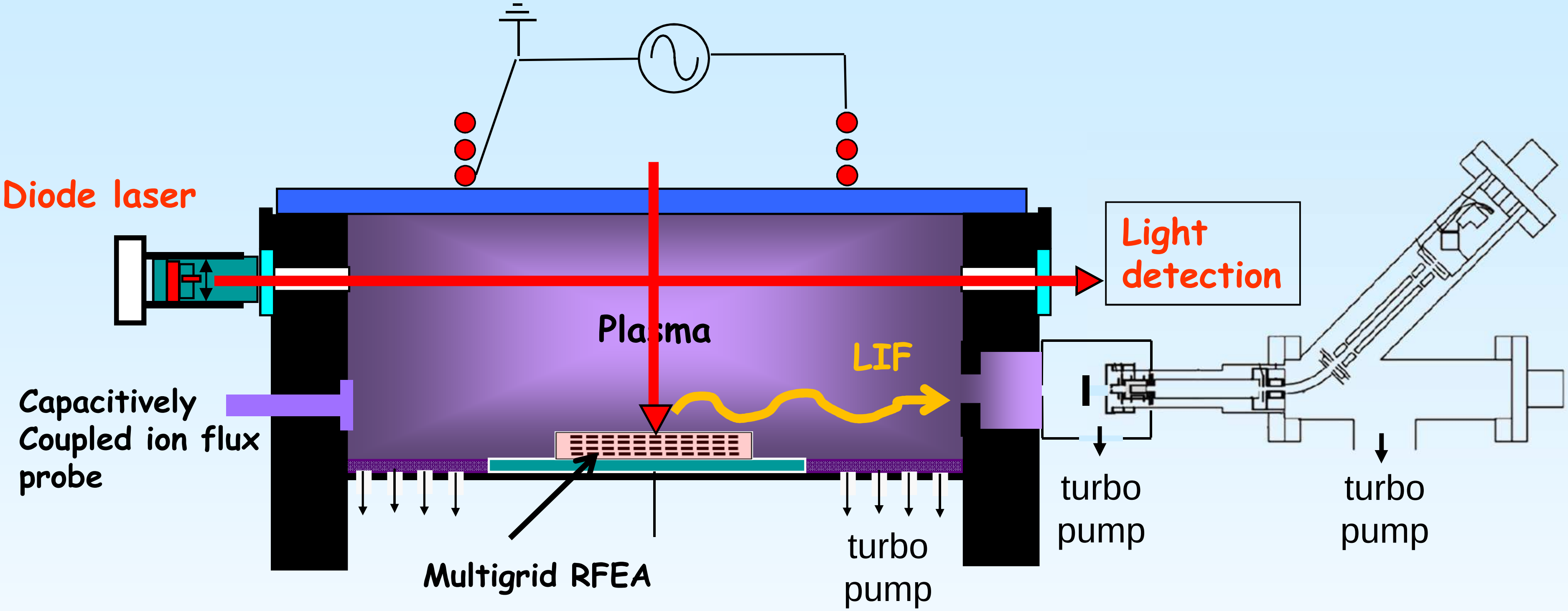

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- Gas Temperature / axial drift velocity: diode laser AS + LIF (Doppler width of Al and Ar*)

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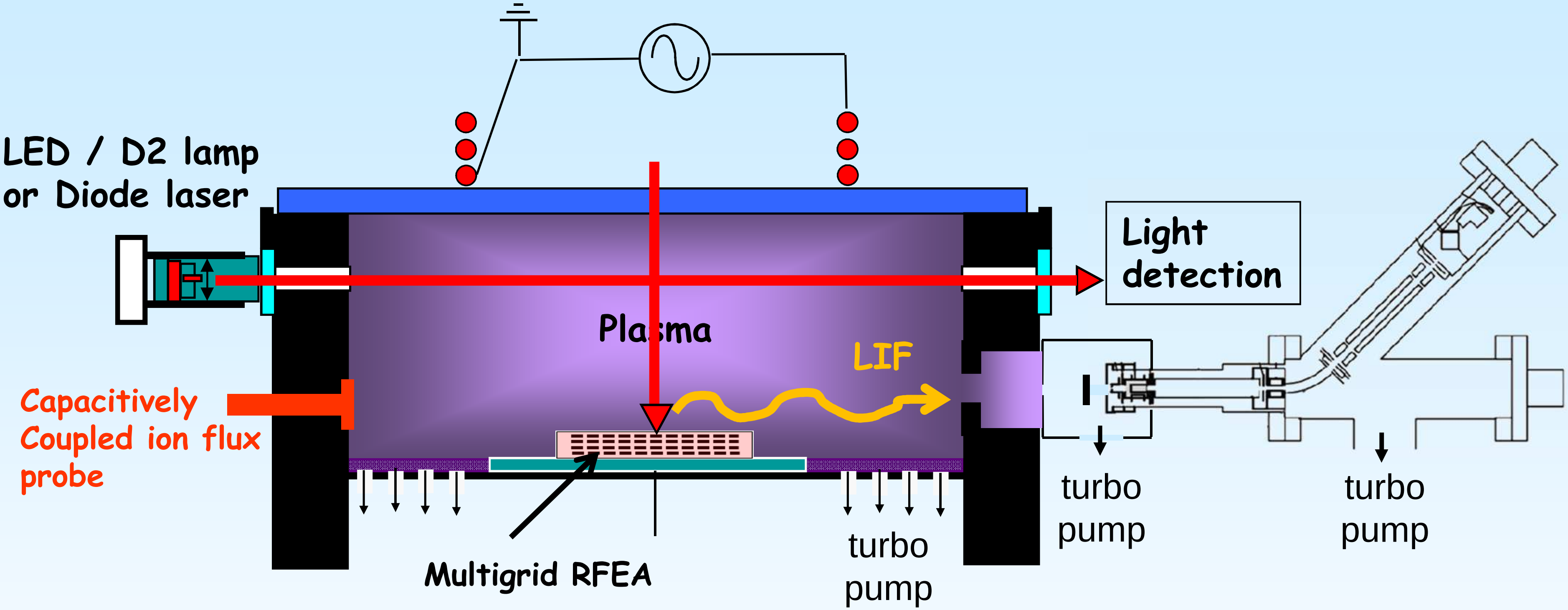

- Radicals detection by BBAS: in the hot/dense region of the ICP plasma
- Radical detection by MS: “downstream” and near the reactor walls
- Gas Temperature / axial drift velocity: diode laser AS + LIF (Doppler width of Al and Ar*)
- Ion flux: “downstream” and near the reactor walls

For details see:
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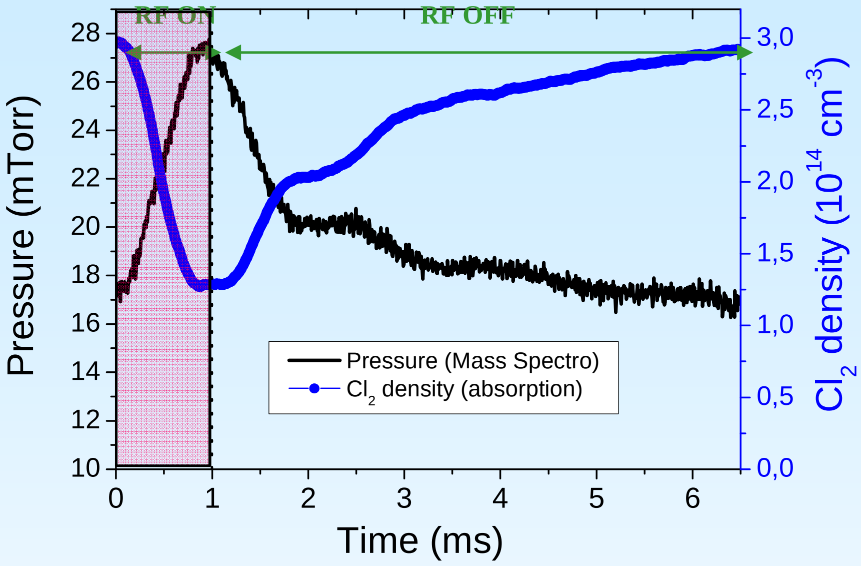
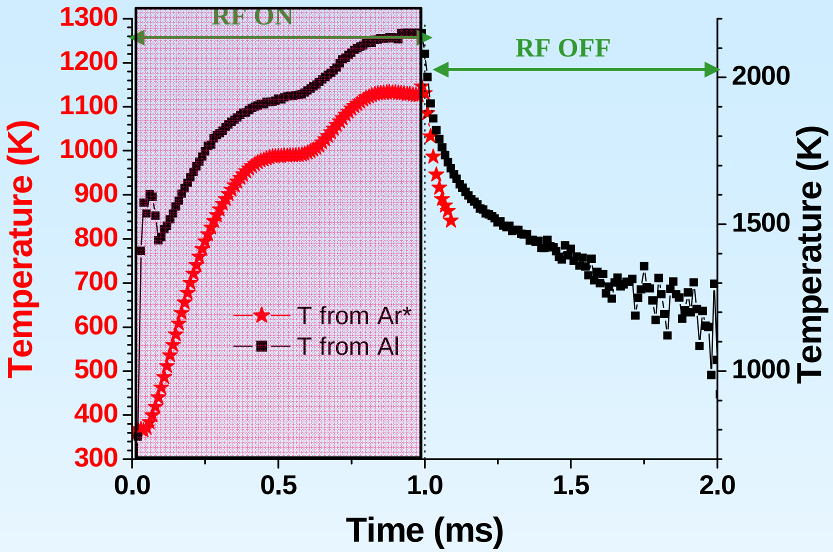
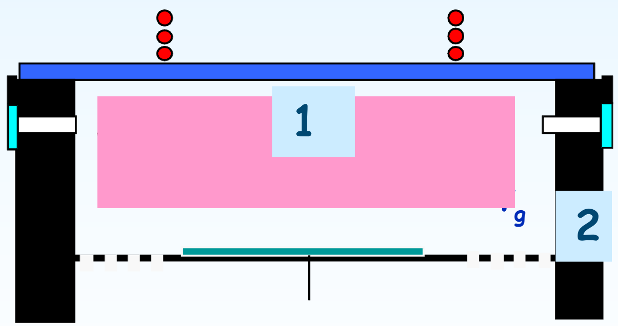
Experimental results



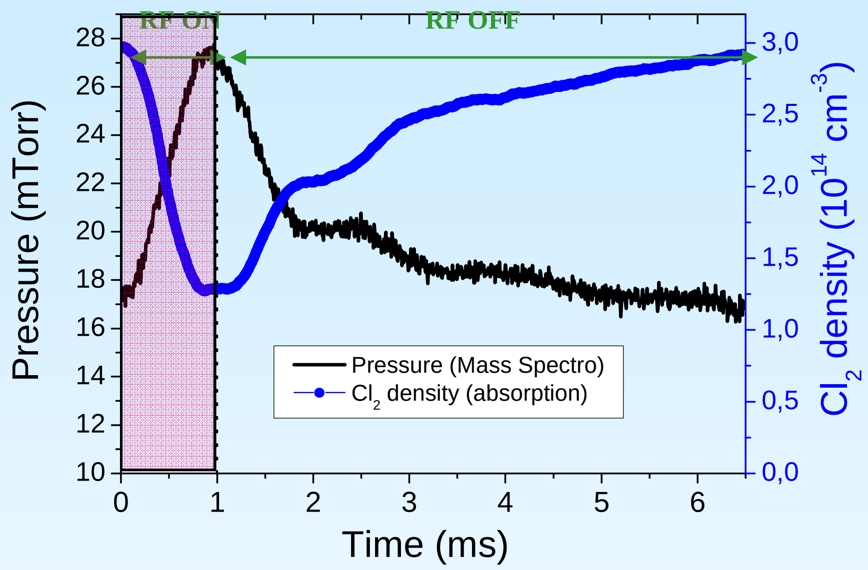


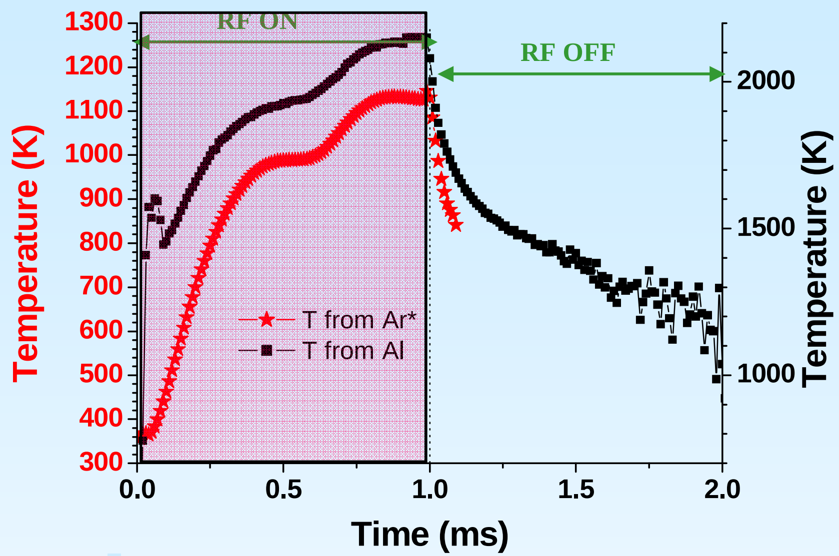


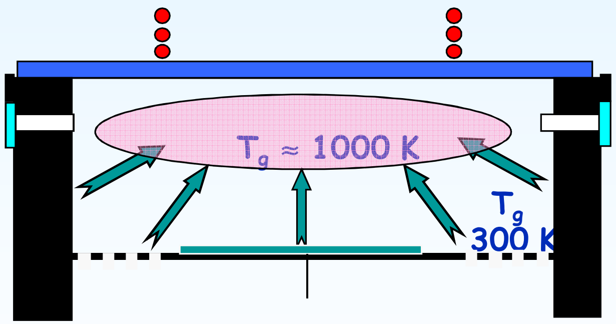
All measured quantities are oscillating: density, pressure, Temperature !

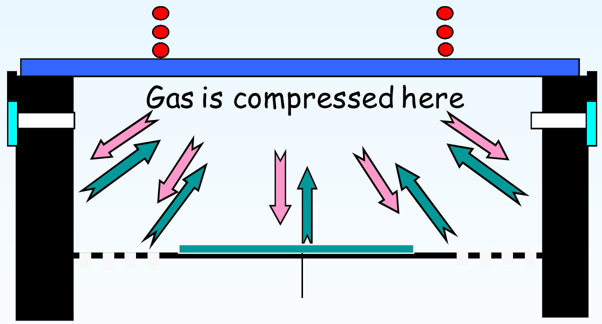
→ An acoustic wave is generated by plasma pulsing !

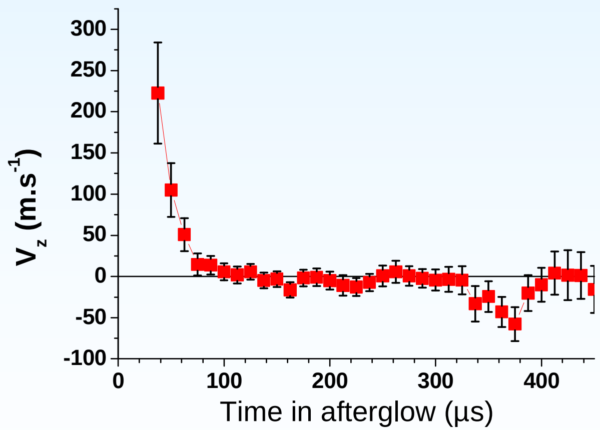
Experimental results











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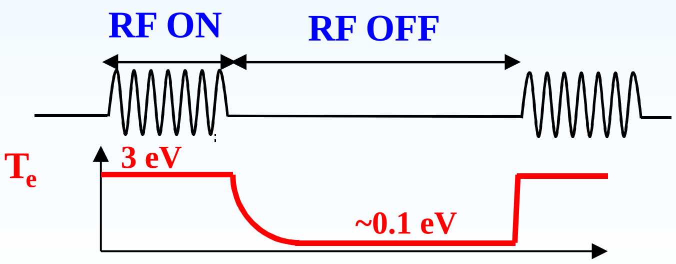
→ An acoustic wave is generated by plasma pulsing !

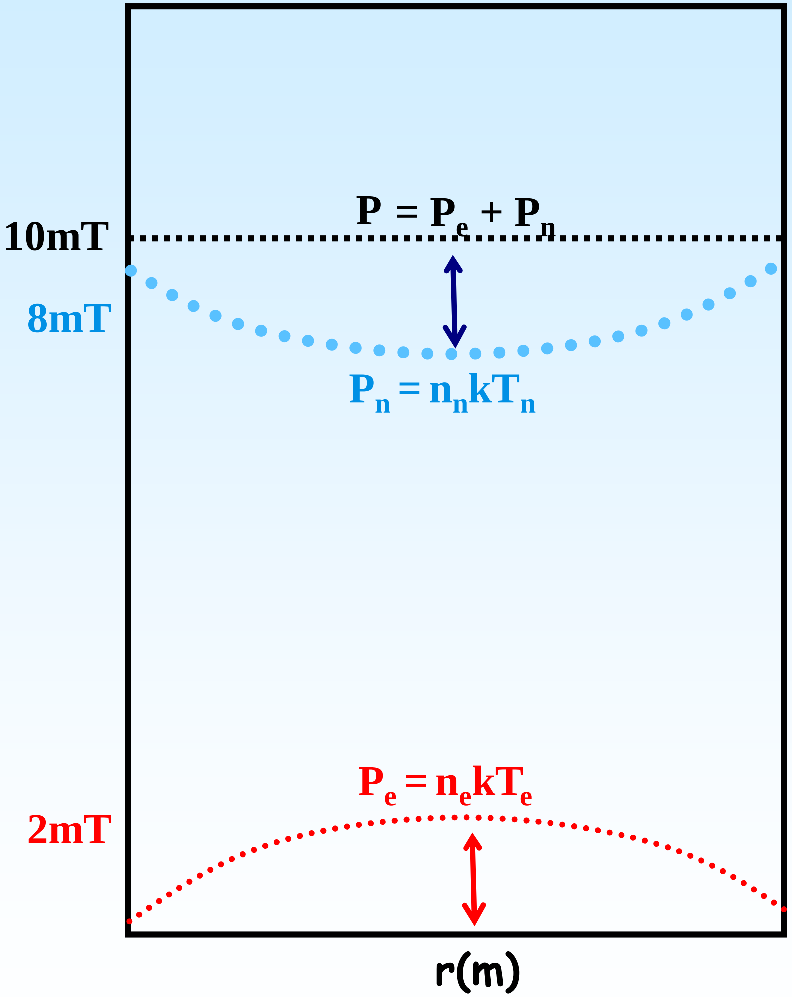
What is at the origin of the pressure gradient which launch the wave → P_e fluctuations ?

Electron/neutral pressure balance in pulsed ICP

In ICP the electron pressure Pe is non negligible and total pressure is the sum of Pe + Pn

In pulsed discharges, Te is rapidly modulated
rapid fluctuations of Pe → fluctuations of Pn

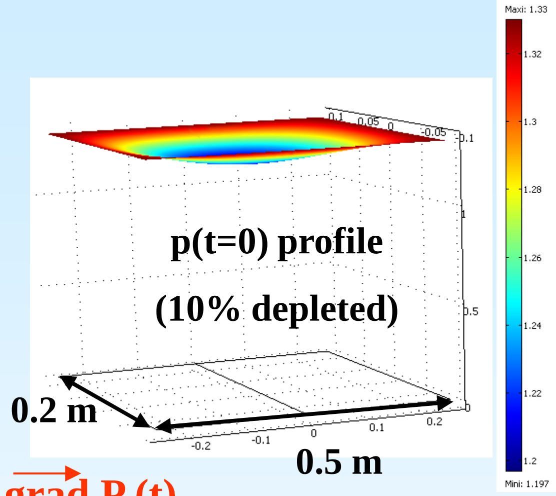


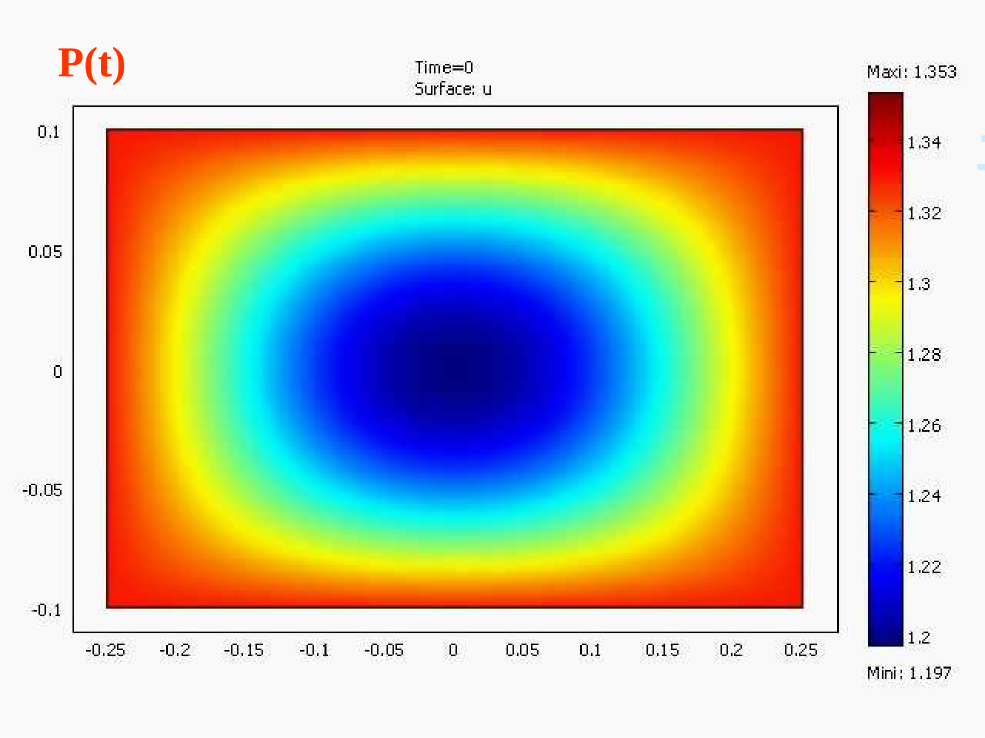


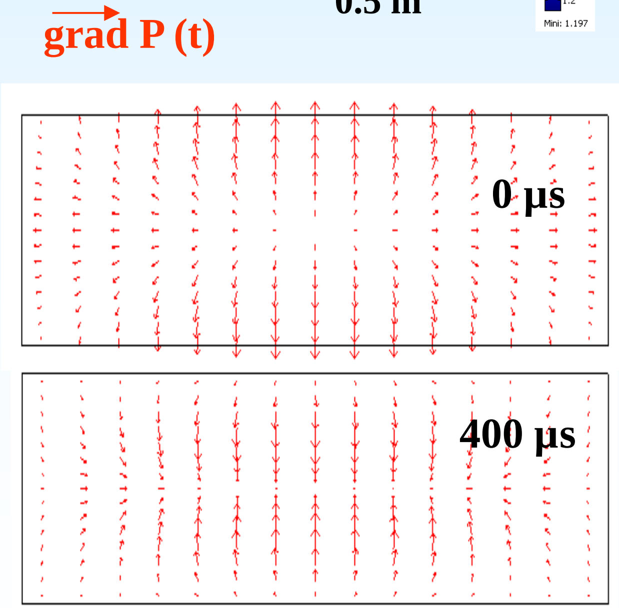
2D Fluid simulations : A simple model of acoustic wave

- **Geometry: 2D axisymetric / D=0.5m / L=0.2m**
- **Equations:** $\frac{\partial^2 p}{\partial t^2} - cs^2 \Delta p = 0$

$$p(t=0) = p_0 * [1 - 0.1 * \cos(\frac{\pi * z}{0.2}) * J_0(\chi_{01} * \frac{r}{0.25})]$$







A 2D Fluid model of the afterglow

(1) Mass continuity $\frac{\partial \rho}{\partial t} + \vec{\nabla}.\rho\vec{v} = 0$ **with** $p = \frac{\rho k_b T}{M}$

$$\rho(t=0) = \frac{m}{k_b T} * p_0 * [1 - 0.1 * \cos(\frac{\pi * z}{0.2}) * J_0(\chi_{01} * \frac{r}{0.25})]$$

$\vec{\Gamma}.\vec{n} = 0 \Leftrightarrow \vec{n}.\rho\vec{v} = 0$ **on all walls**

(2-3) Momentum balance $\rho\frac{\partial \vec{v}}{\partial t} + \rho(\vec{v}.\vec{\nabla})\vec{v} = -\vec{\nabla}p + \vec{\nabla}\overline{\overline{T}}$

$$u(t=0) = v(t=0) = 0$$

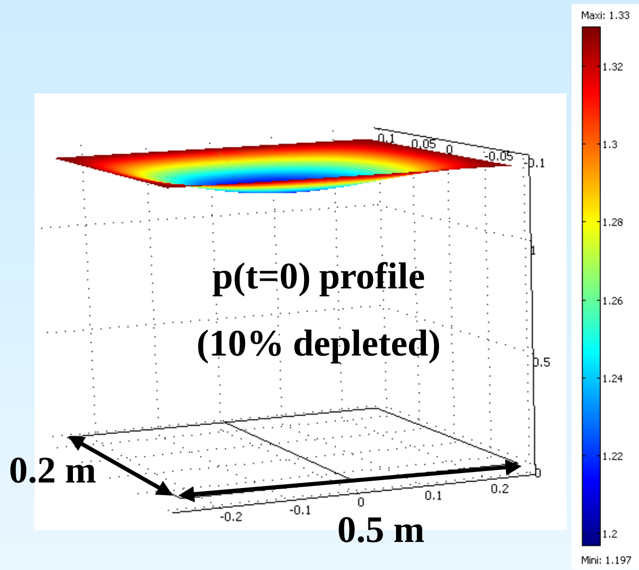
$\vec{v}.\vec{T} = -2\lambda_{mfp}\frac{\partial}{\partial \vec{n}}(\vec{v}.\vec{t})$ **(slip BCs)**

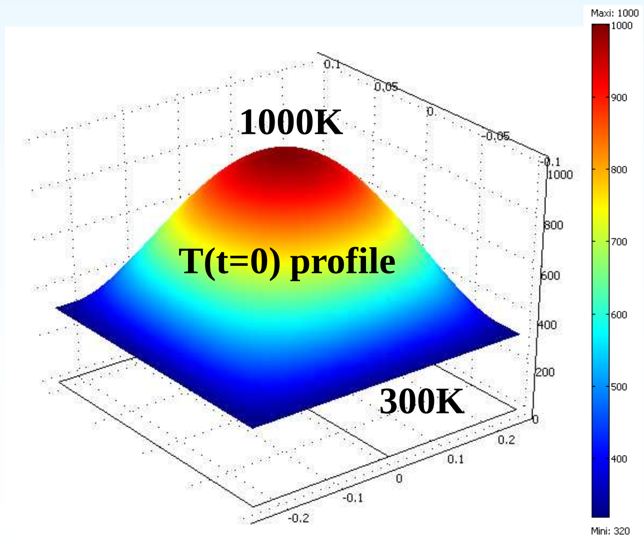
(4) Neutral energy balance

$$\rho C_v \frac{\partial T}{\partial t} + \rho C_v(\vec{v}.\vec{\nabla}T) - \nabla.(k\vec{\nabla}T) = -p(\vec{\nabla}.\vec{v})$$

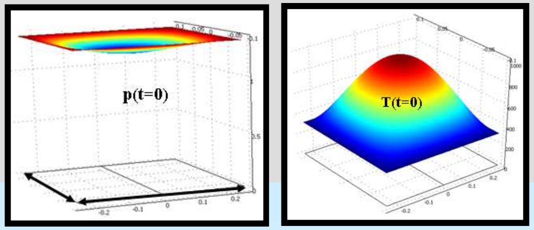
$$T(t=0) = [(Tw - T\max) * \frac{y^2}{0.1^2}] * [1 - \frac{x^2}{0.25^2}] + Tw * \frac{x^2}{0.25^2}$$

$T = T_w - \frac{15\pi}{16k}\lambda_{mfp}\sqrt{\frac{T_w}{T}}\frac{\partial}{\partial \vec{n}}(T)$ **(jump BCs)**





Afterglow model: P_n depleted + gas heating



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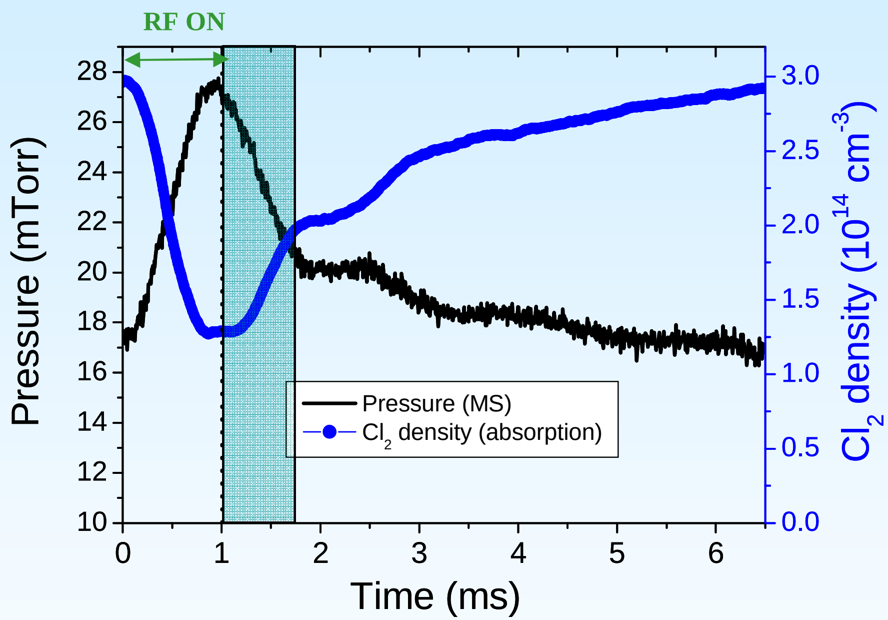
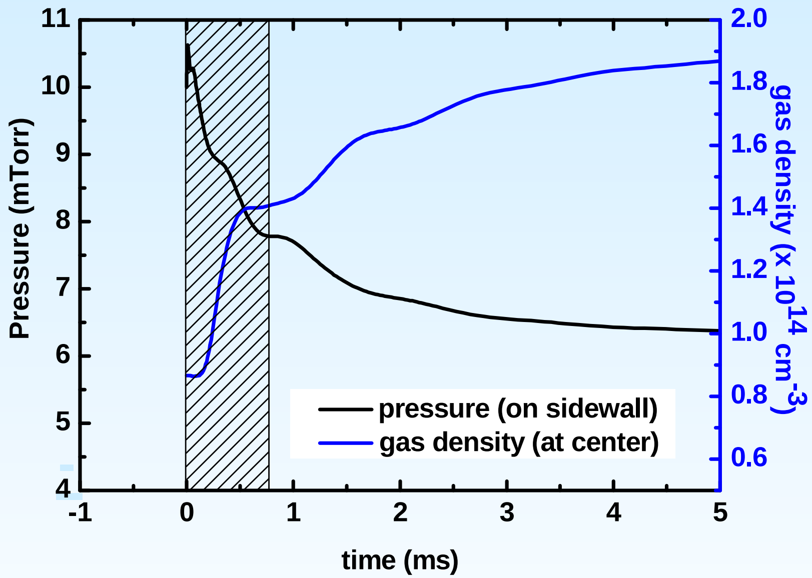


MODEL



- **Gaz density increases in the reactor center while pressure decreases close to the walls**

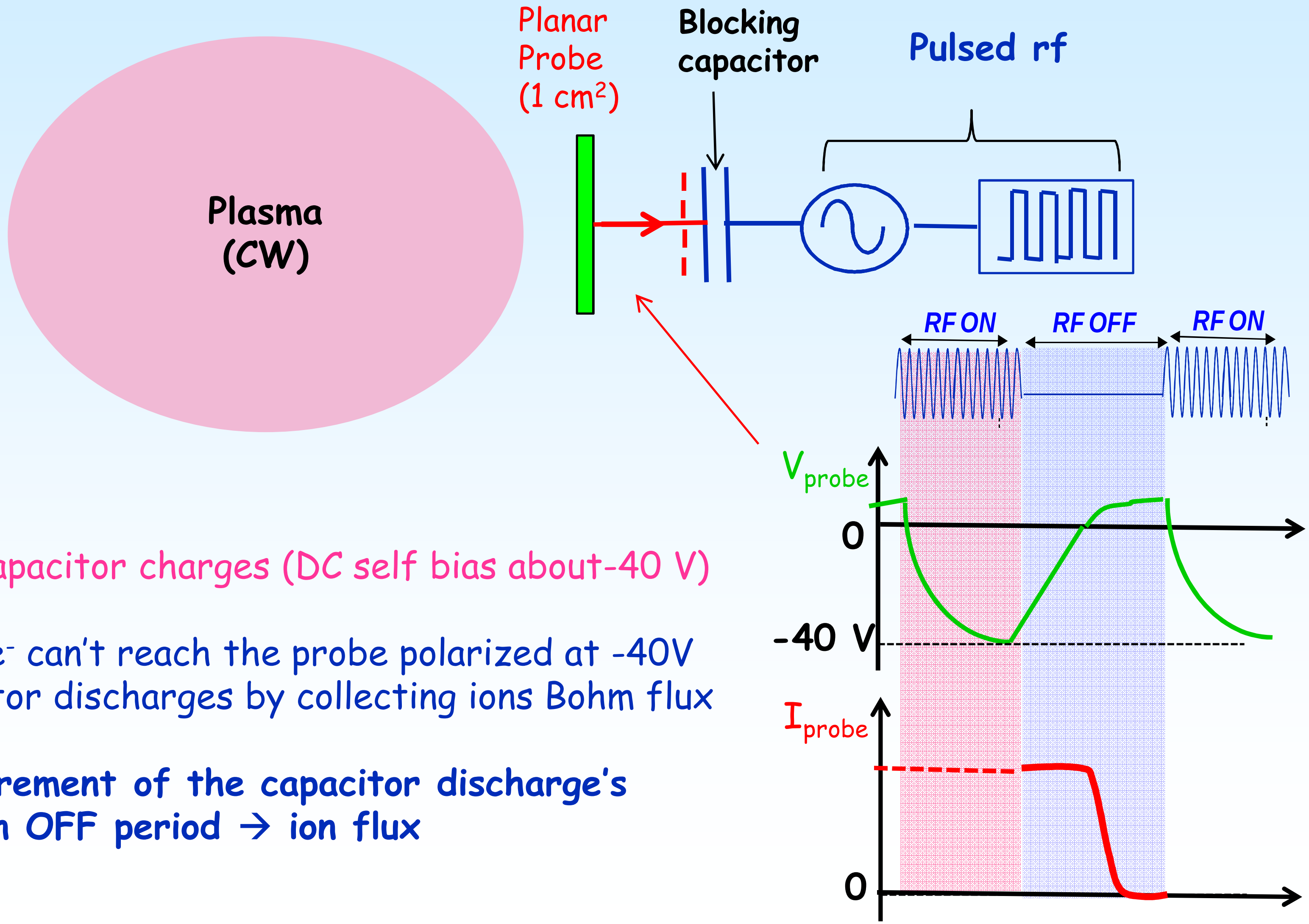
$\Rightarrow$ **relatively good agreement between model and experiment**

→ Neutral depletion caused by electron pressure could be responsible for launching the wave

What about ions ?

Ion flux measurement: principle (in CW plasma)

Well known technique introduced by Braithwaite *et al* in 1996
Principle: fed a planar probe with by RF bursts through a blocking capacitor

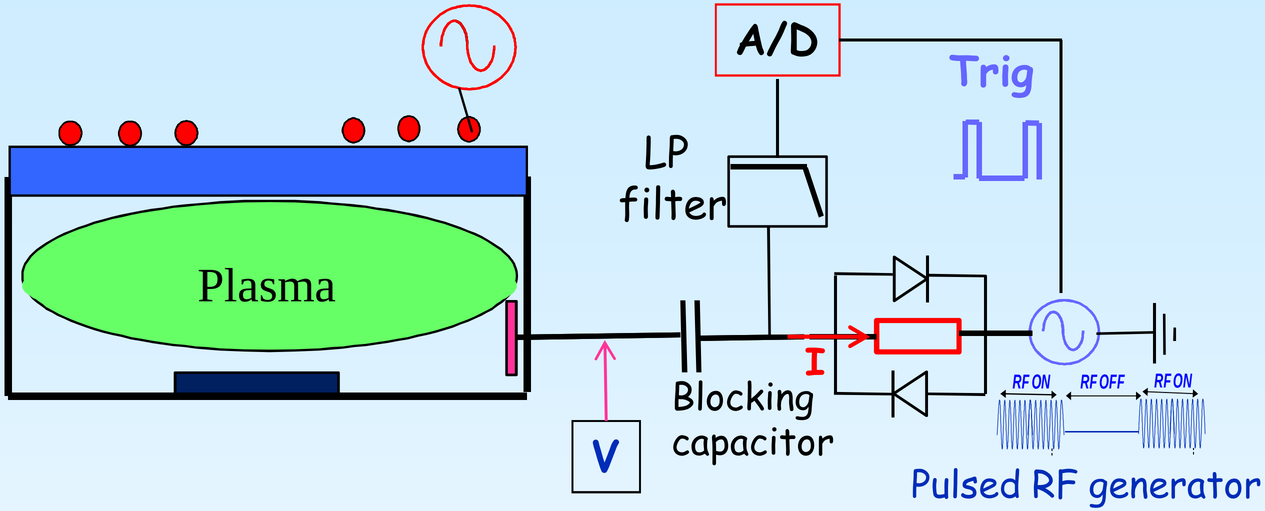


RF ON: capacitor charges (DC self bias about-40 V)

RF OFF: e^- can't reach the probe polarized at -40V
→ Capacitor discharges by collecting ions Bohm flux

→ Measurement of the capacitor discharge's current in OFF period → ion flux

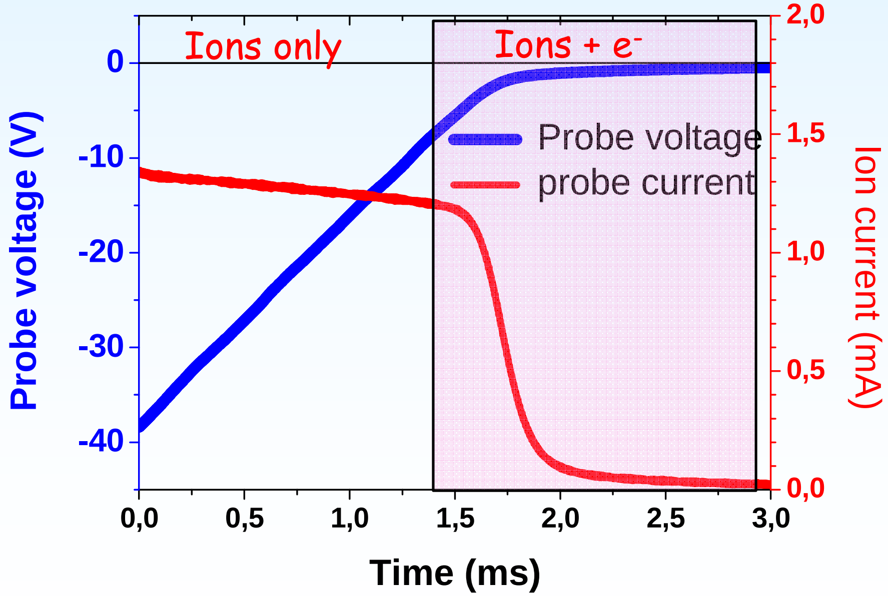
Current (ion flux) measurement in CW plasmas



We use a direct current measurement system through a 1 kΩ serial resistor
(Booth et al, Rev. Sci. Instrum. 71, 2722)

- **RF ON**: RF signal propagates through diodes

- **RF OFF**: capacitor discharge's current flow through resistor and is measured by the A/D (triggered by probe pulses)



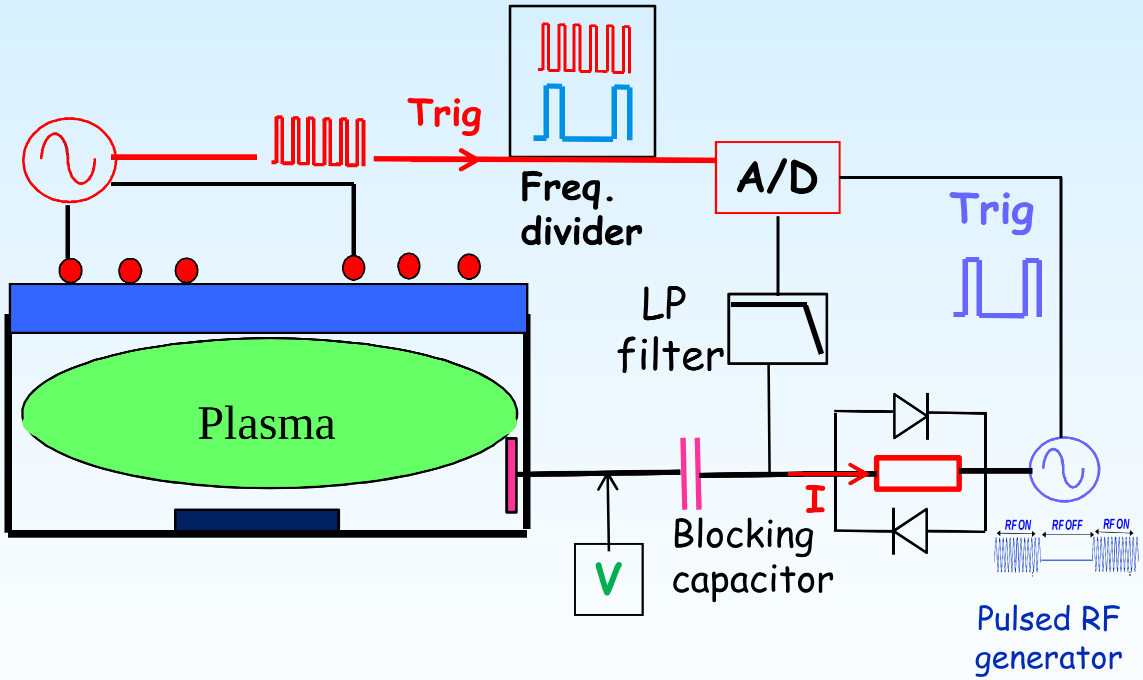
→ **Direct measurement of ion flux from ion saturated current**

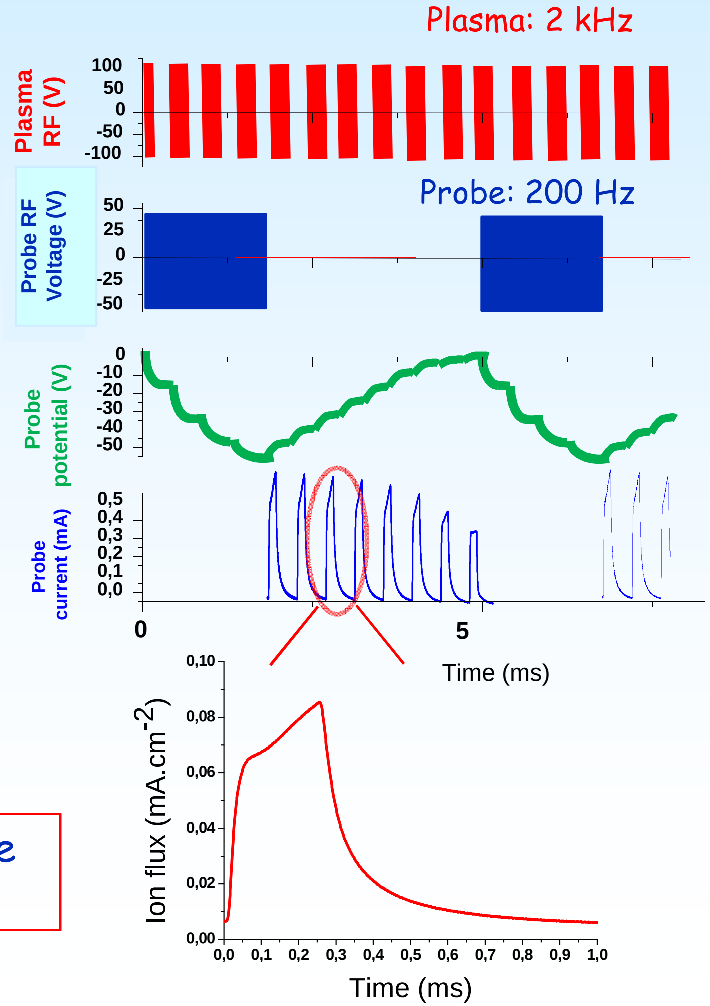
Current (ion flux) measurement in pulsed plasmas

Issue: several plasma pulses are needed to charge blocking capacitor to - 40 V

→ Probe pulsing frequency < Plasma pulsing frequency (but synchronized)

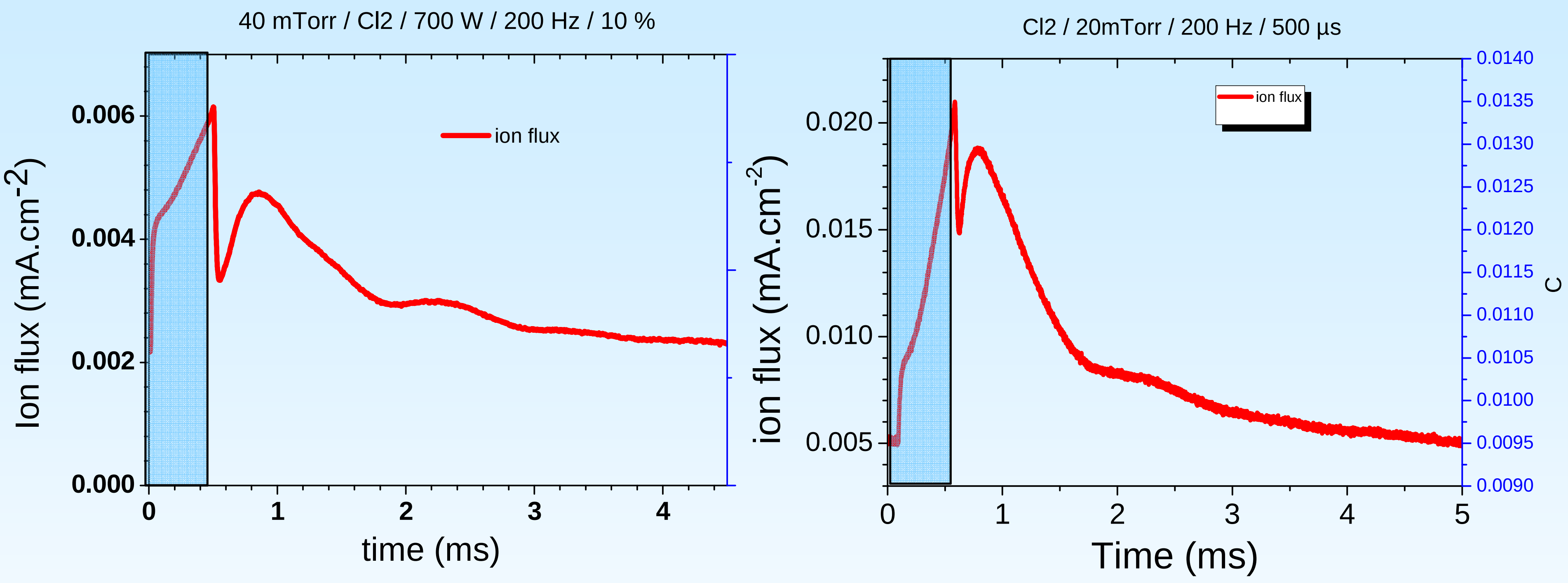
→ Use a frequency divider triggered by the plasma pulses to trigger probe pulses at f/10





→time variations of ion flux during one plasma pulse with an incredible S/N ratio

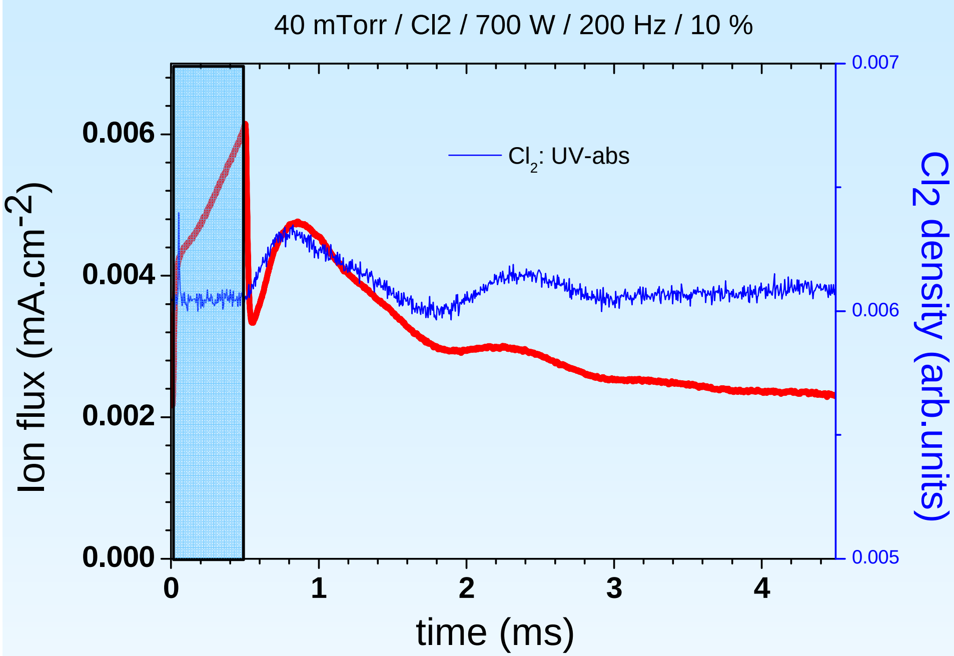
Time-variations of ion flux in pulsed Cl_2 plasma

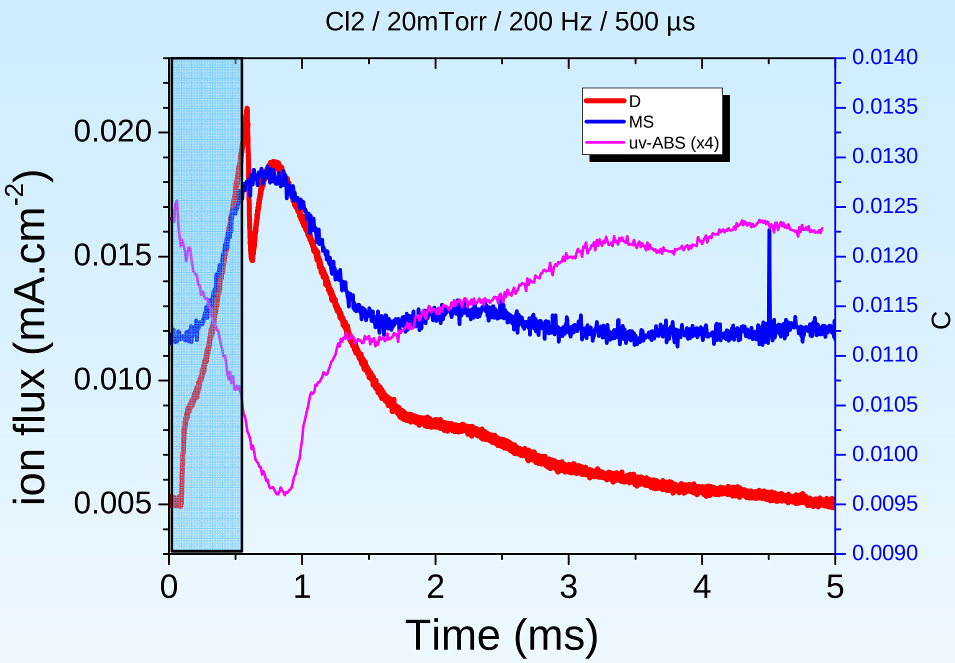


The ion flux is also strongly oscillating in the afterglow (and glow) !!!

Correlation with neutral density oscillations ?

Time-variations of ion flux in pulsed Cl_2 plasma



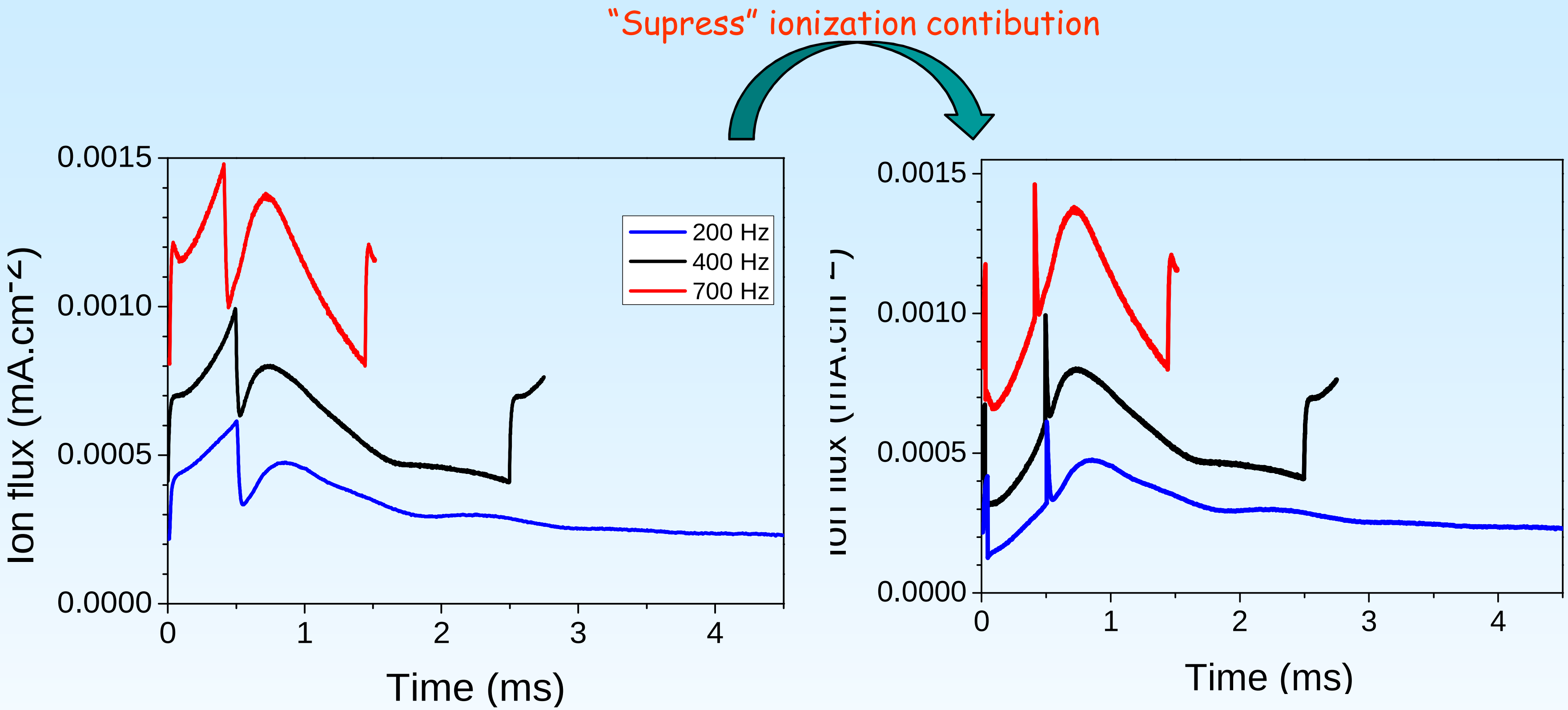


Ion flux at walls is oscillating in phase with accoustic wave !

→ Thanks to frictions forces the neutral « wind » of the accoustic wave pushes ions back and forth towards the reactor walls thus modulating their flux !!!

→ The effect is strong in afterglow (ambipolar field is weak) and obvious when the ion flux is small

Revealing the shape of the ion flux wave caused by the pressure wave



Amazing observation: the time-variations of the ion flux are predominantly driven by the neutral pressure wave and not by ionisation → the ON period just « adds » an extra-ion flux on top of it.

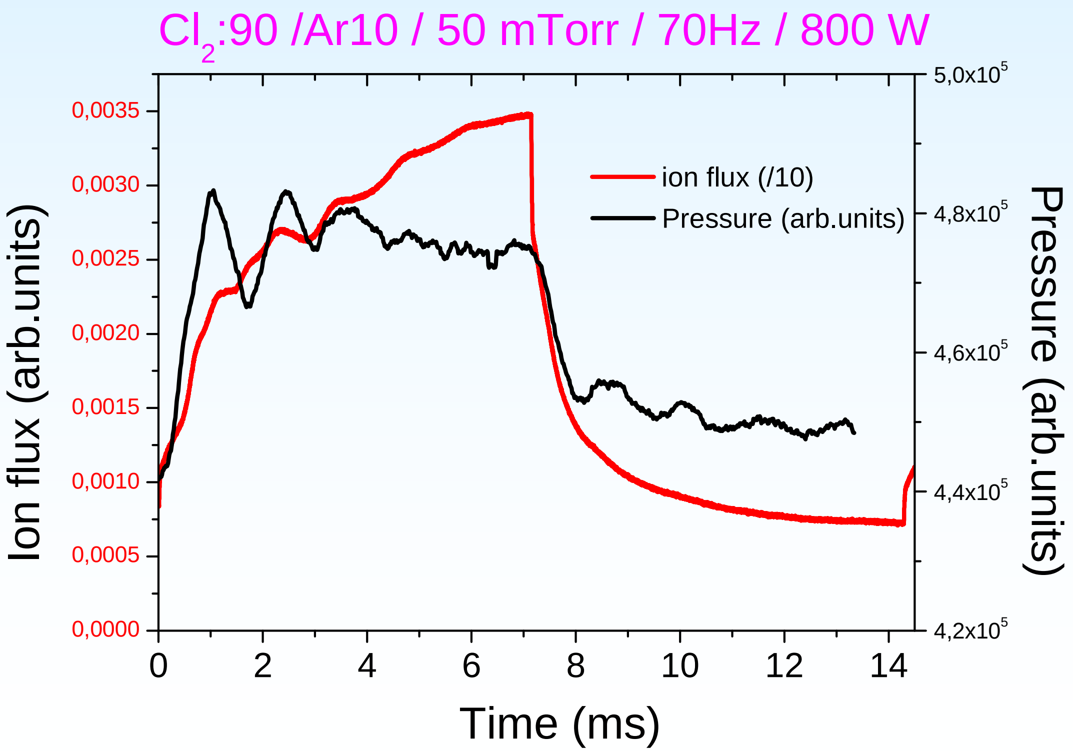
At 700 Hz, the system is probably near accoustic resonnace

Conclusions

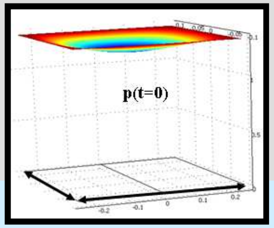
Pressure waves have been observed in pulsed ICP plasmas

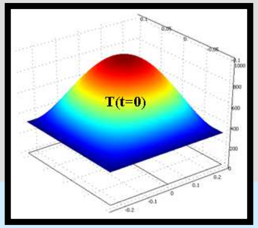
They most probably originate from electron pressure variations, which in turn generate a neutral pressure variation

The neutral-ions friction forces then produce ions flux waves



Afterglow model: P_n depleted + gas heating





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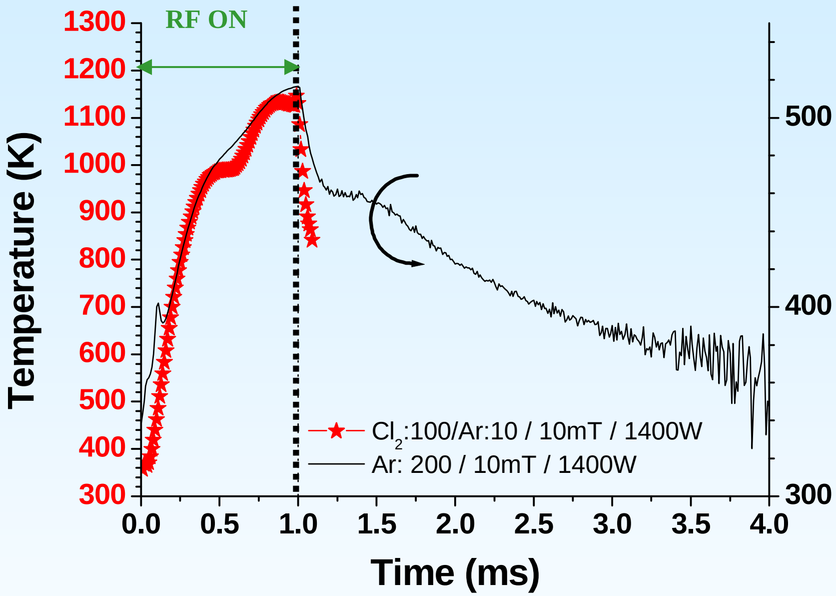

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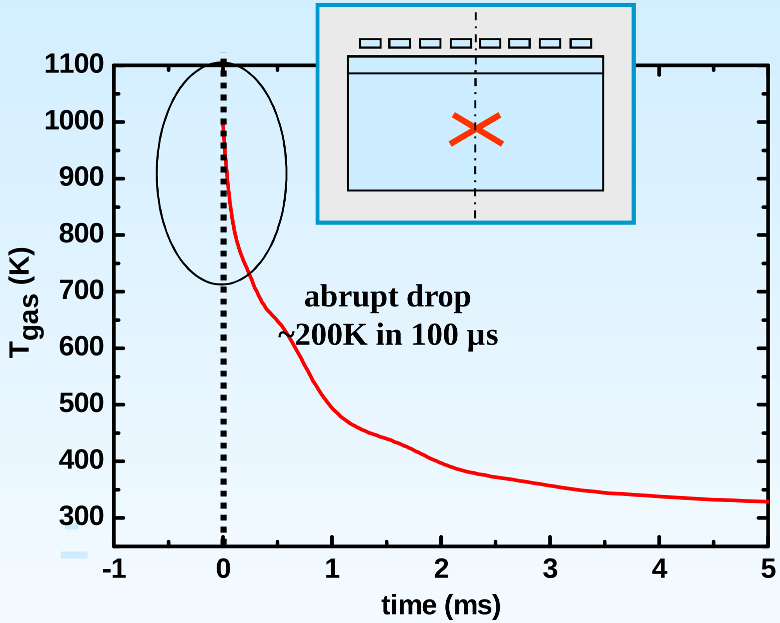

▪ **Fast drop during initial 100 µs (invasion of high density region by cold gas present at walls) followed by a slower T cooling (attributed to the heat conduction to the walls on the millisecond timescale).**

⇒ How fast the gas moves from outer regions toward the central high density volume ?

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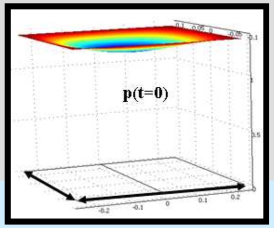

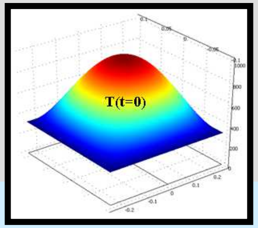

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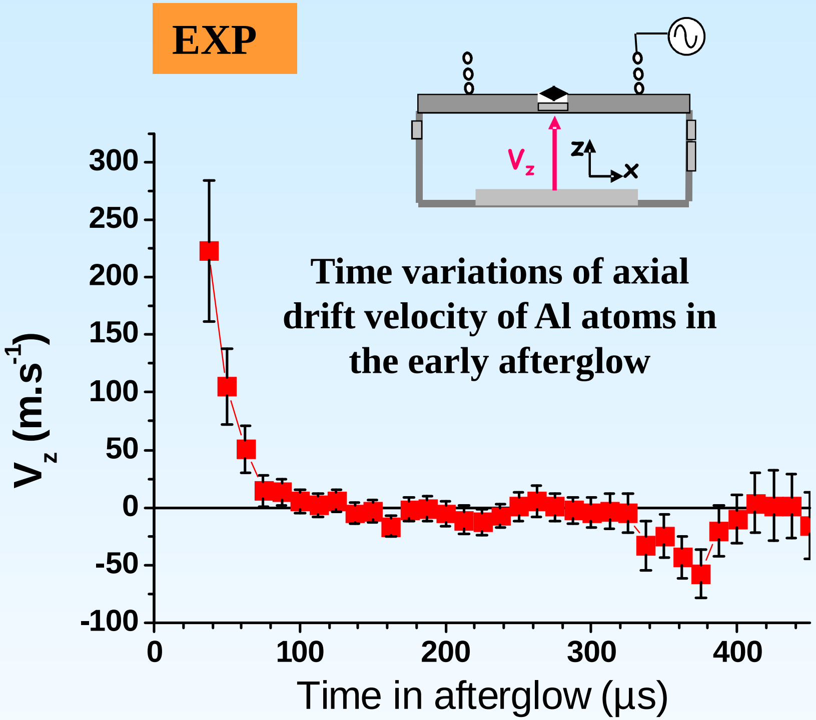

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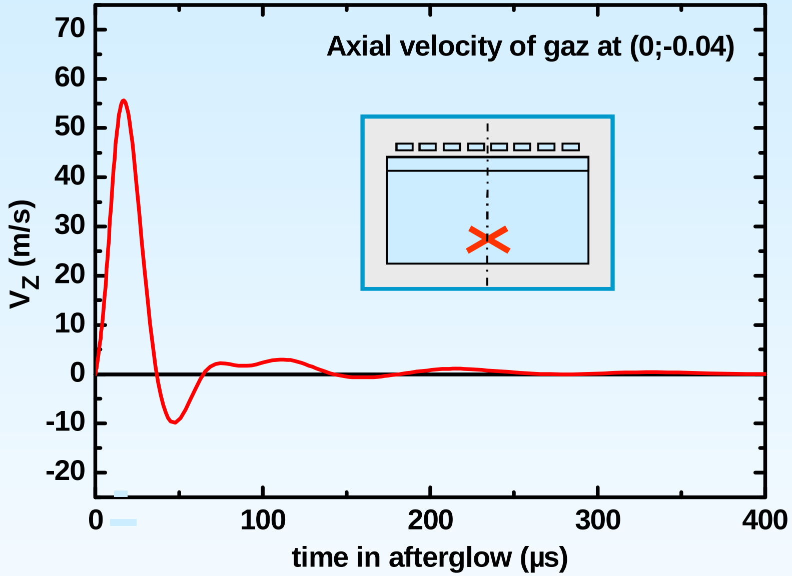


- **Atoms drift from bottom to middle of the reactor**

⇒ gas moves from outer regions toward the central high density volume, and since the gas is much colder near the walls, we observe a rapid cooling of the gas in the middle of the chamber in the early afterglow

Experimental set-up for gas temperature measurement

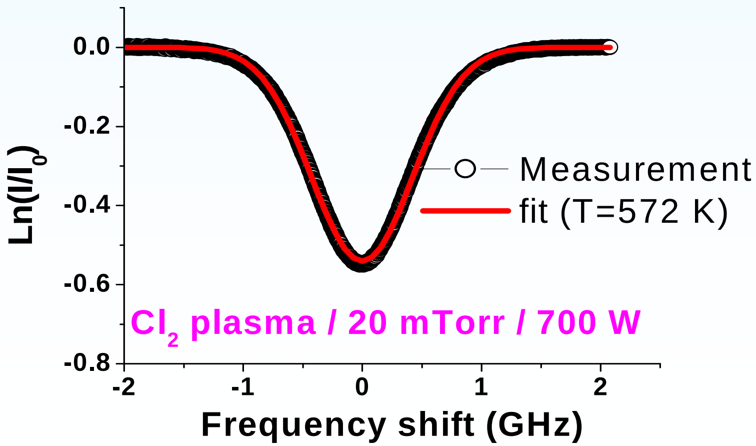
Ar is introduced in small amount (10 %) in the Cl_2 plasma

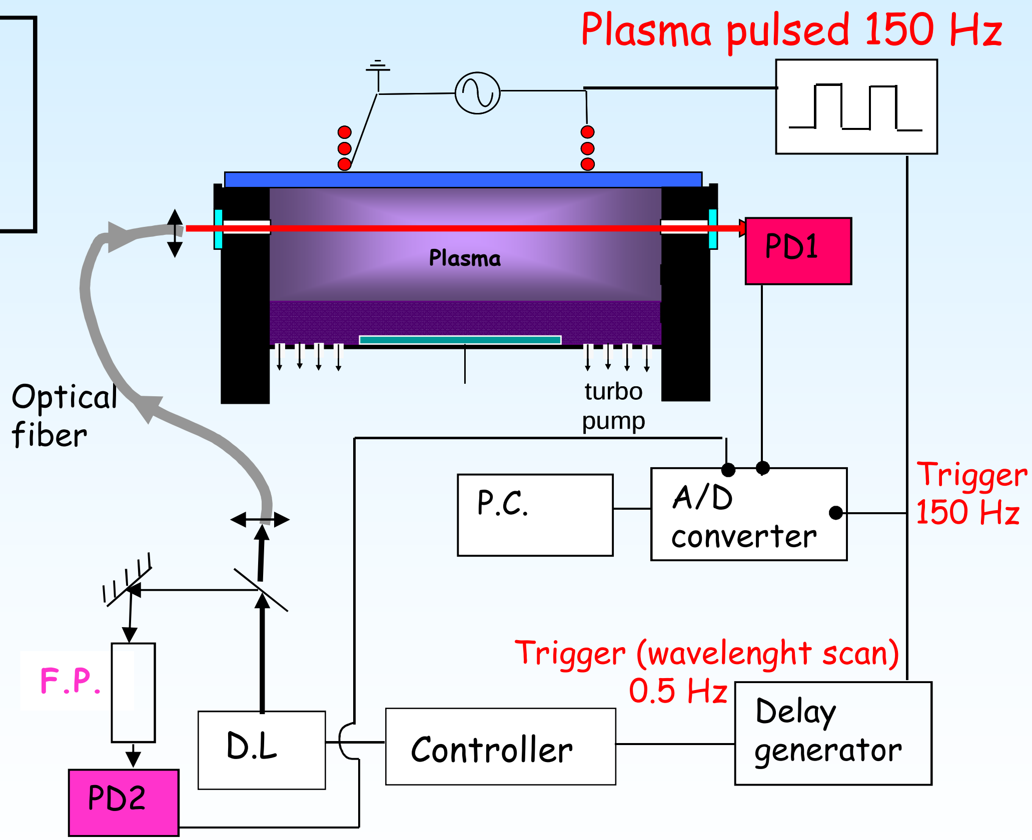
T_{gas} is deduced from the Doppler width of an absorption line from either Ar* metastable atoms or Al atoms (in thermodynamic equilibrium with gas)

Laser wavelength is scanned around the absorbing line (811.5 nm or 396 nm)

$\rightarrow$ Doppler profile $\rightarrow T_{gas}$

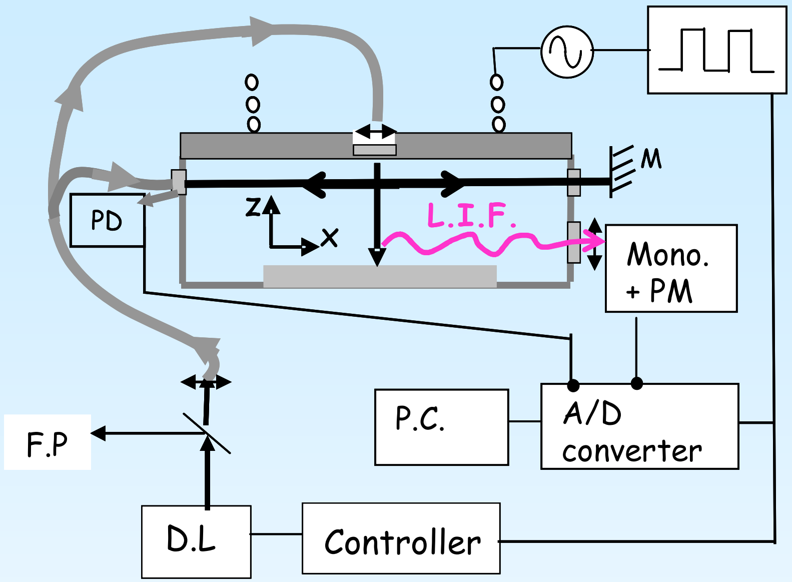
$$\delta\nu_D(\mathrm{GHz}) = 7.16 \cdot 10^{-16} \nu_0 \sqrt{T/M}$$





For details about Time resolved T° measurement see PSST 19, p34017, 2010

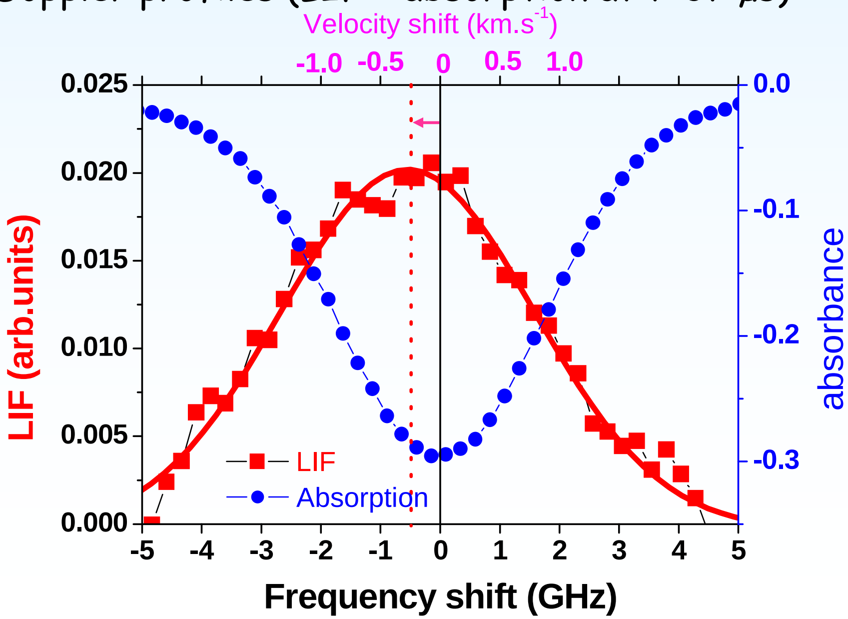
Experimental evidence: measurement of Al axial velocity by LIF



Doppler profile of Al atoms is measured simultaneously by L.I.F and absorption in the afterglow.

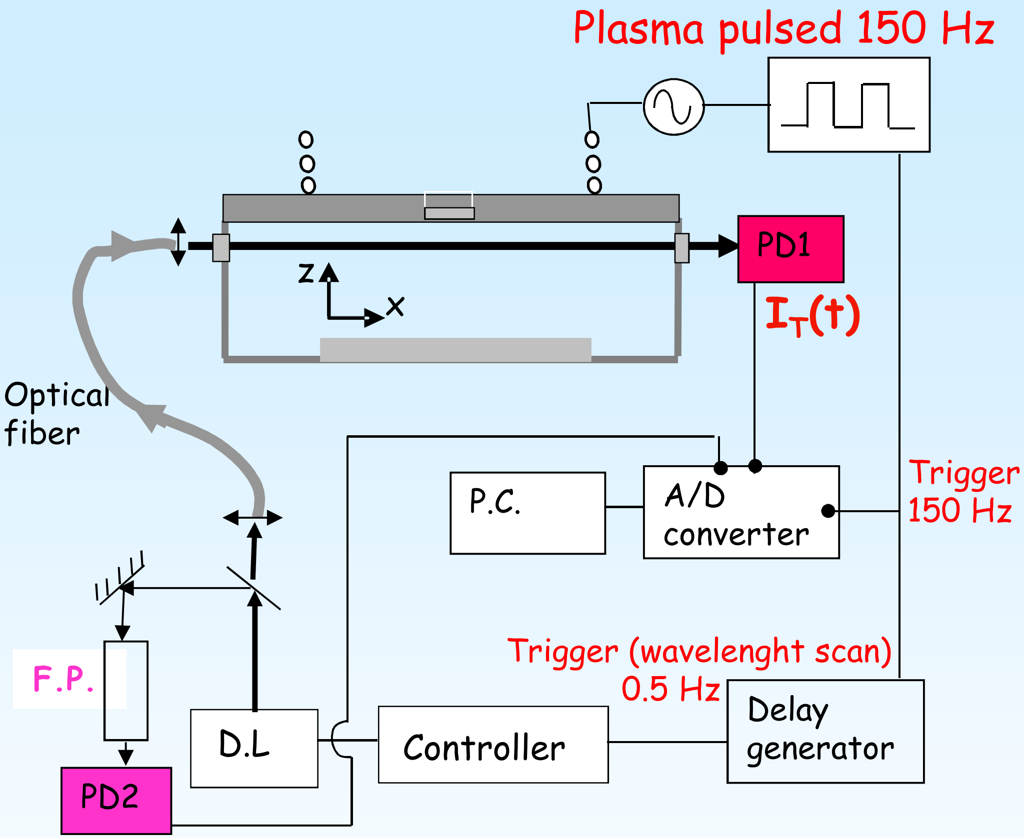
LIF is excited by the laser in the axial direction: if the gas moves vertically the Doppler profile measured by LIF will be shifted toward lower wavelength compared to the absorption (unshifted by symmetry)

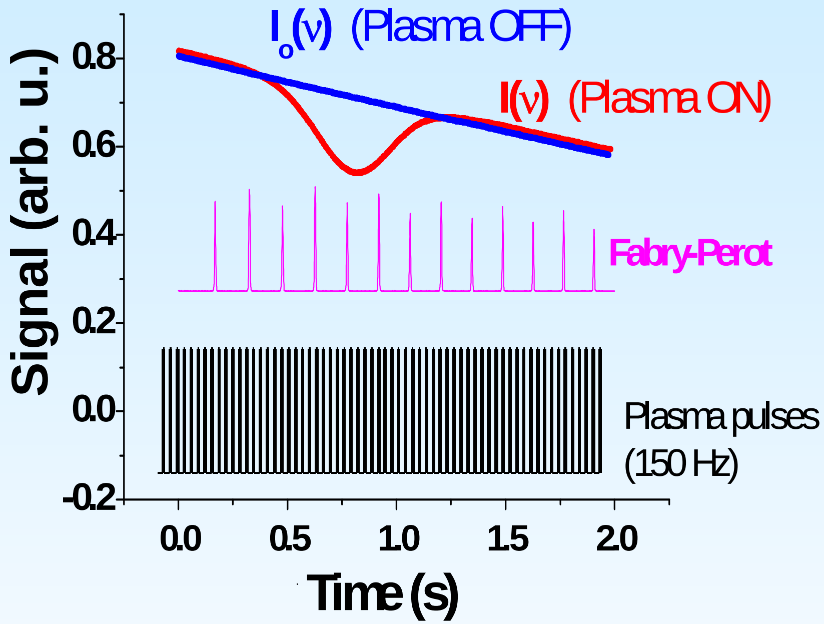
Doppler profiles (LIF + absorption at t=37 μs)



In early afterglow the Doppler profile measured by LIF is shifted / absorption
⇒ the gas moves from bottom to the top of the reactor at about 250 $m.s^{-1}$!

Gas temperature measurement in *pulsed discharges*



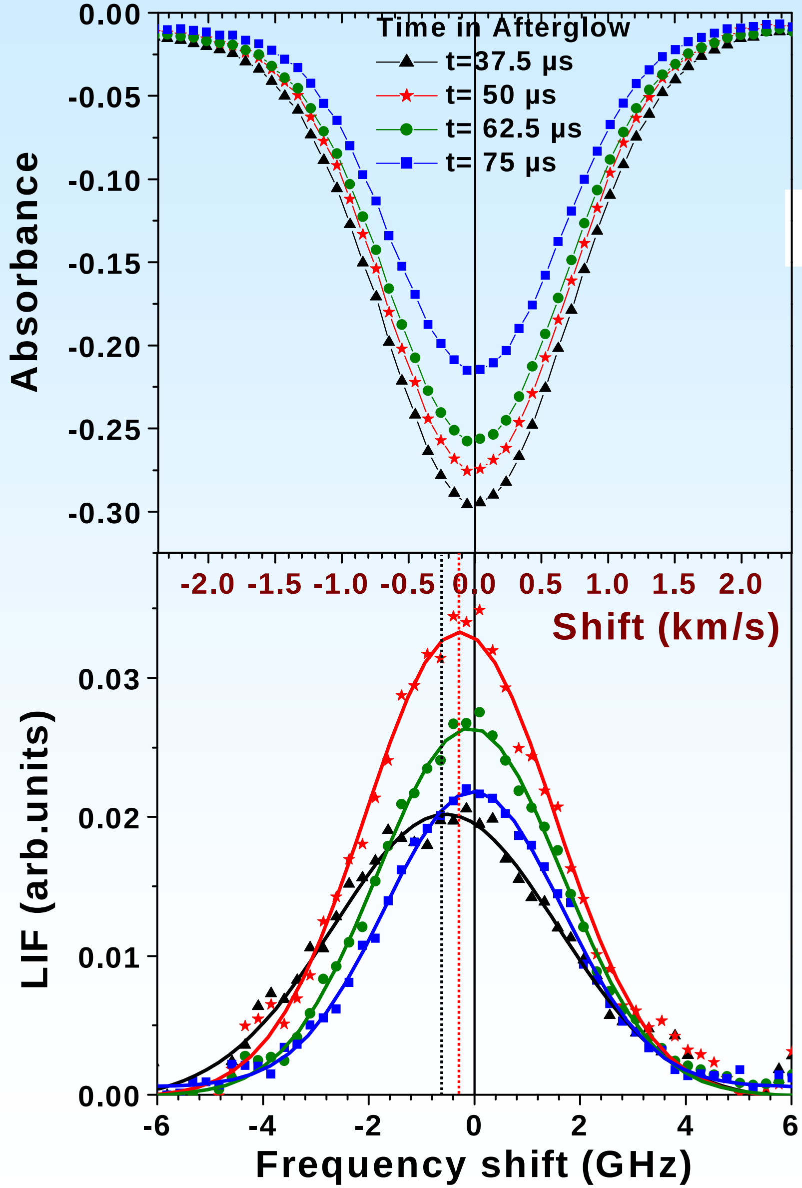


- Signal acquisition synchronized with the plasma pulses: record $I_T(t)$ over each pulsing period
- Laser wavelength is scanned slowly (0.5 Hz) compared to plasma pulsing frequency (150 Hz)

$\Rightarrow$ **During each plasma pulse the laser wavelength is $\approx$ constant**

$\Rightarrow$ We can reconstruct the Doppler profile at each time during one plasma pulse and thus capture the time variations of T_{gas}

Experimental evidence: measurement of Al axial velocity by LIF



Radial velocity profile, by absorption

Axial velocity profile, by LIF

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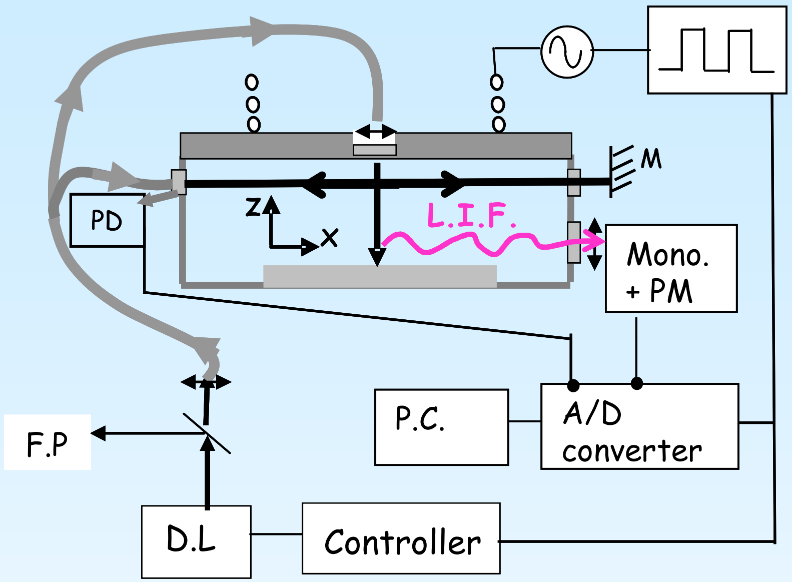

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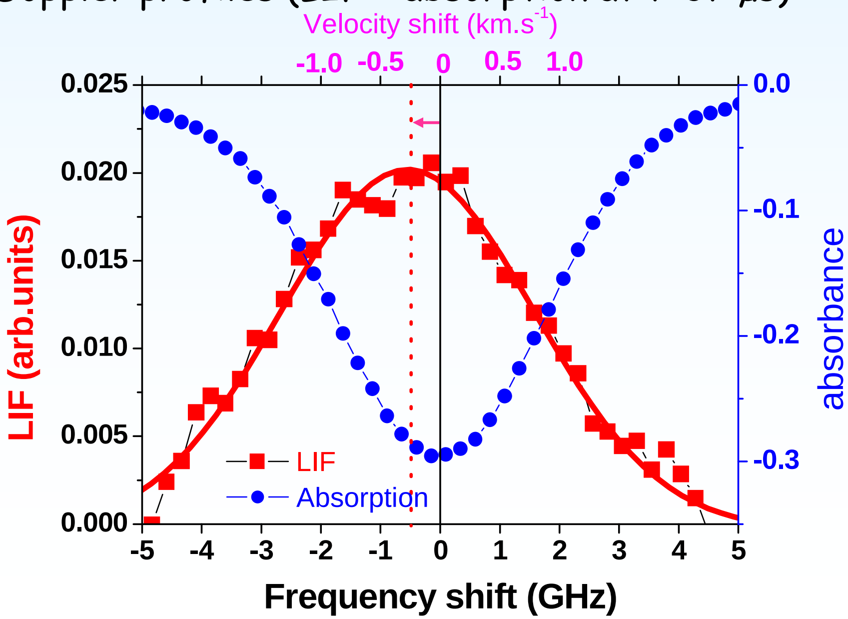

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