Effets de la pression sur les Plasmas d'Entrée Atmosphérique Planétaire et sur les Plasmas induits par Laser

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Horizon 2020

CENTRE NATIONAL D'ÉTUDES SPATIALES

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Sommaire

Earth Natural Entries…

Police patrol at Edmonton, Canada

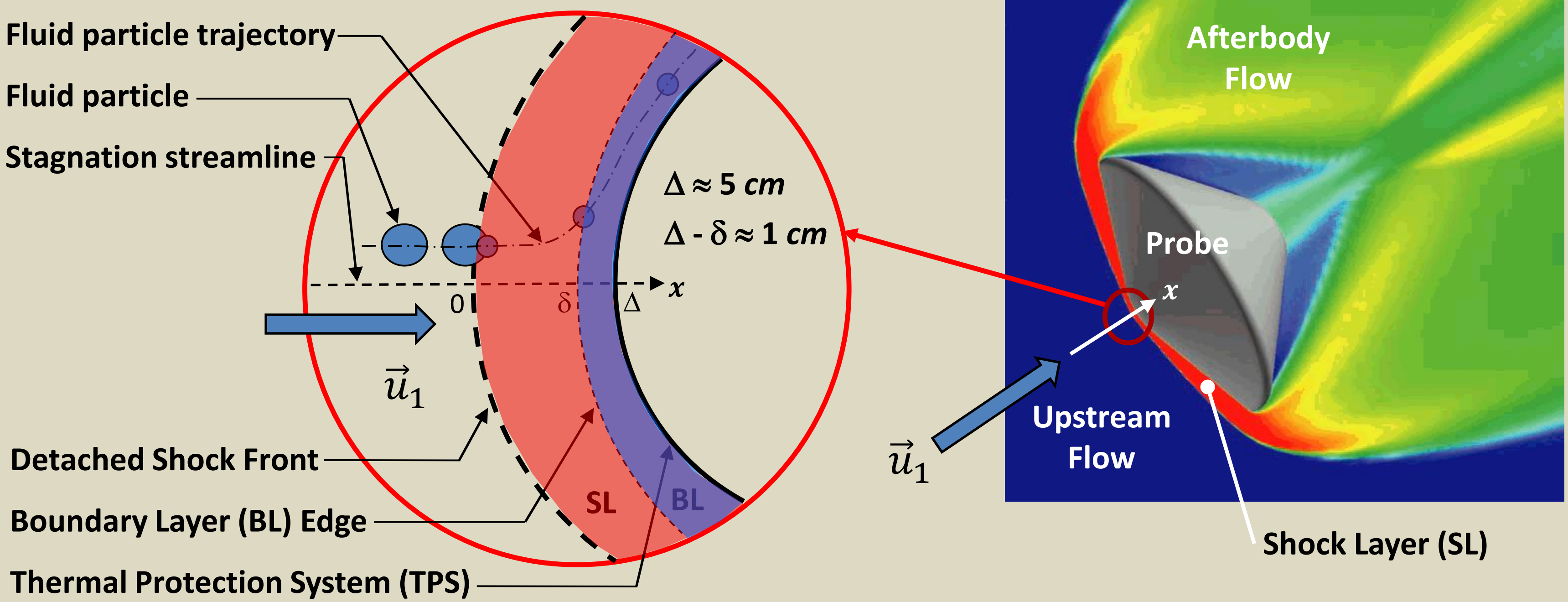
(November, 20th 2008, 23:30 UTC)

Chelyabinsk, Russia

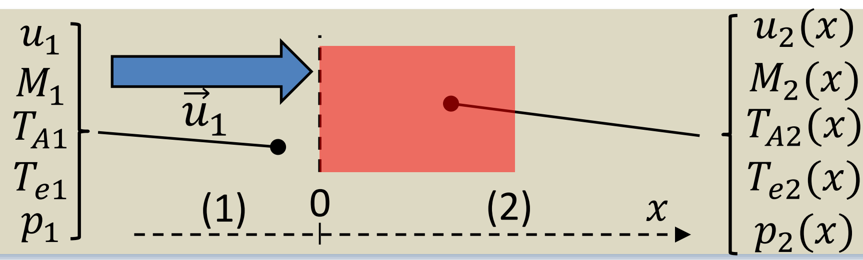
(February, 15th 2013, 03:20 UTC)

Simplification along the stagnation streamline

(u_1 5 to 15 $km\ s^{-1}$)



Post-shock relaxation



$u_2(0), M_2(0), T_{A2}(0), T_{e2}(x), p_2(0)$

Rankine-Hugoniot equations

RH1D codes

RH1D Eulerian codes

J. Annaloro and A. Bultel
JTHT **28** (2014) 608-622

Post-shock relaxation

Species ***Heavies at T_A***

Electrons at T_e

Balance equations (no diffusion)

1. Species balance →
$$\frac{dy_{X_m}}{dx} = \frac{m_{X_m} [\dot{X_m}]}{\rho u}$$

2. Momentum balance →
$$\frac{d(p + \rho u^2)}{dx} = 0$$

3. Energy balance

Heavies (atoms, molecules, ions)
$$\frac{d}{dx}\left[\frac{e_A}{\rho} + \frac{p_A}{\rho} + \frac{\rho_A}{\rho}\frac{u^2}{2}\right] = \frac{-Q_{A\to e} - \varepsilon_{Rad} - Q_{A-RR}}{\rho u}$$

Electrons
$$\frac{d}{dx}\left[\frac{e_e}{\rho} + \frac{p_e}{\rho} + \frac{\rho_e}{\rho}\frac{u^2}{2}\right] = \frac{Q_{A\to e} - \varepsilon_{RR} + Q_{A-RR}}{\rho u}$$

Collisional-radiative source terms

Radiative recombination $X^+ + e^- \to X_i + h\nu$

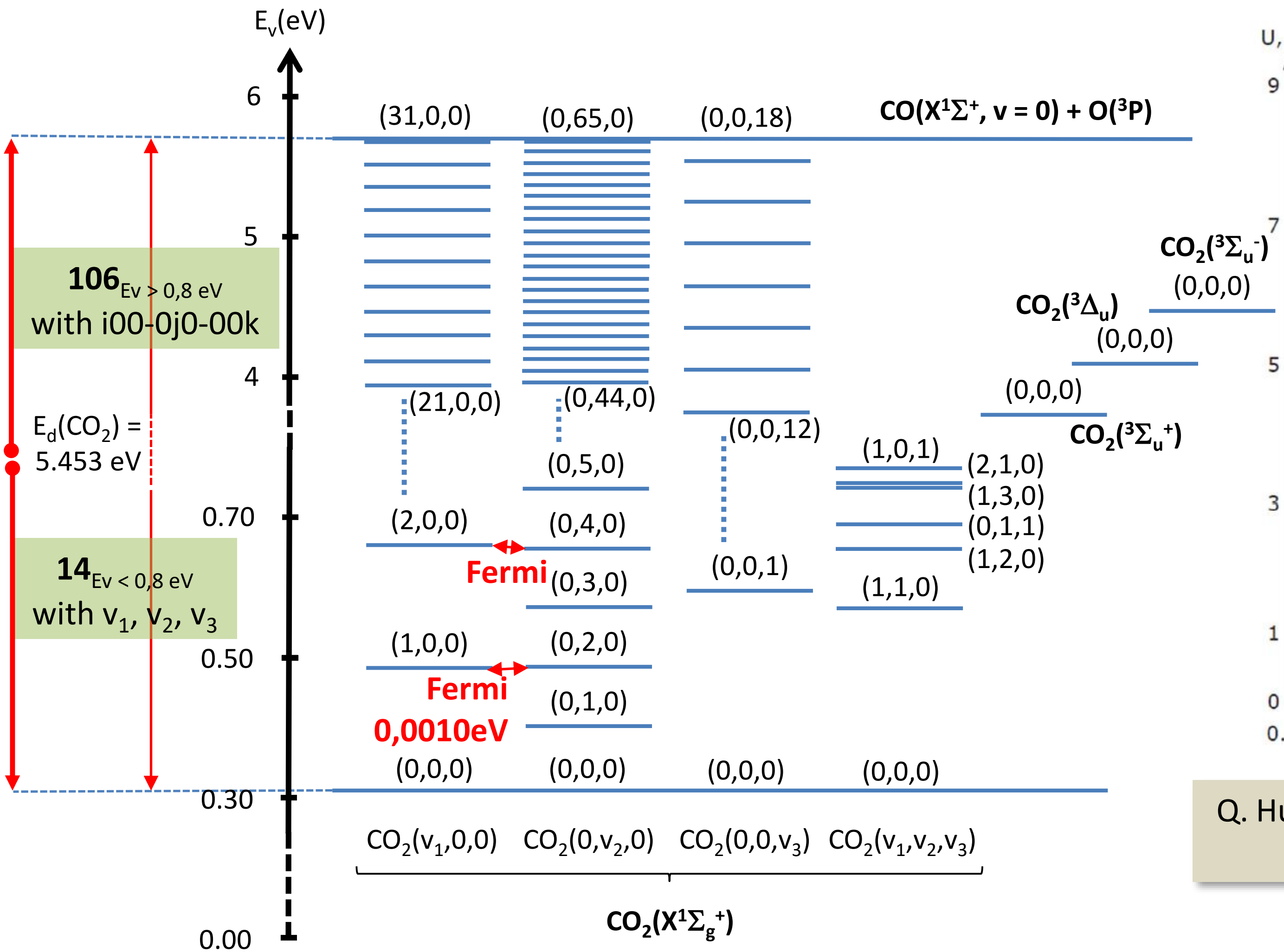
CoRaM-MARS

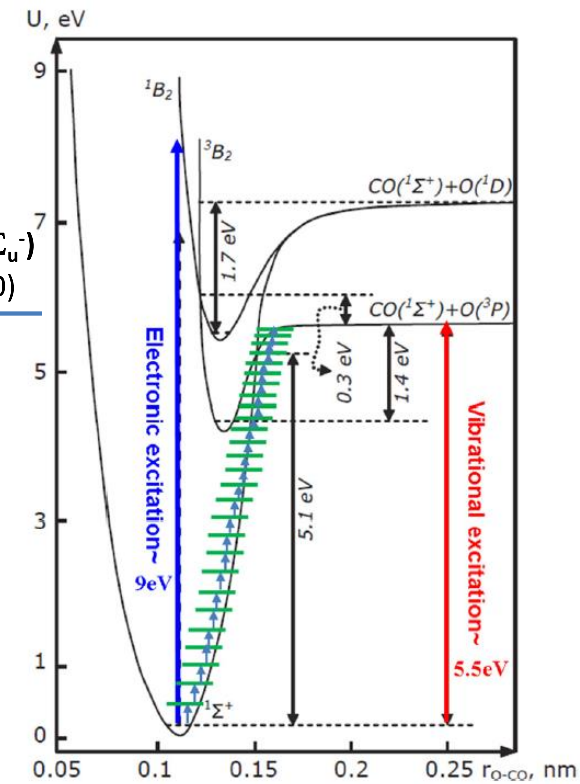
MARS atmosphere 96 % CO_2 2 % N_2 2% Ar

Type	21 species	1600 states
Molecules	CO_2	$X^1\Sigma_g^+$(14$_{Ev < 0,8\ eV}$ with v_1, v_2, v_3, and 106$_{Ev > 0,8\ eV}$ with i00-0j0-00k) $^3\Sigma_u^+$, $^3\Delta_u$, $^3\Sigma_u^-$
	N_2	$X^1\Sigma_g^+(v = 0 \rightarrow 67)$ $A^3\Sigma_u^+, B^3\Pi_g, W^3\Delta_u, B'^3\Sigma_u^-, a'^1\Sigma_u^-, a^1\Pi_g, w^1\Delta_u, G^3\Delta_g, C^3\Pi_u, E^3\Sigma_g^+$
	O_2	$X^3\Sigma_g^-(v = 0 \rightarrow 46)$ $a^1\Delta_g, b^1\Sigma_g^+, c^1\Sigma_u^-, A'^3\Delta_u, A^3\Sigma_u^+, B^3\Sigma_u^-, f^1\Sigma_u^+$
	C_2	$X^1\Sigma_g^+(v = 0 \rightarrow 36)$ $a^3\Pi_u, b^3\Sigma_g^-, A^1\Pi_u, c^3\Sigma_u^+, d^3\Pi_g, C^1\Pi_g, e^3\Pi_g, D^1\Sigma_u^+$
	NO	$X^2\Pi\ (v = 0 \rightarrow 53)$ $a^4\Pi, A^2\Sigma^+, B^2\Pi, b^4\Sigma^-, C^2\Pi, D^2\Sigma^+, B'^2\Delta, E^2\Sigma^+, F^2\Delta$
	CO	$X^1\Sigma^+\ (v = 0 \rightarrow 76)$ $a^3\Pi, a'^3\Sigma^+, d^3\Delta, e^3\Sigma^-, A^1\Pi, I^1\Sigma^-, D^1\Delta^-, b^3\Sigma^+, B^1\Sigma^+$
	CN	$X^2\Sigma^+\ (v = 0 \rightarrow 41)$ $A^2\Pi, B^2\Sigma^+, D^2\Pi, E^2\Sigma^+, F^2\Delta$
Molecular ions	N_2^+	$X^2\Sigma_g^+, A^2\Pi_u, B^2\Sigma_u^+, a^4\Sigma_u^+, D^2\Pi_g, C^2\Sigma_u^+$
	O_2^+	$X^2\Pi_g, a^4\Pi_u, A^2\Pi_u, B^4\Sigma_g^-$
	C_2+	$X^4\Sigma_g^-, 1^2\Pi_u, {}^4\Pi_u, 1^2\Sigma_g^+, 2^2\Pi_u, B^4\Sigma_u^-, 1^2\Sigma_u^+$
	NO^+	$X^1\Sigma^+, a^3\Sigma^+, b^3\Pi, W^3\Delta, b'^3\Sigma^-, A'^1\Sigma^+, W^1\Delta, A^1\Pi$
	CO^+	$X^2\Sigma^+, A^2\Pi, B^2\Sigma^+, C^2\Delta$
	CN^+	$X^1\Sigma^+, a^3\Pi, {}^1\Delta, c^1\Sigma^+$
Atoms	N	${}^4S°_{3/2}, {}^2D°_{5/2}, {}^2D°_{3/2}, {}^2P°_{1/2}$, ...(252 states)
	O	${}^3P_2, {}^3P_1, {}^3P_0, {}^1D_2$, ...(127 states)
	C	${}^3P_0, {}^3P_1, {}^3P_2, {}^1D_2$, ...(265 states)
	Ar	${}^1S_0, {}^2[3/2]°_2, {}^2[3/2]°_1, {}^2[1/2]°_0$, ... (379 states)
Atomic ions	N^+	${}^3P_0, {}^3P_1, {}^3P_2, {}^1D_2$, ... (9 states)
	O^+	${}^4S°_{3/2}, {}^2D°_{5/2}, {}^2D°_{3/2}, {}^2P°_{3/2}$, ...(8 states)
	C^+	${}^2P°_{1/2}, {}^2P°_{3/2}, {}^4P_{1/2}, {}^4P_{3/2}$, ...(8 states)
	Ar^+	${}^2P°_{3/2}, {}^2P°_{1/2}, {}^2S_{1/2}, {}^4D_{7/2}$, ... (7 states)

Vibrational states of CO_2

MARS atmosphere 96 % CO_2 2 % N_2 2% Ar





Q. Huang *et al.*, J. Phys. D: Appl. Phys. **50** 294001 2017

CoRaM-MARS

Elementary processes $T_e \neq T_A$

Collisional processes	(e- and h-) vibrational processes
	(e- and h-) electronic excitation
	Excitation transfer
	Dissociation
	Ionisation
	Charge exchange
	Dissociative recombination
Radiative processes	Main molecular systems
	Main atomic transitions
« Dual » processes	Radiative recombination
	Dielectronic recombination

→ ~ **1 000 000** elementary processes

Rate coefficients and Einstein coefficients

Rate coefficients Forward rate coefficients

$$k_i(T_{A,e}) = \sqrt{\frac{8\,k_B\,T_{A,e}}{\pi\,\mu}} \int_{x_0}^{+\infty} x\,e^{-x}\,\sigma_i(x)\,dx$$

with $\sigma_i(x)$ the cross section and $x = \frac{\varepsilon}{k_B\,T_{A,e}}$ the reduced collision energy

Backward rate coefficients from Detailed Balance

Einstein coefficients NIST database

Ionisation/recombination by heavy particle impact under thermal non equilibrium

$$X_i + M \underset{k_R}{\overset{k_I}{\rightleftarrows}} X^+ + e^- + M$$

J. Annaloro, P. Teulet, A. Bultel *et al.*
Eur. Phys. J. D. **17** (2017) 342

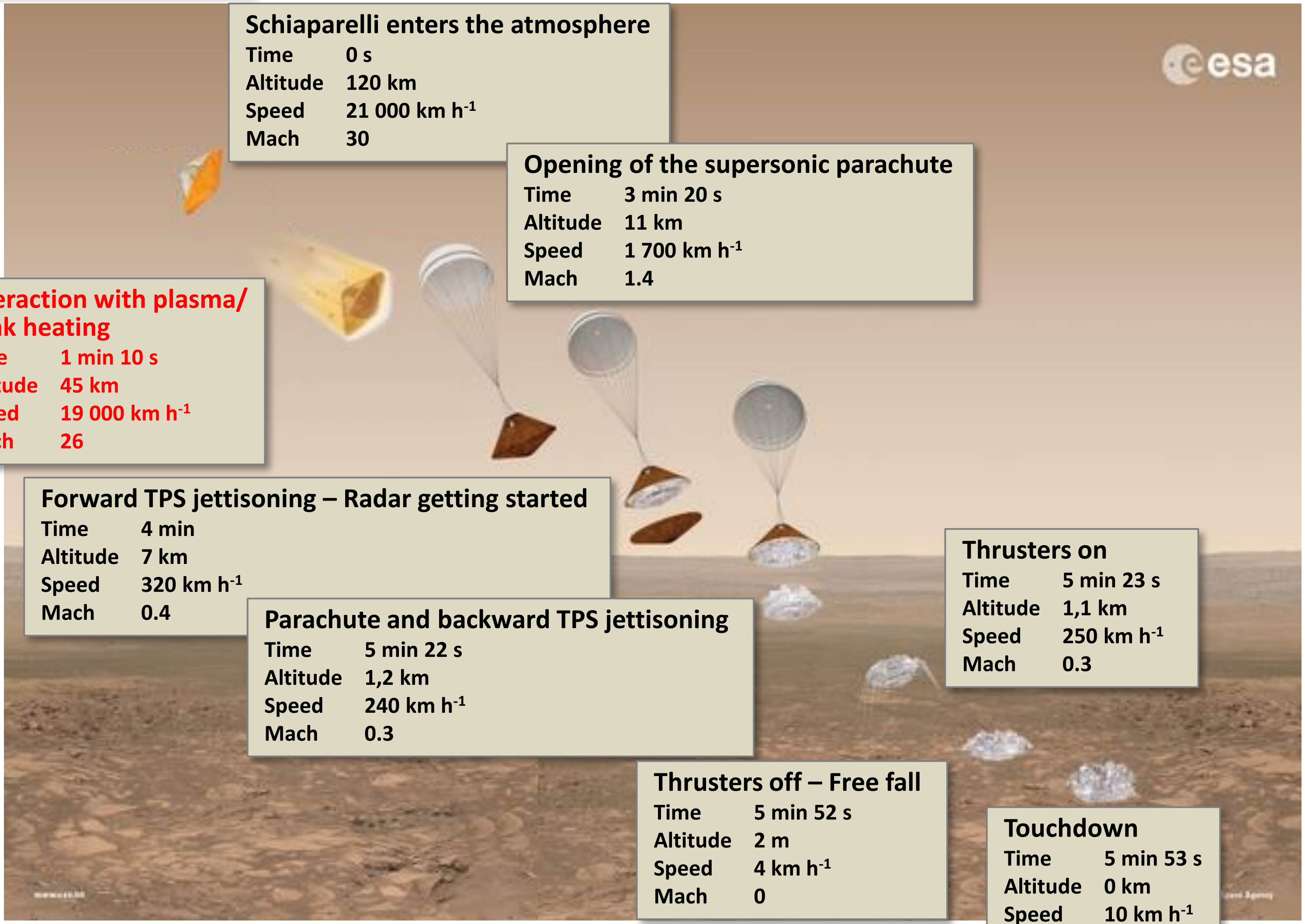
k_I **depends on** T_A

k_R **depends on** T_A **and** T_e

$$\frac{k_I}{k_R} = \frac{g_+\,g_e}{g_i}\left(\frac{2\pi\,m_e\,k_B\,T_e}{h^2}\right)^{3/2} e^{-\frac{E_i^{ioni}}{k_B T_A}}$$

EXOMARS mission

October, 19th 2016



Schiaparelli enters the atmosphere
Time 0 s
Altitude 120 km
Speed 21 000 km h^{-1}
Mach 30

Interaction with plasma/ peak heating
Time 1 min 10 s
Altitude 45 km
Speed 19 000 km h^{-1}
Mach 26

Opening of the supersonic parachute
Time 3 min 20 s
Altitude 11 km
Speed 1 700 km h^{-1}
Mach 1.4

Forward TPS jettisoning – Radar getting started
Time 4 min
Altitude 7 km
Speed 320 km h^{-1}
Mach 0.4

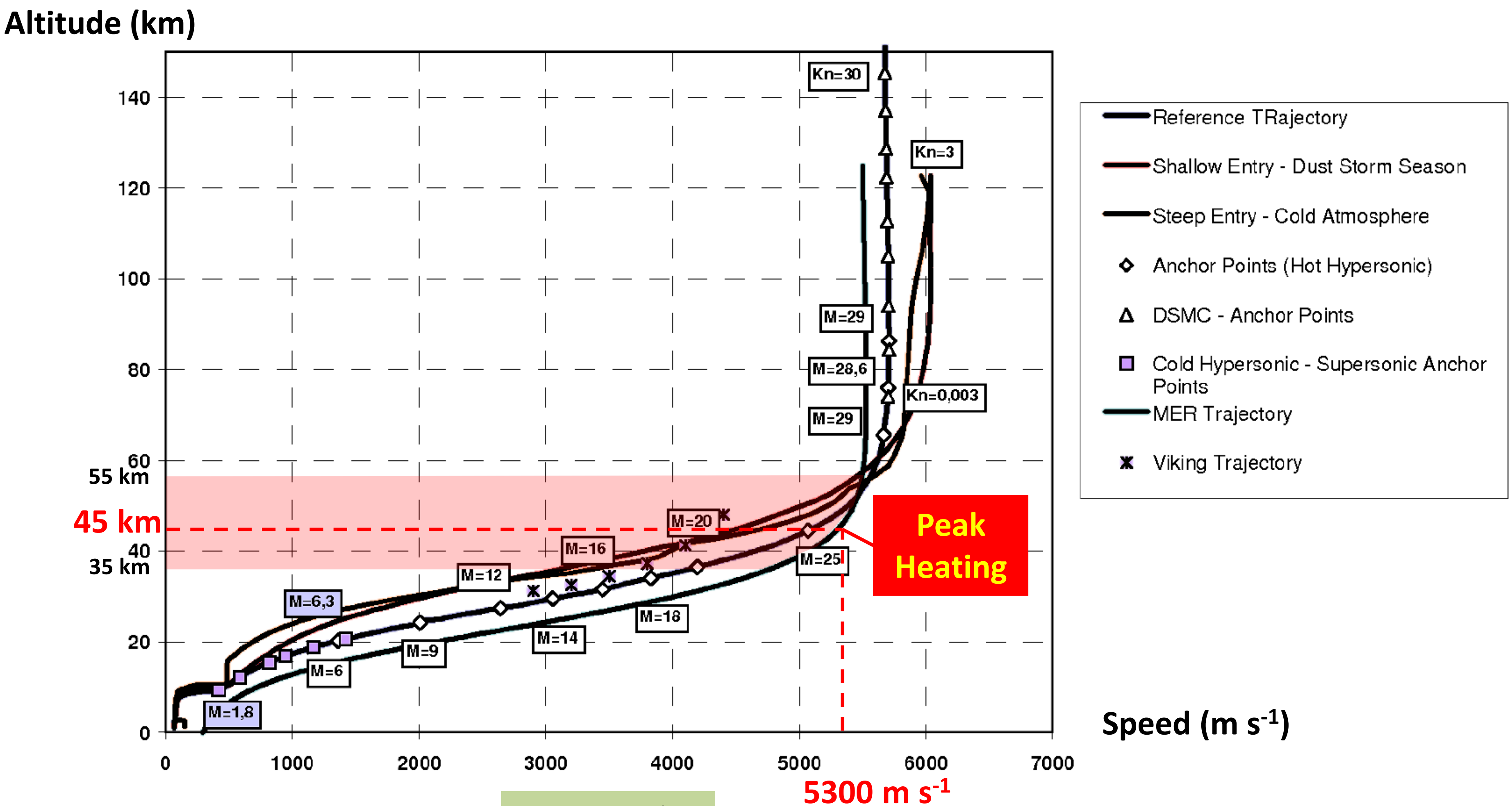
Parachute and backward TPS jettisoning
Time 5 min 22 s
Altitude 1,2 km
Speed 240 km h^{-1}
Mach 0.3

Thrusters on
Time 5 min 23 s
Altitude 1,1 km
Speed 250 km h^{-1}
Mach 0.3

Thrusters off – Free fall
Time 5 min 52 s
Altitude 2 m
Speed 4 km h^{-1}
Mach 0

Touchdown
Time 5 min 53 s
Altitude 0 km
Speed 10 km h^{-1}
Mach 0

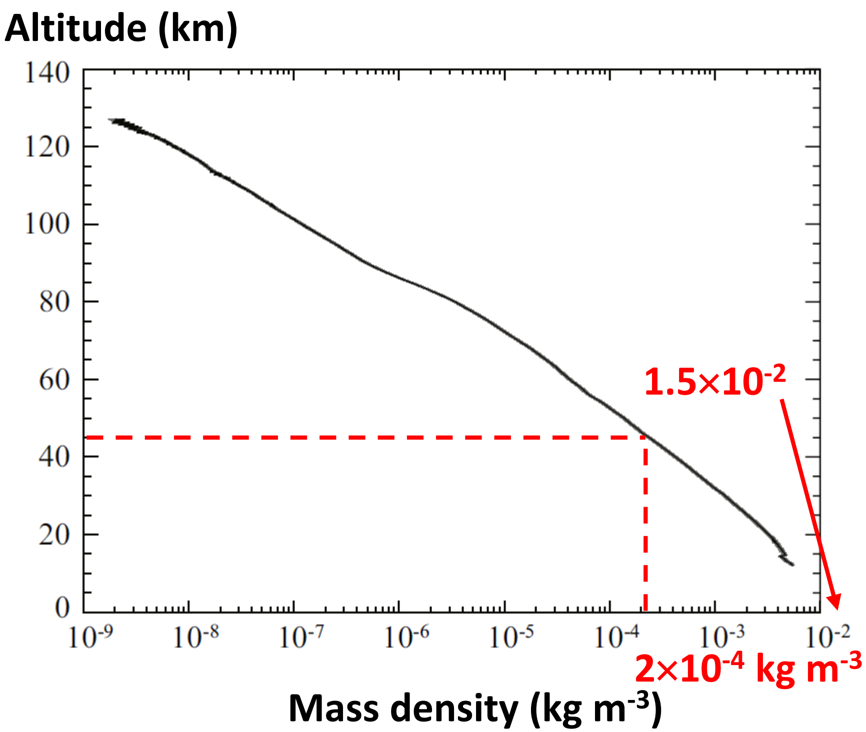
EXOMARS mission
October, 19th 2016

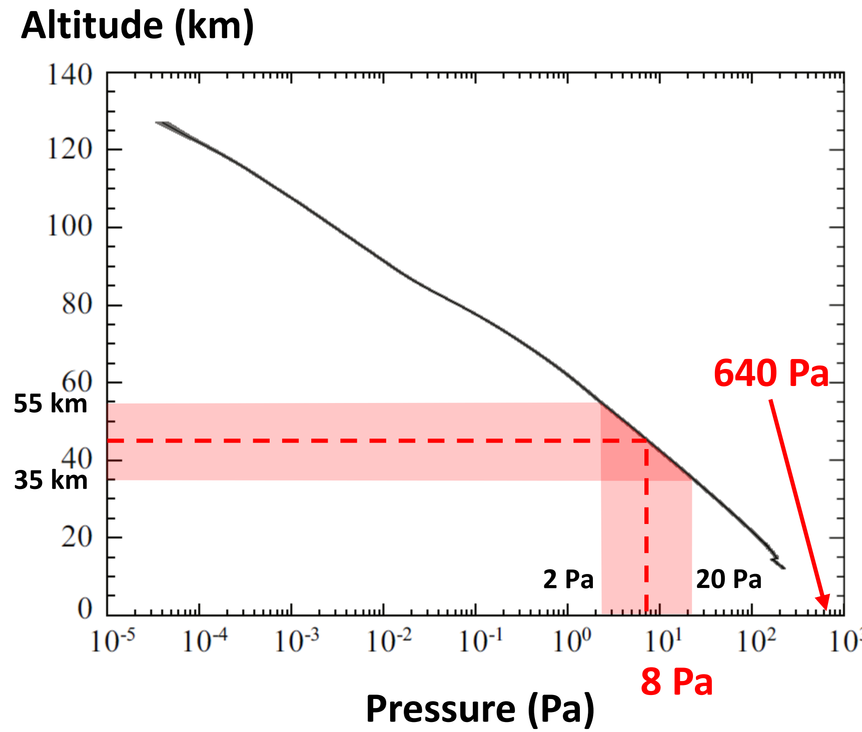


P. Tran *et al.*

ESA SP-692 (2011)

EXOMARS mission
October, 19th 2016





C. Holstein-Rathlou *et al.* Planet. Space Science **120** (2016) 15-23

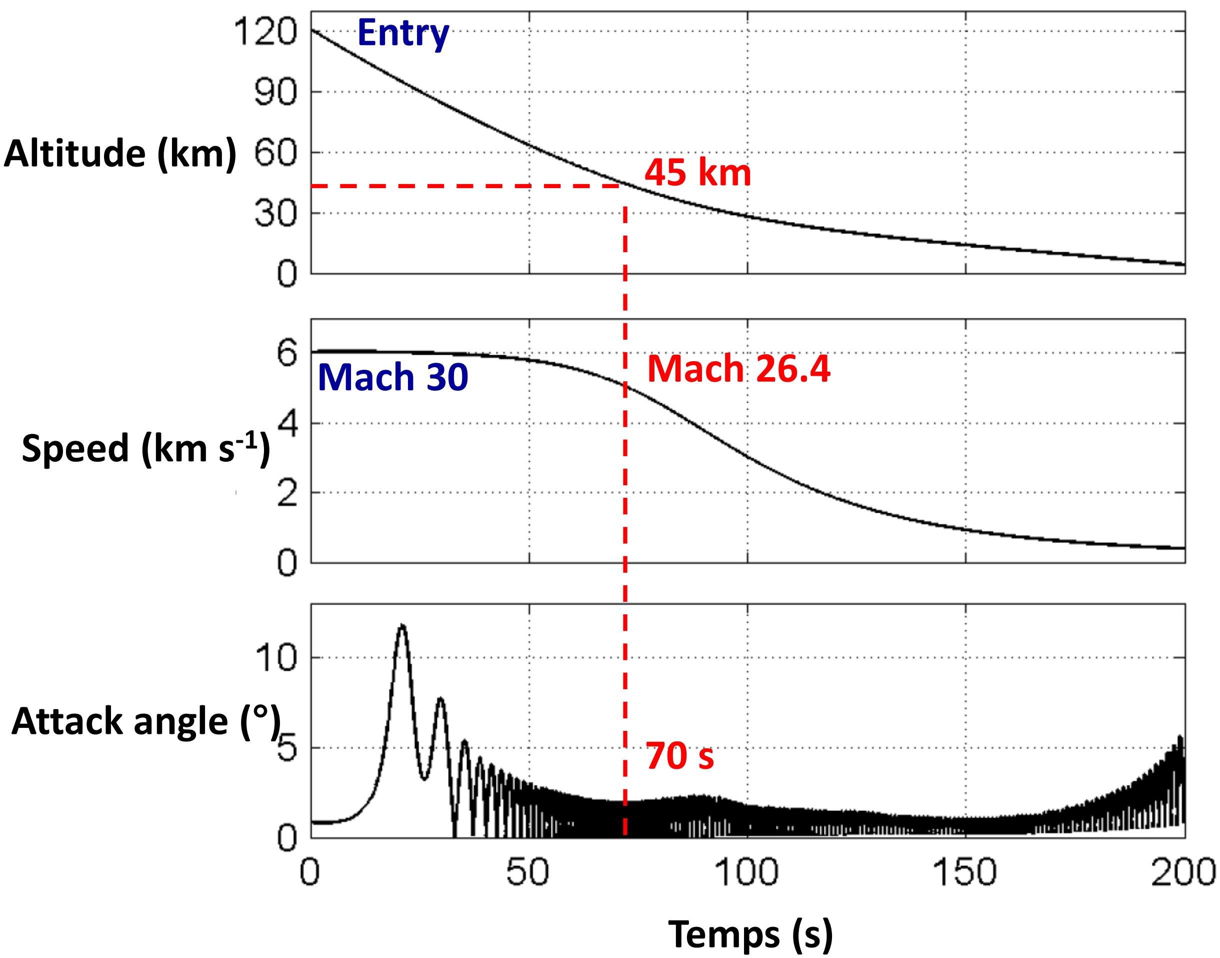
Chemical composition of the Martian atmosphere

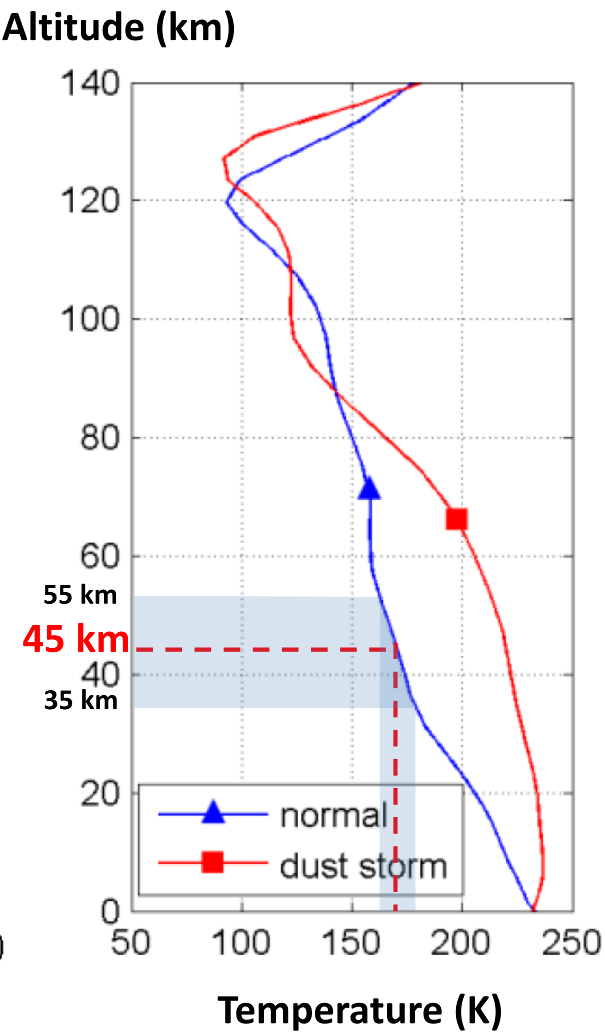
CO_2	95.97 %	**O_2**	0.146 %	**CH_2O**	130×10^{-7} %
Ar	1.93 %	**CO**	0.0557 %	**O_3**	30×10^{-7} %
N_2	1.89 %	**H_2O**	0.03 %	**CH_4**	10.5×10^{-7} %

Mole fractions

EXOMARS mission

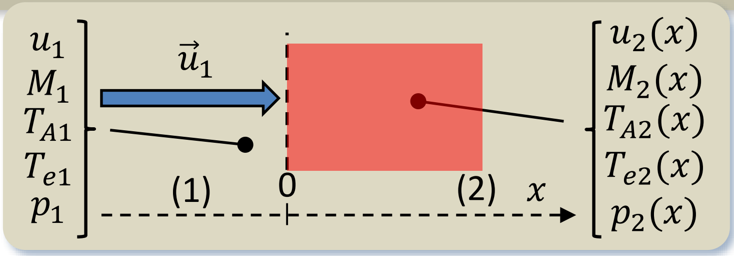
October, 19th 2016





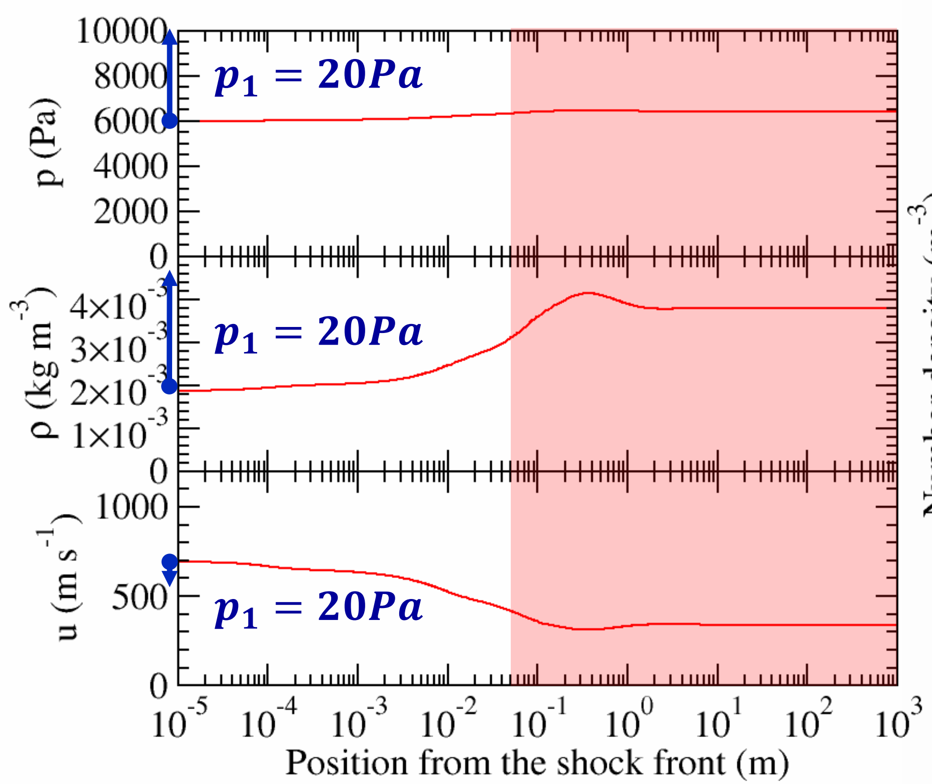
B. Van Hove *et al.* 10th IPPW 17-21 (2013)

CoRaM-MARS and RH1D codes…

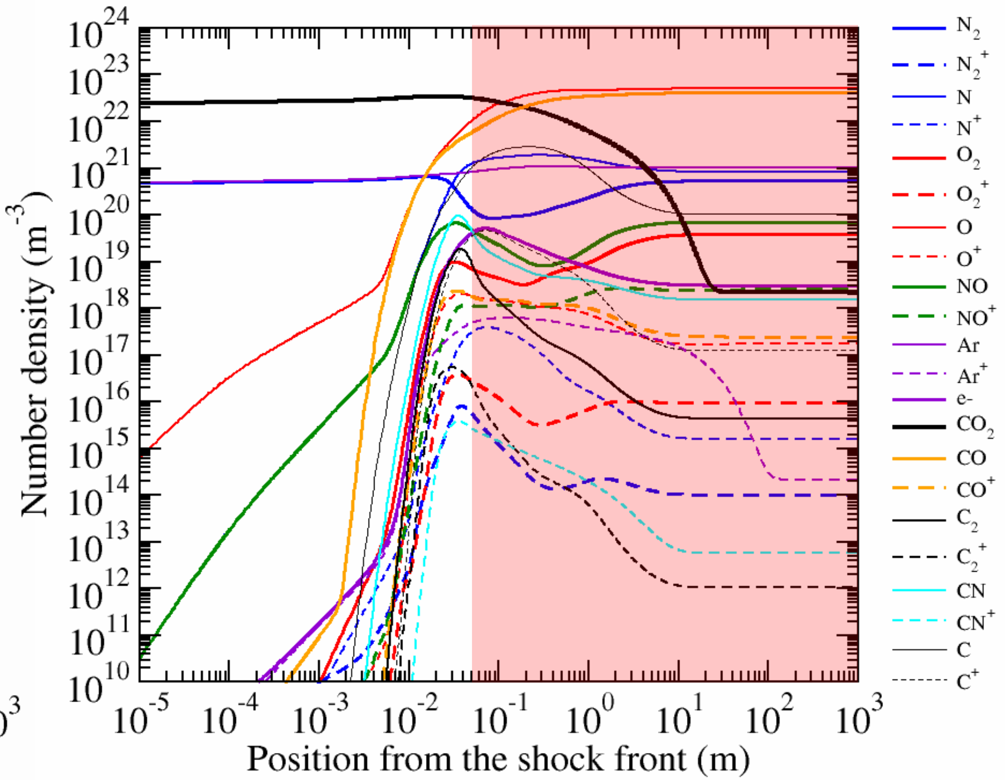


$p_1 = 8\ Pa$

Aerodynamic variables



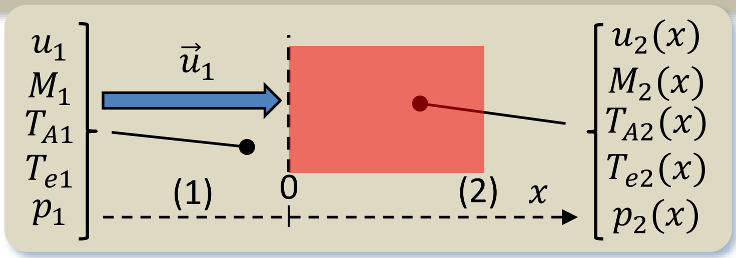
Species number densities



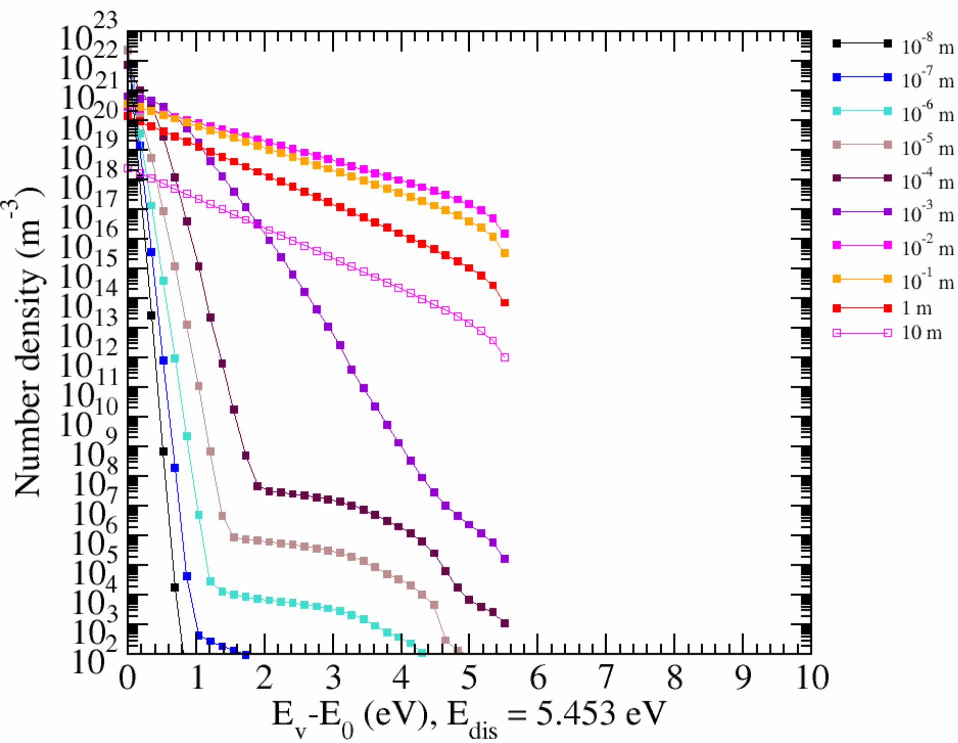
$T_{A2}(0) = 16800\ K$ $T_{A2}(0) = 10900\ K$

J. Annaloro and A. Bultel
To be published in Phys. Plasmas

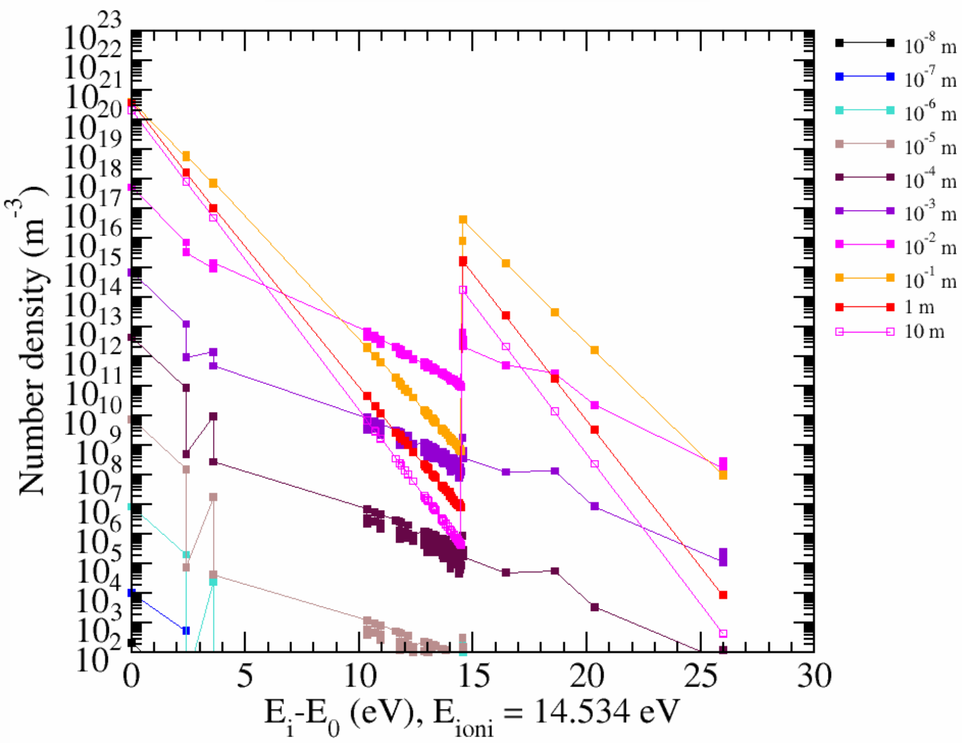
CoRaM-MARS and RH1D codes…



Boltzmann plots CO_2(i00)

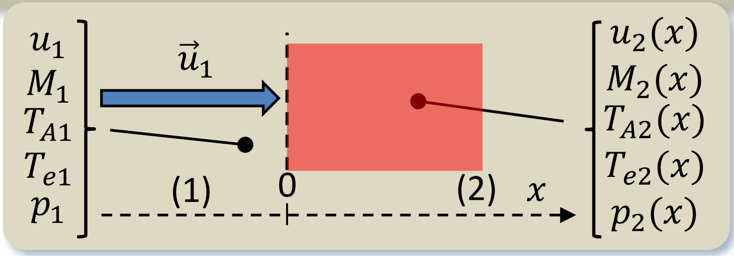


Boltzmann plots N and N^+



J. Annaloro and A. Bultel
To be published in Phys. Plasmas

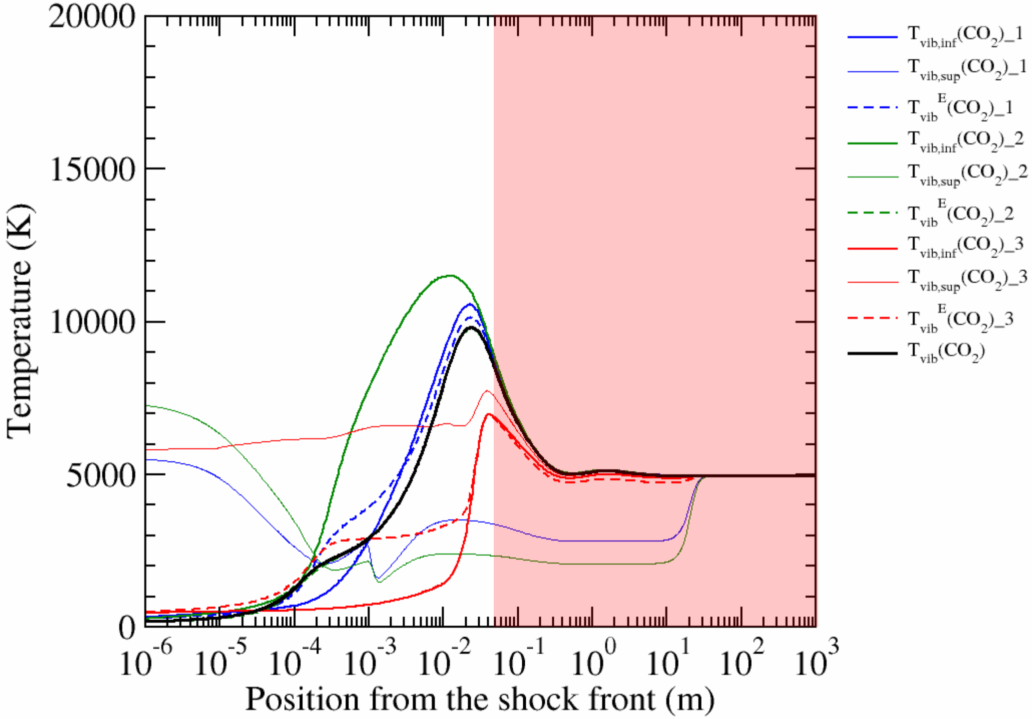
CoRaM-MARS and RH1D codes…



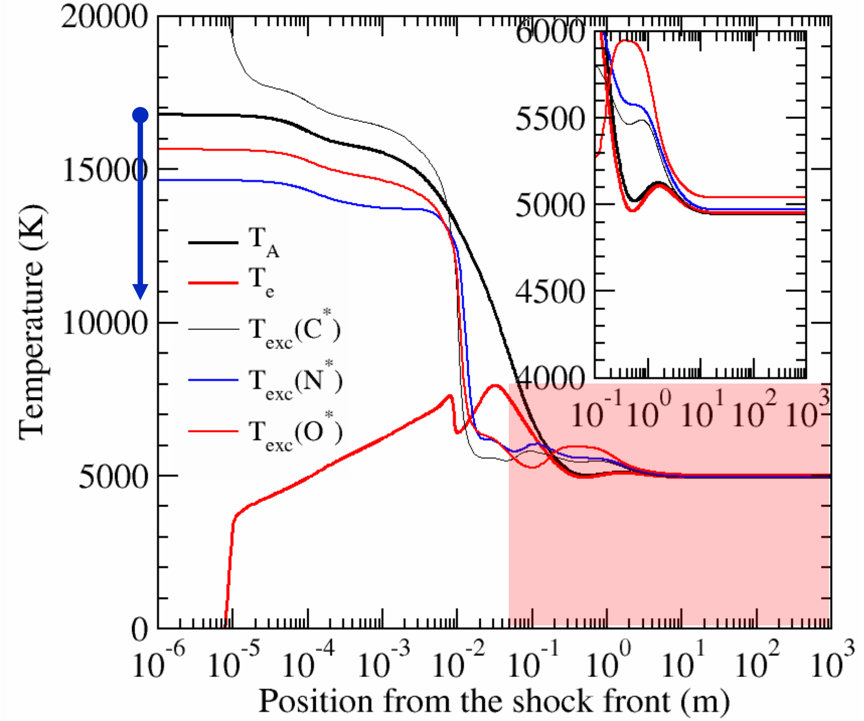
$p_1 = 8\ Pa$

$p_1 = 20 Pa$

Vibrational temperatures



Excitation temperatures



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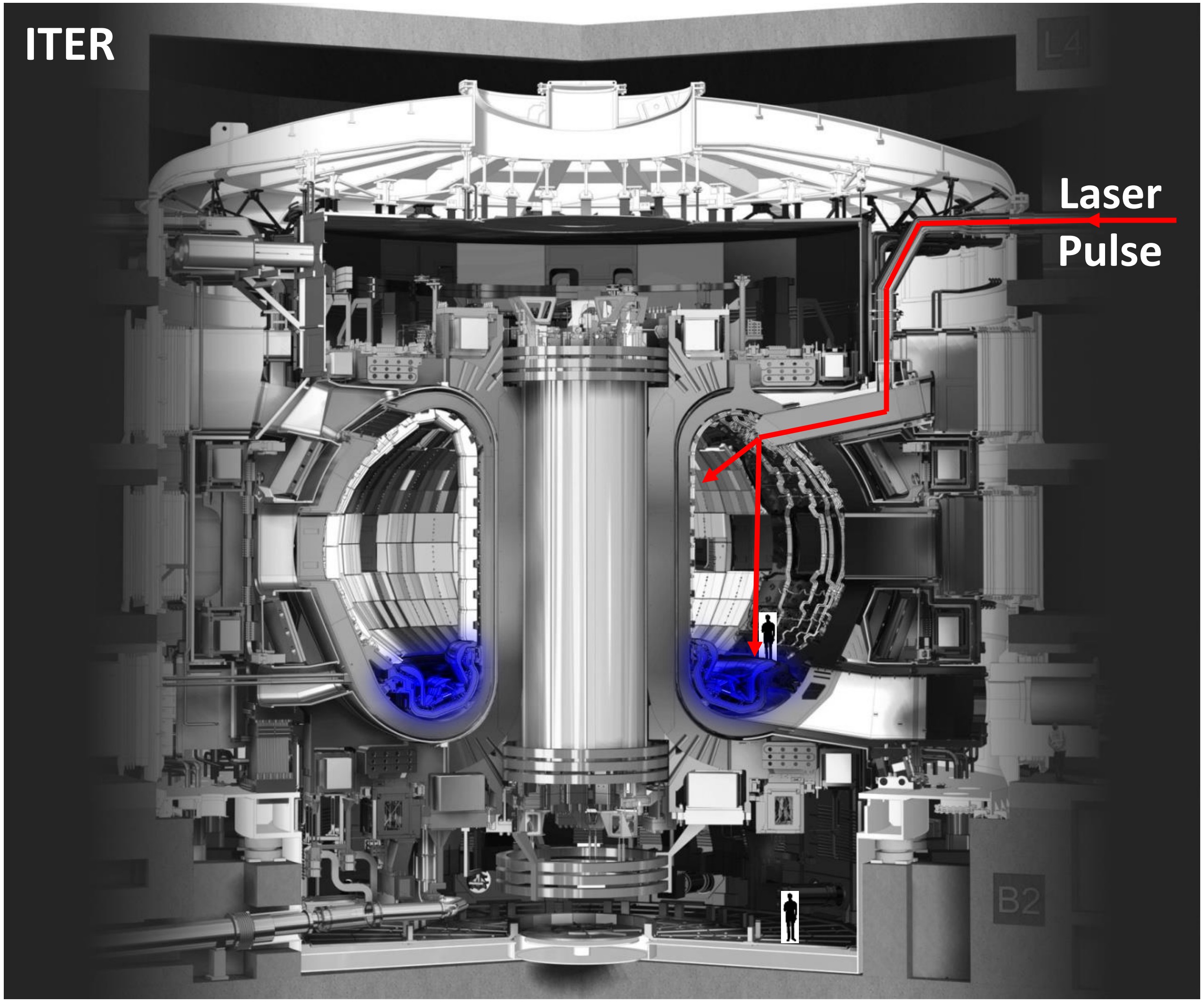
To be published in Phys. Plasmas

Sommaire

Objective ITER



Fusion reaction

$^{2}D + {}^{3}T \rightarrow {}^{4}He + {}^{1}n$

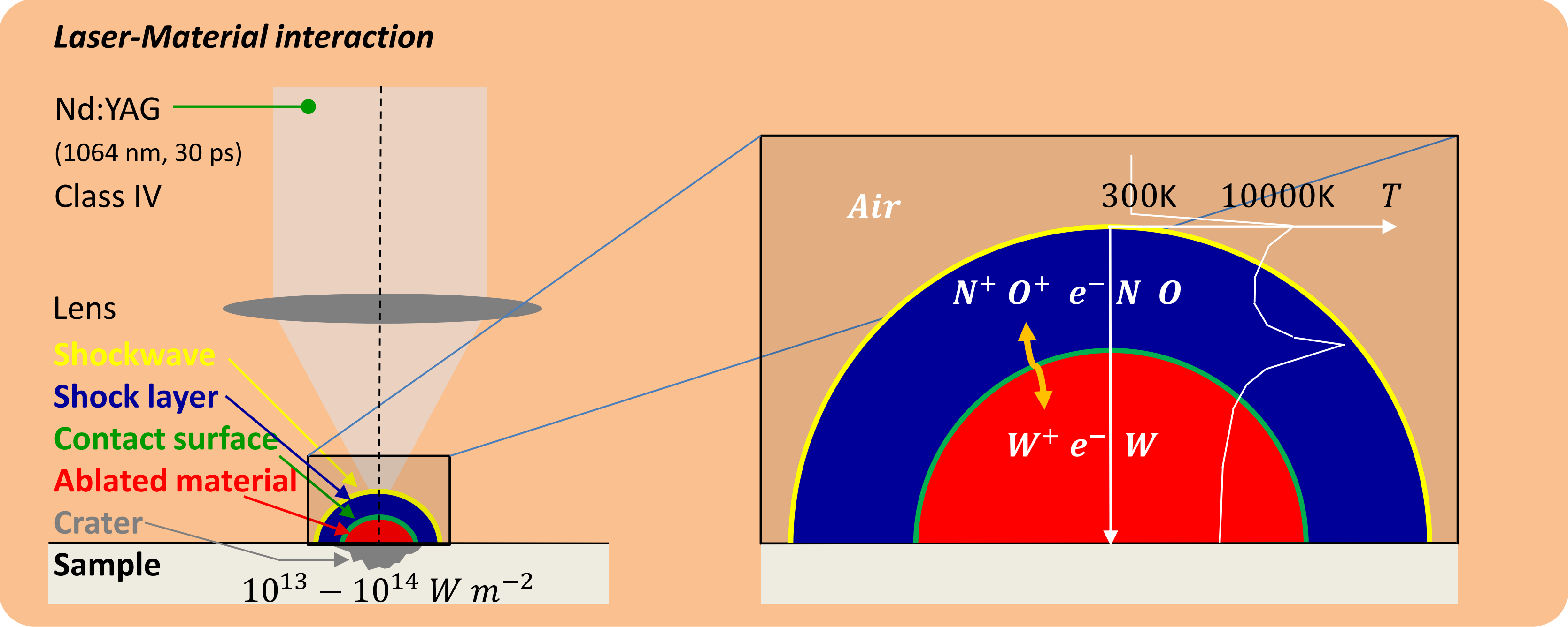
^{3}T radioactive

^{3}T has to be monitored

Implantation of ^{3}T, ^{2}D (fuel) and ^{14}N, ^{16}O ... (impurities) within the **W** divertor
also in the Be wall

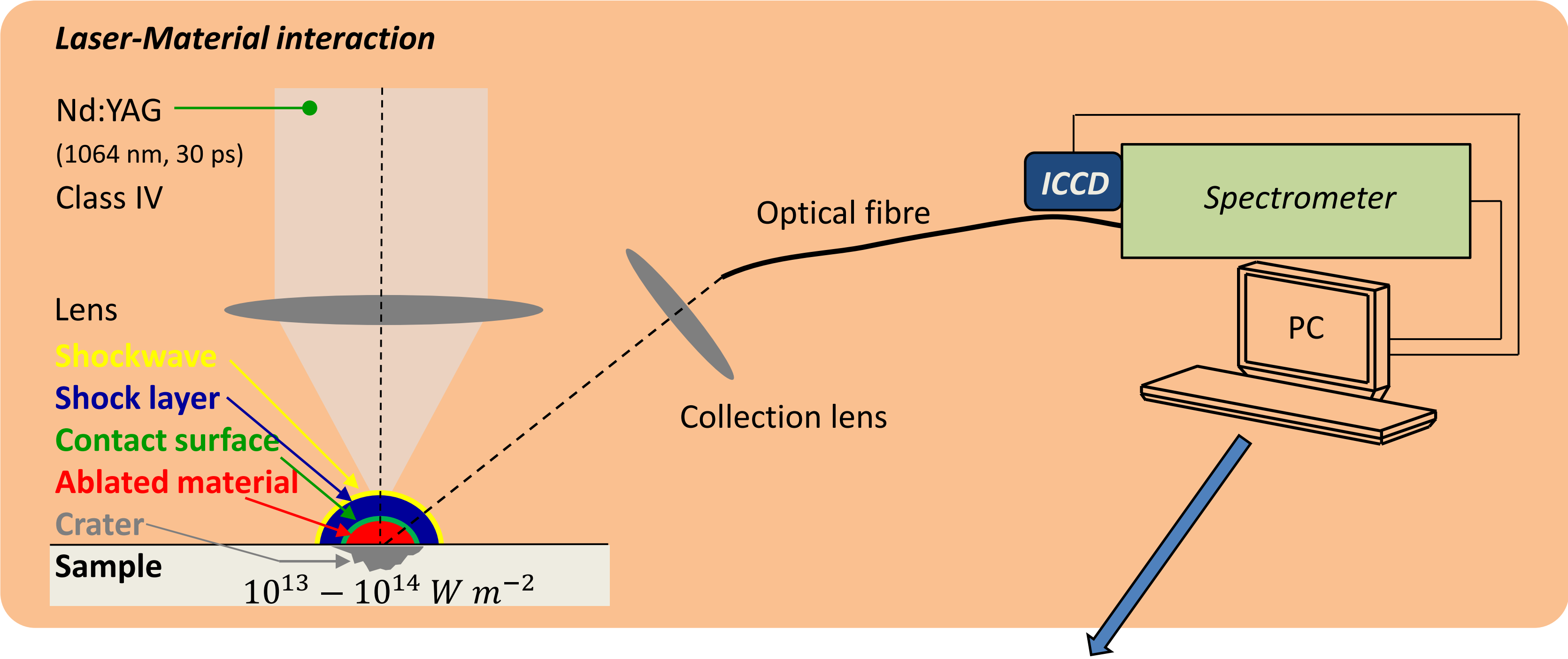
In situ *measurement by*
LIBS

Composition analysis by Laser-Induced Breakdown Spectroscopy – LIBS



- Melting
- Vaporization – explosion phase
- Ionization (MPI & IB)
- Plasma ($10^{10} Pa$, $10\ 000\ K$)
- Shockwave

Composition analysis by Laser-Induced Breakdown Spectroscopy – LIBS



Melting

Vaporization – explosion phase

Ionization (MPI & IB)

Plasma ($10^{10} Pa$, $10\,000\ K$)

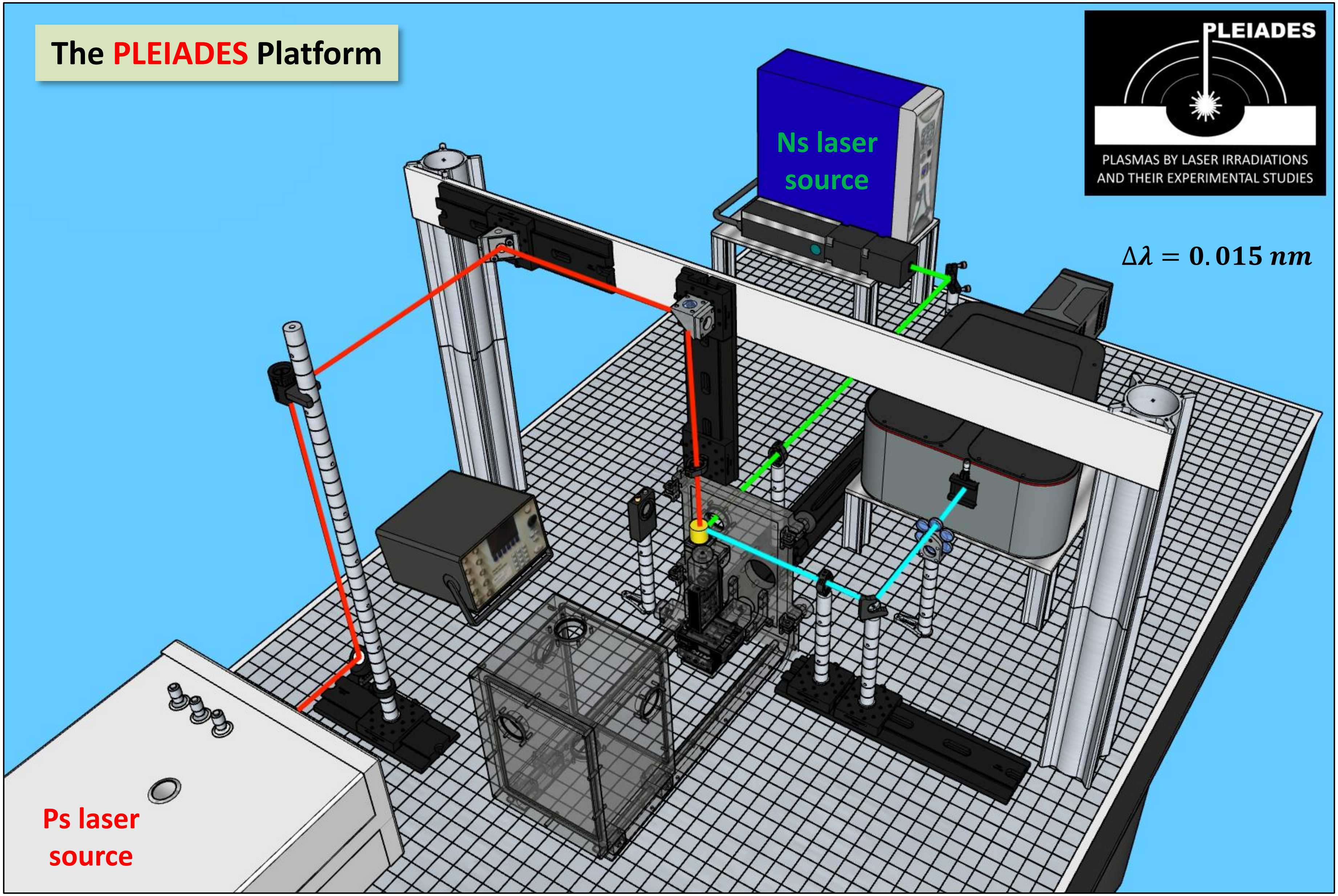
Shockwave

Spectroscopic analysis

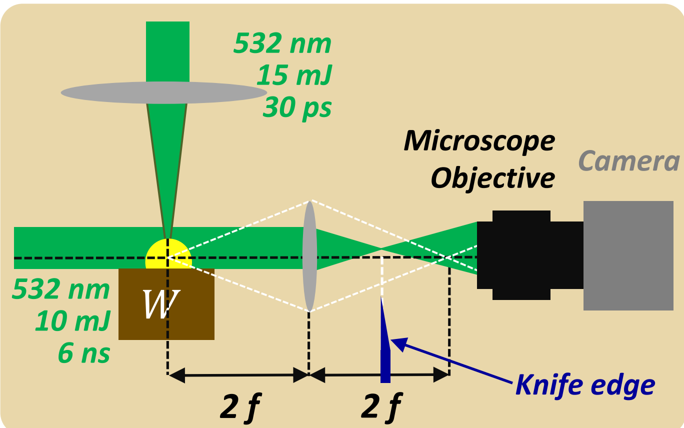
- $0 < t < 100\ ns$ strong continuum
- $t < 500\ ns$ strong departure from equilibrium
- $t > 500\ ns$ low non equilibrium (atom. and molec. Rad.)

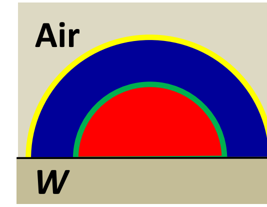
$\Rightarrow$ Exploitation of **Saha-Boltzmann** plots

The PLEIADES Platform



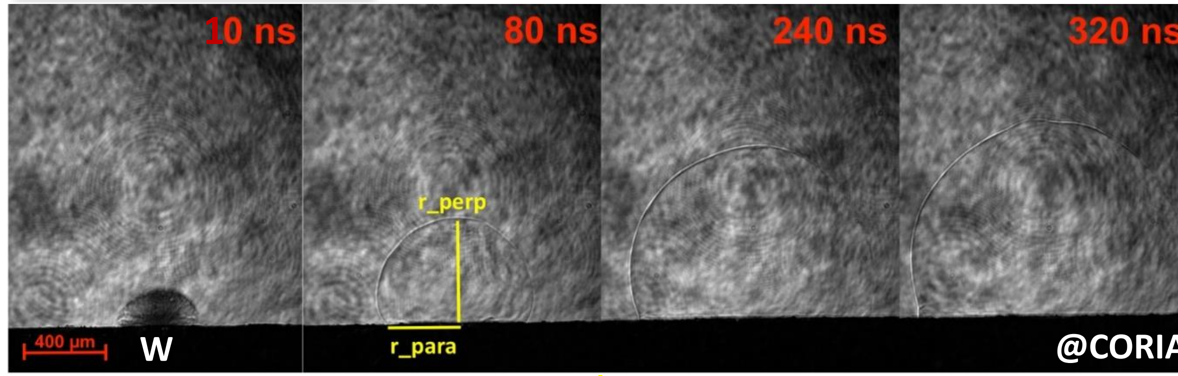
Fluid dynamics / structure





Laser shadowgraphy

Sensitive to $\frac{\partial^2 n}{\partial z^2}$

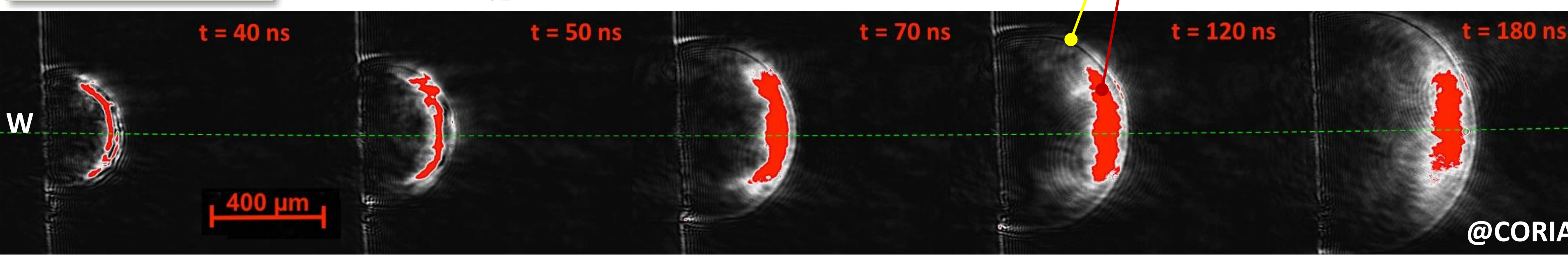


Shockwave

Contact surface

Schlieren Imagery

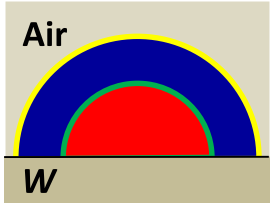
Sensitive to $\frac{\partial n}{\partial z}$



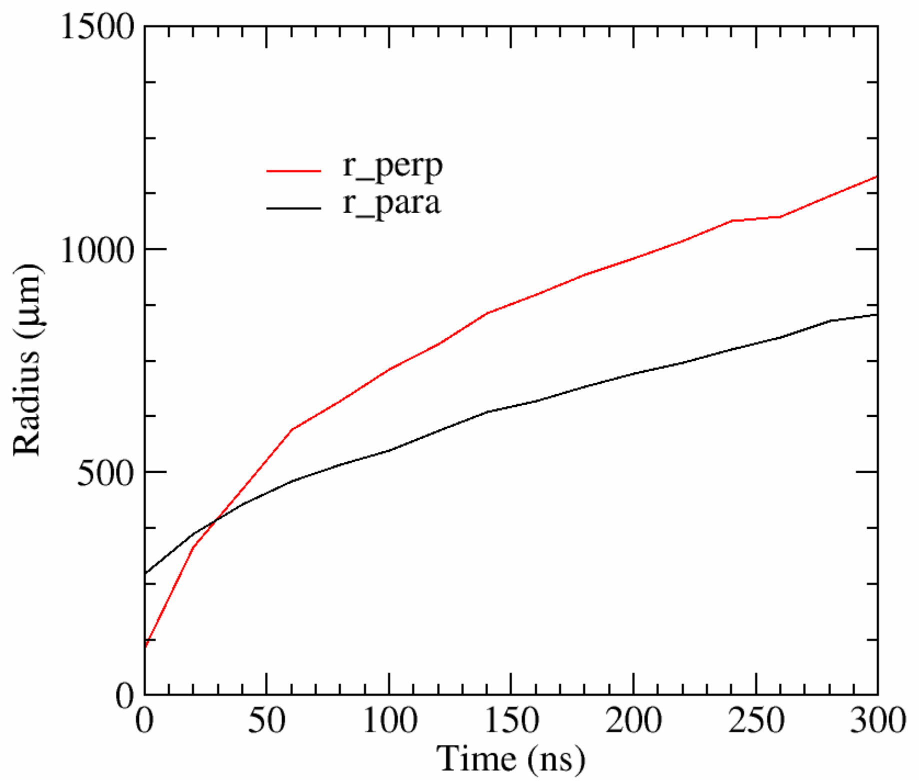
Very rapid evolution over the first 200 ns then slower evolution…

The contact surface remains close to the shock front

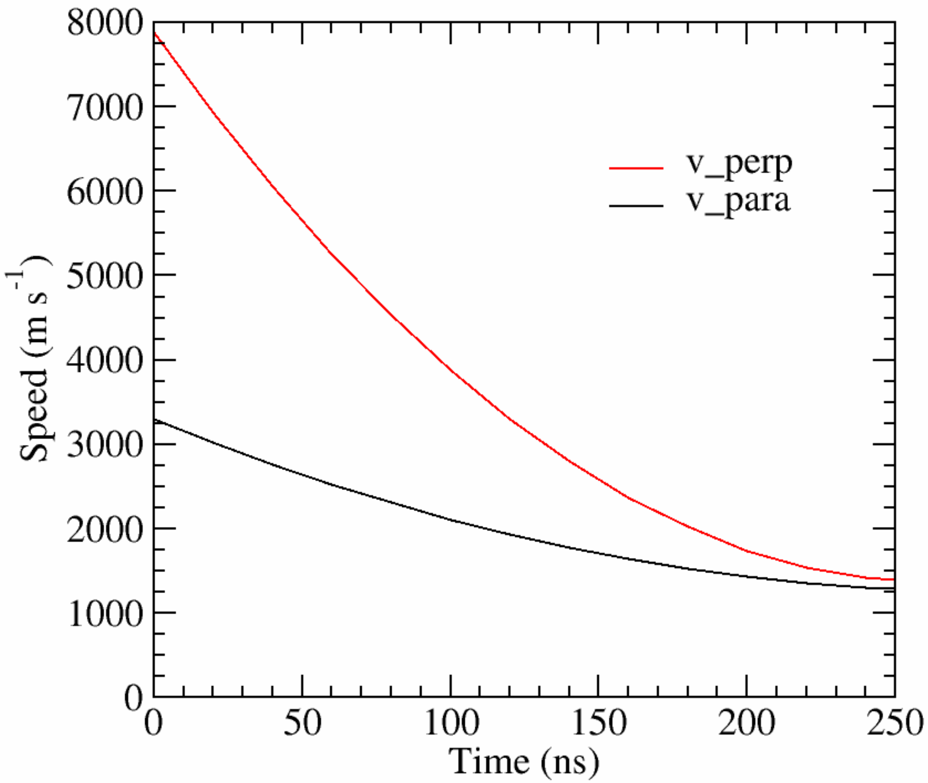
Fluid dynamics / structure



Shockwave radius



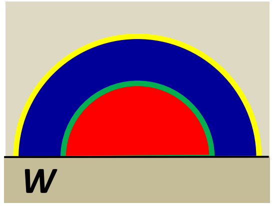
Shockwave speed



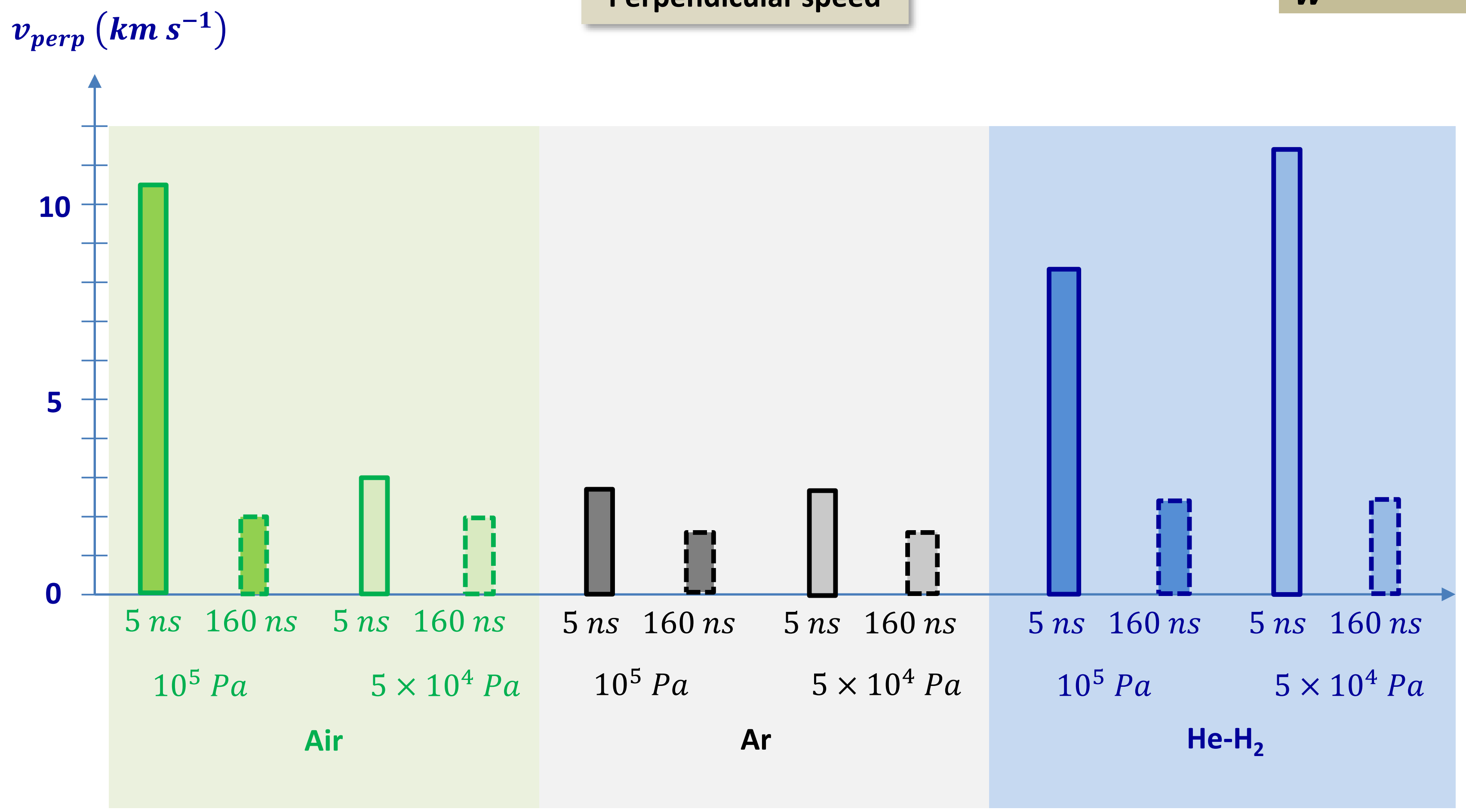
Expansion mainly perpendicular to the sample

Hypersonic expansion ($\mathcal{M}\sim 25$ at the beginning...)

Fluid dynamics / structure

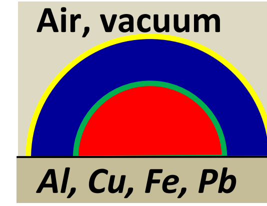


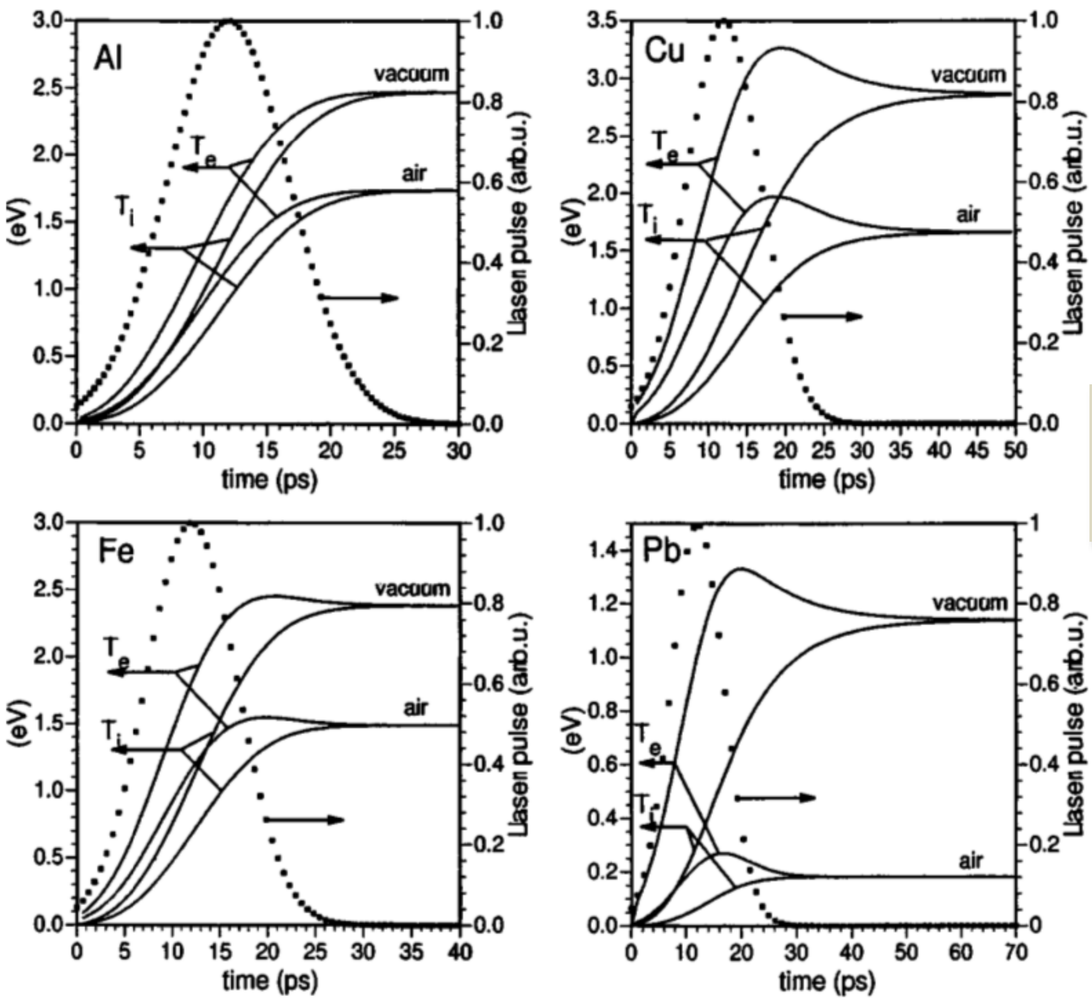
Perpendicular speed



Fluid dynamics / structure

$\tau_p \cong 10$ ps

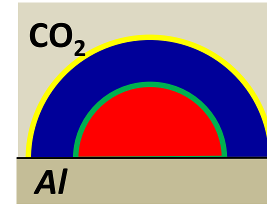




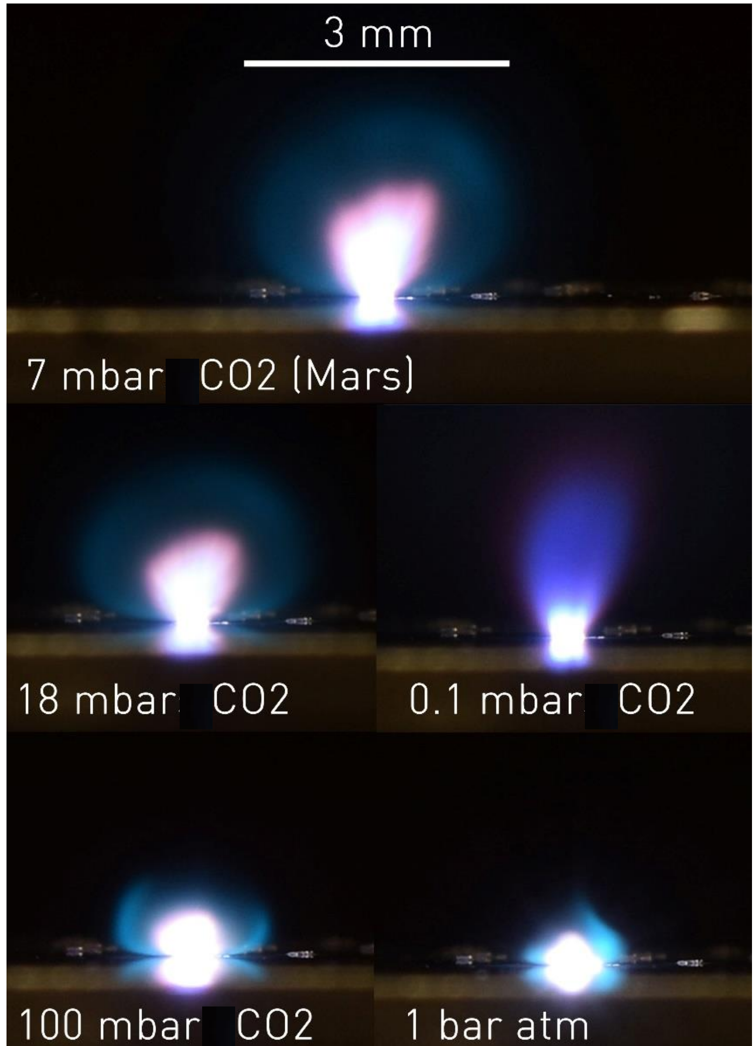
T_e and T_i
in the skin layer close to the ablation threshold

E.G. Gamaly *et al.* Phys. Rev. B **71** (2005) 174405

Fluid dynamics / structure



Plasma plume



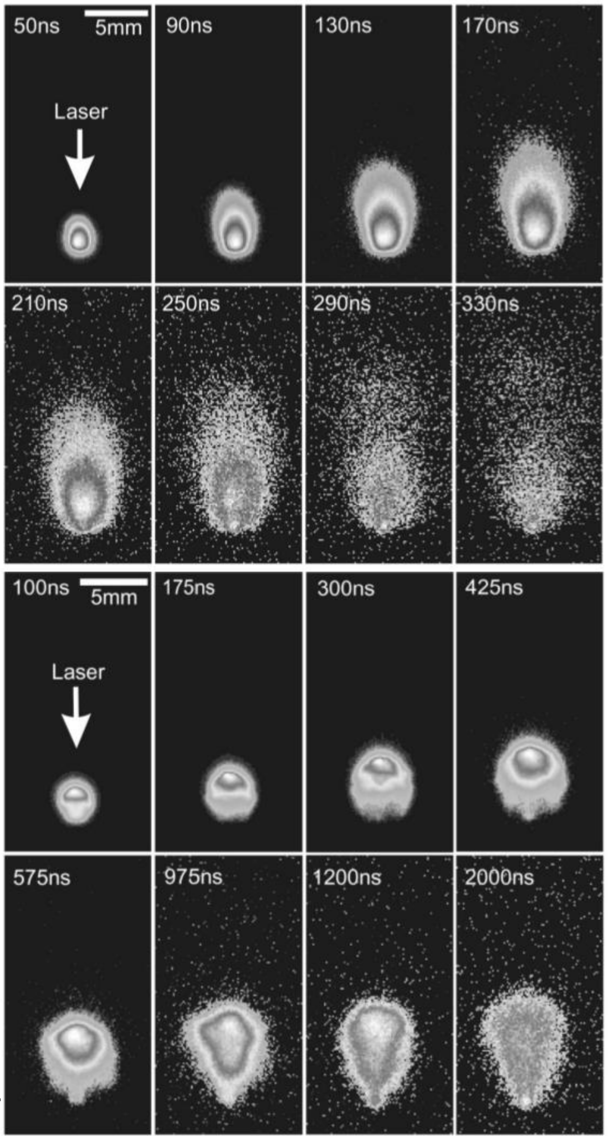
W. Rapin, private comm.

6 ns
1064 nm
40 J cm^{-2}
Al (CO_2)

Fluid dynamics / structure

S.S. Harilal *et al.*
J. Appl. Phys. **93** (2003) 2380

Plasma plume



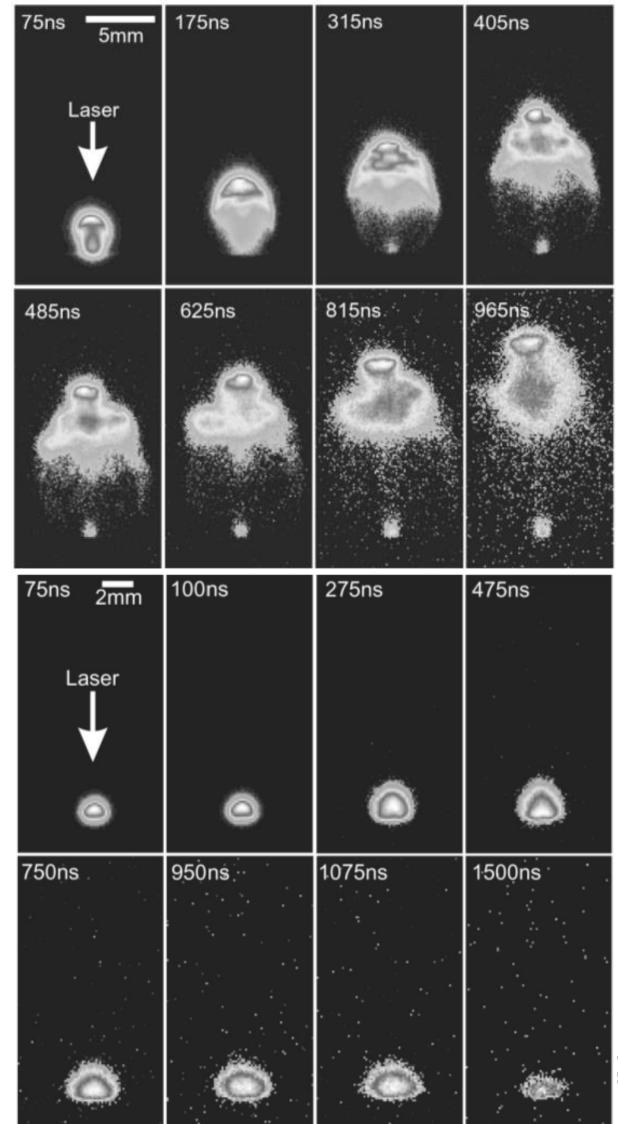
1 Pa

1300 Pa

8 ns
532 nm
24 J cm^{-2}
Al (air)

150 Pa

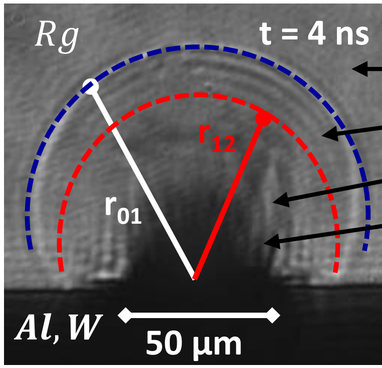
13000 Pa



The ECHREM* code

*Eulerian CHemically REactive Multi-component plasma code

Assumptions



Hypersonic hemispherical expansion

(0)	**External gas**	(rare gas: Ne, Ar, Kr or Xe)
(1)	**Shock layer**	(shocked rare gas)
(2)	**Central plasma**	(ablated W ou Al)
	Ablated material	

r_{01} shock front radius

r_{12} contact surface radius

v_{sf} shock front speed

Bi-layer model
Propagation of the shockwave
Rankine-Hugoniot assumption

Atoms and ions... at T_A
Electrons... at T_e

Balance equations

(1) Shock layer

Mass

$$\rho_0 v_{sf} = \rho_1\left[v_{sf} - u_1(r_{01})\right] \Leftrightarrow \frac{d\rho(\{Rg\}_j^{Z+})}{dt} = \dot{\rho}(\{Rg\}_j^{Z+}) - \frac{\rho(Rg_j^{Z+})}{\rho_1}\frac{d\rho_1}{dt}$$

Energy

$$\epsilon_0 + \frac{p_0}{\rho_0} + \frac{v_{sf}^2}{2} = \epsilon_1 + \frac{p_1}{\rho_1} + \frac{\left[v_{sf} - u_1(r_{01})\right]^2}{2}$$

Momentum

$$p_0 + \rho_0 v_{sf}^2 = p_1 + \rho_1\left[v_{sf} - u_1(r_{01})\right]^2$$

Collisionnal-radiative source term

(2) Central plasma

Mass

$$M_2 = \frac{2\pi}{3}\rho_2 r_{12}^3 \Leftrightarrow \frac{d\rho(\{Al,W\}_j^{Z+})}{dt} = \dot{\rho}(\{Al,W\}_j^{Z+}) - 3\rho(\{Al,W\}_j^{Z+})\frac{u_2(r_{12})}{r_{12}}$$

Energy

$$E_2 = M_2\left(\epsilon^{Al,W} + \epsilon_2\right) + E_{c,2} \Leftrightarrow \frac{dE}{dt} = \rho_0\epsilon_0 v_{sf} 2\pi r_{01}^2 - \frac{M_2}{\rho_2}\left(4\pi\varepsilon_{RR} + 4\pi\varepsilon_{TB} + \varepsilon'_{SE}\right)$$

Momentum

$$\frac{d[u_2(r_{12})]}{dt} = \frac{8\pi}{3}\frac{r_{12}^2}{M_2}(p_2 - p_1)$$

V. Morel, A. Bultel *et al.*
Spectrochim. Acta B **127** (2017) 7

Collisional-radiative models

Shock layer - *Argon*

Collisional-Radiative model CoRaM-RG

$Ar + e^- \rightleftarrows Ar^* + e^-$	Exc. Elec. Impact
$Ar + Ar \rightleftarrows Ar^* + Ar$	Exc. Elec. Impact
$Ar + e^- \rightleftarrows Ar^+ + 2\,e^-$	Ioni. Elec. Impact
$Ar^* + e^- \rightleftarrows Ar^+ + 2\,e^-$	Ioni. Elec. Impact
$Ar + Ar \rightleftarrows Ar^+ + e^- + Ar$	Ioni. Heavy Impact
$Ar^* + Ar \rightleftarrows Ar^+ + e^- + Ar$	Ioni. Heavy Impact
$Ar^* + Ar^* \rightleftarrows Ar^+ + e^- + Ar$	Penning Ioni.
$Ar_2^+ + e^- \rightleftarrows Ar^* ou\ Ar + Ar$	Disso. Recomb.
$Ar^+ + e^- \rightarrow Ar^* ou\ Ar + h\nu$	Rad. Recomb.
$Ar_j \rightarrow Ar_{i<j} + h\nu$	Spont. Emiss.

30 000 elementary processes

LABORATOIRE Aimé Cotton

LABORATOIRE ONDES et MILIEUX COMPLEXES

Central plasma - *Tungsten*

Collisional-Radiative model CoRaM-W

$W_i + e^- \rightleftarrows W_{j>i} + e^-$

$W_i^+ + e^- \rightleftarrows W_{j>i}^+ + e^-$

$W_i + \Sigma_{i,Z} W_i^{Z+} \rightleftarrows W_{j>i} + \Sigma_{i,Z} W_i^{Z+}$

$W_i^+ + \Sigma_{i,Z} W_i^{Z+} \rightleftarrows W_{j>i}^+ + \Sigma_{i,Z} W_i^{Z+}$

$W_i + e^- \rightleftarrows W_j^+ + 2e^-$

$W_j^+ + e^- \rightleftarrows W^{2+} + 2e^-$

$W_i + \Sigma_{i,Z} W_i^{Z+} \rightleftarrows W_j^+ + e^- + \Sigma_{i,Z} W_i^{Z+}$

$W_j^+ + \Sigma_{i,Z} W_i^{Z+} \rightleftarrows W^{2+} + e^- + \Sigma_{i,Z} W_i^{Z+}$

$W^{2+} + e^- \rightleftarrows W_j^+ + h\nu$

$W_j^+ + e^- \rightleftarrows W_i + h\nu$

$W_j^+ \rightarrow W_{i<j}^+ + h\nu$

$W_j \rightarrow W_{i<j} + h\nu$

Thermal Bremsstrahlung

520 000 elementary processes

Collisional Database

$k_i(T_{A,e}) = \sqrt{\frac{8\,k_B\,T_{A,e}}{\pi\,\mu}} \int_{x_0}^{+\infty} x\,e^{-x}\,\sigma_i(x)\,dx$ with

- $\sigma_i(x)$ collisional cross section and
- $x = \frac{\varepsilon}{k_B\,T_{A,e}}$ reduced collision energy

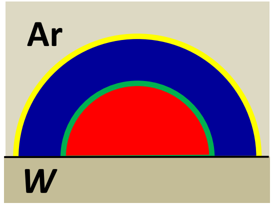
Backward rate coefficient deduced from the ***Detailed Balance***

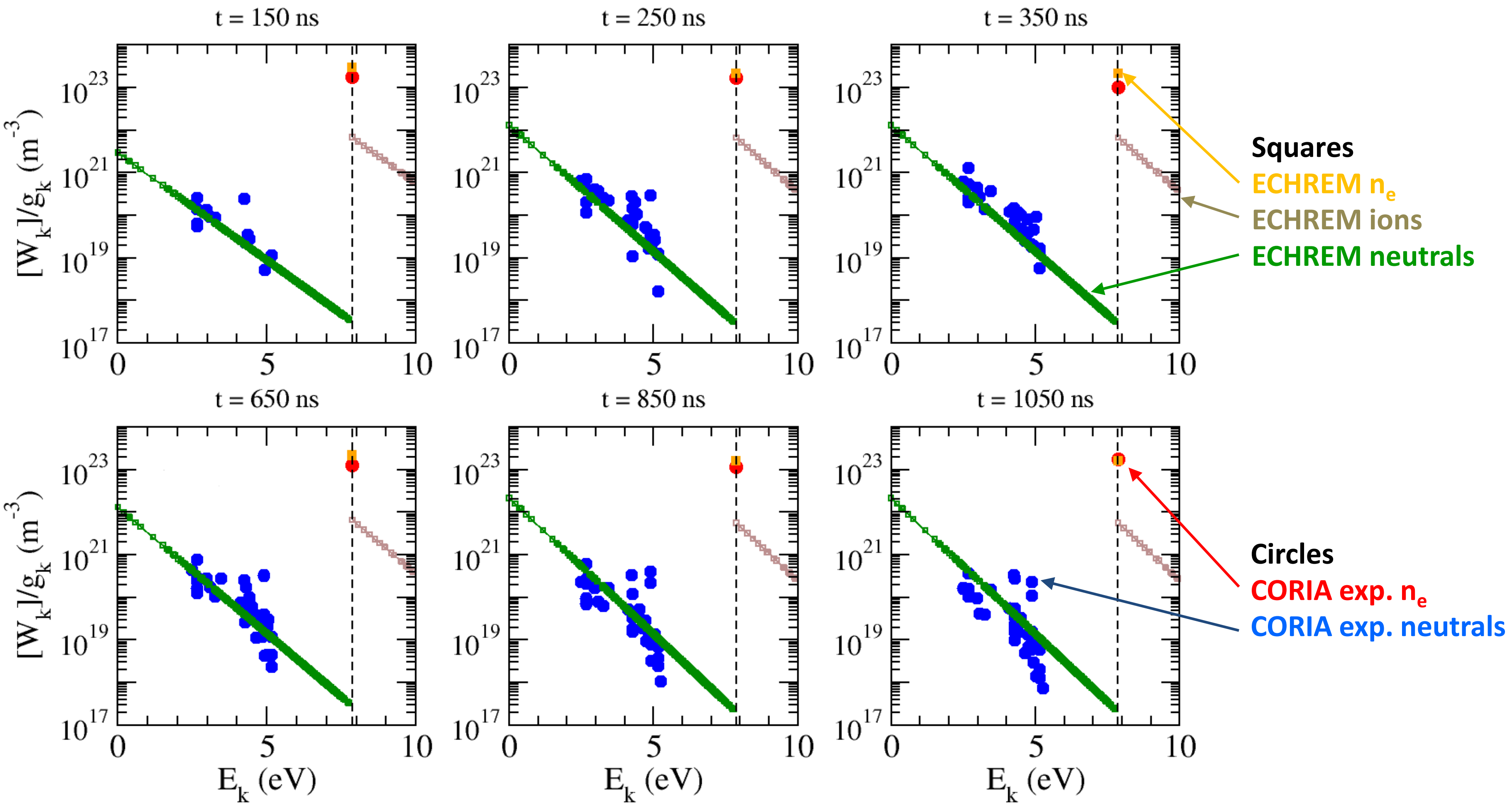
Radiative Database

NIST, Atomic Line List, ADAS, HULLAC…

Boltzmann plots

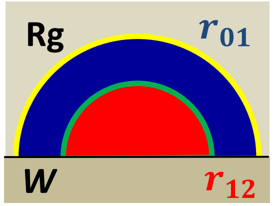
W (Ar, p_{atm}) 30 ps 532 nm 10 J cm^{-2}



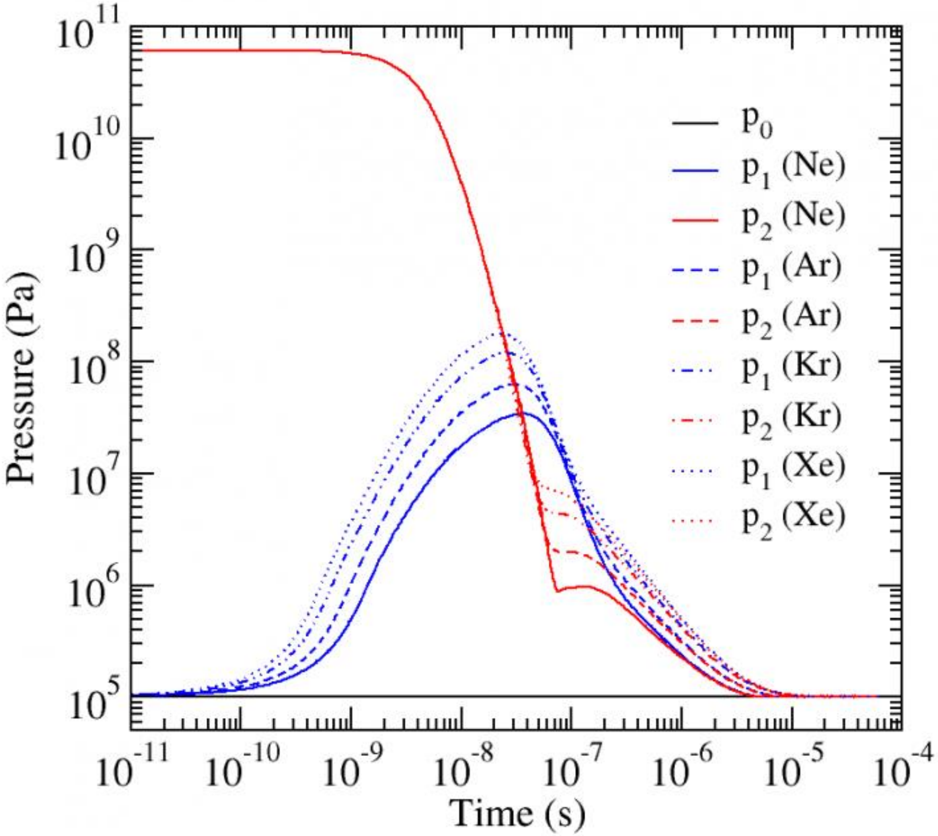


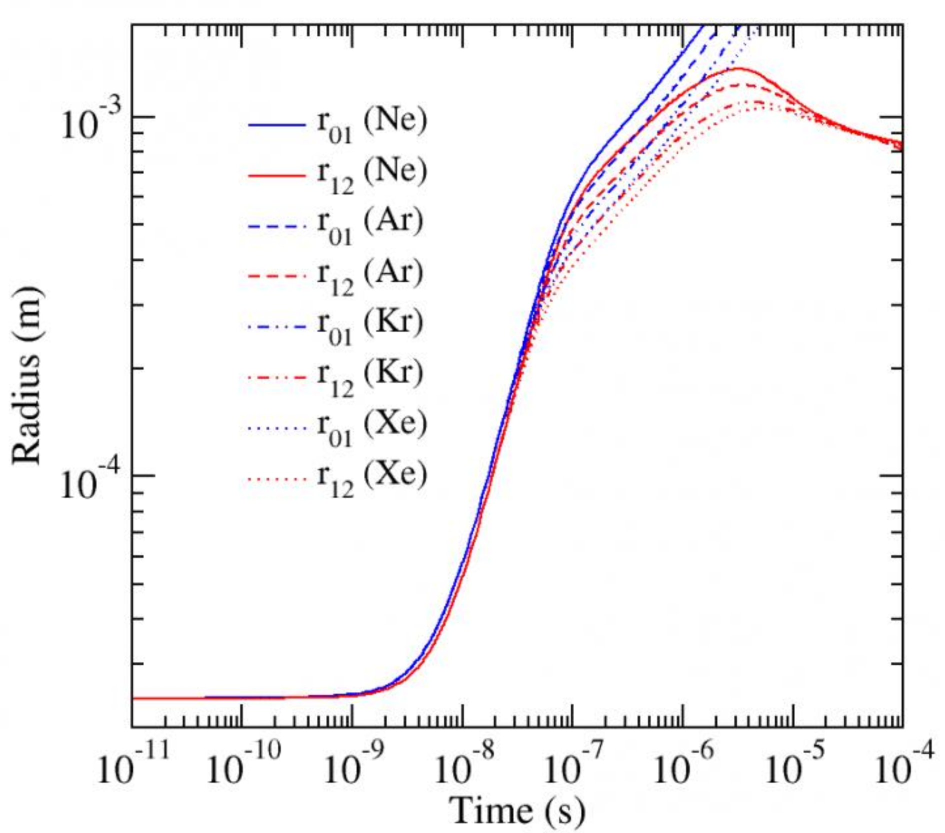
Low precision of the Einstein coefficients for WI transitions

Aerodynamic variables



W (Ar, p_{atm}) 10 ps 532 nm 10 J cm^{-2}





Recompression more efficient with a heavy rare gas

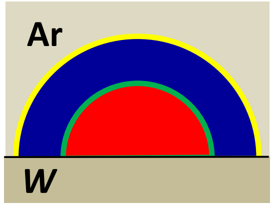
Ratio of 10 for the pressure at t ~ 10^{-7} s

Radius decreased from 20 % for heavy rare gas

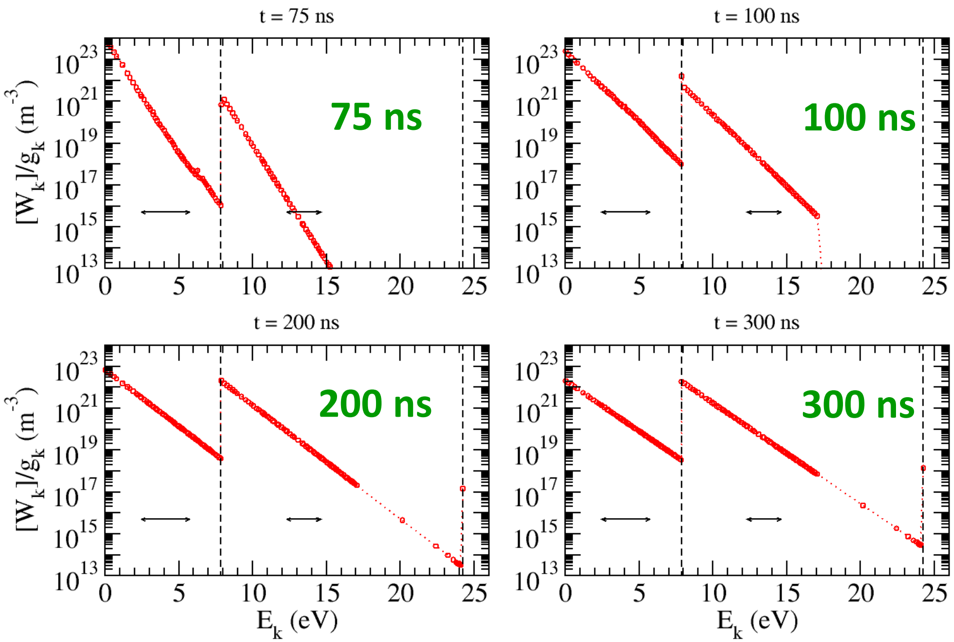
Better confinement with Xe than with Ne

Boltzmann plots

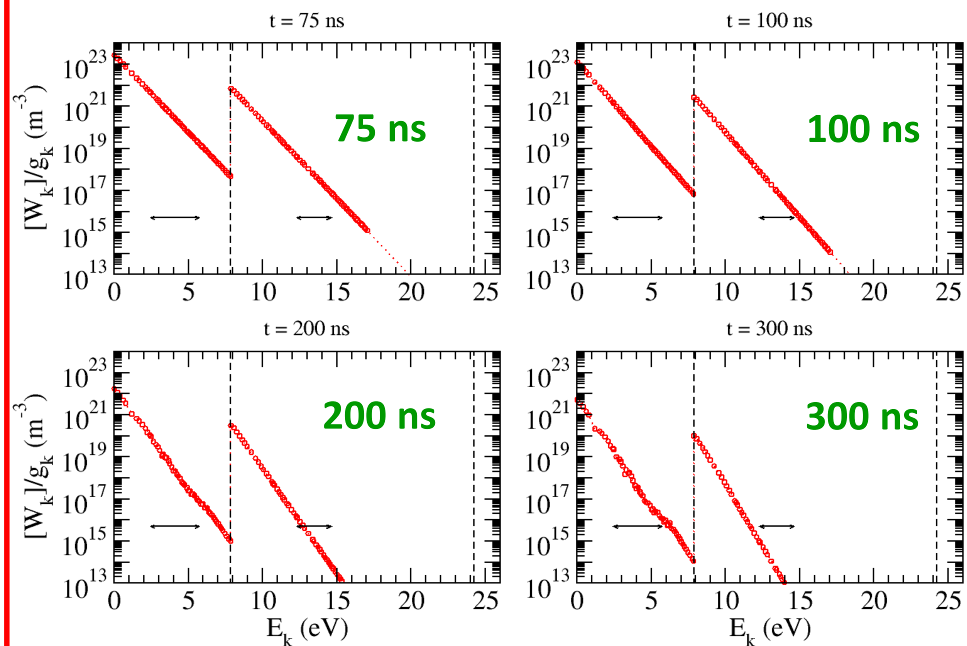
W (Ar) 10 ps 532 nm 10 J cm^{-2}



p = 10^5 Pa



p = 10 Pa



A. Bultel *et al.*

AIP Conference Proc. **1811** (2017) 120002

Excitation non equilibrium

- *At short times* (≈ 75 ns) à 10^5 Pa
- *Later* (> 200 ns) à 10 Pa

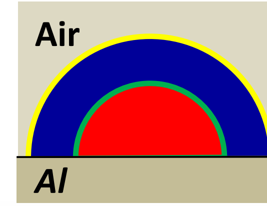
} **Collision frequency**

Spectral lines observation

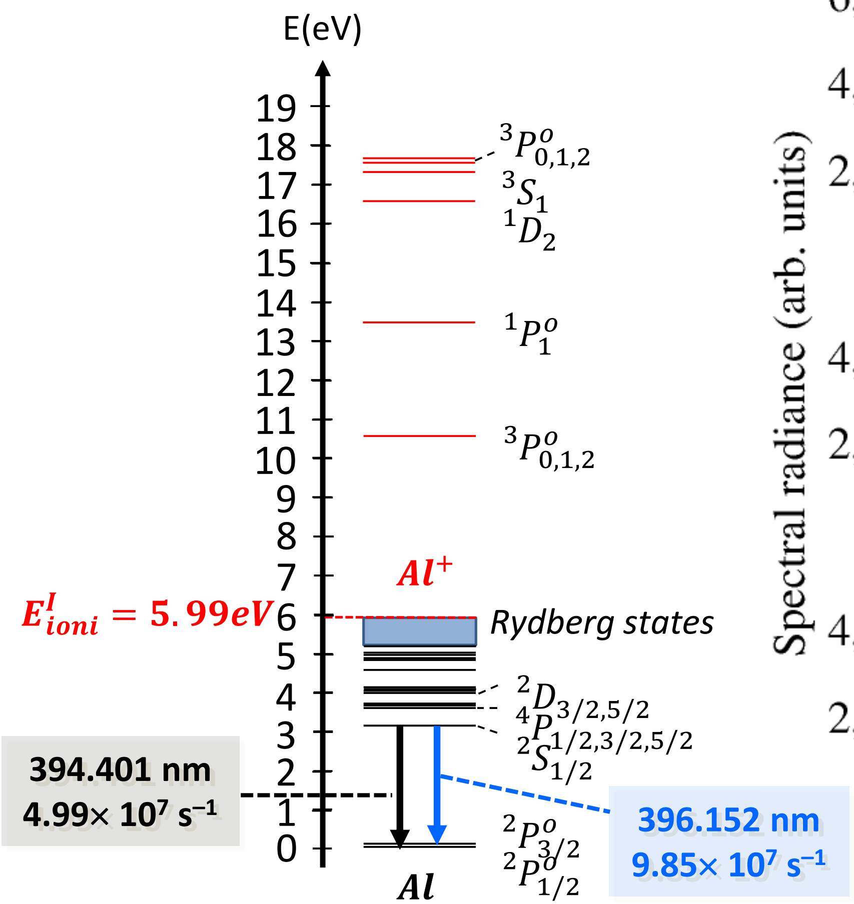
- *Easy at* 10^5 Pa
- *Difficult at* 10 Pa

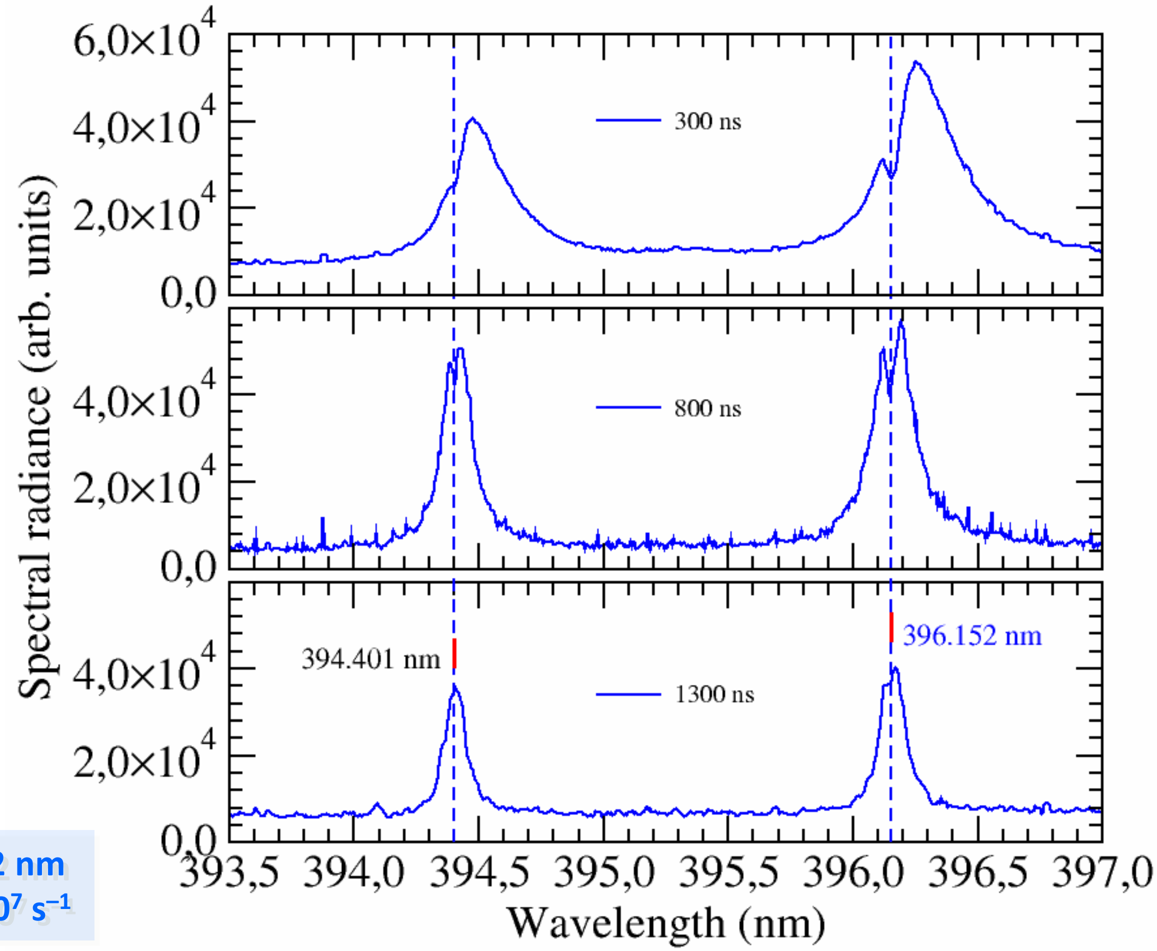
} **Confinement effect**

Spectra for *Al* resonance doublet



Al (Air, p_{atm}) 30 ps 1064 nm 10 J cm^{-2}





Stark shift, Stark width and… cold edge re-absorption

Conclusions

1. **Entrée Atmosphérique Planétaire**

    Rôle de la pression sur les temps de relaxation

    Rôle de la vitesse couplée

2. **Plasmas induits par Laser**

    Influence de la pression sur l'ablation

    Influence de la pression sur le panache

    Influence de la pression sur le confinement

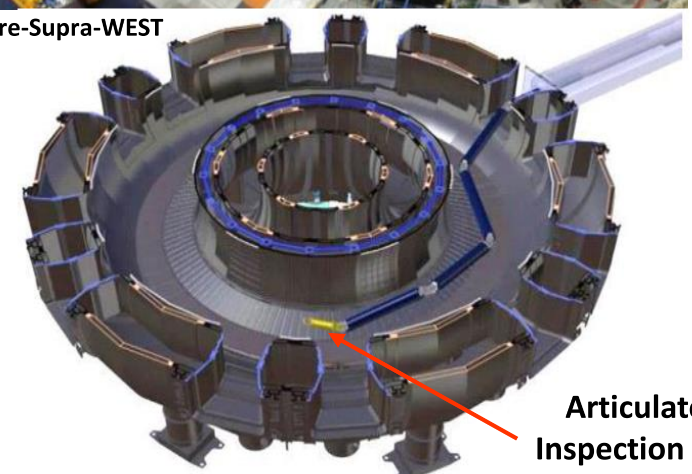
    Influence de la pression sur les écarts à l'équilibre

Perspectives

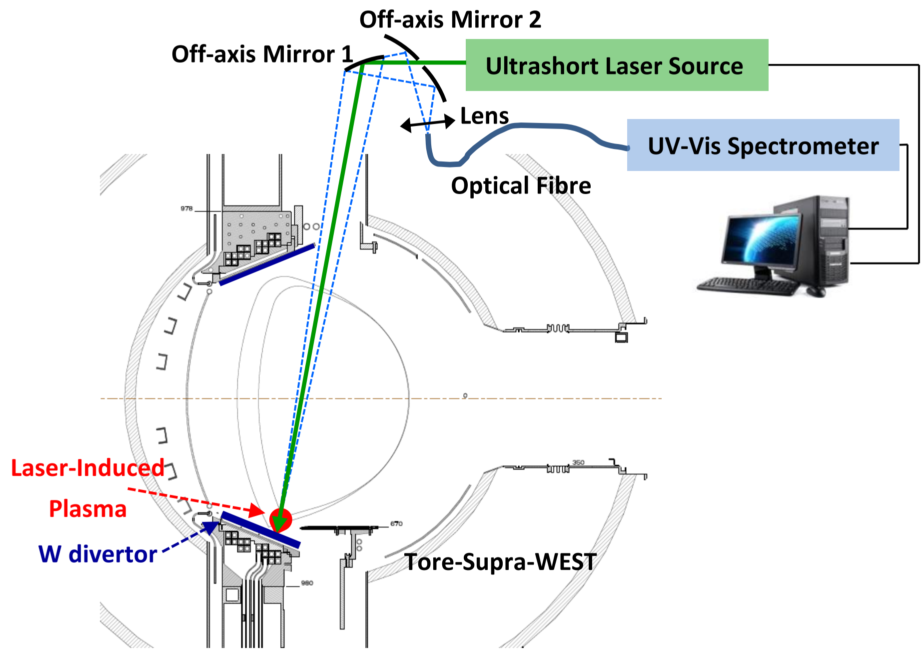
1. **Etudes sur l'entrée de la sonde EXOMARS 2020**
2. **Expériences en Double Pulse sur W et Al avec implantation de H and D**
3. **Tests sur le Tokamak Tore-Supra WEST (CEA Cadarache)**

Tore-Supra – WEST

Tore-Supra-WEST



Articulated Inspection Arm equipped with a LIBS system

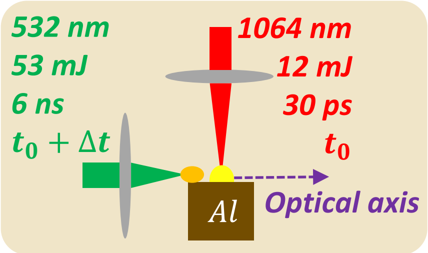


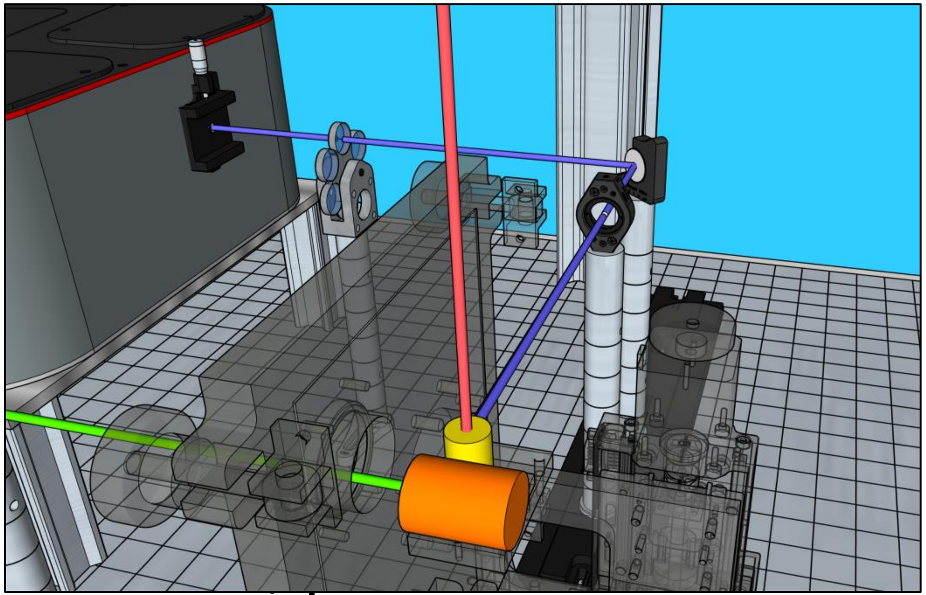
Configuration 1	At the end of the AIA (optical fibres)
Configuration 2	Using off-axis mirrors

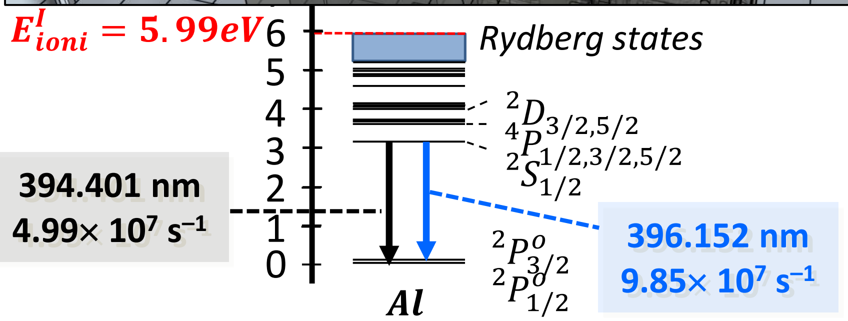
Merci de votre attention…

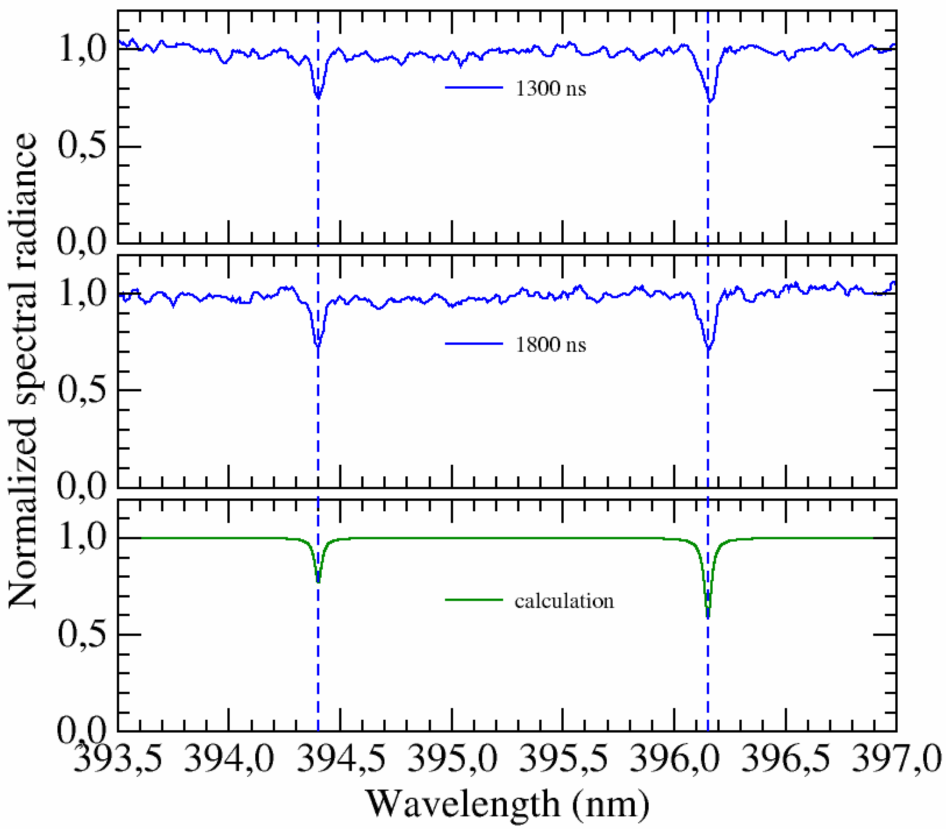
Laser-Induced Absorption Spectroscopy LIAS

Al (Air, p_{atm}) 30 ps 1064 nm 10 J cm^{-2}









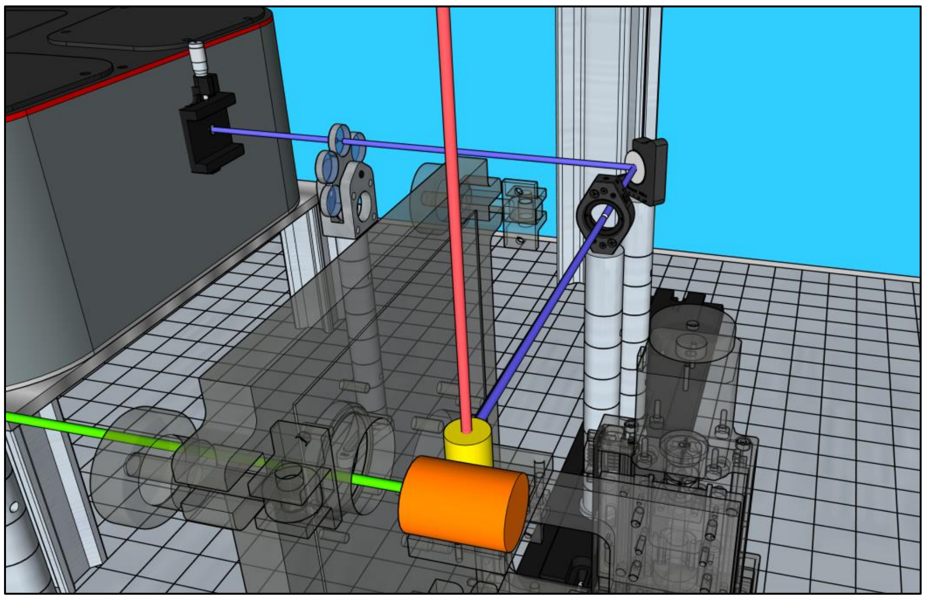
$n_e = 2 \times 10^{23}\ m^{-3}$

$T_e = 10\,000\ K$

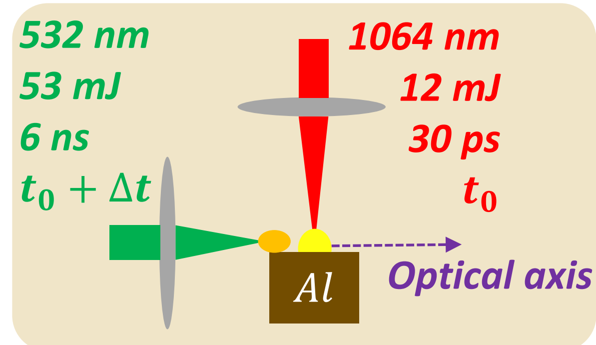
$[Al(\,^2P^o_{1/2}\,)] = 3.5 \times 10^{20}\ m^{-3}$

Laser-Induced Absorption Spectroscopy LIAS

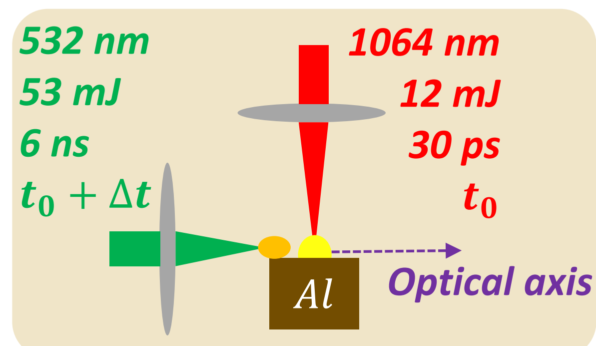
DP – Double Pulse Configuration



LIAS



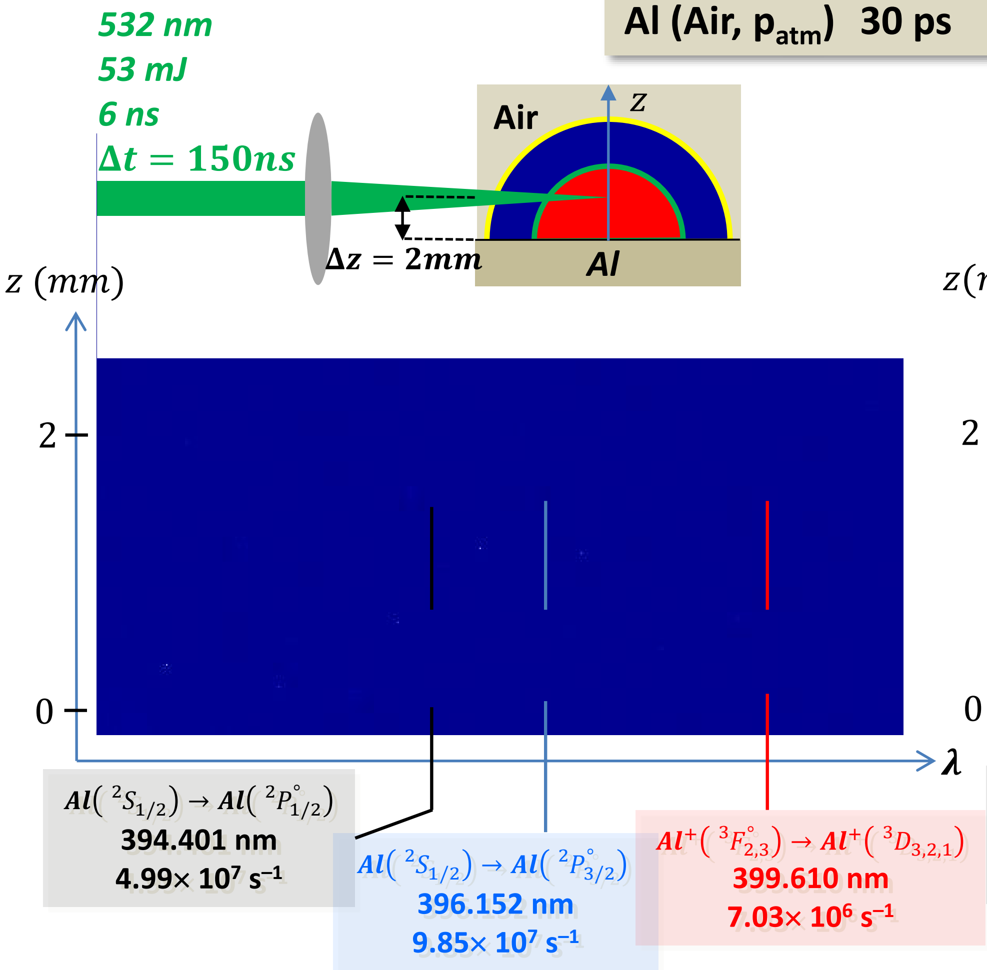
DP

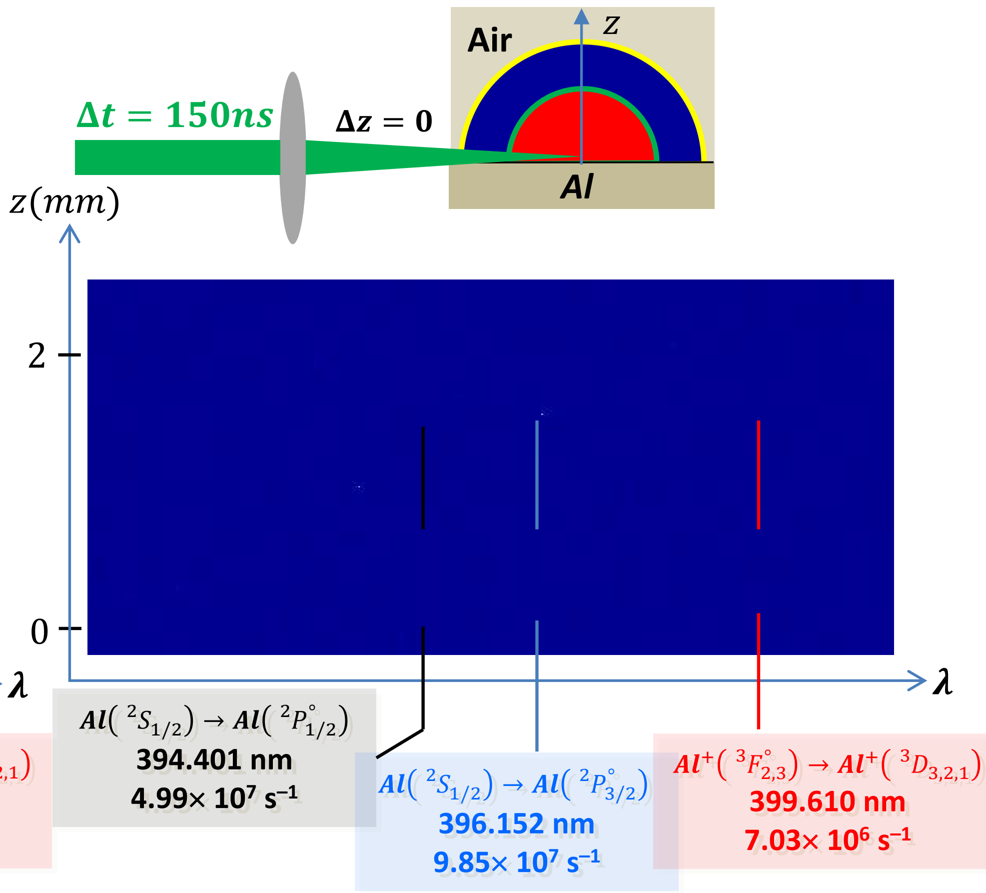


Inverse Bremsstrahlung !!!

DP – Double Pulse Configuration

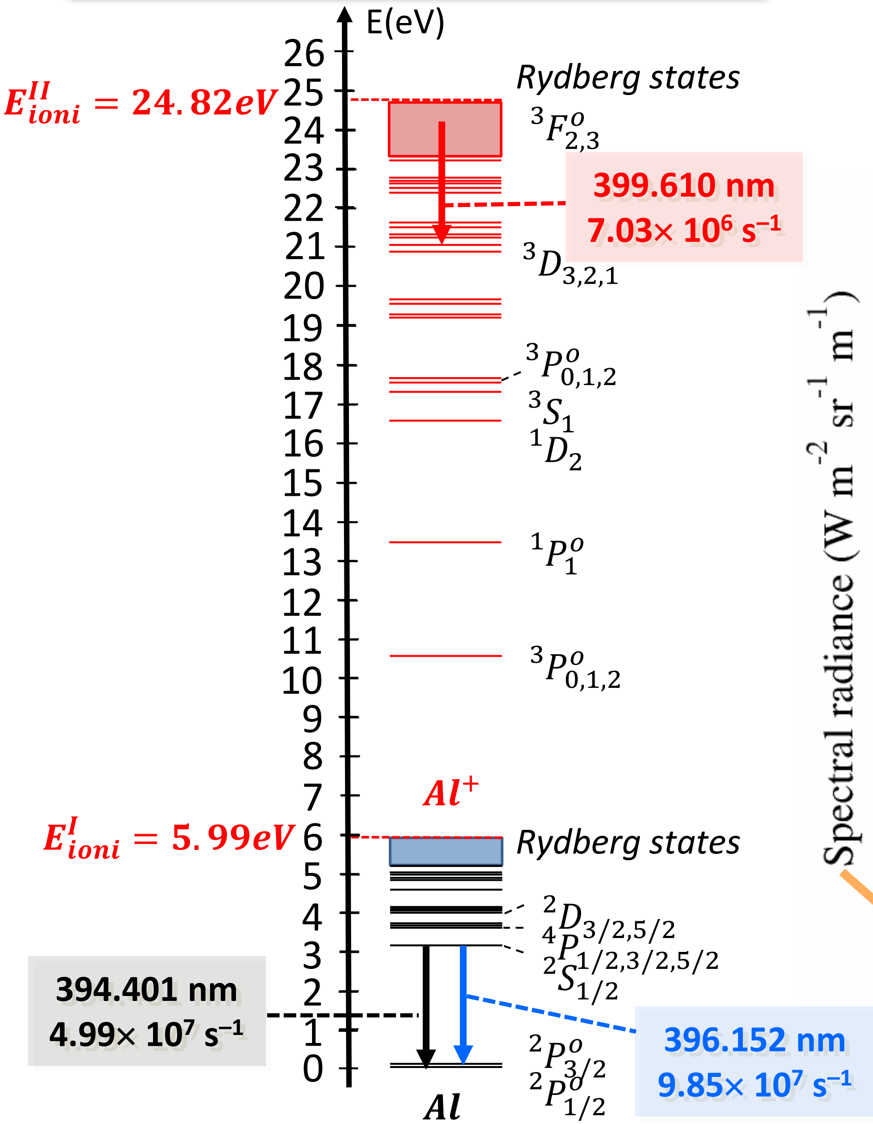
Al (Air, p_{atm}) 30 ps 1064 nm 10 J cm^{-2}

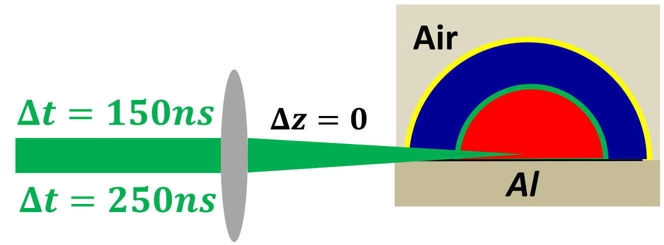


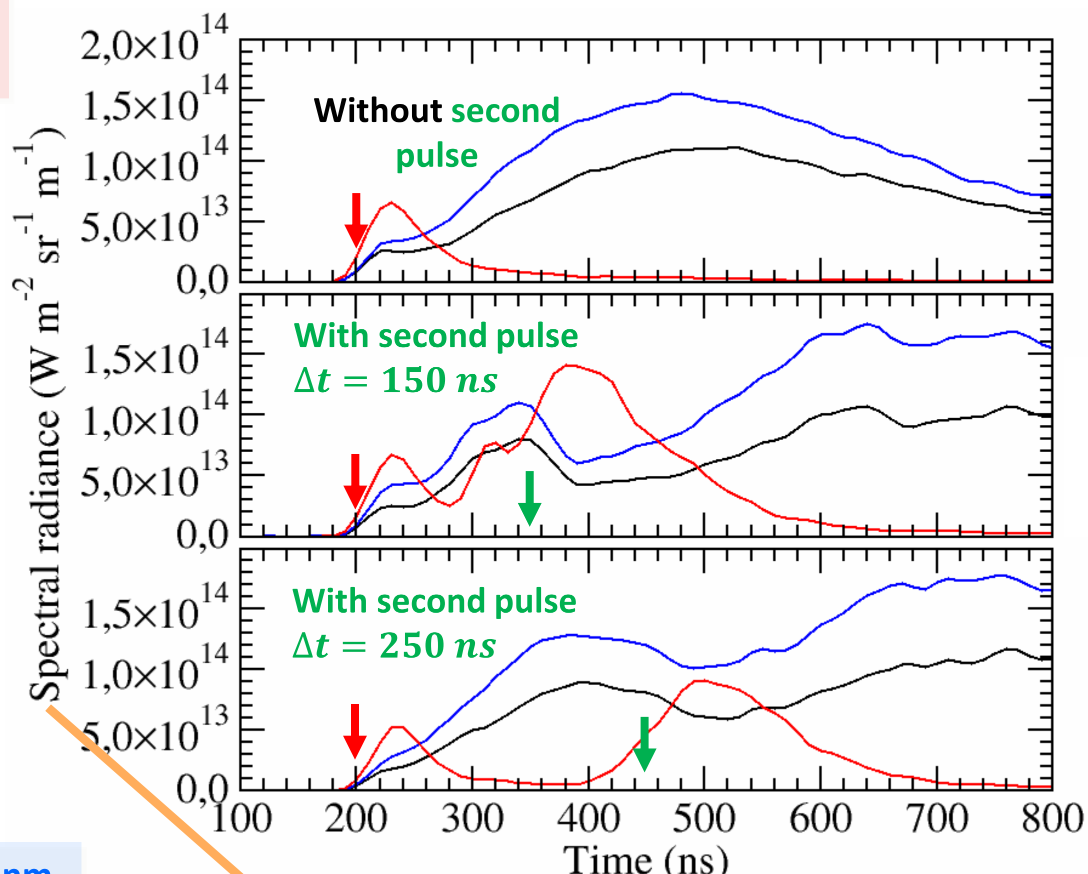


Efficient absorption of the second pulse by the plasma

DP – Double Pulse Configuration

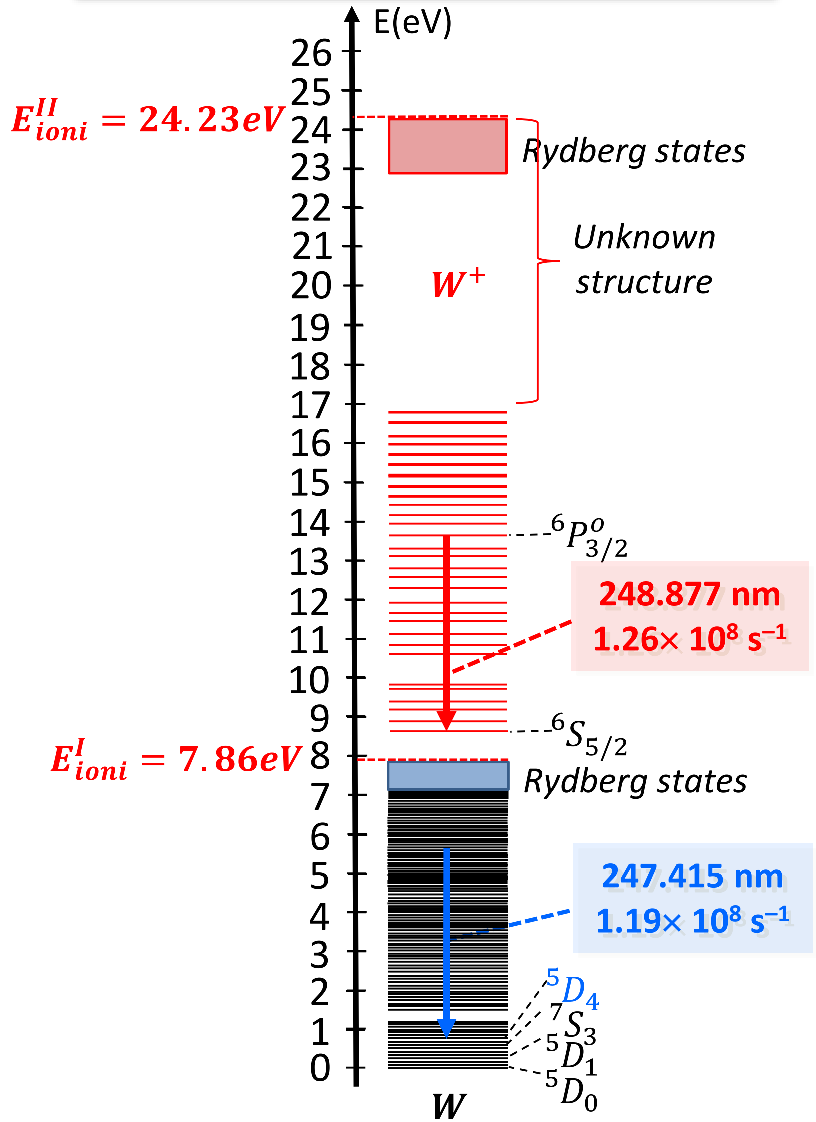


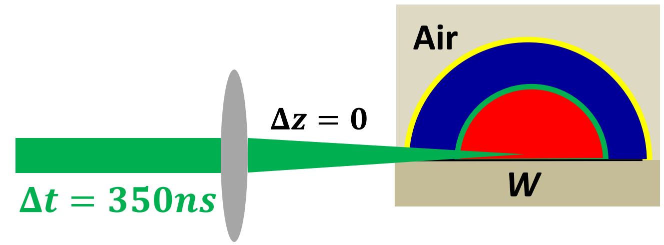


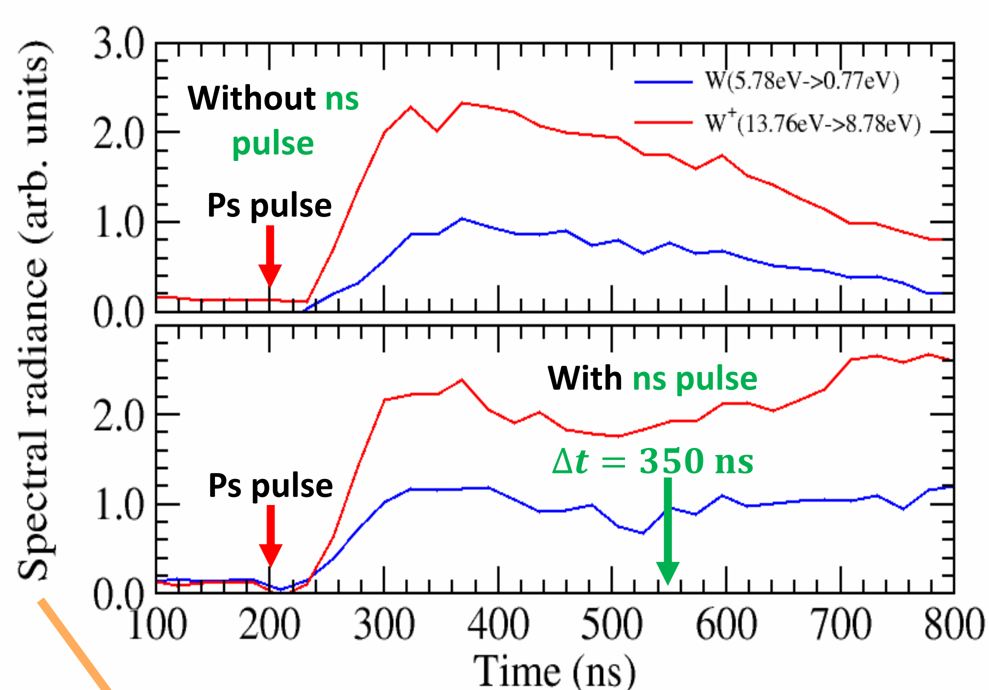


Spectral interval [395, 400] nm

DP – Double Pulse Configuration

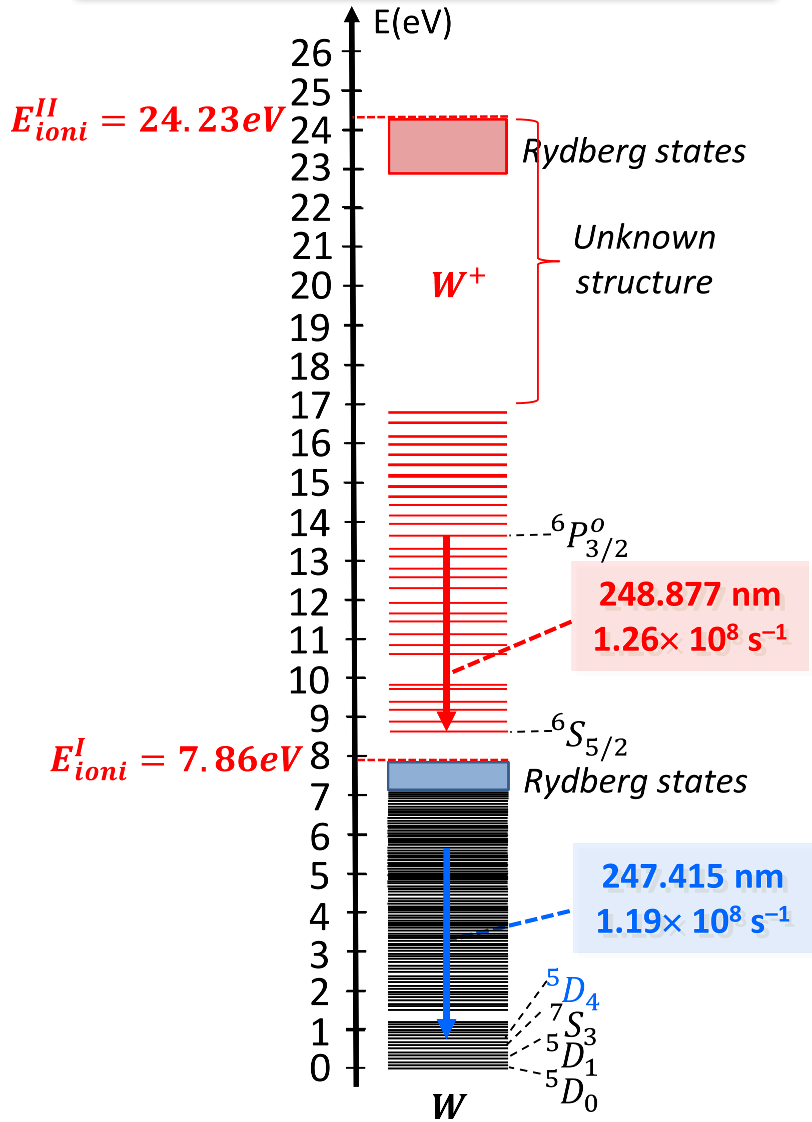


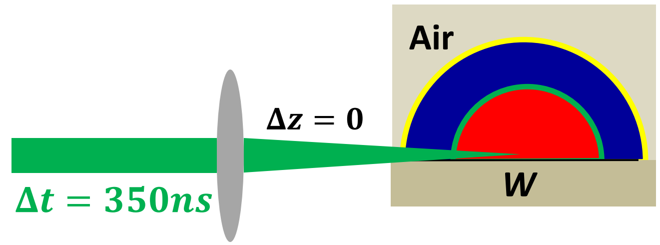


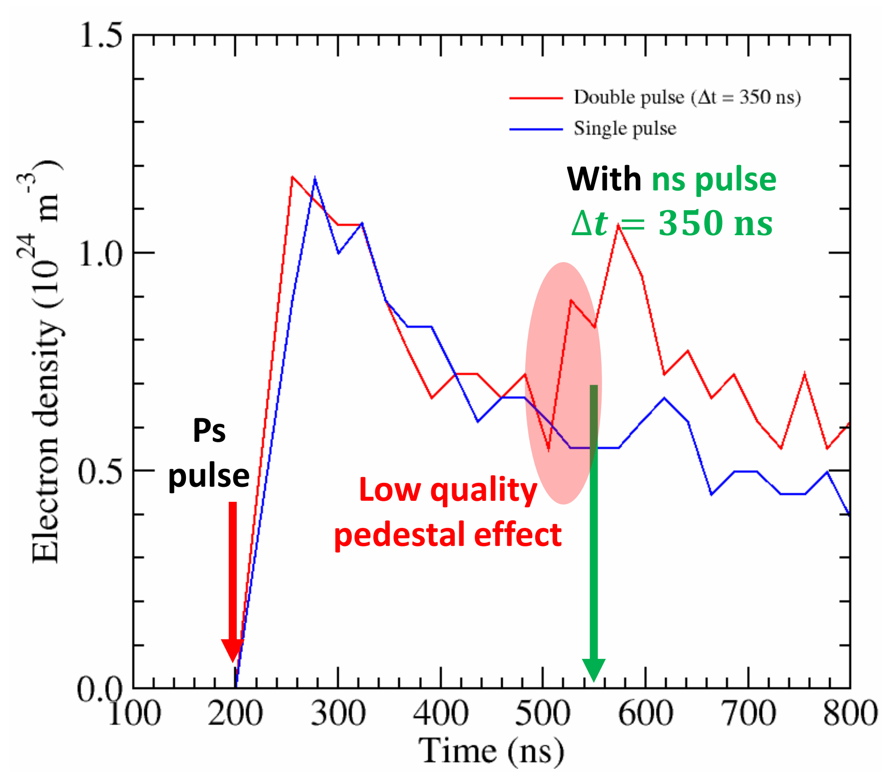


Spectral interval [245, 250] nm

DP – Double Pulse Configuration







Consequences on φ_w

Local parietal heat flux φ_w in chemical non equibrium

$(\varphi_w \approx 1 - 10\ MW\ m^{-2})$

$$\varphi_w \approx \sum_{Modes\ i} k_i \vec{\nabla} T_i . \vec{n}_w + \sum_{Species\ j} \gamma_j\ \beta_j\ \varphi_j^{(E)} + \int_{Freq.\nu} \alpha_\nu \iiint_{V_{Plas.}} \tau_\nu(\vec{r})\ \varepsilon_\nu(r) cos\theta \frac{d^3V}{r^2}\ d\nu$$

Translation and internal modes — *Catalysis* — *Radiation*

Dependence on the Excited States Number Density

k_i thermal conductivity for mode i

T_i temperature for mode i

γ_j recombination probability for species j

β_j energy accomodation coefficient for species j

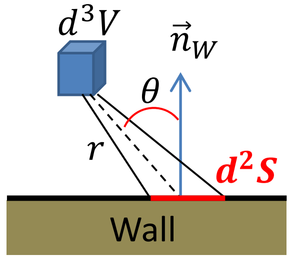
α_ν spectral absorptivity

τ_ν spectral transmittivity along $\vec{r}$

r distance with d^3V

θ angle with respect to $\vec{n}_W$

ε_ν spectral emission coefficient



Thermochemical non equilibrium

Excited states population density

(Species X on an excited state m)

$$\frac{\partial [X_m]}{\partial t} + \vec{\nabla}.\left([X_m]\vec{u} + \vec{J}_{X_m}\right) = \left(\frac{\partial [X_m]}{\partial t}\right)_{Coll.} + \left(\frac{\partial [X_m]}{\partial t}\right)_{Rad.}$$

Convection........................τ_{Conv}

Diffusion...........................τ_{Diff}

Collisional-radiative......τ_{CR}

Damkhöler numbers

$$\left(\frac{\partial [X_m]}{\partial t}\right)_{Coll.} \gg \left(\frac{\partial [X_m]}{\partial t}\right)_{Rad.} \qquad Da_1 = \frac{\tau_{Conv}}{\tau_{CR}} \qquad Da_2 = \frac{\tau_{Conv}}{\tau_{MB}} \qquad Da_3 = \frac{\tau_{Conv}}{\tau_{e-h}}$$

Chemical equilibrium $Da_1 \gg 1$

Chemical non equilibrium $\boldsymbol{Da_1 \approx 1}$

Frozen flow $Da_1 \ll 1$

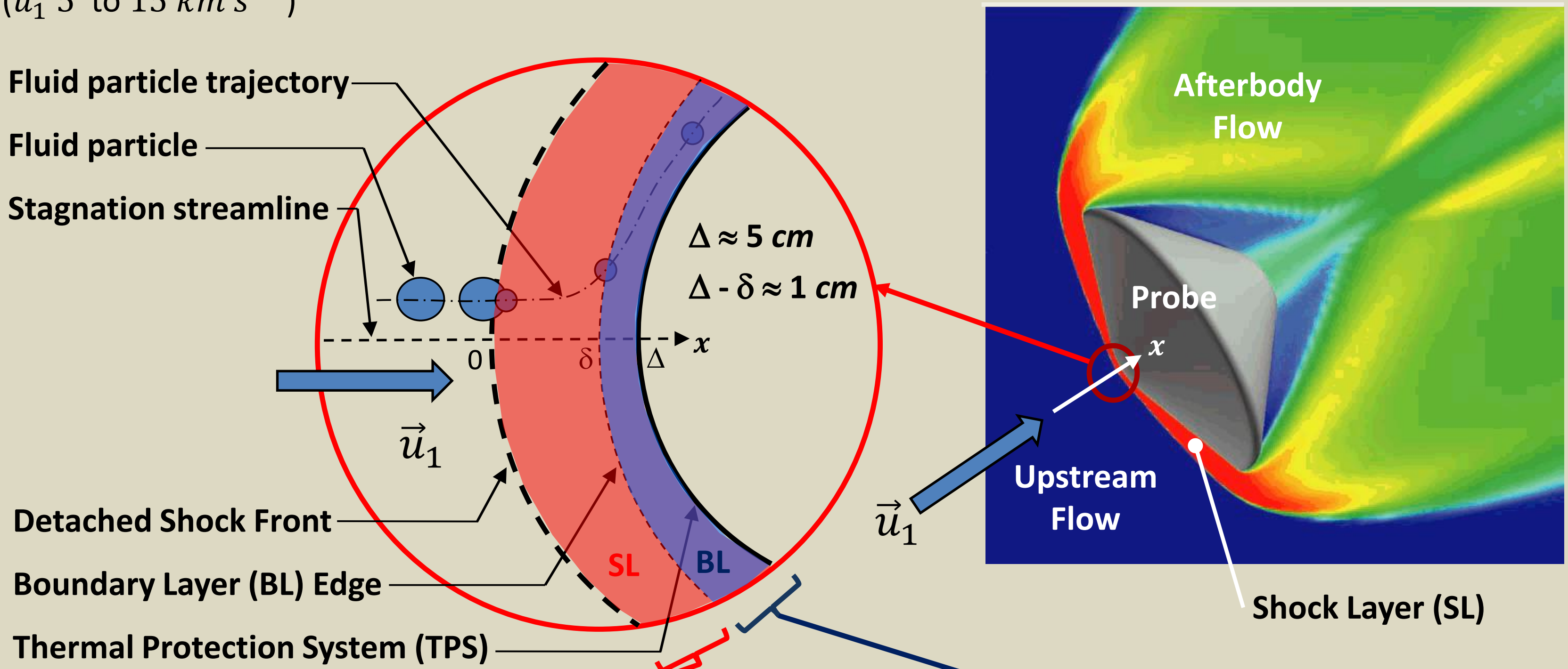
$Da_2 \gg 1$ — *Translation equilibrium*

$\boldsymbol{Da_3 \leq 1}$ — ***Thermal non equilibrium***

Excitation non equilibrium

Planetary Atmospheric Entry

(u_1 5 to 15 $km\ s^{-1}$)



SL Dissociation and Ionisation

Under-population for involved excited states

BL Recombination

Over-population for involved excited states

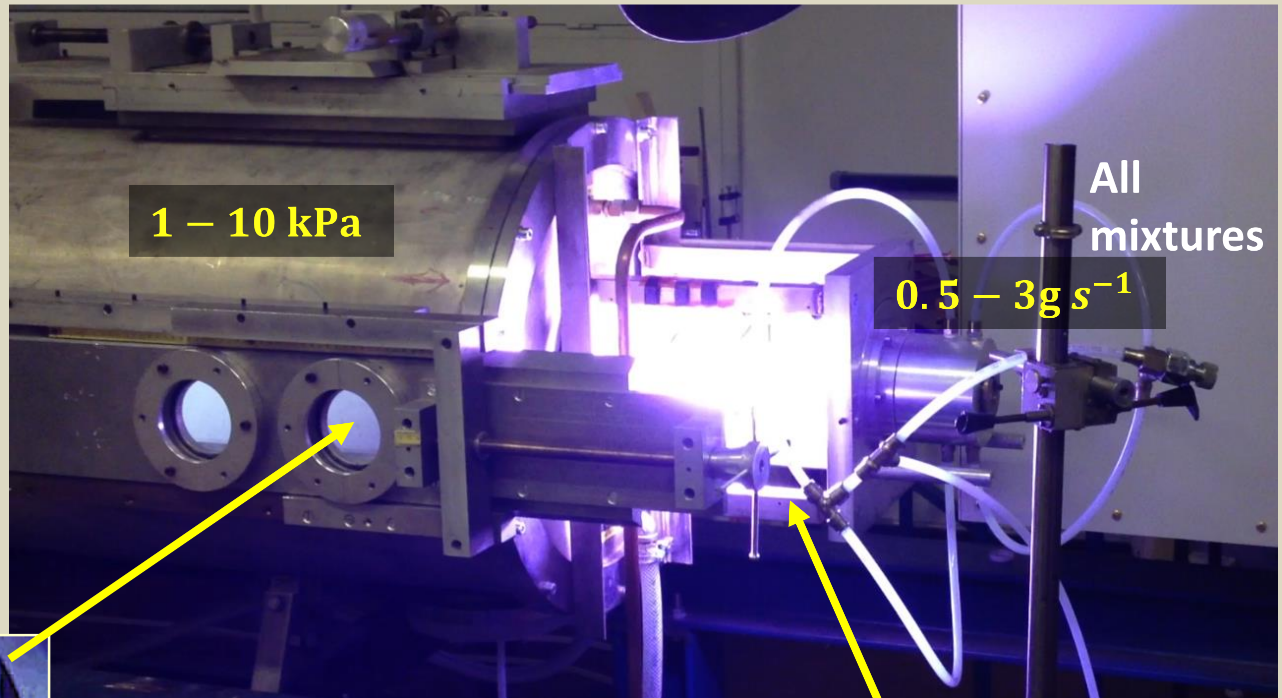
Departure from excitation equilibrium

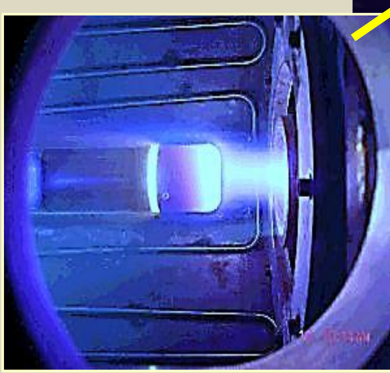
and possible influence of radiation

Validation of CoRaM-MARS and RH1D codes?

High Enthalpy Wind Tunnel

SOUPLIN – CORIA





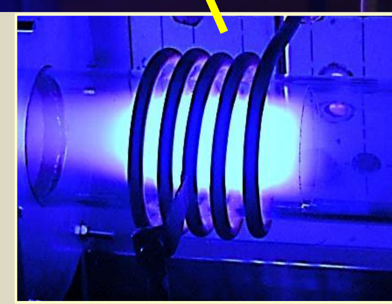
Parietal temperature and heat flux

Thermal sensor, IR Thermography

Emission, absorption spectrocopy

Laser (Absorption, LiF) BL probing

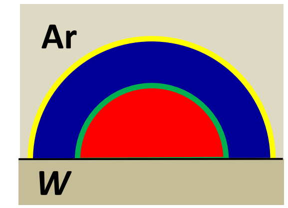
***LIBS** probing of the sample* $(C - SiC\ldots)$

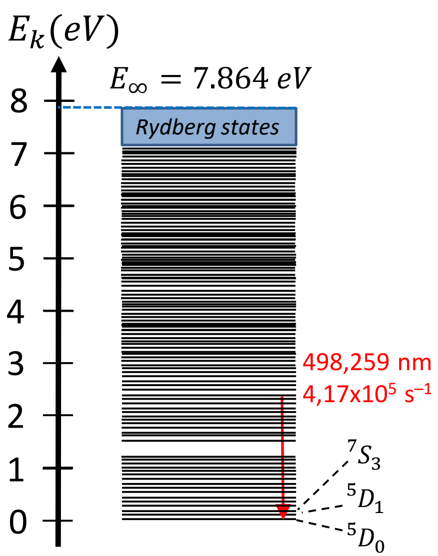


$\mathbf{1.76}\ \boldsymbol{MHz}$

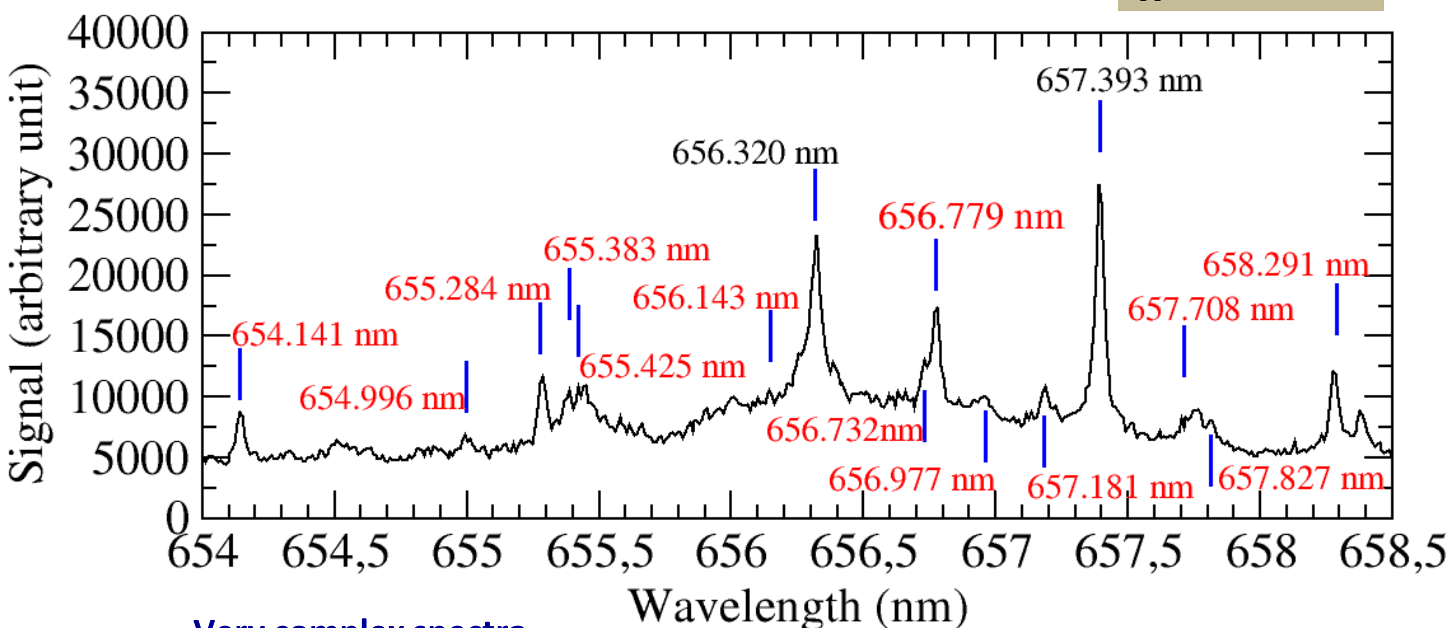
$\mathbf{60}\ \boldsymbol{kW}$

Spectroscopic analysis





$^{184}_{74}W([Xe], 6s^2, 4f^{14}, 5d^4)$



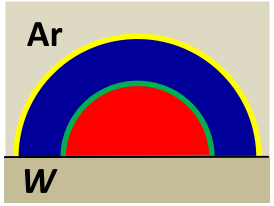
Very complex spectra…

Lines broadened by Stark effect

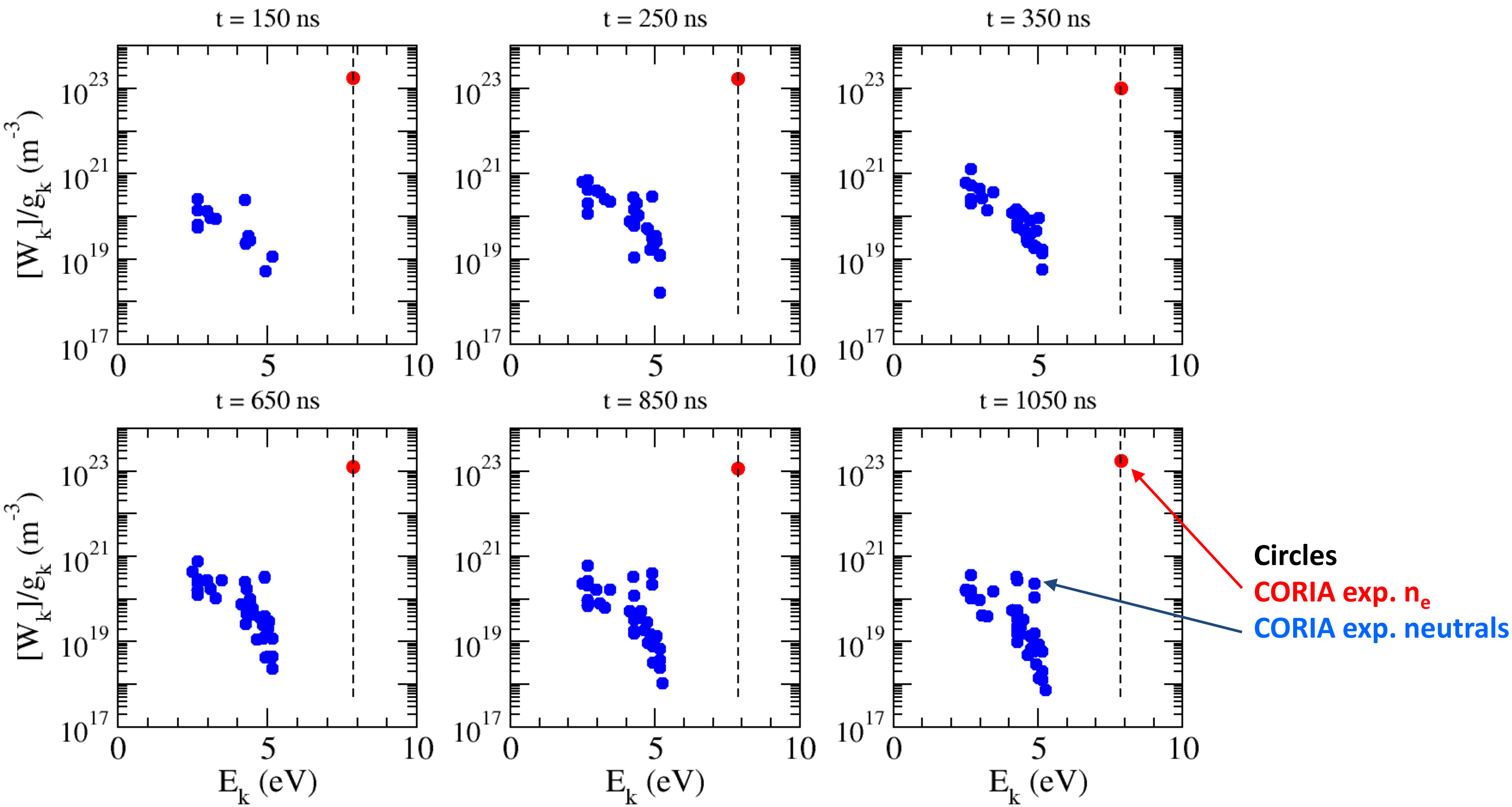
Few lines with known A_{ki}…

W I transitions reported in the NIST database with A_{ki}	**7 %**
W II transitions reported in the NIST database with A_{ki}	**7 %**
W III transitions reported in the NIST database with A_{ki}	**1 %**

Boltzmann plots

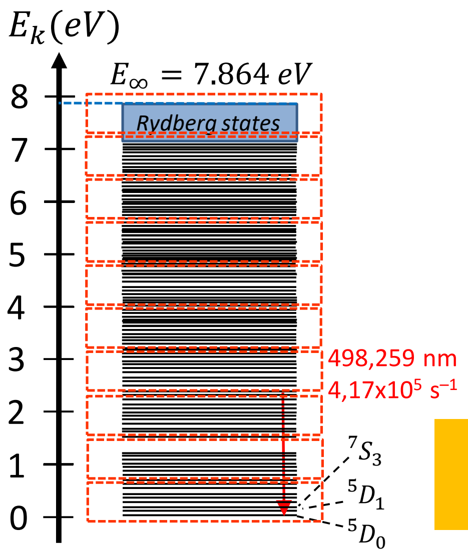


W (Ar, p_{atm}) 30 ps 532 nm 10 J cm^{-2}



Low precision of the Einstein coefficients for WI transitions

Simplification of the energy diagram

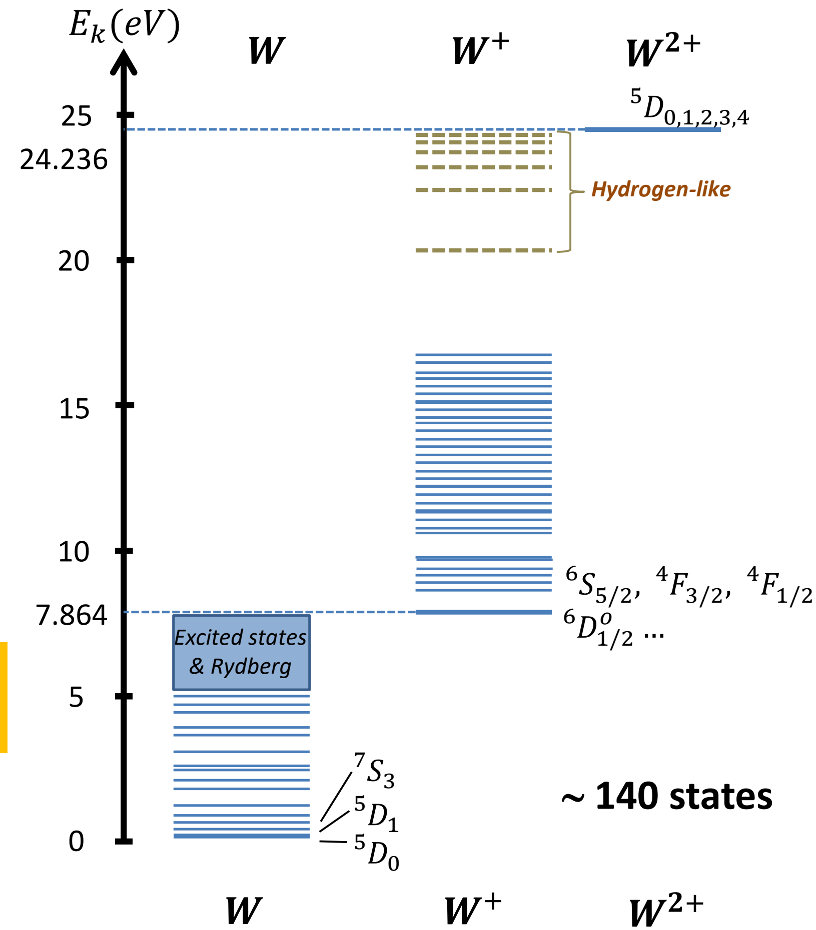


$^{184}_{74}W([Xe], 6s^2, 4f^{14}, 5d^4)$

Number of states reported in the NIST database:

- **508 for W**
- **264 for W^+**

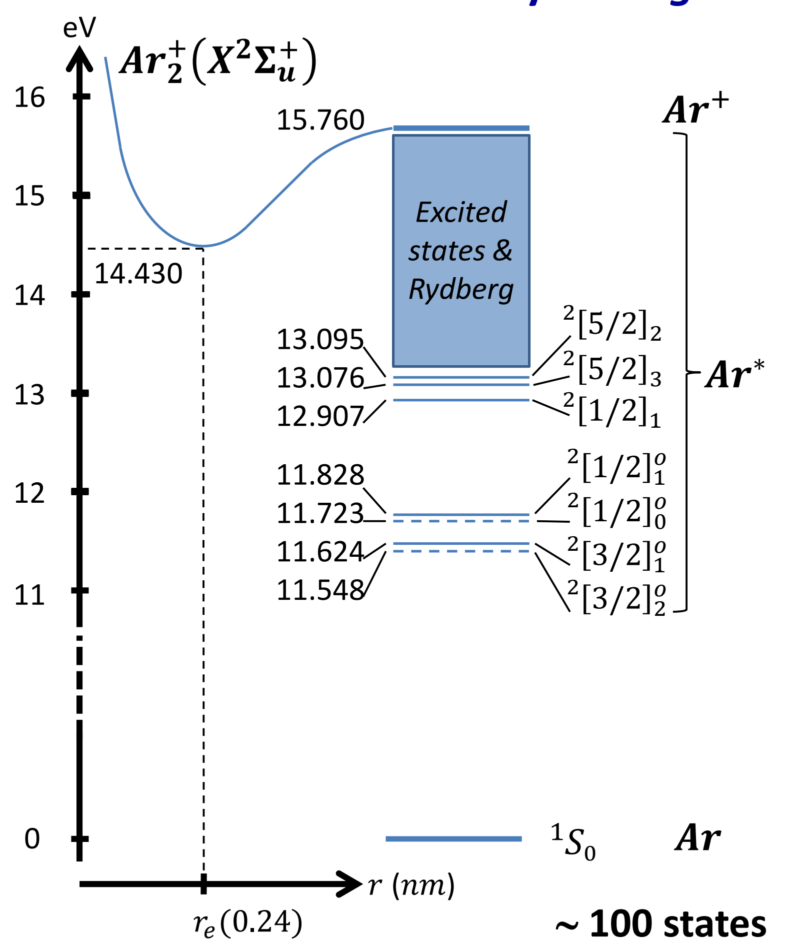
Lumping of levels
$\Delta E \sim 0.1\ eV$



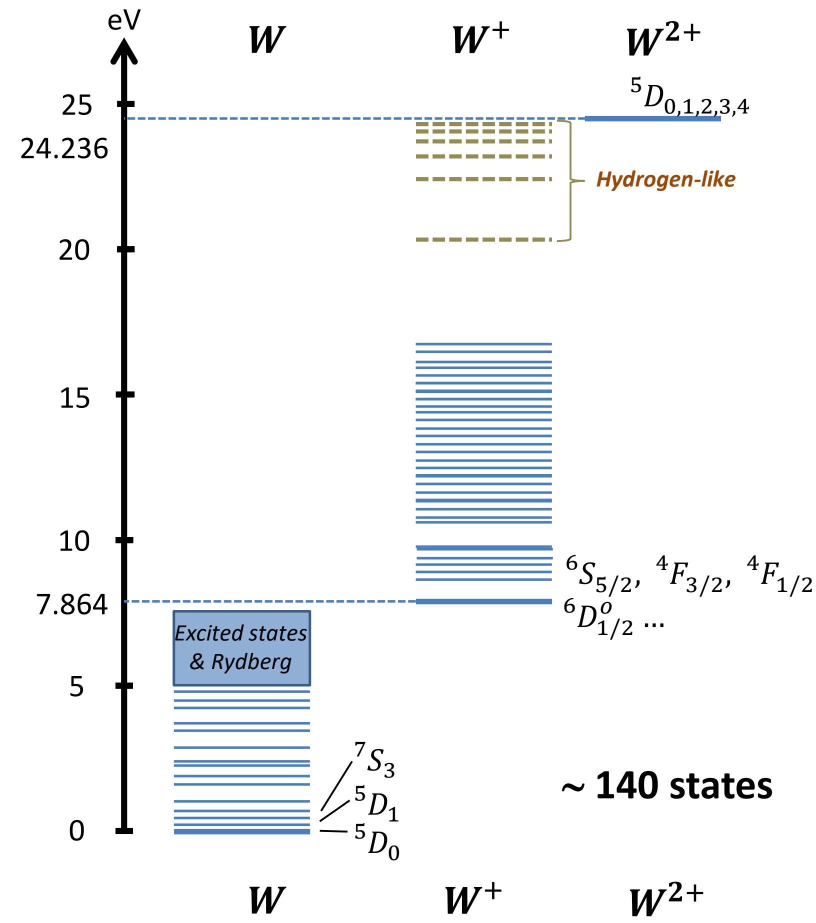
Type	3 spe.	~ 140 states	
Atoms	W	$^5D_0$, $^5D_1$, $^5D_2$, $^5D_3$	(60 states)
Ions	W^+	$^6D_{1/2}$, $^6D_{3/2}$, $^6D_{5/2}$, $^6D_{7/2}$, ...	(74 states)
	W^{2+}	$^5D_{0…4}$, $^3P2_{0…2}$, $^5F_{1…5}$, $^6D_{7/2}$, ...	(5 states)

Example $W - Ar$

Shock layer - *Argon*



Central plasma - *Tungsten*

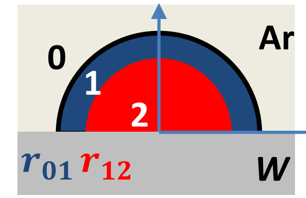


Type	3 spe.	~ 100 states	
Mol. ions	Ar_2^+	$X^2\Sigma_u^+$	
Atoms	Ar	$^1S_0$, $^2[3/2]^\circ_2$, $^2[3/2]^\circ_1$, $^2[1/2]^\circ_0$, ……	(90 states)
Atomic ions	Ar^+	$^2P^\circ_{3/2}$, $^2P^\circ_{1/2}$, $^2S_{1/2}$, $^4D_{7/2}$, ……………	(7 states)

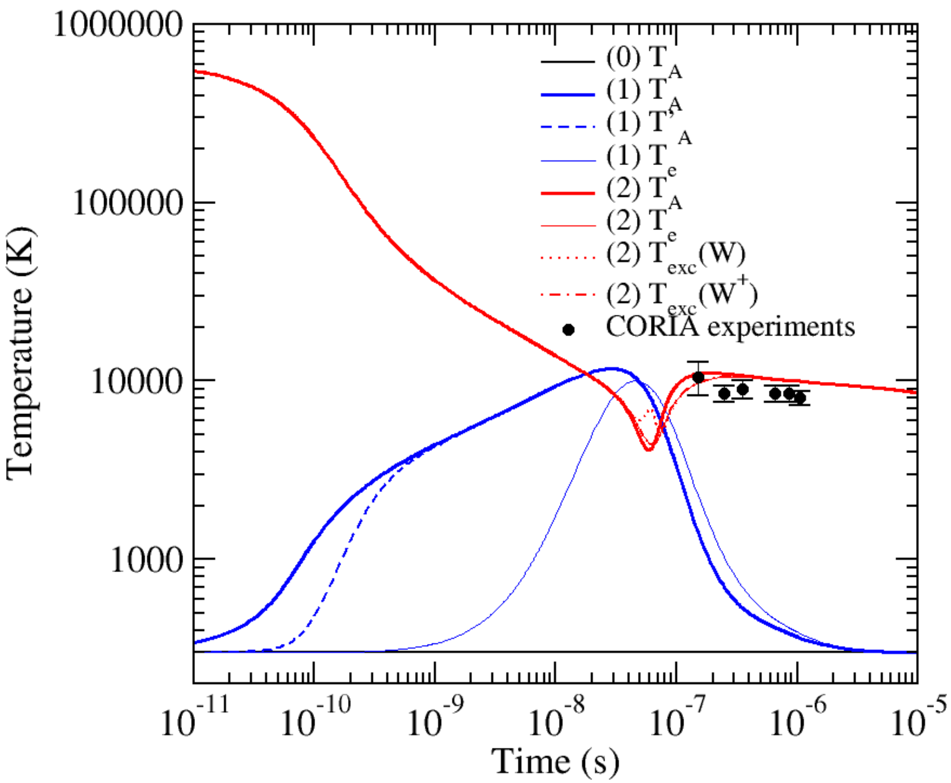
Type	3 spe.	~ 140 states	
Atoms	W	$^5D_0$, $^5D_1$, $^5D_2$, $^5D_3$ …………………………	(60 states)
Ions	W^+	$^6D_{1/2}$, $^6D_{3/2}$, $^6D_{5/2}$, $^6D_{7/2}$, ………………	(74 states)
	W^{2+}	$^5D_{0…4}$, $^3P2_{0…2}$, $^5F_{1…5}$, $^6D_{7/2}$, ……………	(5 states)

Influence of the background gas pressure

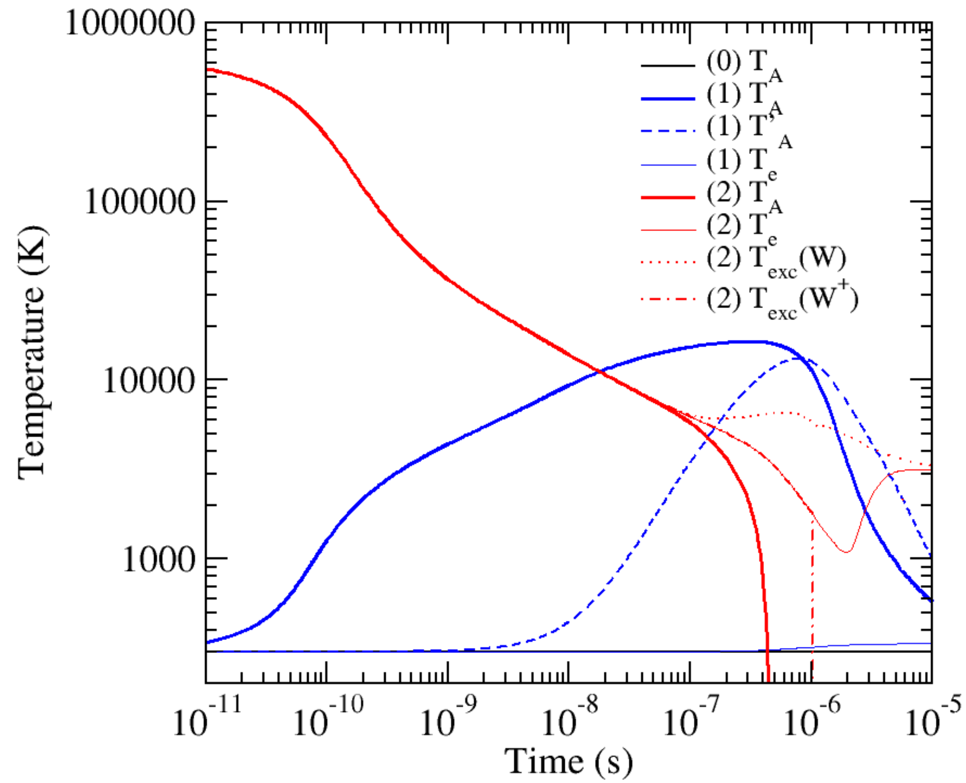
W (Ar) 10 ps 532 nm 10 J cm^{-2}



p = 10^5 Pa



p = 10 Pa

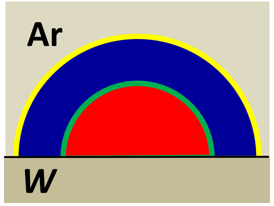


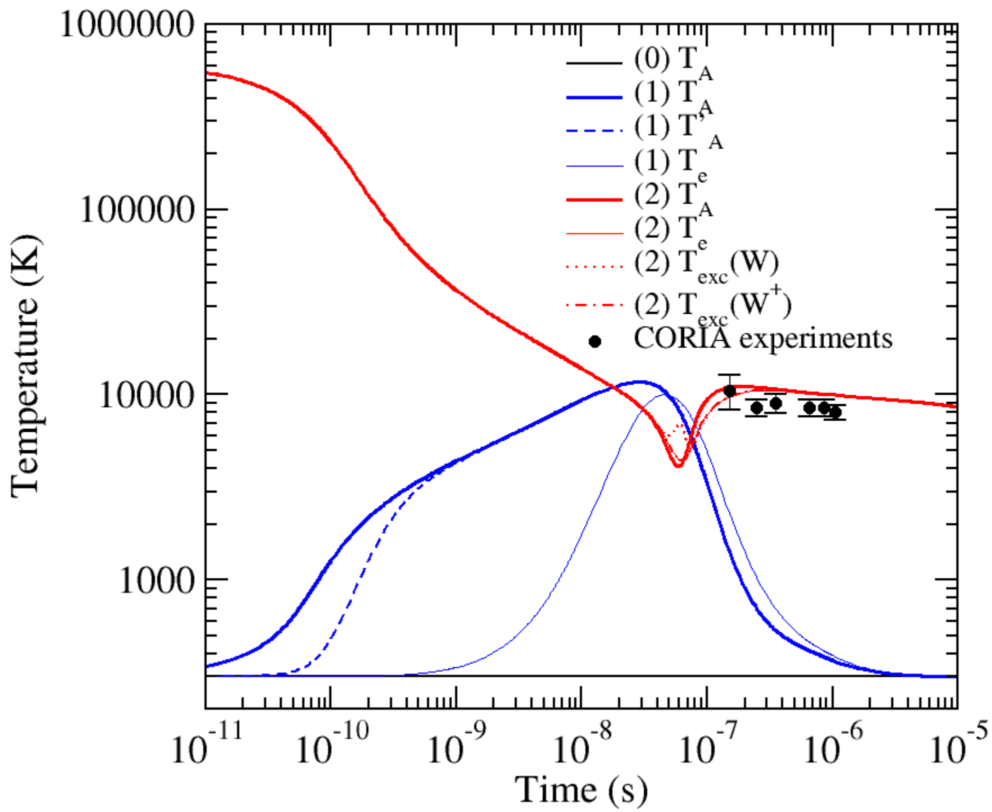
Long lifetime of the plasma

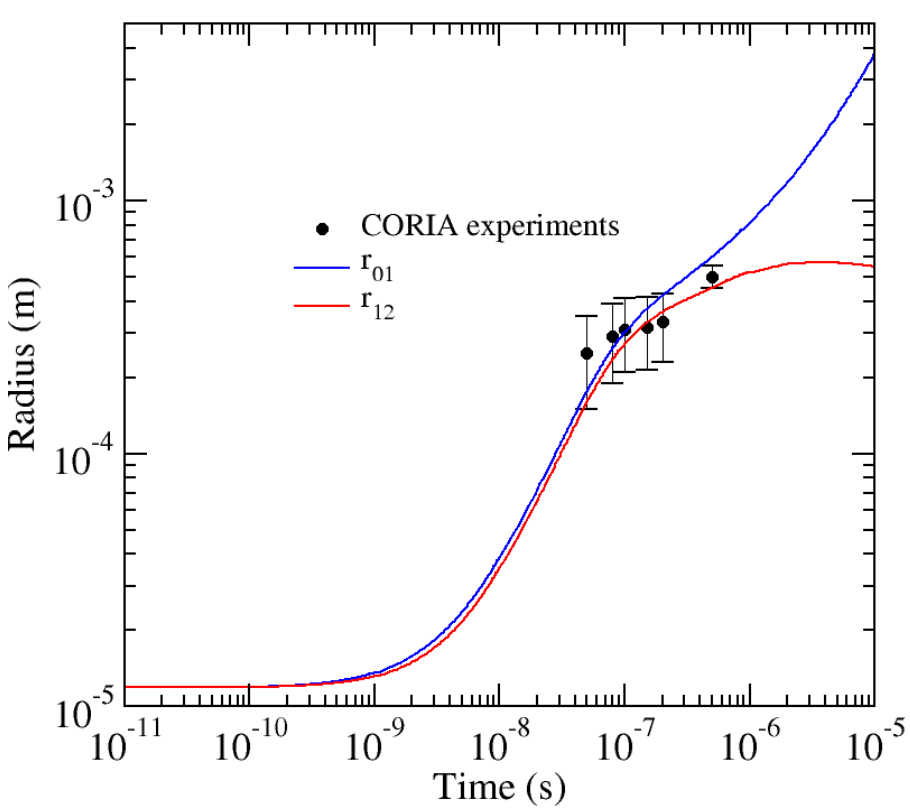
Plasma extinction for t ~ 500 ns

Temperature – Expansion

W (Ar, p_{atm})   30 ps   532 nm   10 J cm^{-2}





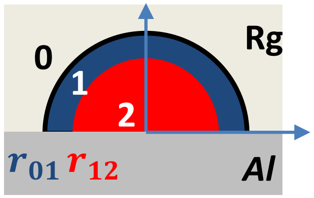


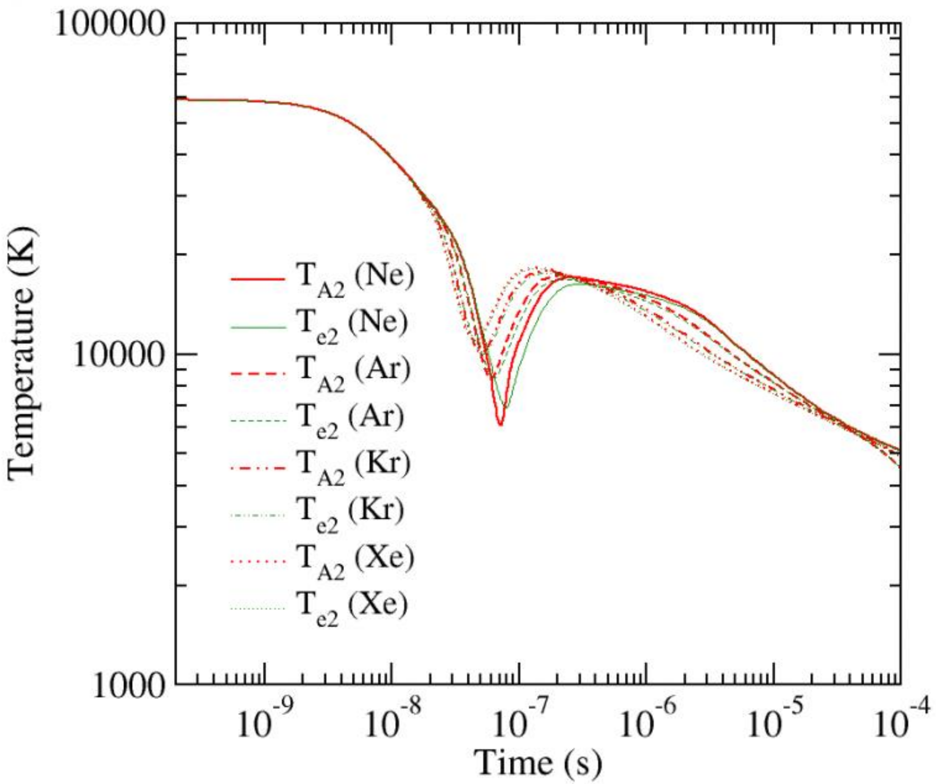
Calculated temperature slightly higher…

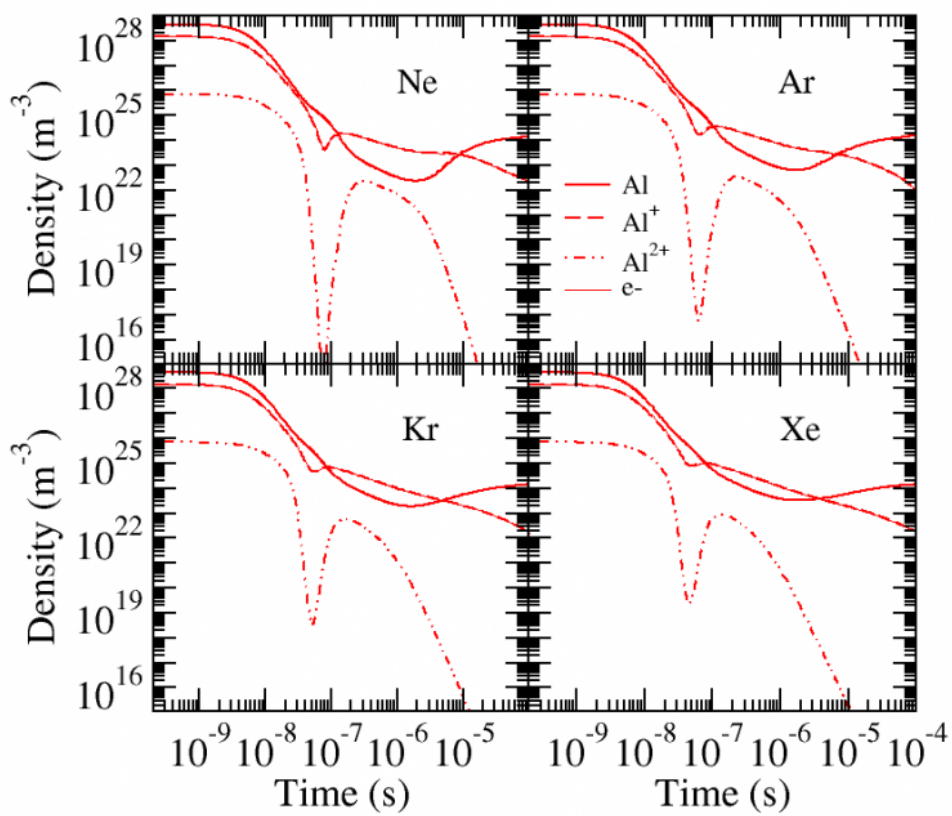
Satisfactory agreement for the radii…

Temperature - Chemistry

Al (p_{atm}) 10 ps 532 nm 10 J cm^{-2}



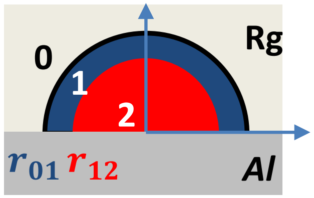




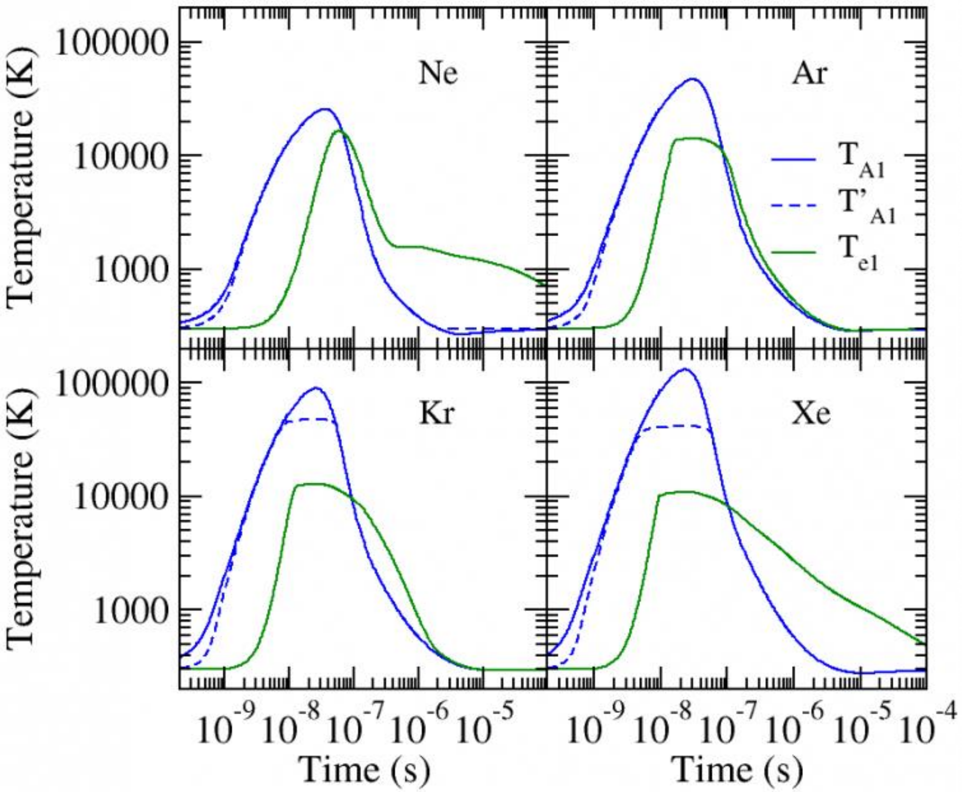
Strong decrease in T_A and T_e ~ 70 ns due to the pressure

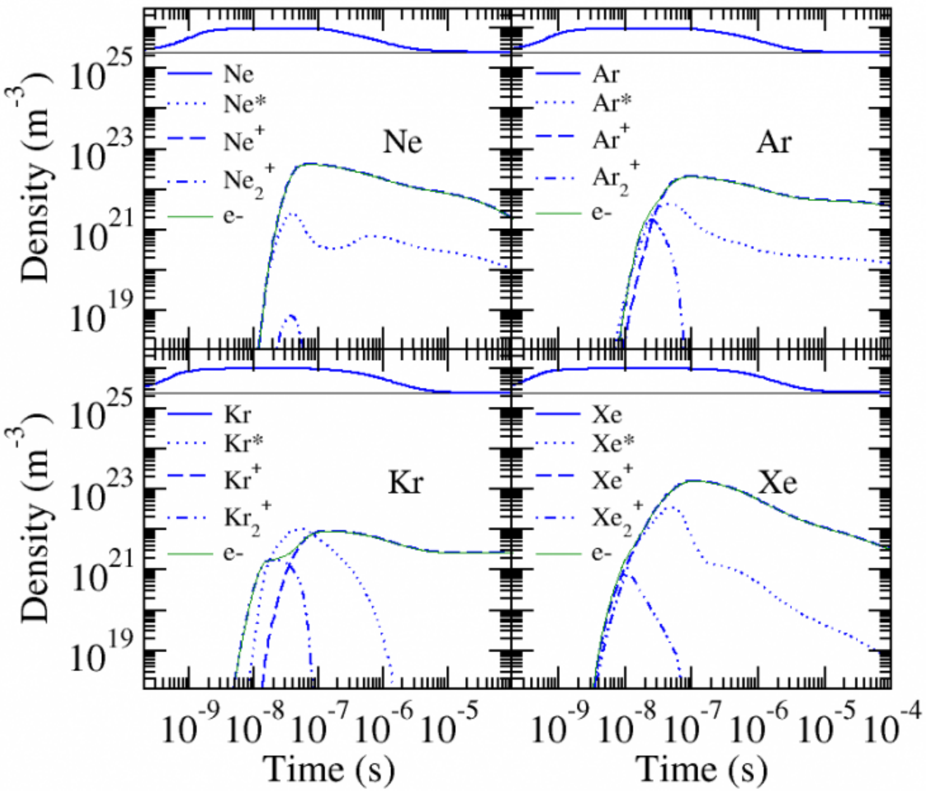
Strong decrease in $[Al^{2+}]$ for ~ 70 ns due to T

Shock layer



Al (p_{atm}) 10 ps 532 nm 10 J cm^{-2}





Strong thermal non equilibrium

Strong influence of Rg_2^+ at the beginning

Then replaced by that of Rg^+