Link between ablation and line emission for hydrogen fuelling pellet in LHD

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Introduction – Pellet

Pellets in nuclear fusion:

Fueling	**Fuel the plasma core after ablation and homogenization (drift phase)** → Cloudlet physical and geometrical characteristics as initial conditions of the drift phase
ELM Pacing	**Local pressure perturbation in the plasma edge** → Depends mainly on the ablation profile
Disruption mitigation	**Shattered pellets for increasing density** → Depends on ablation profile of multiple fragments in rapidly evolving plasma

Up to now :

- Ablation rate ∝ Line emission H_α
- Volume averaged cloudlets parameters determined

Experimental apparatus – LHD

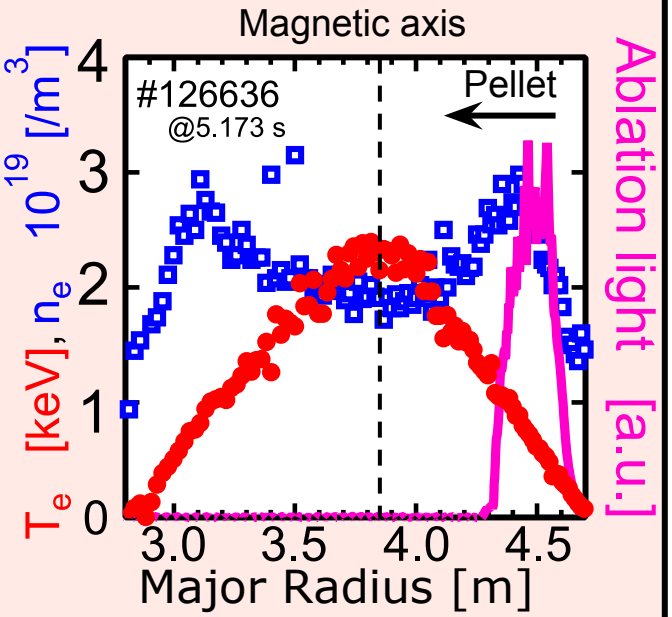
The LHD stellarator :

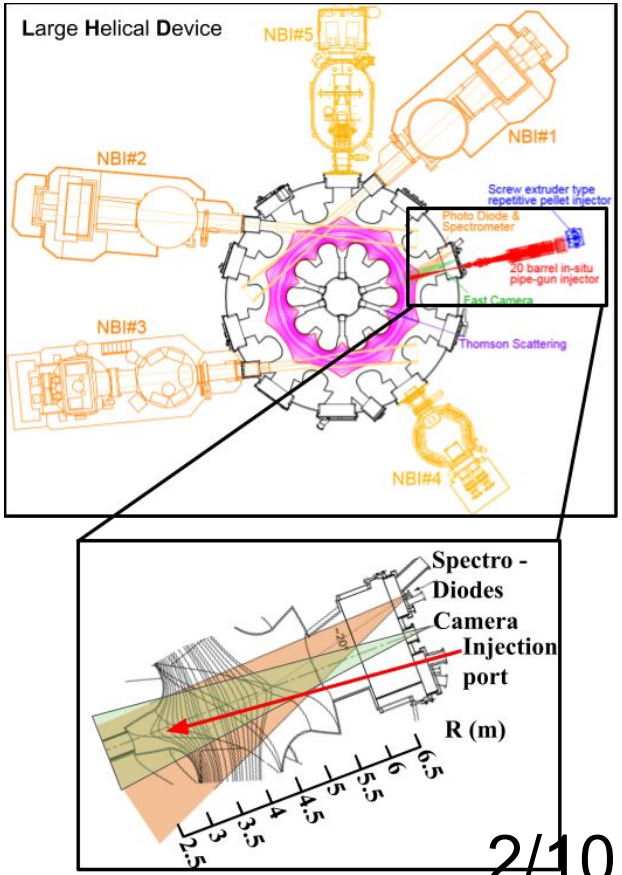
- R = 3.6 m,
- a = 0.6m,
- B = 3 T

Experimental procedure :

- Injected pellets :
  Np ≈ 10^{21} at.,
  Vp = 1 km.s^{-1}

- NBI heated plasmas
  (P =7 MW),





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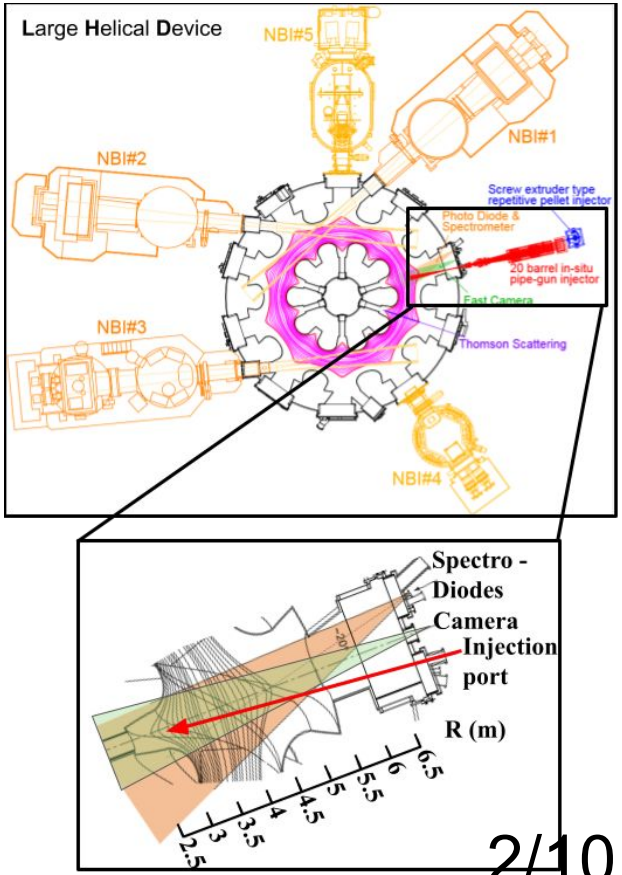
3 diagnostics were used :

- High speed imaging spectroscopy



Experimental apparatus – LHD

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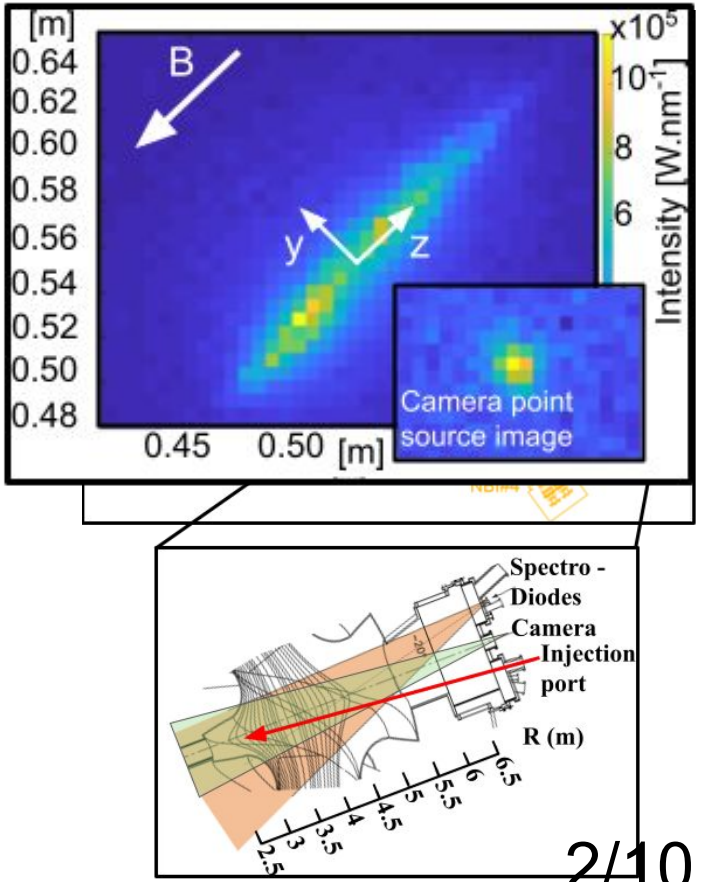
3 diagnostics were used :

- High speed imaging spectroscopy
  - multibranch fiberscope + fast camera
  - 1 image every 20 µs, exposure time: 2 µs.
  - Each objective lens is equipped with a band filter (H_β with two filter widths: 5 and 20 nm, and the continuum close to λ = 576 nm)
  - Spatial resolution : 6mm + degradation (Transfer Function)



Experimental apparatus – LHD

The LHD stellarator :

- R = 3.6 m,
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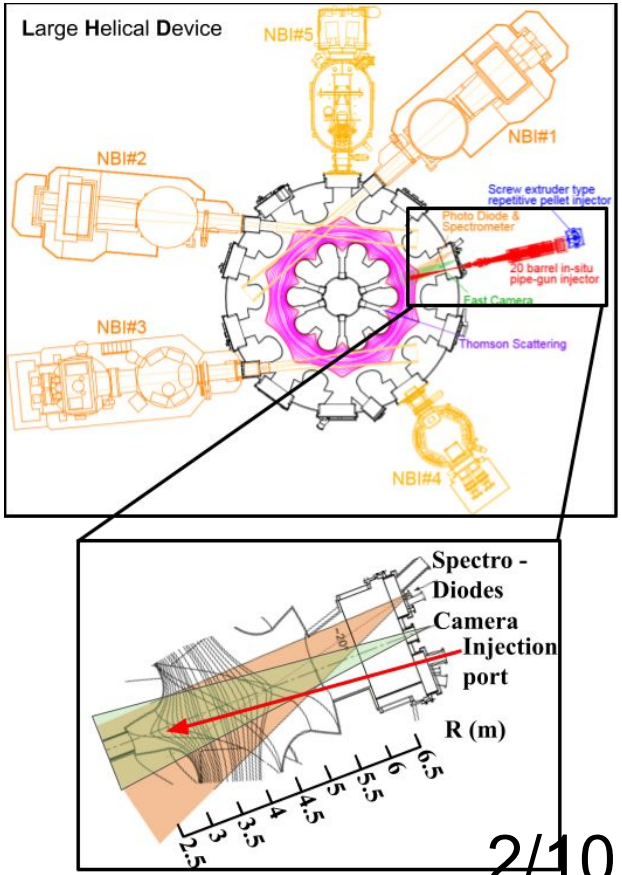
3 diagnostics were used :

- High speed imaging spectroscopy
- Fast diodes



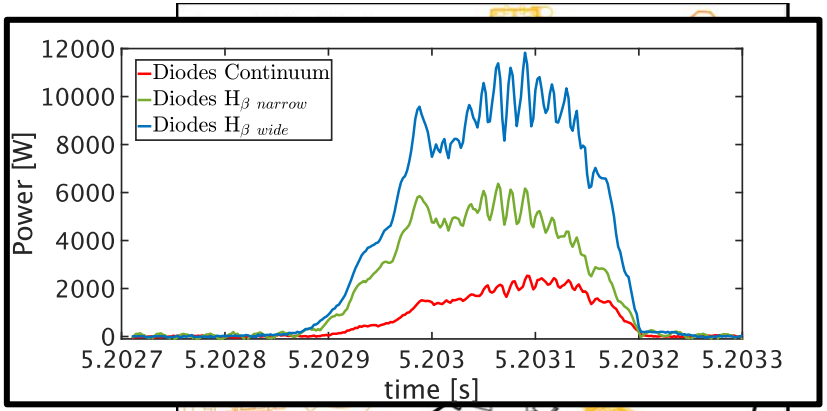
Experimental apparatus – LHD

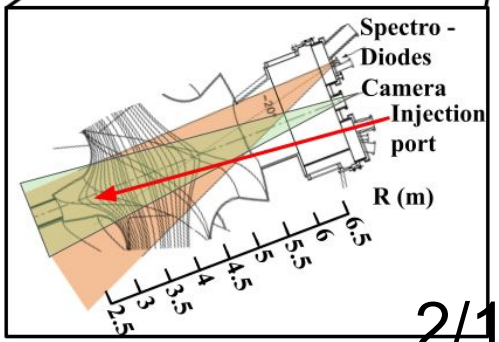
The LHD stellarator :

- R = 3.6 m,
- a = 0.6m,
- B = 3 T

3 diagnostics were used :

- High speed imaging spectroscopy
- Fast diodes
  - Time resolution : 2 μs
  - Same set of filters





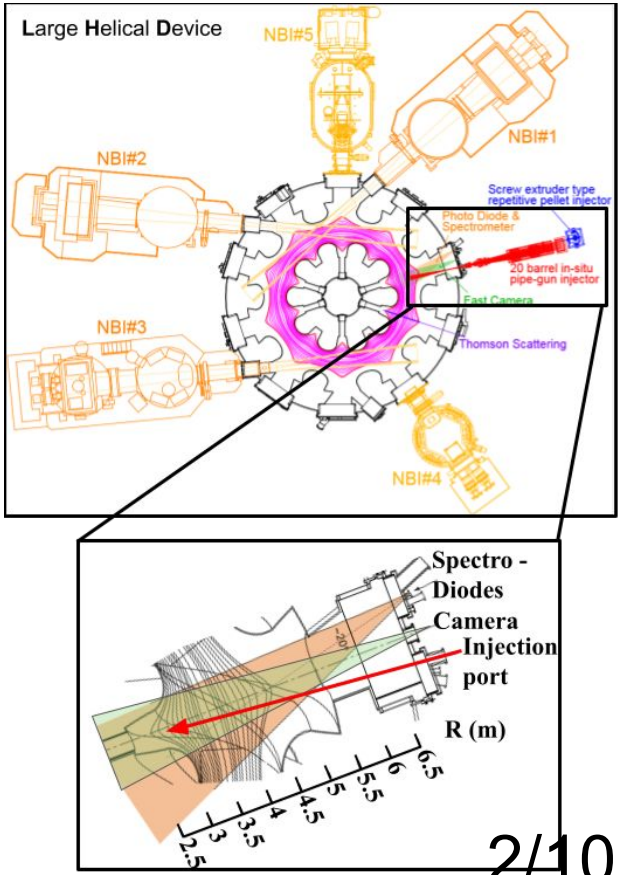
Experimental apparatus – LHD

The LHD stellarator :

- R = 3.6 m,
- a = 0.6m,
- B = 3 T

3 diagnostics were used :

- High speed imaging spectroscopy
- Fast diodes
- Absolutely calibrated high-resolution spectrometer



Experimental apparatus – LHD

The LHD stellarator :

- R = 3.6 m,
- a = 0.6m,
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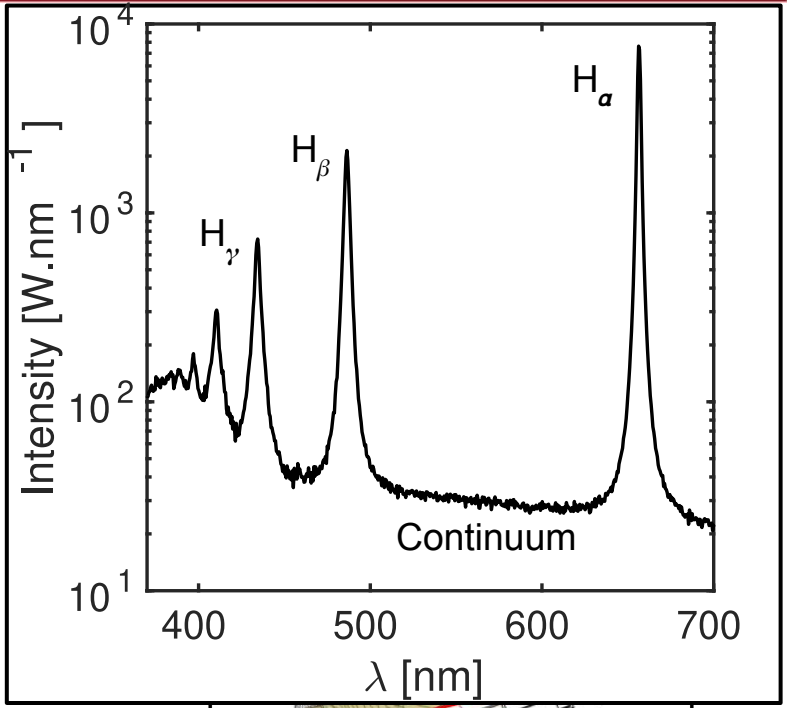
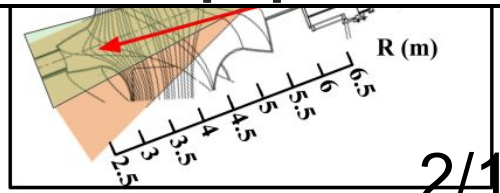
3 diagnostics were used :

- High speed imaging spectroscopy
- Fast diodes
- Absolutely calibrated high-resolution spectrometer
  - 1 spectrum every 16 μs, time resolution 84 μs
  - domain λ = 370 − 710 nm





Experimental apparatus – LHD

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3 diagnostics were used :

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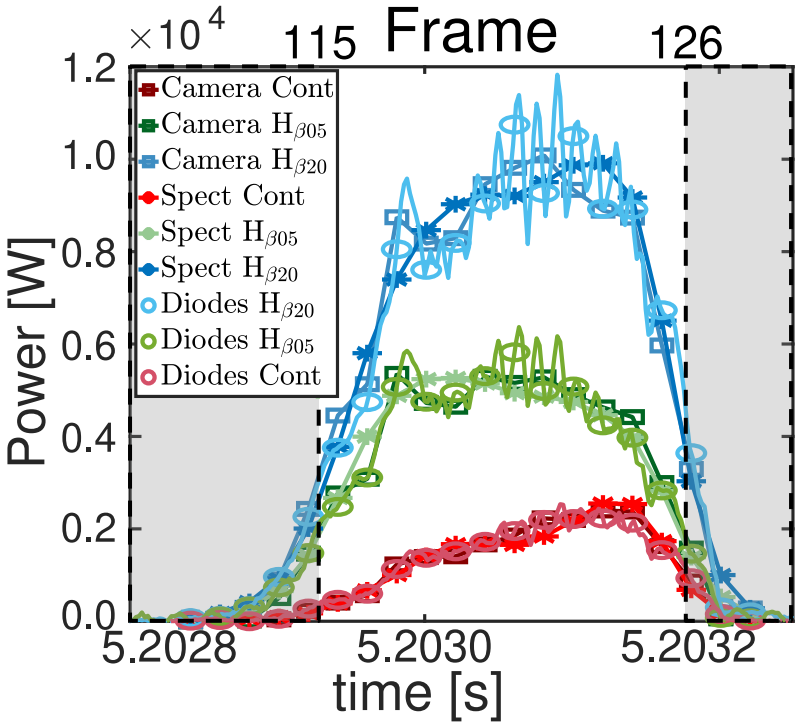
- Fast diodes
- Absolutely calibrated high-resolution spectrometer

⇒ Accurate time cross calibration of the 3 diagnostics

⇒ Camera image + Diode + Spectrum consistent every 20μs



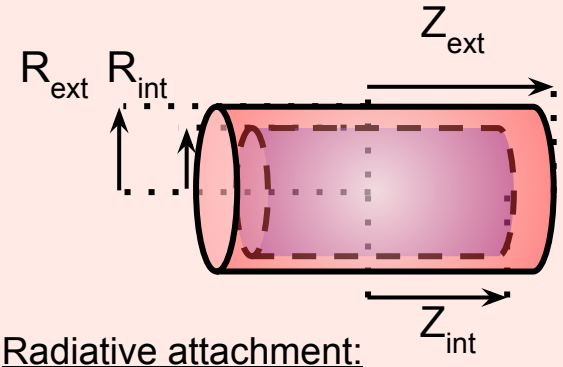
Objectives and Modeling

Objectives:

I. For each cloudlet determine: density(n), temperature(T), radius(R), length(Z)
II. Get the local ablation rate
III. Determine its link with the different line emission

Model:

Radiation model coupled to a 3-D radiative transfer calculation



- ❏ **Local thermodynamic equilibrium** assumed
- ❏ Line Emission / Bremsstrahlung / Radiative attachment / Recombination taken into account
- ❏ Cloudlet assumed **cylindrically symmetric**

Radiative attachment:

$$A + e^- \rightarrow A^- + h\nu$$

Radiative recombination:

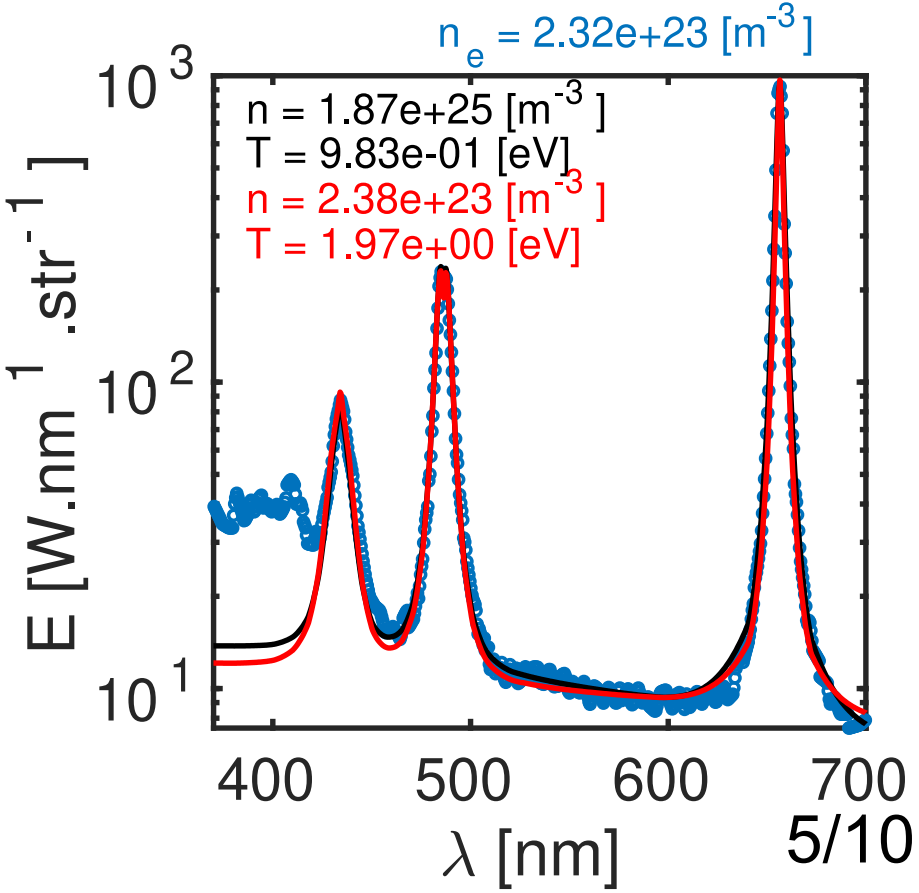
$$A^+ + e^- \rightarrow A + h\nu$$

Result 1 / 5 : Non-unicity of spectrum fit

- The only cloudlet spectrum can be fitted by severals (n,T,R,Z)
  $Z = 2.22$ m , $R = 0.13$ cm
  $Z = 0.05$ m, $R = 1.90$ cm

⇒ Need Spectrum and images simultaneously to get cloudlet characteristics

⇒ Multiple volumes (here 2) are required to get realistic dimensions



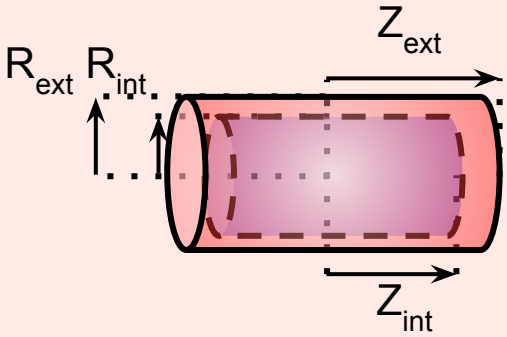
Result 2 / 5: Spectrum + image fit results in unique solution

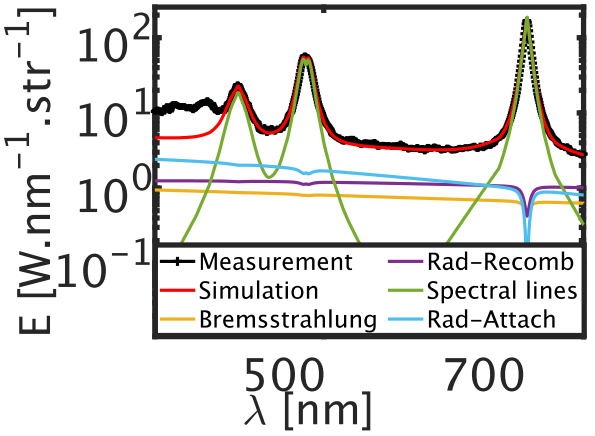
Result from camera & spectrum datas

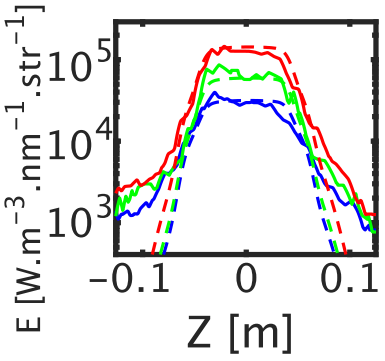
I. Spectrum with the different emission components

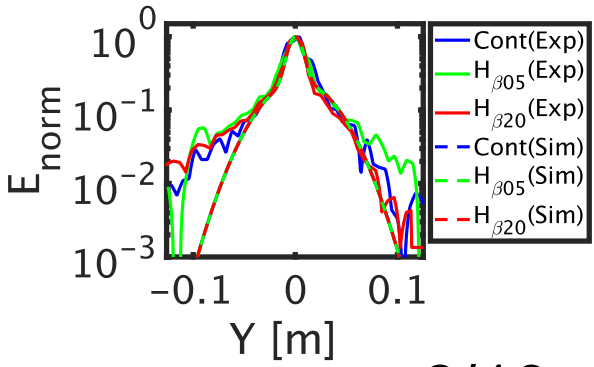
II. Image best fit longitudinal and normalized transverse cuts. Here :

R_{in} = 2.2 mm
R_{ext} = 2.4 mm
Z_{in} = 9.19 cm
Z_{ext} = 12.73 cm
T_{in} = 1.05 eV
n_{in} = 1.88 10^{25} m^{-3}
T_{ext} = 2.72 eV
n_{ext} = 3.87 10^{23} m^{-3}





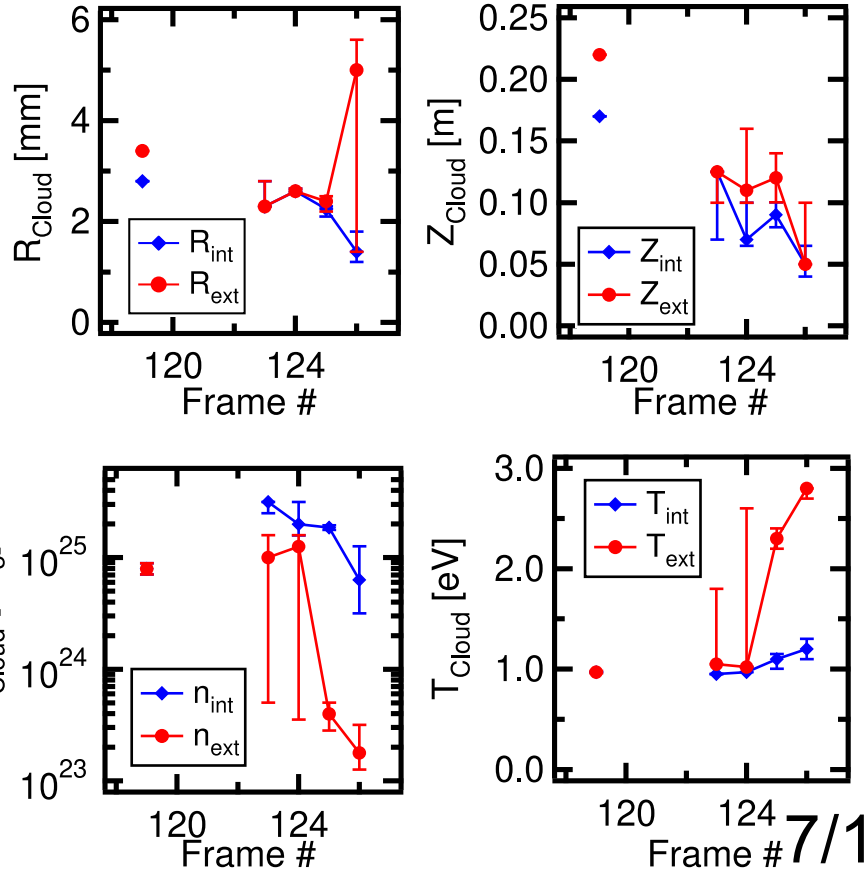




Result 3 / 5: Cloudlet parameters along pellet path

I. Cloudlets are composed of
   A. A dense : ($\approx 10^{25} m^{-3}$) and cold ($\approx$1 eV) core
   B. A thin less dense ($\approx 10^{24} m^{-3}$) and hotter ($\approx$ 2 eV) external layer

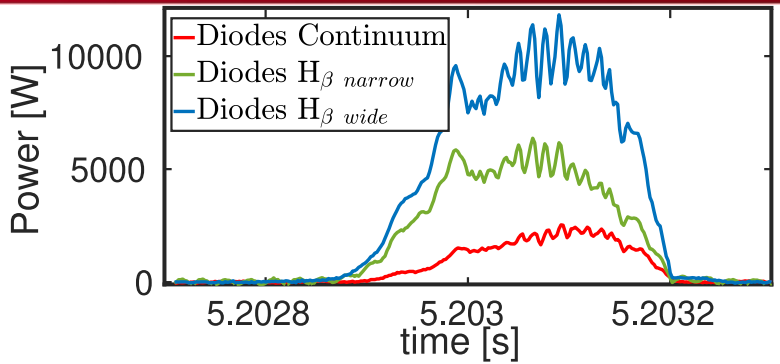
II. The contribution of the thin layer to the spectrum is small but its presence is required for an accurate fit of the images

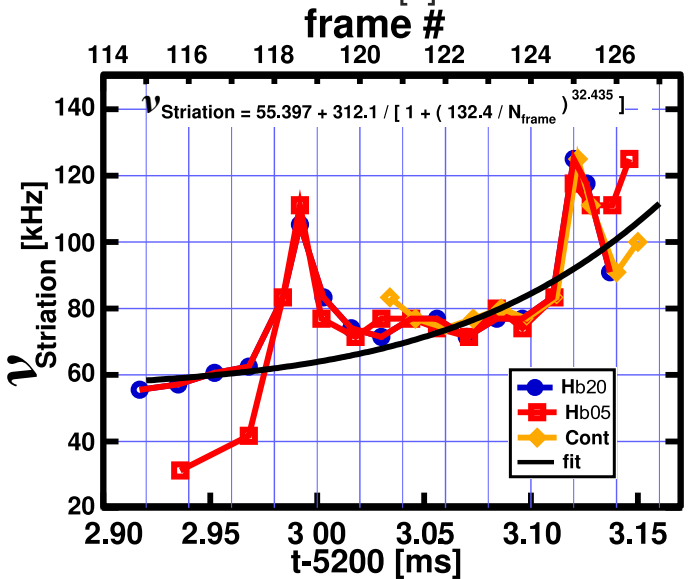


Result 4 / 5: Ablation rate estimation

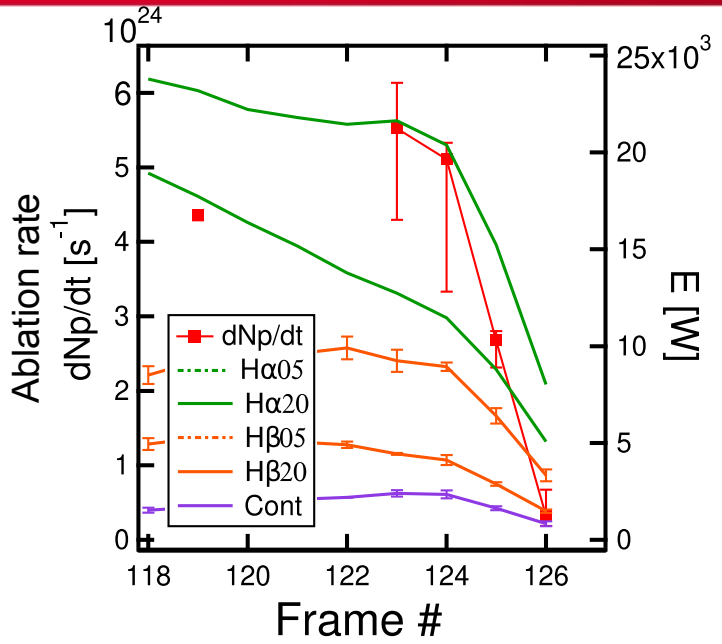
I. Ablation rate is calculated as Nν,
→ <u>cloudlets particle contents N</u> (i.e. the ablation rate multiplied by the time for building a cloudlet)
→ <u>cloudlet ejection frequency ν</u> (i.e. the inverse of the time for building a cloudlet)

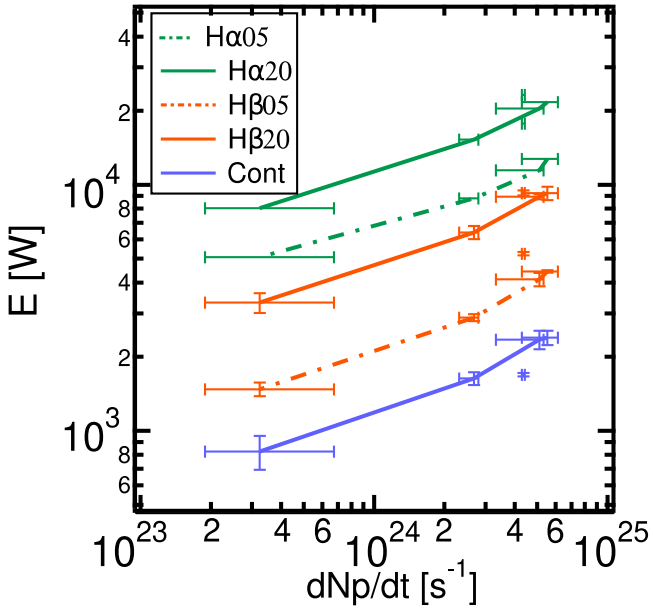
II. ν is determined from the oscillations of the diode signals (from 50 to 100 kHz, increasing along the pellet path).





Result 5 / 5: Link between ablation rate and line emission





The ablation rate and emission dependence with time shows although the general trend of the ablation rate and line emissions are similar,

⇒ **no clear proportionality can be established between them**

⇒ one cannot accurately infer the ablation profile from line emission.

Summary

I. The unambiguous determination of ablation cloudlet characteristics requires the knowledge of calibrated images and spectrum.

II. The model and procedure described here allows to evaluate:

- The cloudlet geometry, density and temperature distributions,
- The local (i.e. instantaneous) ablation rate,
- The relation between line emission (H_{α}, H_{β}…) and the ablation rate

$\Rightarrow$ No strict proportionality is observed between them.

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