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National Institute for Fusion Science

DE LA RECHERCHE À L'INDUSTRIE



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

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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 :

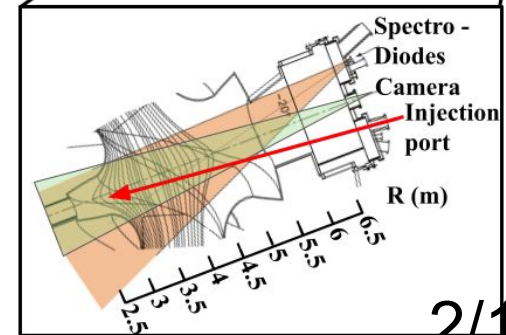
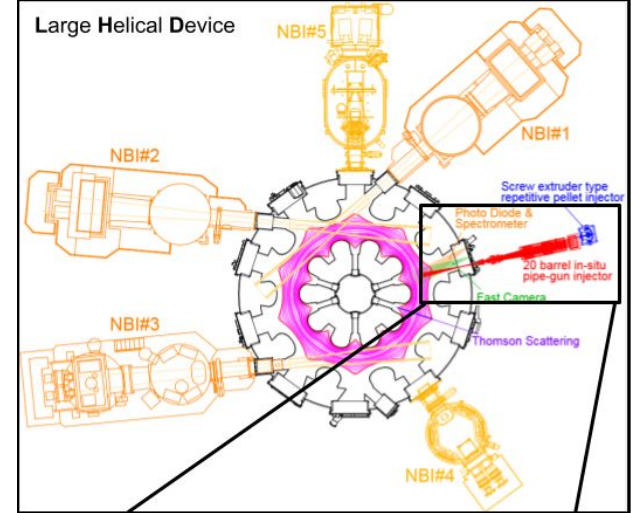
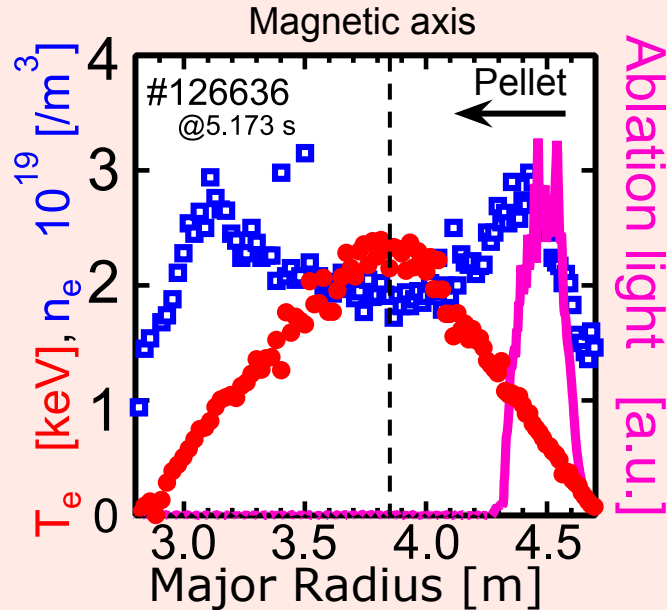
- [Ablation rate](#) \propto Line emission H_{α}
- [Volume averaged](#) cloudlets parameters determined

The LHD stellarator :

- $R = 3.6 \text{ m}$,
- $a = 0.6 \text{ m}$,
- $B = 3 \text{ T}$

Experimental procedure :

- Injected pellets :
 $N_p \approx 10^{21} \text{ at.}$,
 $V_p = 1 \text{ km.s}^{-1}$
- NBI heated plasmas
 $(P = 7 \text{ MW})$,

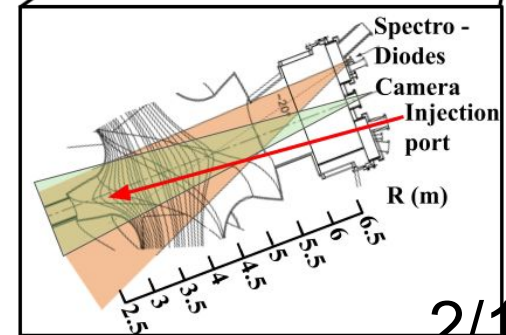
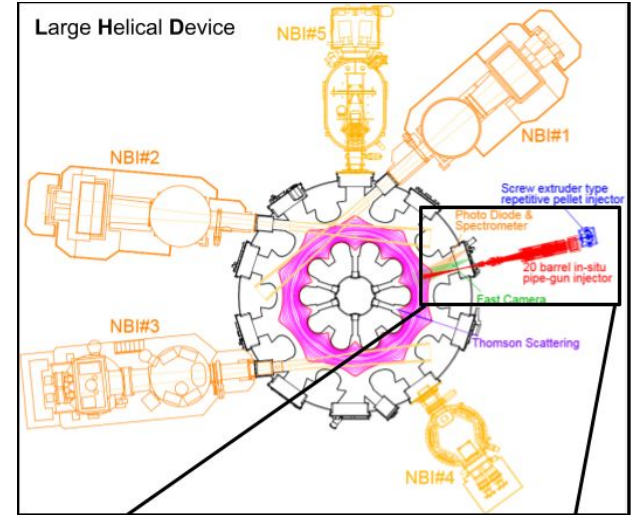


The LHD stellarator :

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

3 diagnostics were used :

- High speed imaging spectroscopy

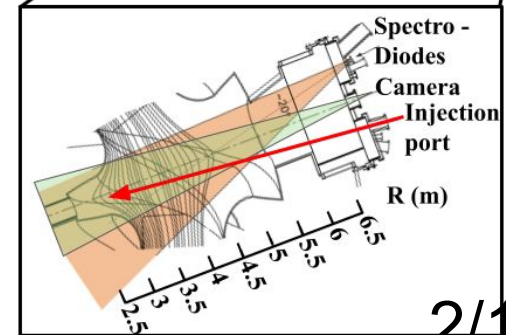
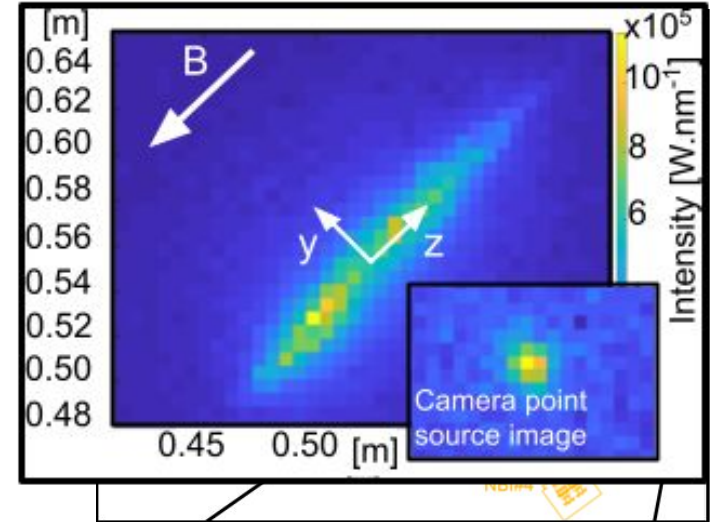


The LHD stellarator :

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

3 diagnostics were used :

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

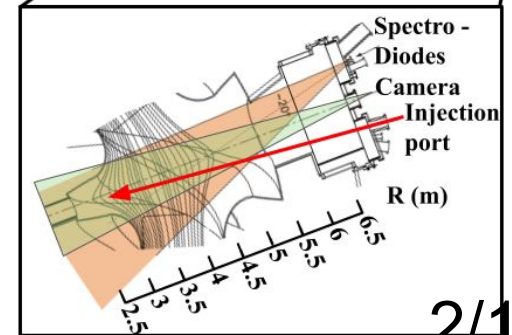
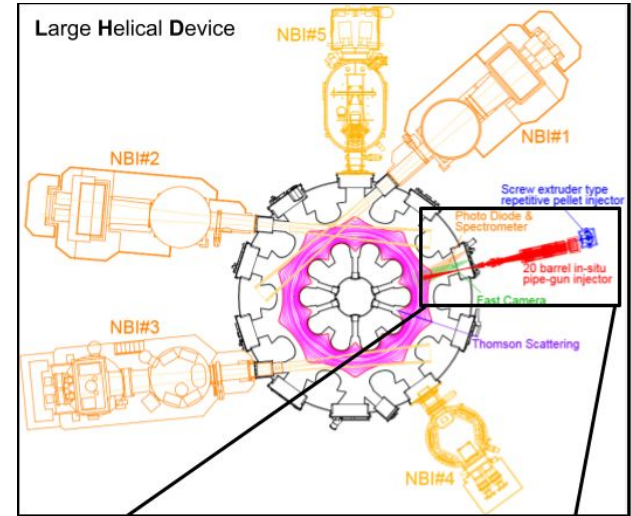


The LHD stellarator :

- $R = 3.6 \text{ m}$,
- $a = 0.6 \text{ m}$,
- $B = 3 \text{ T}$

3 diagnostics were used :

- High speed imaging spectroscopy
- Fast diodes

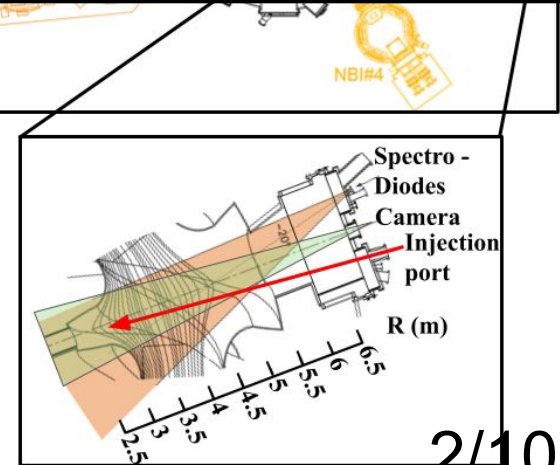
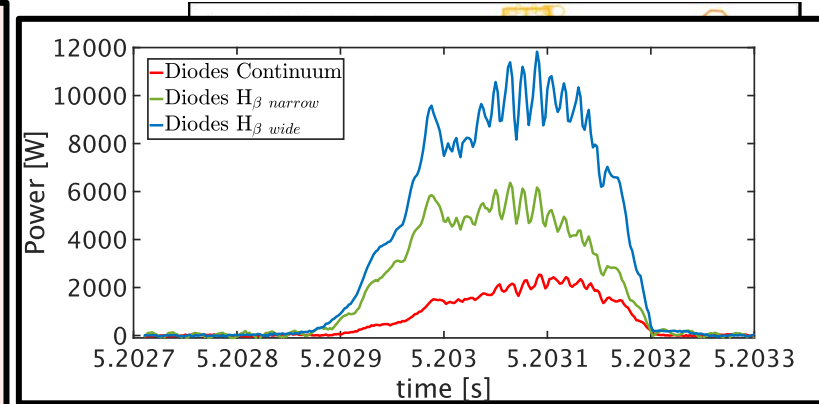


The LHD stellarator :

- $R = 3.6 \text{ m}$,
- $a = 0.6 \text{ m}$,
- $B = 3 \text{ T}$

3 diagnostics were used :

- High speed imaging spectroscopy
- Fast diodes
 - Time resolution : $2 \mu\text{s}$
 - Same set of filters

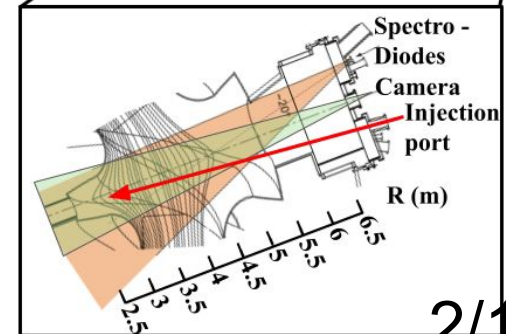
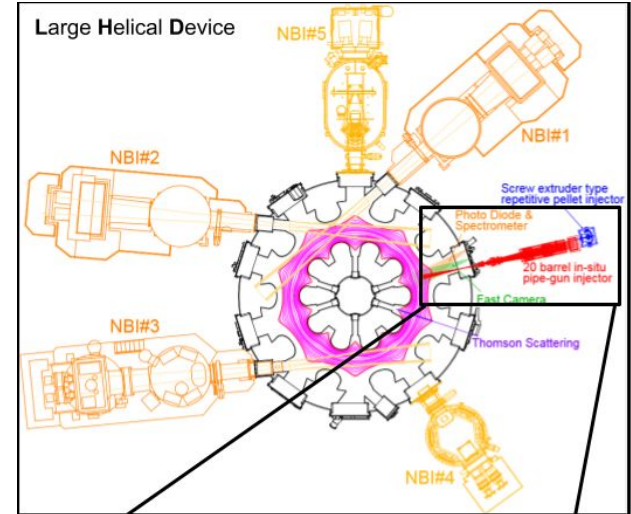


The LHD stellarator :

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

3 diagnostics were used :

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

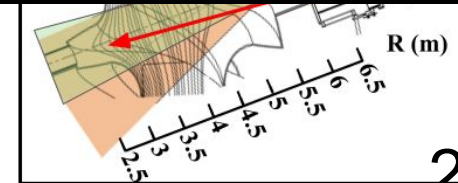
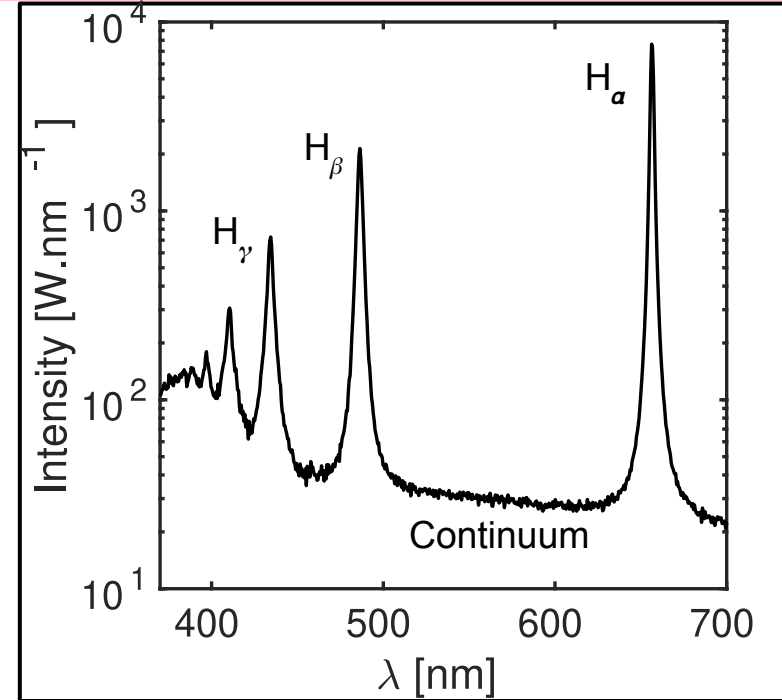


The LHD stellarator :

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

3 diagnostics were used :

- High speed imaging spectroscopy
- Fast diodes
- Absolutely calibrated high-resolution spectrometer
 - 1 spectrum every $16 \mu\text{s}$, time resolution $84 \mu\text{s}$
 - domain $\lambda = 370 - 710$ nm



The LHD stellarator :

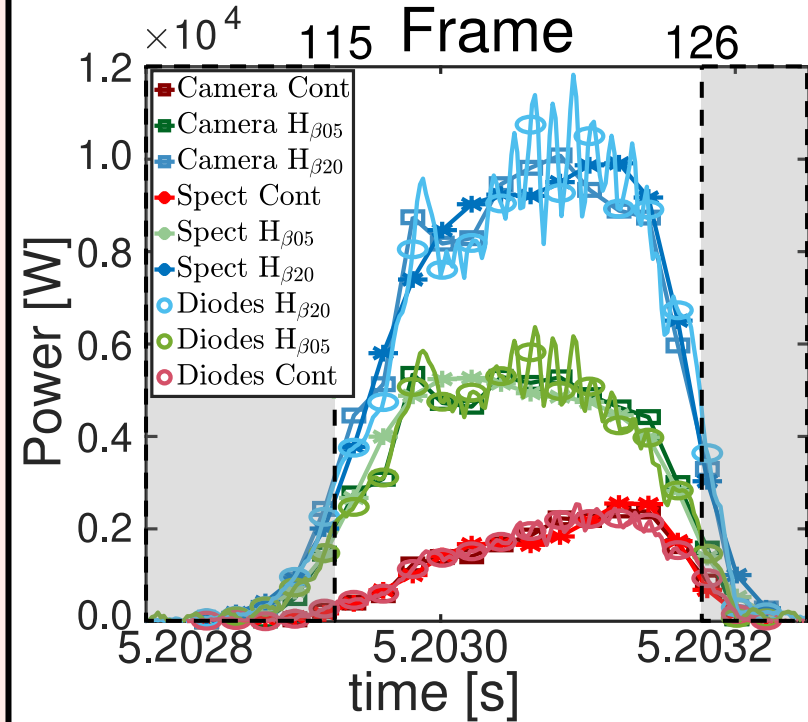
- $R = 3.6$ m,
- $a = 0.6$ m,
- $B = 3$ T

3 diagnostics were used :

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

⇒ Accurate time cross calibration of the 3 diagnostics

⇒ Camera image + Diode + Spectrum consistent every $20\mu\text{s}$



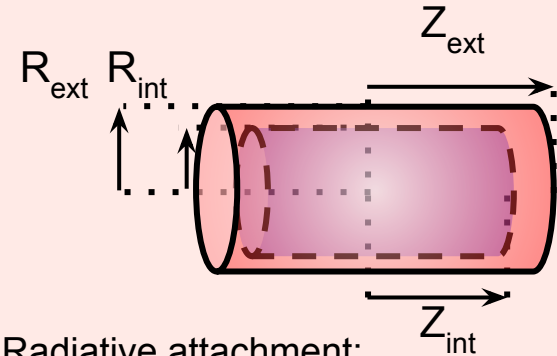
Objectives:

- 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

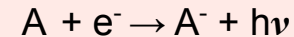
Model:

Radiation model coupled to a 3-D radiative transfer calculation

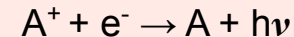
- ❑ **Local thermodynamic equilibrium** assumed
- ❑ Line Emission / Bremsstrahlung / Radiative attachment / Recombination taken into account
- ❑ Cloudlet assumed **cylindrically symmetric**



Radiative attachment:



Radiative recombination:



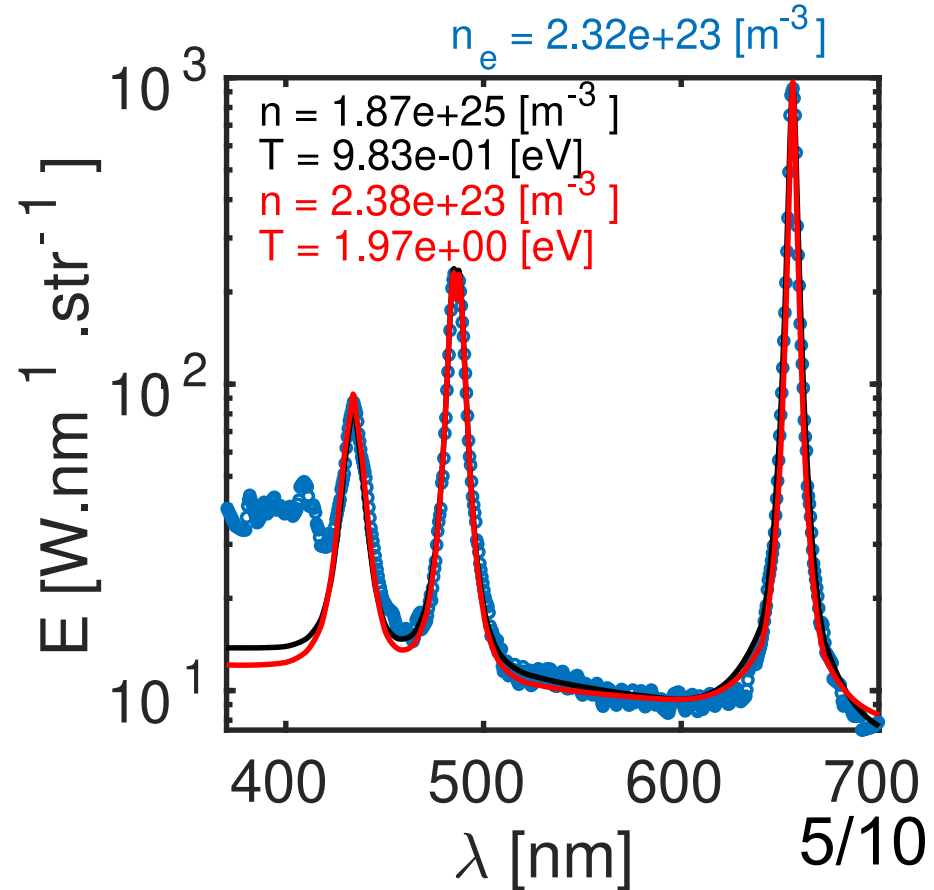
- The only cloudlet spectrum can be fitted by severals (n,T,R,Z)

$Z = 2.22 \text{ m}$, $R = 0.13 \text{ cm}$

$Z = 0.05 \text{ m}$, $R = 1.90 \text{ cm}$

⇒ Need Spectrum and images simultaneously to get cloudlet characteristics

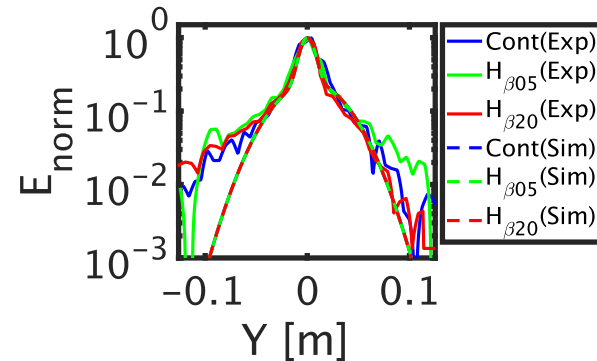
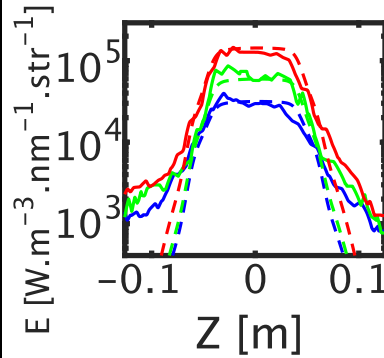
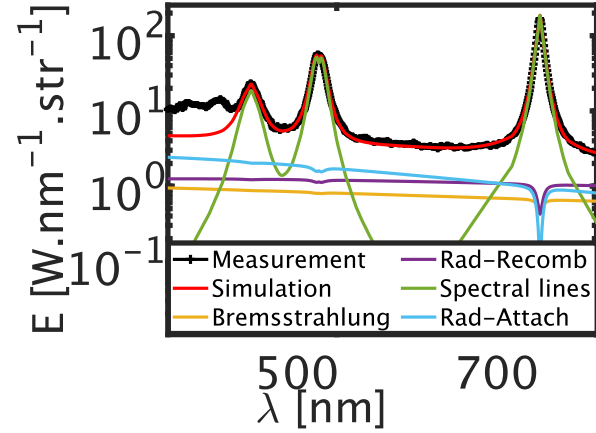
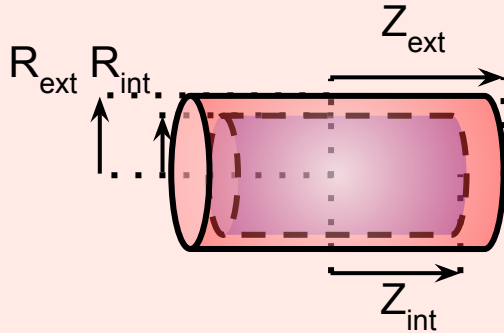
⇒ Multiple volumes (here 2) are required to get realistic dimensions



Result from camera & spectrum datas

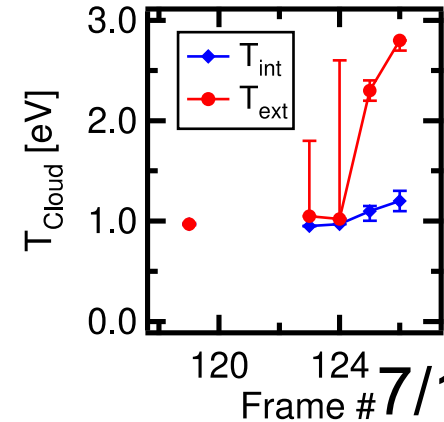
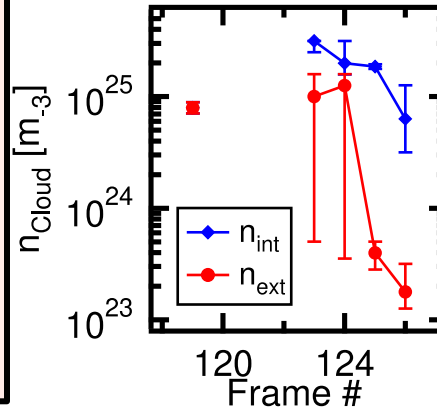
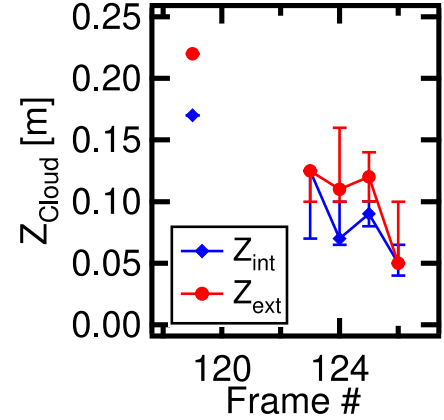
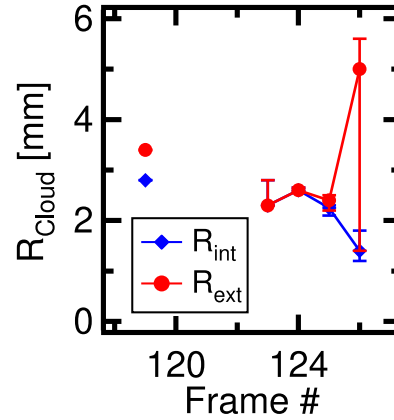
- I. Spectrum with the different emission components
- II. Image best fit longitudinal and normalized transverse cuts. Here :

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



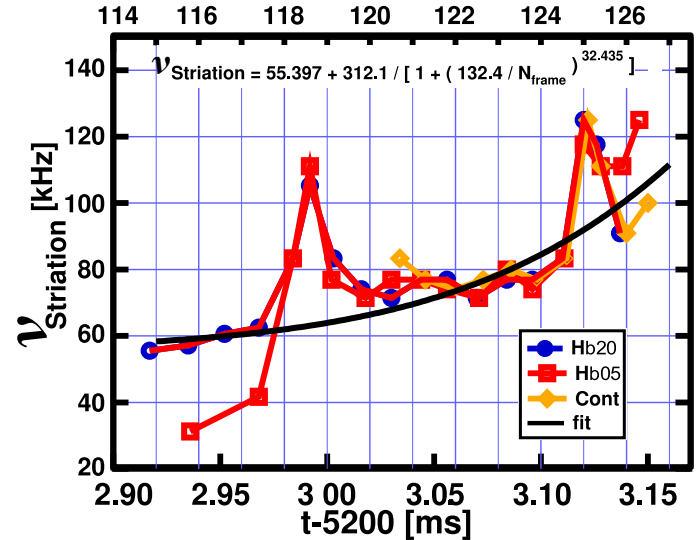
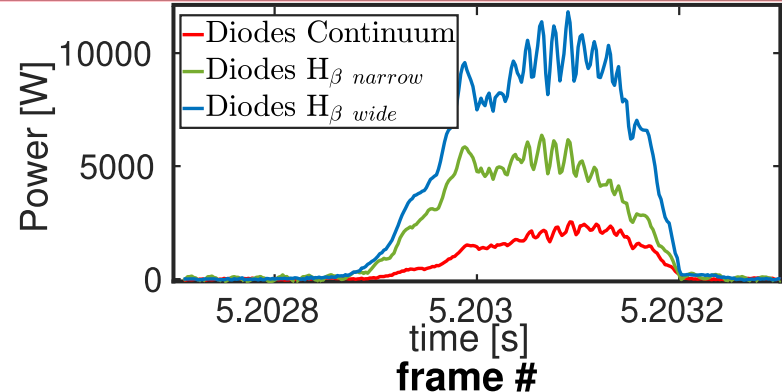
- I. Cloudlets are composed of
 - A. A dense : ($\approx 10^{25} \text{m}^{-3}$) and cold ($\approx 1 \text{ eV}$) core
 - B. A thin less dense ($\approx 10^{24} \text{m}^{-3}$) and hotter ($\approx 2 \text{ eV}$) external layer

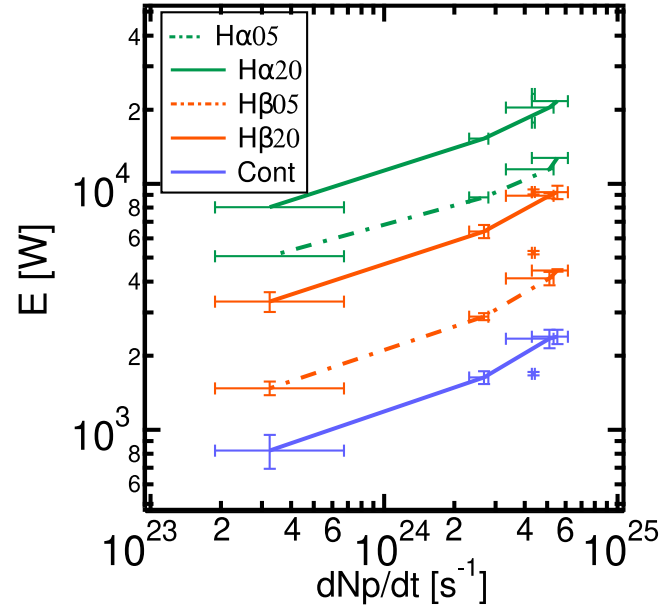
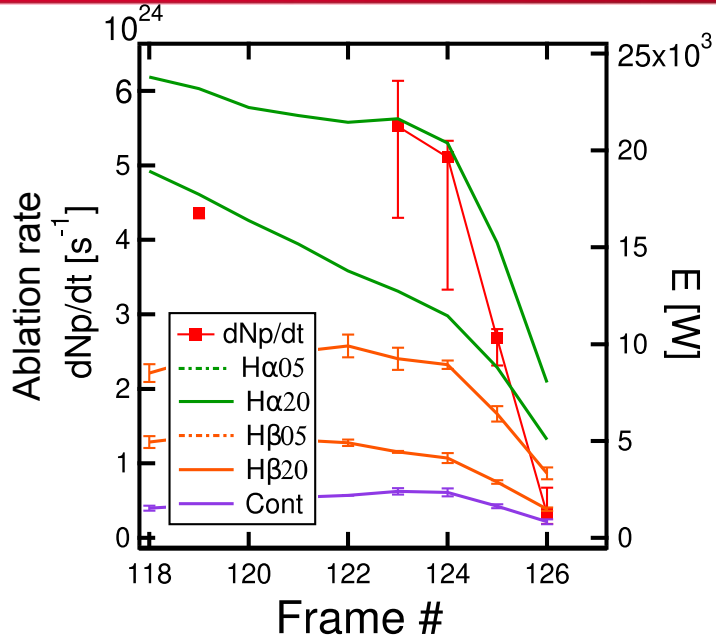
- II. The contribution of the thin layer to the spectrum is small but its presence is required for an accurate fit of the images



- I. Ablation rate is calculated as $N\nu$,
 → cloudlets particle contents N (i.e. the ablation rate multiplied by the time for building a cloudlet)
 → cloudlet ejection frequency ν (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).





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.

- 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
⇒ No strict proportionality is observed between them.

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
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