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FOR FLUID DYNAMICS

Advances in Boundary Layer Investigations and Heat Flux Measurements in 1.2 MW VKI Plasmatron

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Professor
Head of Aeronautics and Aerospace Dept

Contents

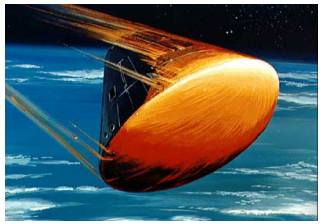
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- **Introduction**
- **Boundary Layer Investigation**
  - Experimental Results
  - Comparison with ICP Code
  - Conclusions
- **High Heat-Flux Measurements**
  - Subsonic
  - Supersonic
  - Conclusions

Introduction

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Start of space flight ⟶ ***today***



ablative

("Space Race", inter-cont. missiles, lunar program)

U_∞ > 10km/s



reusable

(Space Shuttle, Buran, X-38)

U_∞ ~ 7 km/s

$$H_0 = h_s + \frac{U_\infty^2}{2}$$



ablative

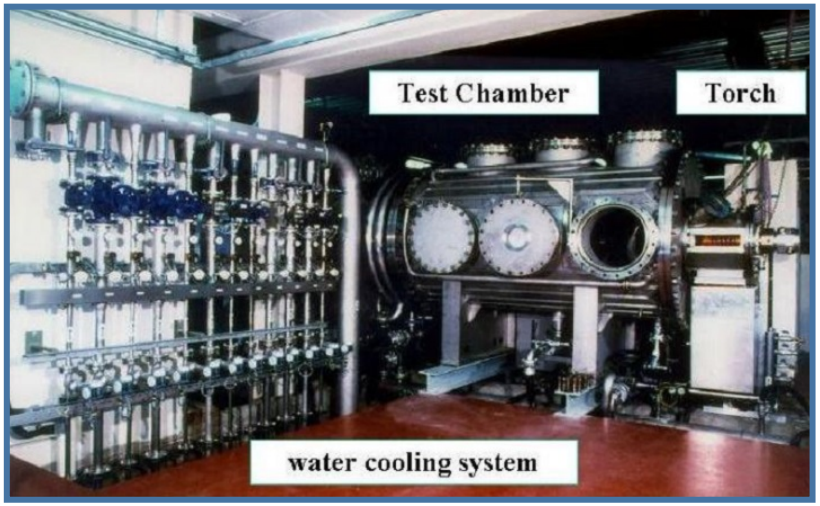
(pushing forward to outer space, interplanetary)

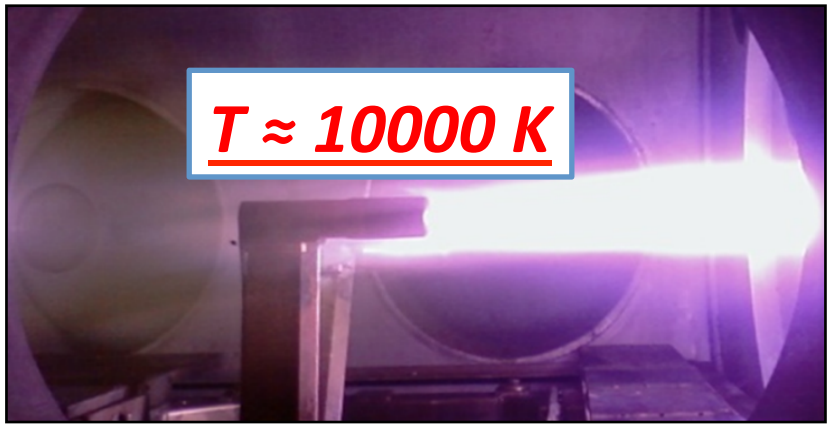
U_∞ > 12km/s

We need facilities capable to simulate very high heat fluxes for extraplanetary re-entry missions

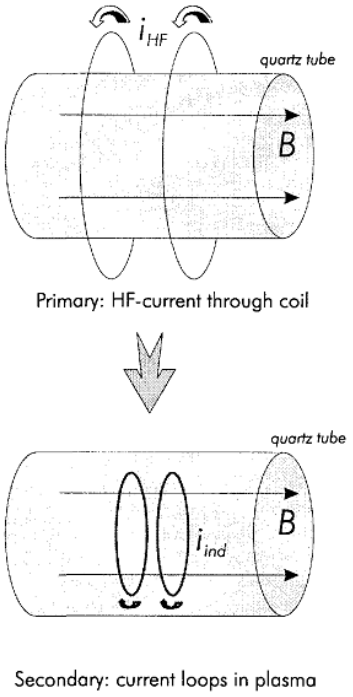
VKI 1.2 MW PLASMATRON

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ICP Inductive Coupled Plasma



State-of-the-Art at VKI

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Boundary layer (non-intrusive)

Experimental: B. Helber, D. Guariglia

Numerical: BL code Barbante et al

Supersonic High Heat Flux Measurements

Experimental: D. Guariglia

Numerical: V. Van der Hagen

Freestream characterization

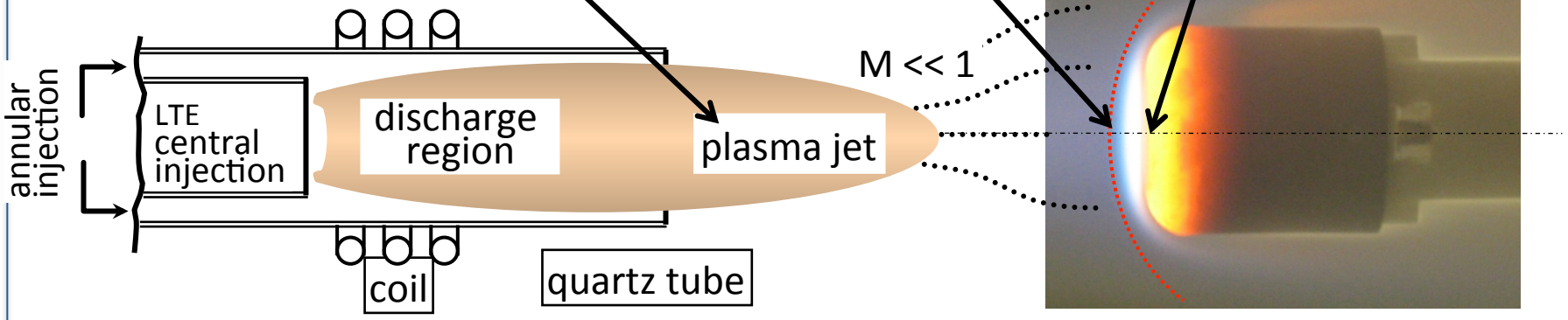
Experimental: A. Cipullo, D. Lequang, Y. Babou

Numerical: ICP code

Gas/Surface Interaction

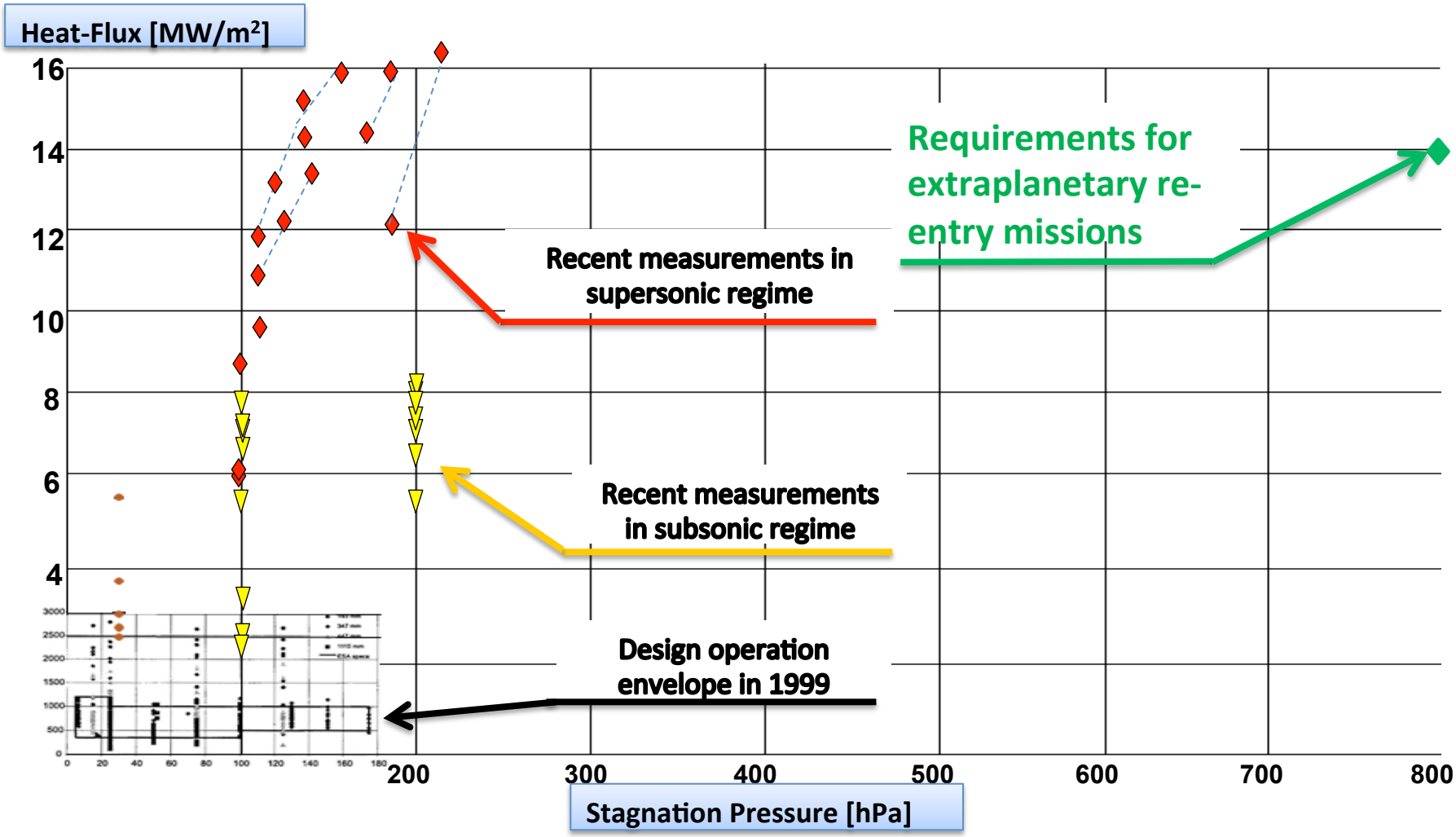
Experimental: F. Panerai, B. Helber, I. Sakraker

Numerical: BL code Barbante et al,



State-of-the-Art at VKI

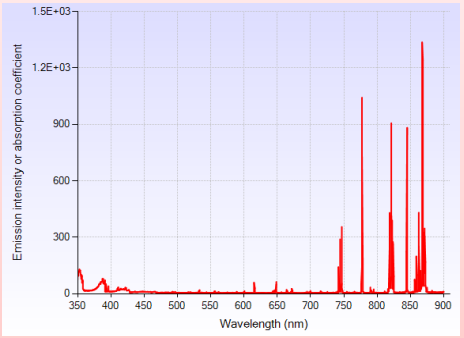
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Research Strategy

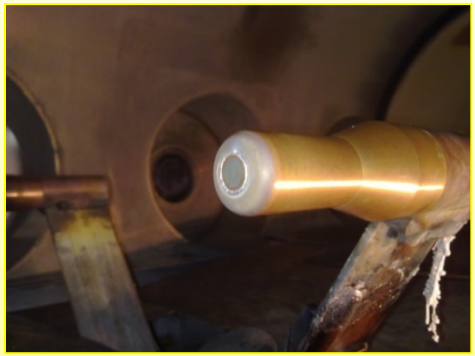
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- Pushing the limits of the Plasmatron facility
- Exploring new methodologies for measurements in HHF



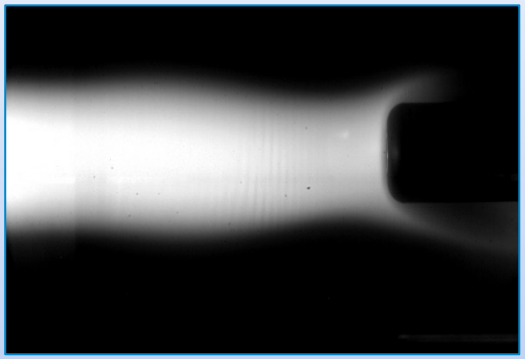
Radiation Field (Chemistry): Emission Spectroscopy

– Thermal BL temperature profile



Surface : Heat Flux

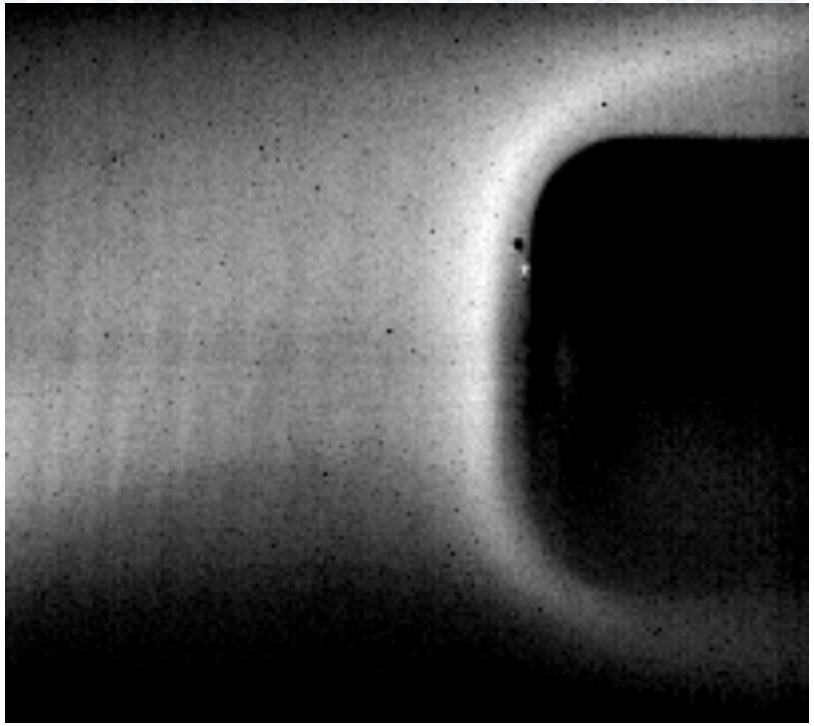
– Gardon Gauge
– Water Cooled Calorim.



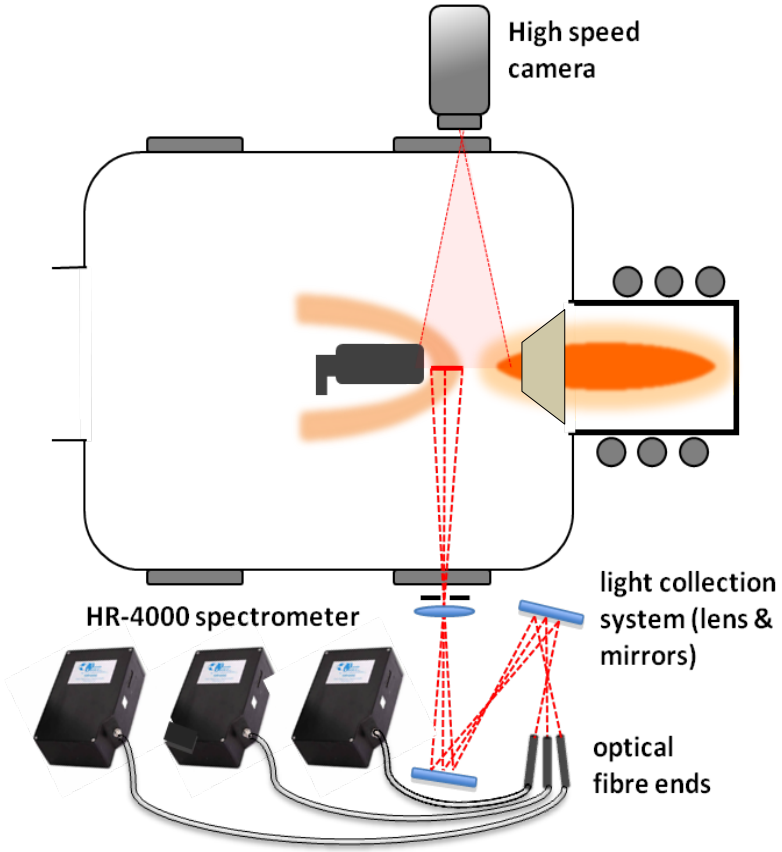
Transient Flow Field : High Speed Camera

– Plasma fluctuations
– Estimation of the thermal BL thickness

BOUNDARY LAYER

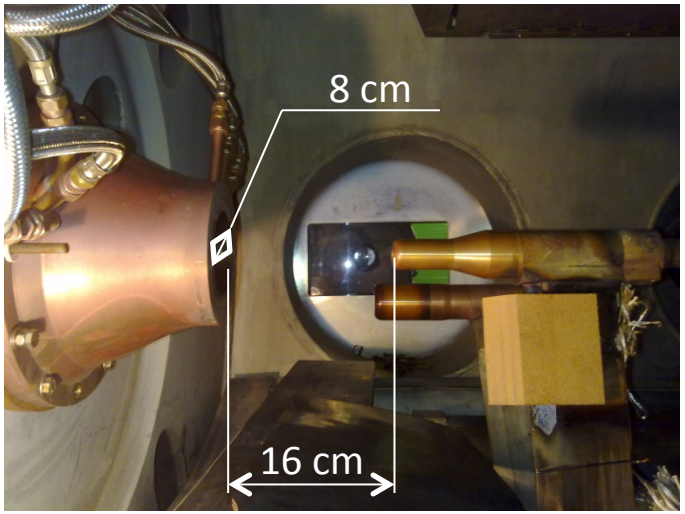


Experimental Setup M<1



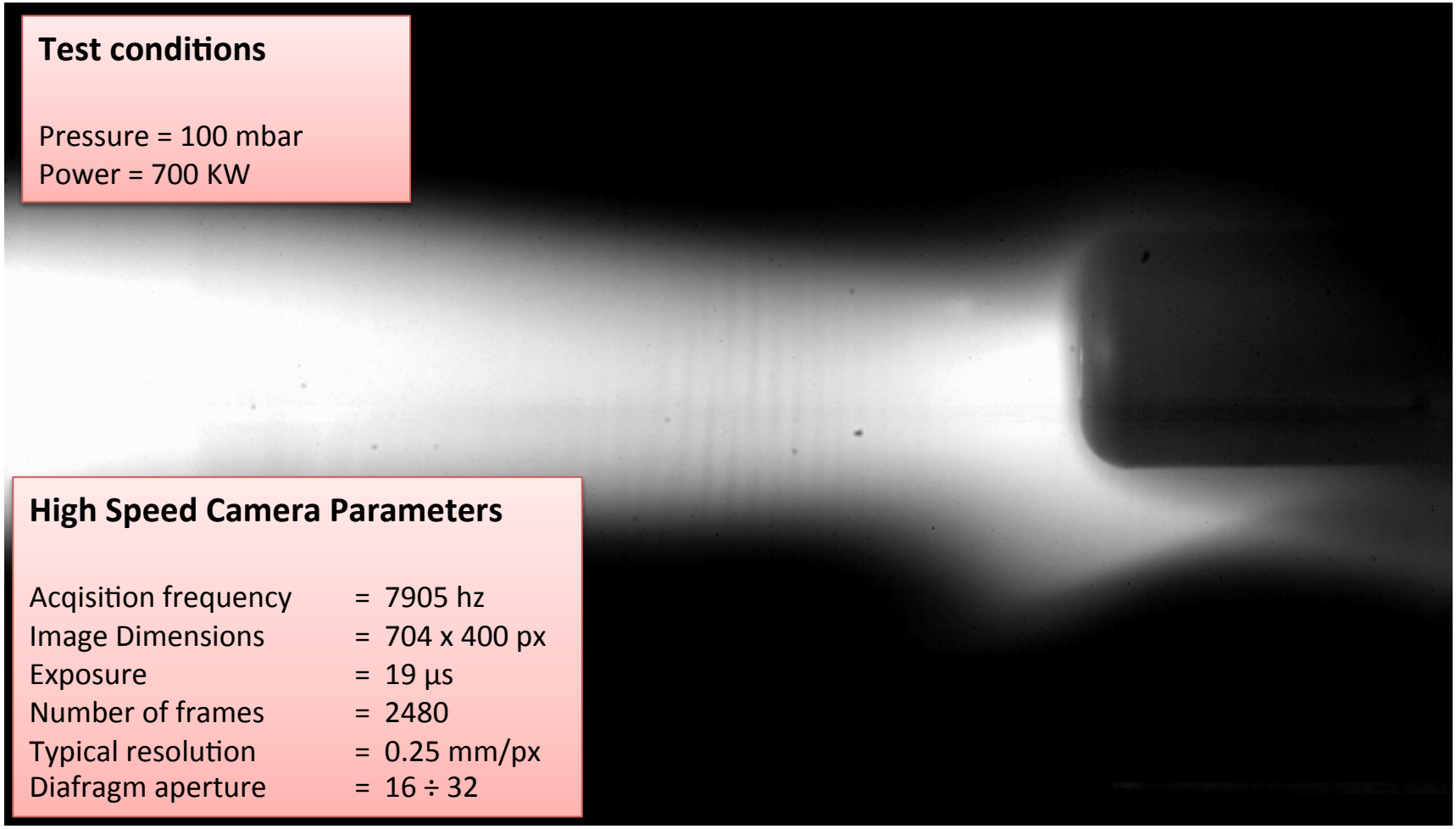
Courtesy of B.Helber

- Subsonic conturned nozzle AR = 4
- Non-LTE probe shape ø = 3.5 cm
- Gardon Gauge Calorimeter
- High Speed Camera
- 3 spectrometers Ocean Optics HR4000



High Speed Camera

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BL Measurements

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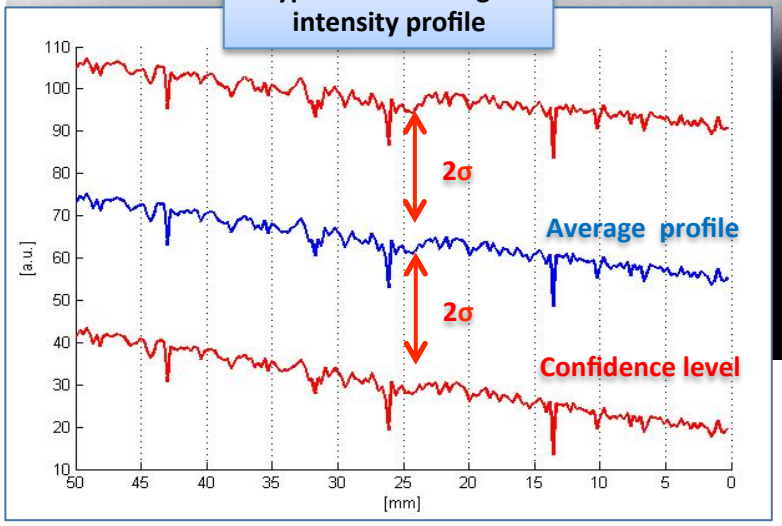
Test conditions

Pressure = 100 mbar
Power = 700 KW

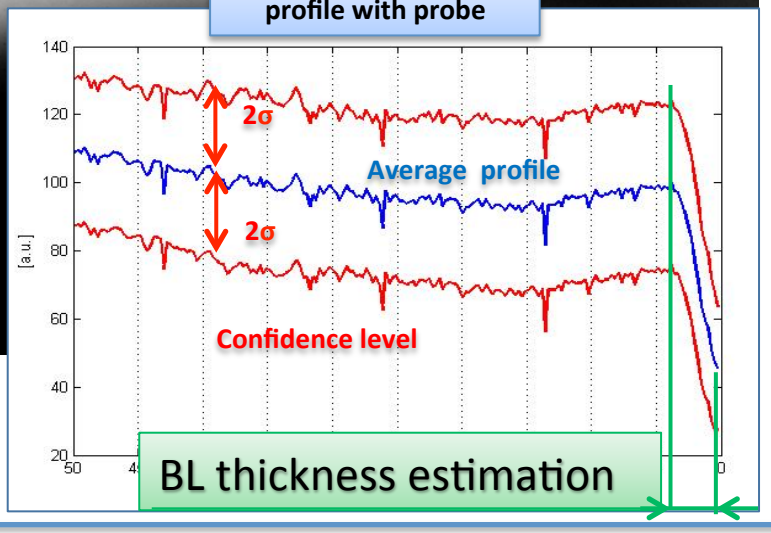
What kind of boundary layer?
Radiation Boundary Layer (RBL)

-
-

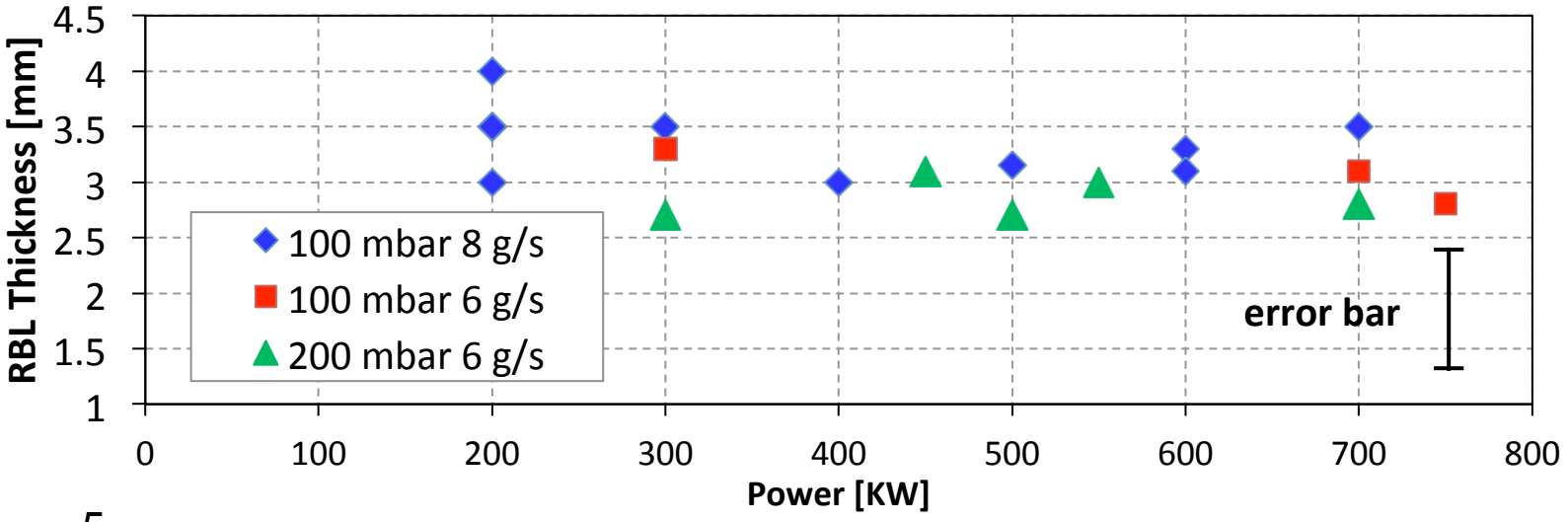
Typ. freestream light intensity profile

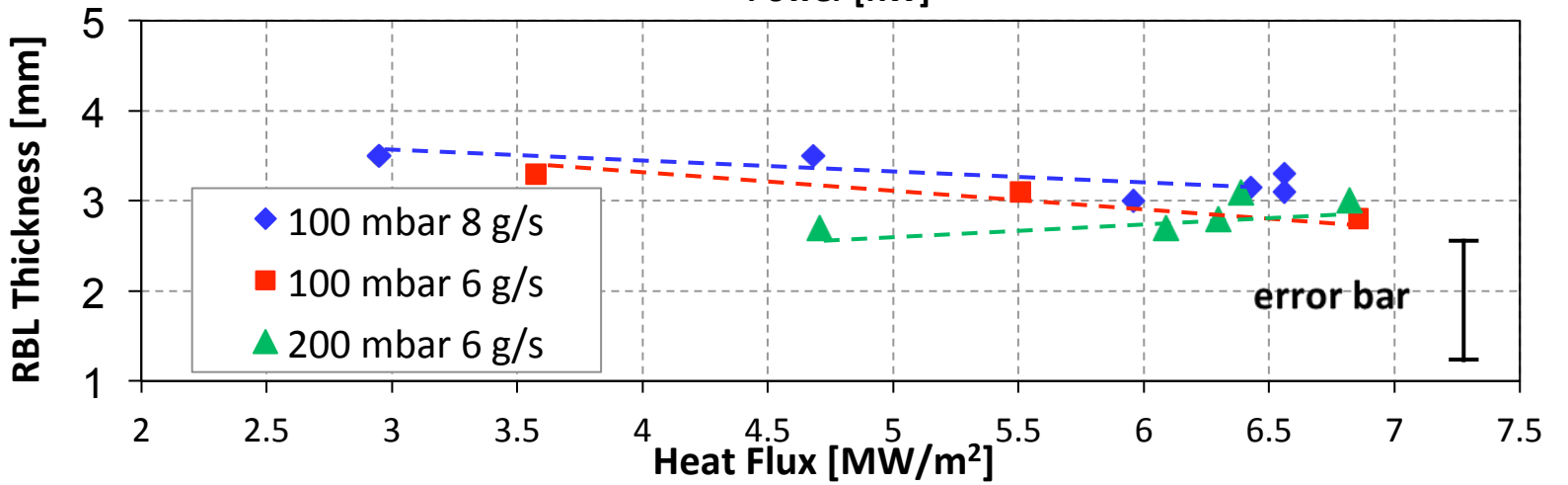


Typ. light intensity profile with probe



RBL Thickness



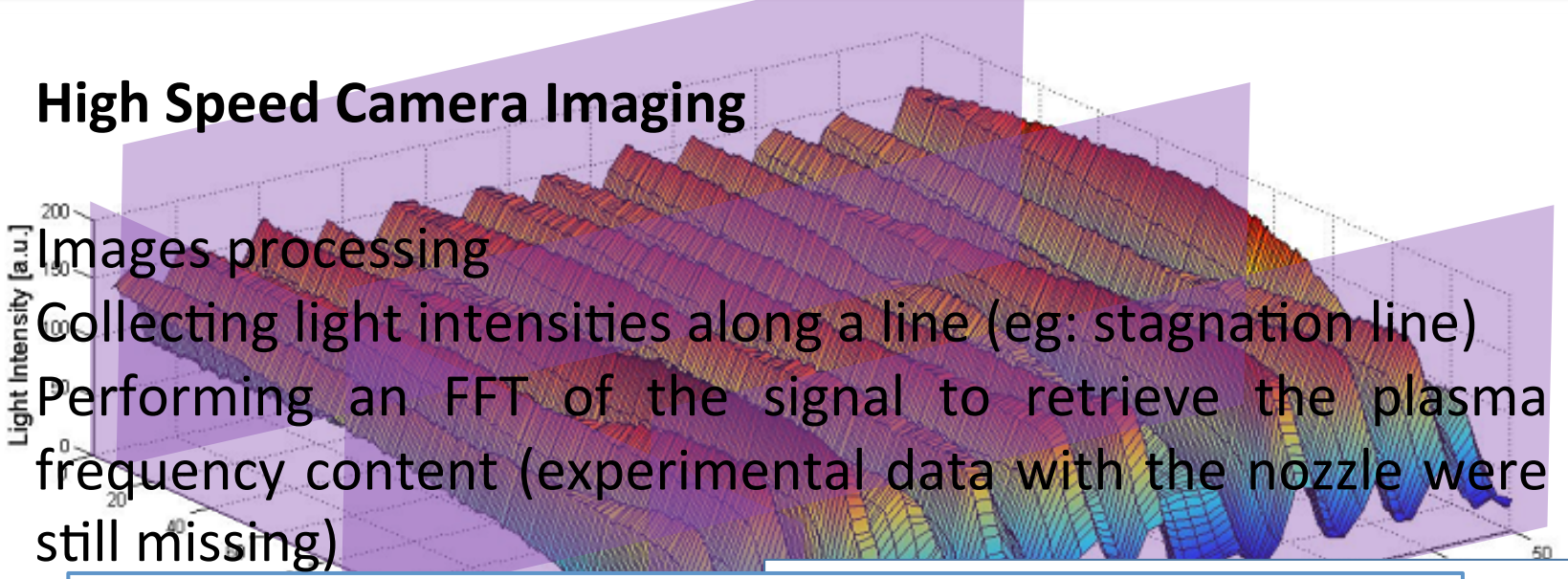


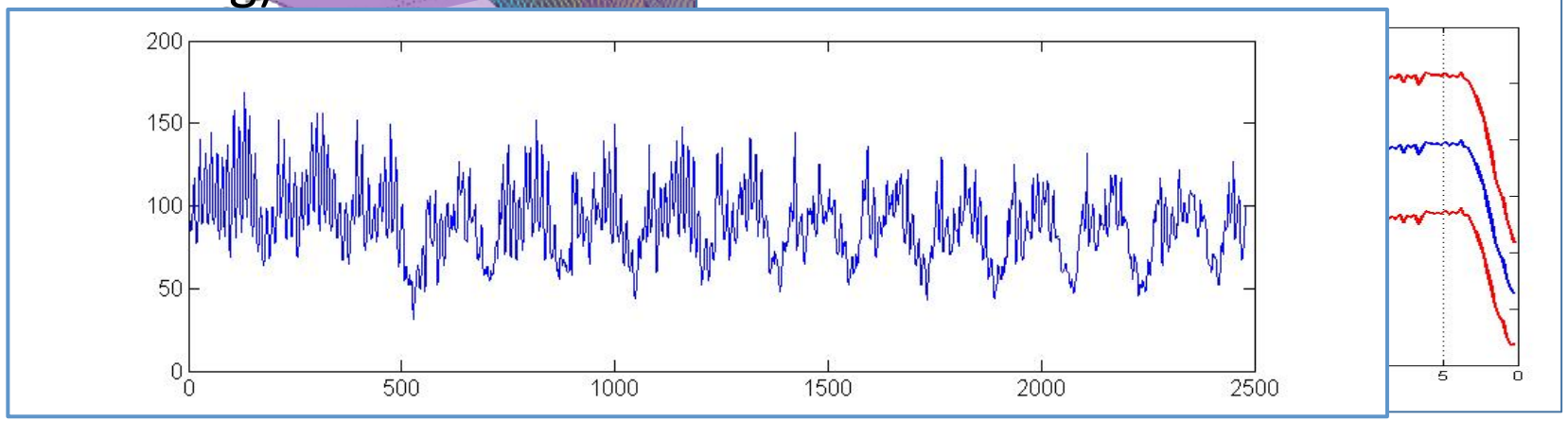
Plasma Frequency Content

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High Speed Camera Imaging

- Images processing
- Collecting light intensities along a line (eg: stagnation line)
- Performing an FFT of the signal to retrieve the plasma frequency content (experimental data with the nozzle were still missing)





Plasma Frequency Content

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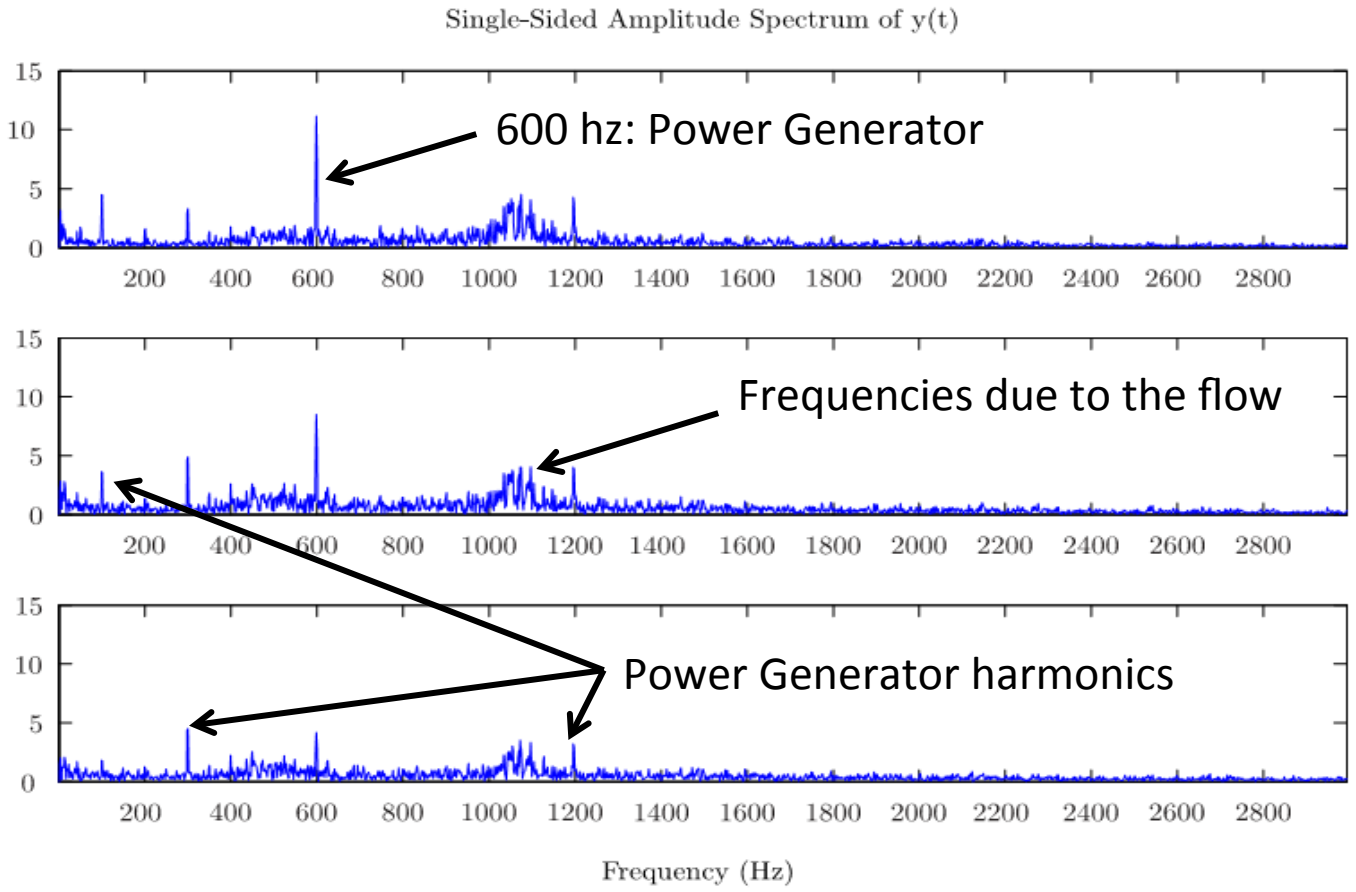
Distance from the probe

Pressure = 100 mbar **Power = 200 KW**

d = 50 mm

d = 25 mm

d = 0.25 mm



Plasma Frequency Content

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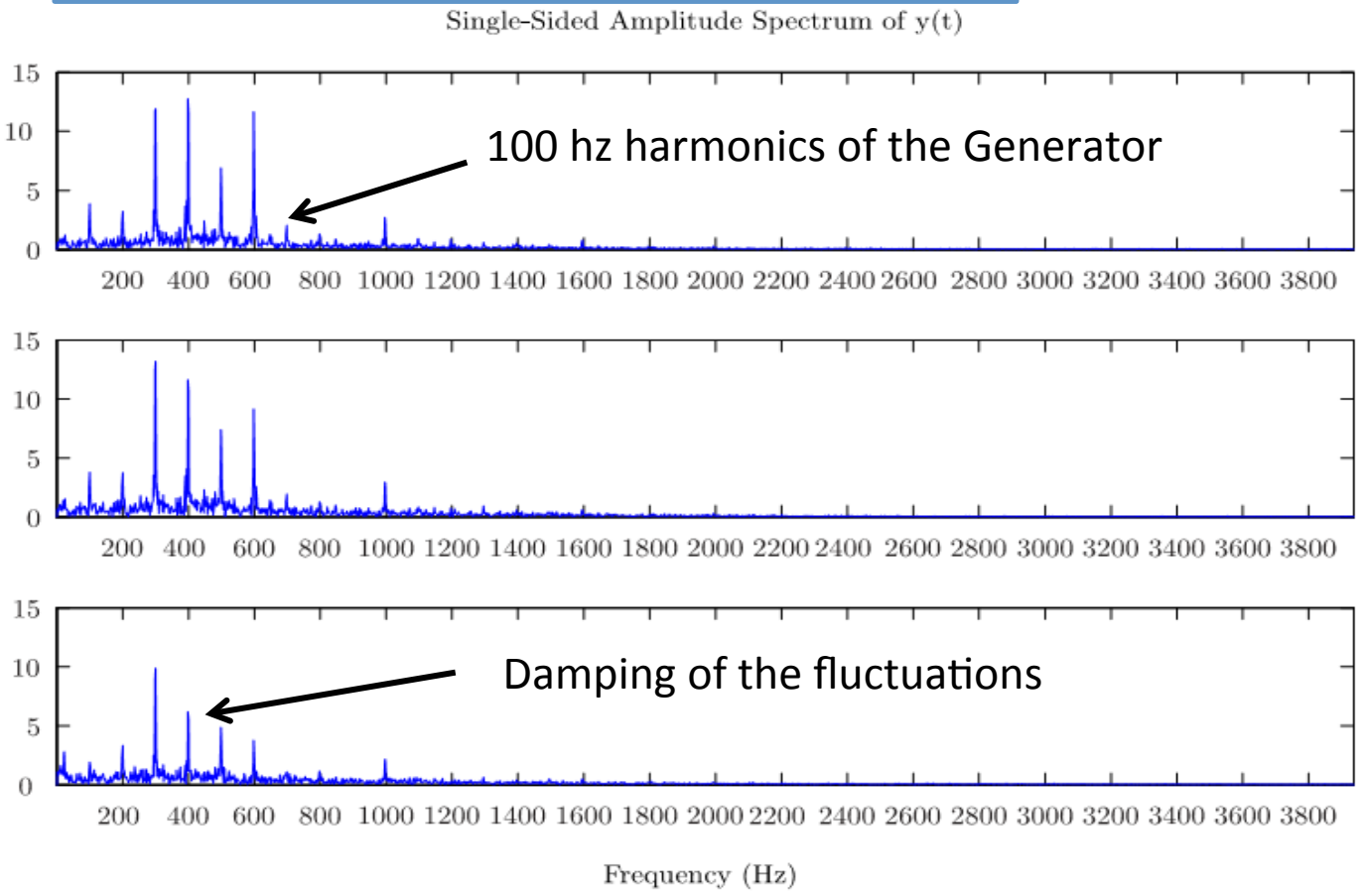
Distance from the probe

Pressure = 200 mbar **Power = 300 KW**

d = 50 mm

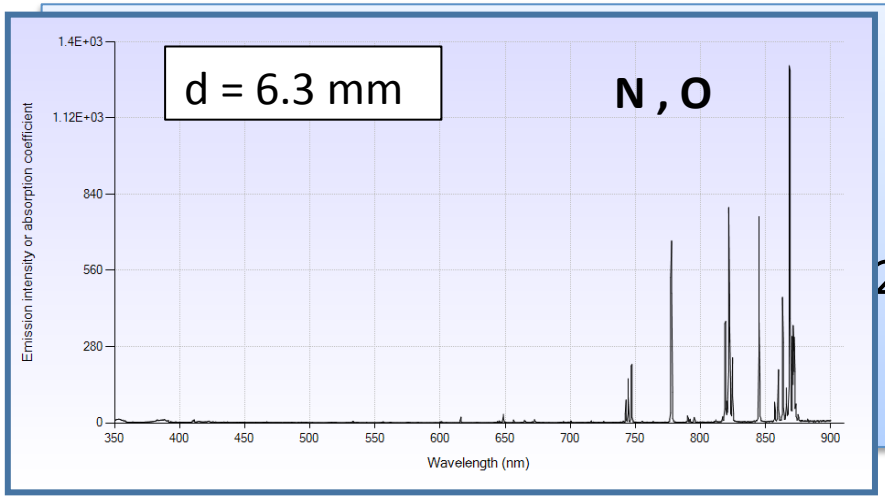
d = 25 mm

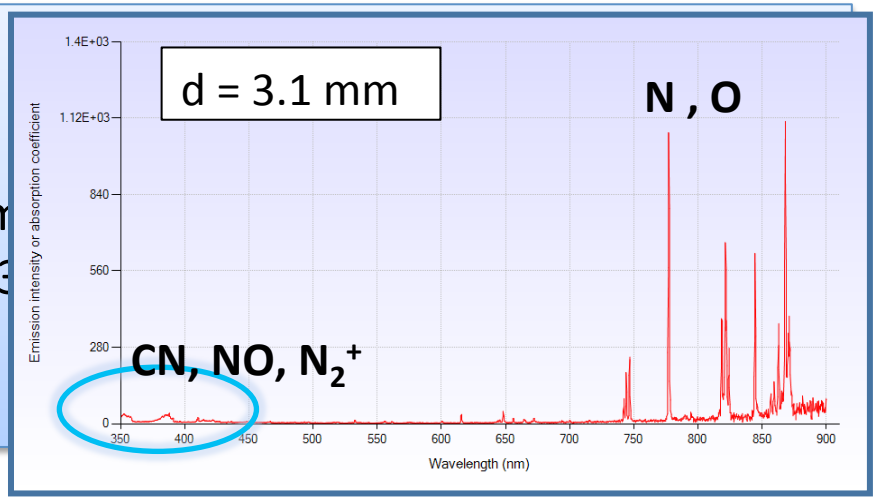
d = 0.25 mm

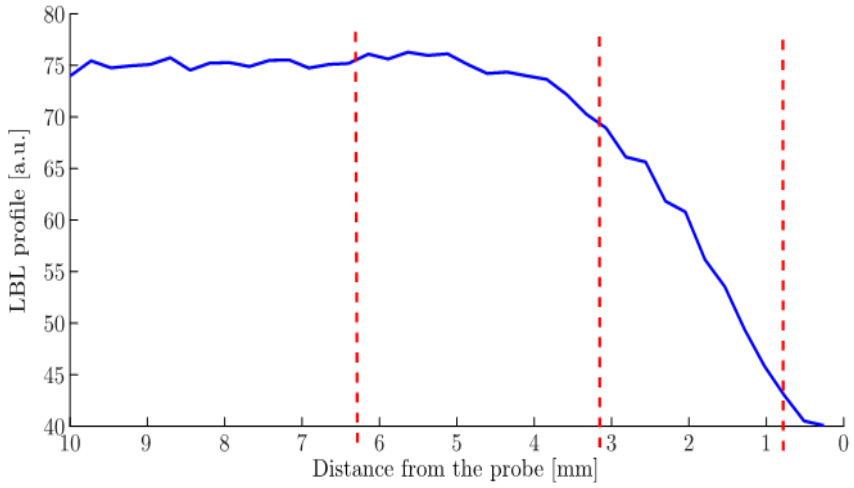


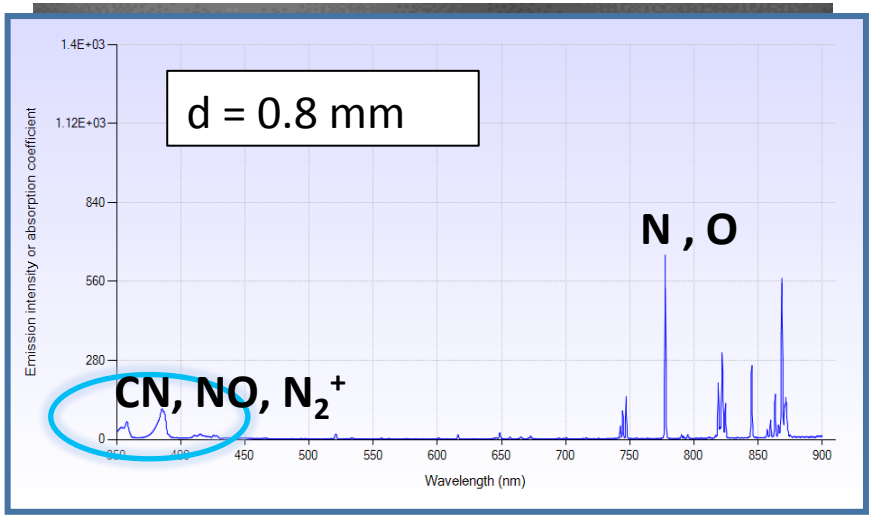
Emission Spectroscopy

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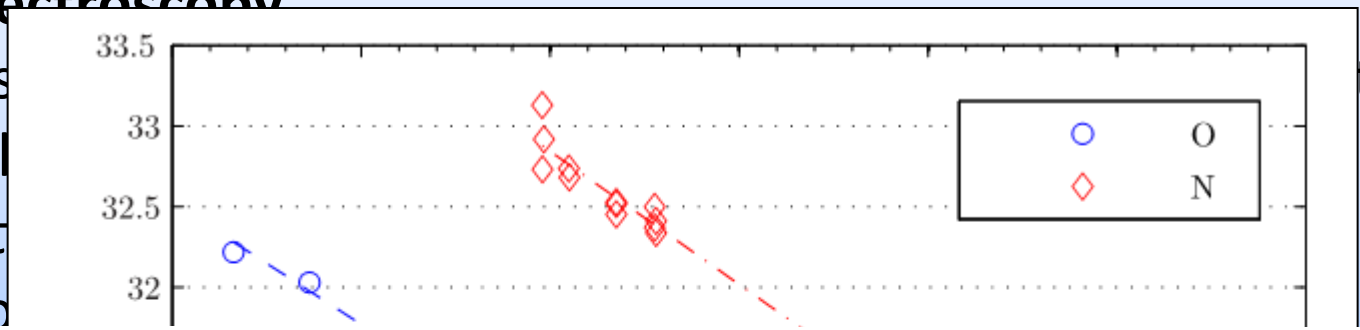


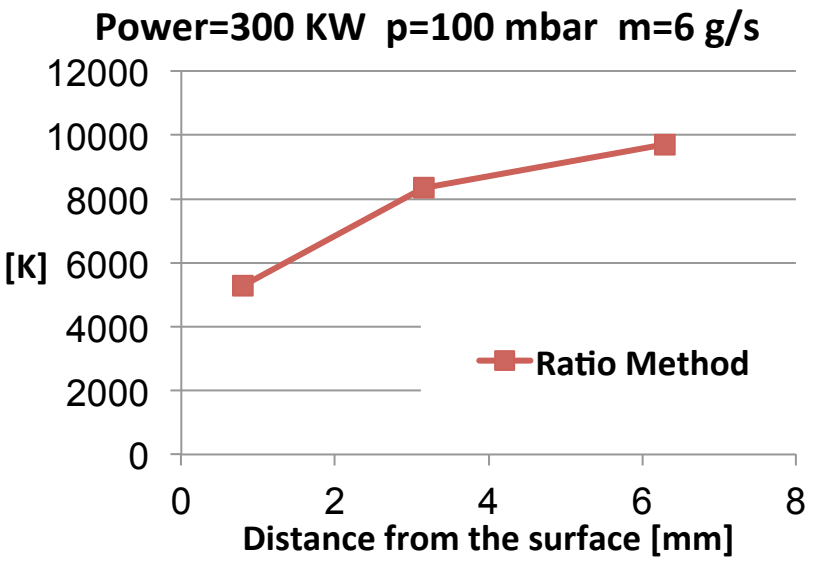
Emission Spectroscopy

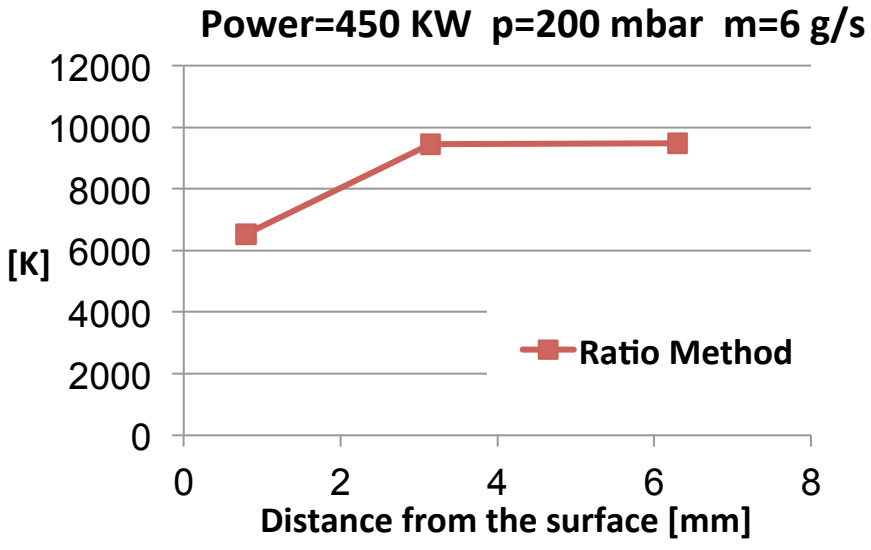
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Spectroscopy

- Ass th the Bol
- Est n two ato

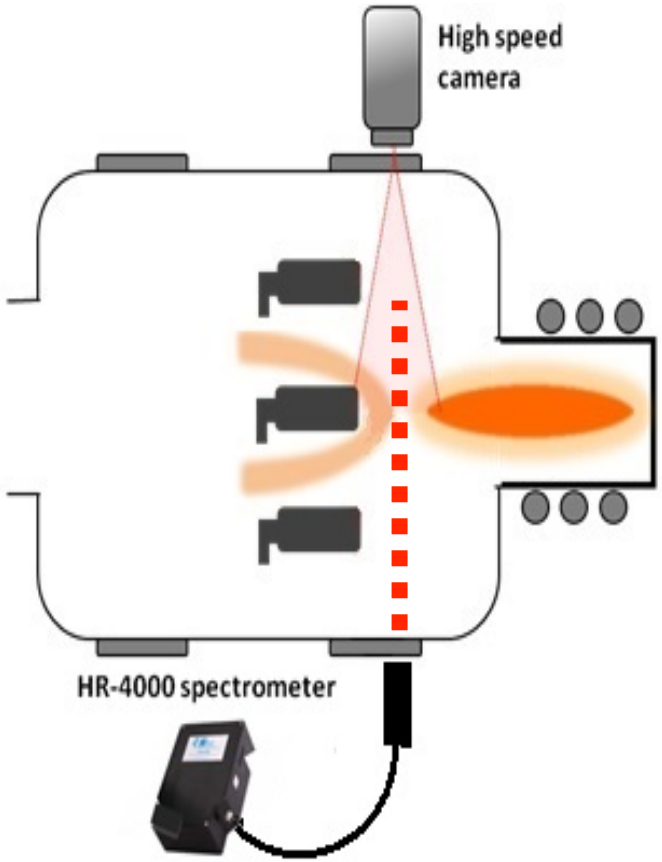




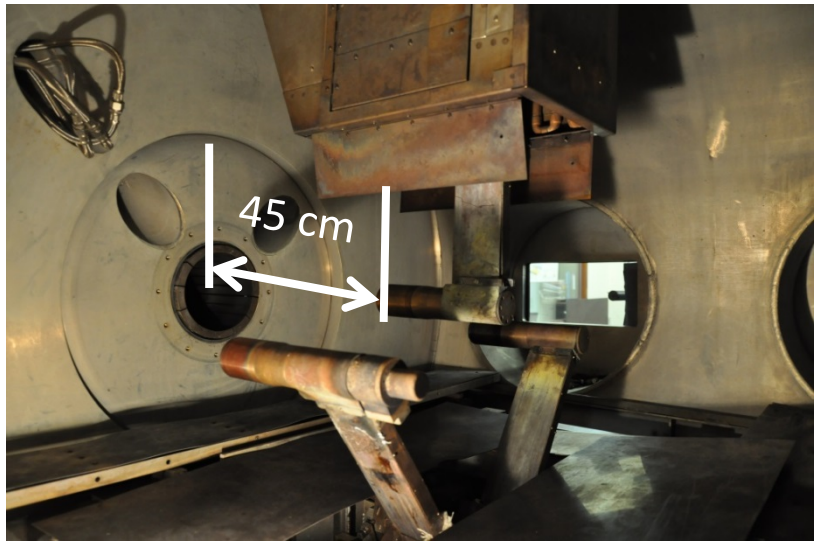


Experimental Setup M<<1

**Test Campaign at low heat flux conditions in collaboration with RM Student J.P.S.P. Leite*

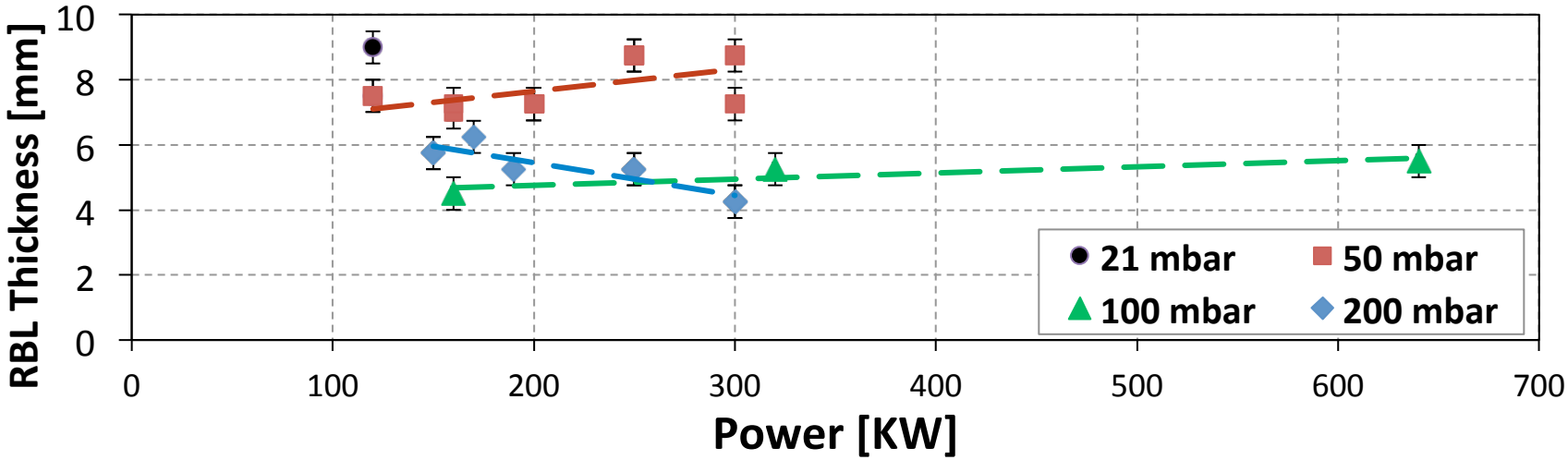


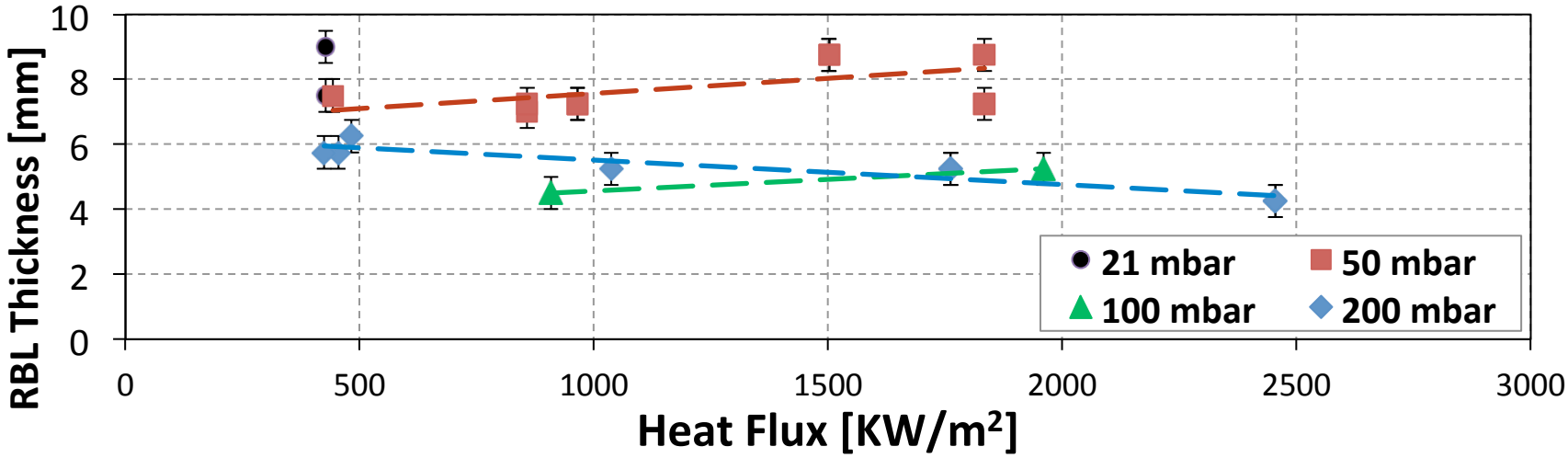
- Standard probe shape ø = 5 cm
- Water Cooled Calorimeter
- Copper Slug Calorimeter
- Gardon Gauge Calorimeter
- High Speed Camera
- 1 spectrometers Ocean Optics HR4000



RBL Thickness

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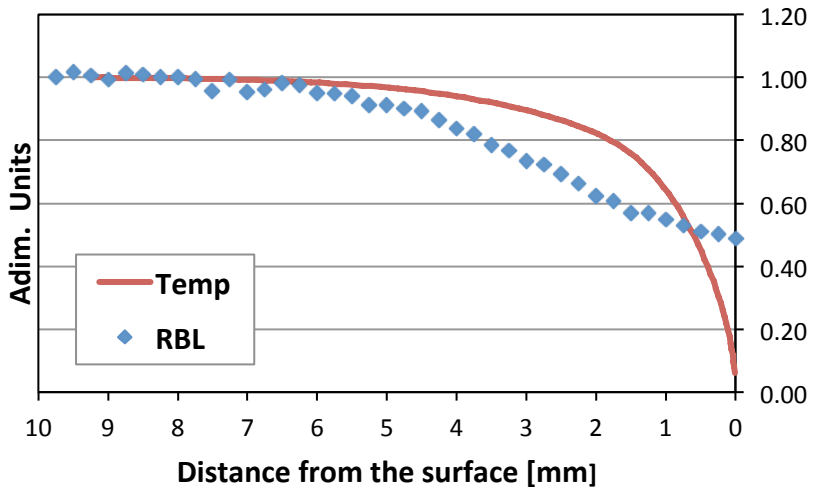
Comparison with BL Rebuilding Code

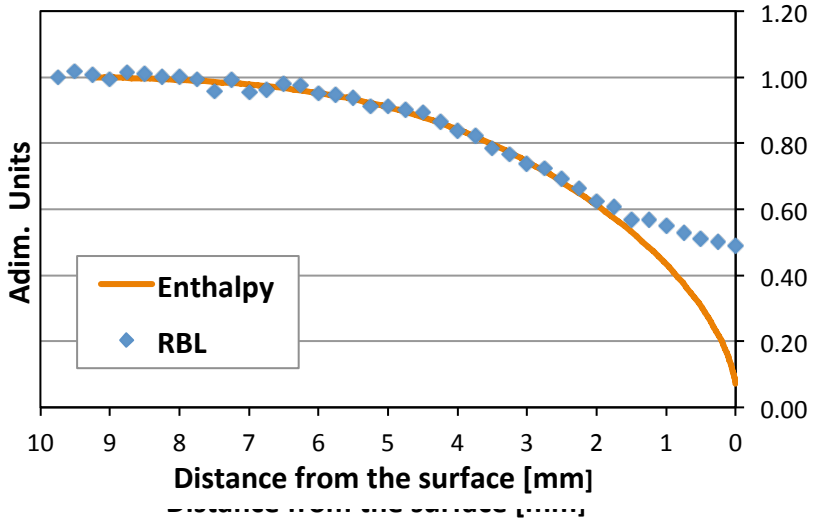
**Data provided by PhD candidate A. Viladegut*

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The BL code has been developed by Barbante et al, but experimental comparison was still missing

- ***p* = 50 mbar HF = 900 KW/m²**
- ***p* = 100 mbar HF = 900 KW/m²**

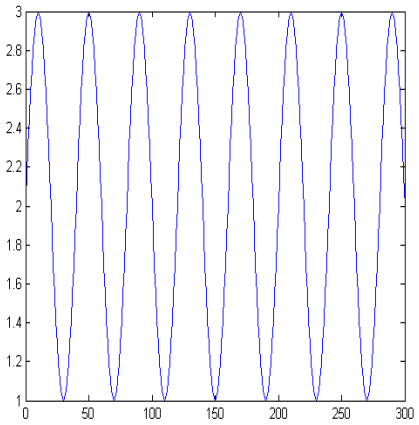




Abel Inversion of the images

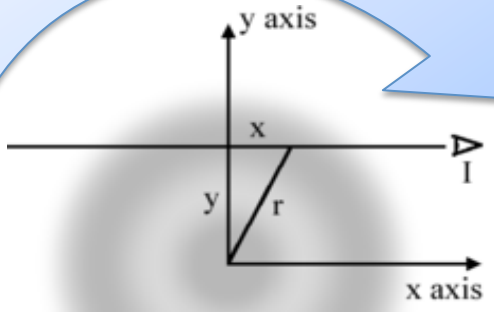
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In image analysis, the forward Abel transform is used to project an optically thin, axially symmetric emission function onto a plane, and the reverse Abel transform is used to calculate the emission function given a projection (i.e. a scan or a photograph) of that emission function.



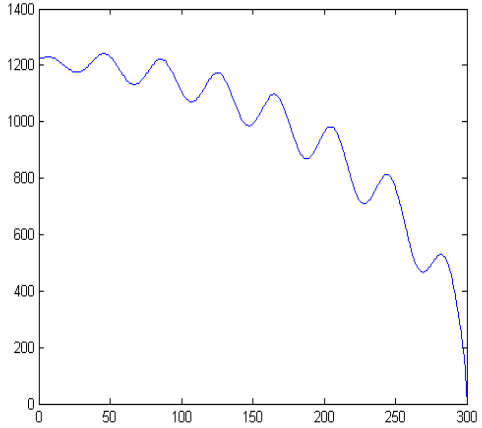
Reference radial profile

$$F(y)=2\int_{y}^{\infty} f(r)r\,dr/\sqrt{r^2-y^2}$$



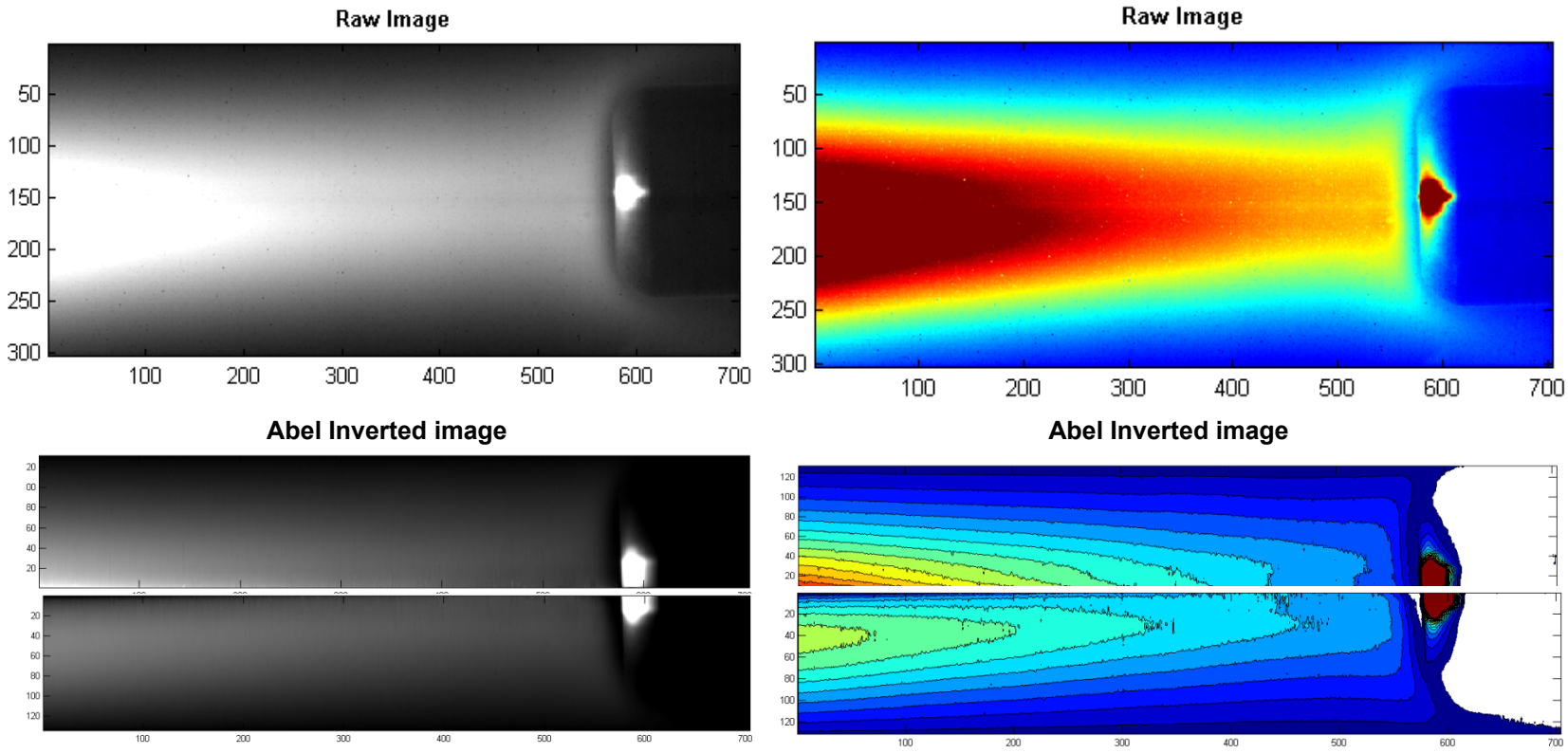
Abel Inversion

$$f(r)=-1/\pi\int_{r}^{\infty} \partial F/\partial y\,dy/\sqrt{y^2-r^2}$$



Abel transformation of reference radial profile

Abel Inversion of the images

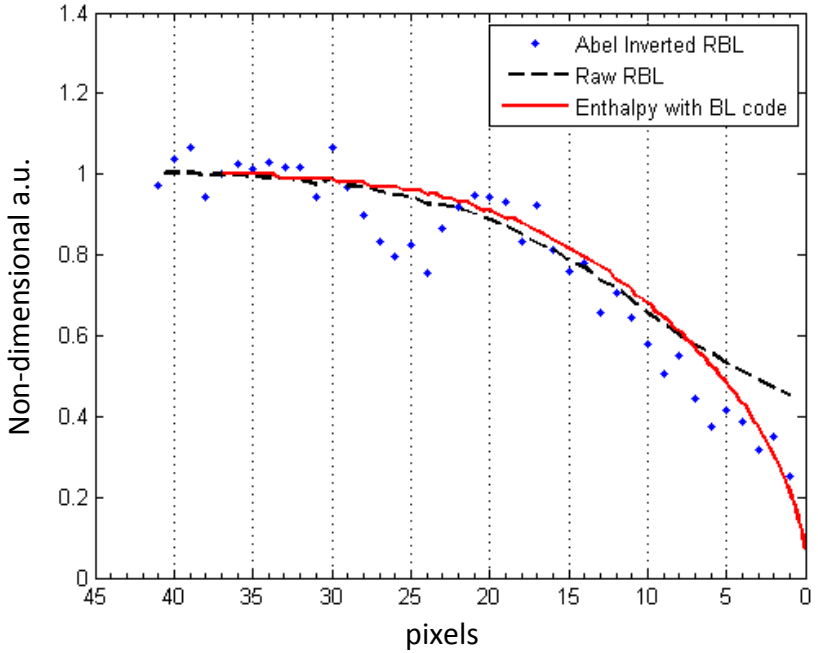


If the image is not perfectly symmetric, Abel Inversion can give different results inverting the upper half-image or the lower half-image. In practical cases, it's impossible to have a perfectly symmetric jet.

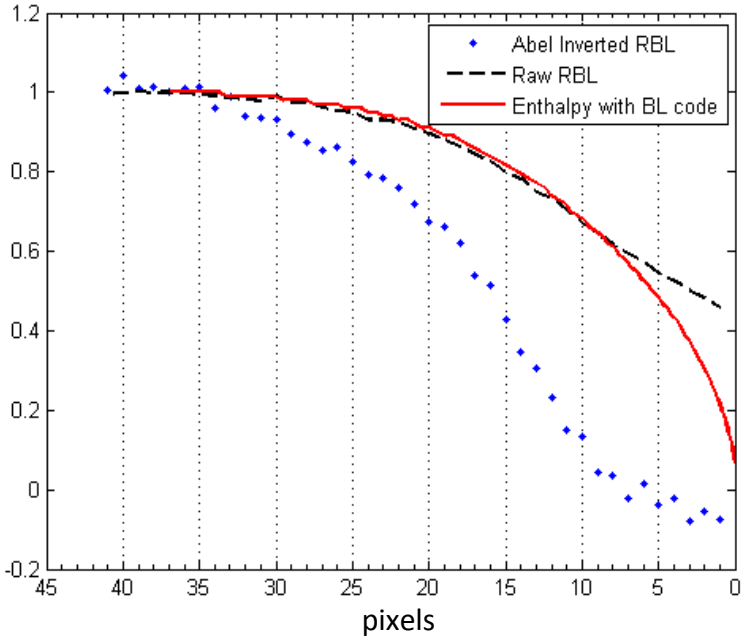
Abel Inversion of the images

Radiation Boundary Layer profile

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RBL profile from the upper half-image



RBL profile from the lower half-image

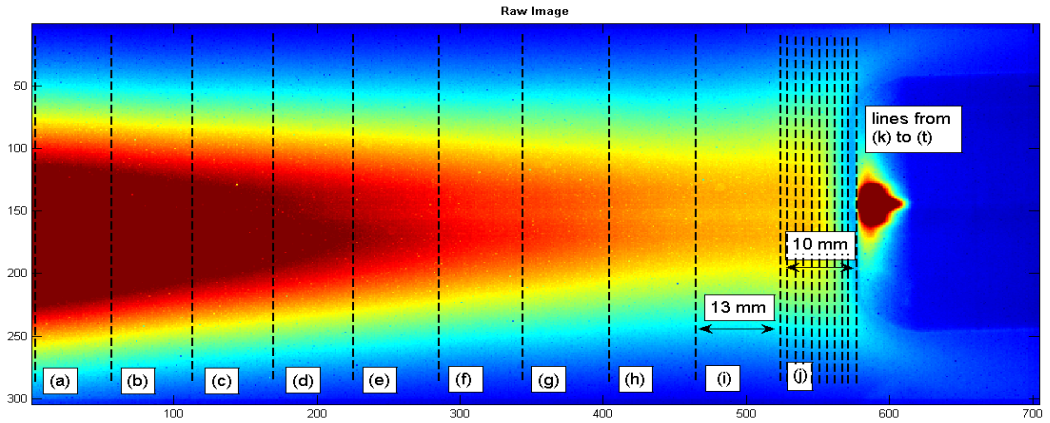
Scatter of the points is due to computational error, because we are close to the centerline, where the Abel function diverges and because of the poor resolution of the camera (few points to Abel invert).

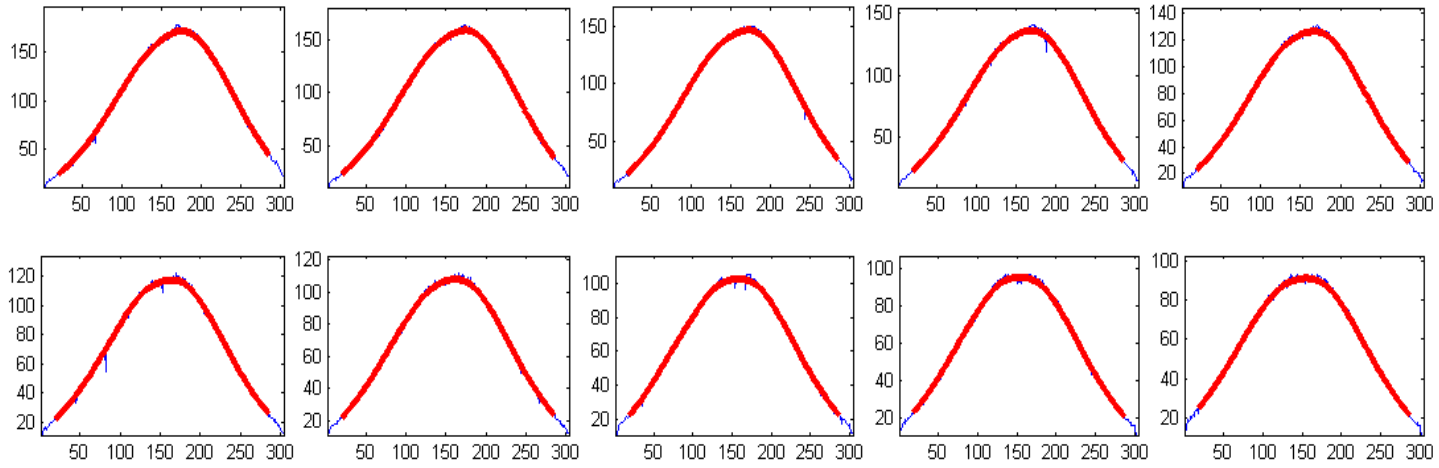
Abel Inversion of the images

Radial profiles of RAW image

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Here are shown the ten RAW radial intensity profiles from the free jet up to 10 mm from the probe.
Is possible so see how the profiles appears almost smooth and symmetric.

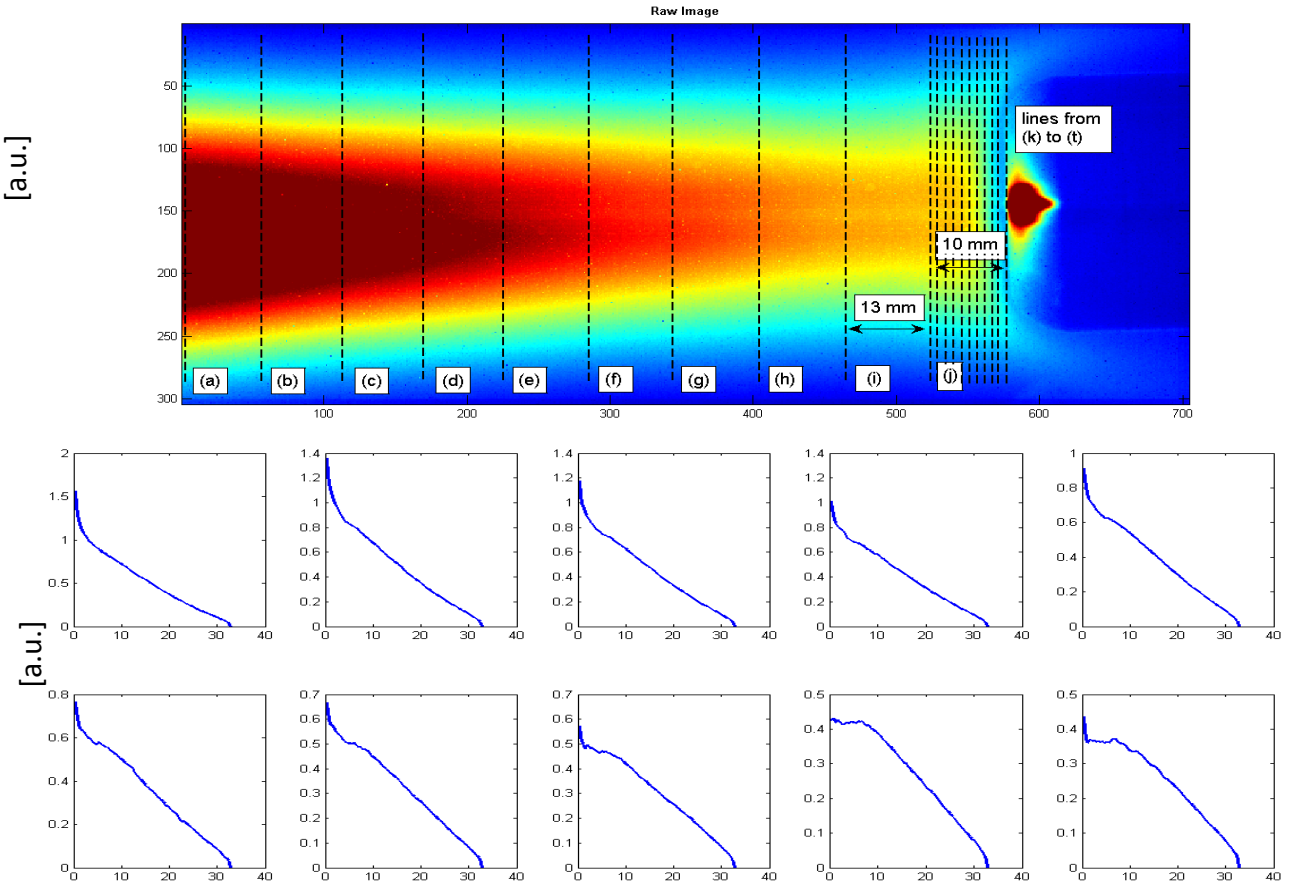




Abel Inversion of the images

Radial light profiles comparison

Radial profiles from 10 mm to 0.25 mm from the probe



- Approaching the
- The intensity of light radial profile is linear
- Close to the probe a plateau starts to form valleys.

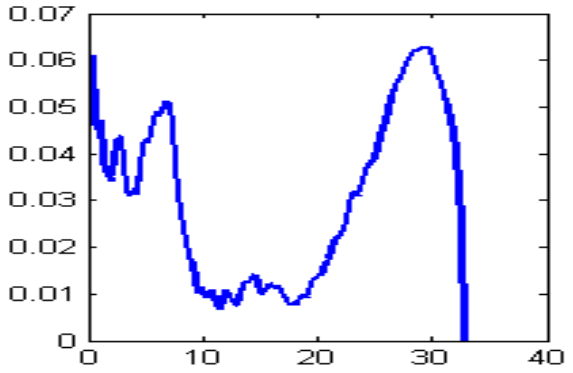
* x axis in mm

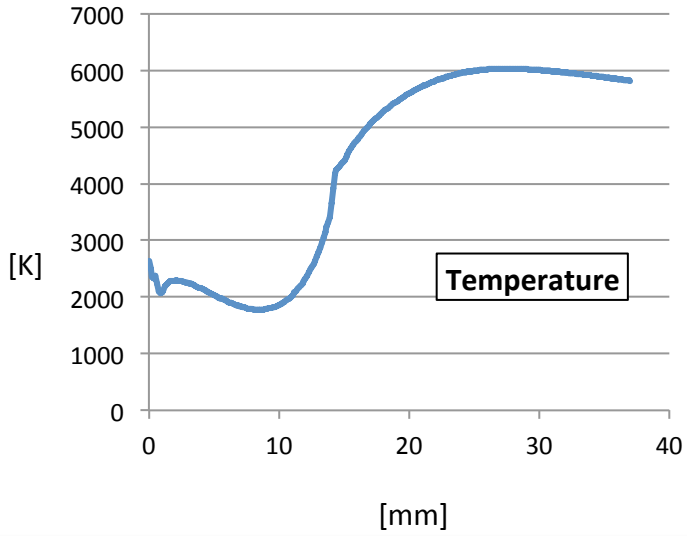
Abel Inversion of the images

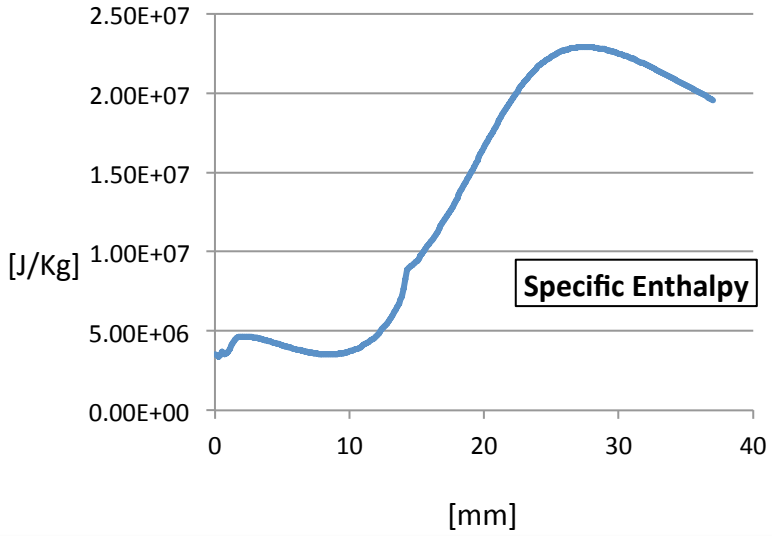
Comparison of radial profiles with the ICP code

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The radial intensity profile doesn't seem to match or to be similar with the temperature nor the enthalpy radial profile



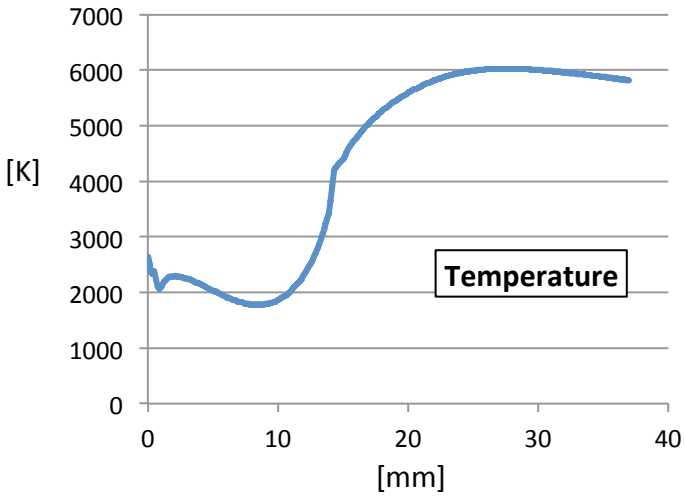


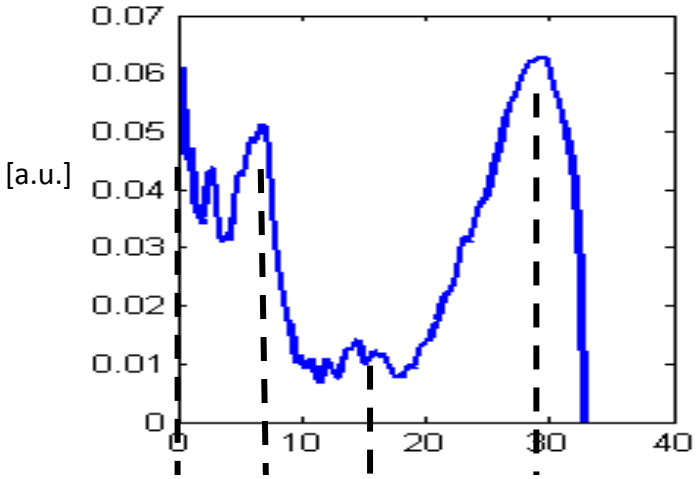


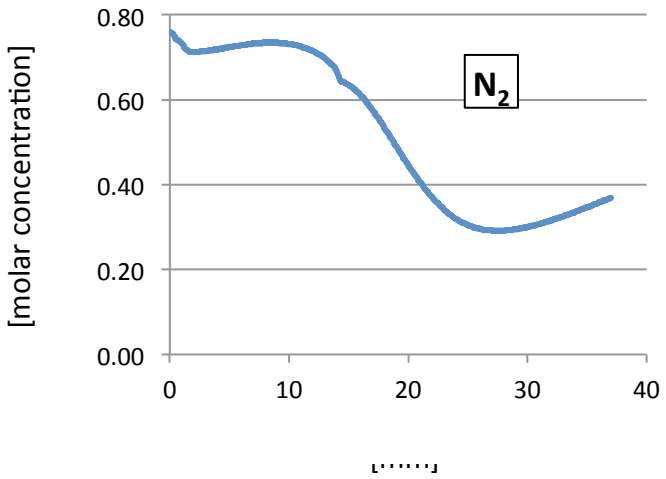
Abel Inversion of the images

Comparison of radial profiles with the ICP code

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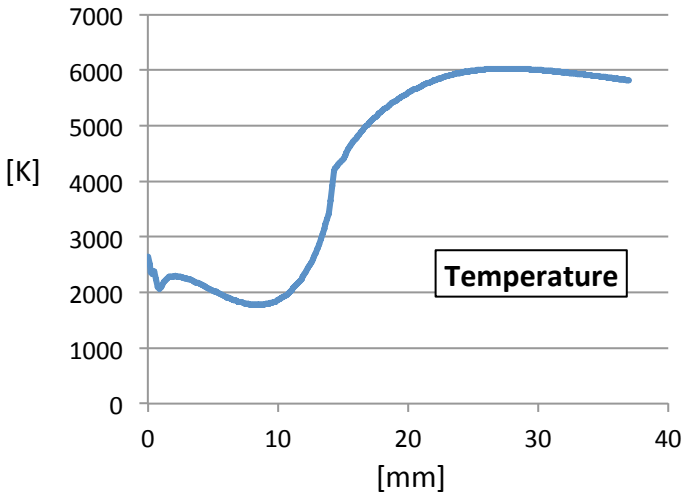


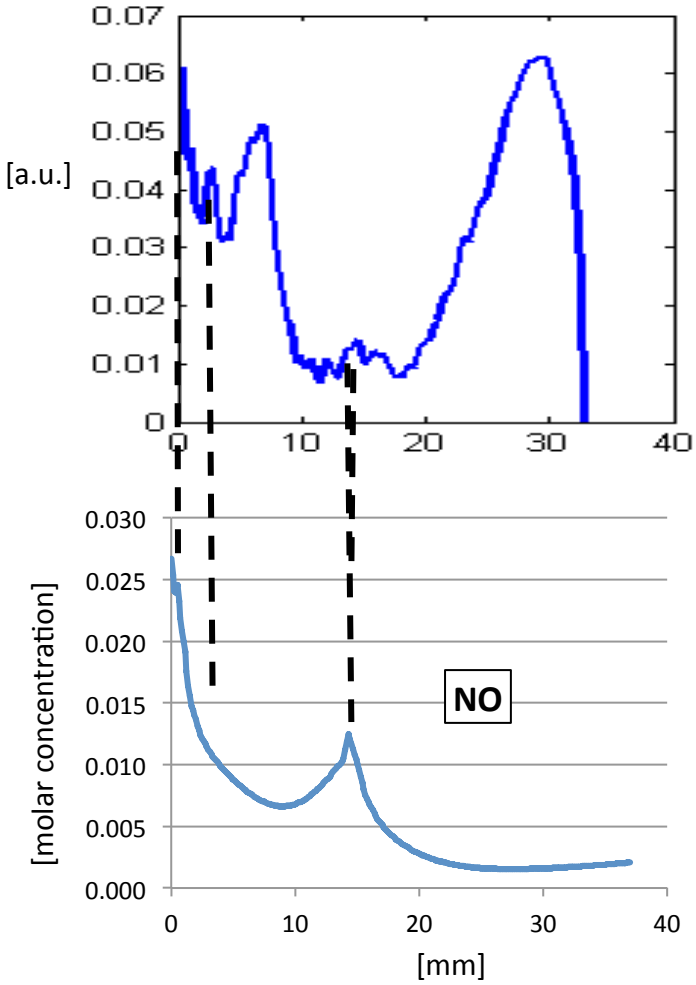


Abel Inversion of the images

Comparison of radial profiles with the ICP code

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Boundary Layer Conclusions

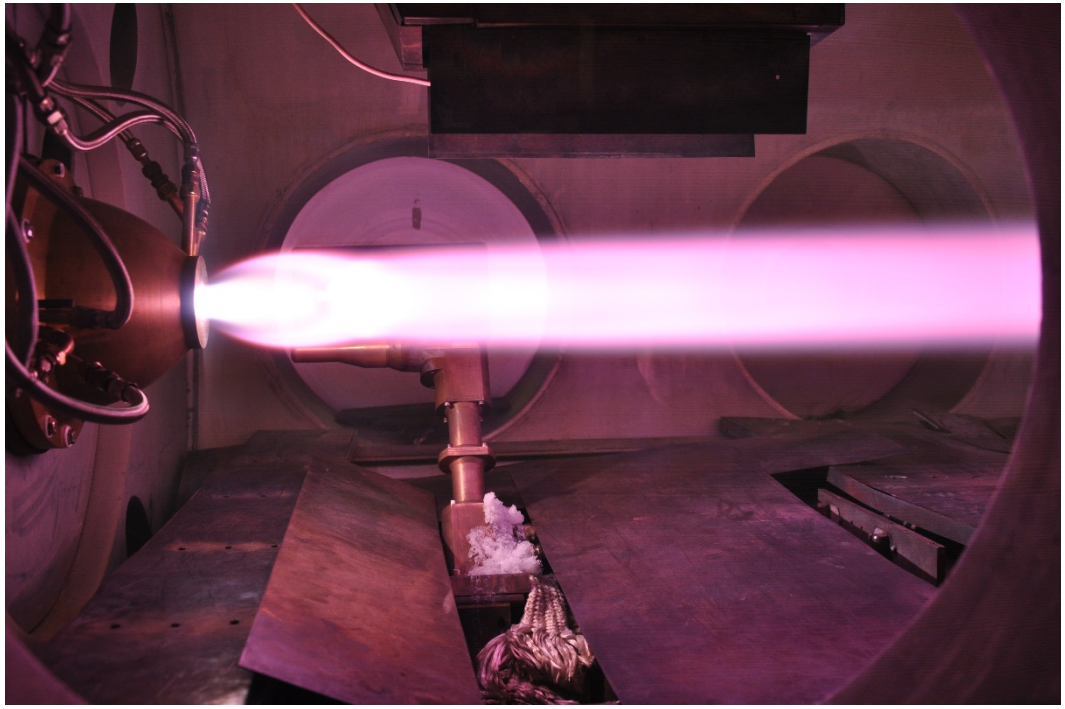
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- We assessed the possibility to use Emission Spectroscopy to study the boundary layer BUT Abel Inversion is mandatory to have reliable results;
- We measured the Radiation Boundary Layer thickness on a cold probe for different static pressures and heat fluxes;
- We retrieved the plasma fluctuation frequencies in subsonic regime, with a nozzle;
- We performed an Abel inversion of the High Speed Camera images and we compared it with with the results from the IPC code, showing traces of the singular species emission in the RBL radial profile.

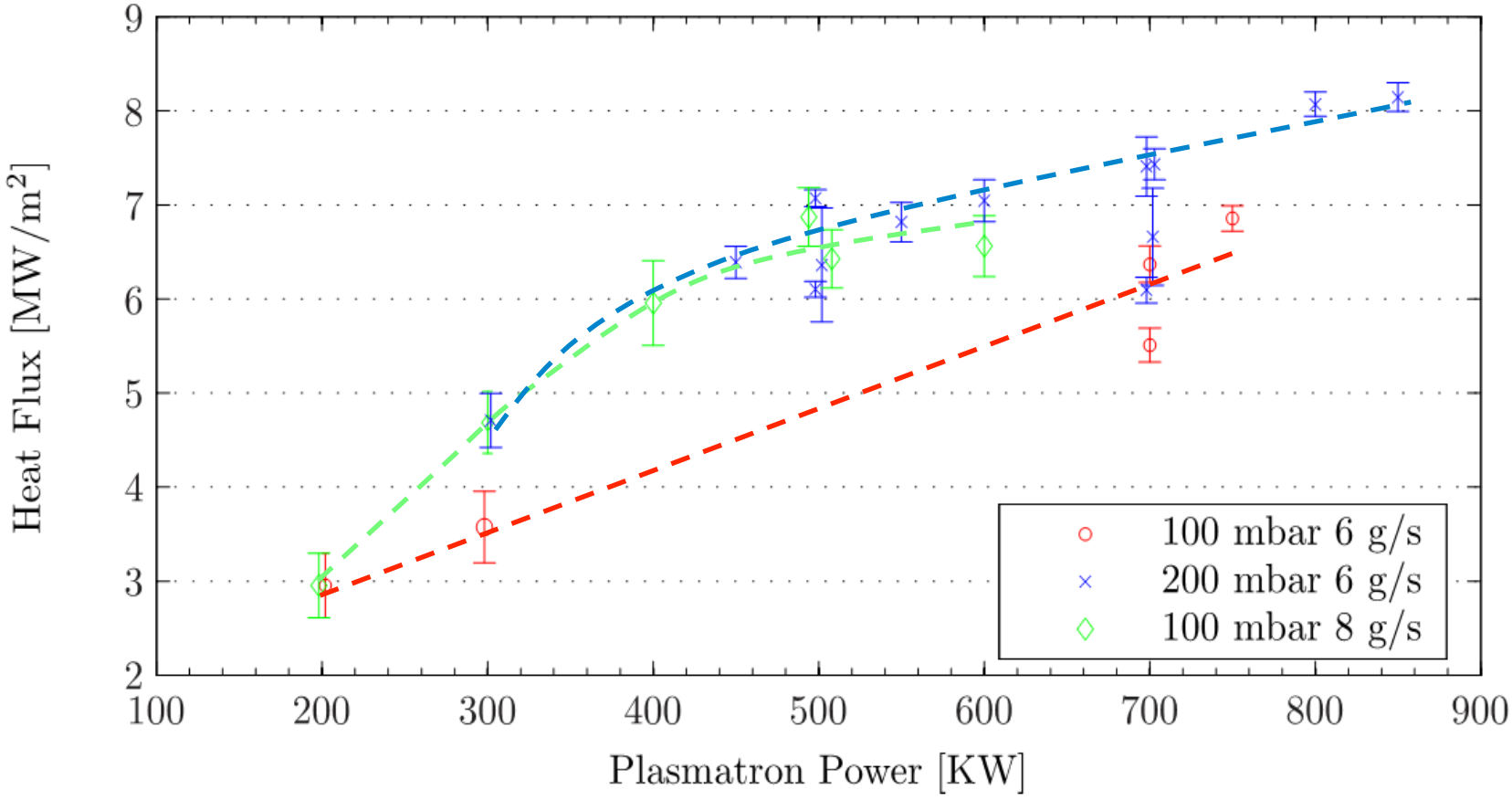
Future Work

- A radiation code could be used to calculate light generated by the plasma, using the results of the ICP code, and compare it with the HSC images;
- Currently experiments are ongoing, using HSC and optical filter, isolating light at oxigen wavelenghts only (P. Solano).

HIGH HEAT-FLUX MEASUREMENTS



High Heat-Flux Measurements M<1

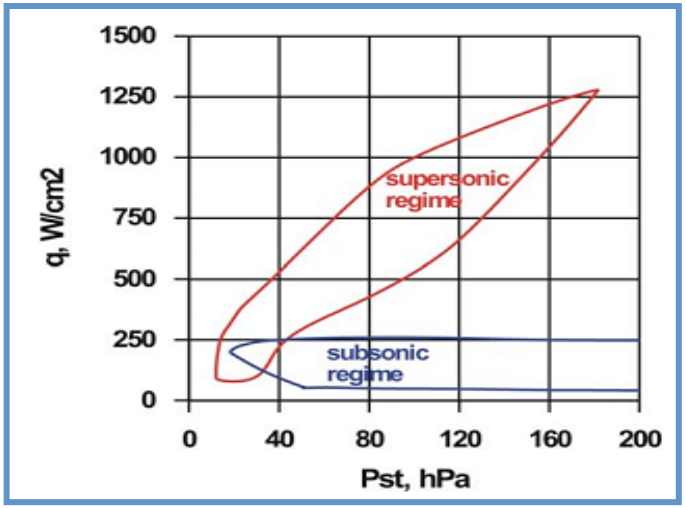


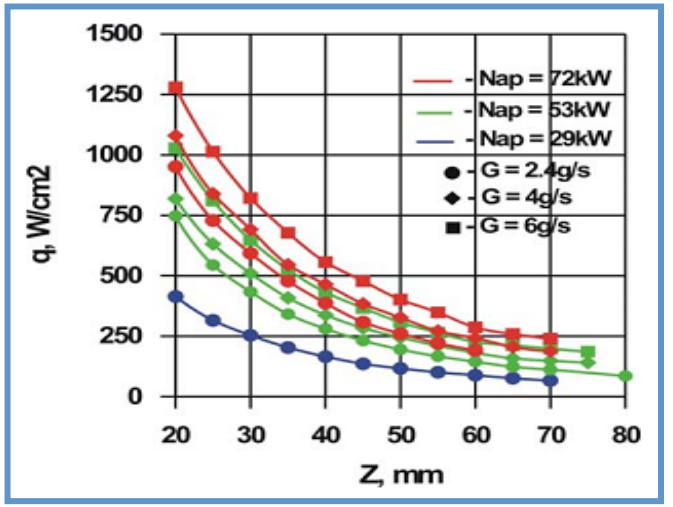
High Heat-Flux Measurements M<1

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The reason for passing to the supersonic regime were:

- It seems we reached a limit in subsonic regime
- From the literature this limit has been overcomed testing in supersonic regime [Kolesnicov]
- The HF should increase: reducind the distance from the nozzle and increasing the stagnation pressure

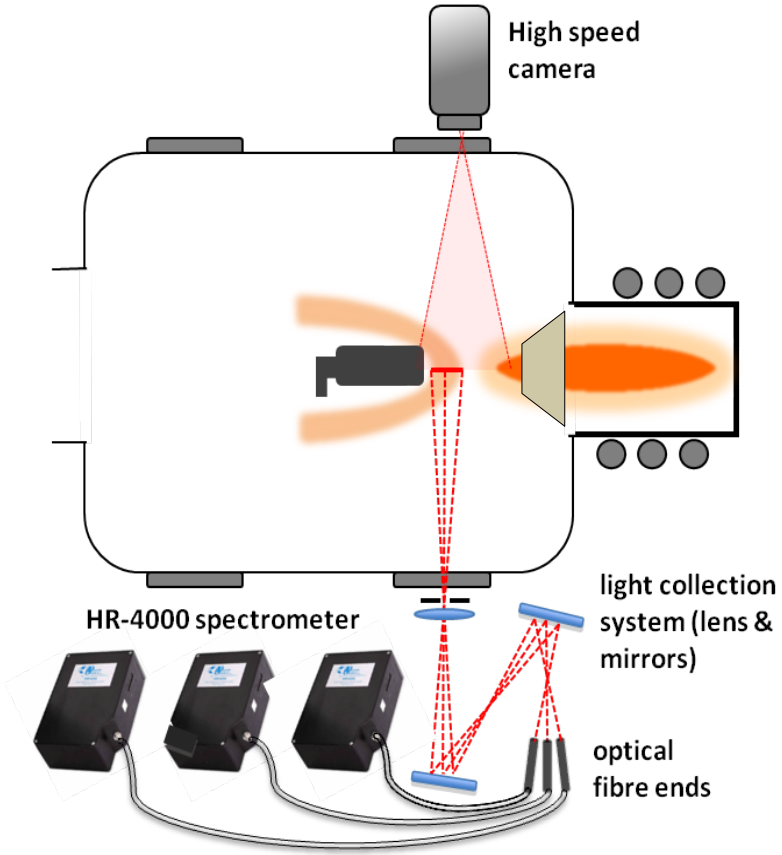




Experimental Setup M>1

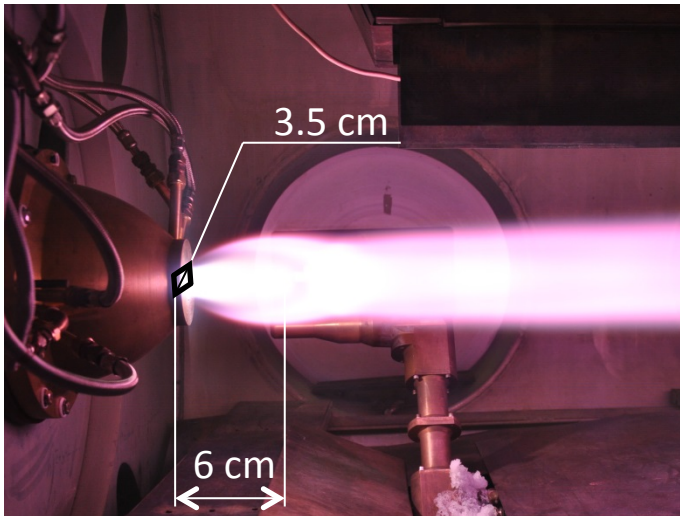
Preliminary test campaign

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Courtesy of B.Helber

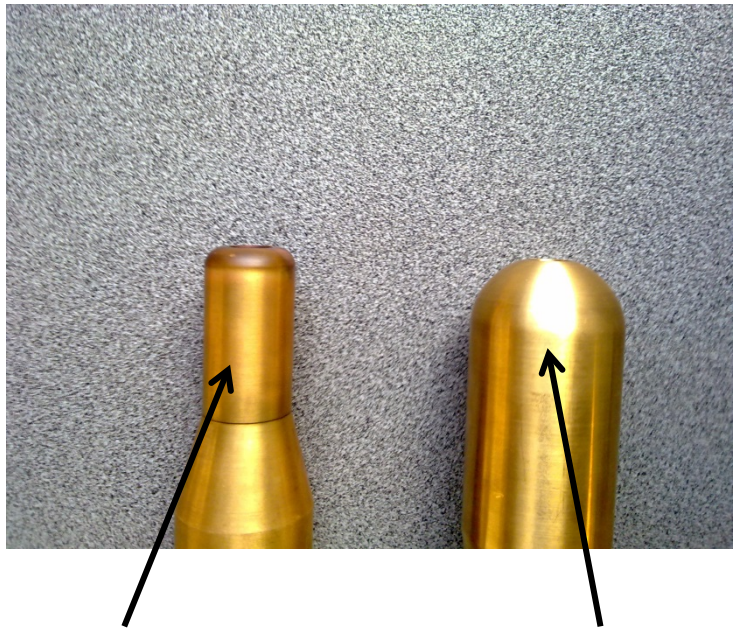
- Supersonic conturned nozzle AR = 20.9
- Non-Equilibrium Probe ø = 3 cm
- Gardon Gauge Calorimeter
- High Speed Camera
- 3 spectrometers Ocean Optics HR4000
- Two distances tried: 6 and 3 cm



Experimental Setup M>1

Main test campaign

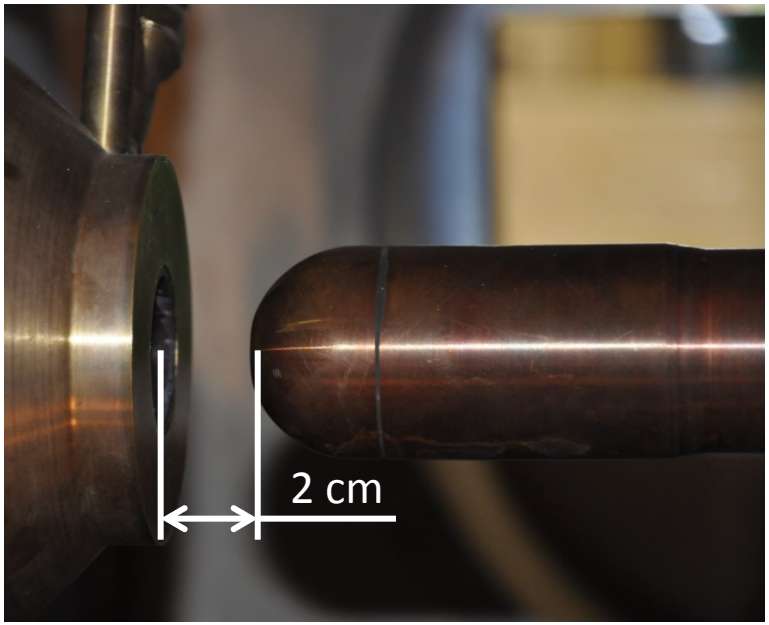
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Flat faced, non-equilibrium probe

Hemispherical probe

- Supersonic conturned nozzle AR = 20.9
- Hemispherical Probe ø = 5 cm
- Water Cooled Calorimeter
- High Speed Camera
- Two distances tried: 3 and 2 cm



Experimental Setup M>1

Preliminary test campaign

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Preliminary Test Campaign Conditions

d = 3 cm

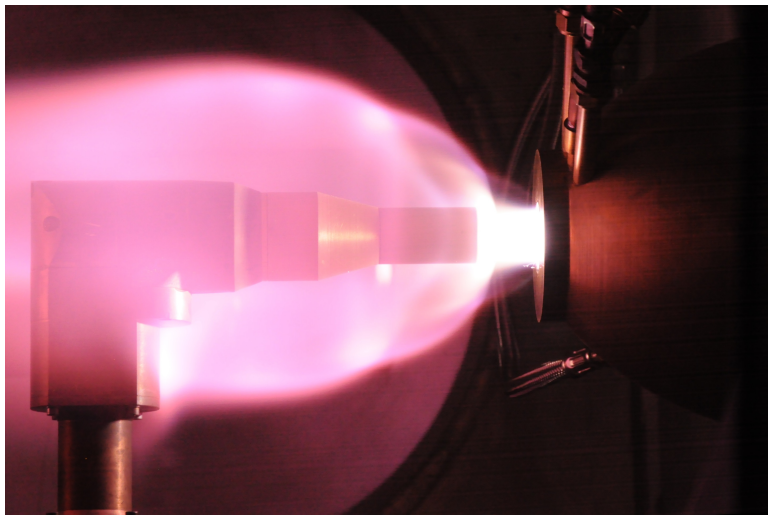
p_{res} = 101.5 mbar

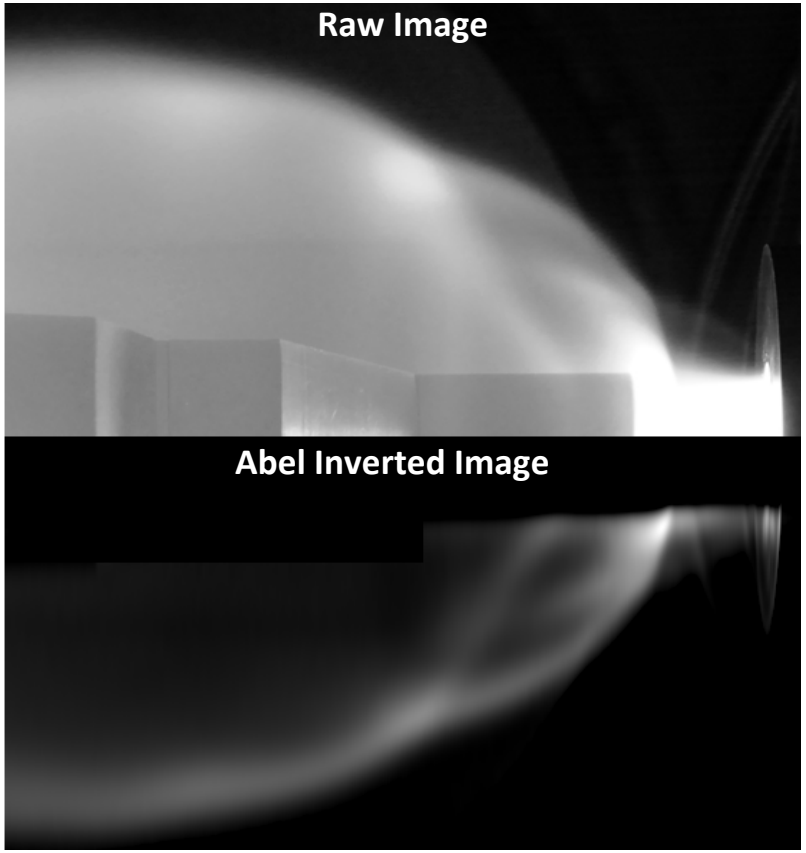
p_{stat} = 4 mbar

$\dot{m}$ = 4.5 g/s

Power = 500 KW ***HF*** = 9.67 MW/m^2

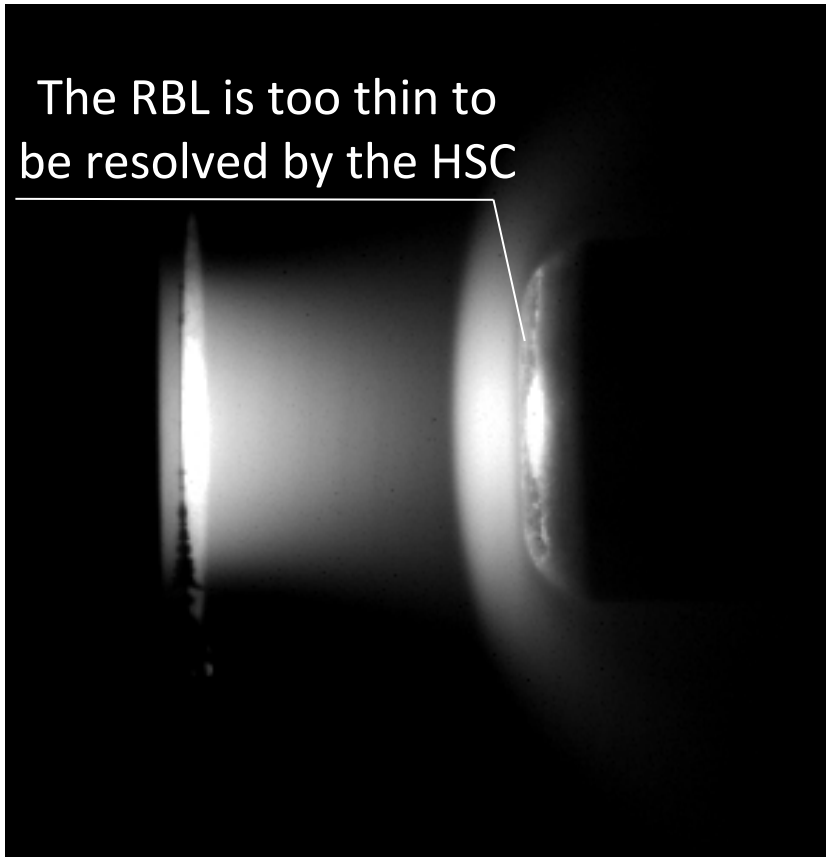
Power = 600 KW ***HF*** = 10.20 MW/m^2

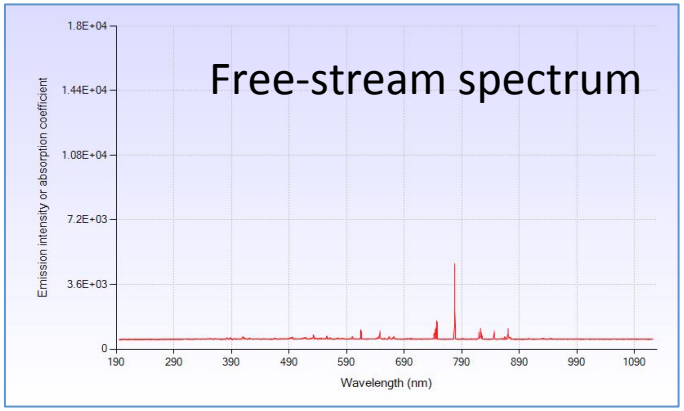


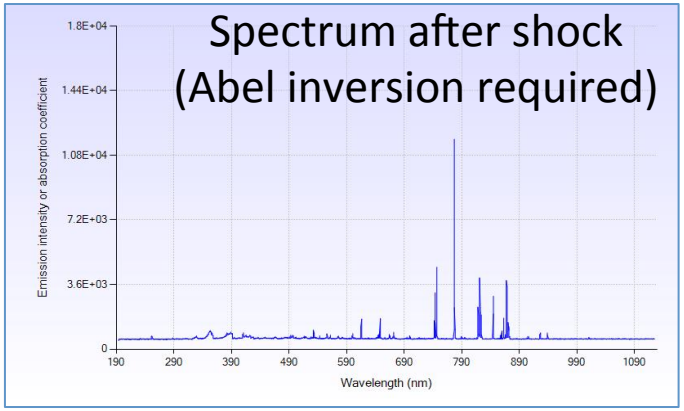


***Courtesy of D. Le Quang**

Boundary Layer fot M>1





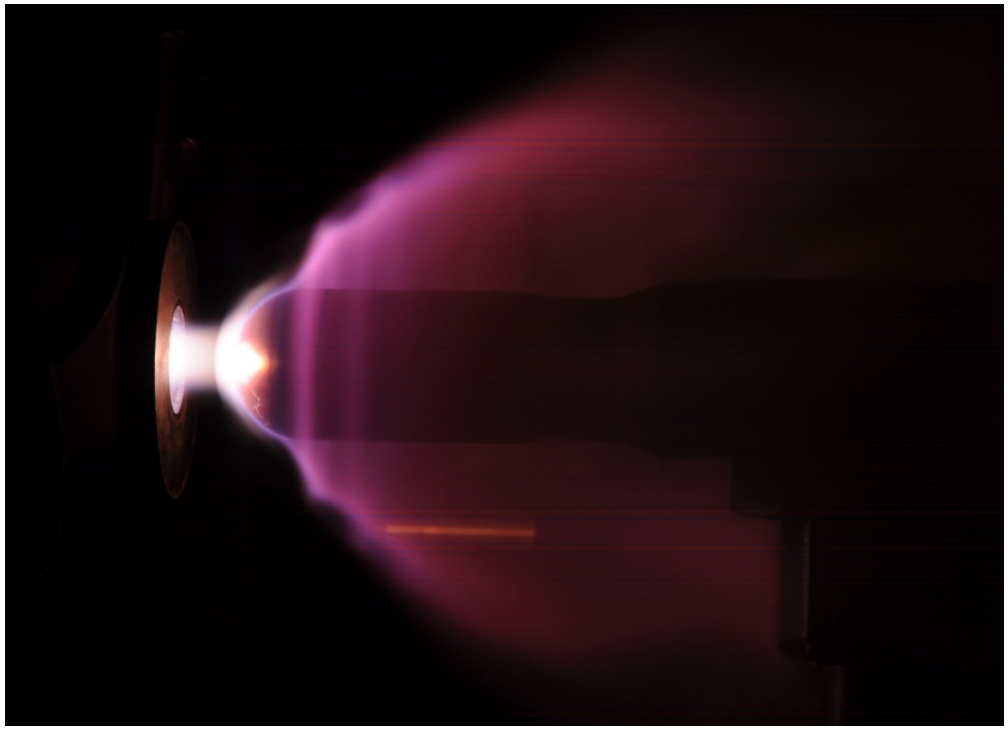


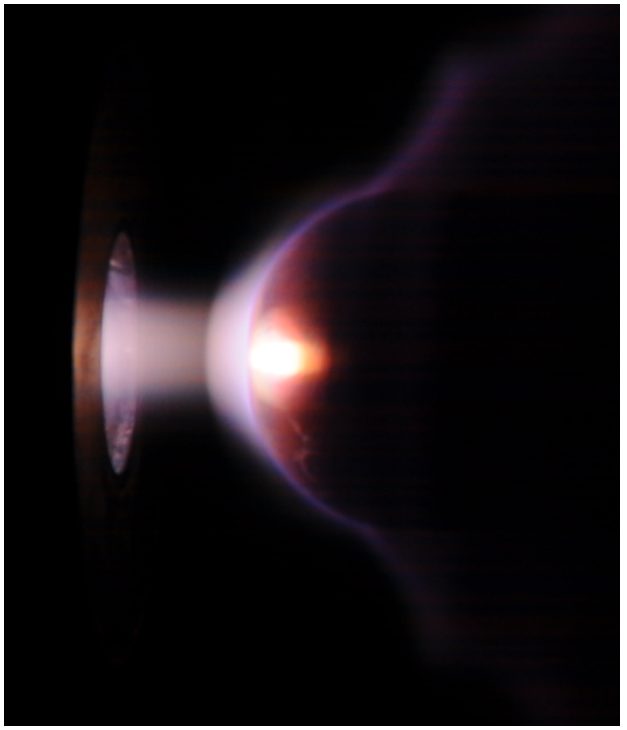
The presence of the shock-wave makes meaningless the point spectroscopy

High Heat-Flux Measurements M>1

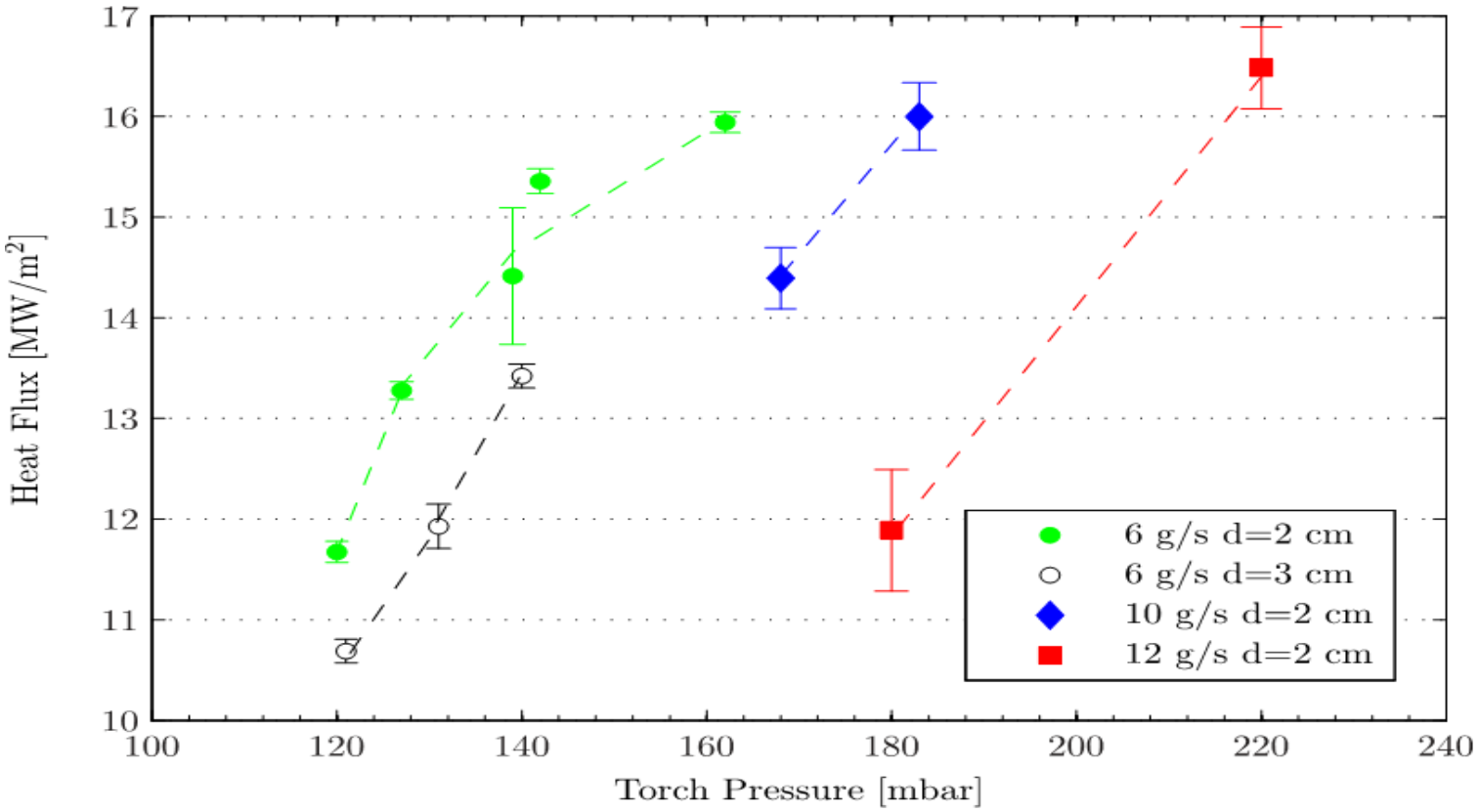
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- Shock waves pattern completely different from the flat faced probe.
- For the same test conditions, the frontal shock wave is more distant from the surface compared to the flat faced probe





High Heat-Flux Measurements M>1



- Max HF measured: 16.7 MW/m^2 with p_0=220 mbar

Plasma Frequency Content M>1

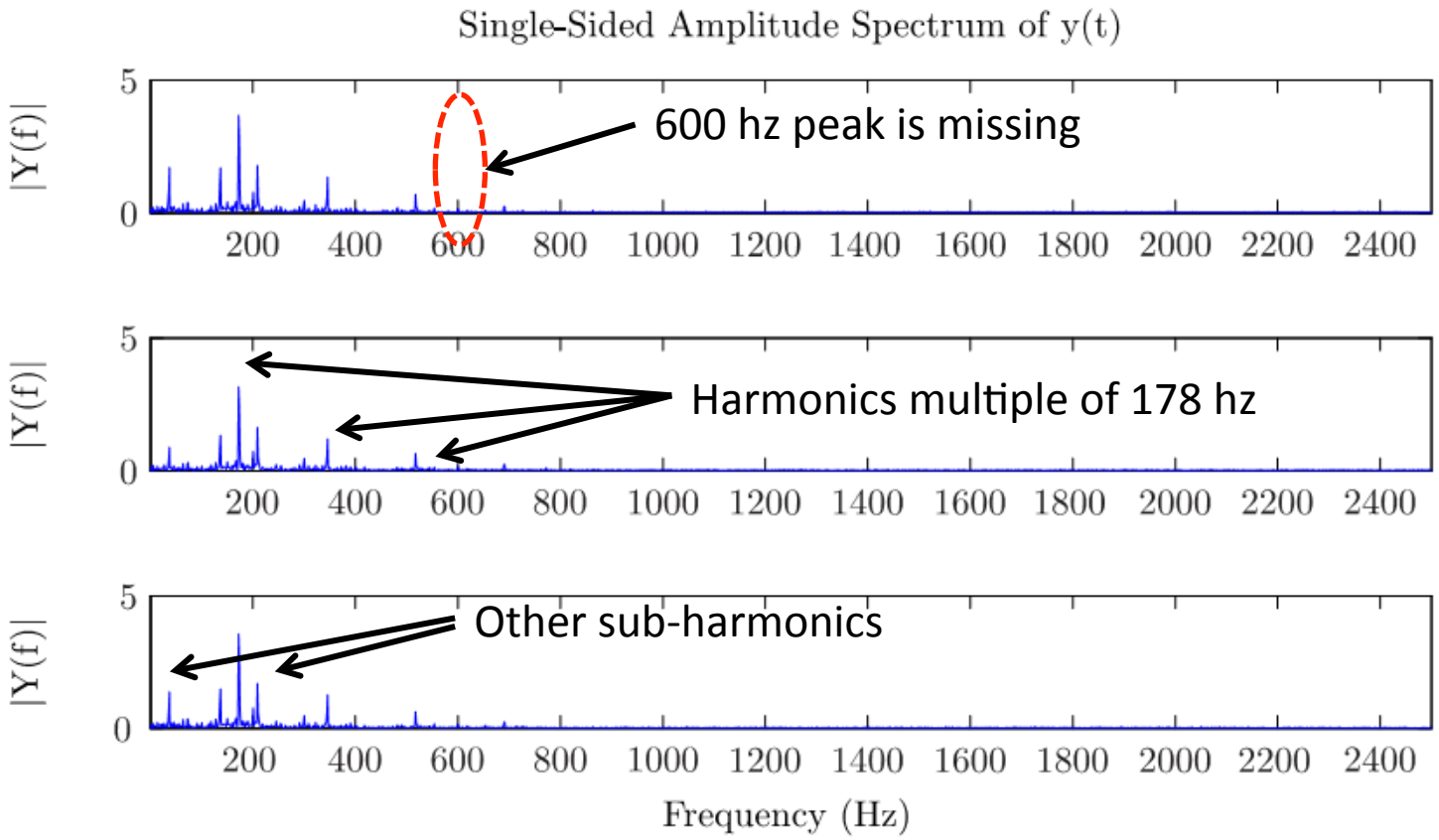
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p_{res}= 101 mbar p_{stat}= 4 mbar $\dot{m}$ = 4.5 g/s Power = 500 KW

d = 30 mm

d = 15 mm

d = 0.25 mm



Conclusions and future works

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- We assessed the capability of the 1.2 MW VKI Plasmatron to generate high heat fluxes of 16.5 MW/m^2;
- We retrieved the plasma fluctuation frequencies in supersonic regime, showing they are far different from the ones in subsonic regime. Here more studies are required to understand such phenomena;

Future Work

- The ICP code for supersonic plasma is ready for validation;
- Works are ongoing to extend the LHTS theory also in presence of shock-waves.

THANK YOU
QUESTIONS?