Experimental and Numerical Characterization of Supersonic and Subsonic Gas Flows for Nuclear Spectroscopy Studies

Alexandra Zadvornaya
24 September 2019

Plan:

A. Stopping and transport of nuclear reaction products in subsonic helium flow

1. Multinucleon-transfer (MNT) reactions within Elemental Nucleosynthesis studies at University of Jyväskylä
2. Experimental and numerical characterization of efficiency of ion survival in subsonic helium flow
3. Outlook

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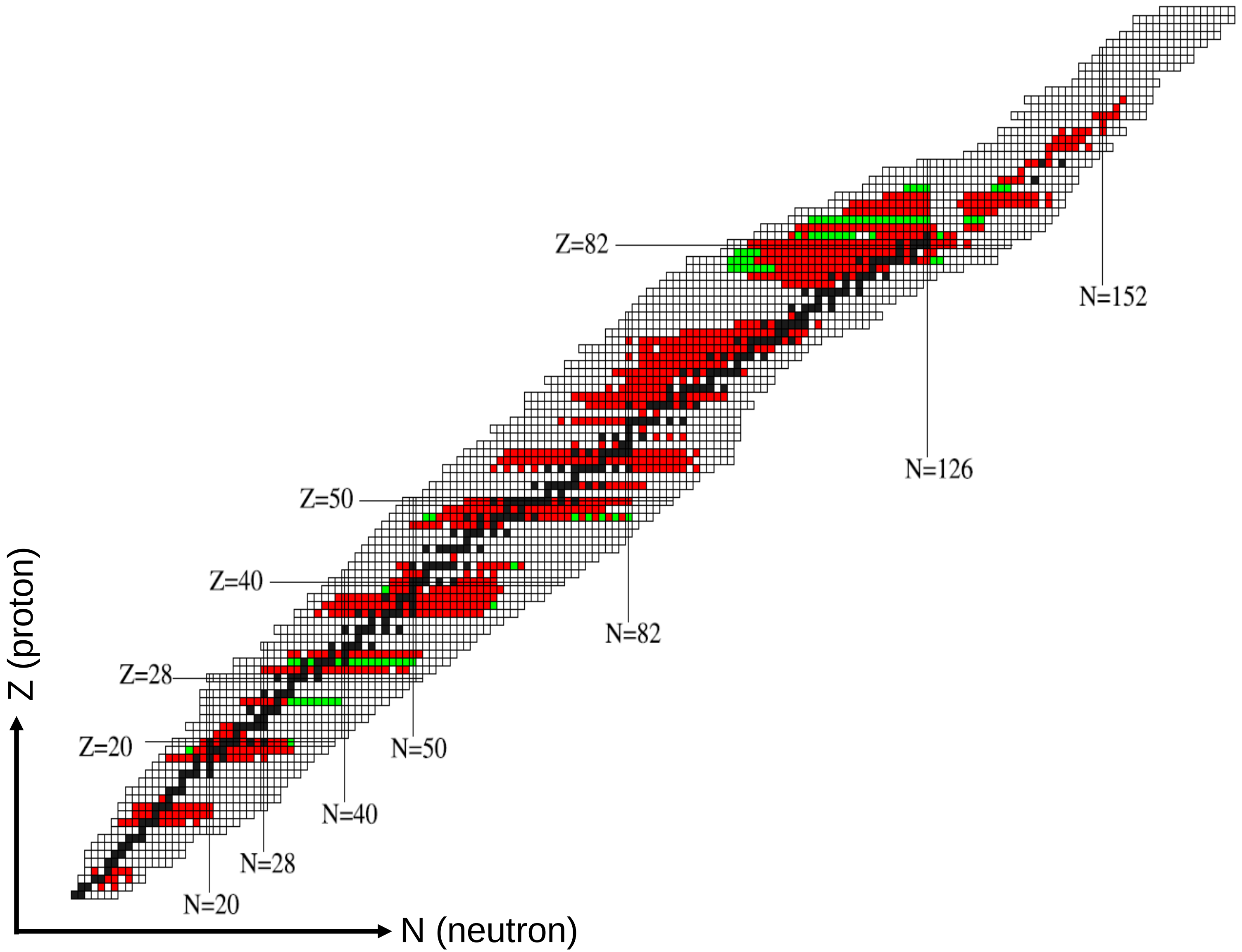
B. In-gas-jet laser ionization spectroscopy in supersonic argon jets

1. In-gas laser ionization spectroscopy in heavy element region
2. PLIF-spectroscopy experiments at KU Leuven
3. Results
- Validation of PLIF-spectroscopy
- Characterization of gas jets formed by de Laval nozzle
4. Conclusions

MAIDEN

Masses, **I**somers and **D**ecay studies for **E**lemental **N**ucleosynthesis



P. Campbell, I. D. Moore, and M. R. Pearson, Prog. Part. Nucl. Phys. 86, 127 (2016)

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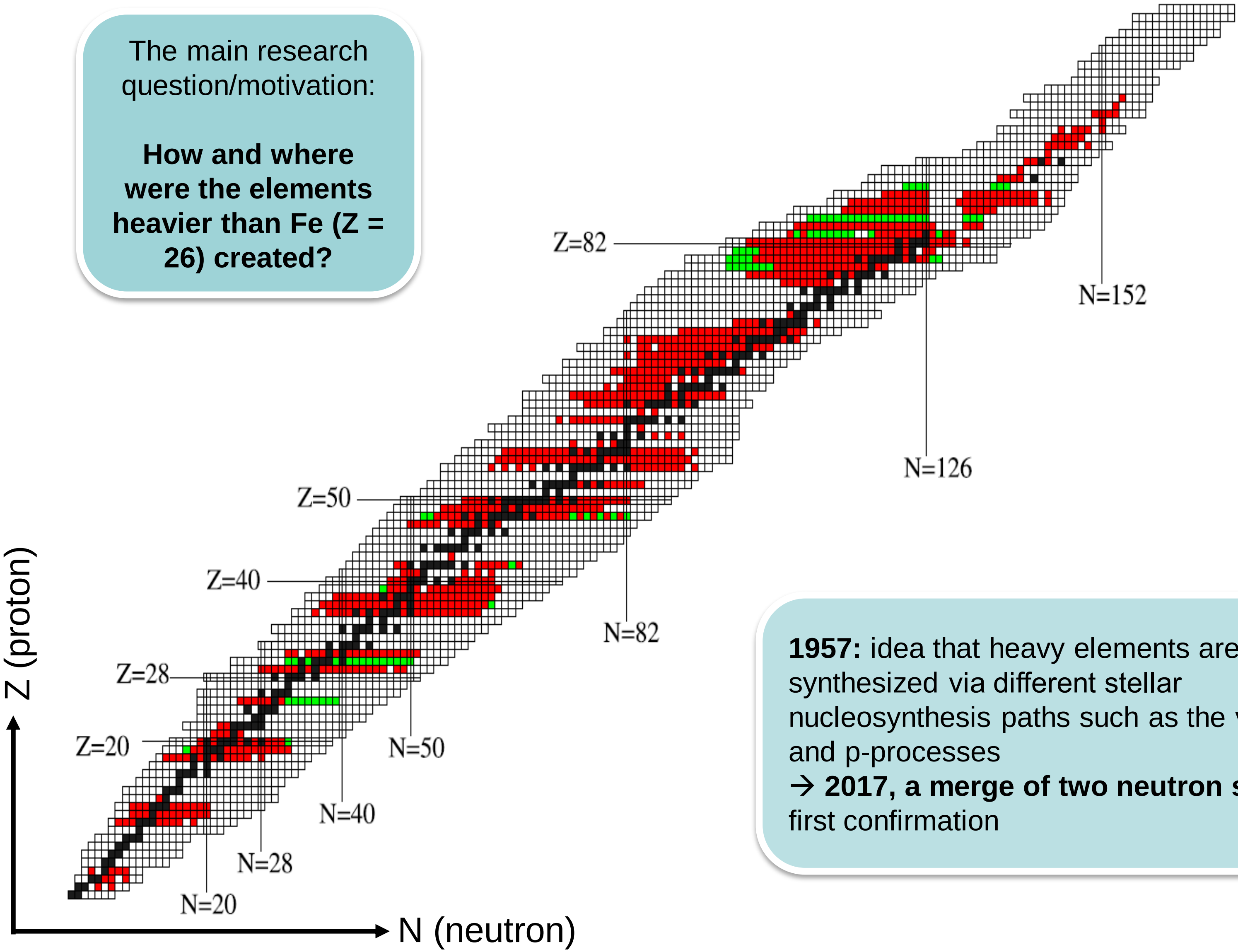
The main research question/motivation:

How and where were the elements heavier than Fe (Z = 26) created?



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→ **2017, a merge of two neutron starts** first confirmation

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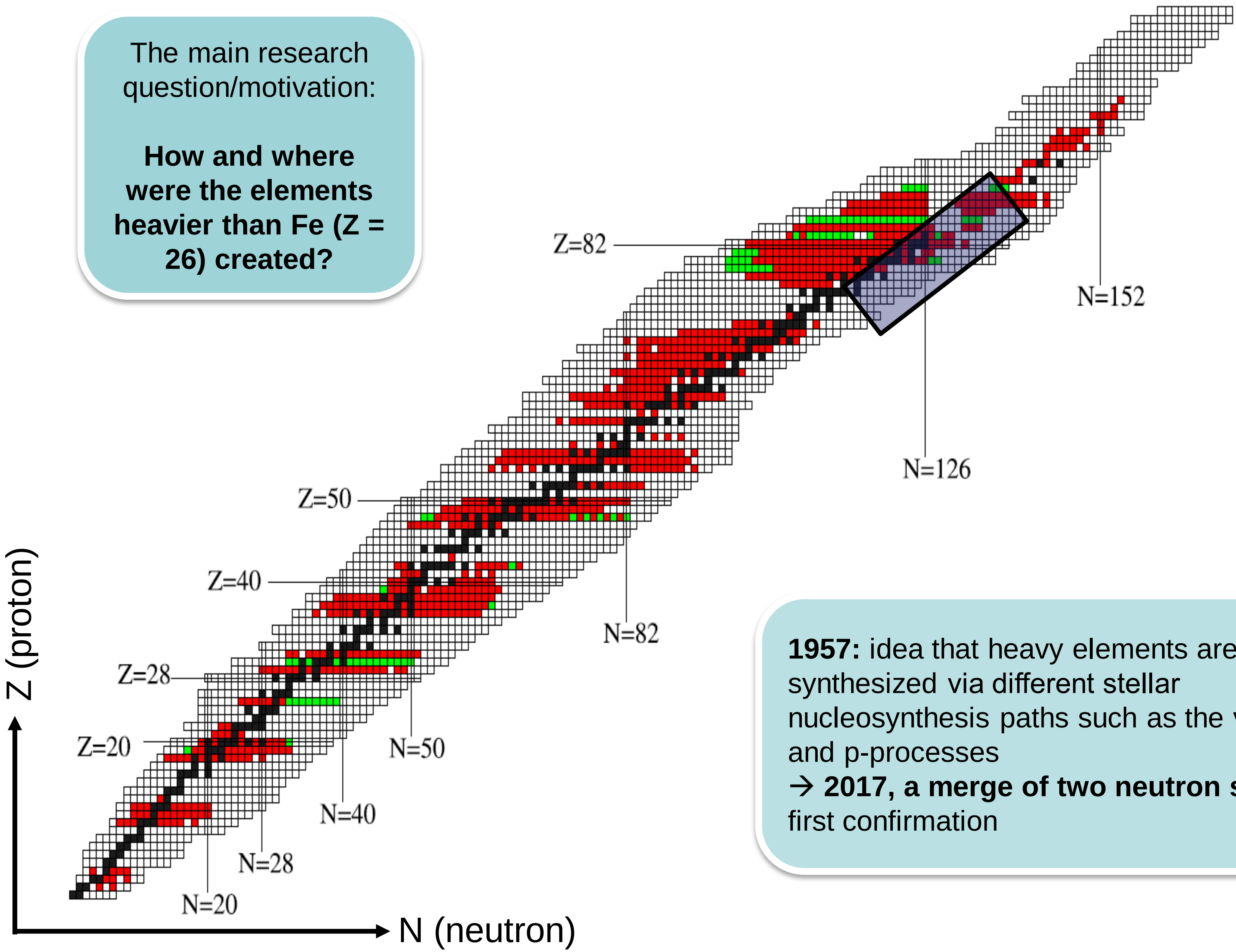

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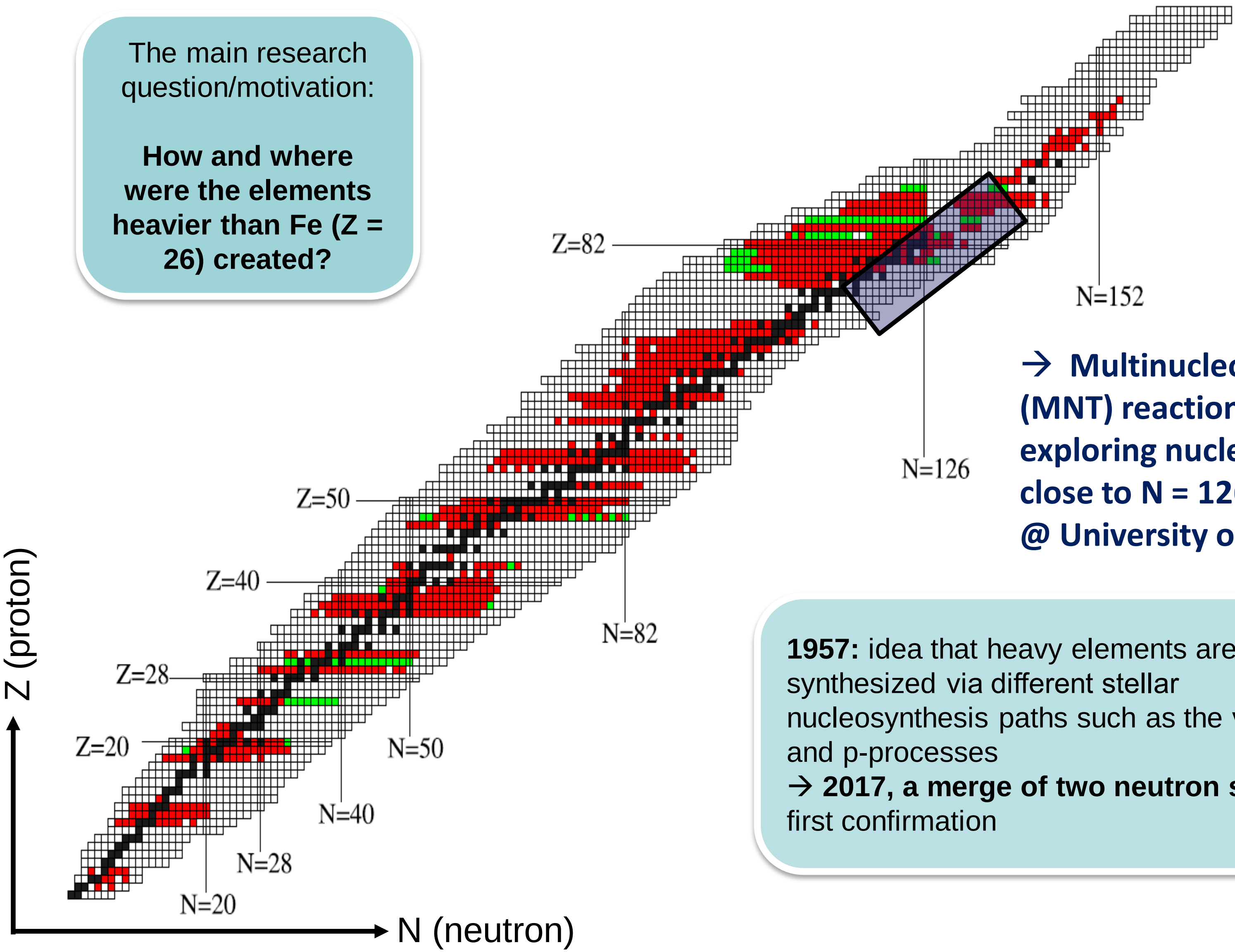

→ **Multinucleon-transfer (MNT) reactions studies for exploring nuclear structure close to N = 126 @ University of Jyväskylä**

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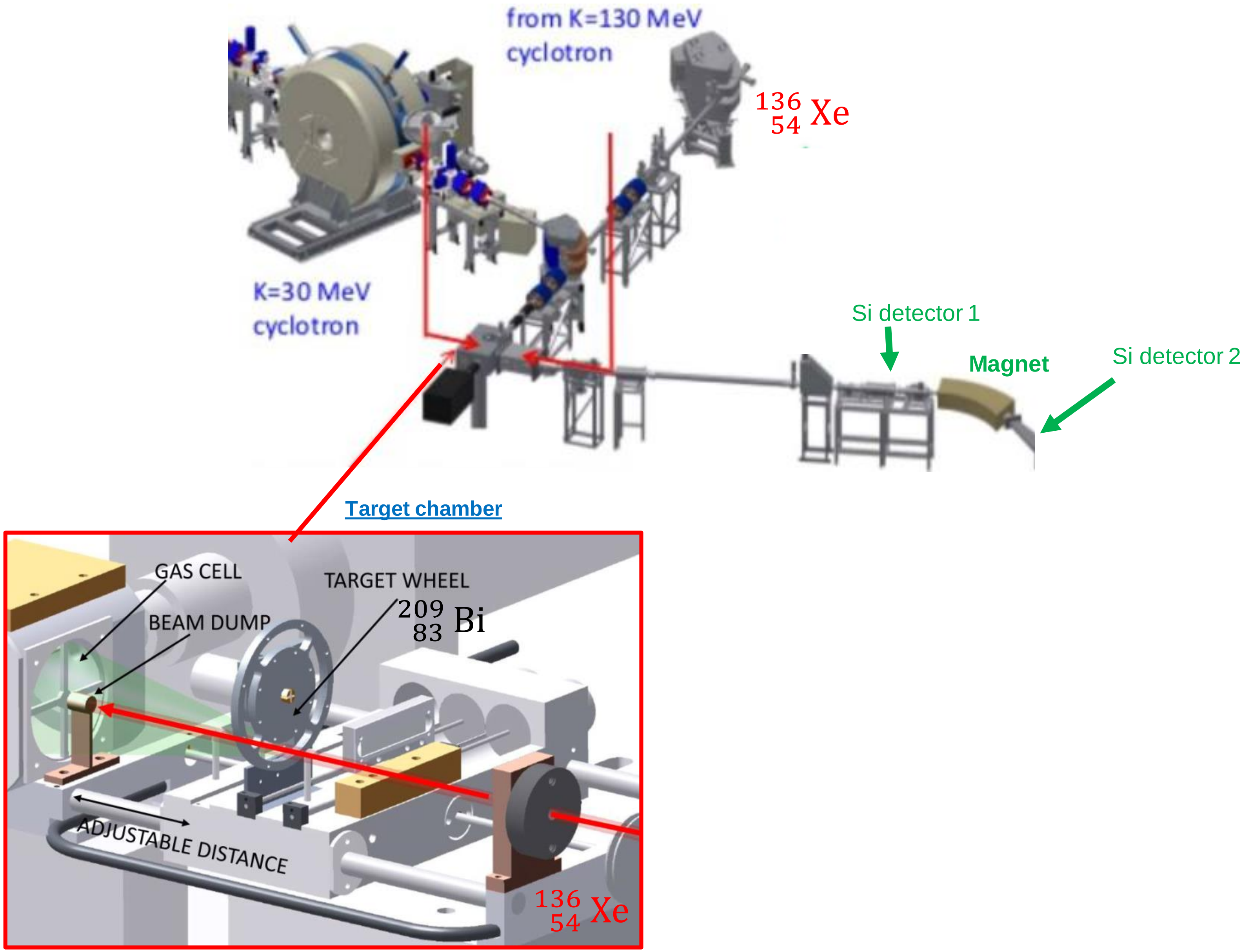

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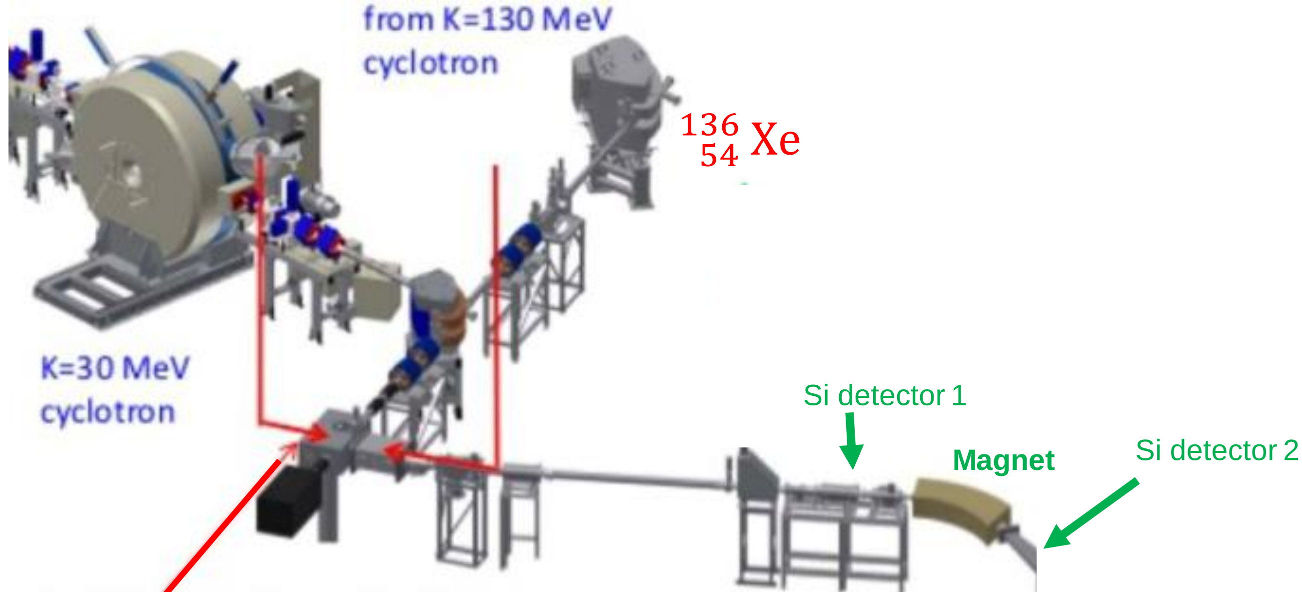
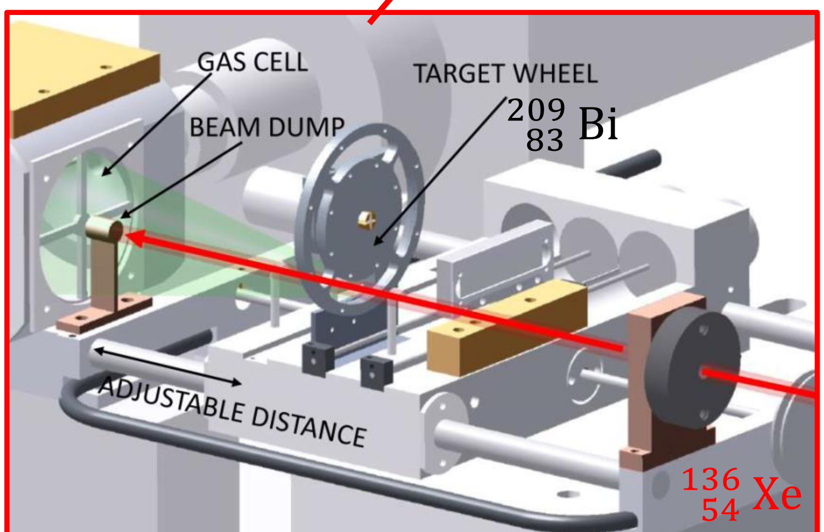
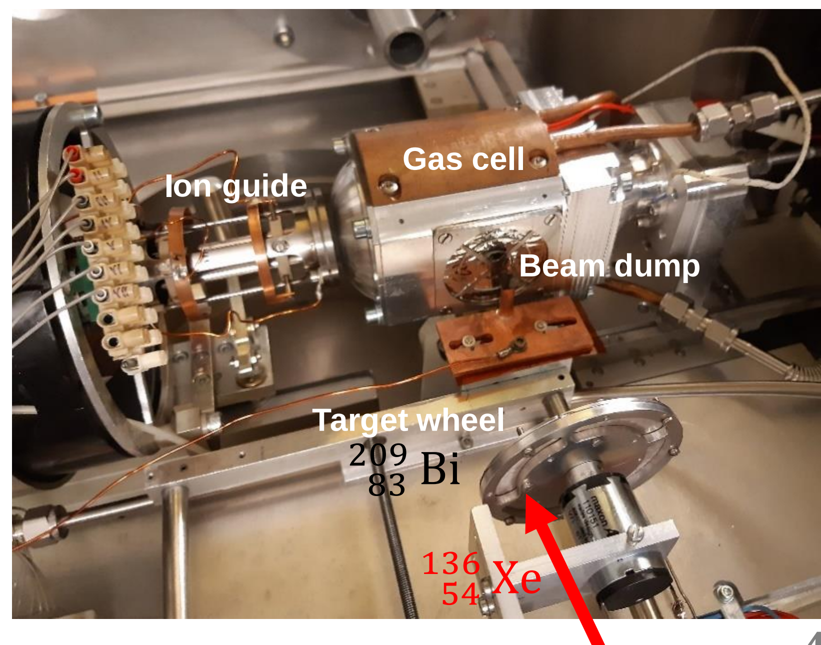


Target chamber





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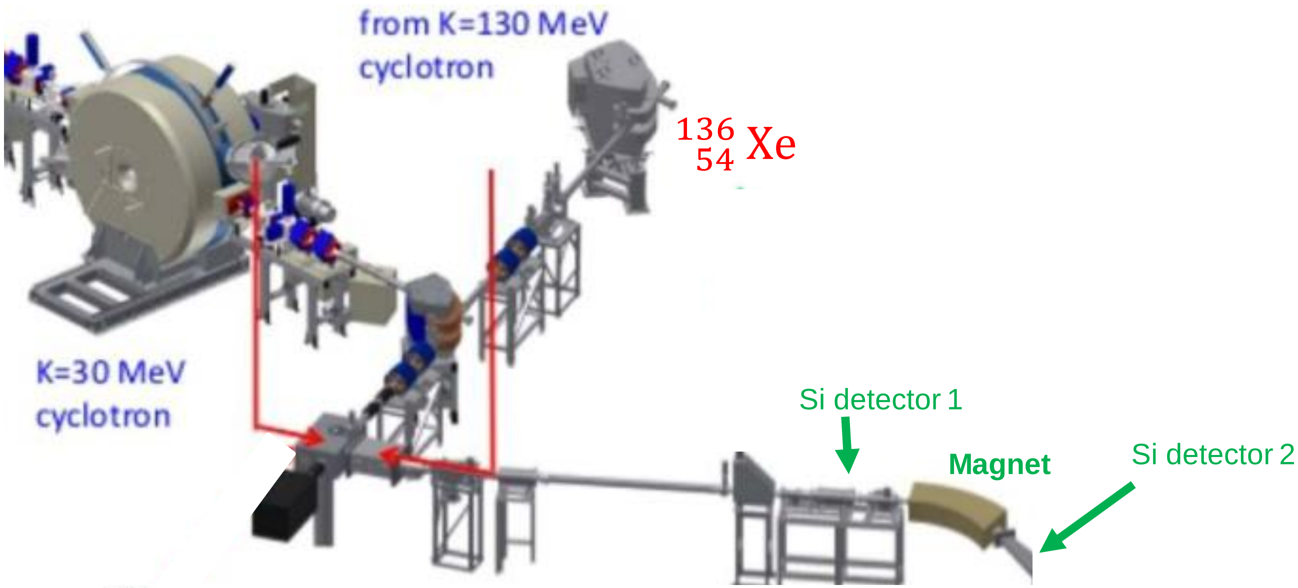
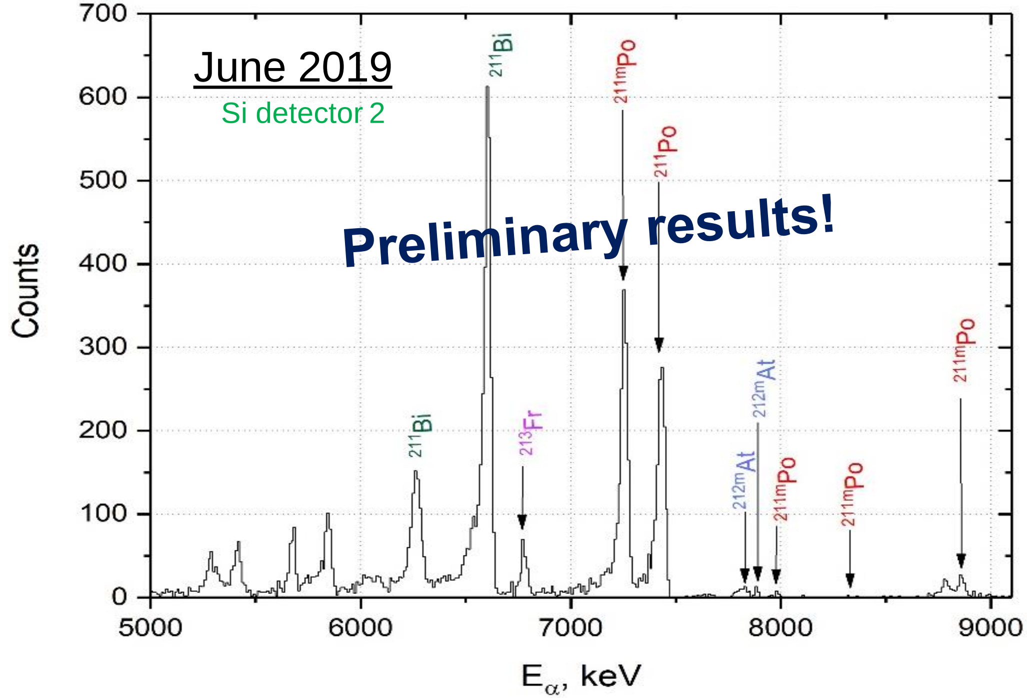
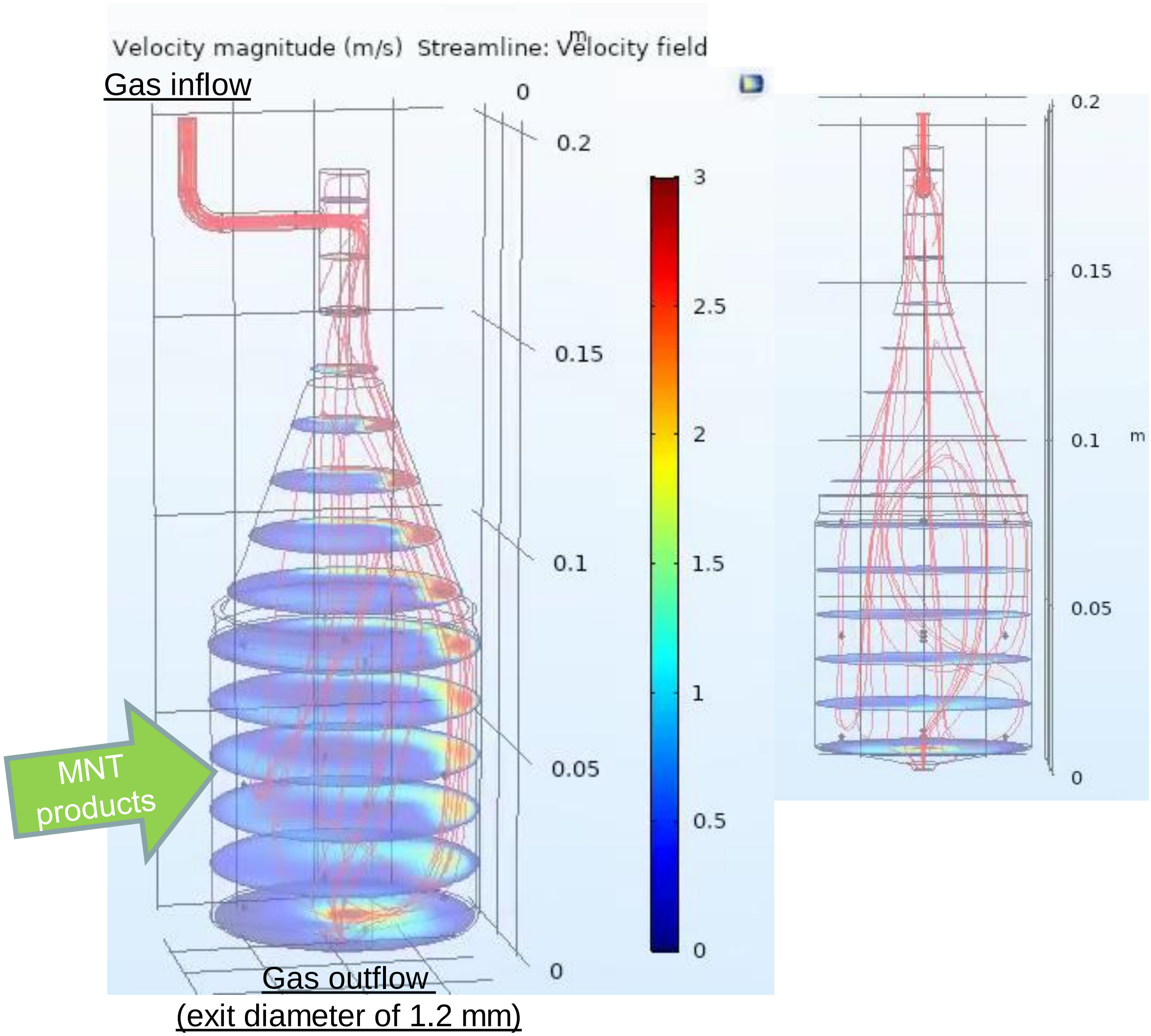




Initial gas cell design



CFD Module

Laminar Flow:

compressible flow;

boundary conditions – no slip.

Transport of Diluted Species:

convection and diffusion.

Helium

Temperature $T_0 = 300$ K

Exit diameter of 1.2 mm

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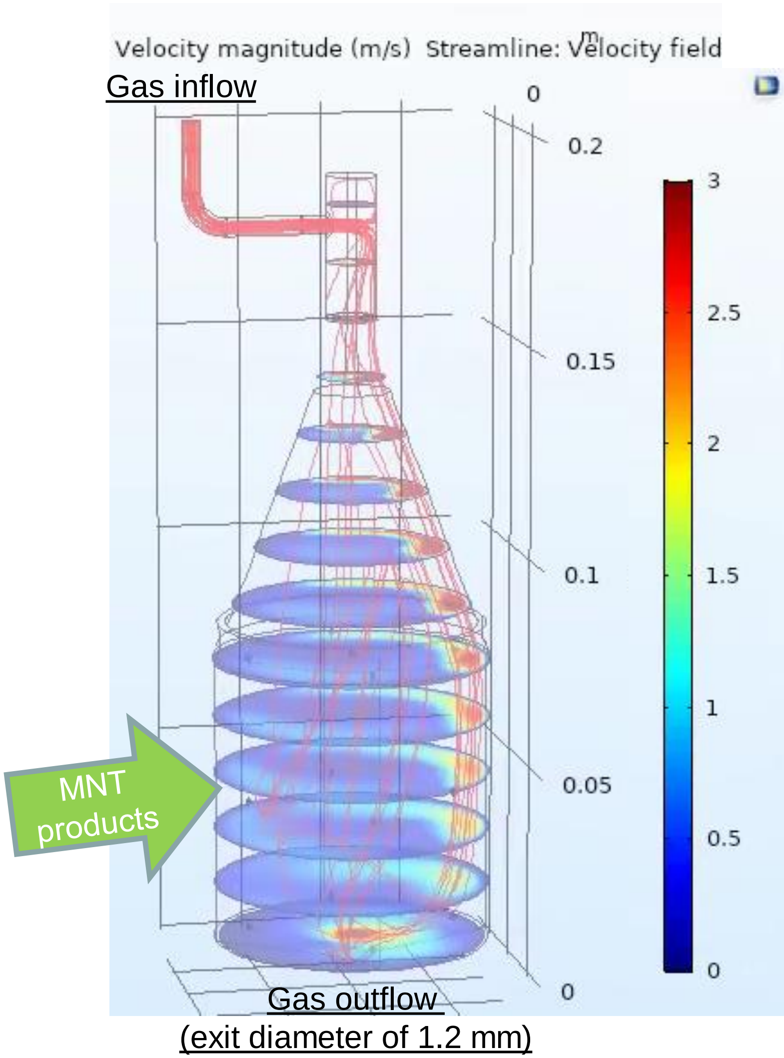

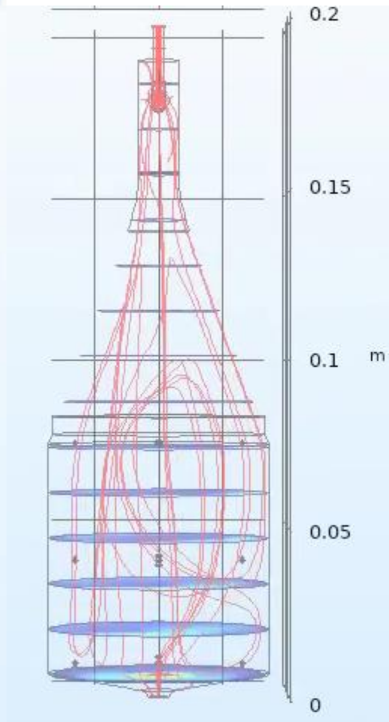

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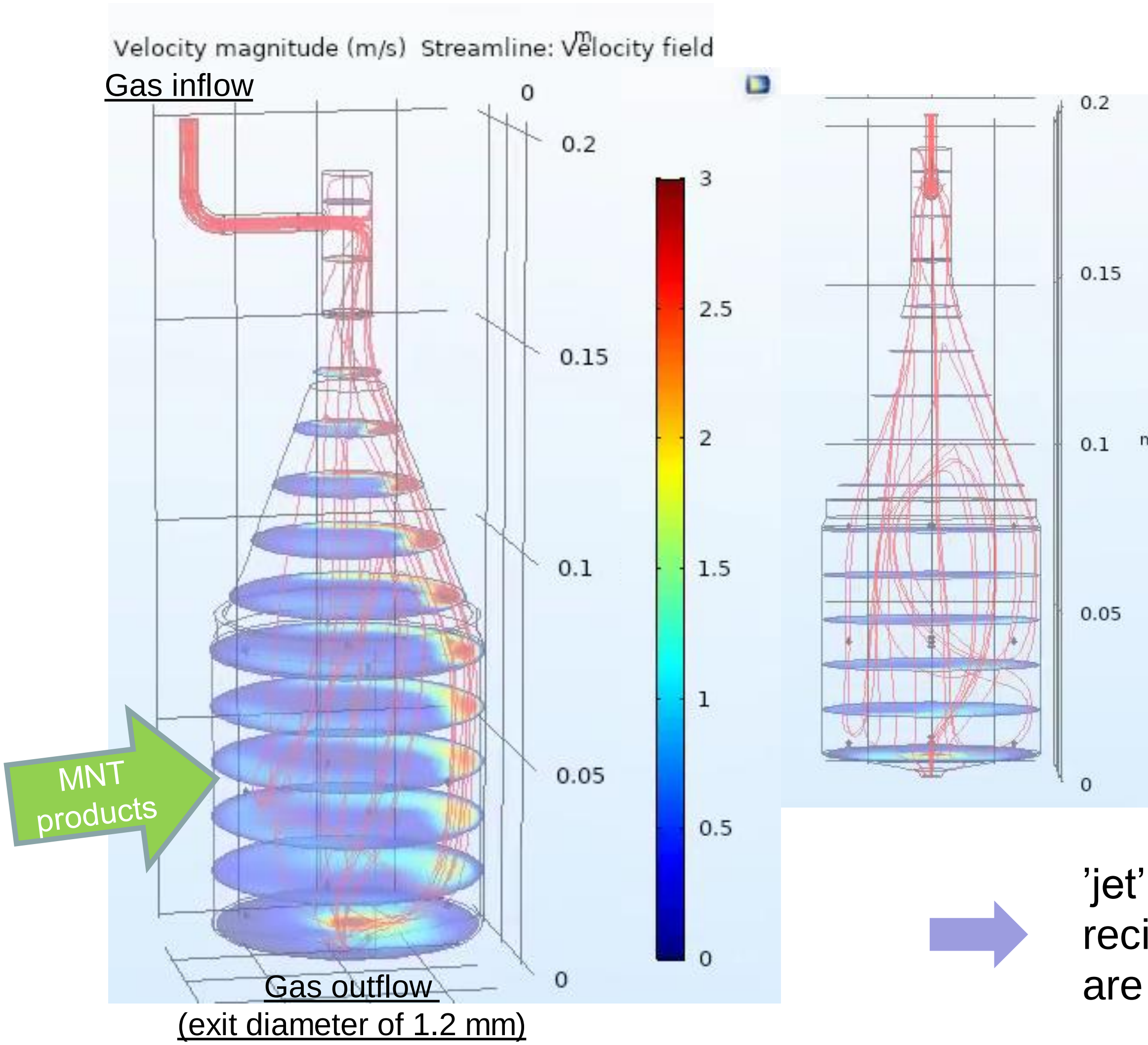

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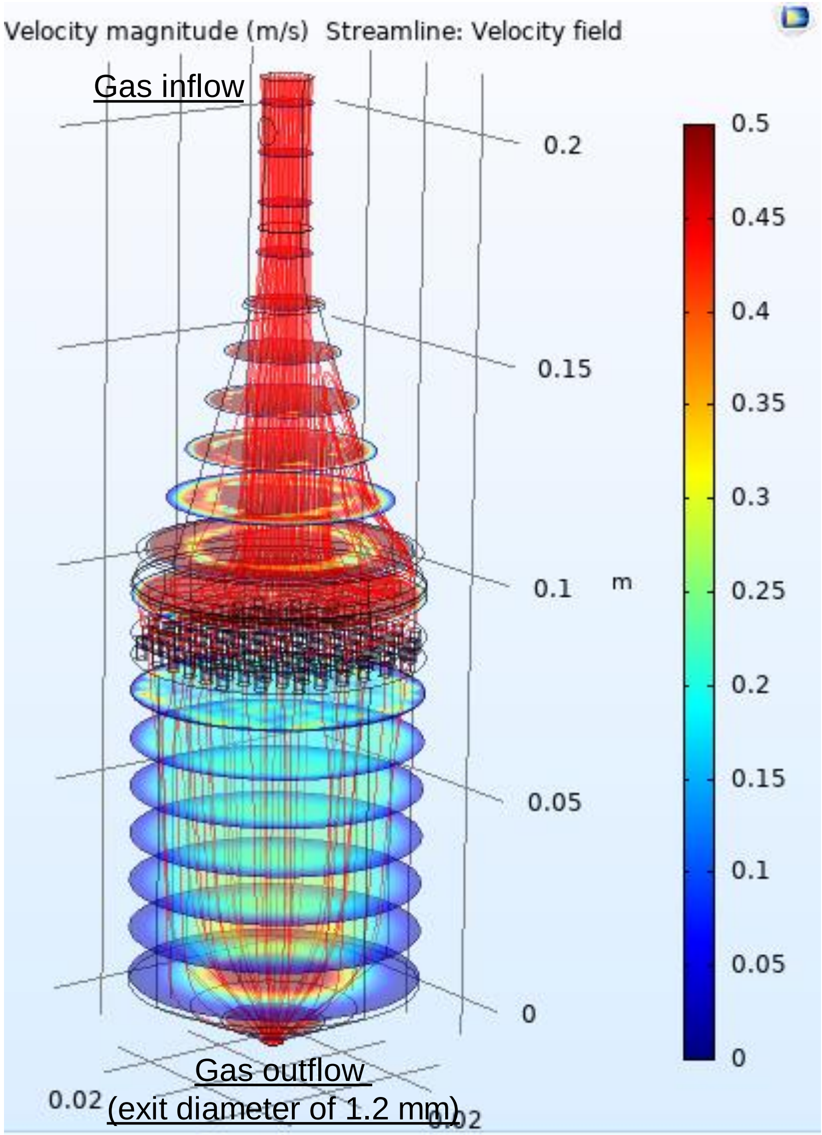
Gas cell design had to be optimized to enable more efficient and fast transportation

Optimization of gas cell design using CFD Module



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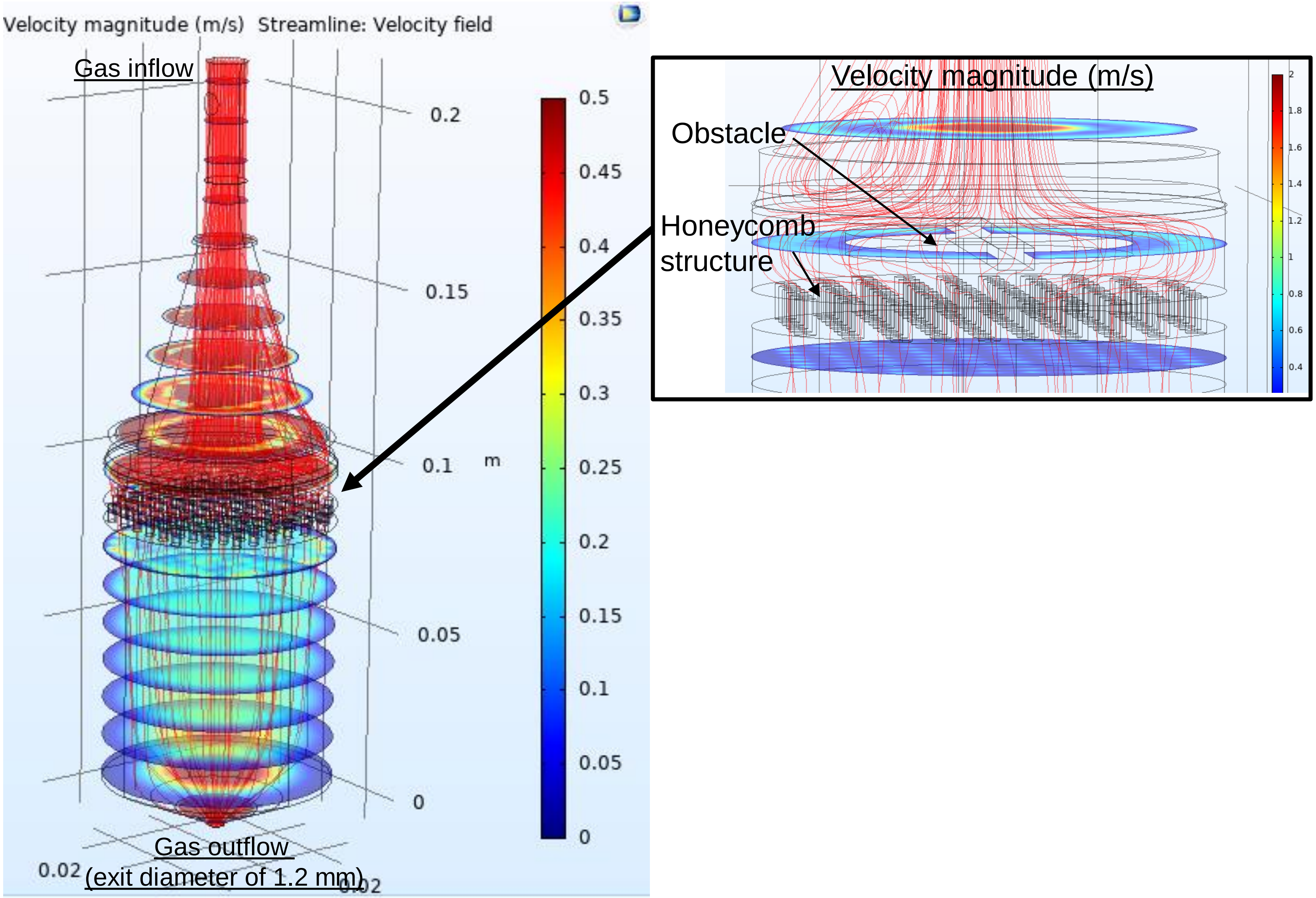

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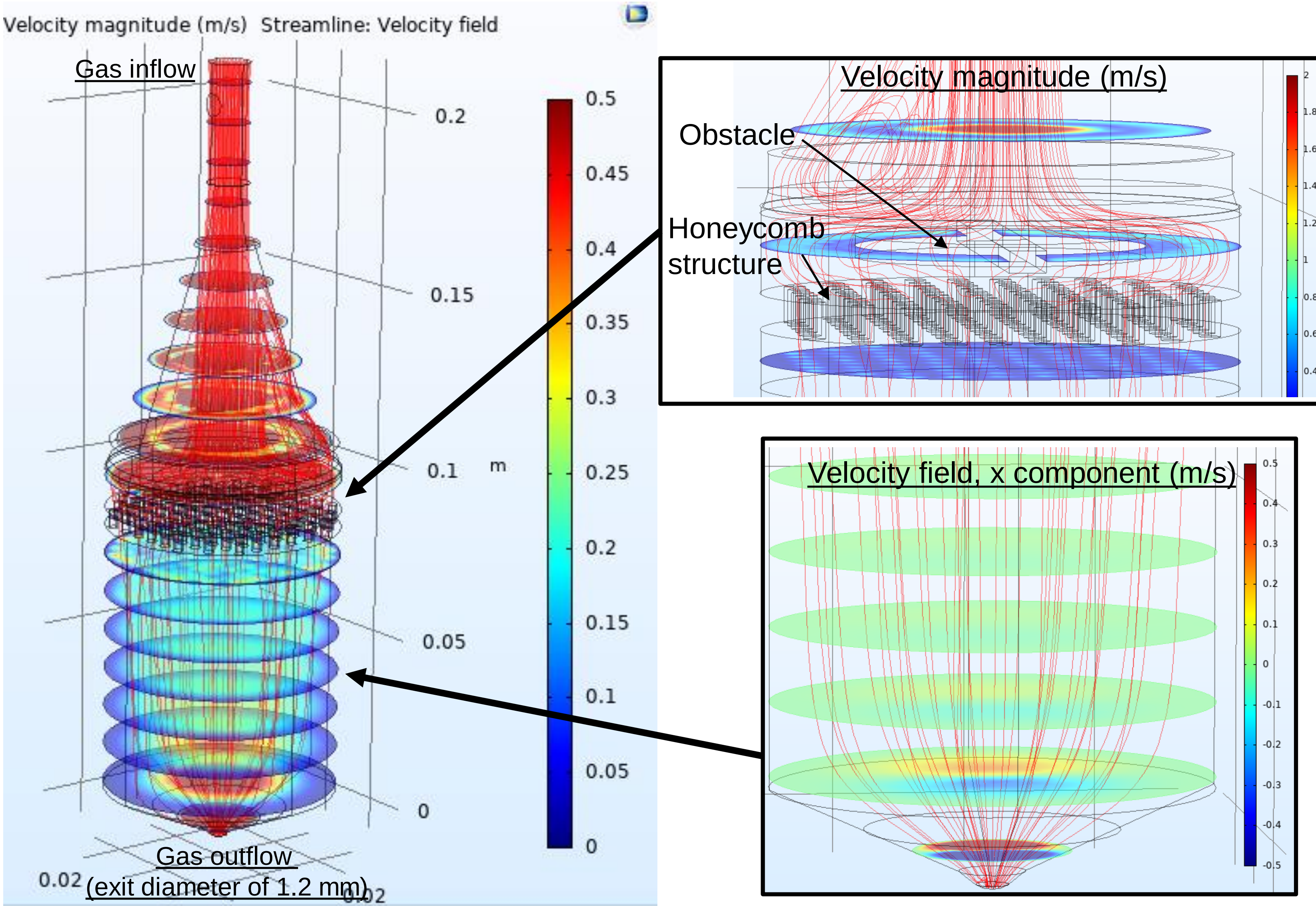
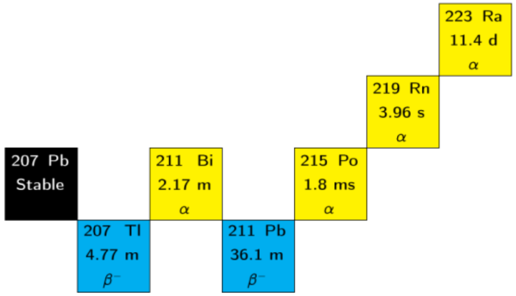
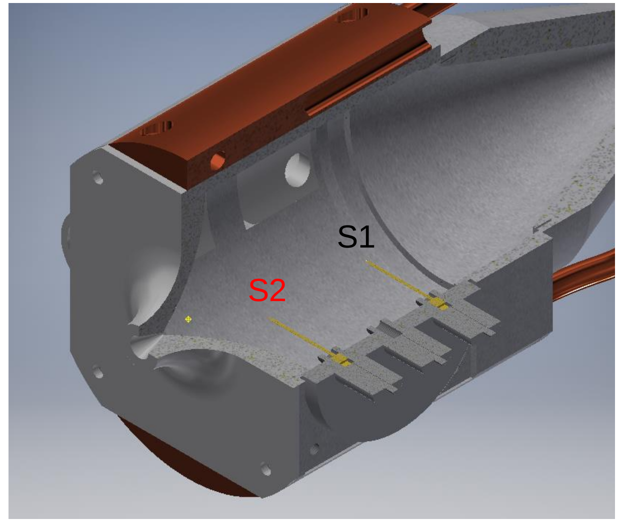


More uniform flow structure

Experimental and numerical characterization of ion survival efficiency by using α-recoil $^{223}_{88}$Ra source



Decay chain for $^{223}_{88}$Ra



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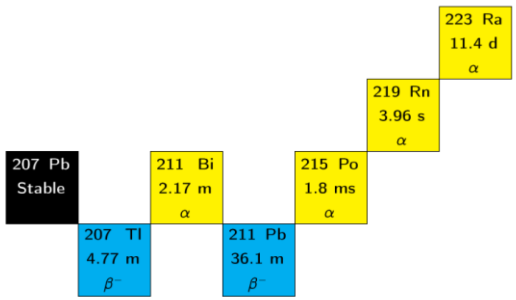

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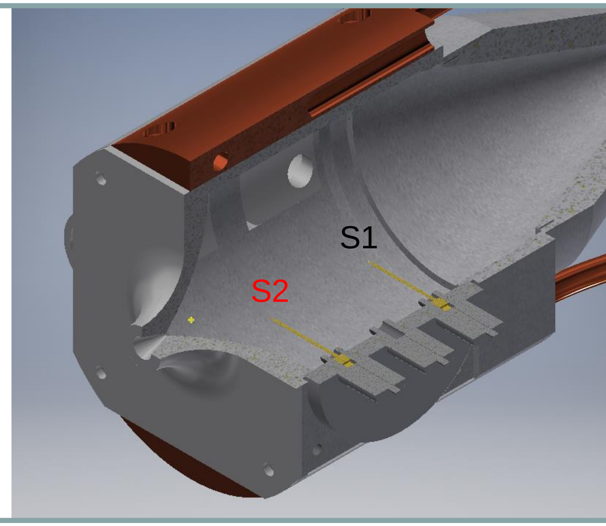

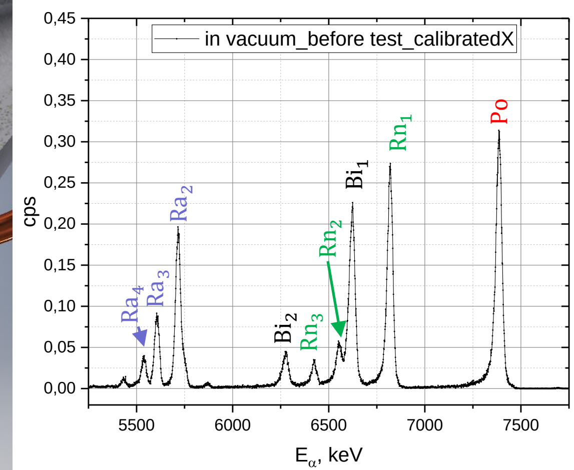

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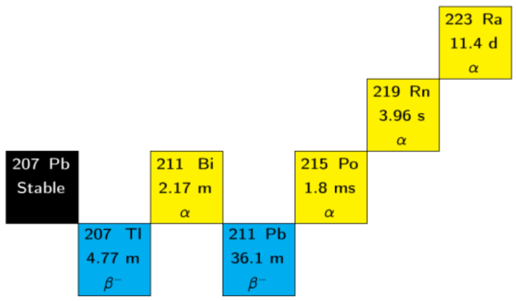

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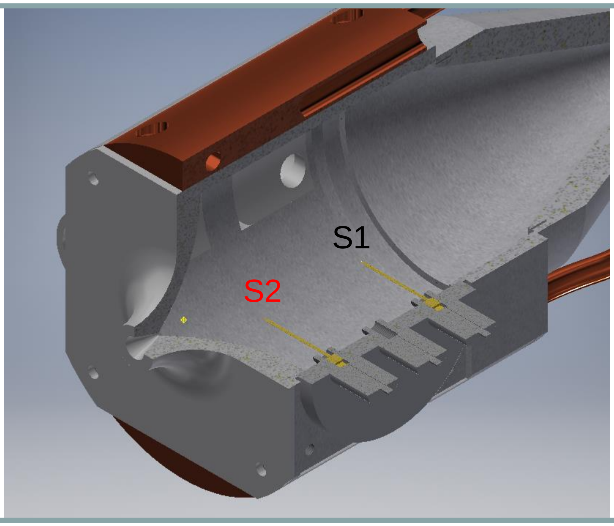
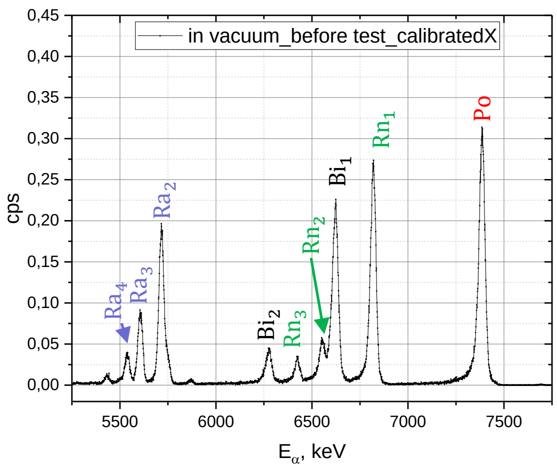
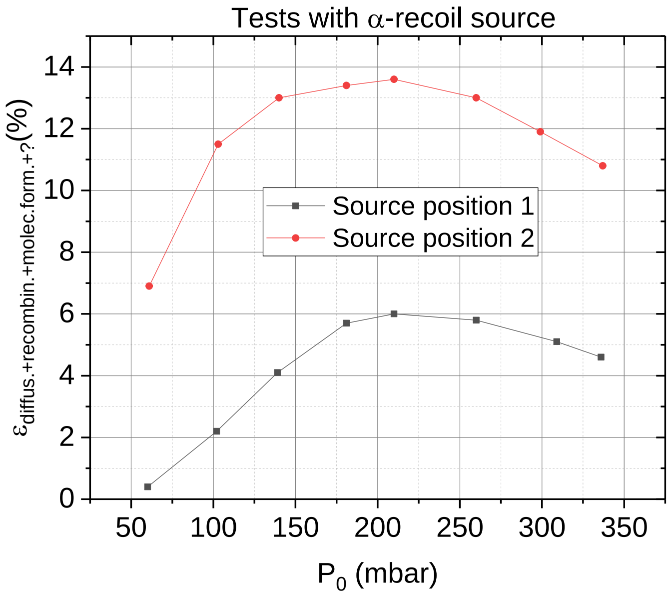
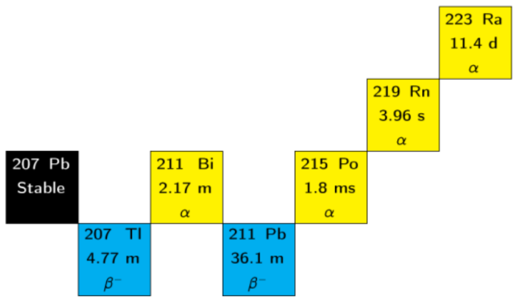






Experimental and numerical characterization of ion survival efficiency by using α-recoil $^{223}_{88}Ra$ source



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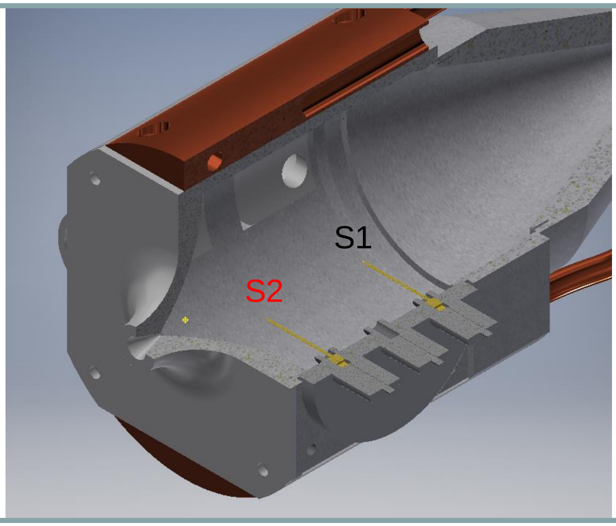
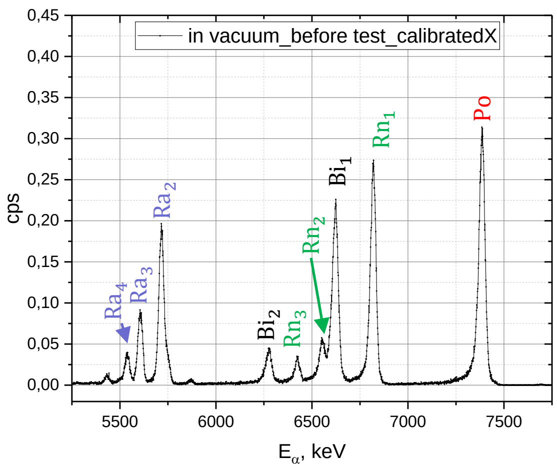
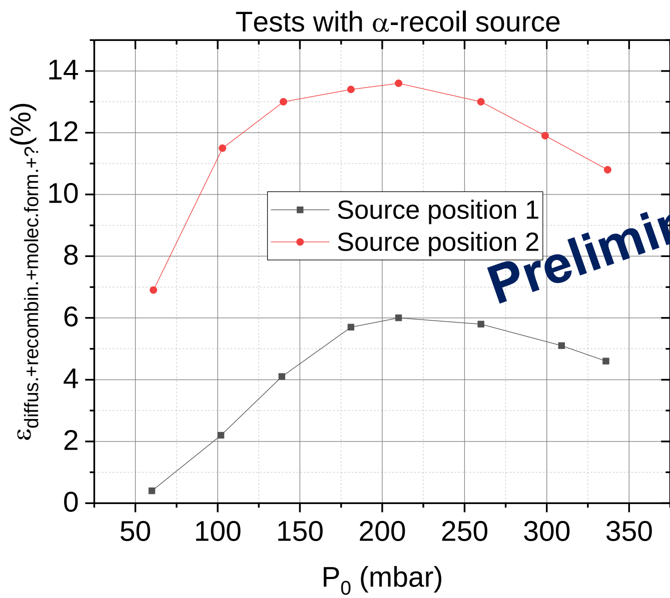
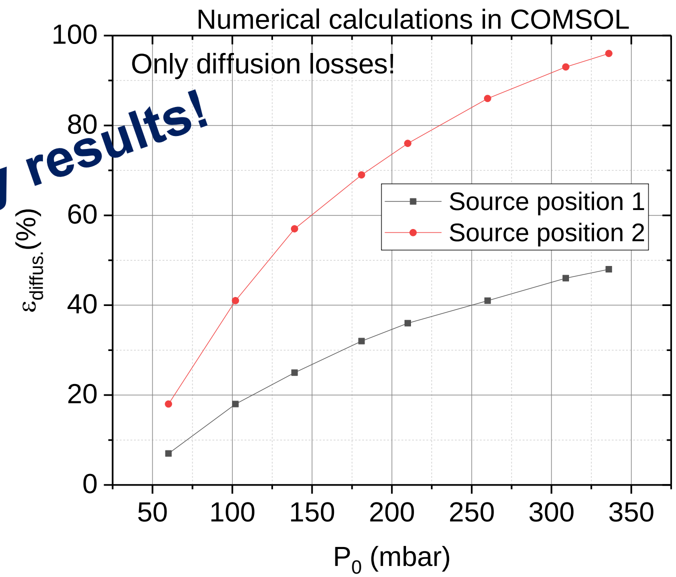






Preliminary results!



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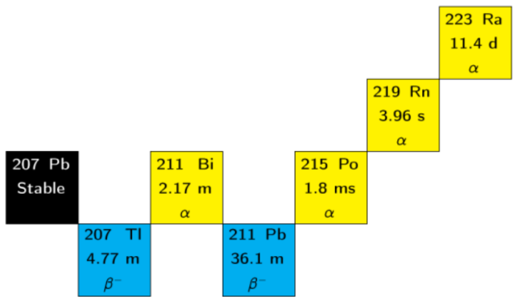

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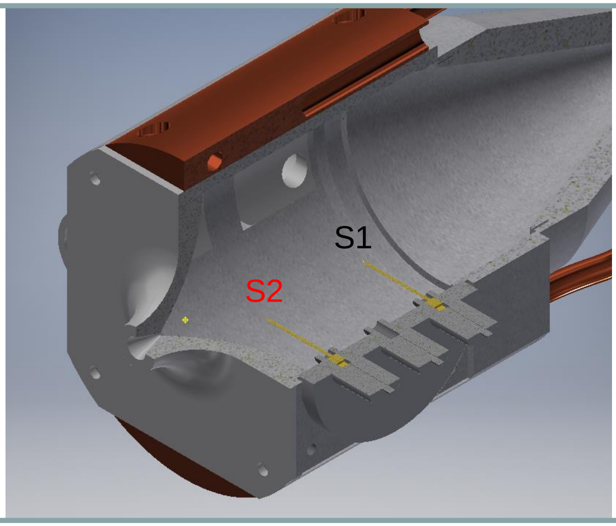

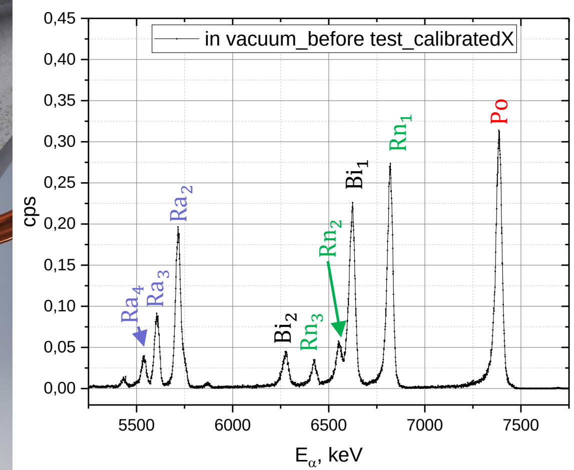

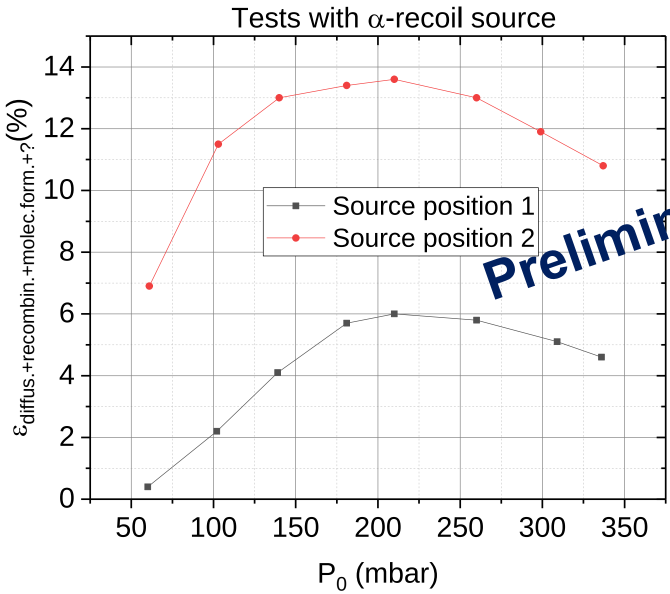

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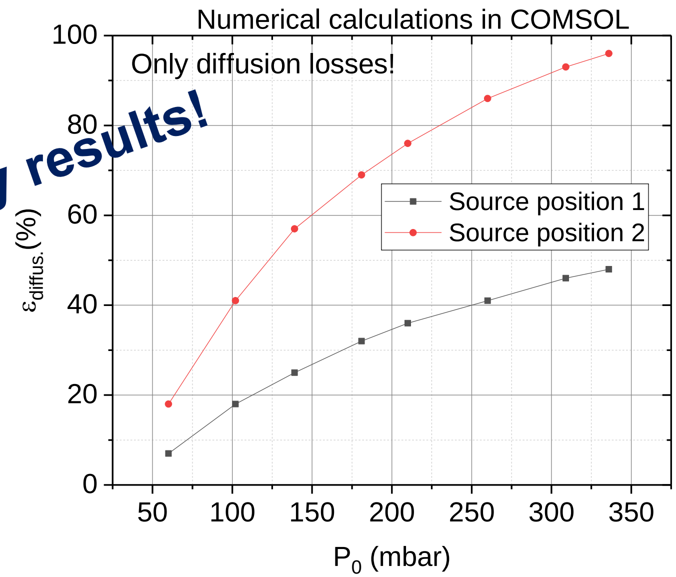

Other loss factors, aside of diffusion
1) Ion survival againts recombination losses?
2) .. against molecular formation with gas impurities?

Outlook

1. Experimental and numerical characterization of efficiency of ion survival

More tests:

- cooling gas cell to cryogenic temperatures
- evacuation time measurements

More numerical calculations in CFD Module

- include other losses factors, e.g. ion losses due to recombination?
- evacuation time calculations

Plan:

A. Stopping and transport of nuclear reaction products in subsonic helium flow

1. Multinucleon-transfer (MNT) reactions within Elemental Nucleosynthesis studies at University of Jyväskylä
2. Experimental and numerical characterization of efficiency of ion survival in subsonic helium flow
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B. Characterization of supersonic argon jets for in-gas-jet laser ionization spectroscopy

1. In-gas laser ionization spectroscopy in heavy element region
2. PLIF-spectroscopy experiments at KU Leuven
3. Results

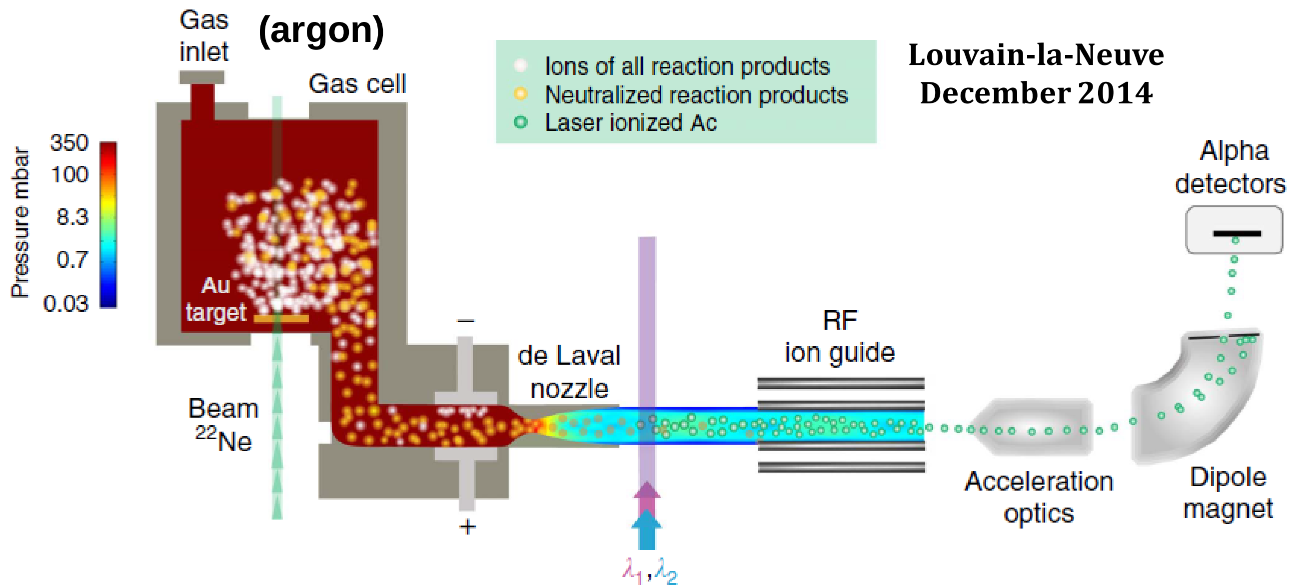
- Validation of PLIF-spectroscopy
- Characterization of gas jets formed by de Laval nozzle

4. Conclusions

KU LEUVEN

Previous experiments

In-gas laser ionization and spectroscopy (IGLIS) @ LISOL



Challenges:

- Low production rates (< 0.1 p.p.s.) and short live-times (< 1 s) → sensitive, efficient and fast technique is needed

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- High spectral resolution to unmask nuclear structure

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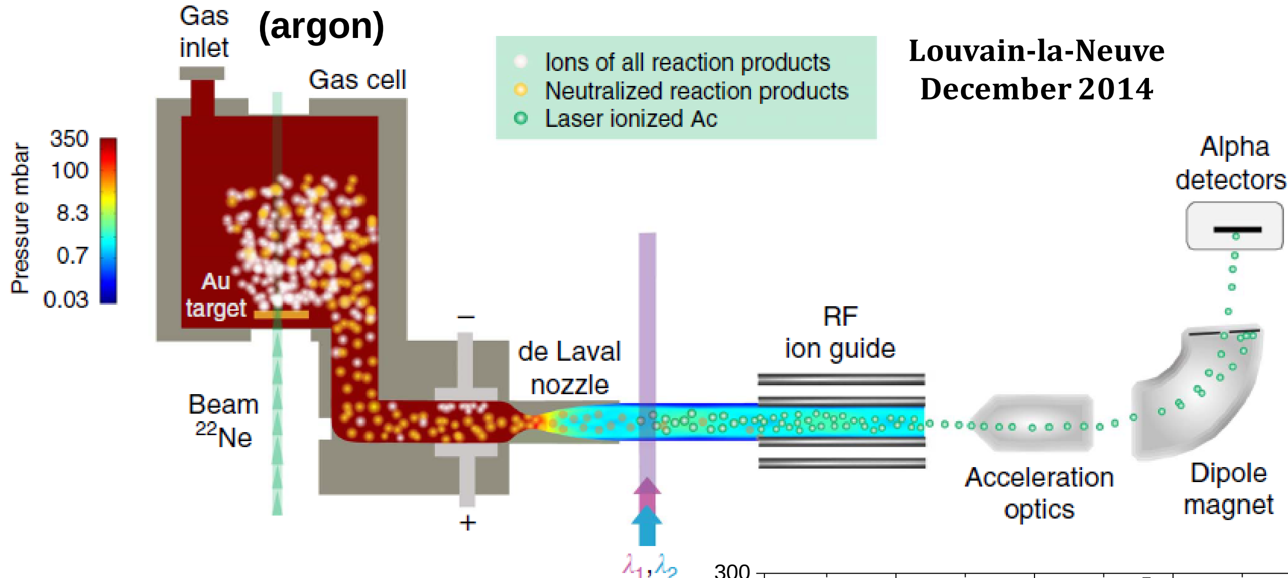
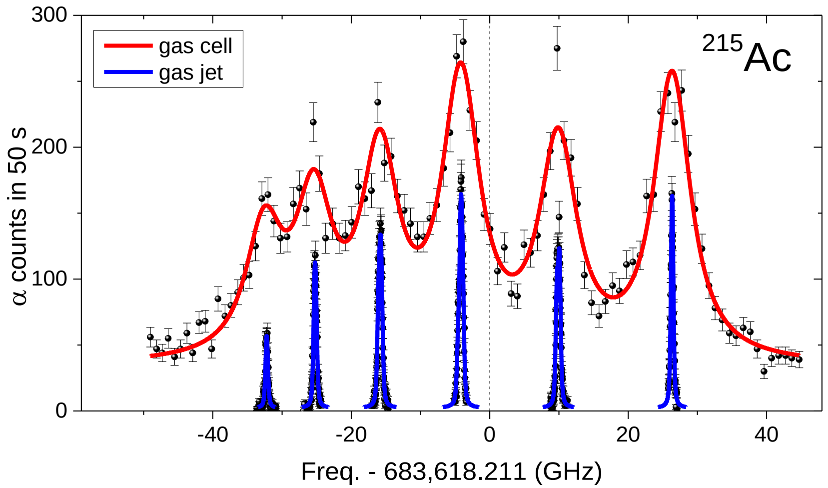
Louvain-la-Neuve
December 2014





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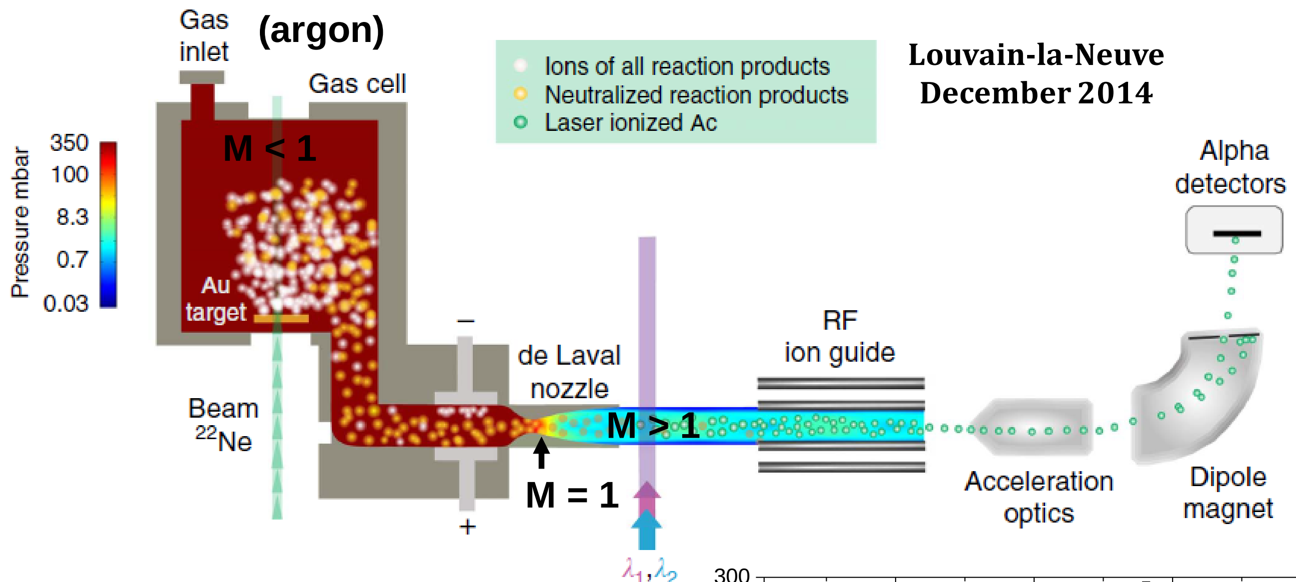

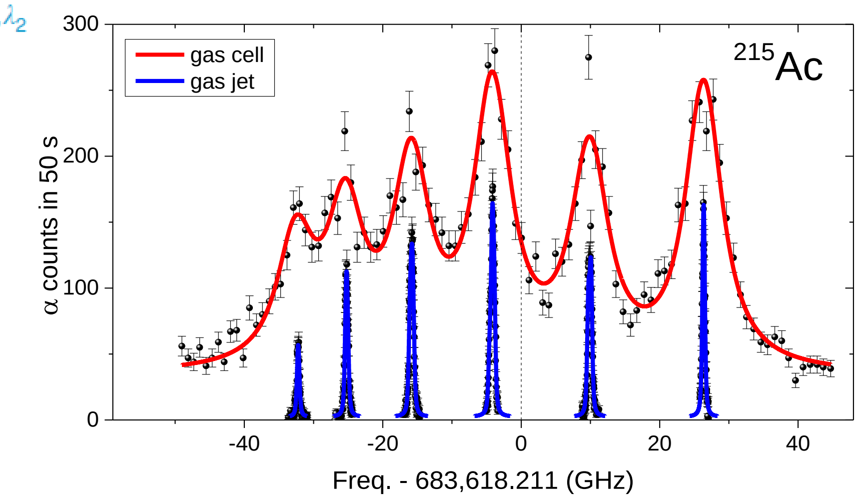

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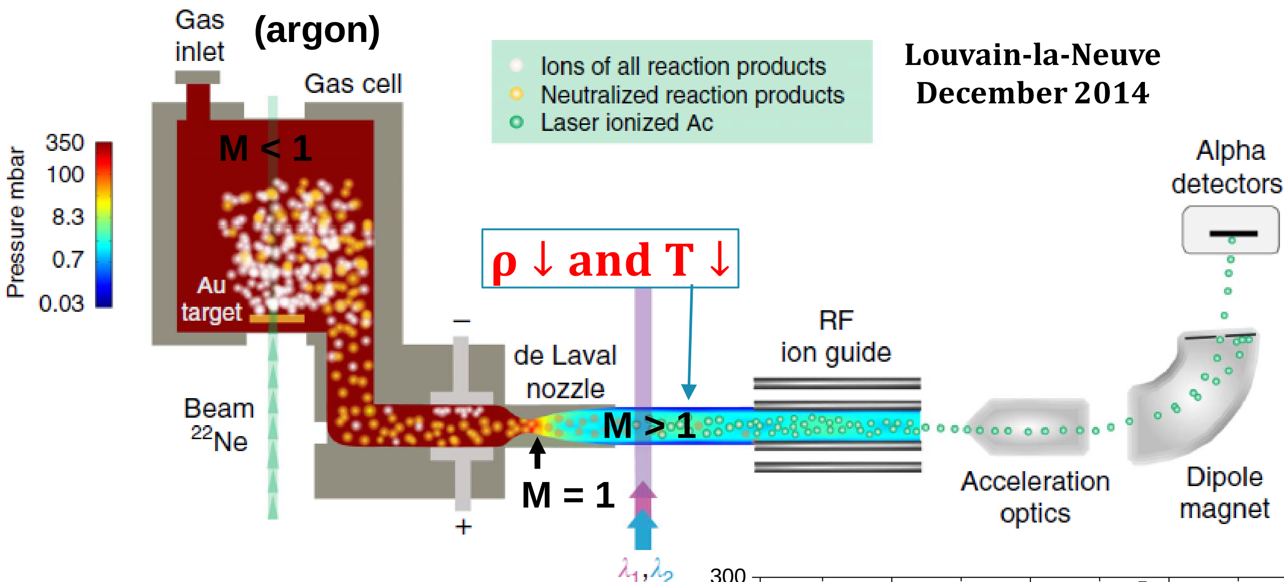

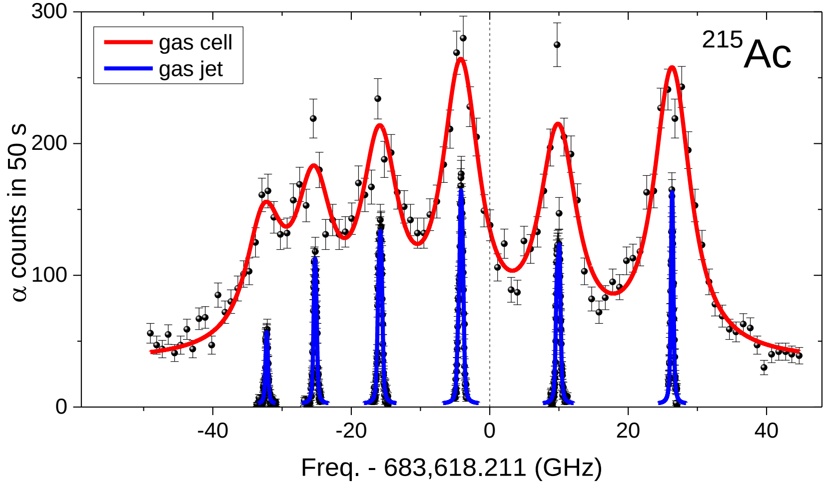

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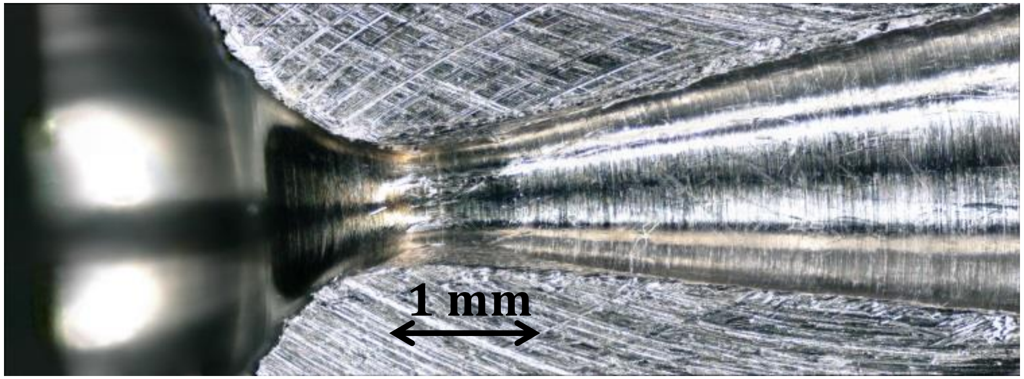
Supersonic jets formed by de Laval nozzles



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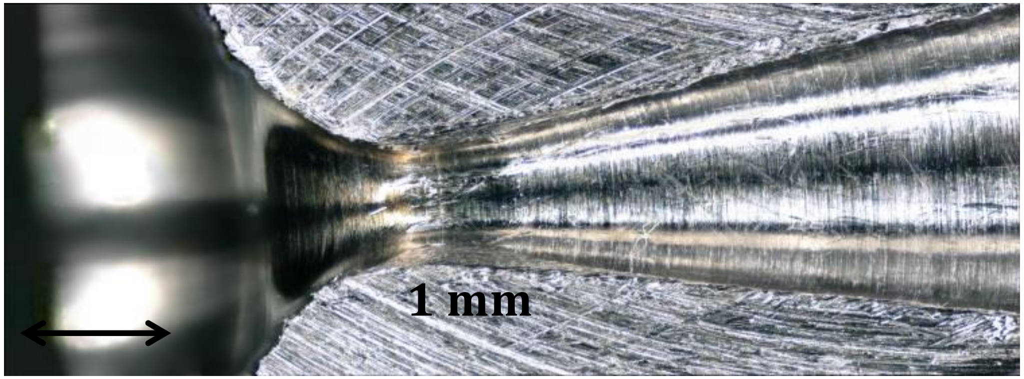
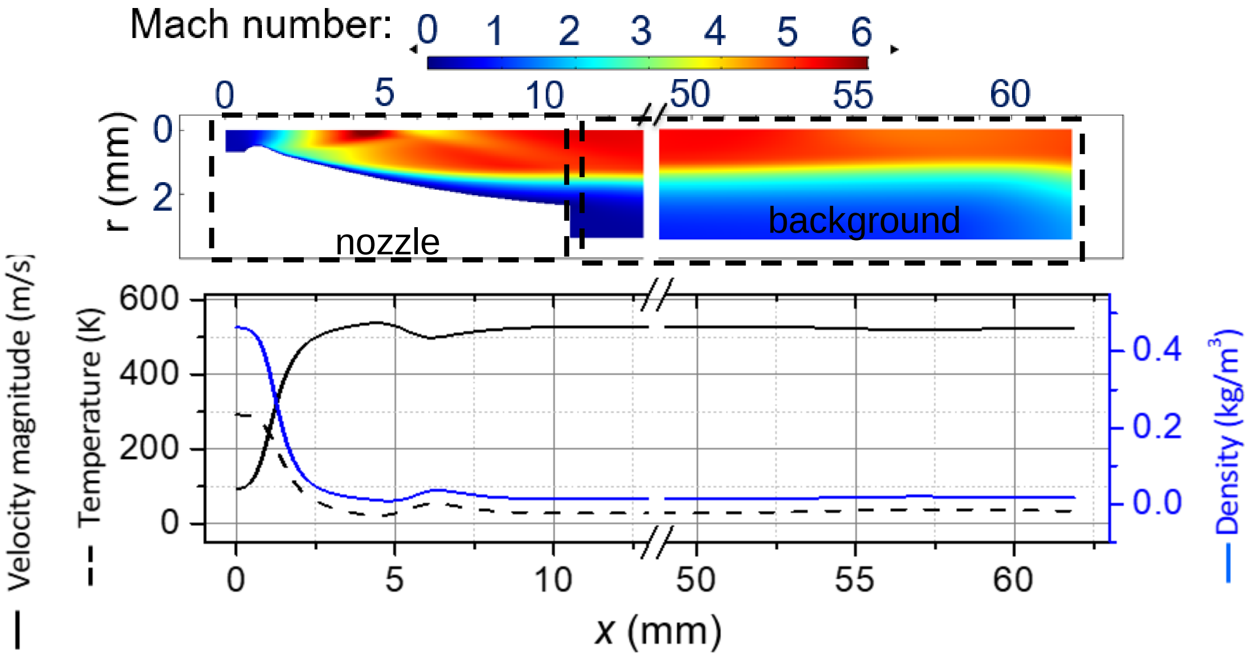


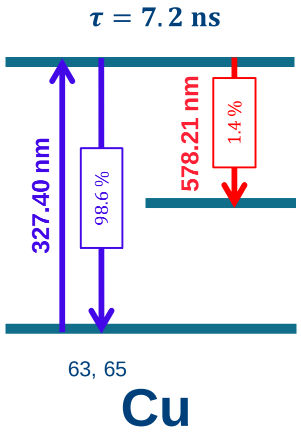


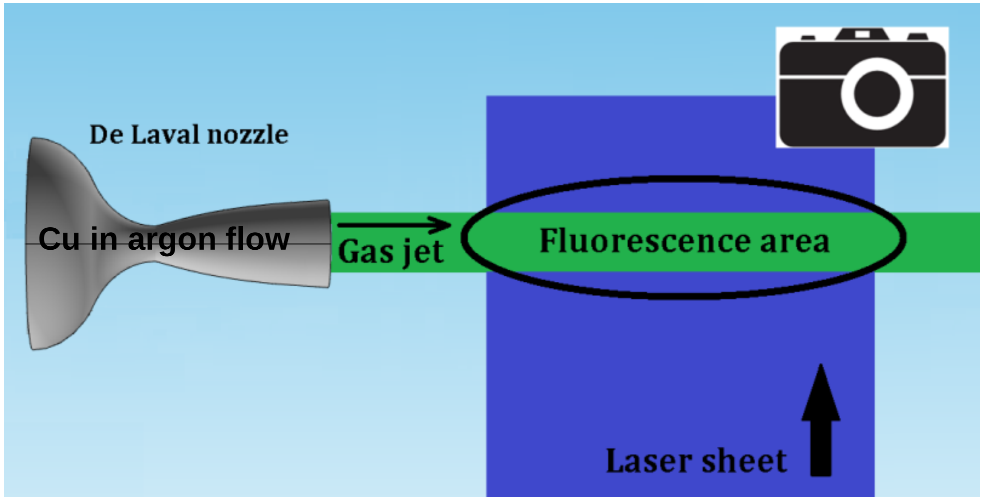
CFD Module

High Mach Number Flow:
turbulence model type – none;
boundary conditions – no slip;
flow conditions for the outflow – supersonic.

Argon
Temperature $T_0 = 300$ K
Pressure $P_0 = 300$ mbar
Nozzle throat diameter of 1 mm

Planar Laser Induced Fluorescence (PLIF)-technique





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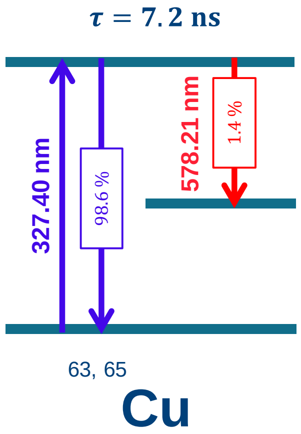

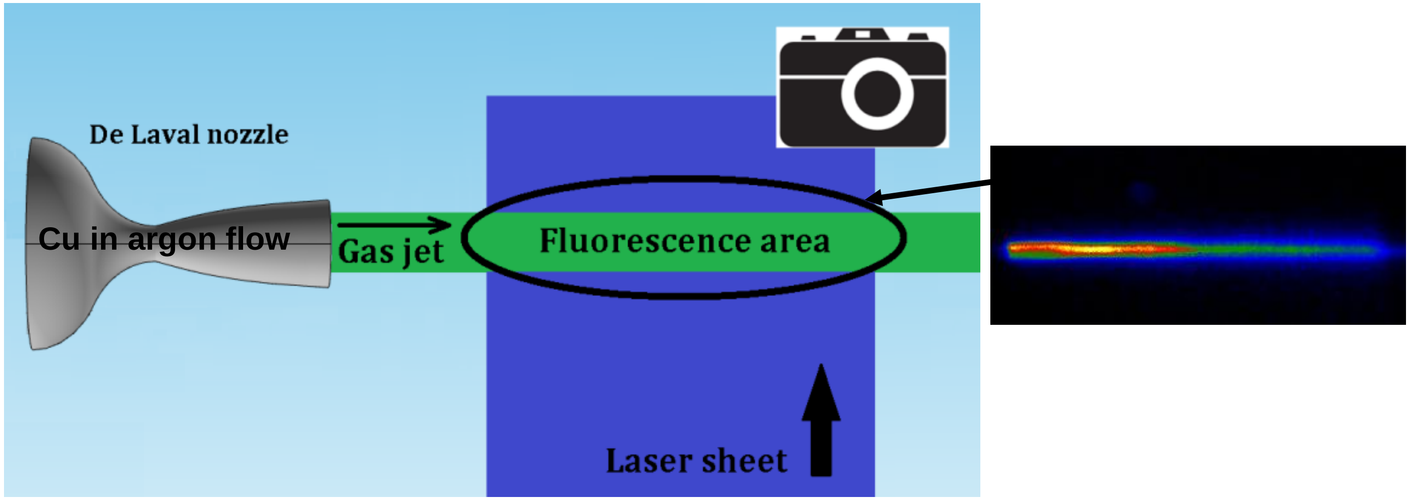

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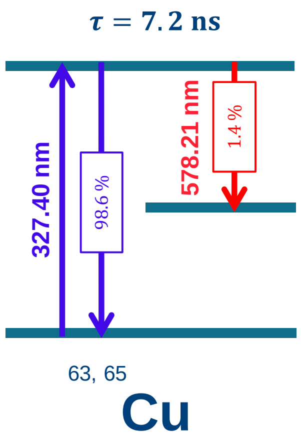

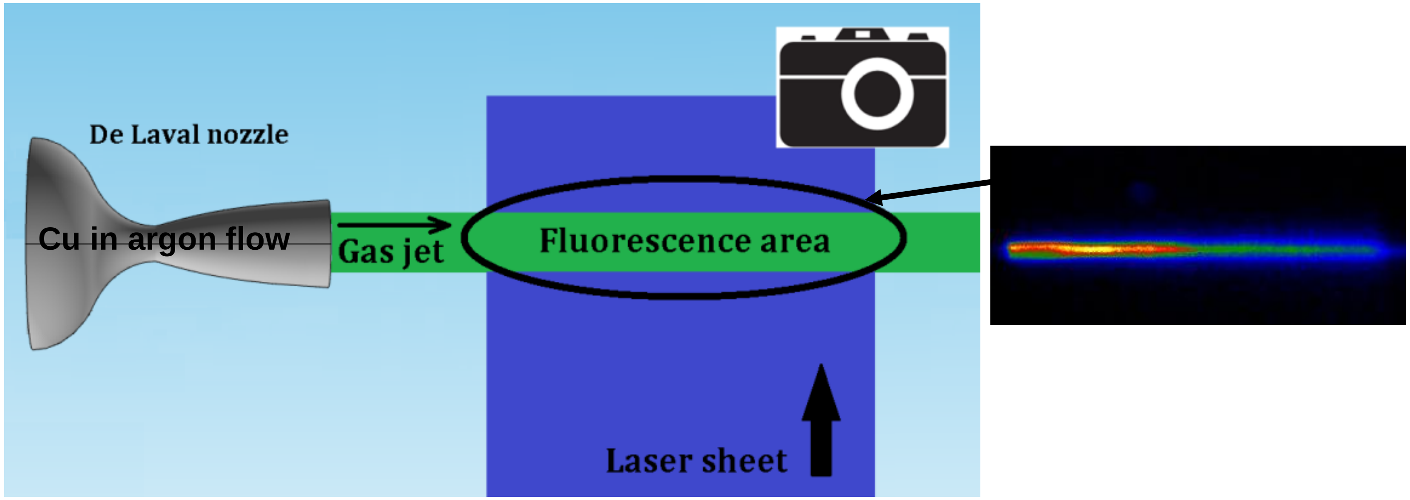

→ relative density from measurements with broadband laser

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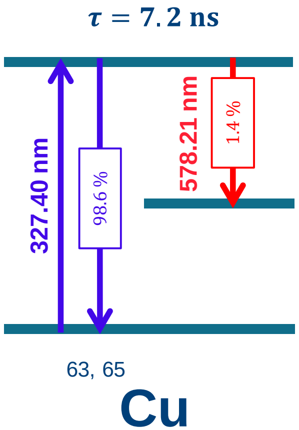

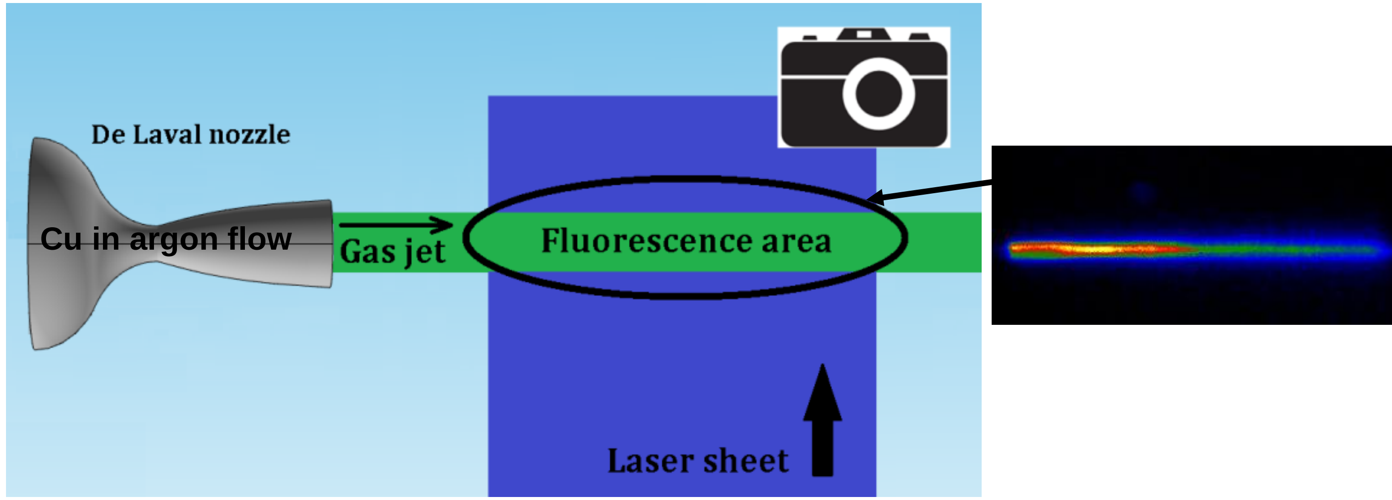

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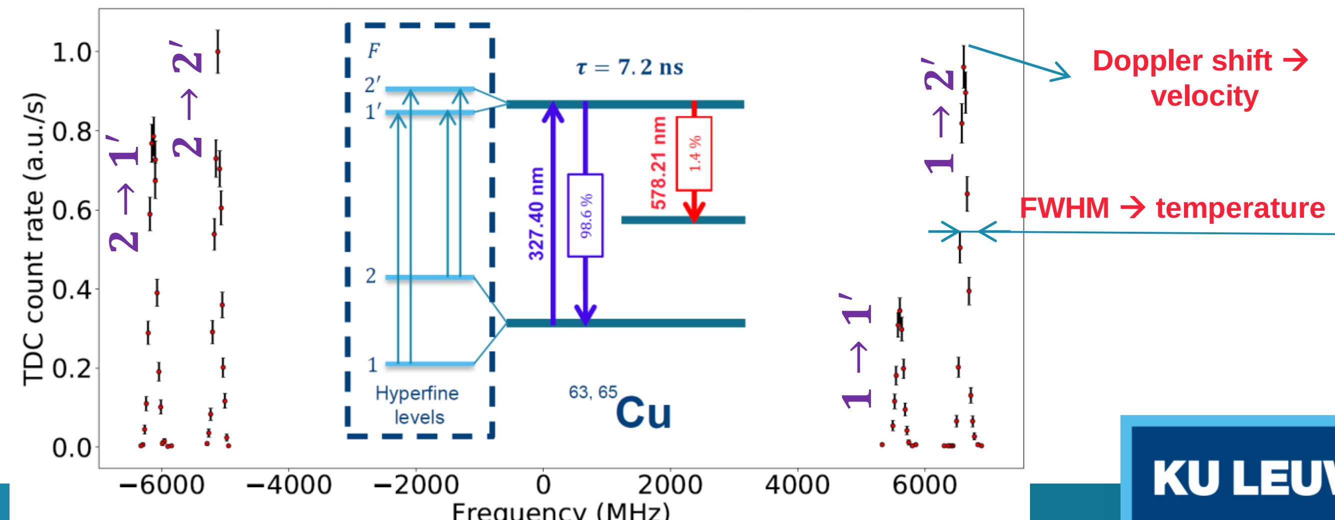
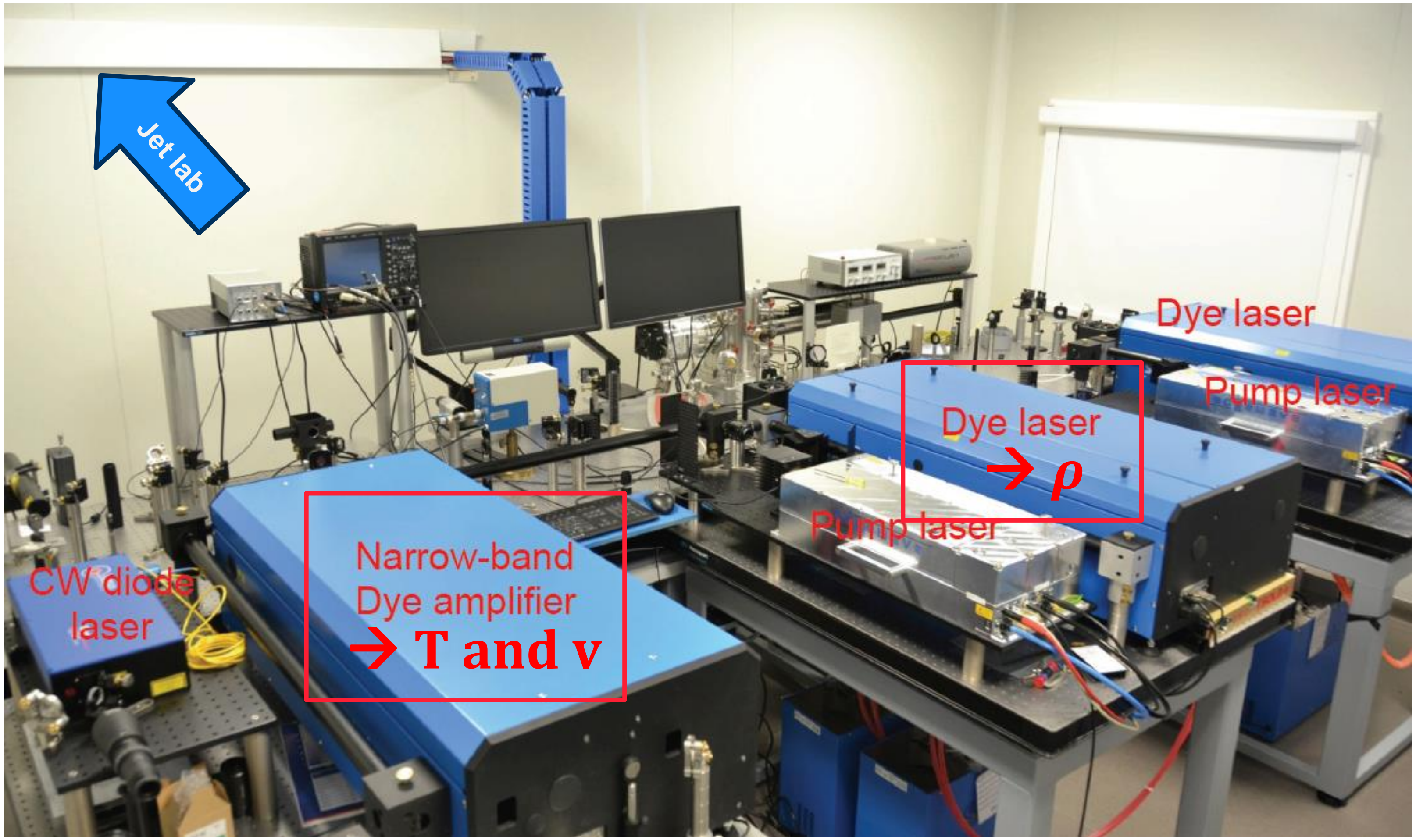
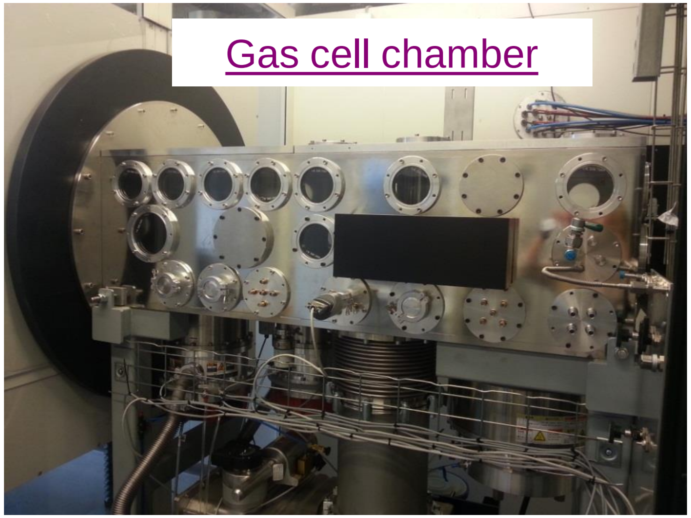
PLIF-spectroscopy

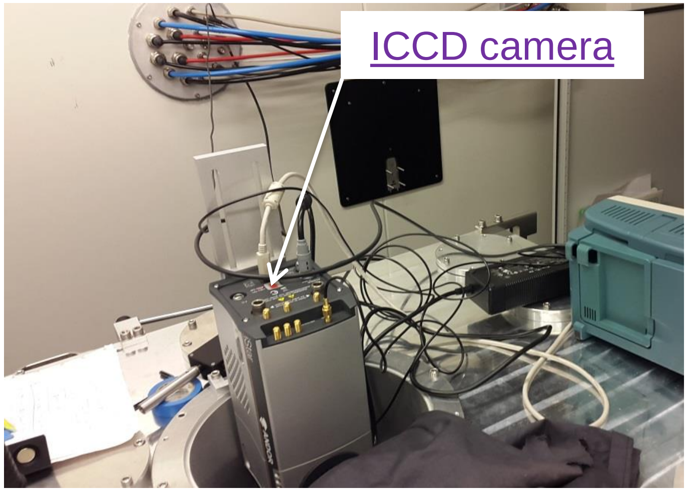


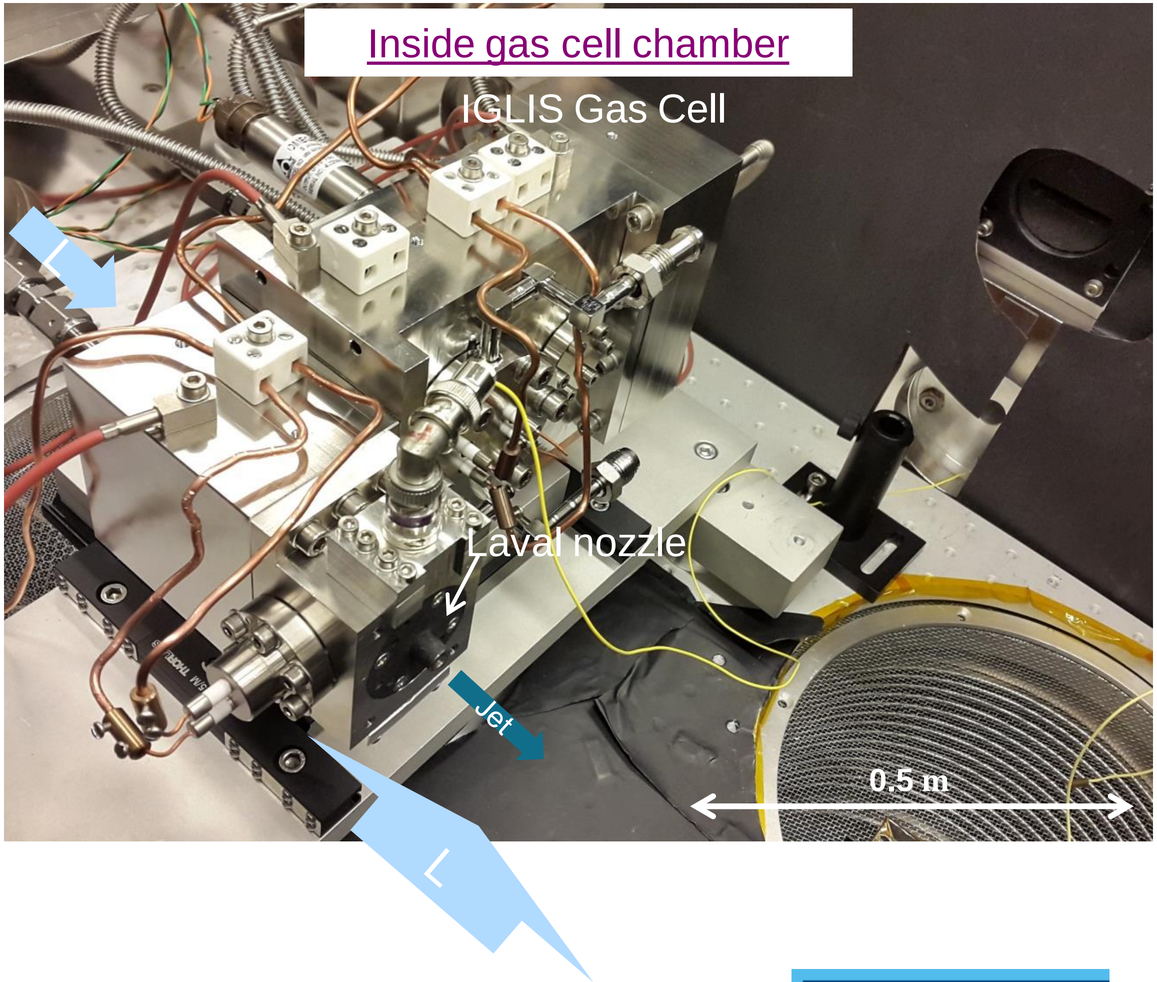
Laser laboratory



Jet laboratory

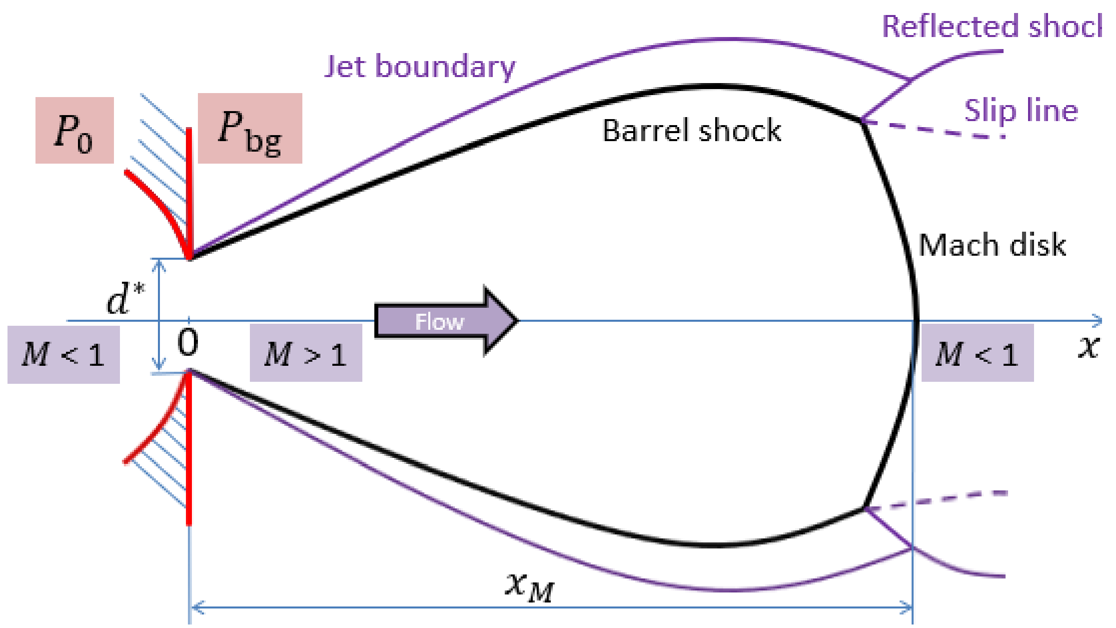






Validation of PLIF-spectroscopy

Mach disk position and density drop in the expansion zone



S. Crist , M. Sherman and D.R. Glass, AIAA Journal Vol. 4, No. 1, 68 - 71 (1966)
H. Ashkenas, M. Sherman, Rarefied Gas Dynamics, Academic. Press, 1965, p. 94
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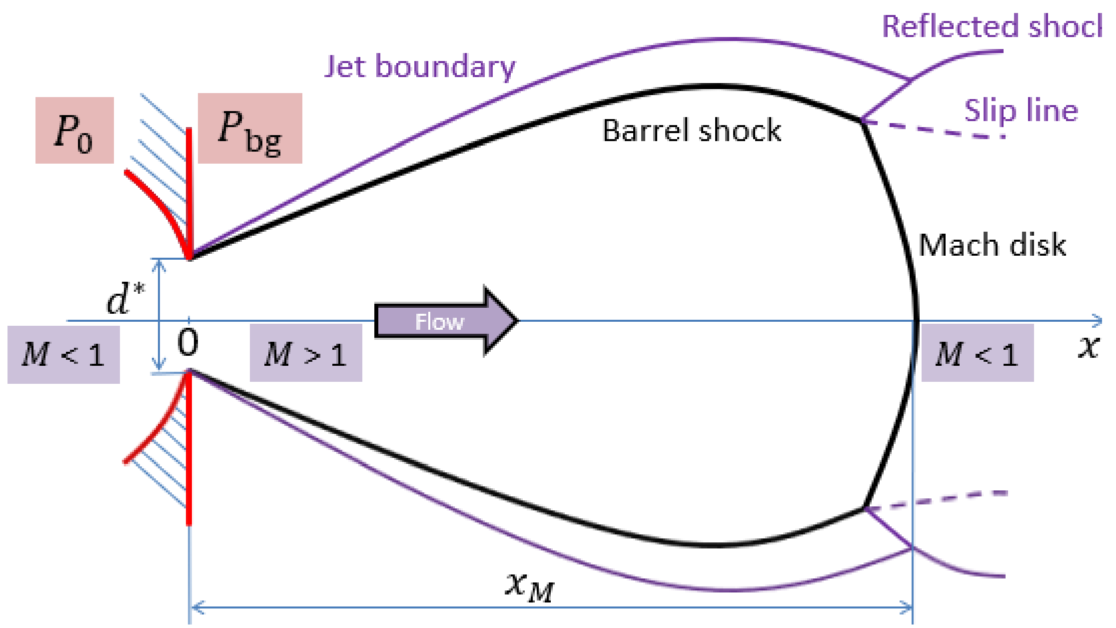

$$1.\ \rho \propto \frac{1}{x^2}$$

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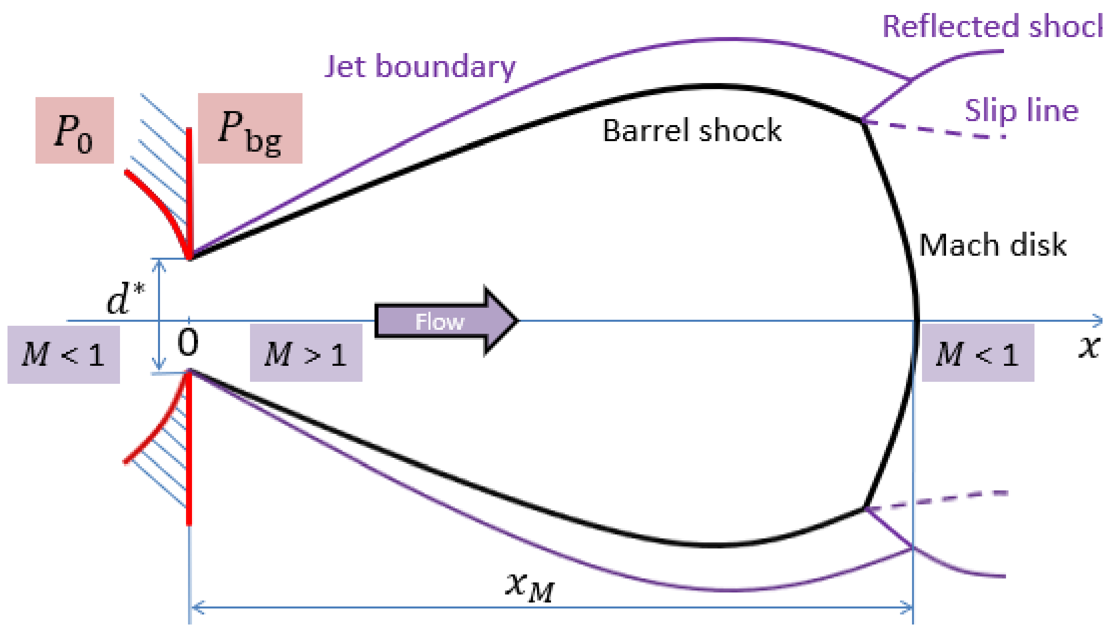

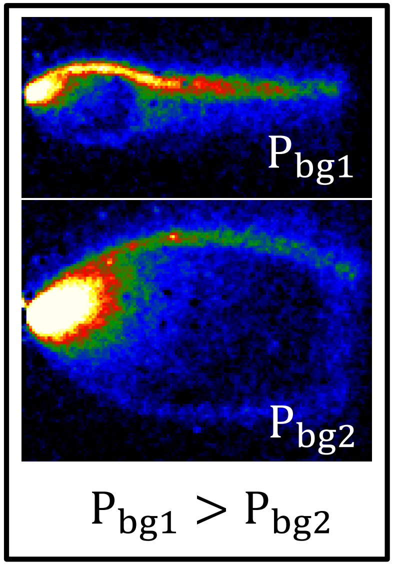

1. $\rho \propto \frac{1}{x^2}$

2. $\frac{x_M}{d^*} = 0.67 * \sqrt{\frac{P_0}{P_{bg}}}$

S. Crist , M. Sherman and D.R. Glass, AIAA Journal Vol. 4, No. 1, 68 - 71 (1966)
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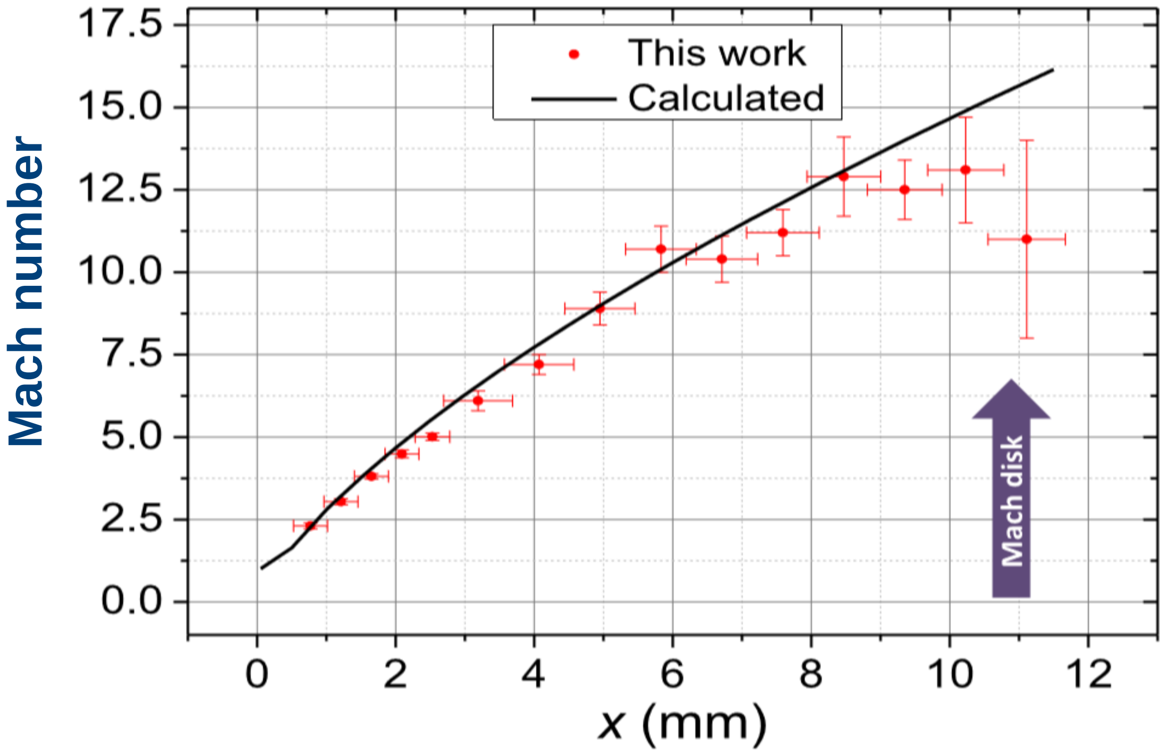
KU LEUVEN

Validation of PLIF-spectroscopy

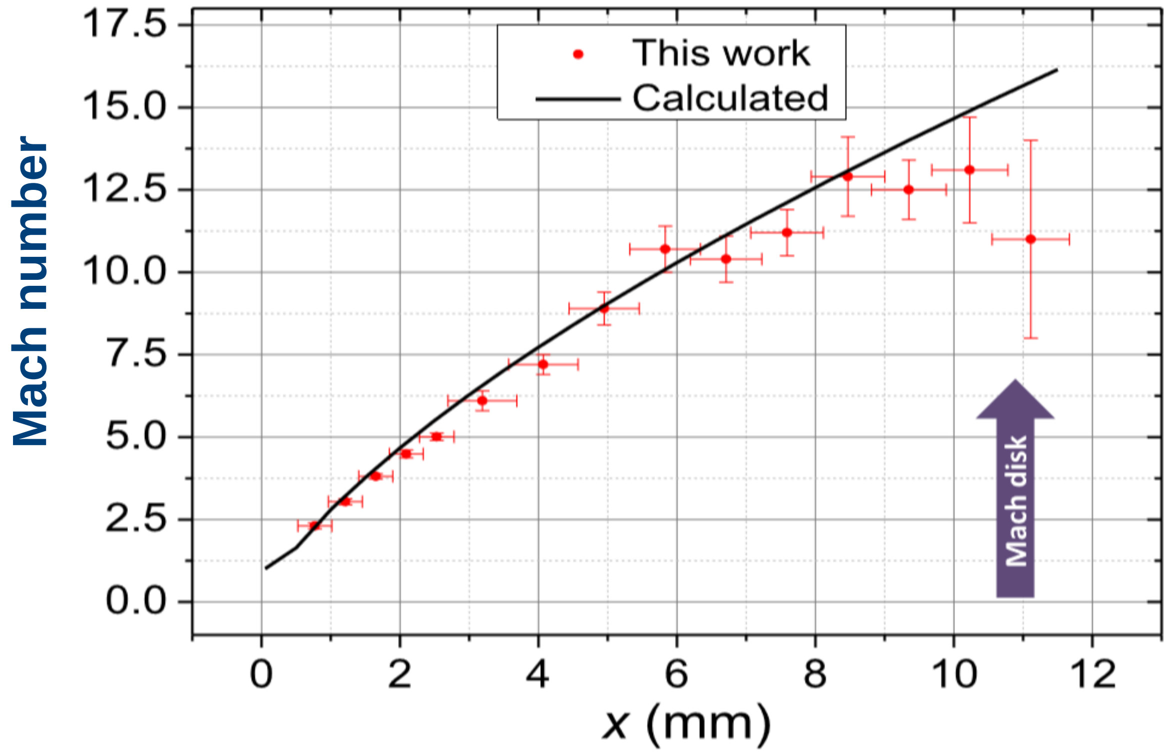
Narrowband PLIF-spectroscopy of $^{63,65}Cu$



$$M = \frac{\text{flow velocity}}{\text{velocity of sound}(\leftarrow temperature)}$$

Validation of PLIF-spectroscopy

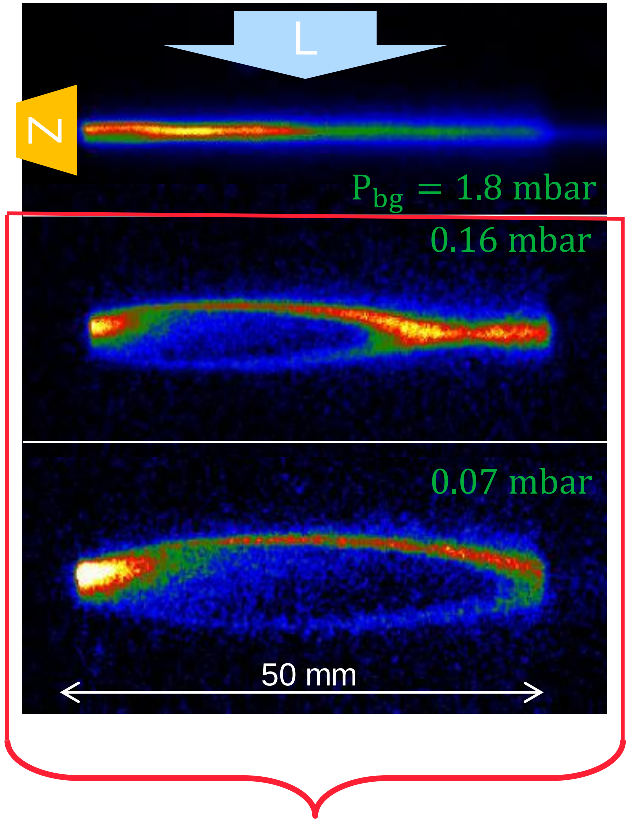
Narrowband PLIF-spectroscopy of $^{63,65}Cu$



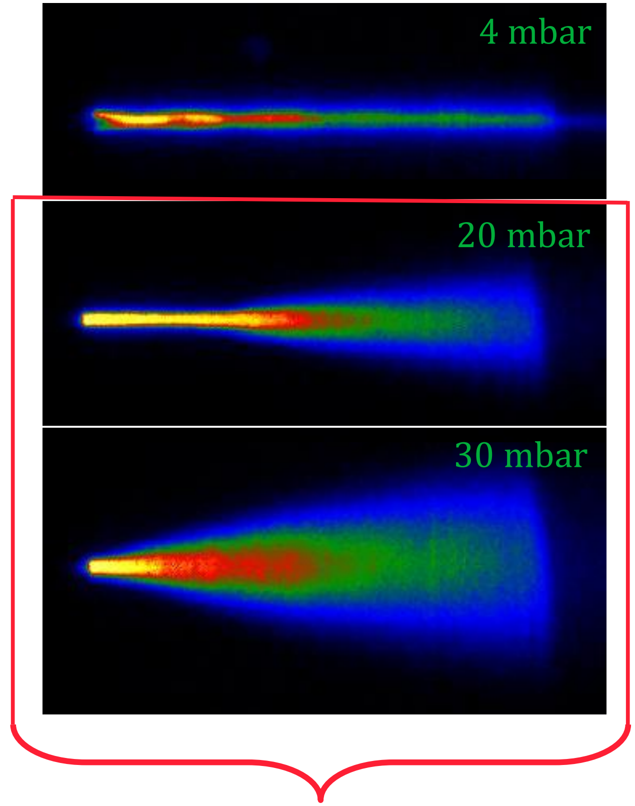
$$M = \frac{\text{flow velocity}}{\text{velocity of sound}(\leftarrow \textit{temperature})}$$

→ good agreement between this work and previous experiments and analytical solutions

Jets formed by de Laval nozzle

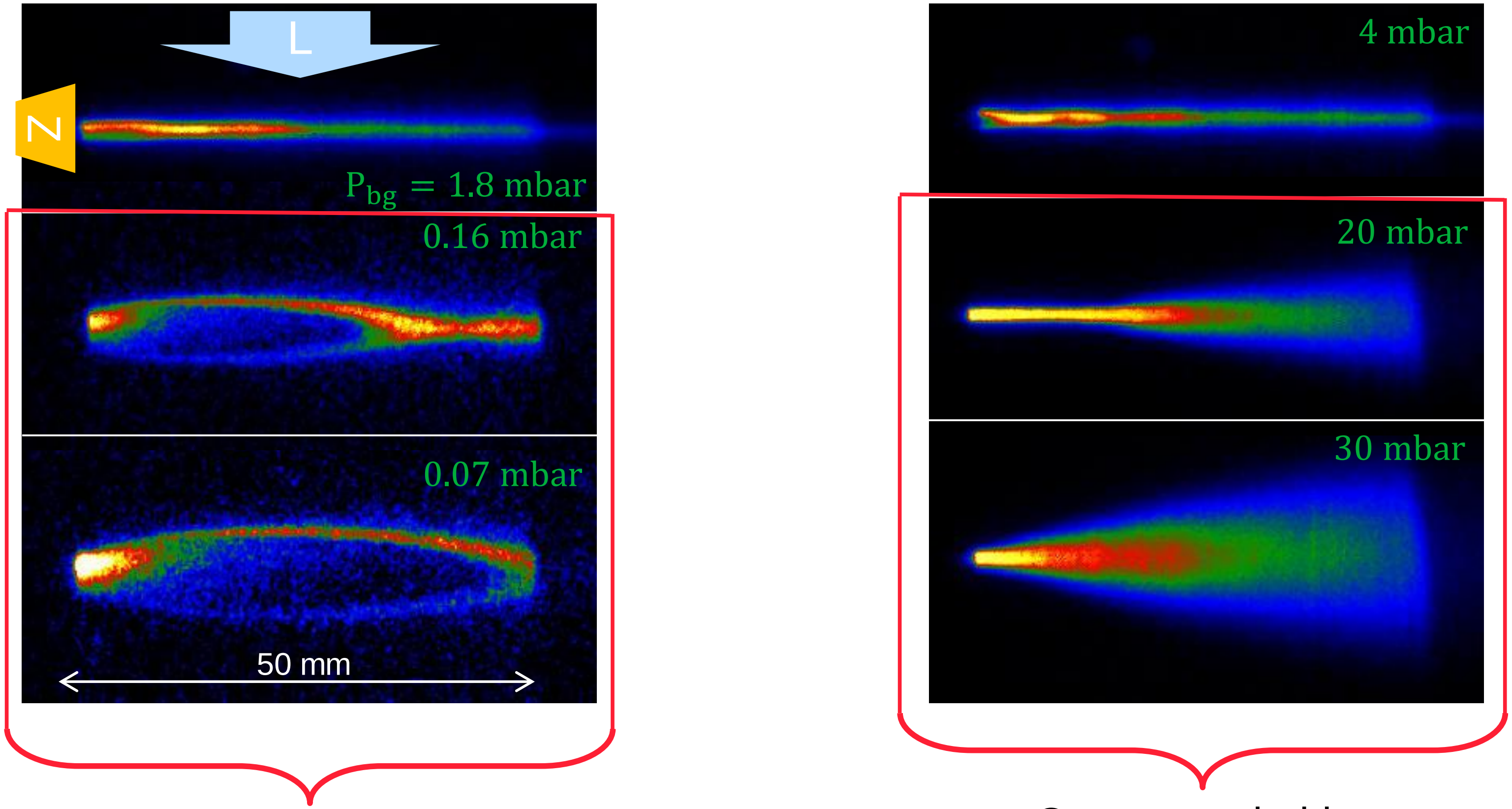


Underexpanded jet



Overexpanded jet

Jets formed by de Laval nozzle



Underexpanded jet

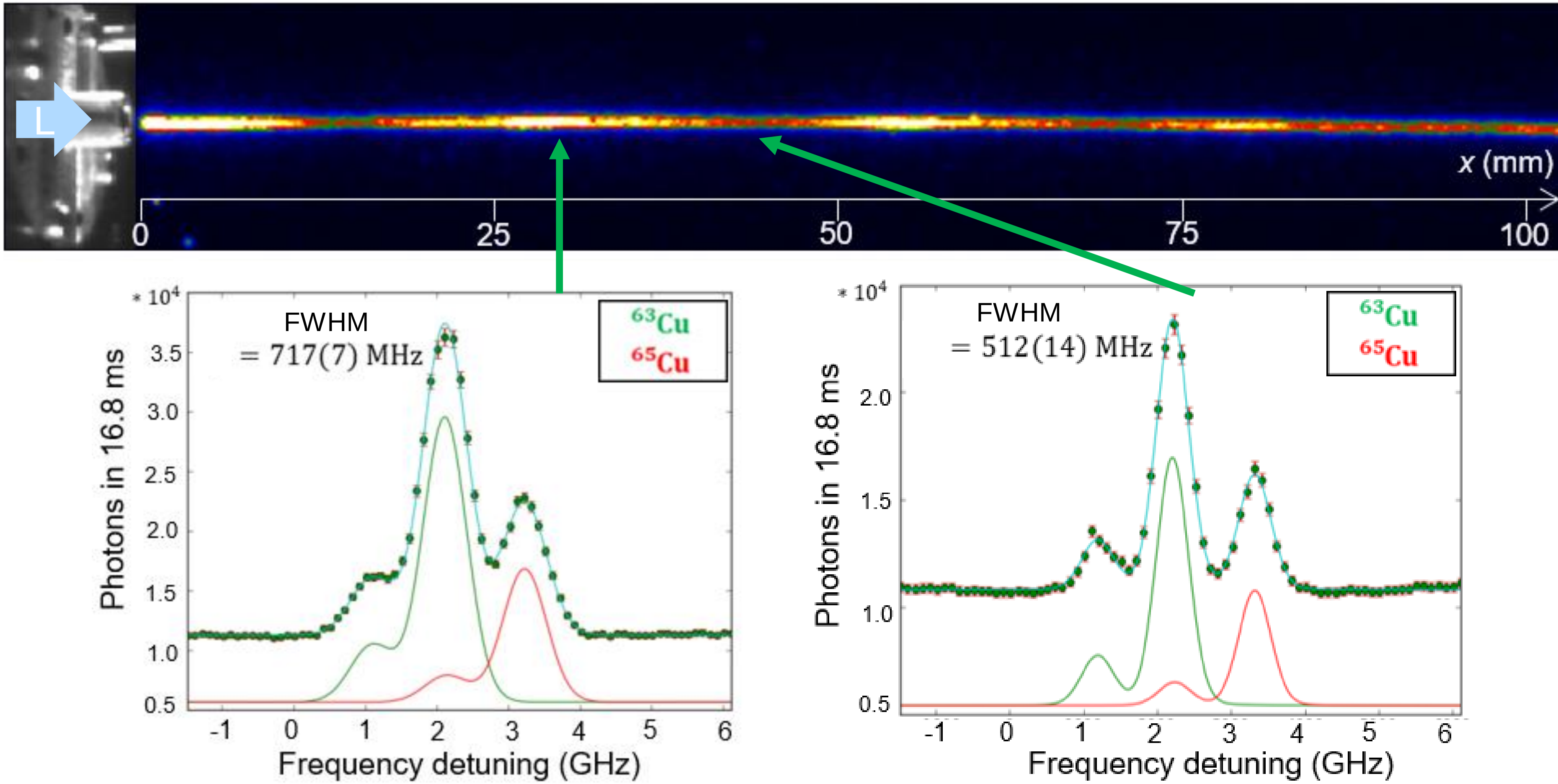
Overexpanded jet

- At extreme cases of pressure mismatch, formation of long jets required for high-efficient in-jet ionization is not possible
- Diameter of non-uniform jet will vary along its length → higher requirements on laser energy

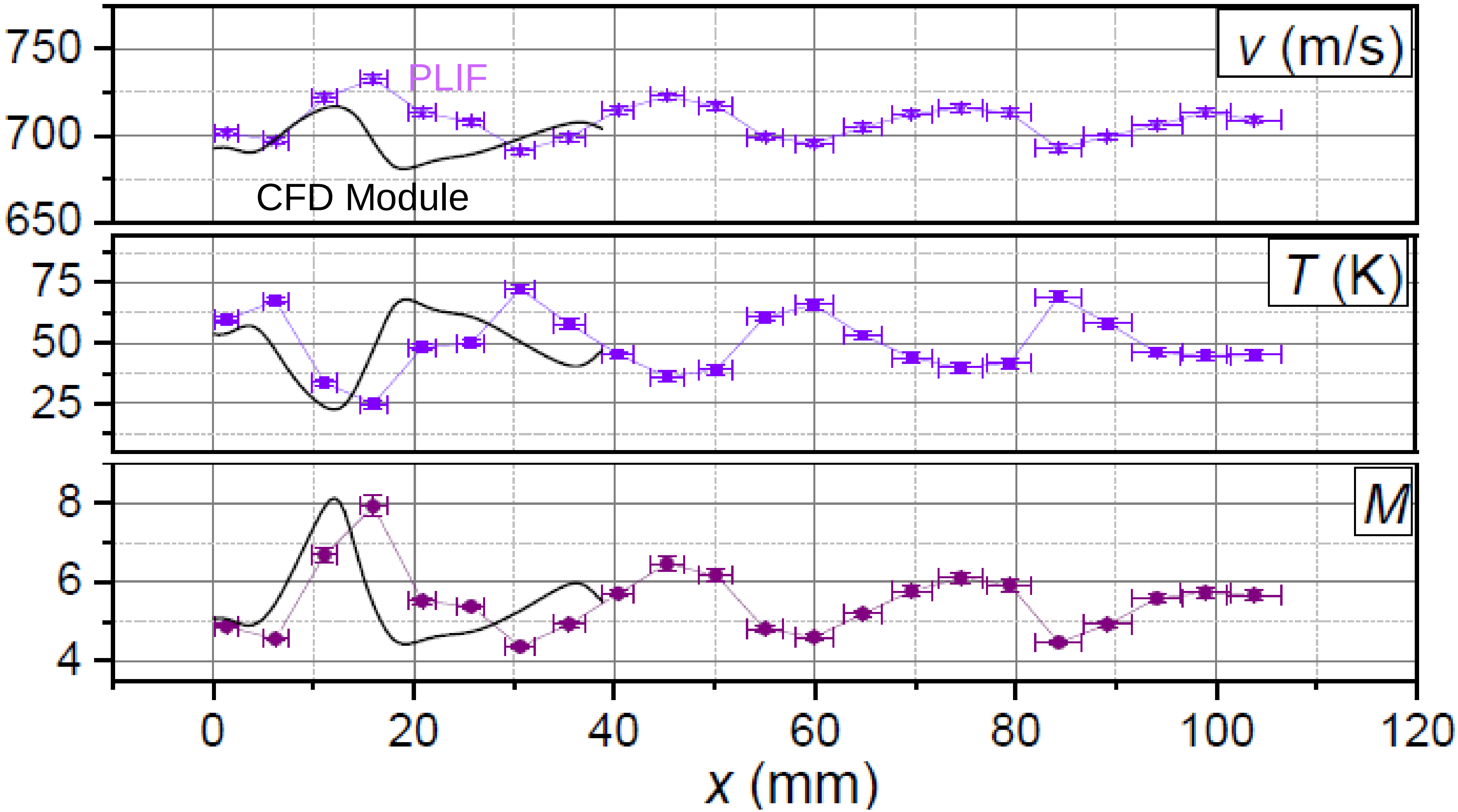
Jets formed by de Laval nozzle

Narrowband PLIF-spectroscopy of $^{63,65}Cu$

Central line of underexpanded jet ($P_{bg} < P_{opt}$)



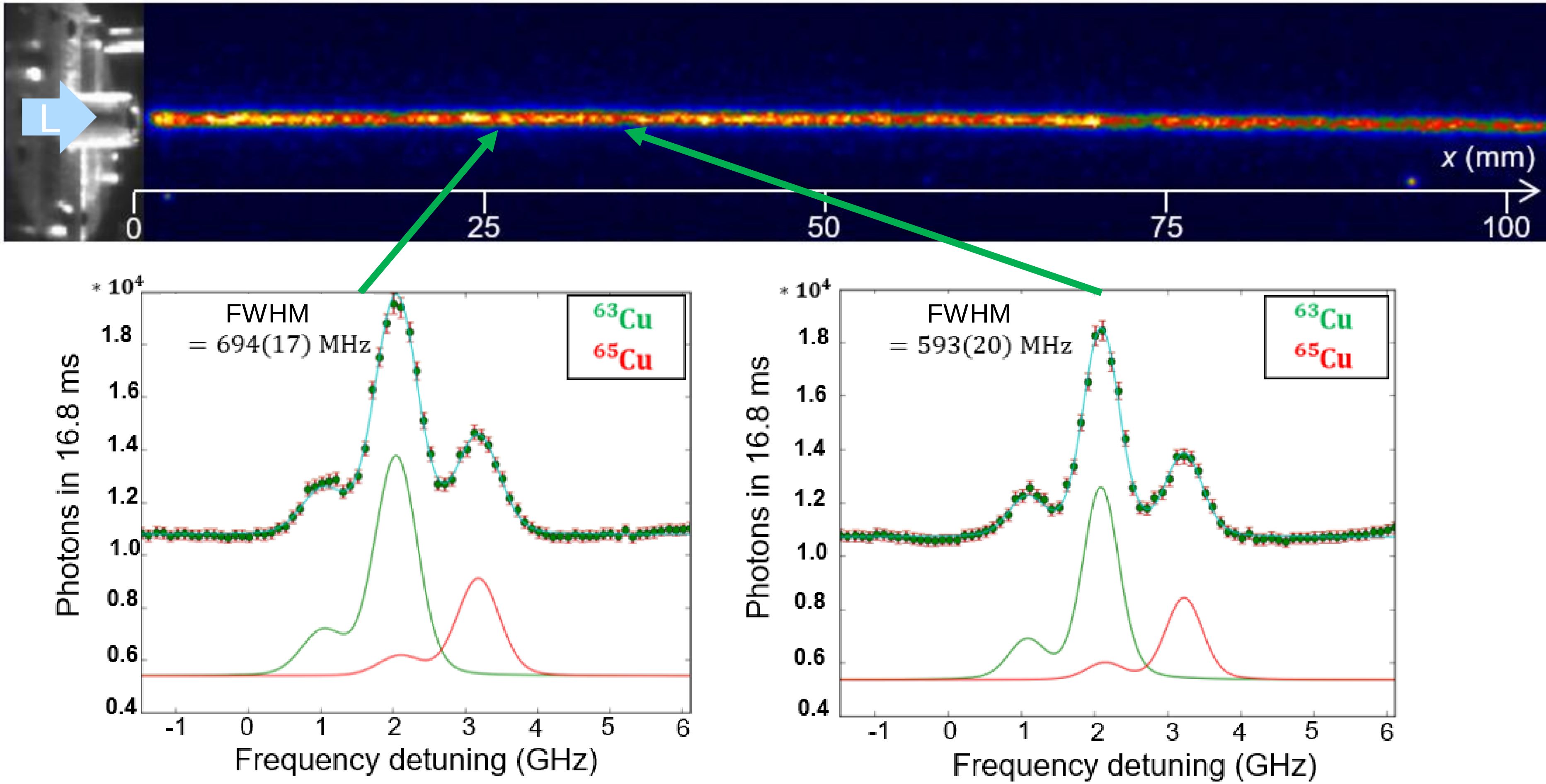
Underexpanded jet



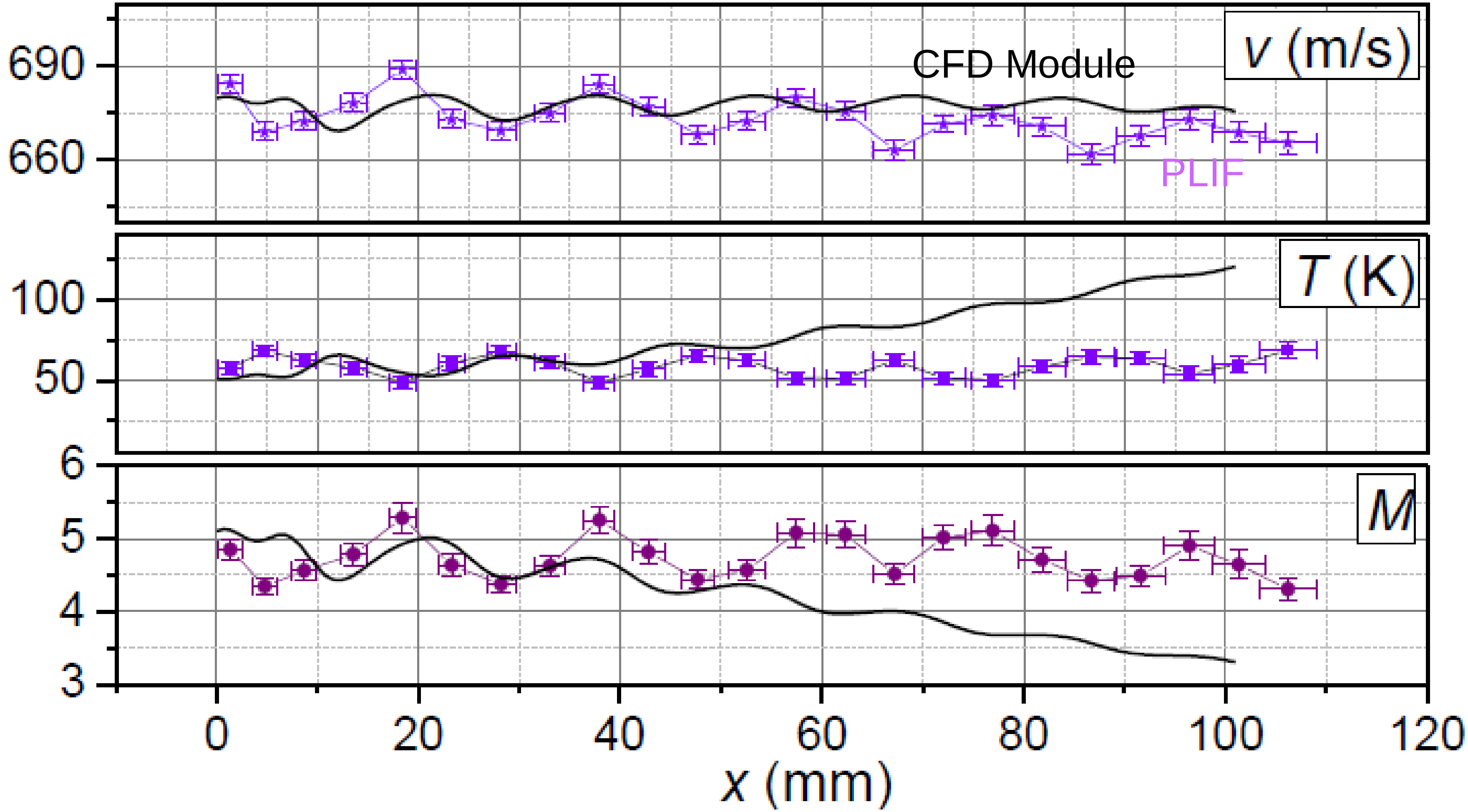
Jets formed by de Laval nozzle

Narrowband PLIF-spectroscopy of ^{63,65}Cu

Central line of quasiuniform jet ($P_{bg} \approx P_{opt}$)



Quasiuniform jet



Conclusions

- ✓ Supersonic gas jets were characterized using PLIF-spectroscopy setup constructed at KU Leuven
- ✓ Partial agreement was reached between experimental results and numerical calculations in CFD Module for jet's flow parameters

PHYSICAL REVIEW X **8**, 041008 (2018)

Characterization of Supersonic Gas Jets for High-Resolution Laser Ionization Spectroscopy of Heavy Elements

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P. Creemers, R. Ferrer, L. Gaffney, C. Granados, M. Huyse, S. Kraemer, Yu. Kudryavtsev, M. Laatiaoui, V. Manea, E. Mogilevskiy, S. Raeder, J. Romans, S. Sels, P. Van den Bergh, P. Van Duppen, M. Verlinde, E. Verstraelen

European Research Council
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O. Beliuskina, M. Brunet, L. Canete, P. Constantin, T. Dickel, T. Eronen, R. de Groote, M. Hukkanen, A. Jokinen, A. Kankainen, A. Karpov, I. Mardor, I. Moore, D. Nesterenko, D. Nichita, H. Penttilä, Zs. Podolyak, I. Pohjalainen, S. Purushothaman, M. Reponen, A. de Roubin, V. Saiko, A. Spataru, M. Vilen, A. Weaver

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

European Research Council
Established by the European Commission

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Thanks for your attention!