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Characterization of supersonic jets for in-gas-jet laser ionization spectroscopy at the IGLIS laboratory + MNT reactions and efficiency characterization with gas cells at the IGISOL-4 facility

Sasha (Alexandra) Zadvornaya

18 July 2019

Characterization of supersonic jets for in-gas-jet laser ionization spectroscopy at the IGLIS laboratory
+
MNT reactions and efficiency characterization with gas cells at the IGISOL-4 facility

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Plan:

1. Laser spectroscopy studies
- Goals and challenges
- Previous experiments and what can be improved

2. Brief theory of supersonic gas flows
3. PLIF-spectroscopy experiments @ IGLIS laboratory
4. Results
- Validation of PLIF-spectroscopy
- Characterization of gas jets formed by de Laval nozzle
- *Latest developments*

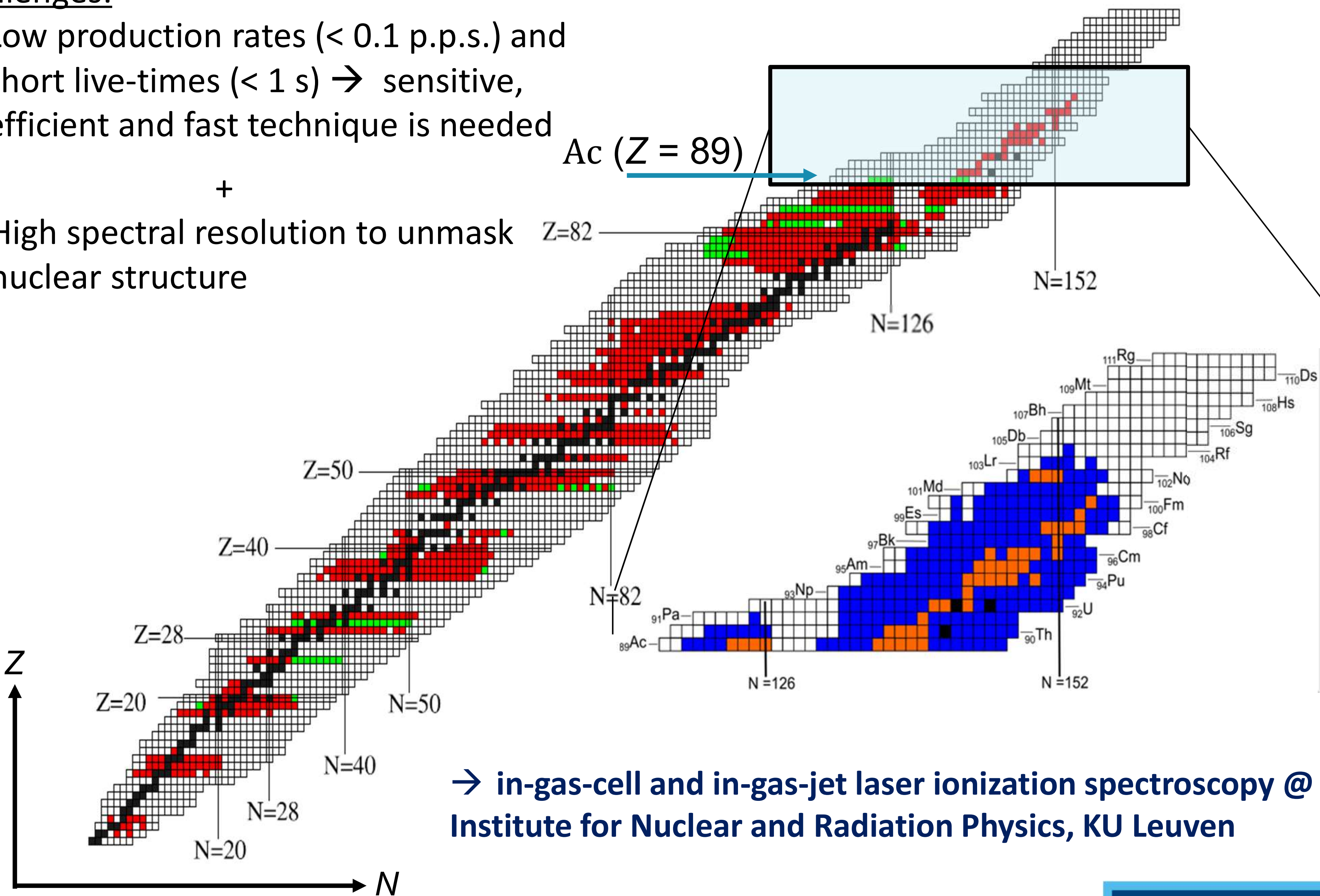
5. Conclusions and Outlook

Challenges:

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

+

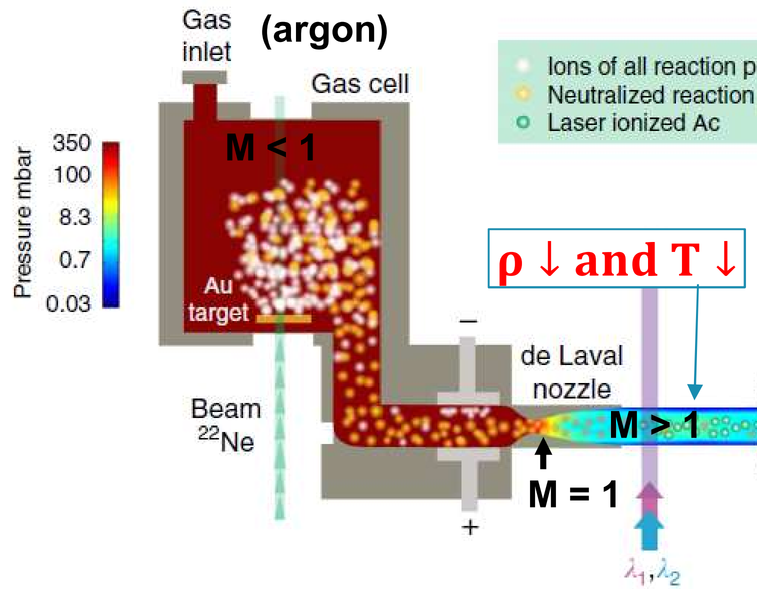
- High spectral resolution to unmask nuclear structure



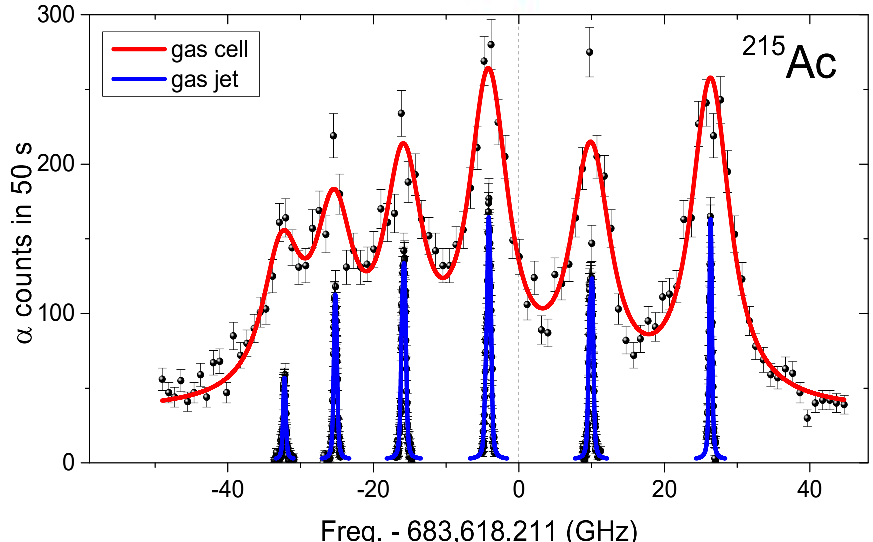
→ in-gas-cell and in-gas-jet laser ionization spectroscopy @ Institute for Nuclear and Radiation Physics, KU Leuven

Previous experiments

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



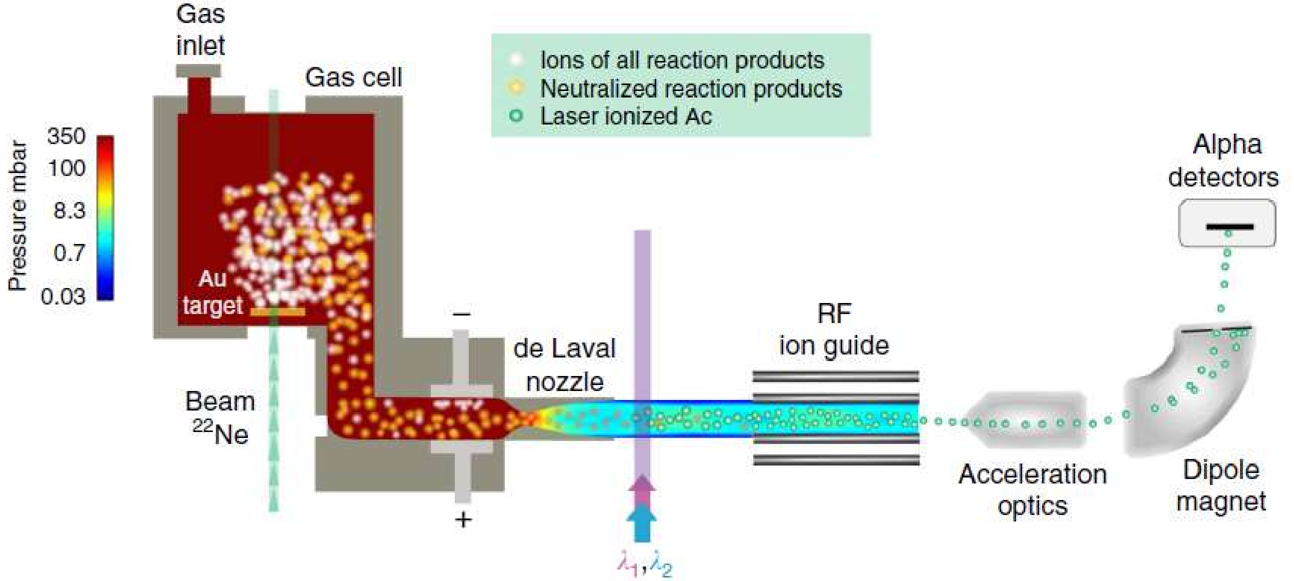
Louvain-la-Neuve
December 2014



$$M \text{ (Mach number)} = \frac{v \text{ (local gas velocity)}}{a \text{ (local velocity of sound)}}$$

Previous experiments

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

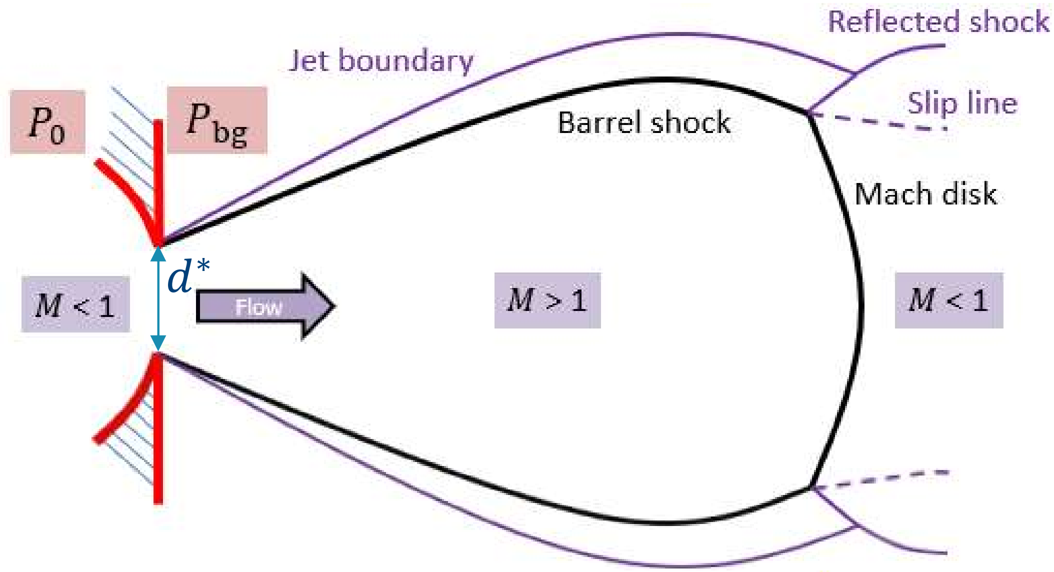


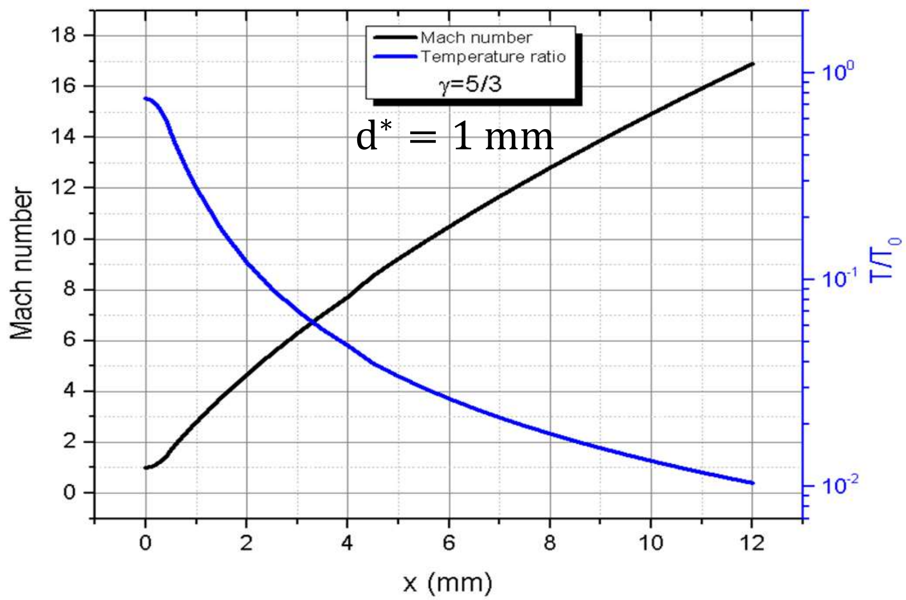
Actual and expected performance of IGLIS on ^{215}Ac.

	Gas cell	Gas jet (this work)*	Gas jet (projected)†
Ionization volume			
Pressure (mbar)	350 (15)	0.7–1	∼0.05
Temperature (K)	350 (25)	25–30	∼9
Jet divergence (deg.)	—	10–11	<1
Linewidth (FWHM)			
Total (MHz)	5,800 (300)	394 (18)	∼100
Lorentz‡ (MHz)	4,000 (400)	42 (6)	<10
Gauss§ (MHz)	1,400 (100)	280 (30)	∼100
Selectivity‖	8.3 (17)	121 (27)	>3,000
Efficiency¶ (%)	0.42 (13)	0.40 (13)	>10

R. Ferrer *et al.*, Nat. Commun. 8, 14520 (2017)

Supersonic free jets

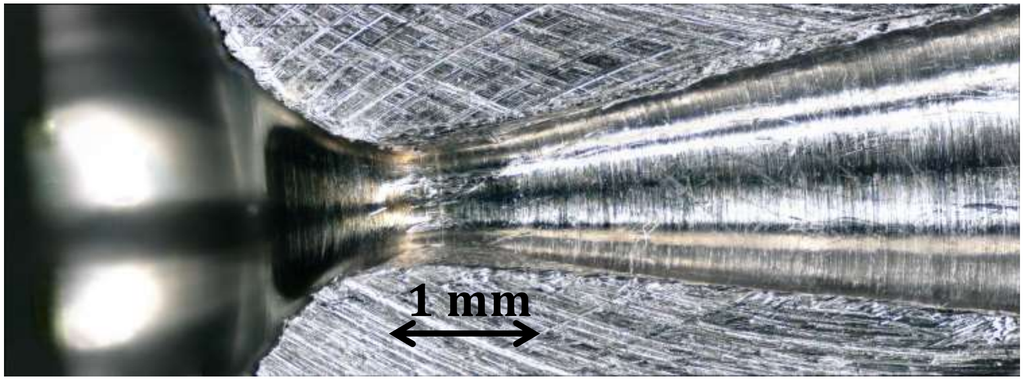


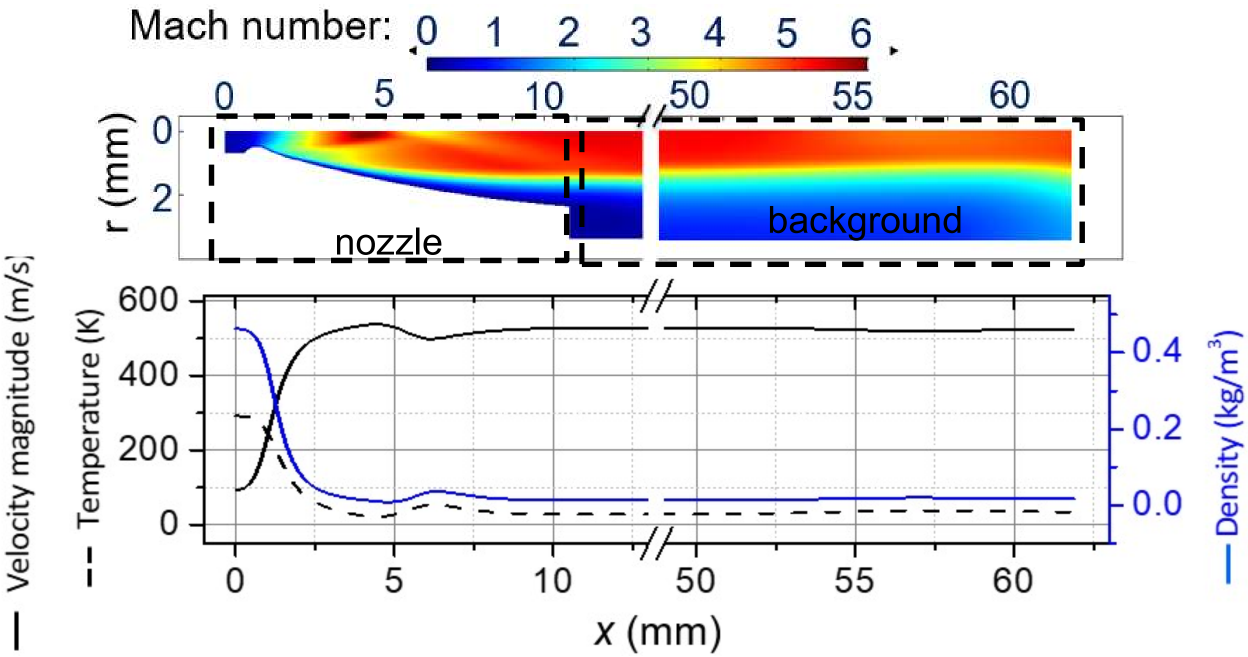


$$T = \frac{T_0}{(1 + \frac{\gamma - 1}{2} M^2)}$$

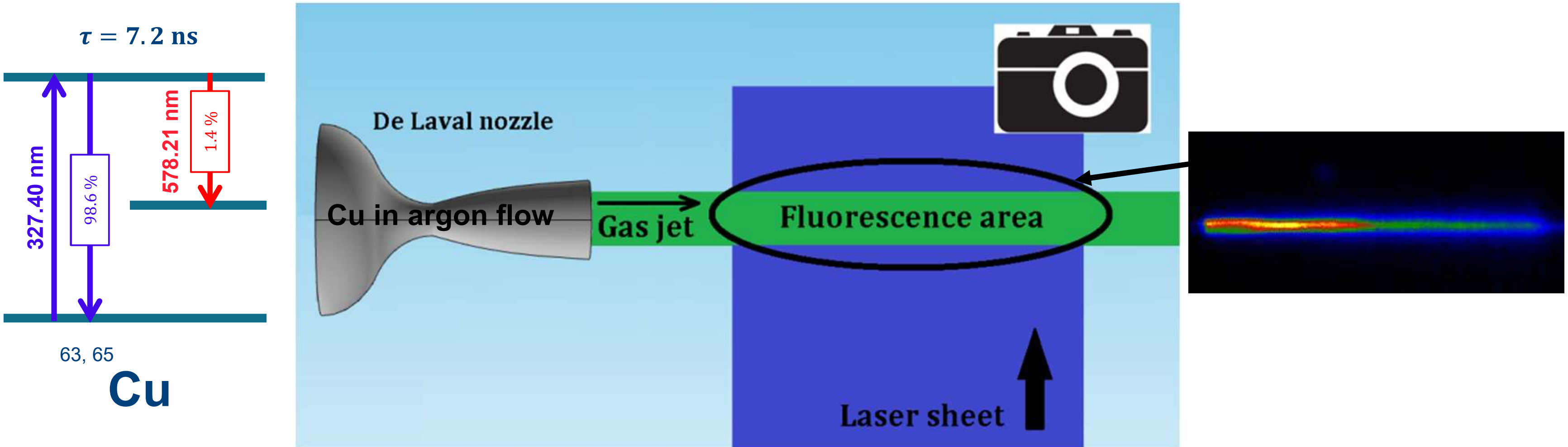
$$\rho = \frac{\rho_0}{(1 + \frac{\gamma - 1}{2} M^2)^{1/(\gamma - 1)}}$$

De Laval nozzle jets



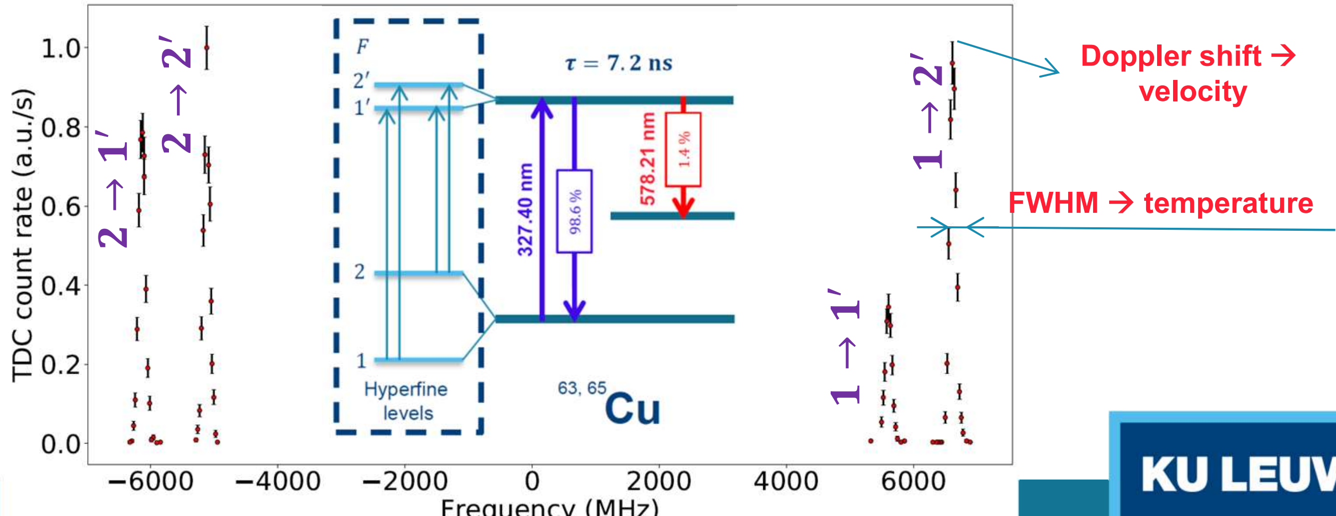


Planar Laser Induced Fluorescence (PLIF)-technique

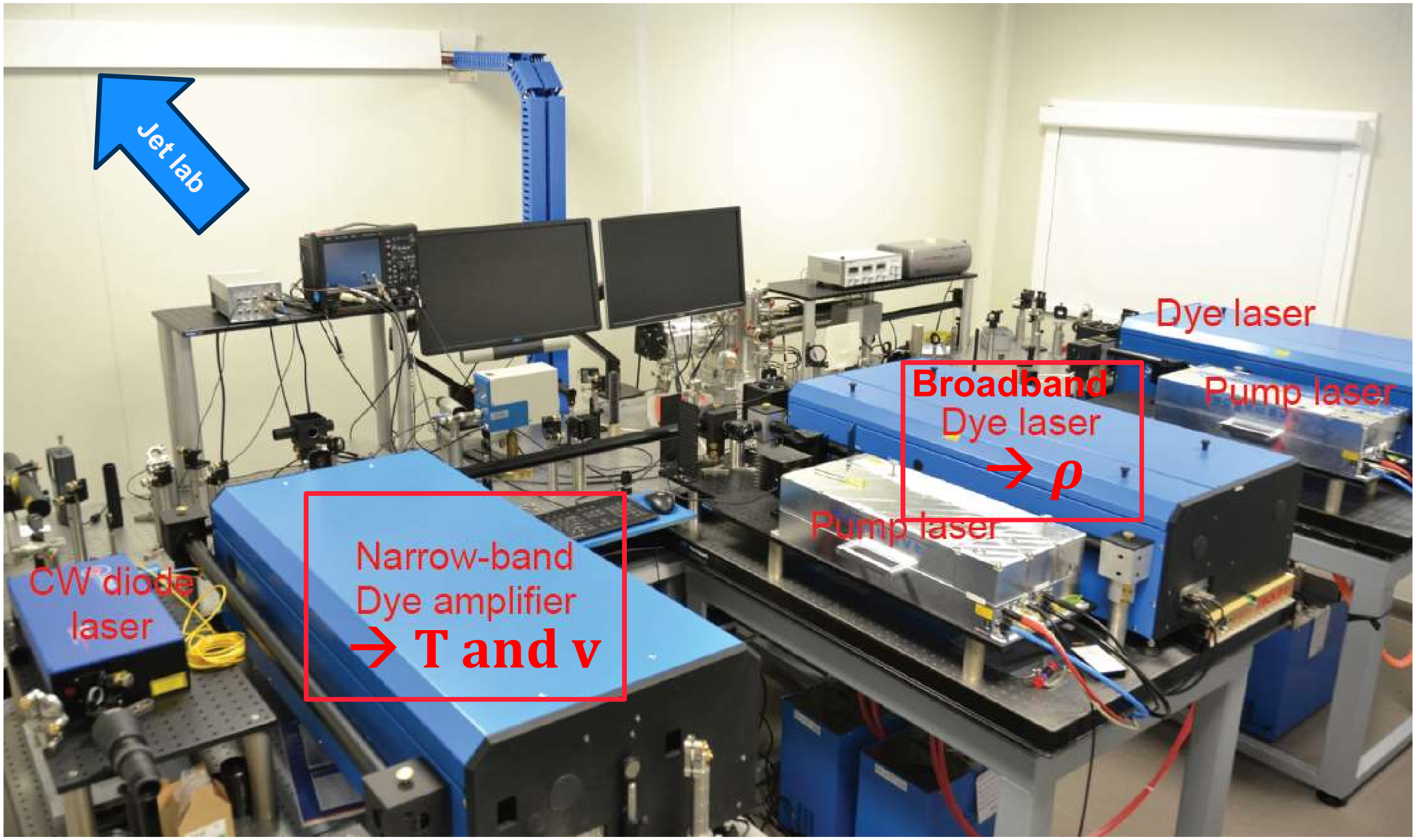


→ relative density from measurements with broadband laser

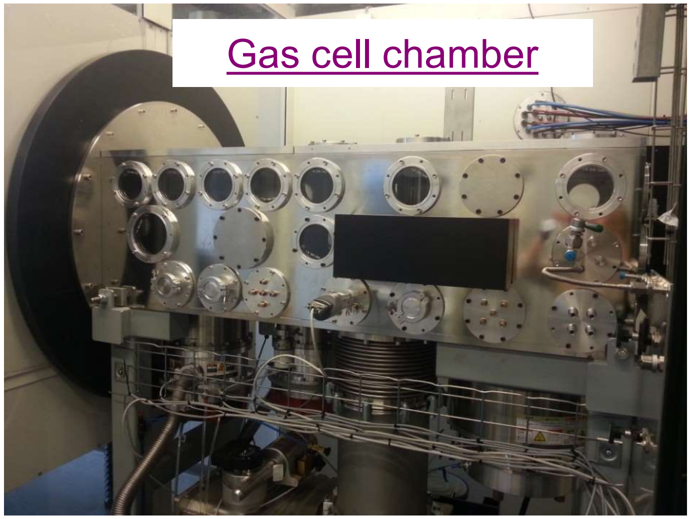
PLIF-spectroscopy

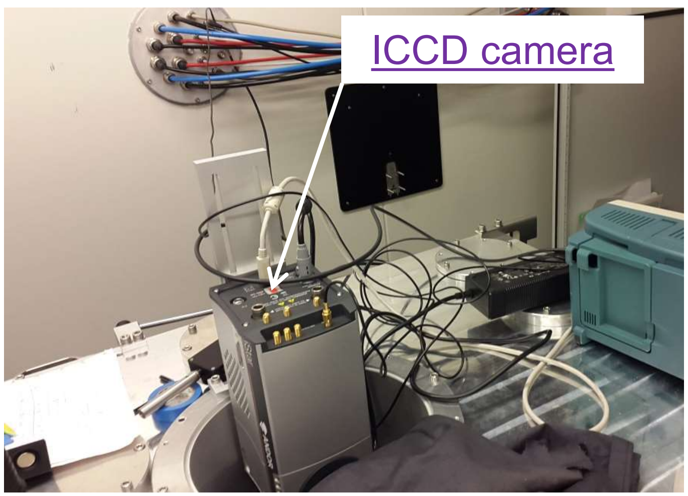


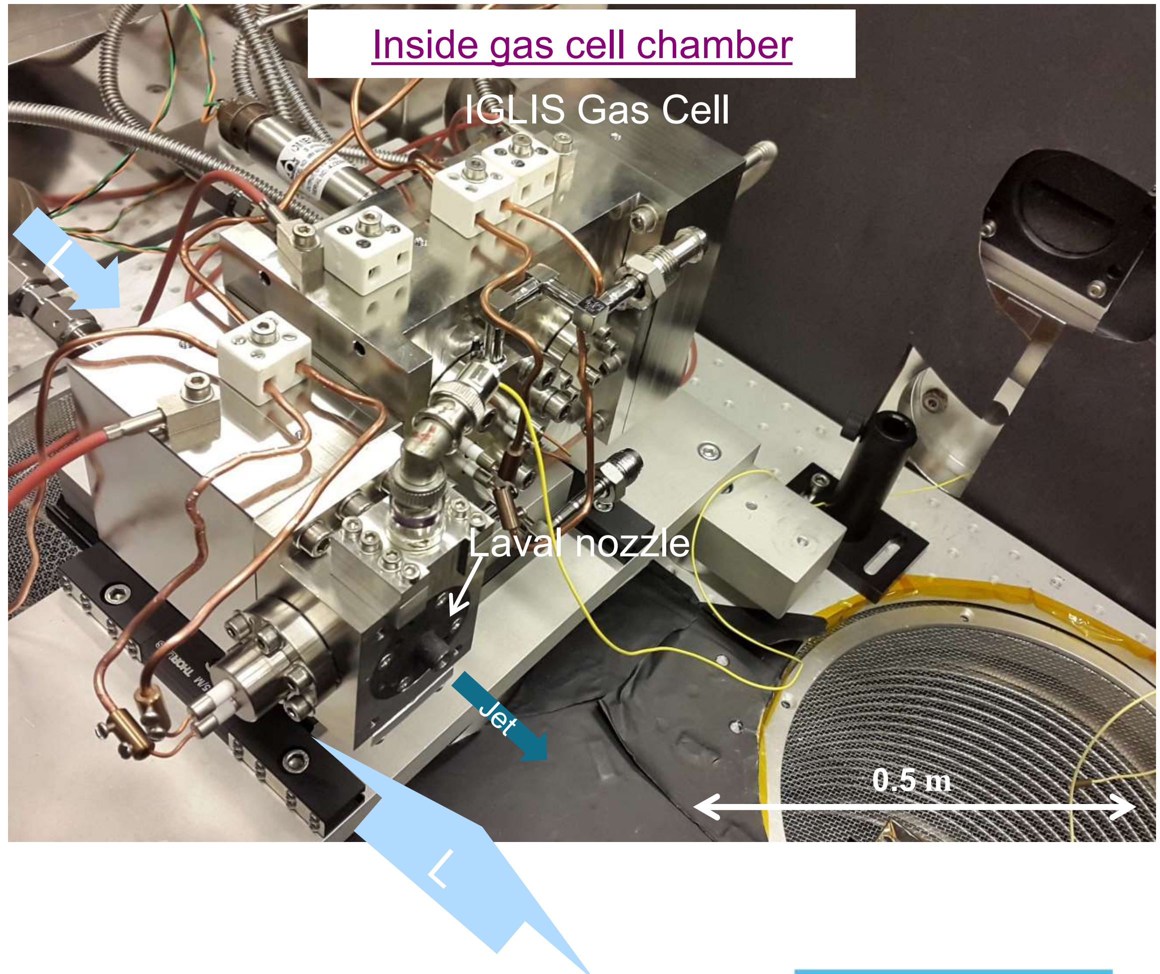
Laser laboratory



Jet laboratory

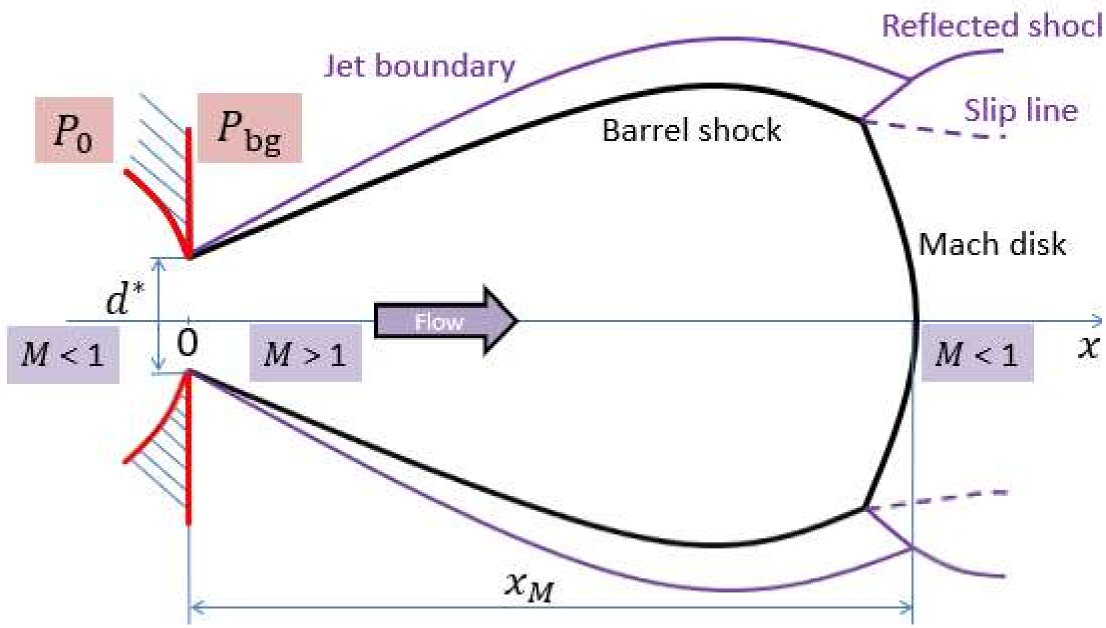


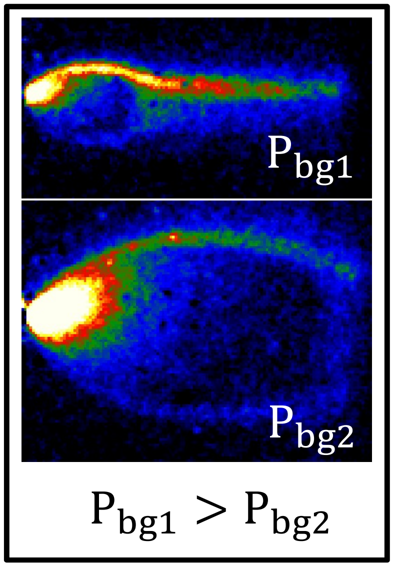




Validation of PLIF-technique

Mach disk position and density drop in the expansion zone





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

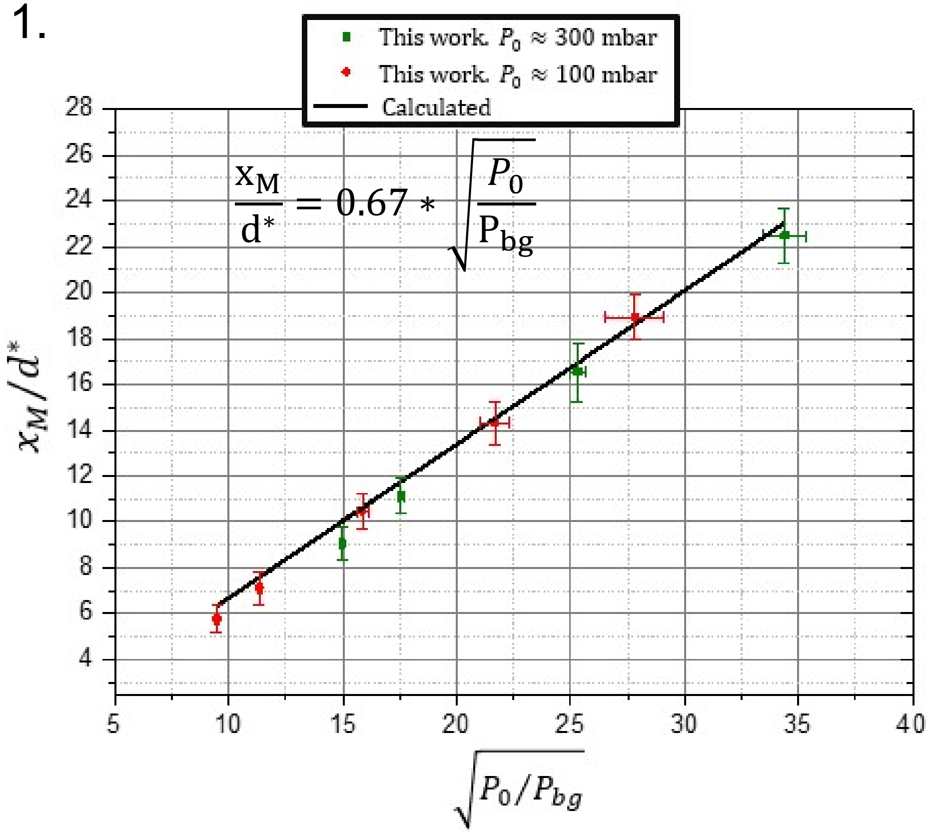
$$\frac{x_M}{d^*} = 0.67 * \sqrt{\frac{P_0}{P_{bg}}}$$

S. Crist , M. Sherman and D.R. Glass, AIAA Journal Vol. 4, No. 1, 68 - 71 (1966)
H. Ashkenas, M. Sherman, Rarefied Gas Dynamics, Academic. Press, 1965, p. 94
P. L. Owen and C. K. Thornhill, in Aeronautical Research Council Reports and Memoranda (1948)

Validation of PLIF-technique

Mach disk position and density drop in the expansion zone

1.



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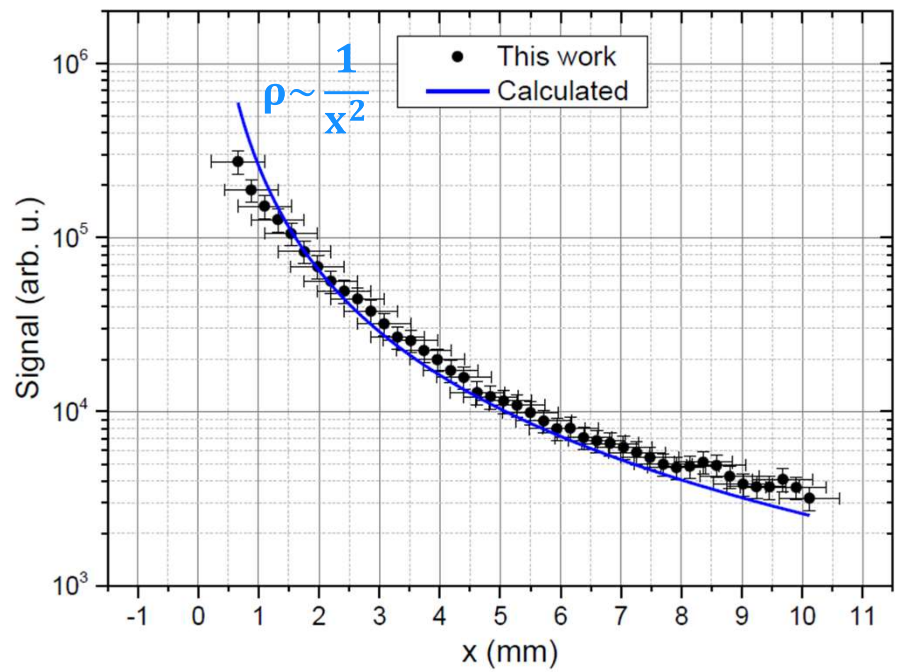

S. Crist , M. Sherman and D.R. Glass, AIAA Journal Vol. 4, No. 1, 68 - 71 (1966)
H. Ashkenas, M. Sherman, Rarefied Gas Dynamics, Academic. Press, 1965, p. 94
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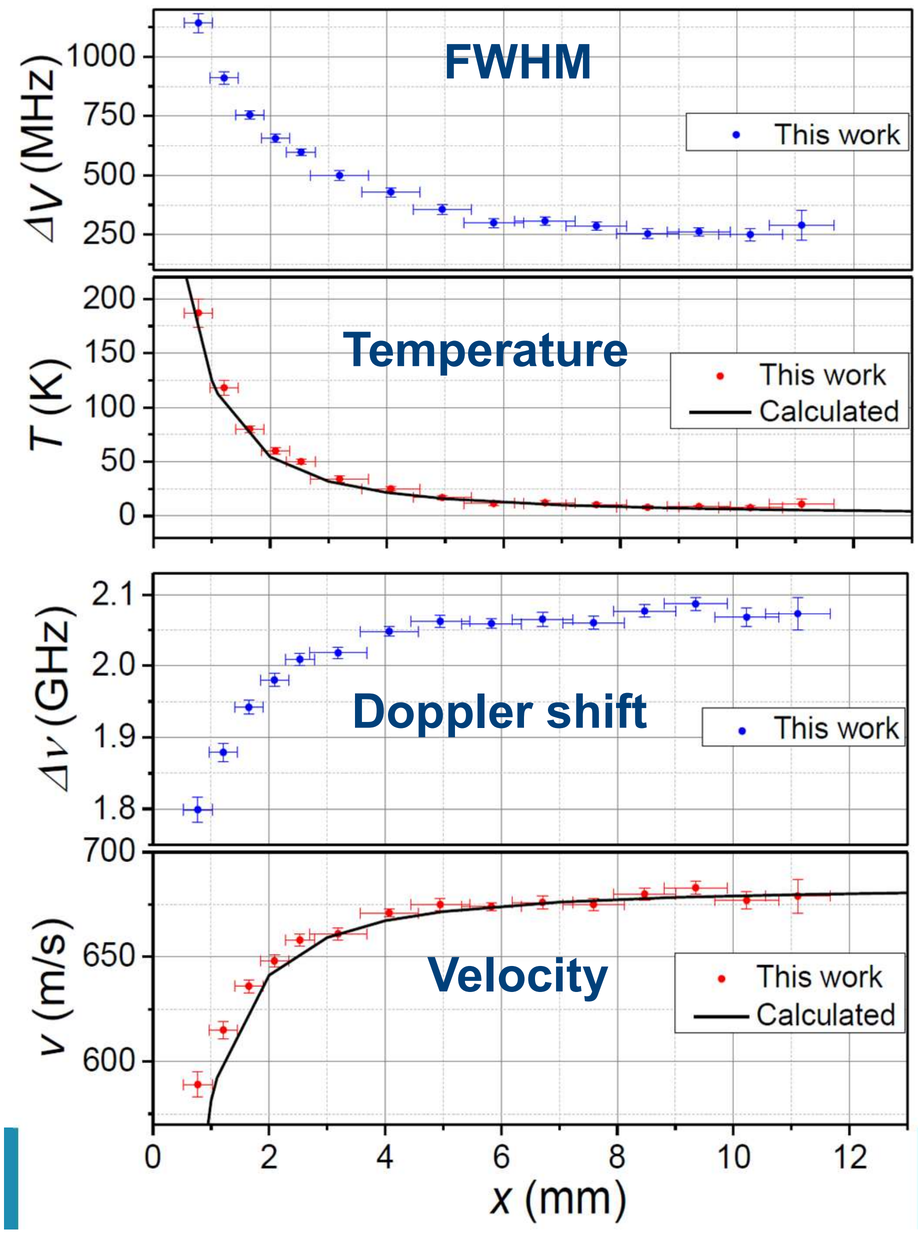
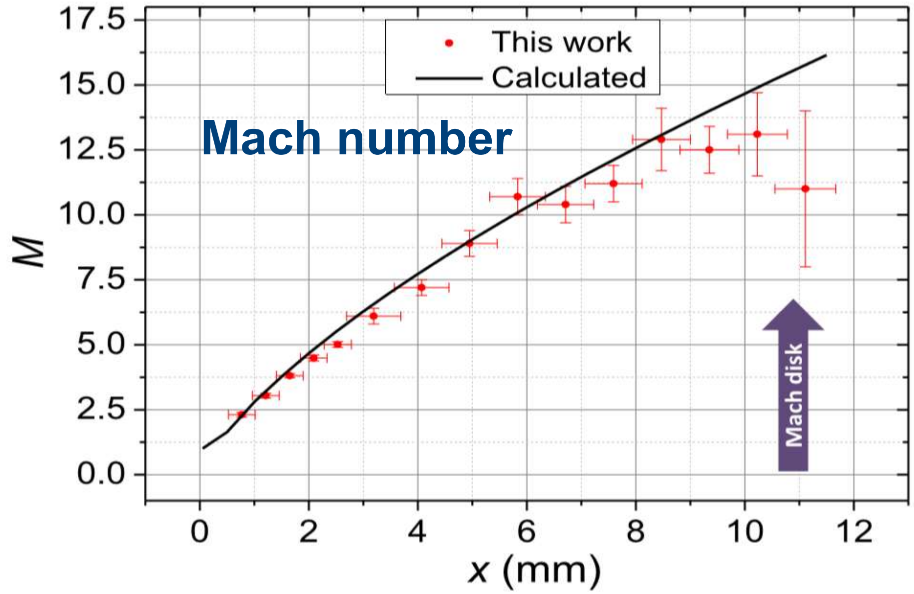
Validation of PLIF-spectroscopy

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

3.

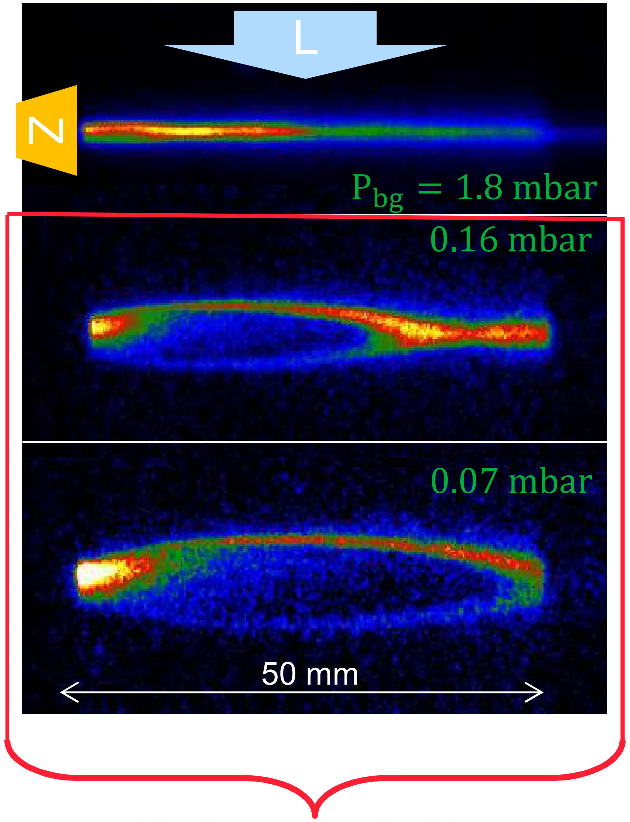


$$M = \frac{\text{flow velocity}}{\text{velocity of sound}(\leftarrow \textit{temperature})}$$

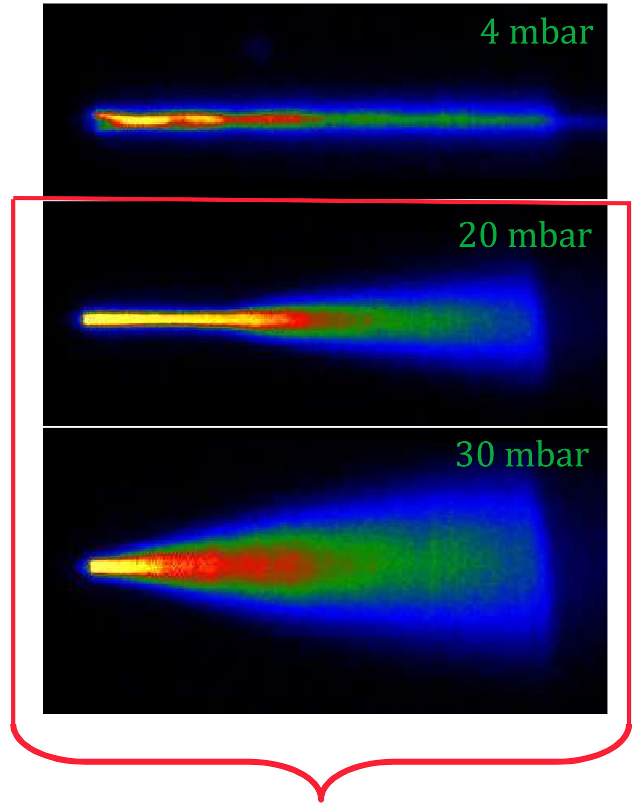


→ good agreement between this work and previous experiments and analytical solutions

Jets formed by de Laval nozzle



Underexpanded jet



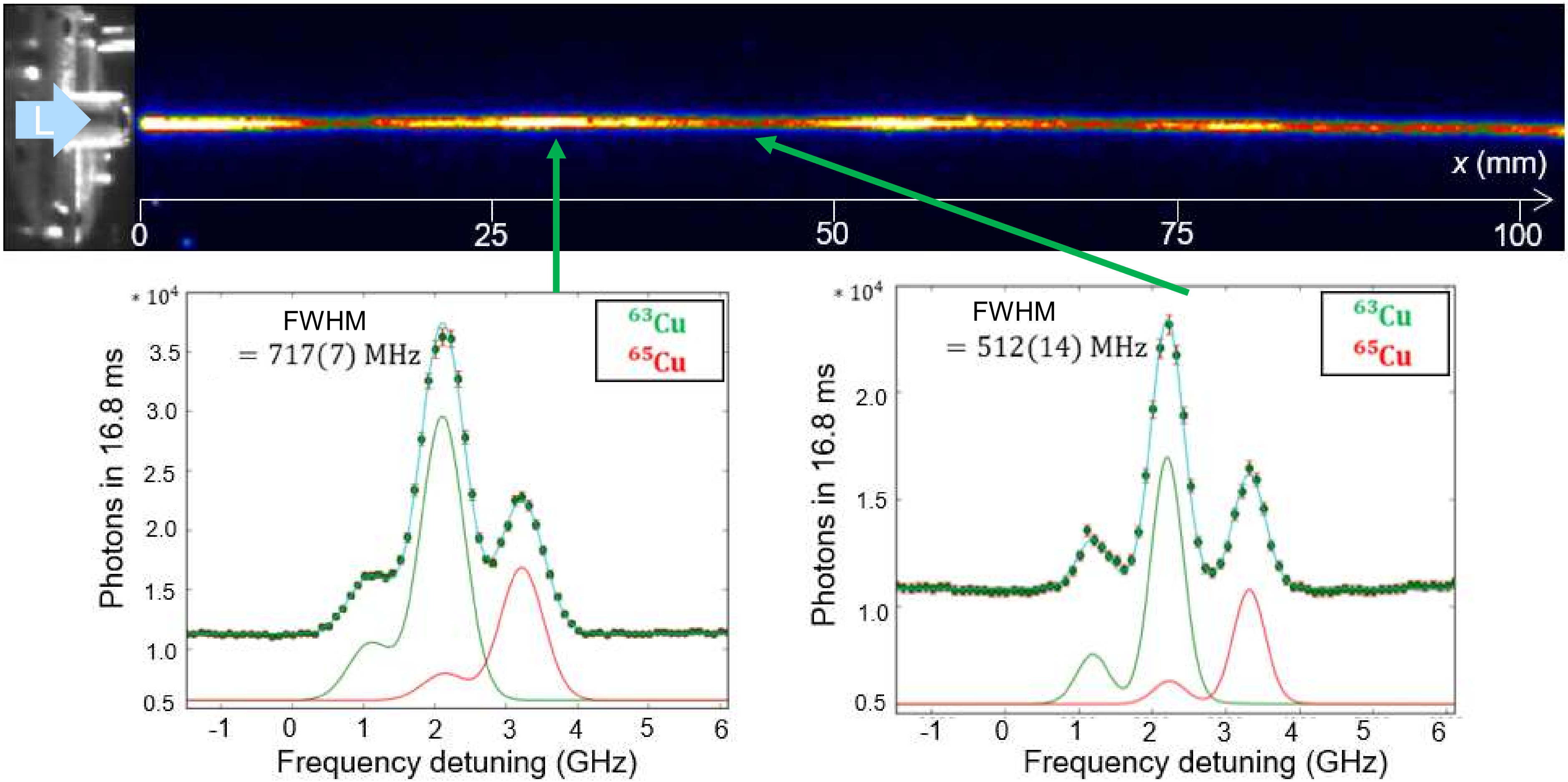
Overexpanded jet

- 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

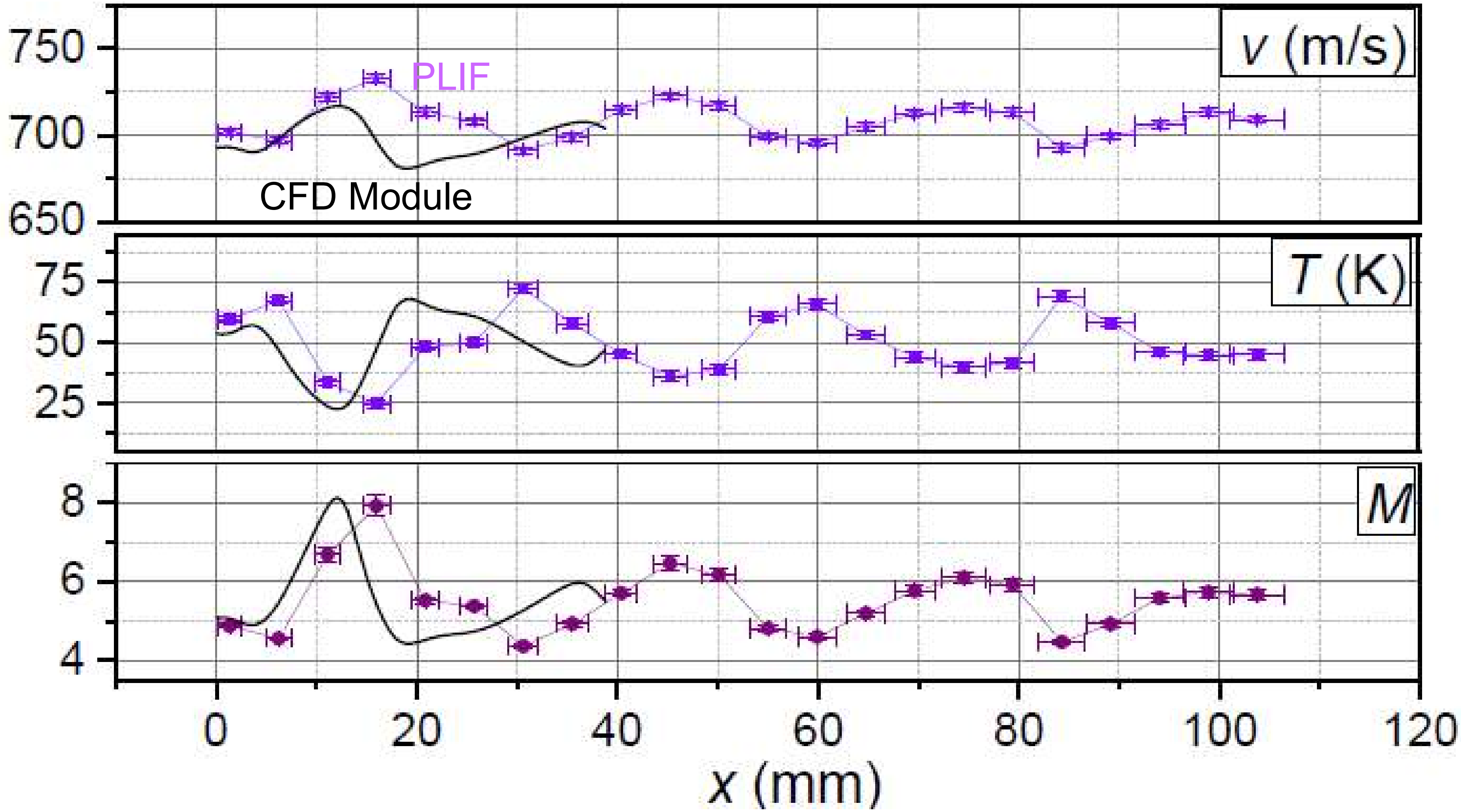
Jets formed by de Laval nozzle

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

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



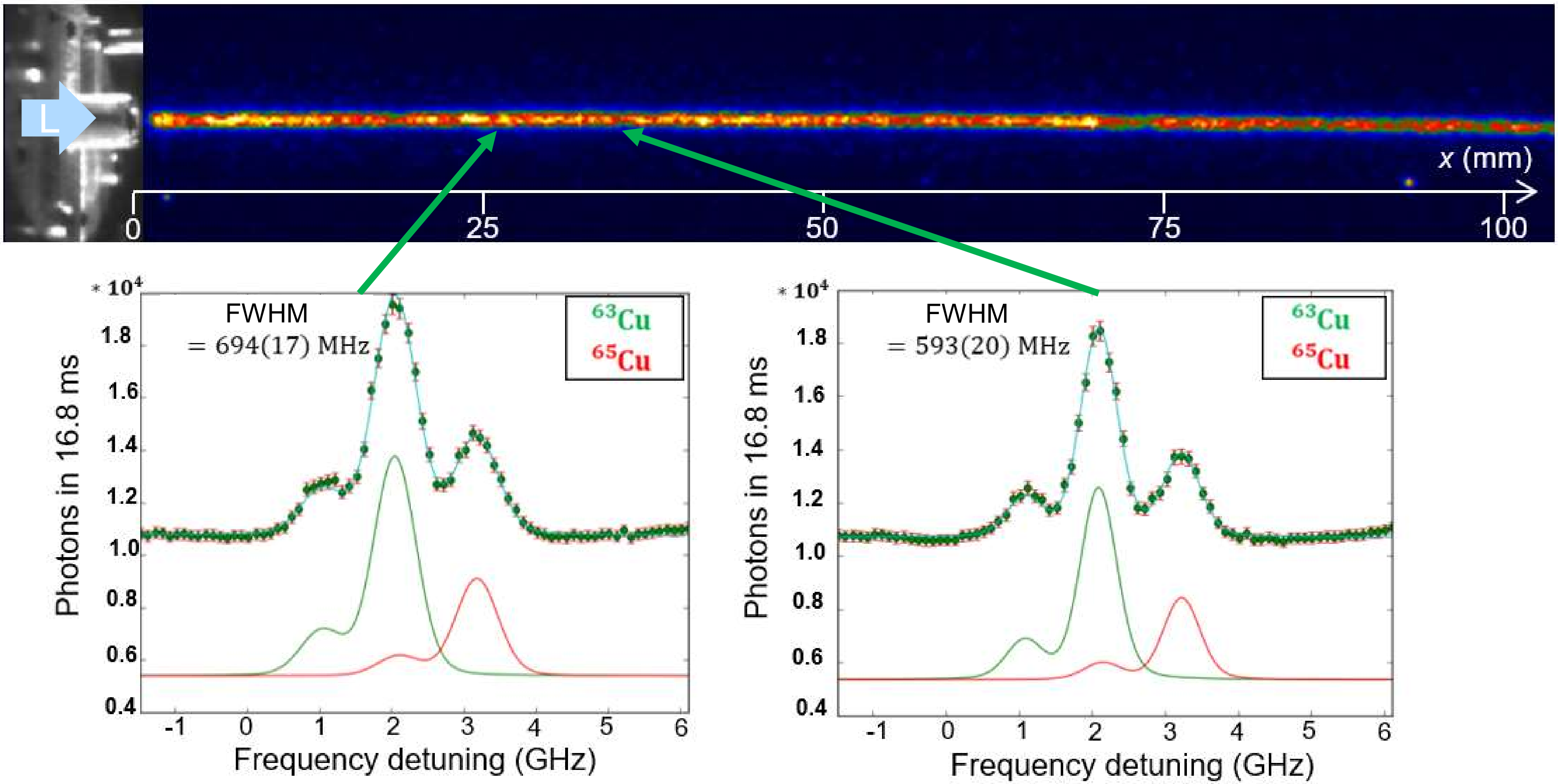
Underexpanded jet



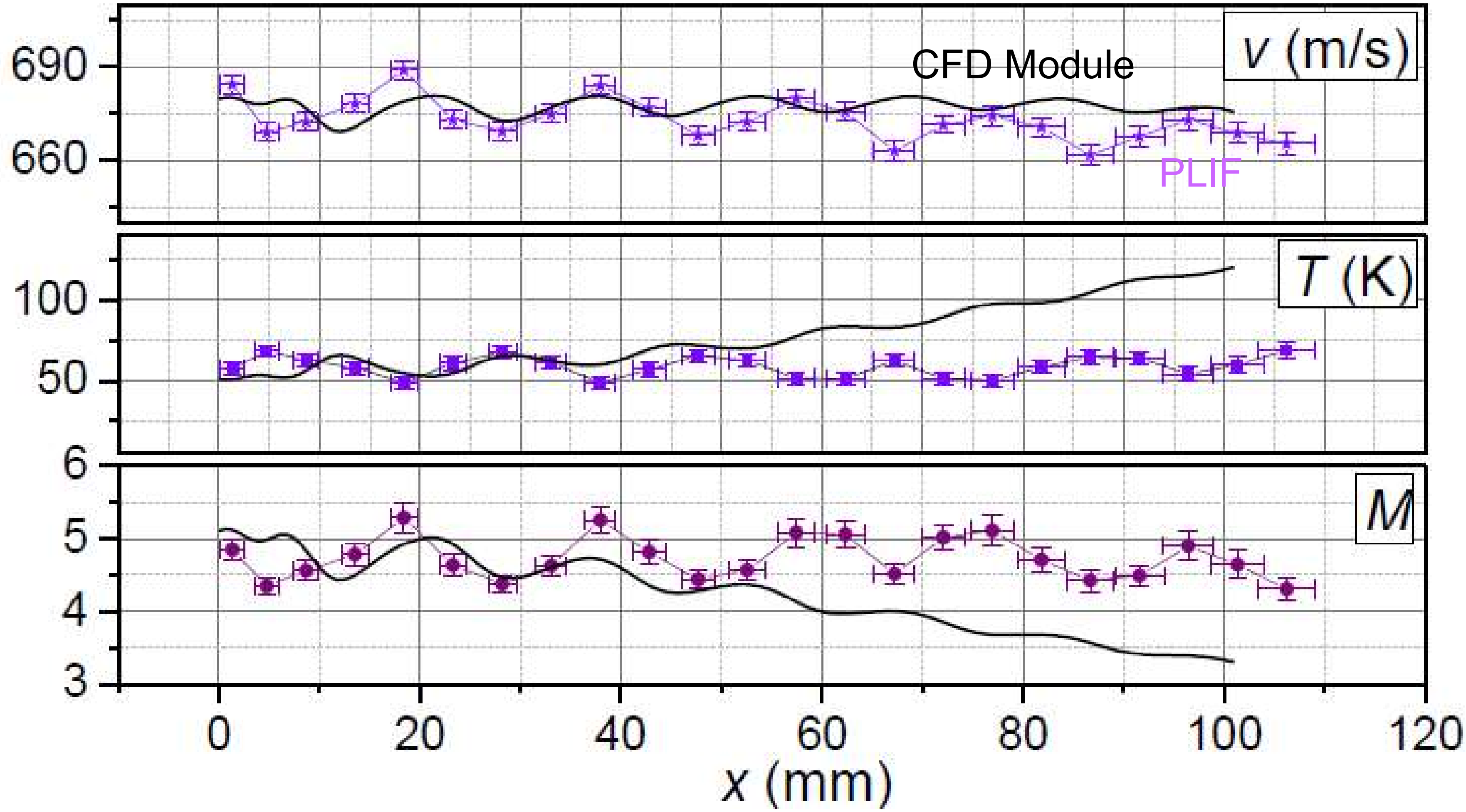
Jets formed by de Laval nozzle

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

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



Quasiuniform jet



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A. Zadvornaya *et al.*, PRX, 8, 041008 (2018)

Steps to further resolution enhancement

Isotope	Electronic transition	T_0 (K)	Mach	T (K)	$\Delta\nu_{\mathrm{Doppler}}$ (MHz)
^{63}Cu	$4s\ ^2S_{1/2} \rightarrow 4p\ ^2P_{1/2}$ 327.40 nm	~ 465	6.7	29	450
^{63}Cu	$4s\ ^2S_{1/2} \rightarrow 4p\ ^2P_{1/2}$ 327.40 nm	300	6.7	19	360
^{253}No	$7s^2\ ^1S_0 \rightarrow 7s7p\ ^1P_1$ 333.76 nm	300	6.7	19	175
^{253}No	$7s^2\ ^1S_0 \rightarrow 7s7p\ ^1P_1$ 333.76 nm	300	8.5	12	140

1. Online conditions

2. Heavier elements

3. Higher Mach numbers

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Latest developments @ IGLIS laboratory

High Mach-number Nozzle (M=8.5): calculations

Nozzle contour calculated using advanced simulation code from Aeronautics and Aerospace Department of *von Karman Institute for Fluid Dynamics (VKI)*

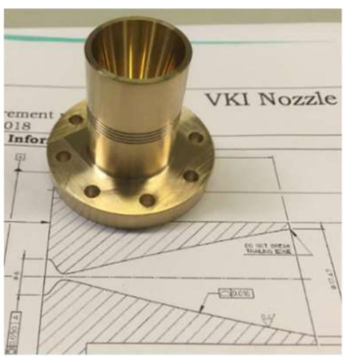
1) T_0= 300 K, P_0 = 350 mbar, Ar perfect gas, 1 mm throat diam., laminar flow

2) + Viscous corrections from Navier-Stokes laminar flow solution

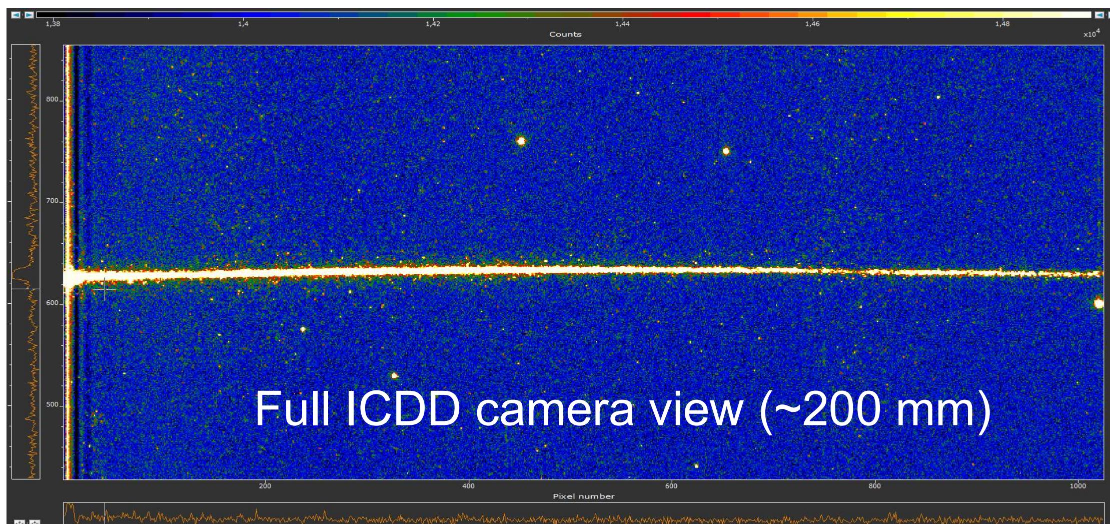
High Mach-number Nozzle: tests with PLIF

Precision machining

- precision inner contour ~ 2 μm
- surface finishing Ra=0.1 μm



Characterization of the flow parameters by PLIF:



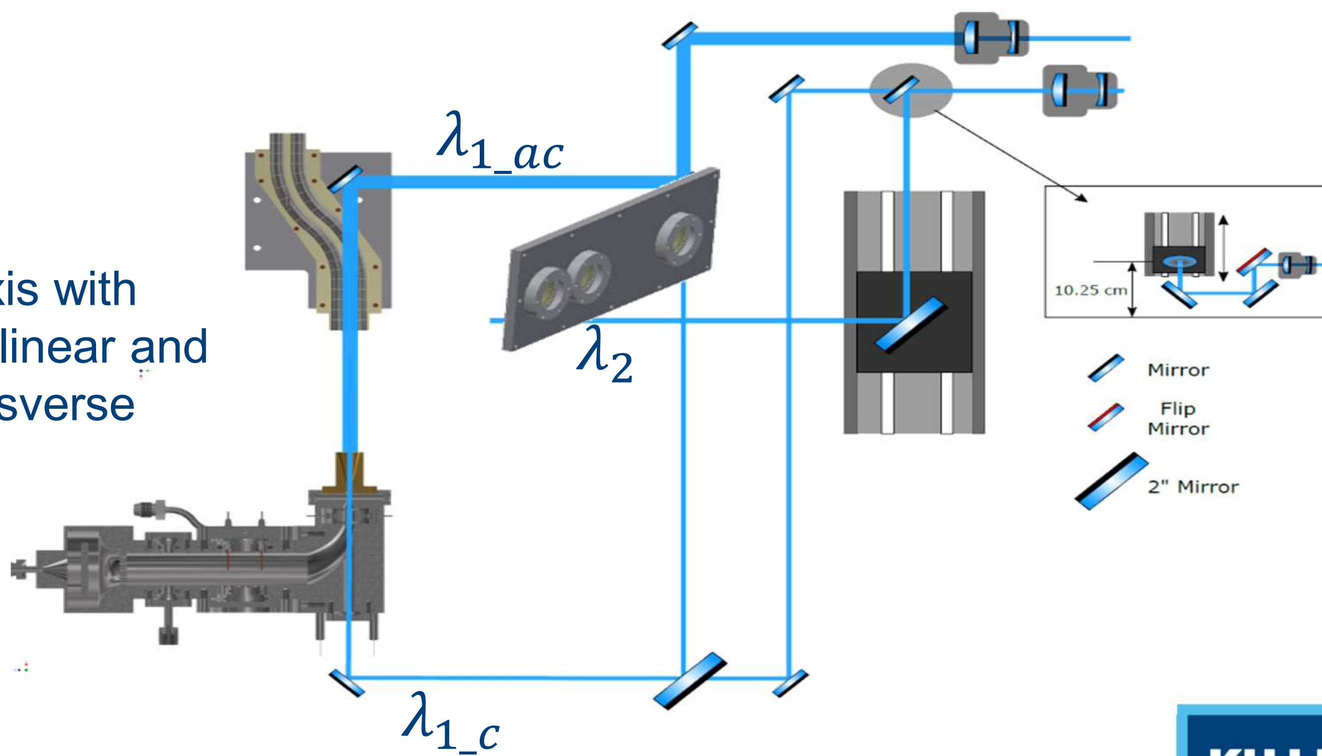
Latest developments @ IGLIS laboratory

High Mach-number Nozzle: tests with RIS

Resonance Ionization Spectroscopy (RIS):

- higher efficiency (~0.2 % with PLIF)
- shorter measurement times
- lower T_0
- geometrical scanning lasers to characterize jet parameters

RIS on jet axis with
1st step (anti)collinear and
2nd step transverse



Latest developments @ IGLIS laboratory

High Mach-number Nozzle: results

$P_{bg} \sim P_{jet}$
RIS: on jet axis with
1st step anticollinear
and 2nd step
transverse

Partial agreement between theory and experiment. Possible explanation:
- Experiment with Cu vs. calculations for Ar?

(moreover, distribution of copper in the jet seems to be dependent on production point in the gas cell)
- Different stagnation parameters (T_0, P_0)?
- ~~Misalignment between jet and laser beam?~~
- ~~Non-accurate manufacturing of the nozzle?~~

Conclusions

- ✓ Supersonic gas jets were characterized using PLIF-spectroscopy setup constructed at IGLIS laboratory
- ✓ Partial agreement was reached between experimental results and numerical calculations in CFD Module for jet's flow parameters
- ✓ Limit of the spectral resolution achieved with the in-gas-jet laser ionization spectroscopy was estimated to be ~ 140 MHz for ^{253}No utilizing de Laval nozzles with Mach 8.5

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

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

A. Zadvornaya,* P. Creemers, K. Dockx, R. Ferrer, L. P. Gaffney,† W. Gins, C. Granados,† M. Huyse, Yu. Kudryavtsev, M. Laatiaoui, E. Mogilevskiy,‡ S. Raeder,§ S. Sels, P. Van den Bergh, P. Van Duppen, M. Verlinde, and E. Verstraelen
KU Leuven, Instituut voor Kern- en Stralingsfysica, Celestijnenlaan 200D, B-3001 Leuven, Belgium

M. Nabuurs and D. Reynaerts
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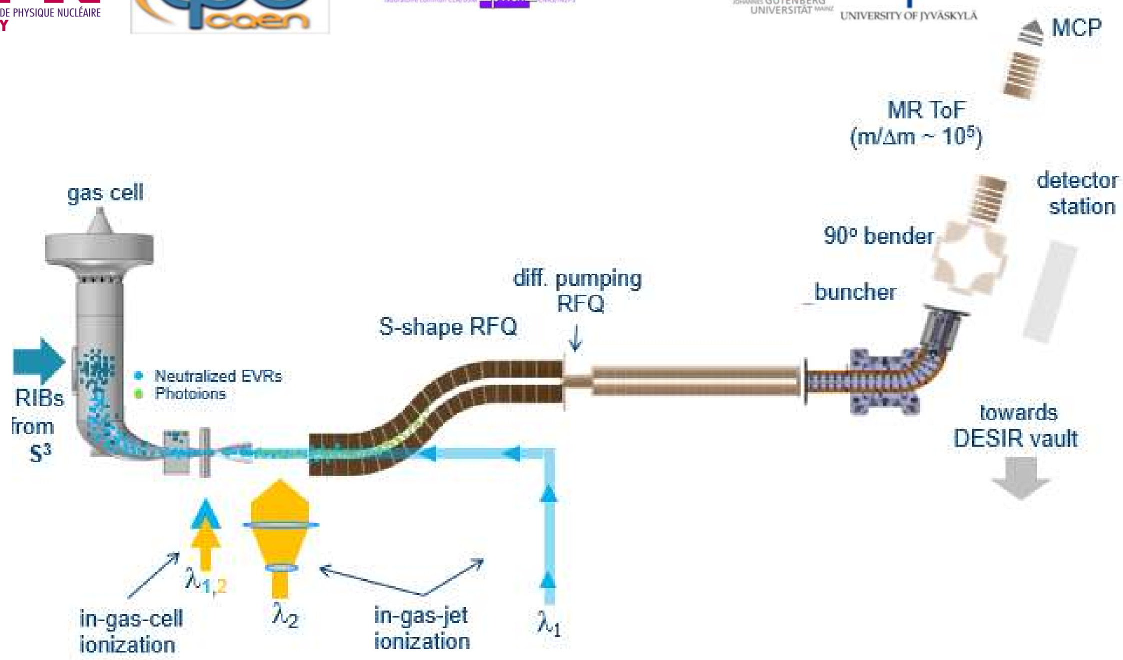
P. Papadakis‖
University of Jyvaskyla, Department of Physics, P.O. Box 35, FI-40014 University of Jyvaskyla, Finland

- ✓ VKI nozzle with higher Mach number → possibility to reach M~8
- ✓ RIS implemented to characterize jet properties
- ✓ VKI nozzle improves beam emittance but makes transport through S-RFQ more difficult (high momentum transfer). Total transport efficiency (nozzle exit to FC in magnet's focal plane) found to be 50(5)% with mass resolving power R= 350

Outlook

- In-gas-jet laser ionization spectroscopy will be implemented for performing high-resolution spectroscopy studies at, e.g., S3-LEB at SPIRAL2 of GANIL
- PLIF technique will be used to characterize the performance of newly constructed nozzles
- Direct comparison PLIF & RIS by simultaneous measurement of jet properties is foreseen
- Characterization of ablation-assisted RIS and PLIF is ongoing. Already obtained promising results



European Research Council
Established by the European Commission

CSC

Characterization of supersonic jets for in-gas-jet laser ionization spectroscopy at the IGLIS laboratory
+
MNT reactions and efficiency characterization with gas cells at the IGISOL-4 facility

Sasha (Alexandra) Zadvornaya
18 July 2019

Plan:

1. Results *(work in progress..)*
- Multinucleon-transfer (MNT) reactions with a modified HIGISOL gas cell within MAIDEN Project
- Ion survival and transportation efficiency tests with a modified fission ion guide

2. Outlook

MAIDEN

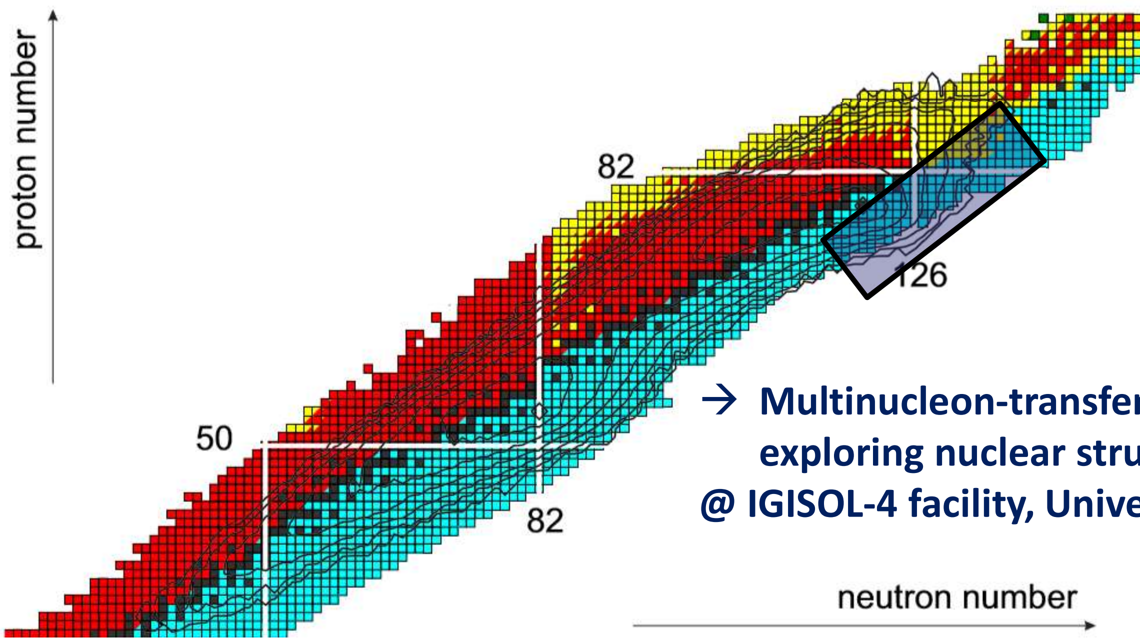
Masses, **I**somers and **D**ecay studies for **E**lemental **N**ucleosynthesis
(ERC Consolidator Grant Project of A. Kankainen)

The main research question/motivation:

How and where are the elements heavier than iron created?

1957, B2FH paper
(idea that heavy elements are synthesized via different stellar nucleosynthesis paths such as the r-, s- and p-processes)

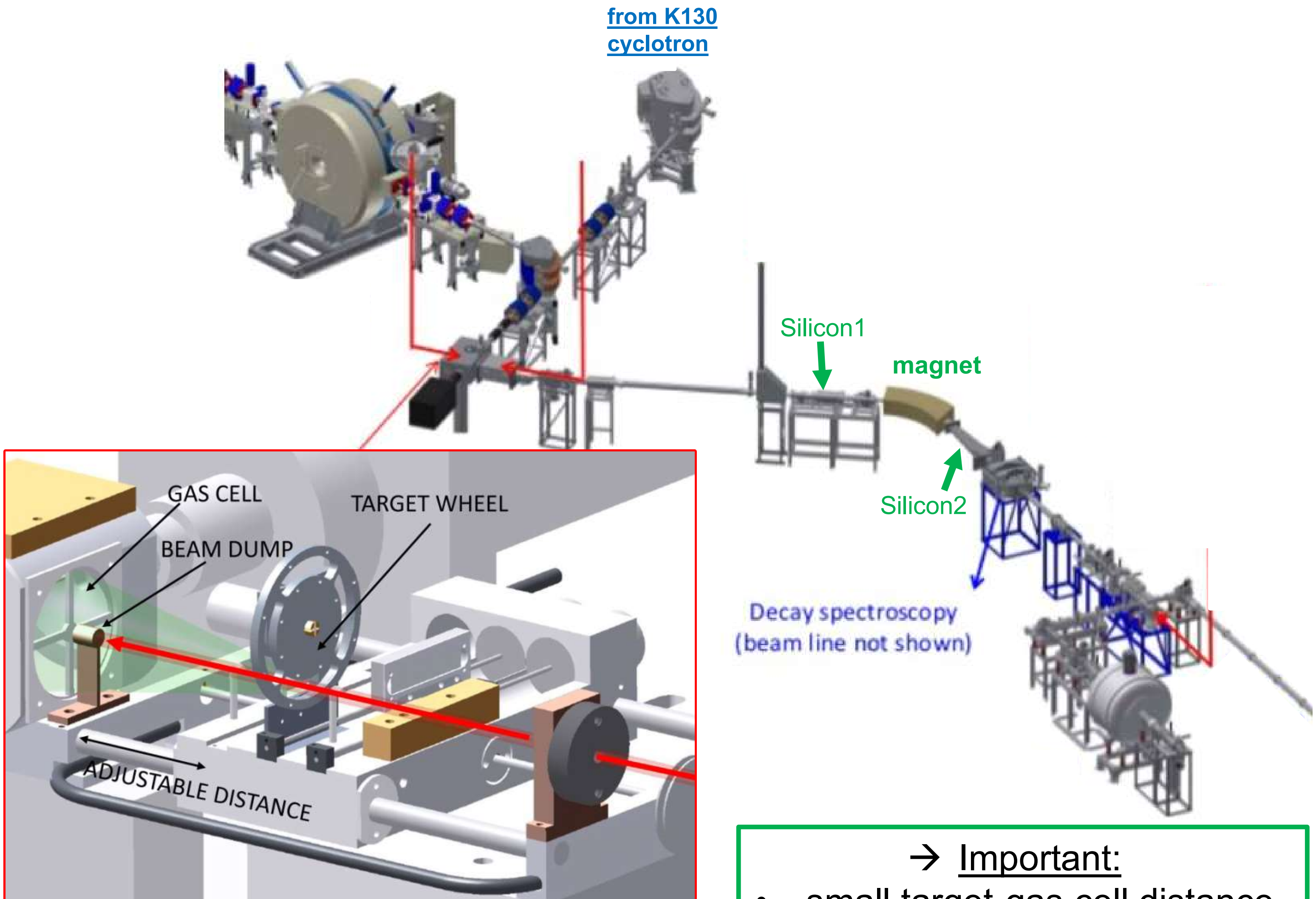
→ **2017, a merge of two neutron starts**
(first confirmation)



→ **Multinucleon-transfer reactions studies for exploring nuclear structure close to N = 126 @ IGISOL-4 facility, University of Jyvaskyla**

A.V. Karpov, V.V.Saiko, PRC 96, 024618 (2017)

Multinucleon-transfer reactions (MNT) @ IGISOL-4

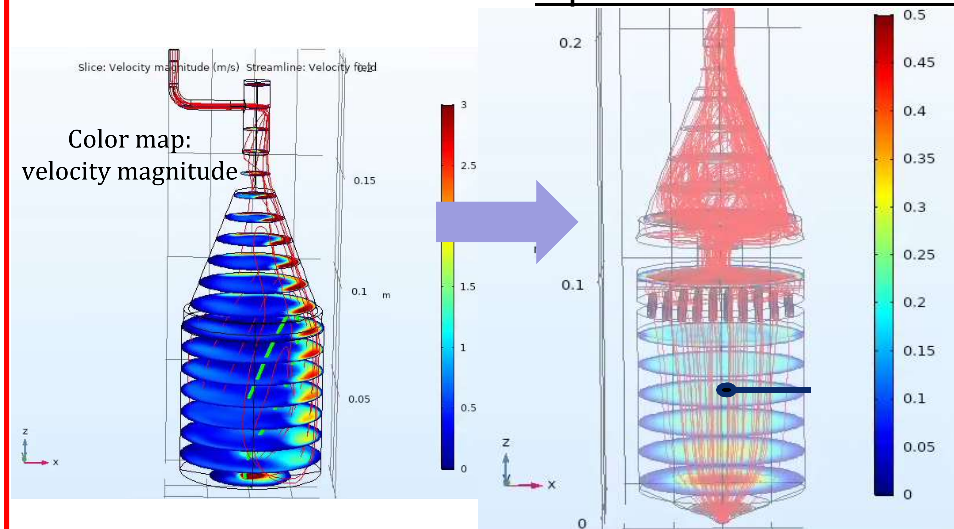


Inside target chamber (HIGISOL gas cell and platform)

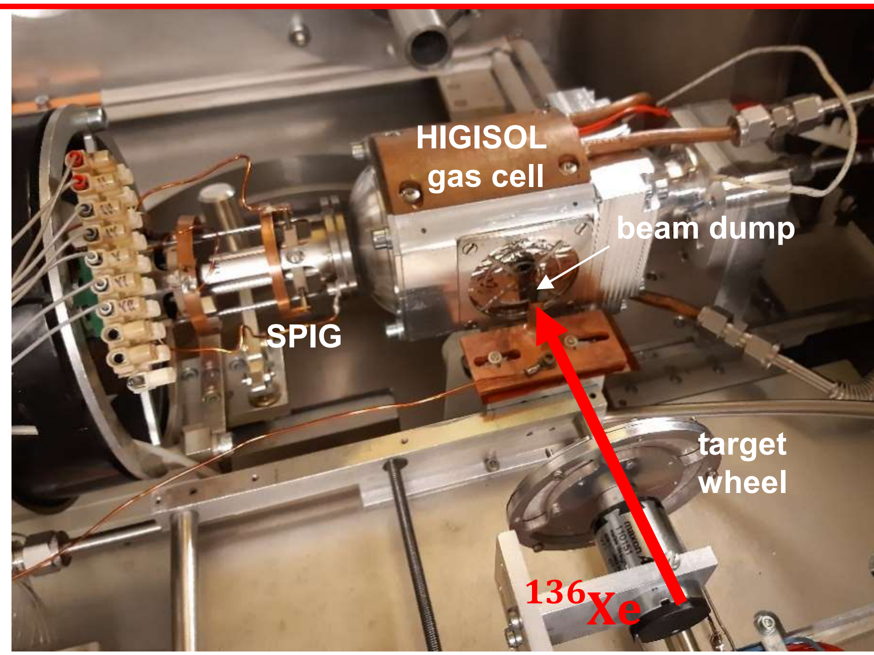
→ Important:
- small target-gas cell distance
- optimized gas cell geometry
- optimized ion survival and transportation efficiency

MNT run in June 2019

Optimization of HIGISOL gas cell



$\text{eff}_{\text{ion surv.+transp.}} \sim \mathbf{7}\ \%$
(measured with Silicon1 for helium gas, P_0 = 150 mbar, ^{223}Ra α-recoil source)



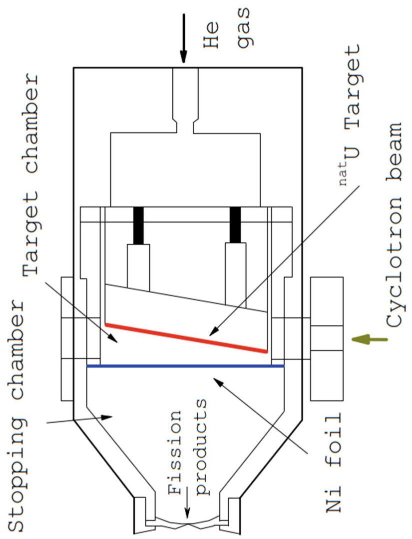
MNT run in June 2019

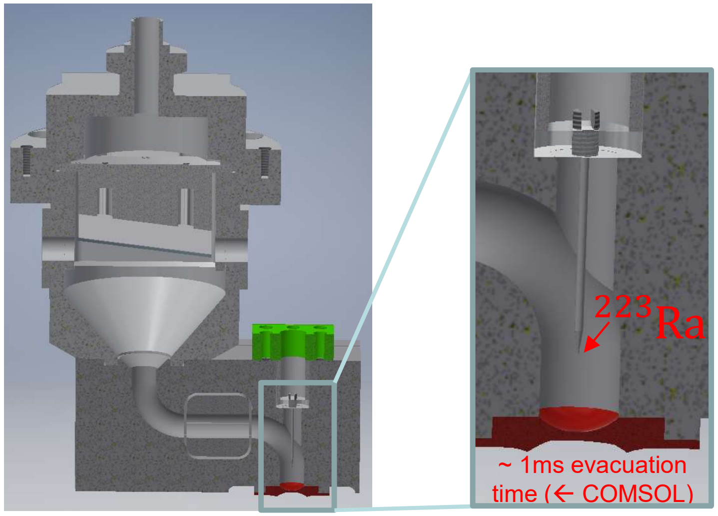
2nd run, August 2019:

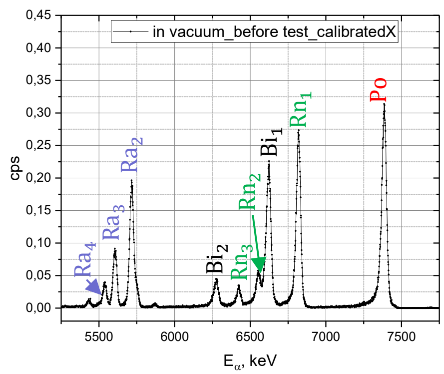
1) changing primary beam energy
2) another target (→ Pt)
3) gamma-beta coincidence spectroscopy
4) the same gas cell

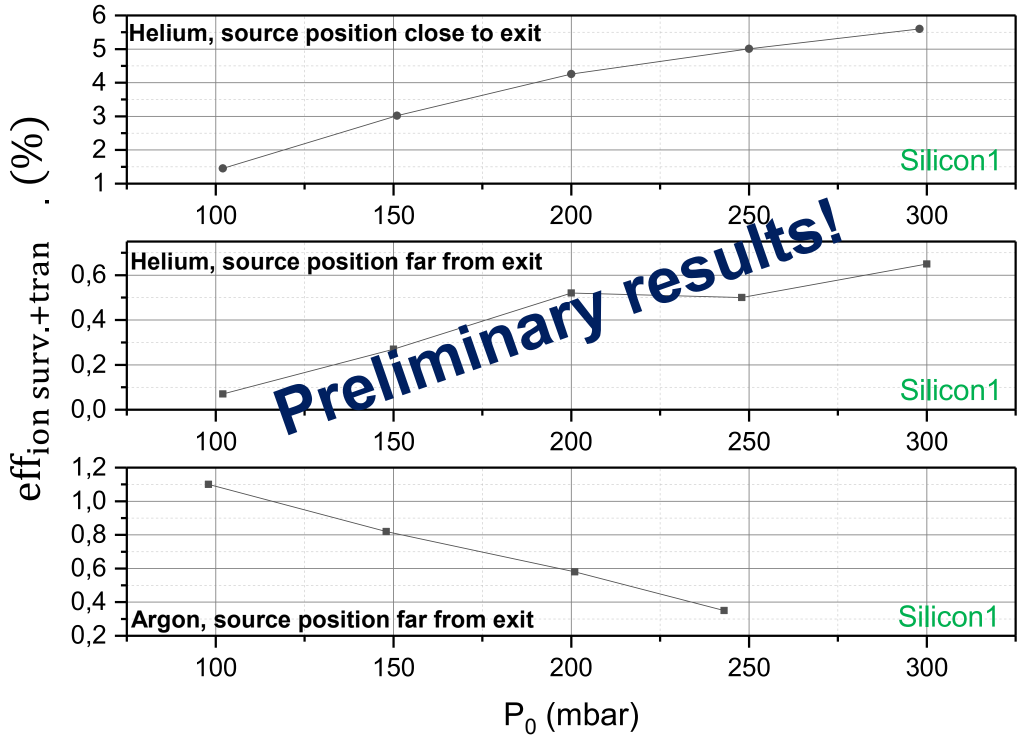
→ 3rd run (2019)

Efficiency tests with ^{223}Ra α-recoil source and fission ion guide









→ more tests upcoming..

Outlook

MNT reactions

- More online tests
- another target
- gas cell with a modified geometry
- argon gas combined with selective laser ionization

Efficiency tests with fission and HIGISOL gas cells

- More systematic studies:
- evacuation time measurements
- baking of gas cells and gas lines prior to tests
- cooling gas cell to cryogenic temperatures
- numerical calculations of subsonic gas flow and transportation

Acknowledgments

Thanks to Nuclear Spectroscopy group (IKS, KU Leuven)

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

Thanks to IGISOL group and MNT collaboration (University of Jyväskylä)

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

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Thanks for your attention!