In-gas jet laser ionization spectroscopy of heavy elements

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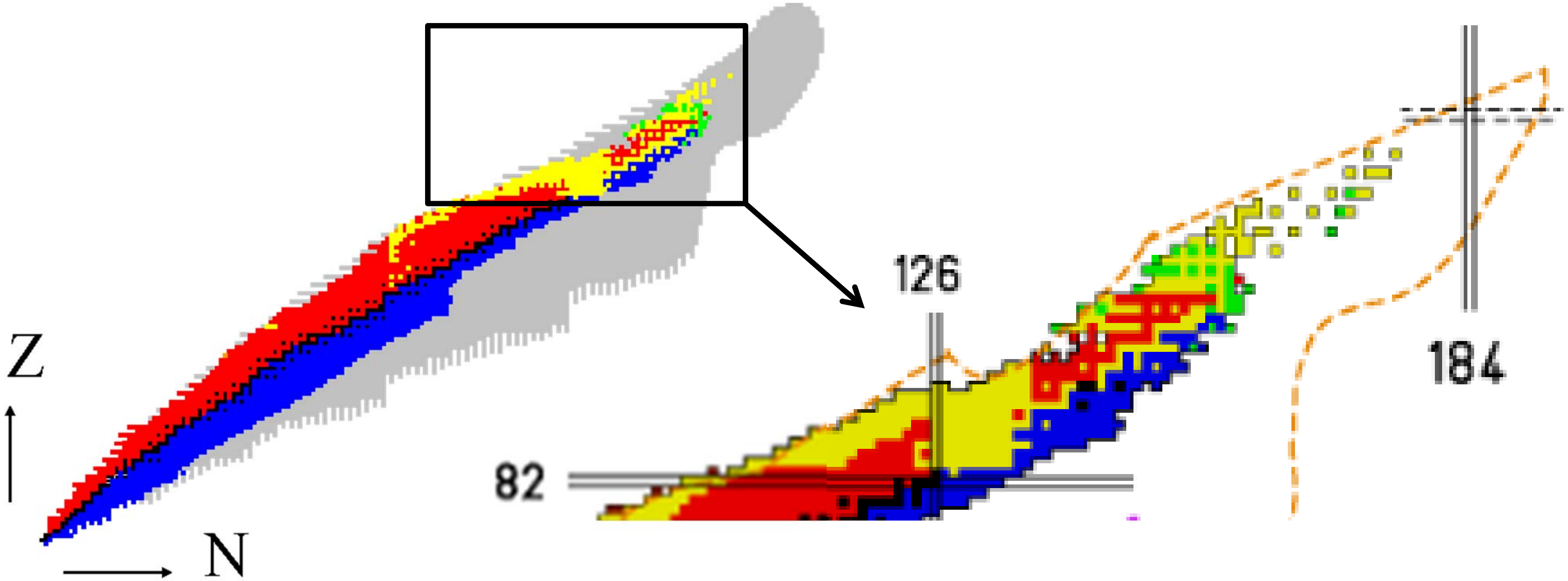

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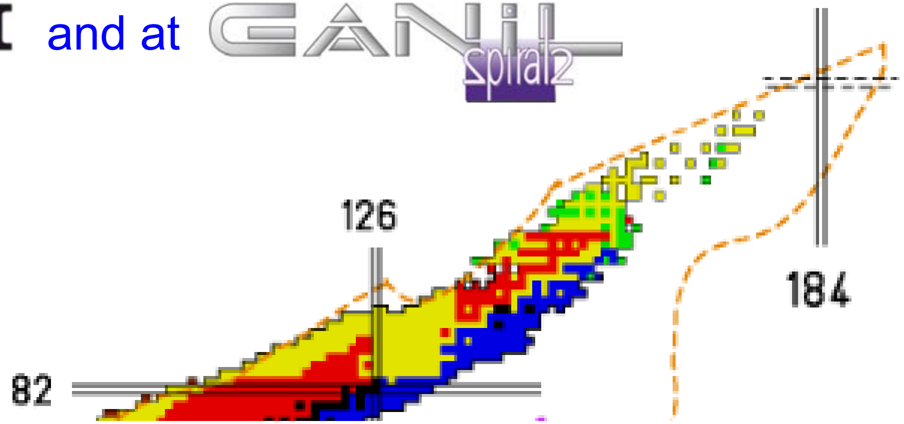
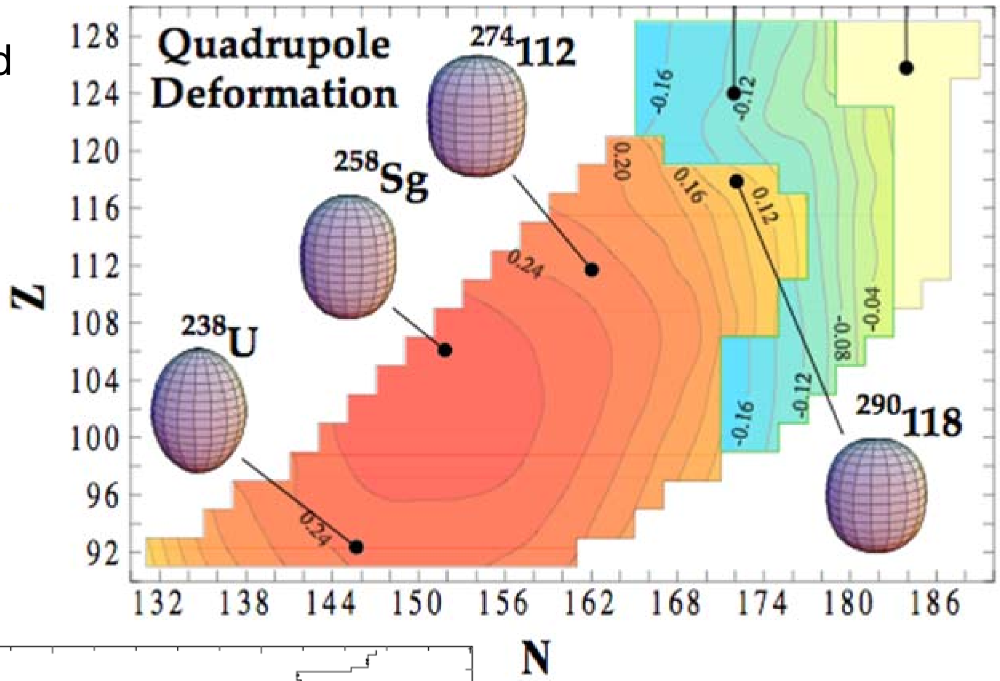
Outline

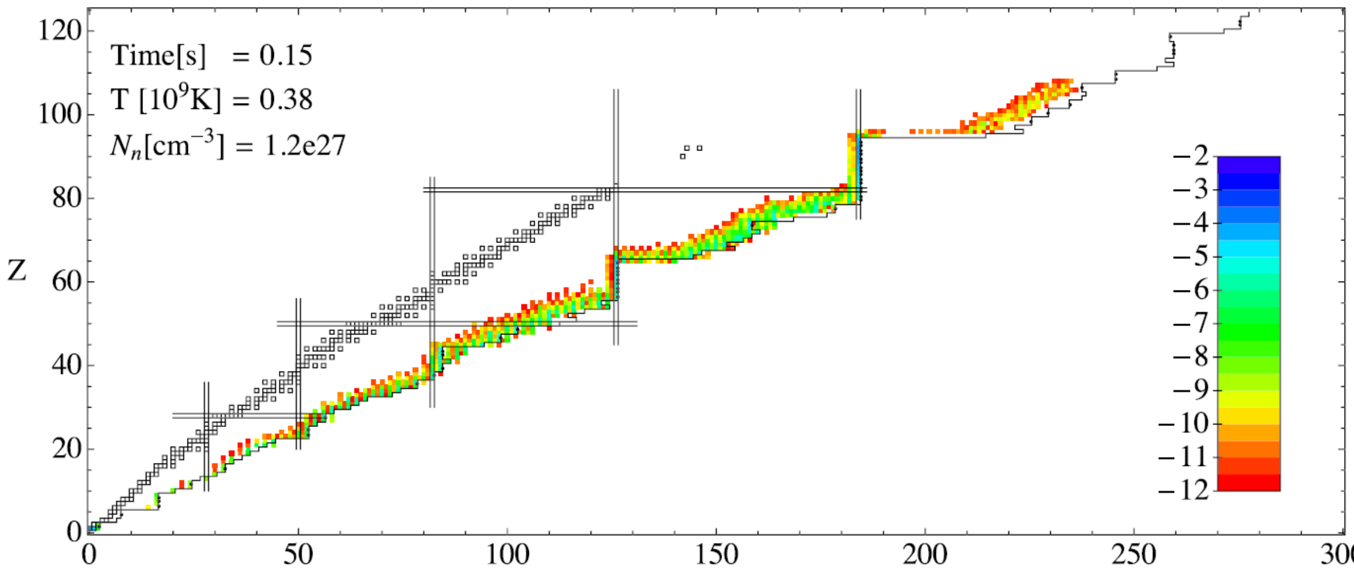
- Studying the heavy element region: motivation
- Basics of laser spectroscopy and the "In-Gas Laser Ionization Spectroscopy - IGLIS"
- Studies of the nobelium and neutron-deficient actinium isotopes
- Improvements of the IGLIS technique and expected performances
- Outlook using IGLIS at GSI and at GANIL spiral2



Study of heavy and super-heavy elements

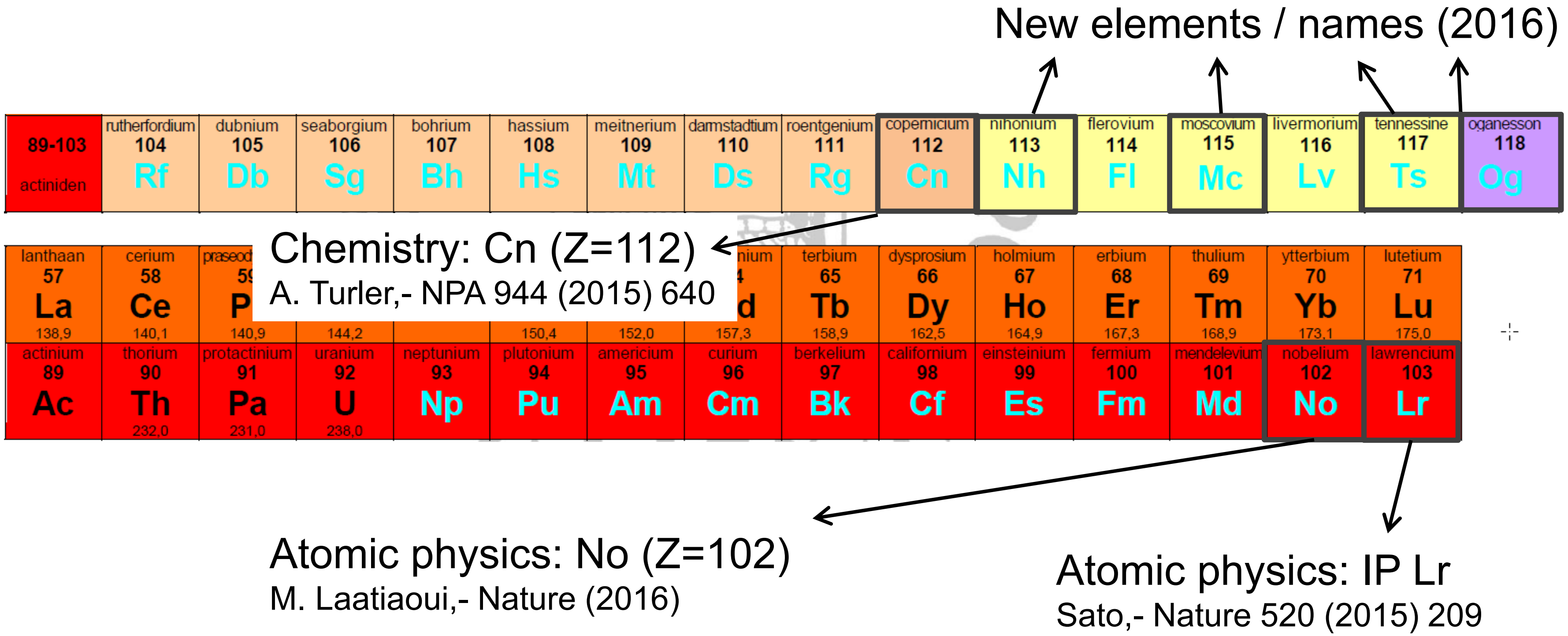
- Competition of the short-range nuclear and long-range Coulomb force
- Validate Energy Density Functionals
- End of the r-process nucleosynthesis
- Microscopic understanding of fission





S. Cwiok,- Nature, 433 (2005), M. Bender,- PLB 515 (2001), Staszczak,- PRC80 (2009)
Y. Oganessian and K. Rykaczewski, Physics Today 68 (2015), S. Goriely – G.M. Pinedo NPA944 (2015)

- What is known about the heaviest elements?



→ Laser spectroscopy in the heavy element region

Nuclear observables: I, μ, Q, Isotope Shift → δ<r^2>

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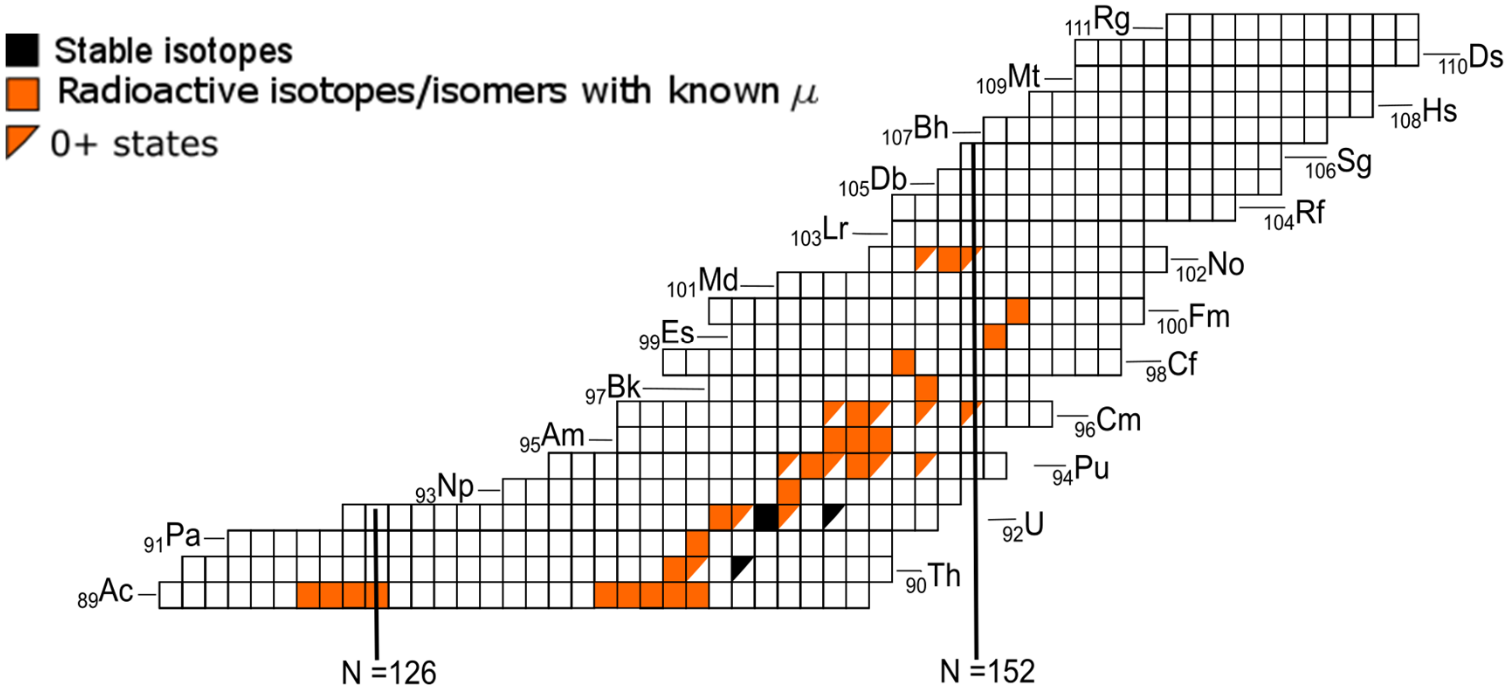
Magnetic Moment



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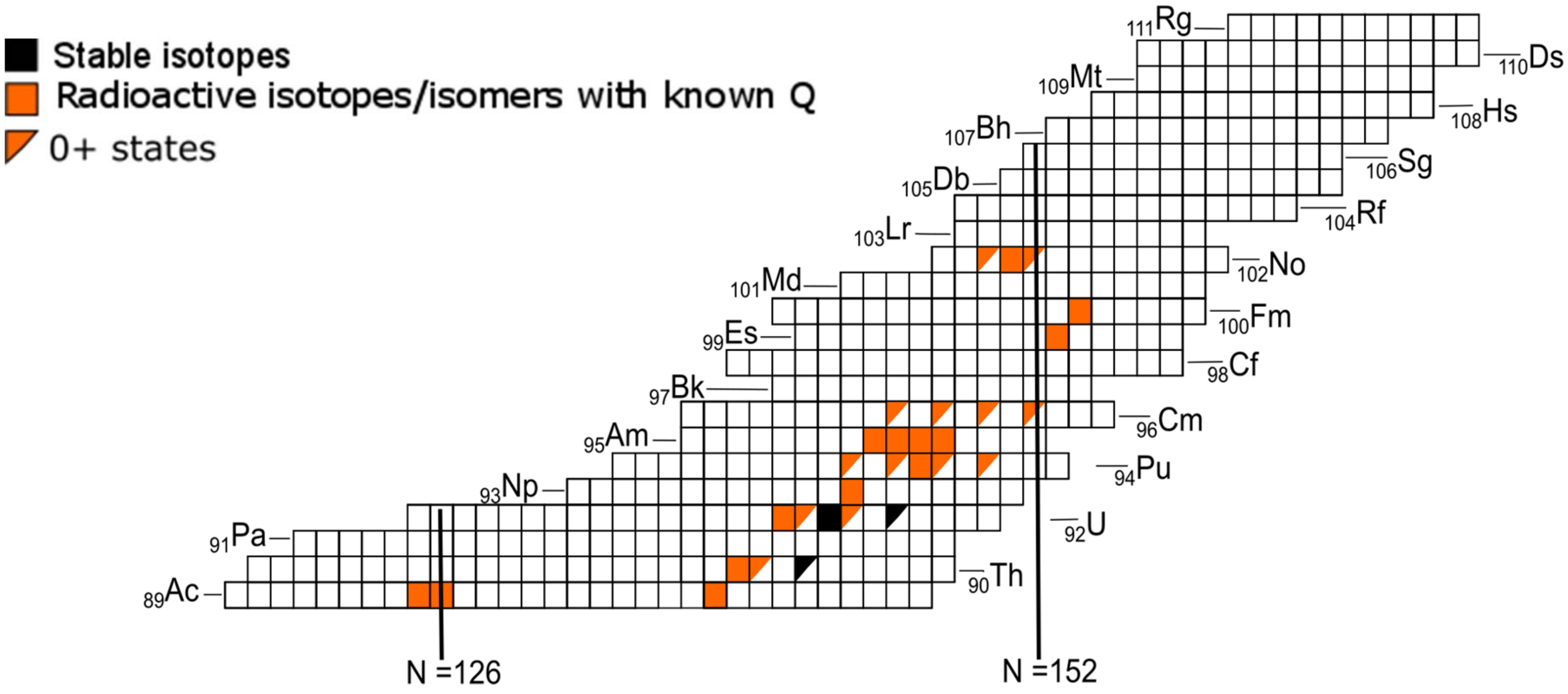
Quadrupole Moment



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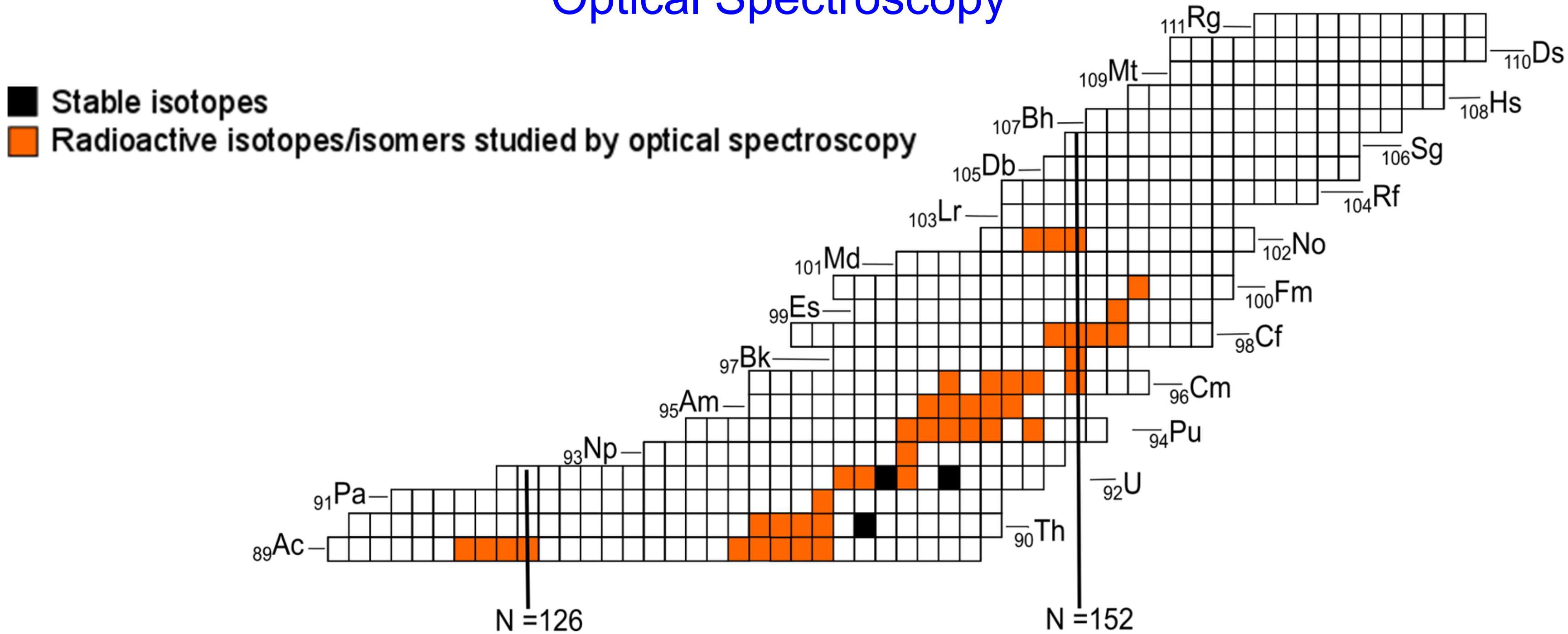
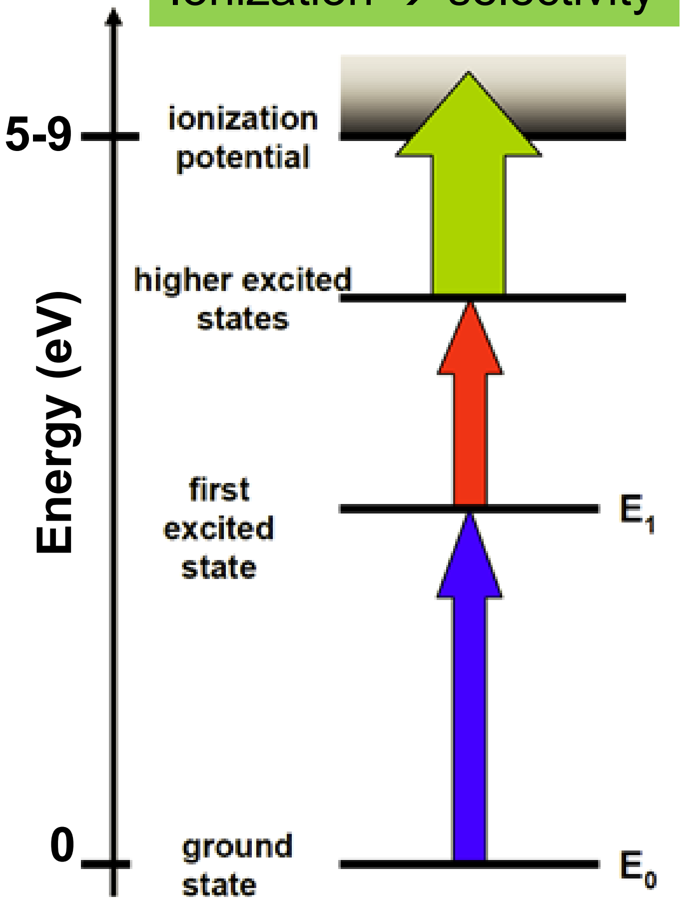
Optical Spectroscopy



- Production mechanism:
  - heavy-ion fusion evaporation reactions
- Low production rates of actinides and trans-actinides:
  - highly sensitive and efficient laser spectroscopy technique
- Short half life:
  - fast technique
- Resolving the hyperfine structure:
  - High spectral resolution to resolve hyperfine structure

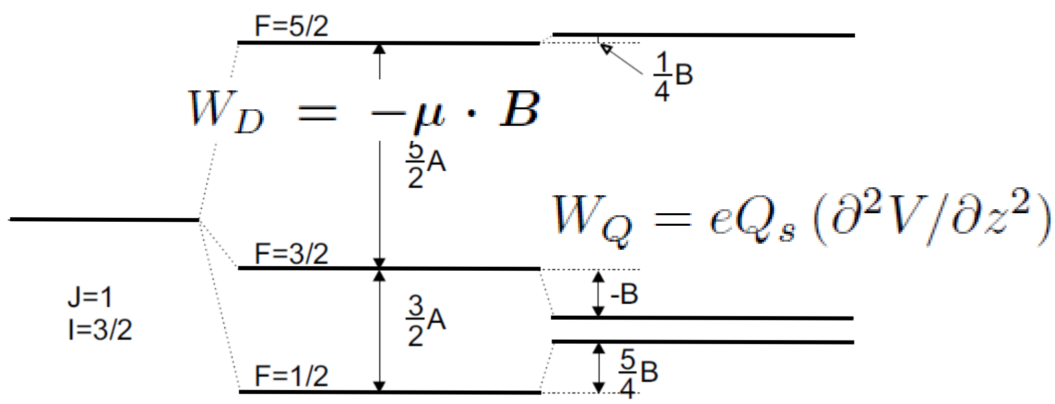
Laser Spectroscopy: basics

Ionization → selectivity



$$\vec{F} = \vec{I} + \vec{J} \quad \left(|I - J| \le F \le I + J\right)$$

Hyperfine Splitting



$$W_F = \frac{1}{2}AC + B\,\frac{\frac{3}{4}C(C+1) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}$$

$$C = F(F+1) - I(I+1) - J(J+1).$$

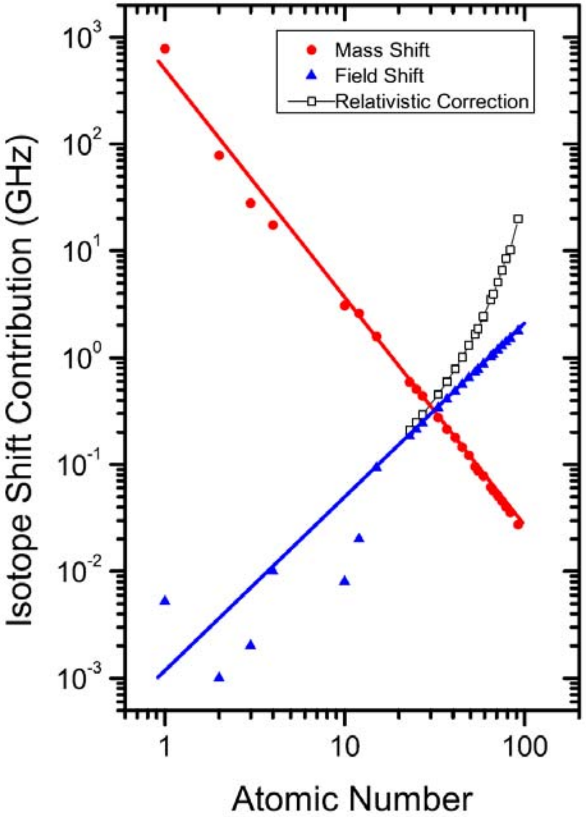
$$A = \mu_I B_e(0)/(IJ)$$

$$B = eQ_S V_{ZZ}(0)$$

Laser Spectroscopy: basics

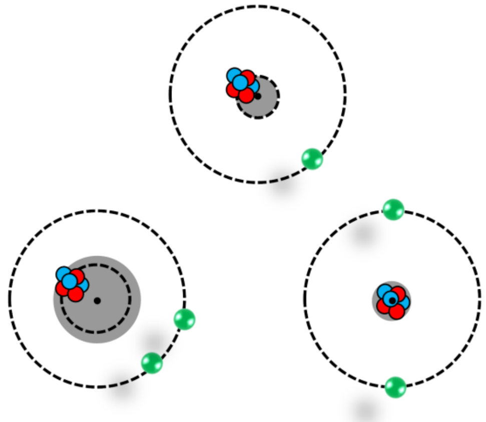
Isotope Shift

$$\delta\nu_{\mathrm{IS}}^{AA'} = K_{\mathrm{MS}} \cdot \frac{M_{A'} - M_A}{M_A M_{A'}} + \frac{2\pi Z e}{3} \Delta \left|\Psi(0)\right|^2 \, \delta \left\langle r^2 \right\rangle^{AA'}$$

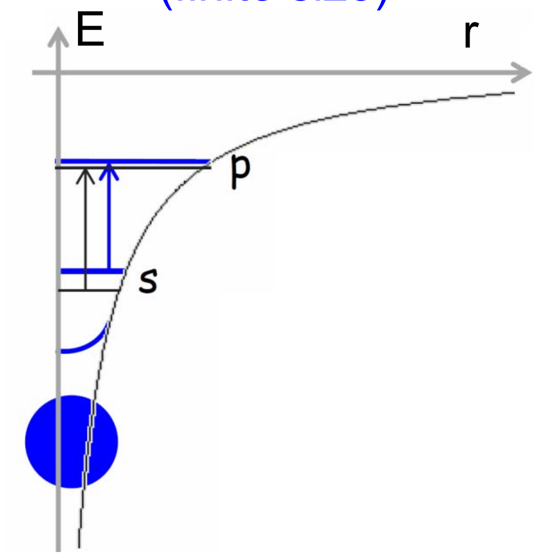


Blaum, Dilling, Nörtershäuser
Phys. Scr. T152 (2013)

Mass shift
(center of mass motion)



Field shift
(finite size)



courtesy W. Nörtershäuser
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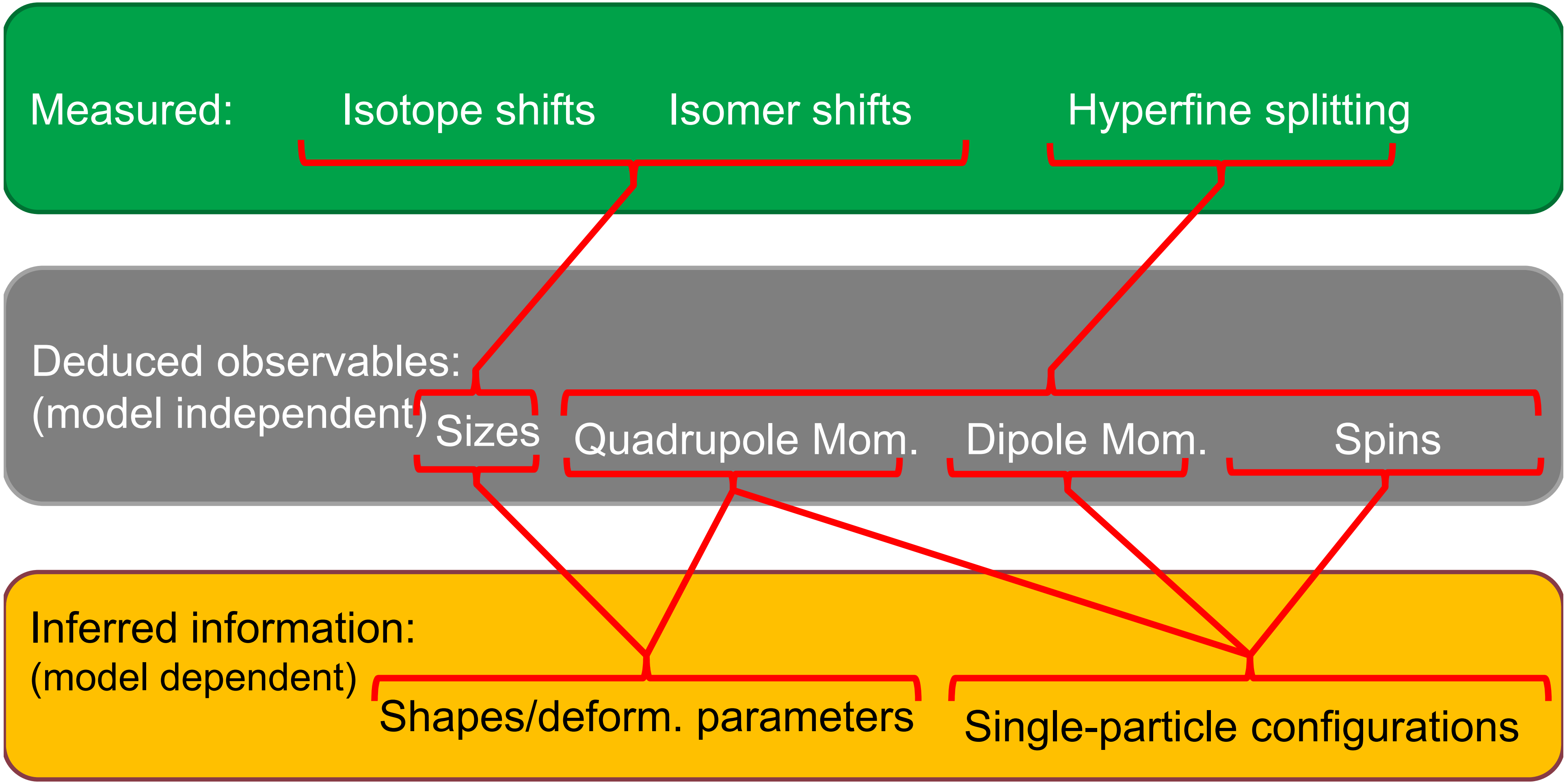
Laser Spectroscopy: basics



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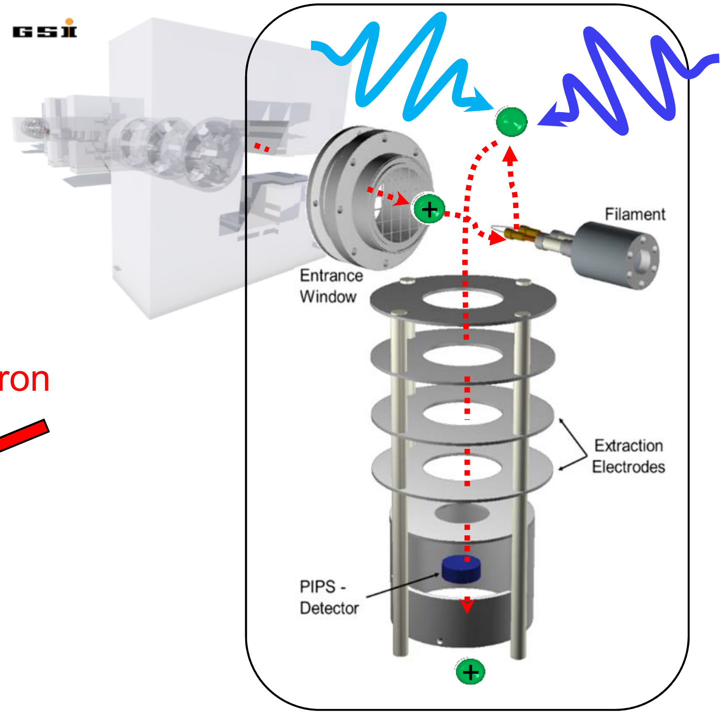
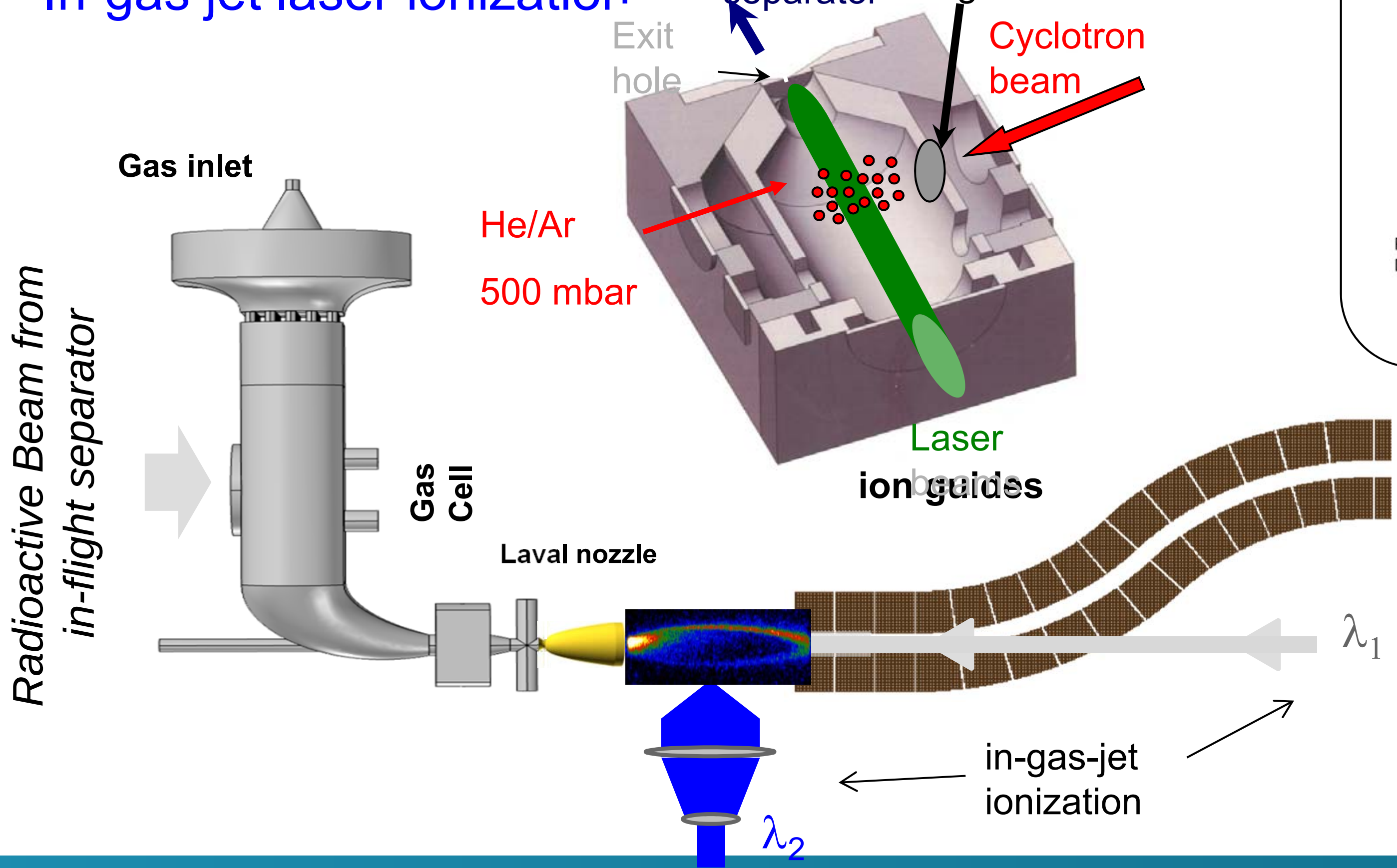
In-Gas Laser Ionization and Spectroscopy - IGLIS

- In-gas cell laser ionization
  - Detection in the gas cell (Mainz - GSI)
  - Detection after mass separation (KU Leuven - LISOL)

- In-gas jet laser ionization





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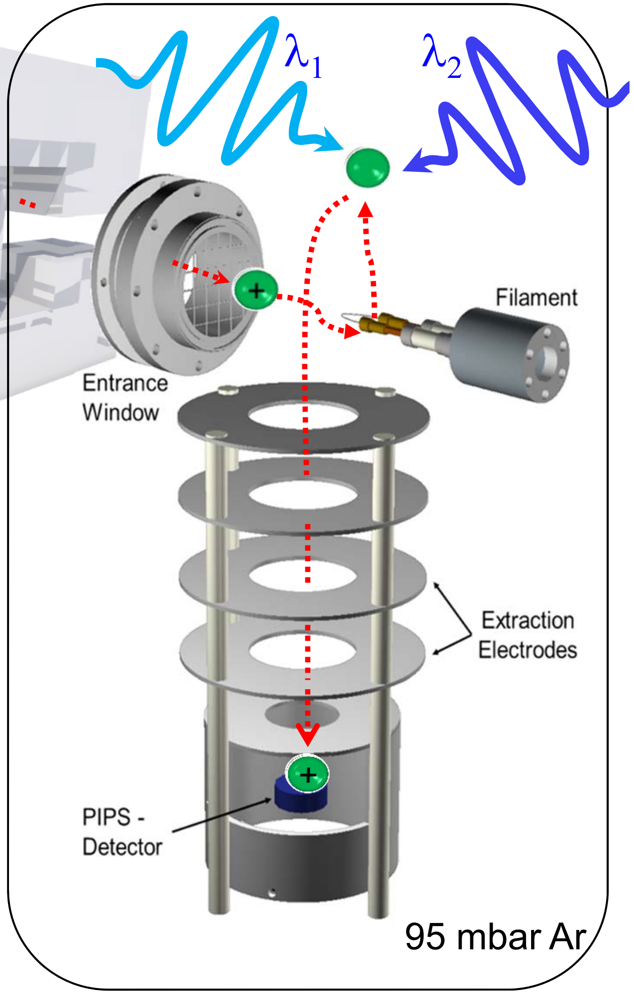
Radiation Detected Resonance Ionization Spectroscopy (RADRIS)

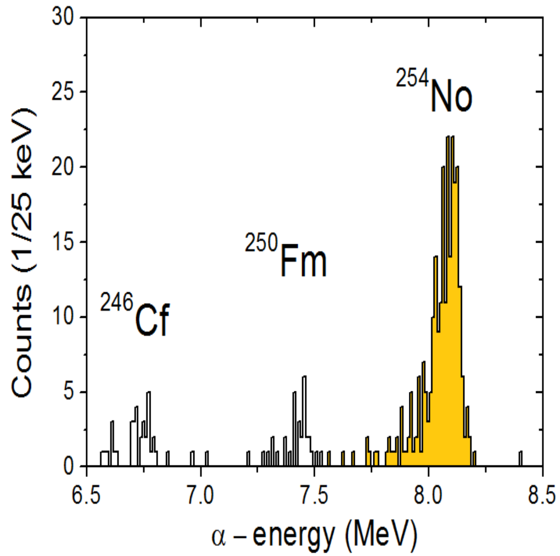
^{254}No ($T_{½}$ = 55 s; I=0)

^{208}Pb(^{48}Ca,2n)^{254}No (SHIP at GSI)

σ=2050 nb → 4 s^{-1}@ gas cell

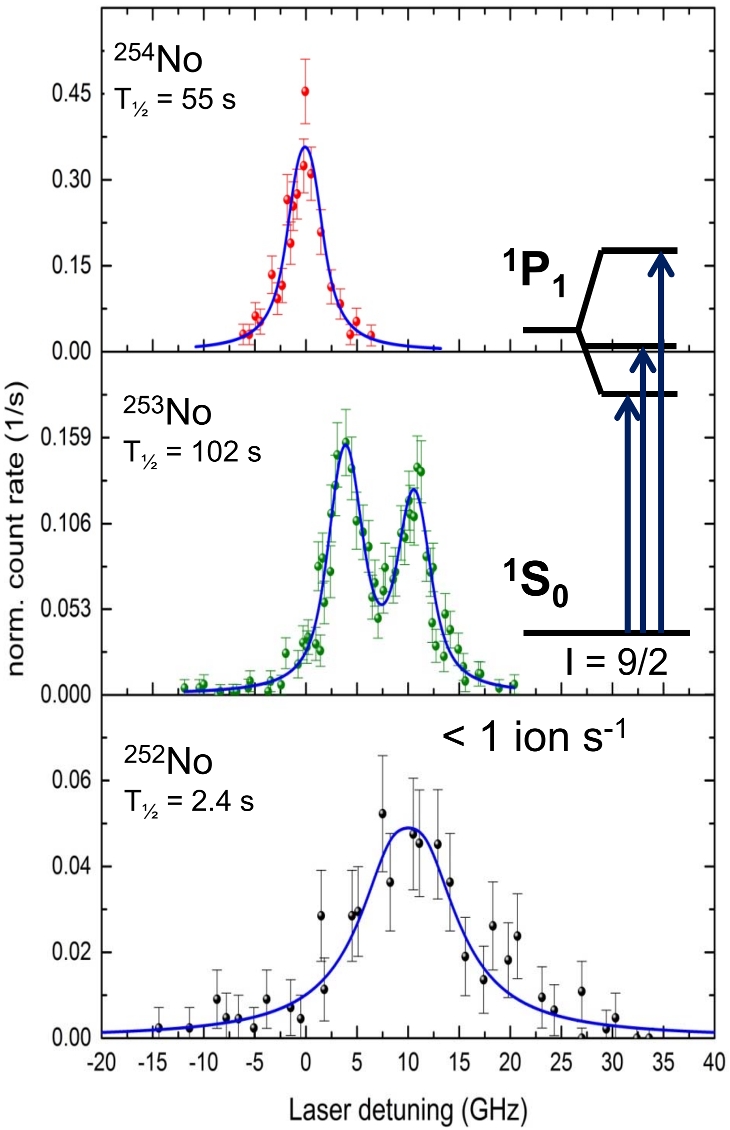
- Thermalizing of incoming fusion products
- Collecting onto thin tantalum wire
- Evaporation and two-step photoionization process
- Transport to detector and detection of alpha decay



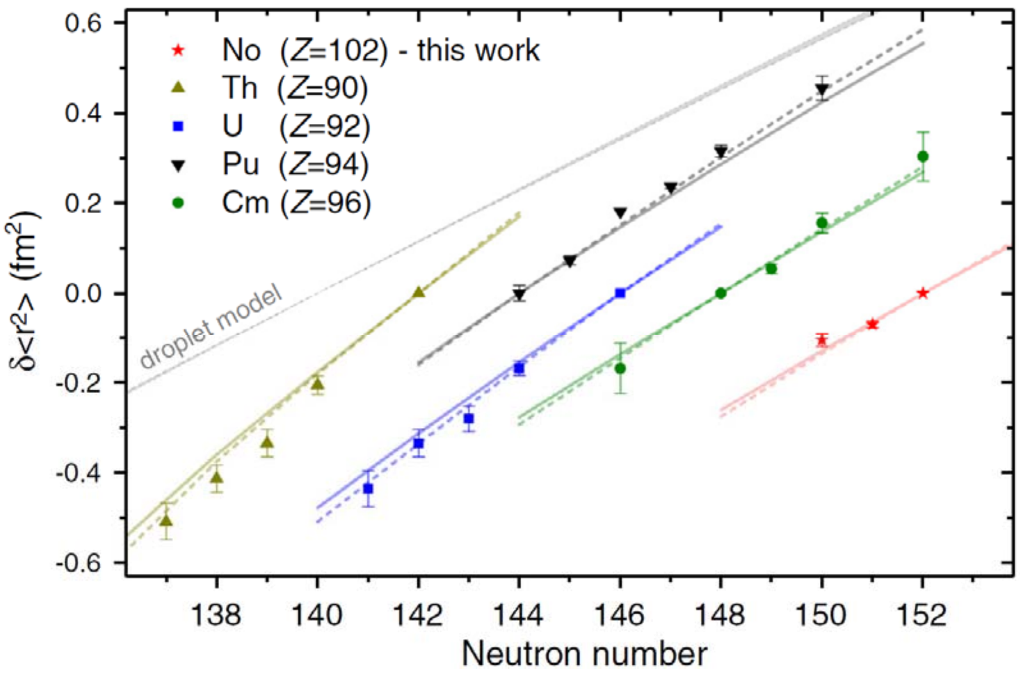


H. Backe et al., Eur. Phys. J. D 45 (2007), M. Laatiaoui et al., Nature 538 (2016)

Laser ionization spectroscopy of $^{252,253,254}No$



- Theory-guided search for the atomic transition
- Ionization potential
- Isotope shift for $^{252-254}No$ measured
- Change in charge radii: Input from atomic theory

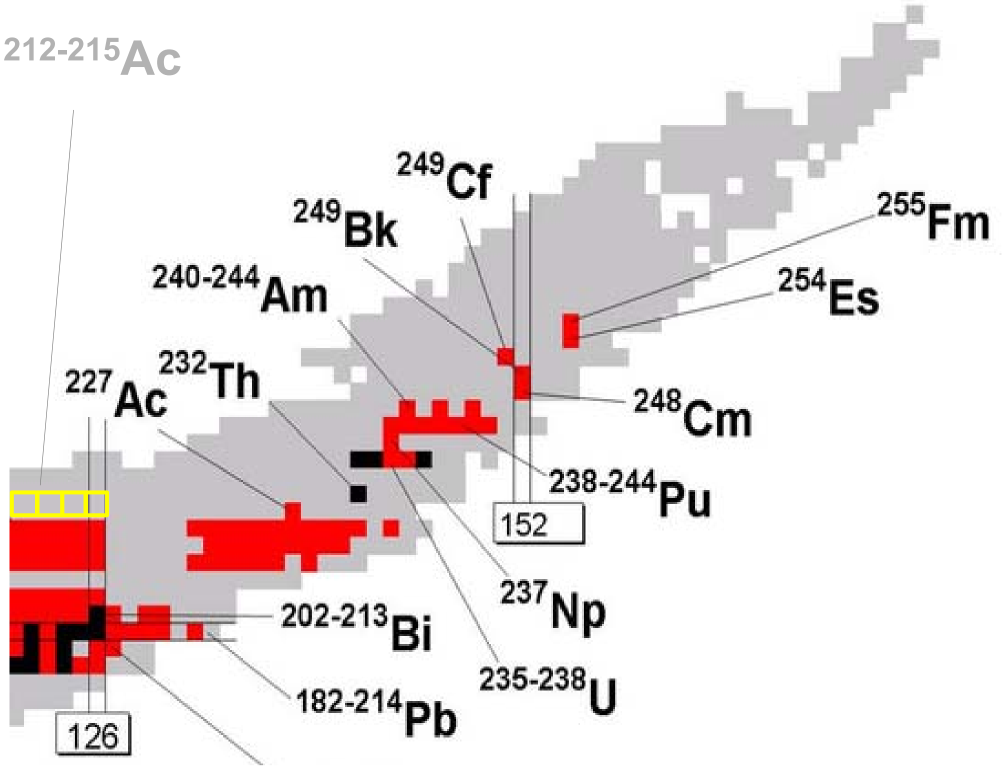


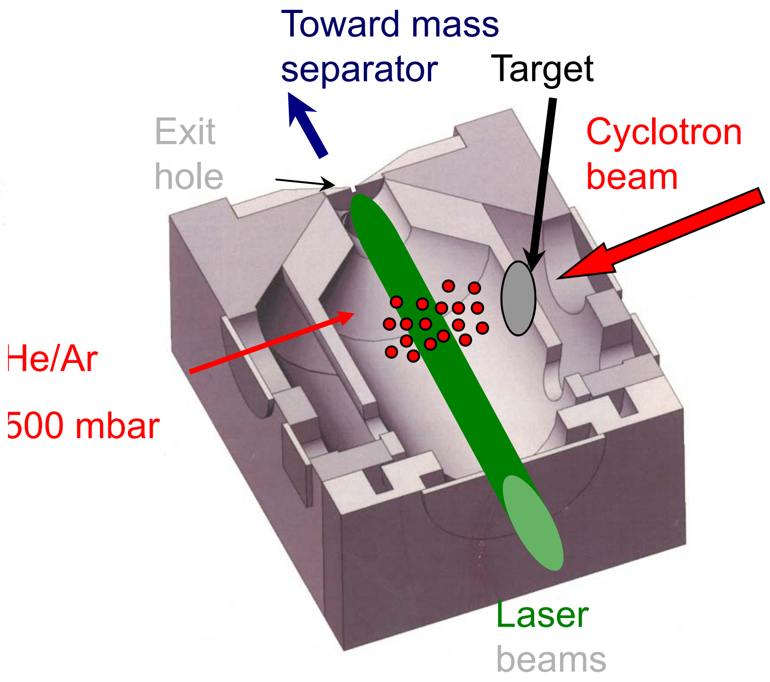
- Nuclear moments of ^{253}No

	μ (μ_N)	Q_s (eb)
Laser spec. (this work)	-0.527(33)[75]	5.8(14)[8]

 M. Laatiaoui et al., Nature 538 (2016), S. Raeder et al., PRL120 (2018), P. Chhetri et al., PRL120 (2018)

Leuven Isotope Separator On-Line (LISOL) facility:
In-Gas Laser Ionization and Spectroscopy of RIBs (IGLIS)





^{197}Au(^{20}Ne-145 MeV,4-5n)^{212,213}Ac

^{197}Au(^{22}Ne-143 MeV,4-5n)^{214,215}Ac

Yu. Kudryavtsev et al., NIM B 114 (1996) 350, T. Cocolios et al., PRL 103 (2009)
M . Facina et al., NIM B 226 (2004) 401, R. Ferrer et al., PLB 728 (2014)

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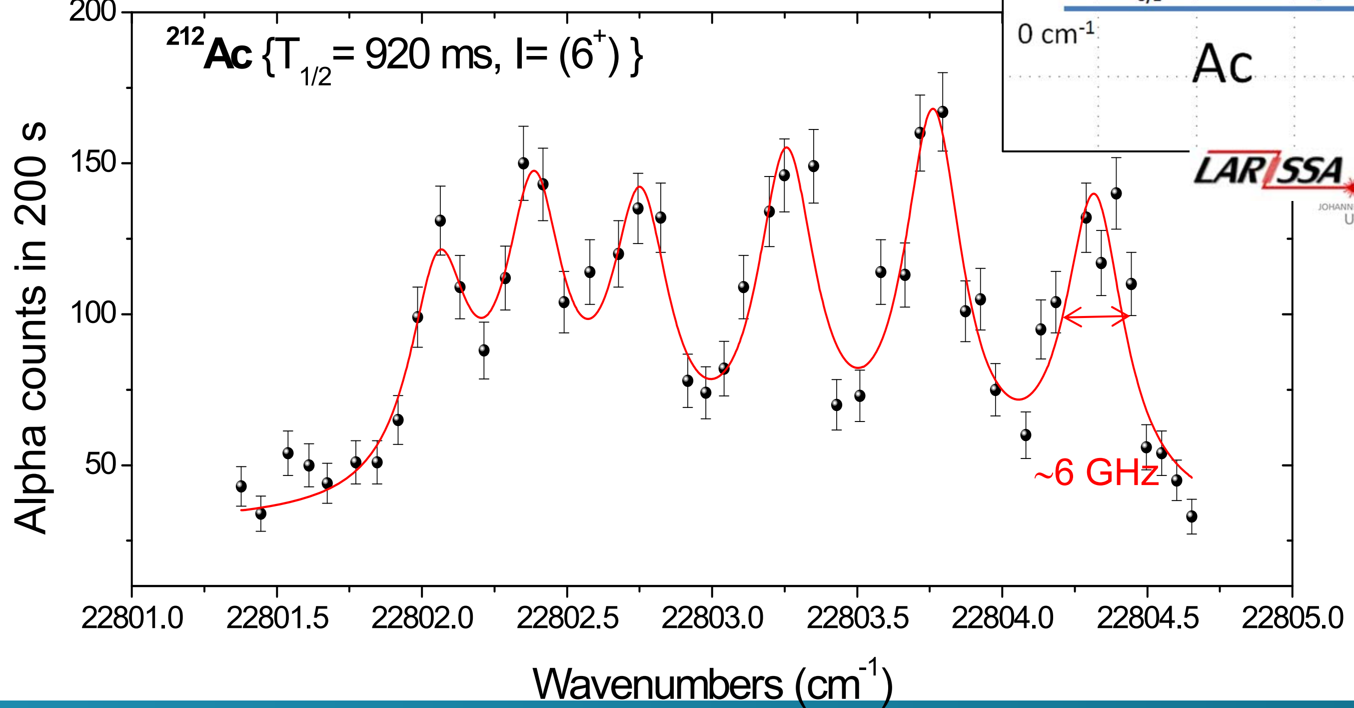
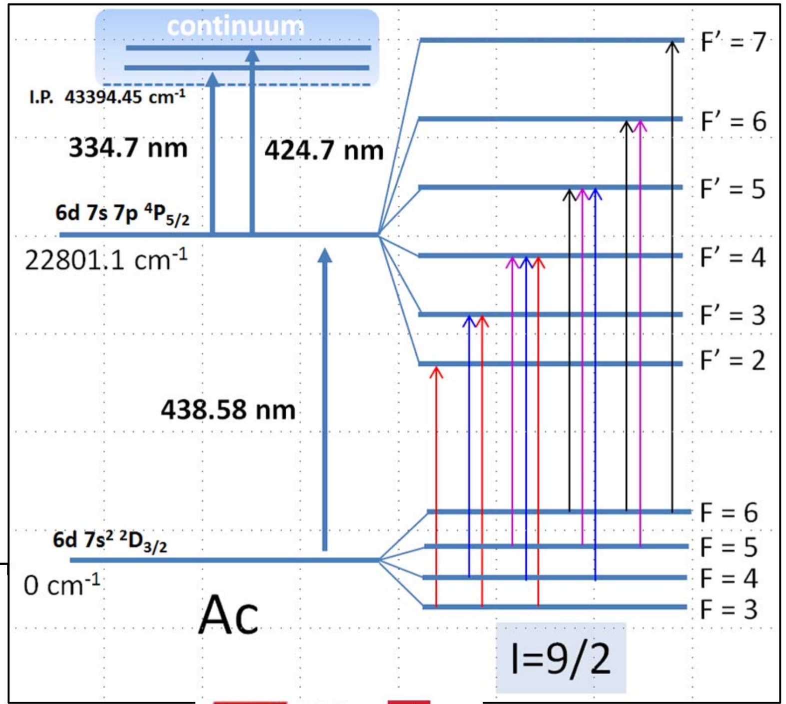
Production & first laser spectroscopy tests of Ac

Limitations of in-gas cell laser spectroscopy:

- Pressure shift and broadening
- Doppler broadening
- Ion-gas interactions

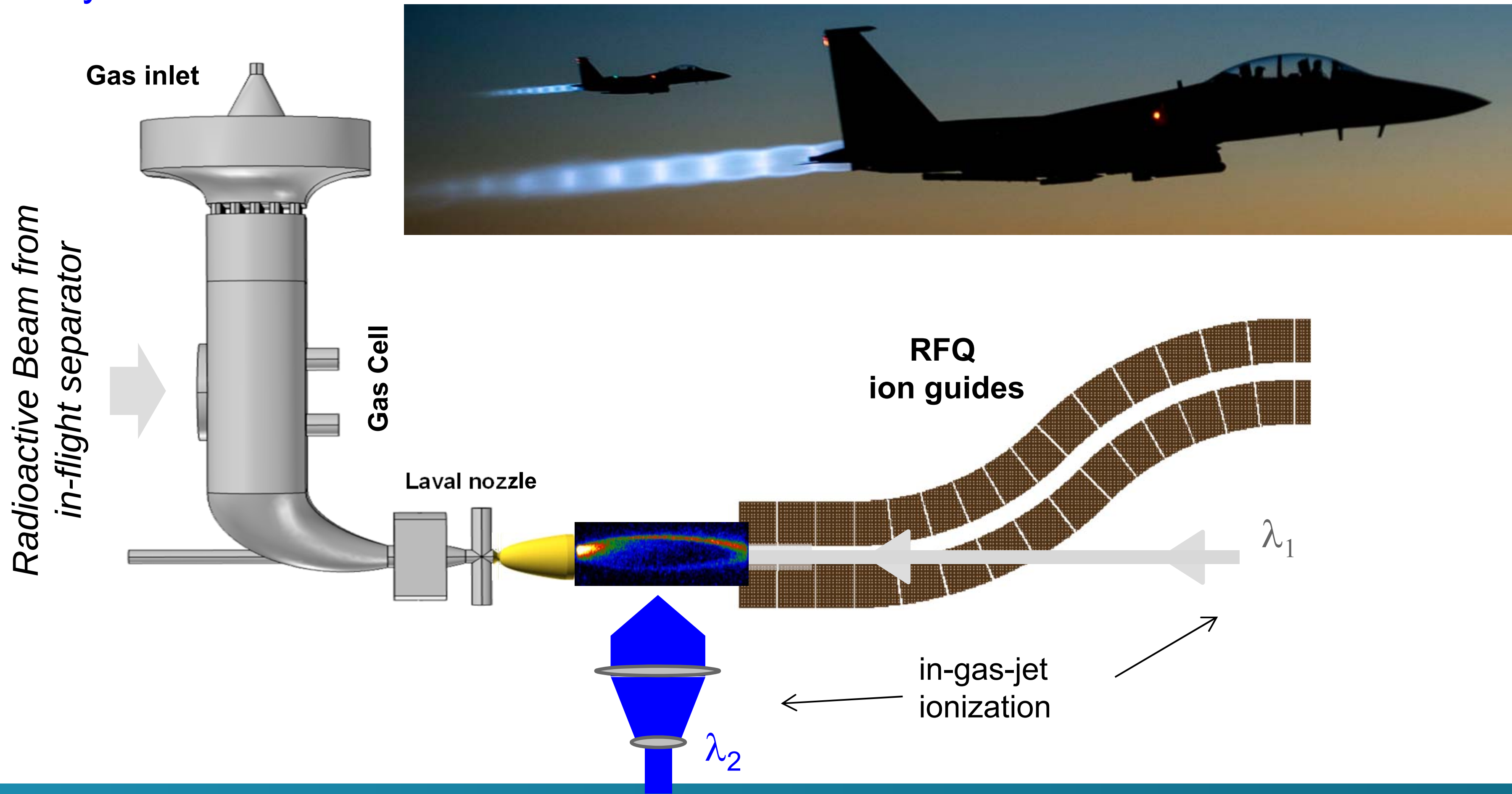




LARISSA
JGU JOHANNES GUTENBERG UNIVERSITÄT MAINZ

In-Gas Jet Laser Ionization Spectroscopy

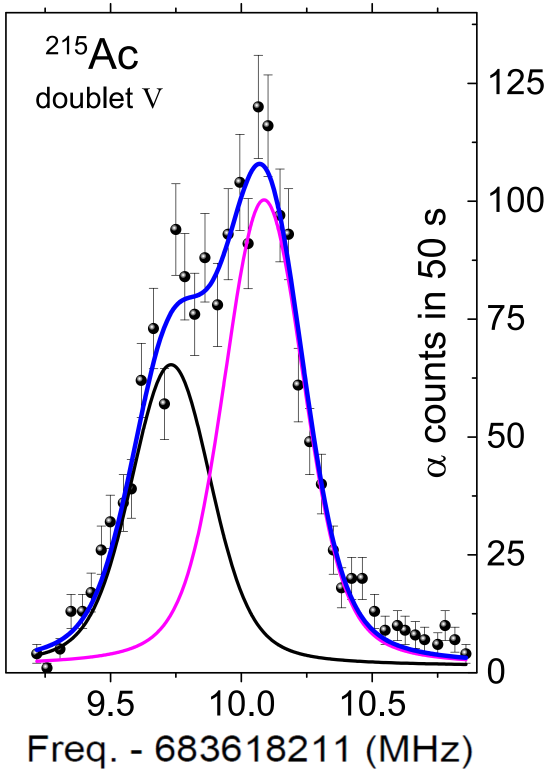
- stopping in the buffer gas cell
- formation of a gas jet through a 'de Laval' nozzle
- homogenous, low-density, cold supersonic gas-jet
- transport of the ions in Radio Frequency Ion Guides → purification/detection system

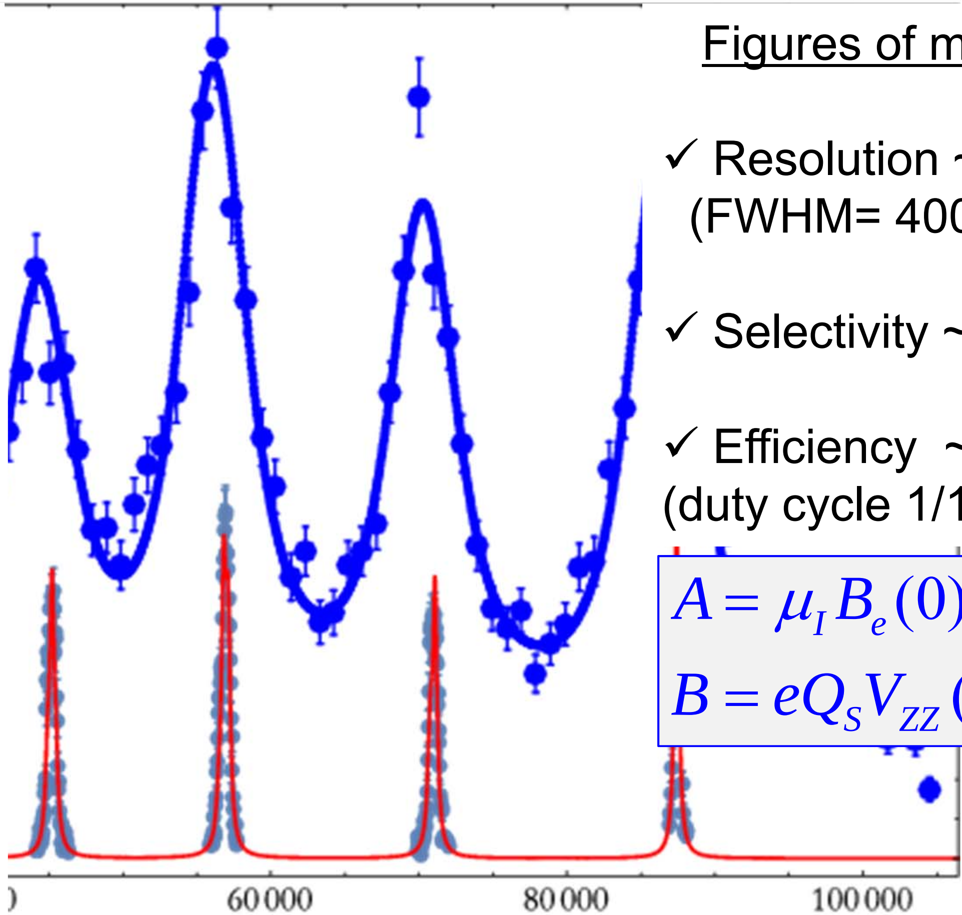


R. Ferrer et al, Nature Commun. 8, 14520 (2017)
Yu. Kudryavtsev et al, NIMB61724, (2016) pp. 345-352

In-Gas Jet versus In-Gas Cell Laser Ionization Spectroscopy

^{215}Ac $T_{1/2}$ = 0.17 s J_π = (9/2$^-$)





Figures of merit:

- ✓ Resolution ~ 5 10^{-7} (FWHM= 400 MHz)
- ✓ Selectivity ~ 200
- ✓ Efficiency ~ 0.4% (duty cycle 1/10)

$$A = \mu_I B_e(0)/(IJ)$$

$$B = eQ_S V_{ZZ}(0)$$

- in gas cell **- in gas jet**

 R. Ferrer et al, Nature Commun. 8 (2017), Yu. Kudryavtsev et al, NIMB61 (2016)

Nuclear Moments of Ac^{227}†

MARK FRED AND FRANK S. TOMKINS, *Chemistry Division, Argonne National Laboratory, Lemont, Illinois*

AND

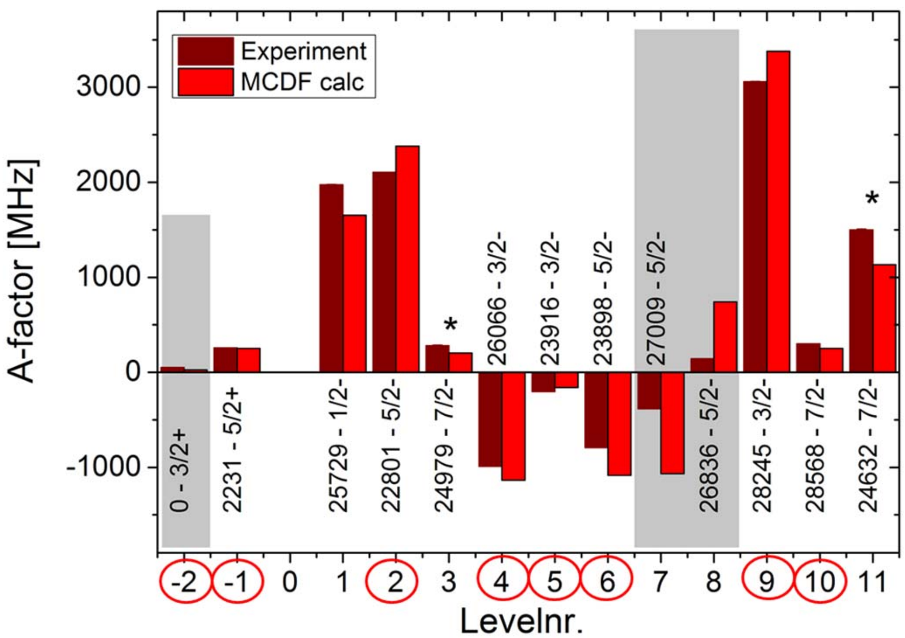
WILLIAM F. MEGGERS, *National Bureau of Standards, Washington, D. C.*

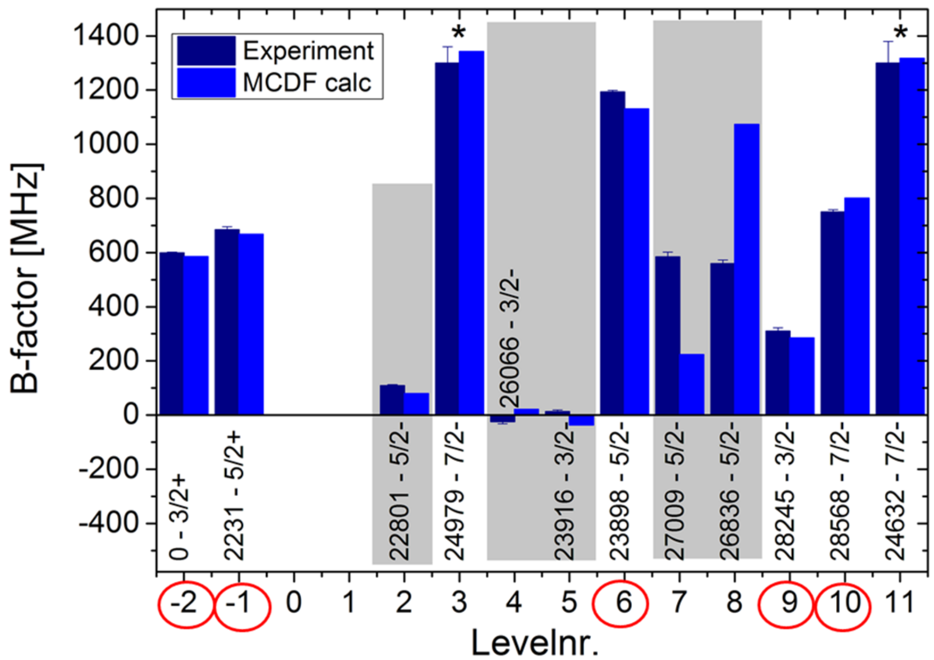
(Received April 11, 1955) Phys. Rev. 98, 1514

The values derived for the moments from the conventional treatment of hfs in intermediate coupling are +1.1 nm and -1.7×10^{-24} cm². The experimental error is believed to be less than 10 percent, but it is difficult to estimate the total error because of the configuration interaction and the large relativity corrections. No correction for closed shell distortion was made.

It is hoped that improved values can be obtained, but meanwhile it appears useful to offer the present results. We should like to acknowledge helpful discussions with Dieter Kurath and R. E. Trees.

Multi-Configuration Dirac Fock atomic physics calculations: ^{227}Ac



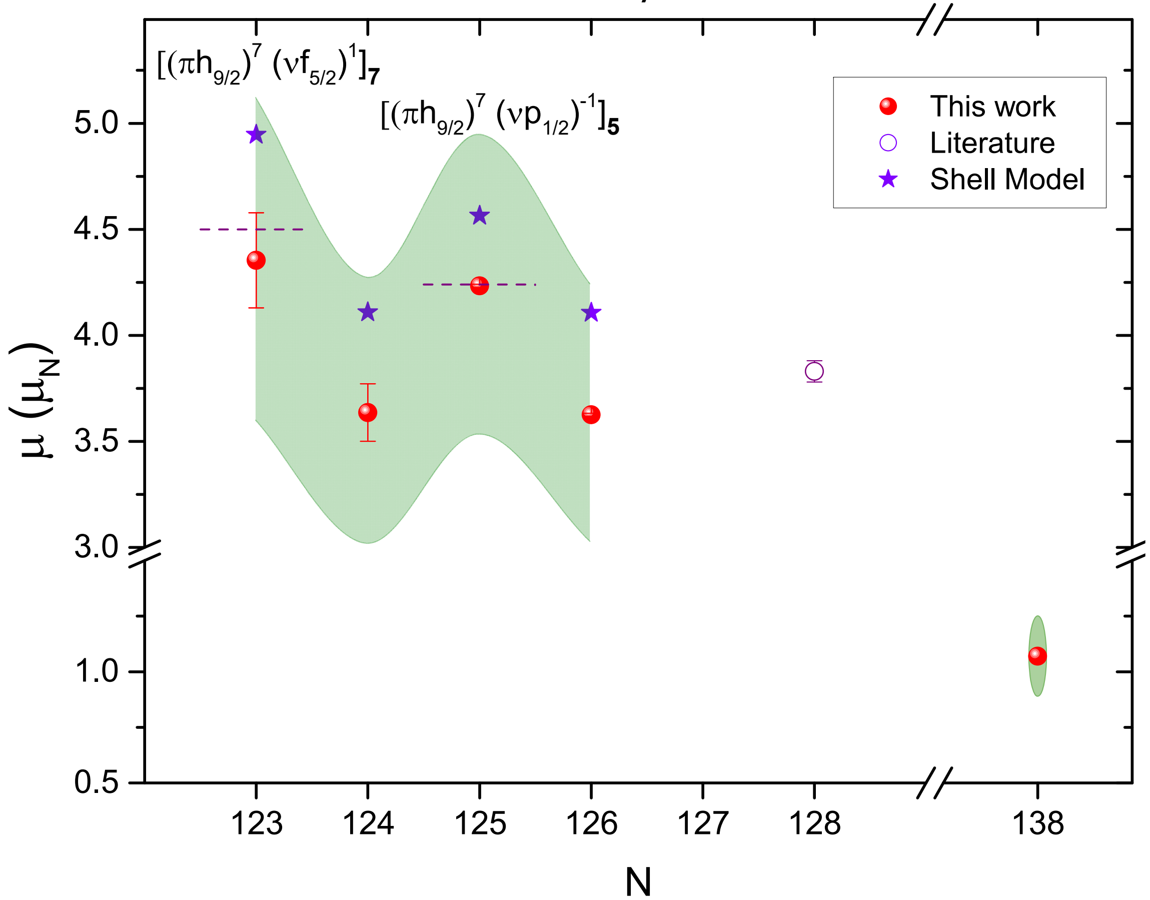


Fred,- Phys. Rev. 98 (1955)	MCDF calculations + experimental data on ^{227}Ac
$\mu_{lit.} = 1.1(1)\ \mu_N$	$\mu_{calc.} = 1.07(18)\ \mu_N$
$Q_{lit.} = 1.7(2)$ eb	$Q_{calc.} = 1.74(10)$ eb

 R. Beerwerth and S. Fritzsche (2016)

Magnetic dipole moments and electical quadrupole moments

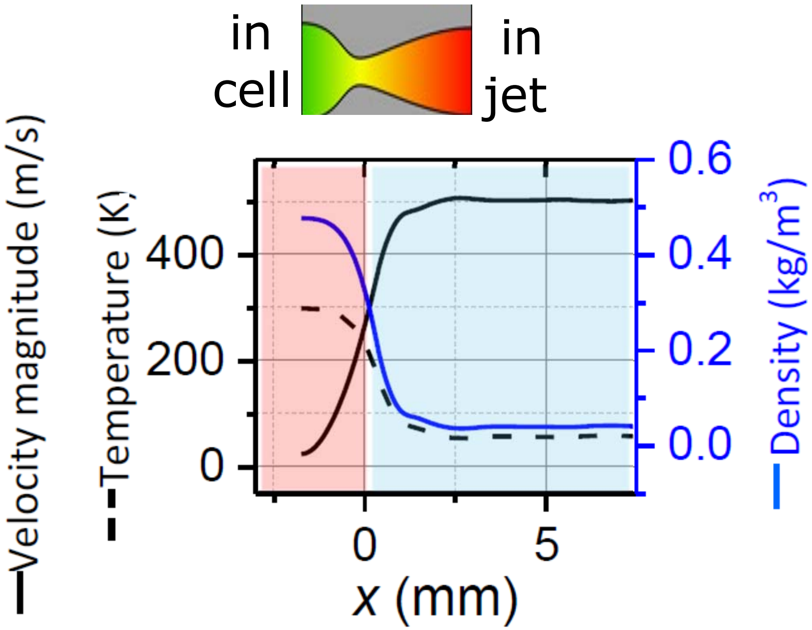
$$\mu^{exp.} = \frac{A^{exp} \cdot I^{exp}}{A^{227} \cdot 3/2} \cdot \mu^{227}_{calc.}$$



- Shell model calc. are in good agreement with experimental quadrupole moments (using atom. physics input) and magnetic dipole moments
- ^{208}Pb good core for shell model predictions (N=126)

C. Granados,- PRC96 (2017) 054331

In-Gas Jet: Expected Performances

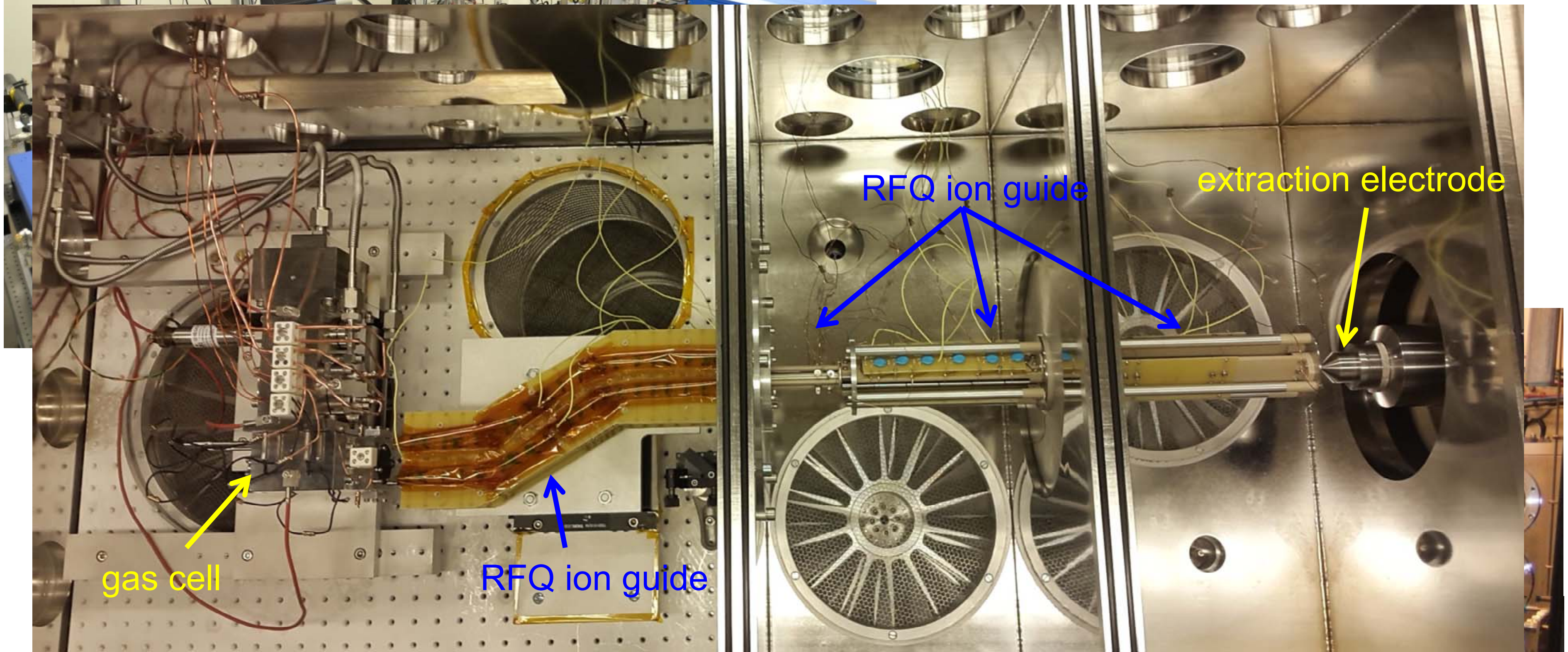


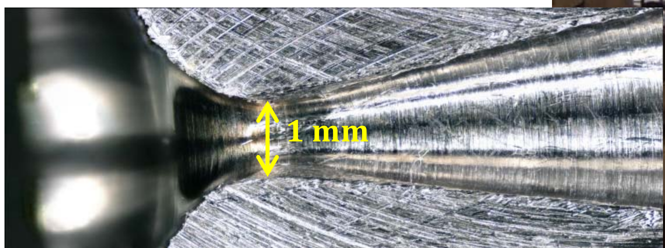
- collisions $\Delta\vartheta_\rho \sim \left(\frac{T_{jet}}{T_{293K}}\right)^{0.3} * \rho_{jet}$
- temperature $\Delta\vartheta_{Doppler} \sim \vartheta_0 \sqrt{T_{jet}/_A}$

	Gas cell	Gas jet	Gas jet (projected)
Linewidth (FWHM), MHz	5800	394	~ 100
Efficiency, %	0.42	0.40	> 10

 Y. Kudryavtsev et al., NIM B297 (2013) 7

- ✓ Laser system (10 kHz rep. rate)
- ✓ New gas cell design
- ✓ Gas-jet properties with nozzles
- ✓ RFQ Ion Guides

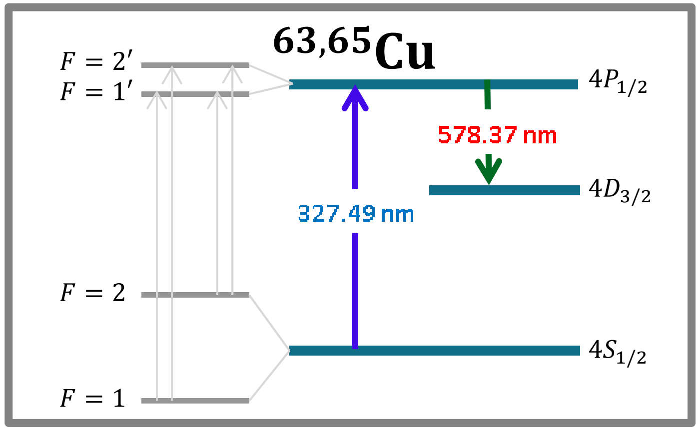


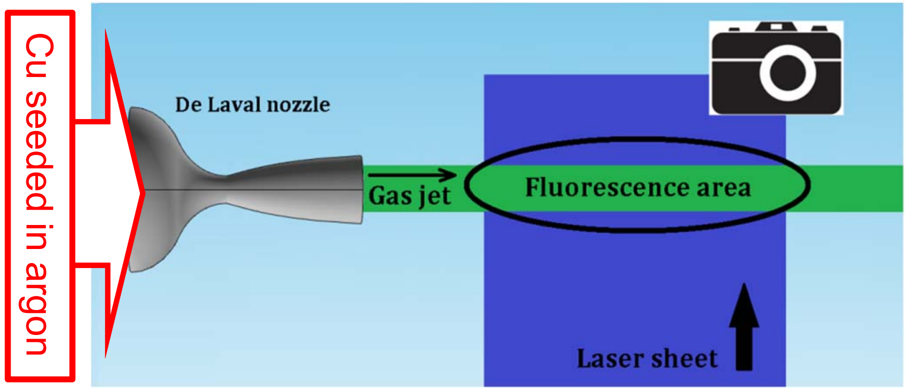


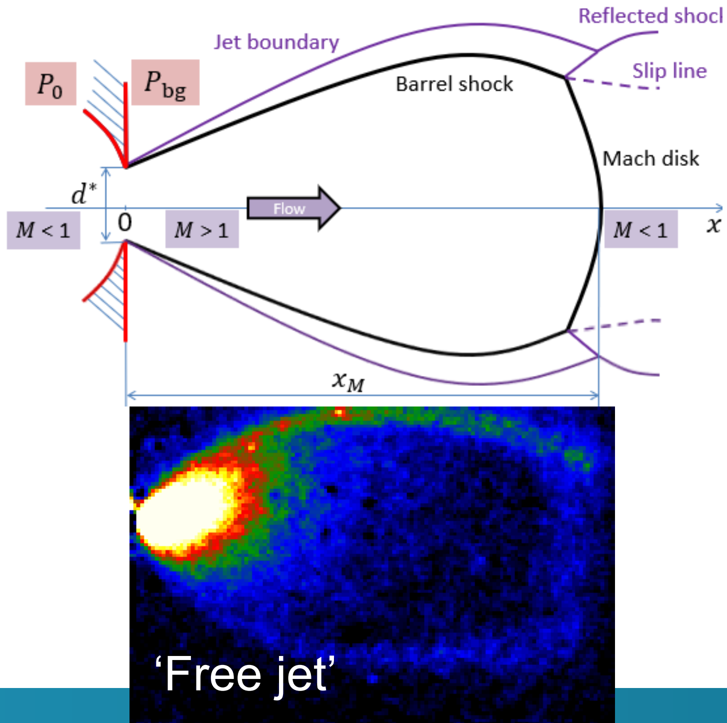
IGLIS @ KU Leuven

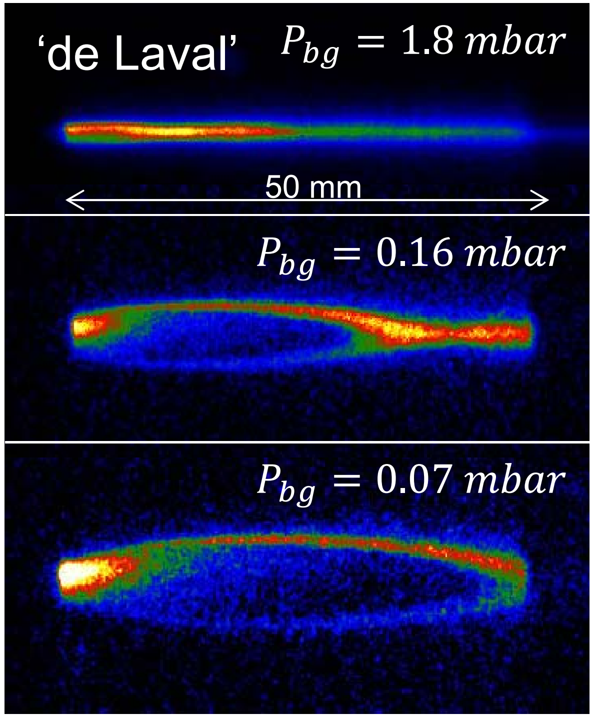
- # Planar Laser Induced Fluorescence (PLIF) - technique

→ *temperature, velocity and density jet 'maps'*





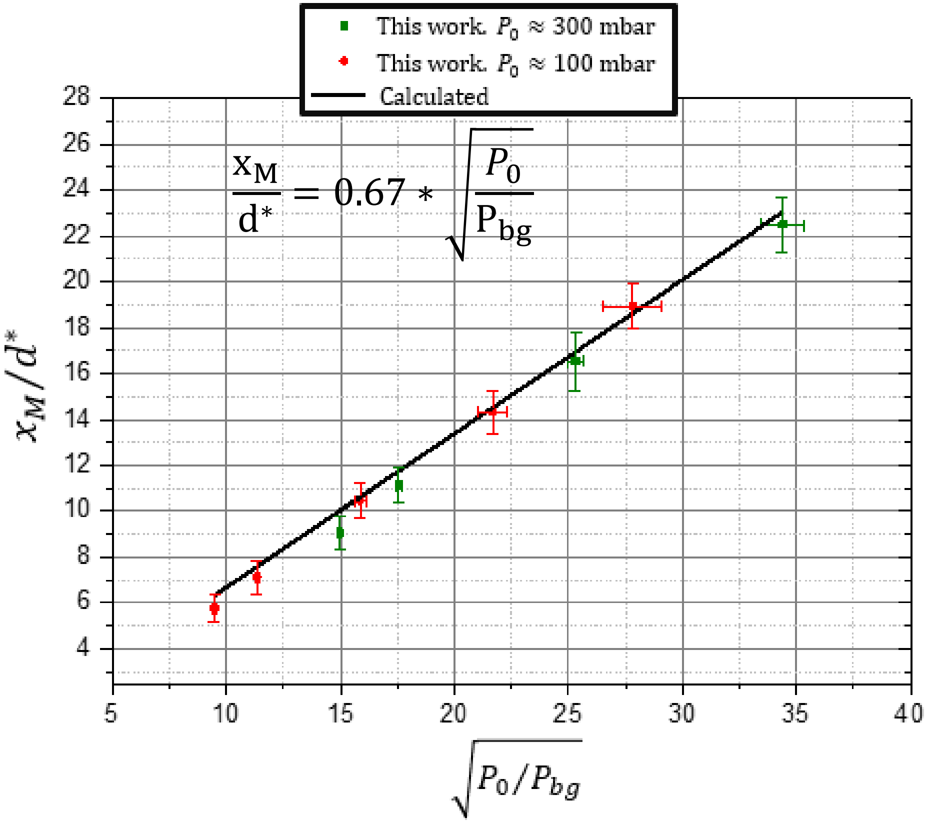


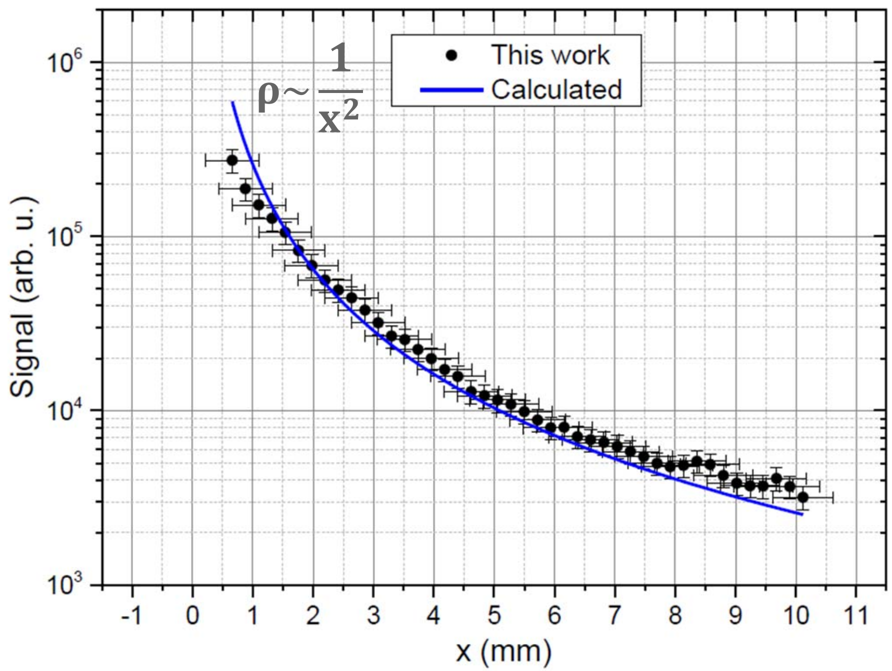


 A. Zadvornaya et al. Phys. Rev. X (2018)

Validation of PLIF-spectroscopy – Free Gas Jet

Mach disk position and density drop in the expansion zone





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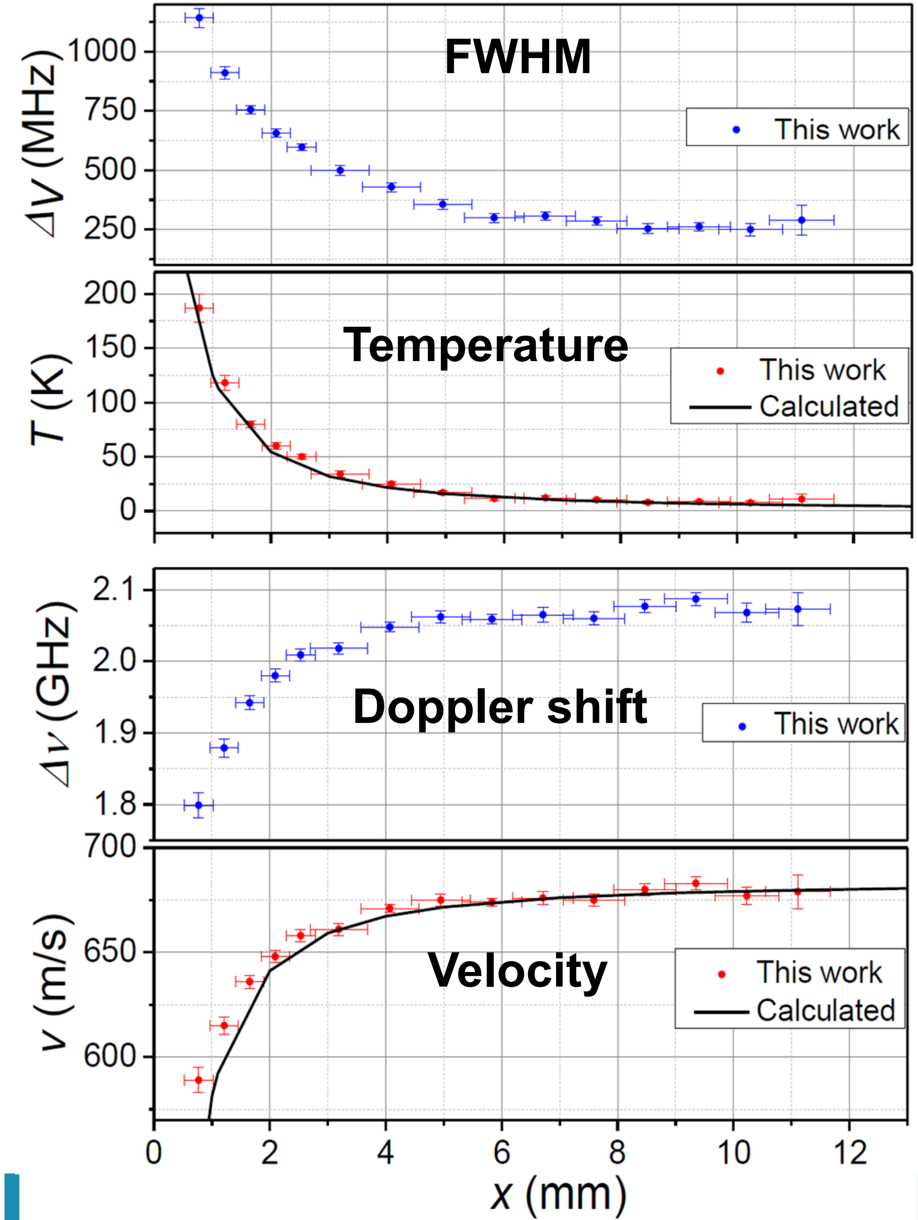
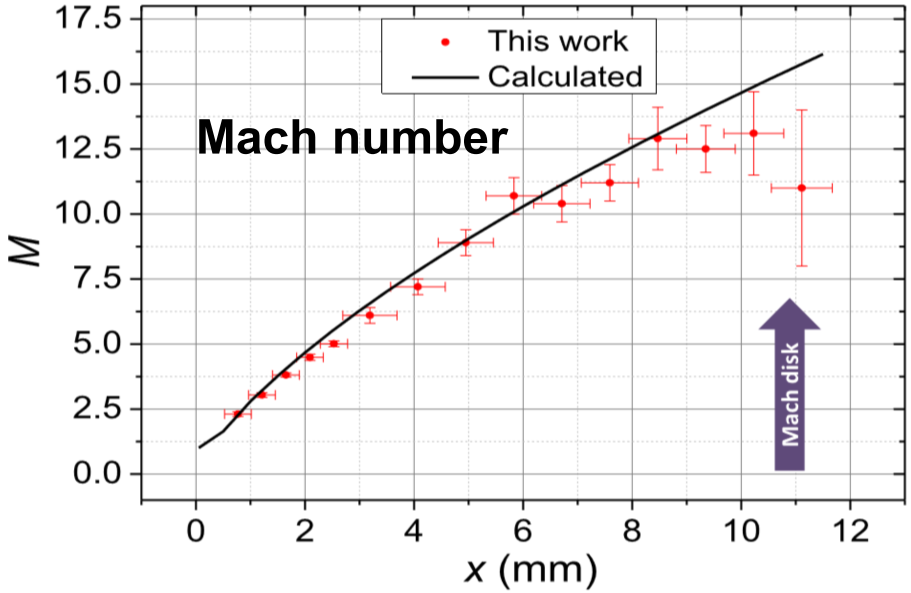
Validation of PLIF-spectroscopy – Free Gas Jet

Narrow-band laser spectroscopy on $^{63,65}Cu$



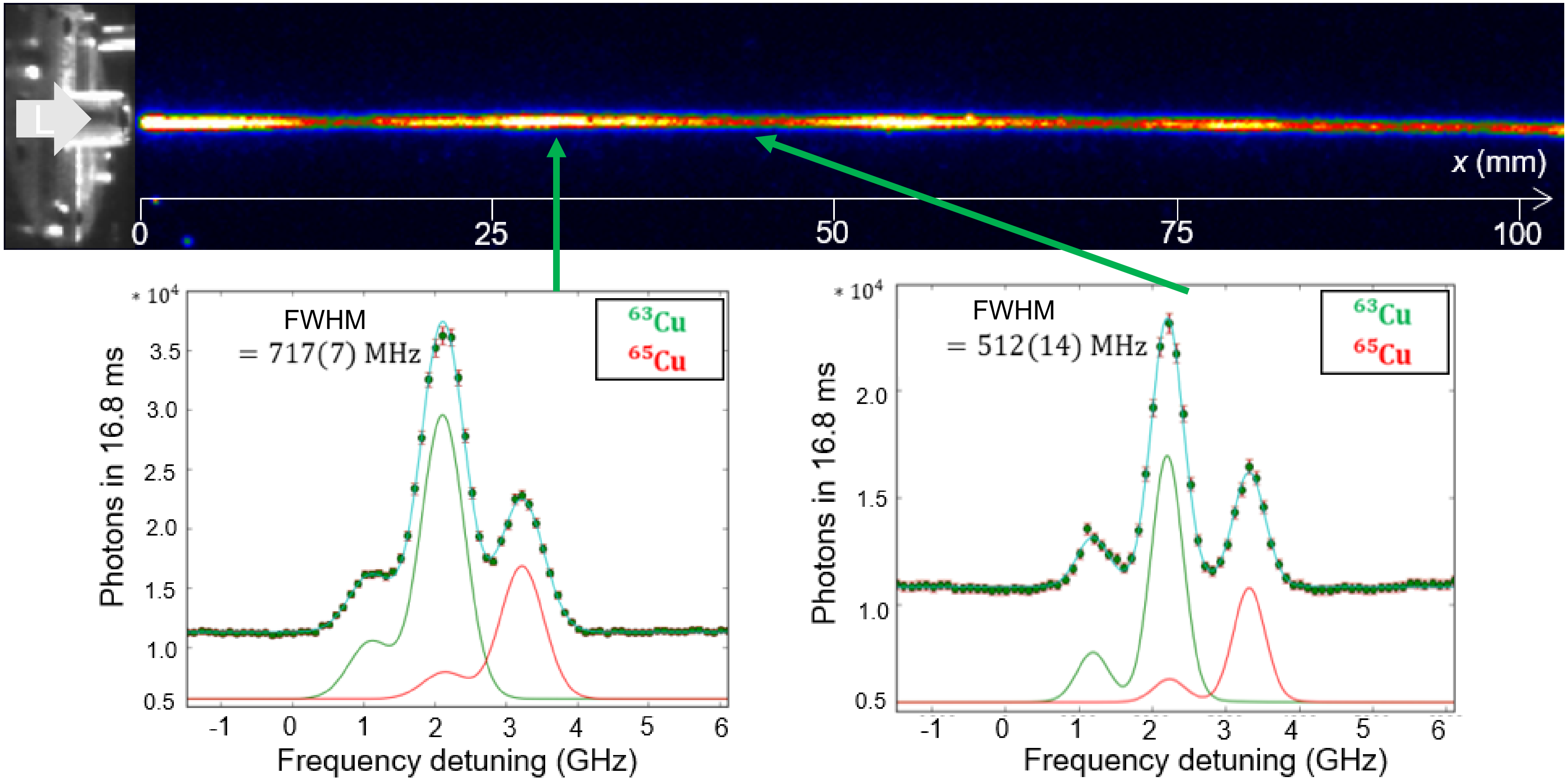
$$M = \frac{\text{flow velocity}}{\text{velocity of sound}(\leftarrow \mathit{temperature})}$$



Jets formed by de Laval nozzle

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

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



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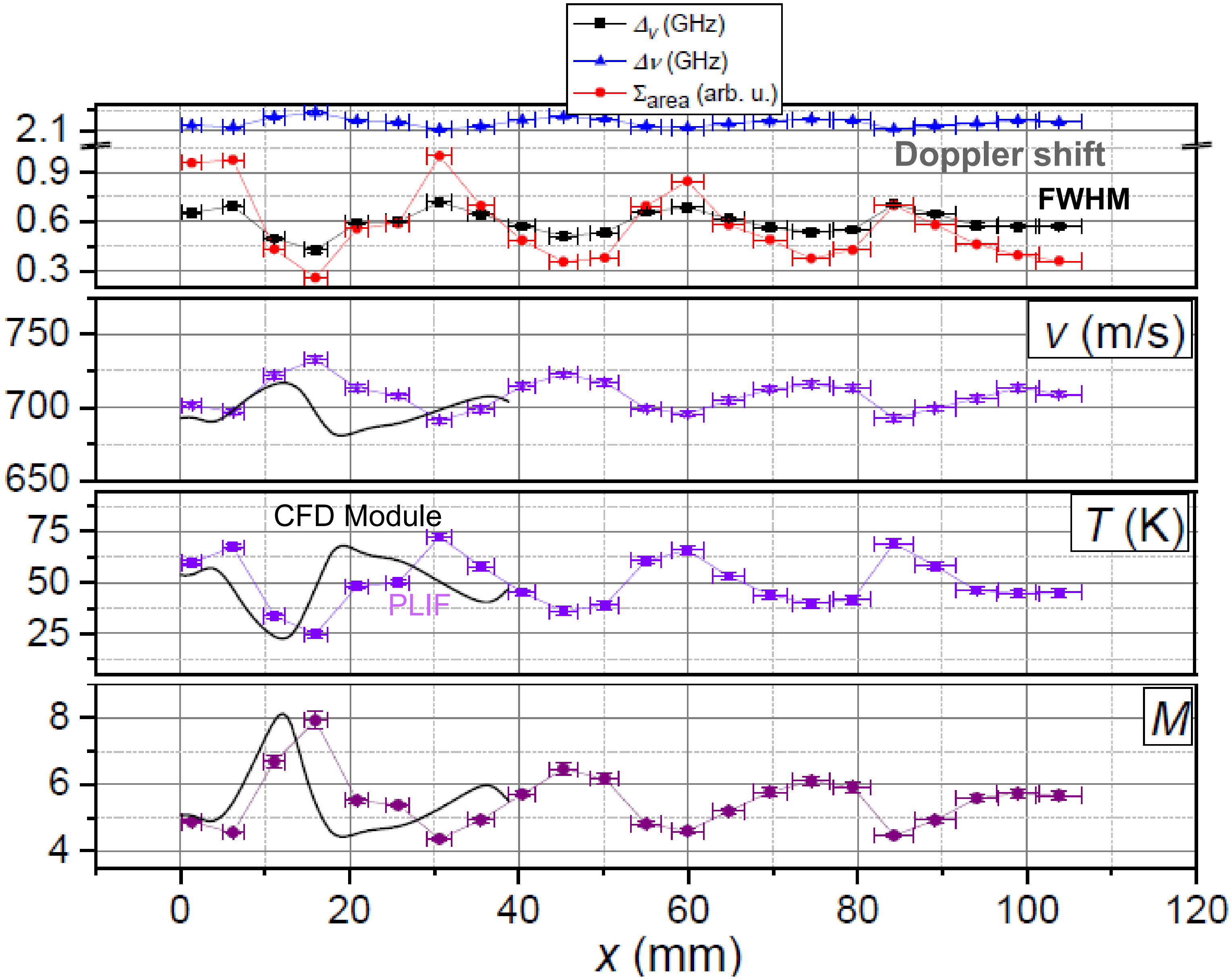
Underexpanded jet



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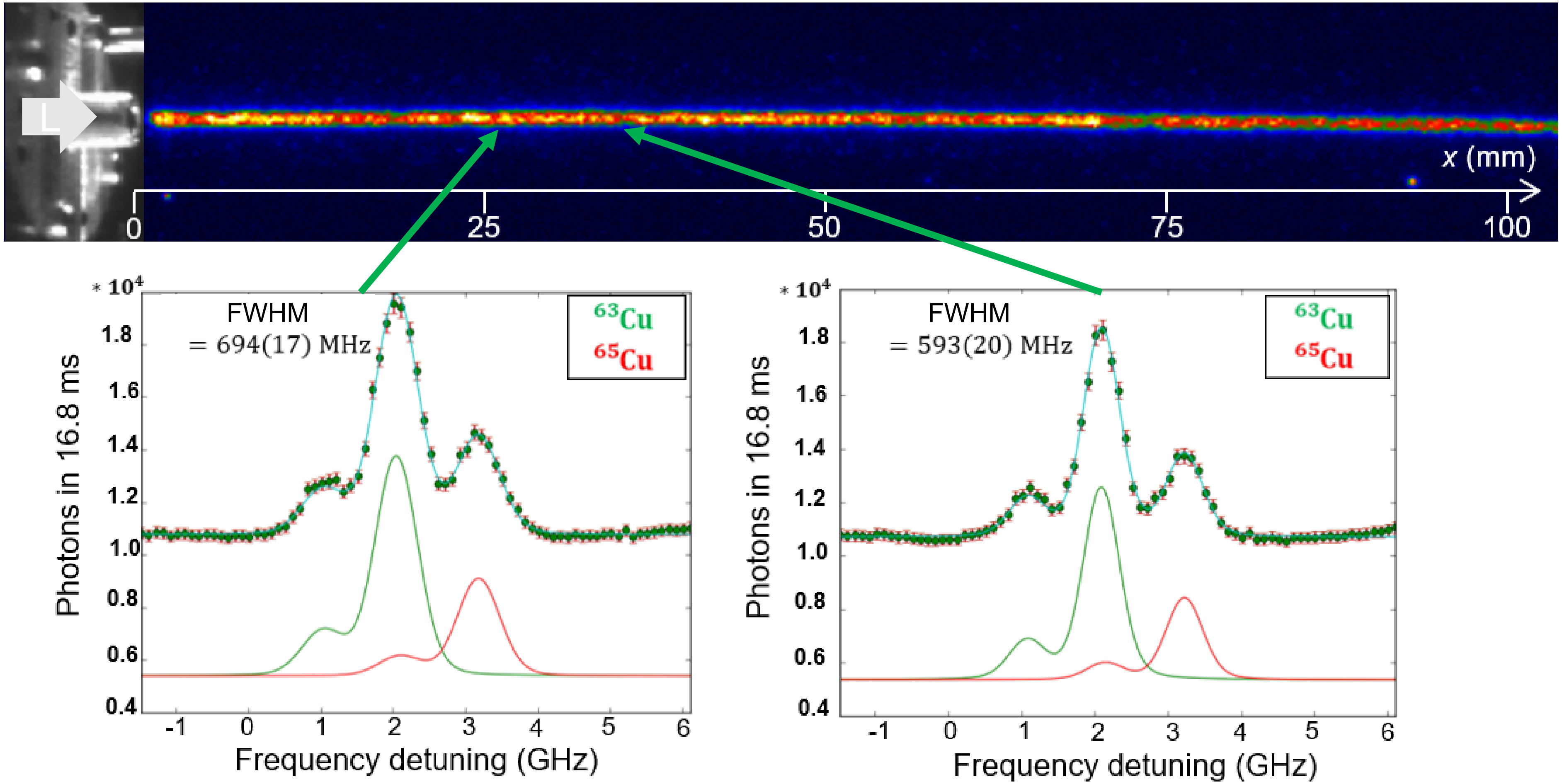
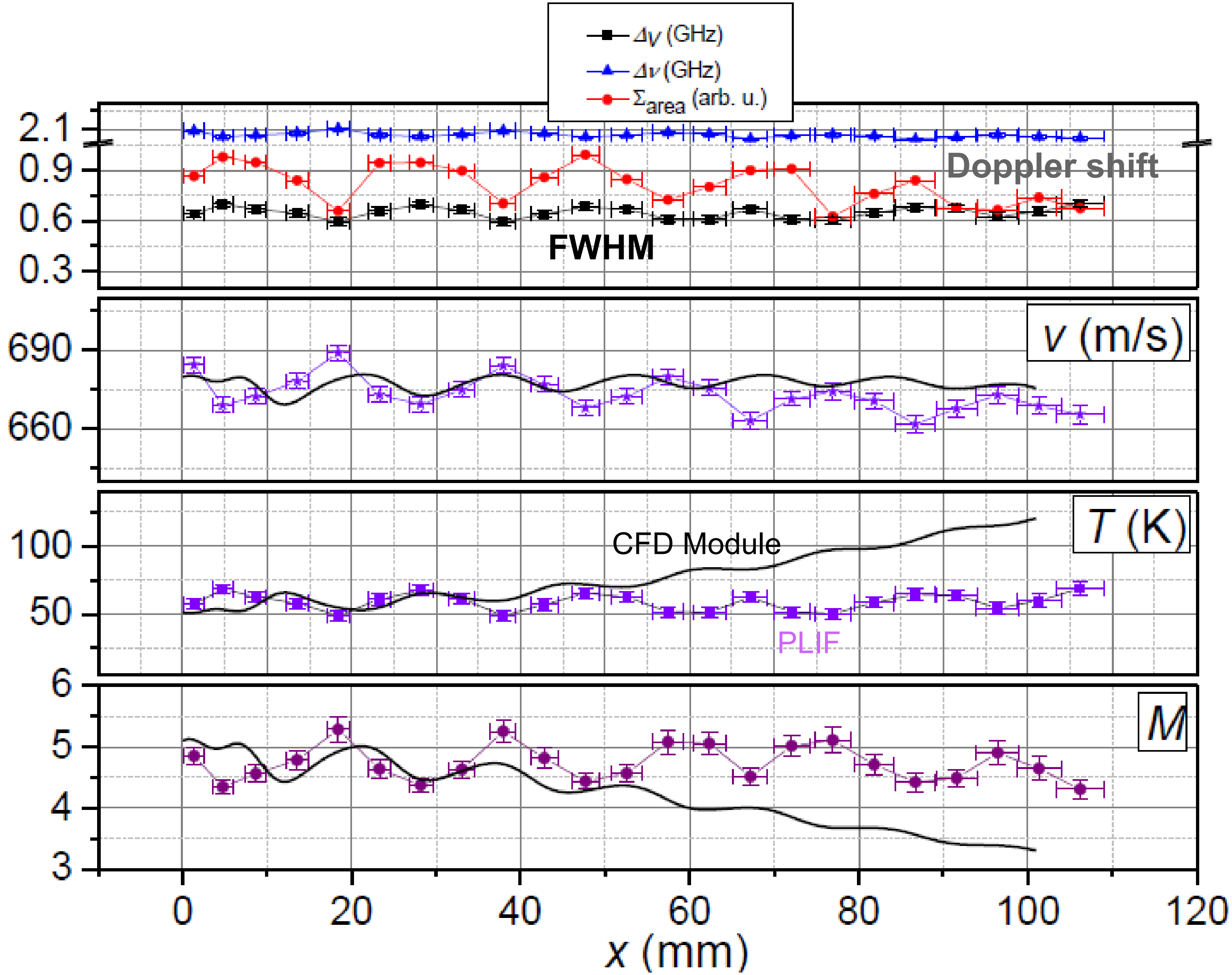
Jets formed by de Laval nozzle

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

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



Quasiuniform jet



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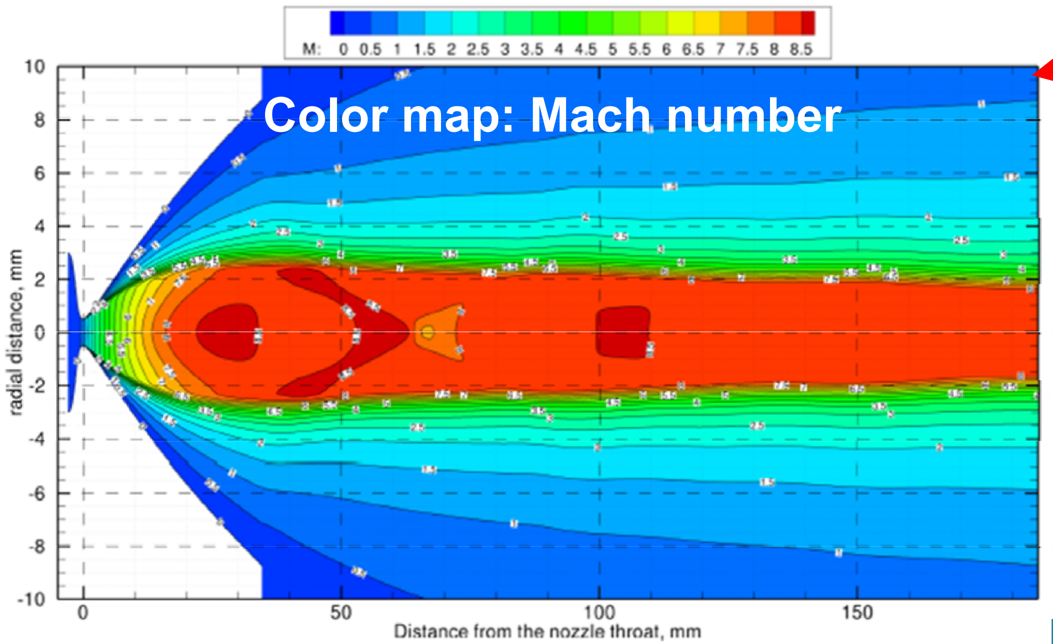
Expected performances

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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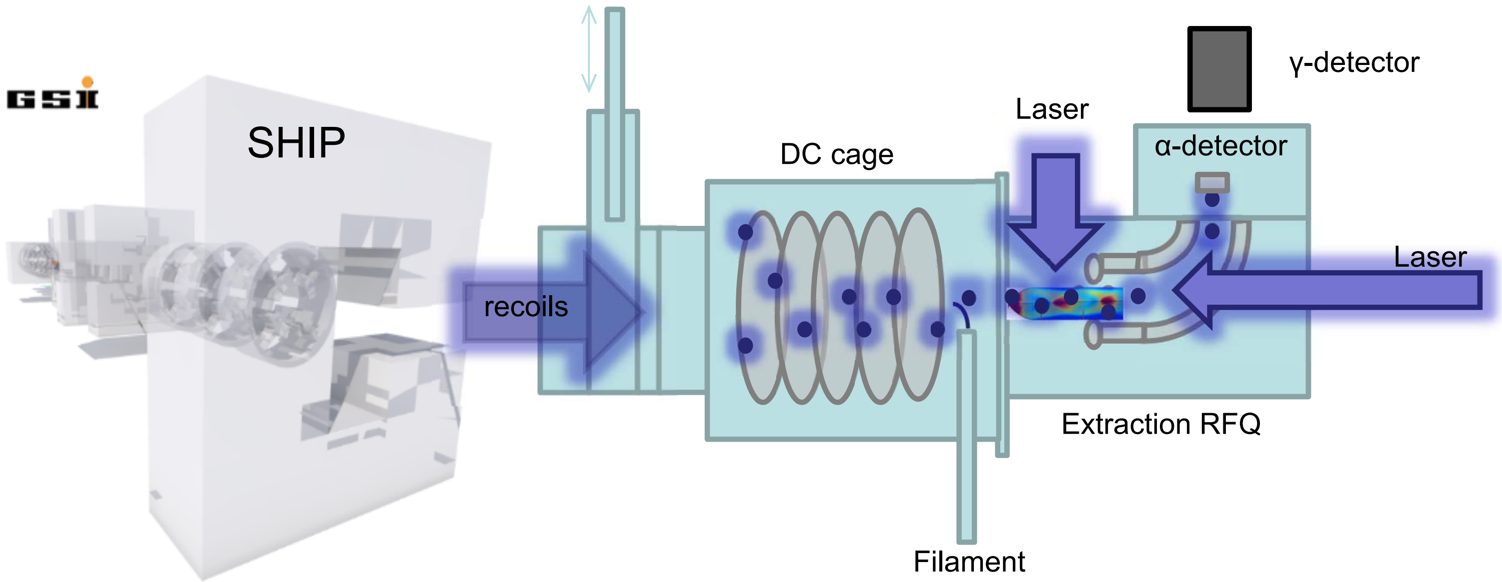
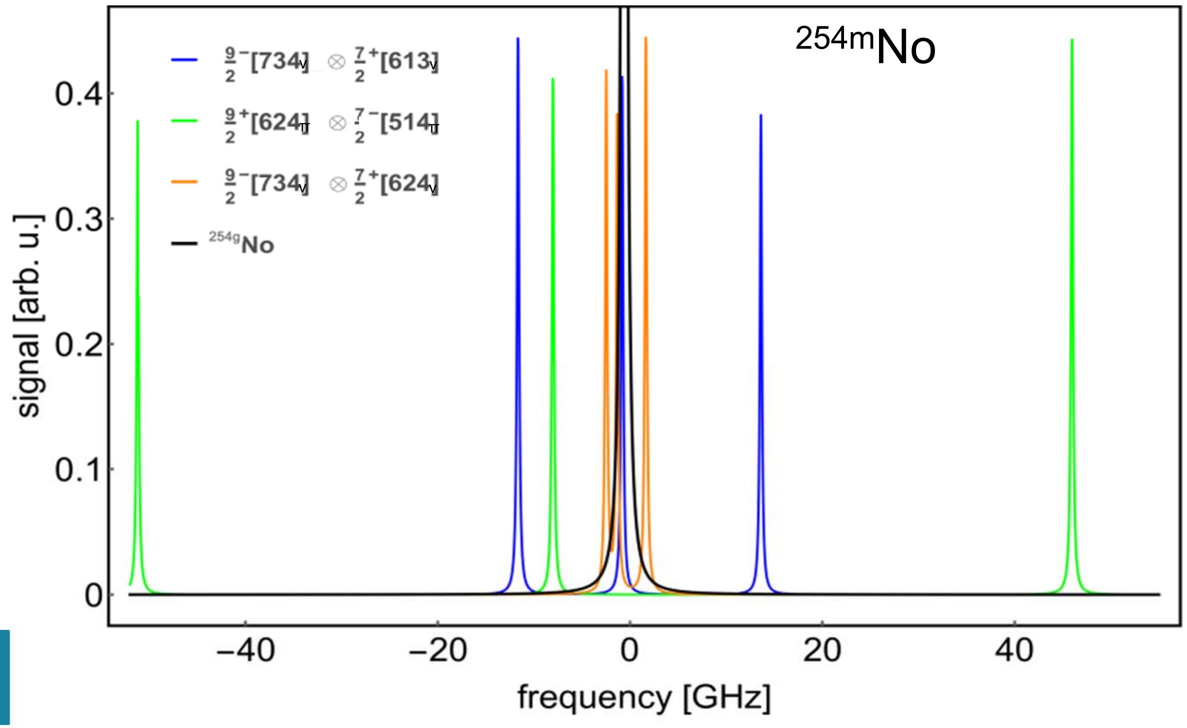
IGLIS at GSI



- In-Gas jet spectroscopy
  - filament neutralization for nobelium → RADRIS



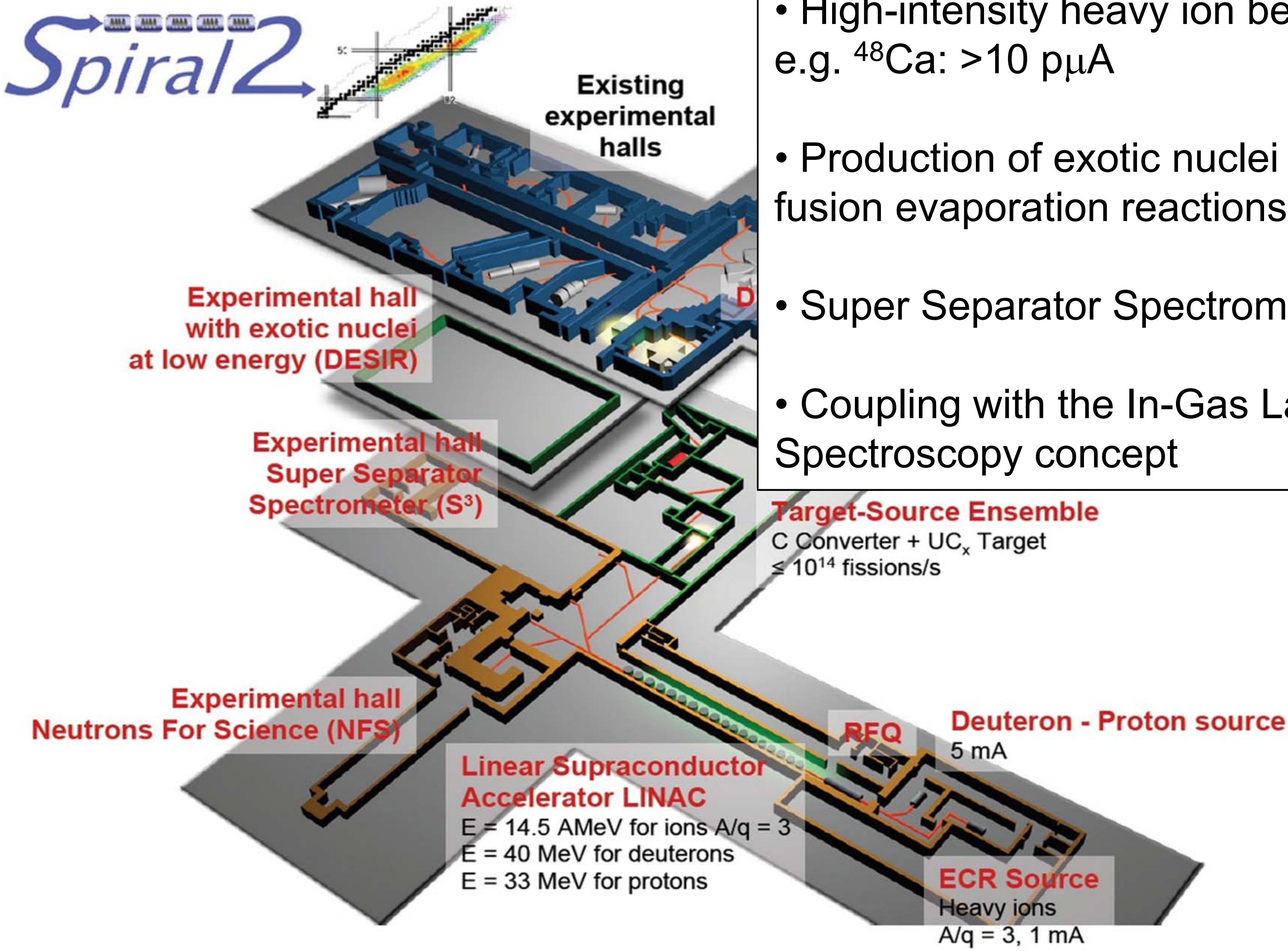
IGLIS at GANIL

- High-intensity heavy ion beams:
e.g. ^{48}Ca: >10 pμA

- Production of exotic nuclei using heavy-ion fusion evaporation reactions

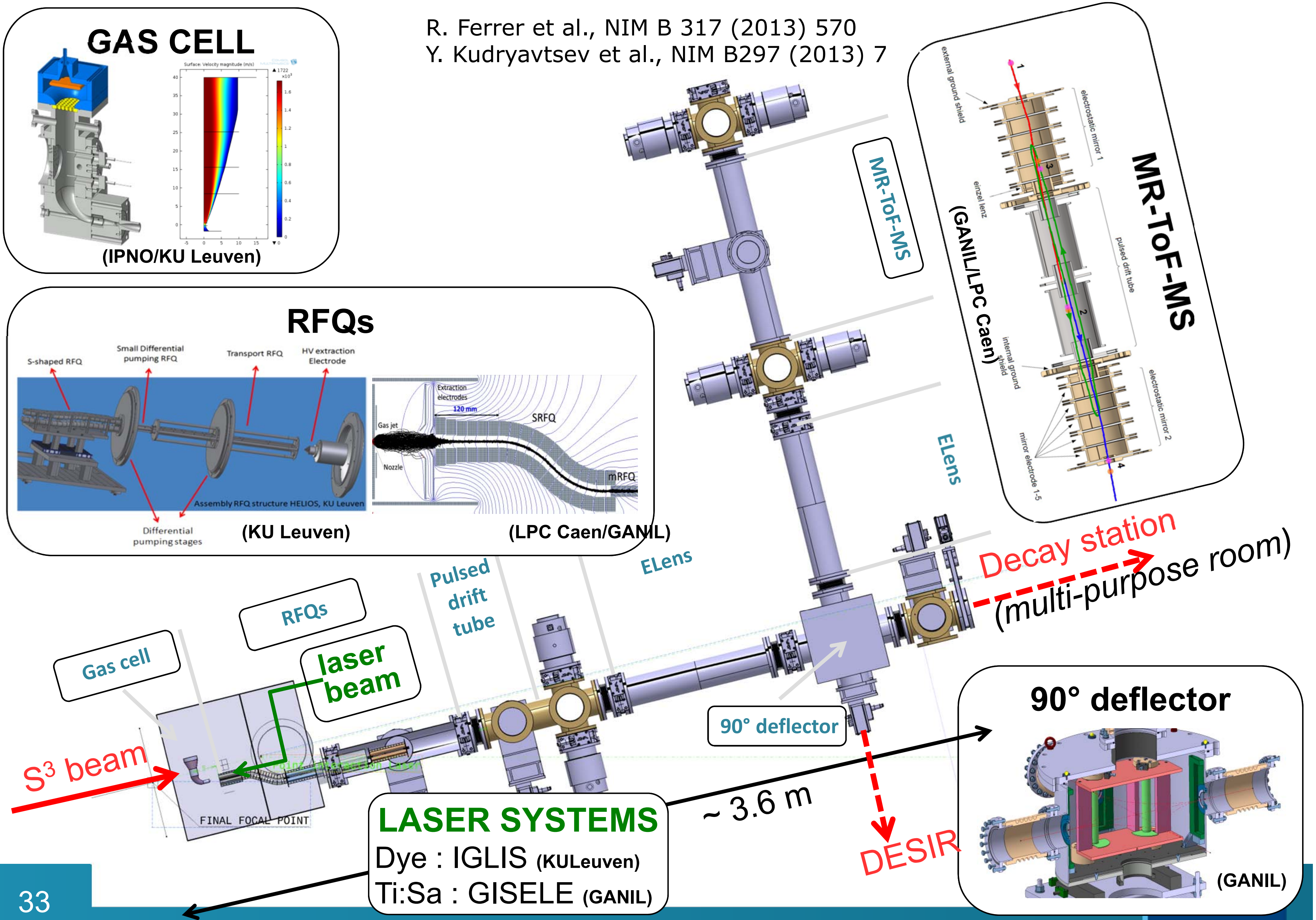
- Super Separator Spectrometer: S3

- Coupling with the In-Gas Laser Ionization Spectroscopy concept



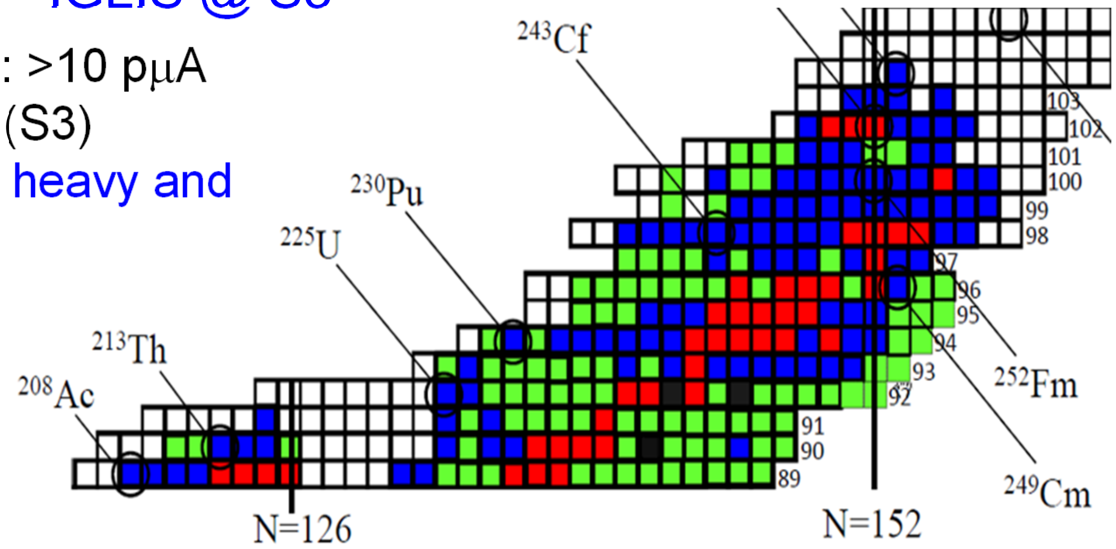
S^3-Low Energy Branch - general layout

R. Ferrer et al., NIM B 317 (2013) 570
Y. Kudryavtsev et al., NIM B297 (2013) 7



IGLIS @ S3

- High intensity heavy-ion LINAC: >10 pμA
- Super Separator Spectrometer (S3)
- N=Z nuclei (towards ^{100}Sn) and heavy and Super Heavy Elements



Conclusion – Outlook

- In-gas jet Laser Ionization Spectrosopy: a new tool to study the heavy element region
  - improved spectral resolution and efficiency
- Production of pure (isomerically), heavy element beams for further studies
- Implementation of IGLIS at GSI and GANIL
  - new atomic and nuclear physics information of the heaviest elements

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