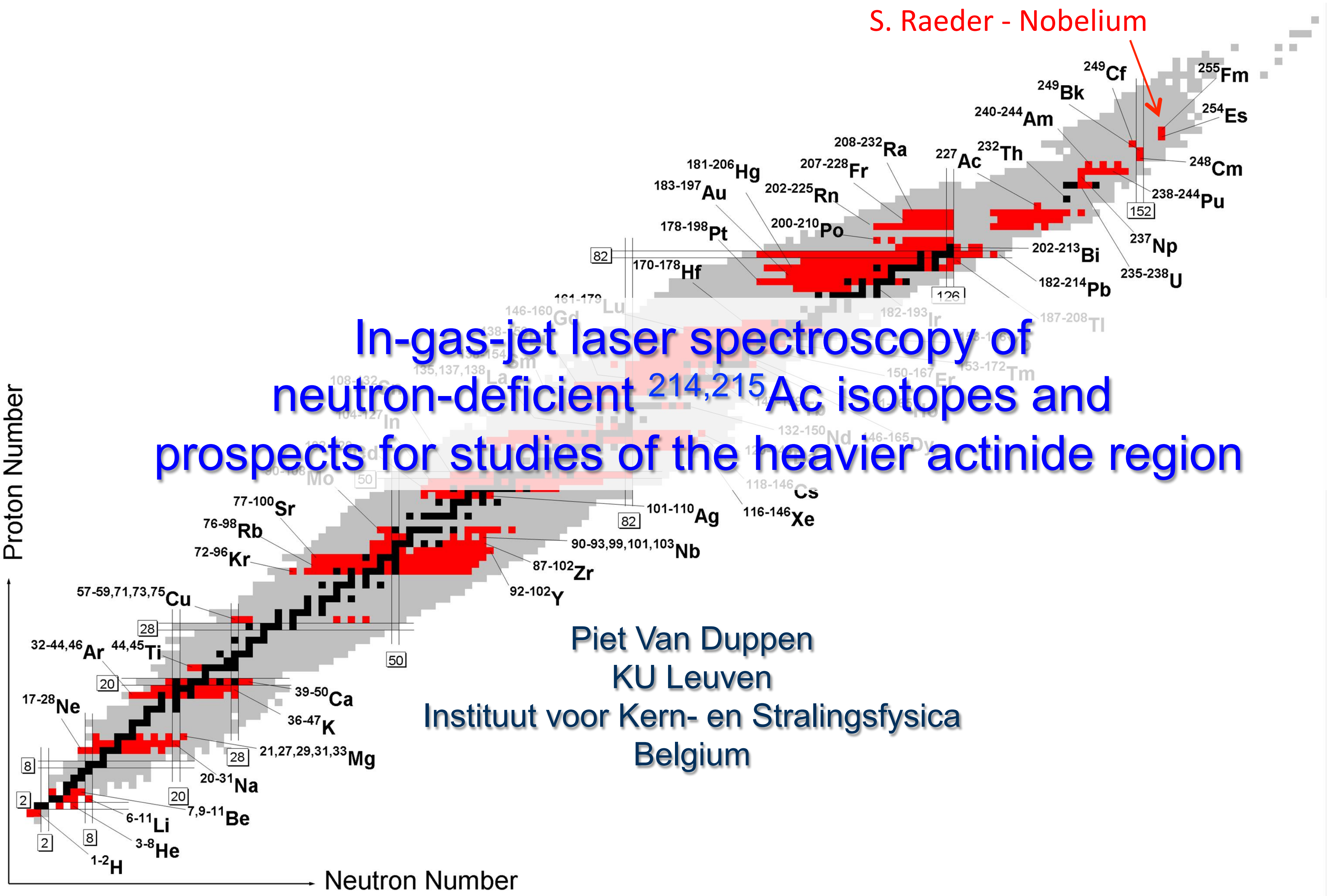
In-gas-jet laser spectroscopy of neutron-deficient ^{214,215}Ac isotopes and prospects for studies of the heavier actinide region



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K. Blaum,- Phys. Scr. T152 (2013) 014017

Outline

- The Heavy Element Laser Ionization Spectroscopy (HELIOS) project:
    - nuclear and atomic physics motivation

- Laser ionization spectroscopy of $^{212-215}$Ac at the Leuven Isotope Separator On Line (LISOL) facility
    - in gas-cell and in-gas jet

- Off-line characterization studies

- Conclusion and Outlook

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BriX

EQUIPEx S3
INVESTISSEMENT D'AVENIR

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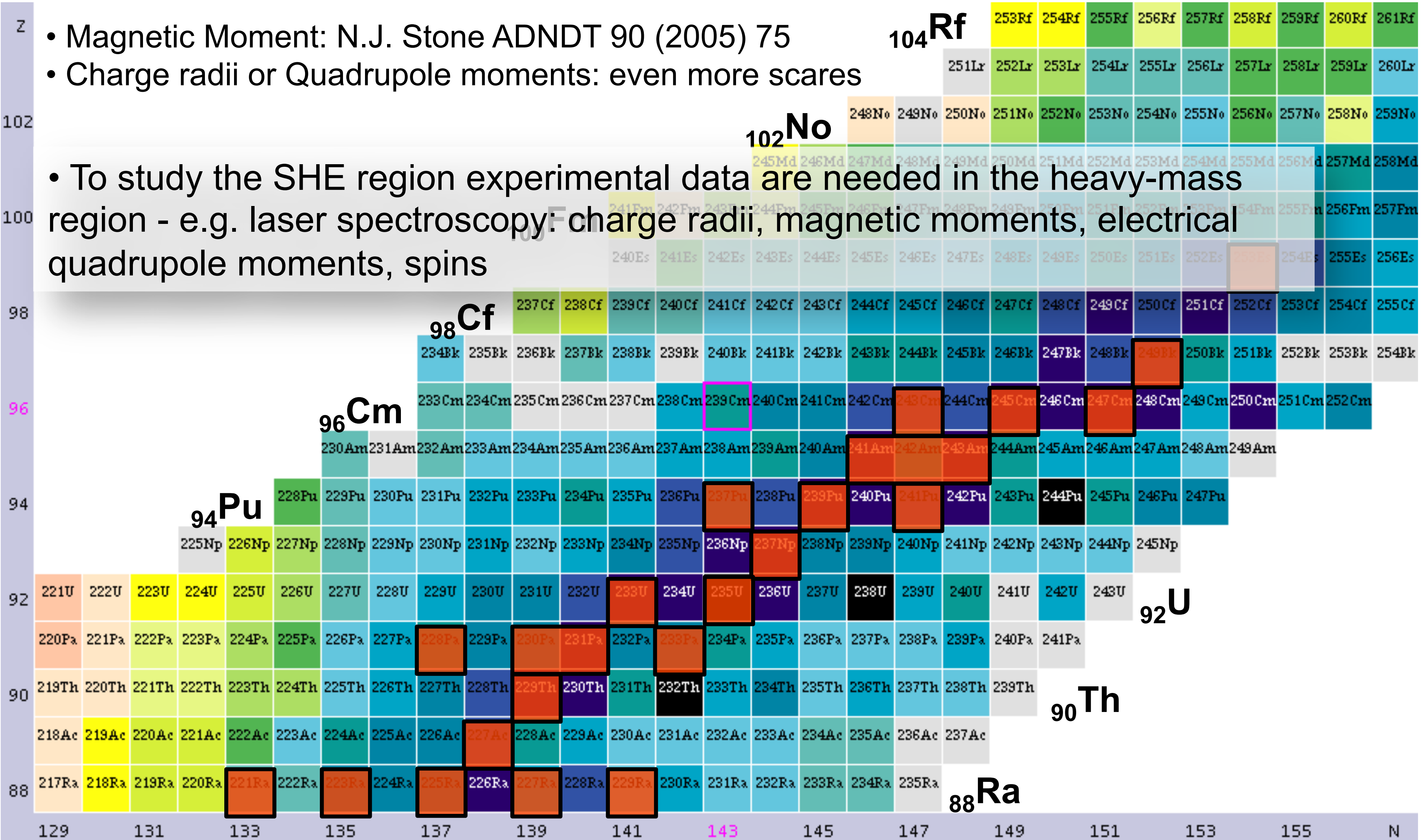
Reported Magnetic Moments

- Magnetic Moment: N.J. Stone ADNDT 90 (2005) 75
- Charge radii or Quadrupole moments: even more scares

- To study the SHE region experimental data are needed in the heavy-mass region - e.g. laser spectroscopy: charge radii, magnetic moments, electrical quadrupole moments, spins



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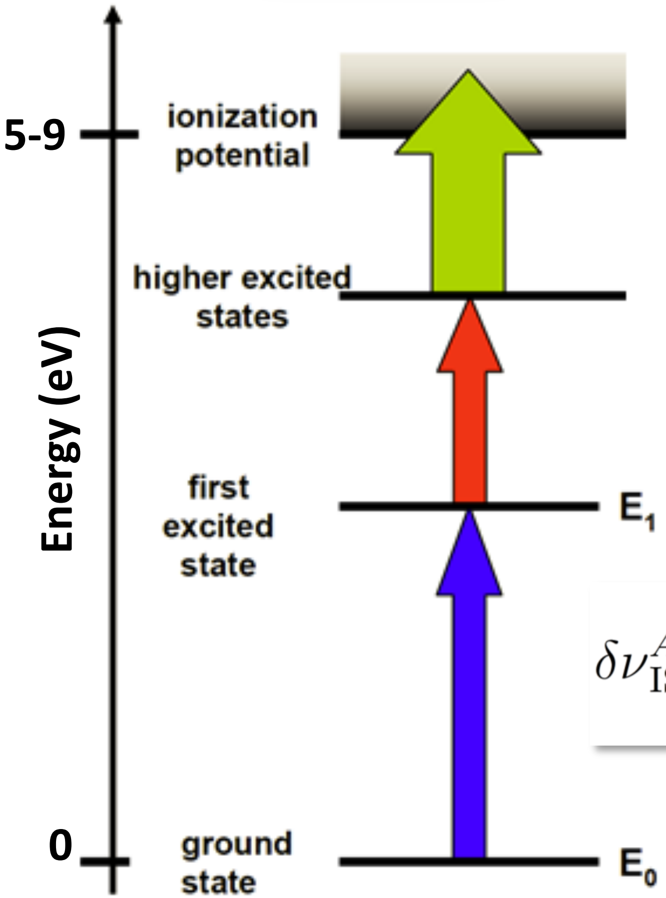
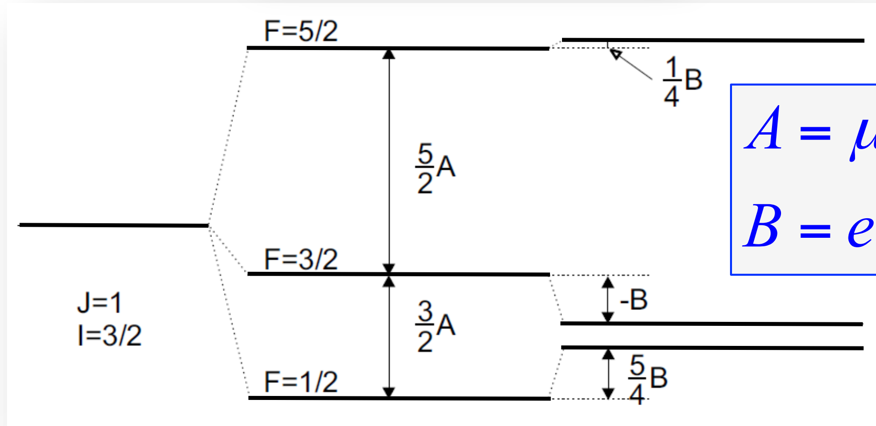
Laser Ionization Spectroscopy: basics

Sensitivity



Hyperfine Splitting



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

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

Isotope Shift

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

$$\delta\left\langle r^2 \right\rangle^{A,A'}$$

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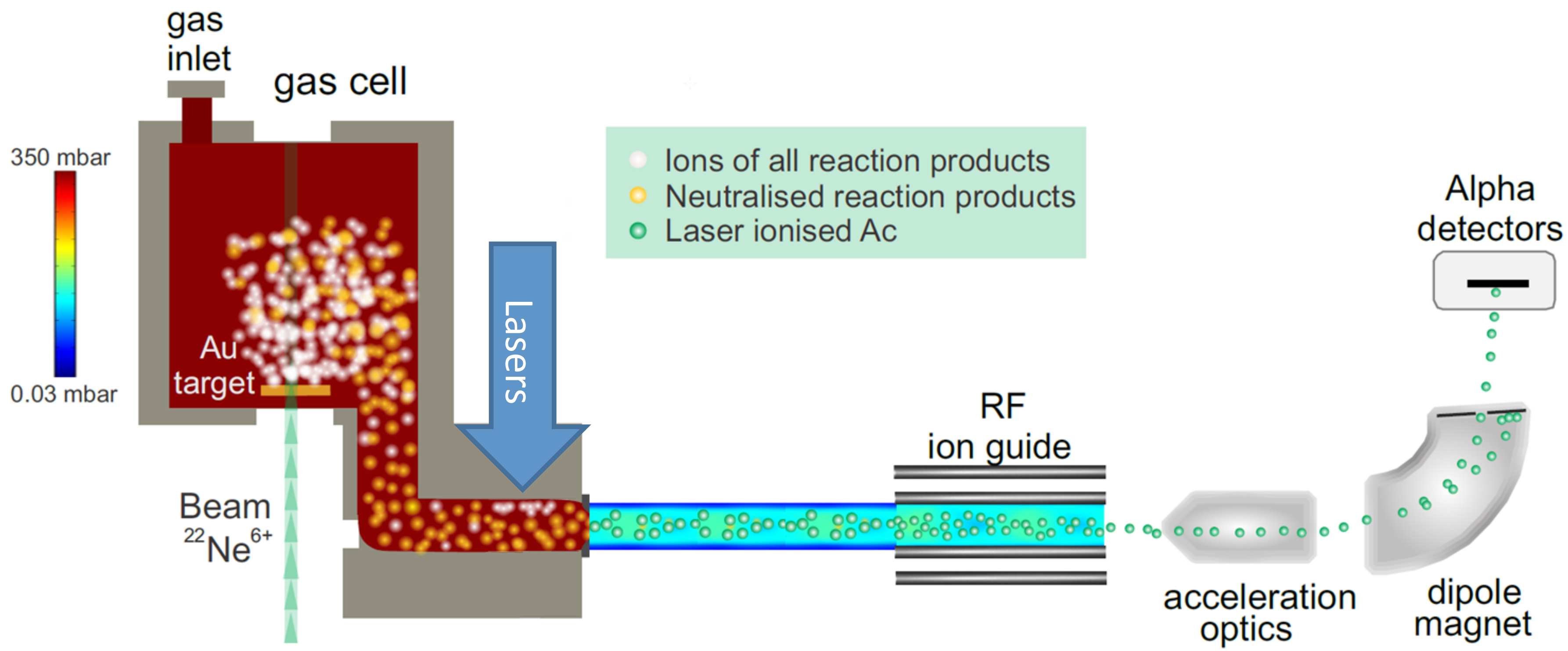
courtesy I. Moore

Laser Ionization Spectroscopy @ LISOL: in-gas cell



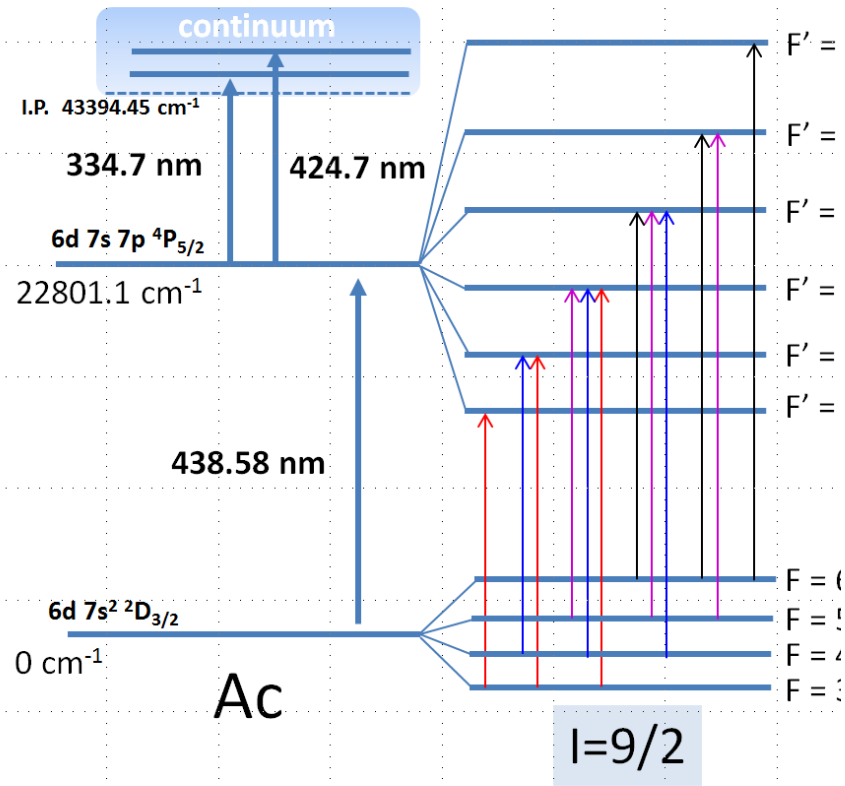
Limitations:
- Pressure shift and broadening
- Doppler broadening
- Ion-gas interactions

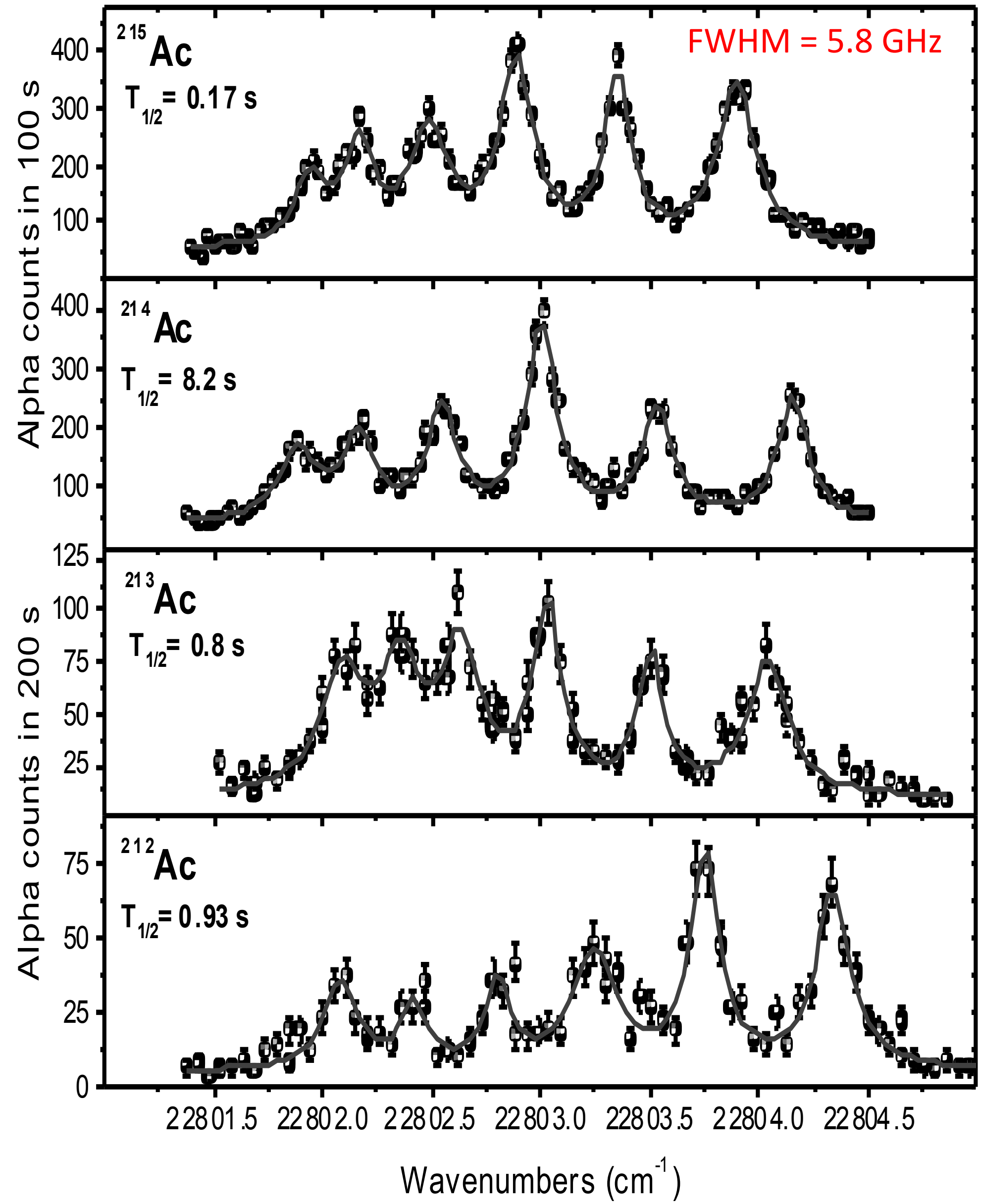
^{57}Cu(Z=29, N=28, $T_{1/2}$=196 ms)
Cocolios,- PRL 103 (2009) 102501
^{97}Ag (Z=47, N=50, $T_{1/2}$= 26 s))
Ferrer,- PLB 728 (2014) 191

HFS of $^{212-215}Ac$ - 439 nm transition

N=126

^{227}Ac ($T_{1/2}$=21.7 y)
J. Rossnagel et al., PRA 85 (2012) 012525



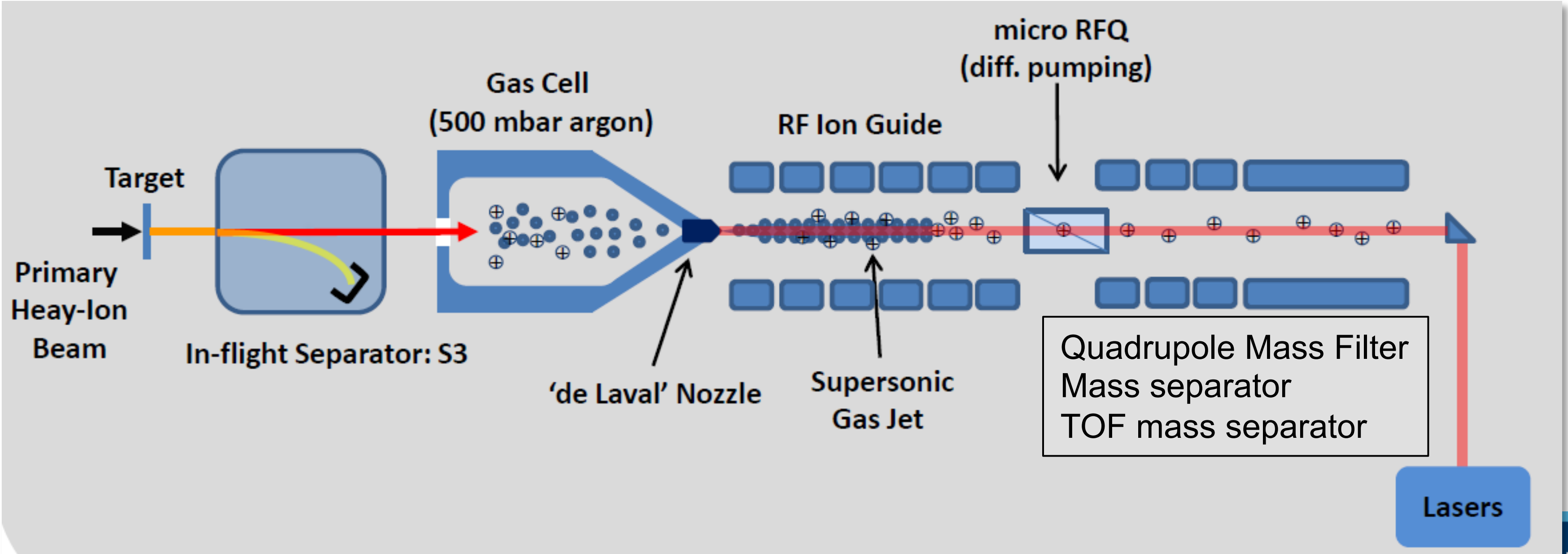


$^{197}Au(^{20}Ne$-145 MeV,4-5n$)^{212,213}Ac$

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

The HELIOS concept

- Production of the heavy elements (or neutron deficient isotopes):
  heavy-ion fusion evaporation reactions
- Separation of the primary and secondary beam: e.g. S3-GANIL, MARA@JYFL
- Thermalization in the gas cell
- Repelling unwanted ions
- Formation of a cooled atomic beam through e.g. a 'de Laval' nozzle (gas jet)
- Resonant laser ionization: high-repetition rate laser system (>10 kHz)
- Ion capture and transport in the RF Ion Guide followed by mass separation
- Detection of the ions: radioactivity / ion counting

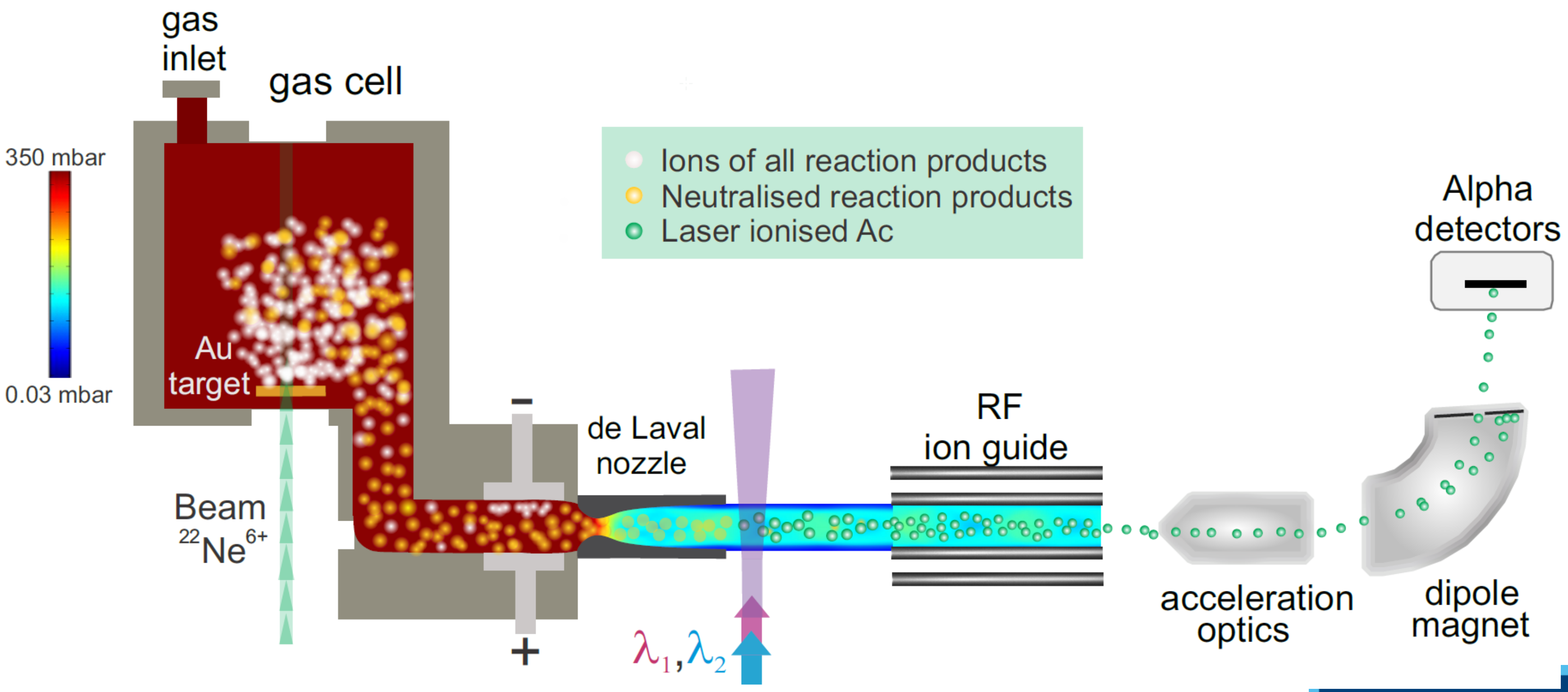


Y. Kudryavtsev et al., NIM B297 (2013) 7, R. Ferrer et al, NIM B 291 (2012) 29
K. Blaum et al., NIM B 204 (2003) 331, I. Moore et al., AIP Conf. Proc. 831 (2006) 51

The HELIOS concept

- Total expected efficiency: 4%
- Strategy
  - In-gas cell laser ionization spectroscopy (broadband – 5 GHz): rough laser scans, search for atomic transitions
  - In-gas jet laser ionization spectroscopy (narrow band – 100 MHz)

From 'in-gas cell' to 'in-gas jet' laser spectroscopy



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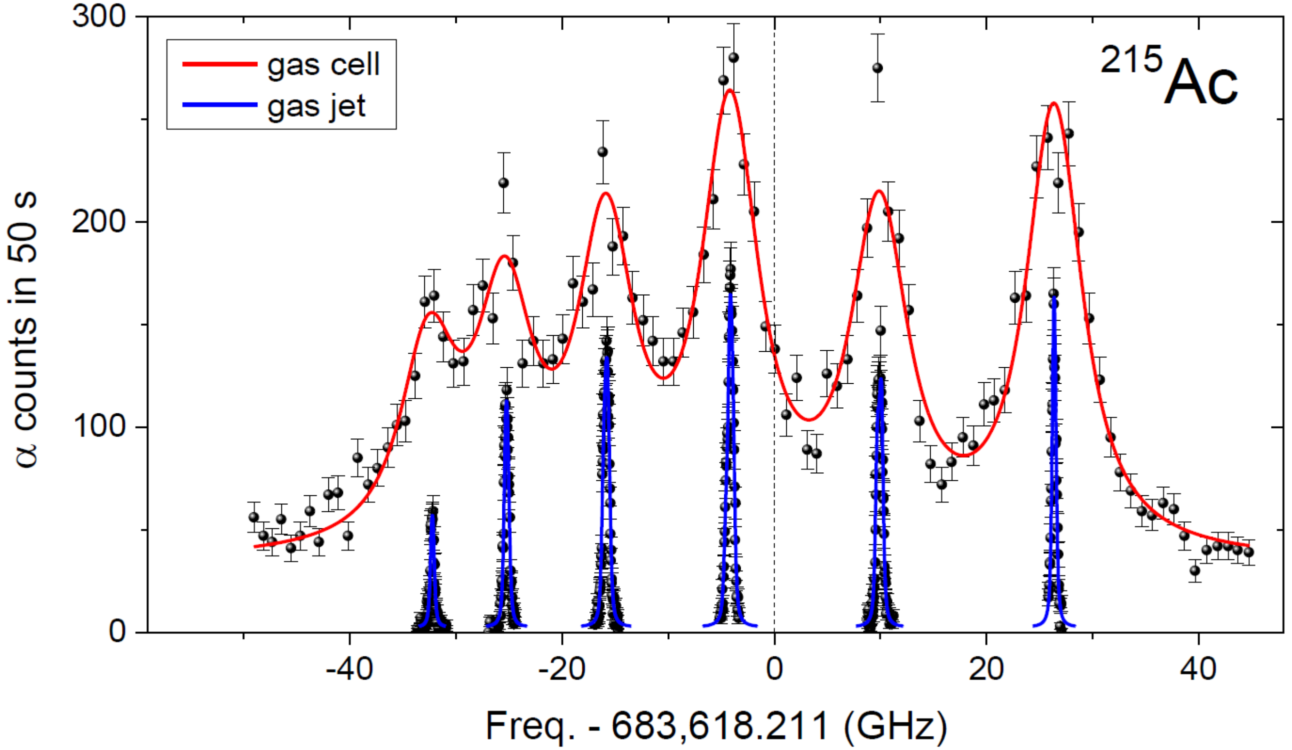
T. Sonoda *et al.* NIM B267 (2009) 2918, R. Ferrer *et al,* NIM B 291 (2012) 29
Y. Kudryavtsev et al., NIM B 297 (2013) 7

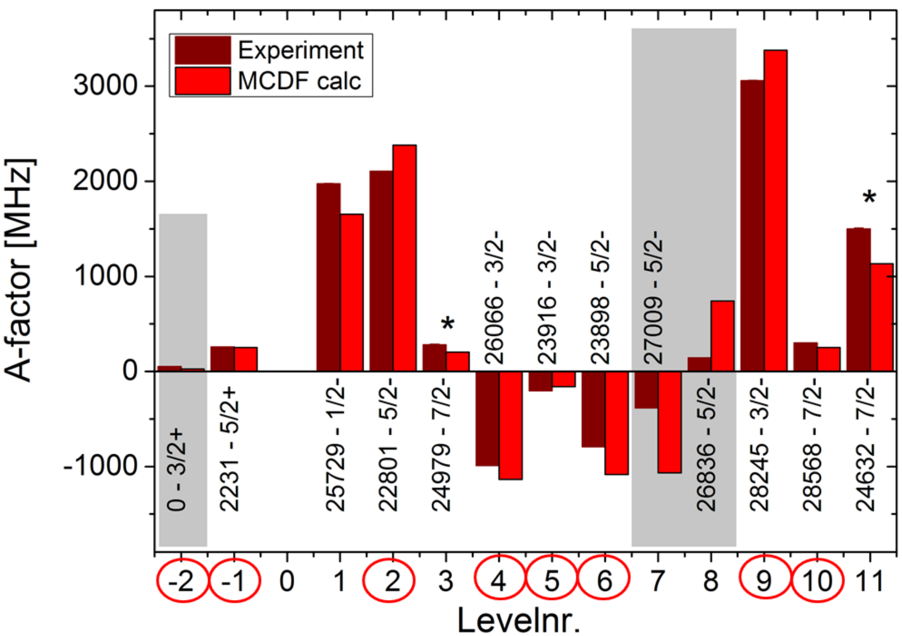
^{215}Ac $T_{1/2}$ = 0.17 s J_{π} = (9/2^{-})

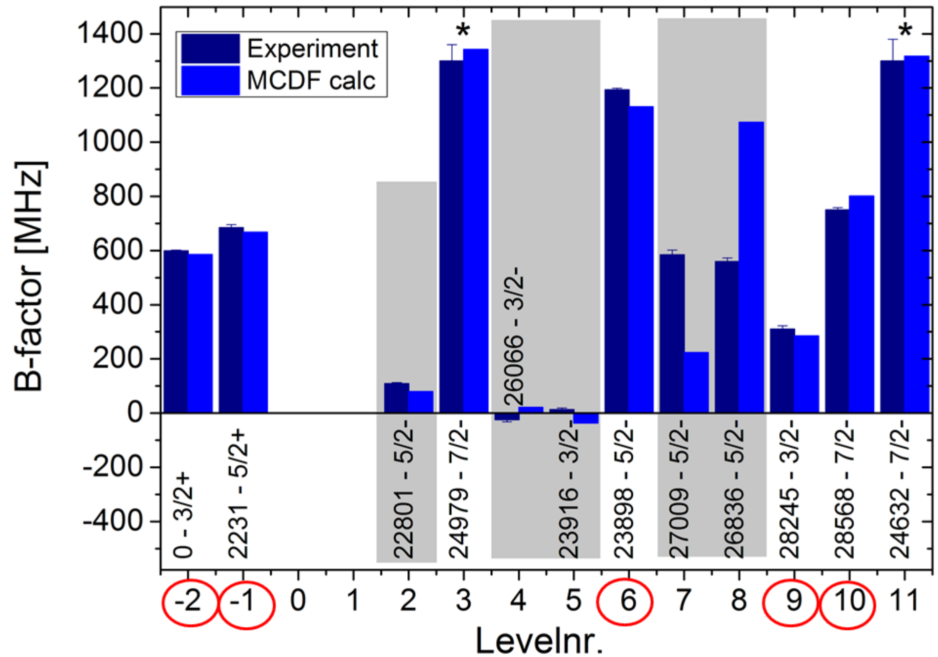


Figures of merit:

- ✓ Resolution - FWHM= 394(18) MHz)
- ✓ Selectivity = 121(27)
- ✓ Efficiency = 0.42(13) % (duty cycle 1/14)

Multi-Monfiguration 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

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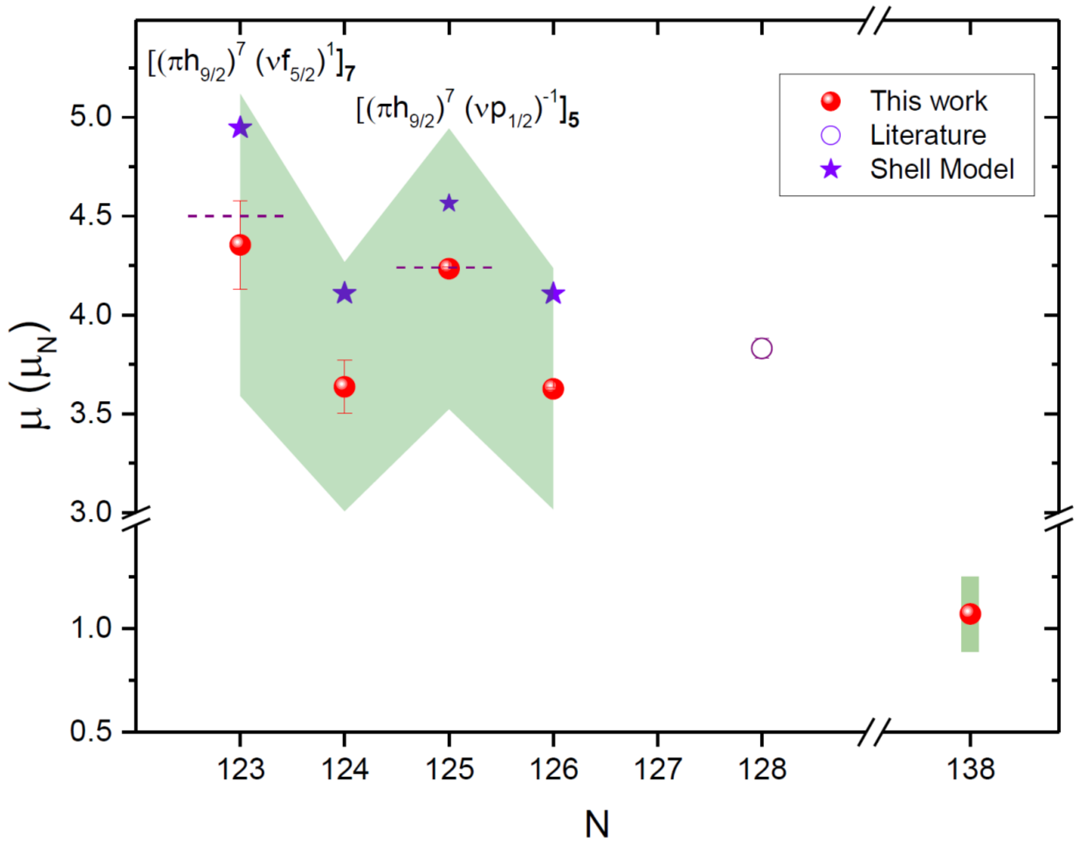
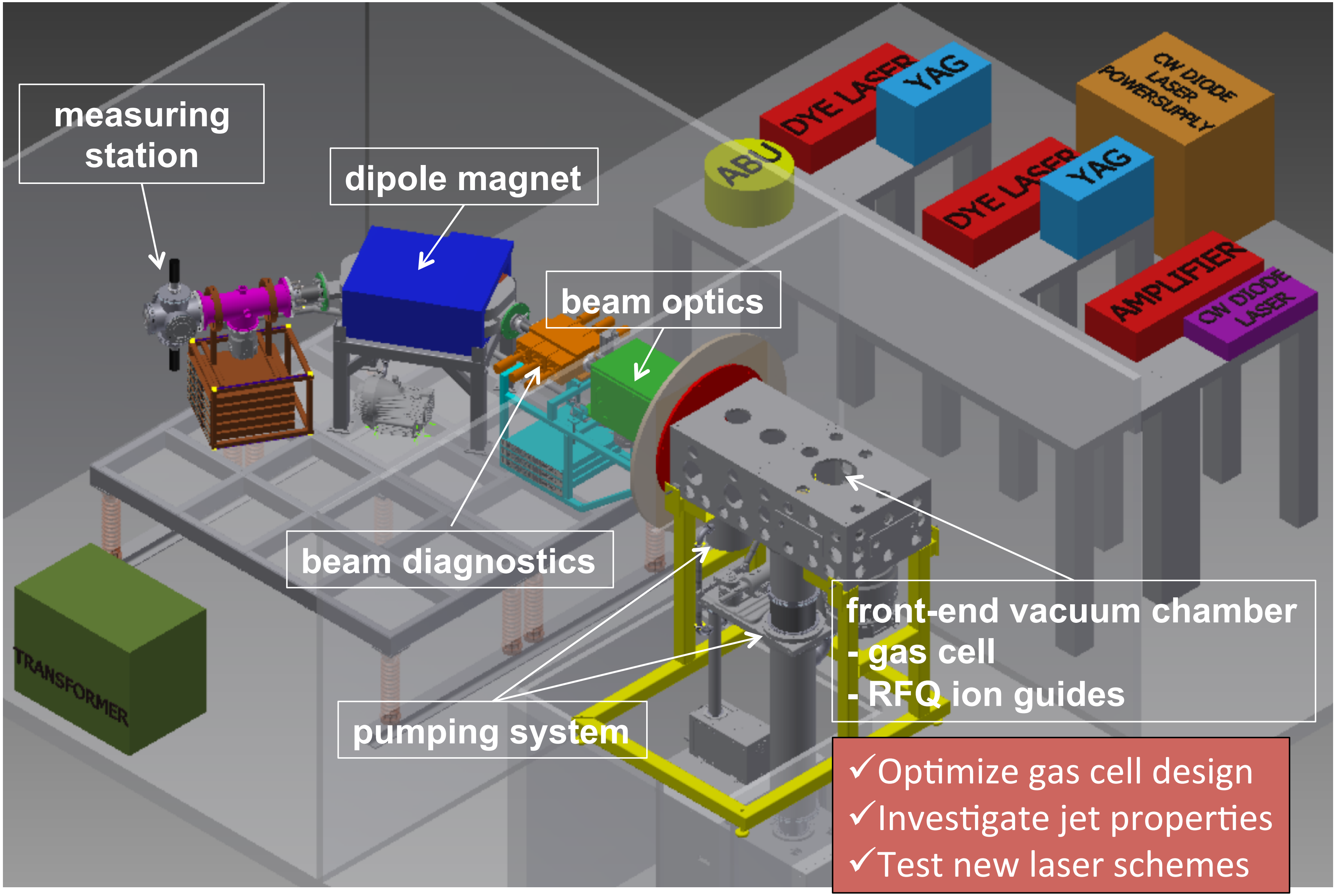
R. Beerwerth and S. Fritzsche (2016)

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 calculations (H. Grawe) are in good agreement with experimental quadrupole moments and magnetic dipole moments
- ^{208}Pb good core for shell model predictions (N=126) (^{218}U: Khuyagbaatar,- PRL 115 (2015))



✓Optimize gas cell design
✓Investigate jet properties
✓Test new laser schemes

Y. Kudryavtsev,- NIM B 376 (2016) 345–352

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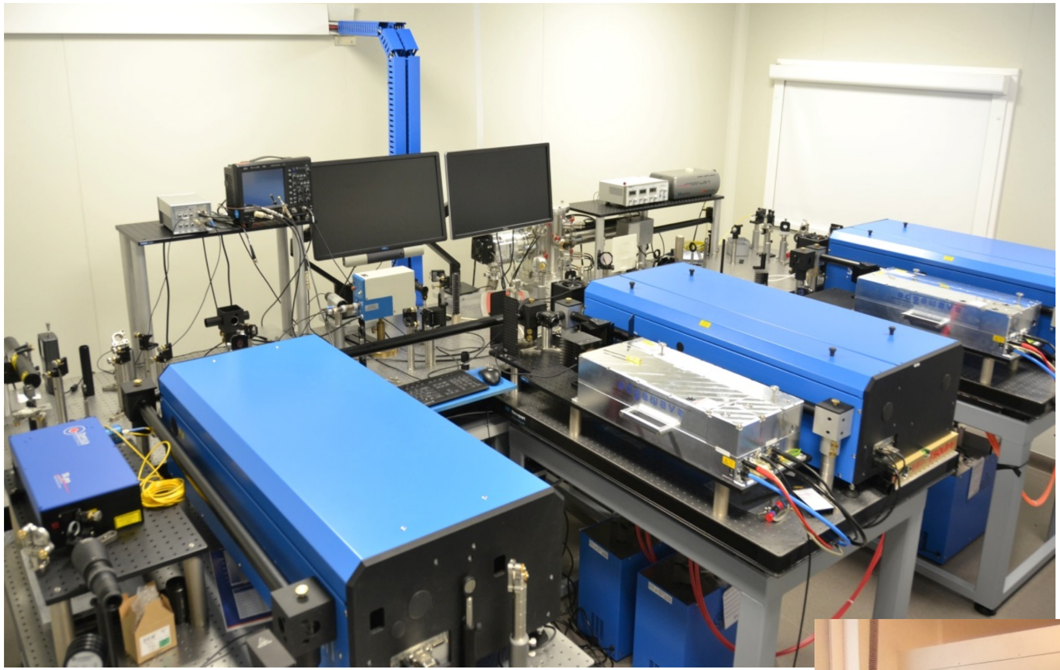
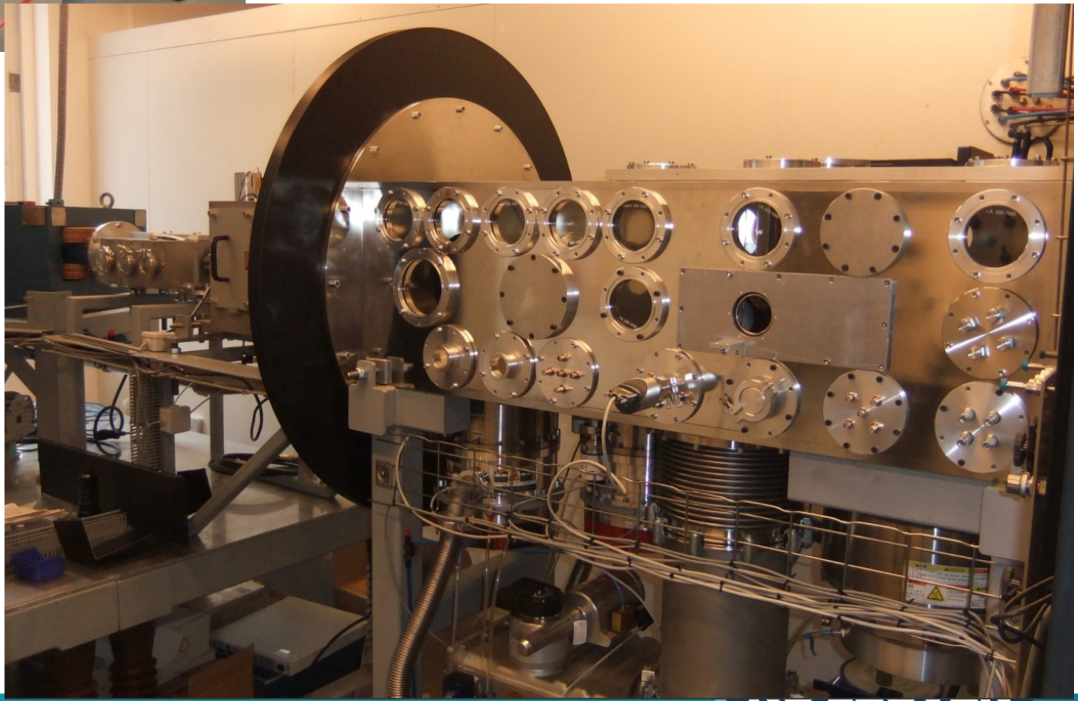
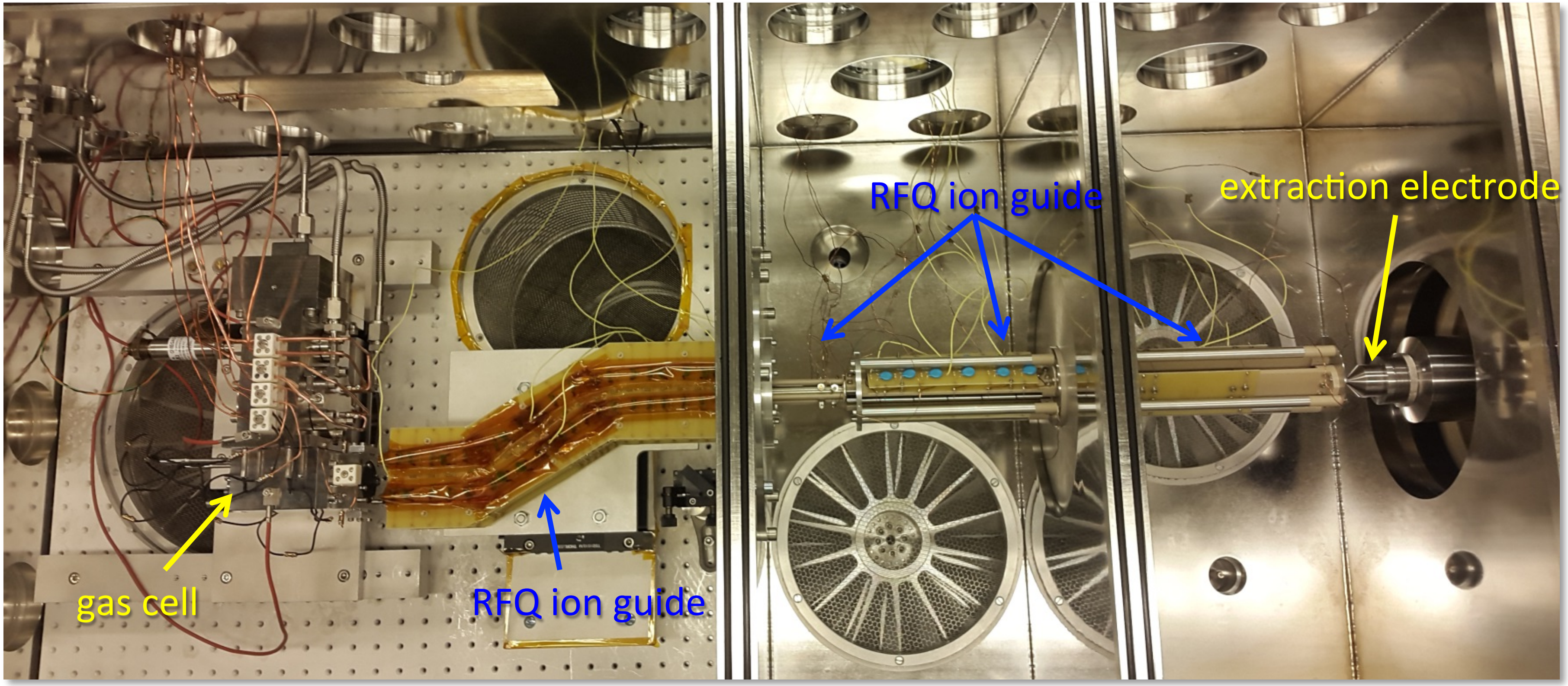
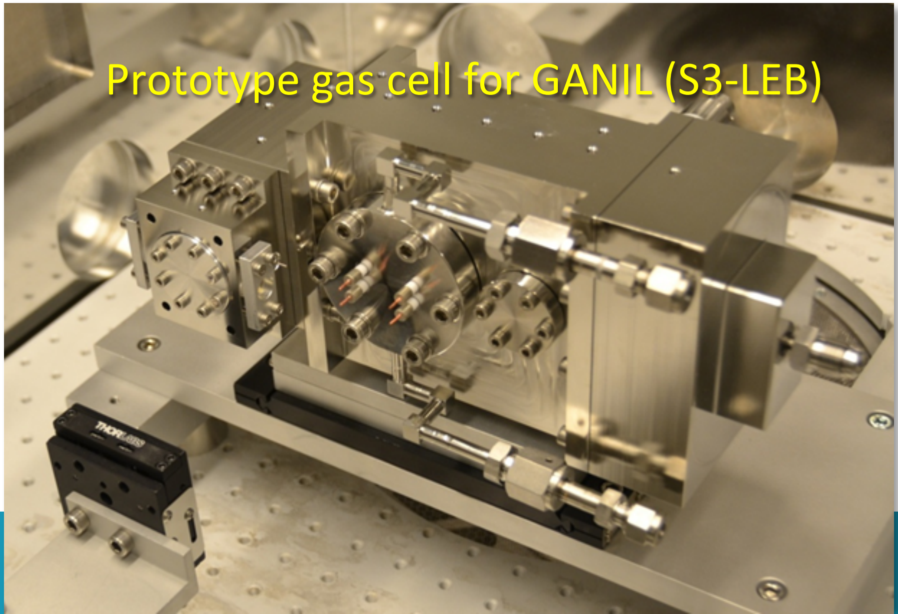
IGLIS @ KU Leuven





IGLIS @ KU Leuven


RFQ ion guide
extraction electrode
gas cell
RFQ ion guide


Prototype gas cell for GANIL (S3-LEB)

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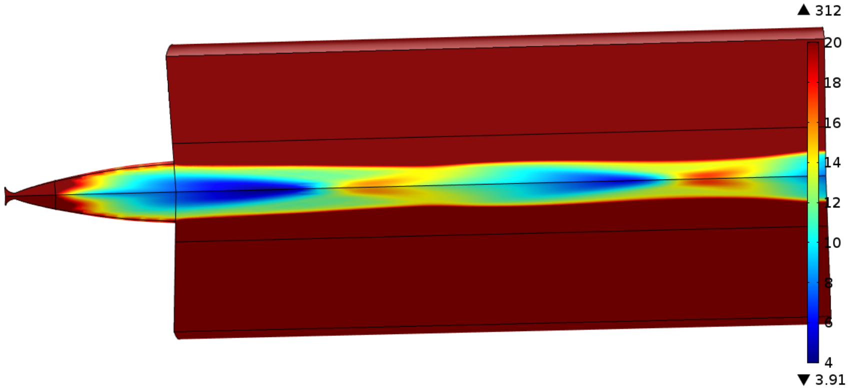
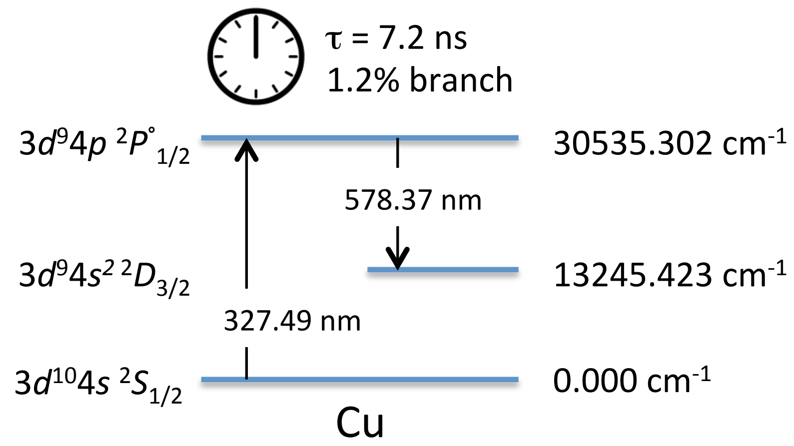
Gas Flow Simulation and Validation

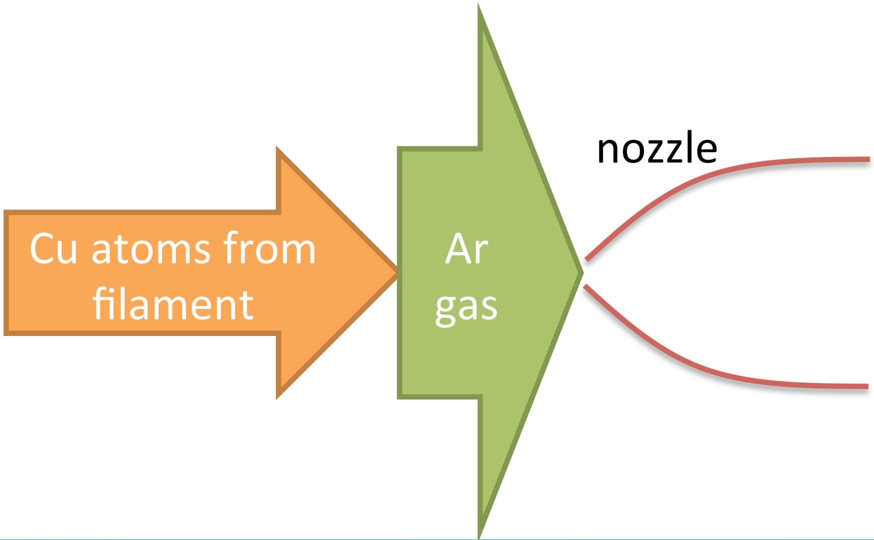
- M=8: T=4 to 20 K (ideal case: 13K)

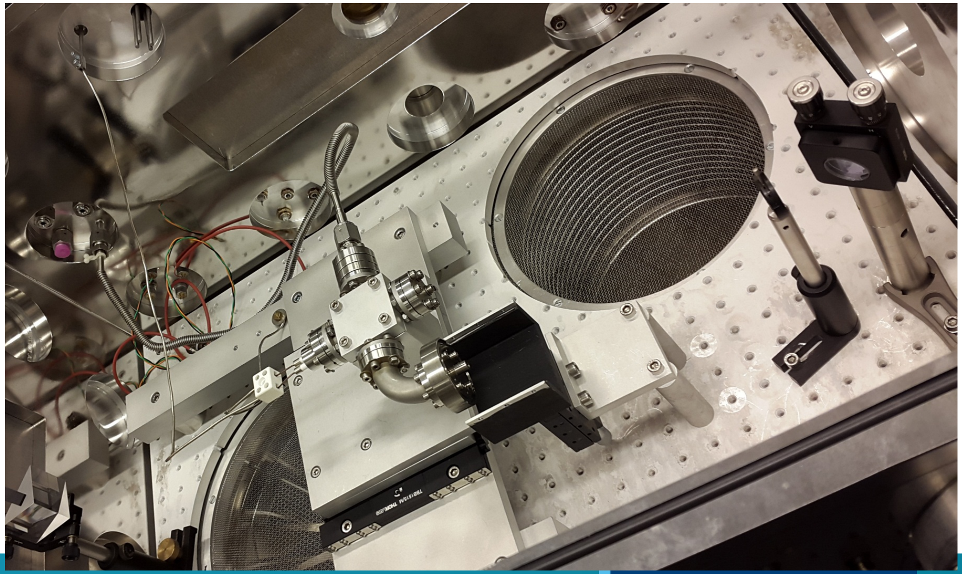




- Visualisation of the gas jet

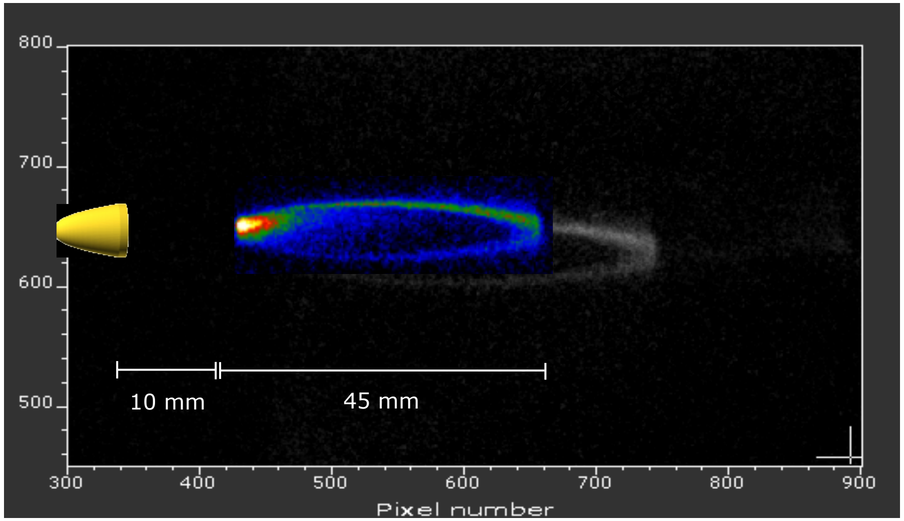
with planar-laser induced fluorescence (PLIF)

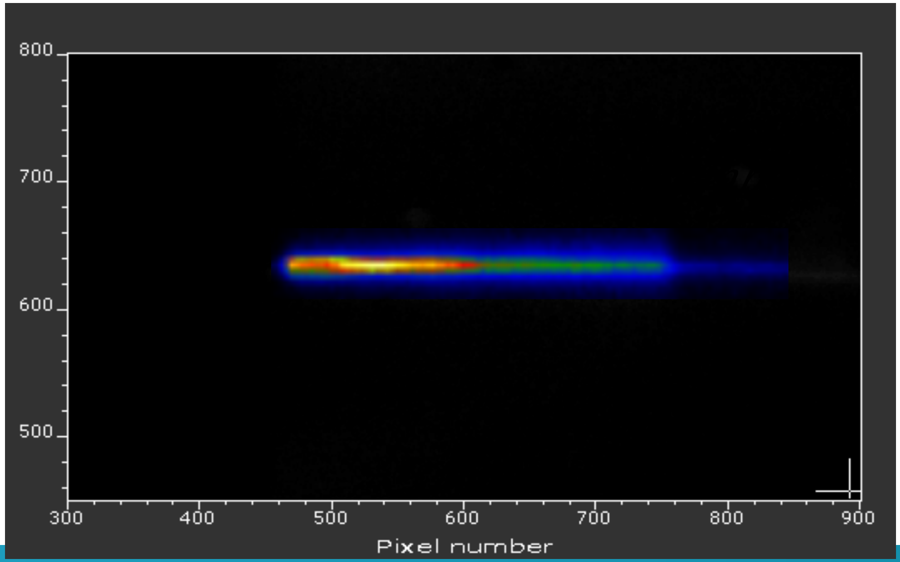




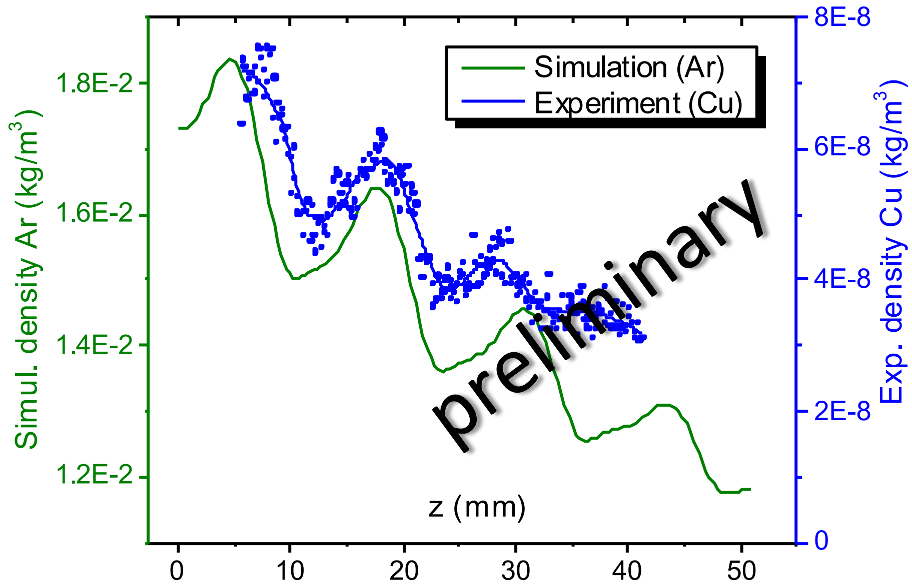
PLIF with copper atoms: first tests

Stagnation pressure 290 mbar, P_{jet}~ 1 mbar, Mach 5.5





- Simulations vs. Experimental data



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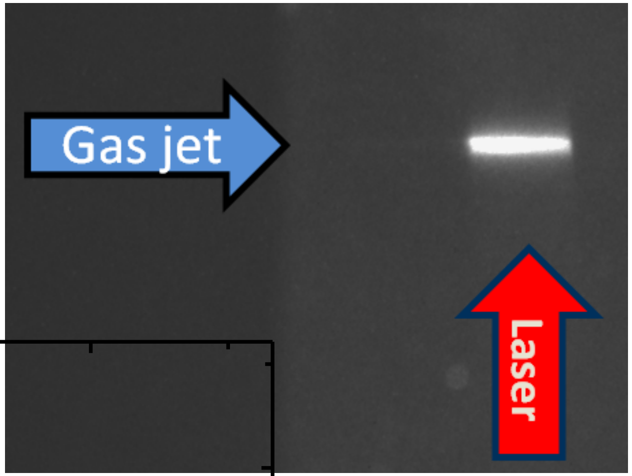
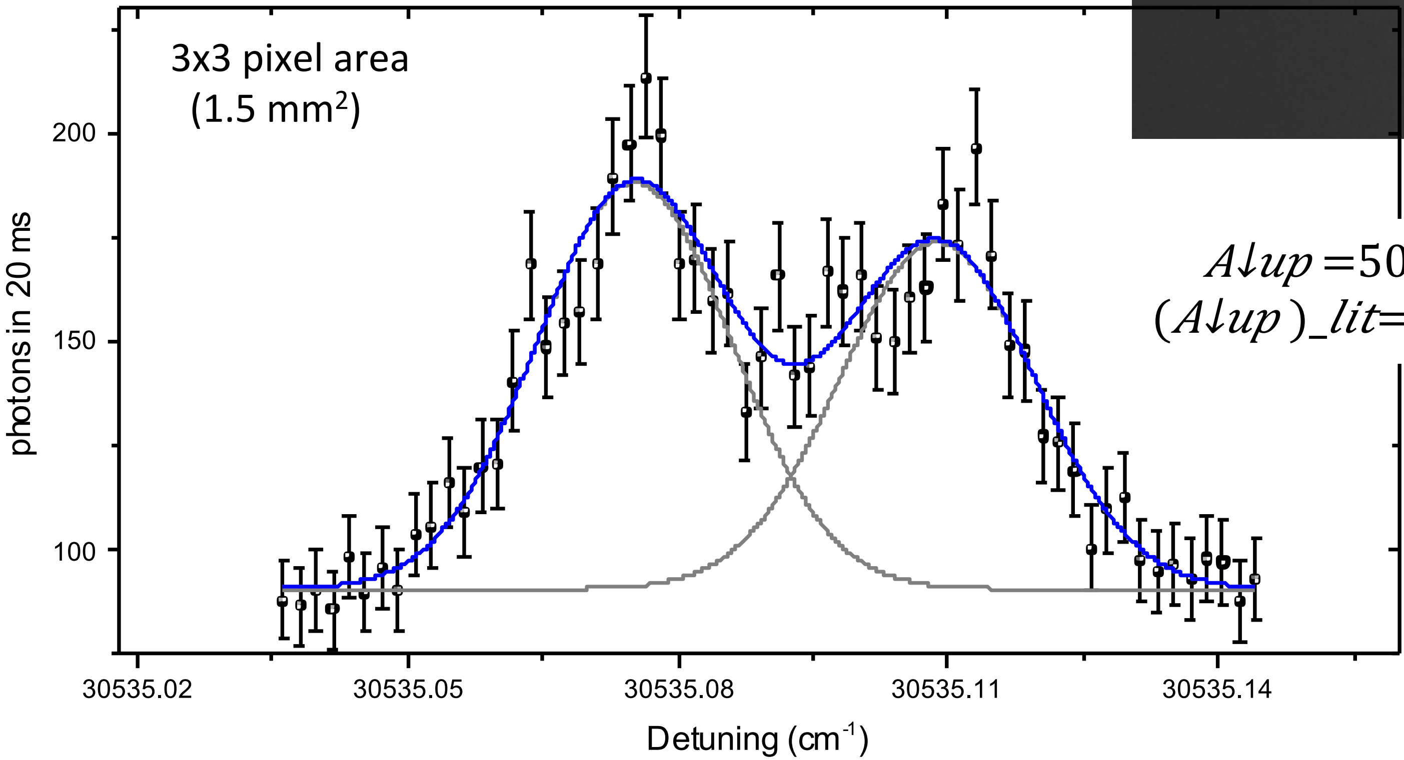
PLIF with copper atoms: first tests

- Characterize density, temperature and velocity distributions by laser spectroscopy in different areas of the jet.

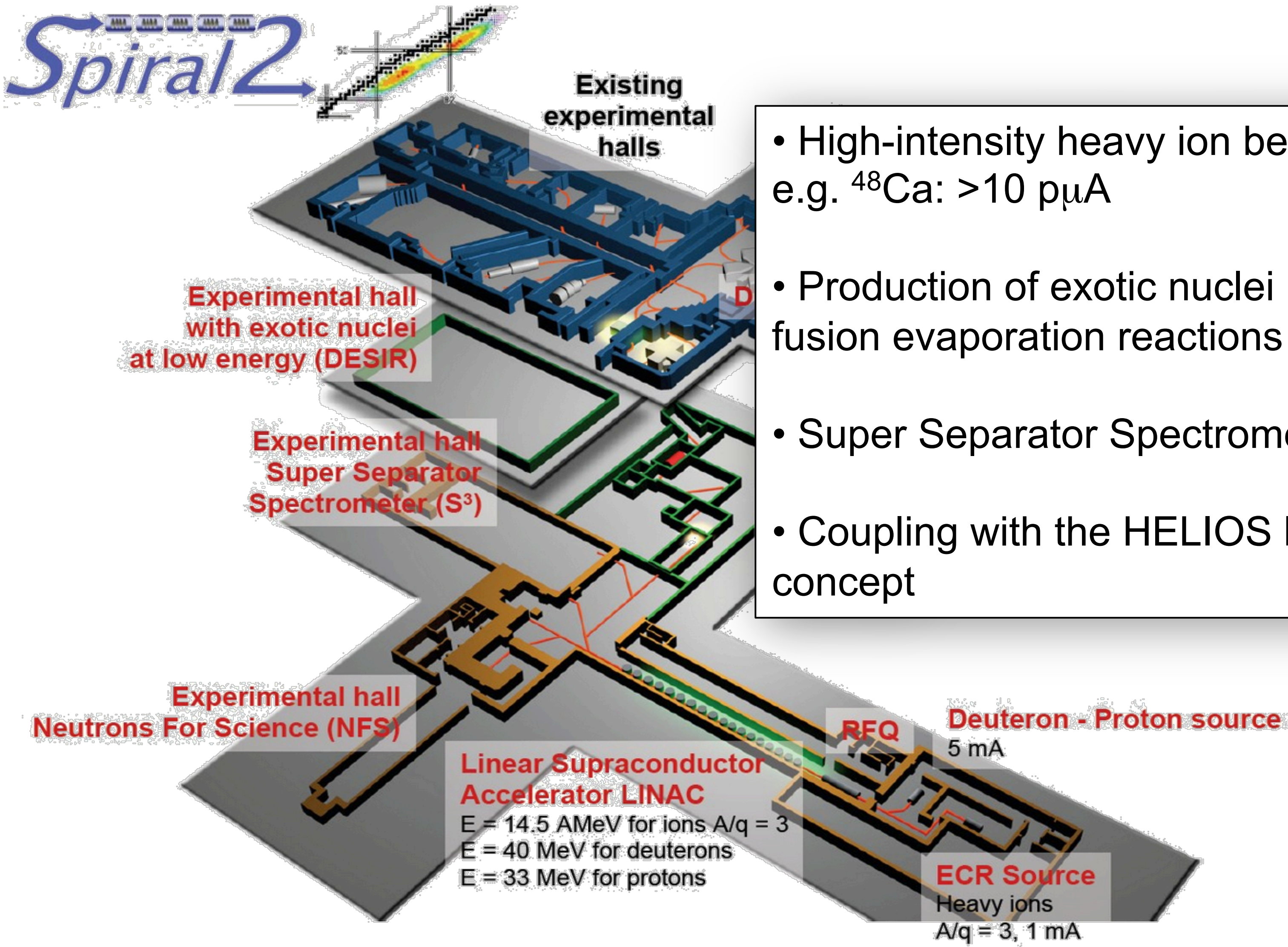


^{63,65}Cu (natural abundance)



$A_{up} = 504(28)\ MHz$

$(A_{up})_{lit} = 506(1)\ MHz$

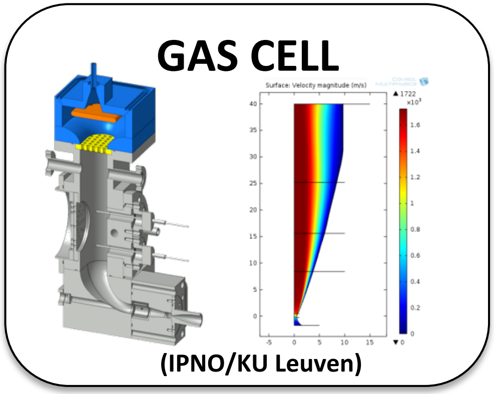


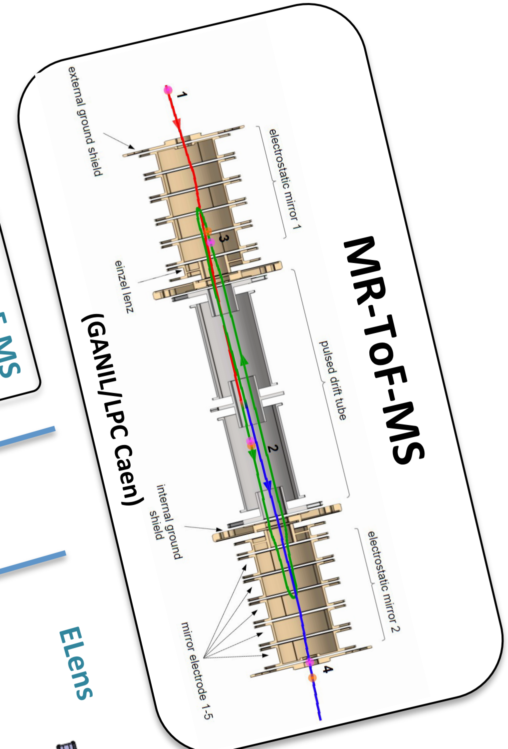
- High-intensity heavy ion beams:
  e.g. ^{48}Ca: >10 pμA
- Production of exotic nuclei using heavy-ion fusion evaporation reactions
- Super Separator Spectrometer: S3
- Coupling with the HELIOS laser ionization concept

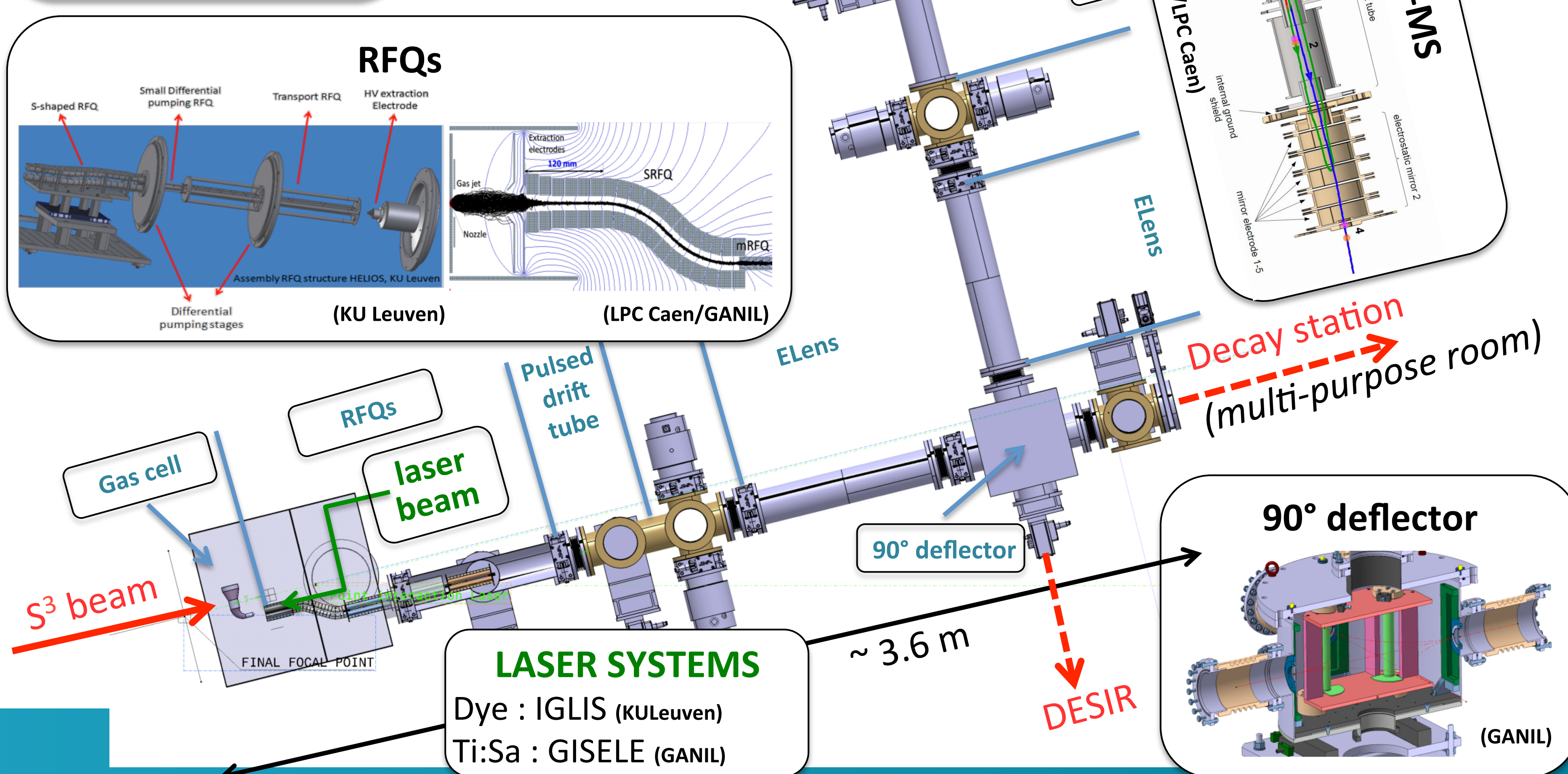
IGLIS @ S3LEB - SPIRAL2 - GANIL
IGLIS @ MARA - JYFL

S^3-LEB general layout

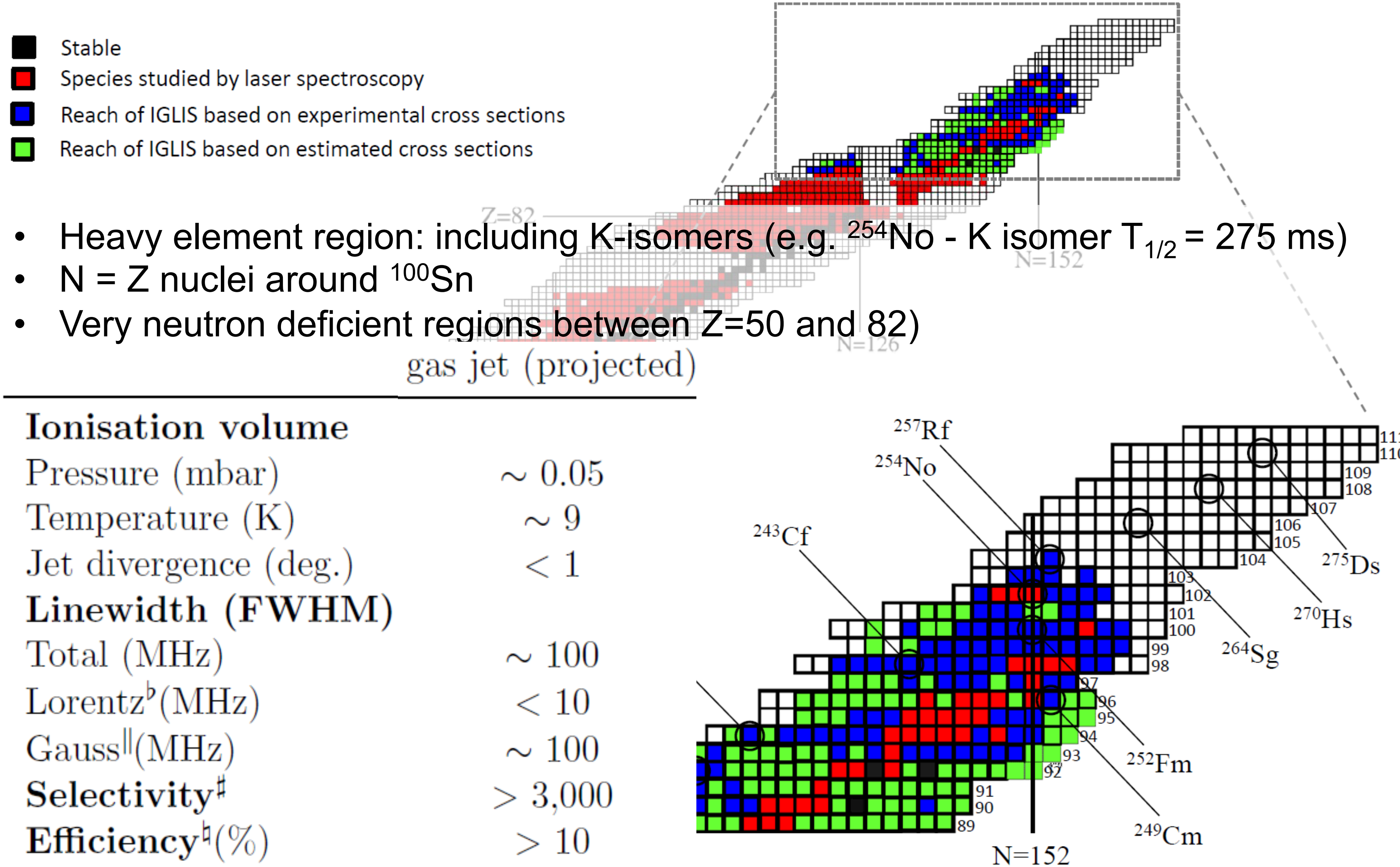
R. Ferrer et al., NIM B 317 (2013) 570
Y. Kudryavtsev et al., NIM B297 (2013) 7







New opportunities with IGLIS



- Heavy element region: including K-isomers (e.g. ^{254}No - K isomer $T_{1/2}$ = 275 ms)
- N = Z nuclei around ^{100}Sn
- Very neutron deficient regions between Z=50 and 82)

	gas jet (projected)
Ionisation volume	
Pressure (mbar)	~ 0.05
Temperature (K)	~ 9
Jet divergence (deg.)	< 1
Linewidth (FWHM)	
Total (MHz)	~ 100
Lorentz[♭] (MHz)	< 10
Gauss[‖] (MHz)	~ 100
Selectivity[♯]	$> 3{,}000$
Efficiency[♮] (%)	> 10

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Conclusion and outlook

- Feasibility for **in-gas jet laser ionization spectroscopy** of actinium is proven
  - good efficiency (5.6 % duty factor corrected), good spectral resolution (~400 MHz)

- Further off-line characterization will be performed at the IGLIS lab at KU Leuven

- Opens new route for precision laser spectroscopy measurements of neutron-deficient isotopes and study of pure isomeric beams produced in heavy-ion fusion evaporation reactions
  - N=Z line around and below ^{100}Sn
  - neutron-deficient deformed region A~150
  - very heavy element region

- On-line experiments at S3 (SPIRAL2 - GANIL)

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KU Leuven LISOL team

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GSI: M. Laatiaoui, M. Block

JYFL University of Jyväskylä: I. Moore, V. Sonnenschein

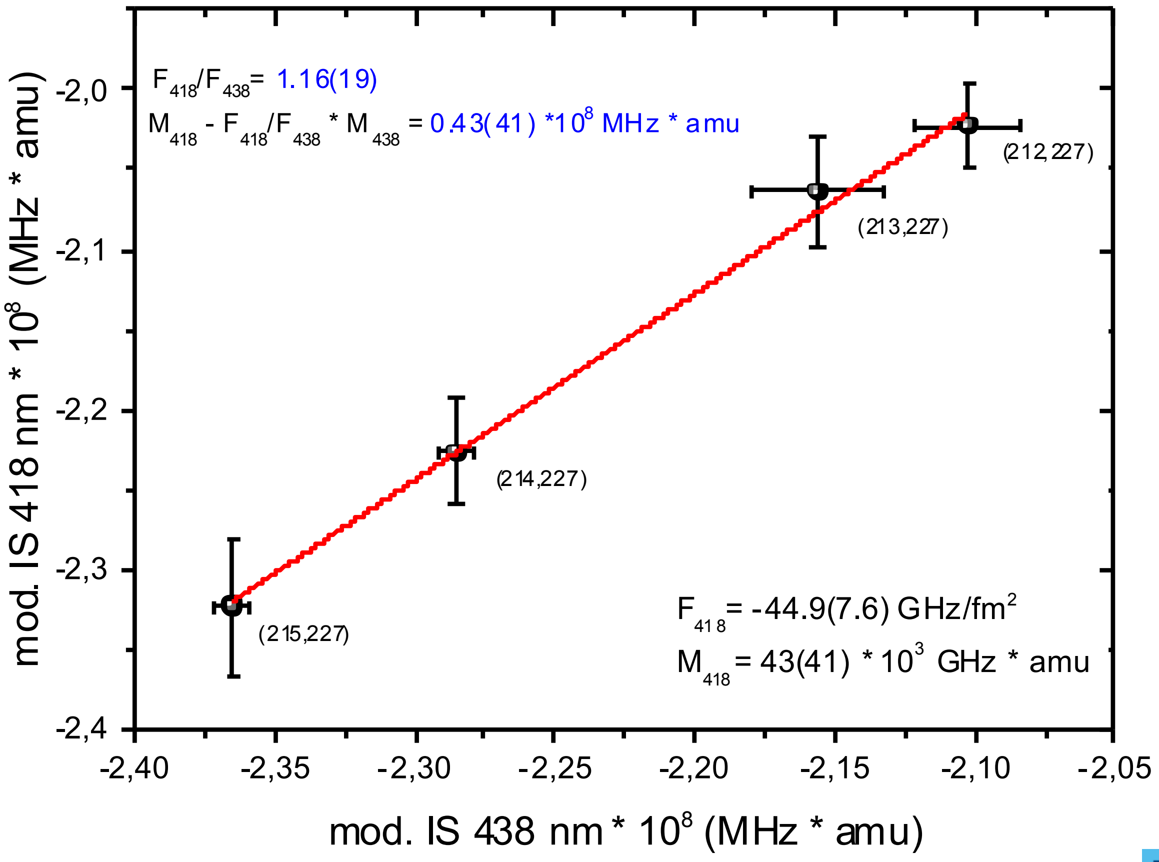
RILIS-ISOLDE: S. Rothe **TRIUMF:** P. Kunz, J. Lassen, A. Teigelhoefer

Mean charge radii

In order to determine mean charge radii:

- Calculate electronic factor and specific mass shift (R. Beerwerth, S. Fritzsche)

- Use King plot to test calculations



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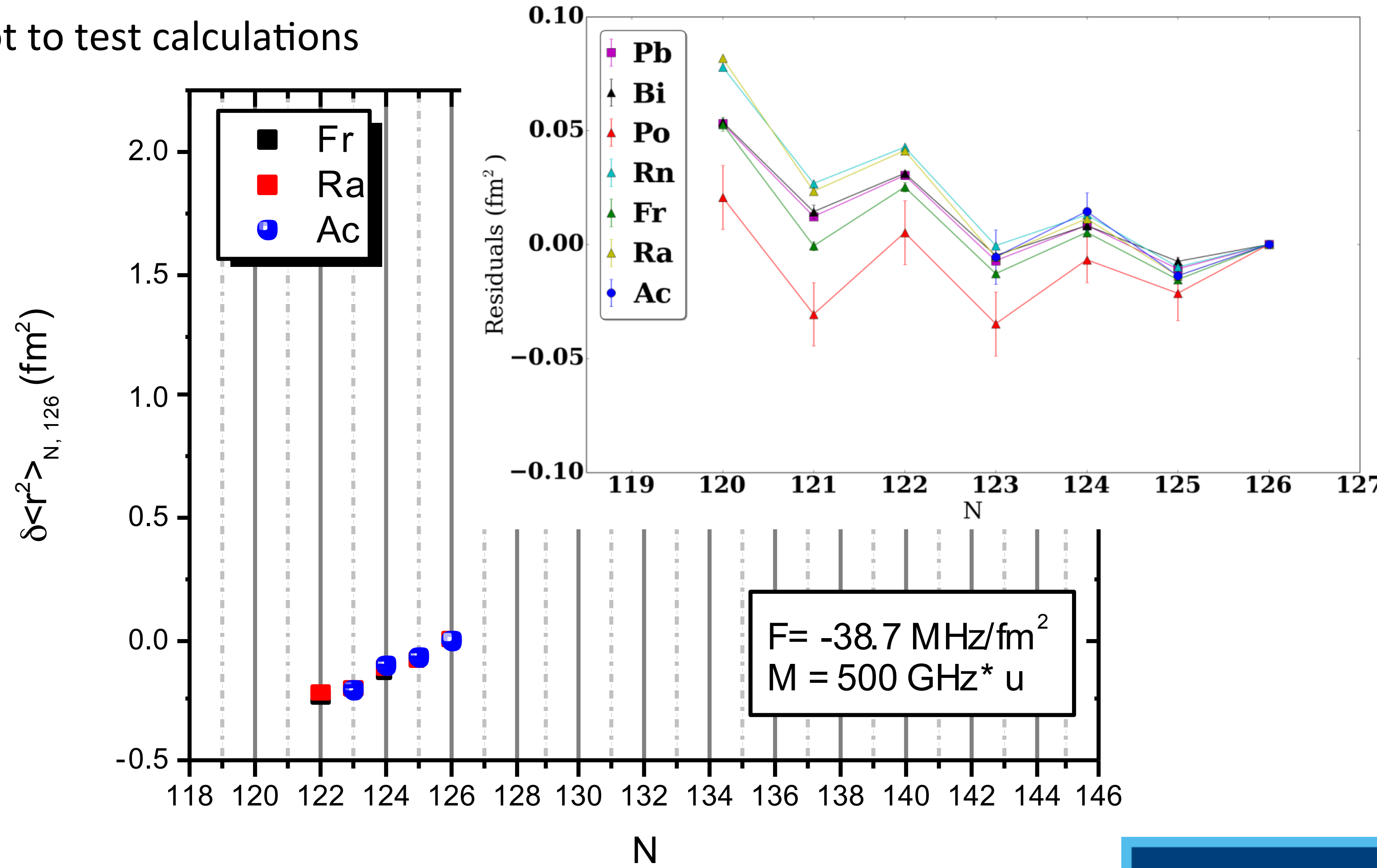

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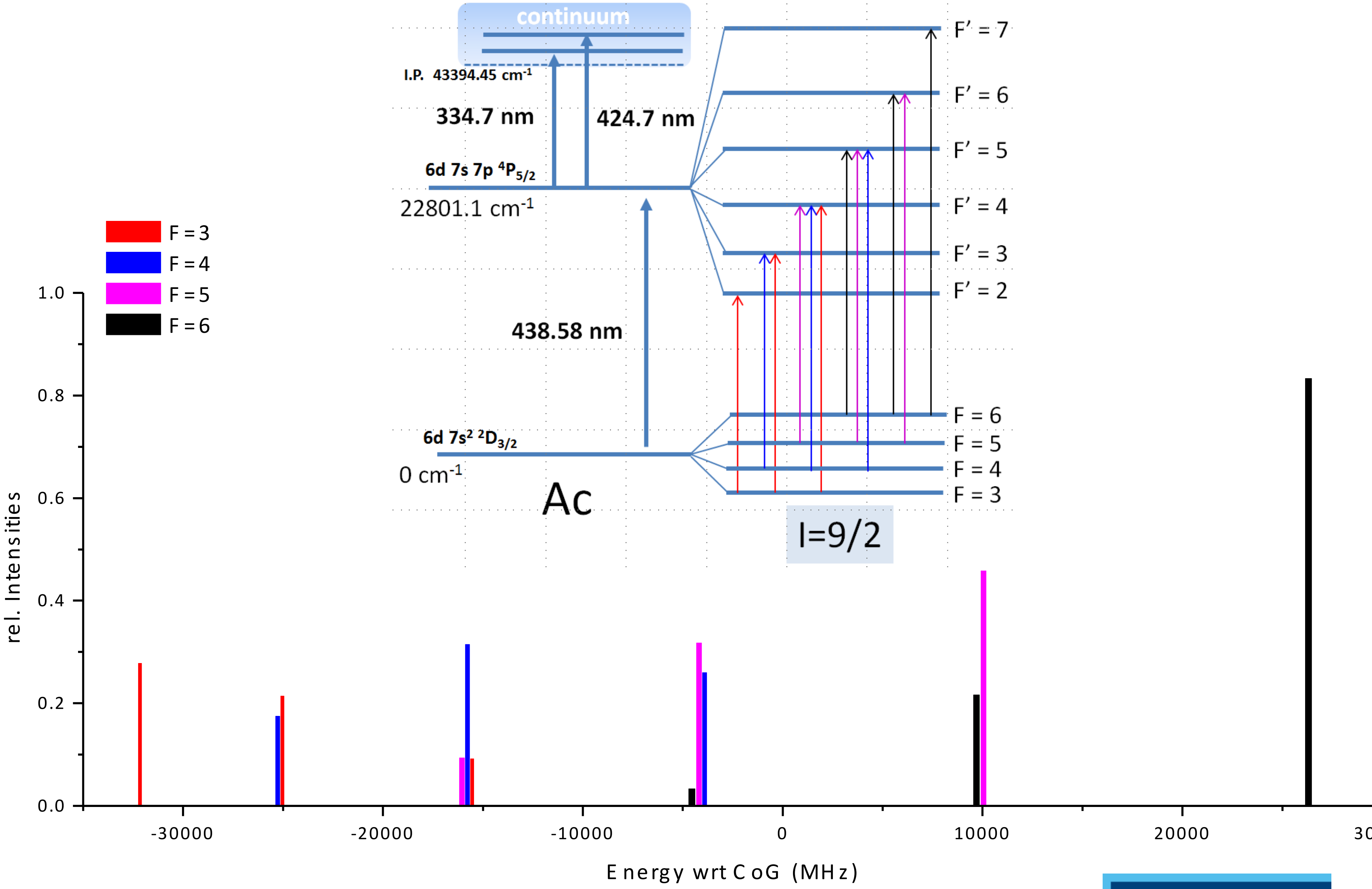
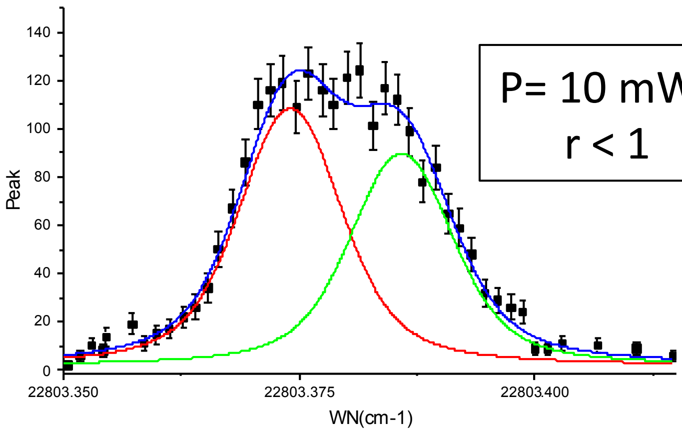
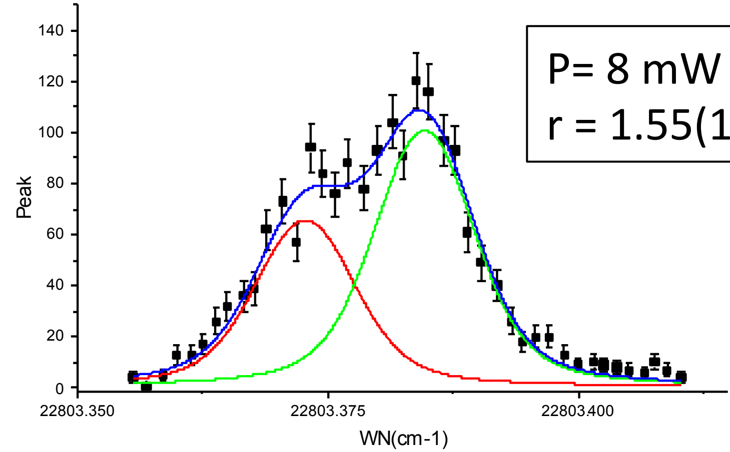
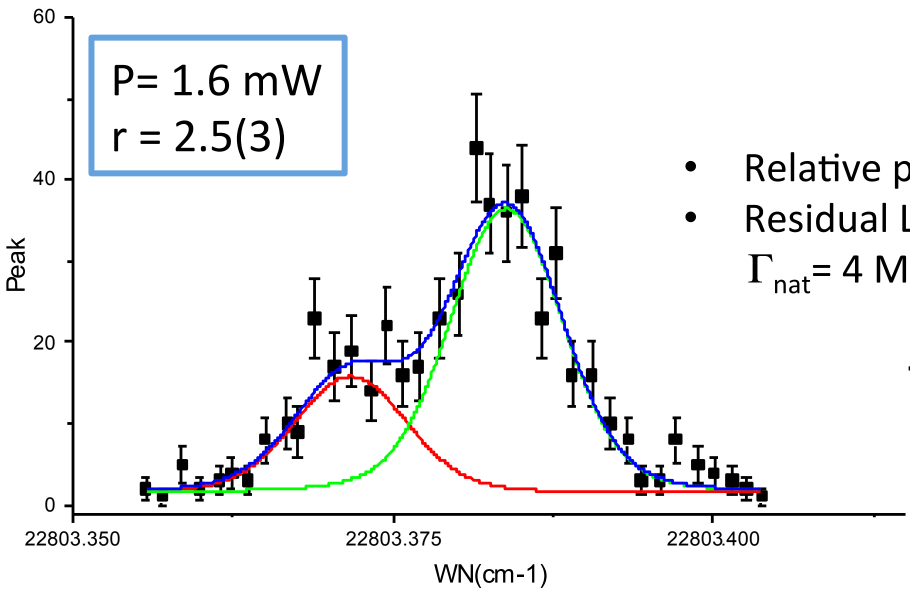


continuum
I.P. 43394.45 cm-1
334.7 nm
424.7 nm
6d 7s 7p 4P5/2
22801.1 cm-1
438.58 nm
6d 7s2 2D3/2
0 cm-1
Ac
I=9/2
F' = 7
F' = 6
F' = 5
F' = 4
F' = 3
F' = 2
F = 6
F = 5
F = 4
F = 3
F = 3
F = 4
F = 5
F = 6
rel. Intensities
Energy wrt CoG (MHz)

- Racah relative intensity ratio 5 ->6’ to 6 -> 6’ r = 2.33 only followed at low power







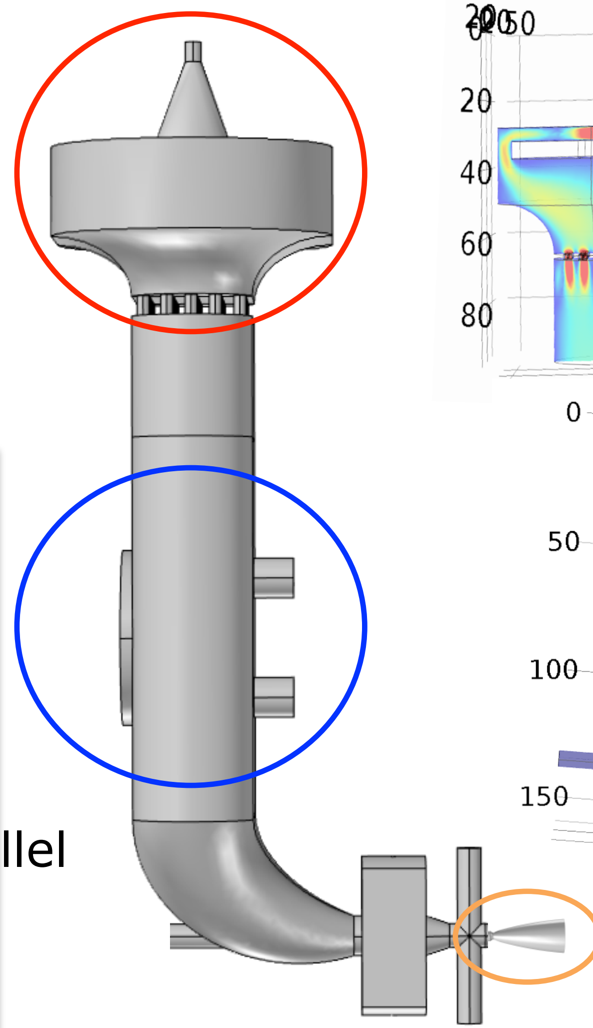
- Relative position between centroids constant within 2%
- Residual Lorentzian broadening ~42(6) MHz (reproduced in singlet)
  Γ_{nat}= 4 MHz (A= 2e7 s^{-1})

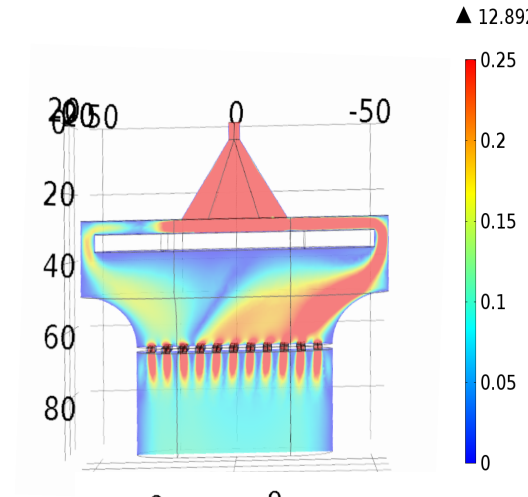
→ Γ_{br} = 38(6) MHz [$(\Gamma_{br})_{theo}$= 60(7) MHz]

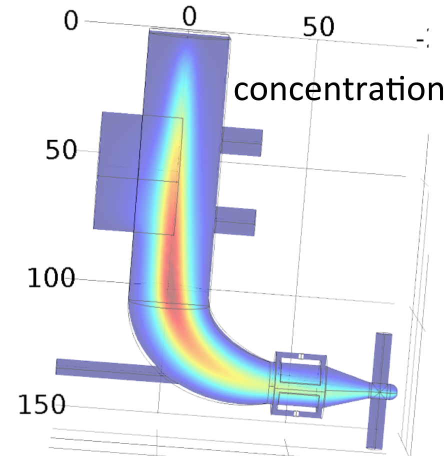
Γ_{sh} ~ 13 MHz

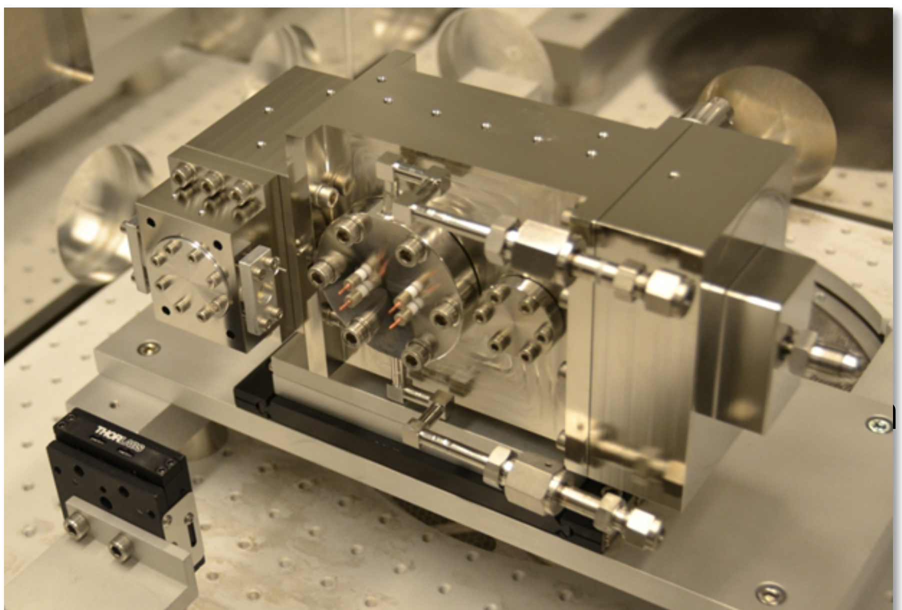
New Gas Cell Design for S3@GANIL

- The gas inlet
  - Obstacle to reduce vortices
  - Honeycomb tube structure to produce a homogeneous flow through the cell









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