HÜBNER Photonics
UNIVERSITY OF GOTHENBURG

Laser development towards resonant laser ionization spectroscopy of actinides

LISA Conference, CERN
2.09.2024

Mitzi Urquiza

LISA
LASER IONISATION AND SPECTROSCOPY OF ACTINIDES

This Marie Sklodowska-Curie Action (MSCA) Innovative Training Networks (ITN) receives funding from the European Union's H2020 Framework Programme under grant agreement no. 861198

Motivation

Laser **I**onization and **S**pectroscopy of **A**ctinides

Actinides are complicated to study.

- Provide atomic and nuclear structures
- For the heaviest elements, limited by [1]
  - Low production rates
  - Scarce information on atomic levels

[1] M. Block, et al., Progress in Particle and Nuclear Physics 116, 103,834 (2021).

Motivation

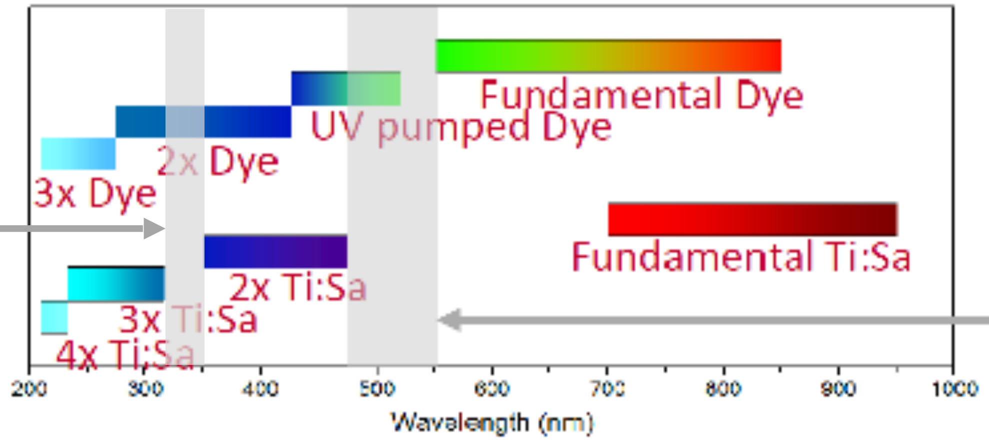
Laser **I**onization and **S**pectroscopy of **A**ctinides

Lasers need pulses with enough power density, stability, and narrowband operation.

Challenges:

- Produce *difficult* wavelengths
- Optical linewidth << GHz
- Frequency stability

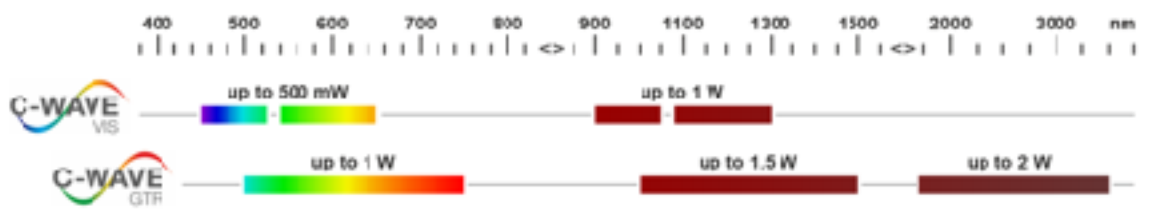
Spectral coverage at RILIS [5]



Dyes are 'complicated'

Am 28009 cm-1 [2] 357 nm
Fm 28185 cm-1 [3], 354.8 nm
No 29961 cm-1 [4], 333.8 nm

cw → pulsed amplification → SHG

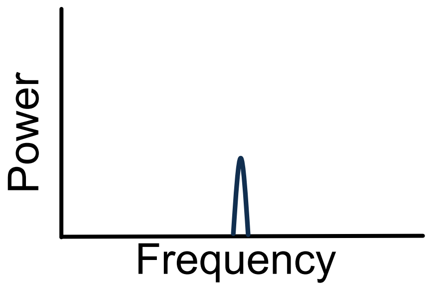


470 - 540 nm is difficult or impossible to access

*[2] Fred et al., J. opt. Soc. Am., **47**, 1076-87 (1957).*
*[3] Allehabi et al., JQSRT **253**, 107137 (2020)*
*[4] Laatiaoui et al., Nature **538**, 495–498 (2016)*
[5] Marsh, Leuven Pb-U workshop (2019)

Laser linewidth at FWHM

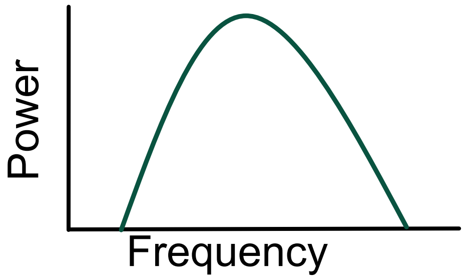
cw OPO



- Single frequency spectrum
  (< 500 kHz linewidth)

+

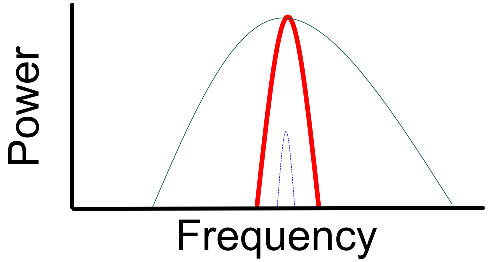
Pulsed amplifier



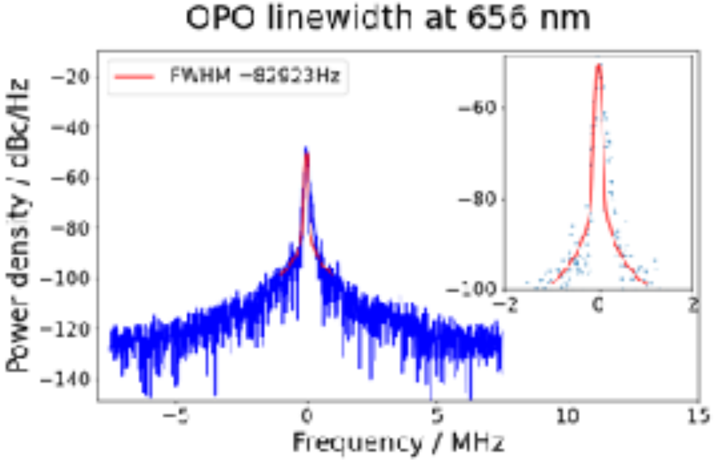
- Wide spectrum
  (GHz- THz)

=

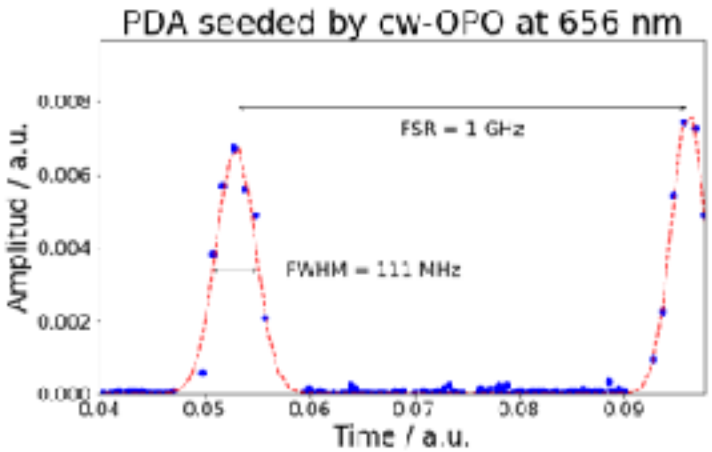
Injection seeded/locked pulsed laser



- Narrow spectrum
  ~ 10 - 100 MHz (Fourier transform limit)

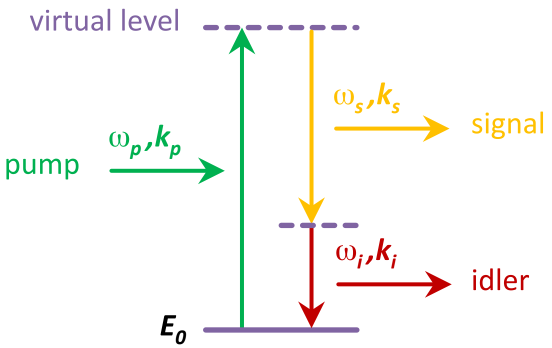


- Dye amplifier
- Ti:Sa cavity
- OPA



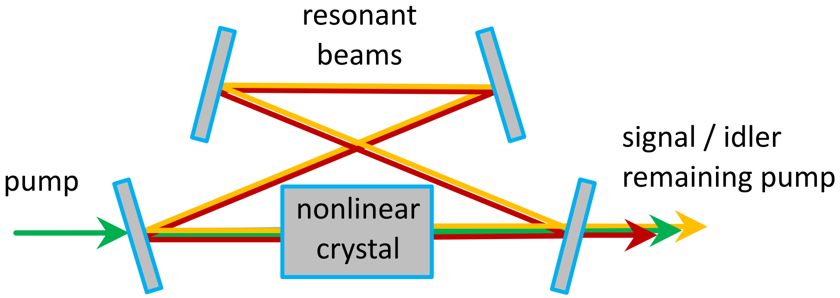
OPO basics

PRINCIPLE



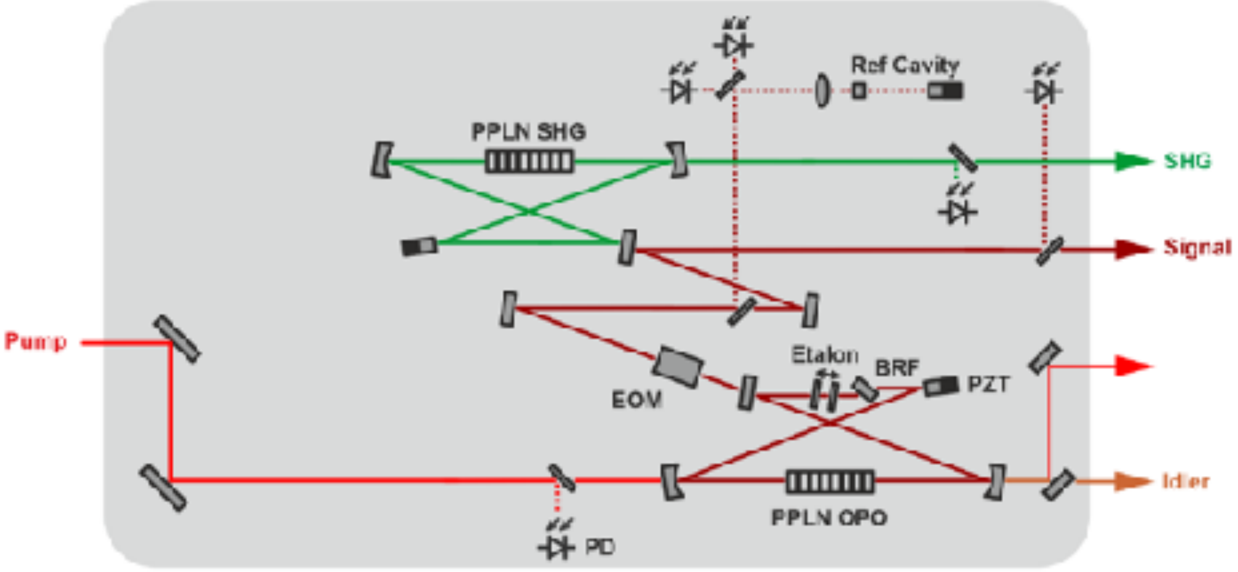
- Three-wave-mixing of pump, signal, and idler
- $\omega_p = \omega_s + \omega_i$
- $k_p = k_s + k_i + \Delta k$

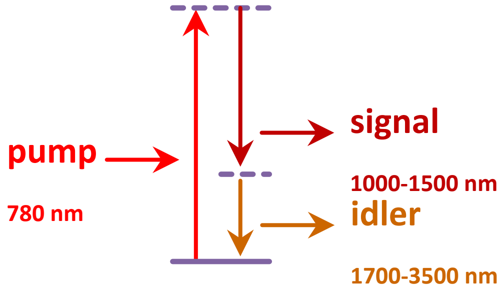
REALIZATION

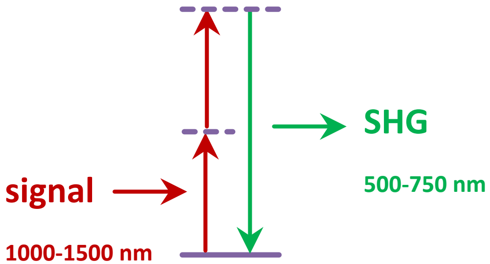


- Source of coherent pump light
- $\chi^{(2)}$ nonlinear medium
- Bow-tie optical resonator

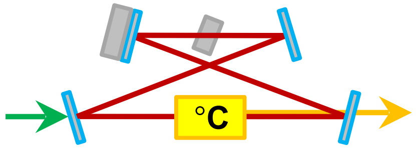
Beam Path Step-by-Step

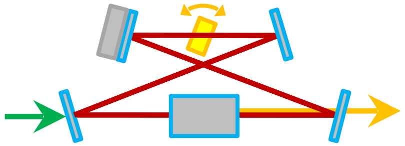


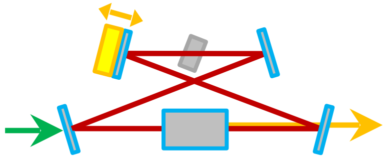




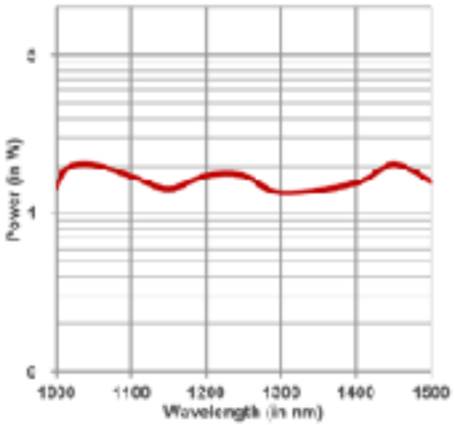
Wavelength Tuning Mechanisms



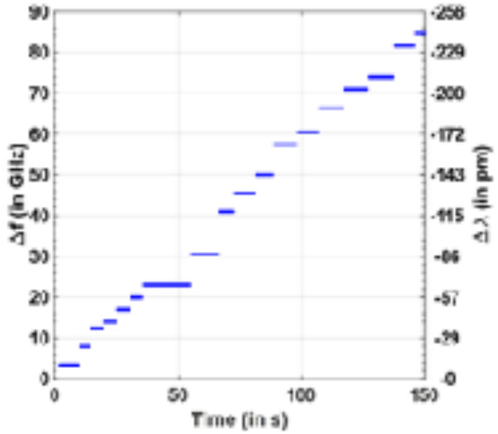




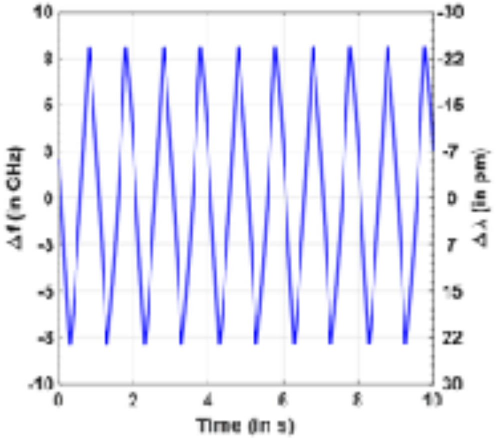
Coarse tuning | **Stepwise tuning** | **Continuous tuning**



A few nm per centigrade,



up to 100 GHz,

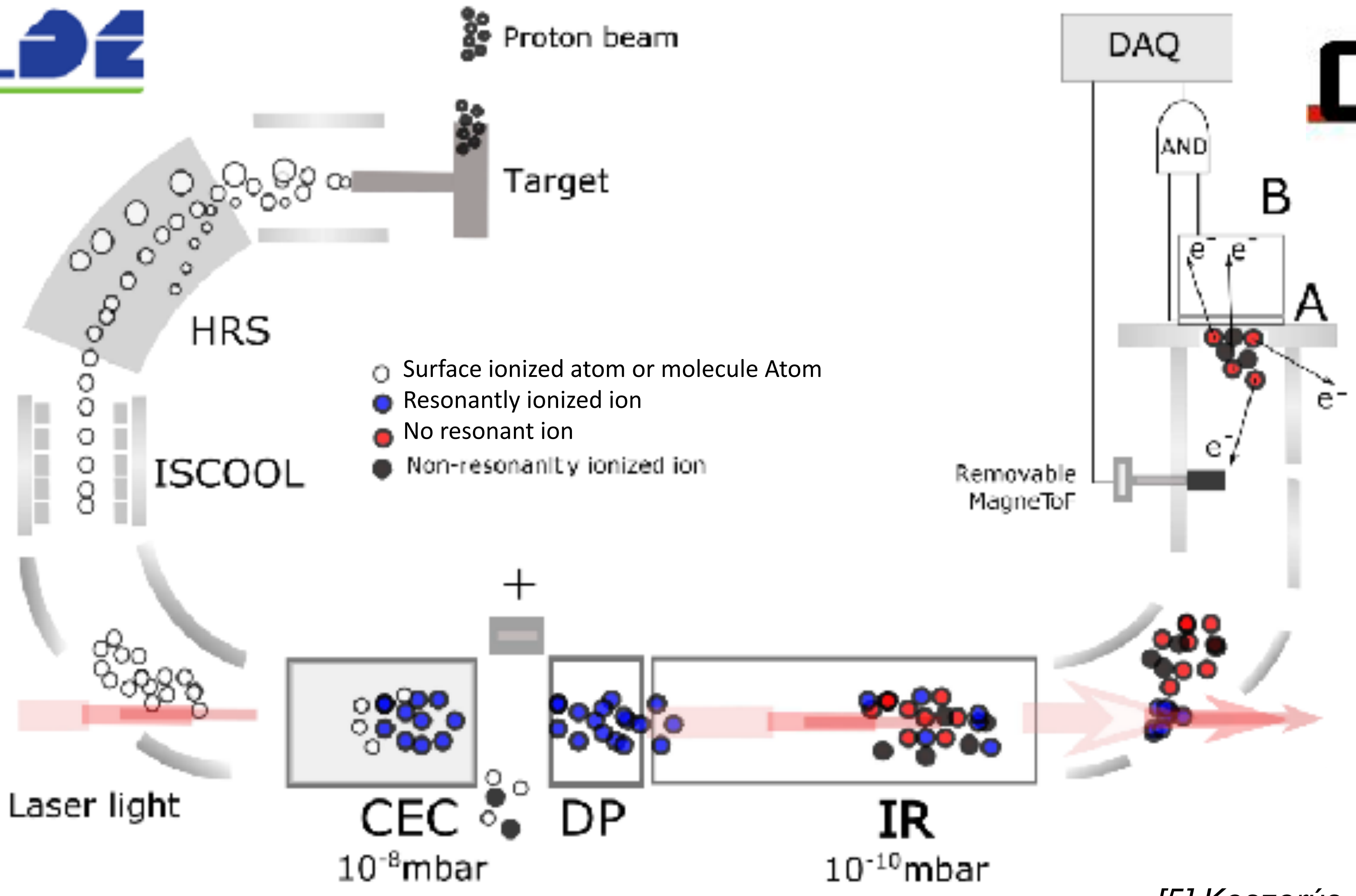


up to 20 GHz per scan.

First experiment

Benchmark evaluation of an OPO seeded system with silver @ 328 nm

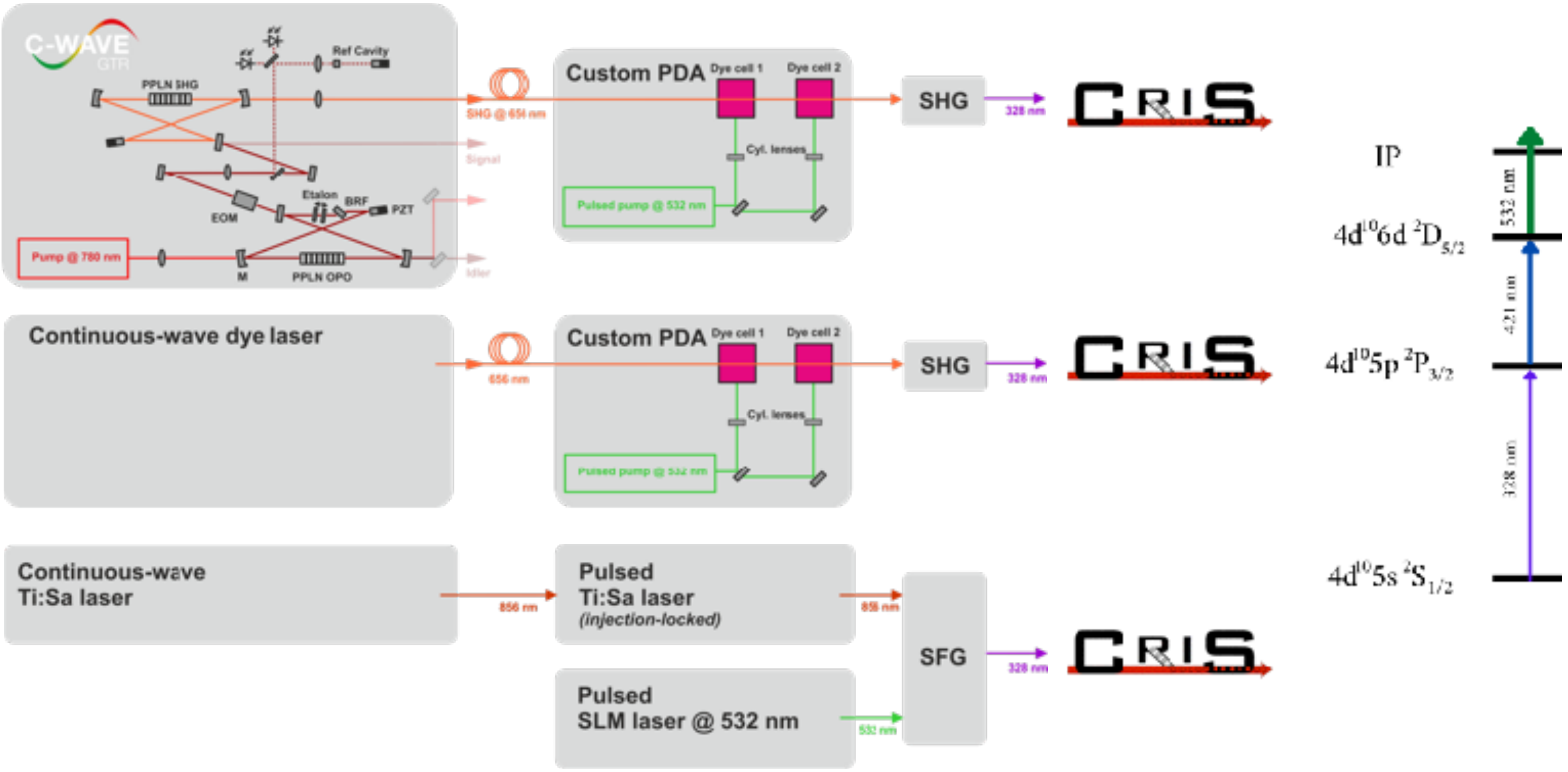
CRIS setup at ISOLDE, CERN [5]



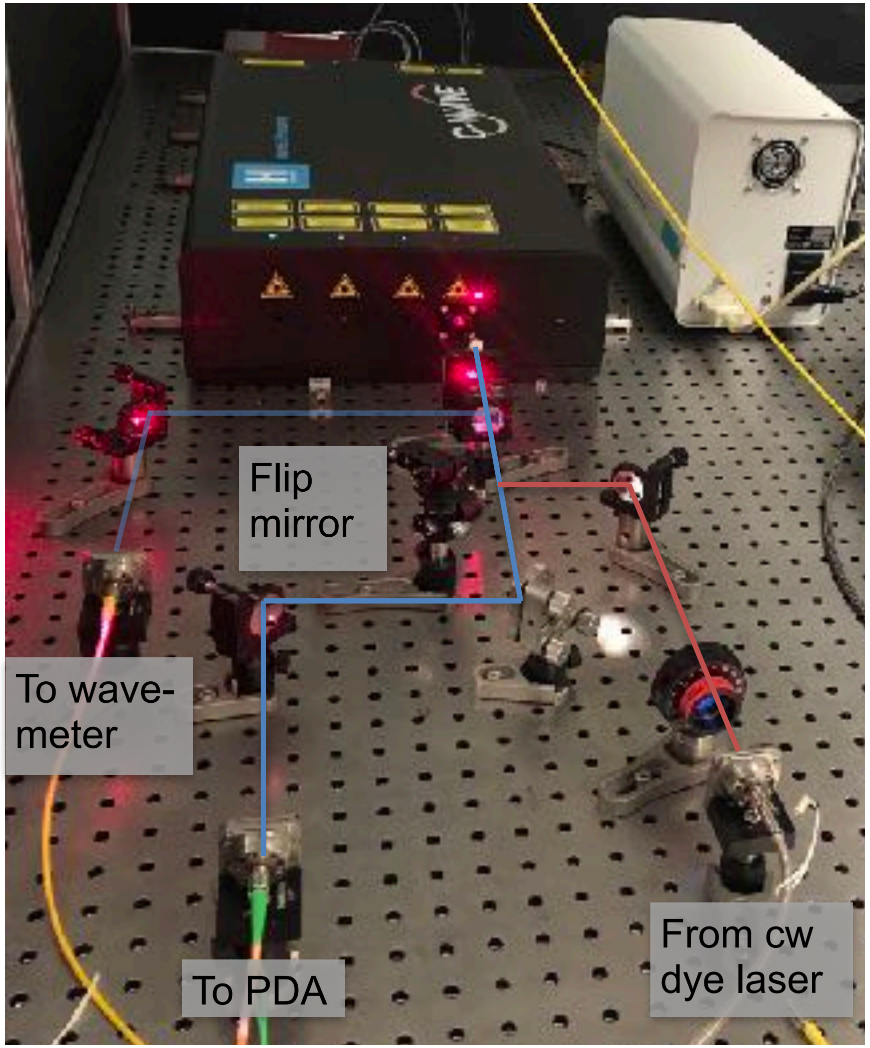
[5] Koszorús et al., *Nat. Phys.* **17**, 539 (2021).

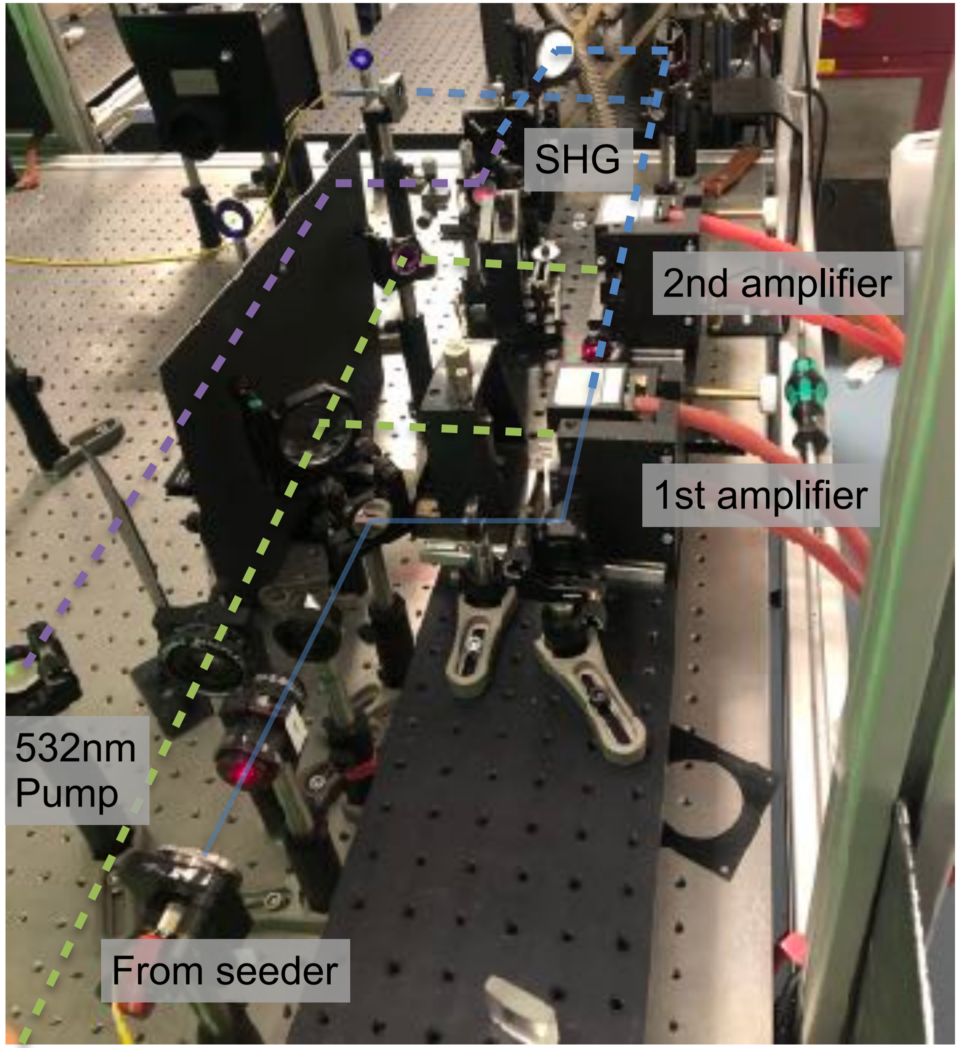
Laser systems to generate 328 nm pulses

- OPO
- Dye
- SFG



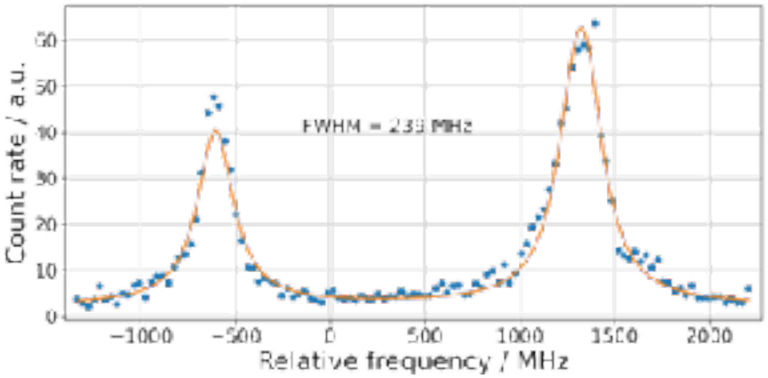
Experimental setup



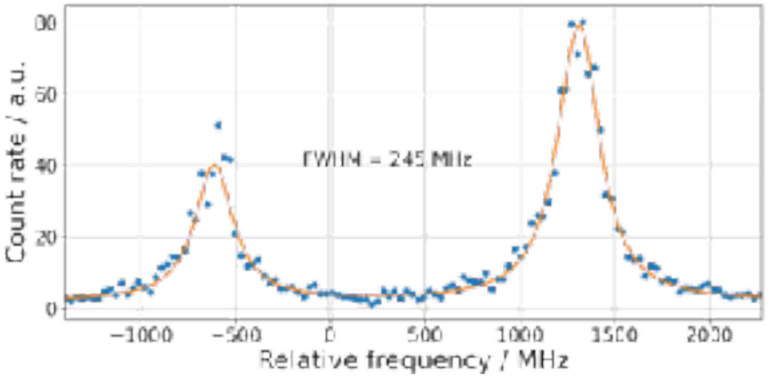


Benchmarking the OPO system for laser spectroscopy

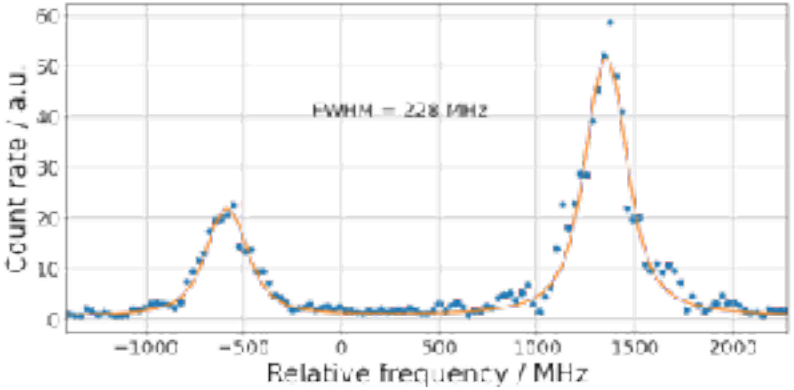
- Compare 109-Ag with three systems
  - Optical and transition linewidth
  - Handling and maintenance



a) HFS with OPO.



b) HFS with Dye.



c) HFS with SFG.

Optical LW	156(17) MHz	140(17) MHz	141(14) MHz
Transition LW	239(14) MHz	245(10) MHz	228(15) MHz

PRELIMINARY

Results

Transition linewidth, hf splitting, dipole moment, IS, and change in the mean-squared charge radii

A	FWHM				
109	239(14)	**1.959(21)**[a]	Ref. b	0	0
111	221(5)	2.153(8)	**-0.144(2)** [c]	-436(5)	0.181(27)
111m	188(10)	38.684(8)	4.52(5)	-357(4)	0.162(26)
117	232(17)	2.615(17)	-0.174(3)	**-1198(10)** [d]	**0.578(94)**[e]
117m	**173(9)**	37.960(2)	4.43(5)	-1113(2)	0.558(91)

Literature values

a 1976.932075(17) MHz [6]

b -0.1306906(2) μ_N [7]

c -0.146(2) μ_N [8]

d −1181(6) MHz [9]

e 0.568 (73) fm^2 [9]

*[6] Dahmen et al., Z. Physik **200**, 456–466 (1967)*
*[7] Sahm and Schwenk, Z. Naturforsch. A **29**,1763(1974)*
*[8] Woodgate and Hellwarth, Proc. Phys. Soc. A **69**, 581 (1956)*
*[9] Reponen et al., Nat Commun **12**, 4596 (2021)*

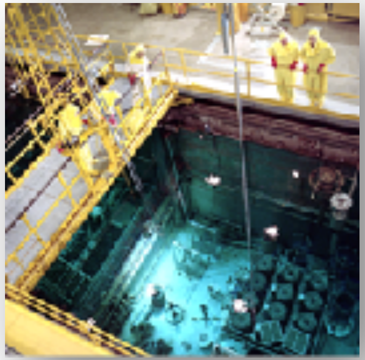
Second experiment

High-resolution spectroscopy of Fm-255

(Attempted) evaluation an OPO injection-locked Ti:sa system with fermium @ 355 nm

Production of fermium-255

High Flux Isotope Reactor (HFIR) at ORNL



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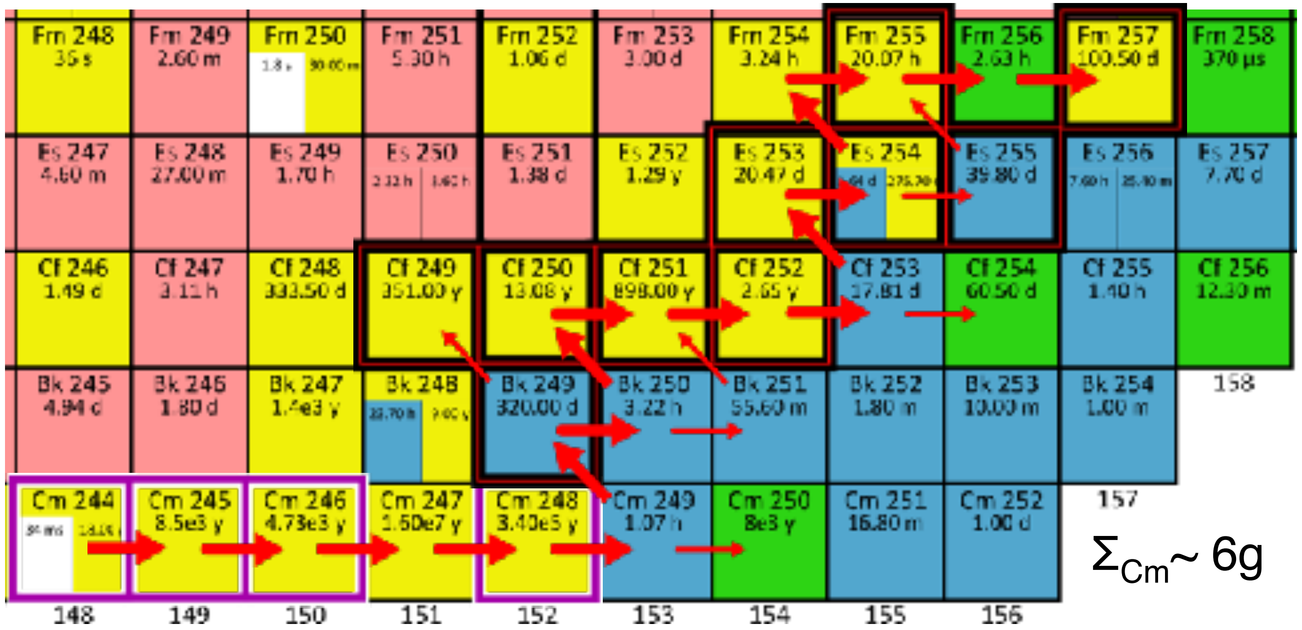
OAK RIDGE National Laboratory



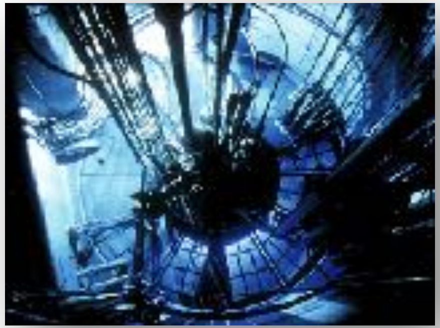
$\Sigma_{Cm} \sim 6g$

Initial nuclides

Produced nuclides

See:
- Jessica Warbinek Tomorrow 10:15

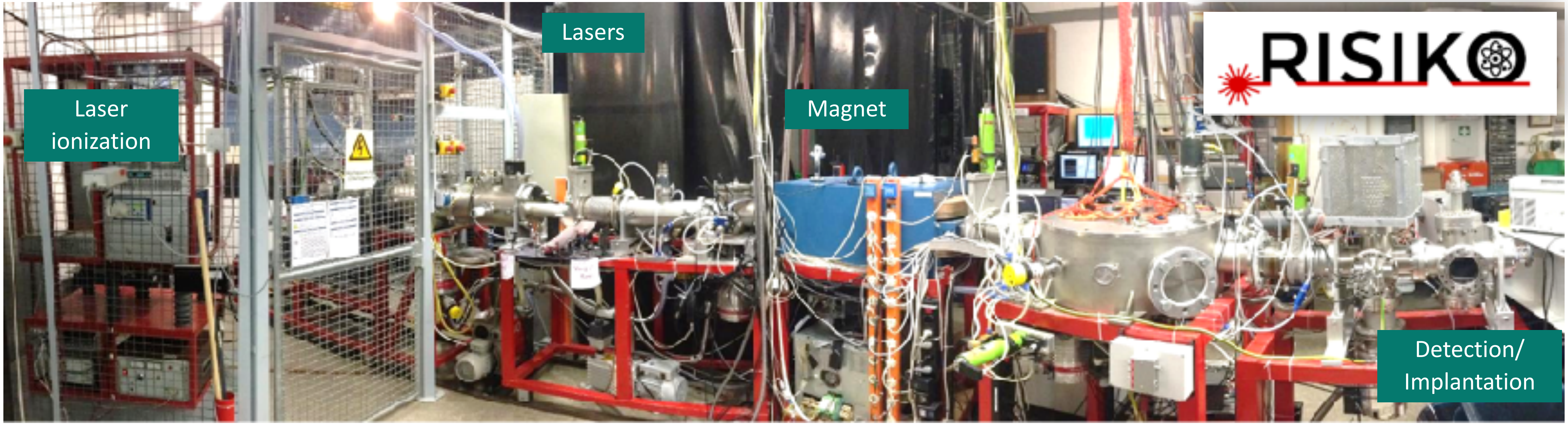
High Flux Reactor at ILL



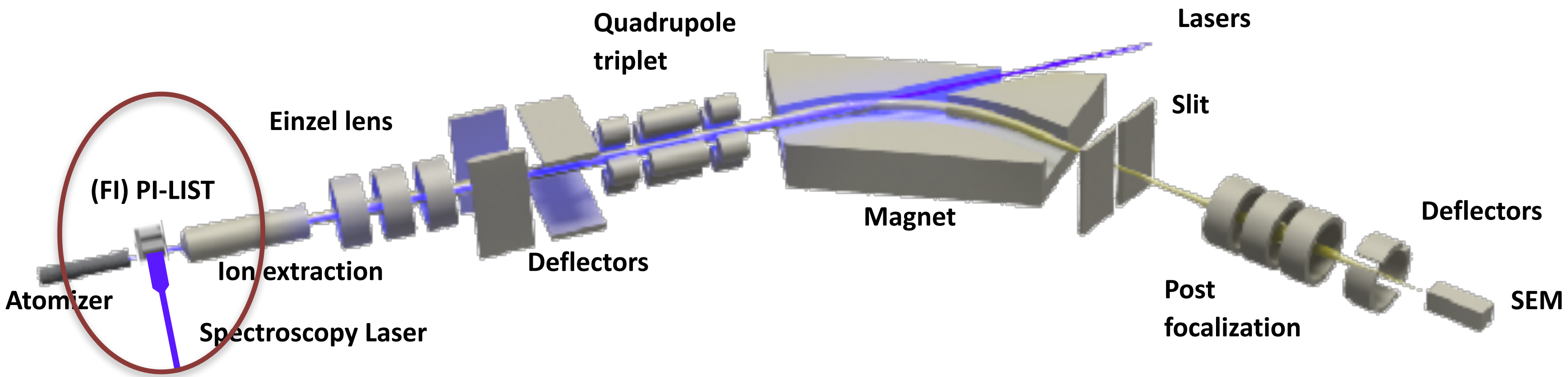
NEUTRONS FOR SOCIETY

The isotopes used in this research were supplied by the U.S. Department of Energy, Office of Science, by the Isotope Program in the Office of Nuclear Physics. The ^{253,254,255}Es and ^{255,257}Fm were provided to Florida State University and the University of Mainz via the Isotope Development and Production for Research and Applications Program through the Radiochemical Engineering and Development Center at Oak Ridge National Laboratory.

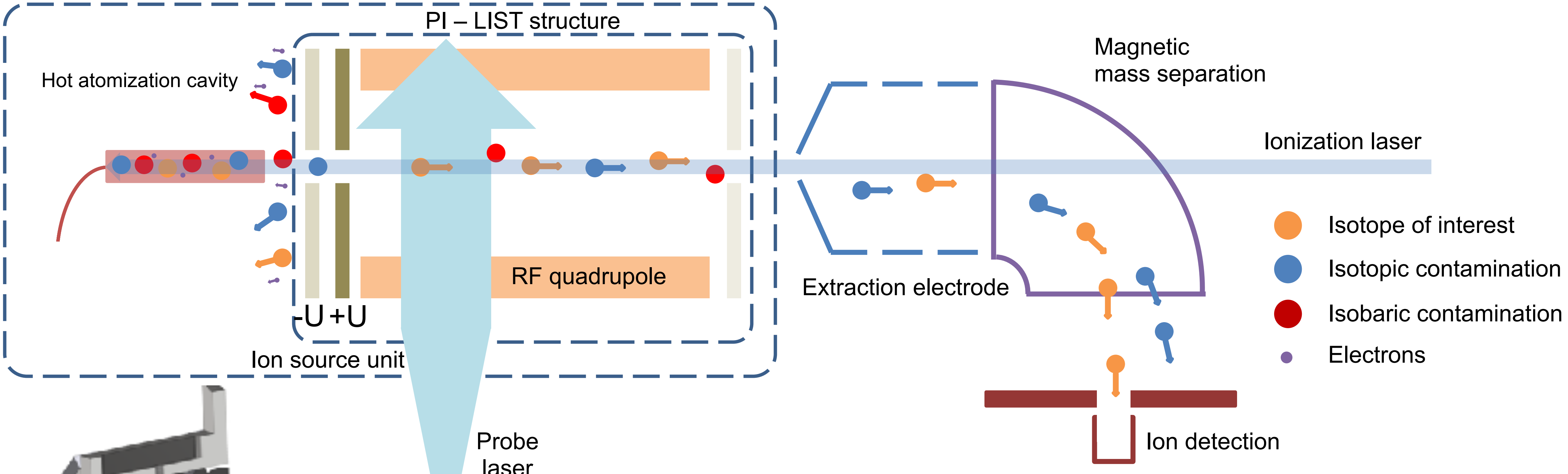
RISIKO mass separator

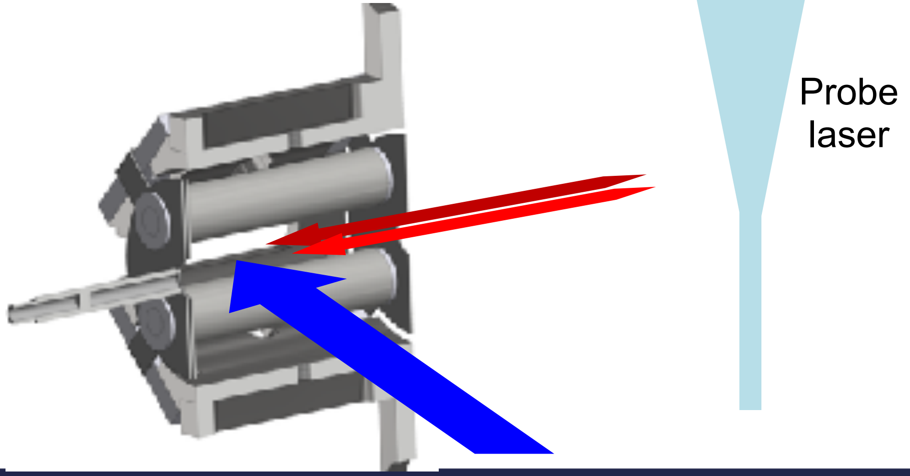


- Hot cavity laser ion source
- Standard in-source ionization
- Perpendicular laser interaction geometry for high-resolution spec.



PI-LIST Perpendicularly Illuminated - Laser Ion Source and Trap [10]

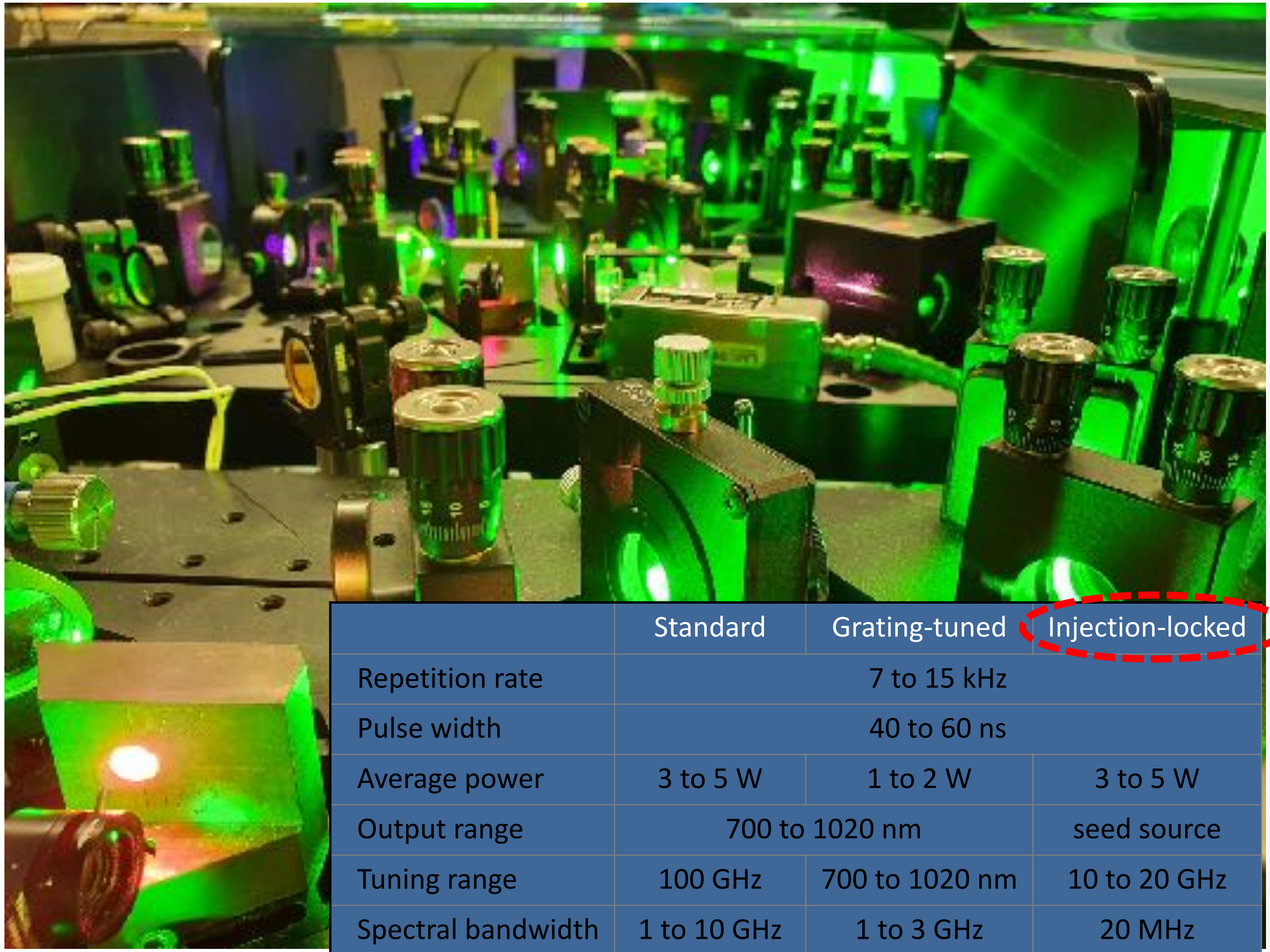




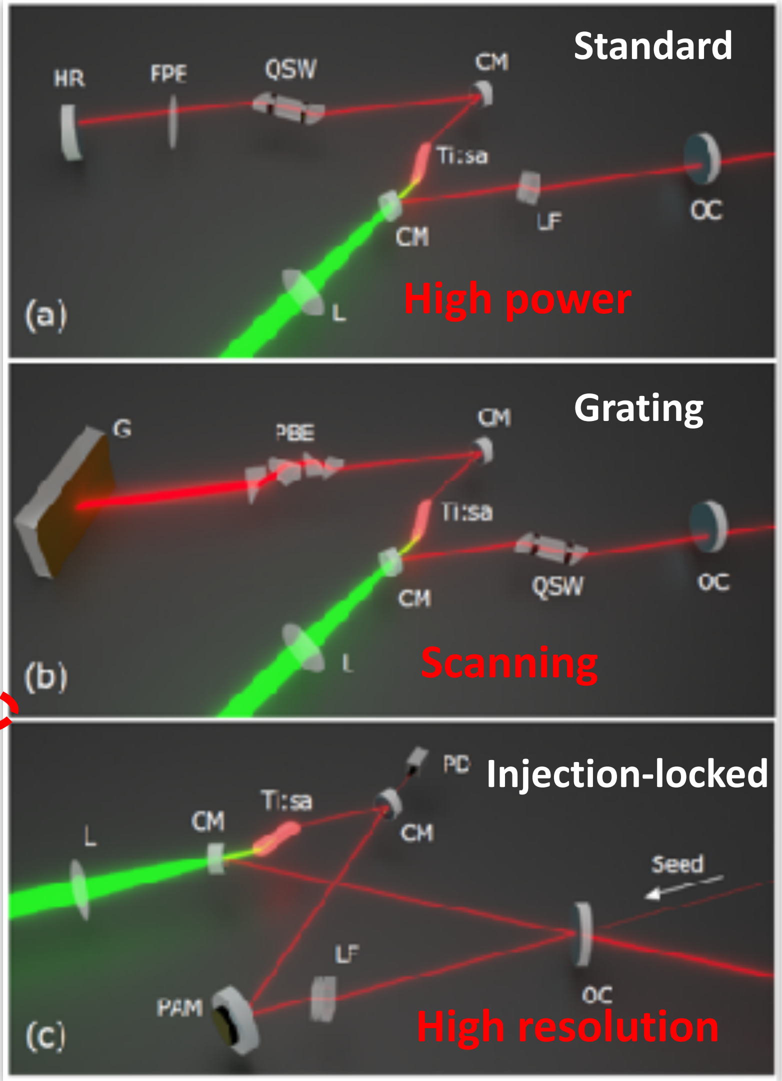
- Suppression of surface ionized species
- Pulsed laser ionization inside RF quadrupole structure
- High-resolution spectroscopy with reduced Doppler broadening

[10] Heinke et al., Nucl. Instrum. Methods Phys. Res. B, 8-12 (2023)

Laser systems at Mainz

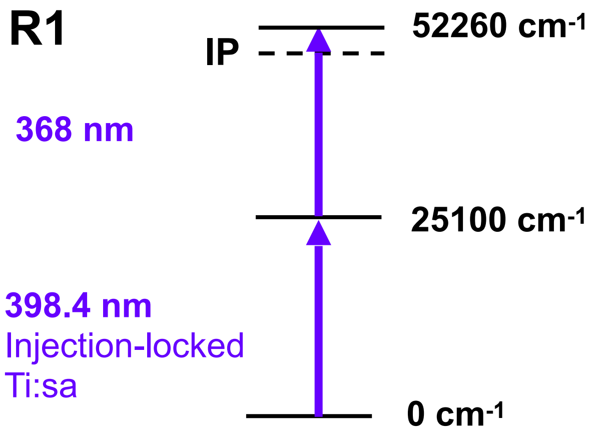


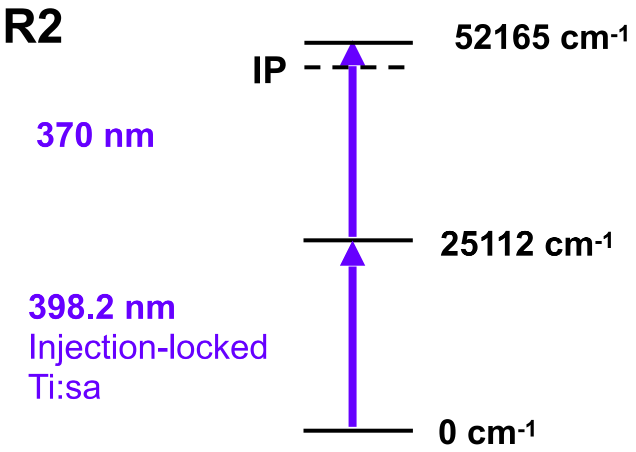
	Standard	Grating-tuned	Injection-locked
Repetition rate	7 to 15 kHz		
Pulse width	40 to 60 ns		
Average power	3 to 5 W	1 to 2 W	3 to 5 W
Output range	700 to 1020 nm		seed source
Tuning range	100 GHz	700 to 1020 nm	10 to 20 GHz
Spectral bandwidth	1 to 10 GHz	1 to 3 GHz	20 MHz

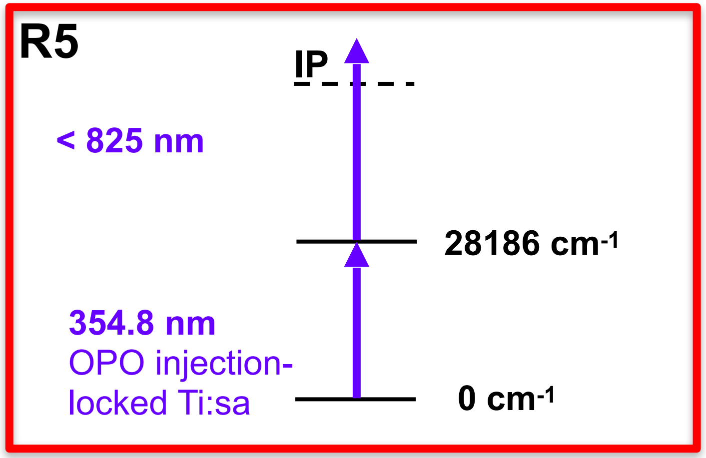


Ionization schemes [11]

No.	WN (cm-1)	FWHM (cm-1)	WN fund. (cm-1)	WL fund. (nm)	WN to IP (cm-1)	WN to IP fund. (cm-1)	WL to IP fund. (nm)
R1	25,099.80 pm 0.2		12,549.90	796.8	27,300.2	13650.1	732.6
R2	25,111.80 pm 0.2	-	12,555.90	796.4	27,288.2	13644.1	732.9
R3	27,389 pm 1.5	0.85 pm 0.16	13,694.5	730.2	25,011	12505.5	799.6
R4	27,466 pm 1.5	1.34 pm 0.09	13,733	728.2	24,934	12467	802.1
R5	28,185 pm 1.5	1.08 pm 0.05	14,092.5	709.6	24,215	12107.5	825.9
R6	28,377 pm 1.5	0.75 pm 0.05	14,188.5	704.8	24,023	12011.5	832.5
R7	28,391 pm 1.5	0.61 pm 0.03	14,195.5	704.4	24,009	12004.5	833.0



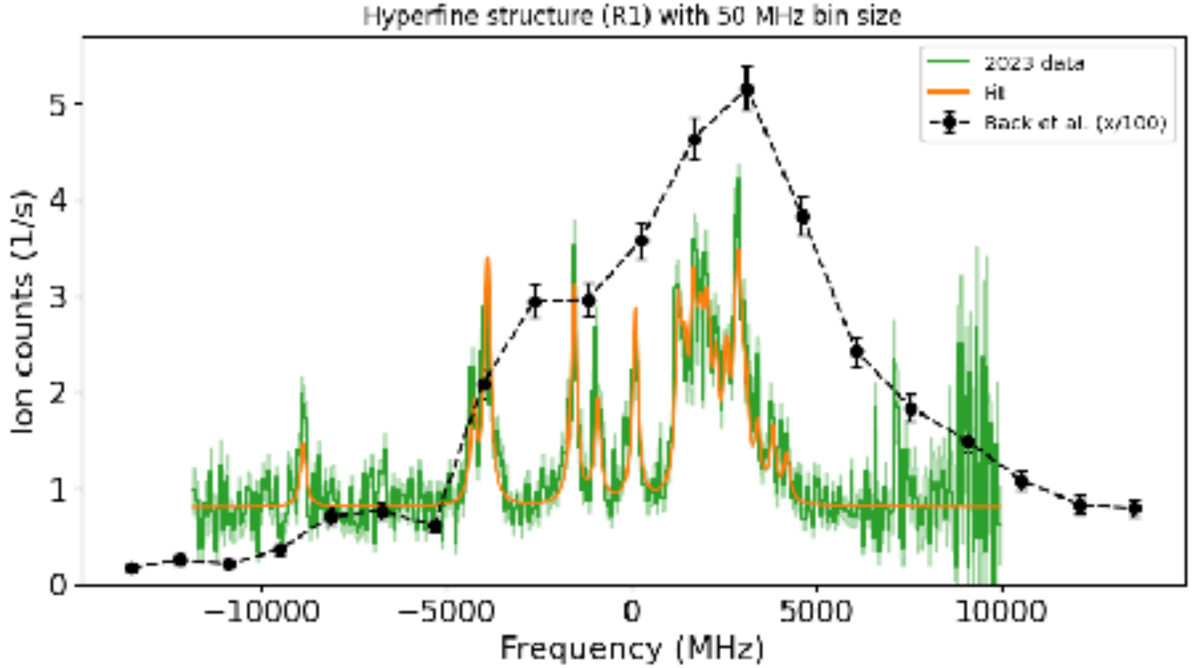


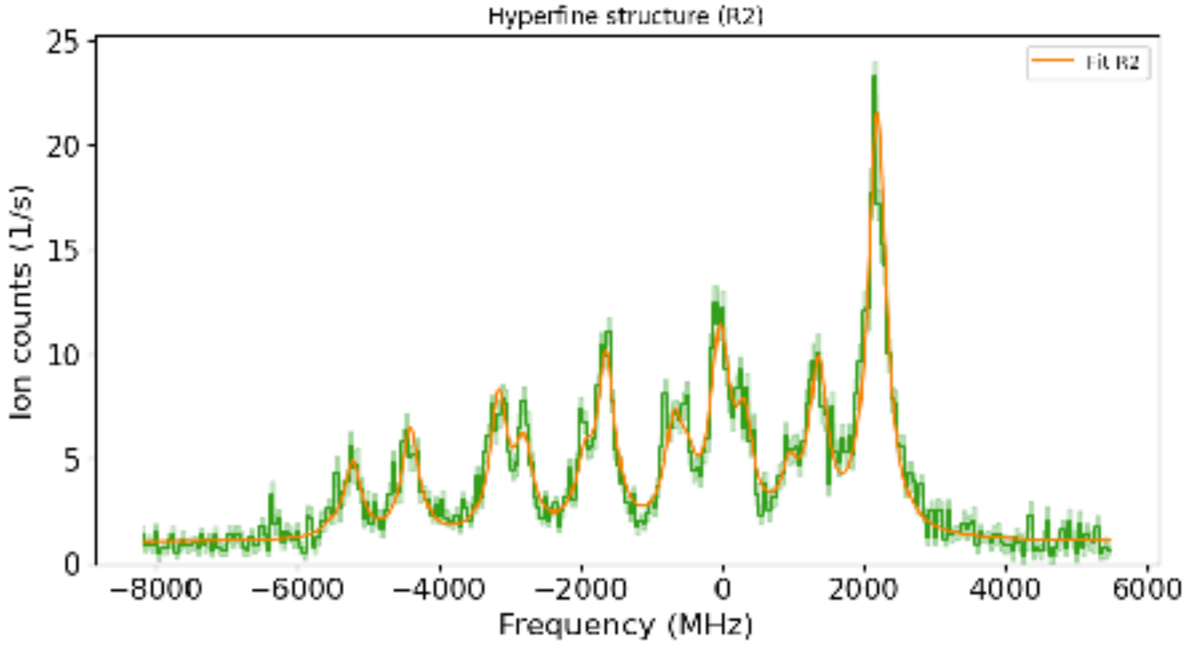


[11] H. Backe, et al., Hyperfine interactions 162(1-4), 3–14 (2005

PRELIMINARY

PI-LIST measurements





	J	E (cm^{-1}) [12]	A (MHz)	B (MHz)
Ground state	6	0	-149 (5)	-10454 (100)
Excited state R1	6	25100	-309 (5)	-12821 (100)
Excited state R2	5	25112	-9 (5)	-13529 (100)

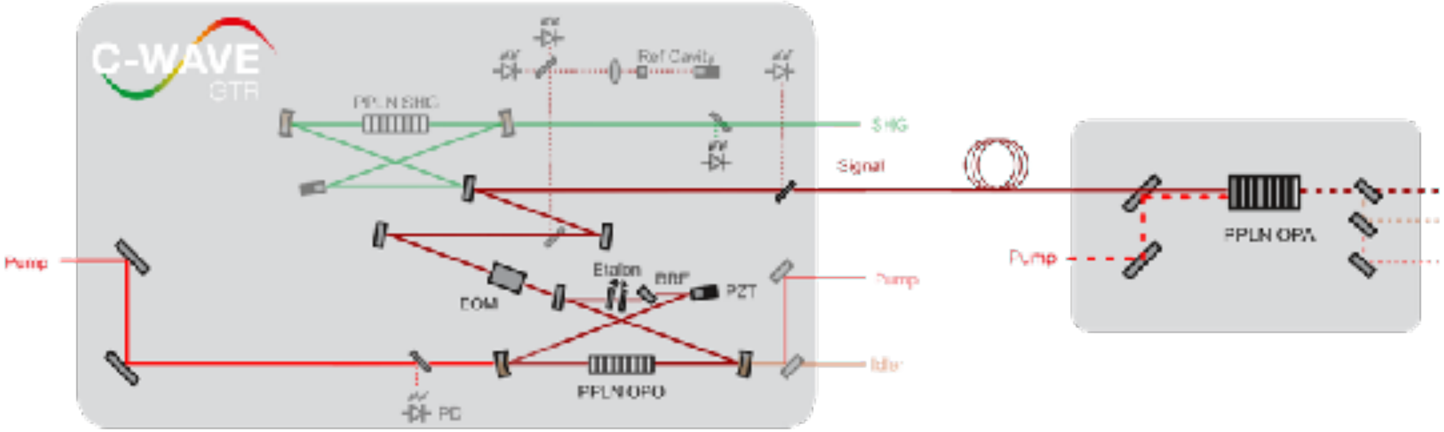
[12] H. Backe, et al., Hyperfine interactions 162(1-4), 3–14 (2005

Conclusions

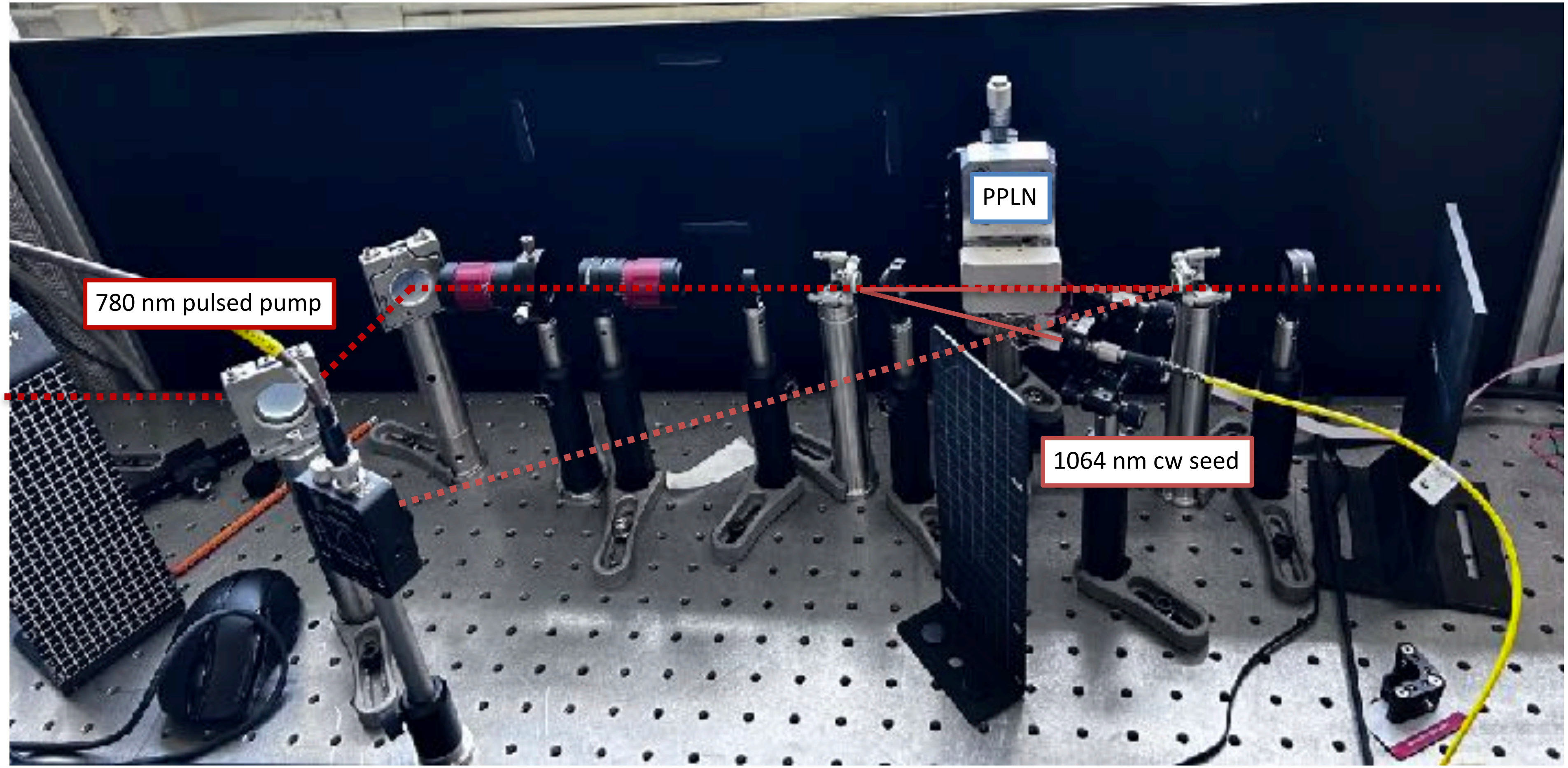
- OPO injection-seeded PDA is suitable for high resolution spectroscopy
  - FWHM ≤173 MHz
  - Known values are in good agreement with literature
  - New measurements for some silver isotopes
- First attempt OPO injection-locked Ti:Sa limited by pump availability
  - Good data from other two excitation schemes

Current work

- OPO/OPA system, all solid state
  - Uses same crystal as the OPO
  - 780 nm pulsed pump (Ti:Sa)
  - No cavity needed
  - Amplified pulses in the OPO fundamental (1000nm - 1500nm)
- Further frequency doubled or tripled stages needed

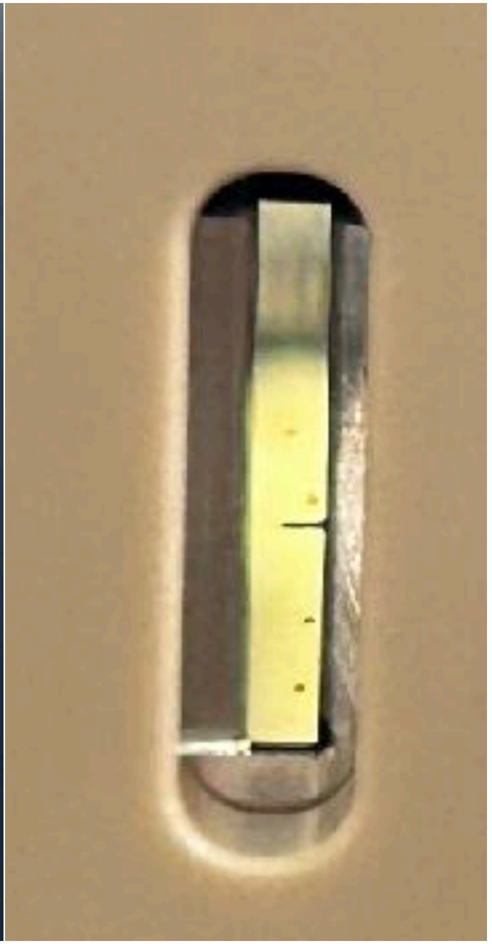


Experimental setup



Current setbacks

- 140mW pump light at 1kHz:
- Unseeded
- No optimization
  - 12% conversion rate



Acknowledgements silver experiment

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The fermium collaboration

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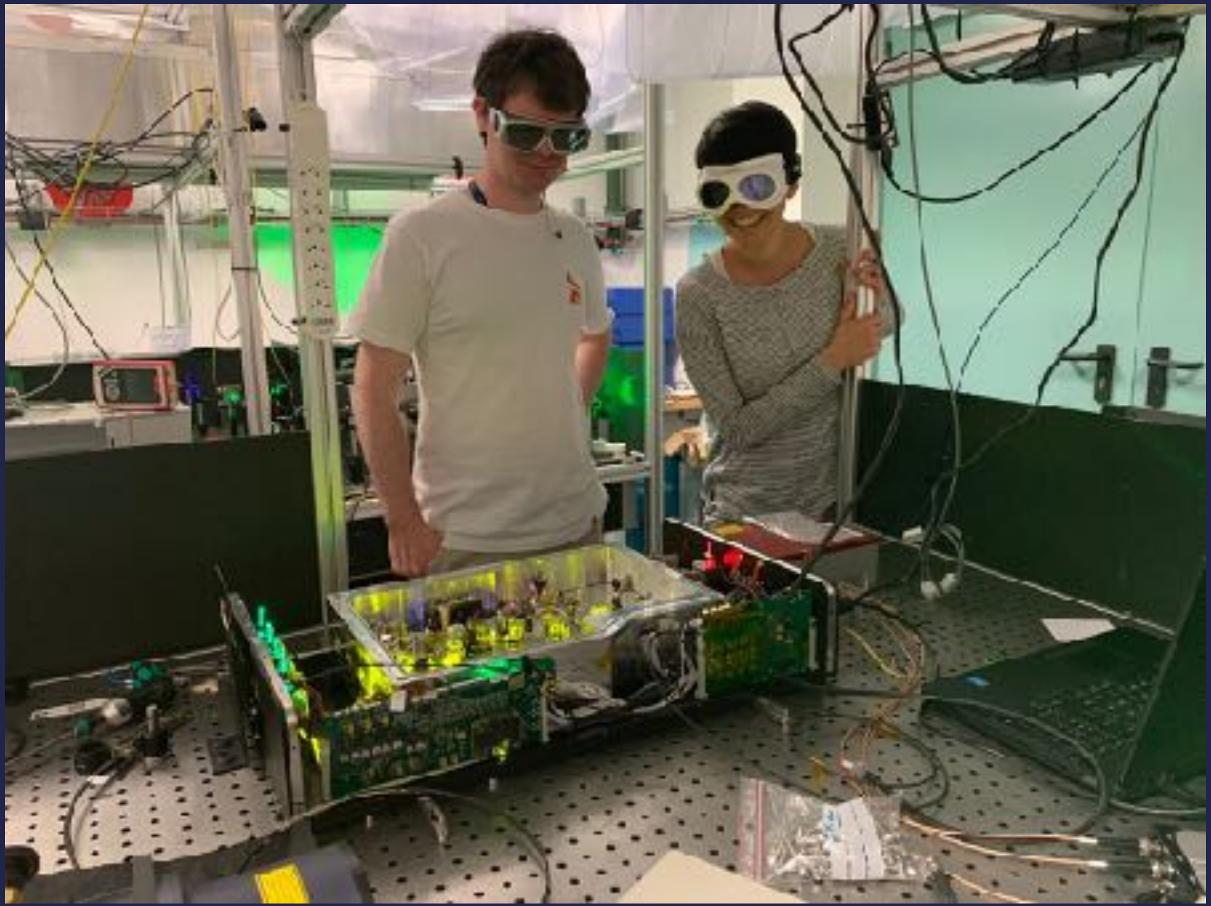
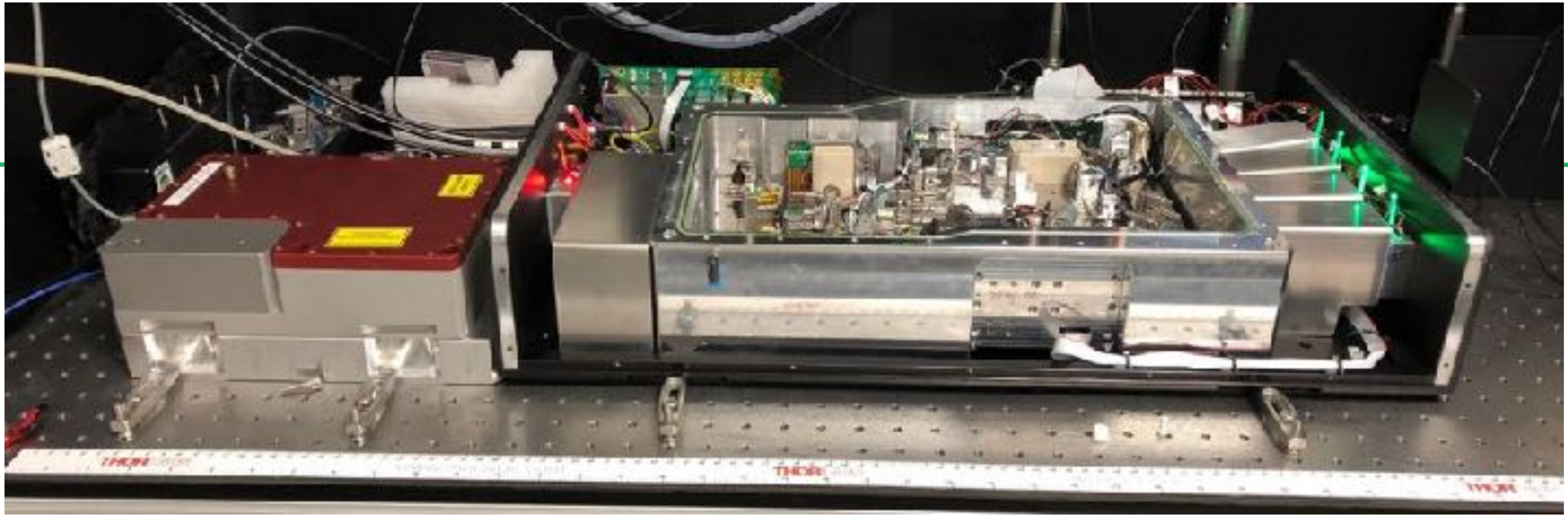
Thanks for your attention!

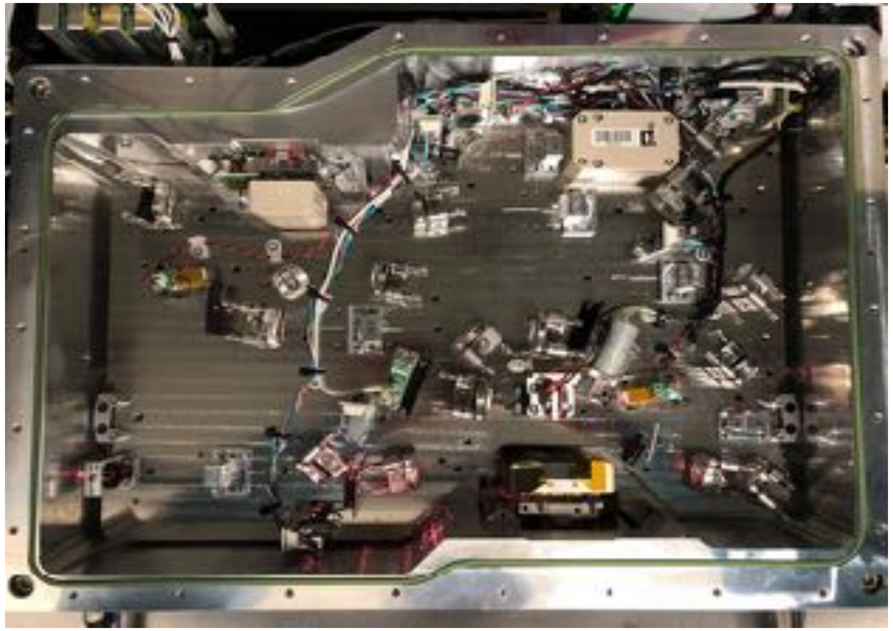


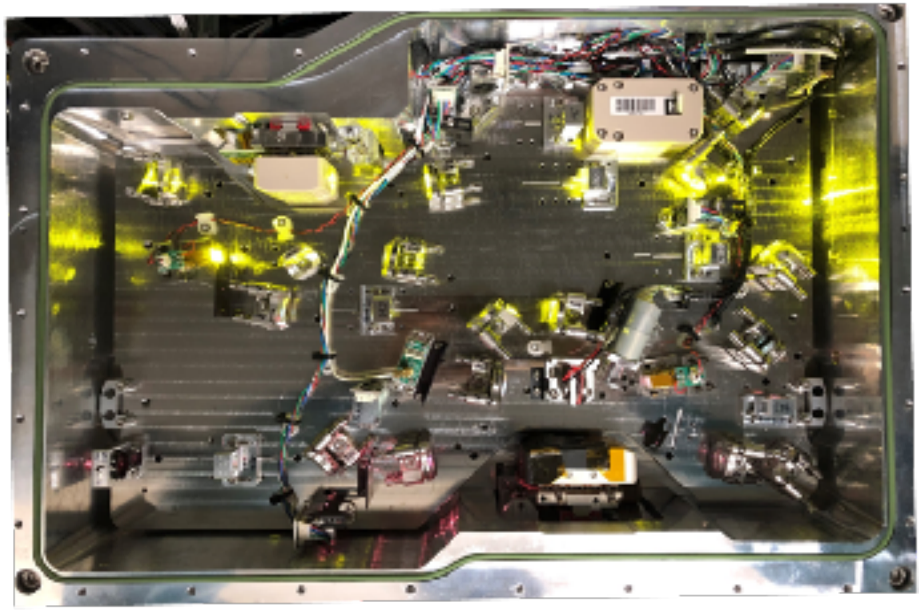
LISA
LASER IONISATION AND SPECTROSCOPY OF ACTINIDES

This Marie Sklodowska-Curie Action (MSCA) Innovative Training Networks (ITN) receives funding from the European Union's H2020 Framework Programme under grant agreement no. 861198

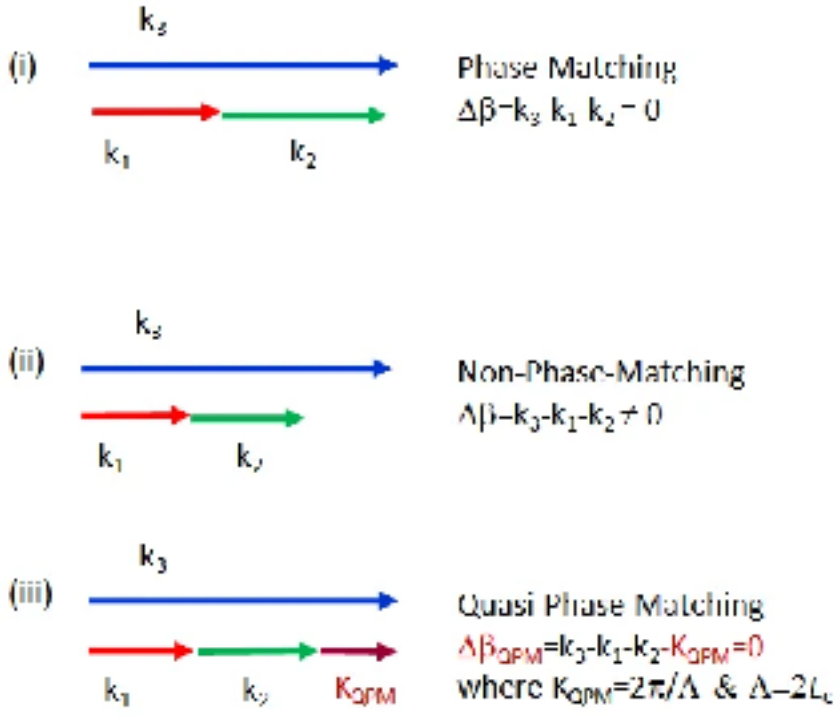
Back-up slides

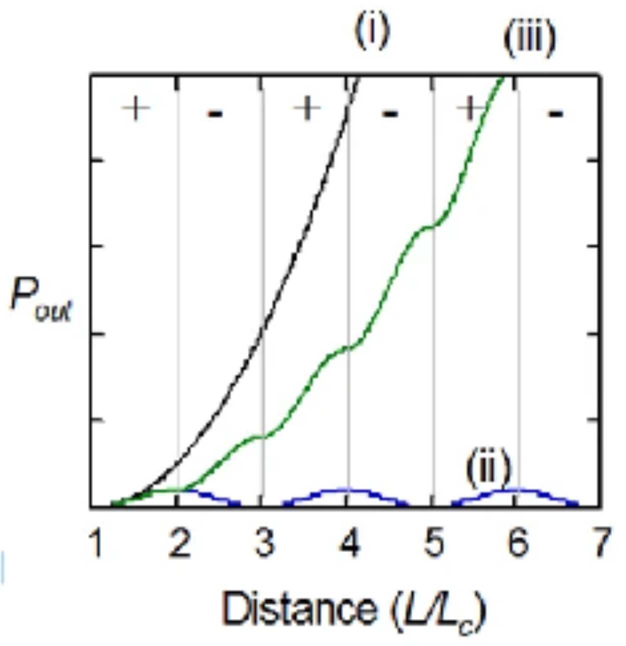


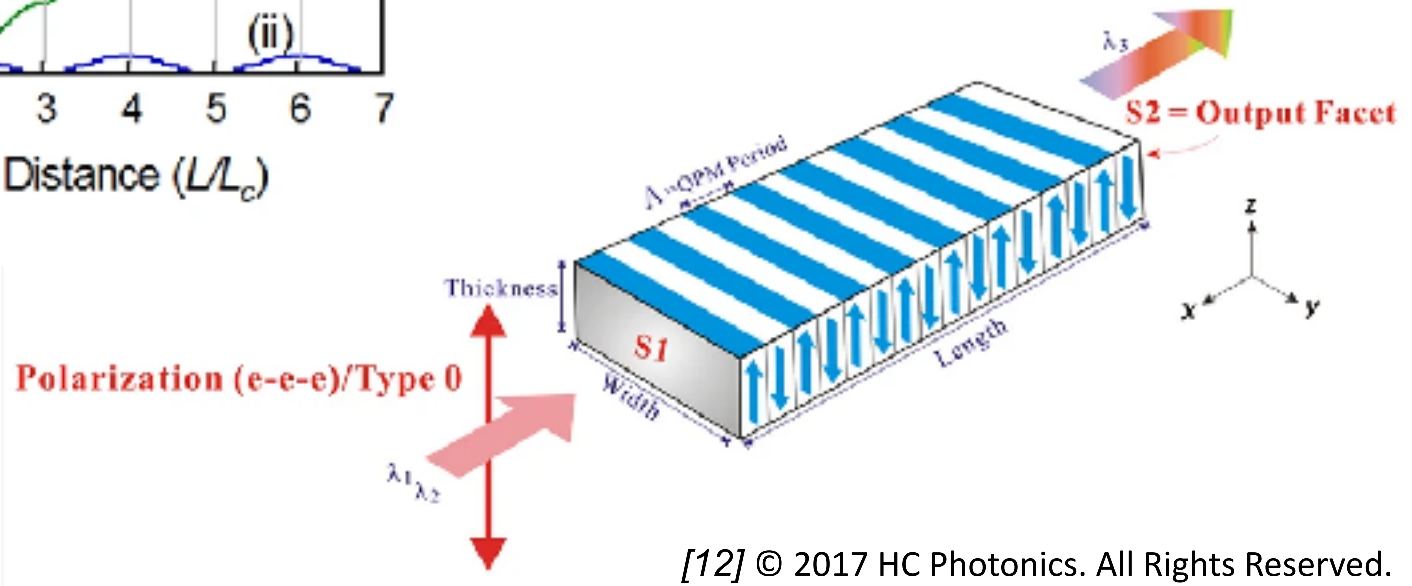




PPLN crystal





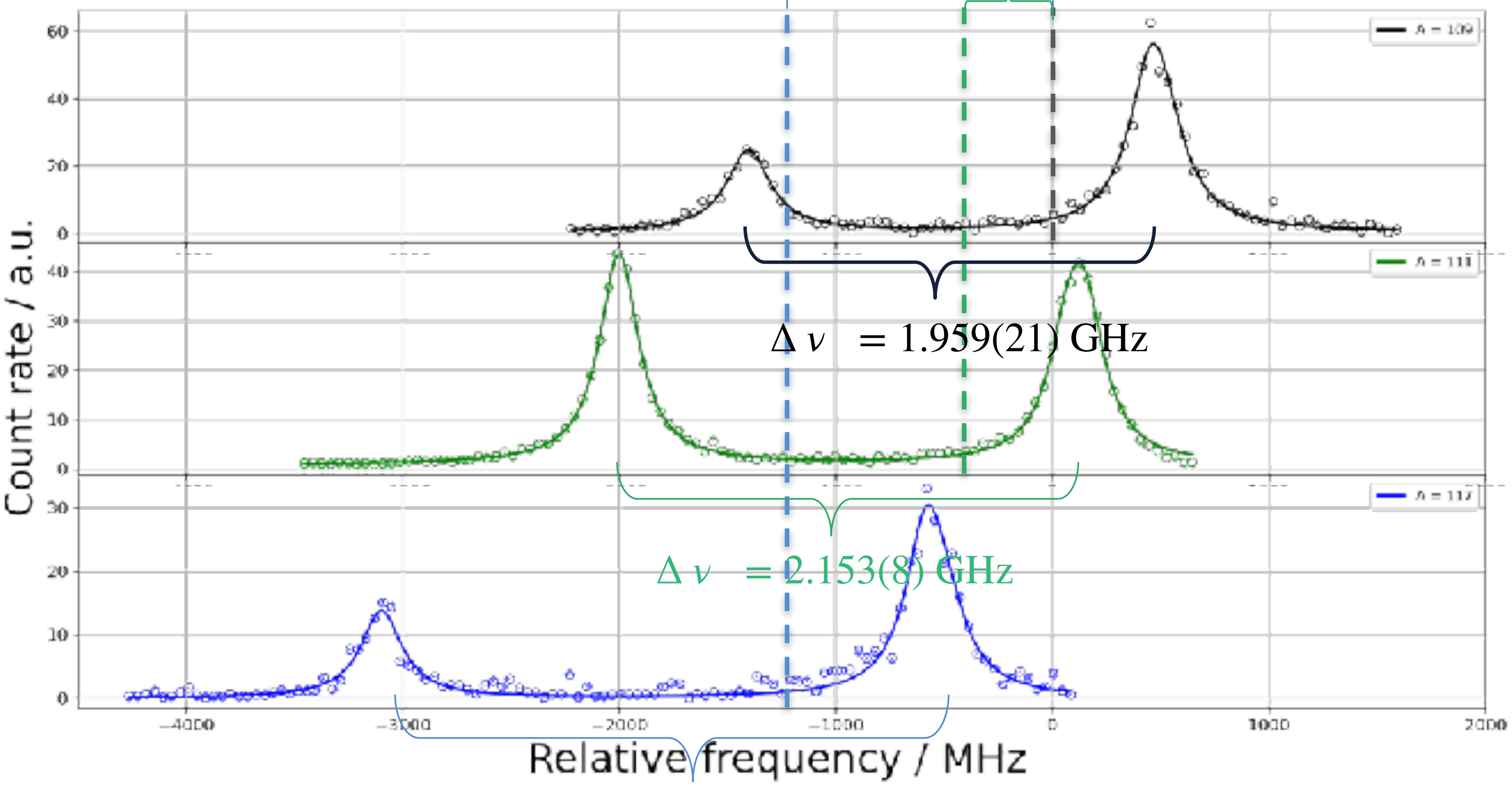


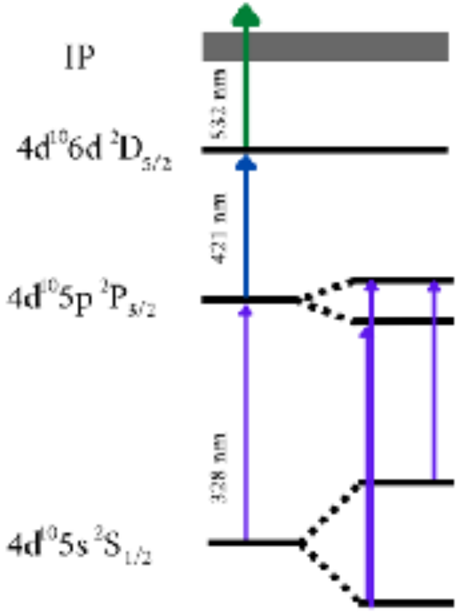
HFS ^{109,111,117}Ag

$\delta\nu_{IS}^{109,117} = -1198(10)$ MHz

$\delta\nu_{IS}^{109,111} = -436(5)$ MHz

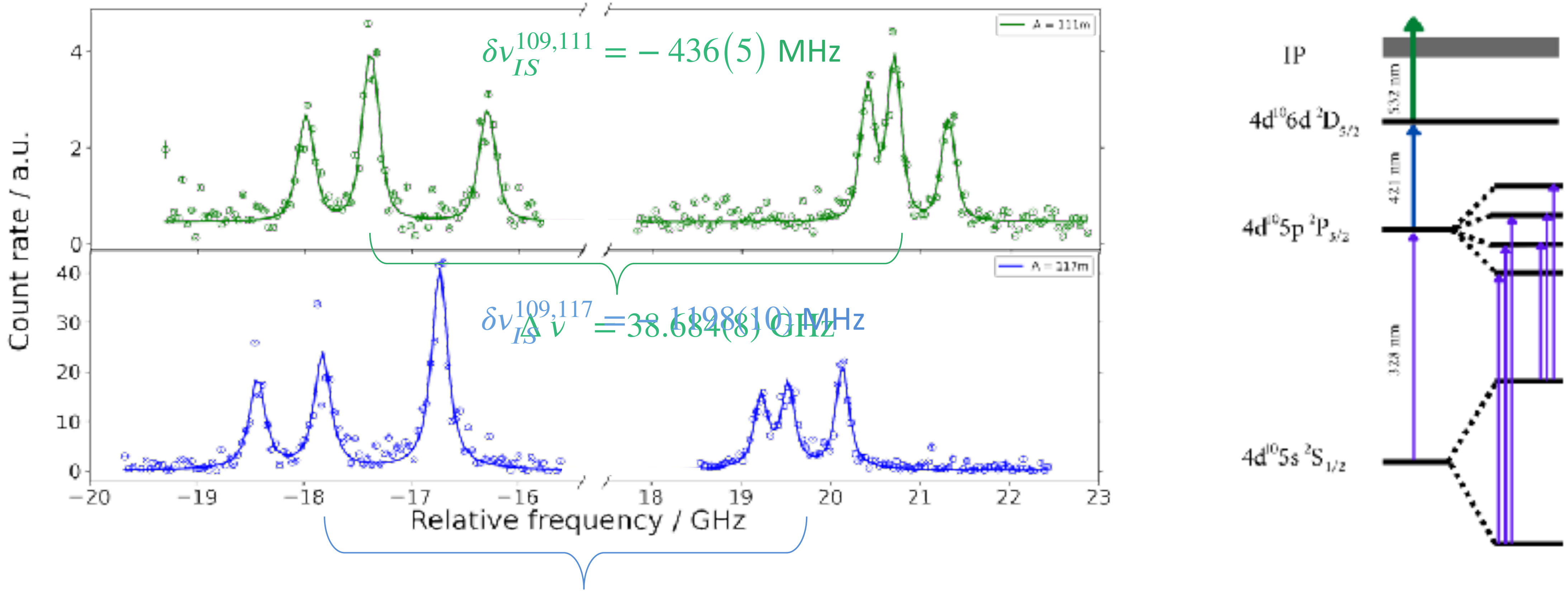
$\delta\nu_{IS}^{109,A}$ = $COG_A - COG_{109}$





For J = $\frac{1}{2}$ and I = $\frac{1}{2}$ => $\Delta\nu$ = A

HFS $^{111m,117m}Ag$



$\delta\nu_{IS}^{109,111} = -436(5)$ MHz

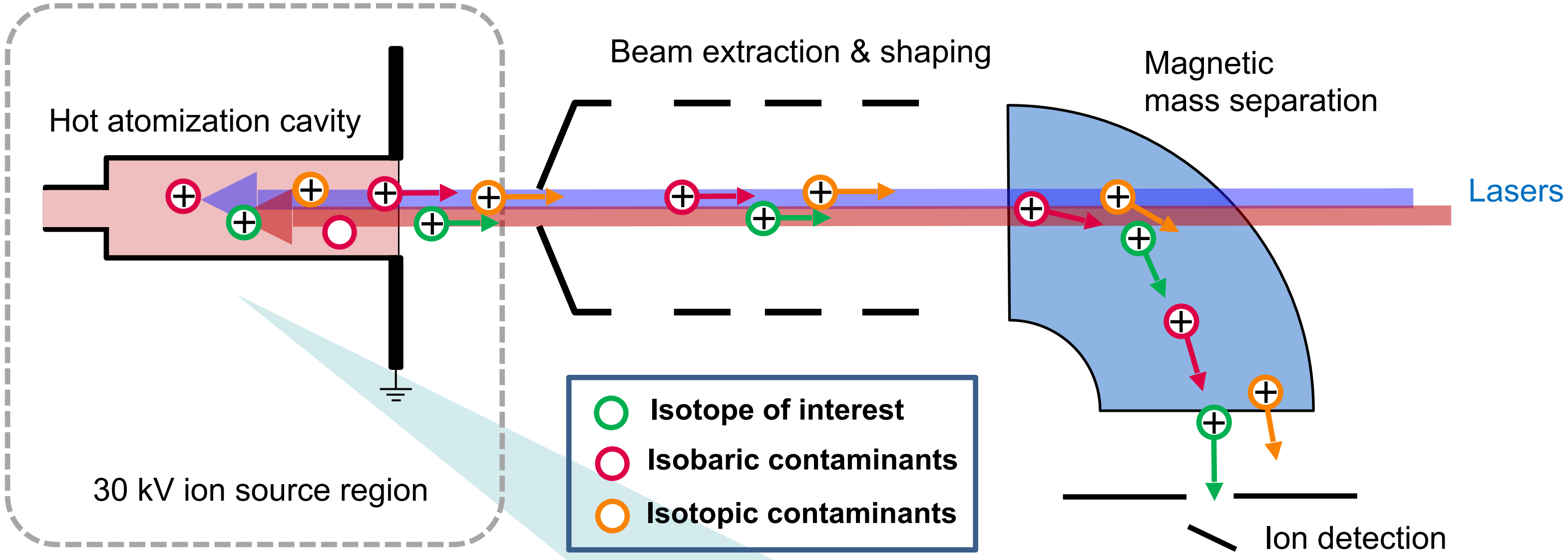
$\delta\nu_{IS}^{109,117} = -1198(10)$ MHz

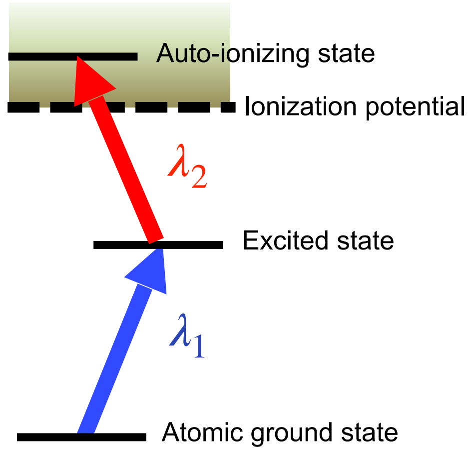
$\Delta\nu = 38.684(8)$ GHz

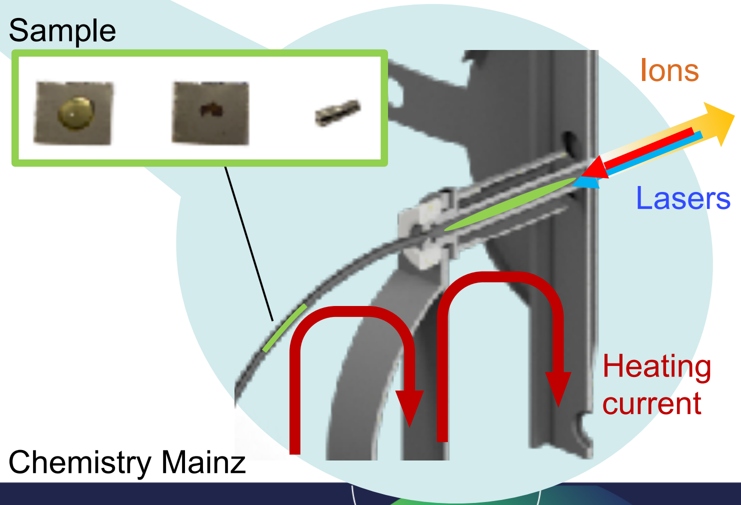
$\Delta\nu = 37.960(2)$ GHz

For J = $\frac{1}{2}$ and I = $\frac{7}{2}$ => $\Delta\nu$ = 4A

RISIKO mass separator







- Chemical sample preparation*
- Sample evaporation in hot cavity
- Multi-step photoionization by pulsed lasers
- Mass separation in dipole magnet $m/\Delta m \approx 800$
- Single ion detection

*in collaboration with Dpt. of Nuclear Chemistry Mainz

RISIKO

Medium resolution scans

- R1, R2, R5
- Seeded laser insource
- Influence of AI studied
- New AIS for R1, R2