

Resonance Ionization Laser Ion Sources and their Applications

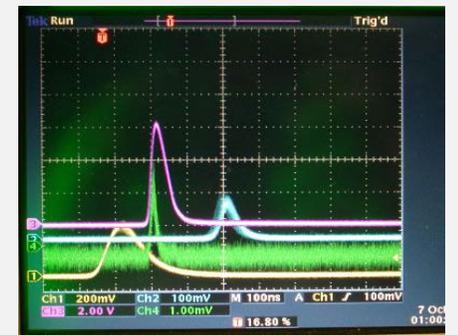
Efficiency and Selectivity at on- and off-line Radioactive Ion Beam Facilities

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Once upon at time.....on the History of Laser Isotope Interaction: AVLIS

Appl. Phys. B 46, 253–260 (1988)

...1973 – more than 50 years ago...

Atomic Vapor Laser Isotope Separation*

J. A. Paisner

Laser Isotope Separation, Lawrence Livermore National Laboratory,
P.O. Box 5508, Livermore, CA 94550, USA

Received 19 April 1988/Accepted 25 April 1988

Abstract. Atomic Vapor Laser Isotope Separation (AVLIS) is a general and powerful technique applicable to many elements. A major present application to the enrichment of uranium for lightwater power reactor fuel has been under development at the Lawrence Livermore National Laboratory since 1973. In June 1985, the Department of Energy announced the selection of AVLIS as the technology to meet future U.S. needs for the internationally competitive production of uranium separative work. Major features of the AVLIS process will be discussed with consideration of the process figures of merit.

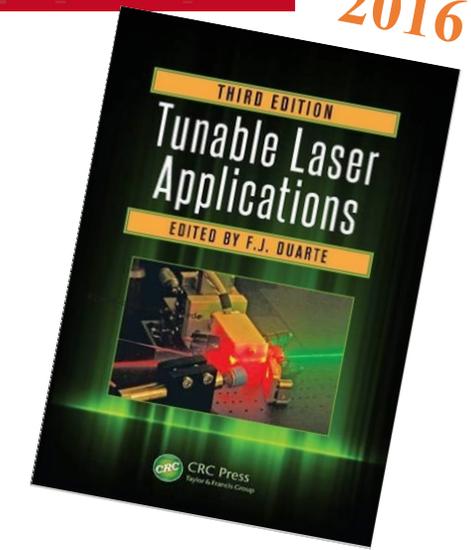


...it's just what we are doing today... on a somewhat smaller scale...
...less brute force – bit more delicate technology...

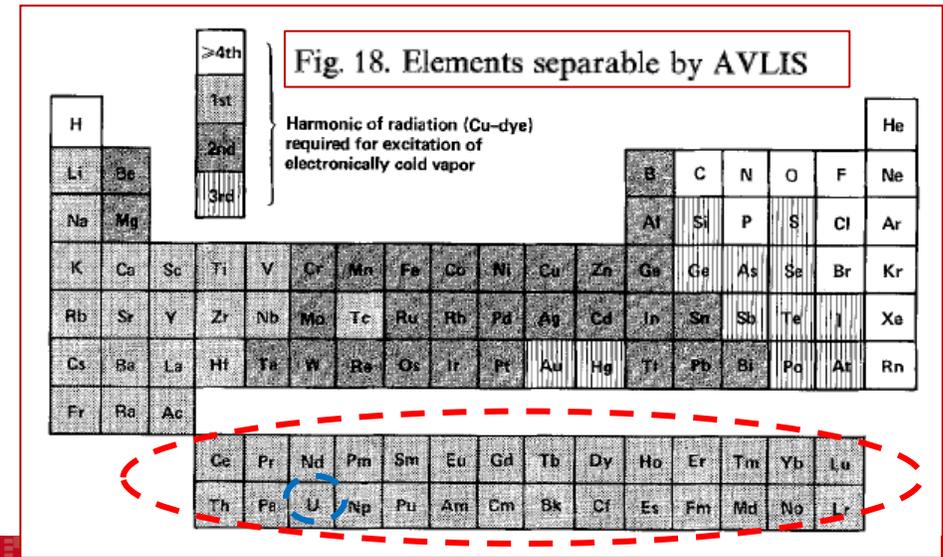
2006



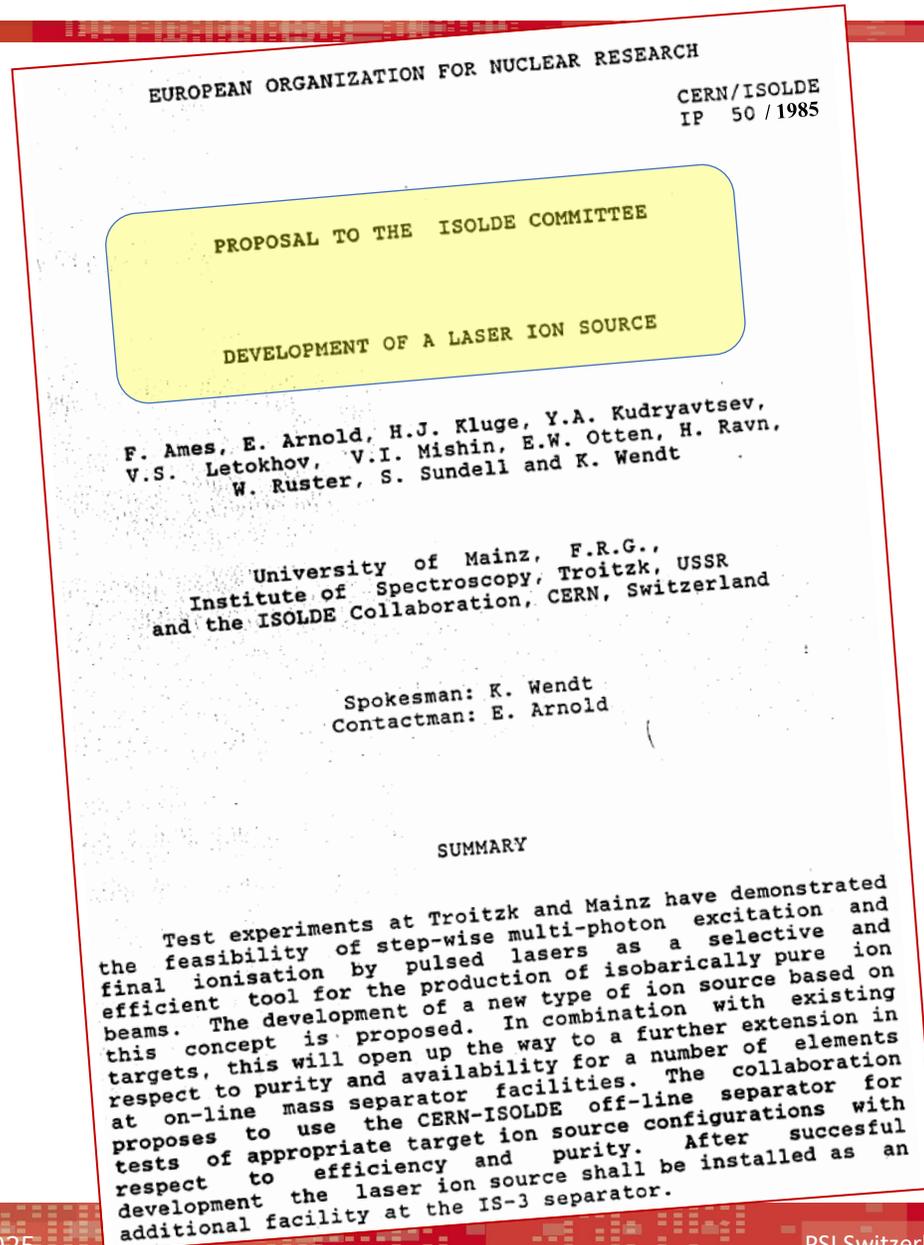
2016



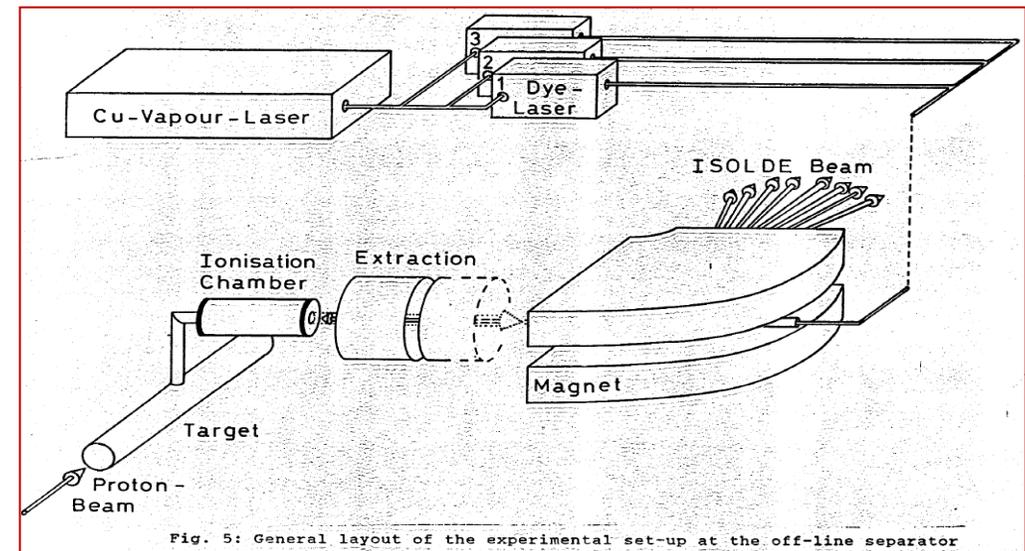
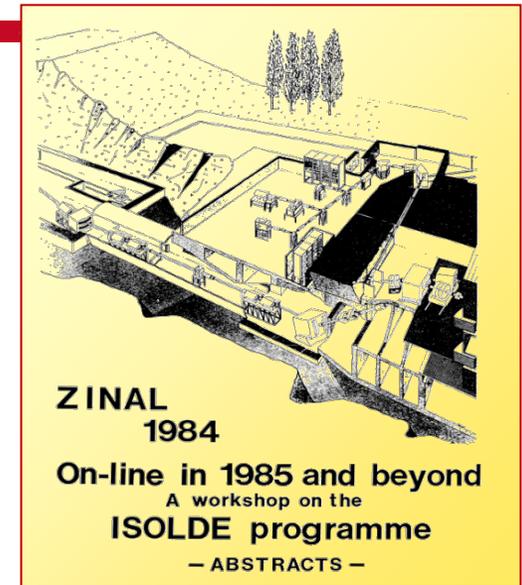
...up to today of relevance for specific (radio)isotopes...



Implementation of on-line Laser Ionization at CERN ISOLDE

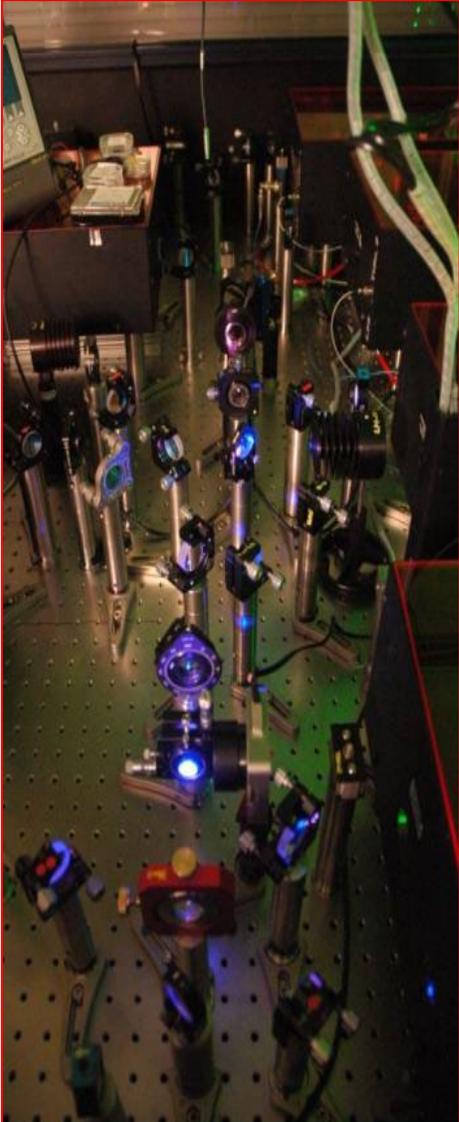


The Pioneer Vladilen V. Letokhov 1984



Outline

- **History & Motivation for Resonance Ionization Laser Ion Source Developments**
 - Relevance of radioactive isotopes (or elements), their generation and analysis
- **Physics Background, Technology and Experimental**
 - Resonant laser excitation & Ionization processes in **Mass Spectrometry - RIMS**
 - **Lasers & RILIS Laser Ion Source Units** at radioactive ion beam facilities (RIB)
 - Developments towards efficiency (**sensitivity**) & selectivity (**ion beam purity**)
- **Applications**
 - RILIS ionization for generation and collection of pure ion beams
 - i.e. ^{53}Mn , ^{55}Fe , ^{157}Tb , ^{163}Ho , ^{226}Ra , ^{247}Cm , ...
 - In-source spectroscopy on stable & radioisotope in the RILIS, i.e. lanthanides & actinides
 - RILIS for analytics of radiotoxic isotopes
- **Summary, Outlook & Credits**



Relevance of radioisotope studies today

<https://www.nndc.bnl.gov/nudat2/>

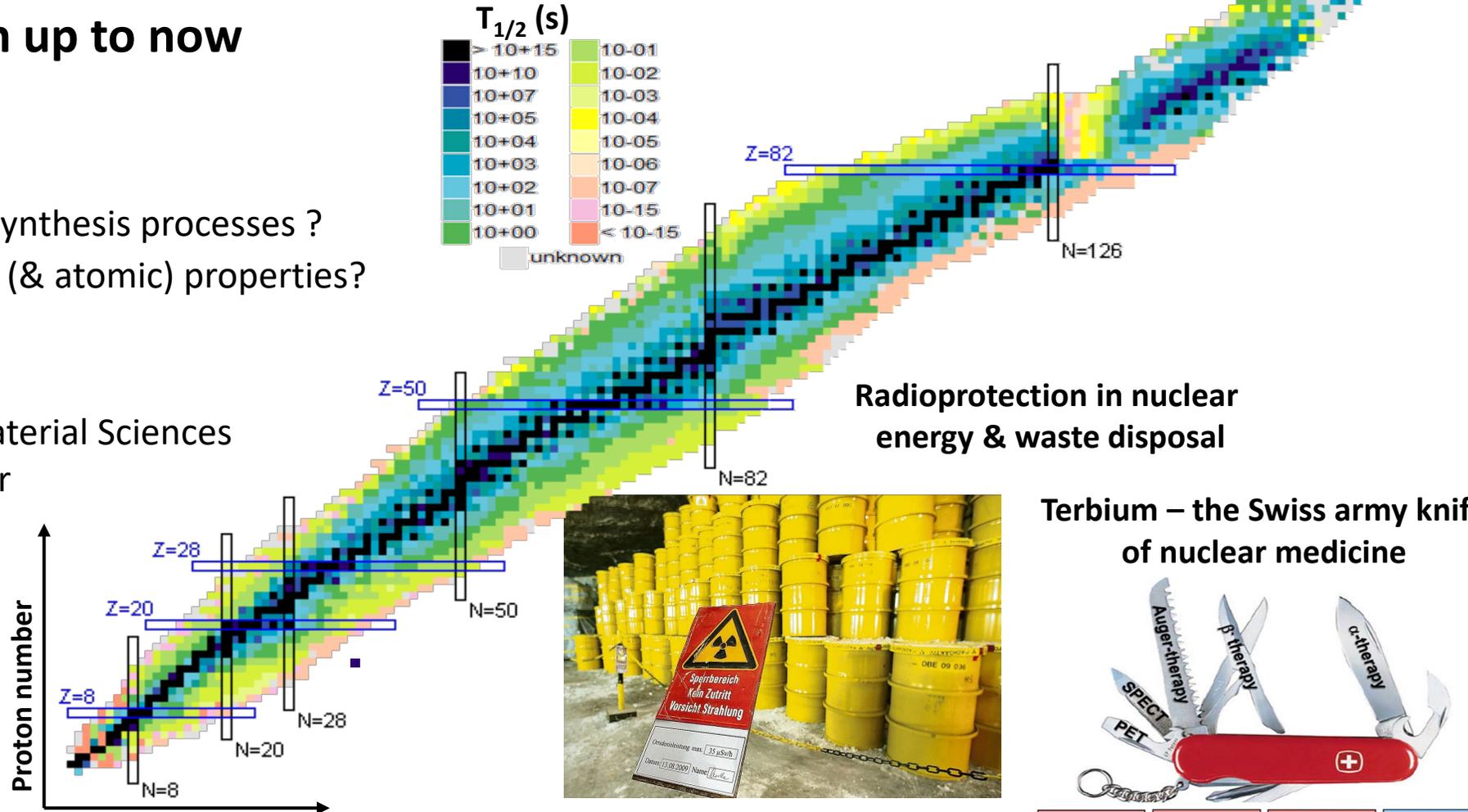
≈ 3300 isotopes known up to now

Open questions:

- Origin → Nucleosynthesis processes ?
- Behavior → Nuclear (& atomic) properties?
- Useful applications
 - Nuclear Industry and Material Sciences
 - Environmental behavior
 - Nuclear Dating
 - Nuclear Medicine
 - others...

Some nuclear data for experimental determination

Half-life	Decay Mode	Q_{β^-}	Q_{EC}	Q_{β^+}	Q_{α}	ΔQ_{α}	$Q_{2\beta^-}$	Q_{2EC}	$Q_{EC,p}$	$Q_{\beta-n}$	$Q_{\beta-2n}$	S_n	S_p	S_{2n}	S_{2p}	$E_{1^{st} \text{ ex. st.}}$	E_{2^+}	E_{3^-}
(BE-LDM Fit)/A	β_2	$B(E2)_{4 \rightarrow 2}/B(E2)_{2 \rightarrow 0}$	$\sigma(n,\gamma)$	$\sigma(n,F)$	235U IFY	239Pu IFY	252Cf IFY	Excited States	Fission Yields									



Radioprotection in nuclear energy & waste disposal

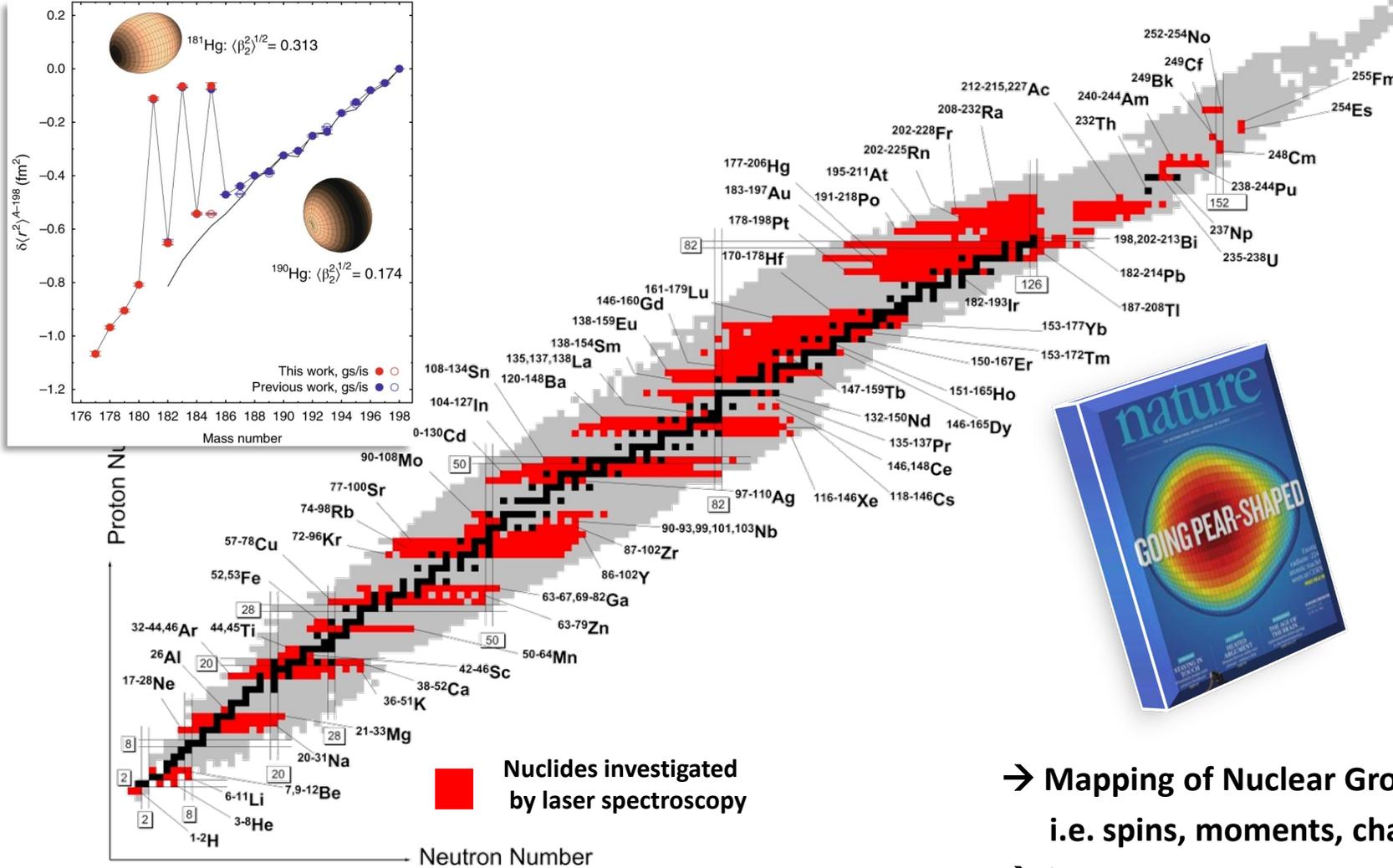
Terbium – the Swiss army knife of nuclear medicine



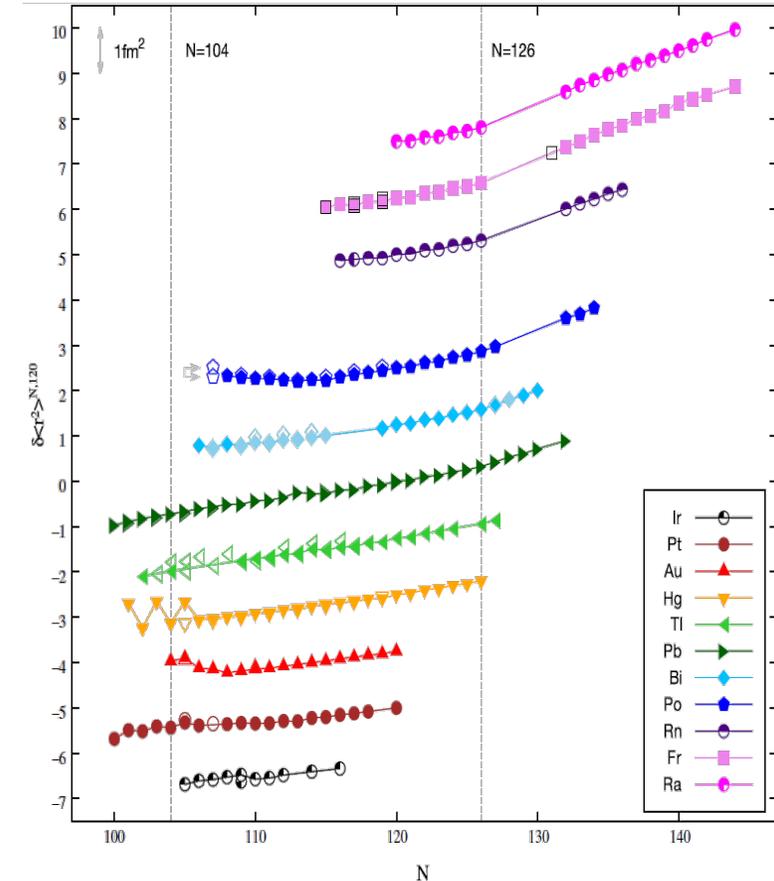
Tb 149 4.2 m e β ⁺ α 3.99 γ 736; 165...	Tb 152 4.1 h e α 3.97 β ⁺ 1.8 γ 352; 165...	Tb 155 17.5 h e β ⁺ 2.8... γ 344; 586; 411...	Tb 161 5.32 d e γ 87; 105...; 180, 262	Tb 161 6.90 d β ⁻ 0.5; 0.6... γ 26; 49; 75... e ⁻
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Contributions by on-line Laser Spectroscopy at RIB facilities

B. Marsh et al, *Nature Physics* 14, 1163–1167 (2018)



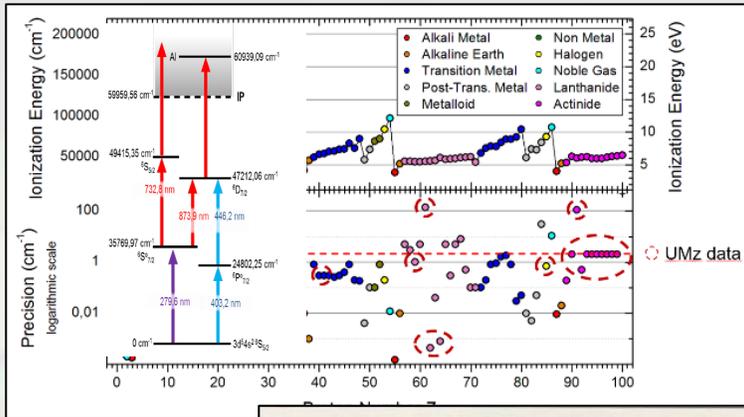
P. Campbell et al, *Prog. Part. Nucl. Phys.* 86 (2017) 127-180



→ Mapping of Nuclear Ground State Properties,
i.e. spins, moments, charge radii, deformations

→ further data usually nuclear techniques on pure samples....

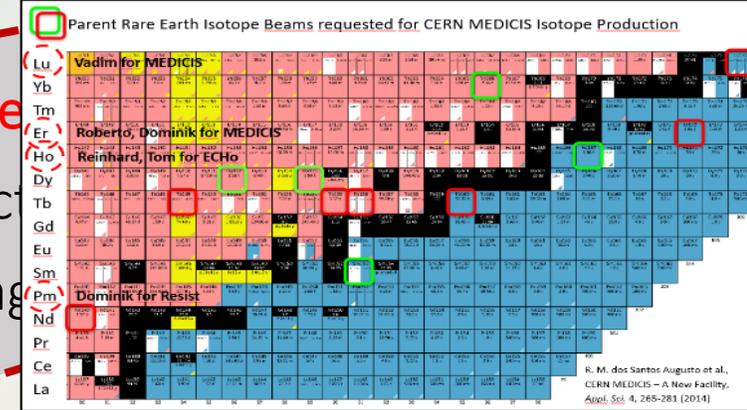
Today's Research Goals in the Field of Exotic Isotopes by RILIS



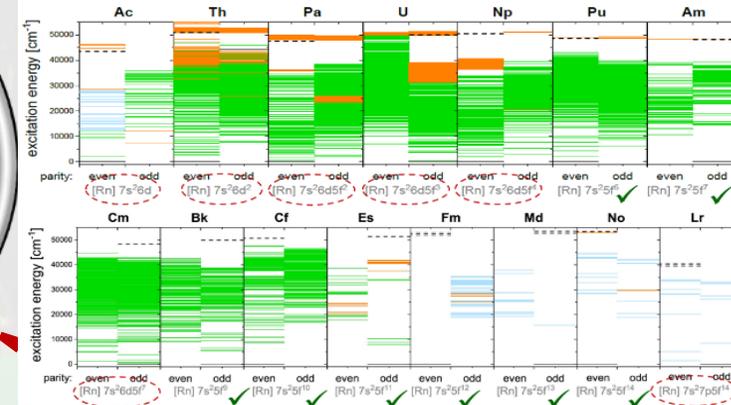
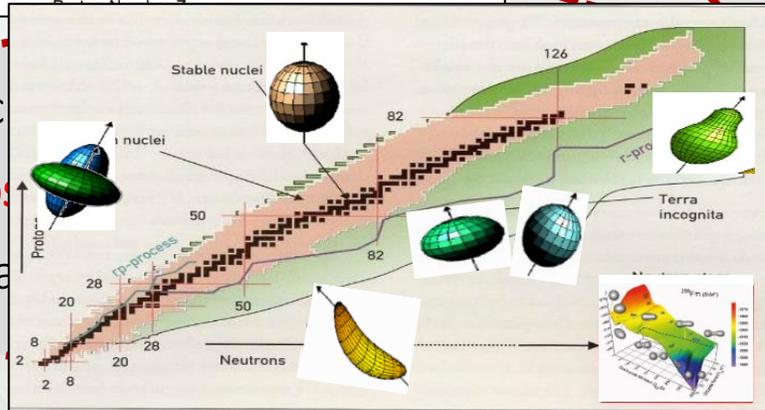
carried out or prepared at the LARISSA Lab of JGU Mainz

including Affinities

Production Diagram



Nucleosynthesis Pathways



ions and parent

ECHO 1k Chip

2D Scanning with μm Resolution

Ion Beam 0.7(1) mm FWHM

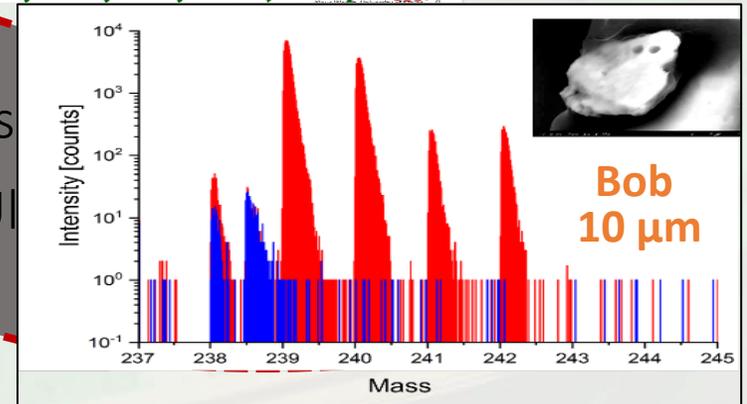
7 mm

Interlaced:
 • Implantation
 • Live beam-spot control (MCP / Pepperpot)
 • Gold PLD

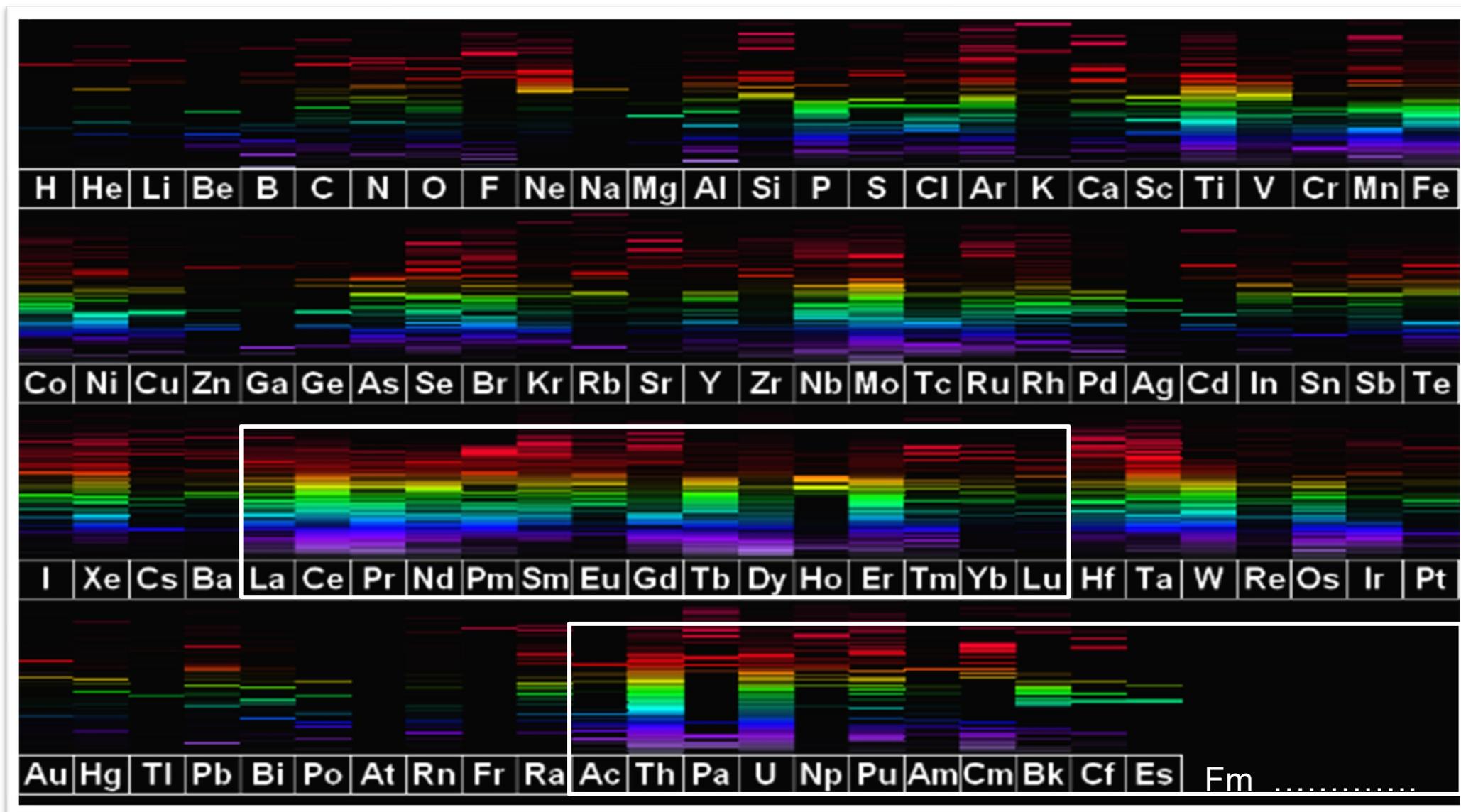
${}^6\text{Li}$
 ${}^{53}\text{Mn}$
 ${}^{55}\text{Fe}$
 ${}^{157}\text{Tb}$
 ${}^{163}\text{Ho}$
 ${}^{226}\text{Ra}$
 ${}^{247}\text{Cm}$

for S, i.e.

Las U



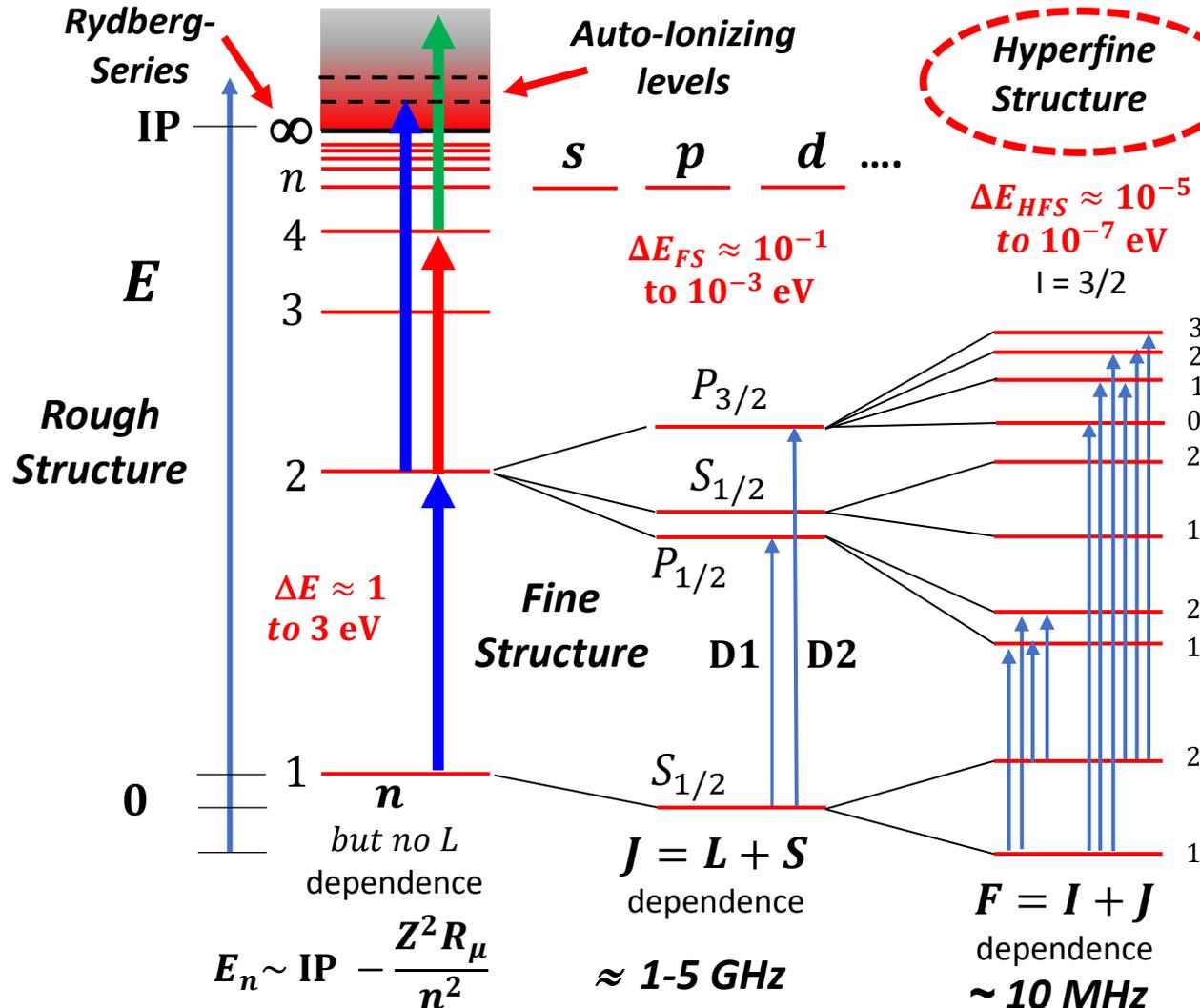
RIS: Employing Atomic Excitation for Efficiency and Selectivity



Basics: Atomic Spectroscopy within the Elements --- from ${}^1\text{H}$ to ${}_{100}\text{Fm}$

Resonance Ionization Spectroscopy in Atomic Systems

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



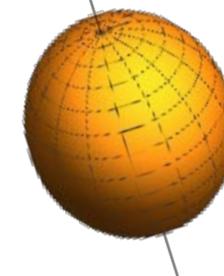
$$\begin{aligned} \Delta E_H &= \Delta E_\mu + \Delta E_Q \\ &= A \frac{C}{2} + B \frac{3(C+1) - 2I(I+1)J(J+1)}{8I(2I-1)J(2J-1)} \end{aligned}$$

Magnetic dipole & Electric quadrupole moment of the atomic nucleus

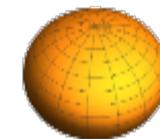
$$A = \frac{\mu_I \overline{H(0)}}{IJ}$$

$$B = eQ_s \left\langle \frac{\partial^2 \phi}{\partial z^2} \right\rangle_{r=0}$$

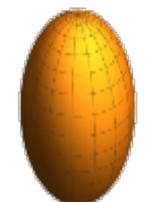
I, μ_I



$Q_s < 0$



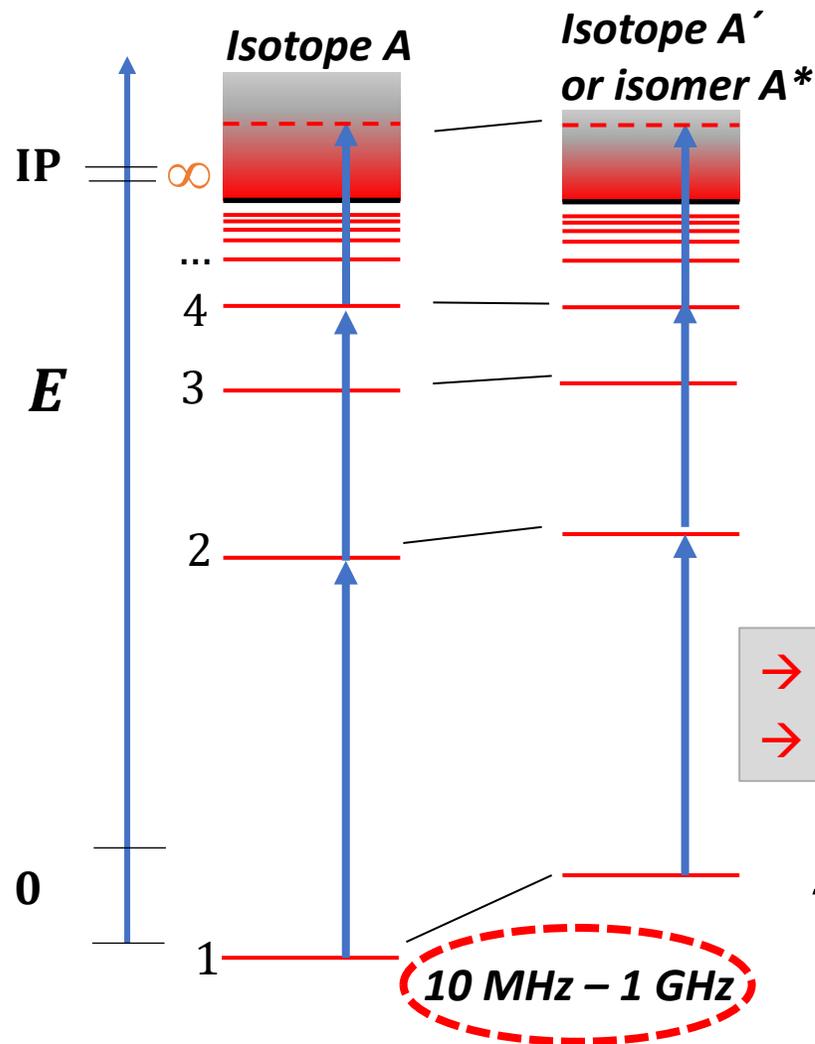
$Q_s > 0$



→ High spectral resolution required

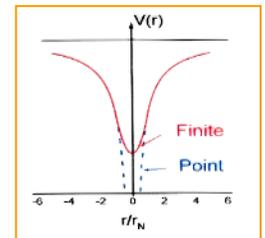
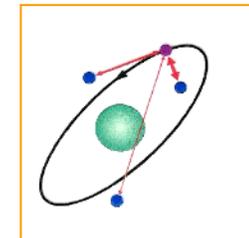
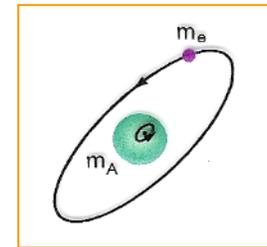
Isotope and Isomer Selection in Optical Excitation

Unique excitation sequence and also isotope (and isomer) shifts for each element



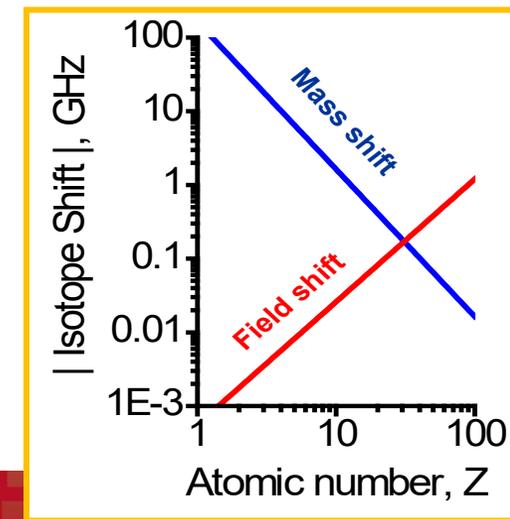
Two Mass shifts contributions + Field shift

$$\delta\nu_{A,A'} = \nu_{A'} - \nu_A = \underbrace{(K_{\text{NMS}} + K_{\text{SMS}}) \frac{m_A - m_{A'}}{m_A \cdot m_{A'}}}_{\text{Mass shifts}} + \underbrace{F_{\text{FS}} \cdot \delta\langle r^2 \rangle_{A,A'}}_{\text{Field shift}}$$



- Size and deformation of the atomic nucleus
- Odd isotopes: additional shift from hyperfine structure

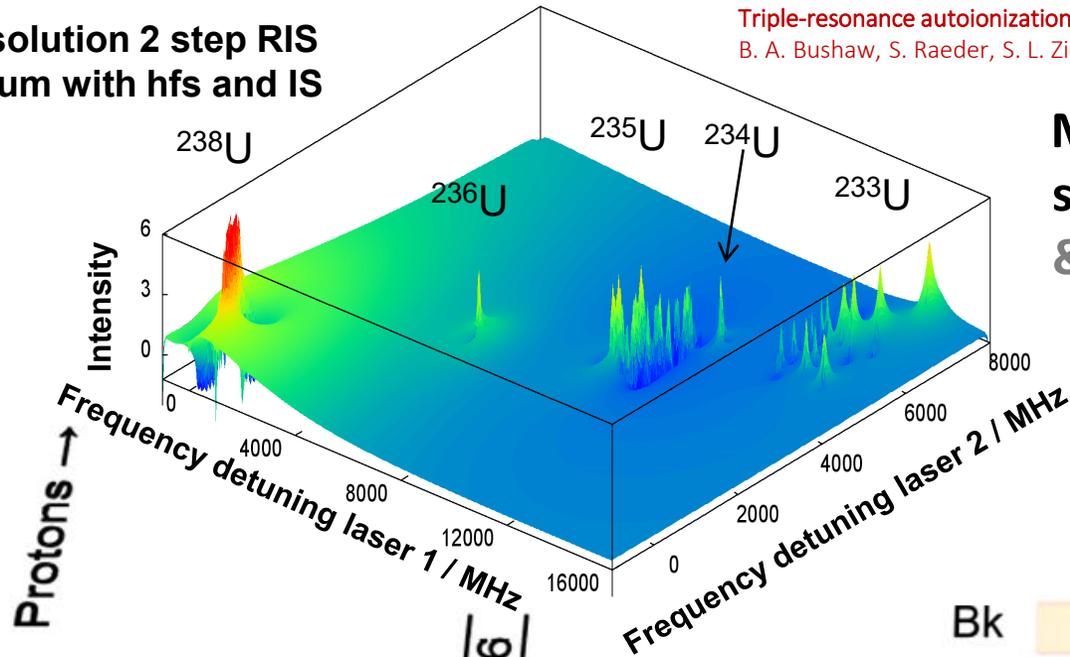
→ Highest optical isotope selectivity up to 10^6 in the suppression of neighboring isotopes



P. Müller, B.A. Bushaw et al., Fresenius J. Anal. Chem. 370, 508-512 (2001)

Example for RIS: Off-line and on-line Spectroscopy on Actinide Isotopes

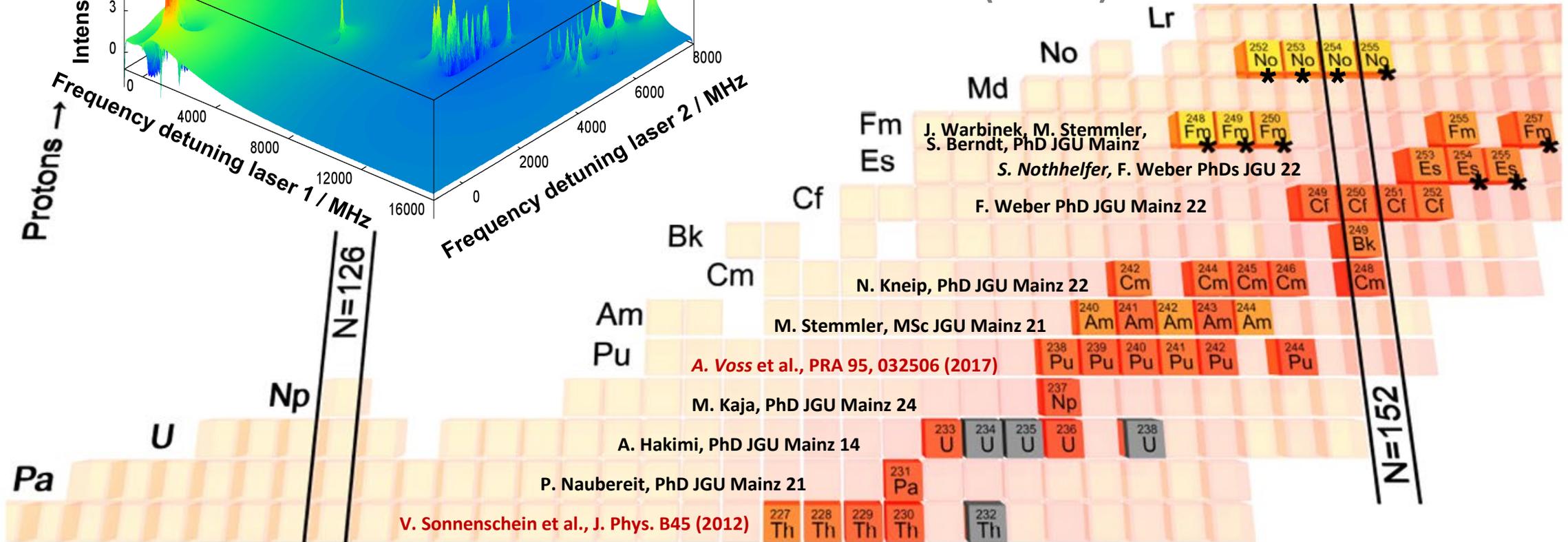
High resolution 2 step RIS in Uranium with hfs and IS



Triple-resonance autoionization of uranium optimized for diode laser excitation
B. A. Bushaw, S. Raeder, S. L. Ziegler, K. W. *Spectrochim. Acta B* 62, 485–491(2007)

Medium and high resolution laser spectroscopy off-line at JGU RILIS & on-line at GSI (JET RIS)

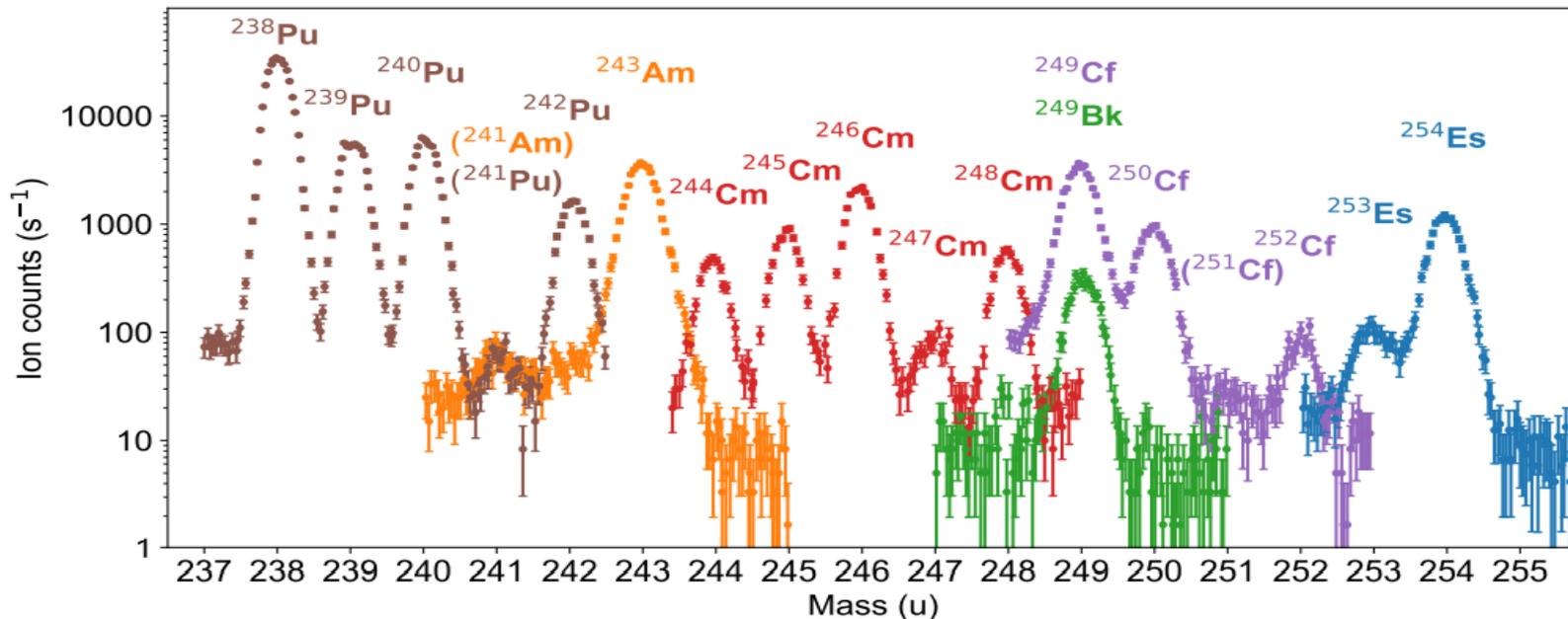
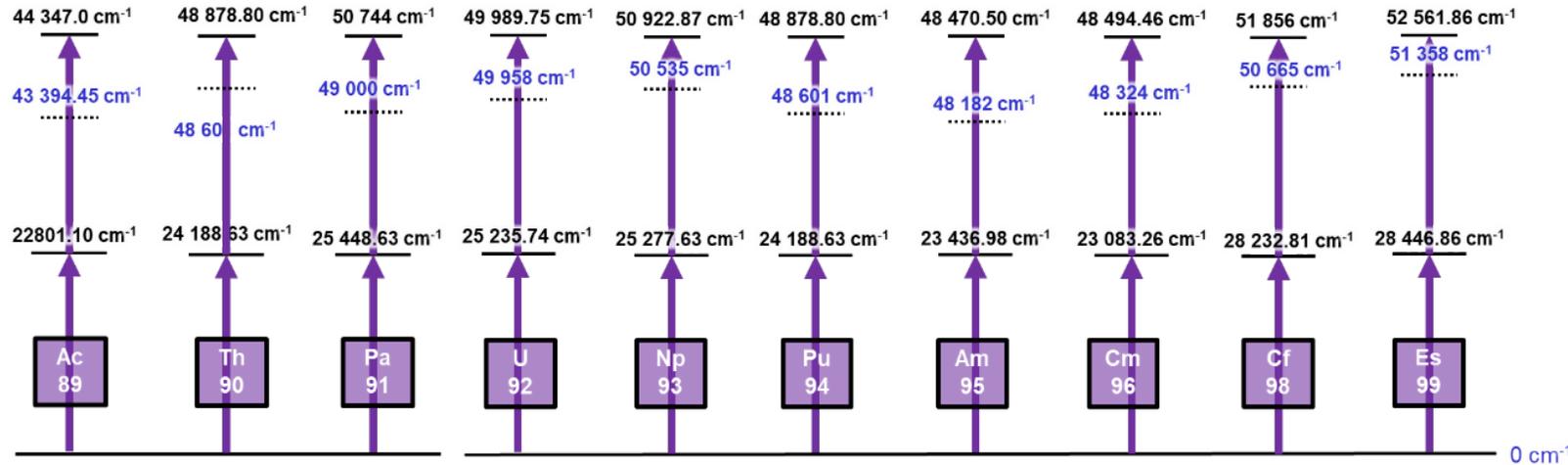
* Isotopes accessible only on-line at GSI
M. Block, M. Laatiaoui., S. Raeder
Prog. Part. Nucl. Phys 116 (2021)



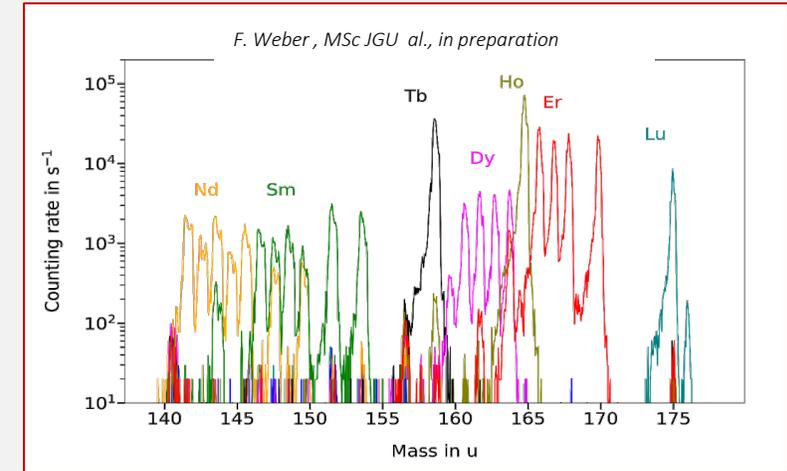
off-line activities at JGU Mainz in close collaboration with C. Düllmann JGU and J. Etzold ORNL

Neutrons →

Multielement RIMS: Rapid Element Change e.g for Full Sample Characterization

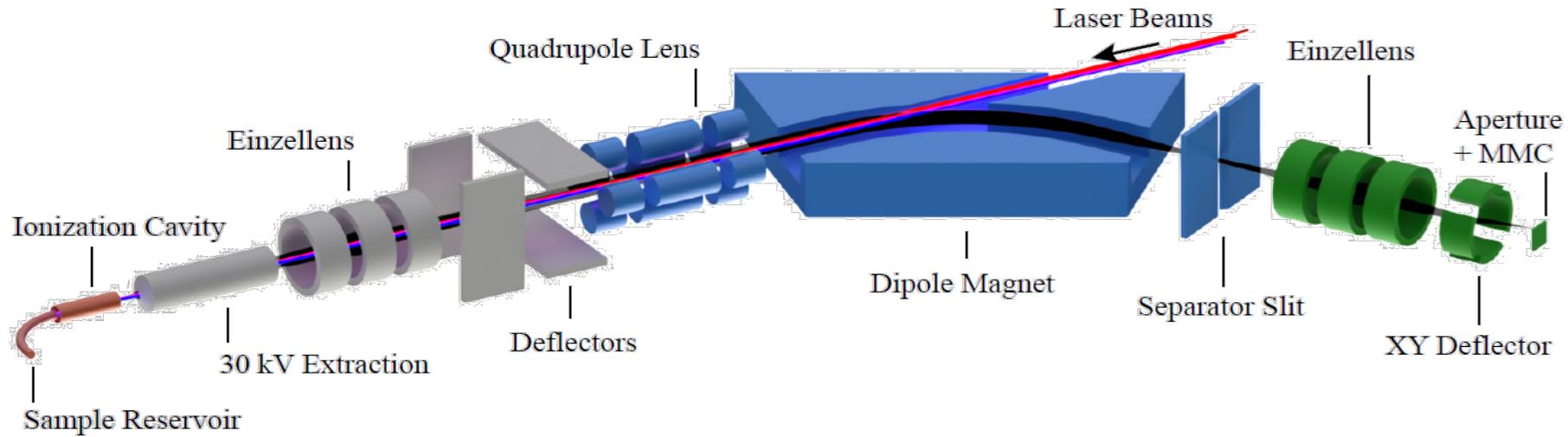


- Simple & efficient two-step RIS
- Rapid exchange of elements developed in isoelectronic sequence of lanthanidesEs

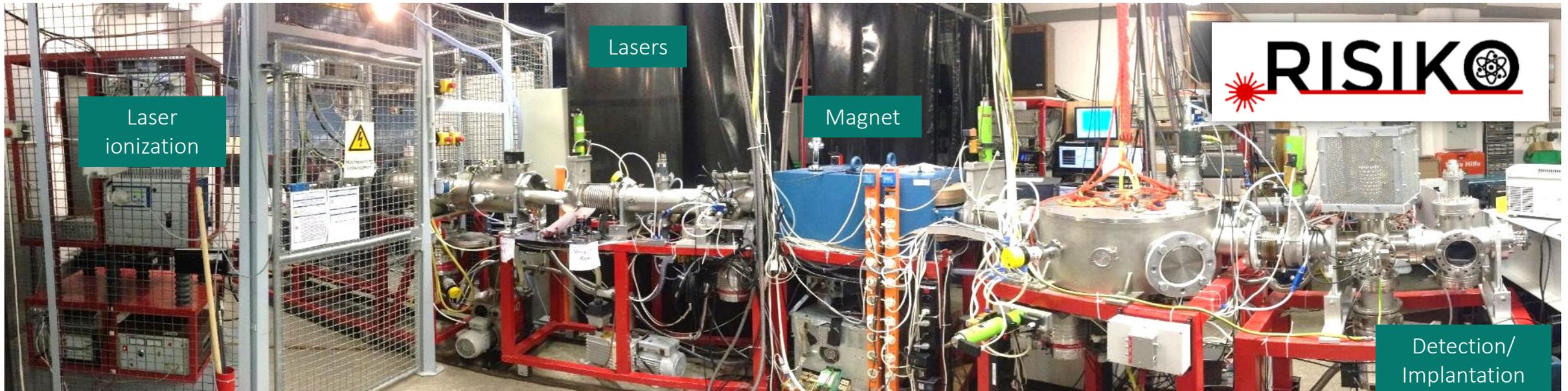


- Rapid sample characterization
 - Isobar-free, low-background isotope selection
 - Element and isotope ratio determination
- ➔ Relevant for ultratrace analysis & fundamentals studies

RISIKO – The RILIS development & off-line RIB facility at JGU



Optimum tool for laser spectroscopy, ion implantation, on-line laser ion source development and RIMS analytics



The LARISSA off-line Radioactive Ion Beam Lab at JGU Mainz

RISIKO –
60 kV ISOLDE-like
sector-field mass separator

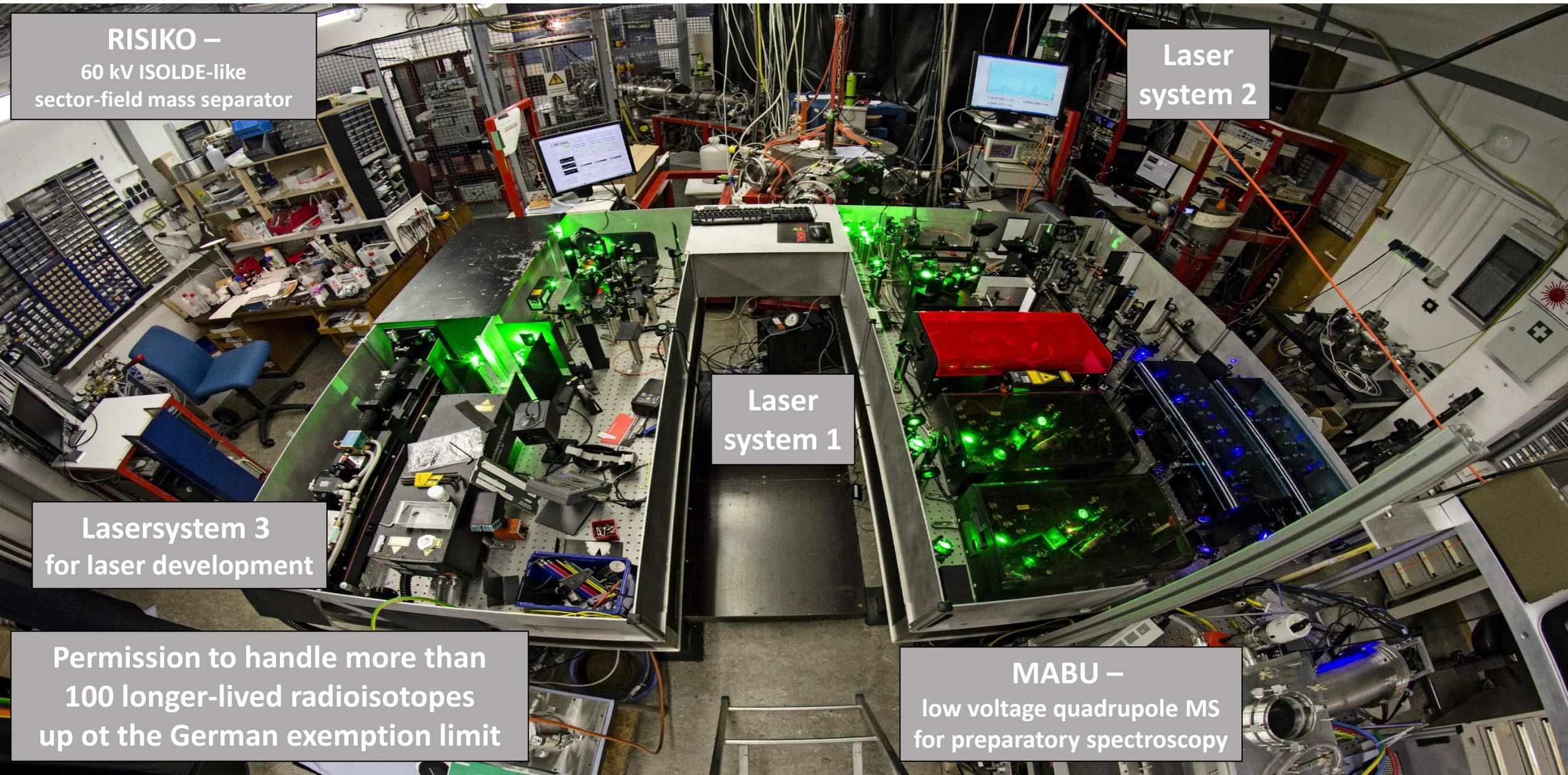
**Laser
system 2**

**Laser
system 1**

**Lasersystem 3
for laser development**

**Permission to handle more than
100 longer-lived radioisotopes
up to the German exemption limit**

MABU –
low voltage quadrupole MS
for preparatory spectroscopy

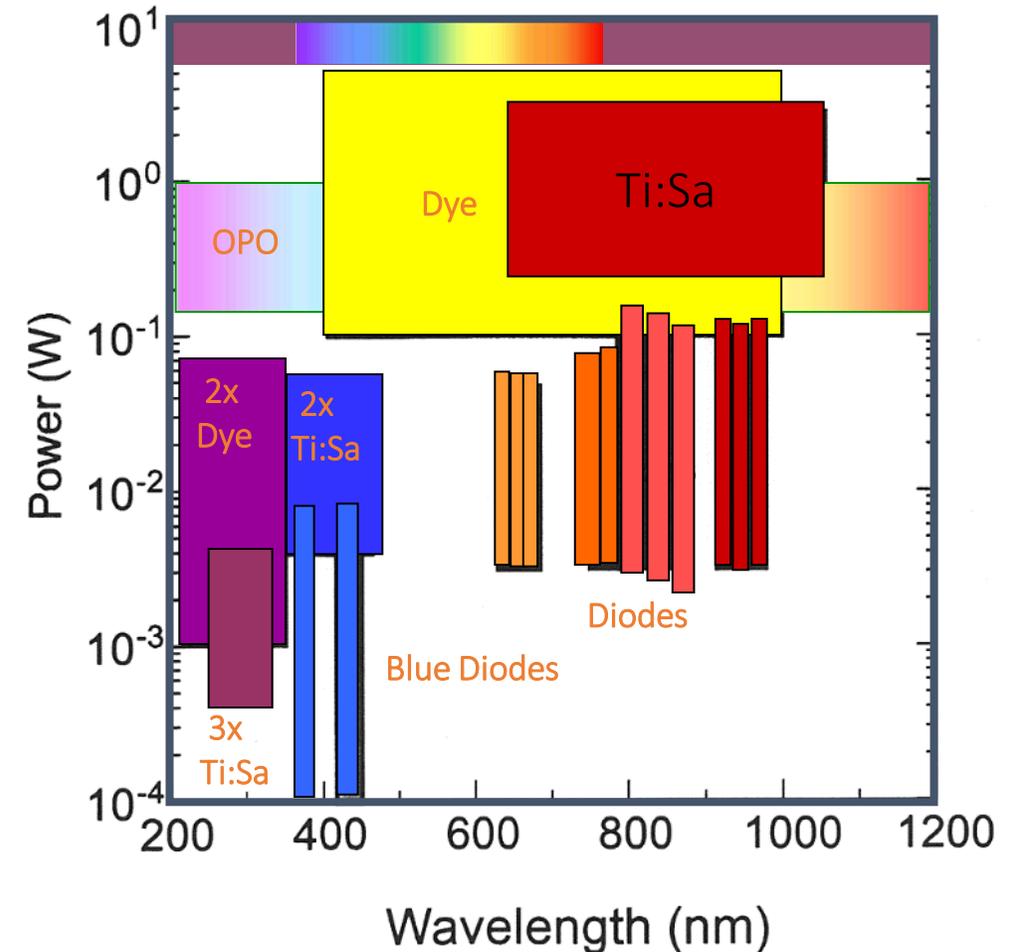


Advancements on Tunable Laser Systems for RIS 1980 – 2025...

Basic requirements for RILIS ionization, spectroscopy & analytics

- **Broadest accessible spectral range for universality**
using fundamental & higher harmonics SHG, THG, FHG
- **Well controlled, easy and rapid tuning**
for long range Rydberg scans, spectroscopy and element change
- **Precise frequency control** (down to ~ 1 MHz)
via wavemeter with additional active stabilization to reference
- **Adaptation of spectral laser profile to specific application**

RILIS (atomic vapor) spectroscopy	(~ 3 GHz)
Atomic beam spectroscopy	(~ 100 MHz)
high resolution spectroscopy	(~ 10 MHz)
- **Temporal structure** (in combination with continuous evap.)
high pulse repetition rate ~ 10 kHz (or continuous wave operation)
- **High power** limited by pump power, especially for cw operation and HHG



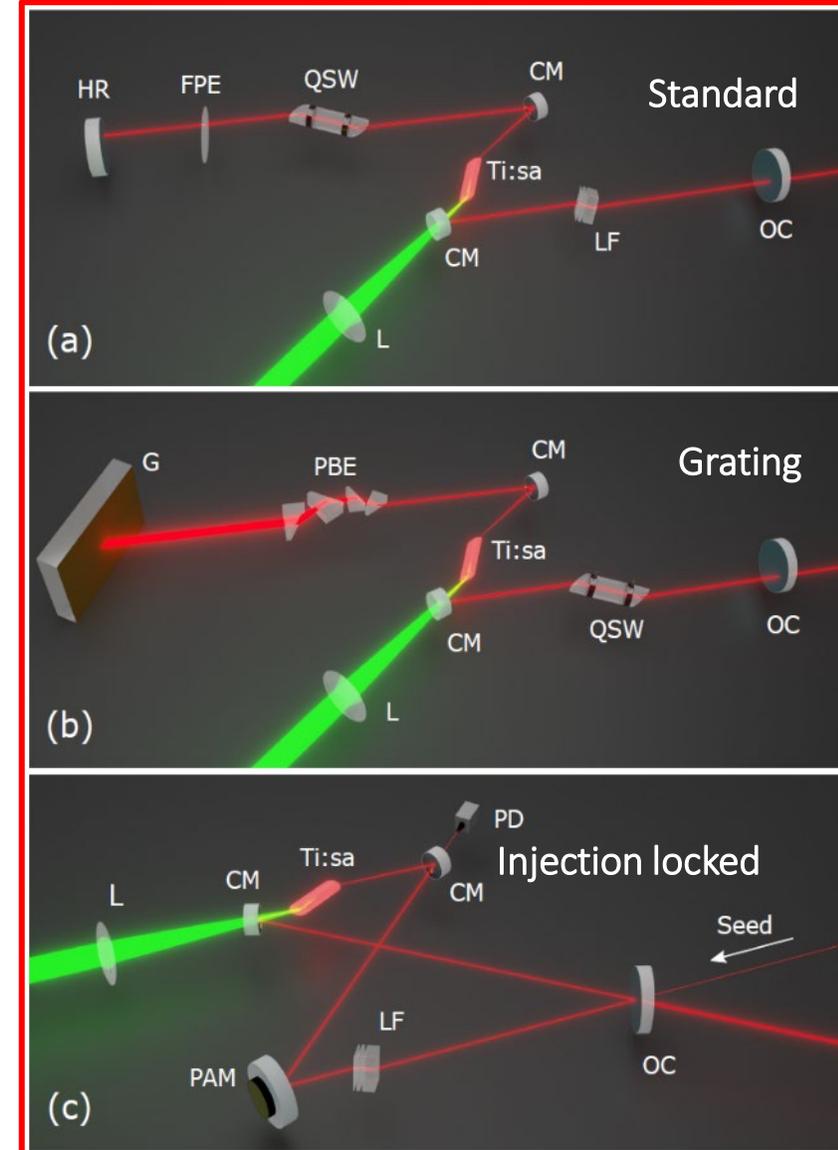
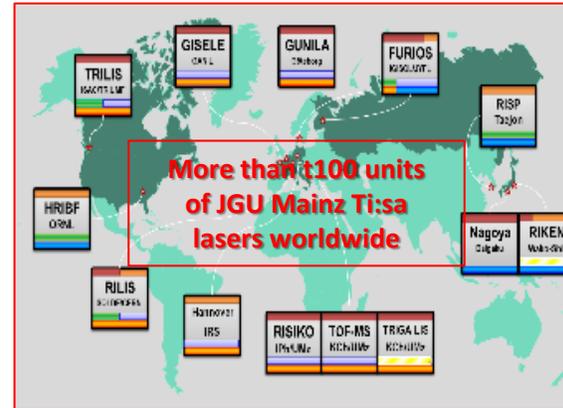
The JGU family of **pulsed**, **powerful** & **narrow-band** lasers for use in RIMS

Custom-built **Ti:sa** laser cavities for pulsed high repetition rate operation

- Three different designs - tailored for
 - High power (**standard** laser) → efficiency
 - Fast continuous wide-range scanning (via **grating-assist**) → quasi-simultaneous multi element analysis
 - Narrowband operation (**injection-locked** laser) → high resolution spec
- Resonator internal SHG for blue and single pass THG or FHG for UV

R. Horn, PhD. JGU 2003

	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	5 W	1020 nm	$\lambda_c \pm 10 \text{ nm}^*$
Tuning range	100 GHz	700 to 1020 nm	10 to 20 GHz*
Spectral bandwidth	1 to 10 GHz	~300 nm	20 MHz
Beam quality (M^2)		< 1.3	20 MHz



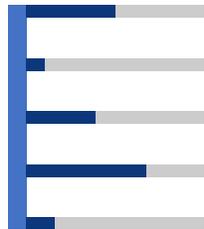
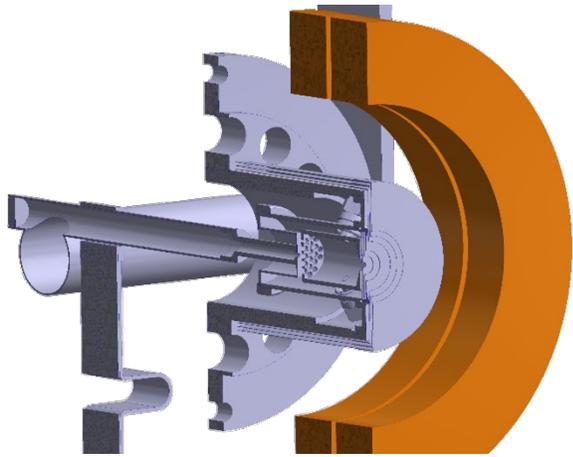
V. Sonnenschein et al., Laser Phys. 27.8 (2017)
 P. Naubereit, Masterthesis, JGU Mainz (2014).

C. Mattolat, Dissertaton, JGU Mainz (2010)
 S. Rothe, Dissertation, JGU Mainz (2012)

Standard Ion Source Designs for RIBs (taken from CERN ISOLDE)

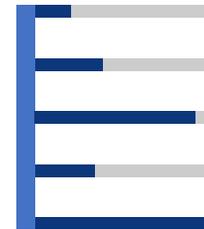
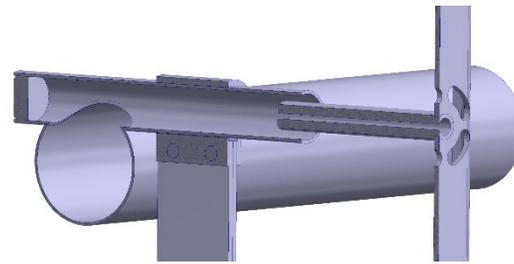
Plasma / electron impact ionization

- For all Elements (independent of IP)
- Break up & ionization of molecules



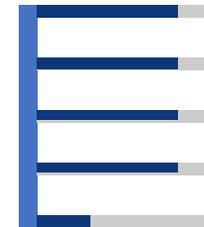
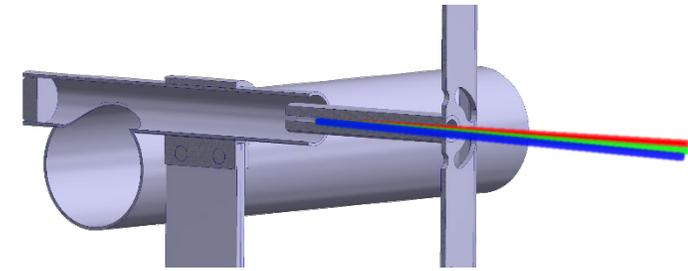
Surface ionization

- Hot cavity ($> 2000^{\circ}\text{C}$ - W, Re or Ta)
- For low (< 6.5 eV) IP elements



Resonant laser ionization

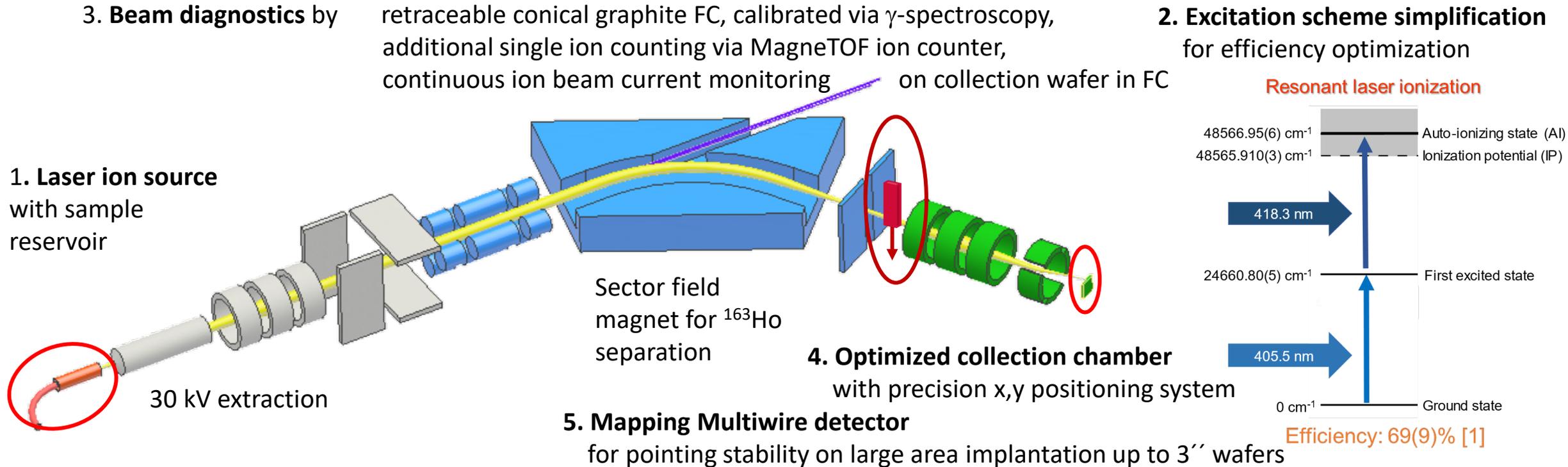
- For almost all IPs
- Intrinsic element selectivity



Efficiency
Selectivity
Reliability
Universality
Simplicity

... basic source geometry and Materials designed in 1975 by H. L. Ravn, S. Sundell et al., NIM 123 (1975)

RILIS Refinements for high purity & high efficiency studies at RISIKO



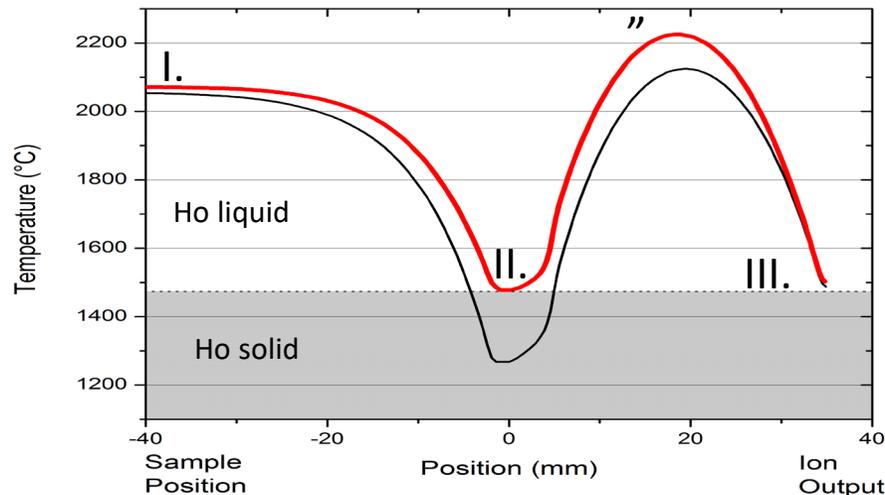
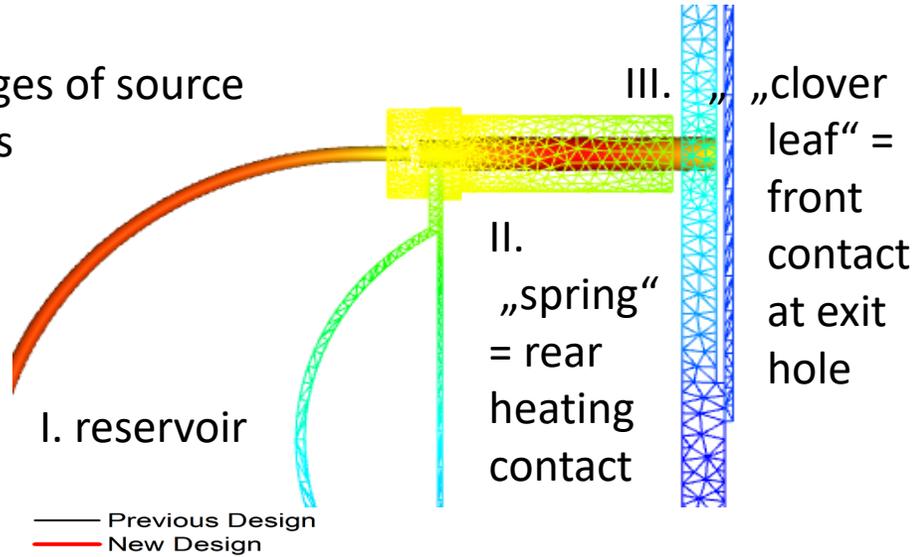
Towards high efficiency, high quality, well quantified isotope implantations and spectroscopy

- | | |
|--|---|
| 1. Detail Optimizations of the laser ion source unit | → Highly efficient atomization of precious species, i.e. ^{163}Ho , ^{55}Fe , actinides |
| 2. Permanently ongoing search & identification of efficient excitation schemes | → highest ionization demonstrated in efficiency curves |
| 3. Optimum and well quantified beam diagnostics | → Absolute ion current measurement for implantation quantification |
| 4. Implantation chamber for wafer exchange & positioning | → up to 3'' wafer implantation |
| 5. Mapping Aperture Detector + Pulsed Laser Deposition | → Accurate ion beam positioning and implantation on collection target |

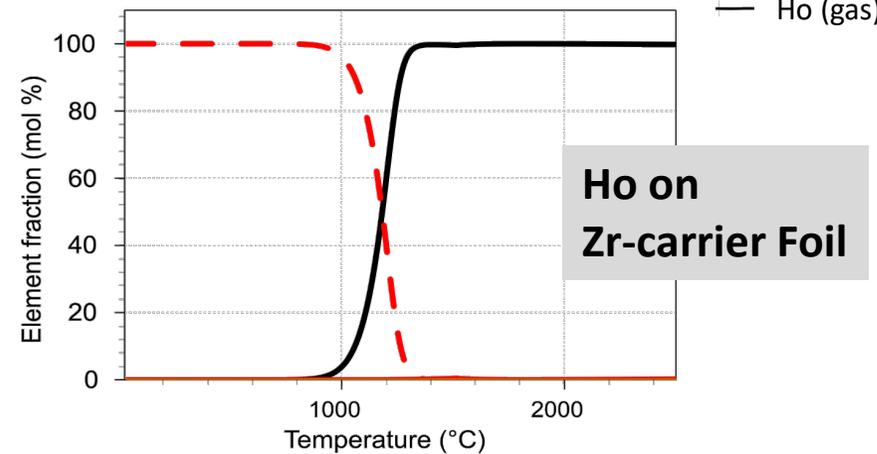
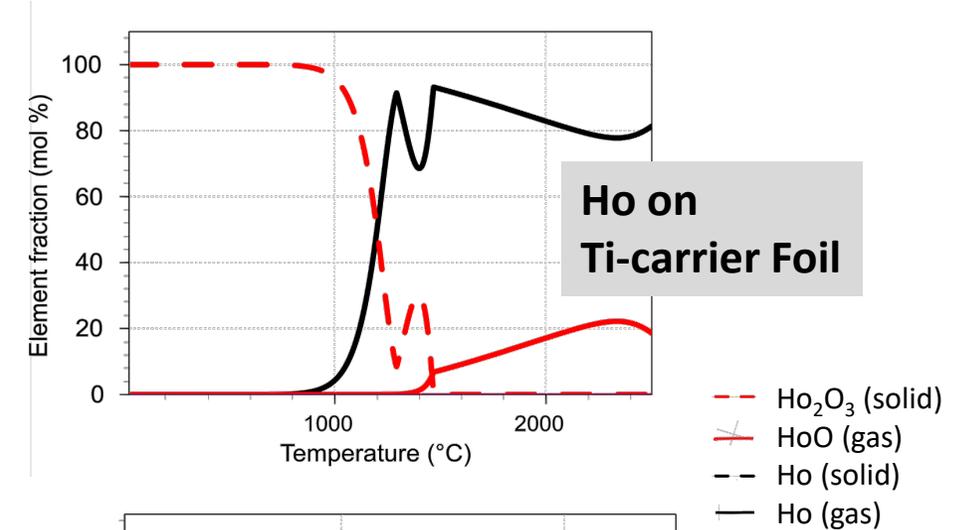
1. RISIKO Ion Source Optimization for ^{163}Ho ECHO Source Production

Finite Element Method (FEM) for Thermal Simulation

Detail changes of source components



Choice of reduction agent through Chemical Simulation Code using Gibbs Energy Minimization Method

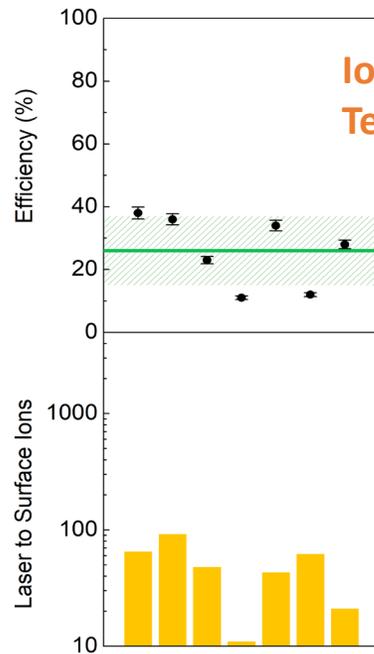


2. Efficiency Optimization for $^{163}\text{Holmium}$ Purification

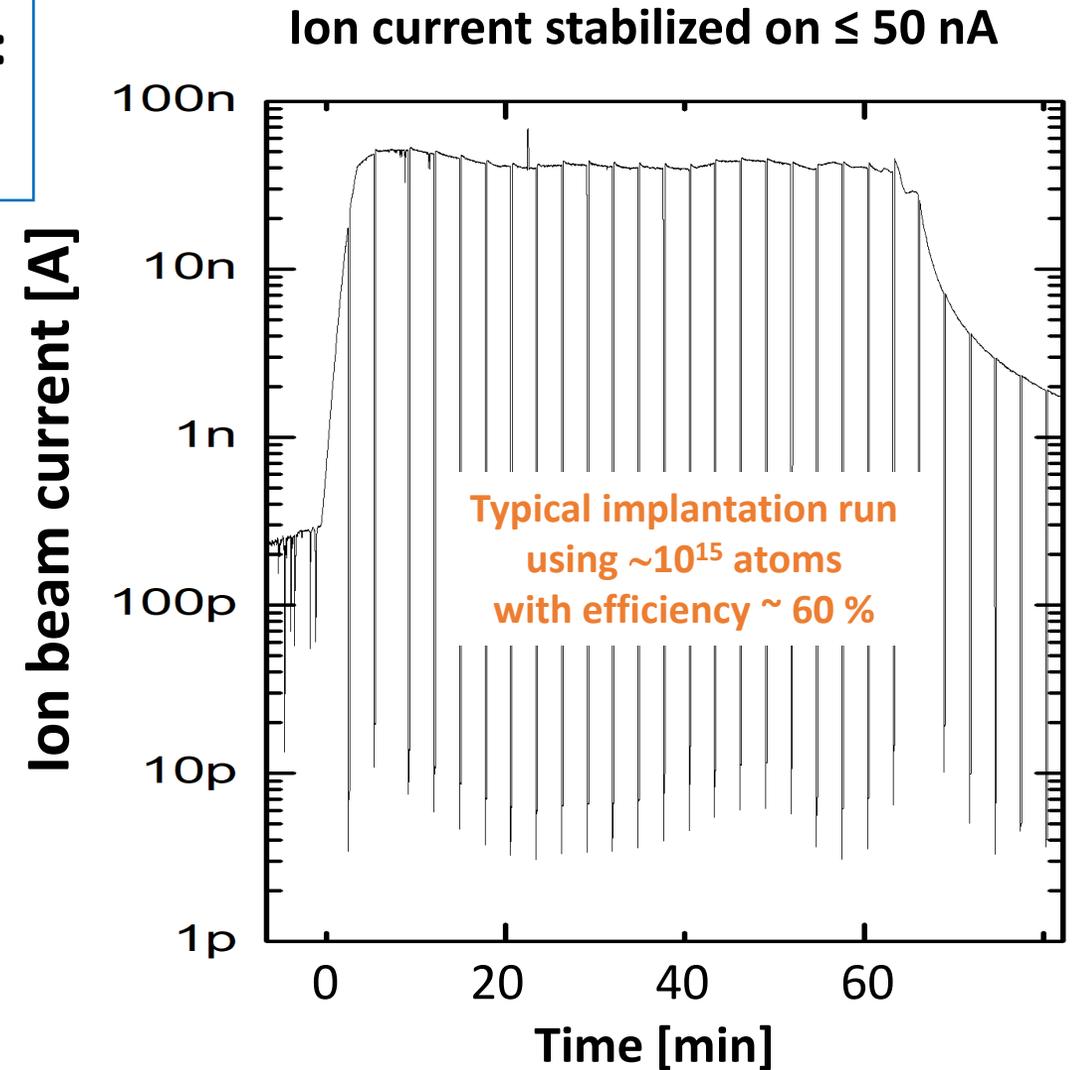
Ionization and Transmission Efficiency:

$26_{(11)}\%$

Evolution of Implantation Efficiency & Selectivity



Measurement



Ion current stabilized on ≤ 50 nA

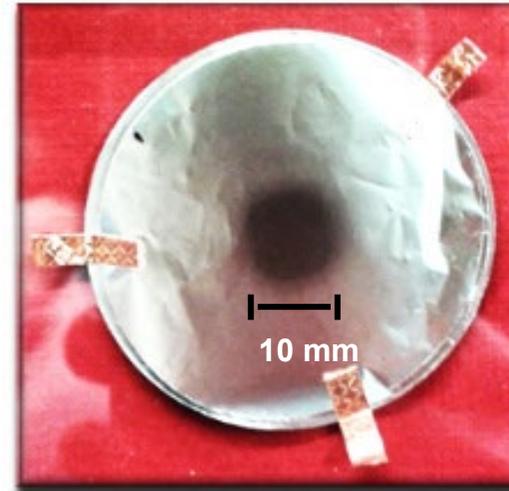
Ion beam current [A]

Time [min]

2. Efficiency Reduction for large Sample Size and Throughput - ^{53}Mn

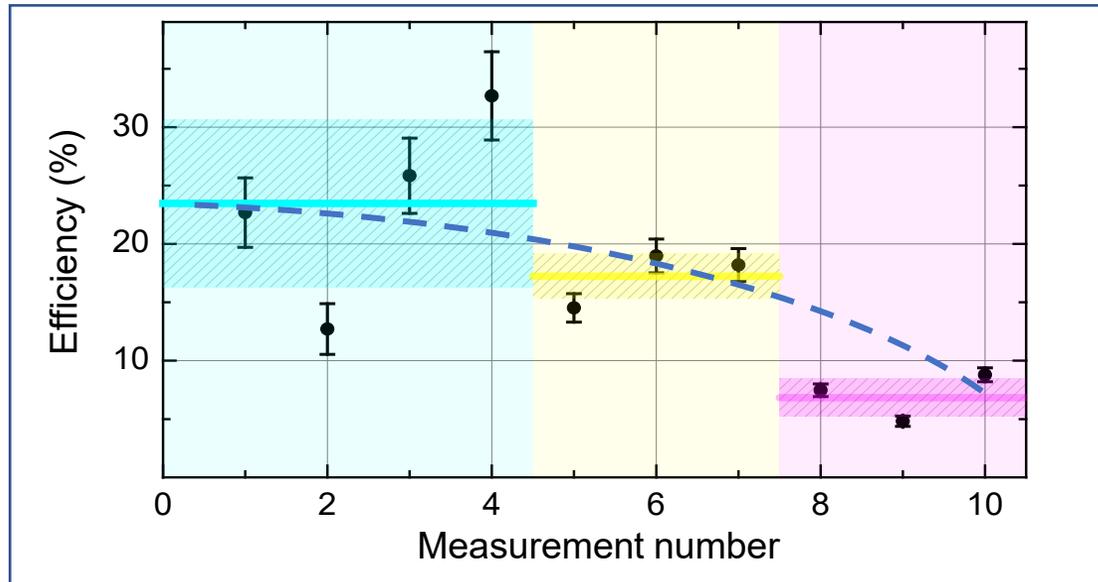
Pretests on stable ^{55}Mn

Individual sample size	10^{14} Atoms	10^{15} Atoms	10^{16} Atoms
Max. ion current	< 10 nA	~ 50 nA	~ 500 nA
Efficiency	23(7) %	17(2) %	6,8(5) %

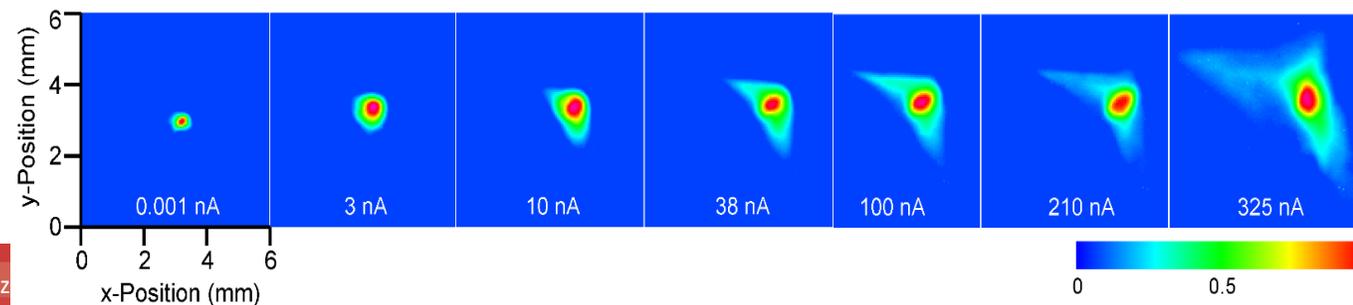


Implanted ^{53}Mn
in Al foil

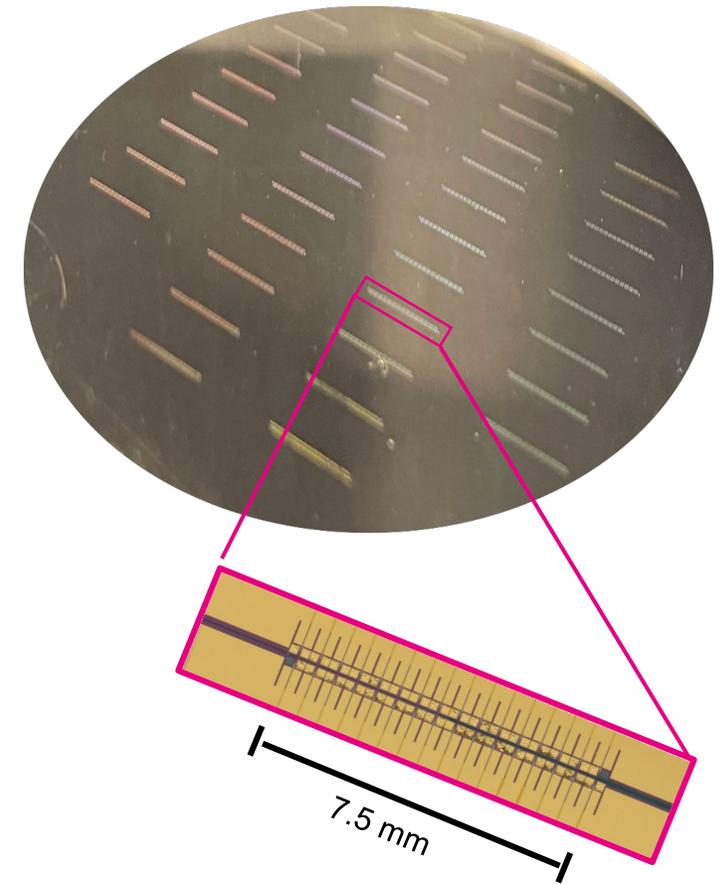
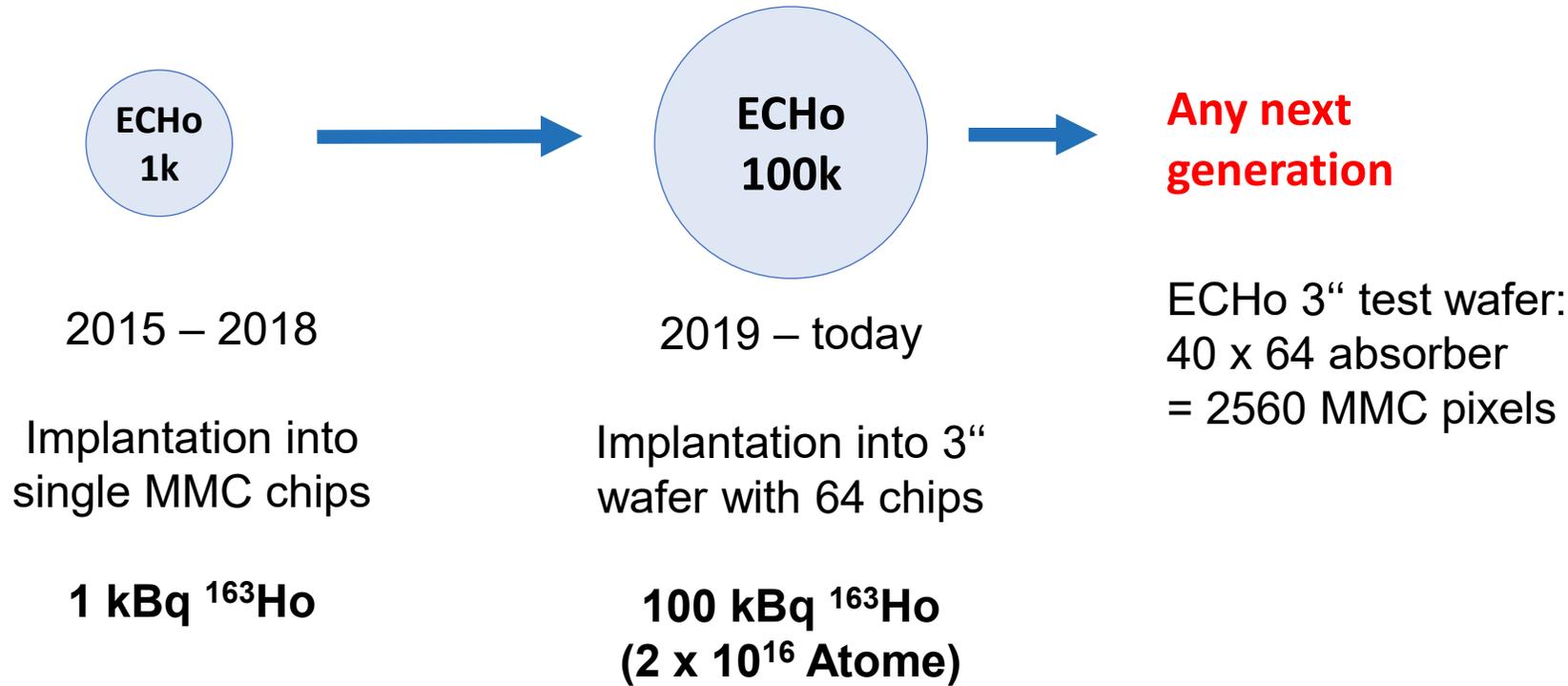
Implantation of ^{53}Mn :
5 samples, 1.1×10^{18} atoms overall



Sample size ^{53}Mn	$1 \cdot 10^{17}$ Atoms	$2 \cdot 10^{17}$ Atoms	$3 \cdot 10^{17}$ Atoms
Max. ion current	~ 50 nA	~ 100 nA	~ 100 nA
Implantation efficiency	20,5 %	17,6 % 14,5 %	12,2 % 12,1 %



The ECHo Project and Scalability – Electron Capture in ^{163}Ho

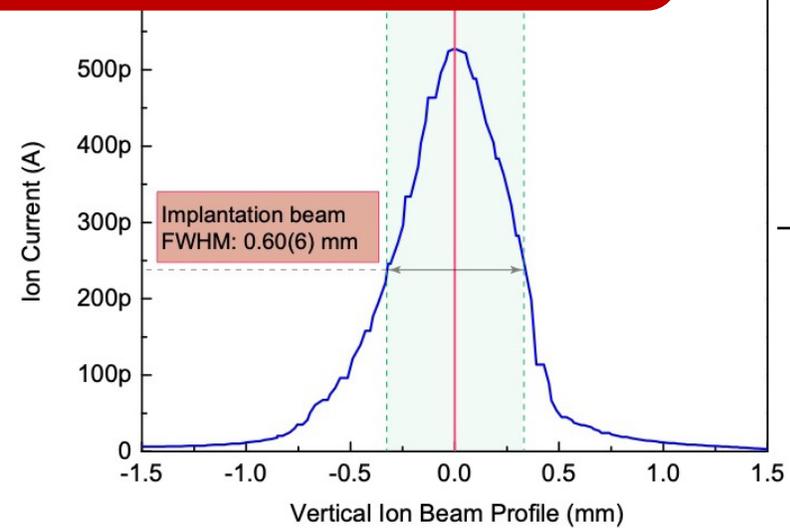
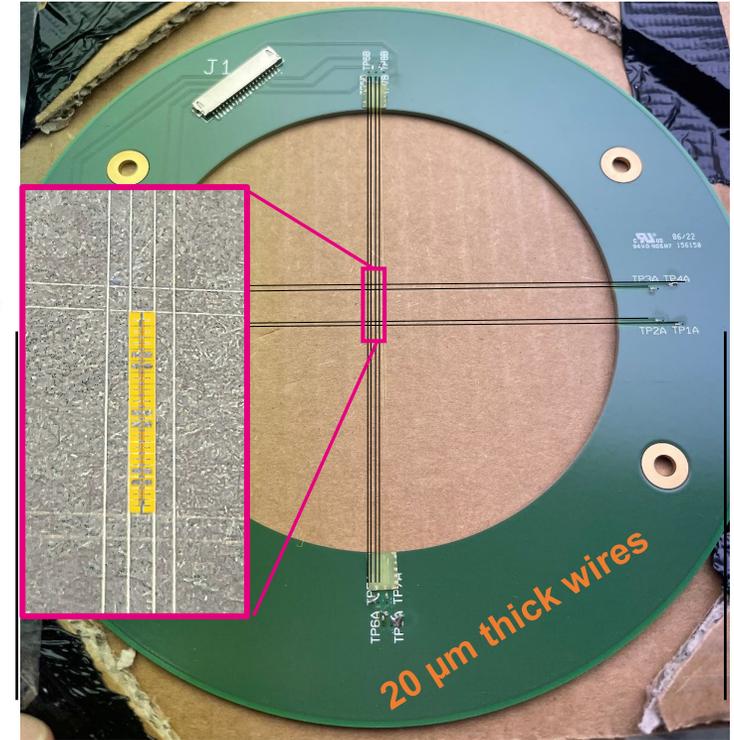
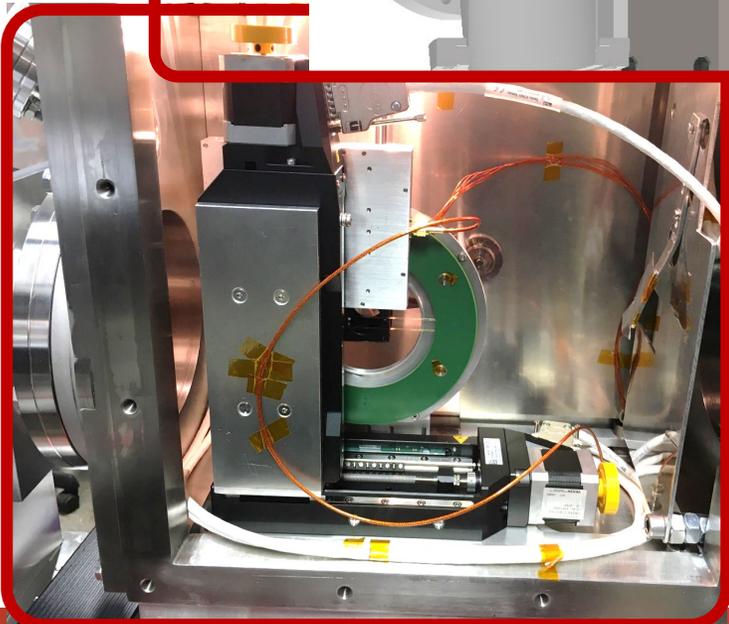
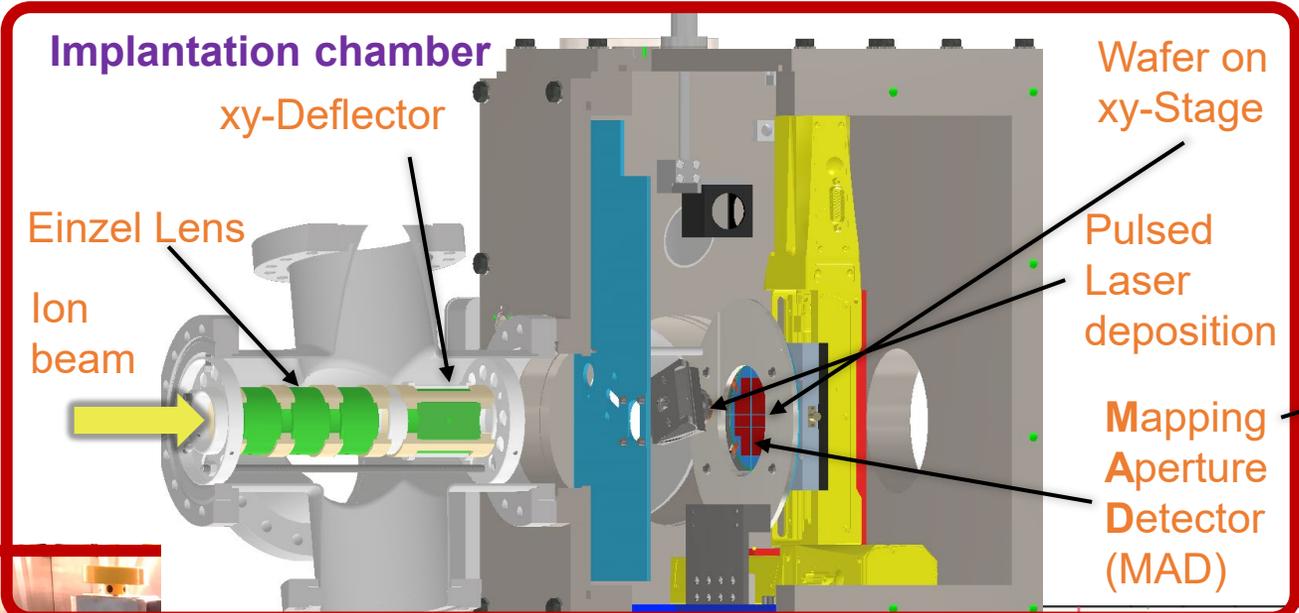


Requirements for source production

- ^{163}Ho to be implanted in $160 \times 160 \times 10 \mu\text{m}^3$ gold absorber
- Echo 1k - 10 Bq/ detector (2×10^{14} atoms into 100 pixels)
- Echo 100 k (2×10^{16} atoms into 10 000 pixels)

Precise beam steering of highest relevance for geometrical efficiency

4. Implantation into Microstructures



160 mm
MAD 8 wire detector
for precision positioning

Wafer test implantation using ^{177}Lu and Autoradiography

Implantation of ^{177}Lu



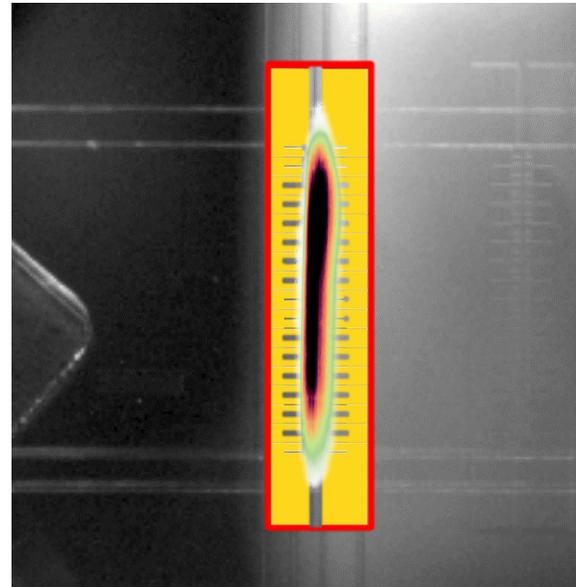
Positioning and fine adjustment of wafer using MAD



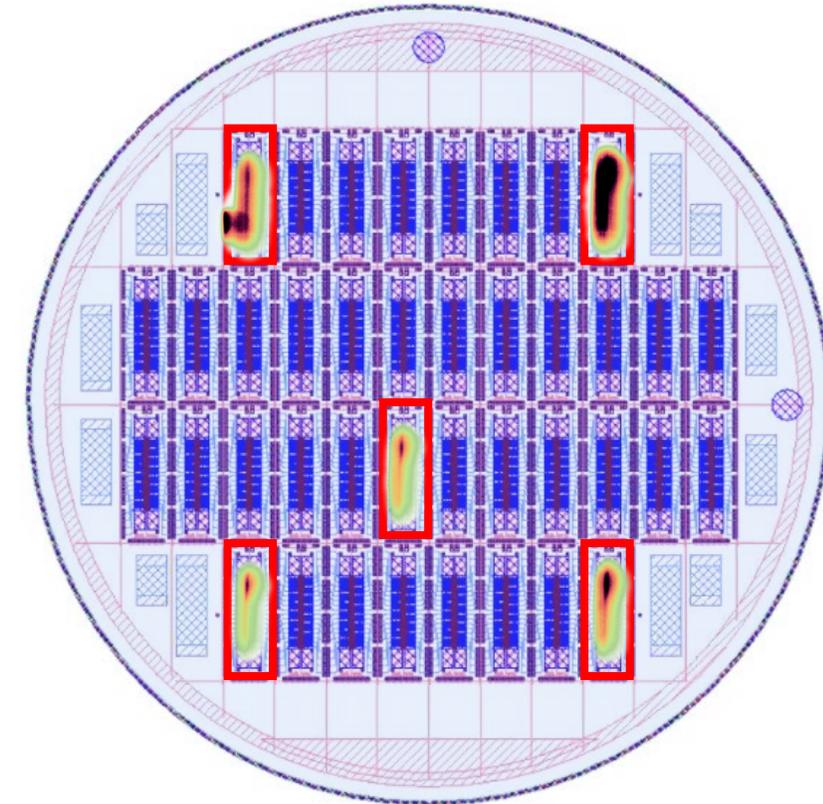
Verification by autoradiography [1]

Hf 176 5.26	Hf 177 18.6	Hf 178 31.00 y 4.0 s	Hf 179 27.28 25.10 d 18.67 s 13.62
Lu 175 97.41	Lu 176 3.64 h 2.59	Lu 177 6.65 d	Lu 178 3.10 m

Rapid γ decay of ^{177}Lu



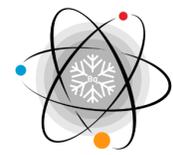
View by adjustment camera inside vacuum chamber with overlaid autoradiography



Drawing of ECHO 100 kBq wafer

[1] N. Bittner, Bachelor Thesis (2022).

Nect Challenge: ^{55}Fe implantation on Prima-LTD MMC pixels



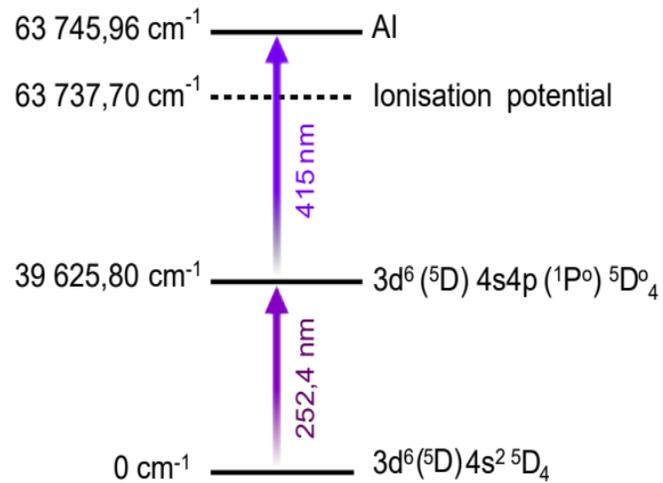
PrimA-LTD

Request: 5 Bq ^{55}Fe implantation per absorber pixel

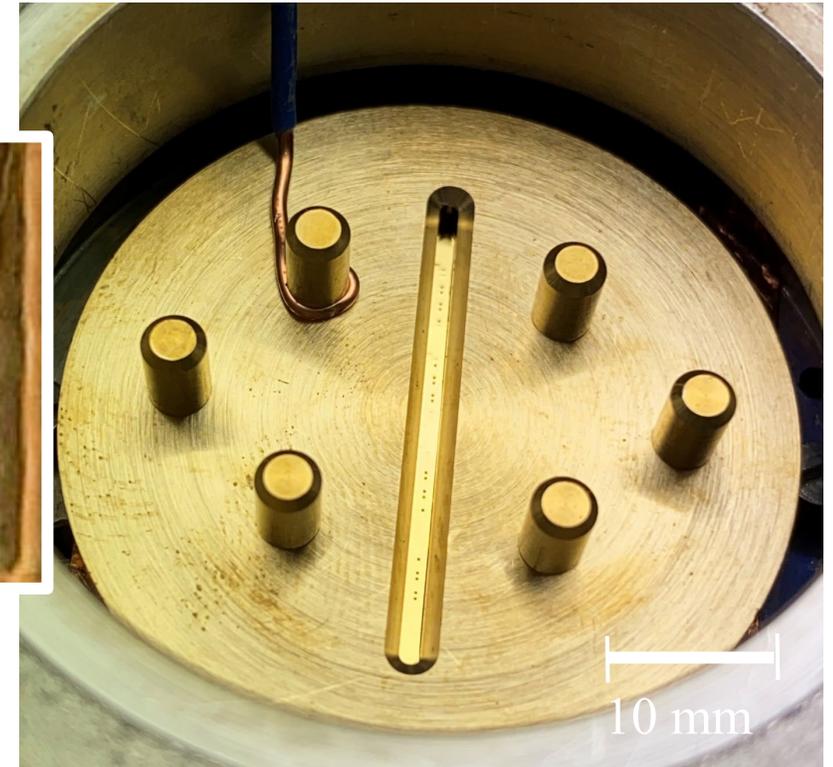
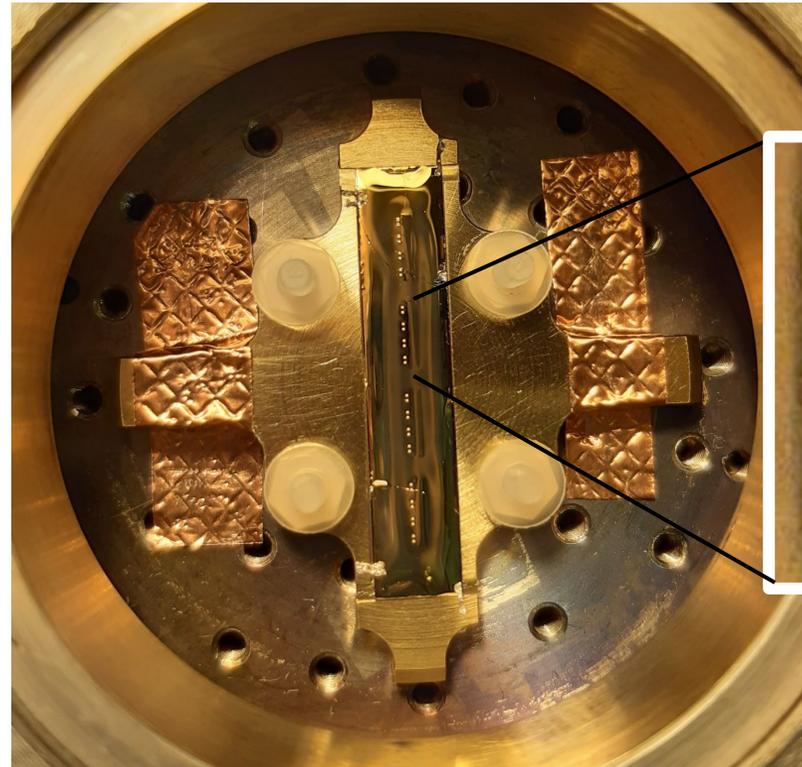
→ No PLD required

1 test chip for autoradiography

4 actual chips for EMPIR studies on EC energies

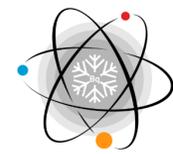


Two step RIS scheme for Fe

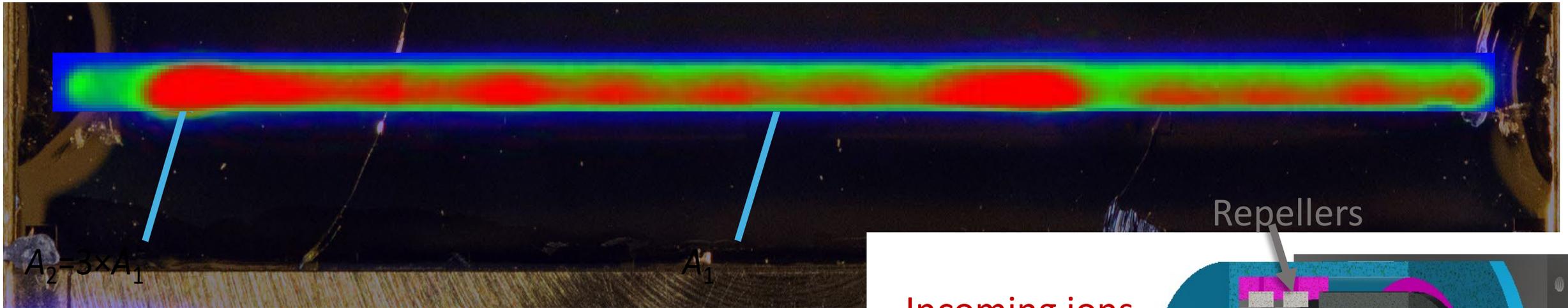


Row of 4 x 8 absorbers of $140\ \mu\text{m} \times 140\ \mu\text{m}$ size

Ion implantation of ^{55}Fe into MMCs for the EMPIR project



- 5 Bq requested per absorber - plus one test absorber of 1 Bq for autoradiography
- vertical displacement determined to be < 0.2 mm – intensity variation $<$ than 50%
- high dose artefacts of 3x and 2x average due to initial implantation routine - corrected



4 chips delivered:

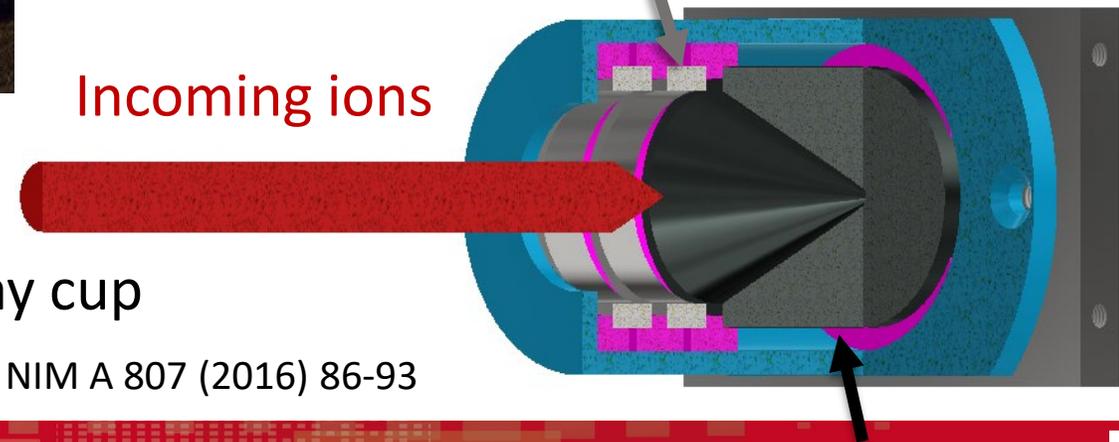
4.2 (1.1) Bq	4.3 (1.1) Bq
--------------	--------------

3.5 (1.1) Bq	5.0 (1.2) Bq
--------------	--------------

Atom number quantification
via calibrated conical Faraday cup

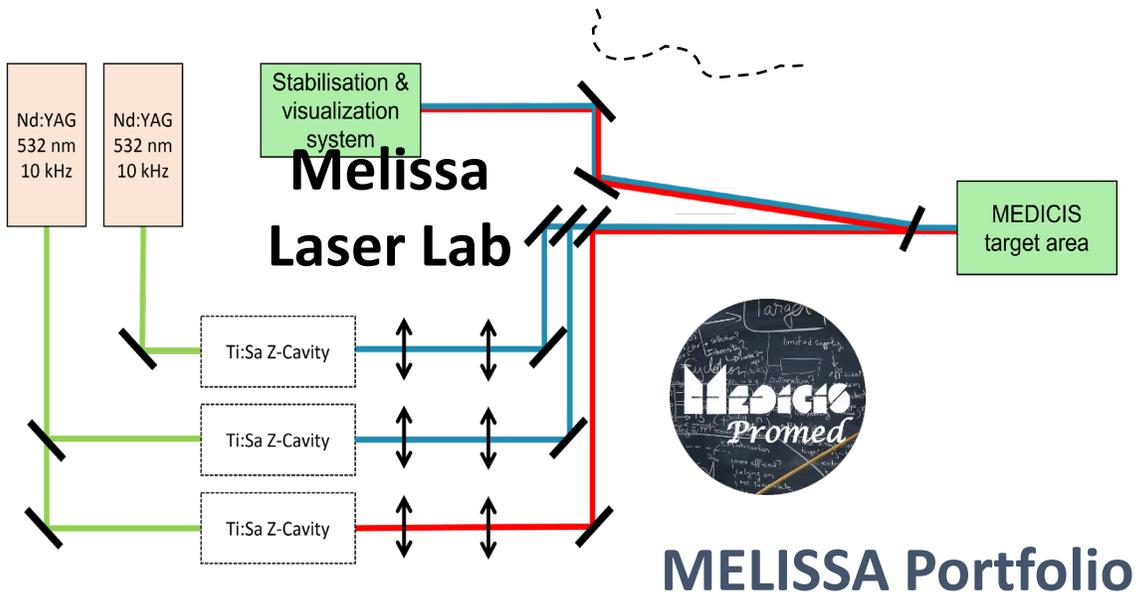
Incoming ions

Repellers



E.D. Cantero, C.P Welsch, et al., NIM A 807 (2016) 86-93

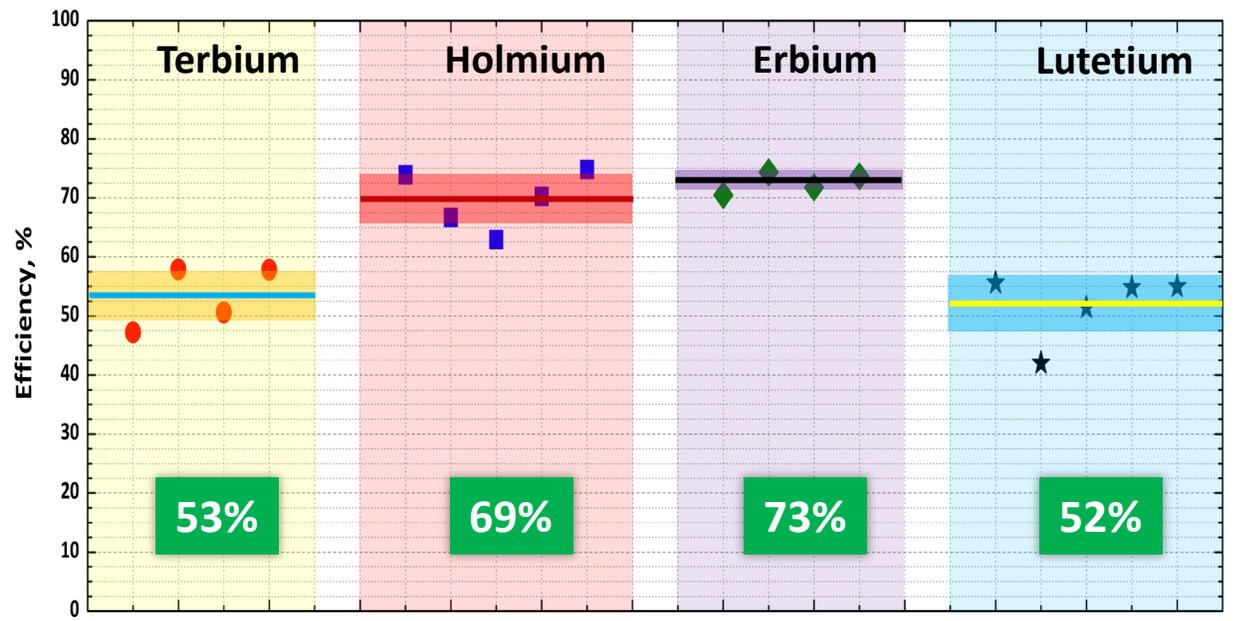
Technology applied for CERN MEDICIS Isotope Collection



MELISSA Portfolio

44Sc 47Sc 225Ac 128Ba 175Yb 169Er **New 2024**
167Tm 149Tb 152Tb 155Tb 153Sm 145Eu 149Gd

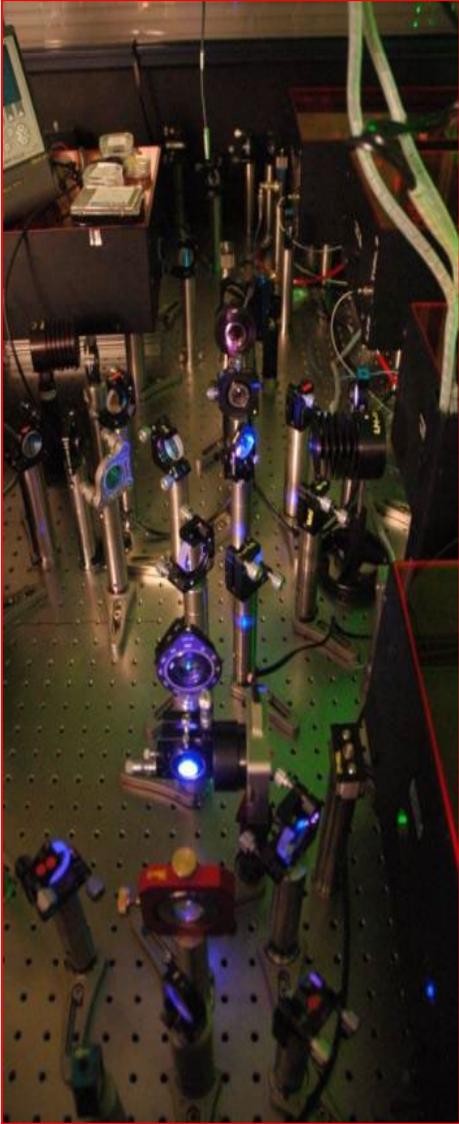
Based on schemata and efficiencies from JGU



CERN MEDICIS Isotope Collection 2024

Month	May				June				July				August				September				October				November				D				
Week n°	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49		
Element		Tb Dy	Tb Dy	Tb Dy		Tb Dy	Sm			Cu	Tb Dy				Tm	Tm	Tb				Tm	Tb Dy			Gd Eu	Tb Dy	Tb Dy	Tb Dy		Tb Dy	Tb Dy	Sc	Sc

Interlude

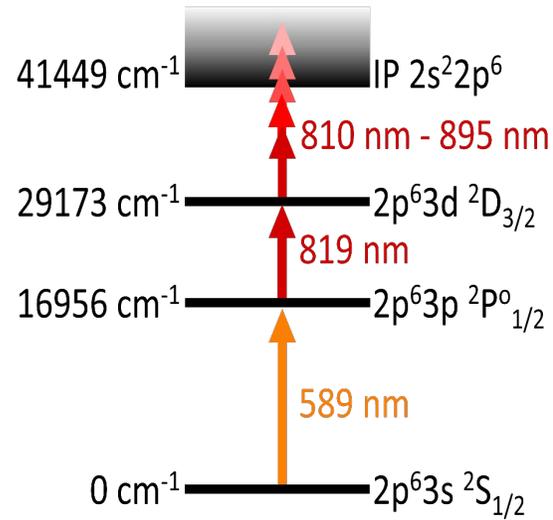


- **History and Motivation for RILIS - Laser Ion Source Developments**
 - Importance of radioactive isotopes, elements, their generation and analysis
- **Physics Background, Technology and Experimental**
 - Resonant laser excitation & Ionization processes in Mass Spectrometry
 - **Lasers & Ion Source Units**
 - Developments towards efficiency (sensitivity) & selectivity (ion beam purity)
- **Applications**
 - Ionization for collection of pure ion beams
 - i.e. ^{53}Mn , ^{55}Fe , ^{157}Tb , ^{163}Ho , ^{226}Ra , ^{247}Cm , ...
 - **Back to the starting point: sodium versus protactinium**
 - **Mid and high resolution spectroscopy in the RILIS**
- **Summary, Outlook & Credits**

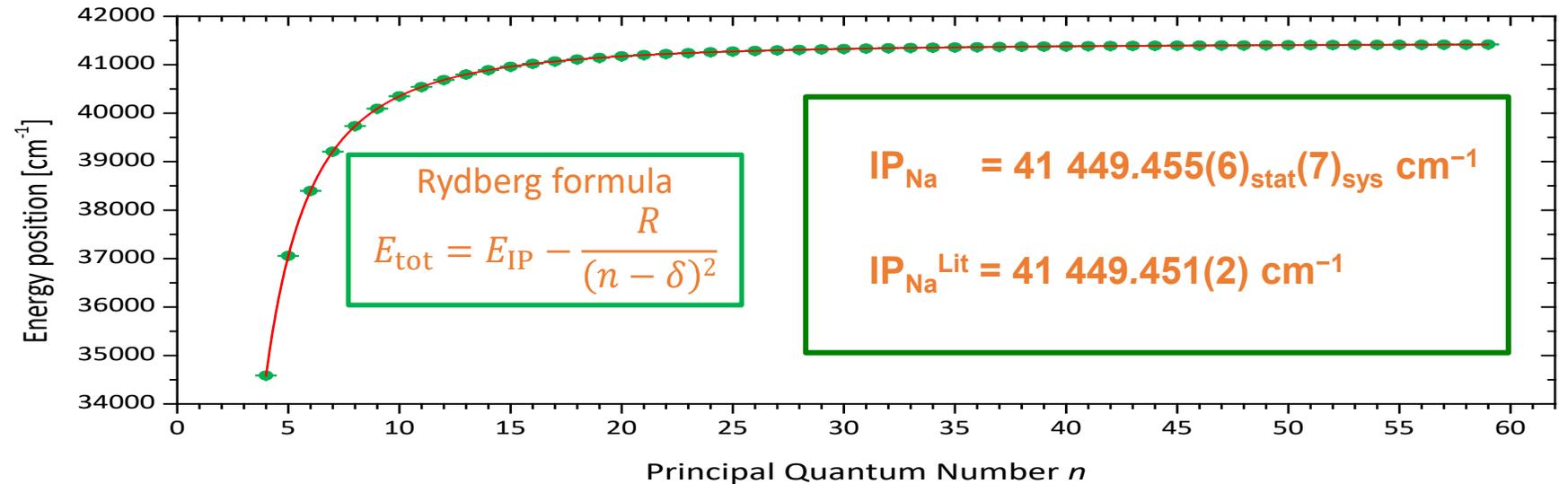
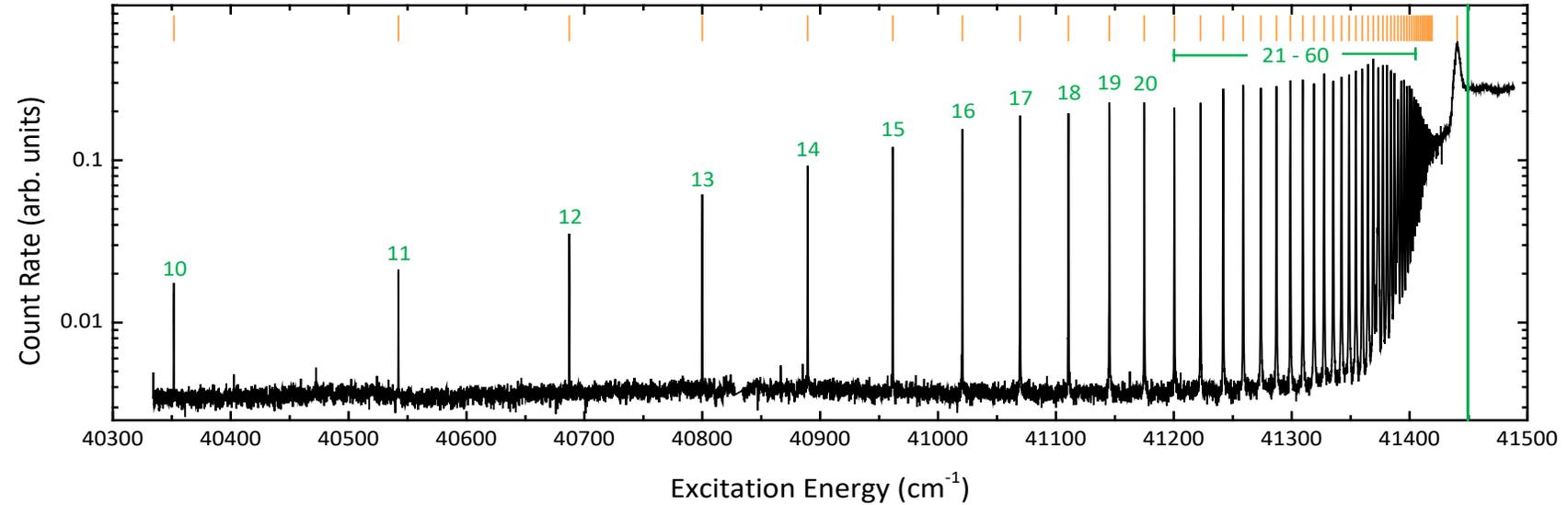
Mid Resolution In-Source Laser Spectroscopy: Rydberg Convergences

Test in $_{11}\text{Sodium}$

wide range laser scan
for $> 1000 \text{ cm}^{-1}$ in TES
around the expected IP



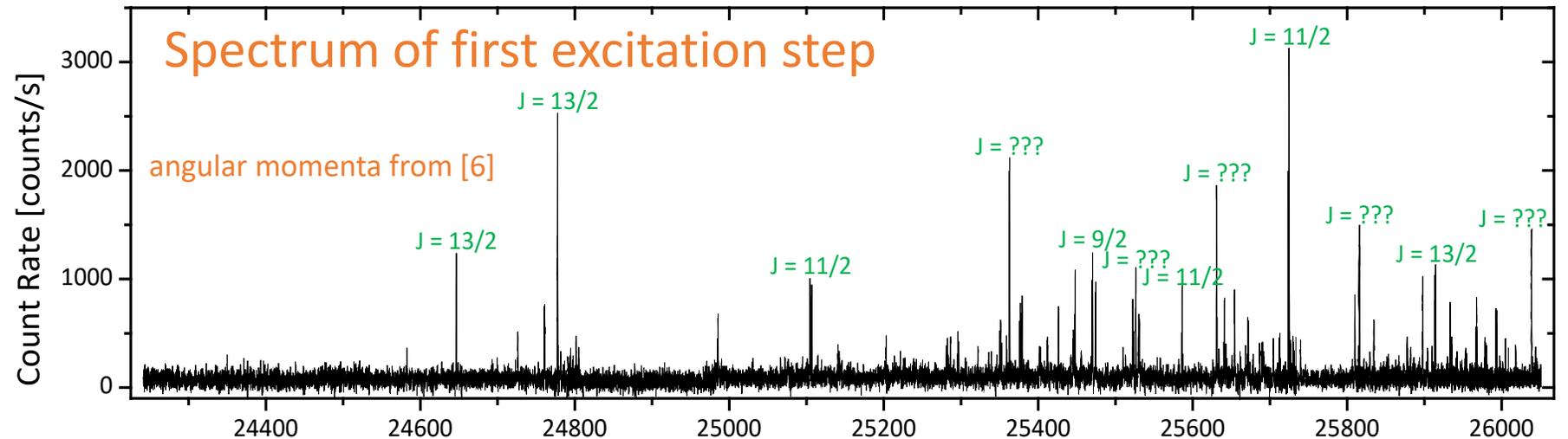
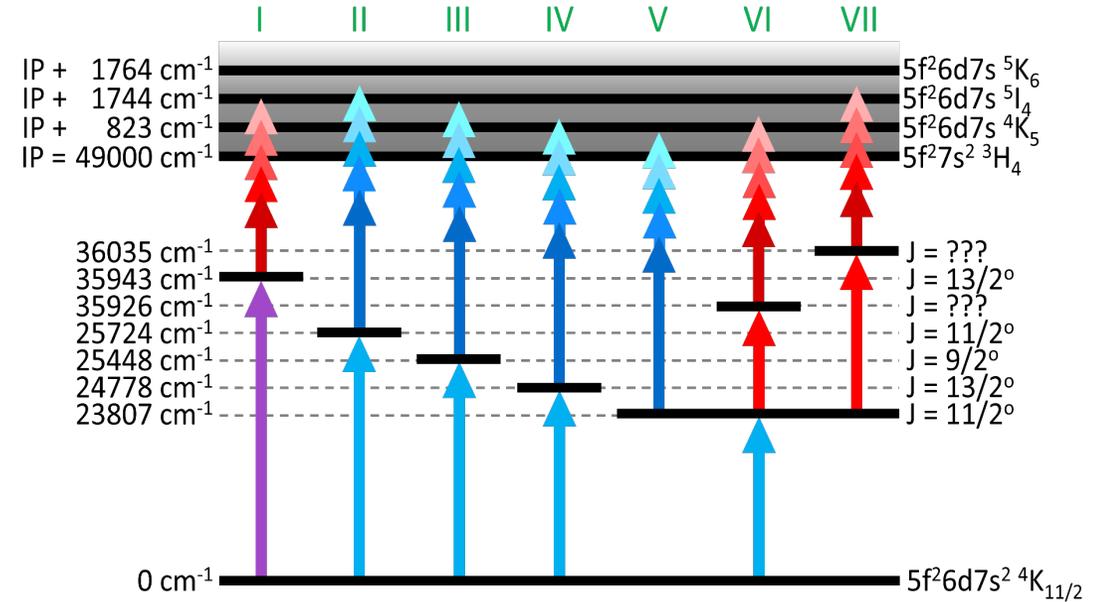
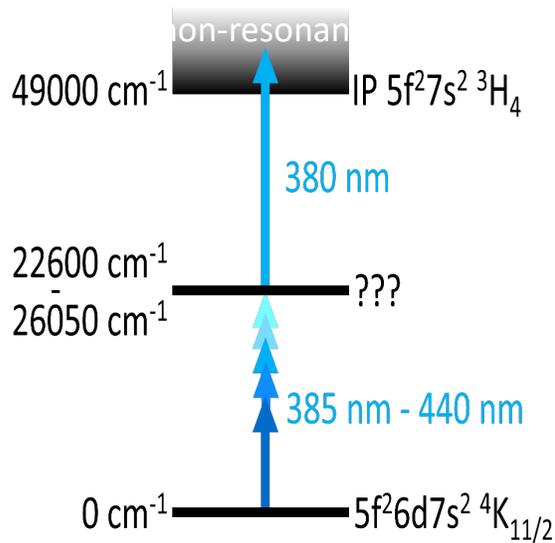
...an optimum situation...



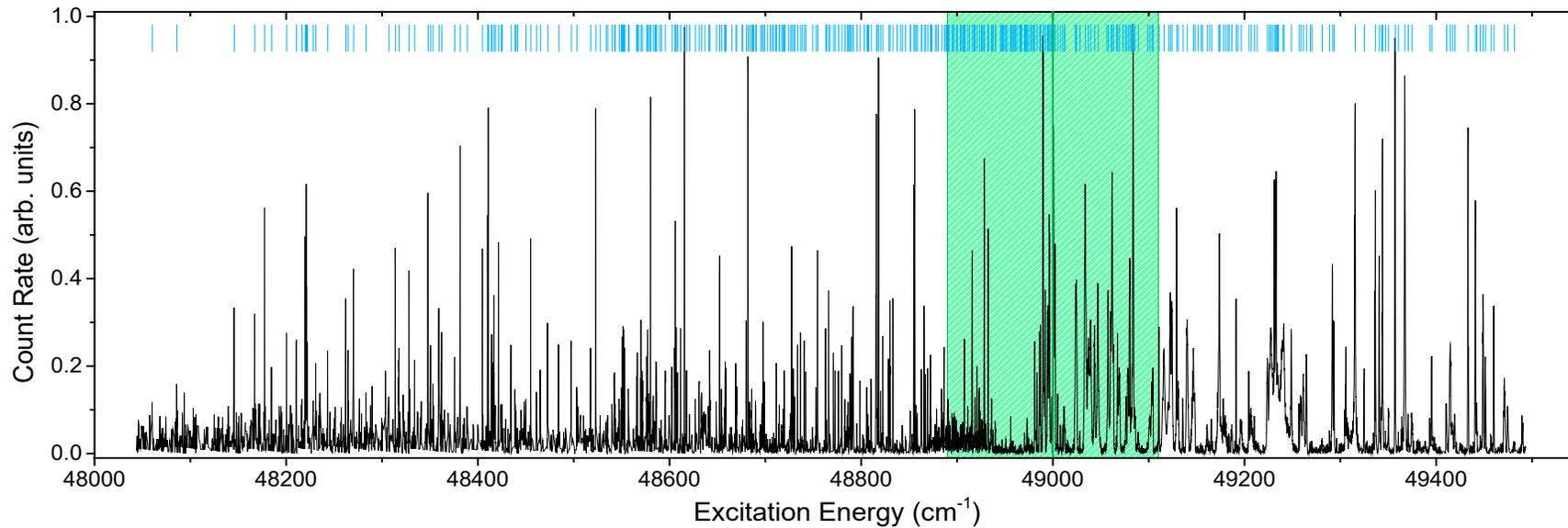
Mid Res Spectroscopy in Complex Spectra: ${}_{91}\text{Protactinium}$

Step 1: Search for suitable first excited states (FES)

- scan the first laser in a broad wavelength range
- set a powerful second laser at an energy well above the IP for non-resonant ionization
- scan laser 2 (or 3) across the IP range to find Rydberg levels



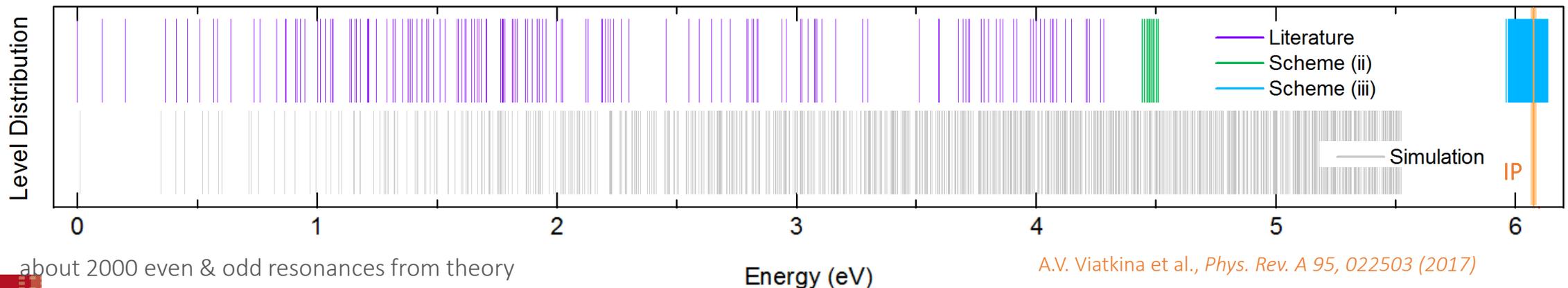
Chaotic Spectra on Higher Excited Levels in Protactinium



Scheme	Energy range	Parity	# Level	Range of J's
(i)	3.0 eV - 3.2 eV	Odd	88	7/2 - 13/2
(ii)	4.4 eV - 4.5 eV	Even	28	9/2 - 13/2
(iii)	6.0 eV - 6.1 eV	Even	423	9/2 - 13/2
(iv)	6.1 eV - 6.3 eV	Even	74	7/2 - 11/2
(v)	6.0 eV - 6.1 eV	Even	70	11/2 - 15/2
(vi)	6.0 eV - 6.1 eV	Even	187	9/2 - 13/2
(vii)	5.9 eV - 6.1 eV	Odd	472	7/2 - 15/2
(viii)	6.0 eV - 6.2 eV	Odd	233	9/2 - 13/2
Literature	0.0 eV - 4.3 eV	Even	156	3/2 - 17/2
Literature	0.2 eV - 4.8 eV	Odd	494	3/2 - 17/2
Simulation	0.0 eV - 5.5 eV	Even	989	1/2 - 19/2
Simulation	1.0 eV - 5.1 eV	Odd	989	1/2 - 19/2

156 even and 494 odd resonances from literature

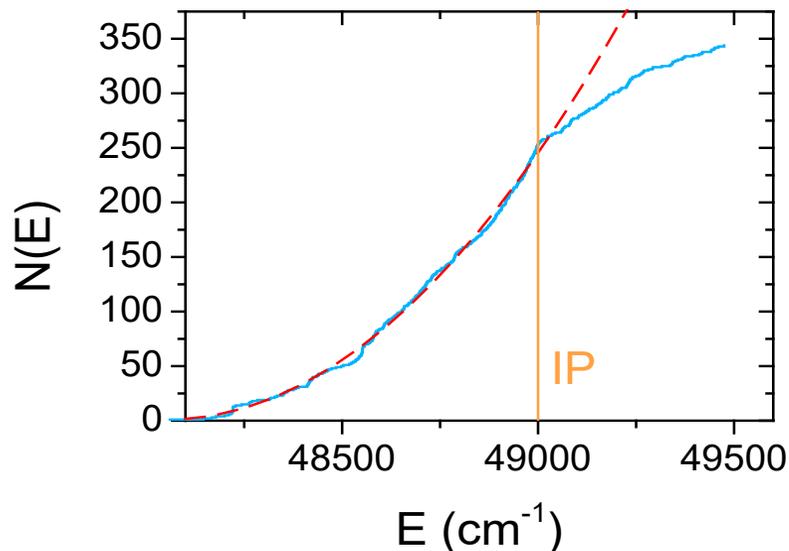
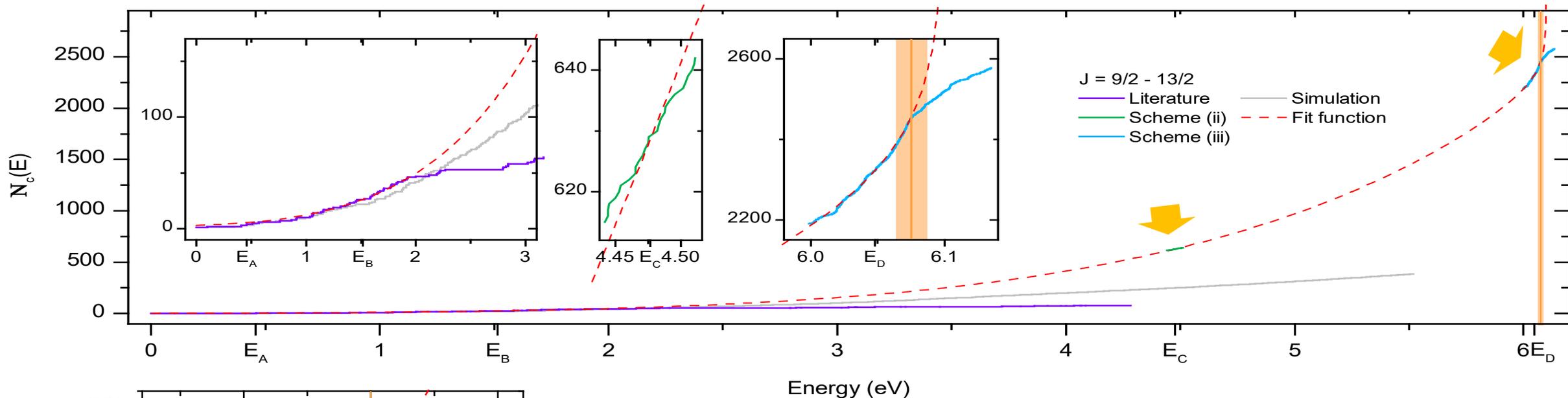
about 800 even & 800 odd resonances measured



about 2000 even & odd resonances from theory

A.V. Viatkina et al., *Phys. Rev. A* 95, 022503 (2017)

Analysis of the Protactinium Spectrum by Distribution Functions



Theoretical data analysis via

1. *Level Density Collaps* or
2. *Rydberg Correlation*

yields

$$IP_{Pa} = 49\,034\ (10)\ \text{cm}^{-1}$$

$$IP_{Pa}^{\text{Expect}} = 49\,000\ (110)\ \text{cm}^{-1}$$

from systematics (K.W.)

Excited atomic energy levels in protactinium by resonance ionization spectroscopy

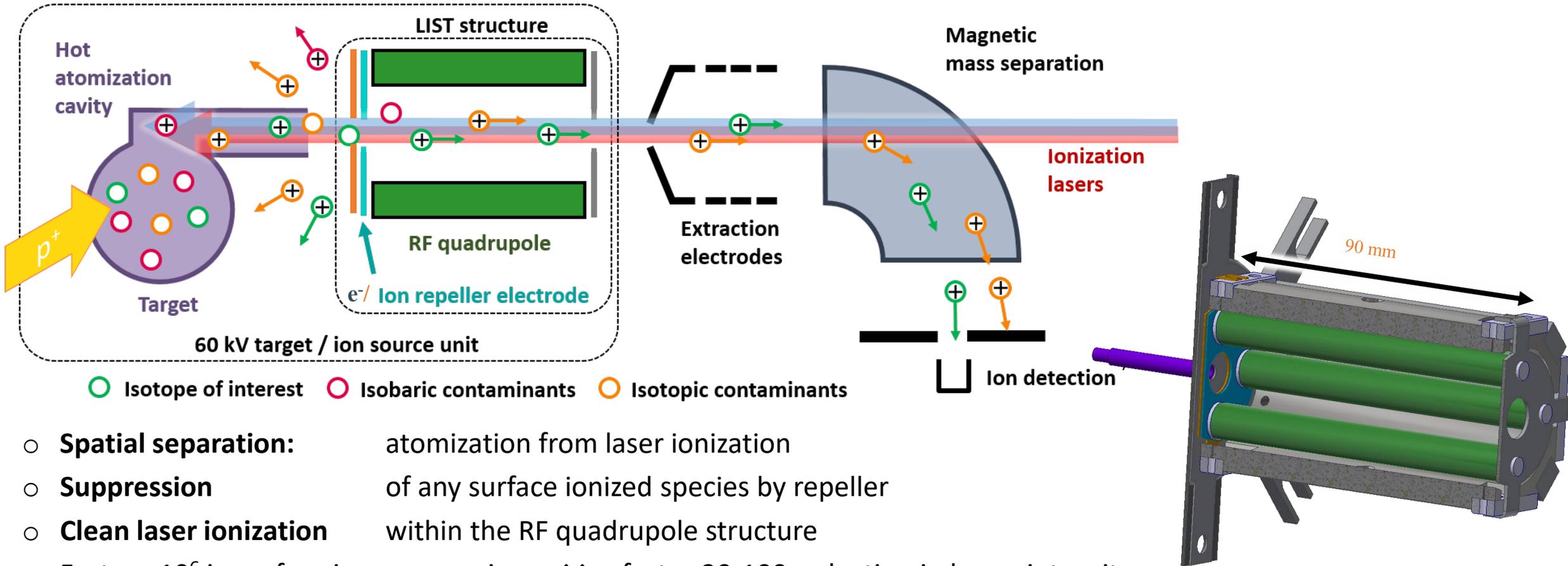
P. Naubereit, T. Gottwald, D. Studer, and K. W., *PR A* **98**, 022505 (2018)

Intrinsic quantum chaos and spectral fluctuations within the protactinium atom

P. Naubereit, D. Studer, A.V. Viatkina, A. Buchleitner, B. Dietz, V.V. Flambaum, and K.W. *PR. A* **98**, 022506 (2018)

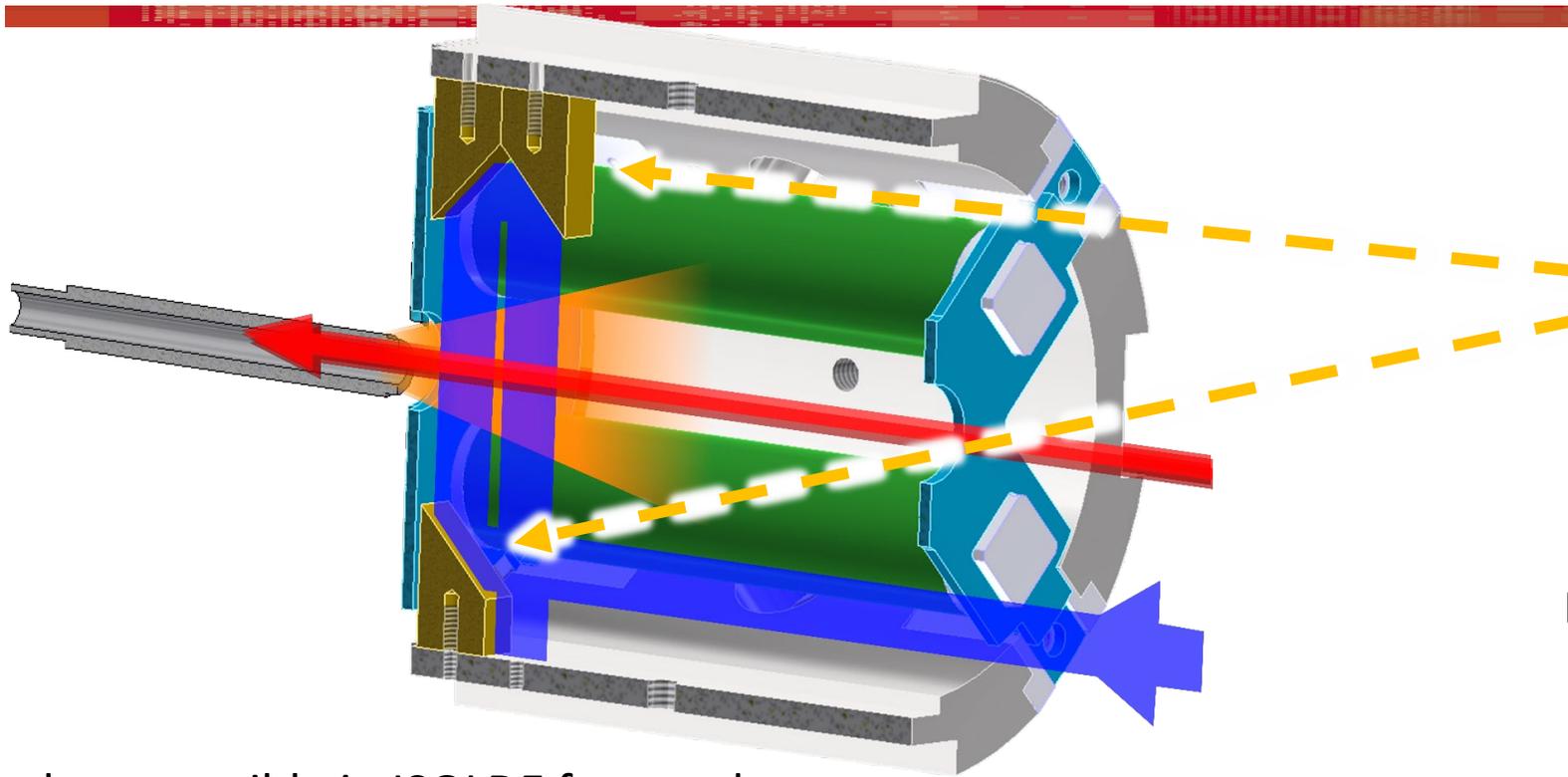
The Supreme Discipline: High resolution in-source laser spectroscopy

...the family of Laser Ion Source & Trap units LIST, PI-LIST, oL-PI-LIST, FI-LIST

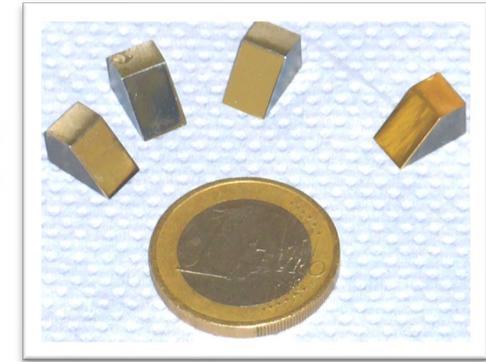


- **Spatial separation:** atomization from laser ionization
- **Suppression** of any surface ionized species by repeller
- **Clean laser ionization** within the RF quadrupole structure
- Factor $\sim 10^6$ in surface ion suppression \leftrightarrow factor 20-100 reduction in beam intensity
- Versatility for highest selectivity and high spectral resolution by perpendicular illumination

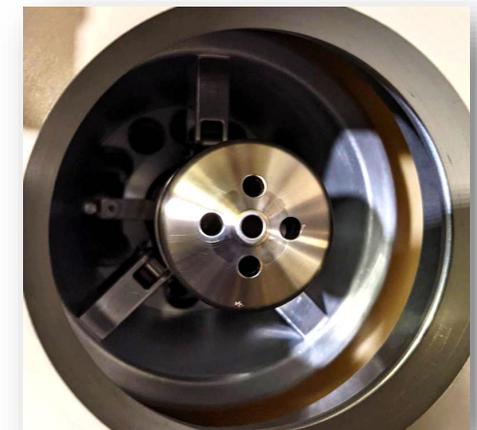
From RISIKO to ISOLDE: Adaption of the PI-LIST to the oL-PI-LIST



Robust metallic mirrors



Perforated HV extraction electrode



No windows possible in ISOLDE front end

- Reflection by **metallic mirror** surfaces (Mo)
- **Off-axis guiding** of laser through ion beam line and extractor electrode
- Beam profile and emittance simulated and verified experimentally

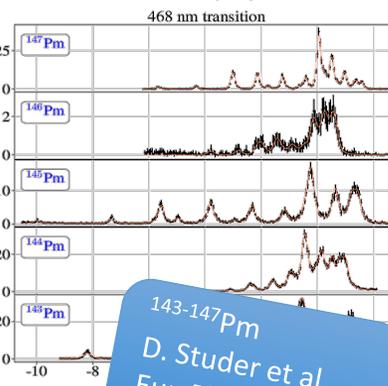
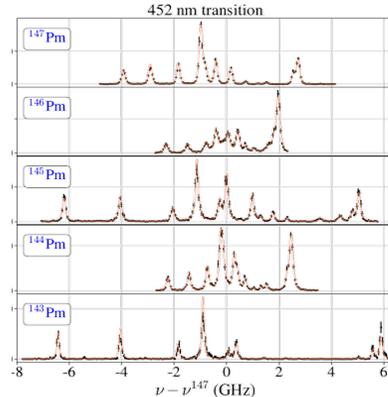
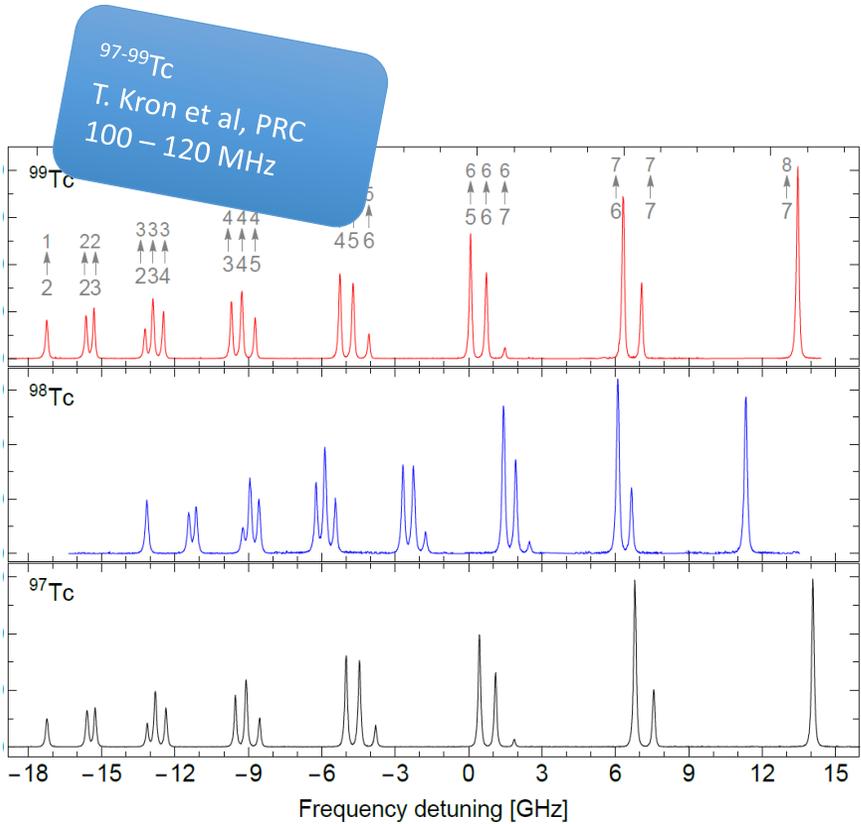
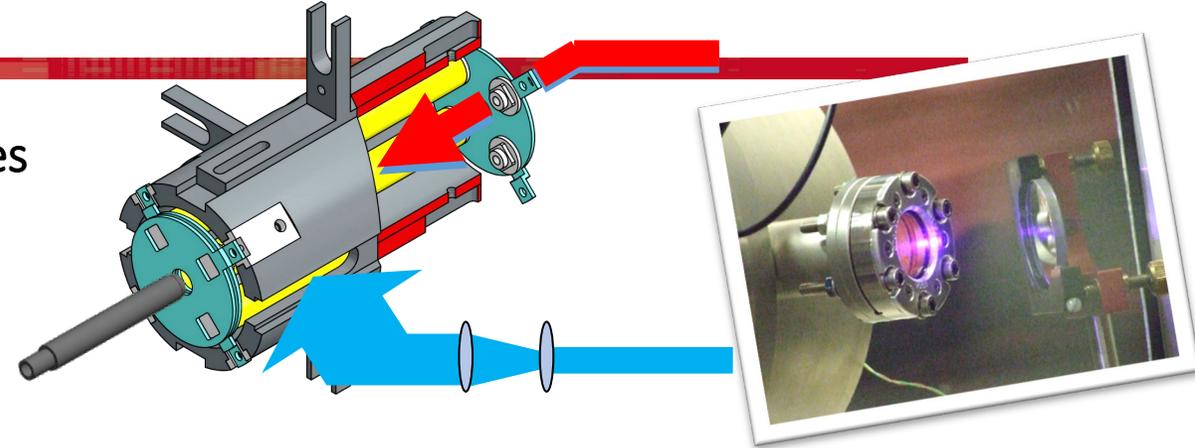
First on-line application of the high-resolution spectroscopy laser ion source PI-LIST at ISOLDE

R. Heinke, et al., Nuclear Inst. and Methods in Physics Research B 541, 8-12 (2023)

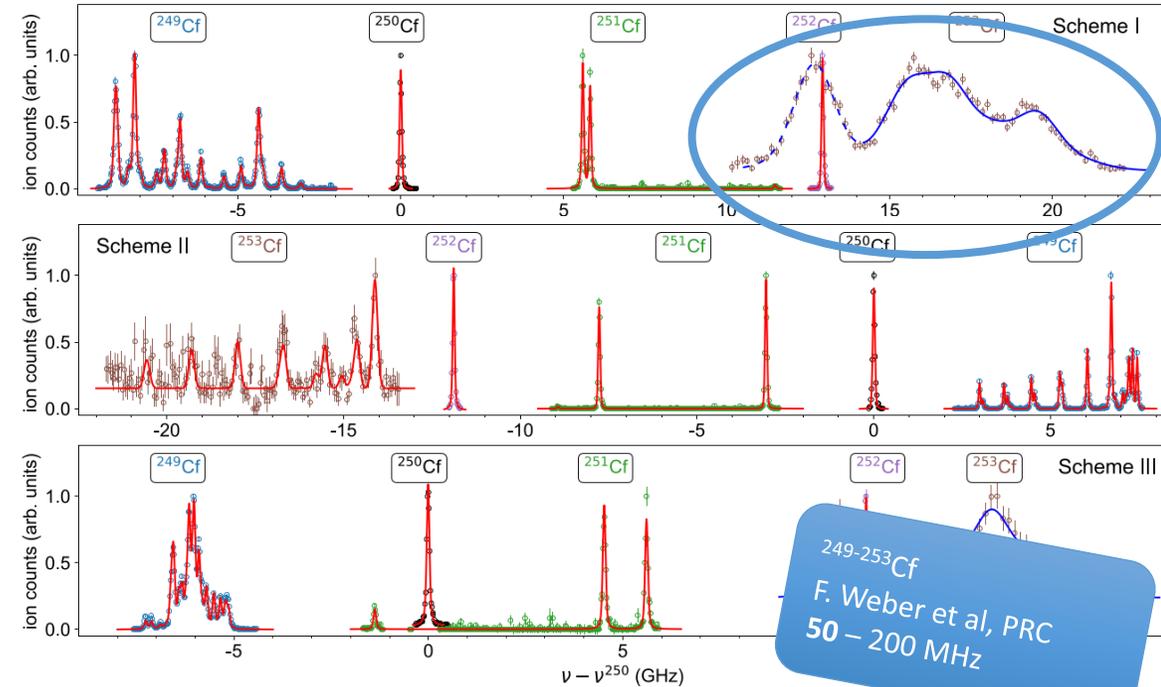
High resolution spectroscopy results from the PI-LIST

- Nuclear structure investigations on long-lived radioisotopes
- Standard tool for high resolution spectroscopy

off-line at RISIKO, on-line at ISOLDE



143-147Pm
D. Studer et al,
Eur. Phys. J. A.
100 - 250 MHz



249-253Cf
F. Weber et al, PRC
50 - 200 MHz

Conclusion and Outlook

RILIS in on- and off-line Mass Spectrometry

→ sensitive, selective and significant technique

with still great development potential even after 40 years

Technological developments during the last 40 years

Isotope Purification & Enrichment (in Research Quantities)

all along the Periodic Table

Fundamental Spectroscopy on Atomic & Nuclear Structure

of radioelements or ultratrace isotopes

Routine Operation in Analytics: Bulk-RIMS & Particle-SNMS

