EMIS 2018

17th September 2018, CERN

Bruce Marsh, *CERN EN-STI-LP*

The laser ionisation toolkit for ion beam production at thick-target ISOL facilities

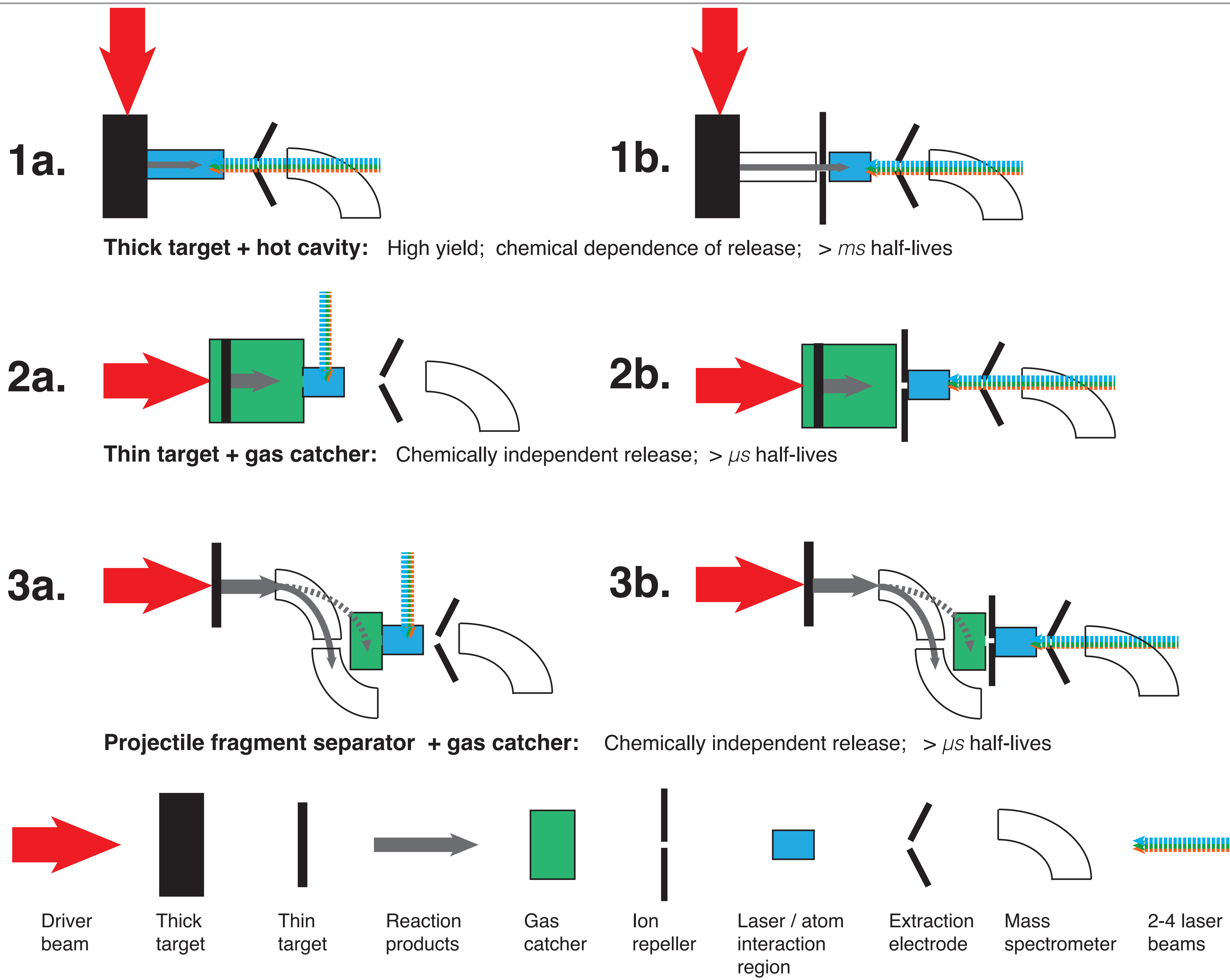
EN Engineering Department

ISOLDE

Outline

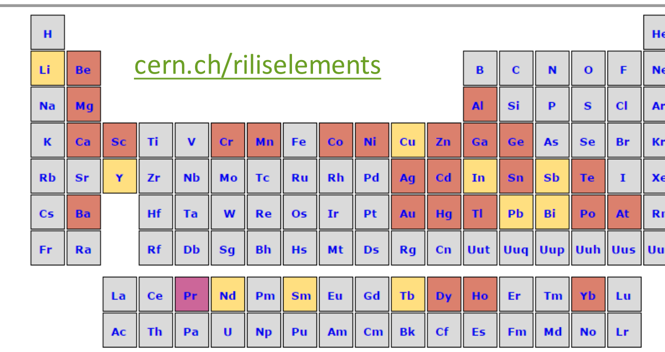
- ★ Laser ion source types
- ★ Operating principle and goals
- ★ The ISOLDE RILIS (Laser technologies, setup and capabilities)
- ★ Thick target RILIS options (selectivity, efficiency, spectral resolution)
- ★ Future possibilities

Laser Ion Source Types



Purpose

Radioactive ion beam production
for most ISOLDE experiments

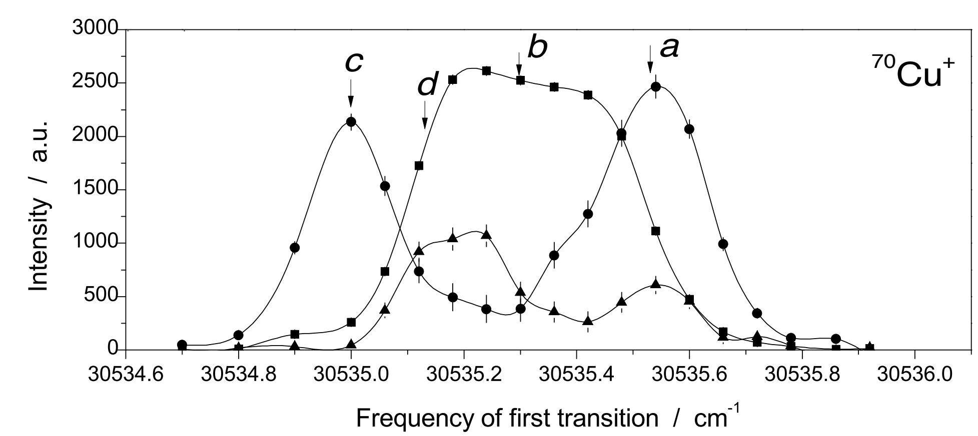


Broad linewidth lasers

Efficiency

Most metallic elements

Isomer-selective ionization
for nuclear physics experiments

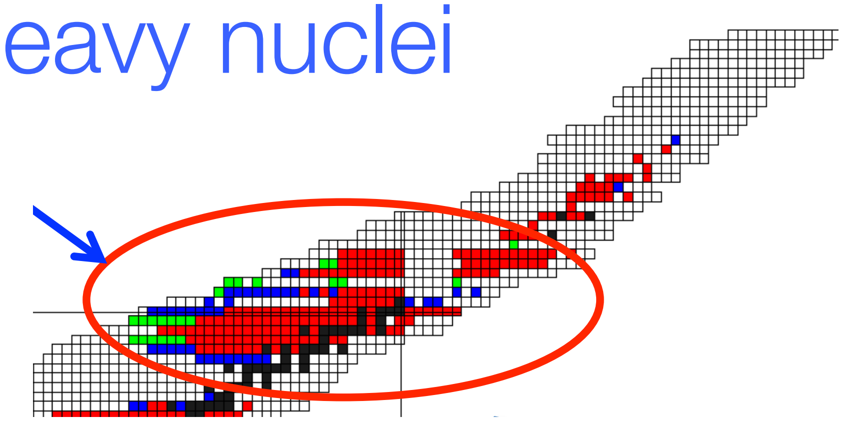


Narrow linewidth lasers

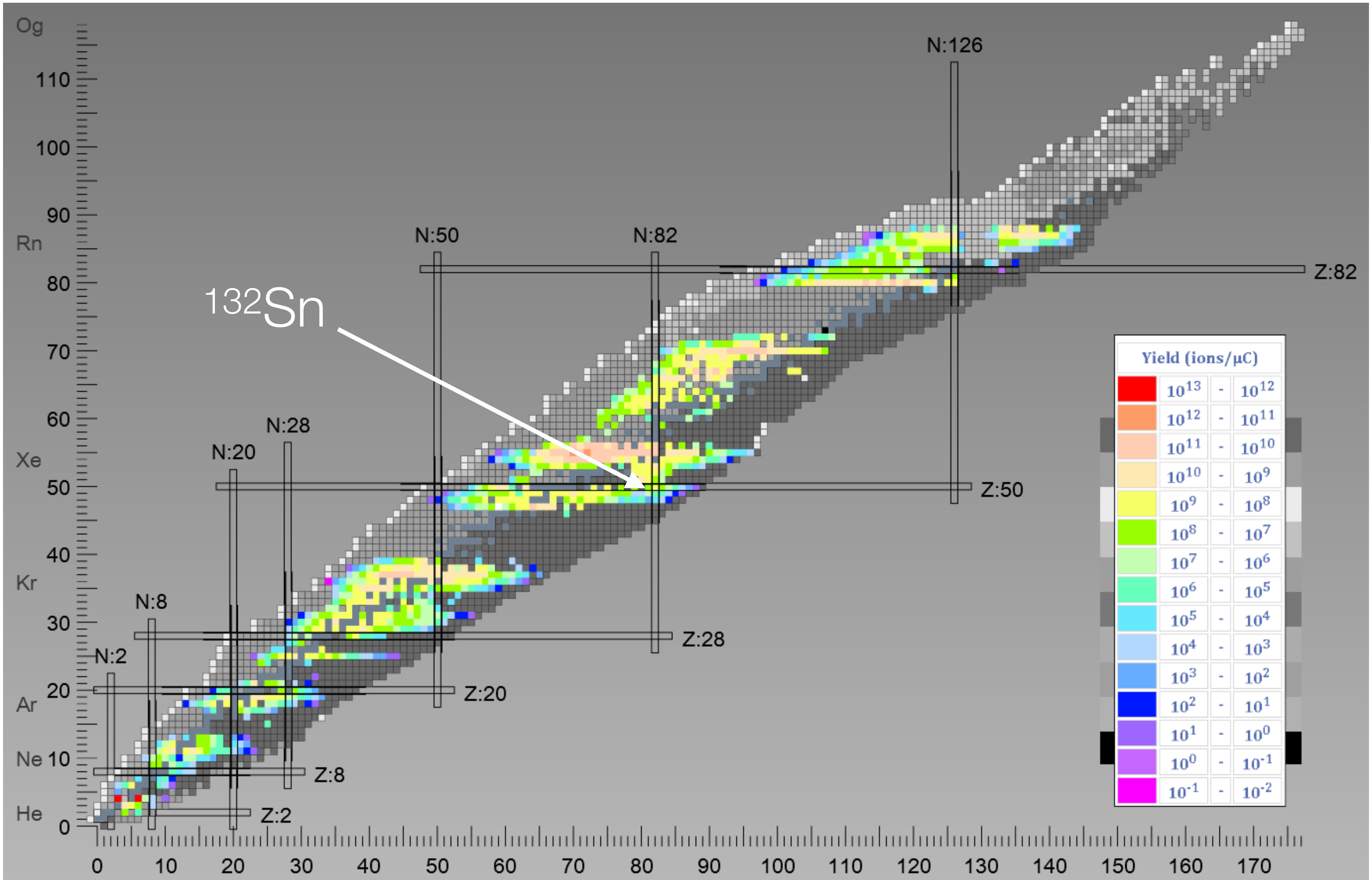
Selectivity

Heavy nuclei

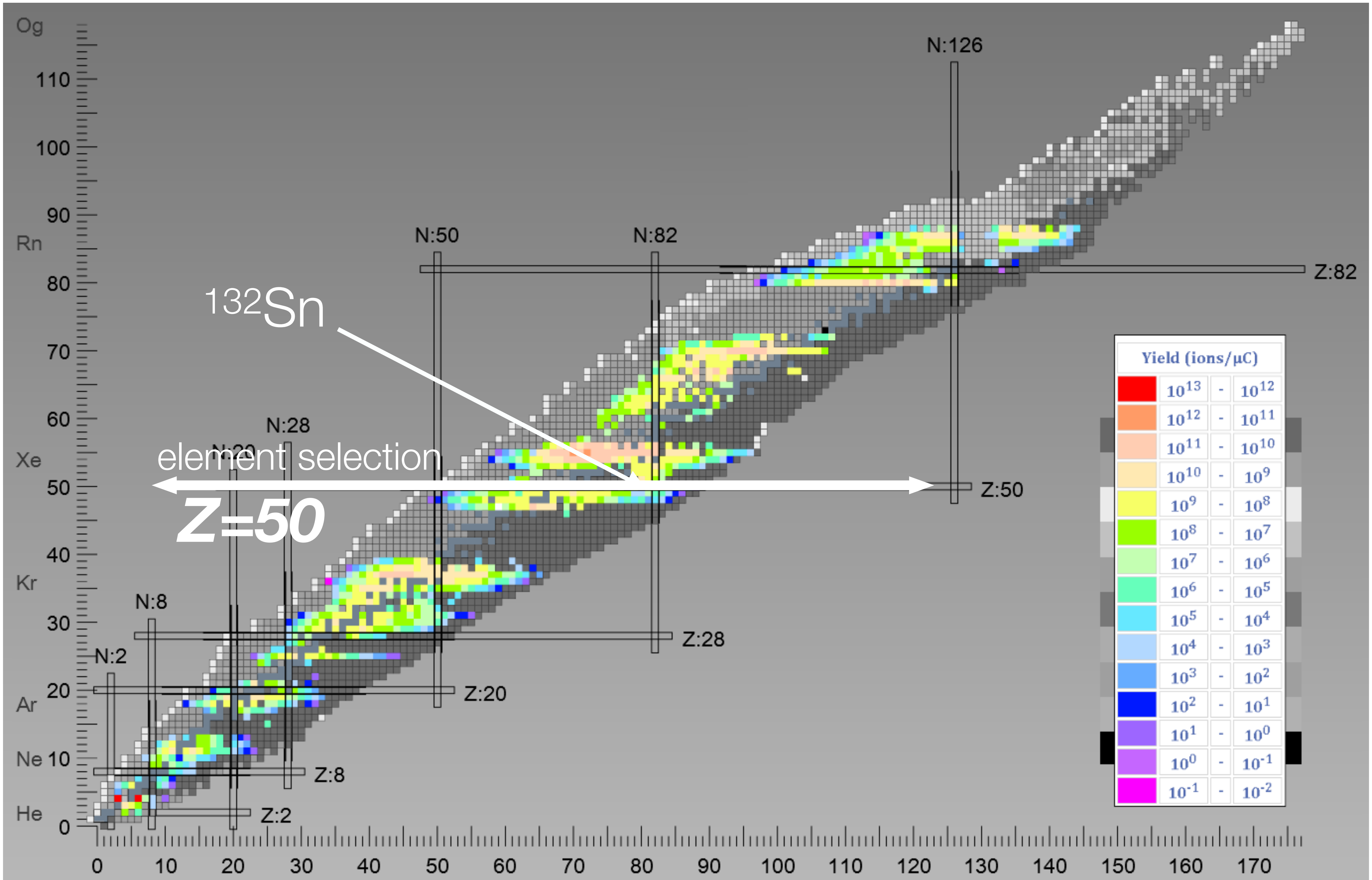
Highly-sensitive laser spectroscopy
for atomic and nuclear structure physics



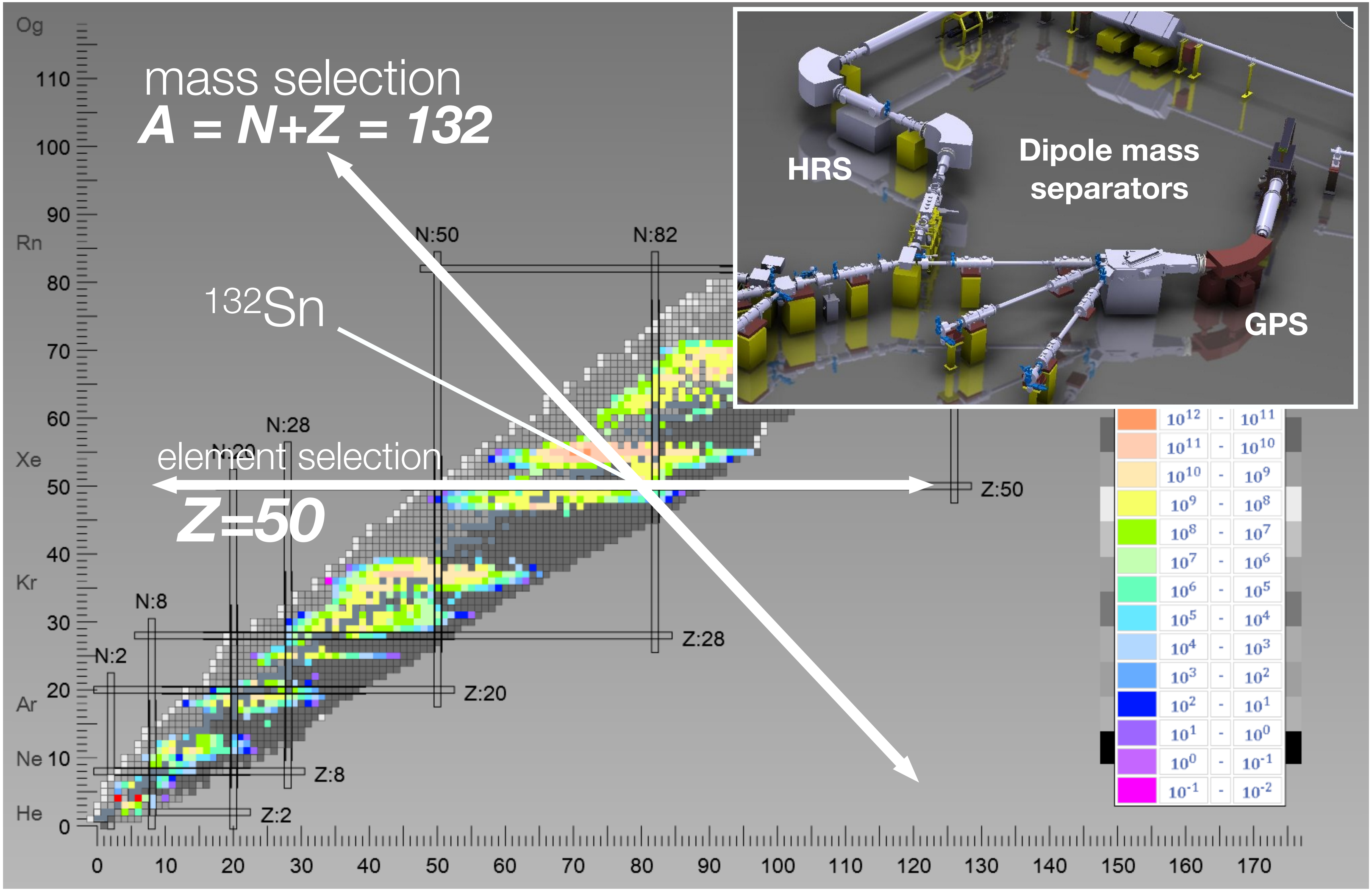
Producing isotope-pure beams



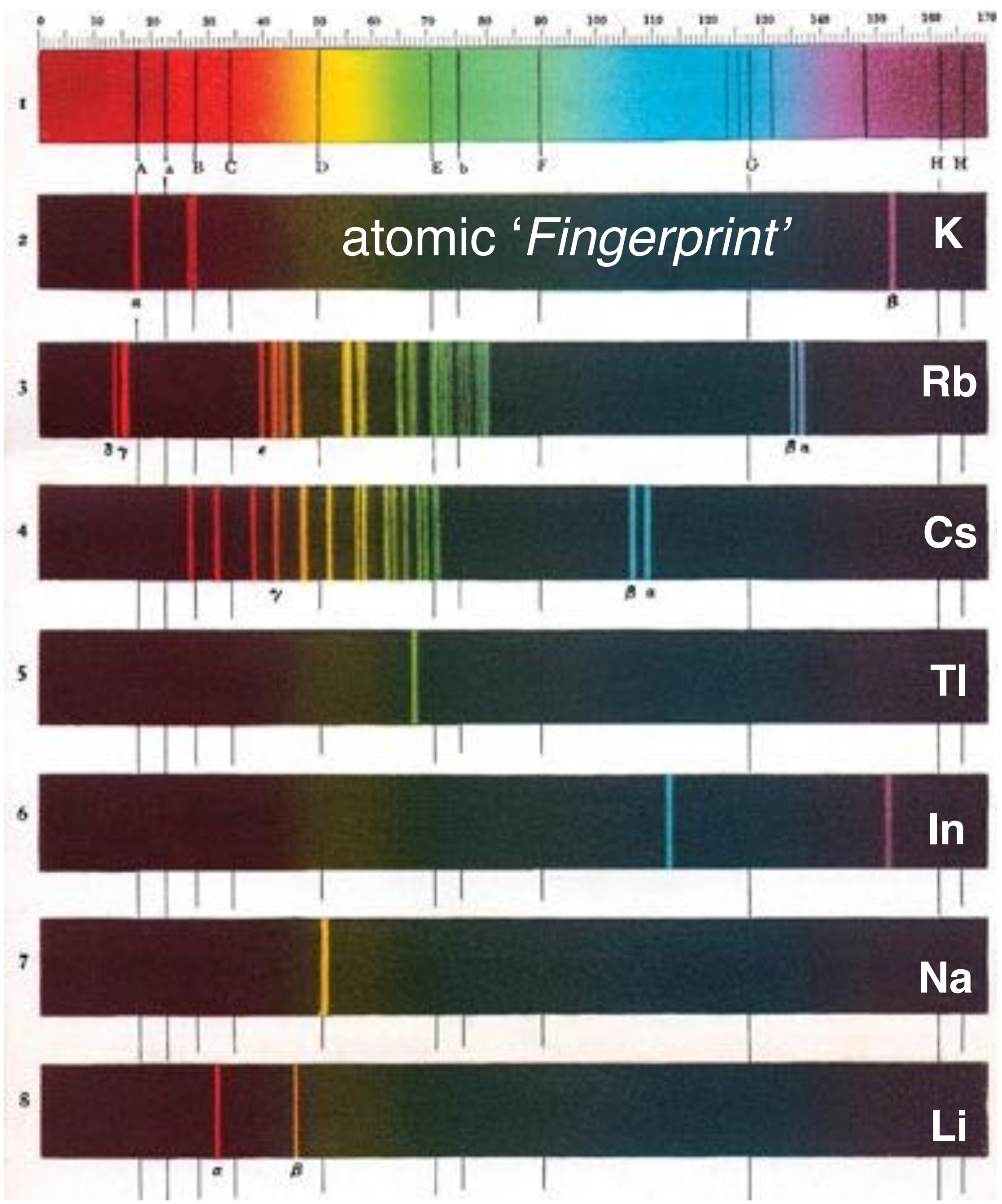
Producing isotope-pure beams

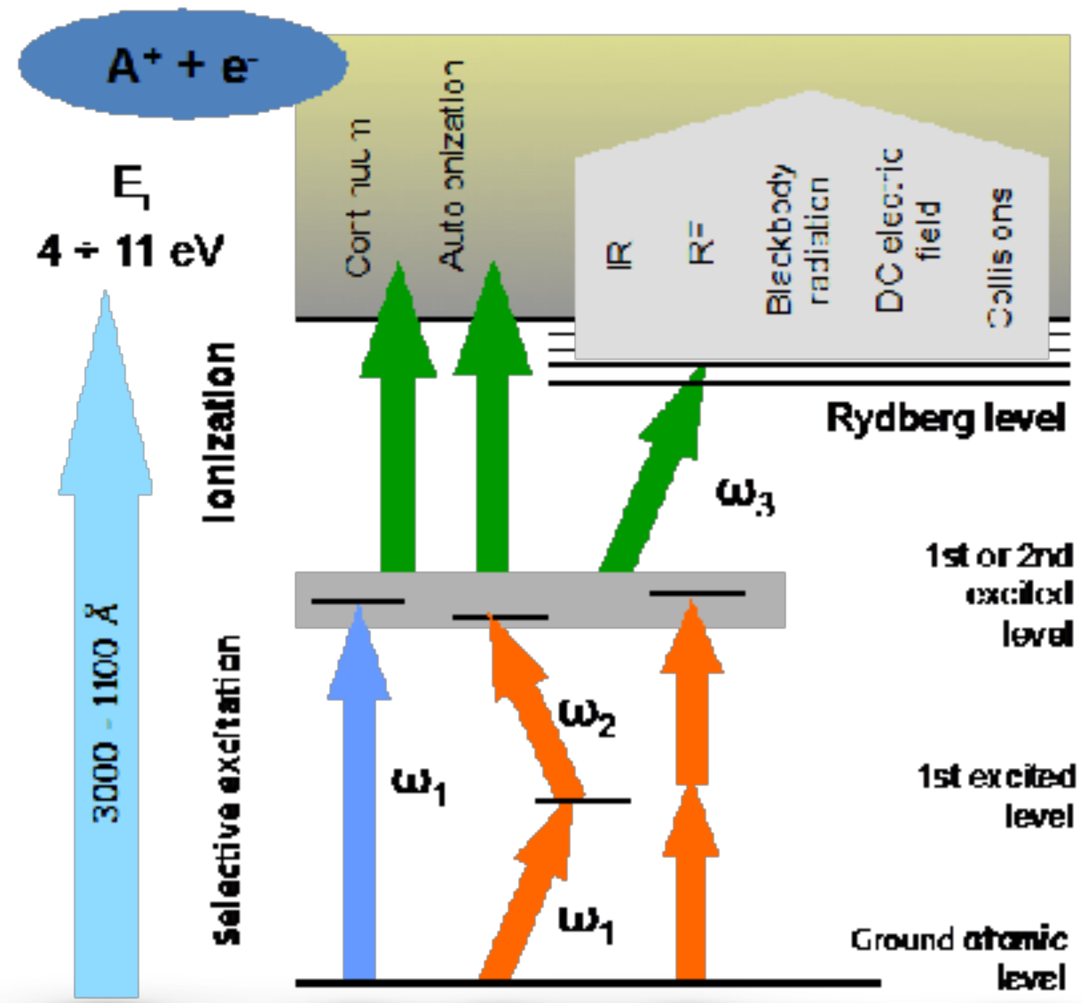


Producing isotope-pure beams

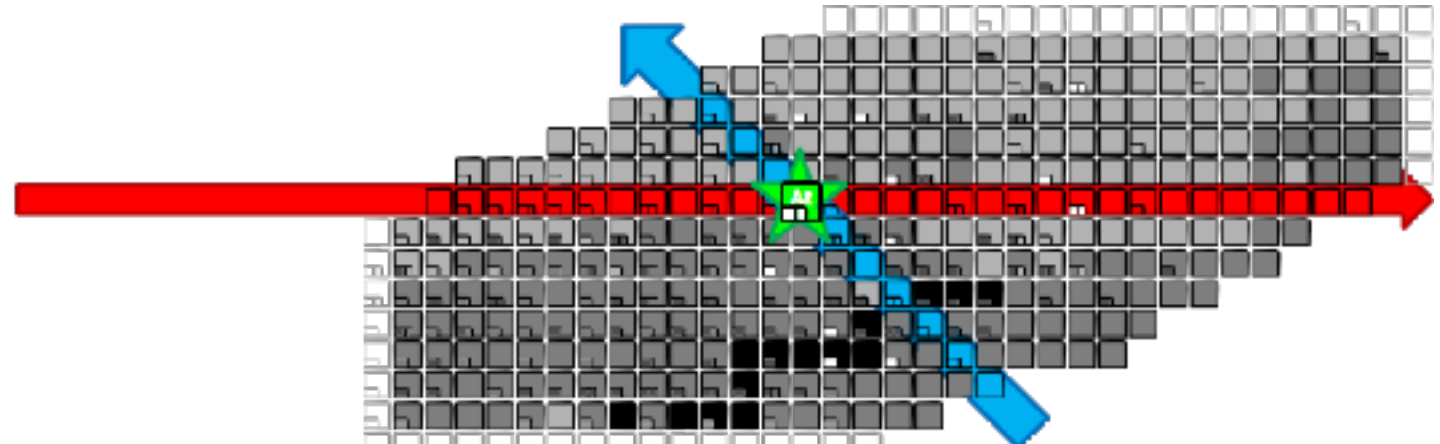


Element selection by Laser Resonance Ionisation

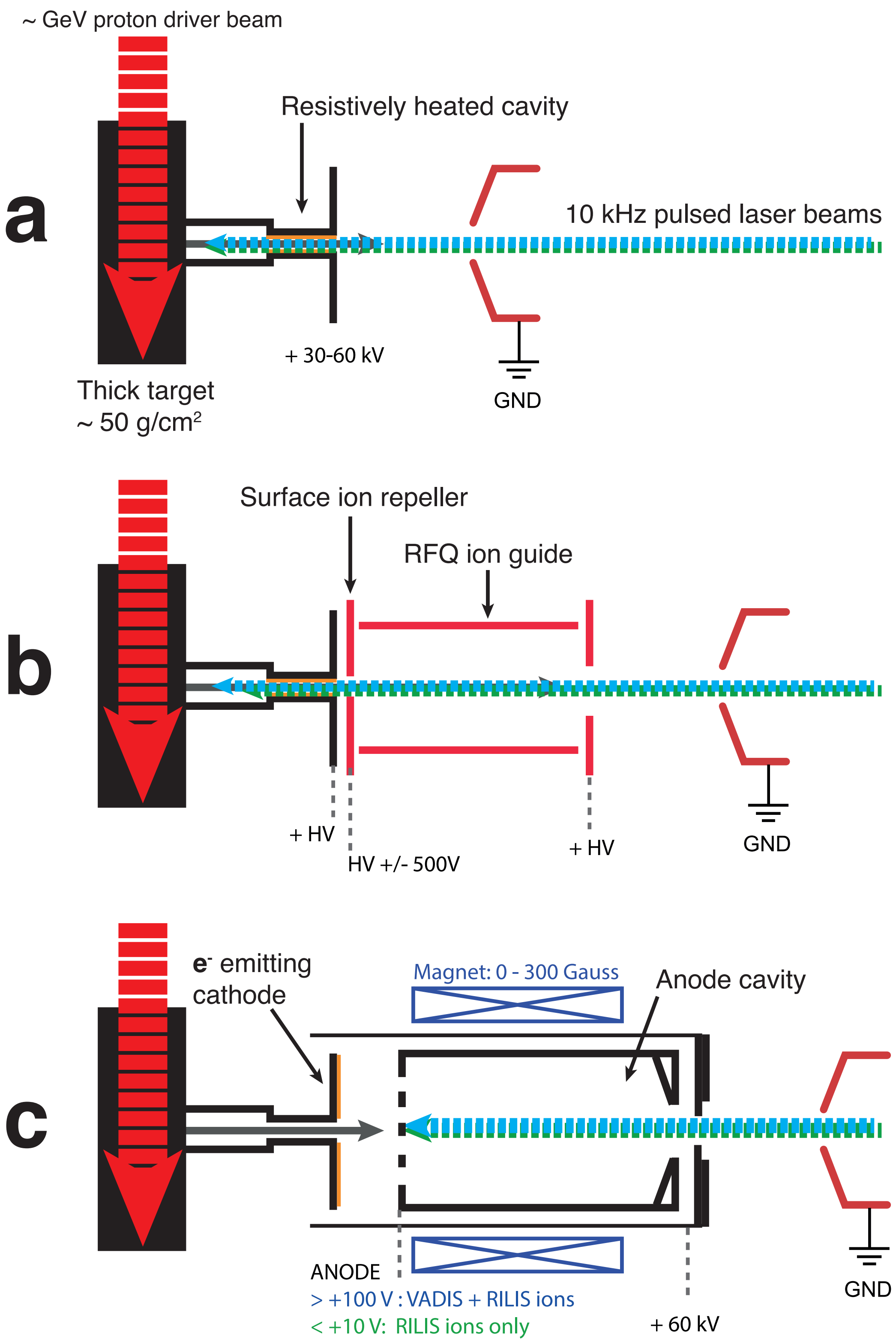




V. Mishin



Thick-target ISOL RILIS options



‘**STANDARD**’ RILIS

Hot Cavity Laser Ion Source

LIST (OR **IG-LIS**)

Laser Ion Source Trap

Ion-Guide Laser Ion Source

VADLIS

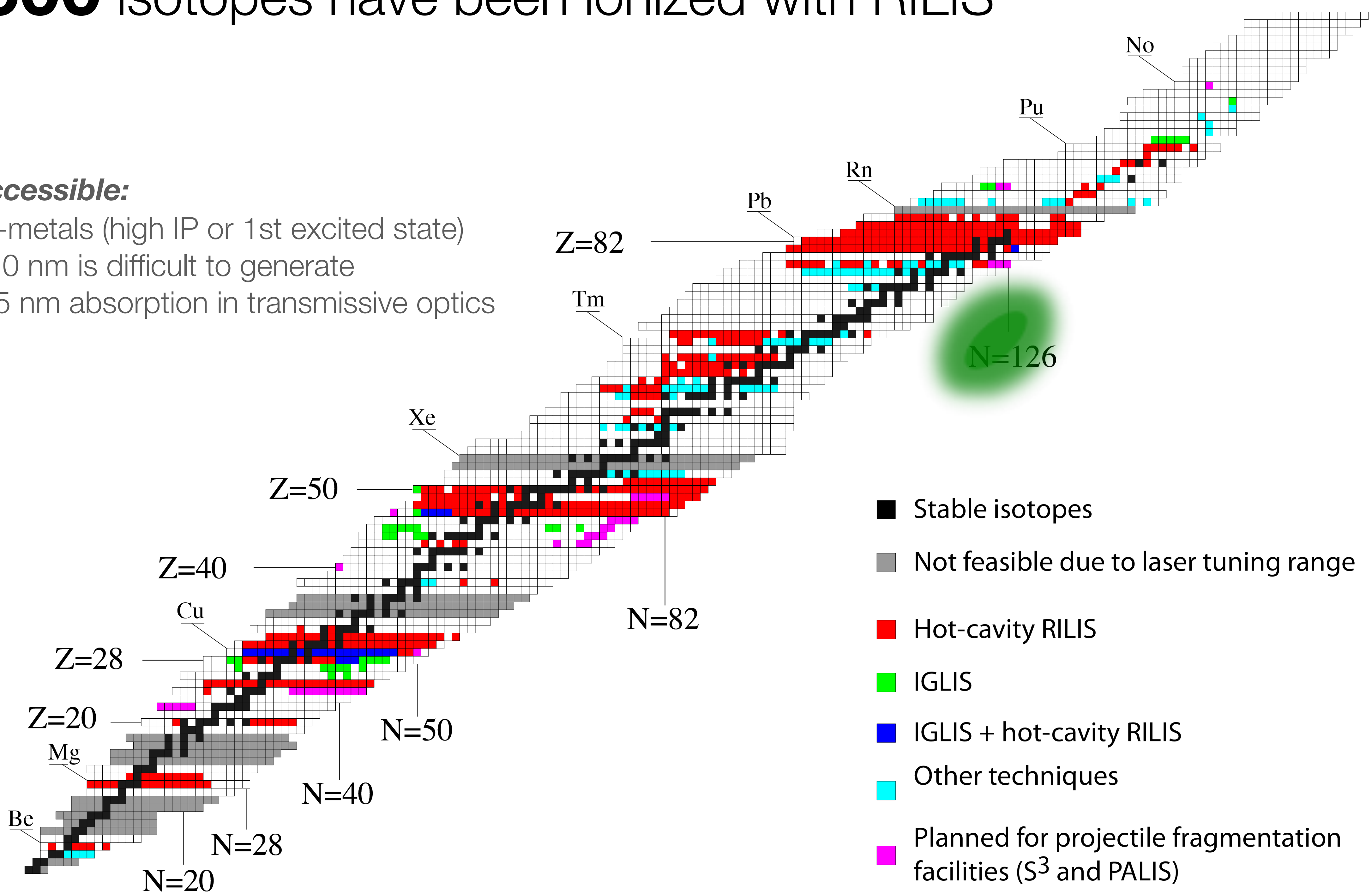
Versatile Arc Discharge and Laser Ion Source

Accessible isotopes

>600 isotopes have been ionized with RILIS

Inaccessible:

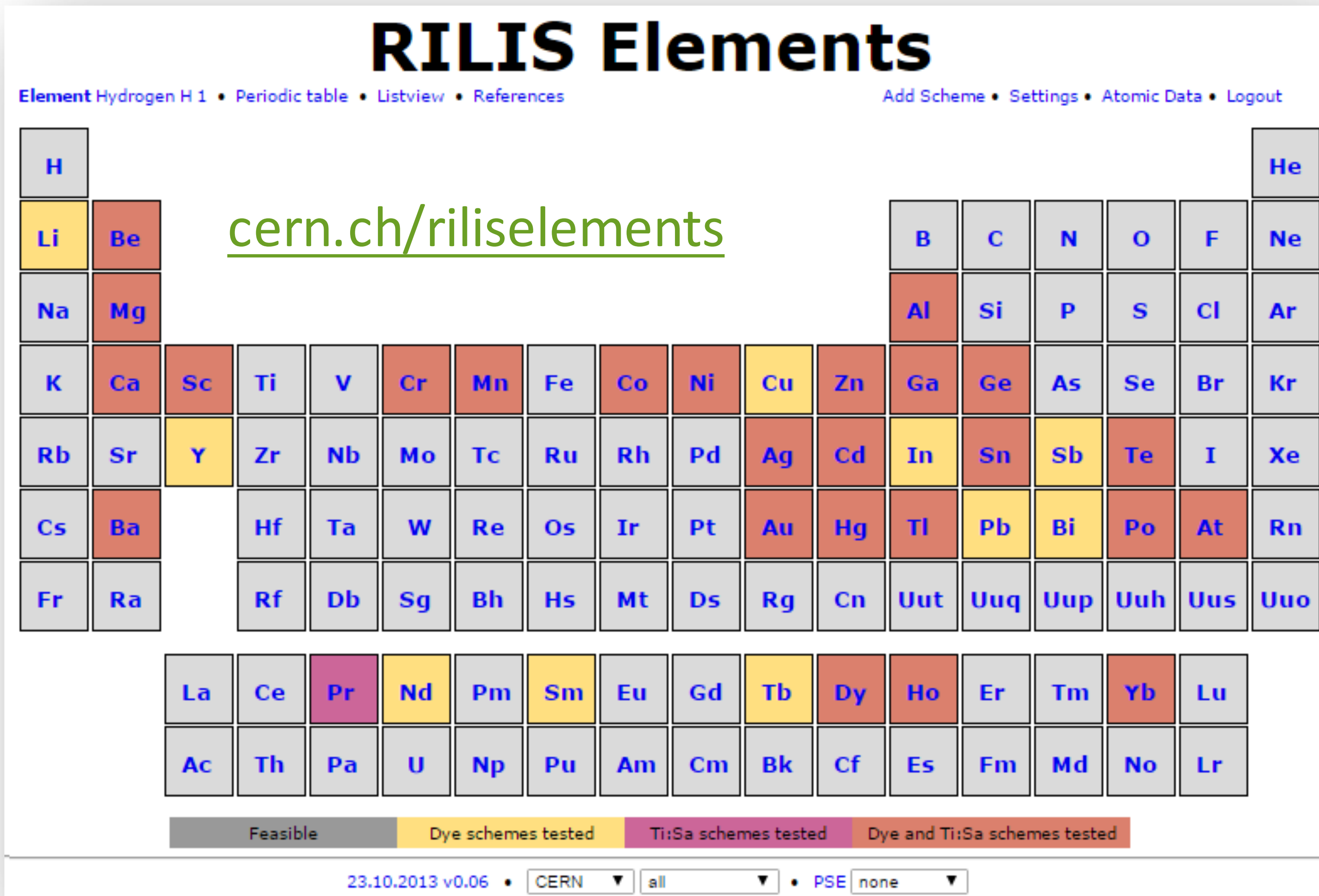
Non-metals (high IP or 1st excited state)
< 210 nm is difficult to generate
<205 nm absorption in transmissive optics



B. A. Marsh, Resonance ionization laser ion sources for on-line isotope separators

http://dx.doi.org/10.1063/1.4858015

Accessible elements



Every element requires dedicated atomic spectroscopy study to determine the optimal ionization pathway

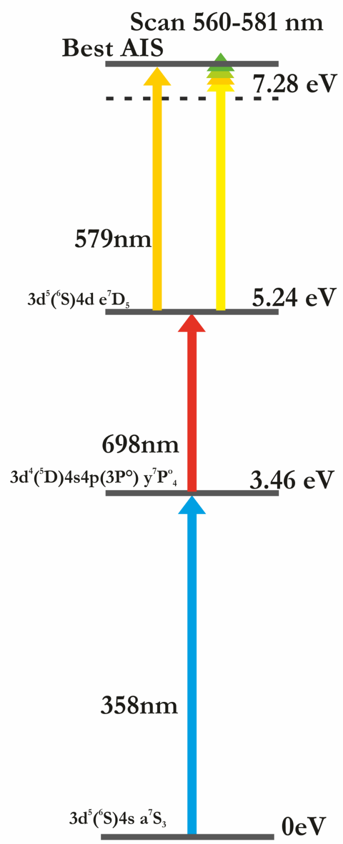
cern.ch/riliselements

40 elements have so far been laser ionized at CERN/ISOLDE

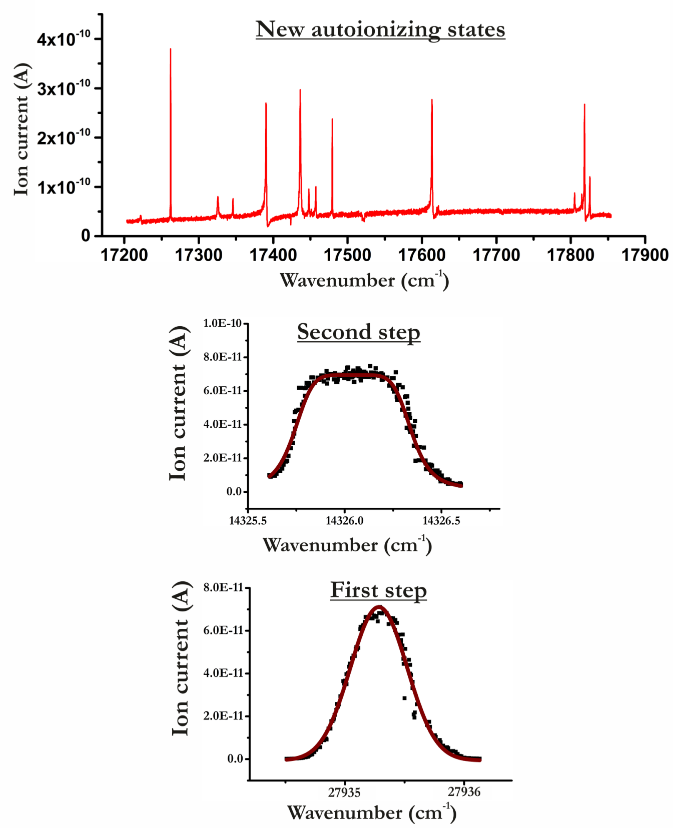
Useful 'new' on-line resource: http://grotrian.nsu.ru/en/

Ionization scheme development for **Ba, Ba^{2+}, Li, Cr, Ge** and **Hg**

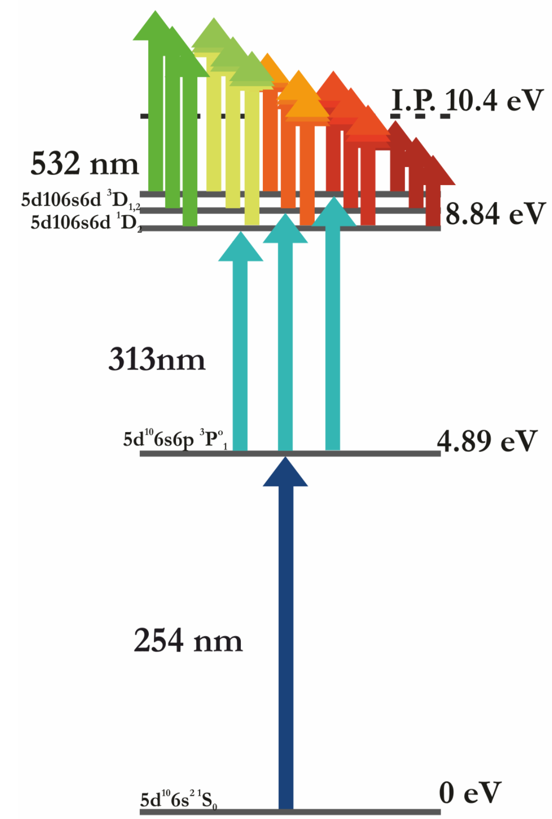
Cr scheme



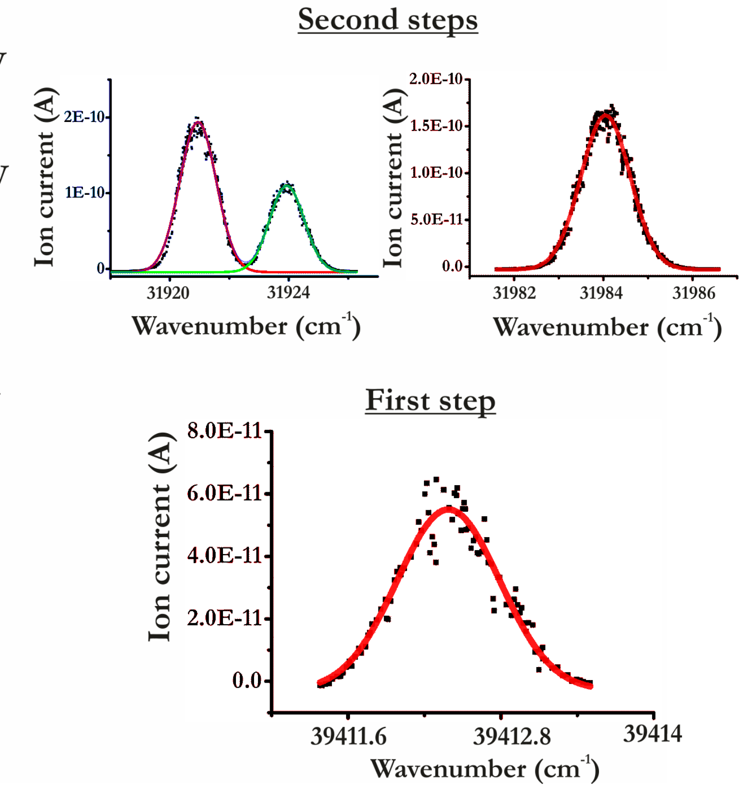
Cr laser scans



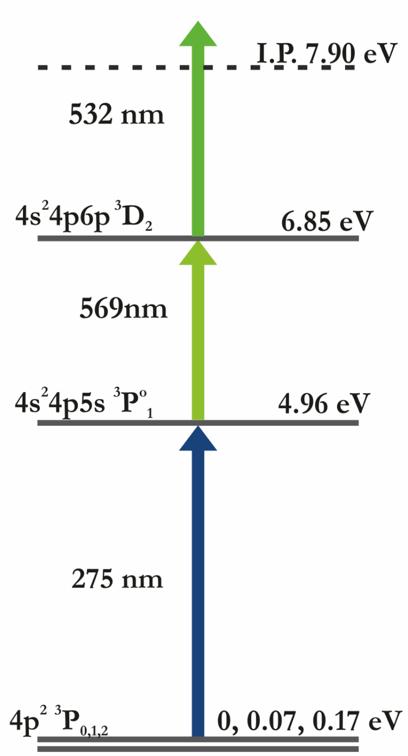
Hg scheme



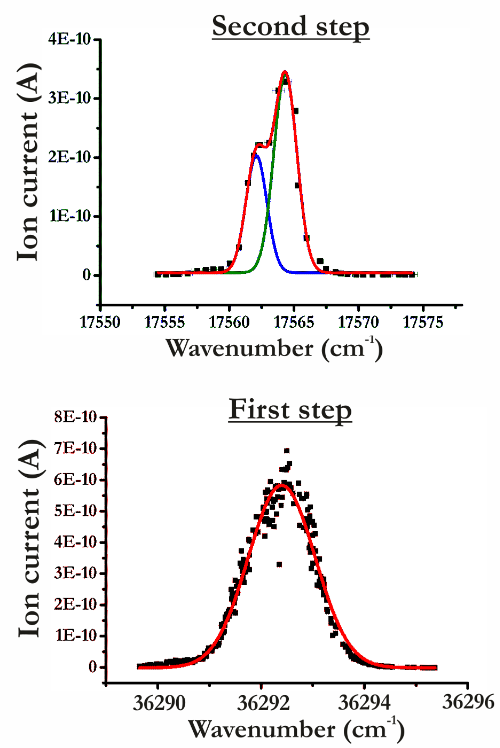
Hg laser scans

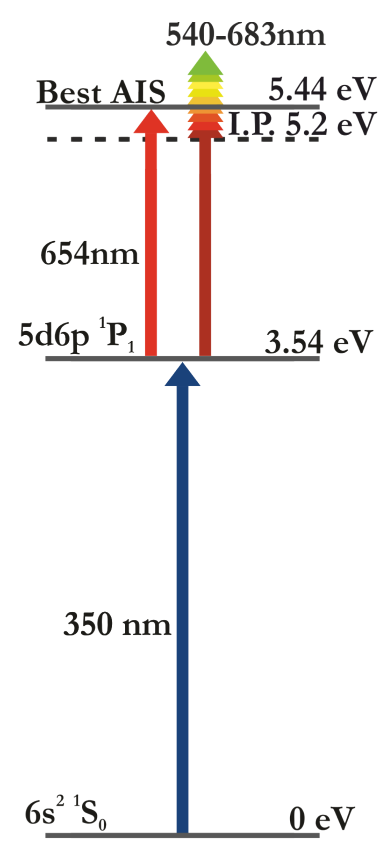


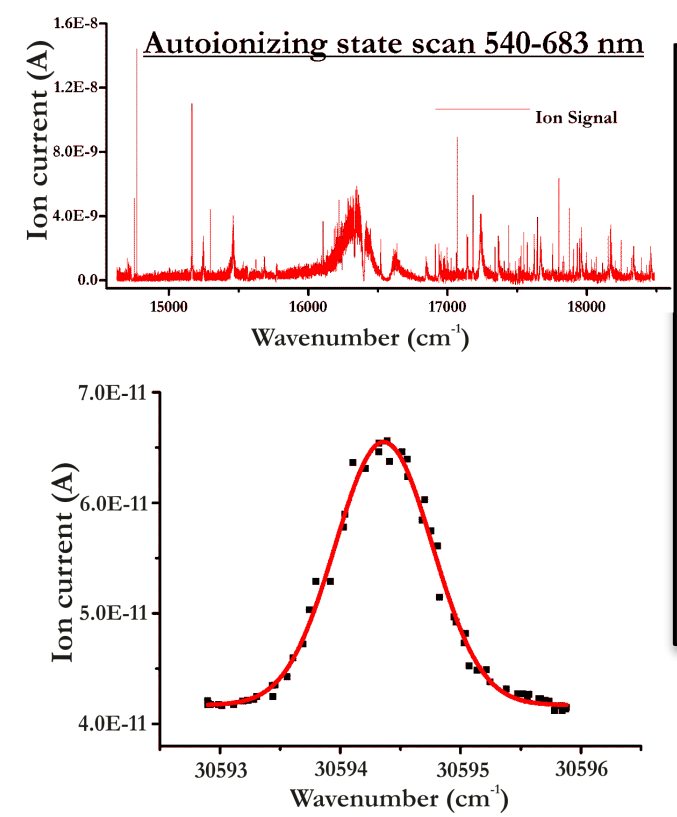
Ge scheme



Ge laser scans







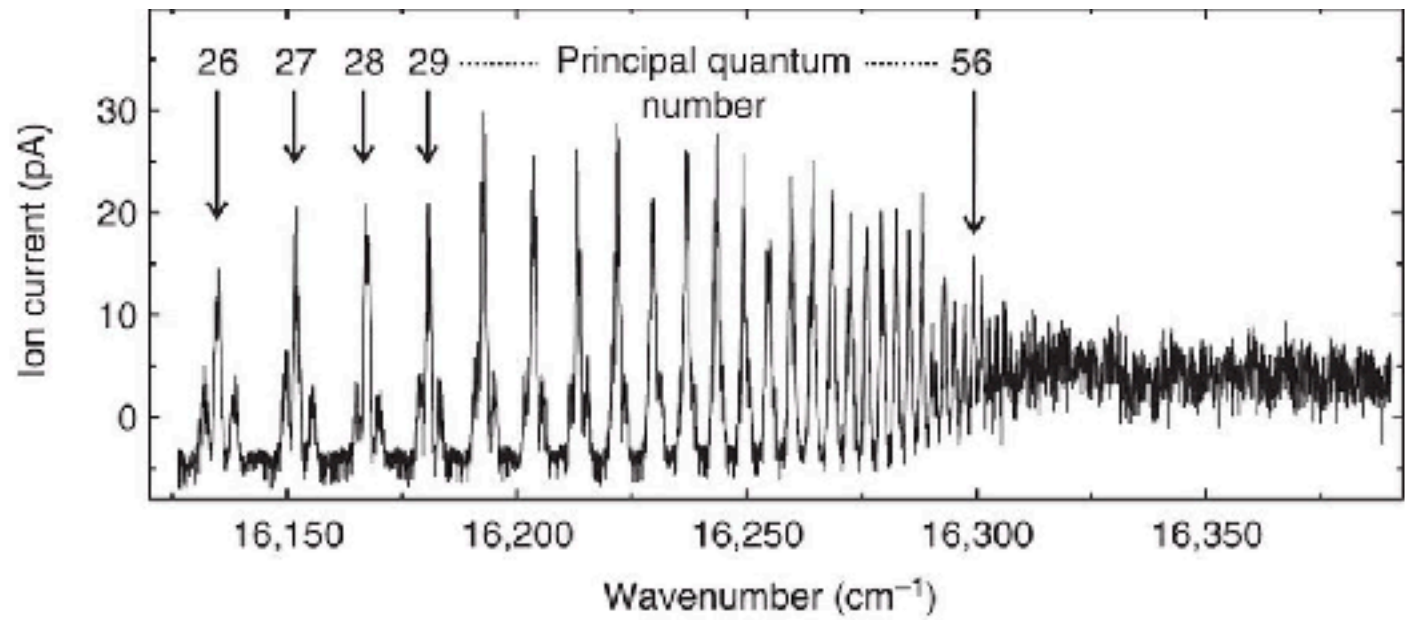
PhD work:

Tom Day Goodacre

Atomic physics results as a side-effect!

nature COMMUNICATIONS

IP (At) = 9.31751(8) eV



ARTICLE

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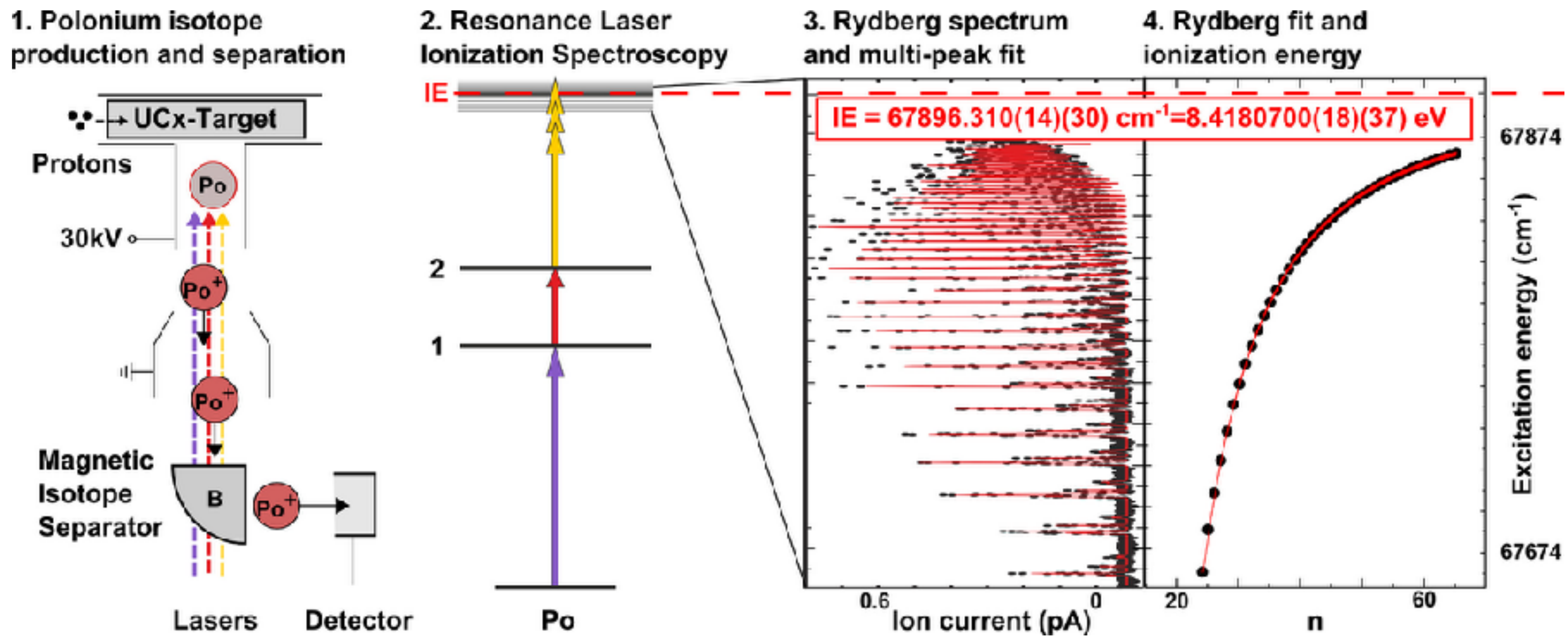
DOI: 10.1038/ncomms2819

OPEN

Measurement of the first ionization potential of astatine by laser ionization spectroscopy

S. Rothe[1,2], A.N. Andreyev[3,4,5,6], S. Antalic[7], A. Borschevsky[8,9], L. Capponi[4,5], T.E. Cocolios[1], H. De Witte[10], E. Eliav[11], D.V. Fedorov[12], V.N. Fedosseev[1], D.A. Fink[1,13], S. Fritzsche[14,15,†], L. Ghys[10,16], M. Huyse[10], N. Imai[1,17], U. Kaldor[11], Yuri Kudryavtsev[10], U. Köster[18], J.F.W. Lane[4,5], J. Lassen[19], V. Liberati[4,5], K.M. Lynch[1,20], B.A. Marsh[1], K. Nishio[6], D. Pauwels[16], V. Pershina[14], L. Popescu[16], T.J. Procter[20], D. Radulov[10], S. Raeder[2,19], M.M. Rajabali[10], E. Rapisarda[10], R.E. Rossel[2], K. Sandhu[4,5], M.D. Seliverstov[1,4,5,12,10], A.M. Sjödin[1], P. Van den Bergh[10], P. Van Duppen[10], M. Venhart[21], Y. Wakabayashi[6] & K.D.A. Wendt[2]

Atomic physics results as a side-effect!



Spectrochimica Acta Part B: Atomic Spectroscopy

Available online 28 August 2018

In Press, Corrected Proof

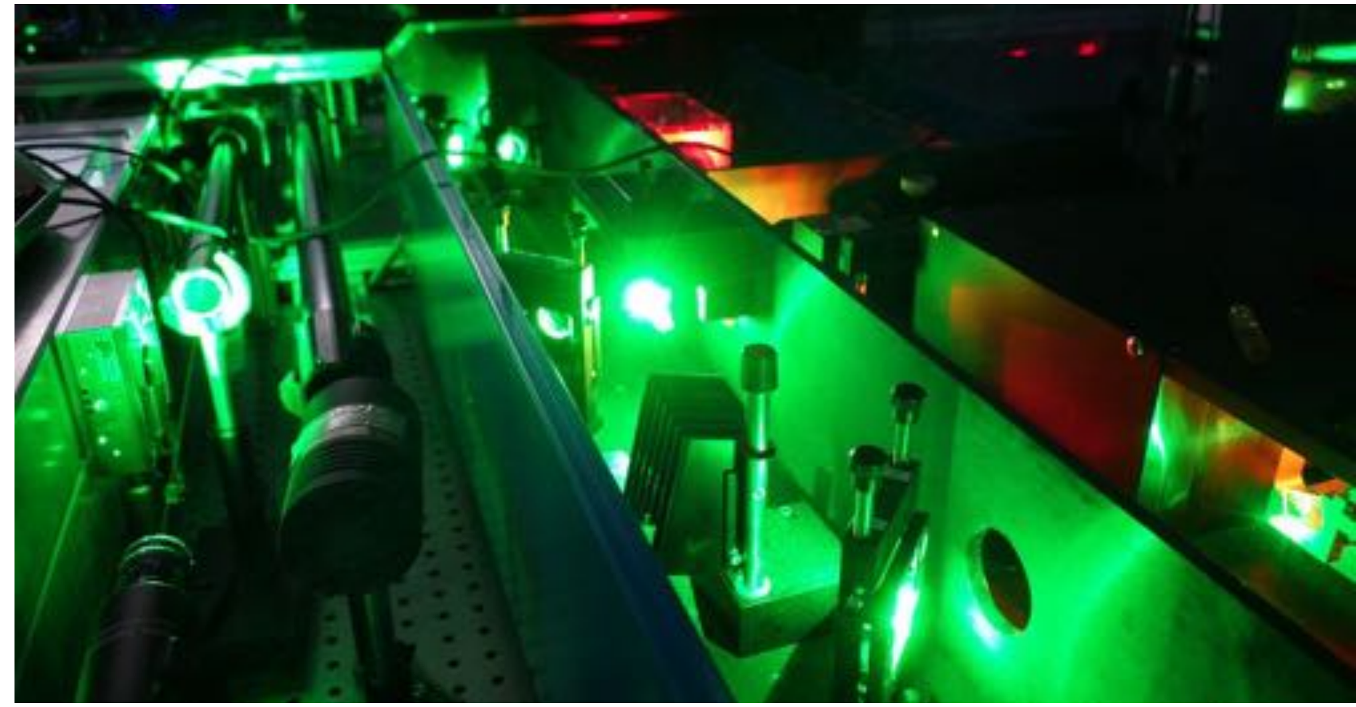
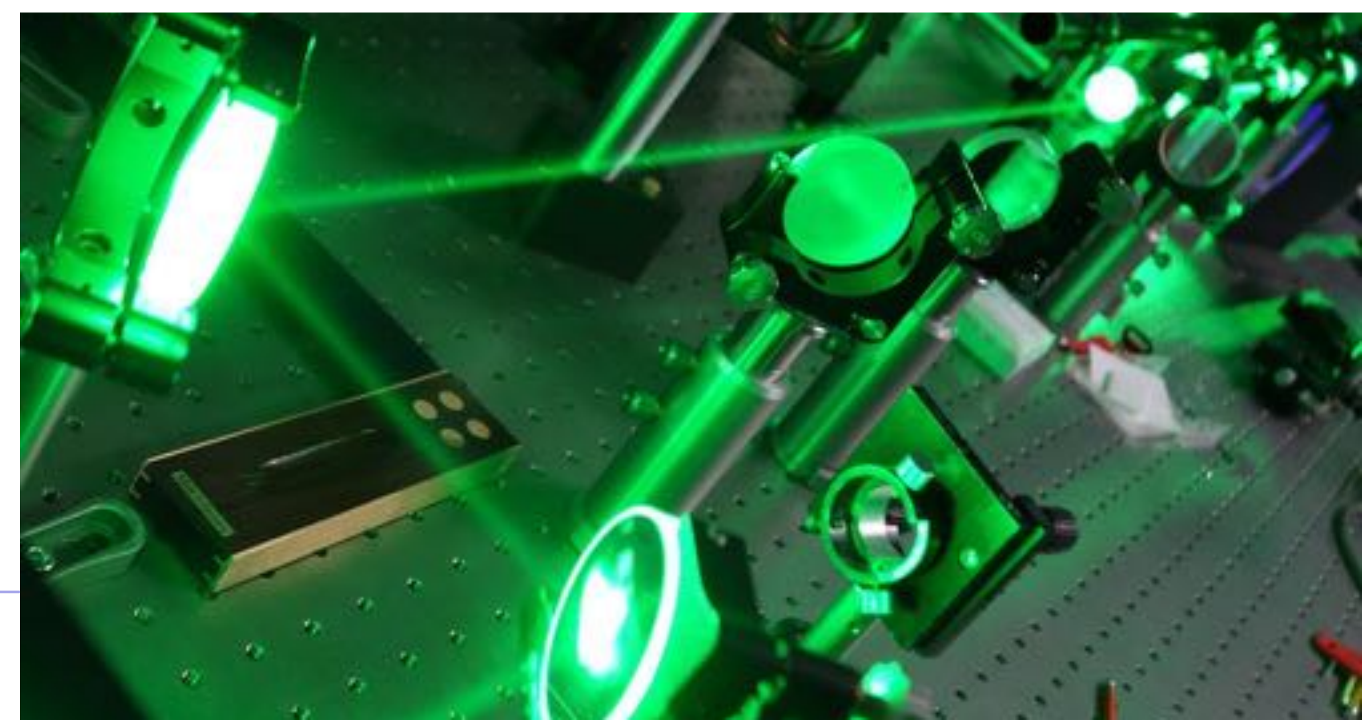
Determination of the first ionization energy of polonium by resonance ionization spectroscopy – Part II: Measurement of odd-parity Rydberg states at CERN–ISOLDE

D.A. Fink [a] [1, 2], K. Blaum [b], V.N. Fedosseev [a], B.A. Marsh [a], R.E. Rossel [a], S. Rothe [a]

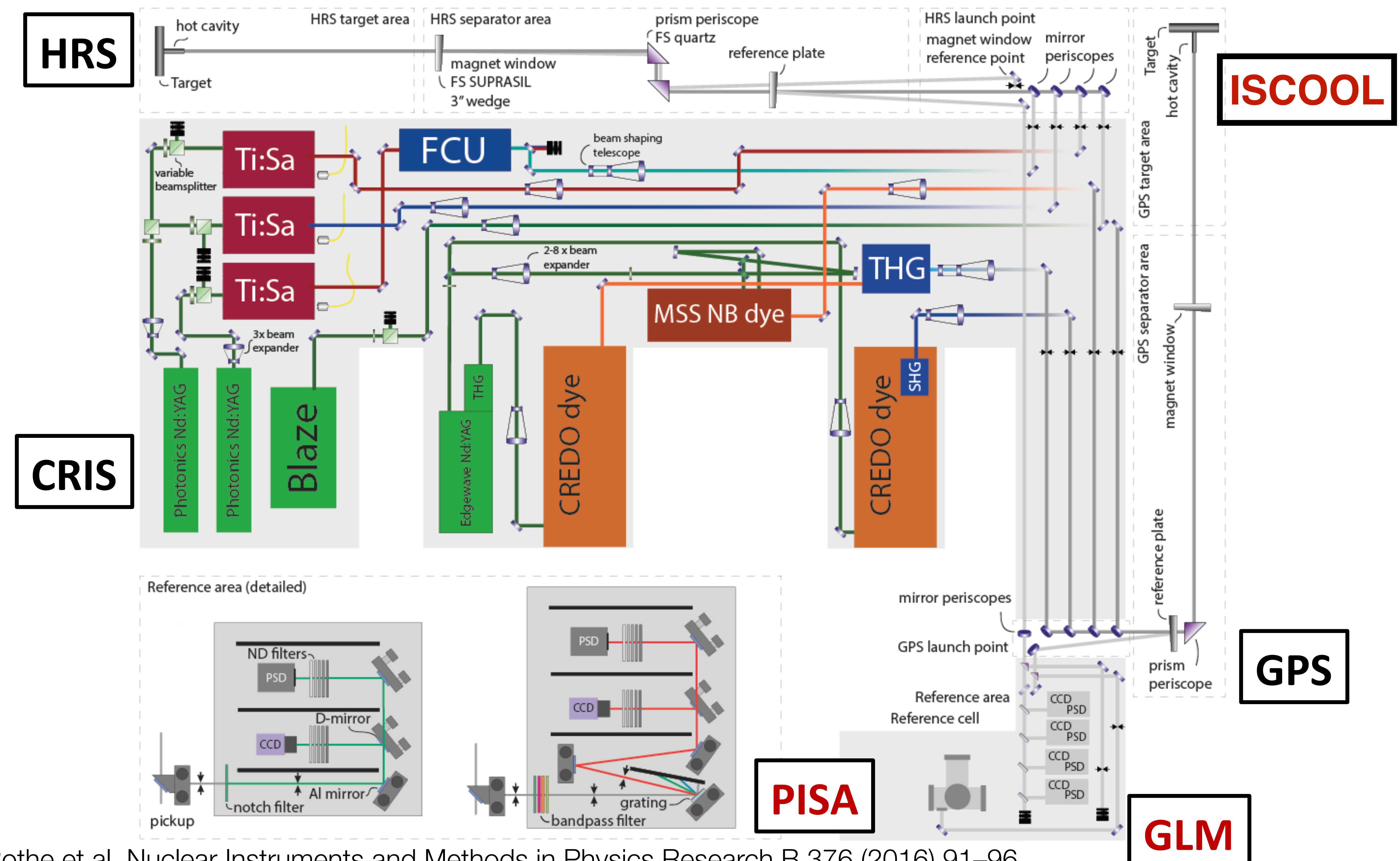
Show more

https://doi.org/10.1016/j.sab.2018.08.004


TiSa 2

ISOLDE RILIS setup - detailed

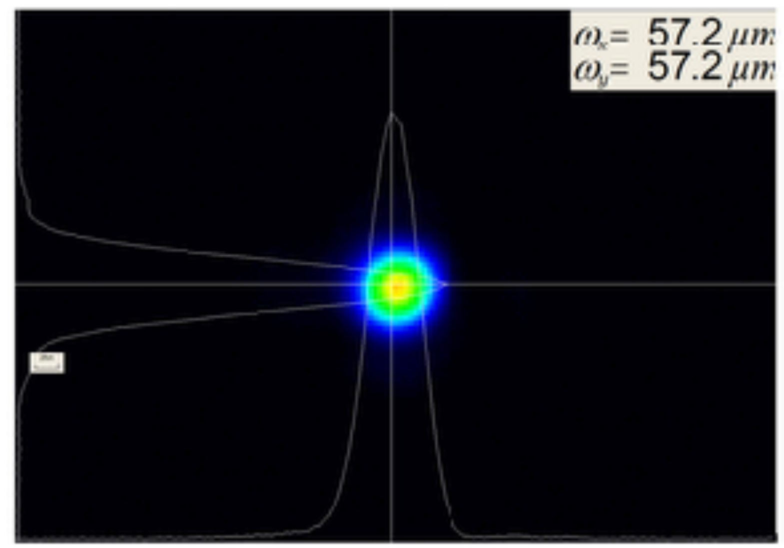


S. Rothe et al. Nuclear Instruments and Methods in Physics Research B 376 (2016) 91–96

Dye pump laser

The first RILIS DPSS system is now almost 10 years old!

10 kHz (9 ns), 100 W @ 532 nm



TEM 00

$M^2 = 1.1$

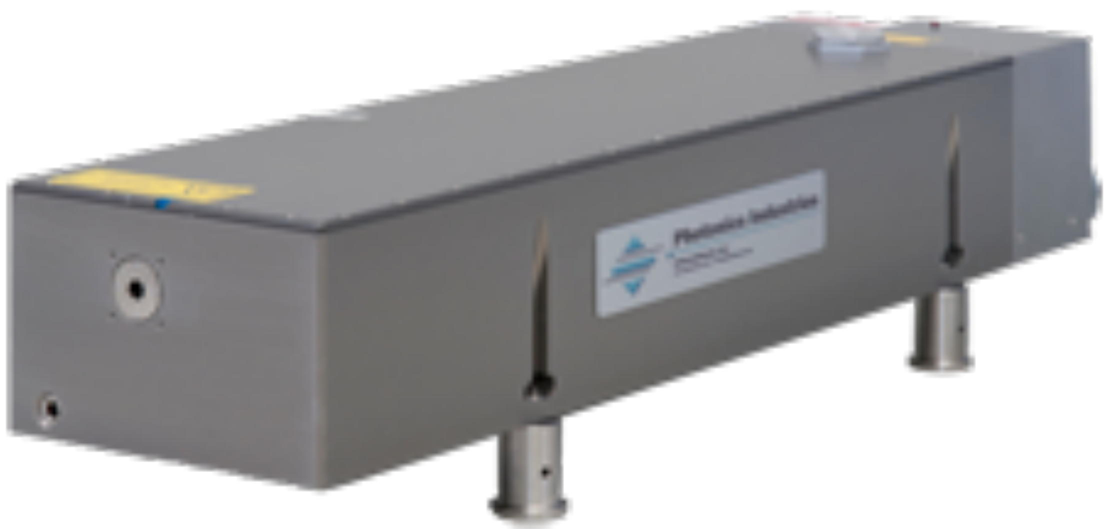
Circular, gaussian beam

- Simple operation; better dye laser efficiency and beam quality
- Easier to transmit the beam to the ion source
- Objective assessment of degradation of beam quality
- Better compatibility with commercial dye lasers

Photonics Industries
International, Inc.

Compact **60 W** Ti:Sa pump lasers

CERN



2 lasers in use

1 spare

Smallest footprint on the market for 60 W @ 10 kHz

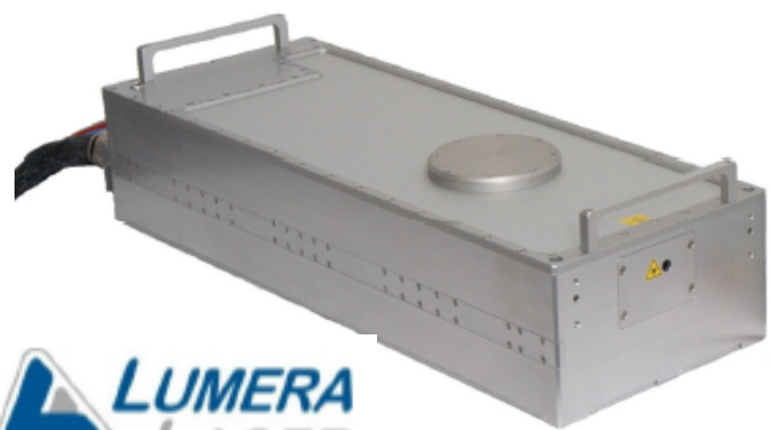
M^2 > 10 (Lower damage risk for Z-resonator TiSa pumping)

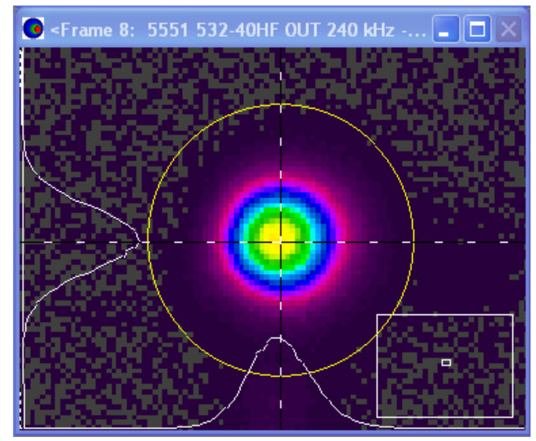
t_{pulse} ~ 150 ns (not suitable for dye laser pumping)

1 independent, low-jitter triggered pump laser
per TiSa facilitates pulse timing synchronization

COHERENT

Blaze laser for non-resonant ionisation

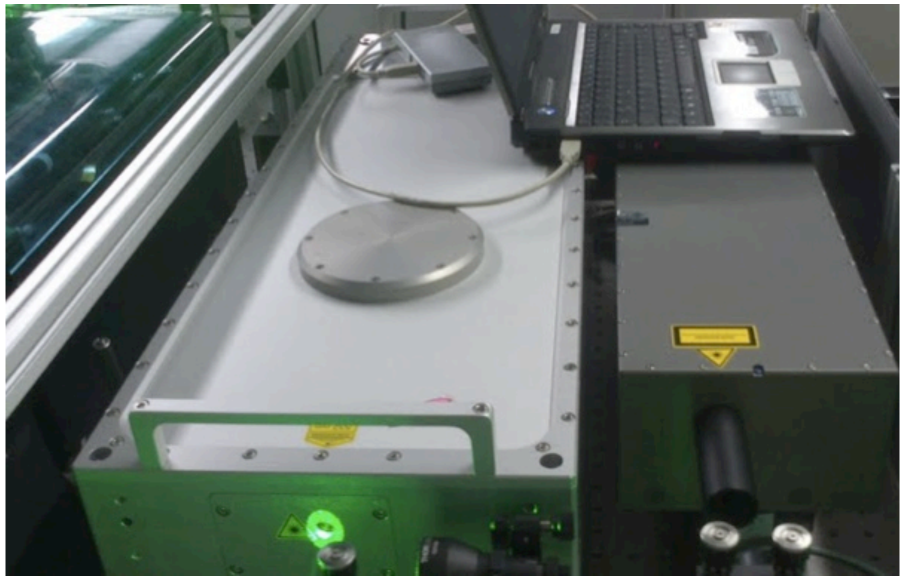




No longer available to buy

Independent laser for non resonant ionization
2/3 of RILIS schemes benefit

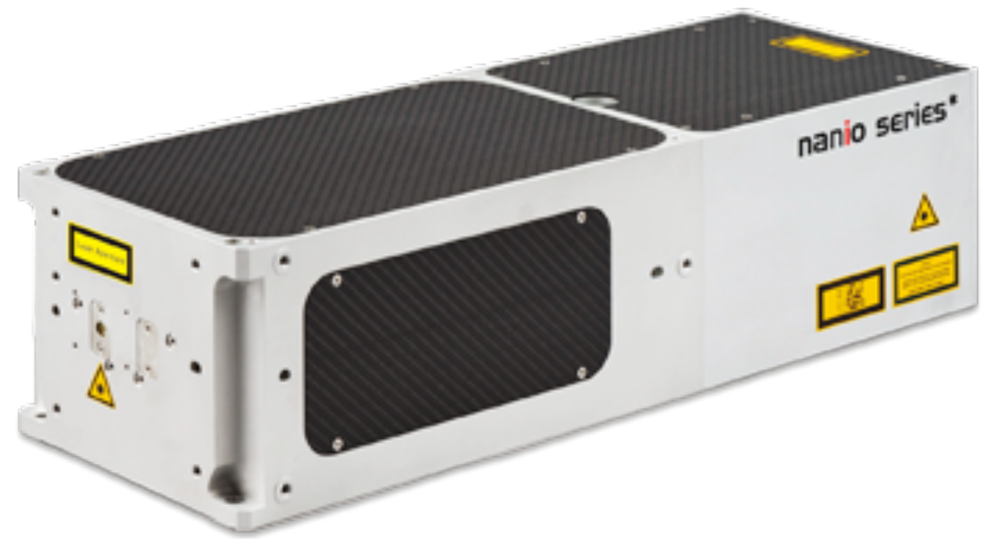
- 40W at 10 kHz
- 17ns Pulse
- Low Jitter
- Gaussian beam
- Much better transmission to source
- can be used for Dye and Ti:Sa pumping



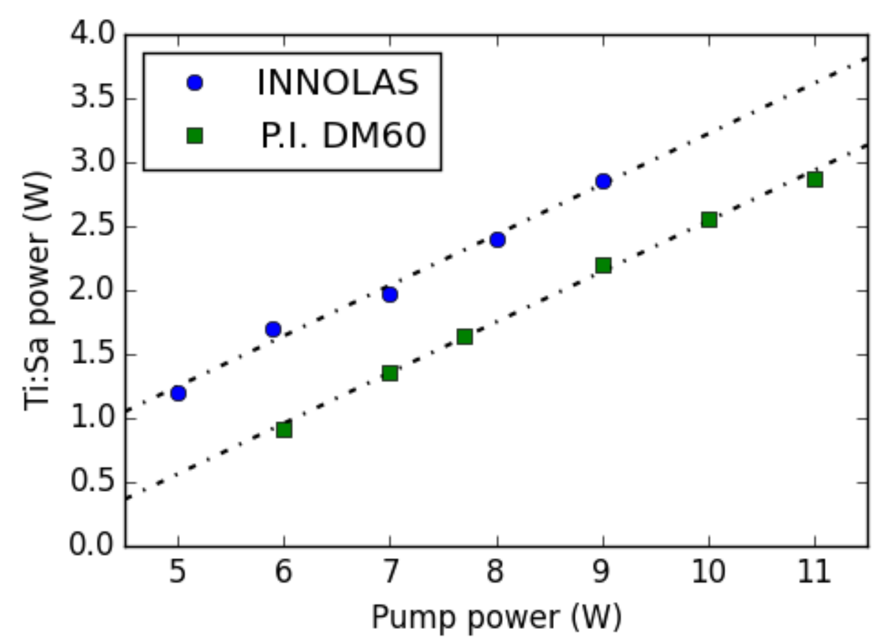
B. Marsh et al., *CERN-ATS-Note-2013-007 TECH*

Multi-purpose pump laser

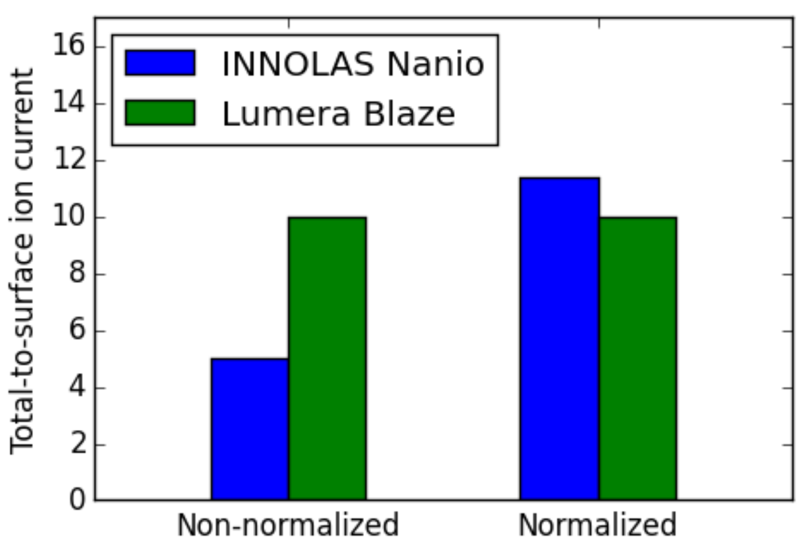
- New DPSS laser **Innolas Nanio** for Ti:Sa pumping and other applications
  - TEMoo – mode
  - 18W outpout @ 10kHz pulse rate, 30ns pulse length
- Simpler cooling mechanism → decreased risk for chiller failures
- Proposed laser for CERN-MEDICIS (Tender underway)



Ti:Sapphire pumping test:
Increased efficiency:
lasing at <5W pump power

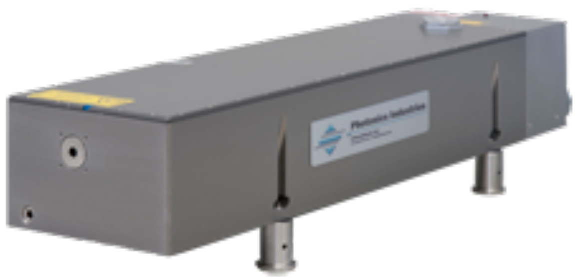


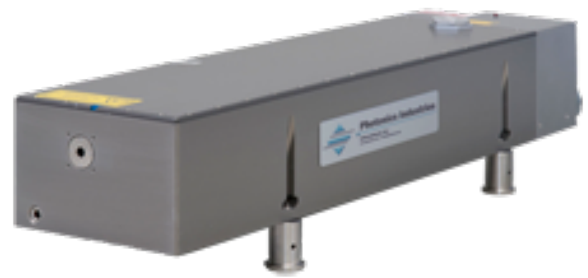
Non-resonant ionization test:



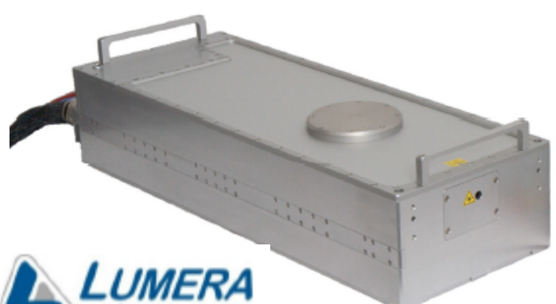
Demonstrated to be effective for non-resonant ionization

Prerequisite for ~3000 h operation / year:
Laser redundancy / reliability

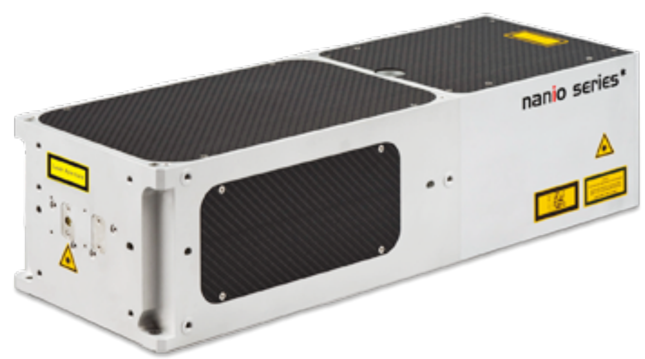




Just repaired

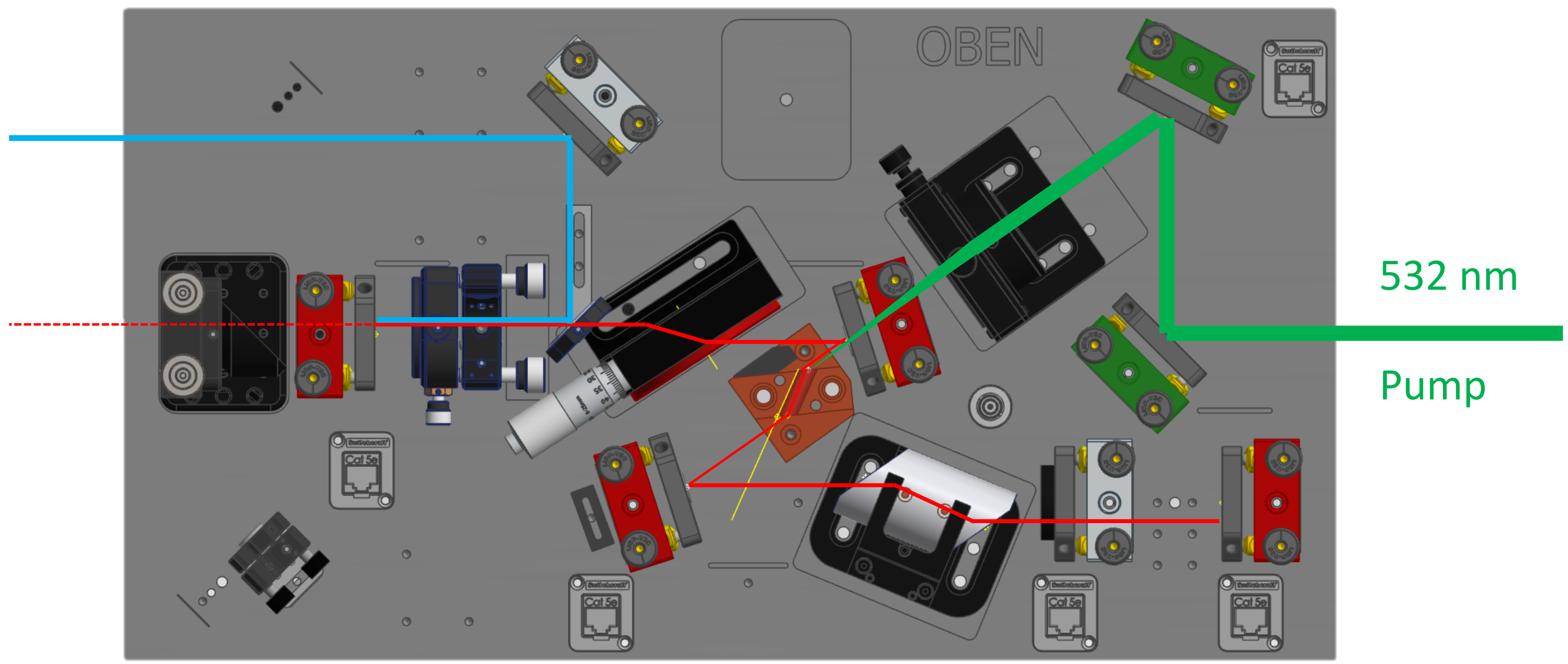


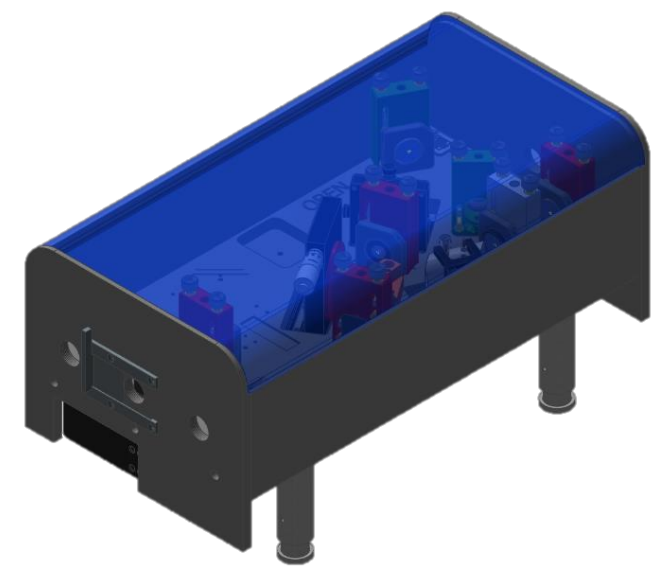
LUMERA LASER



Purchased in 2017/8

New Tisa cavities from Mainz / LARISSA





Improved alignment system
Smaller footprint
Easier change between
fundamental, 2w, dual etalon etc modes

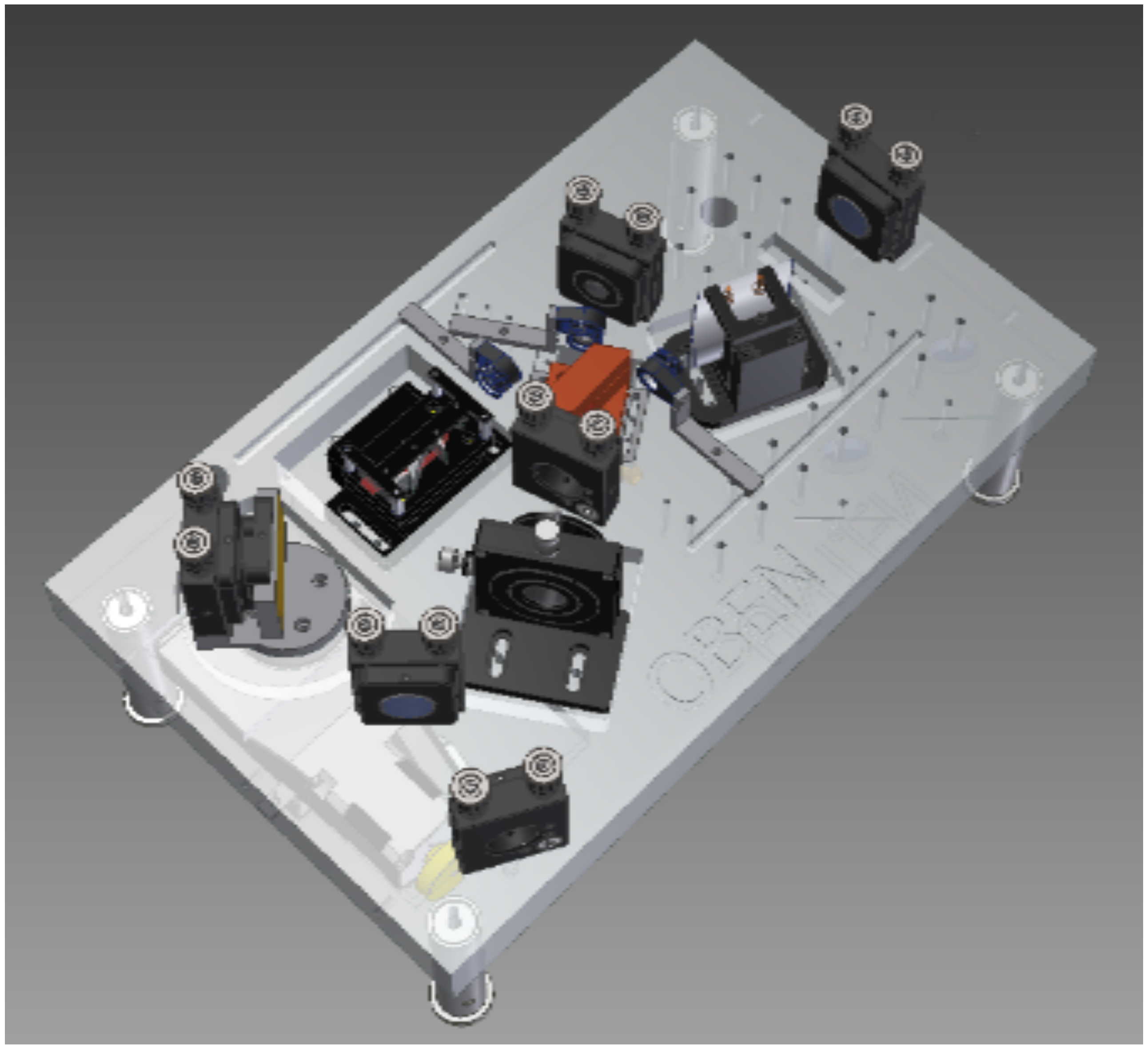
Dr Tobias Kron

JG|U LARISSA
JOHANNES GUTENBERG-UNIVERSITÄT MAINZ

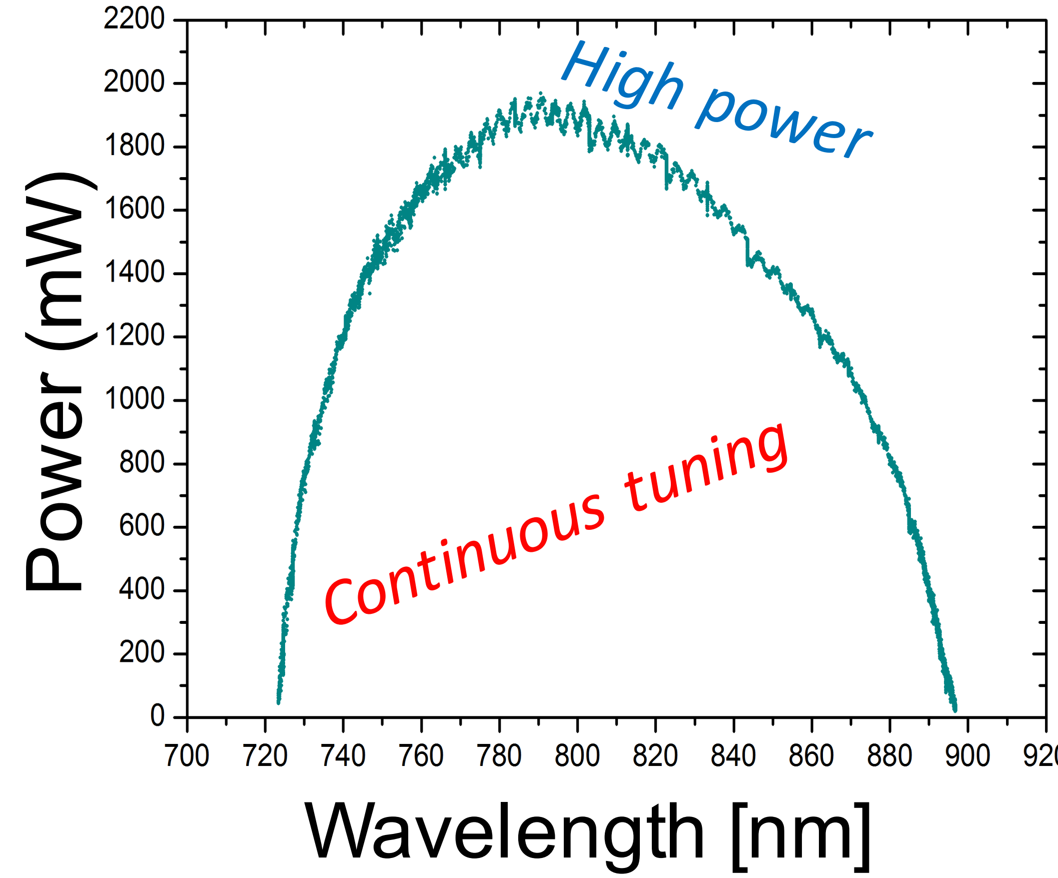
New addition:
Closed-loop piezo-actuated etalons

SmarAct
PERFECT MOTION

Grating-TiSa for broad-range atomic spectroscopy



P. Naubereit, master thesis, Nov. 2014, JGU Mainz

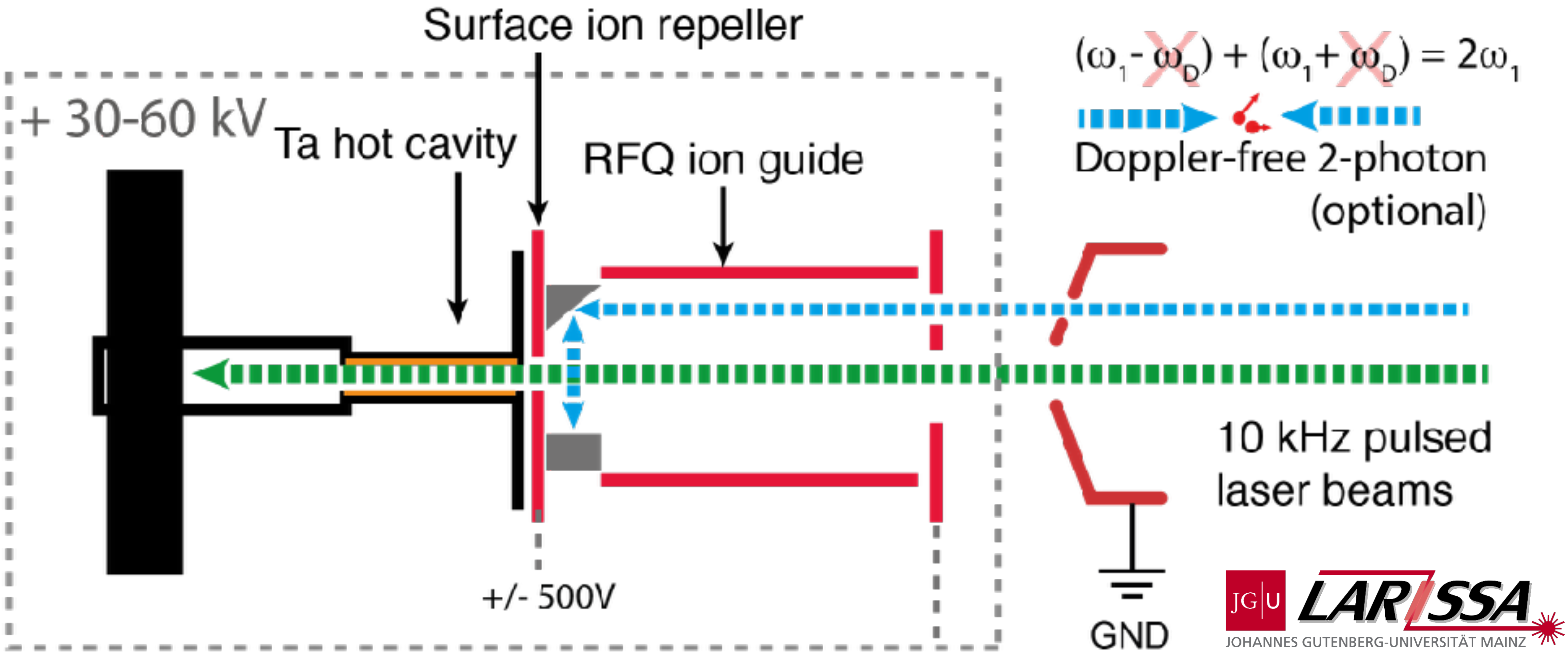


Now capable of scanning in narrow-band mode and in the blue range (with intra-cavity frequency doubling

Thanks to
Katerina Chrysalidis and
Felix Weber

JOHANNES GUTENBERG-UNIVERSITÄT MAINZ

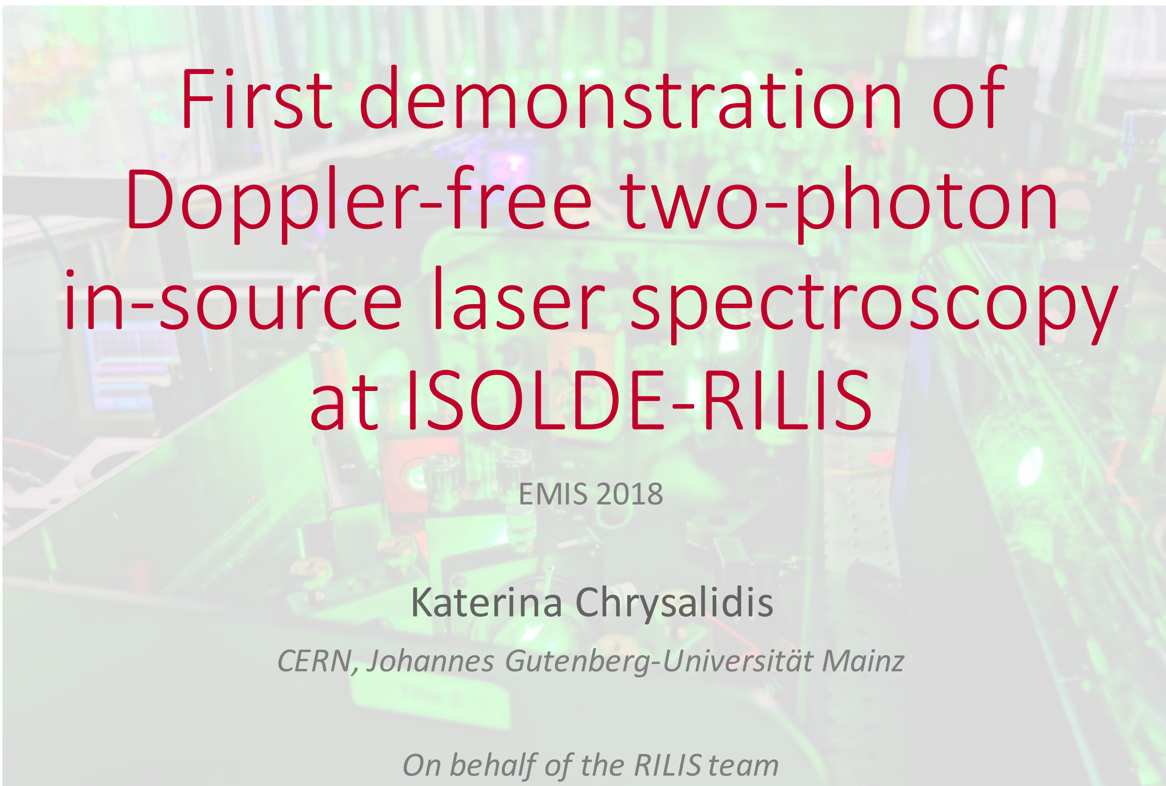
Towards 'high-resolution' spectroscopy

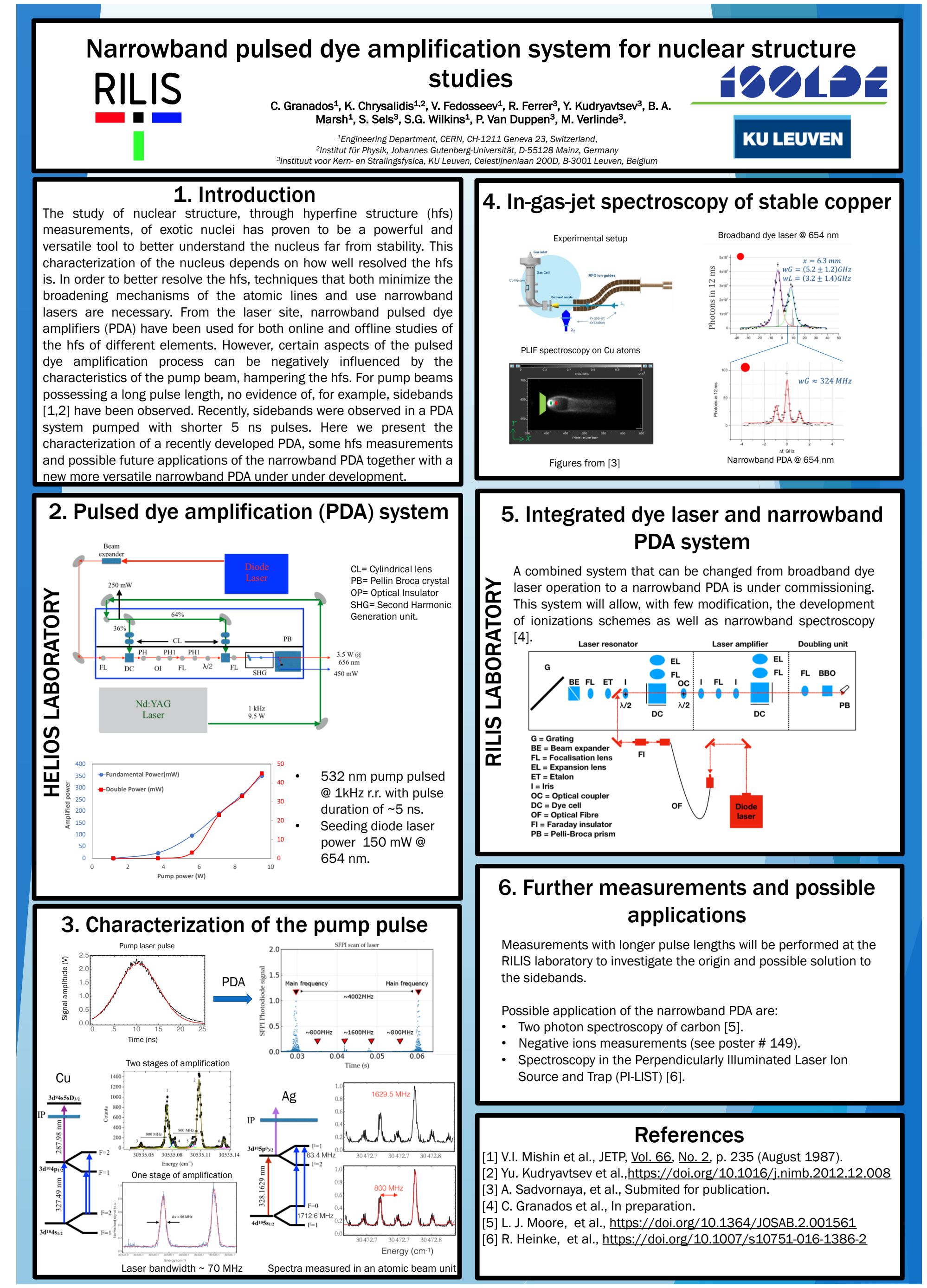


RILIS lasers with Fourier-limited Linewidth

Injection-seeded Ti:Sapphire laser cavity

Pulsed dye amplifier





97. An injection-locked Titanium:Sapphire laser system for a high-resolution resonance ionization spectroscopy.
Dr Mikael Reponen (University of Jyväskylä)

31. Development of new Ti:sapphire based laser sources for selective ionization and spectroscopy applications
Dr Volker Sonnenschein (University of Nagoya)

Standard 'Hot-Cavity' RILIS

Laser requirements:

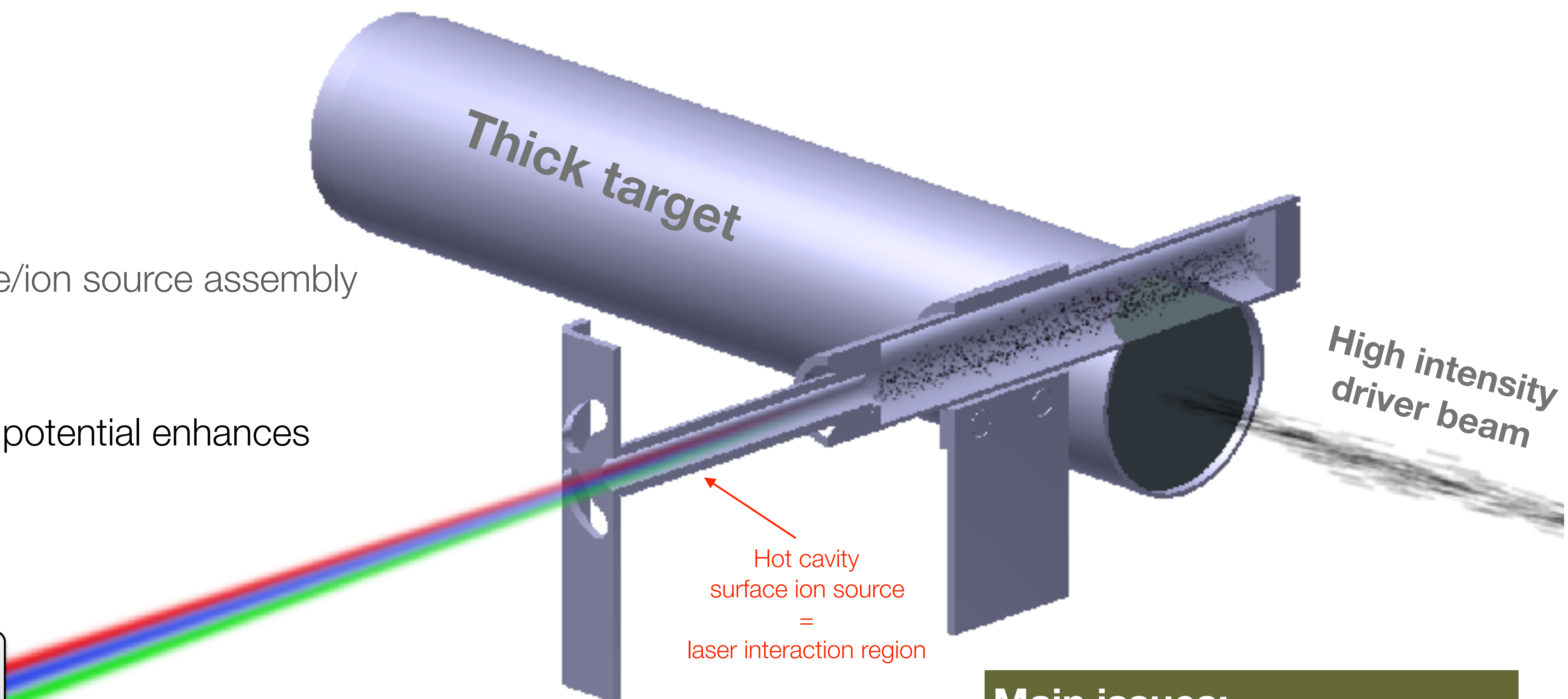
High peak power, therefore short pulse length (**<50 ns, 0.1-10 mJ**)

High Rep rate: **>10 kHz** (100 μs laser/atom temporal overlap)

Laser line width **> 5 GHz** (> Doppler-broadened atomic line width)

T ≈ 2100 °C
High temperature
target/transfer line/ion source assembly

- High efficiency
- Cavity plasma potential enhances ion survival



G. D. Alkhazov et al.
NIM B69 (1992) 517

V.N. Fedoseev *et al.*
NIM B266 (2008) 4378

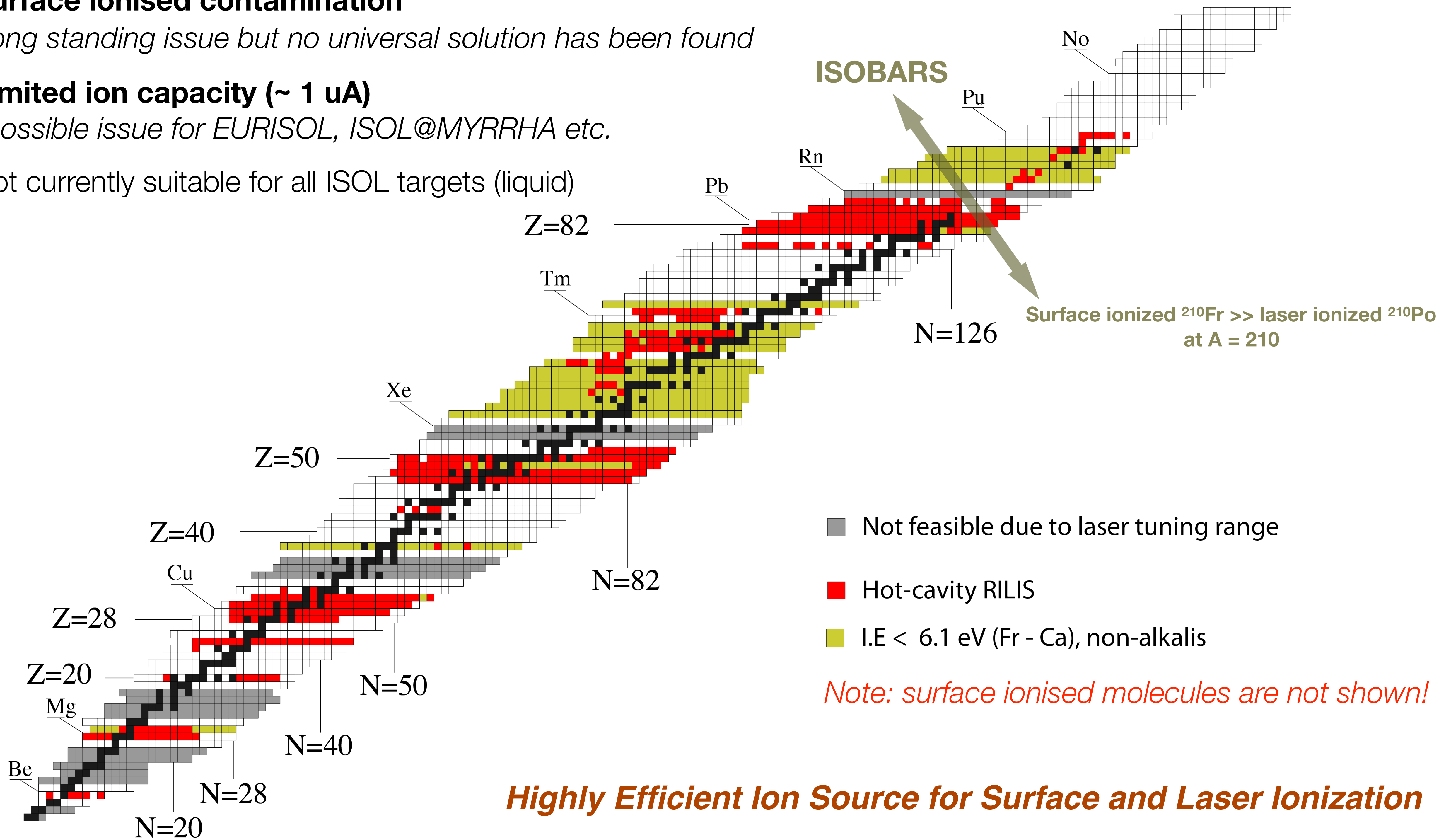
U. Koester et al.
Nucl. Phys. A 701 (2002) 441

Highly Efficient Ion Source for Surface and Laser Ionization
Dr Maxim Seliverstov (NRC "Kurchatov Institute" PNPI)
POSTER SESSION 2

Main issues:
Surface ionized contaminants
Doppler broadened line-width

Drawbacks of hot-cavity laser ion sources

- **Surface ionised contamination**
  - *long standing issue but no universal solution has been found*
- **Limited ion capacity (~ 1 uA)**
  - *possible issue for EURISOL, ISOL@MYRRHA etc.*
- Not currently suitable for all ISOL targets (liquid)



Note: surface ionised molecules are not shown!

Highly Efficient Ion Source for Surface and Laser Ionization

Dr Maxim Seliverstov (NRC “Kurchatov Institute” PNPI)

POSTER SESSION 2

Active surface-ion suppression (LIST)

Nuclear Instruments and Methods in Physics Research B 317 (2013) 417–421

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

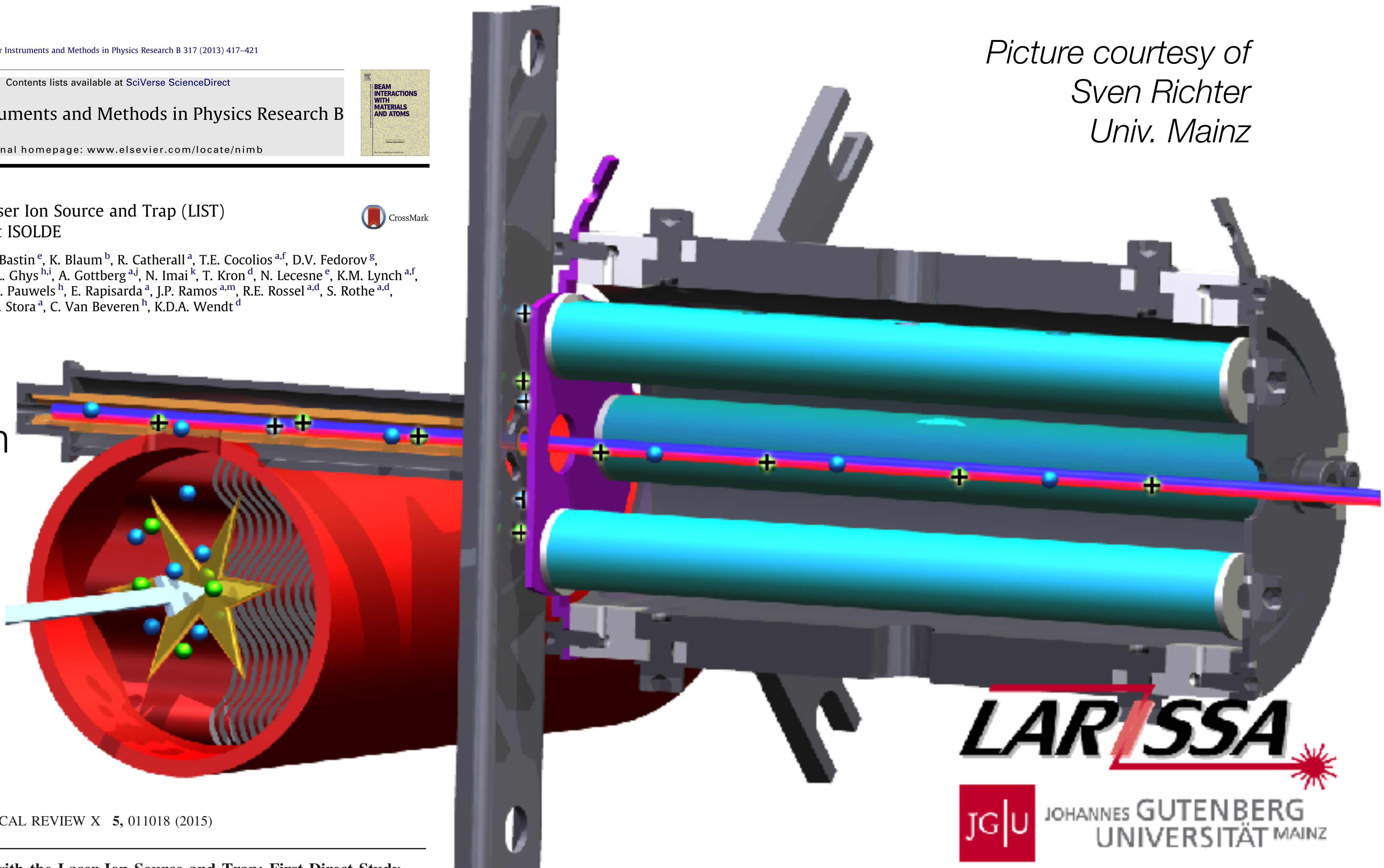
First application of the Laser Ion Source and Trap (LIST) for on-line experiments at ISOLDE

D.A. Fink [a,b,c,*,1], S.D. Richter [d], B. Bastin [e], K. Blaum [b], R. Catherall [a], T.E. Cocolios [a,f], D.V. Fedorov [g], V.N. Fedosseev [a], K.T. Flanagan [f], L. Ghys [h,i], A. Gottberg [a,j], N. Imai [k], T. Kron [d], N. Lecesne [e], K.M. Lynch [a,f], B.A. Marsh [a], T.M. Mendonca [a,l], D. Pauwels [h], E. Rapisarda [a], J.P. Ramos [a,m], R.E. Rossel [a,d], S. Rothe [a,d], M.D. Seliverstov [g,n], M. Sjödin [e], T. Stora [a], C. Van Beveren [h], K.D.A. Wendt [d]

Picture courtesy of
Sven Richter
Univ. Mainz

SI Suppression
$\sim 10^6$

Efficiency loss
~20-40

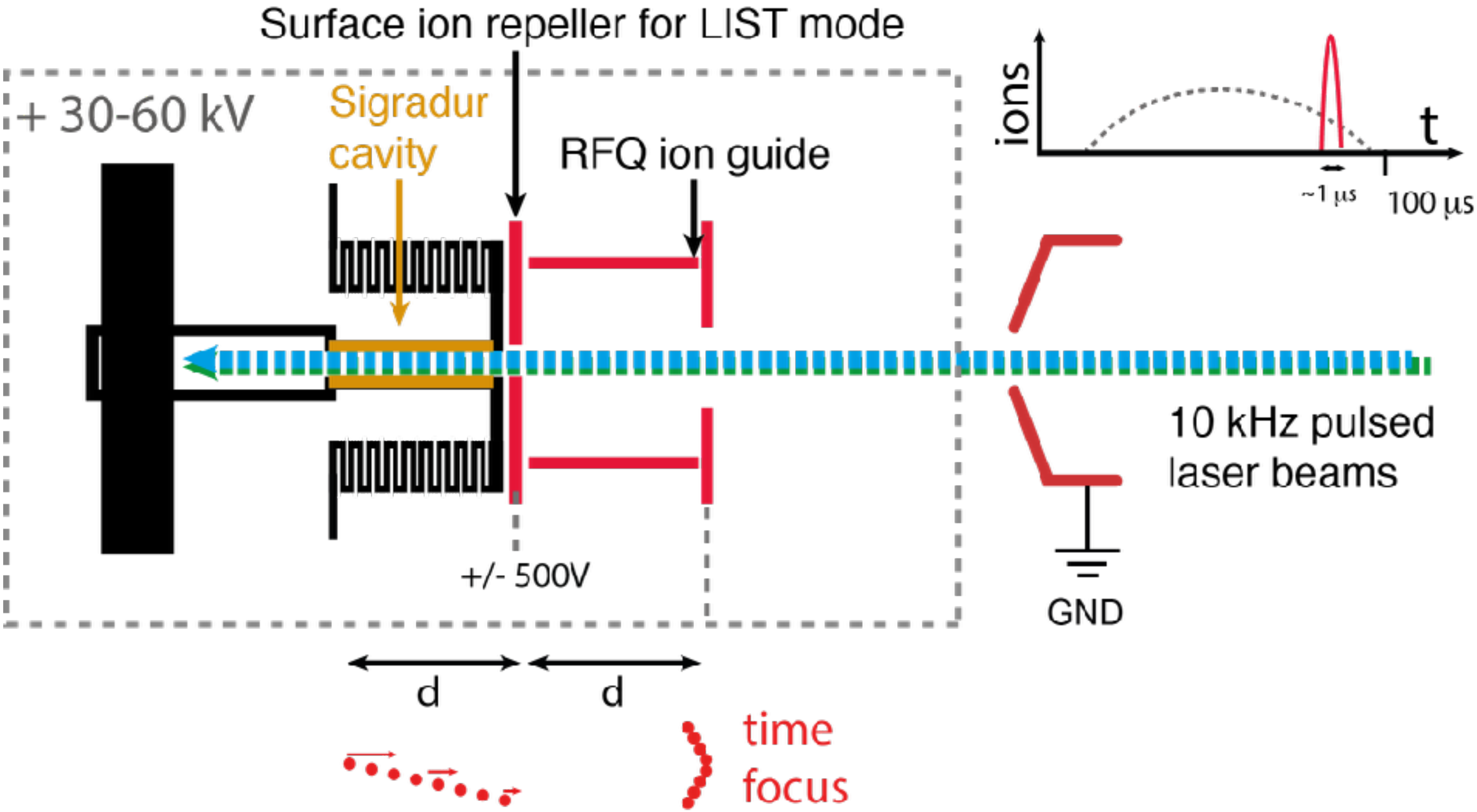


PHYSICAL REVIEW X 5, 011018 (2015)

In-Source Laser Spectroscopy with the Laser Ion Source and Trap: First Direct Study of the Ground-State Properties of ^{217,219}Po

D. A. Fink,[1,2,3,*] T. E. Cocolios,[4,5] A. N. Andreyev,[6,7] S. Antalic,[8] A. E. Barzakh,[9] B. Bastin,[10] D. V. Fedorov,[9] V. N. Fedosseev,[1] K. T. Flanagan,[4] L. Ghys,[11,12] A. Gottberg,[1,13] M. Huyse,[11] N. Imai,[14] T. Kron,[15] N. Lecesne,[10] K. M. Lynch,[4,5,11] B. A. Marsh,[1] D. Pauwels,[12] E. Rapisarda,[5] S. D. Richter,[15] R. E. Rossel,[1,15] S. Rothe,[1,15] M. D. Seliverstov,[6,9] A. M. Sjödin,[10] C. Van Beveren,[11] P. Van Duppen,[11] and K. D. A. Wendt[15]

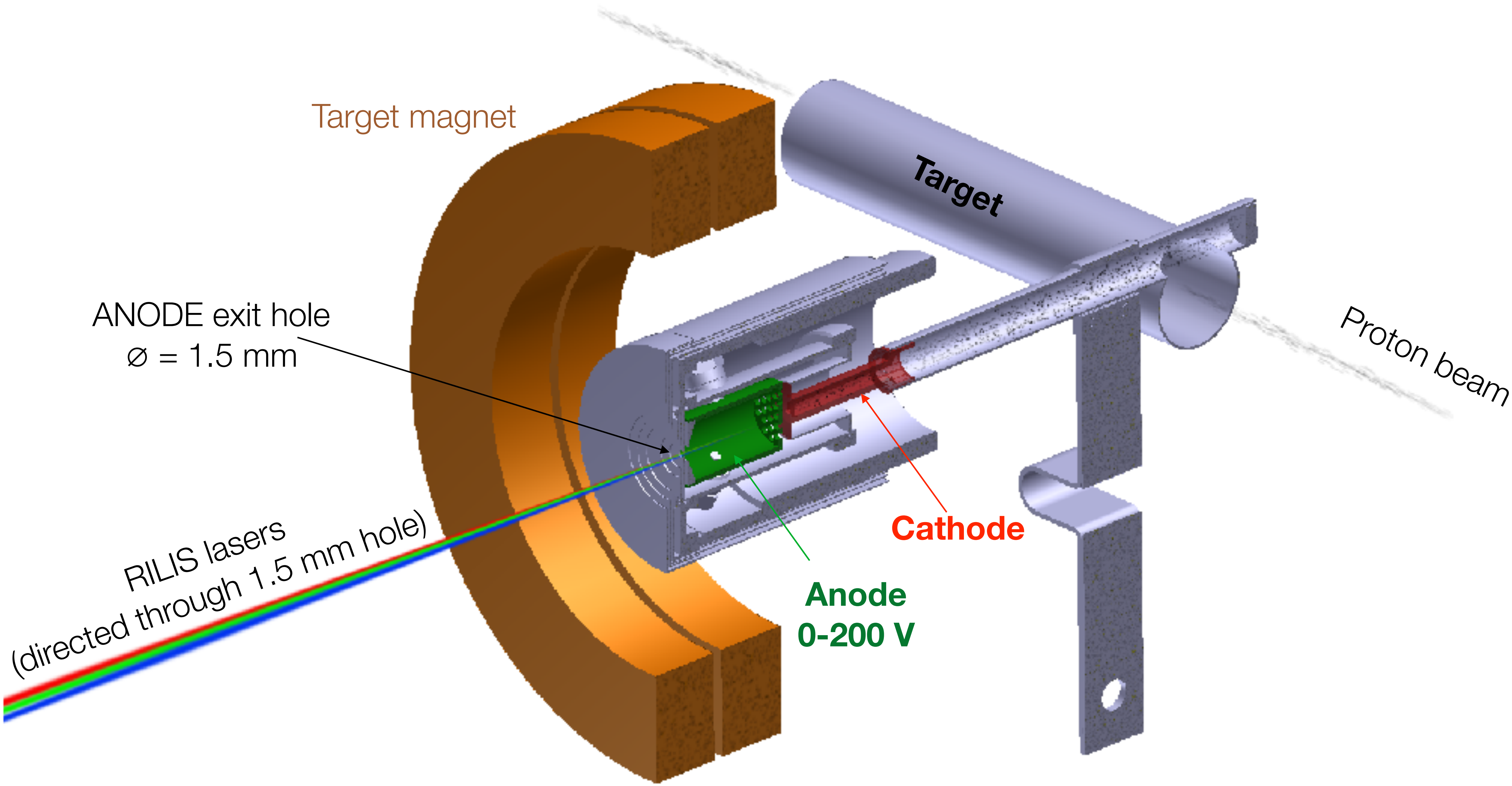
High Selectivity RILIS — ToF-LIS



LIST provides transverse confinement along 'drift' region

Hot-cavity (ion-guide) and standard LIST mode still available

VADLIS: an alternative to hot-cavity RILIS



So far demonstrated for:

Ga, **Cd**, **Hg (2015)**, **Ba**, **Ba+, Sn, Mg (2016), Hg (2017), Mo, Hg (scheduled 2018).**

VADLIS development

Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms
Volume 376, 1 June 2016, Pages 39-45

Blurring the boundaries between ion sources: The application of the RILIS inside a FEBIAD type ion source at ISOLDE

T. Day Goodacre [a, b], J. Billowes [b], R. Catherall [a], T.E. Cocolios [b], B. Crepieux [a], D.V. Fedorov [c], V.N. Fedosseev [a], L.P. Gaffney [a, 1], T. Giles [a], A. Gottberg [a], K.M. Lynch [a], B.A. Marsh [a], T.M. Mendonça [a], J.P. Ramos [a, d], R.E. Rossel [a, f, g], S. Rothe [a], S. Sels [e], C. Sotty [e] ... M. Veinhard [a]

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https://doi.org/10.1016/j.nimb.2016.03.005

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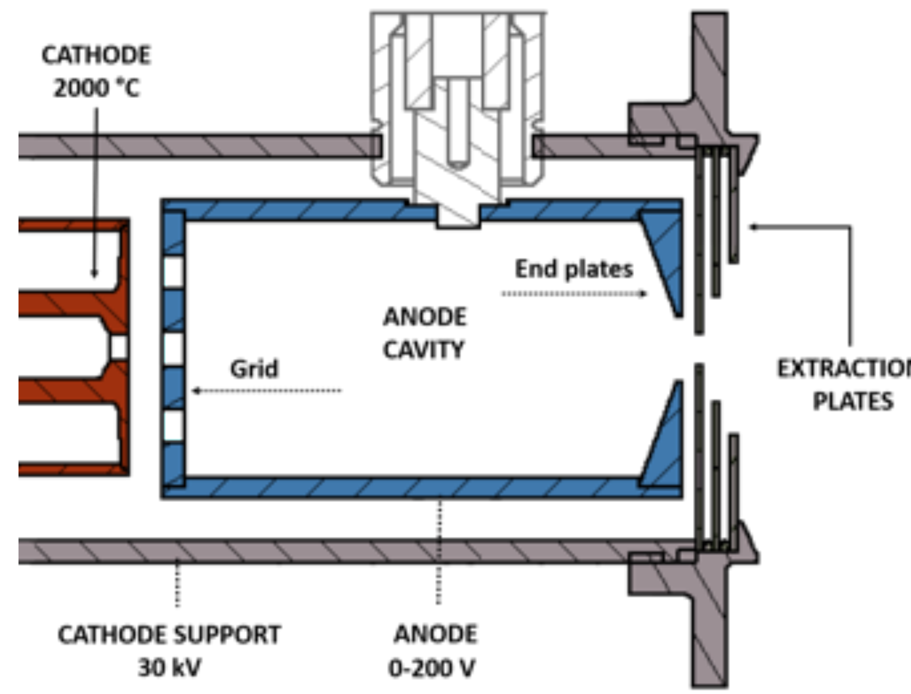

Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms
Volume 431, 15 September 2018, Pages 59-66

Enhancing the extraction of laser-ionized beams from an arc discharge ion source volume

Y. Martinez Palenzuela [a, c], B.A. Marsh [a], J. Ballof [a, b], R. Catherall [a], K. Chrysalidis [a, d], T.E. Cocolios [c], B. Crepieux [a], T. Day Goodacre [a, e, f], V.N. Fedosseev [a], M.H. Huyse [c], P.B. Larmonier [a, g], J.P. Ramos [a], S. Rothe [a], J.D.A. Smith [h], T. Stora [a], P. Van Duppen [c], S. Wilkins [a]

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https://doi.org/10.1016/j.nimb.2018.06.006

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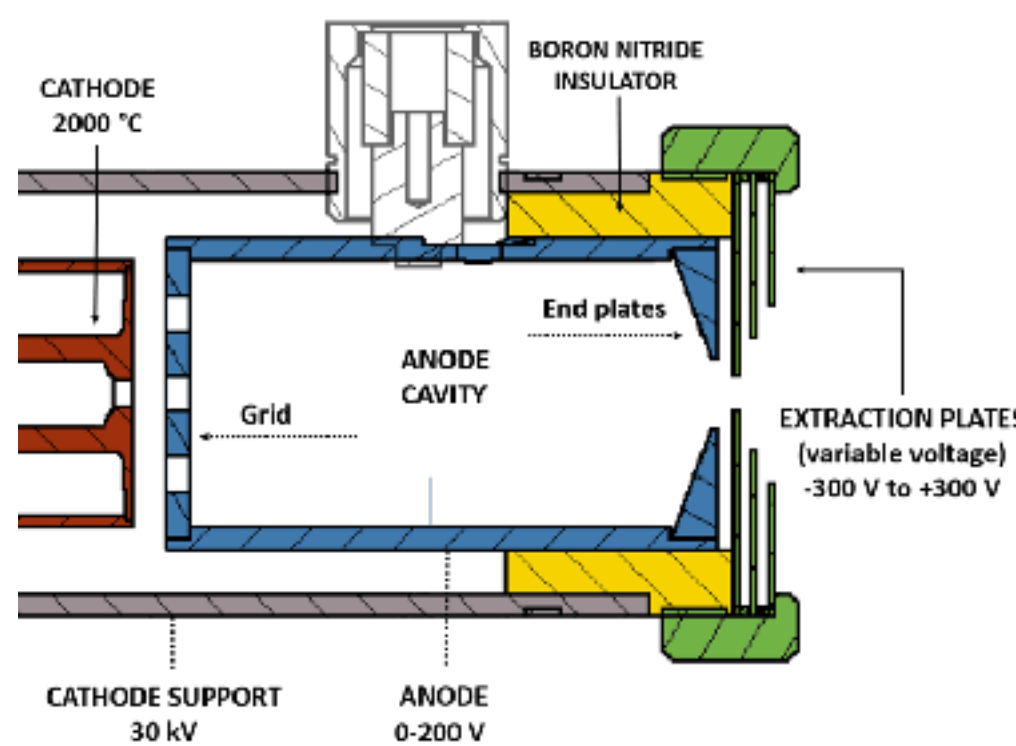
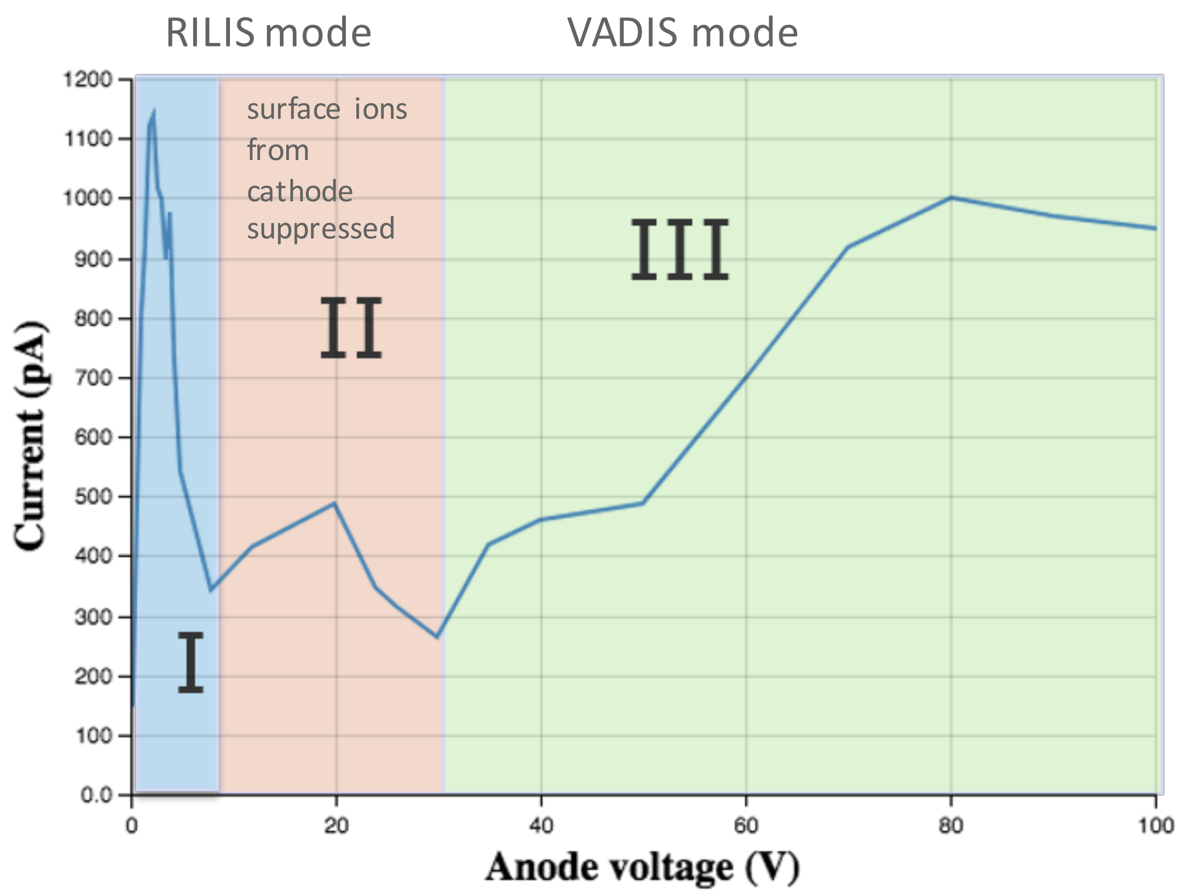
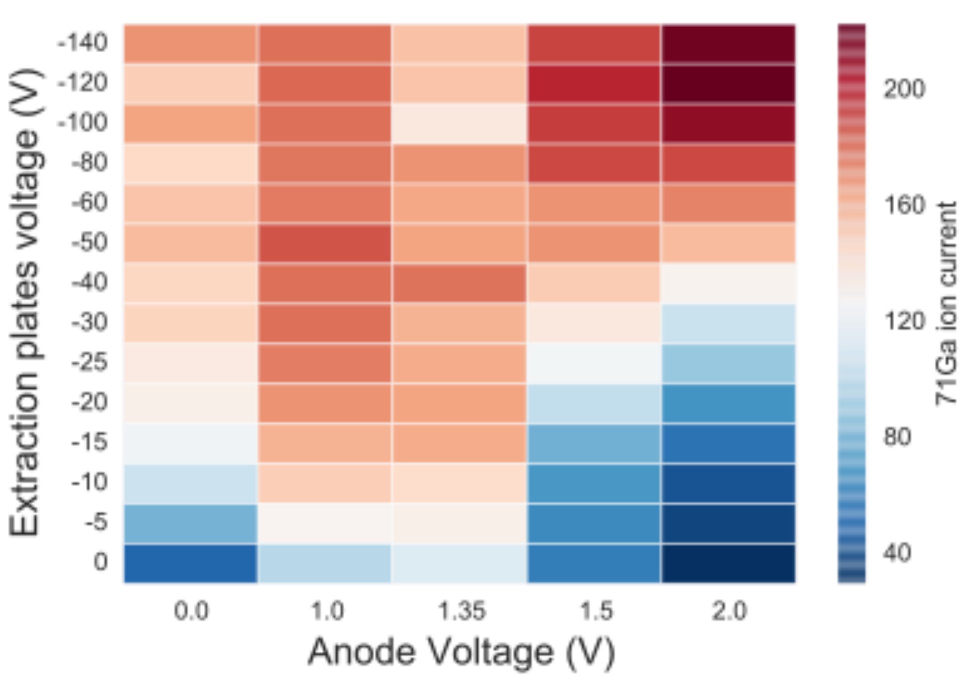
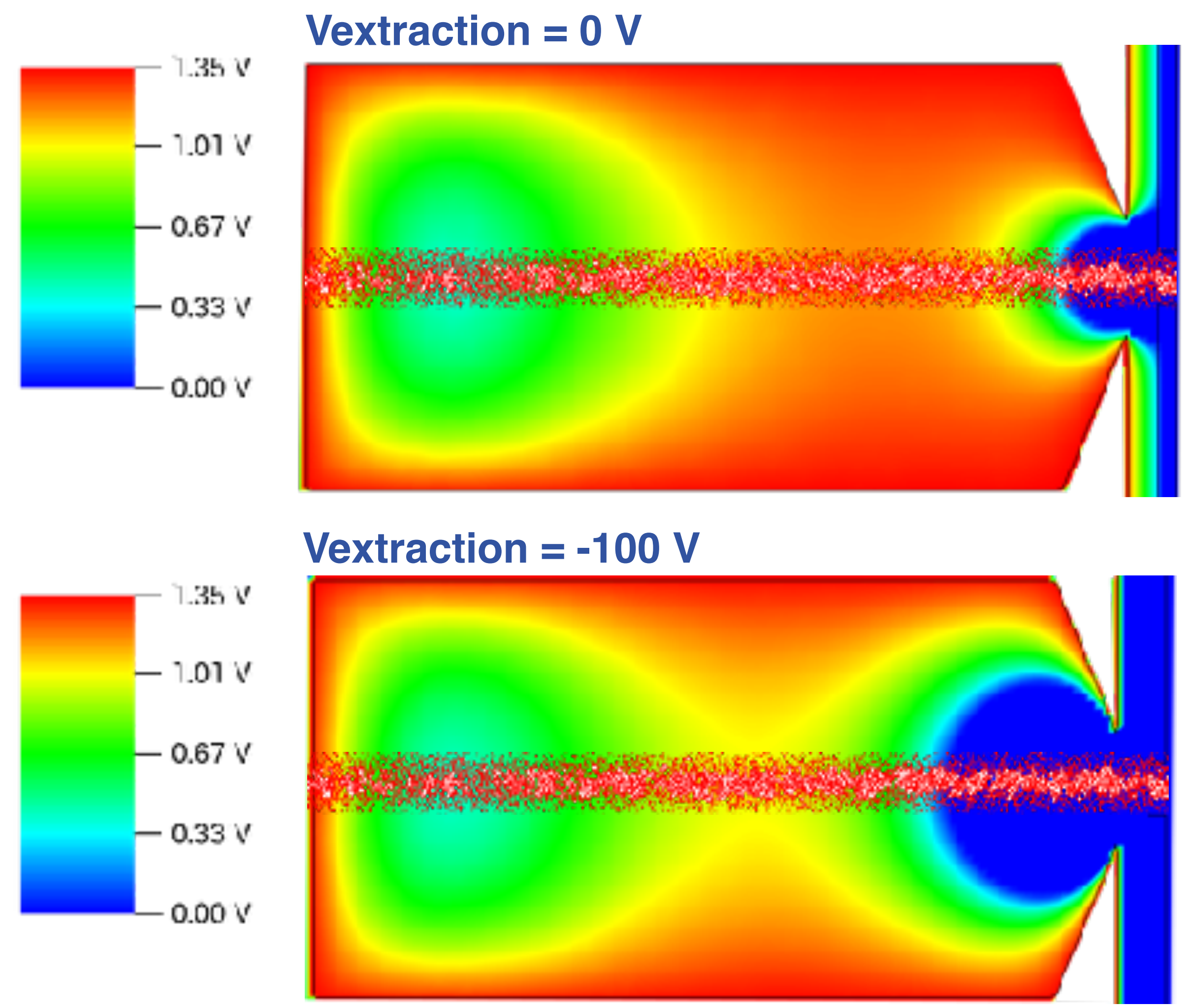


VADLIS modes of operation







- New design with variable extaction voltage improves laser ion extraction
- Demonstrated off-line with Ga
- Demonstrated on-line with Mg: factor 3 extraction efficiency improvement when voltage was adjusted!

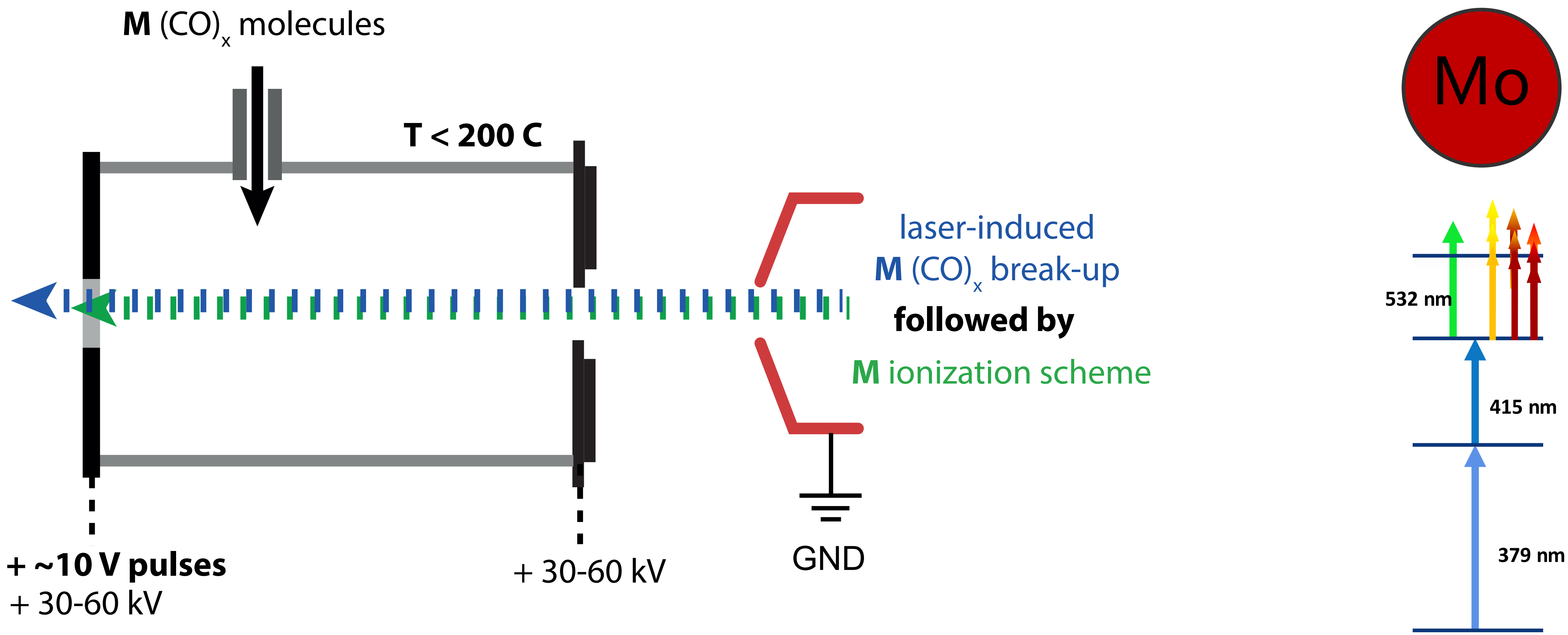
Credit: Y. Martinez Palenzuela

$Mo(CO)_6$ - Molecular breakup + ionisation

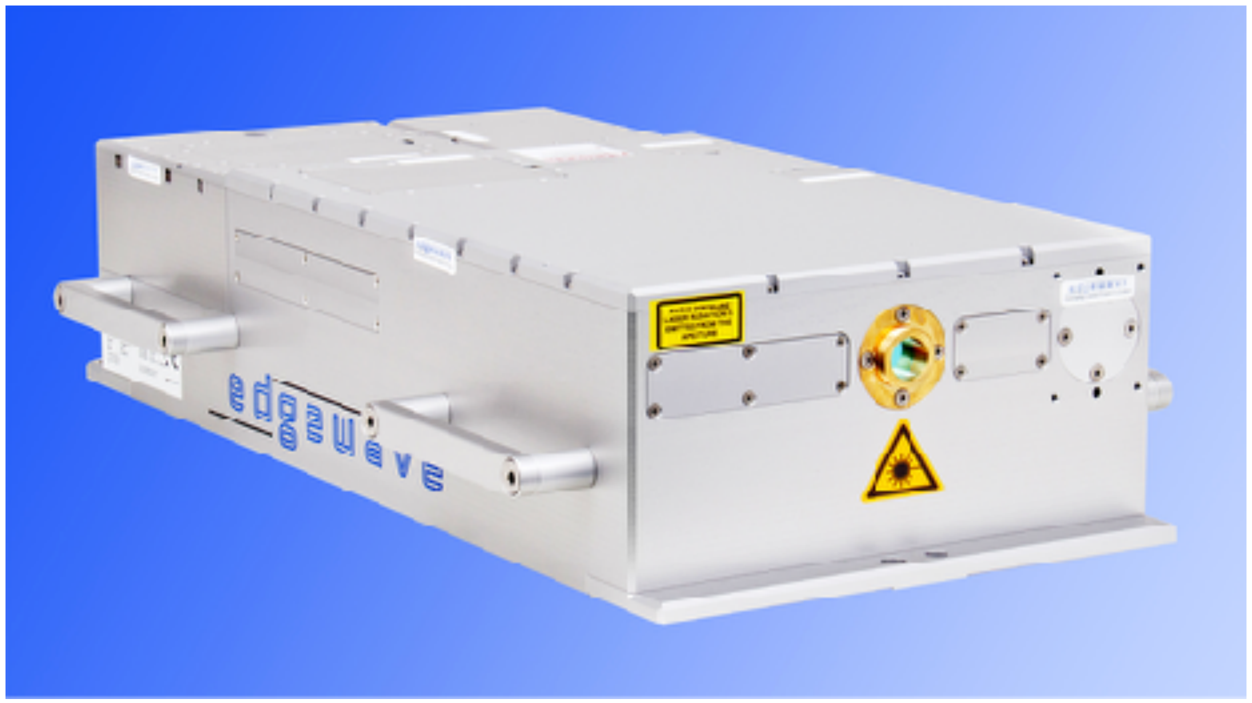
1) Creation and transport of volatile molecules of refractory metals

2) Dissociation by laser pulse

3) Resonance ionisation before atom/wall collision

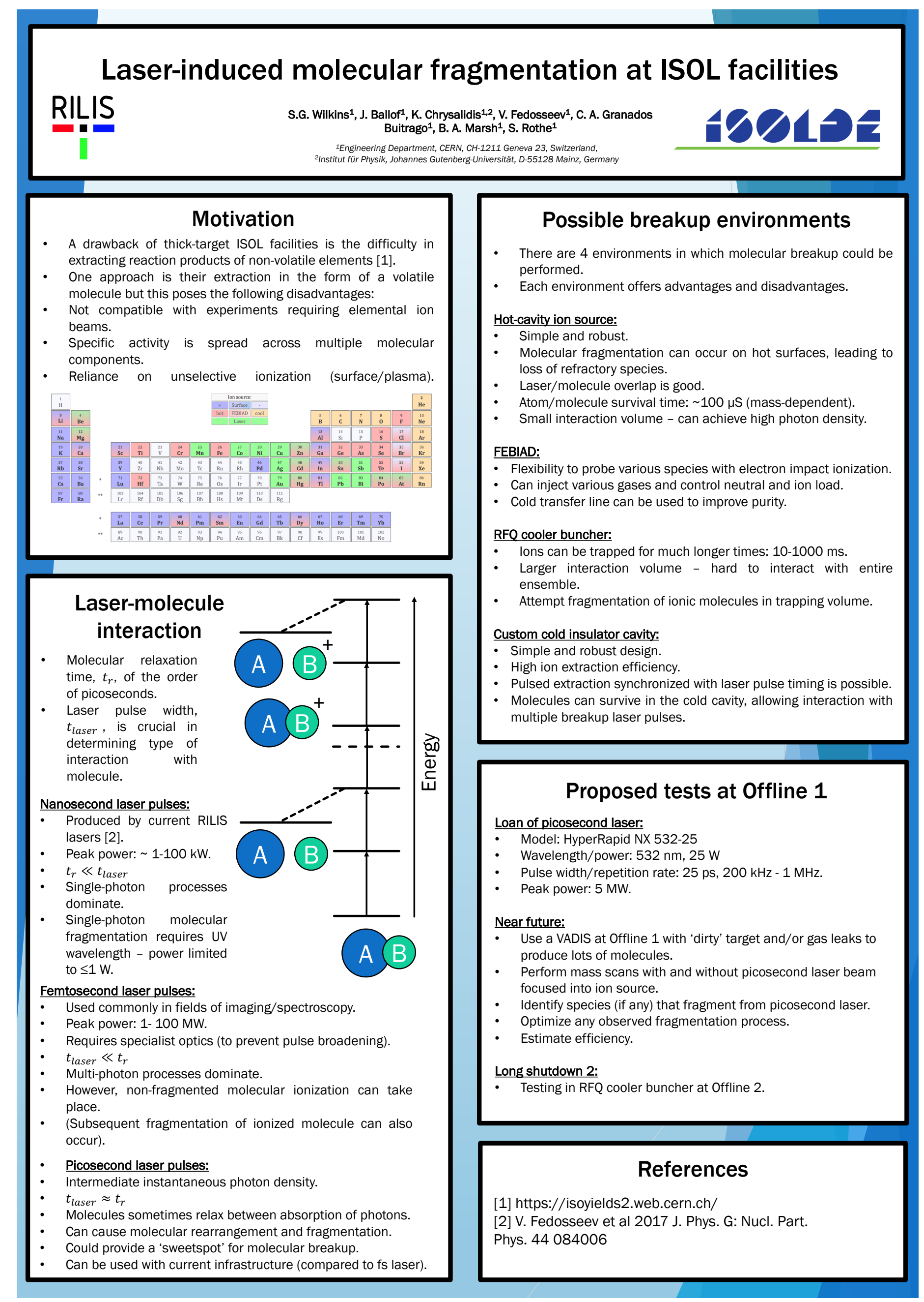


~picosecond laser for molecular breakup



0-200 kHz (600 fs), 100W @ 515 nm

FX series INNOSLAB laser



Laser-induced molecular fragmentation at ISOL facilities

S.G. Wilkins[1], J. Ballof[1], K. Chrysalidis[1,2], V. Fedosseev[1], C. A. Granados Buitrago[1], B. A. Marsh[1], S. Rothe[1]

[1]Engineering Department, CERN, CH-1211 Geneva 23, Switzerland,
[2]Institut für Physik, Johannes Gutenberg-Universität, D-55128 Mainz, Germany

Motivation

- A drawback of thick-target ISOL facilities is the difficulty in extracting reaction products of non-volatile elements [1].
- One approach is their extraction in the form of a volatile molecule but this poses the following disadvantages:
- Not compatible with experiments requiring elemental ion beams.
- Specific activity is spread across multiple molecular components.
- Reliance on unselective ionization (surface/plasma).

Laser-molecule interaction

- Molecular relaxation time, t_r, of the order of picoseconds.
- Laser pulse width, t_{laser}, is crucial in determining type of interaction with molecule.

Nanosecond laser pulses:
- Produced by current RILIS lasers [2].
- Peak power: ~ 1-100 kW.
- $t_r \ll t_{laser}$
- Single-photon processes dominate.
- Single-photon molecular fragmentation requires UV wavelength – power limited to ≤1 W.

Femtosecond laser pulses:
- Used commonly in fields of imaging/spectroscopy.
- Peak power: 1- 100 MW.
- Requires specialist optics (to prevent pulse broadening).
- $t_{laser} \ll t_r$
- Multi-photon processes dominate.
- However, non-fragmented molecular ionization can take place.
- (Subsequent fragmentation of ionized molecule can also occur).

- **Picosecond laser pulses:**
- Intermediate instantaneous photon density.
- $t_{laser} \approx t_r$
- Molecules sometimes relax between absorption of photons.
- Can cause molecular rearrangement and fragmentation.
- Could provide a 'sweetspot' for molecular breakup.
- Can be used with current infrastructure (compared to fs laser).

Possible breakup environments

- There are 4 environments in which molecular breakup could be performed.
- Each environment offers advantages and disadvantages.

Hot-cavity ion source:
- Simple and robust.
- Molecular fragmentation can occur on hot surfaces, leading to loss of refractory species.
- Laser/molecule overlap is good.
- Atom/molecule survival time: ~100 μS (mass-dependent).
- Small interaction volume – can achieve high photon density.

FEBIAD:
- Flexibility to probe various species with electron impact ionization.
- Can inject various gases and control neutral and ion load.
- Cold transfer line can be used to improve purity.

RFQ cooler buncher:
- Ions can be trapped for much longer times: 10-1000 ms.
- Larger interaction volume – hard to interact with entire ensemble.
- Attempt fragmentation of ionic molecules in trapping volume.

Custom cold insulator cavity:
- Simple and robust design.
- High ion extraction efficiency.
- Pulsed extraction synchronized with laser pulse timing is possible.
- Molecules can survive in the cold cavity, allowing interaction with multiple breakup laser pulses.

Proposed tests at Offline 1

Loan of picosecond laser:
- Model: HyperRapid NX 532-25
- Wavelength/power: 532 nm, 25 W
- Pulse width/repetition rate: 25 ps, 200 kHz - 1 MHz.
- Peak power: 5 MW.

Near future:
- Use a VADIS at Offline 1 with 'dirty' target and/or gas leaks to produce lots of molecules.
- Perform mass scans with and without picosecond laser beam focused into ion source.
- Identify species (if any) that fragment from picosecond laser.
- Optimize any observed fragmentation process.
- Estimate efficiency.

Long shutdown 2:
- Testing in RFQ cooler buncher at Offline 2.

References

[1] https://isoyields2.web.cern.ch/
[2] V. Fedosseev et al 2017 J. Phys. G: Nucl. Part. Phys. 44 084006

75 x peak power increase w.r.t our 100 W IS-series laser

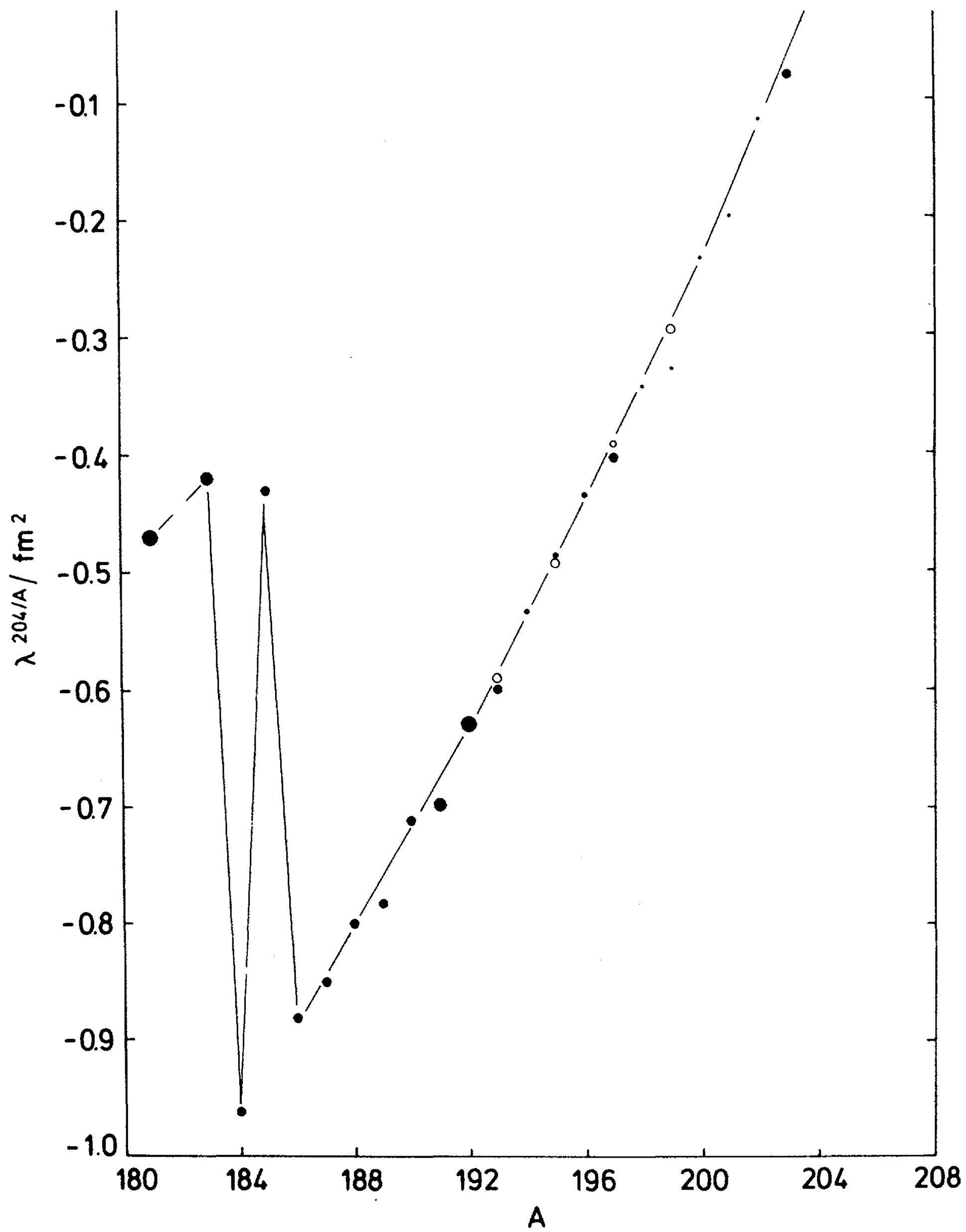
> 20 laser-molecule interactions per molecule (in hot cavity)

Test planned for Winter 2018/19

Revisiting to the 40-year old mercury story

Nuclear Shape Staggering in Very Neutron-Deficient Hg Isotopes Detected by Laser Spectroscopy [a]

T. Kühl, P. Dabkiewicz, C. Duke,[b] H. Fischer, H.-J. Kluge, H. Kremmling, and E.-W. Otten
Institut für Physik, Universität Mainz, Mainz, Germany
(Received 1 April 1977)



unprecedented odd-even staggering
< ^{186}Hg

The extension of these measurements down to ^{180}Hg might be made feasible by improving experimental details. It could thus be determined whether the shape staggering extends further, and where the nuclear shape becomes stabilized finally.

Requirements to continue this measurement:

> 10 x RILIS efficiency improvement

RILIS compatibility with Liquid Pb target

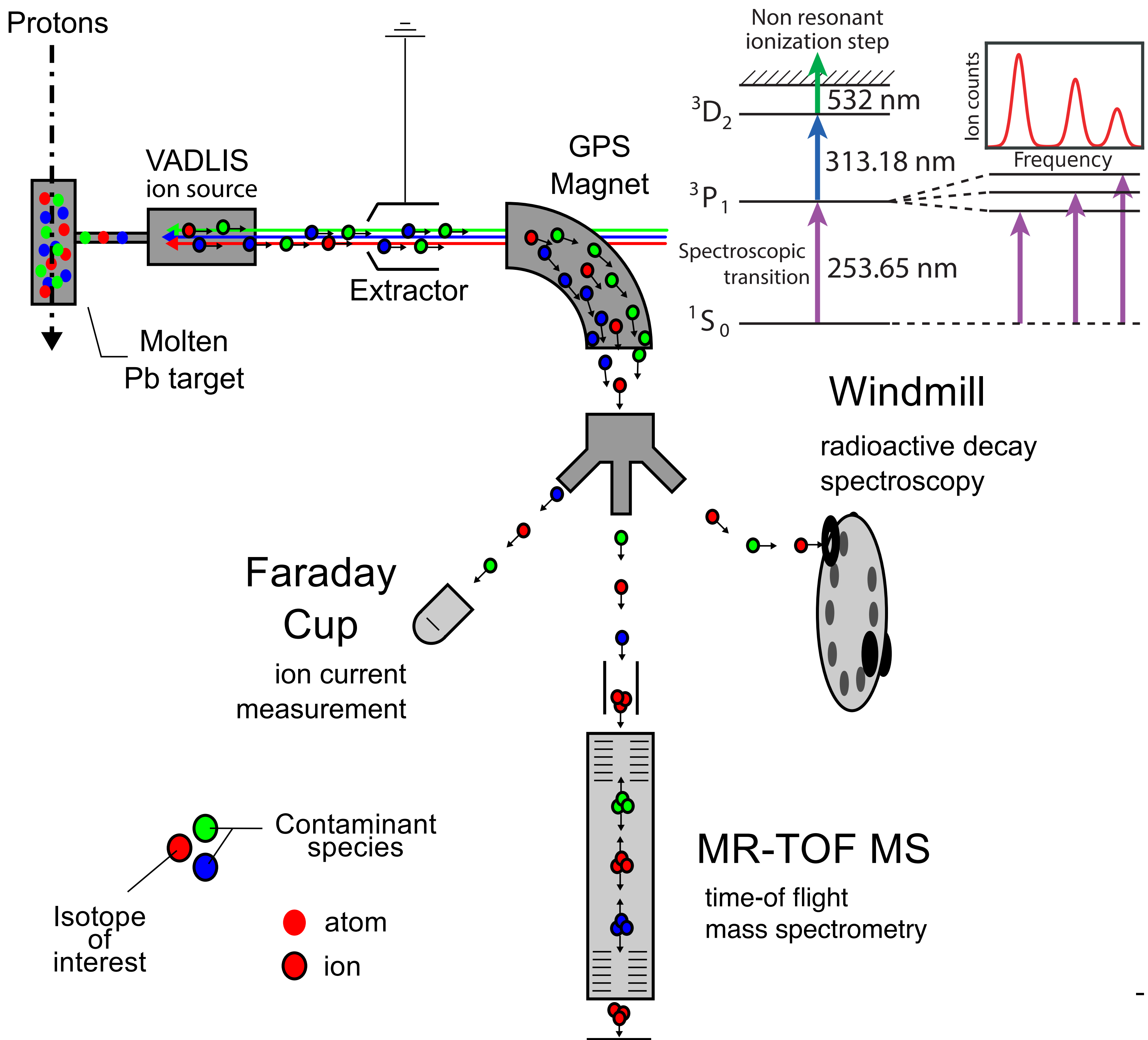
sensitive enough
to measure < 1 ion / sec

Collection time limited by half-life

Low sensitivity of PMT

In-Source RIS of Mercury

First laser spectroscopy in the FEBIAD ion source



60 x
Efficiency
improvement

The In-Source RIS collaboration at ISOLDE

Comenius University, Bratislava, Slovakia
GANIL, Caen, France
Helmholtz Institut Jena, Germany
ILL, Grenoble, France
Institut für Physik, Universität Mainz, Germany
IPN Orsay, France
JAEA, Tokai, Japan
KU Leuven, IKS, Belgium
PNPI, Gatchina, Russian Federation
RILIS and ISOLDE, CERN, Switzerland
SCK-CEN, Mol, Belgium
The University of Manchester, United Kingdom
The University of York, United Kingdom
University of Liverpool, United Kingdom
University of the West of Scotland, United Kingdom

>50 participants

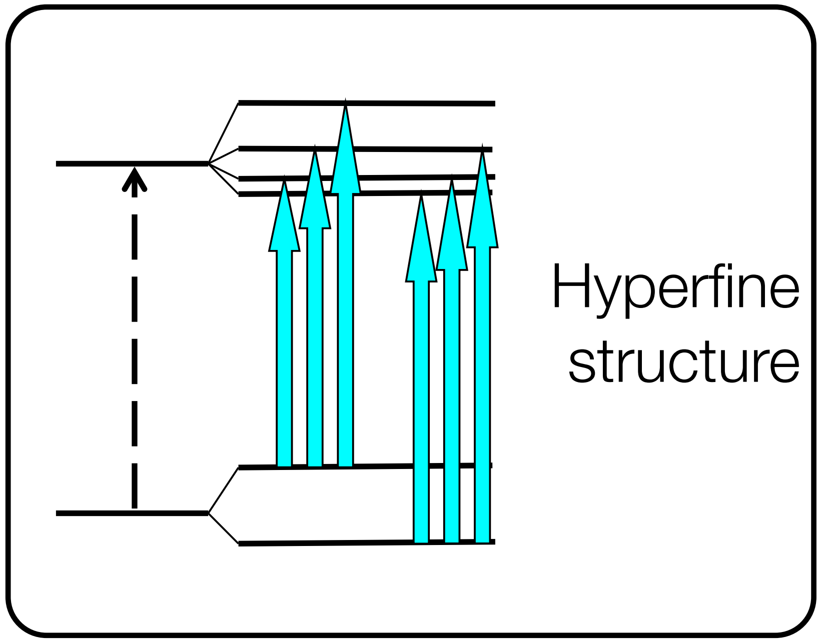
14 institutes

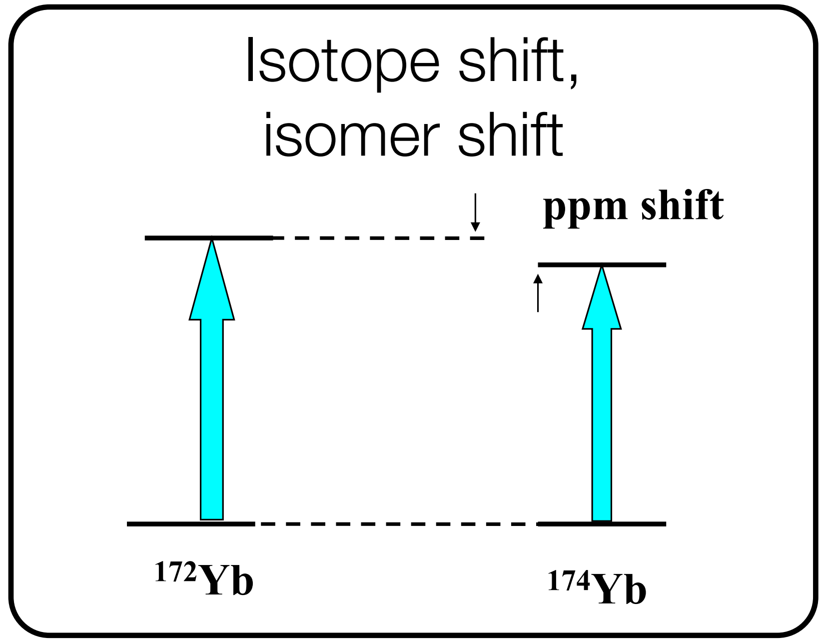
RILIS

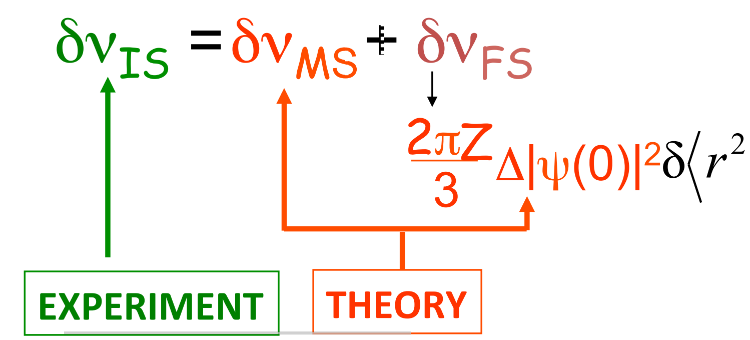
WINDMILL

ISOLTRAP

Nuclear properties from atomic spectroscopy







SPIN

Quadrupole moments

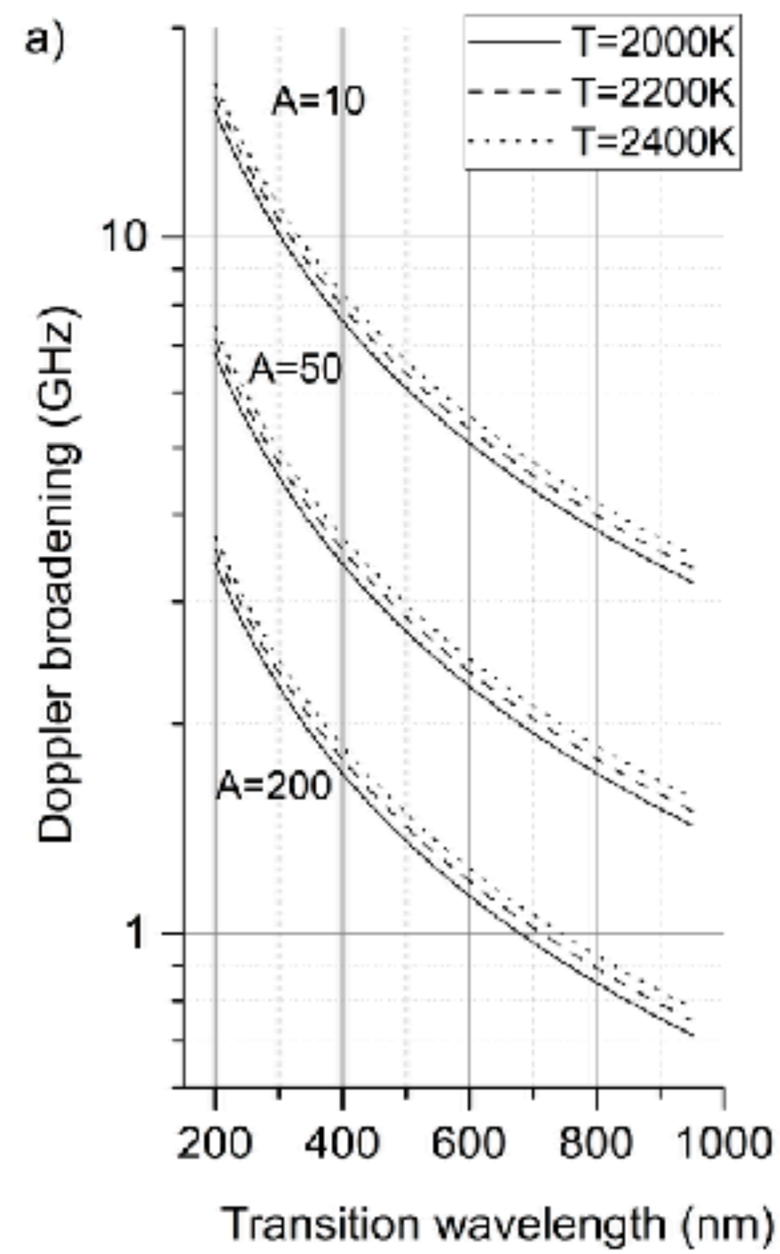
Dipole moment

Nuclear charge radii

Shapes, deformations

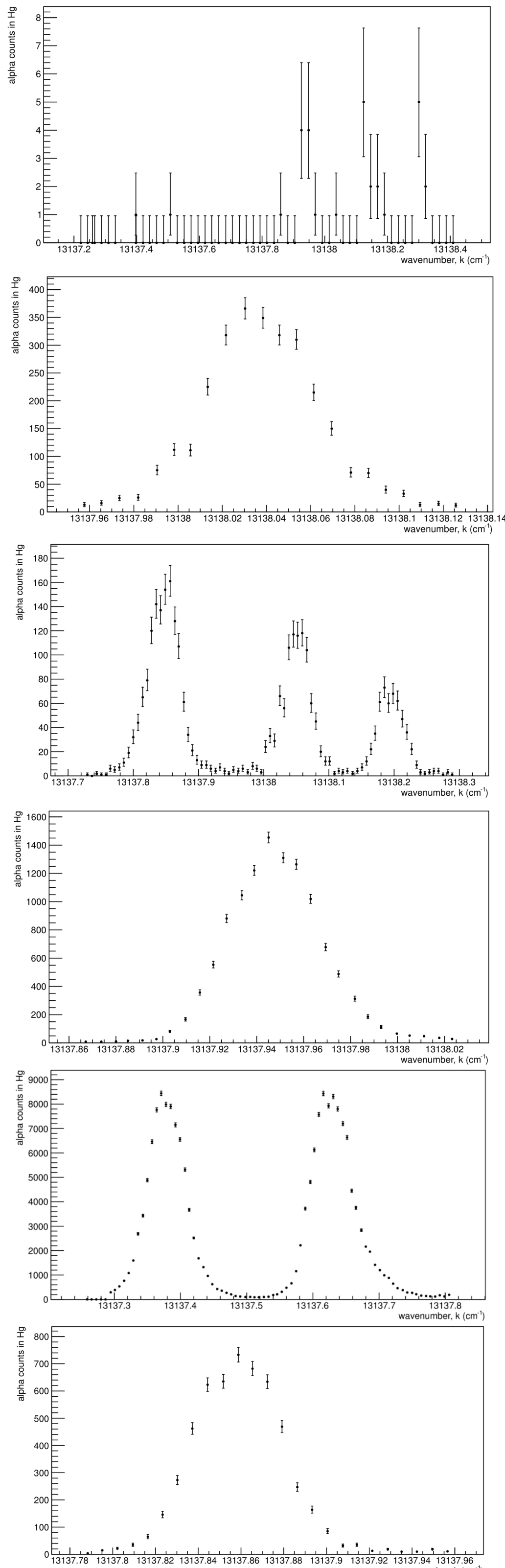
Single particle / collectivity

The application of RILIS for nuclear structure studies is **limited by the achievable resolution** of these very small scale observables

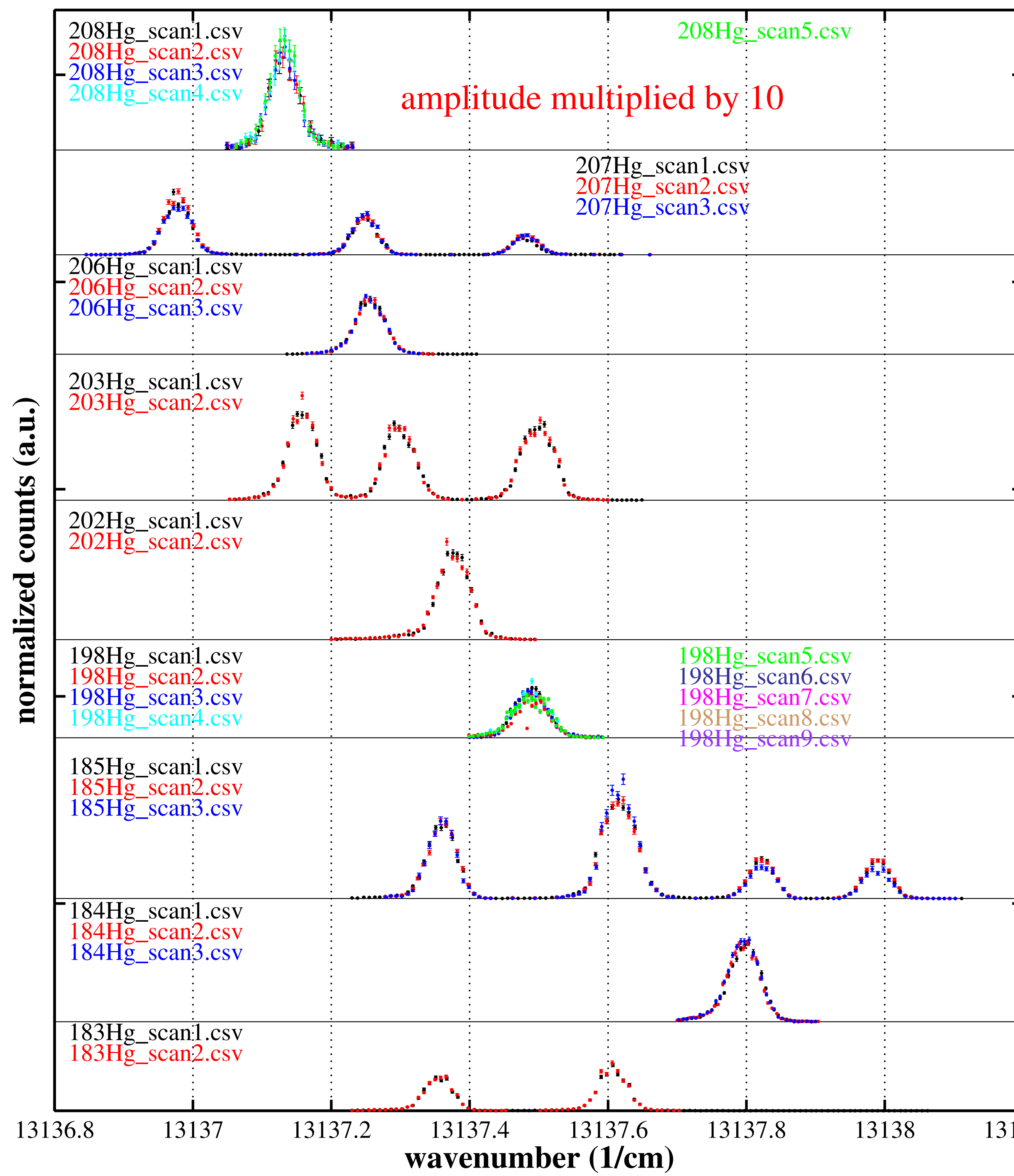


Hg Windmill + MRToF-MS spectra

^{177}Hg
^{178}Hg
^{179}Hg
^{180}Hg
^{181}Hg
^{182}Hg



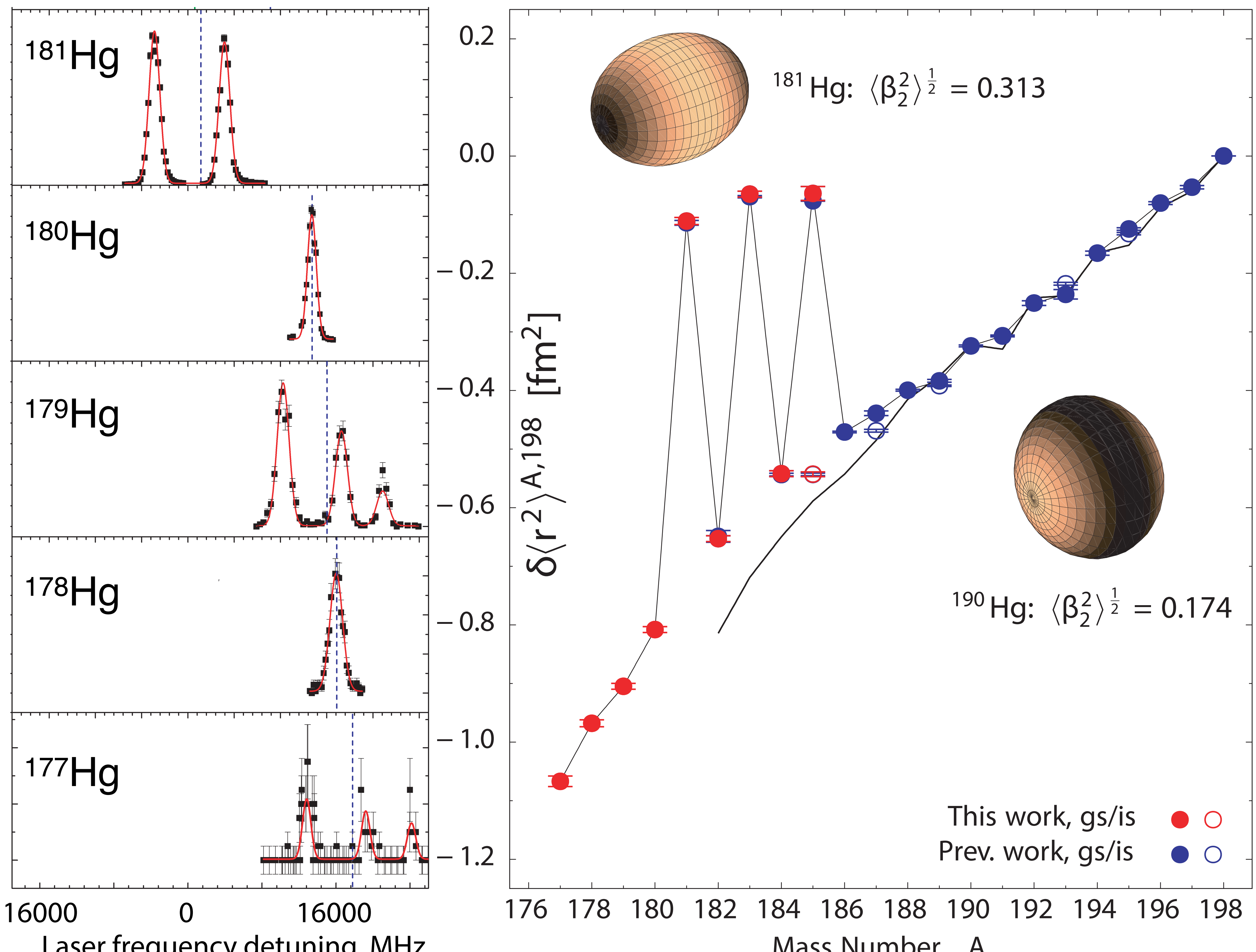
^{208}Hg
^{207}Hg
^{206}Hg
^{203}Hg
^{202}Hg
^{198}Hg
^{185}Hg
^{184}Hg
^{183}Hg



nature physics

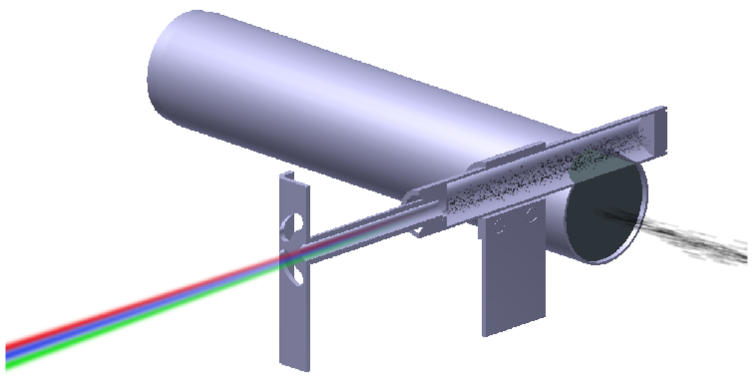
Characterization of the shape-staggering effect in mercury nuclei

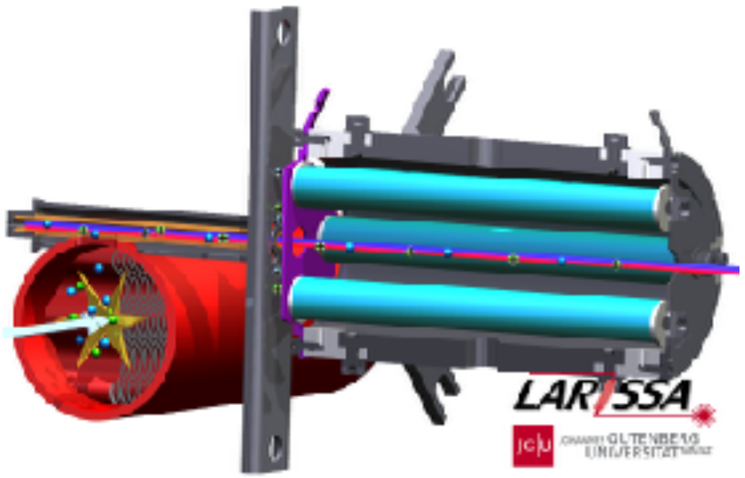
LETTERS

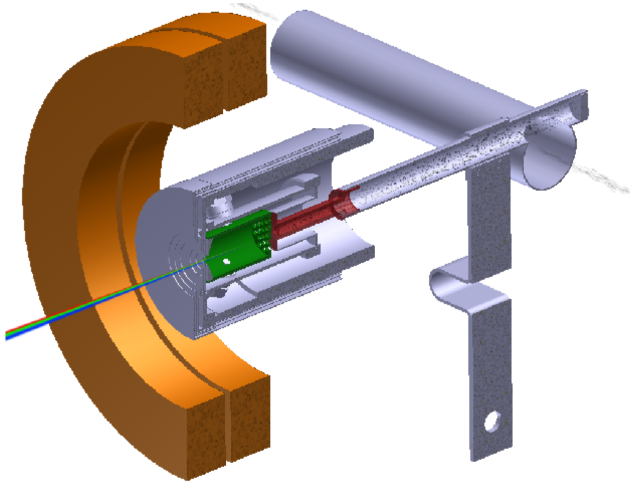


RILIS cavity development directions

HC-RILIS **HC-LIST** **VADLIS**







HIGH SELECTIVITY

High resistance cavity
Pulsed line heating

'DC-offset'
Short LIST
Inverted-LINE

LWF-VADLIS

HIGH RESOLUTION

2-photon HC-RILIS

PI-LIST

HIGH EFFICIENCY

New materials

ToF-LIS

Adjustable EXTRACTOR VOLTAGE

+ RILIS for M(CO)x breakup + Ion load issues for next-gen facilities

Lets pool our resources for RILIS development!

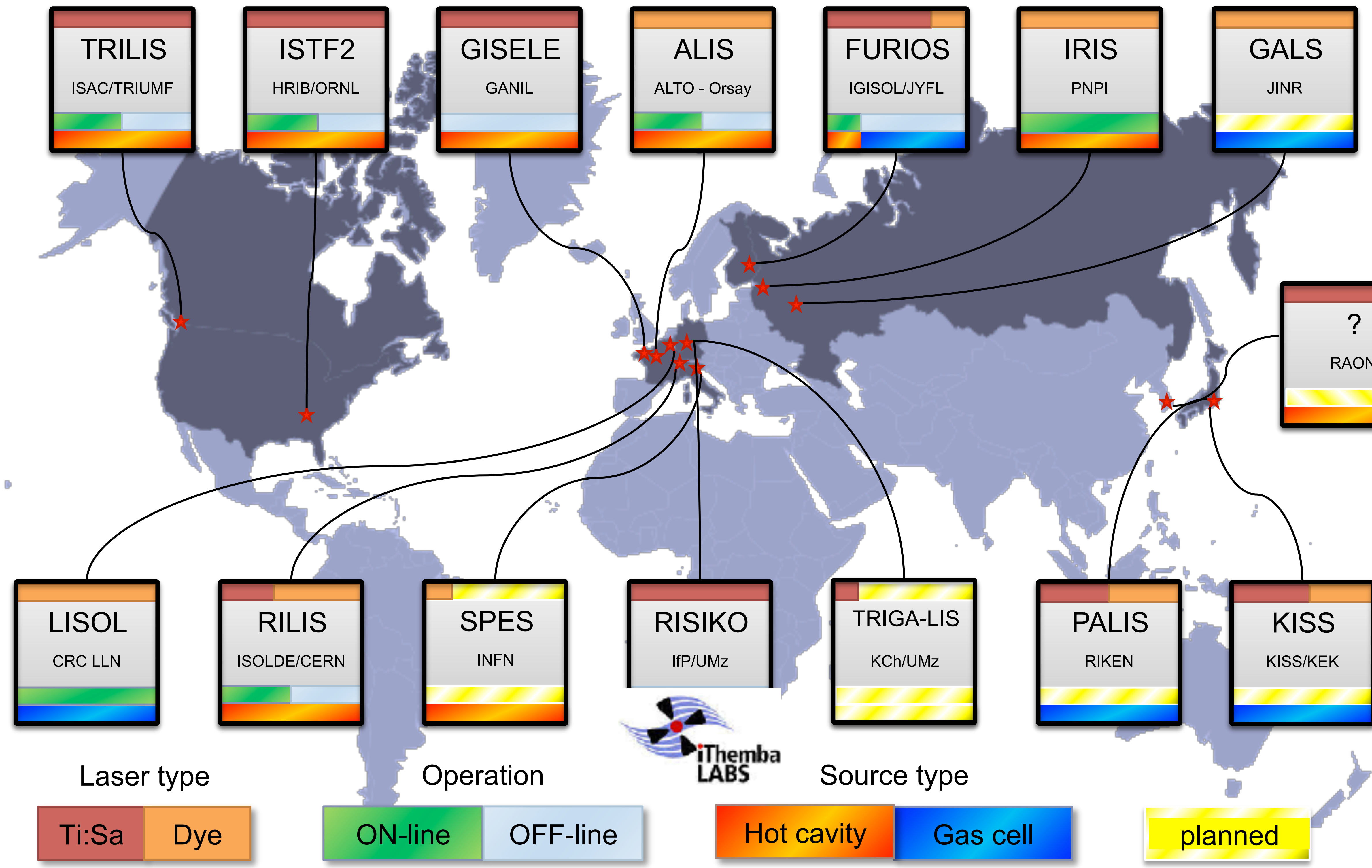


Figure by S.Rothe

Acknowledgements

The (*recent*) ISOLDE RILIS team

V. Fedosseev, B. Marsh, S. Rothe, T. Day Goodacre, R. Rossel, D Fedorov, M. Seliverstov, P. Molkanov, P. Larmonier, K. Chrysalidis, C. Seiffert, S. Wilkins, C. Granados Buitrago.

+ the group of K. Wendt

JOHANNES GUTENBERG-UNIVERSITÄT MAINZ

The In-Source RIS collaboration

On behalf of York-KU Leuven-Gatchina-Mainz-Manchester-Bratislava-Liverpool-ISOLDE collaboration

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