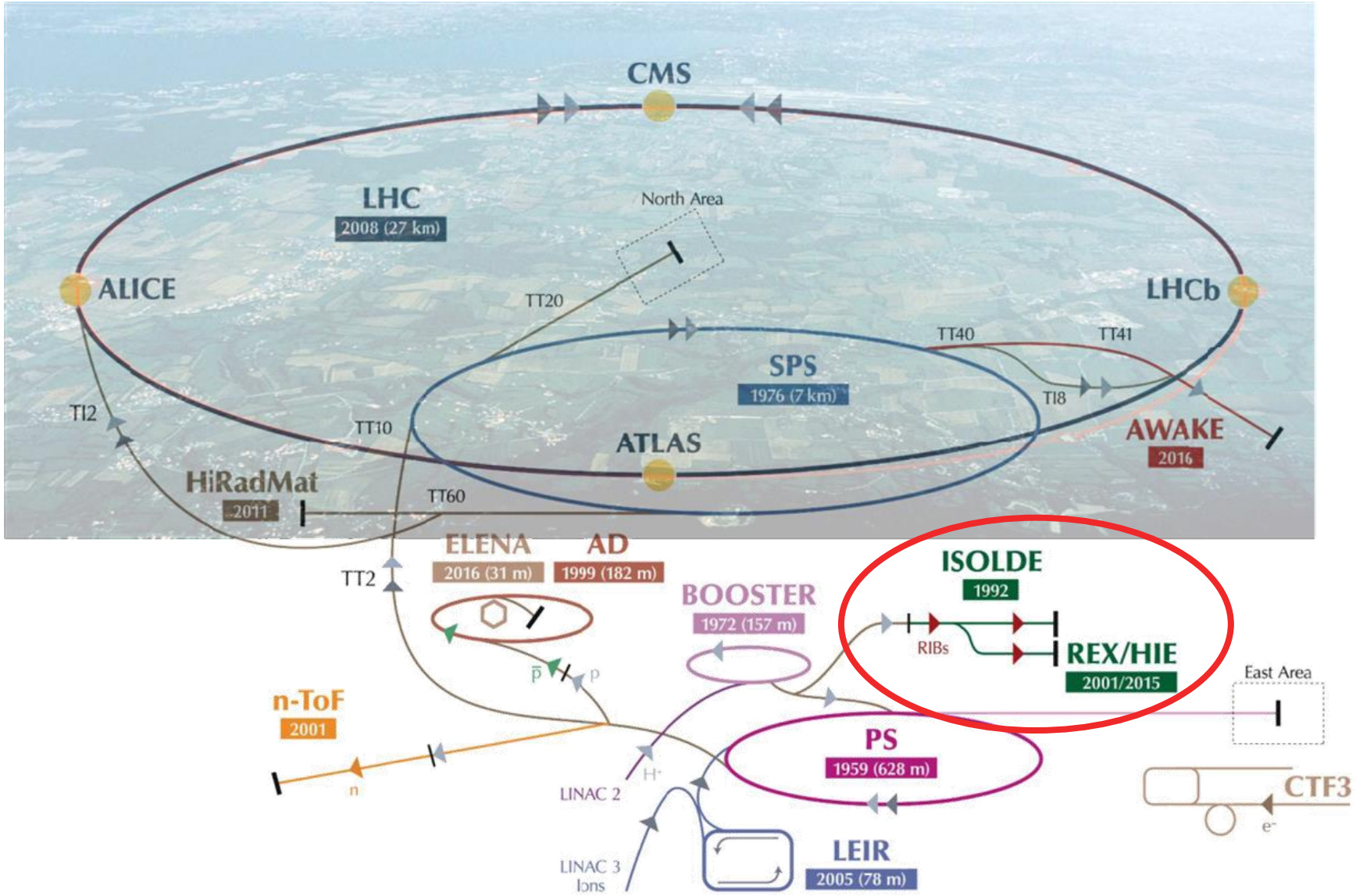
CERN-ISOLDE's new high-resolution laser ion source PI-LIST: Results, characteristics, and developments

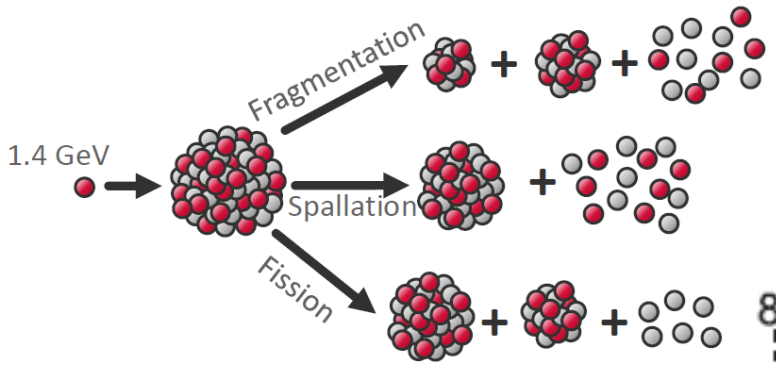
Reinhard Heinke

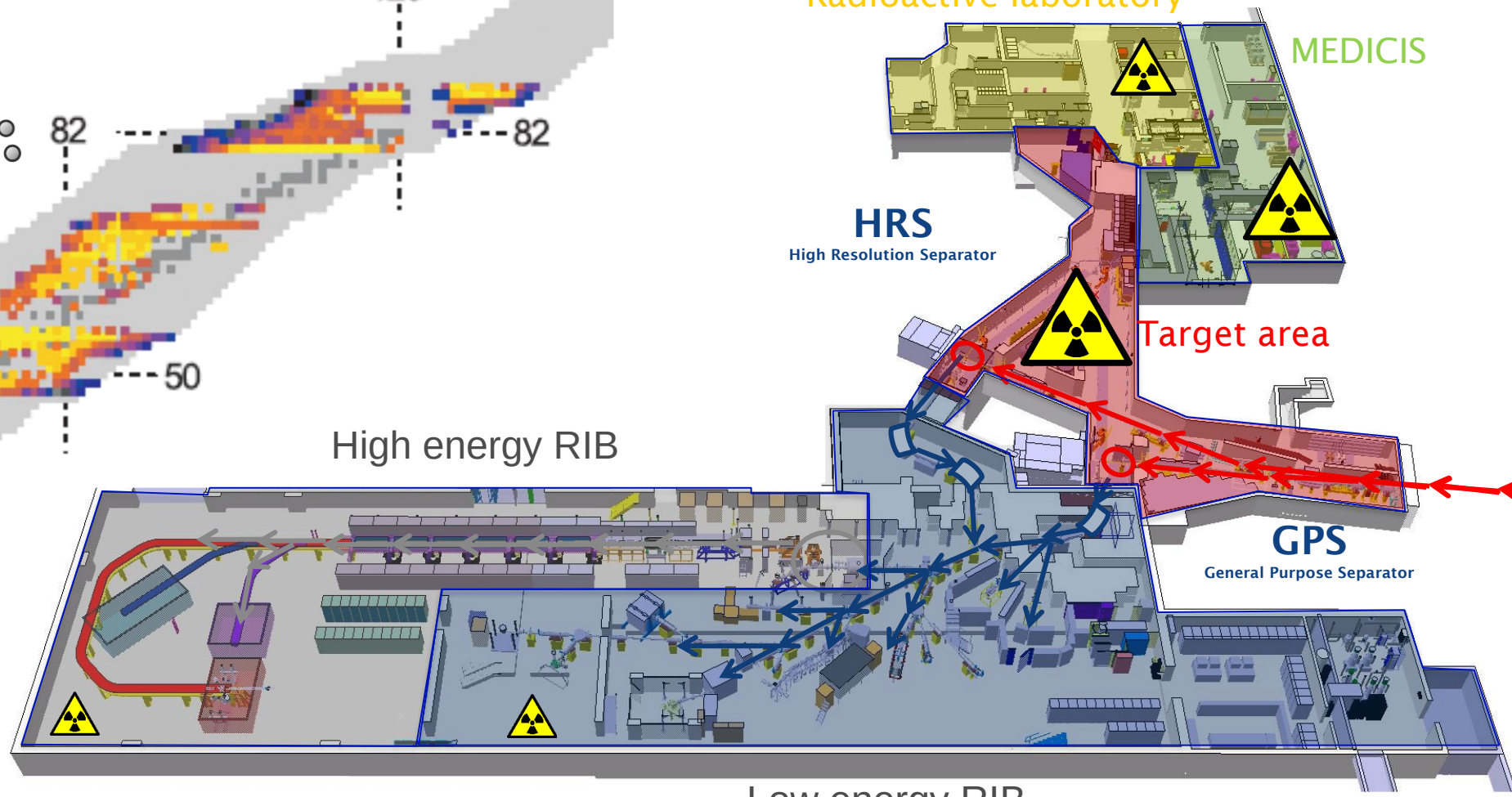
for the **PI-LIST** collaboration

ISOLDE at CERN

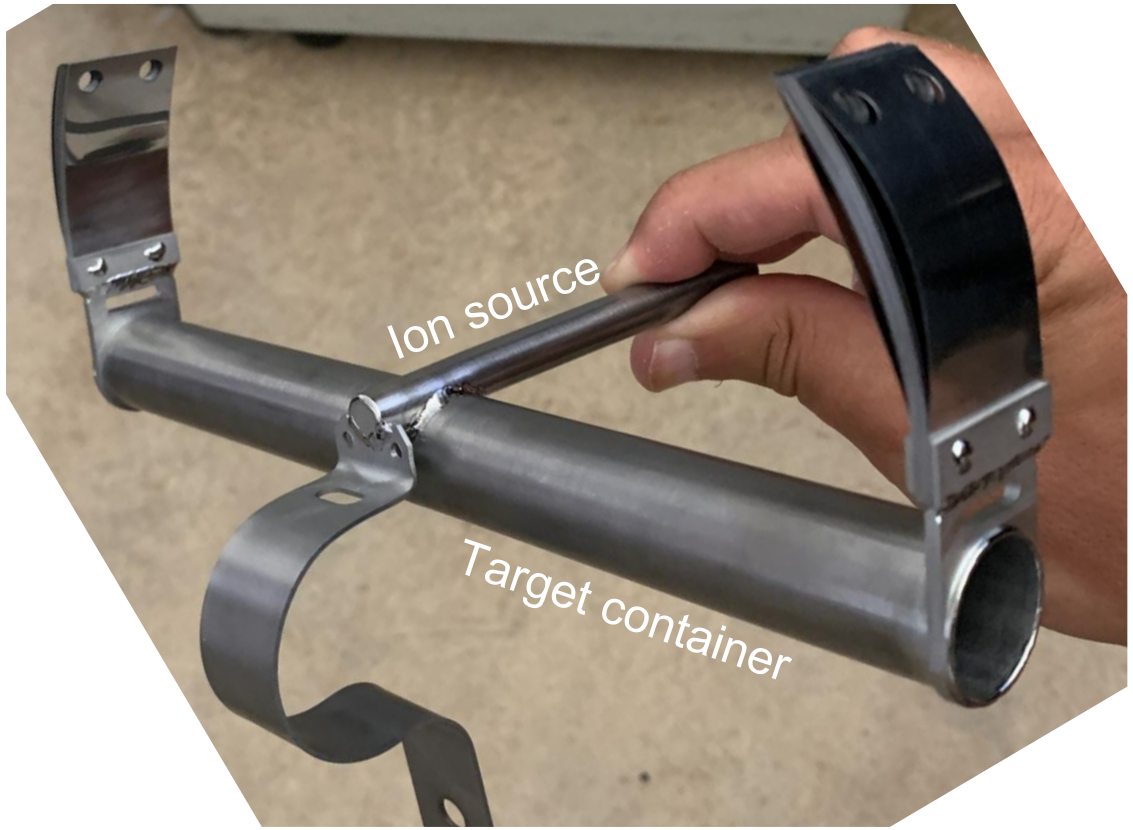


The ISOLDE facility at CERN

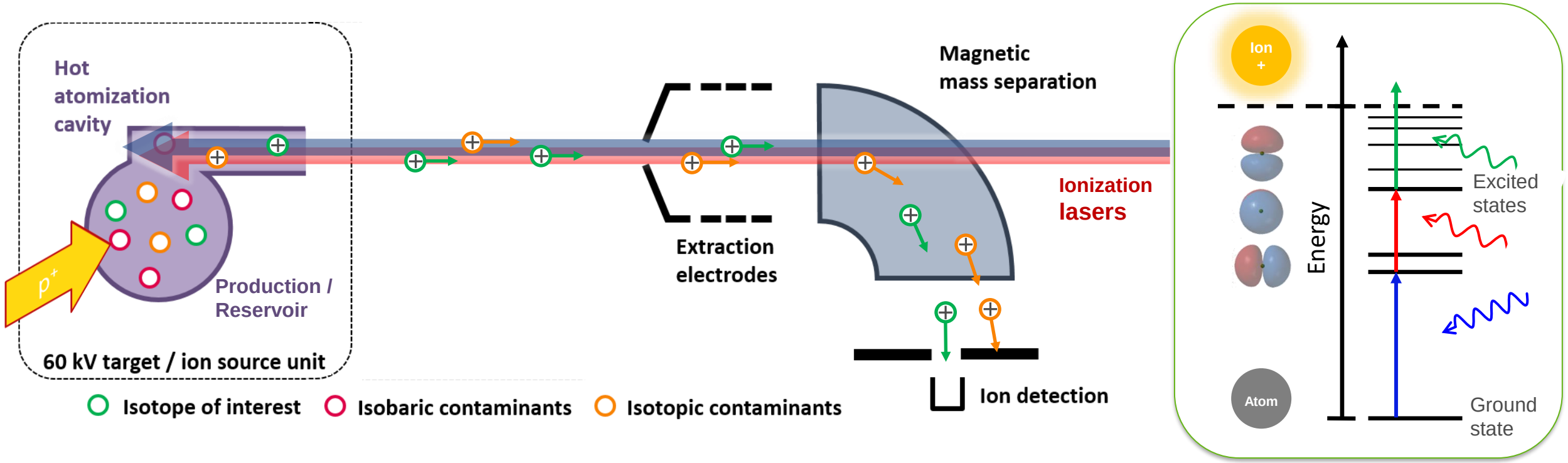




ISOLDE frontend and target/ion source unit



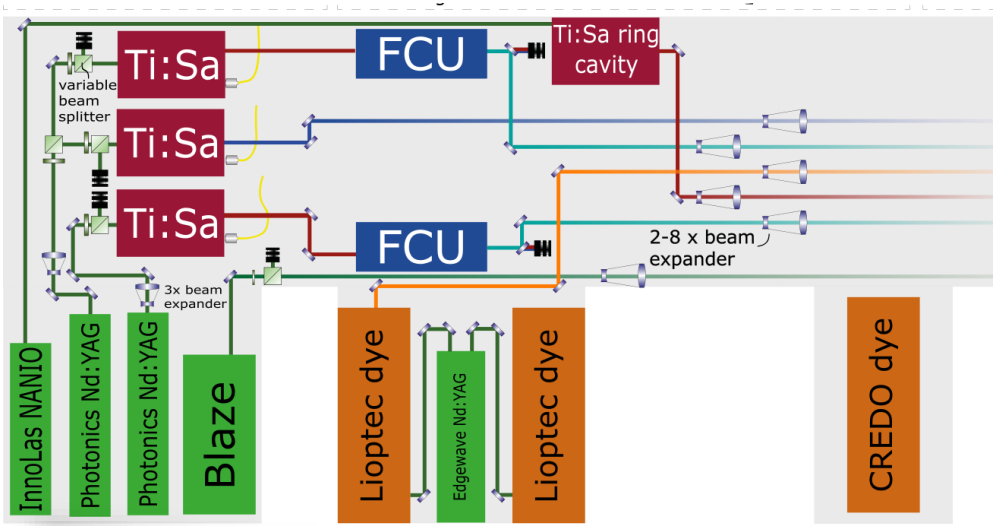
ISOLDE's resonance ionization laser ion source RILIS

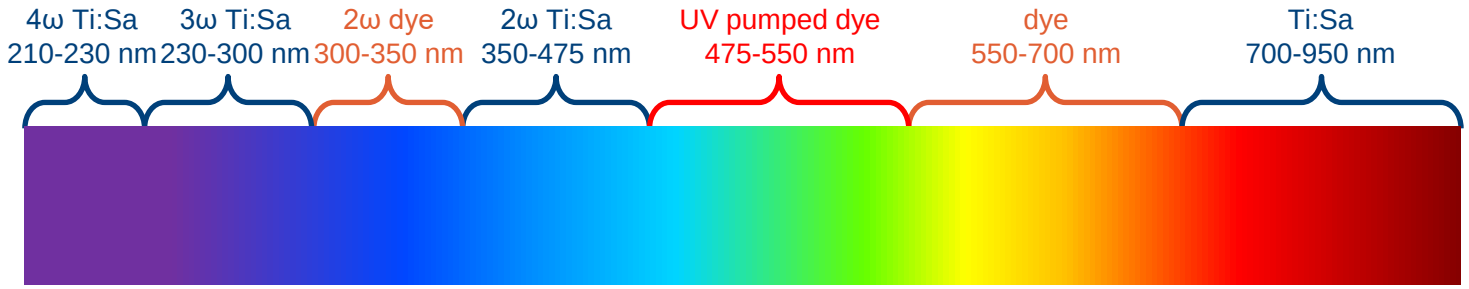


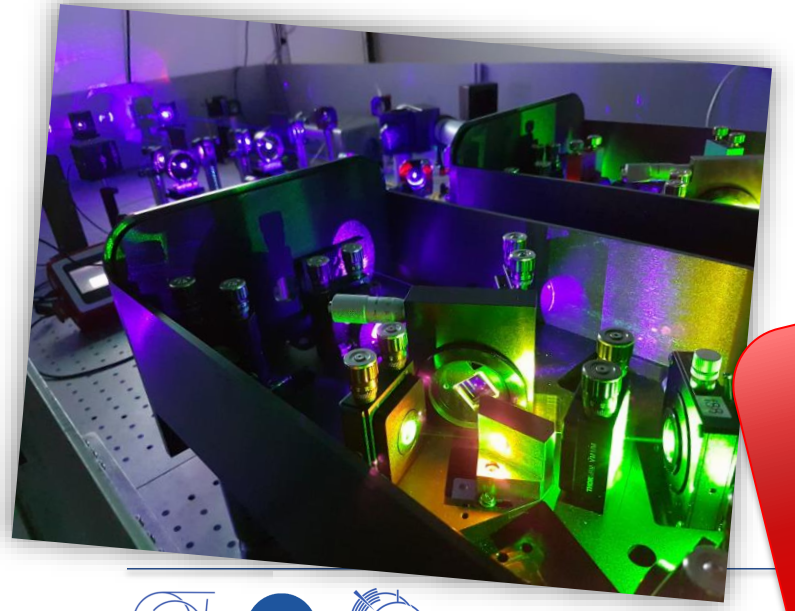
- Effusion of reaction products provided as **hot atomic vapor** (> 2000°C)
- Highly efficient laser ionization of **element of choice** *as function of laser wavelength ➔ in-source spectroscopy (<< 1pps)*
- Extraction and mass separation as **ion beam**

The RILIS laser setup

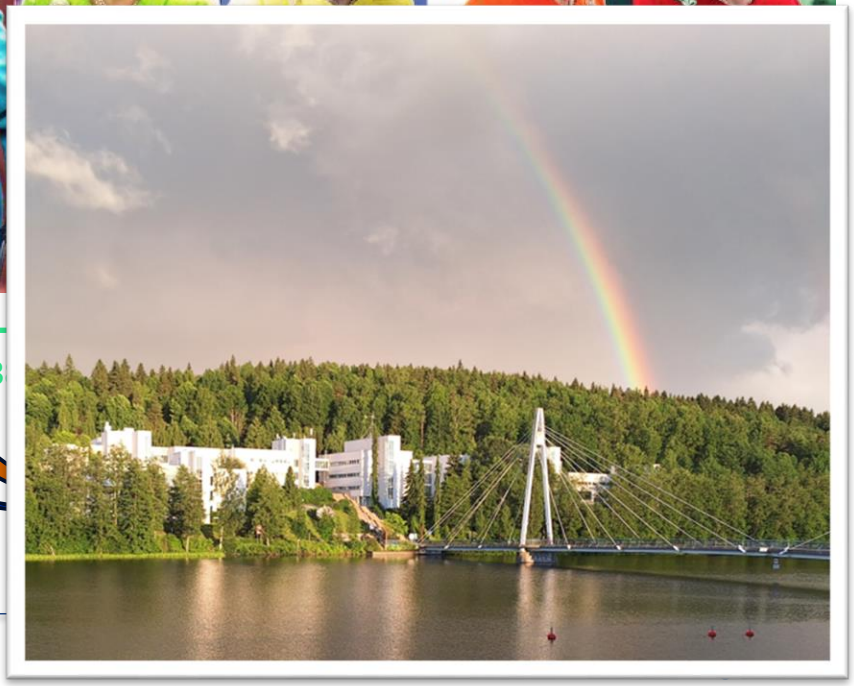
10kHz rep-rate wavelength-tunable systems (commercial + development)



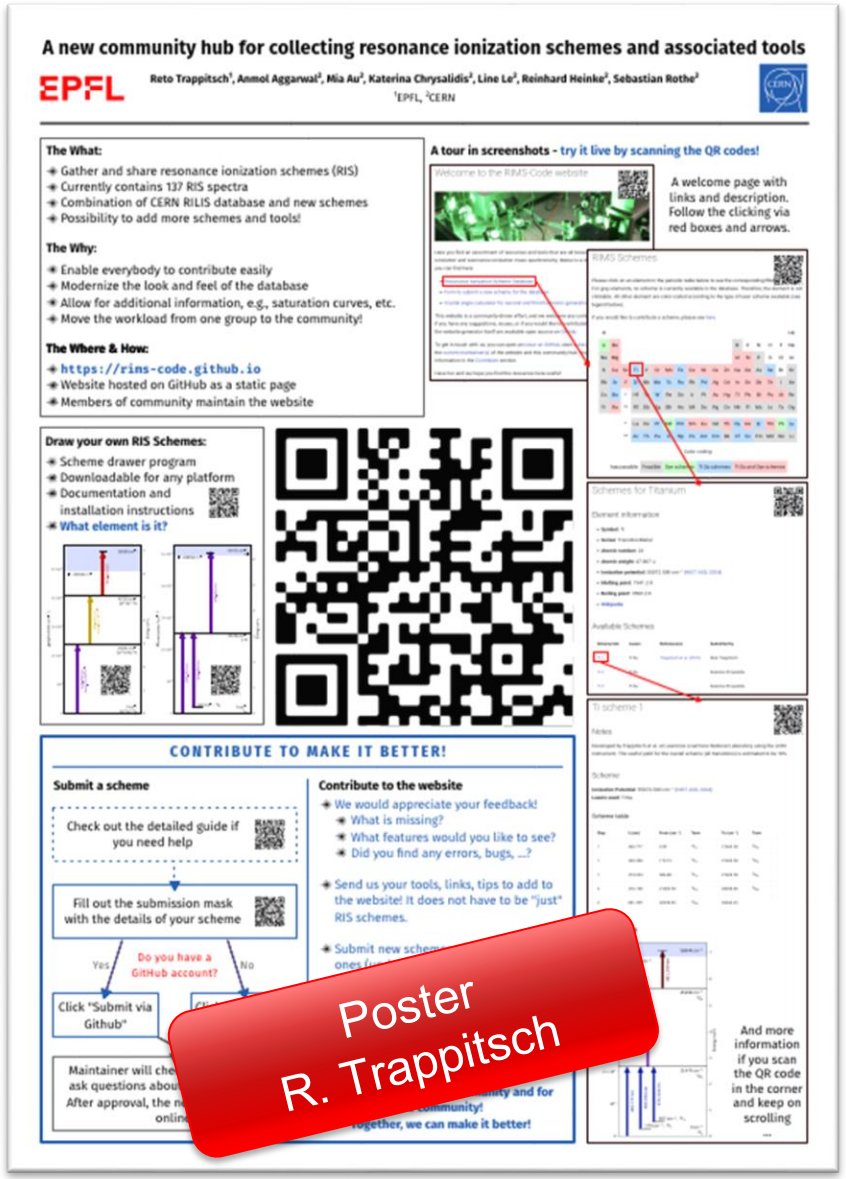


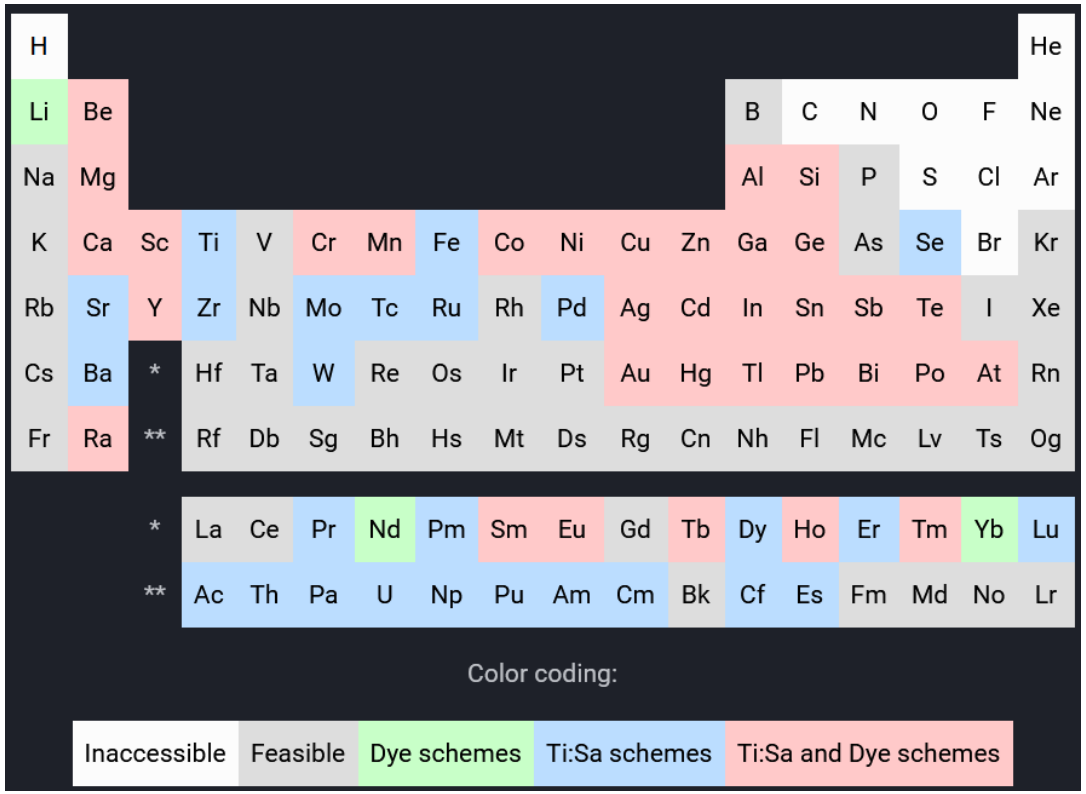


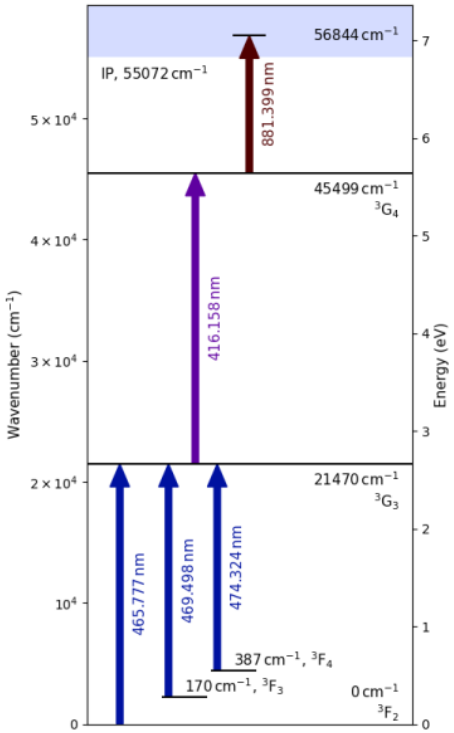
Solid state laser development:
Mixing (poster J. Wessolek),
Raman shifting (poster C. Bernerd)



A new community-driven laser scheme database







https://rims-code.github.io

From community for community:
Feedback, feature requests, extension to tool hub, …

RILIS @ ISOLDE: The workhorse ion source

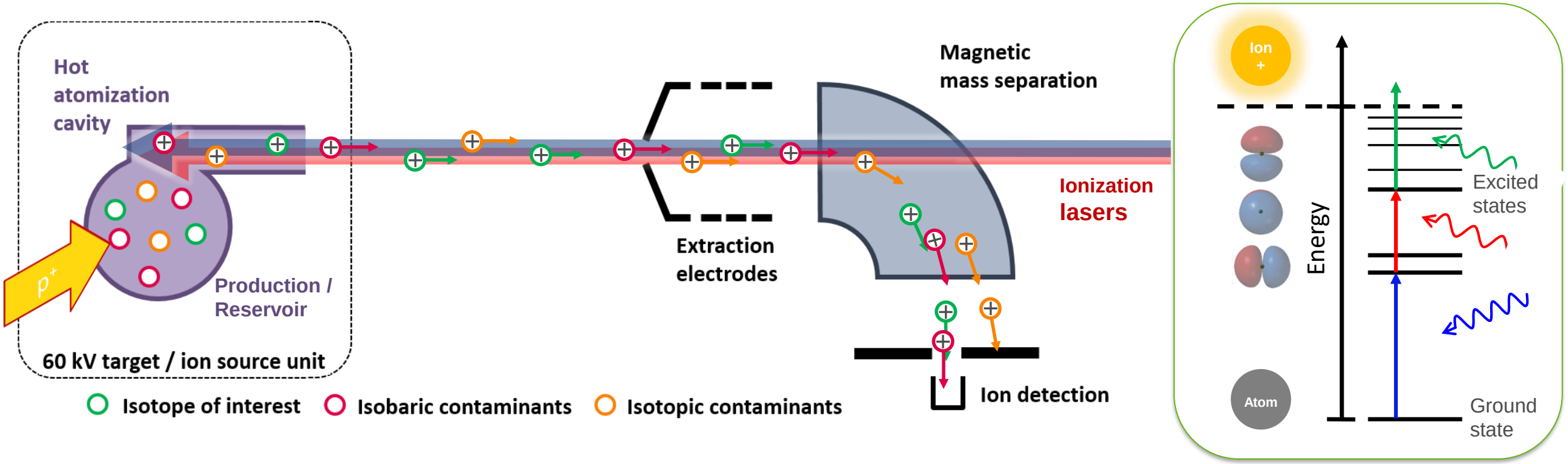
2023 ISOLDE operation schedule

22 elements: Pm, Er, Yb, Gd, In, Dy, Tl, Cd, Hg, Al, Cr, Ac, Ca, Mg, Tm, Zn, Mn, Pb, Sb, Be, Ag, Pr

28 out of 33 weeks *(including weekends)* + development

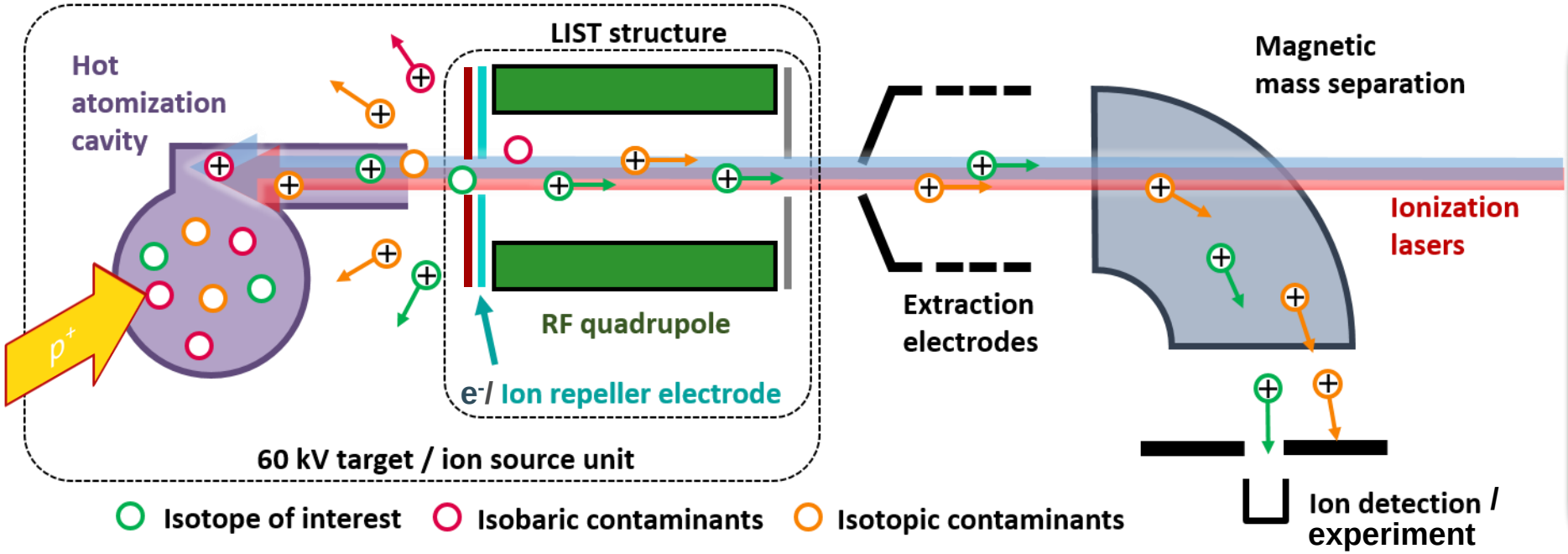
RIB delivery *and* nuclear structure experiments

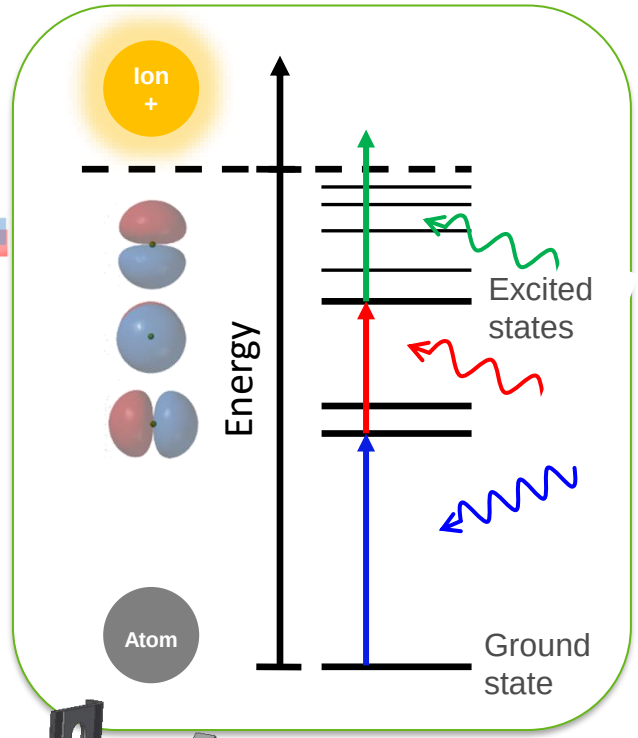
ISOLDE's resonance ionization laser ion source RILIS



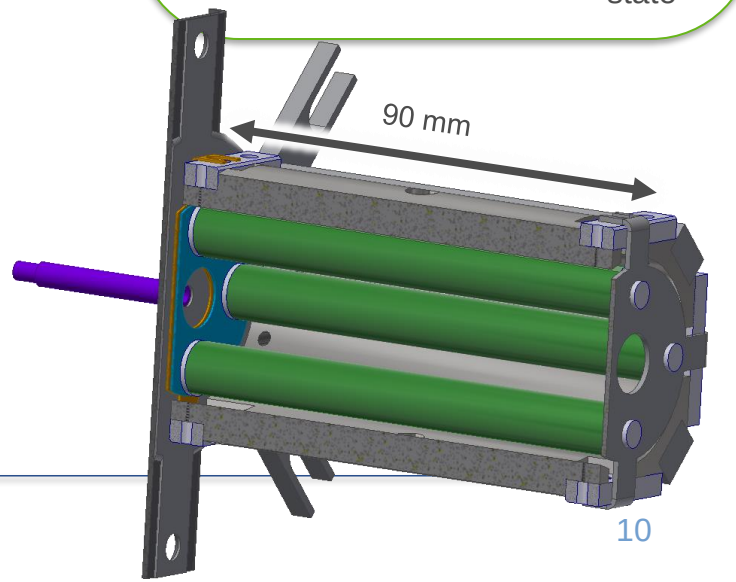
- Effusion of reaction products provided as **hot atomic vapor** (> 2000°C)
- Highly efficient laser ionization of **element of choice** *as function of laser wavelength ➔ in-source spectroscopy (<< 1pps)*
- Extraction and mass separation as **ion beam**
- **Beam purity influenced by competing ionization mechanisms**

The Laser Ion Source and Trap LIST



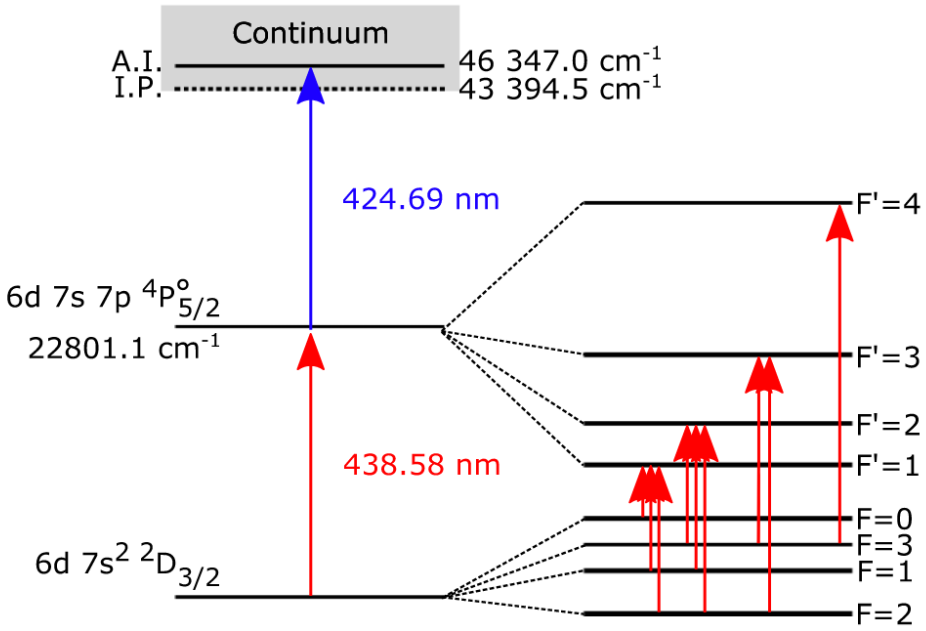


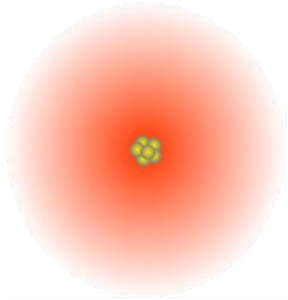
- **Spatial separation:** hot cavity ↔ laser ionization volume
- **Suppression** of surface ionized species
- **Pure laser ionization** inside **RF quadrupole** structure
- Factor up to 10^6 in suppression ↔ Factor 20-100 reduction in beam intensity
- Versatility: Mimic standard RILIS by extracting and guiding ions from hot cavity

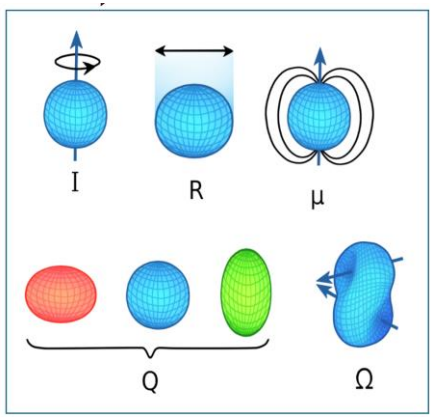


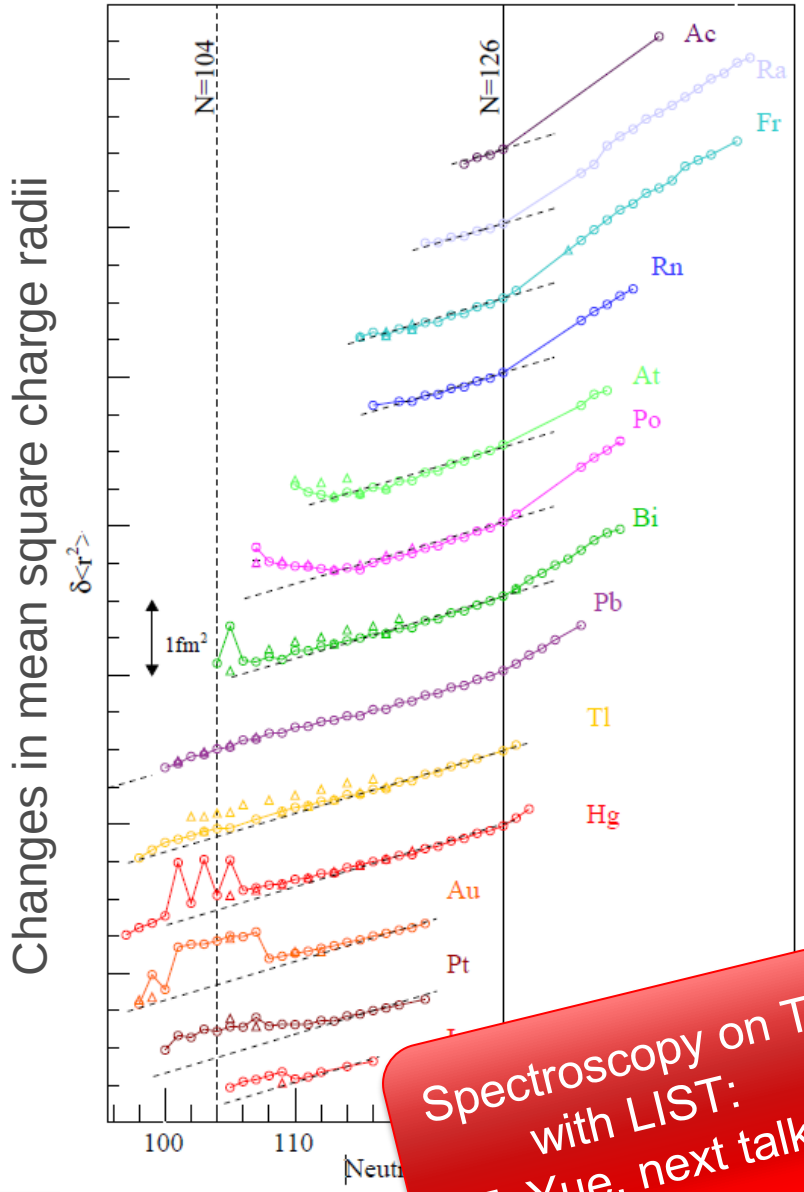
Nuclear structure laser spectroscopy

Ac laser ionization scheme
(used at LISOL, TRIUMF, ISOLDE, JGU, …)









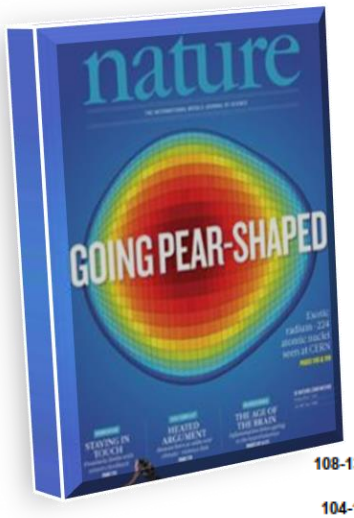
Hyperfine structure spectroscopy:

Interaction of nucleus with electron shell

- Nuclear spin, deformation
- Changes in charge radii

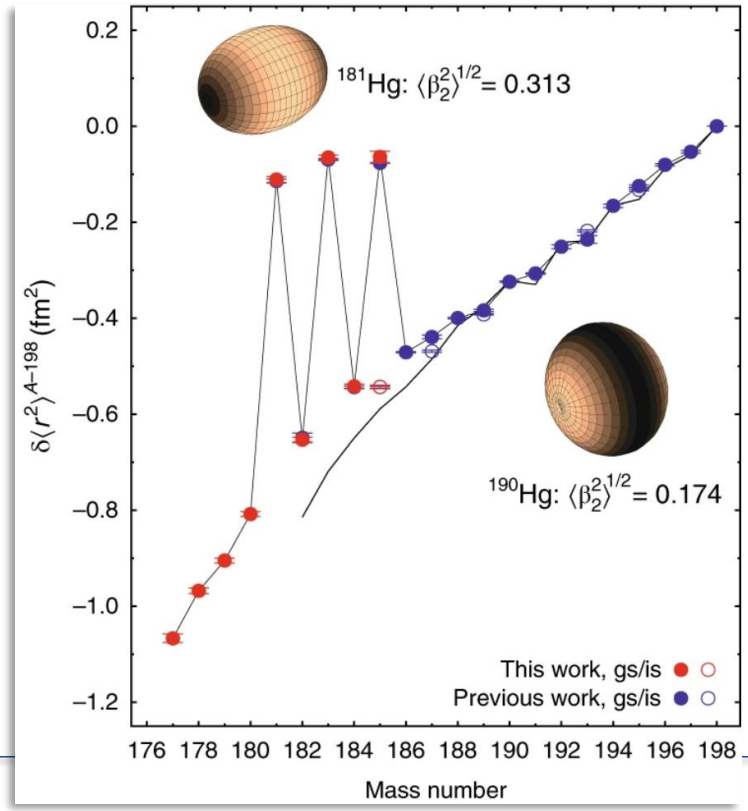
Spectroscopy on Tl with LIST: Z. Yue, next talk!

A laser spectroscopist's playground



Collective effects of protons and neutrons

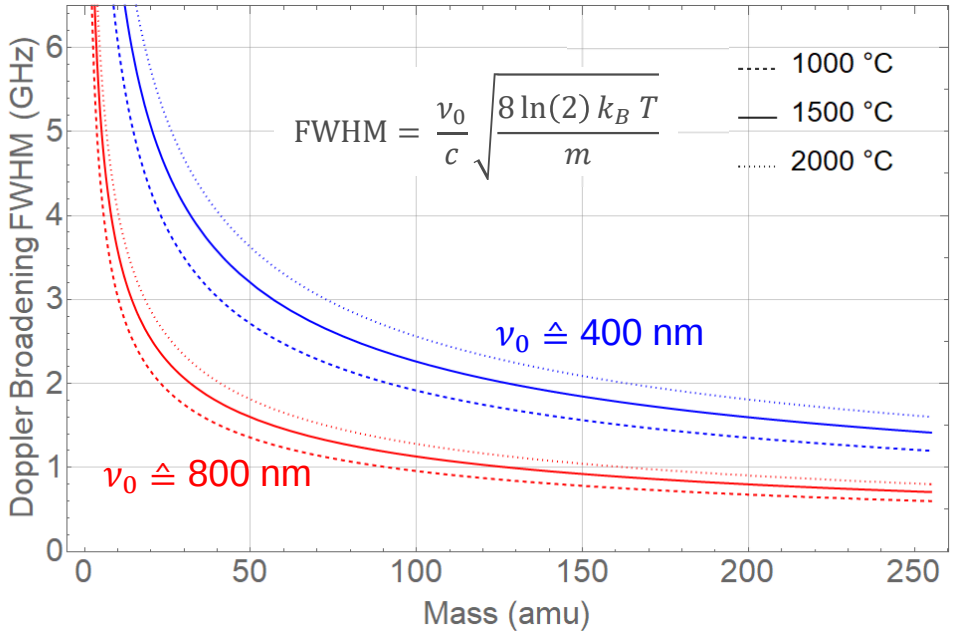
➔ How to derive from first principles / strong force?

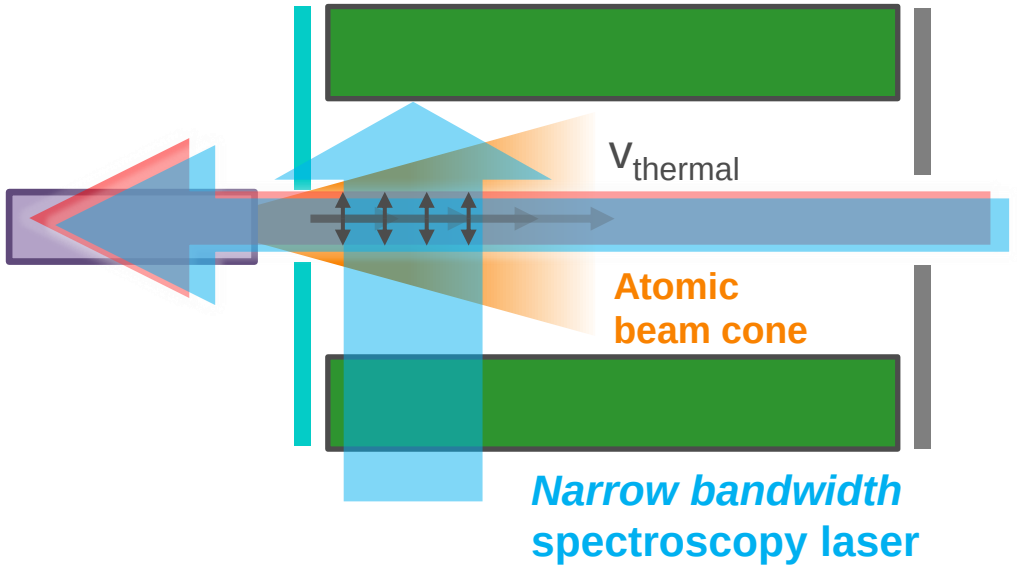


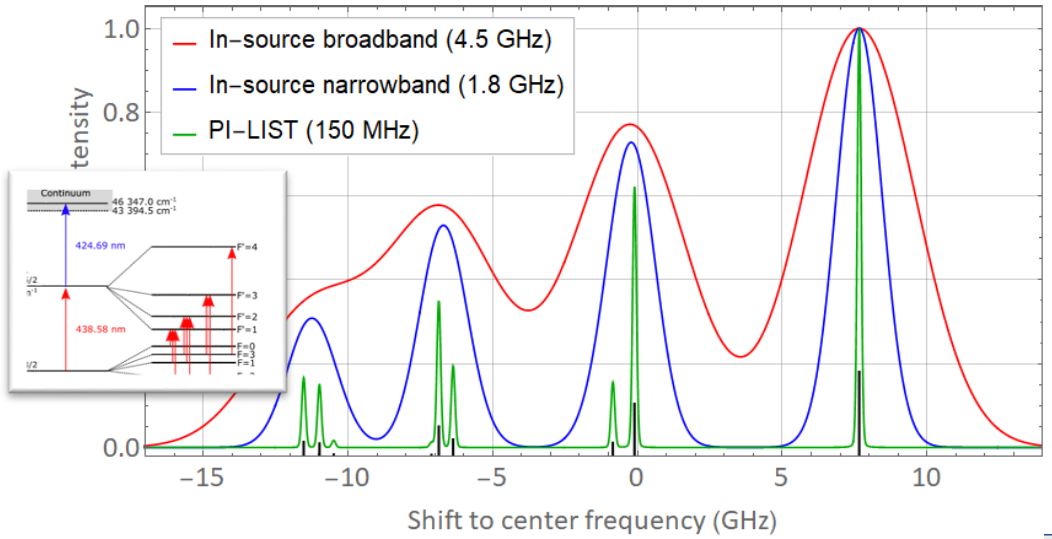
B. Marsh et al, *Nature Physics* **14**, 1163–1167 (2018)

https://www.ikp.tu-darmstadt.de/gruppen_ikp/ag_noertershaeuser/research_wn/exotic_nuclei_wn/uebersicht_2/laserspectroscopy_survey.de.jsp

“Sub-Doppler” hot cavity in-source spectroscopy







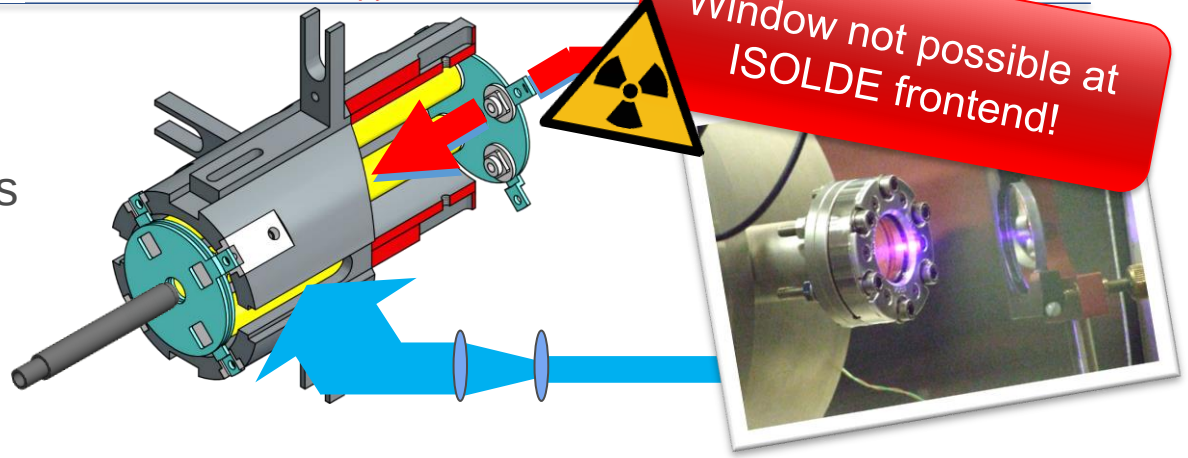
Crossed atom beam / laser geometry in LIST structure:

The **P**erpendicularly **I**lluminated **PI-LIST**

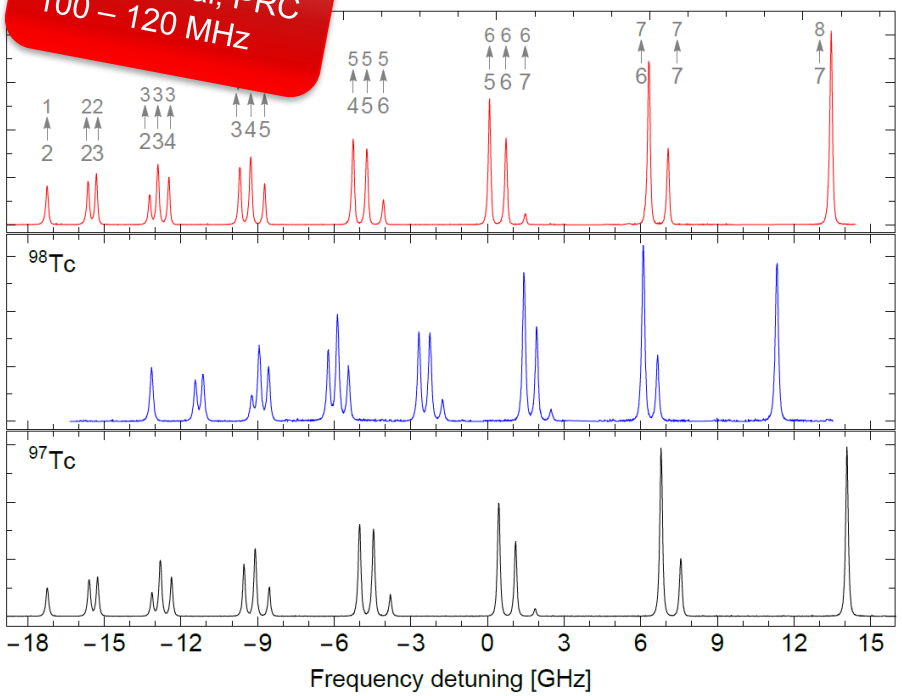
- Selection of **reduced Doppler ensemble** in laser intersection volume
- Suitable **narrow-band laser**
  - ➢ Resolution improvement by >1 order of magnitude

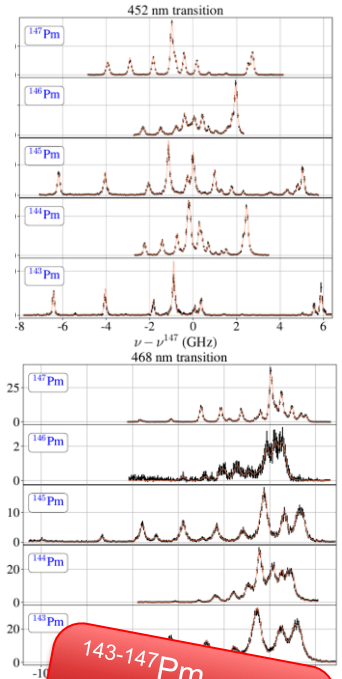
Off-line results from PI-LIST

- Lateral laser incoupling through window in vacuum vessel
- Nuclear structure investigations on long-lived radioisotopes
- Standard tool for high resolution spectroscopy

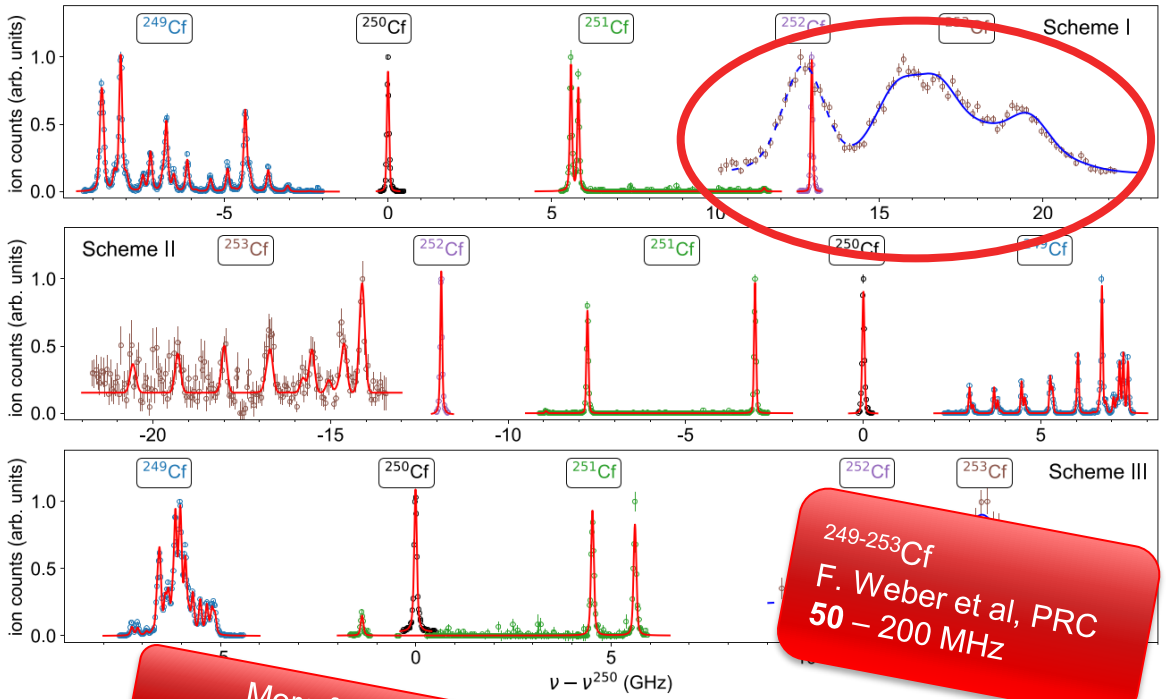


97-99Tc
T. Kron et al, PRC
100 – 120 MHz





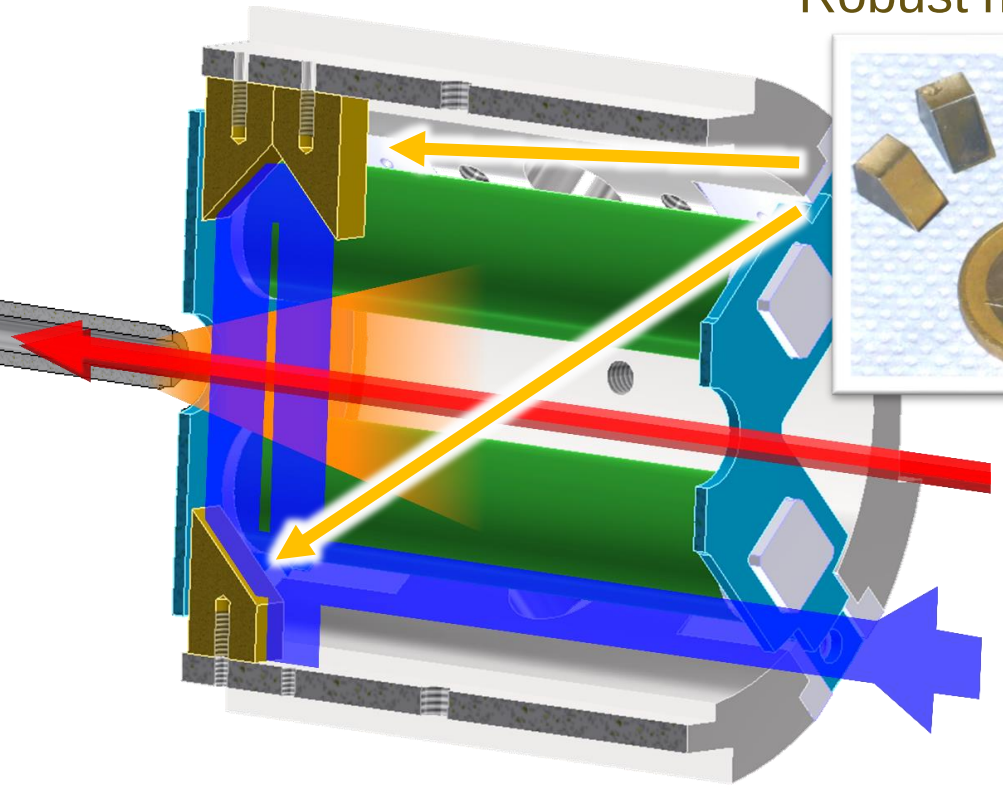
143-147Pm
D. Studer et al,
Eur. Phys. J. A.
100 – 250 MHz



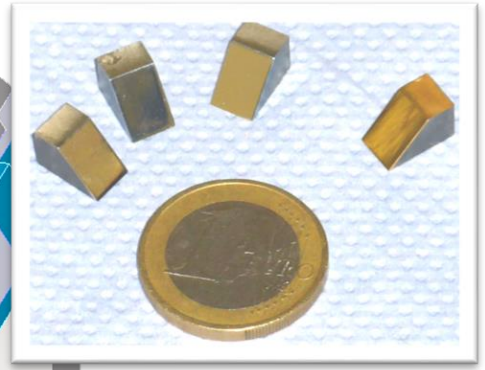
249-253Cf
F. Weber et al, PRC
50 – 200 MHz

More from Mainz!
Es, Fm, … (Tuesday talks)

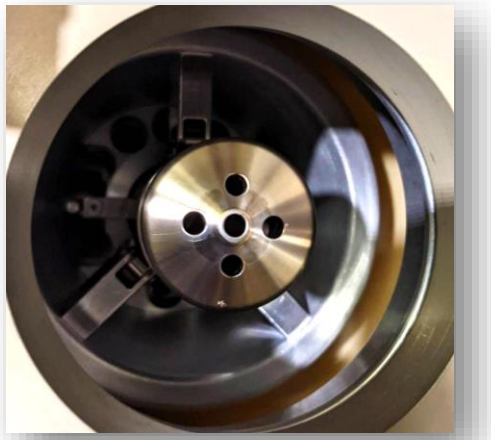
ISOLDE adaption of PI-LIST

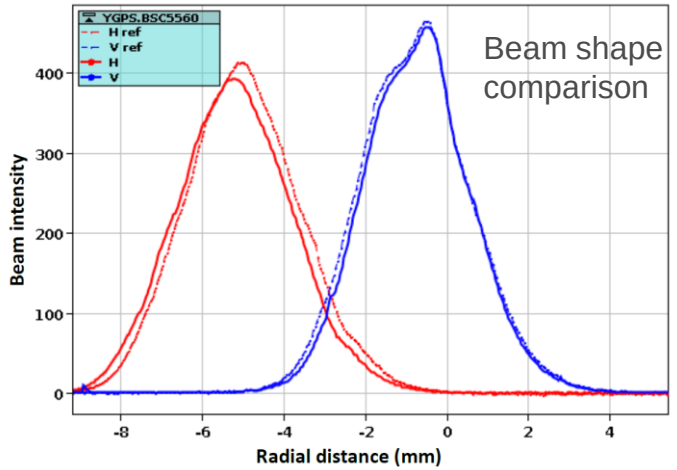


Robust metallic mirrors



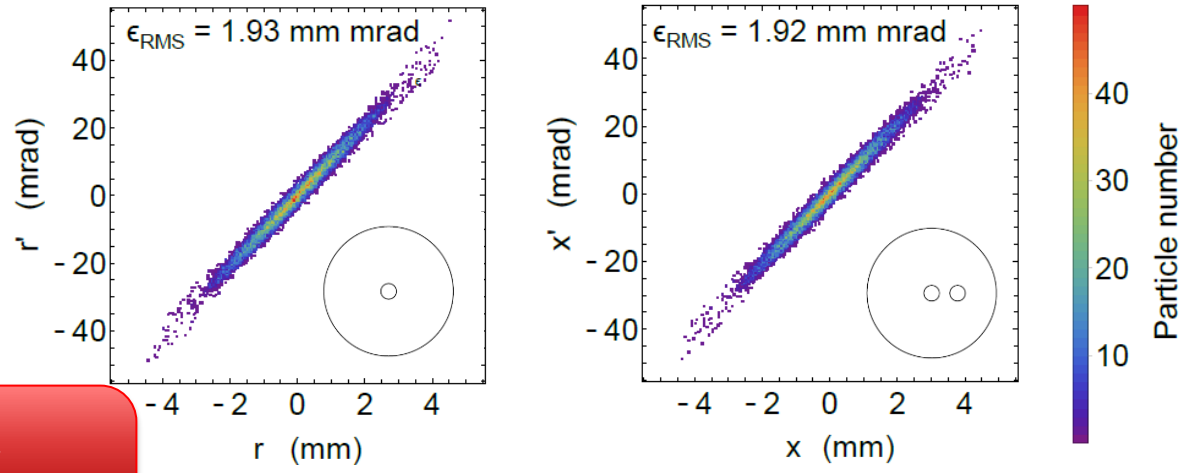
Adapted extraction electrode





Beam shape comparison

Emittance simulations



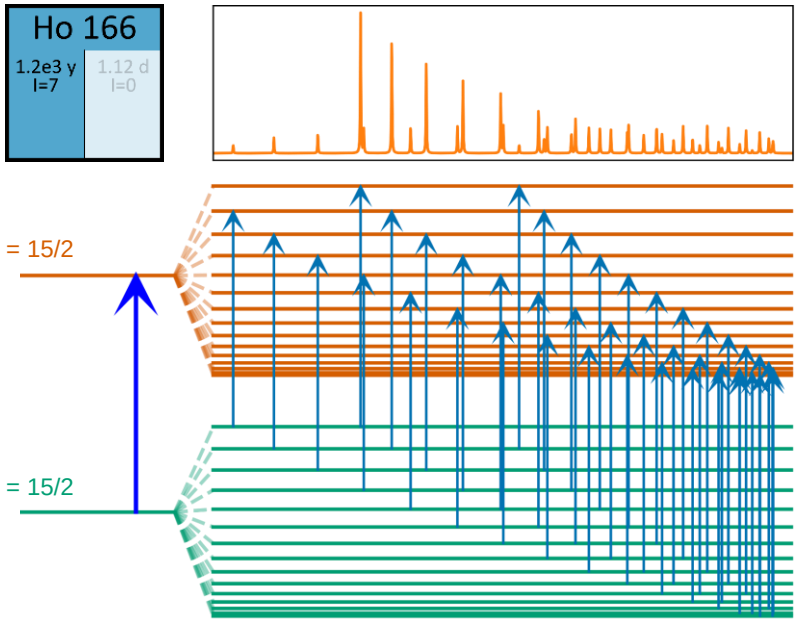
No windows possible in ISOLDE frontend

- Reflection by **metallic mirror** surfaces
- **Off-axis guiding** of laser through

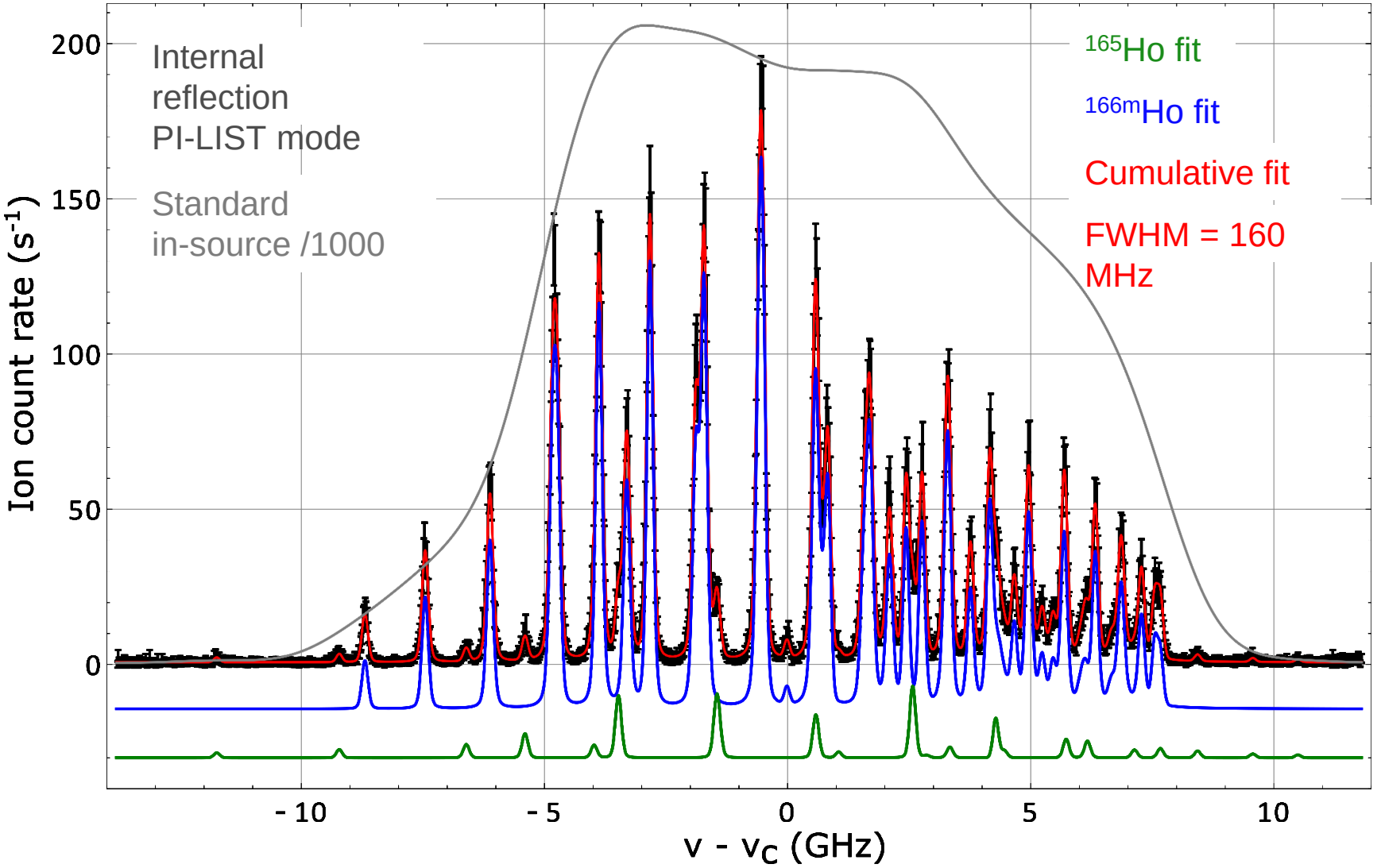
PI-LIST ready for on-line experiment!

Holmium – a showcase

Hyperfine structure studies on long-lived ^{163,166m}Ho for the ECHo project



43 HFS components
+ 23 from leaking ^{165}Ho



Nuclear shape effects in the heavy-element region

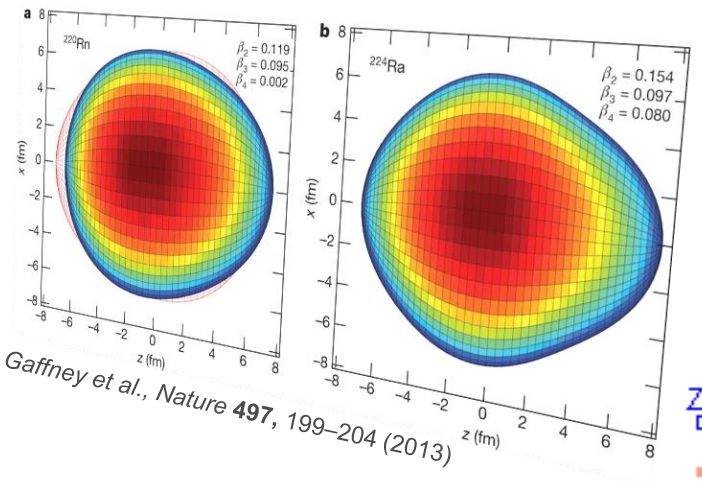
- Pear shaped intrinsic nuclear configurations
- Breaking of reflection symmetry
- Prominent around ^{222}Ra (Z ≈ 88, N ≈ 134)
- Inverted odd-even staggering

  of charge radii? (Po, At, Fr, Rn, Ra)
- Within EU ITN LISA:

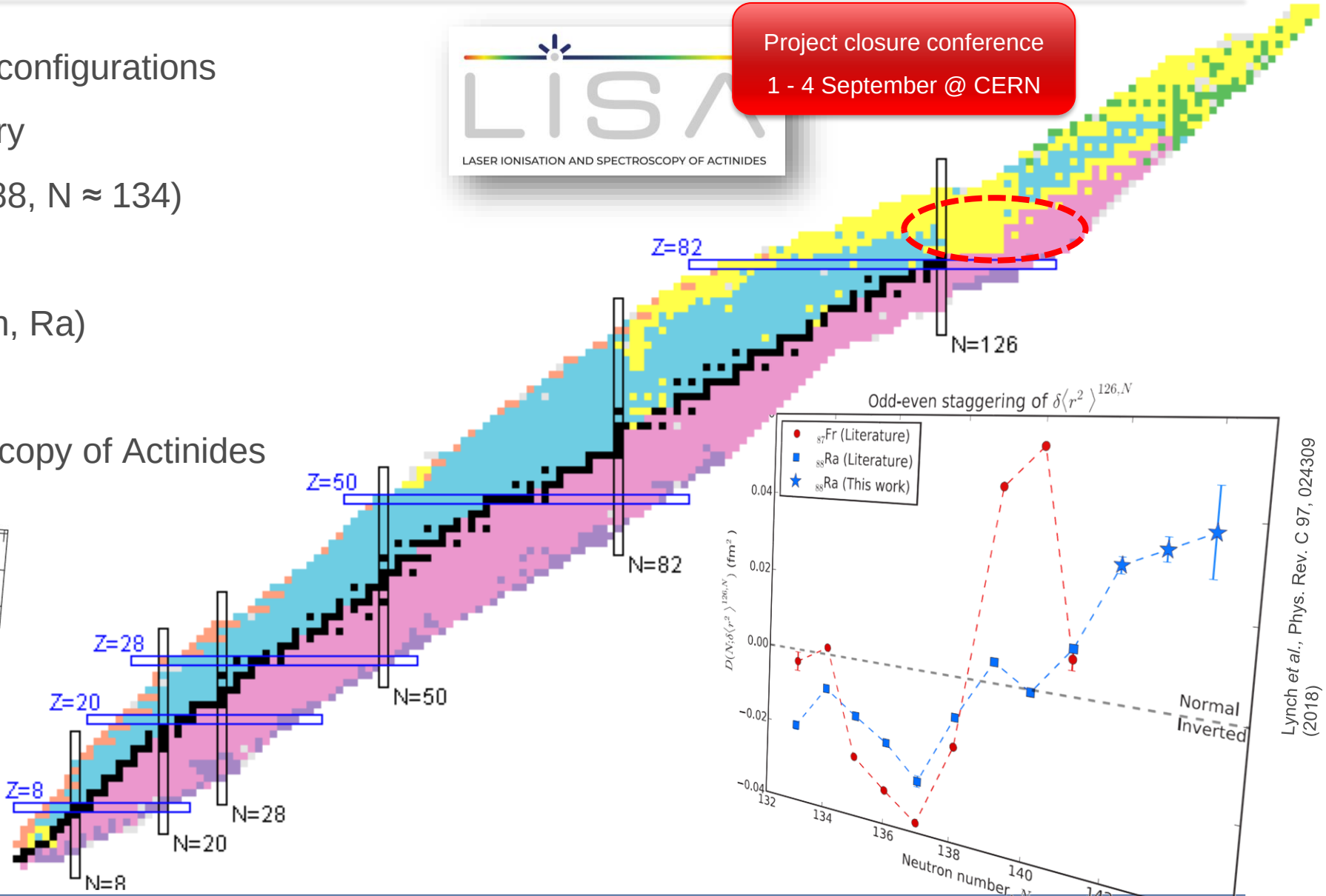
  Laser Ionization and Spectroscopy of Actinides

LISA
LASER IONISATION AND SPECTROSCOPY OF ACTINIDES

Project closure conference
1 - 4 September @ CERN

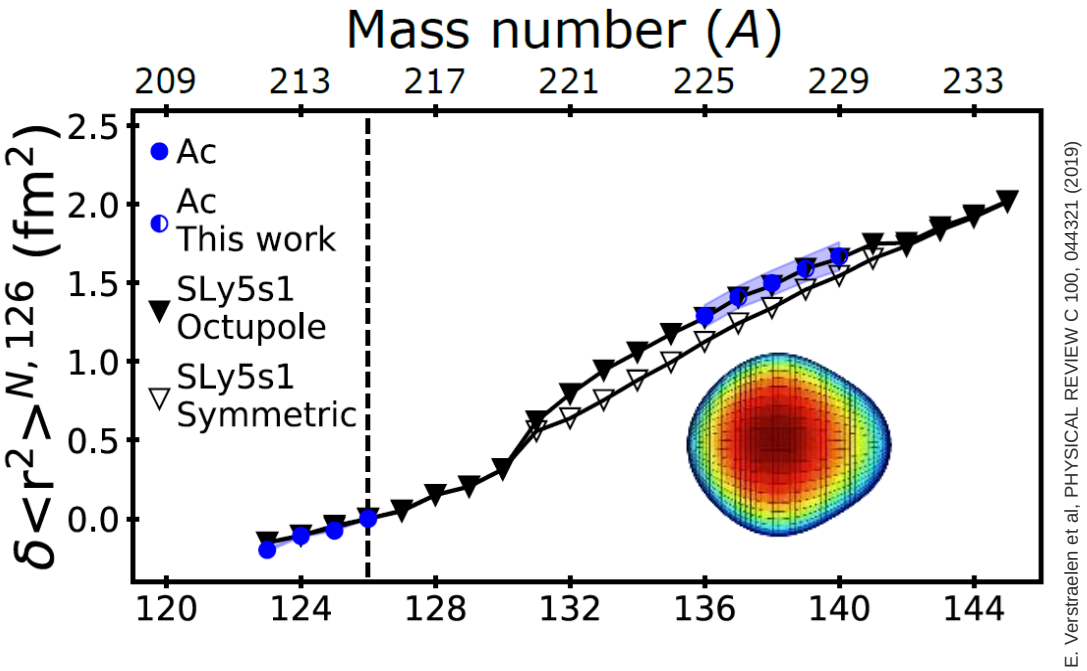


Gaffney et al., Nature **497**, 199–204 (2013)



Lynch *et al.*, Phys. Rev. C 97, 024309 (2018)

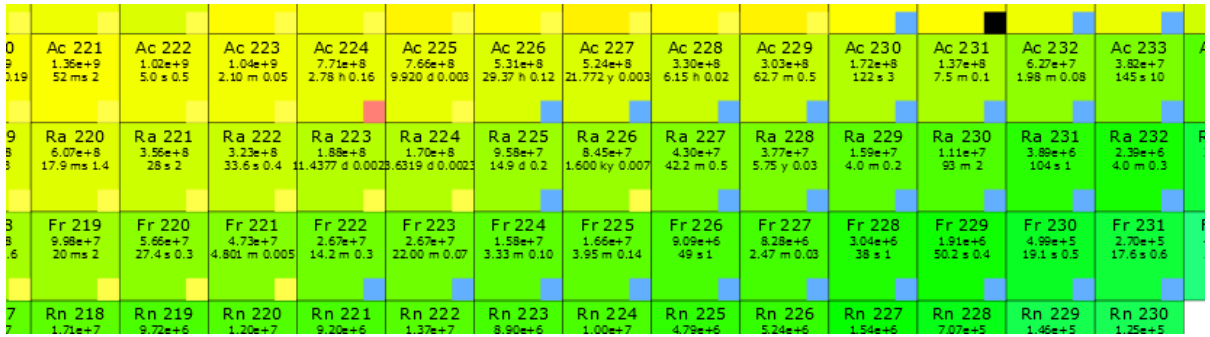
Octupole deformation in Ac isotopes



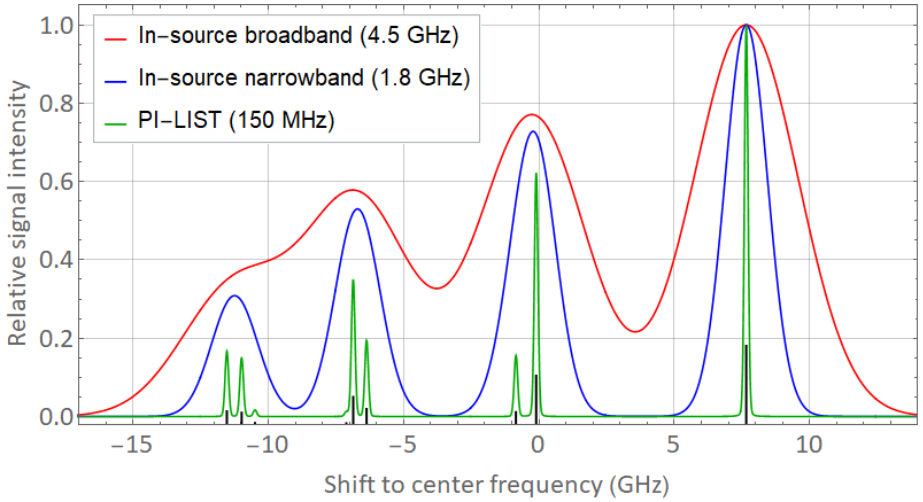
E. Verstraelen et al. PHYSICAL REVIEW C 100, 044321 (2019)

Recent investigations and EDF theory on Ac:

- Available data matched only with octupole asymmetry
- Distinct kink as benchmark case
- Nuclear moments as supporting data



Significant isobaric contamination ➔ LIST suppression



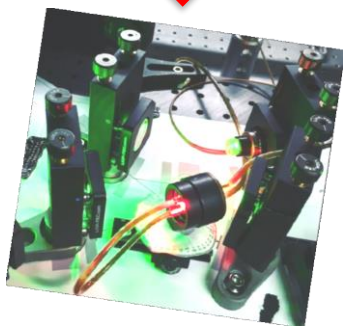
Low sensitivity to Q_S ➔ PI-LIST high resolution

IS664: Experimental setup

Joined NB laser infrastructure

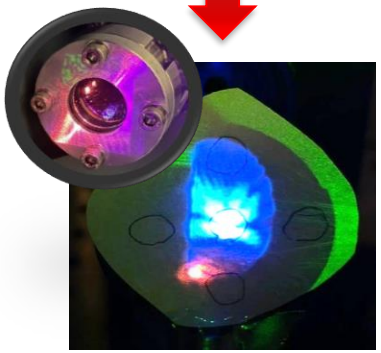
CRIS Matisse
cw Ti:Sa

Cross-hall fiber



RILIS injection-locked
pulsed ring cavity

Separator launch

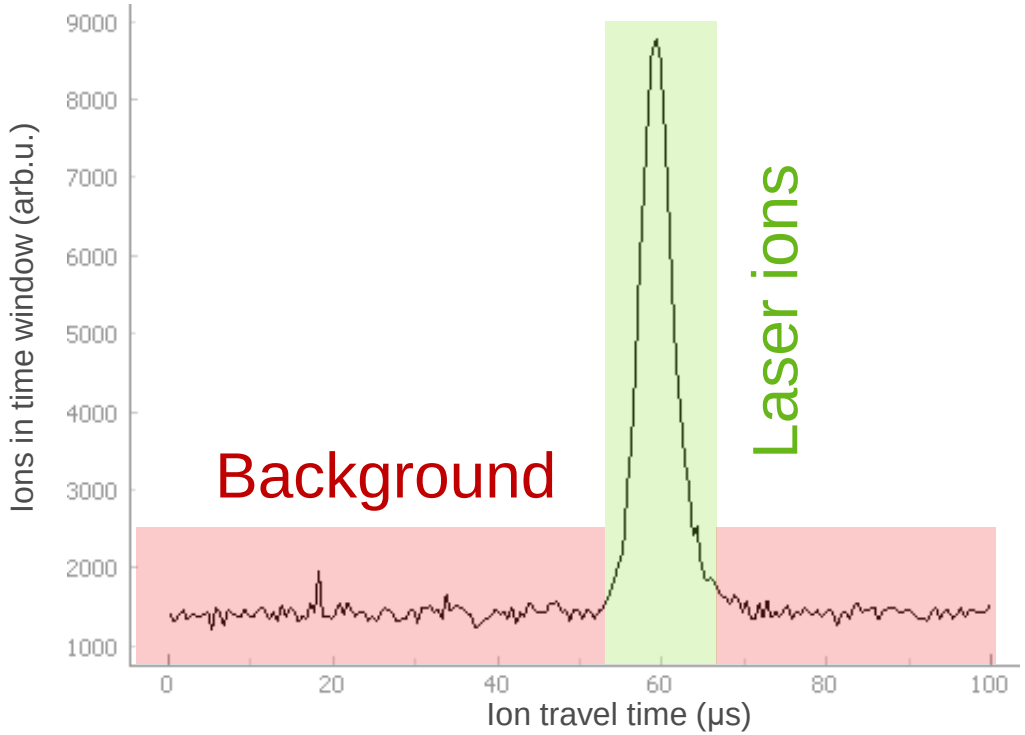


PI mode
referencing

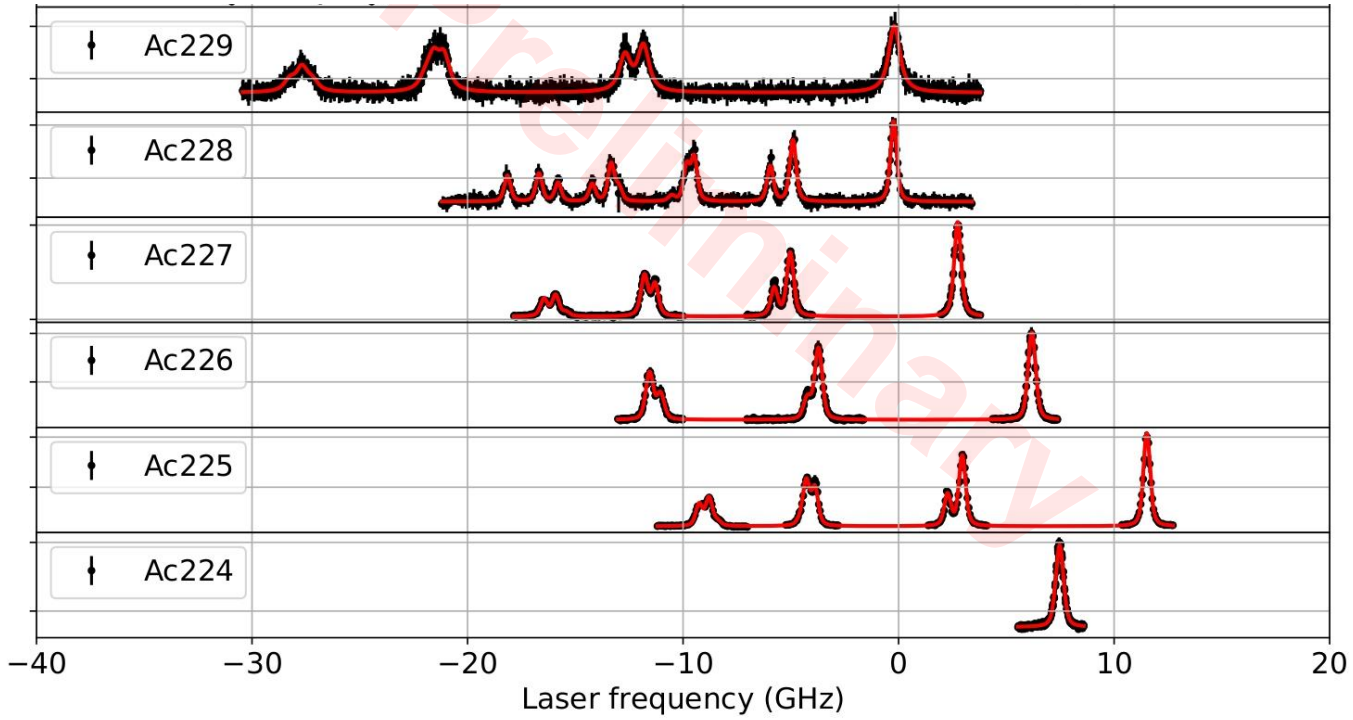
Detector and DAQ

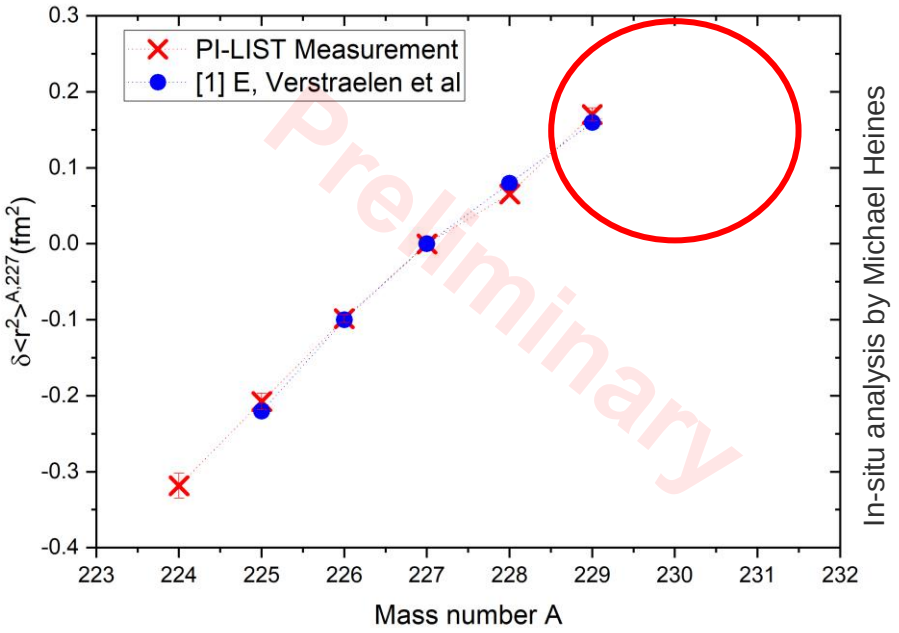
MagneTOF single ion counter at GLM/LA1 beam lines

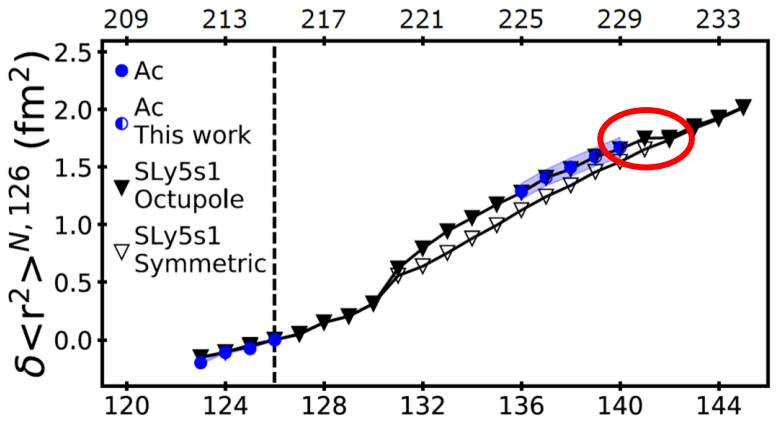
- Highly sensitive
- Laser-synchronized 10kHz DAQ (CRIS time tagger)



Preliminary results: Radii kink confirmed?

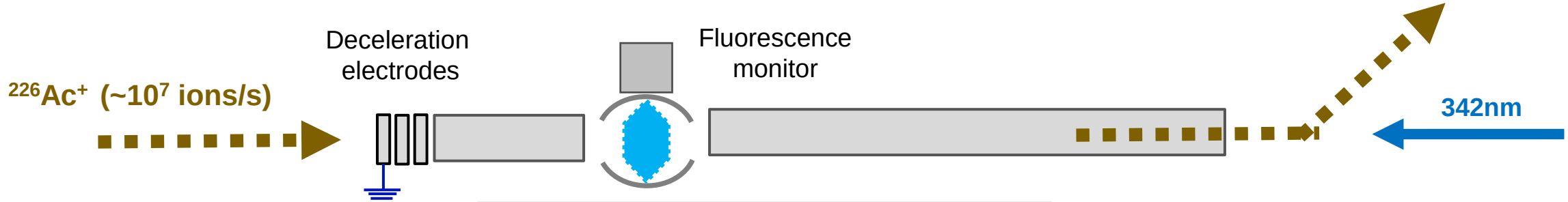


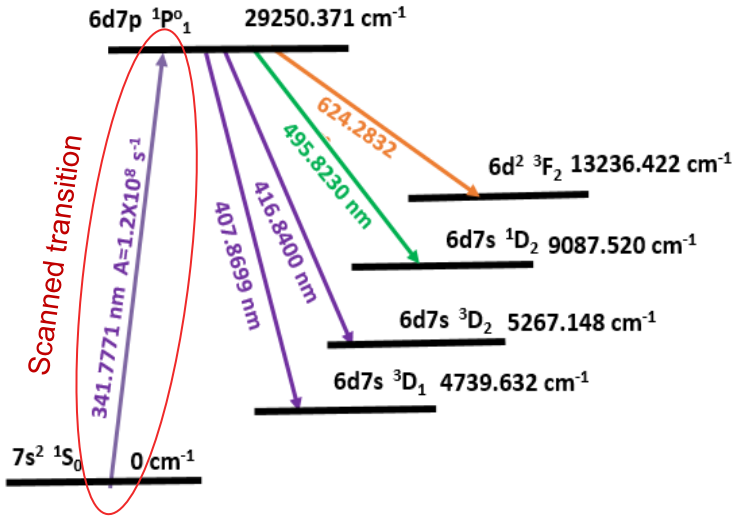


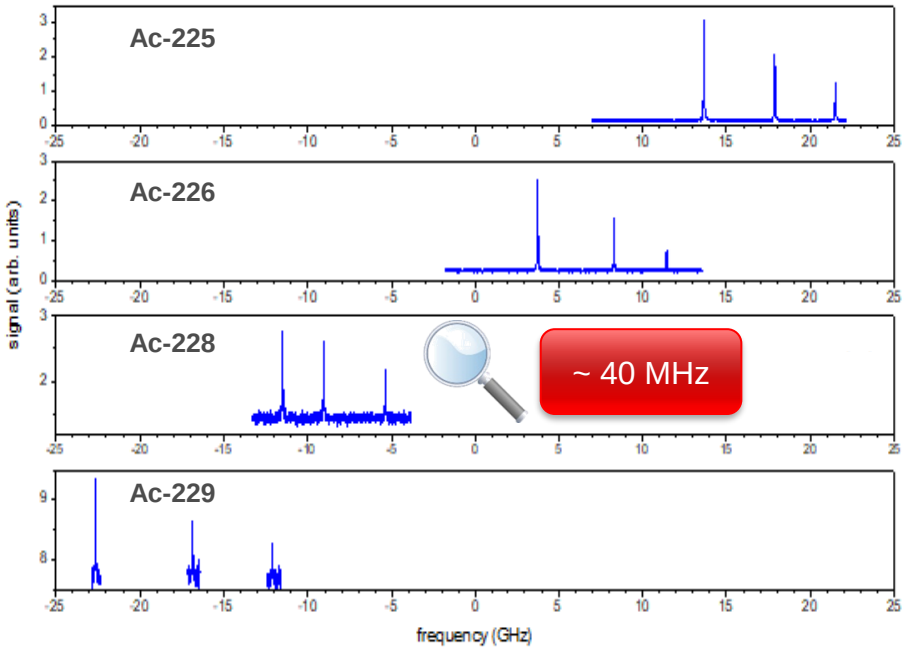


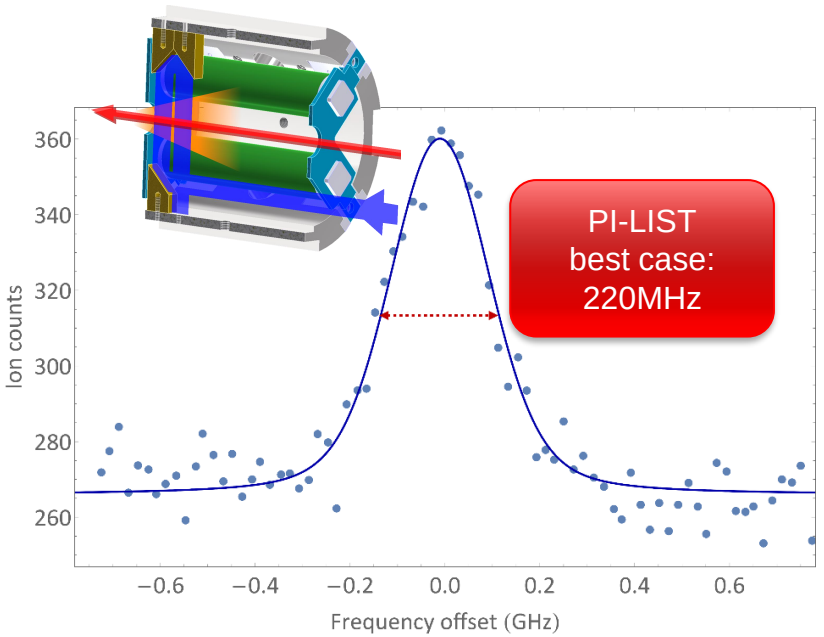
Complementary data: Collinear laser spectroscopy at TRIUMF

COLLAPS principle: Fluorescence detection after exciting **ionic** transition







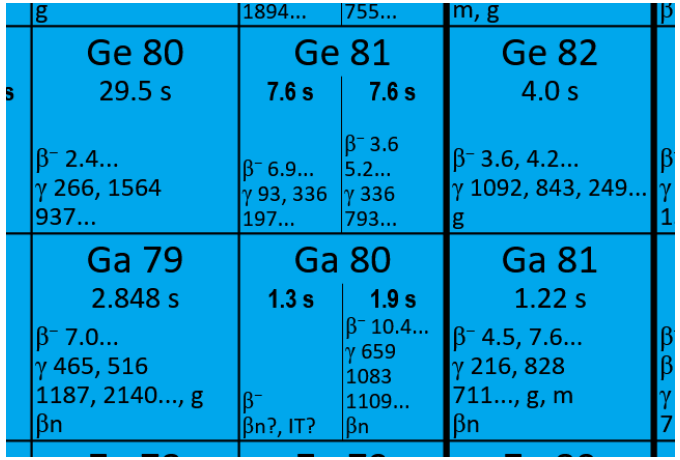


➔ Complementary high-resolution data; Systematic check of nuclear structure results

PI-LIST for isomer-pure RIB production

Example case for inspiration

Search for the 0_2^+ state in ^{80}Ge from isomerically purified ^{80}Ga states

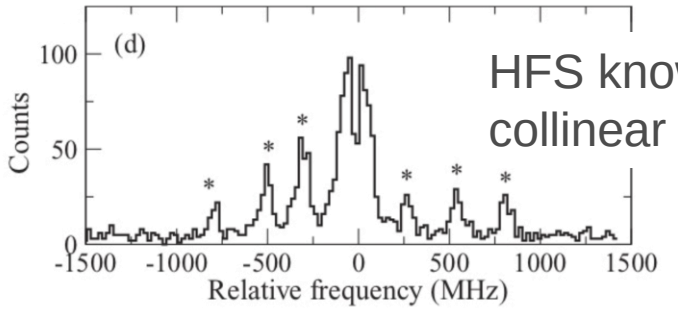


I = 3- / 6-

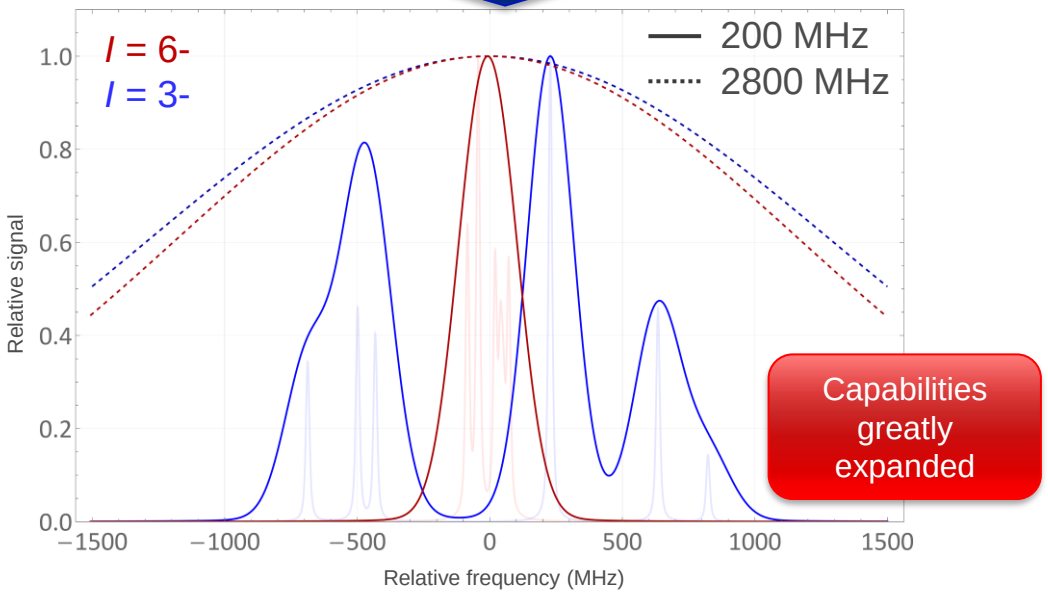
Isomer-pure RIB's

- Direct spectroscopy in clean samples
- (Spin-)Controlled feeding
- Switch ID ↔ efficiency

B. Cheal et al., Phys. Rev. C 82, 051302(R) (2010)



HFS known from collinear spectroscopy

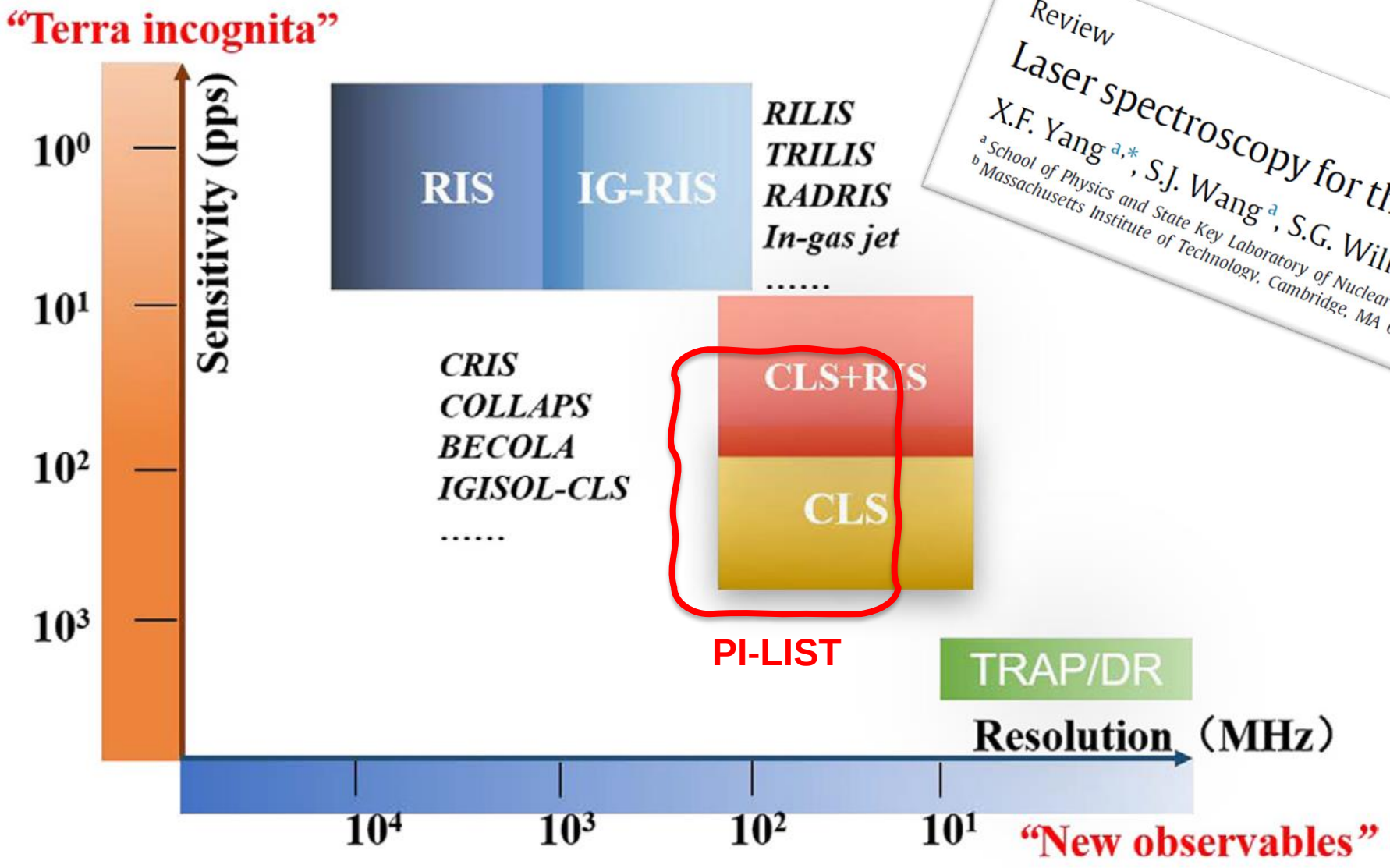


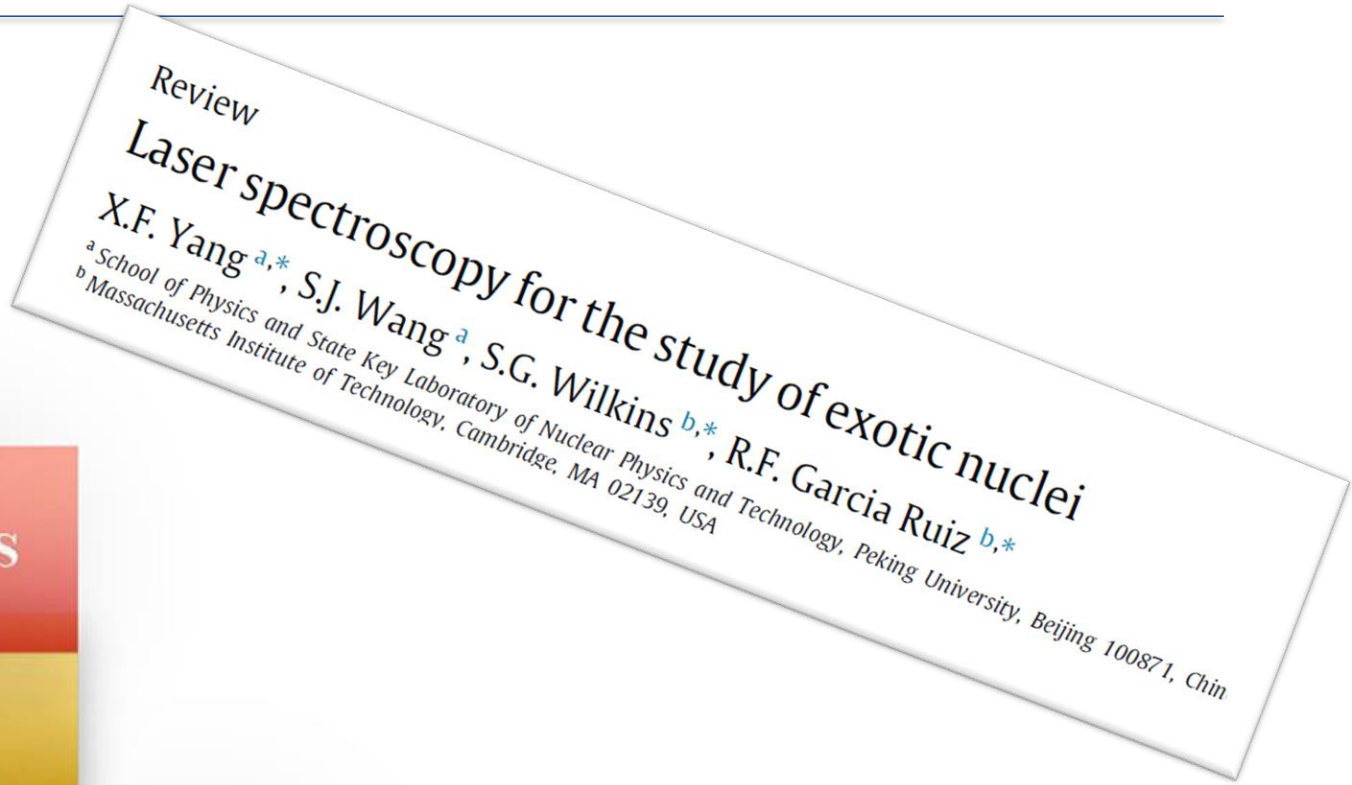
Capabilities greatly expanded

Table 1: Summary of estimated implanted ions.

^{80}Ga state	$T_{1/2}$ (s)	Yield (ions/μC)	p current (μA)	trans. (%)	PI-LIST eff. (%)	ions /s	duty cycle (%)	ions /hour	ions /shift
3^-	1.3	4.5E6	1.7	90	0.1	6.9E3	74	1.8E7	1.5E8
6^-	1.9	4.5E6					65	1.6E7	1.3E8

PI-LIST in the landscape of laser spectroscopy




Review

Laser spectroscopy for the study of exotic nuclei

X.F. Yang [a,*], S.J. Wang [a], S.G. Wilkins [b,*], R.F. Garcia Ruiz [b,*]

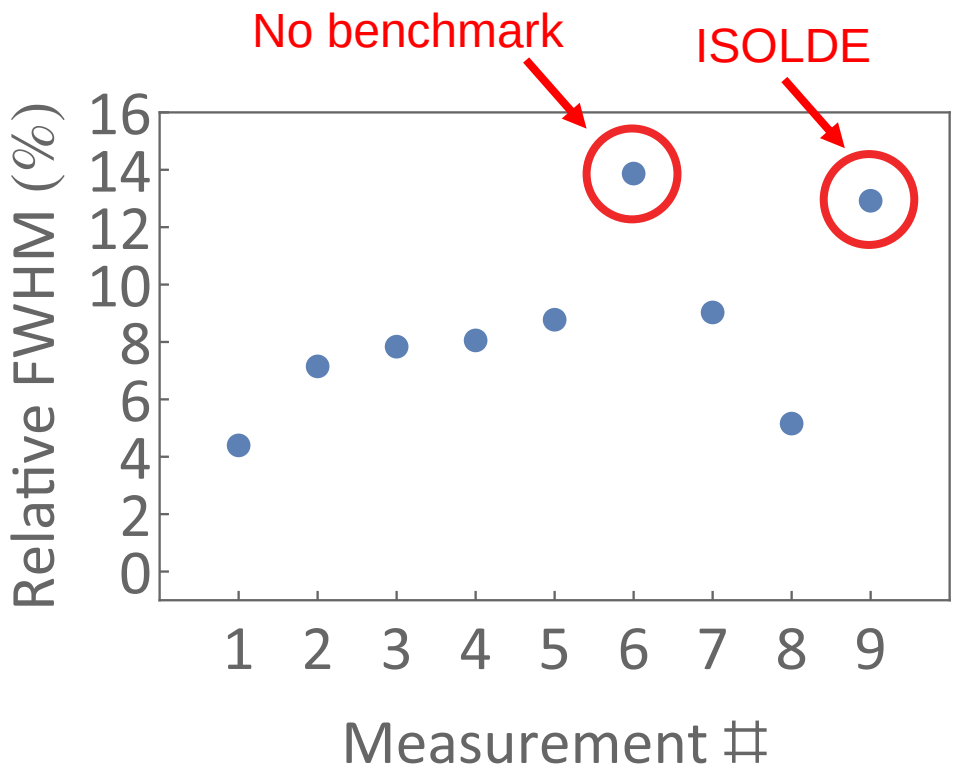
[a] School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, Chin
[b] Massachusetts Institute of Technology, Cambridge, MA 02139, USA

- PI-LIST still "young"
- "Simple" unit instead of beamline
- Versatile operation modes
- Isomer-selective RIB production

Resolution meta-analysis

#		Mass (amu)	WL (nm)	Temp. (C)	LIST type	FWHM (MHz)	Opt?	Doppler (MHz)	Fraction
1	Tc	99	430	1700	JGU	98	yes	2230	4%
2	Ho	165	410	1000	JGU	104	yes	1455	7%
3	Ho	165	410	1000	JGU mirror	114	yes	1455	8%
4	U	238	830	1700	JGU	60	yes	745	8%
5	Rb	87	780	300	JGU mirror	62	yes	707	9%
6	Ac	225	418	1500	JGU	200		1442	14%
7	Pm	145	452	1500	JGU	150		1661	9%
8	Cf	250	417	800	JGU	55	yes	1067	5%
9	Ac	227	439	2000	ISOLDE	200	yes	1548	13%

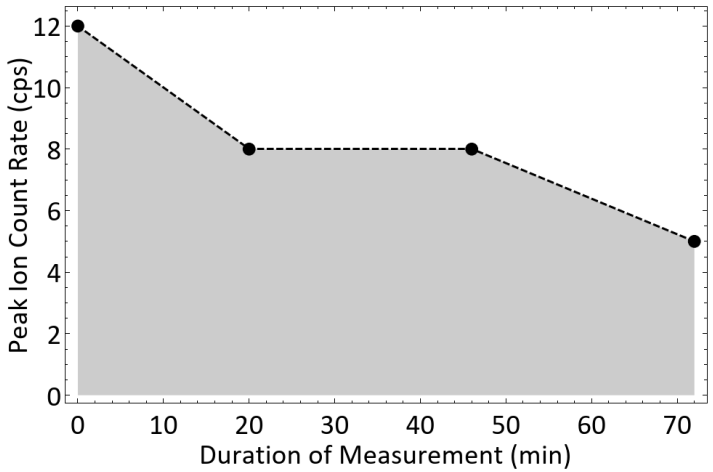
$$\mathrm{FWHM}_{\mathrm{Doppler}} = \frac{\nu_0}{c}\sqrt{\frac{8\ln(2)\,k_B\,T}{m}}$$



Efficiency considerations

Loss factors

RILIS → LIST	~ 30
LIST → PI-LIST	~ 2
PI-LIST opt.	~ 10
Total:	**~ 500 - 1000**

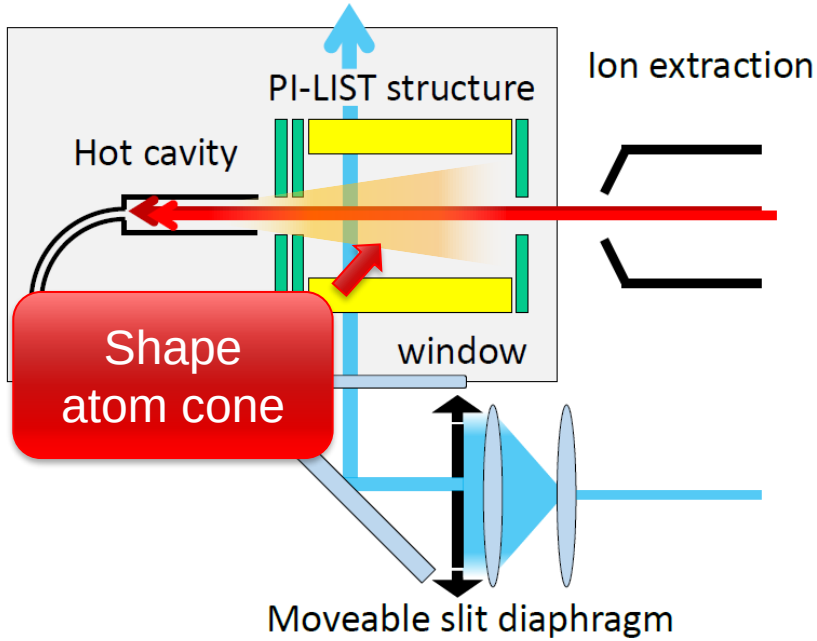


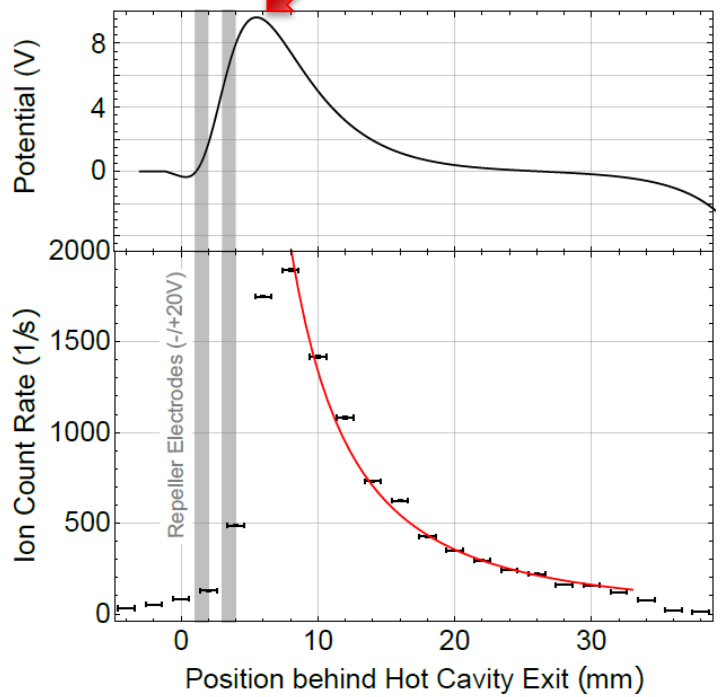
Efficiency extrapolation with ^{225}Ac:

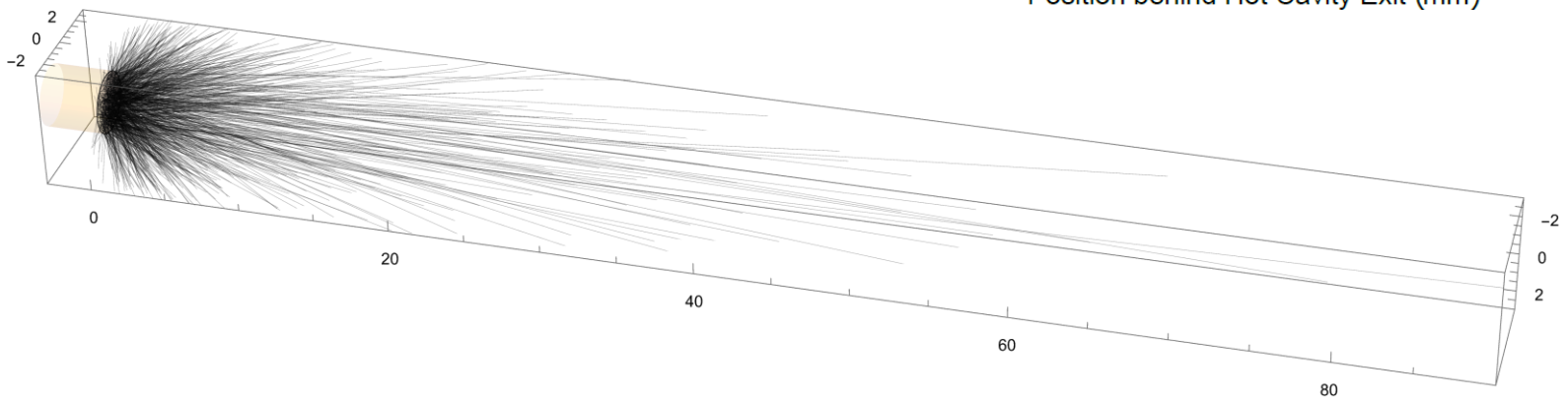
~10^{-4} (Standard RILIS: 10%)

Geometric atom beam losses: Opening angle

Move potential ridge closer

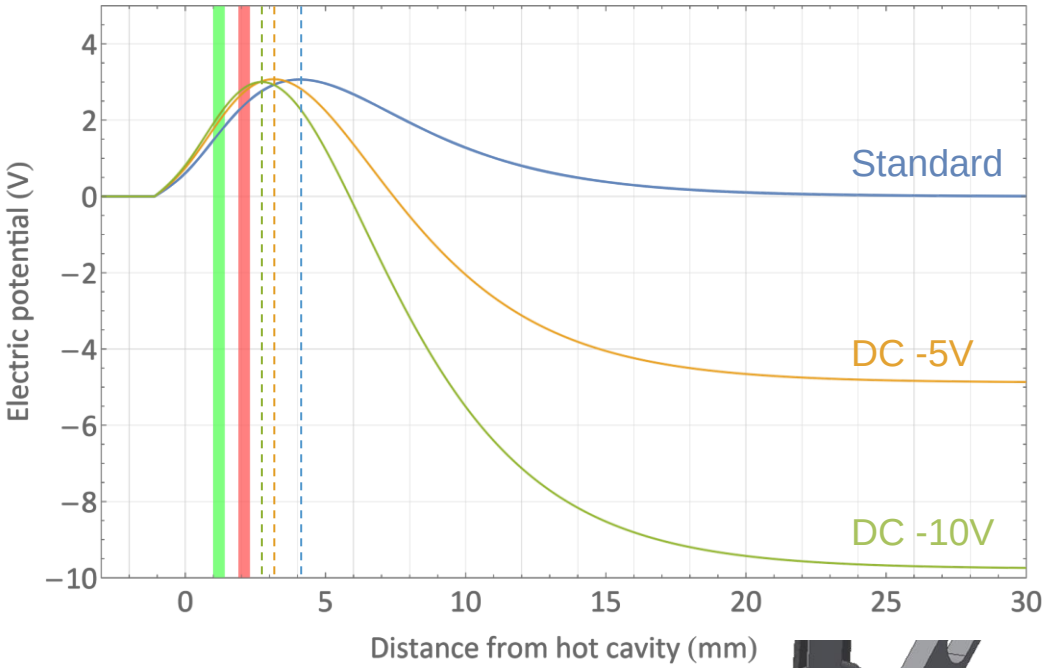




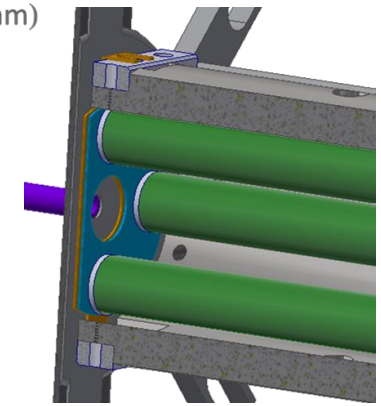


Optimization pathways

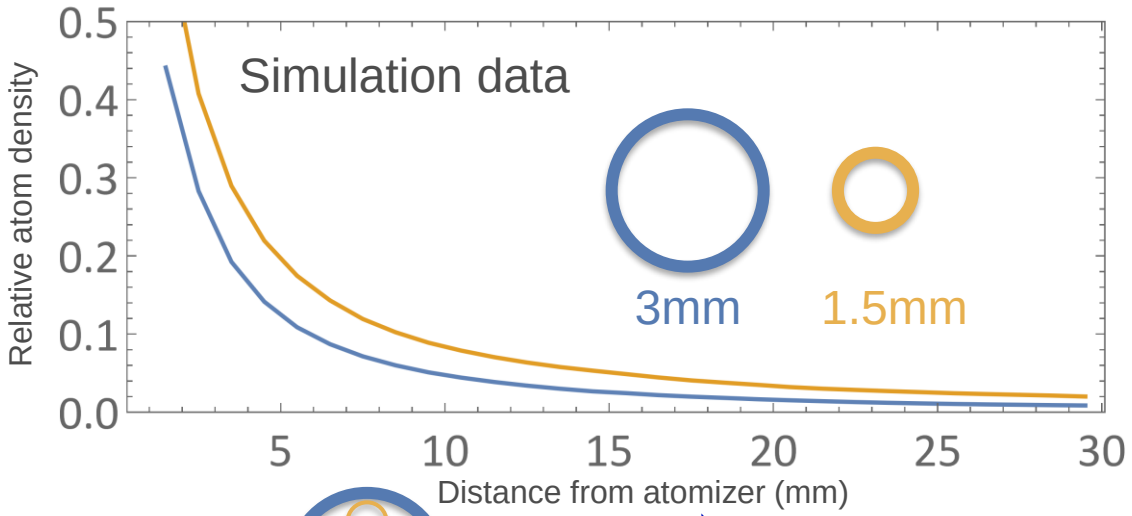
➔ Improve active volume: Shape electric potential

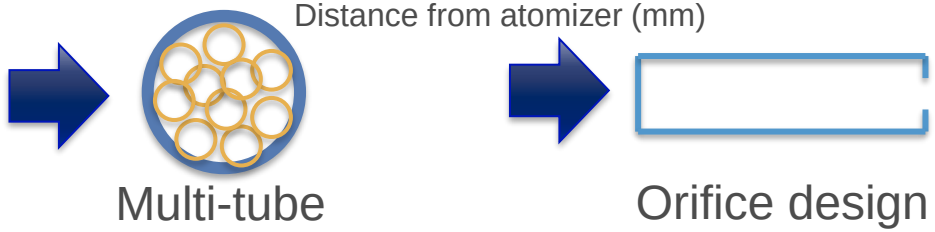


- DC offset of LIST corpus
- Improve repeller geometry
- Also facilitates ion guiding



➔ Shape effusing atom cone





➔ Laser duty cycle

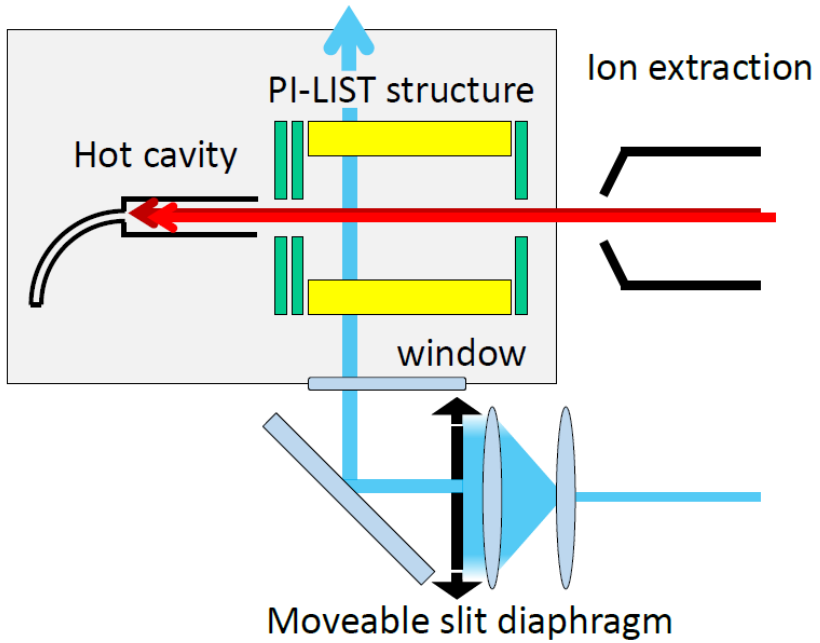
- Multiple chances in tube vs. ~1 in atom cone

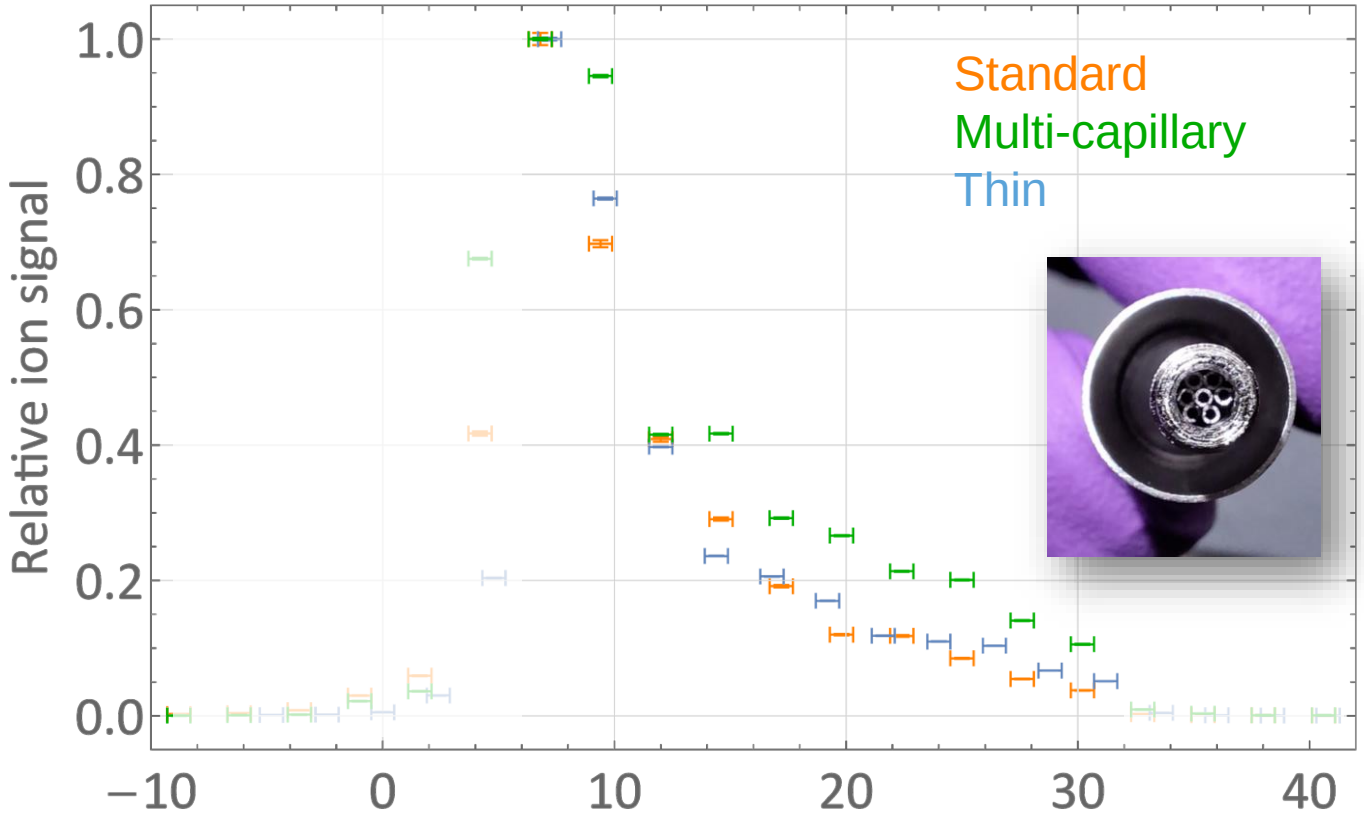
➔ RF phase synchronization

- Trapping efficiency, investigated at TRIUMF

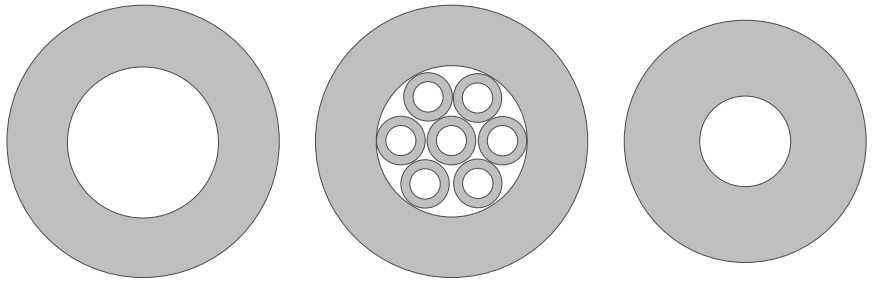
Dedicated off-line development infrastructure highly beneficial

Atom beam collimation – experimental investigation





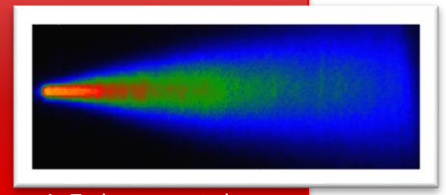
Test atomizer cross sections



Data analysis and feedback into simulation infrastructure ongoing

-

Experimental alternatives:
Planar laser induced fluorescence /
Deposition on catcher foils



A. Zadvornaya et al., Phys. Rev. X 8, 041008

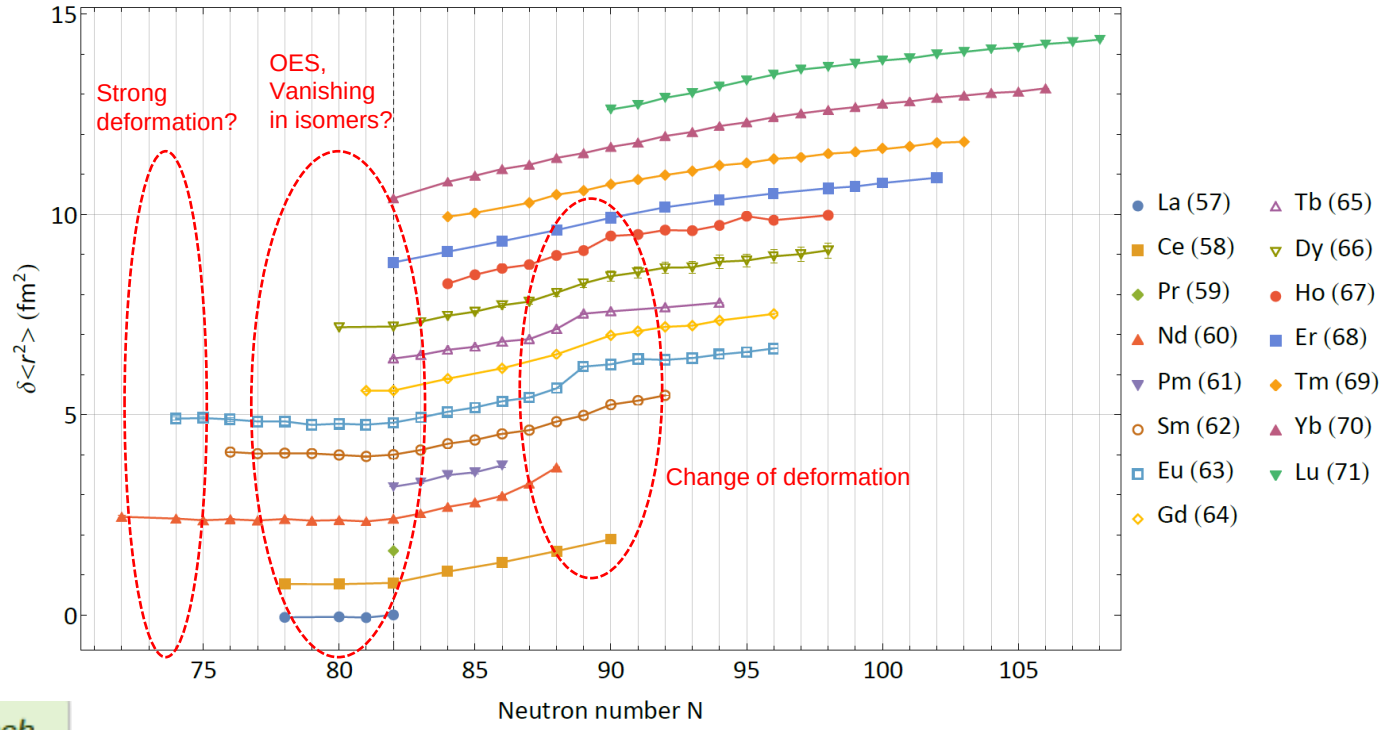
Future plans: Lanthanide campaign (LoI246)

Lanthanide elements as fitting case for (PI-)LIST:

- Surface-ionizable → suppression needed
- Extensive laser scheme groundwork done
- PI-LIST off-line spectroscopy successful
- Release behavior studied (MEDICIS)
- High atomic level density (open shells) disadvantage for charge exchange
- Interest in various nuclear structure phenomena, including **p+ emitters beyond dripline**

Plans for laser spectroscopy at the proton drip line *Kara Marie Lynch*

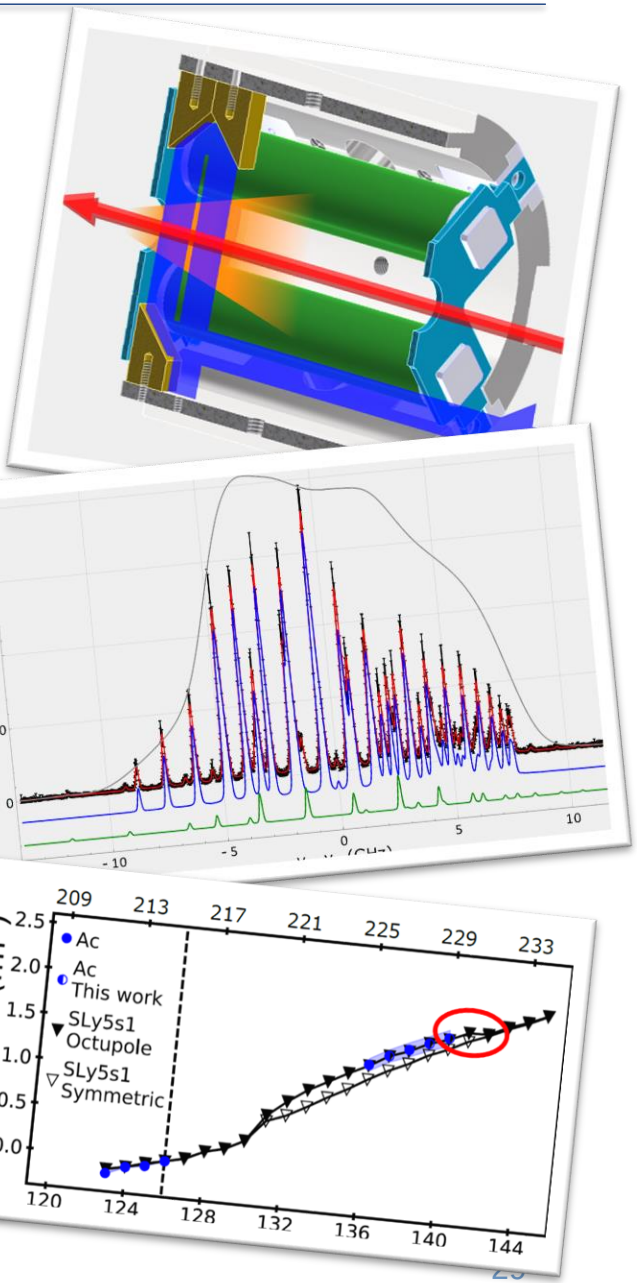
Charge radii around N = 82



➔ Ta target + LIST: lanthanide yield measurement campaign up to CERN LS3

Summary

- RILIS @ ISOLDE: The workhorse RIB source and its evolution
- PI-LIST: “Sub-Doppler” resolution enhancement
  - High resolution spectroscopy: Ac octupole deformation
  - Isomer-selective ionization
  - Ongoing developments (FI-LIST → K. Wendt later)



Thanks to you for *LIST*ening…

… and to all the collaborators!

Contribute to sharing!

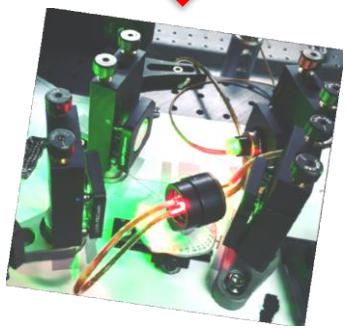
https://rims-code.github.io

IS664: Experimental setup

Joined NB laser infrastructure

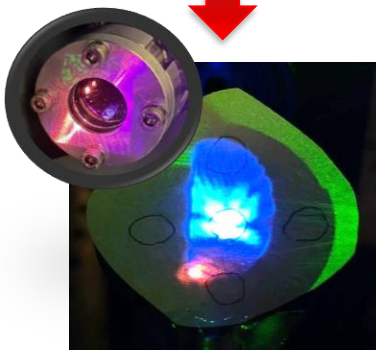
CRIS Matisse
cw Ti:Sa

Cross-hall fiber



RILIS injection-locked
pulsed ring cavity

Separator launch

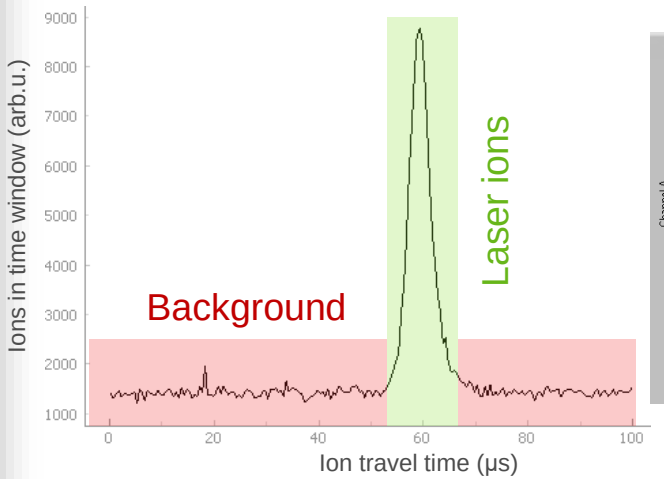


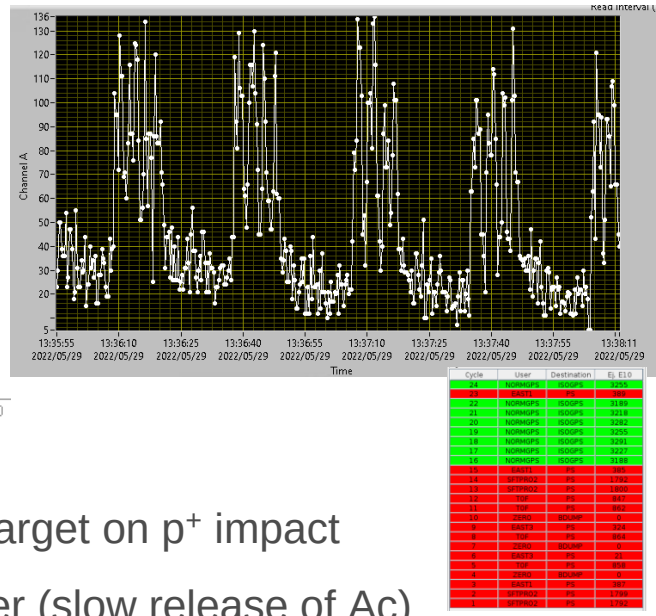
PI mode
referencing

Detector and DAQ

MagneTOF single ion counter at GLM/LA1 beam lines

- Highly sensitive
- Laser-synchronized 10kHz DAQ (CRIS time tagger)

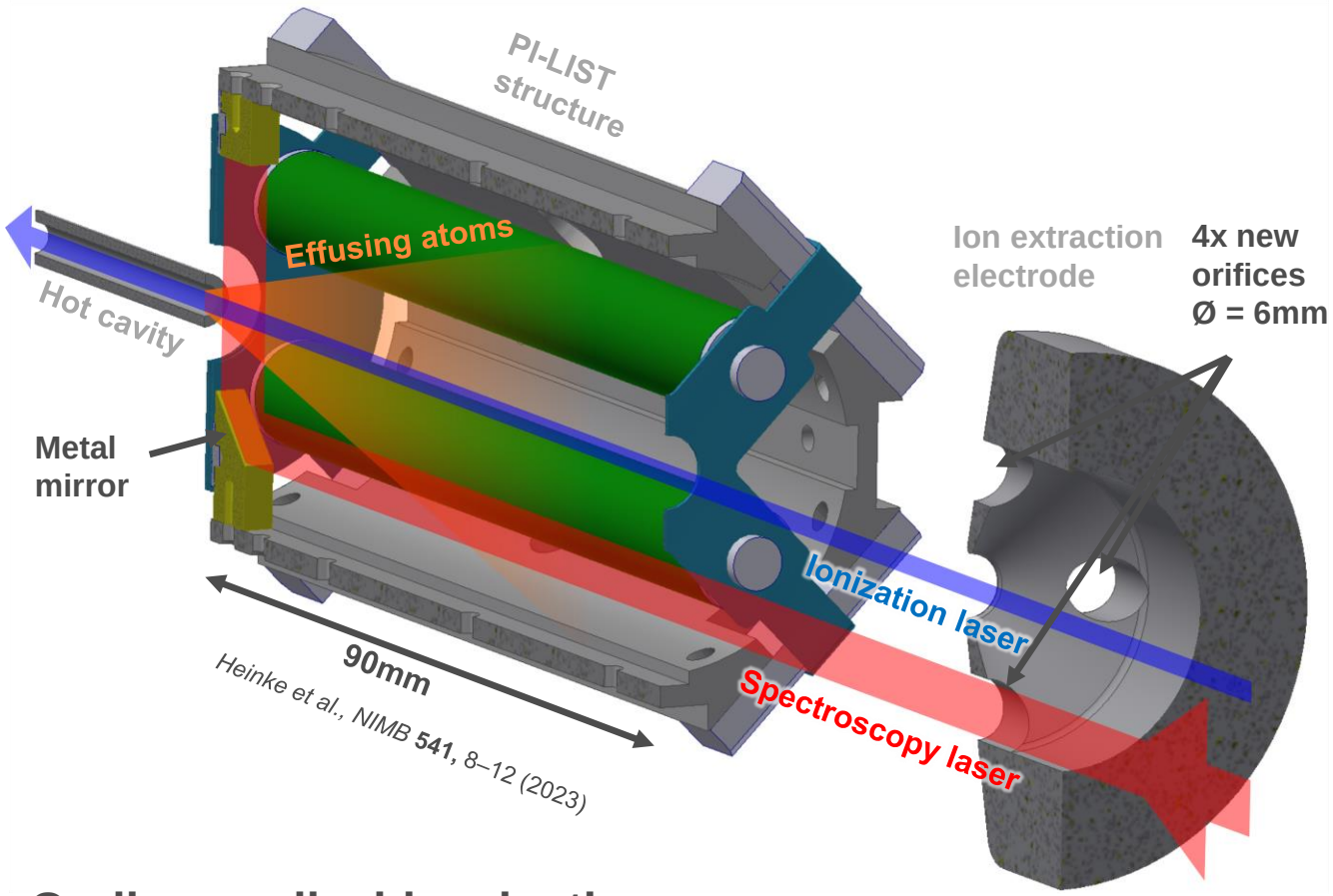


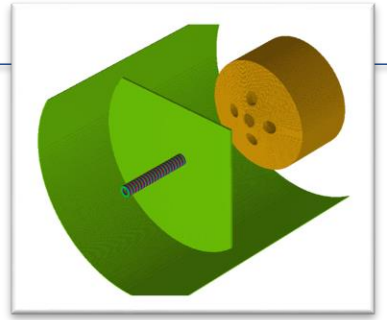


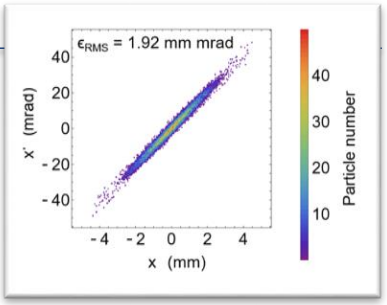
Radioactive noble gases from target on p^+ impact

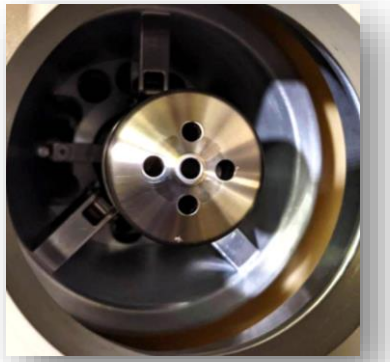
- Group protons, measure later (slow release of Ac)
- Detector moved to CB0
- IDS/ASET on standby / parallel experiments

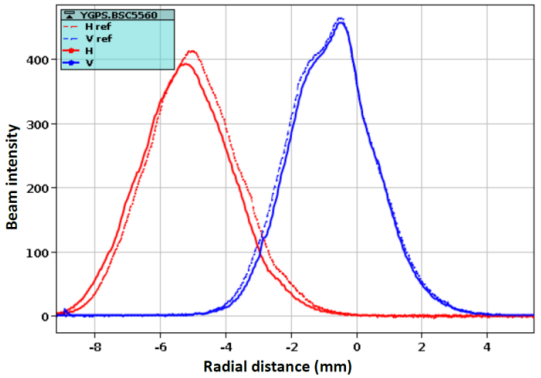
PI-LIST at ISOLDE

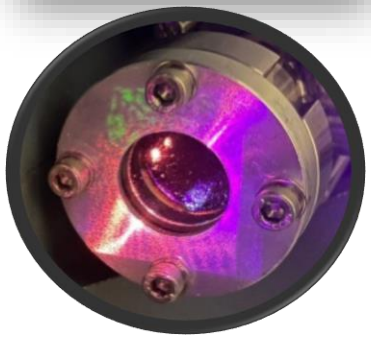












On-line applicable adaption

- Alternative for external laser access through window
- Robustness

Technical implementation

- Confirmation of operation transparency of changes
- Control and feedback systems (LabVIEW)