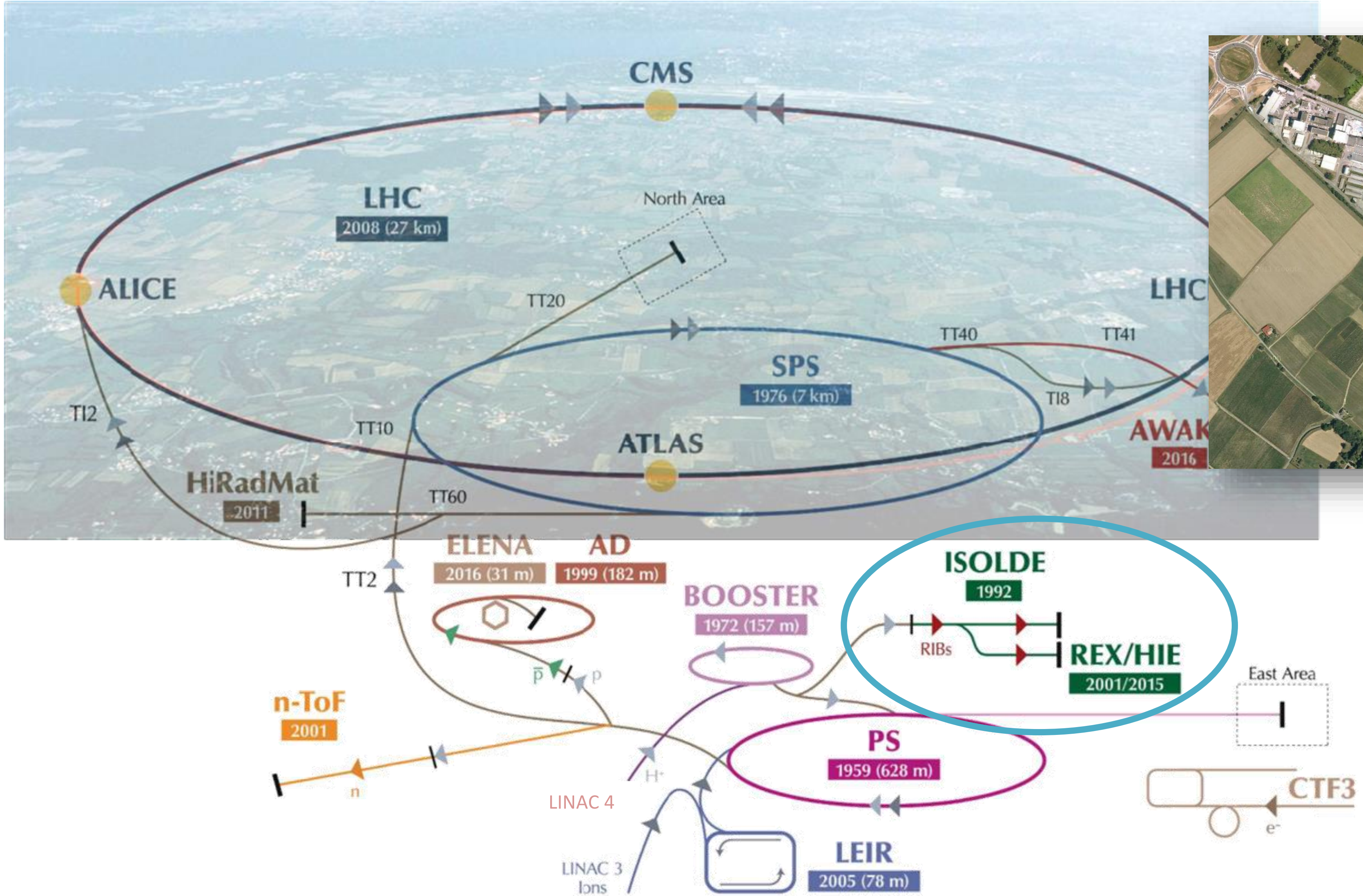
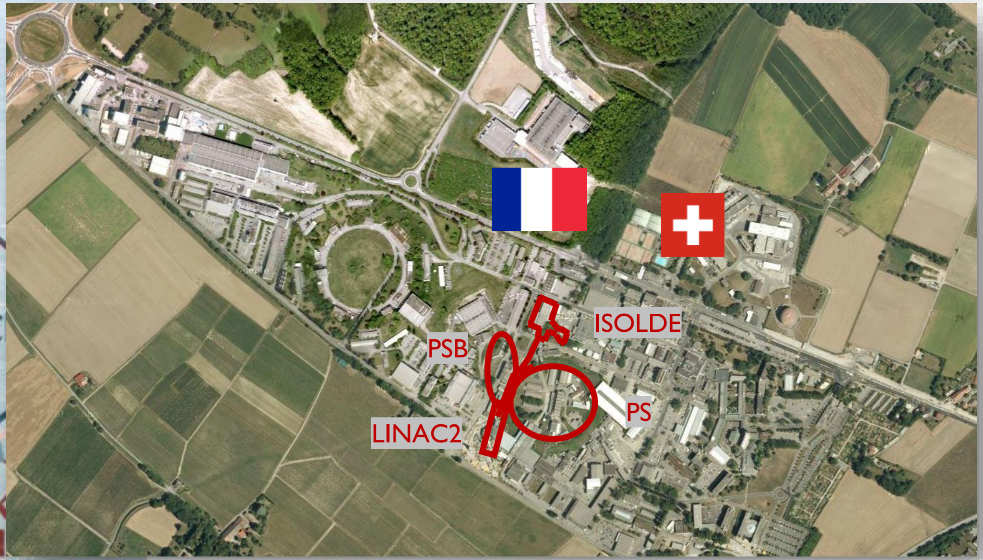
The PI-LIST: High-Resolution Crossed-Beams Laser Spectroscopy inside the ISOLDE Laser Ion Source

Asar AH Jaradat for the PI-LIST collaboration
University of Manchester

This project has received funding from the European Union's Horizon 2020 Research and Innovation Program (grant number 861198 project 'LISA' MSC ITN) and CERN

ISOLDE at CERN

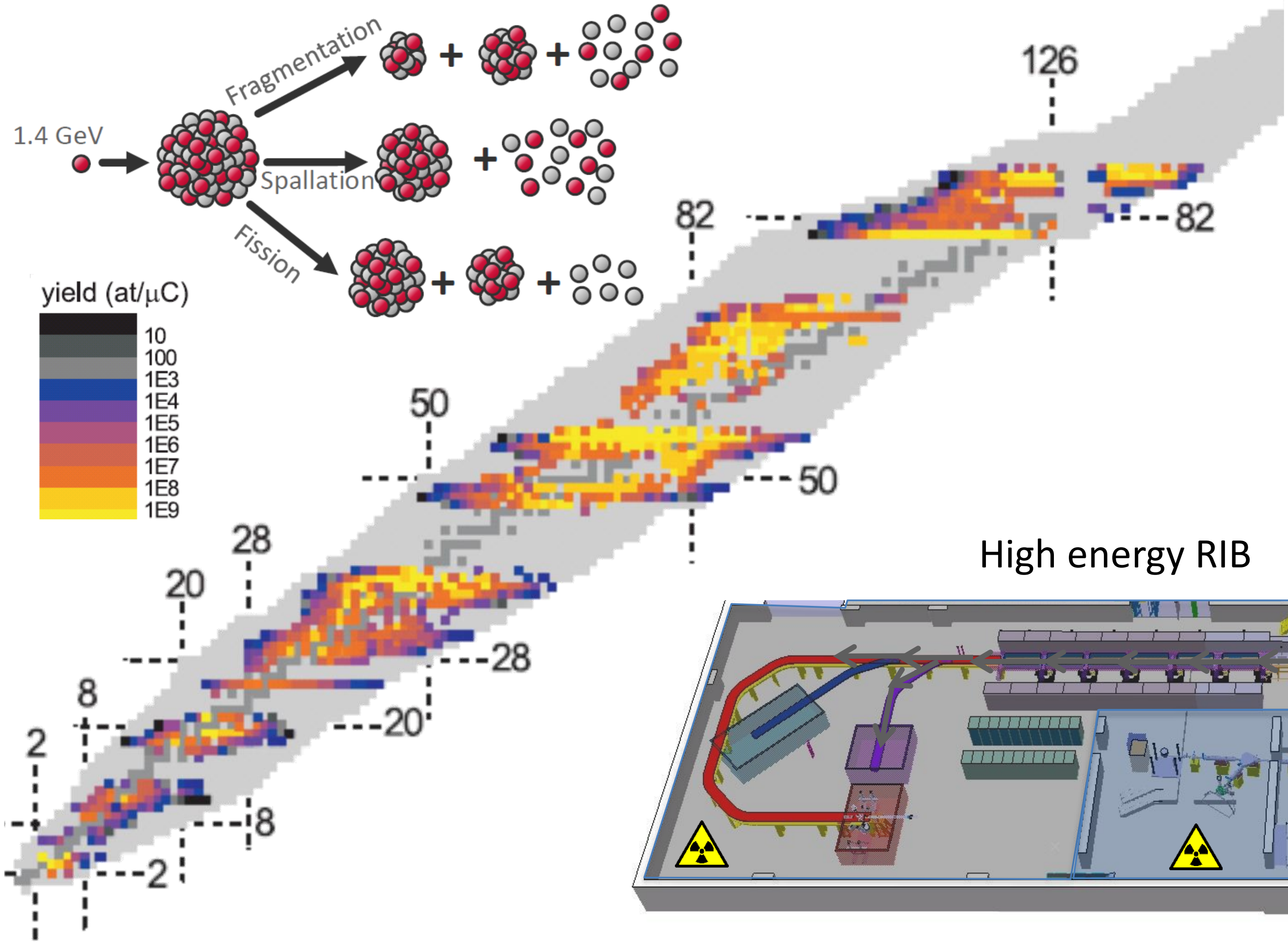


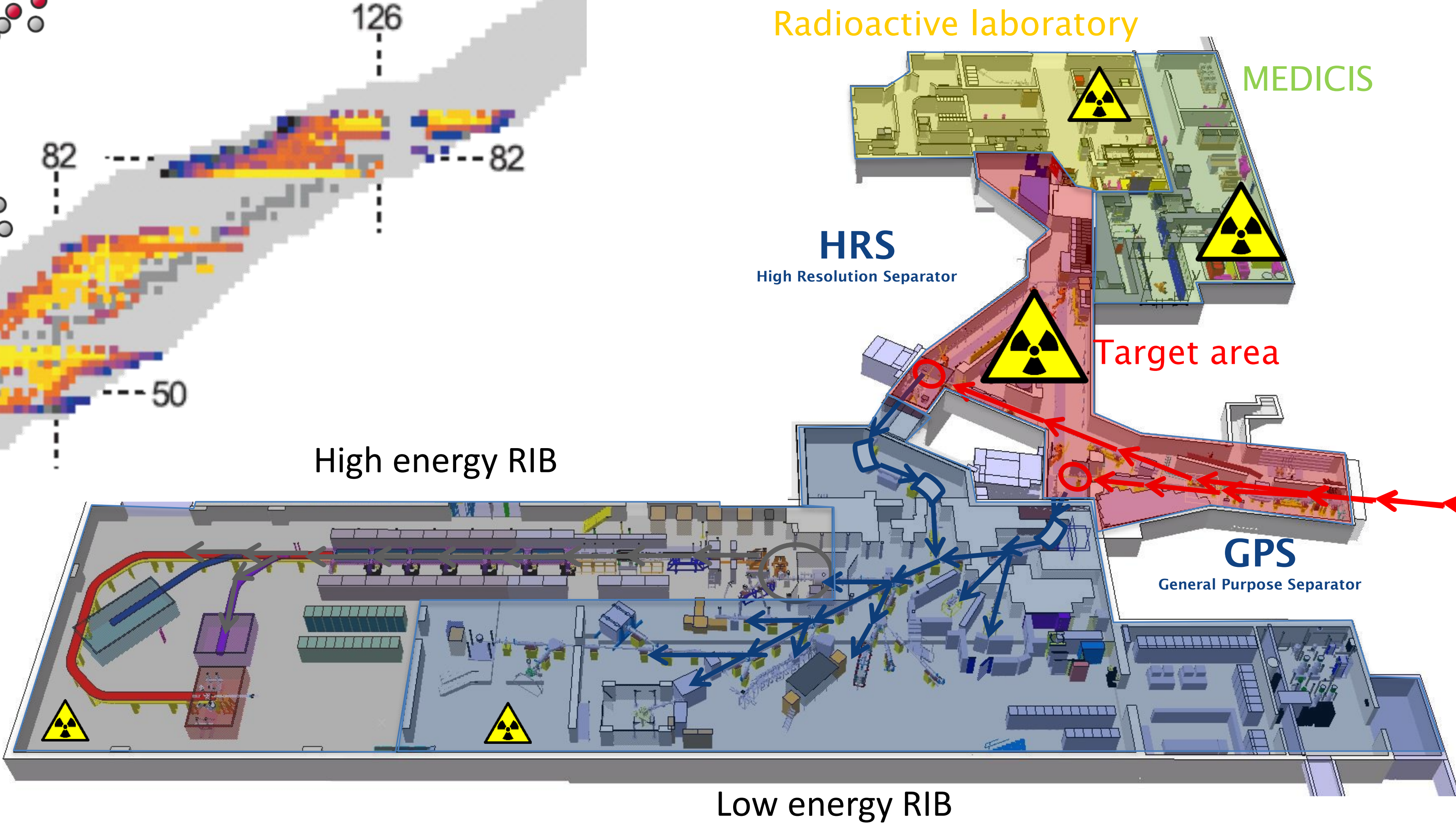


"Isotope Separator On-Line"

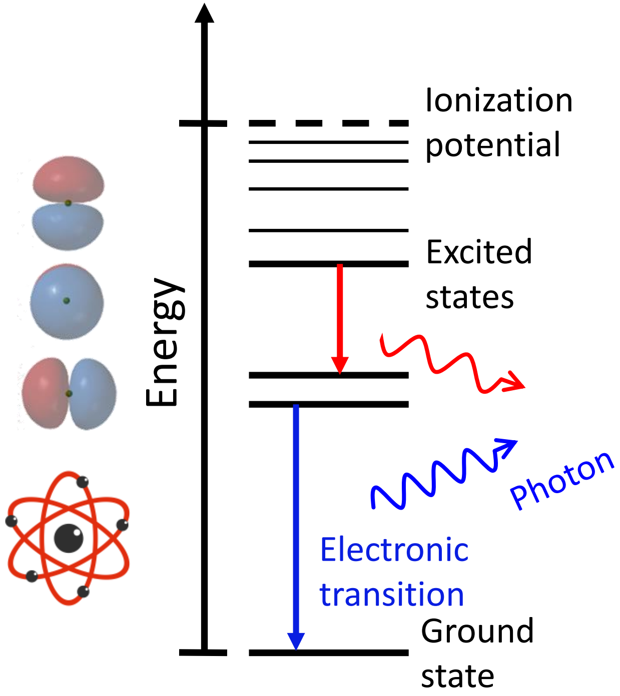
radioisotope production, selection and transport to an experiment in one machine

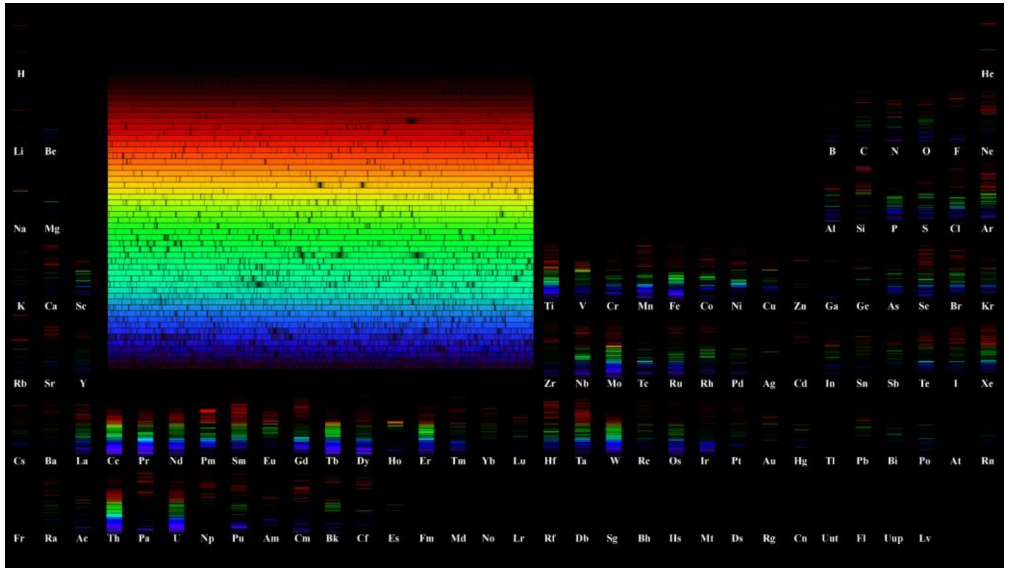
The ISOLDE facility at CERN





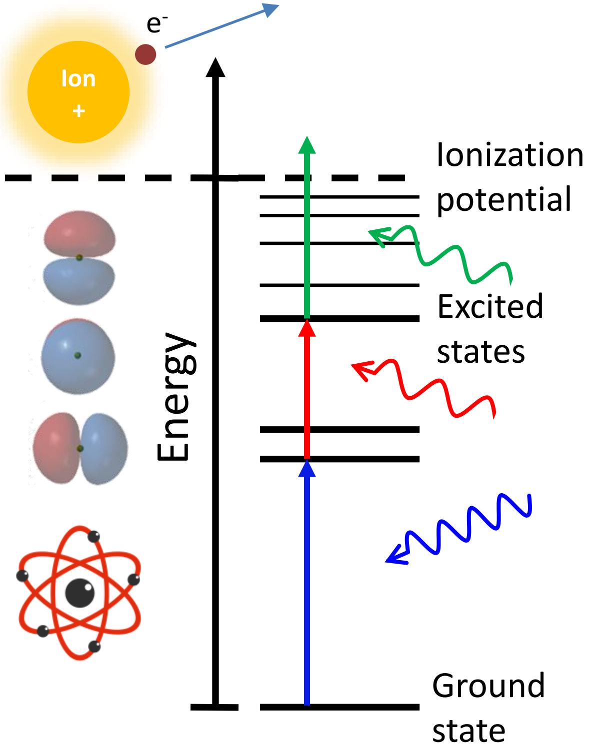
Laser Resonance Ionization



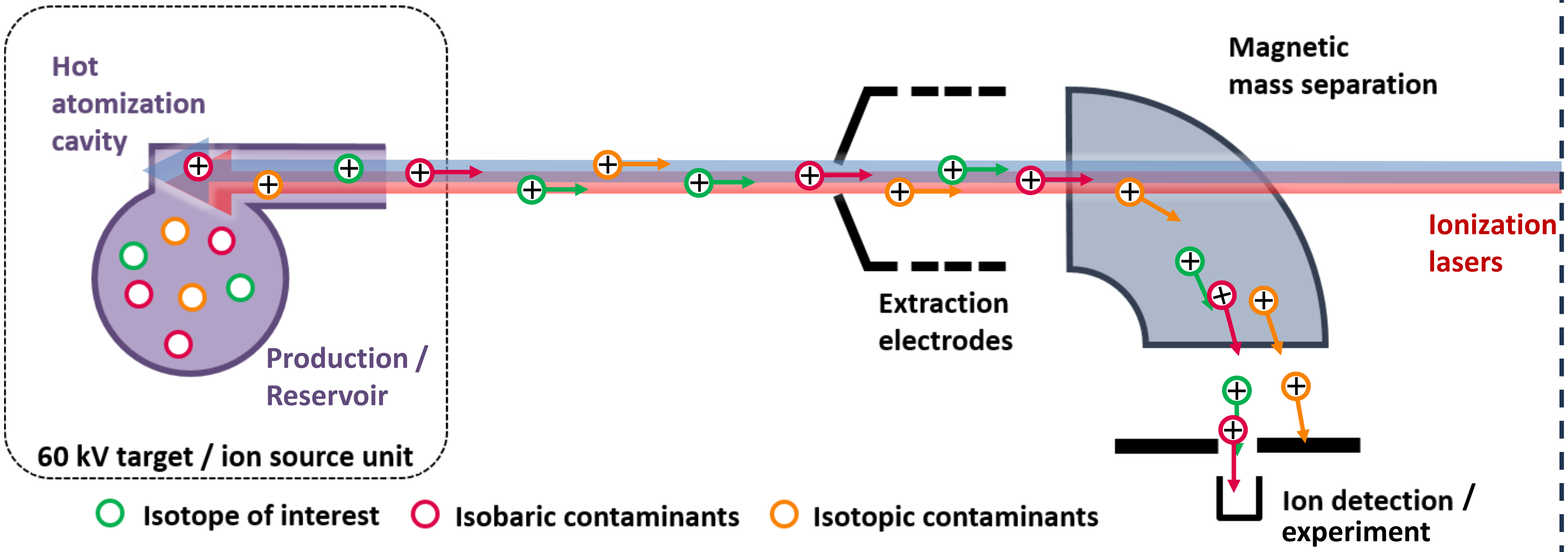


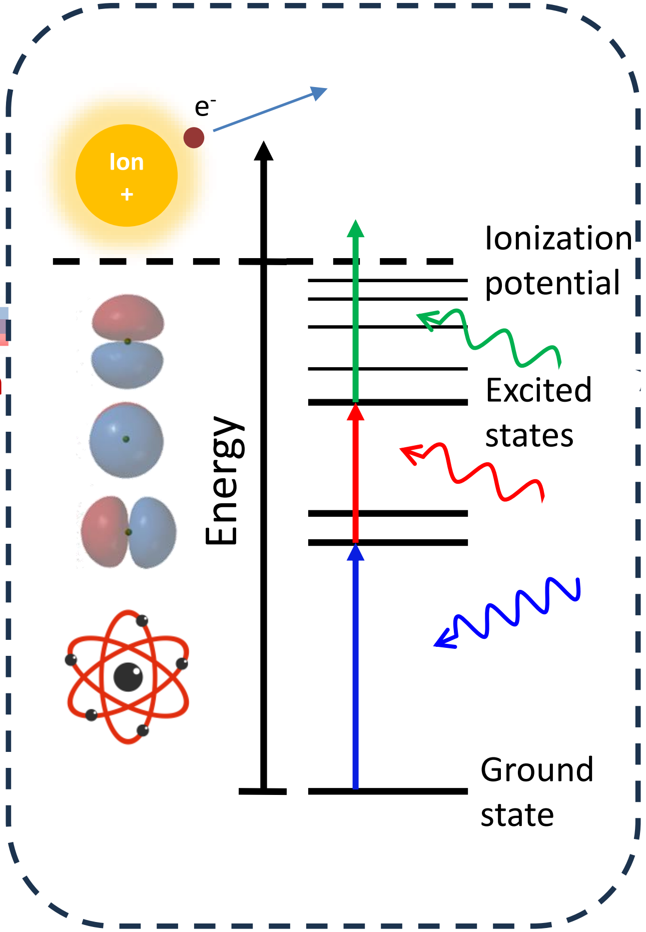
By Julie Gagnon (C) 2007, 2013. CC-BY-SA 4.0

Photonic markers of chemical elements

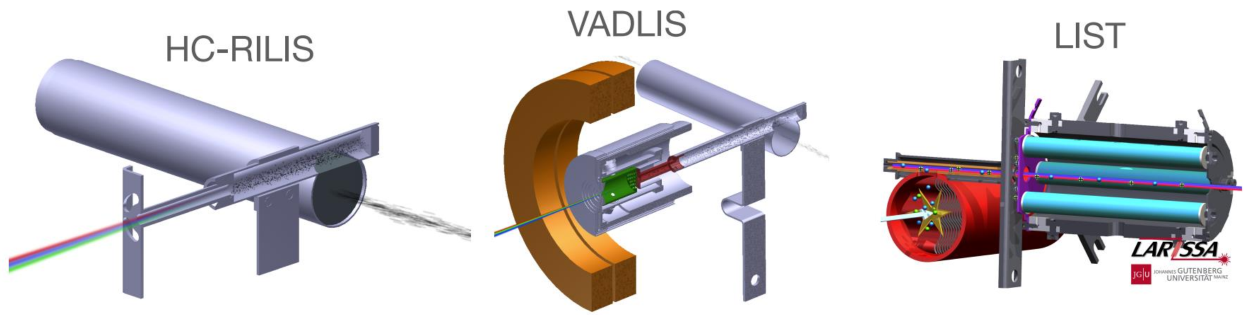


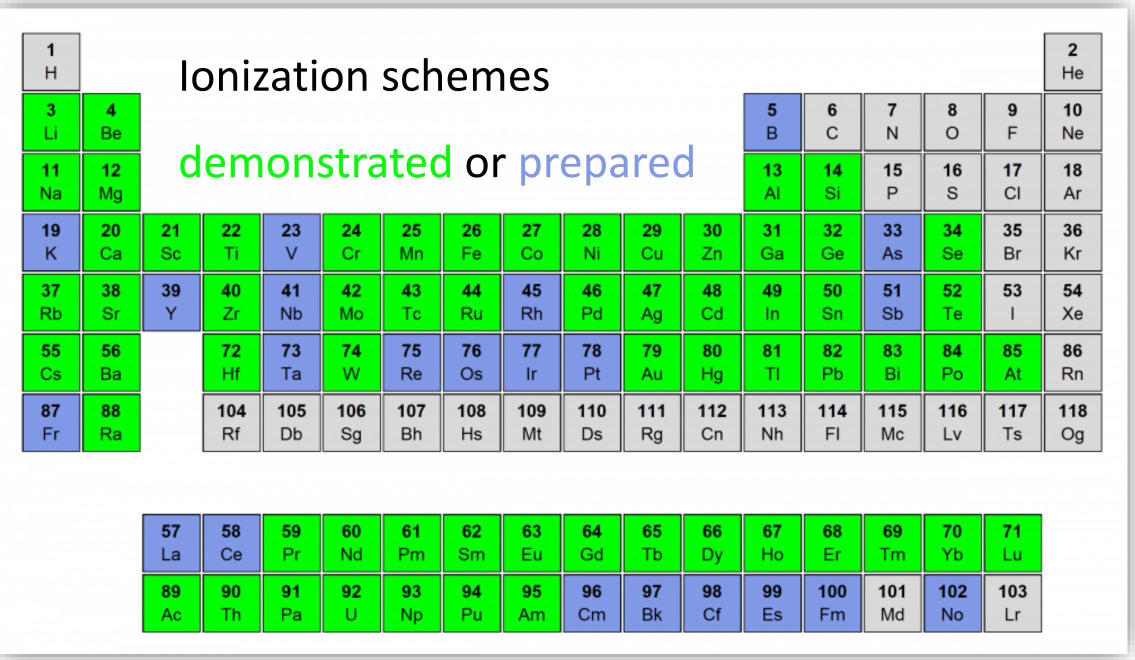
ISOLDE’s Resonance Ionization Laser Ion Source - RILIS

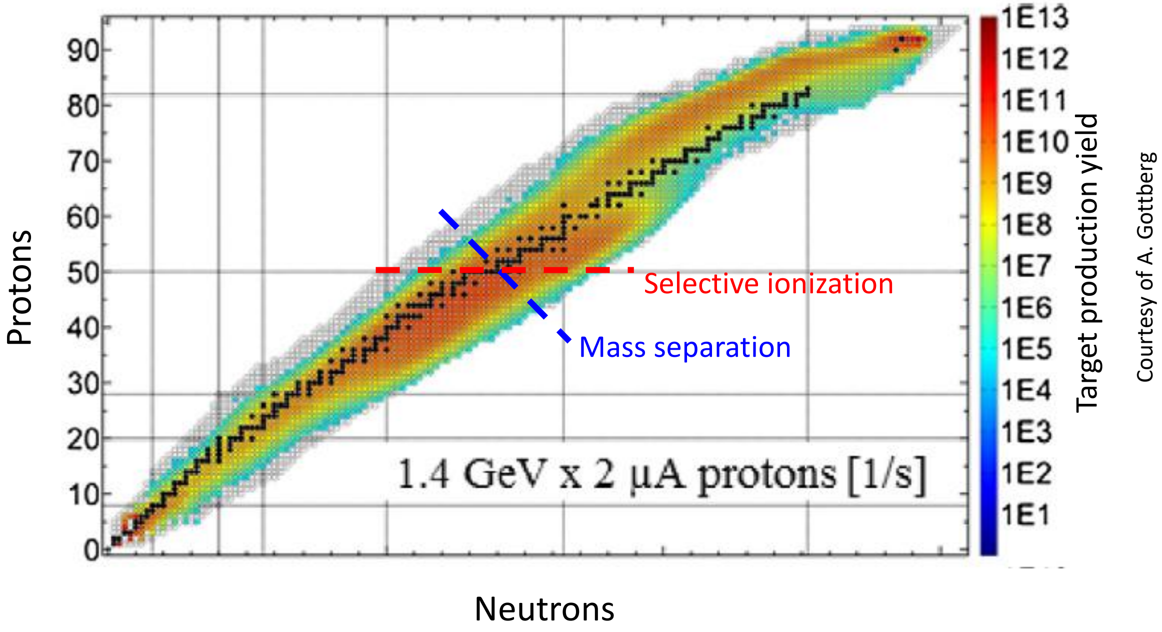




ISOLDE's Resonance Ionization Laser Ion Source - RILIS



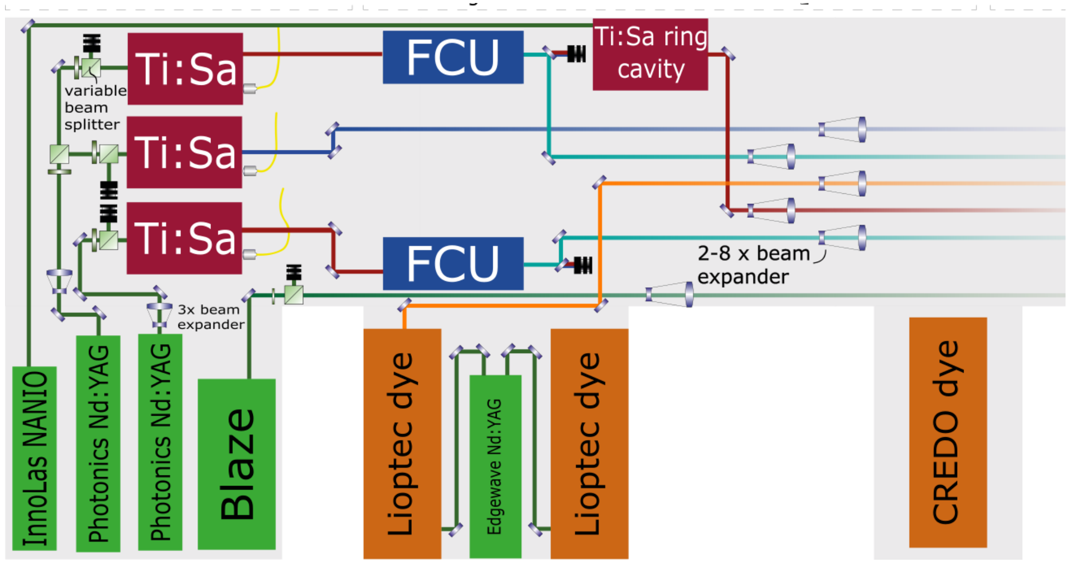




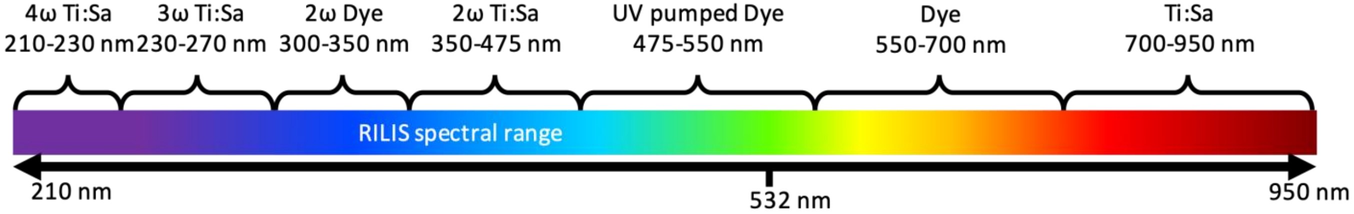
Radioisotope production linked to creation of contamination

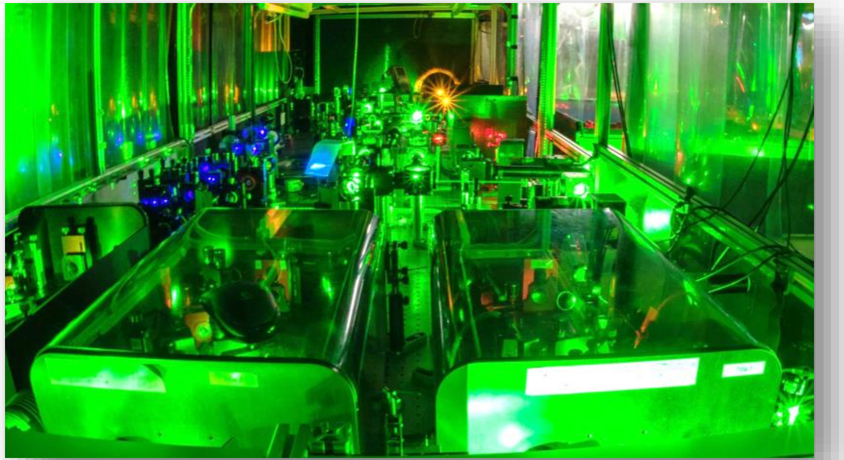
- Element/isotope selectivity of ionization process → Clean beam
- Efficiency of process → Access low yield species / don't waste sample

The RILIS Laser Setup

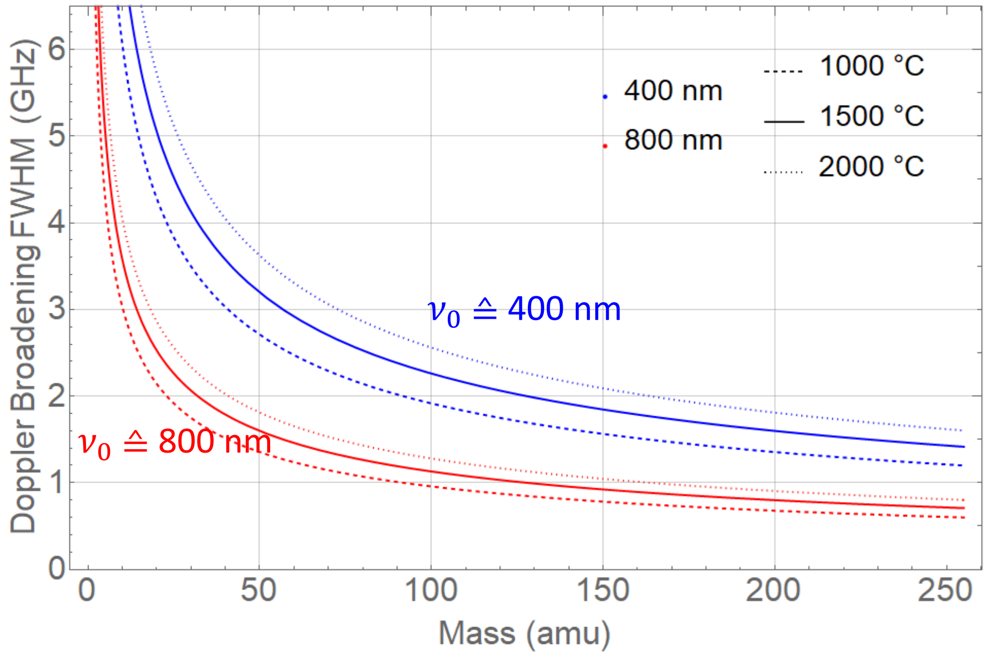


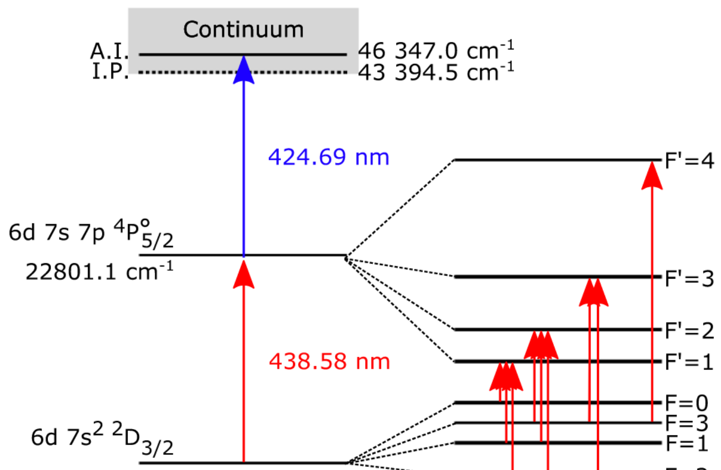
Repetition rate	10kHz
Pulse duration	5 – 50ns
Output power	1 – 5W

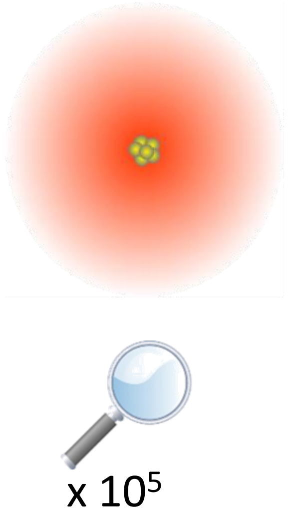




Resolution Limitations: Doppler Broadening

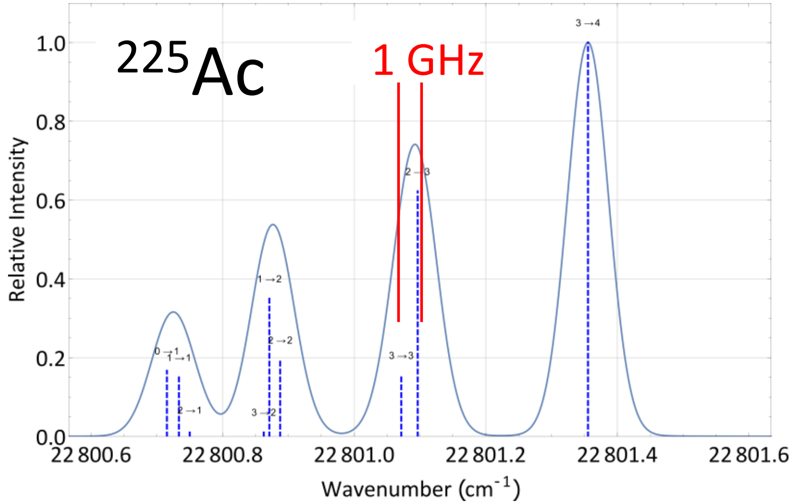


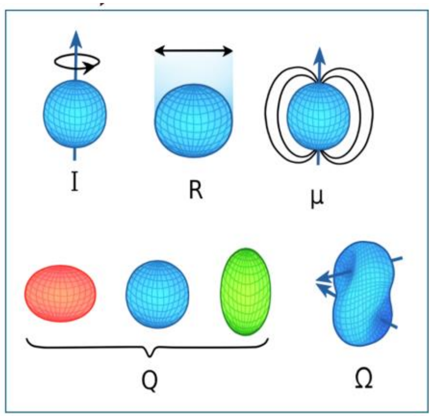




$$\mathrm{FWHM} = \frac{\nu_0}{c}\sqrt{\frac{8\ln(2)\, k_B\, T}{m}}$$

➔ **A few GHz** as ultimate resolution limit



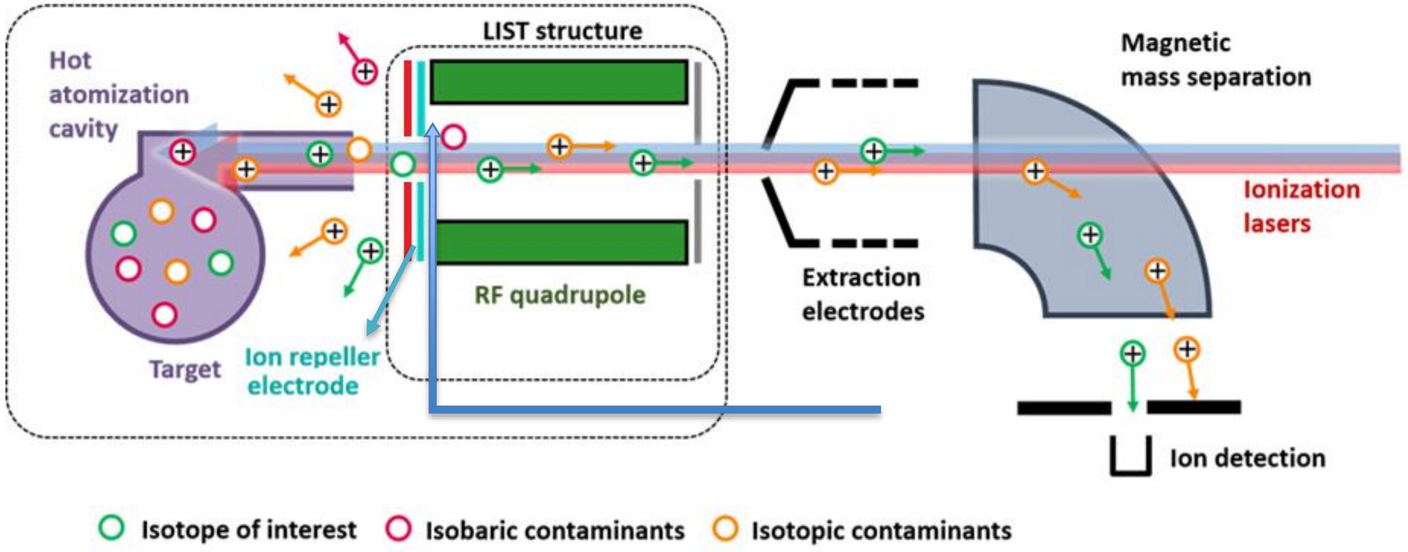


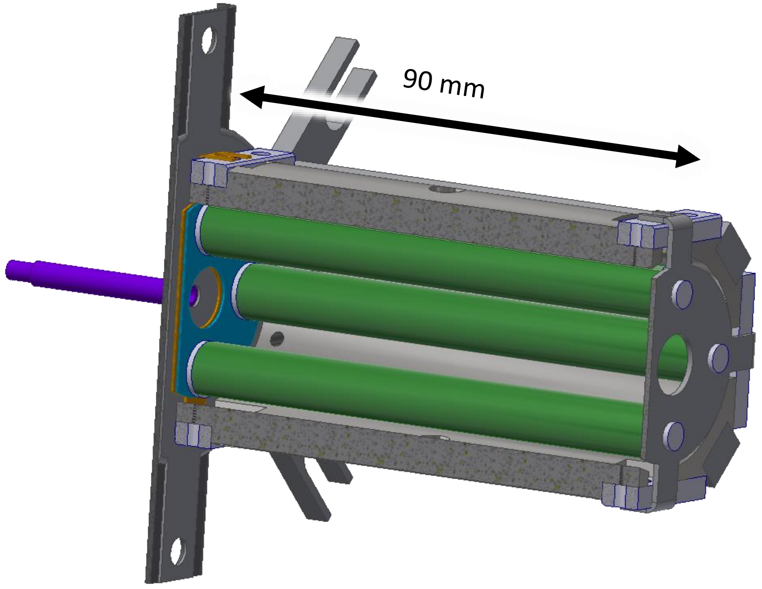
Nuclear investigations limited to

high masses / large splittings

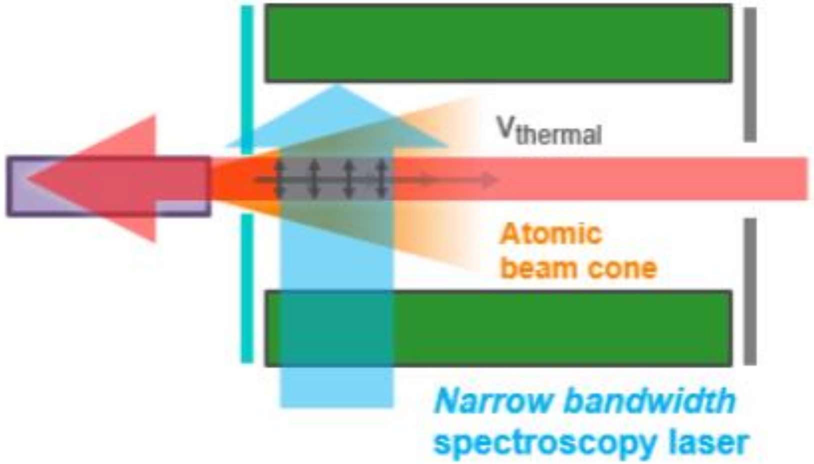
The Laser Ion Source and Trap - LIST

30-60kV



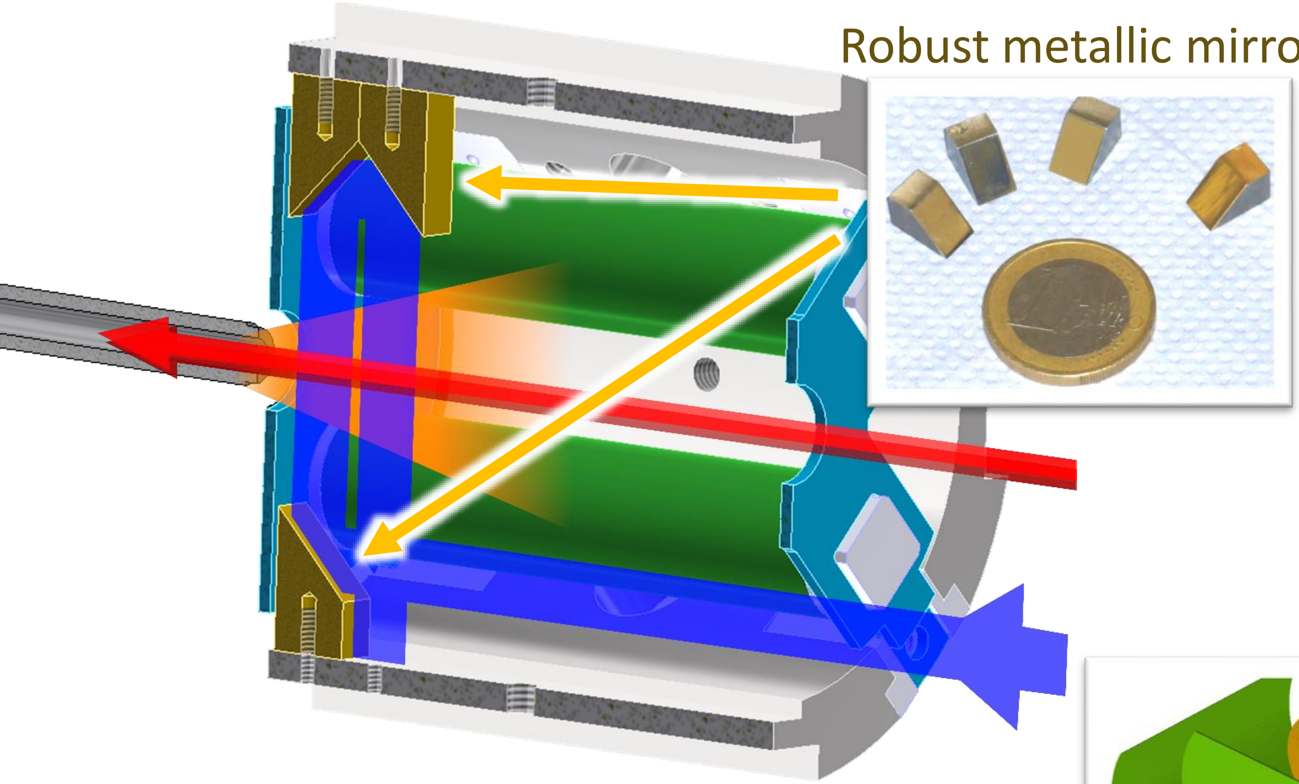


PI-LIST concept



- **Suppression** of surface ions
- **A field-free laser ionization region**
- **Pure laser ionization** inside **RF quadrupole** structure
- **PI-LIST** structure enables high-resolution spectroscopy

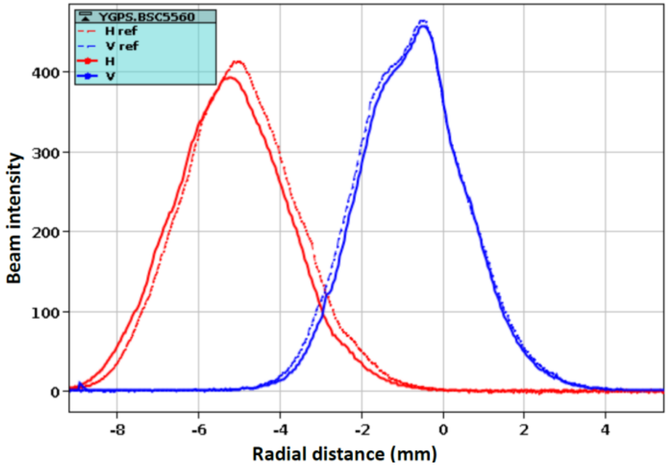
ISOLDE adaption of PI-LIST

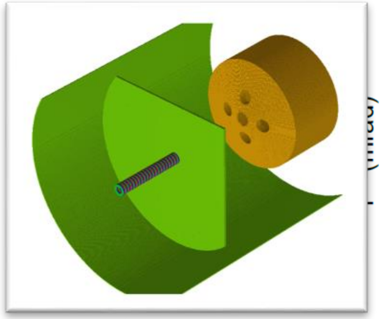


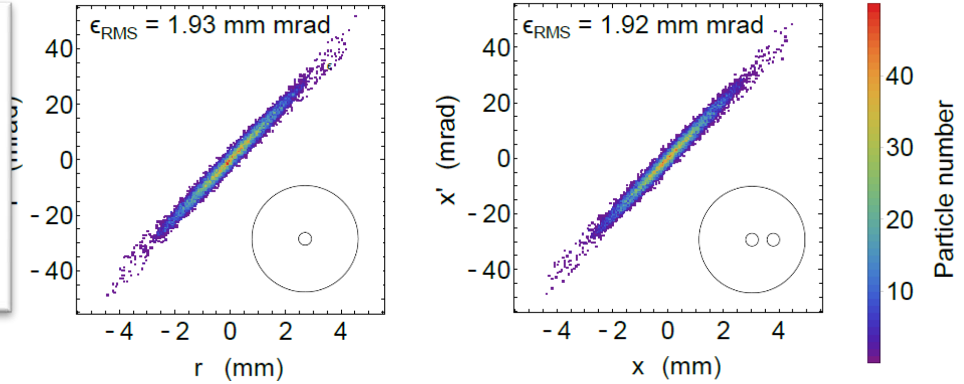
Robust metallic mirrors

Adapted extraction electrode

Beam shape comparison





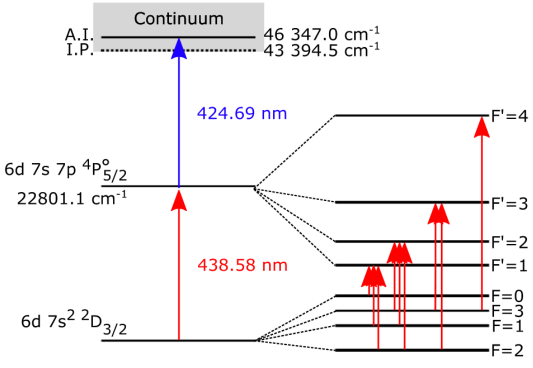


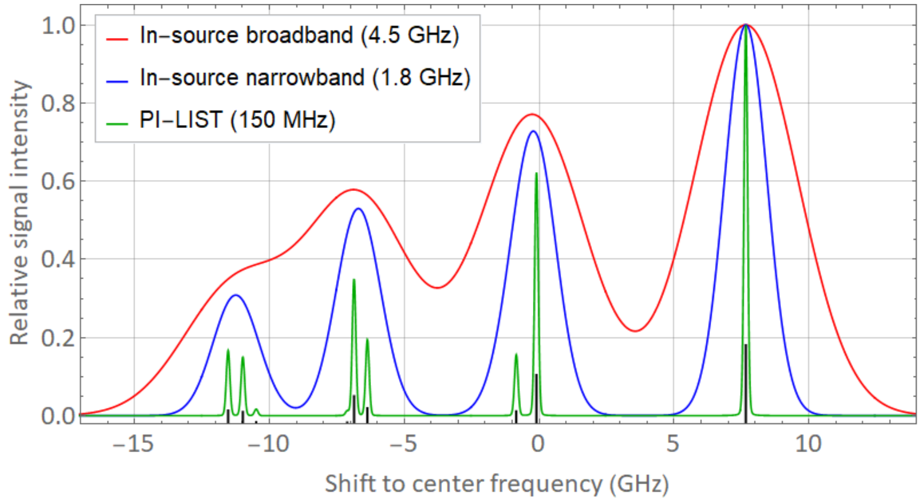
Emittance simulations

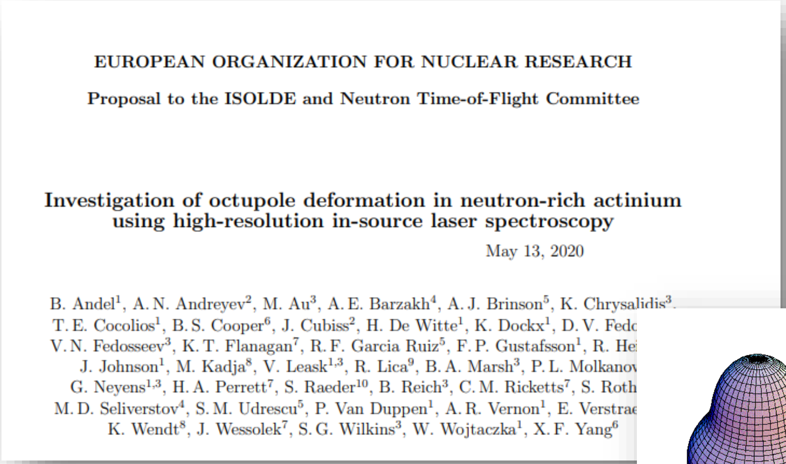
No windows possible in ISOLDE frontend

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

PI-LIST Experiments: IS664





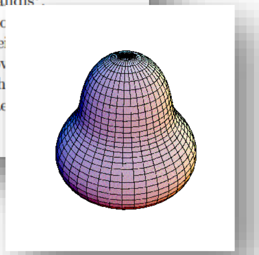

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Investigation of octupole deformation in neutron-rich actinium using high-resolution in-source laser spectroscopy

May 13, 2020

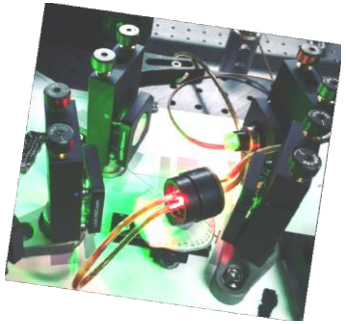
B. Andel[1], A. N. Andreyev[2], M. Au[3], A. E. Barzakh[4], A. J. Brinson[5], K. Chrysalidis[3], T. E. Cocolios[1], B. S. Cooper[6], J. Cubiss[2], H. De Witte[1], K. Dockx[1], D. V. Fedo… V. N. Fedosseev[3], K. T. Flanagan[7], R. F. Garcia Ruiz[5], F. P. Gustafsson[1], R. He… J. Johnson[1], M. Kadja[8], V. Leask[1,3], R. Lica[9], B. A. Marsh[3], P. L. Molkanov… G. Neyens[1,3], H. A. Perrett[7], S. Raeder[10], B. Reich[3], C. M. Ricketts[7], S. Roth… M. D. Seliverstov[4], S. M. Udrescu[5], P. Van Duppen[1], A. R. Vernon[1], E. Verstrae… K. Wendt[8], J. Wessolek[7], S. G. Wilkins[3], W. Wojtaczka[1], X. F. Yang[6]



CRIS

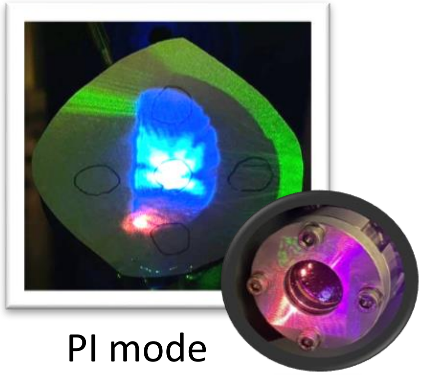
CRIS Sirah Matisse
cw Ti:Sa

Cross-hall fiber

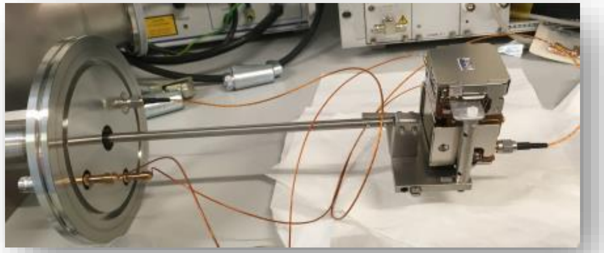


RILIS injection-locked
pulsed ring cavity

Separator launch

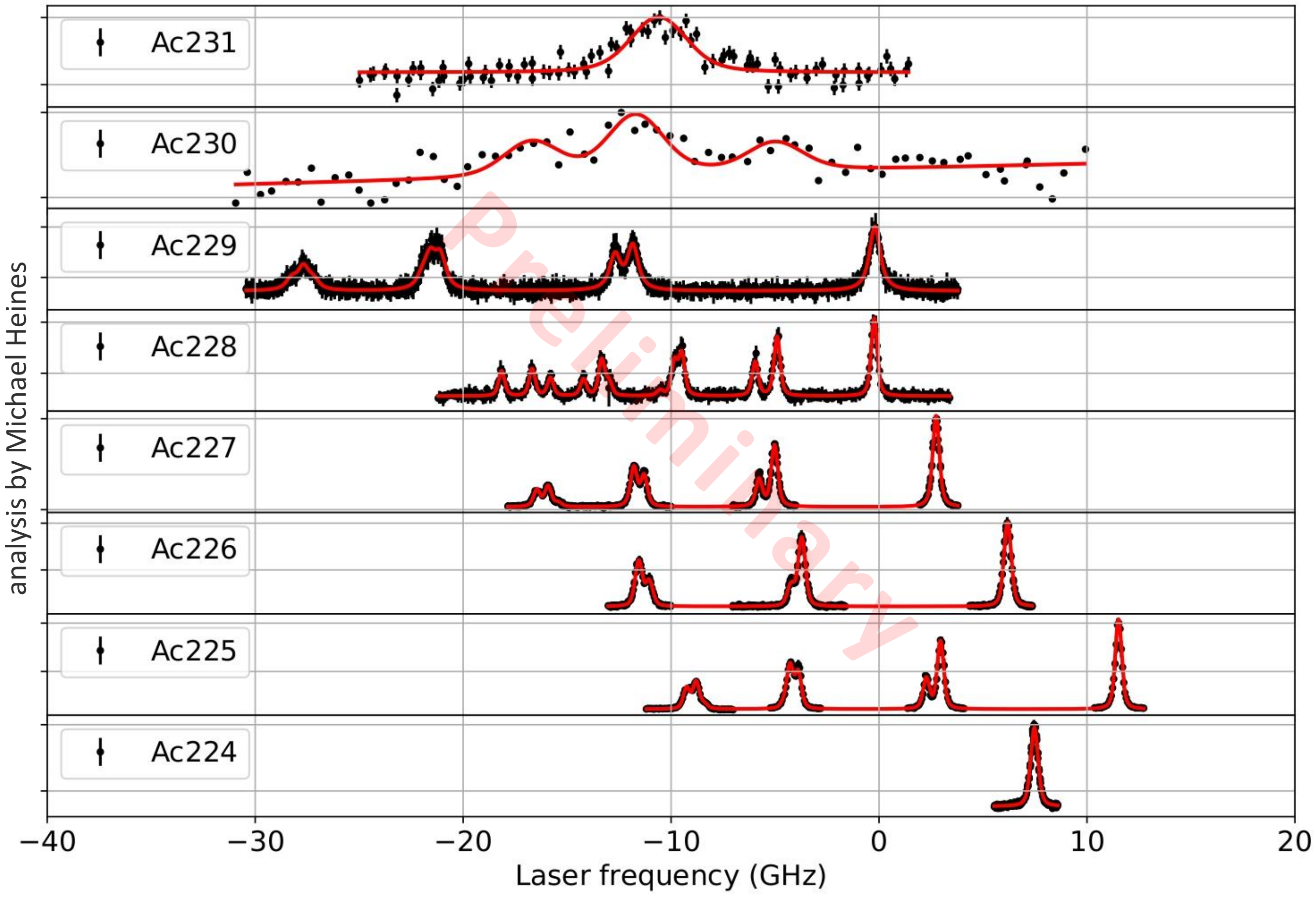


PI mode
referencing

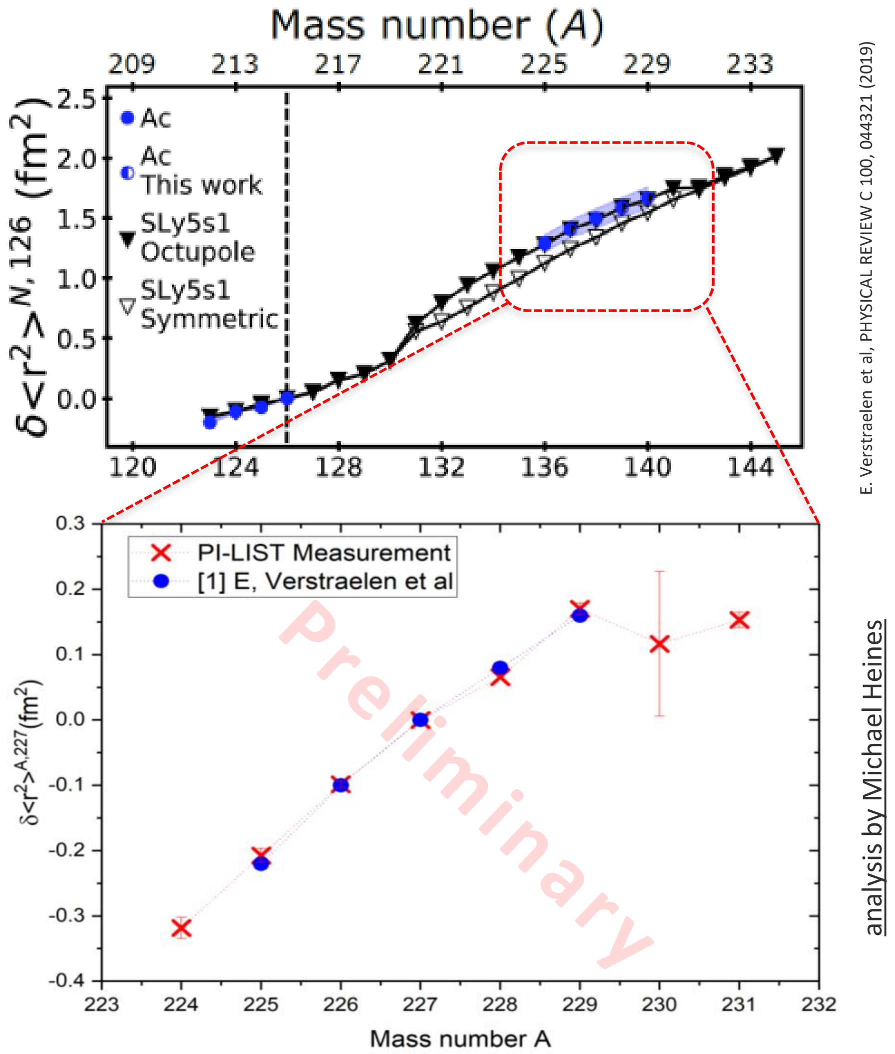


https://doi.org/10.1016/j.nimb.2023.04.057

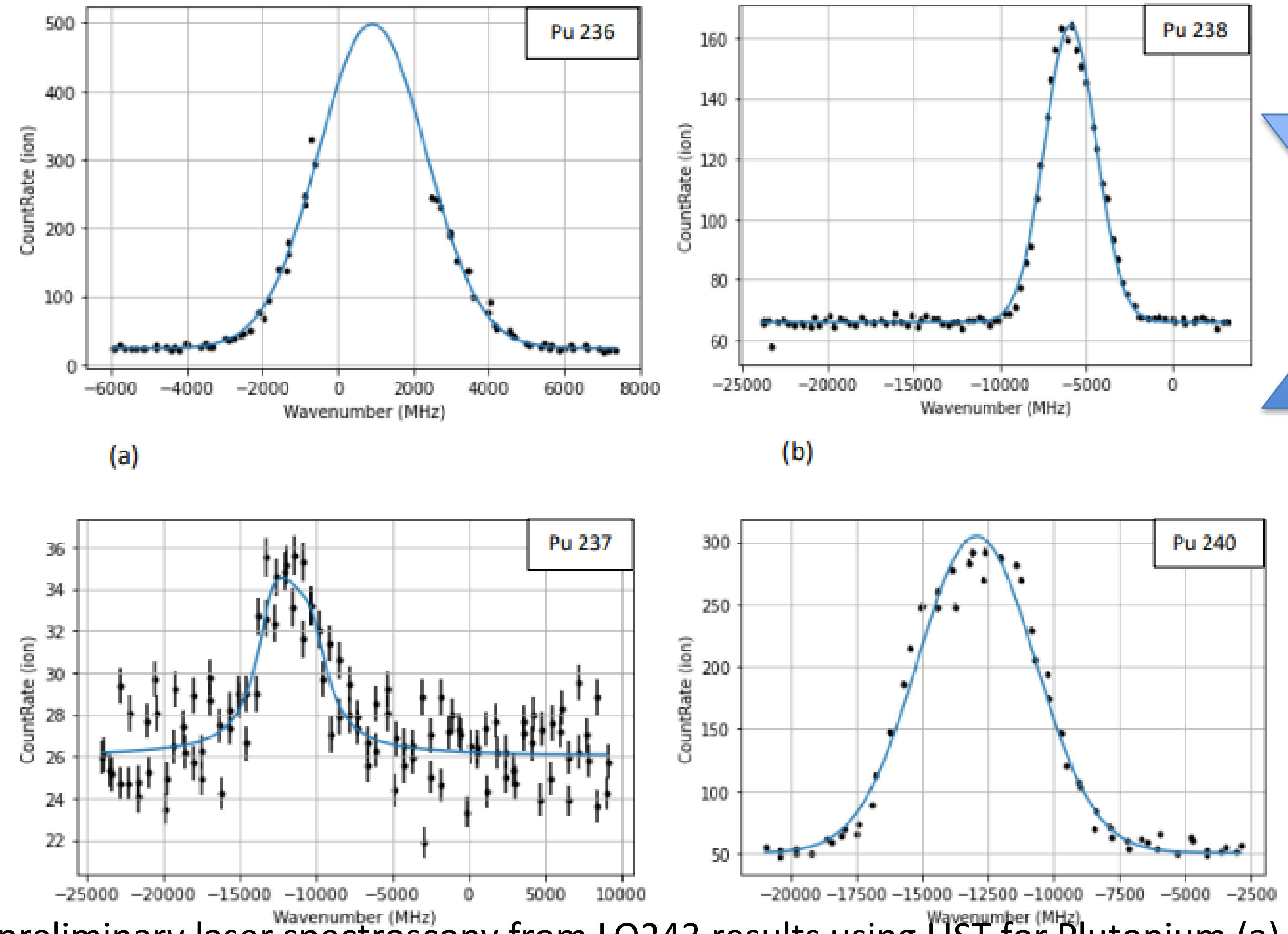
Preliminary Results



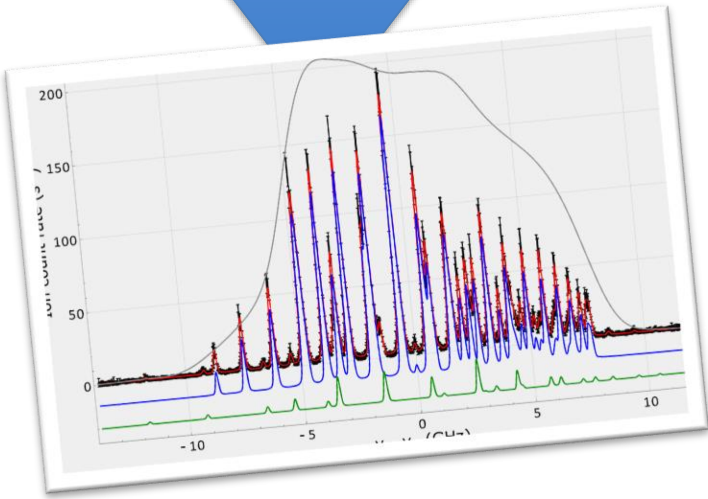
200-300 MHz vs 1.5 GHz



LIST Experiments: LO243

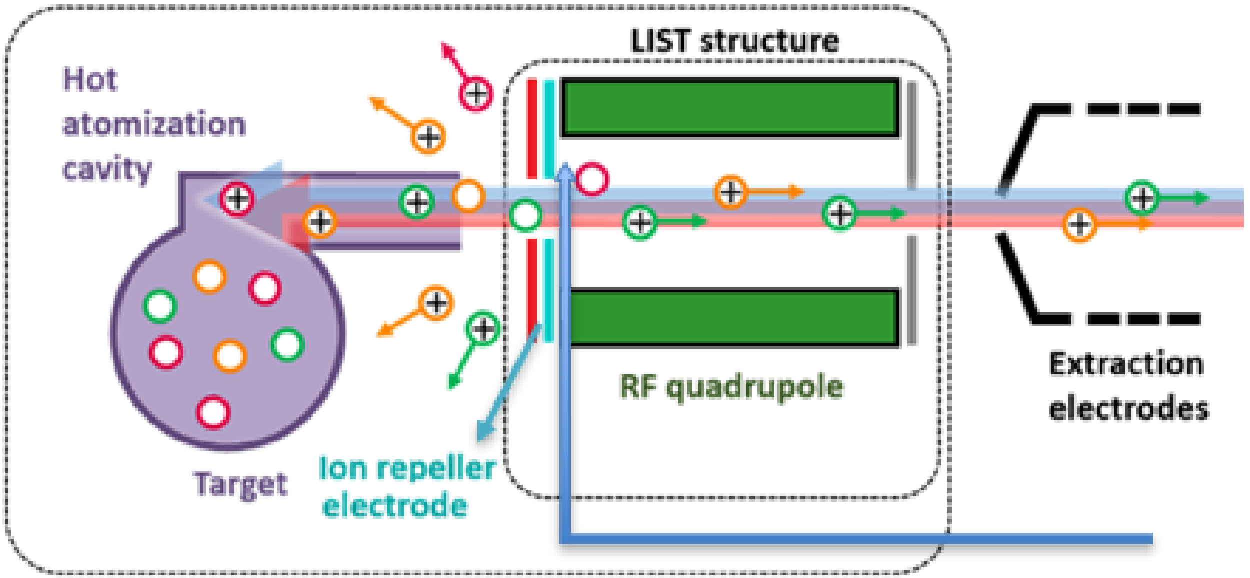


Coming up: Dr. Kara Lynch Lu/Ho yield measurements with PI-LIST



preliminary laser spectroscopy from LO243 results using LIST for Plutonium (a) isotope 236, (b) isotope 238, (c) isotope (237), and isotope (240)

Optimization: Efficiency Considerations

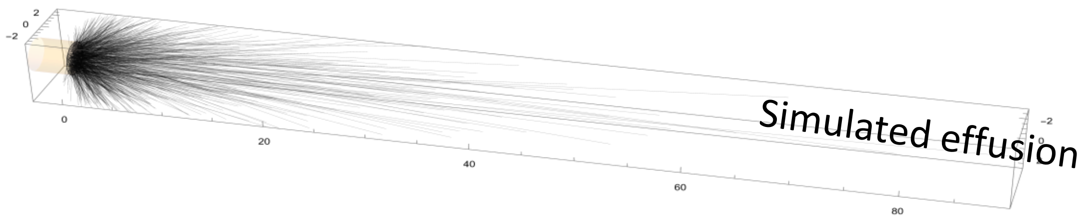


Modes of operation:

- **Ion guide mode**
- **LIST mode**
- **PI-LIST mode**

Improved temporal overlap
Improved spatial overlap

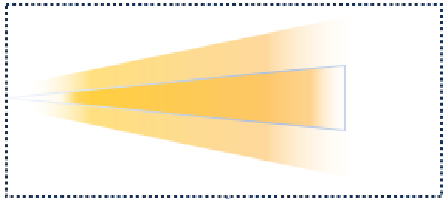
Operation mode	Mode loss factor	Combined loss factor	Est. total efficiency (%)
Standard RILIS	-	-	10
LIST ion guide	3	3	3.3
LIST	33	100	0.1
PI-LIST	2	200	0.05
PI-LIST optimised	10	2000	0.005



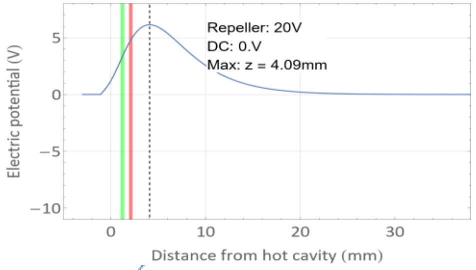
**Based on Ac data presented previously

Areas of Optimization

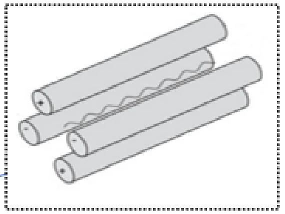
- Atomizer geometry optimization



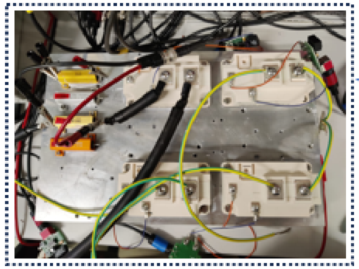
- DC offset for more atoms

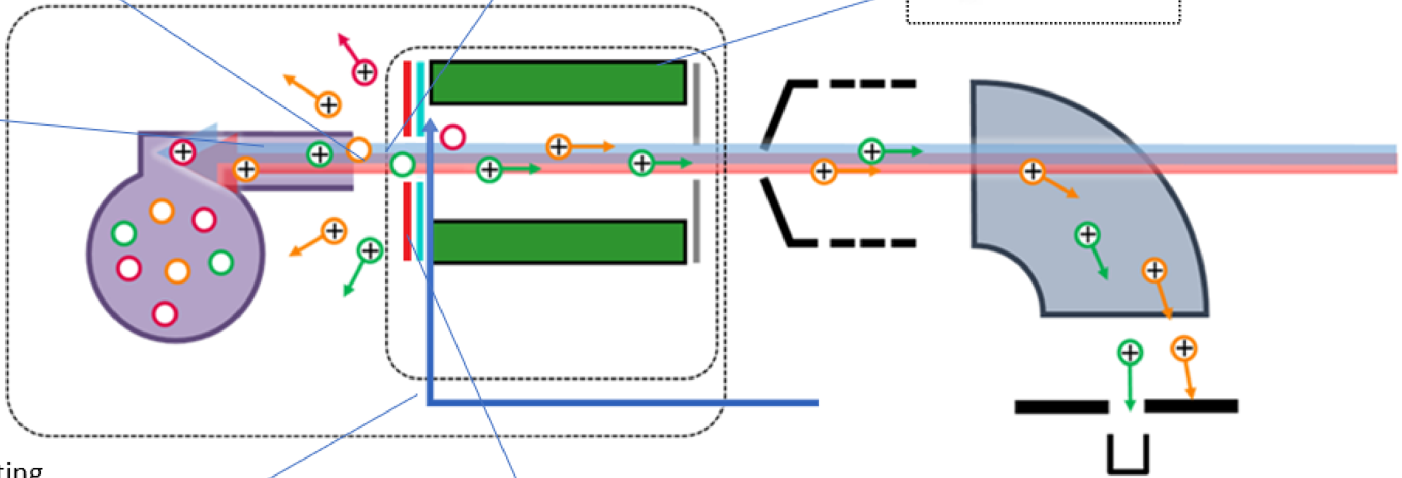


- RFQ phase angle and laser pulse synchronization

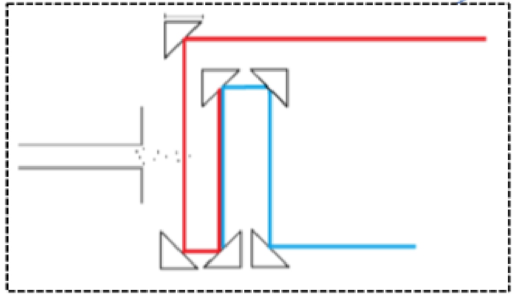


- Hot cavity voltage polarity

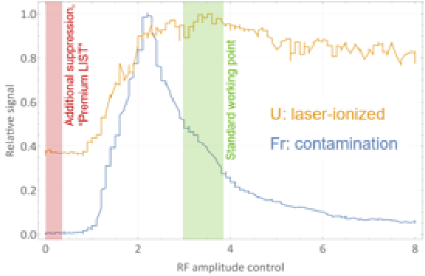




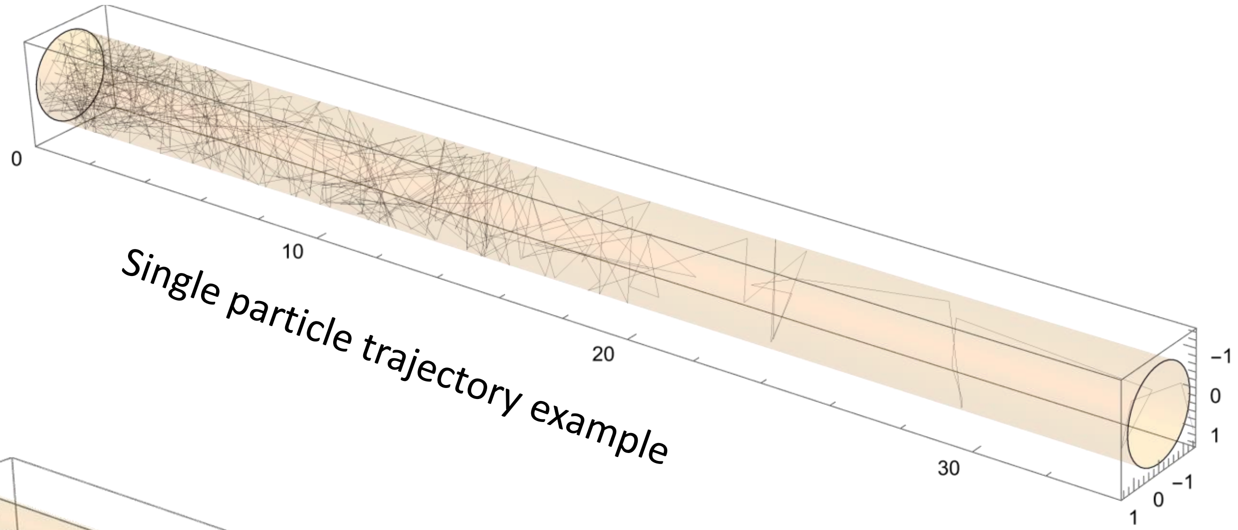
- Better reflective coating
- Optimized mirror setup



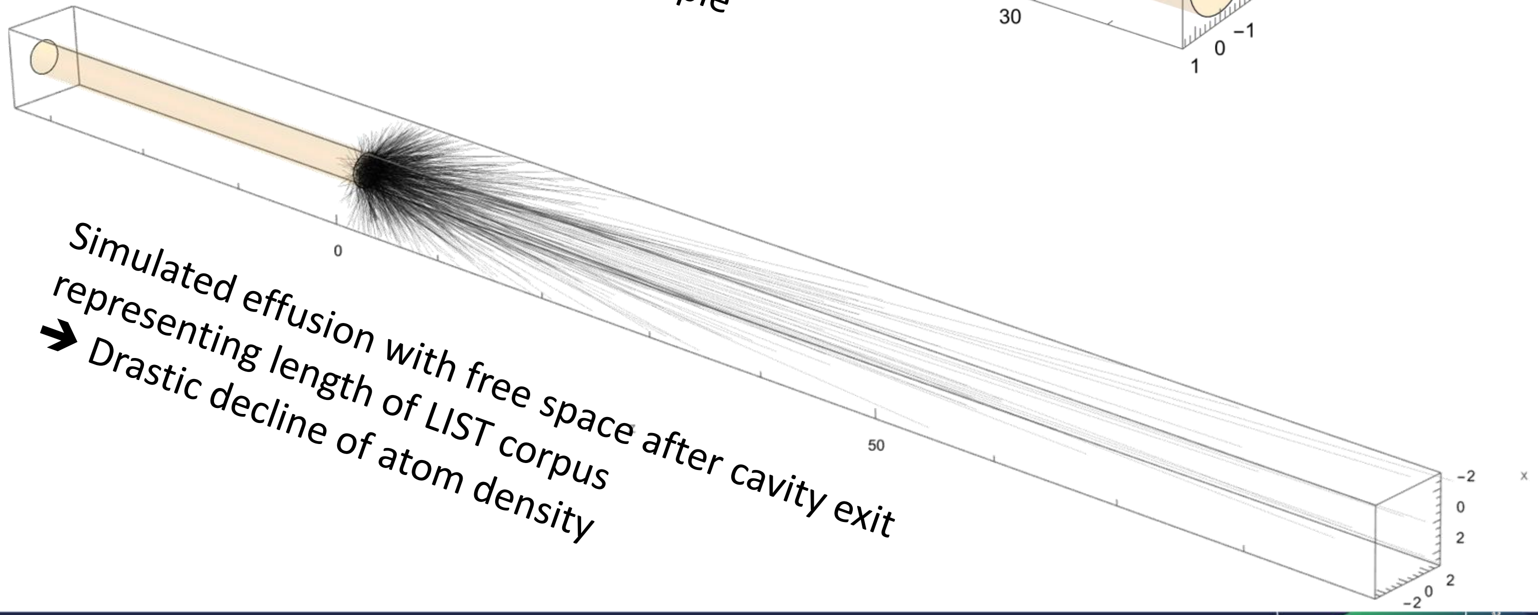
Contamination investigation and optimization



Atom beam collimation – Computational model



Single particle trajectory example



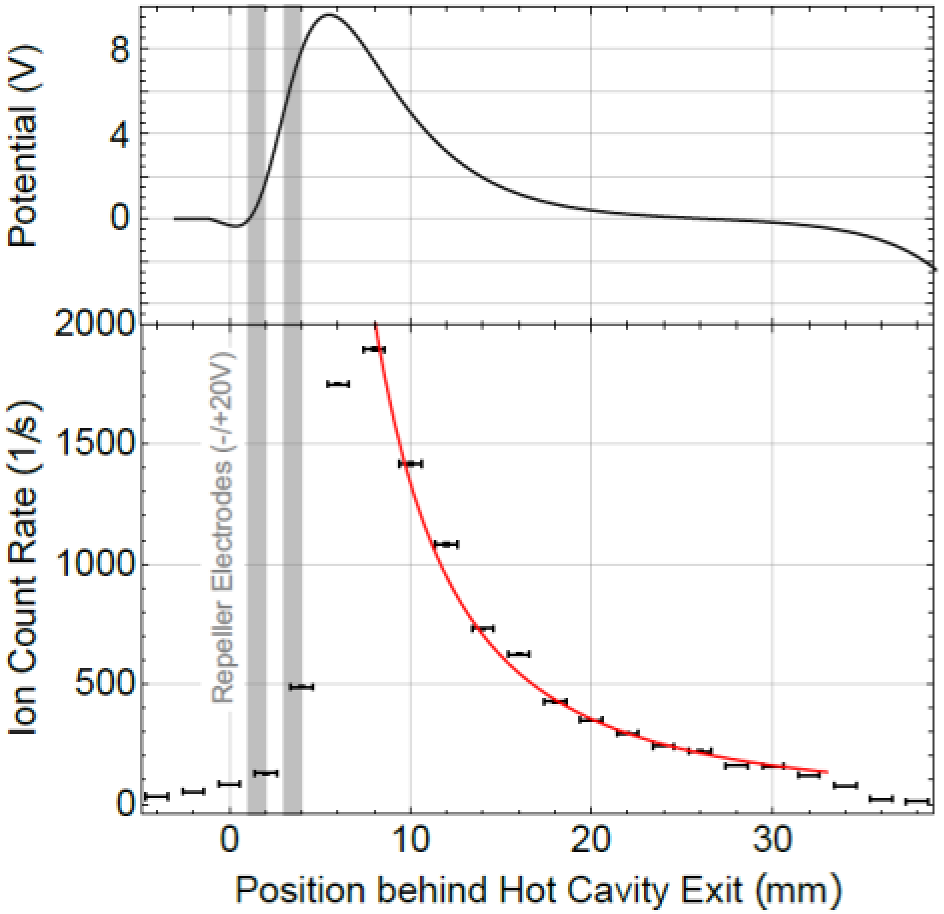
Simulated effusion with free space after cavity exit representing length of LIST corpus
➔ Drastic decline of atom density

Monte Carlo simulation of particle trajectories within hot cavity

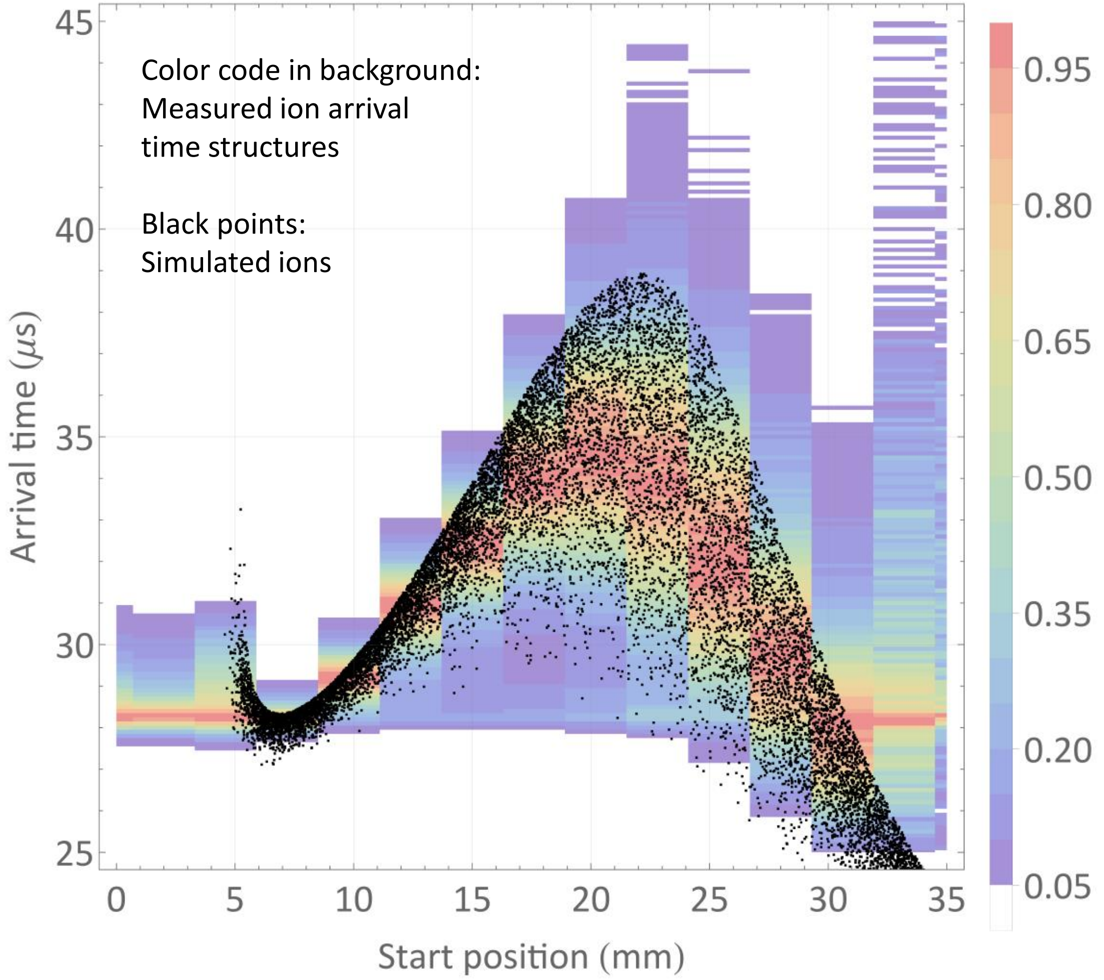
- Atom re-emission from surfaces by cosine law
- Maxwell-Boltzmann velocity distribution

Comparison to established Clausing model of effusion per solid angle for simulation validation

Atom beam collimation – Experimental access

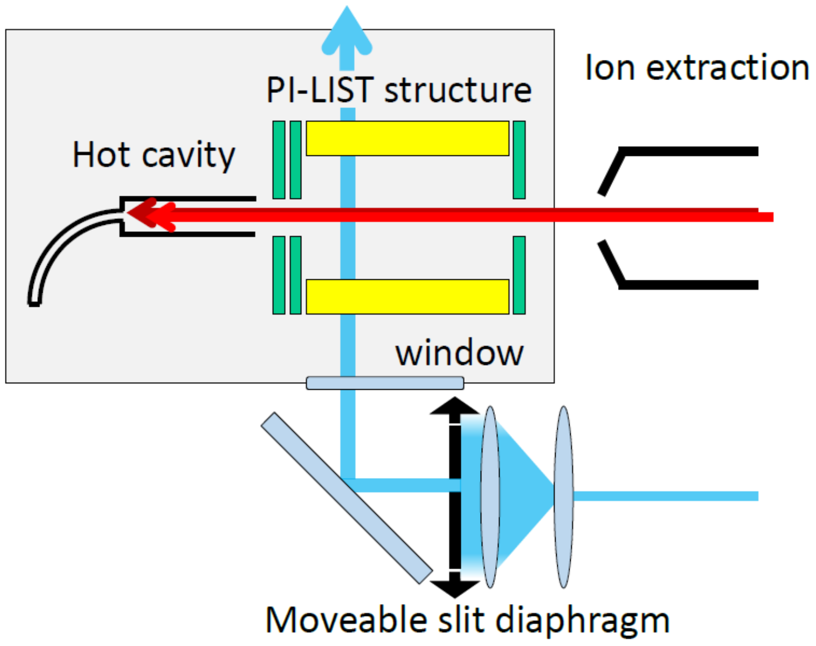


Experimental data on atom density along LIST central axis

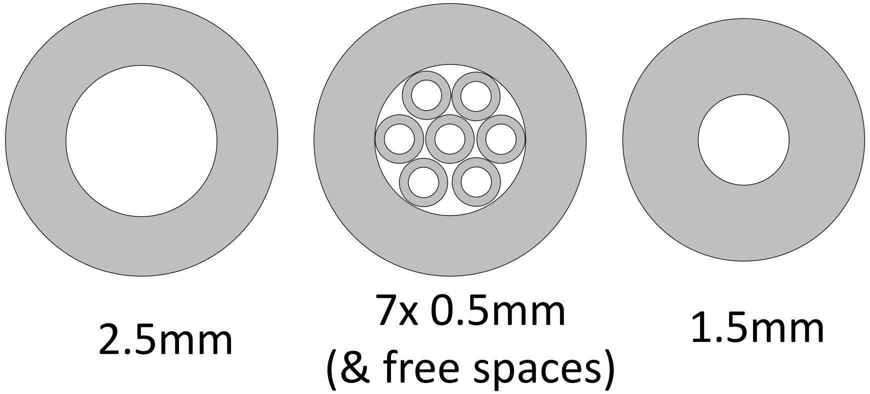


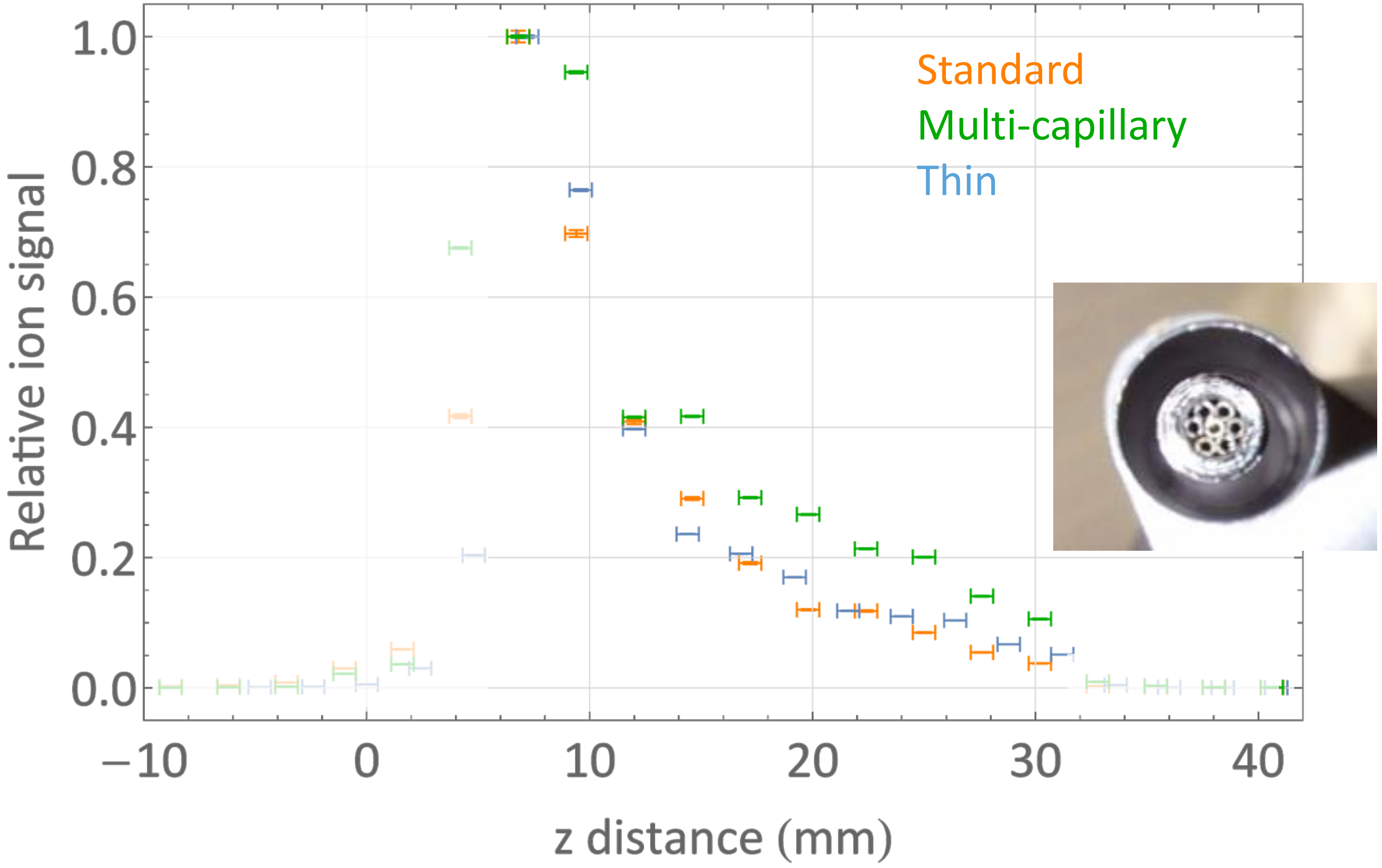
Arrival time of ions in relation to point of creation along LIST central axis: Validation of simulation model

Atom beam collimation – Investigation at RISIKO (JGU)



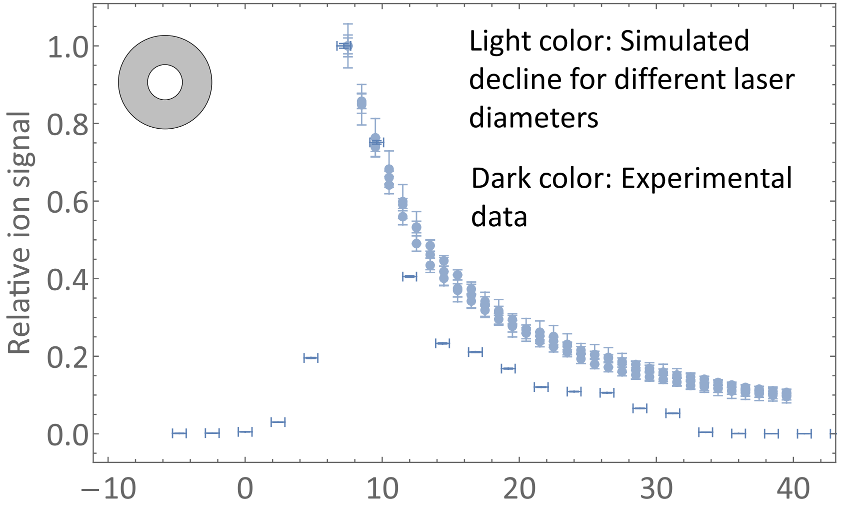
Test atomizer cross sections

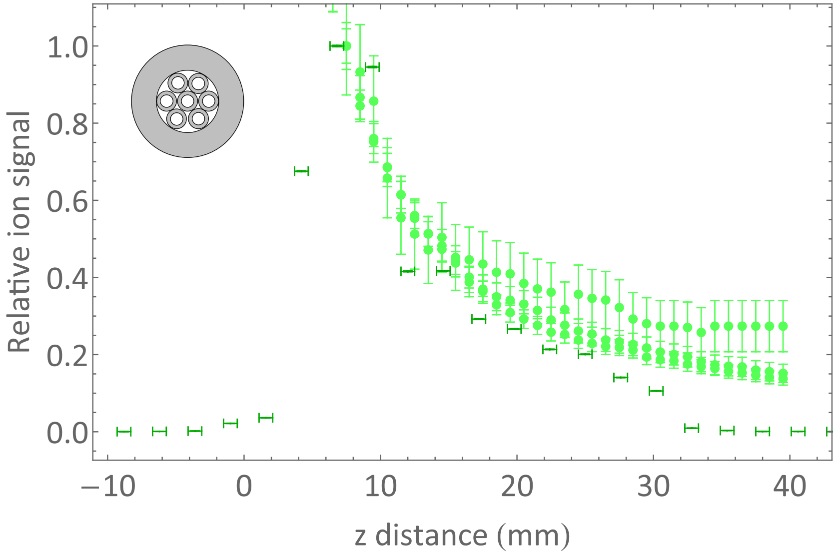


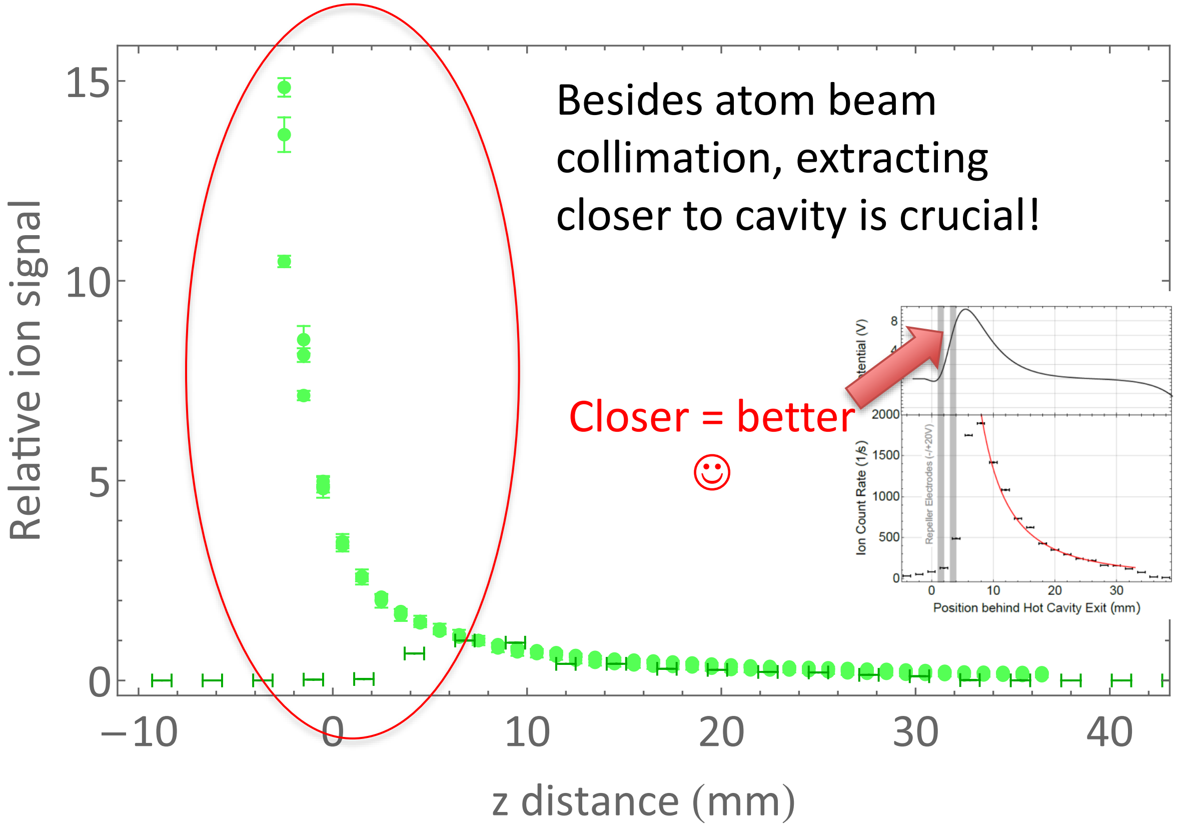


Measured relative density decline
for different hot cavity geometries

Atom beam collimation – Comparison data to model

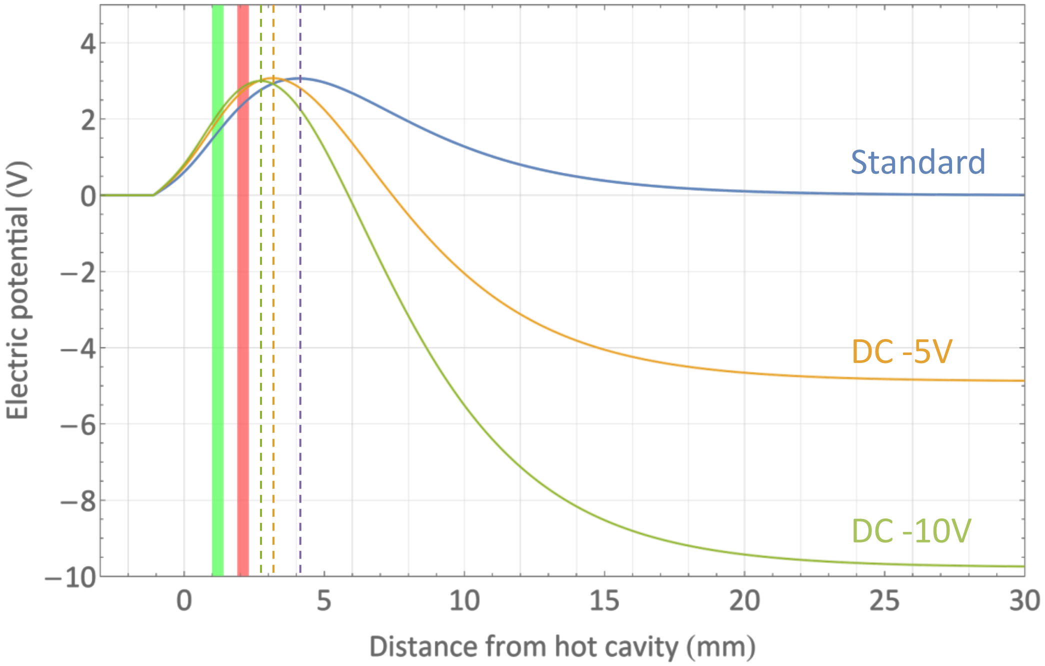


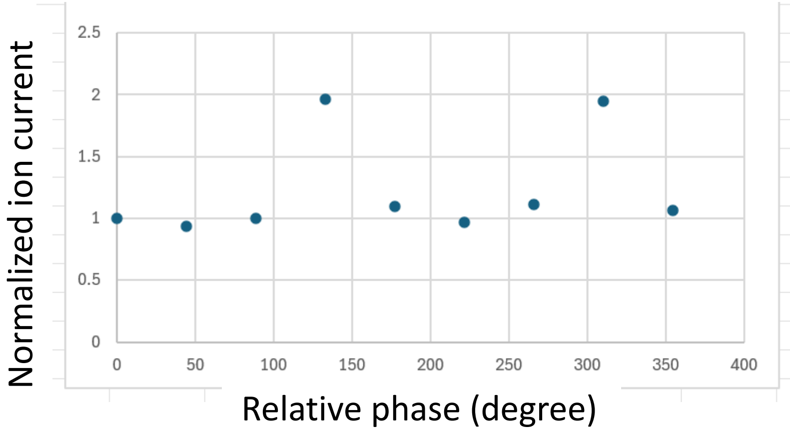


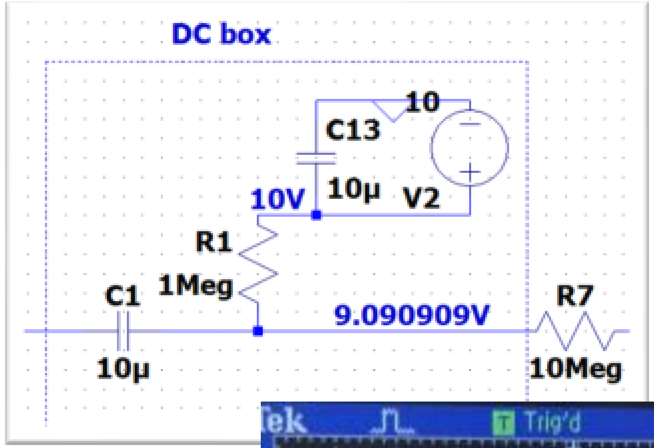


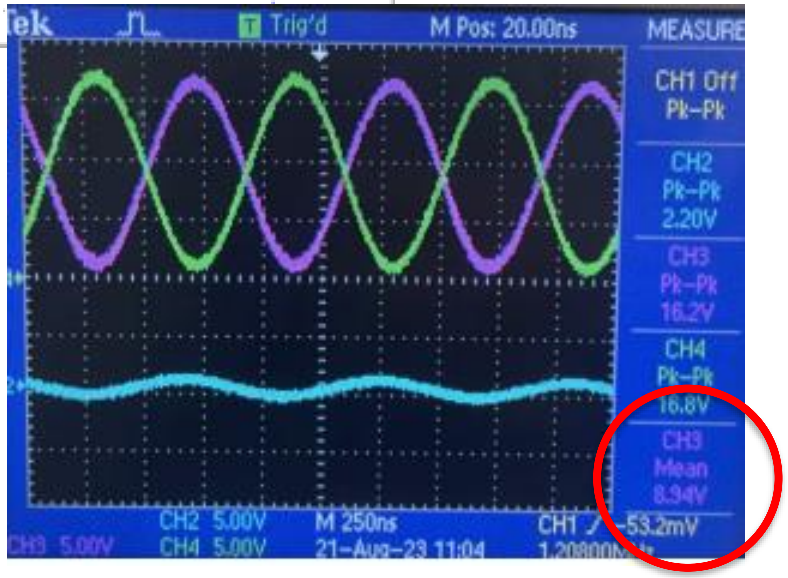
Zooming out...

Electric potential shaping: DC offset









Infrastructure designed, built and validated in summer student project
➔ Application with actual LIST ongoing

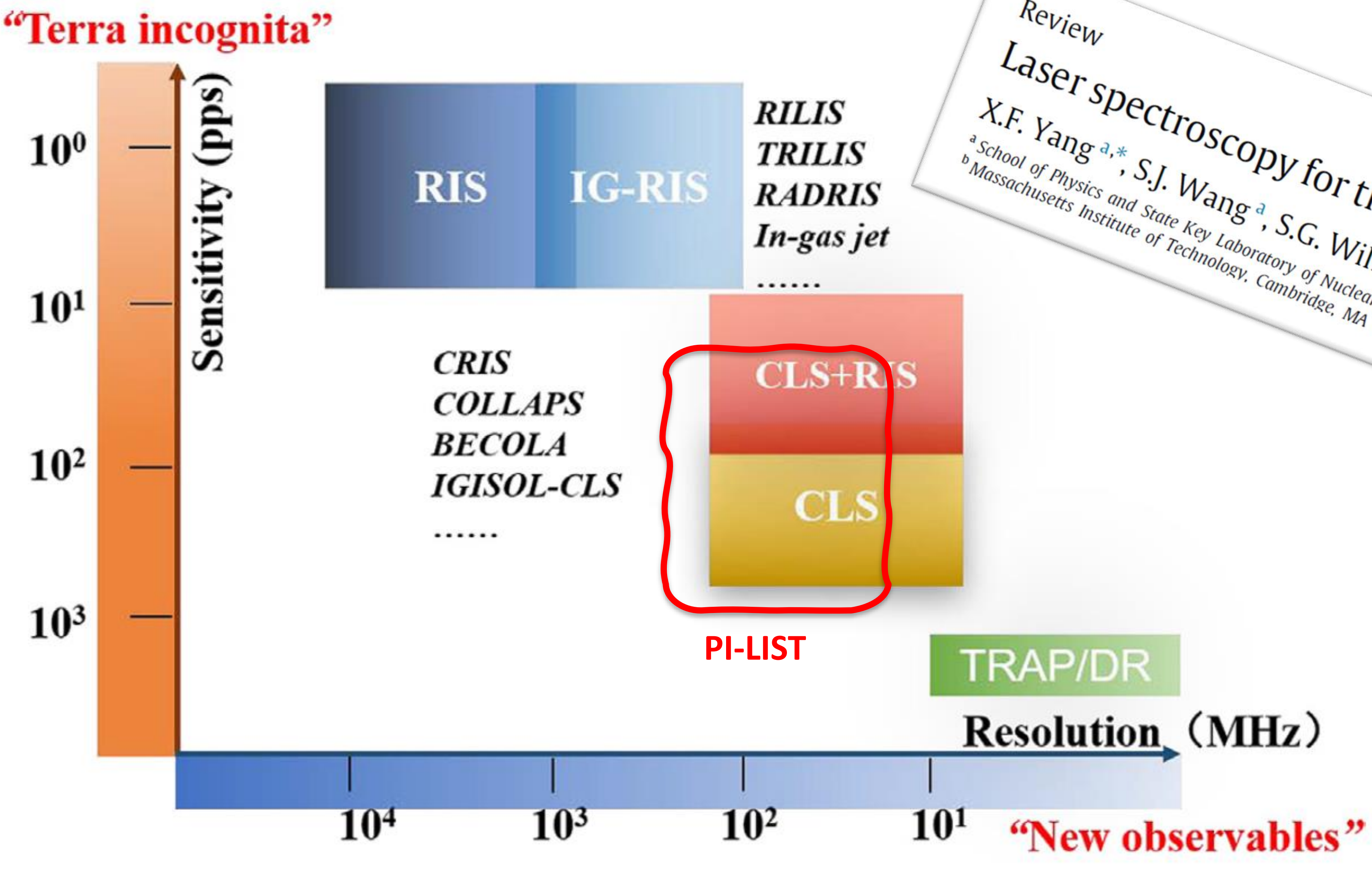
Conclusion and Future Directions

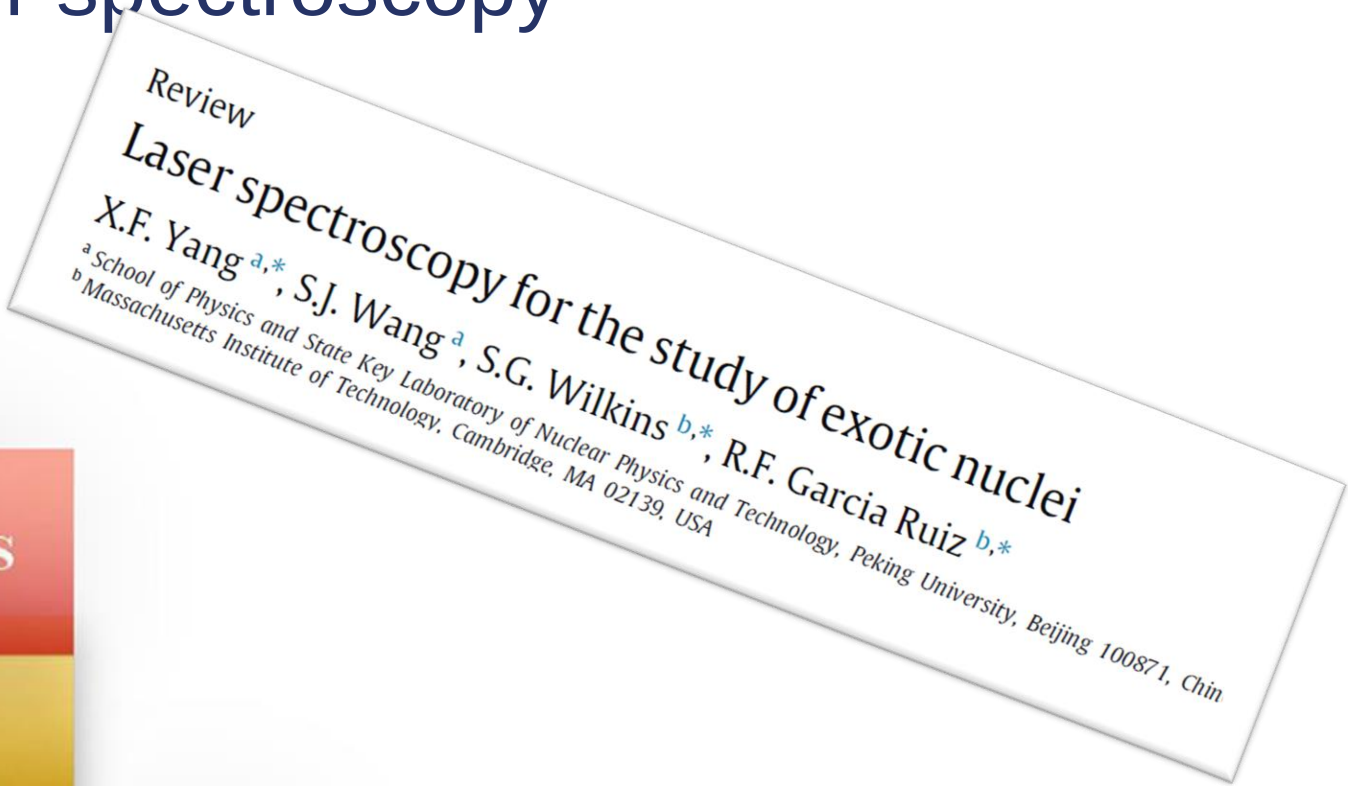
- Laser resonance ionization for element selective RIB production
- “Sub-doppler” in-source spectroscopy at online facilities achieved
- First Neutron-rich Actinium laser spectroscopy scan
- PI-LIST usage in other regions, such: Lanthanides – cool things coming up with Dr Kara Lynch
- PI-LIST is great! But can be greater….

THANK YOU FOR PI-LISTENING ☺

SUPPORTING SLIDES

PI-LIST in the landscape of laser spectroscopy





Review

Laser spectroscopy for the study of exotic nuclei

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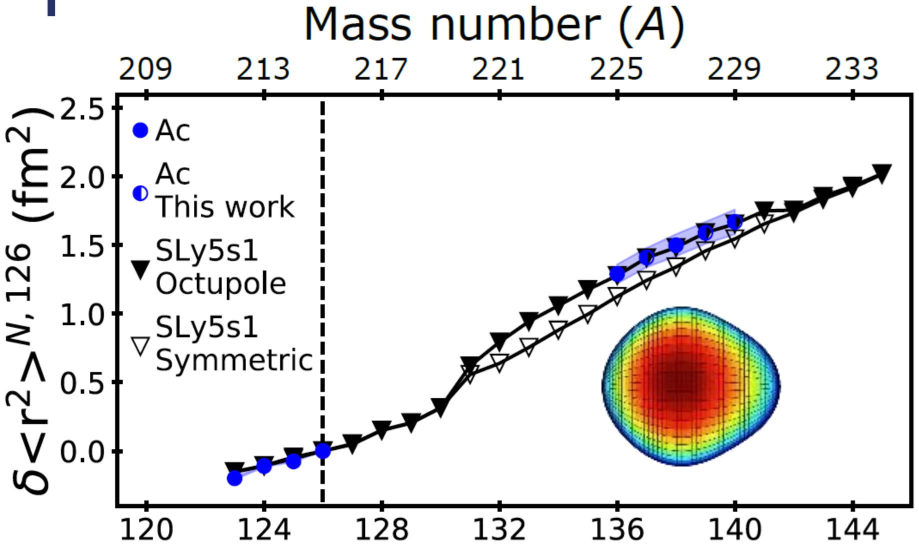
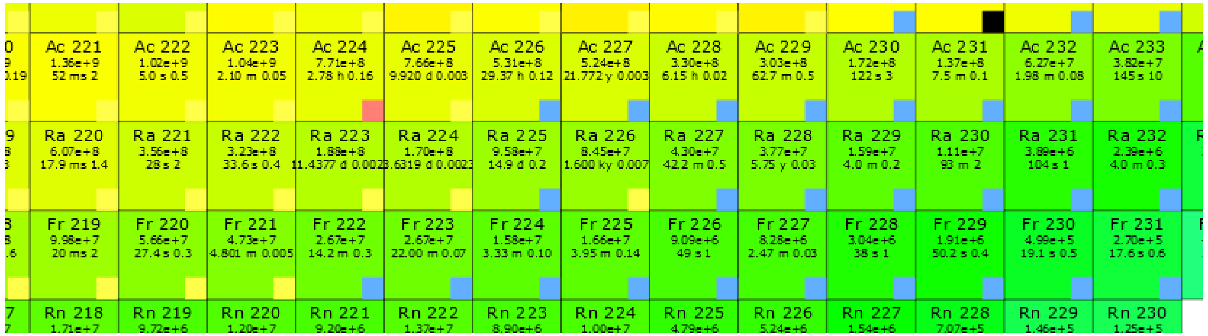
- PI-LIST still “young”
- “Simple” unit instead of beamline
- Versatile operation modes
- Isomer-selective RIB production

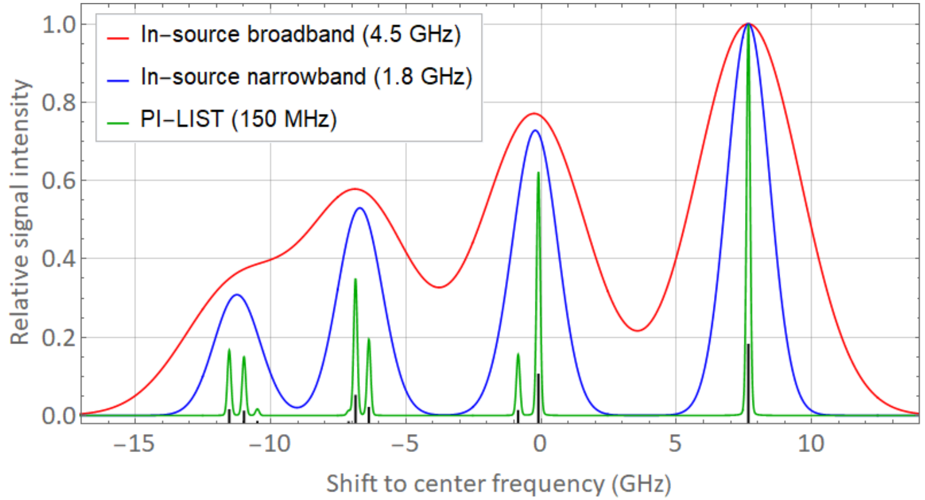
Octupole deformation in Ac isotopes



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

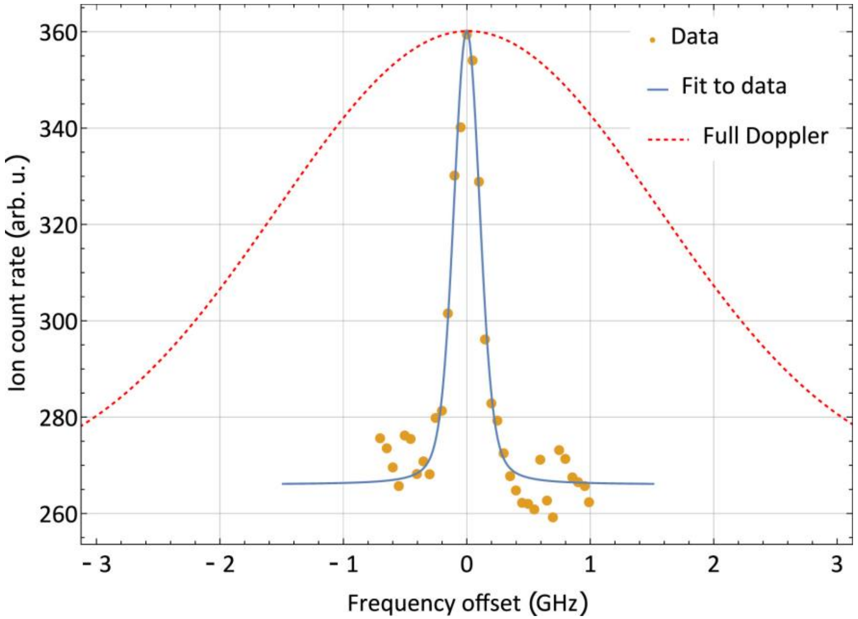


Significant isobaric contamination ➔ LIST suppression



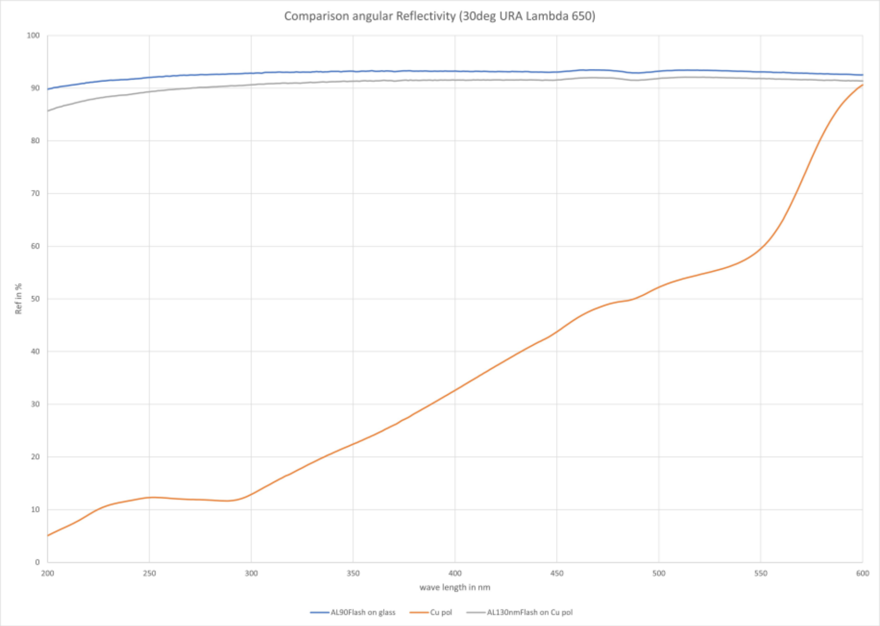
Low sensitivity to Q_S ➔ PI-LIST high resolution

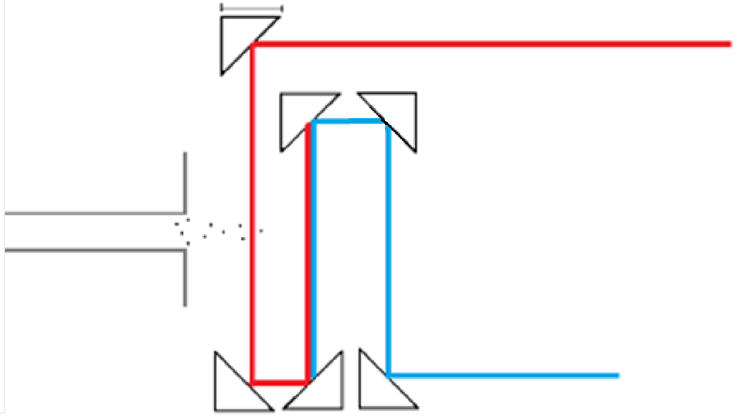
200 MHz achieved in experiment



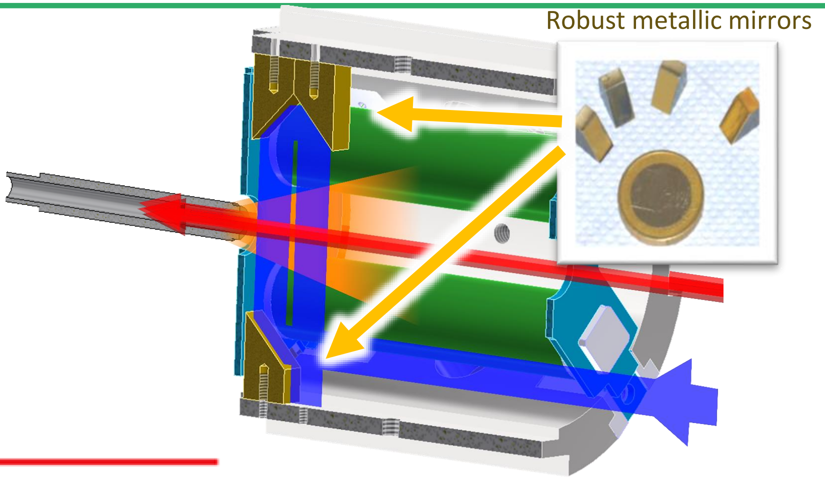
Optimization: Mirrors

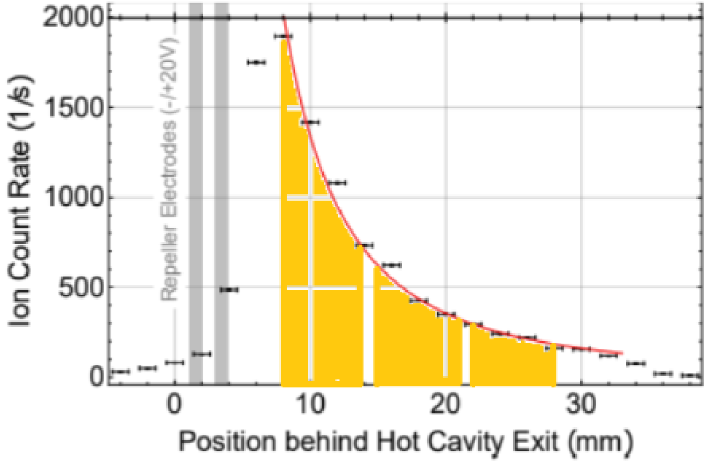
- Better reflective coating
- Optimized mirror setup



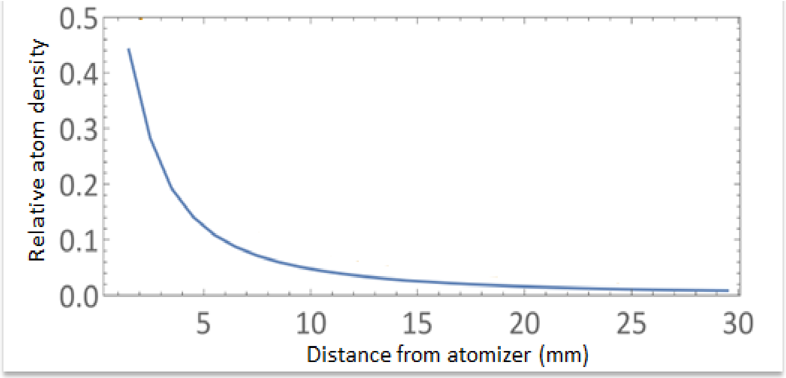


Robust metallic mirrors

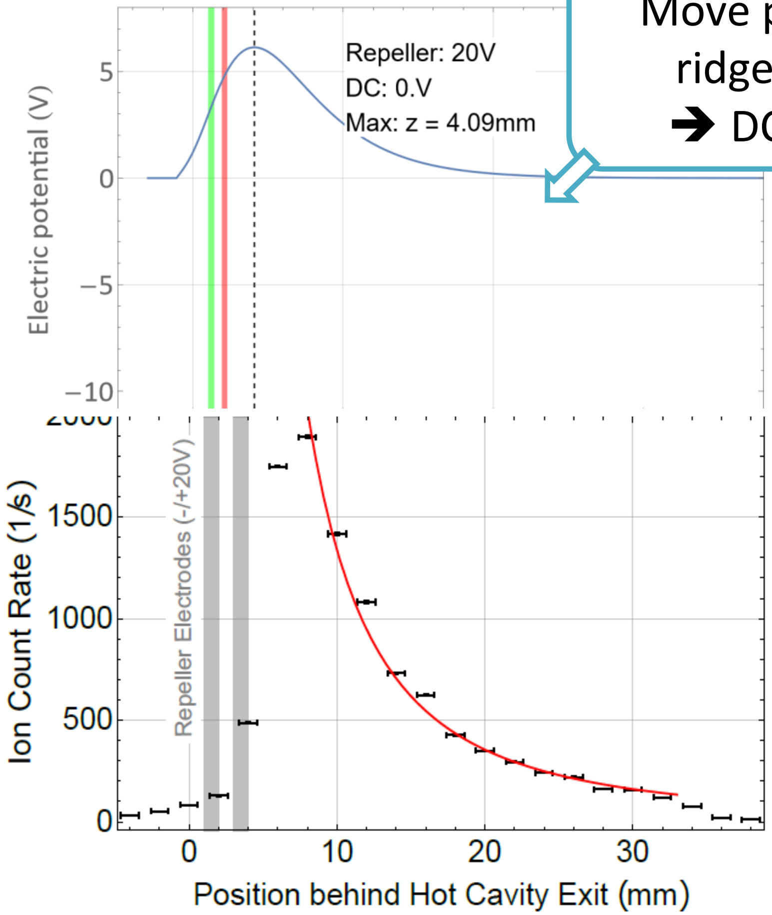




Optimization: Opening Angle

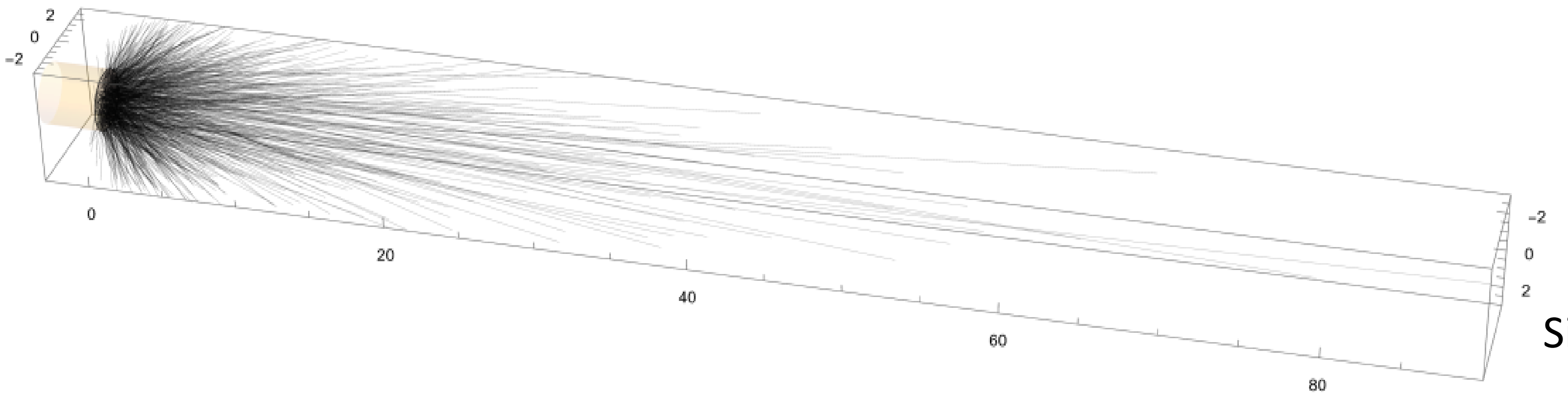


~50% gain



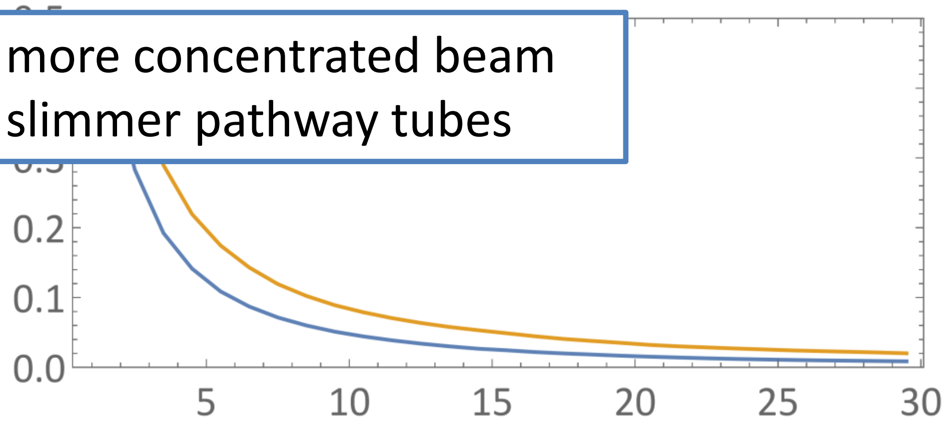
Move potential ridge closer
➔ DC offset

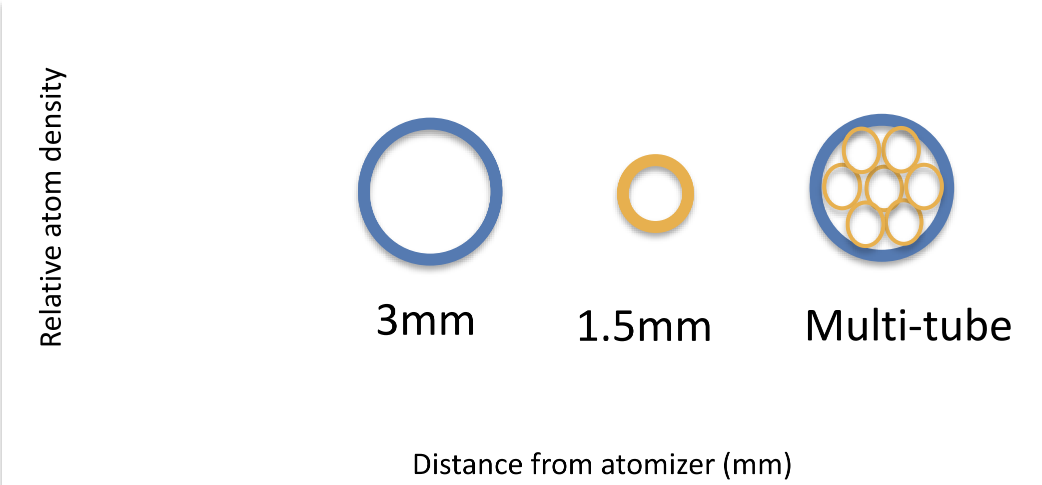
Optimization: Atomizer



Simulation data

Goal : more concentrated beam
How: slimmer pathway tubes

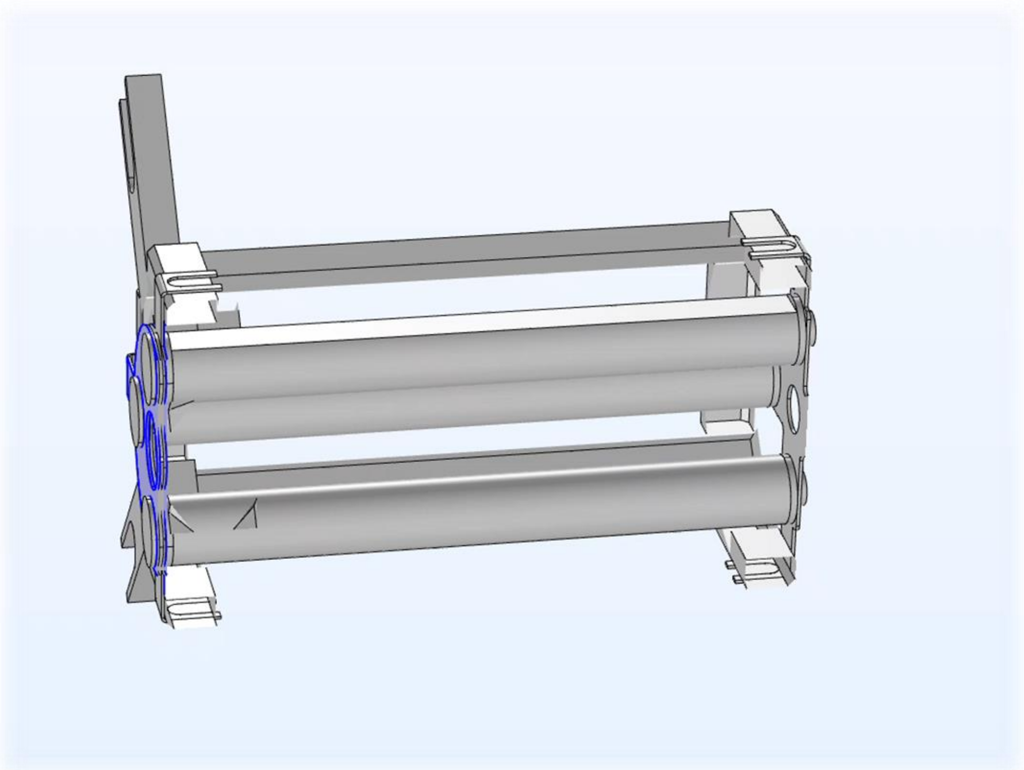


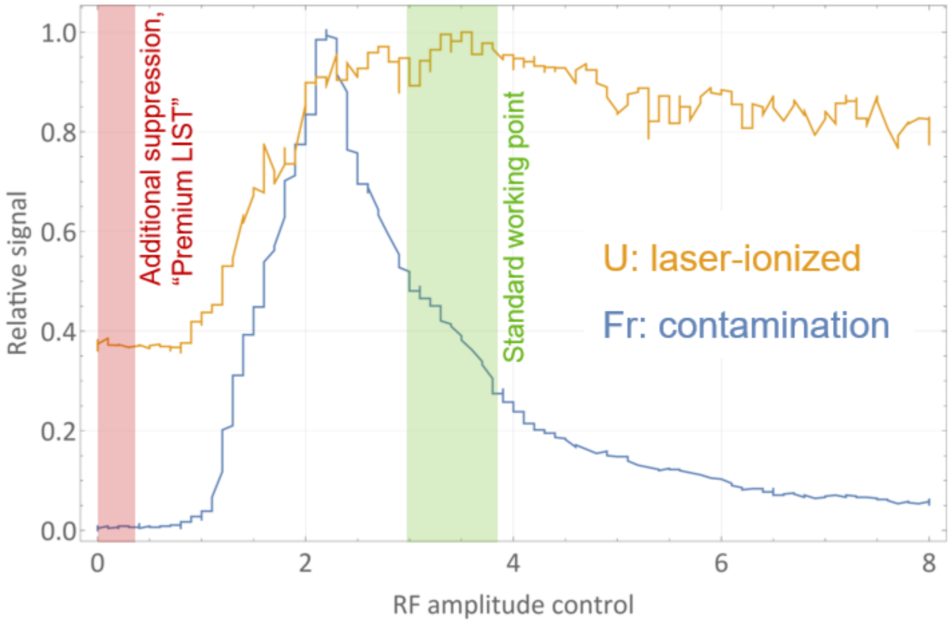


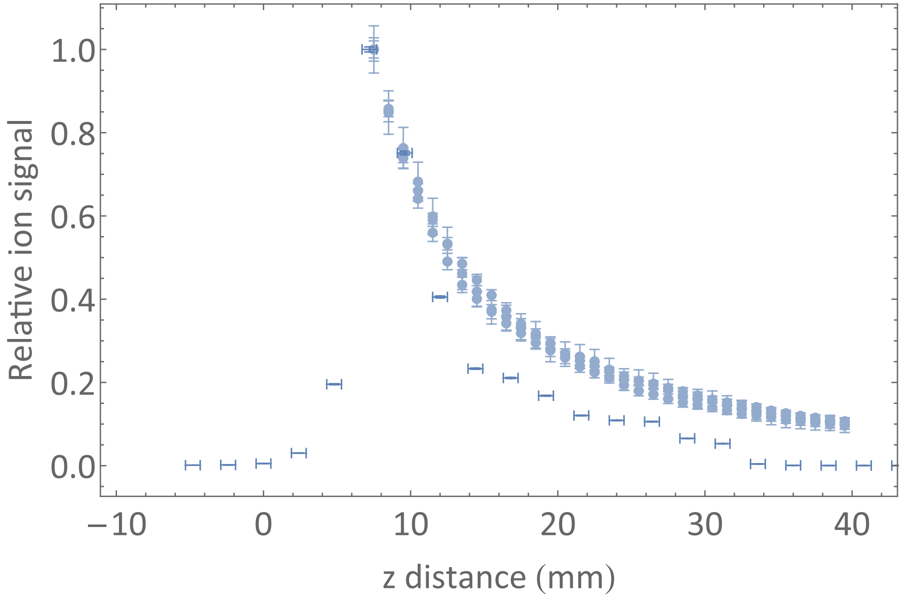
~40% gain at 3mm from the atomizer

Optimization: Contamination Source

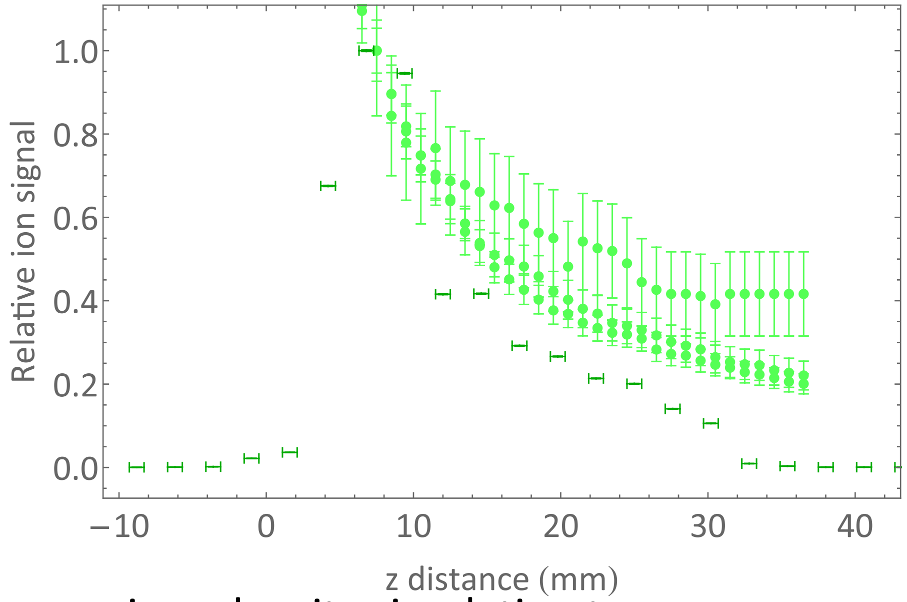
⚠ Highlighted part is source of contamination (?) → simulations



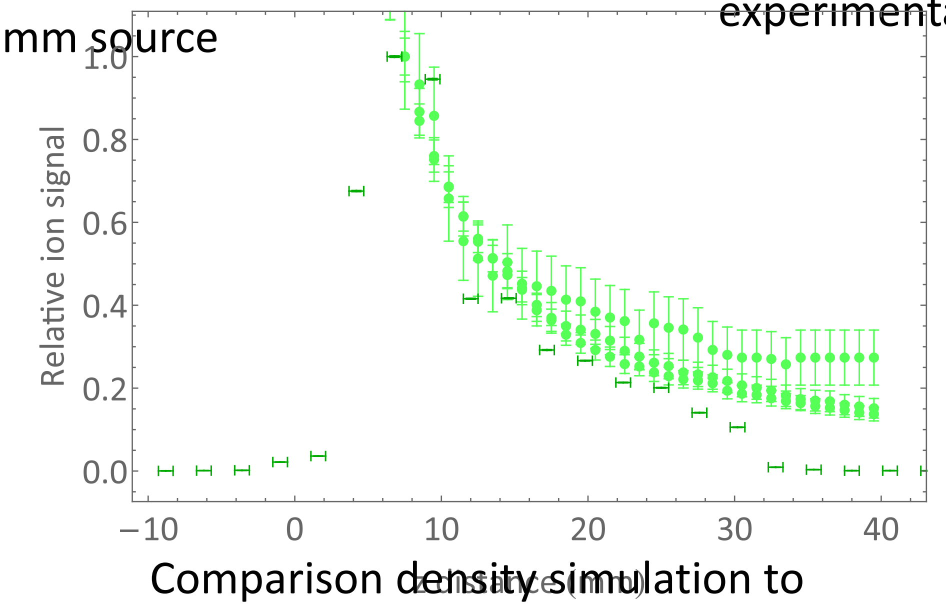




Comparison density simulation to experimental data: D1.5mm source



Comparison density simulation to experimental data: Multi-source with 3mm offset



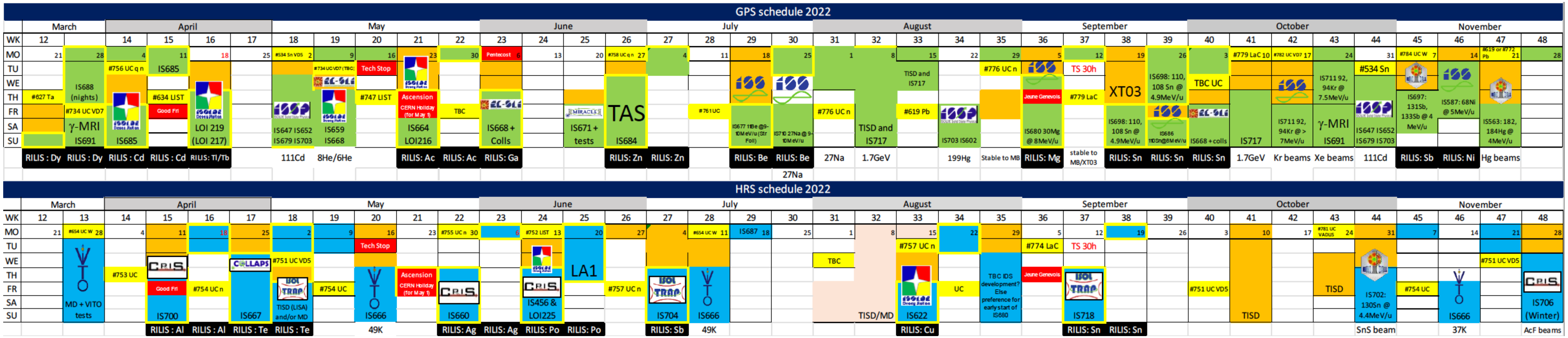
Comparison density simulation to experimental data: Multi-source without offset

Summary of Modes

	Broadband (10 GHz)	Narrowband (1 GHz)	Fourier limited (< 100 MHz)
Ion guide	Efficiency ***** Resolution * Isobar suppression –	Efficiency **** Resolution ** Isobar suppression -	-
LIST (collinear)	Efficiency ** Resolution * Isobar suppression ****	Efficiency ** Resolution ** Isobar suppression ****	-
PI-LIST	Not applicable.	Efficiency * Resolution **** Isobar suppression ****	Efficiency * Resolution ***** Isobar suppression ****

RILIS @ ISOLDE: The workhorse ion source

2022 ISOLDE operation schedule



24 elements: Yb, Ba, Dy, Cd, Al, Tl, Tb, U, Gd, Te, Ac, As, Ga, Po, Zn, Sb, Be, Ca, In, Cu, Mg, Sn, Ni, Cr

29 out of 36 weeks *(18 weekends)* + development

RIB delivery *and* nuclear structure experiments