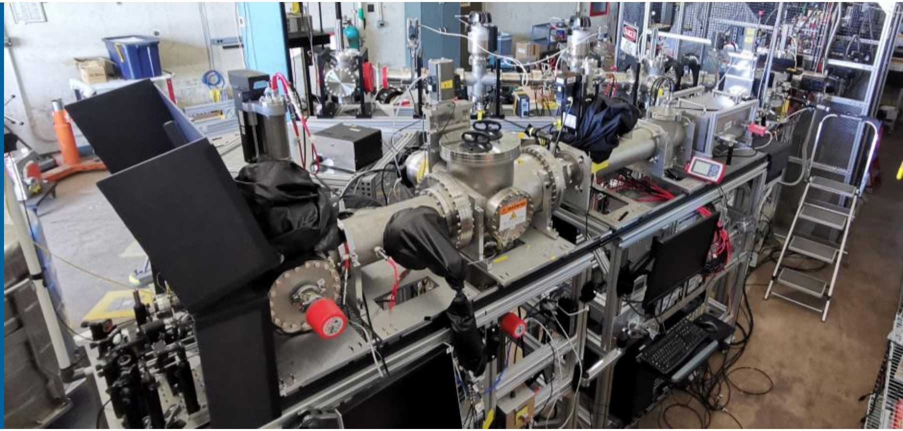
FIRST RESULTS FROM *ATLANTIS*

COLLINEAR LASER SPECTROSCOPY AT ANL



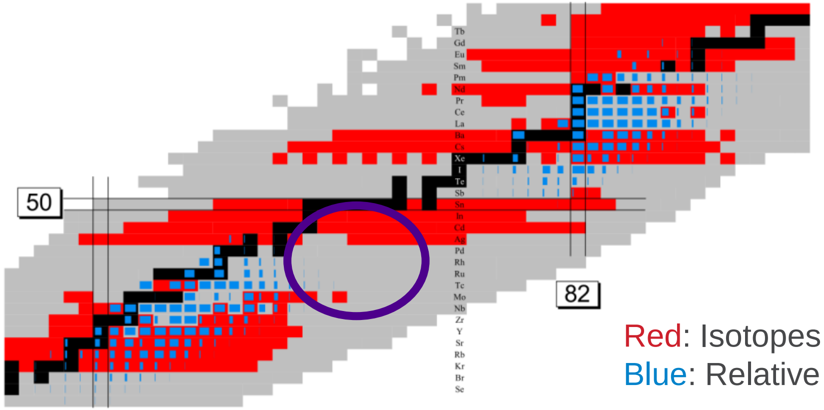
BERNHARD MAASS

ARGONNE NATIONAL LABORATORY

June 6th 2023
ARIS Avignon

CARIBU AT ANL

- Cf-252 spontaneous fission source
- Inside gas catcher/low energy transport system
- ~100mC, typical beams of few 1000/s ions per second
- Problems with the thin film deposition
  - Never reached the design production rates
  - Switch to neutron-induced Uranium fission in near future: ***NuCARIBU***



Red: Isotopes investigated with LS
Blue: Relative fission yields U/Cf

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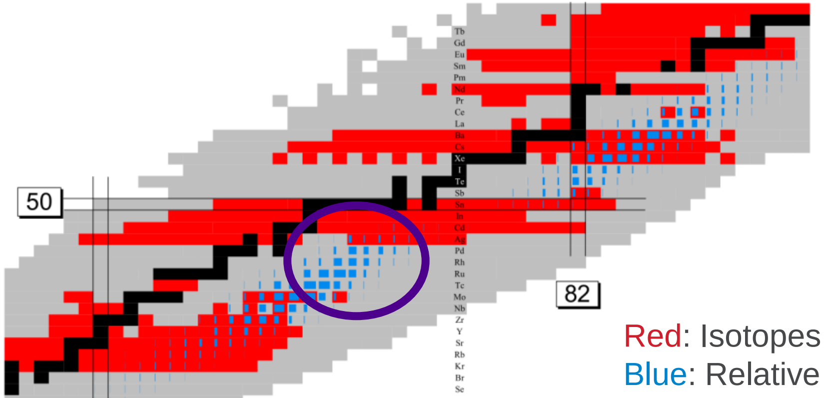

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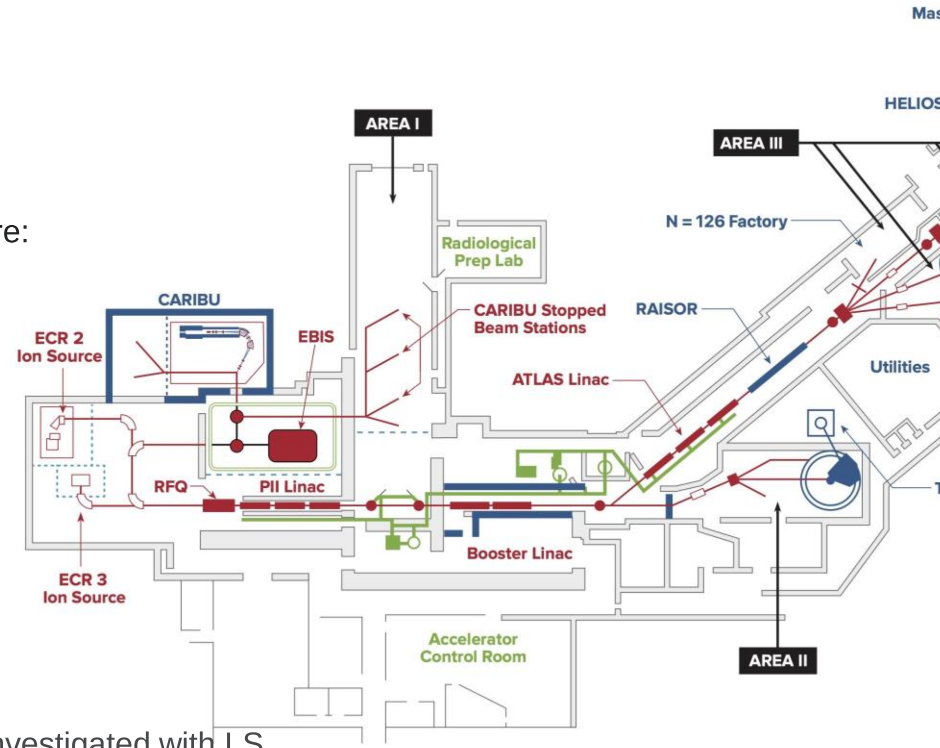
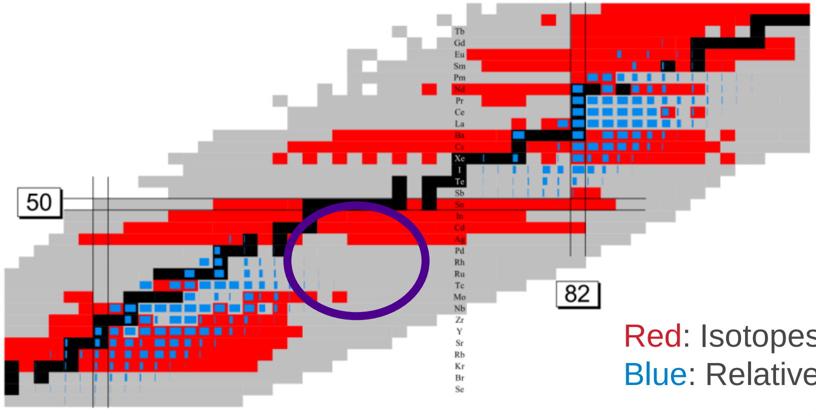
ATLAS
ARGONNE TANDEM LINAC
ACCELERATOR SYSTEM





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CARIBU AT ANL

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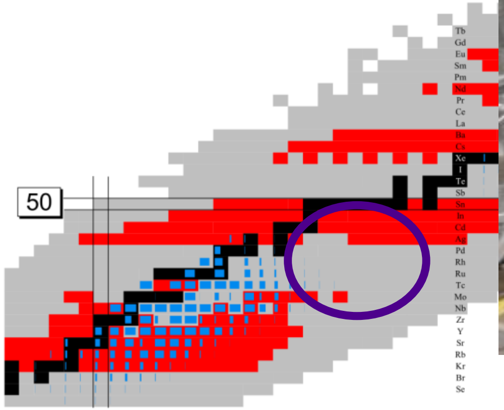

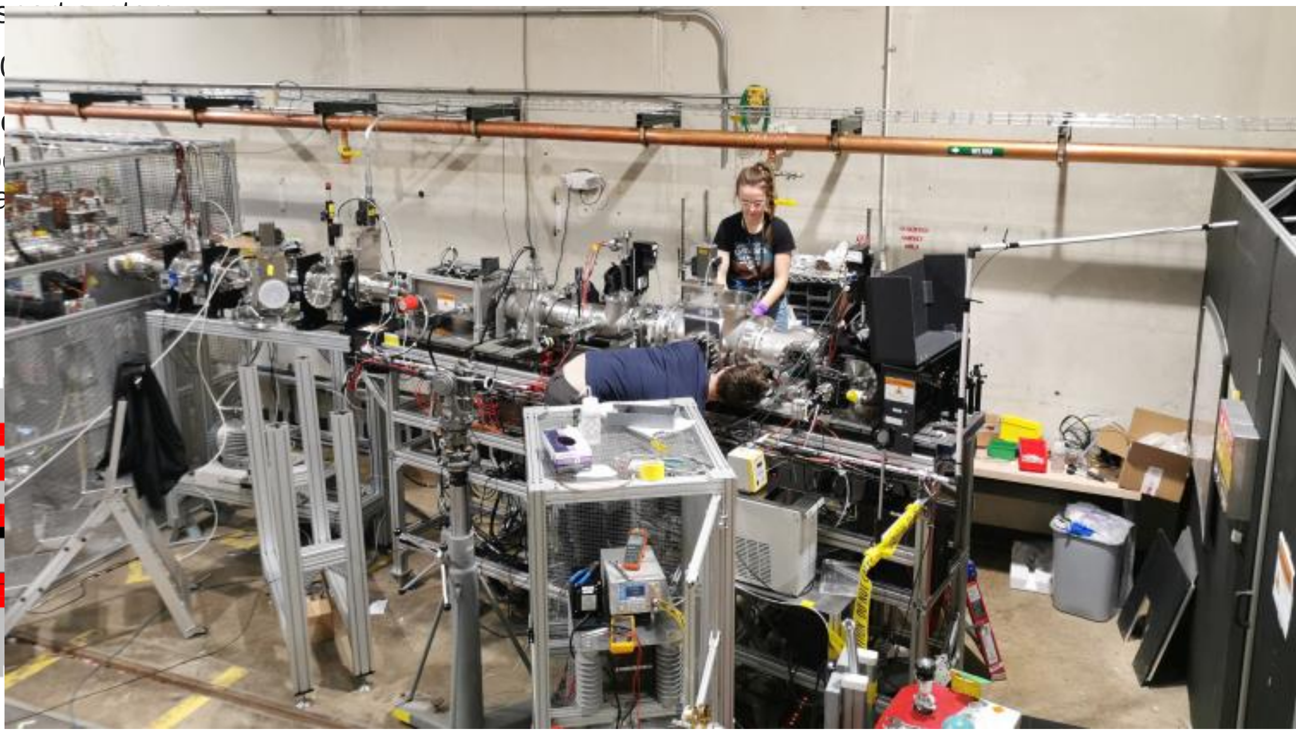

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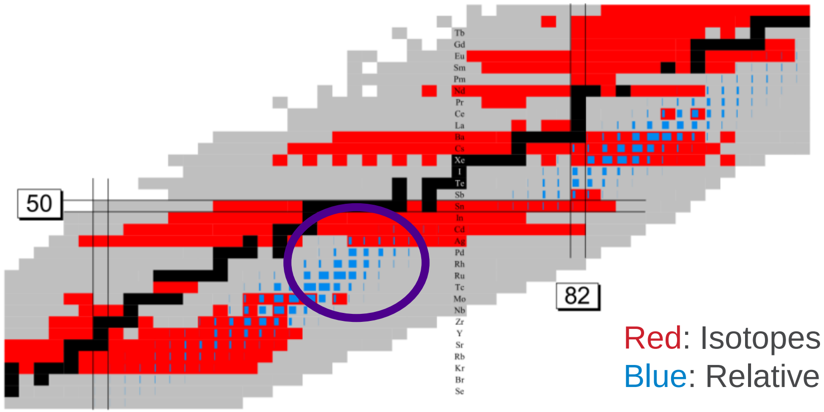

Red: Isotopes investigated with LS
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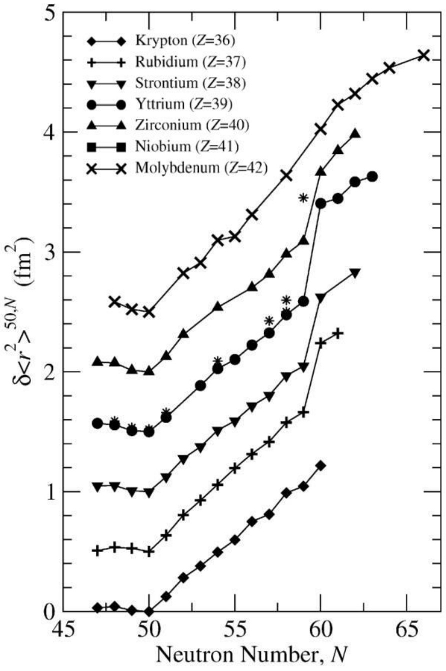
Ruthenium

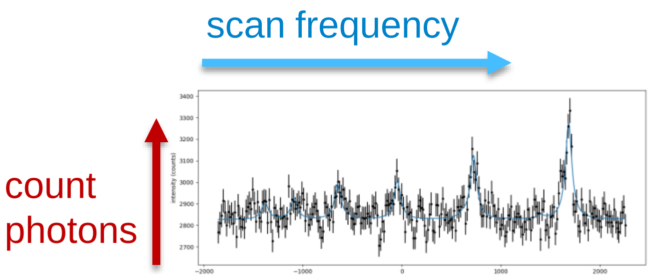
- Complement the „medium mass“ region (Pd-2p)
- Nuclear Moments in the Pd-Cd region
- Triaxialtiy in Ru 108,110,112?

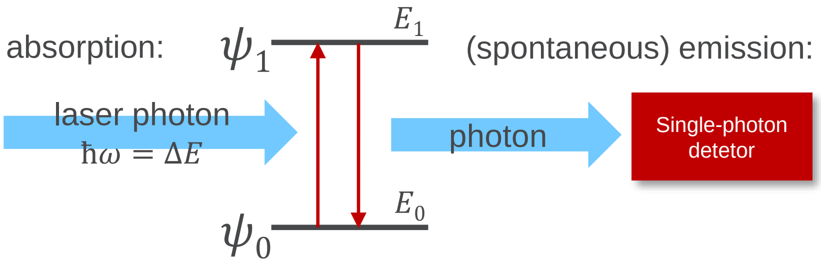


Charlwood, F. et al., Phys. Lett. B 674 (1), 23–27, 2009

COLLINEAR LASER SPECTROSCOPY

- Atomic levels are influenced by nuclear effects – size, mass, moments
- Precise measurement allows extraction of these observables
- Applicable to short-lived isotopes and isomers





Accessible observables:

- **(difference in) mean-square nuclear charge radii**
- **Magnetic dipole moment**
- **Electric quadrupole moment**
- **Static deformation parameters**

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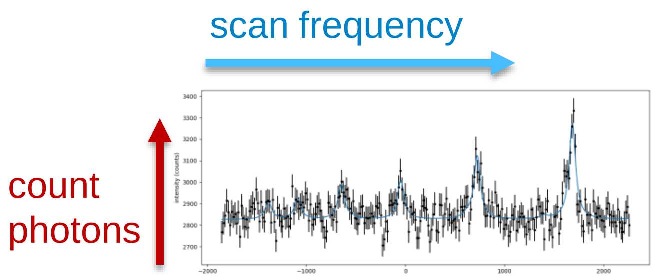

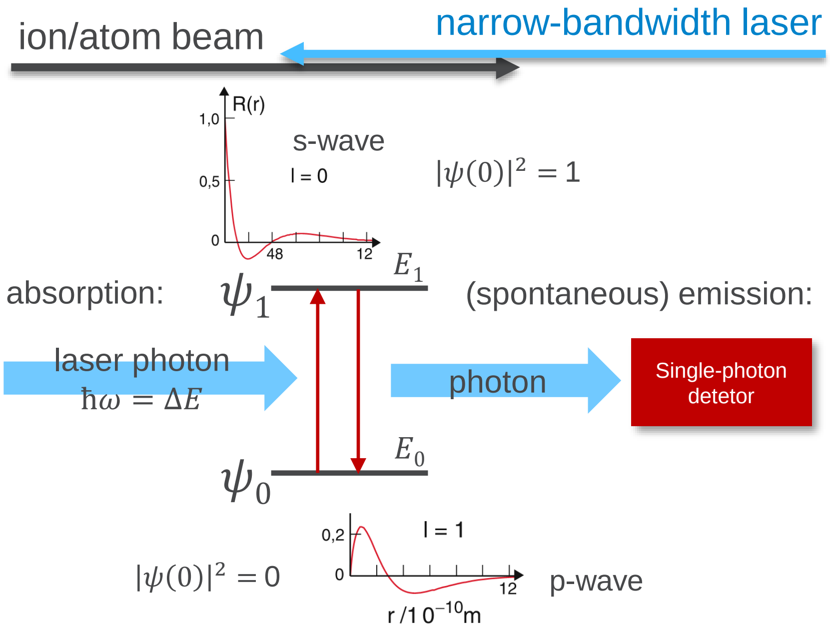

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ISOTOPE SHIFT AND KING PLOTS

- The same atomic transition in two isotopes of the same element shows:

normal mass shift + specific mass shift

change in reduced mass + changing electron correlations

field shift

change in nuclear size

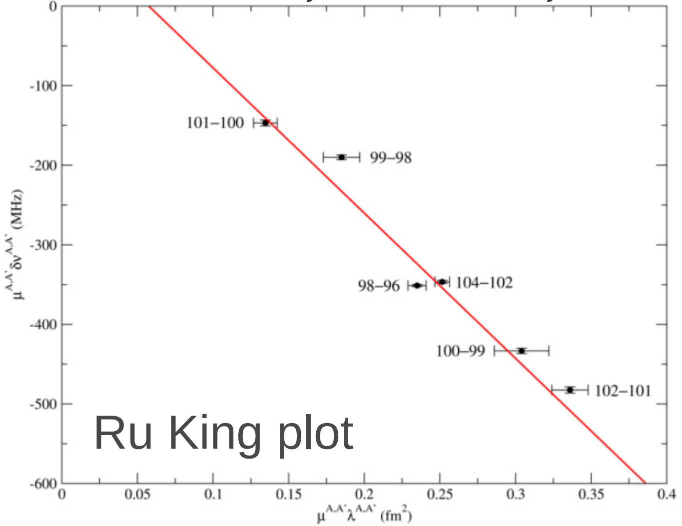
$$\delta\nu_i{}^{A,A'} = \nu_i{}^{A'} - \nu_i{}^{A} = F_i\,\delta\langle r^2\rangle^{A,A'} + M_i\,\frac{m'_A - m_A}{m'_A m_A}$$

- Field and Mass shift can‘t be calculated for many-electron system
- Extract them by comparison with stable reference radii: King Plot
- Use values of F_i and M_i to calculate radii of radioactive isotopes
- Stable radii from Muonic atom spectroscopy

Landolt-Börnstein / Nuclear Charge Radii, Vol 20 and references therein

  – Need for good references between stable and radioactive nuclei!
  – Allows to remove many systematic error contributions

D H Forest *et al* 2014 *J. Phys. G: Nucl. Part. Phys.* **41** 025106

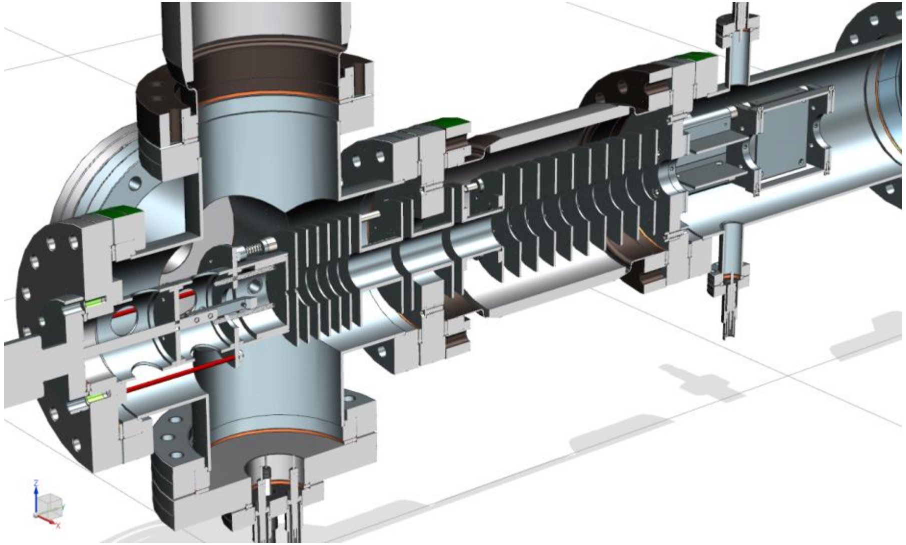


F_i = -1826(200) MHz fm^{-2}
M_i = 105(48) MHz

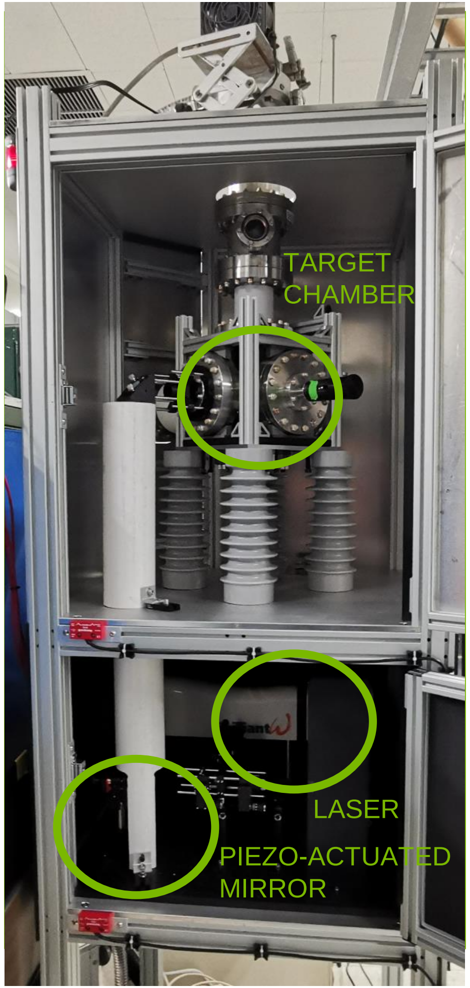
$4d^7 5s\ a\ ^5F_5 \rightarrow 4d^7 5p\ z\ ^5G_6$ (349.8942nm)

OFFLINE SOURCE

- Reference measurements on stable isotopes:
  - Need reliable, constant-intensity, versatile ion source
- Laser ablation source with ~50mJ, 100Hz, Nd:YAGx2
- Confirmed beams: Pd, Ru, Rh, Gd, Sm, Zr, Ti
- Target swap < 2h beam-beam

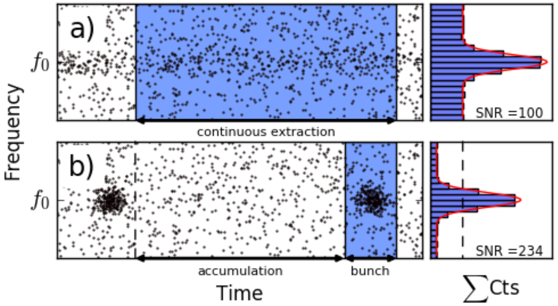


„pure“ targets

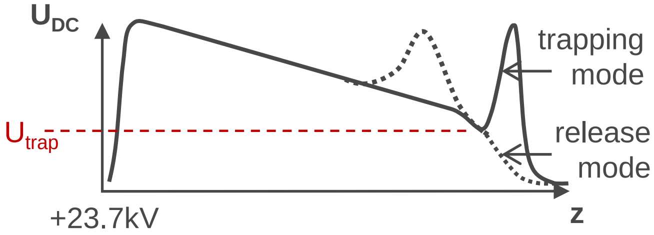


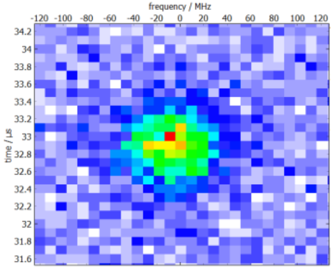
BUNCHING THE BEAM

- Bunching compresses the beam into a short time window



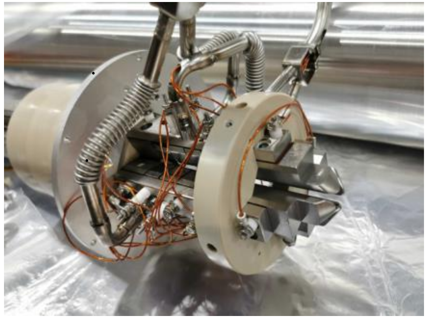
  - time focussing:
    - make the bunch as short as possible
  - ion stacking
    - collect as many ions as possible in one bunch

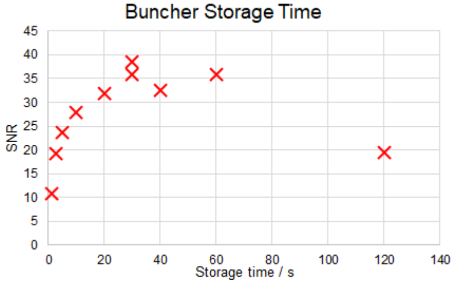




$\Delta t < 1\mu s$

$\Delta E < 40MHz\ (3V)$





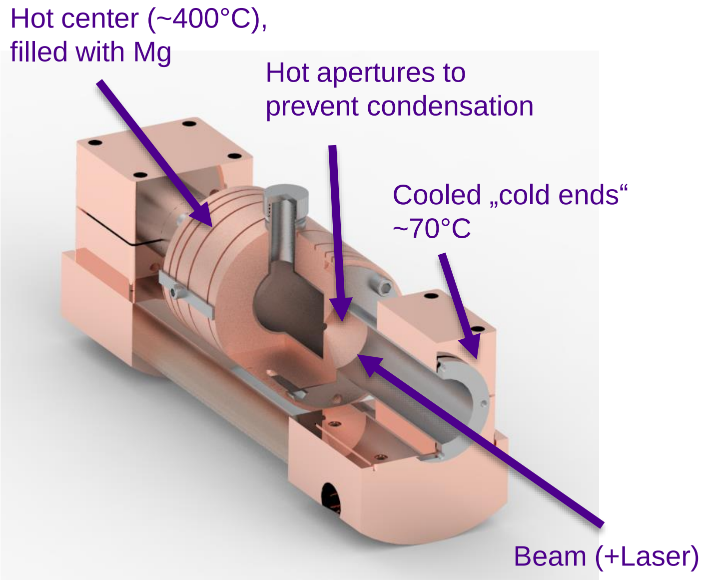
$1{:}10^7$ background suppression (vs. cw)

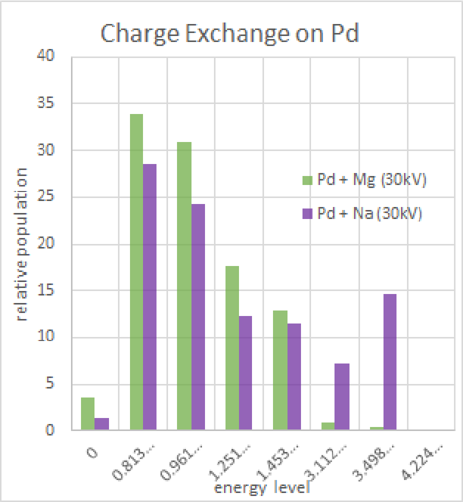
Storage times > 30s

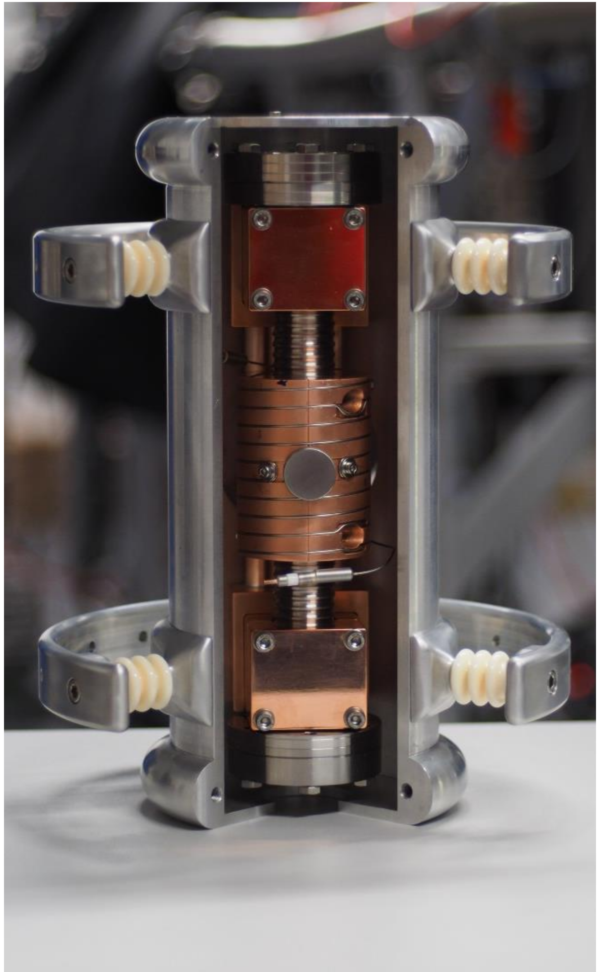
($> t_{1/2}$ for low-rate isotopes)

ATOMIC BEAMS

- Upgraded charge-exchange cell was developed by Felix Sommer
- Optimized for higher temperature to work with Magnesium
- Near-resonant charge exchange (neutralization) with Ru/Pd ions
- 100% efficiency in neutralization
- No reflow, small apertures

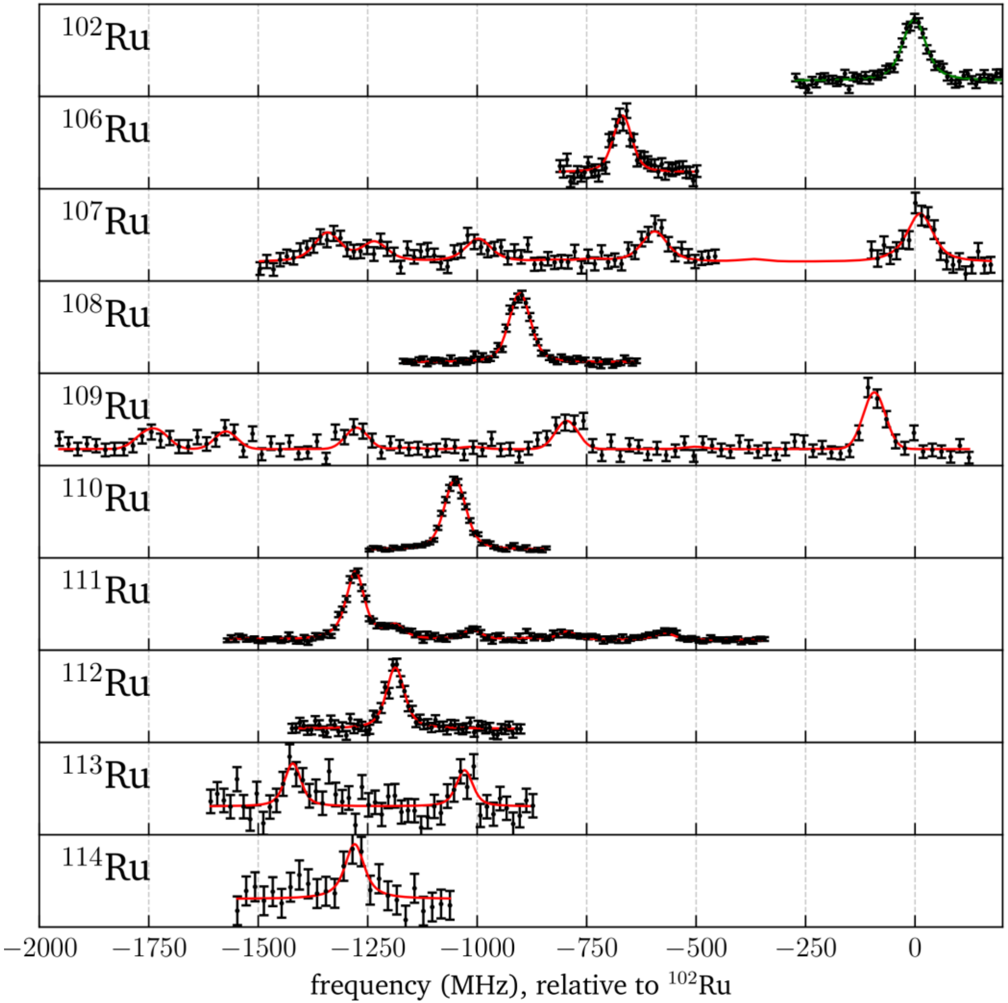






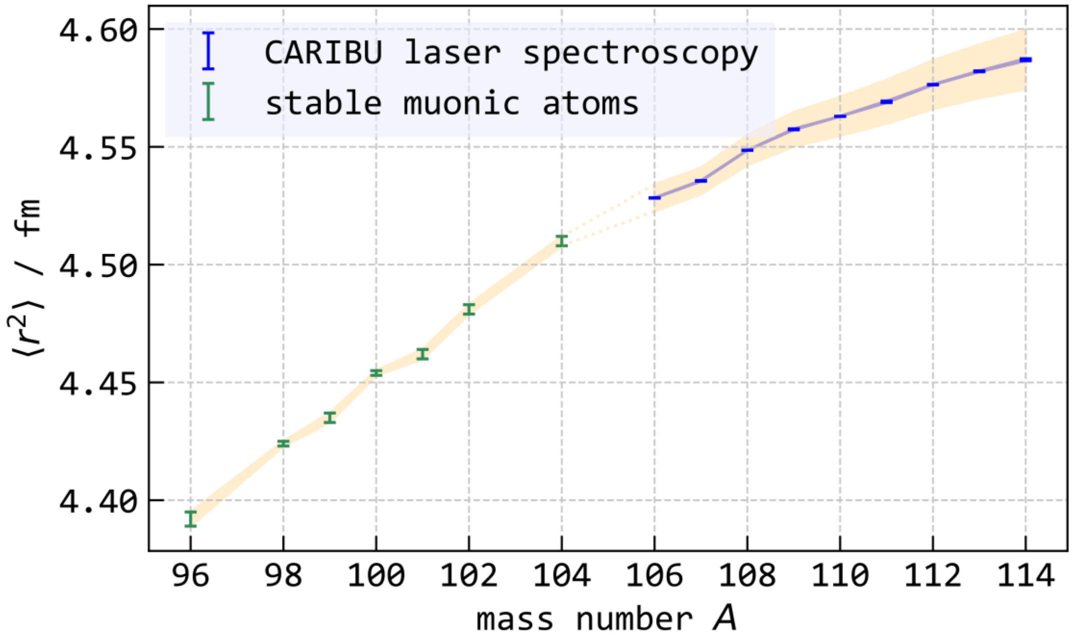
RUTHENIUM

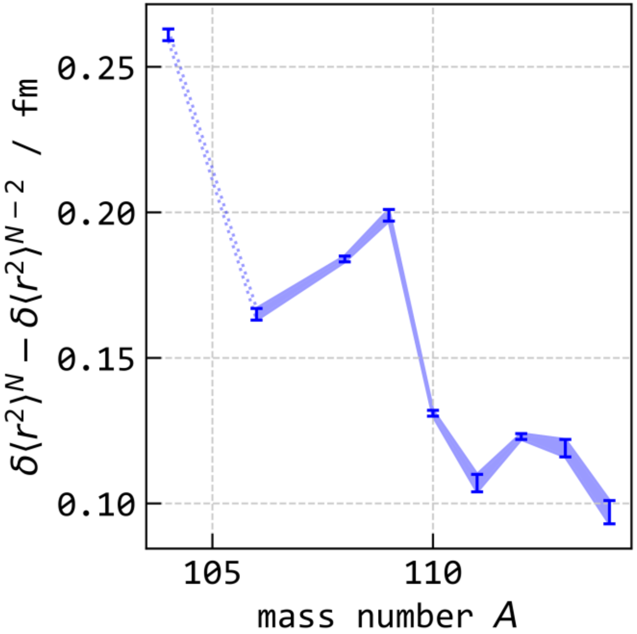
- Measured the optical spectra of 9 neutron-rich Ruthenium isotopes
- More data than presented here
  – search & exclude, statistics, systematics
- Referenced on stable/offline ^{102}Ru
  – Produced in laser ablation ion source
  – Similar beam properties due to bunching
- Confirmed the spin-1/2 assignment for Ru-113
- No isomers were detected
  – adds some ambiguity to some datasets where isomeric half-lives are long



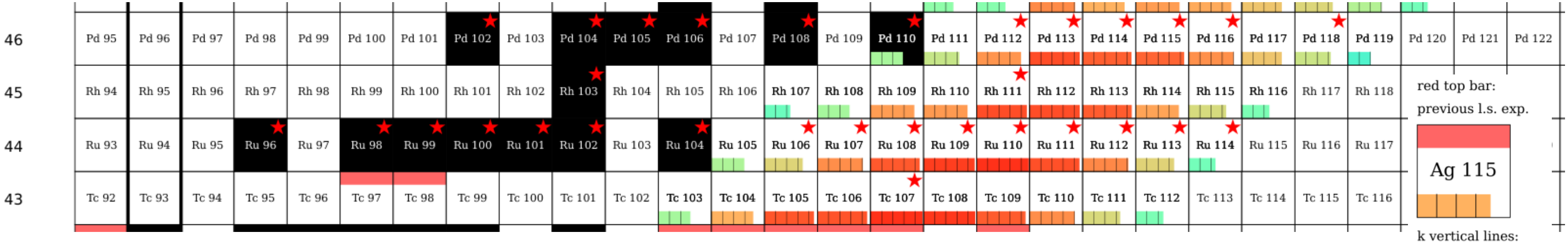
THE NUCLEAR CHARGE RADII OF RU

- Preliminary dataset for Ruthenium nuclear charge radii
- Stable: Radii from muonic atoms used as reference
- Error bars include statistical errors, expect some systematic contributions especially to uneven isotopes.
- Errors are still highly correlated



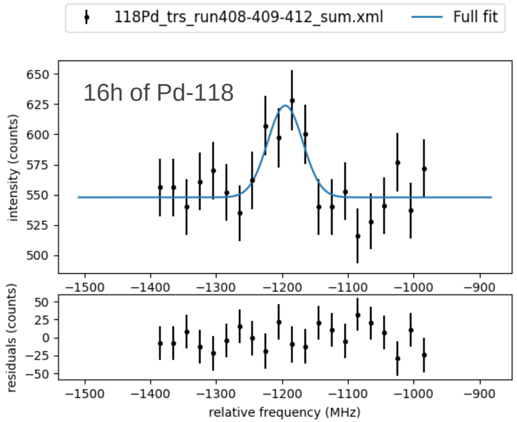


SUMMARY



Cf-252 spontaneous fission yield from CARIBU 2022 (x1000)

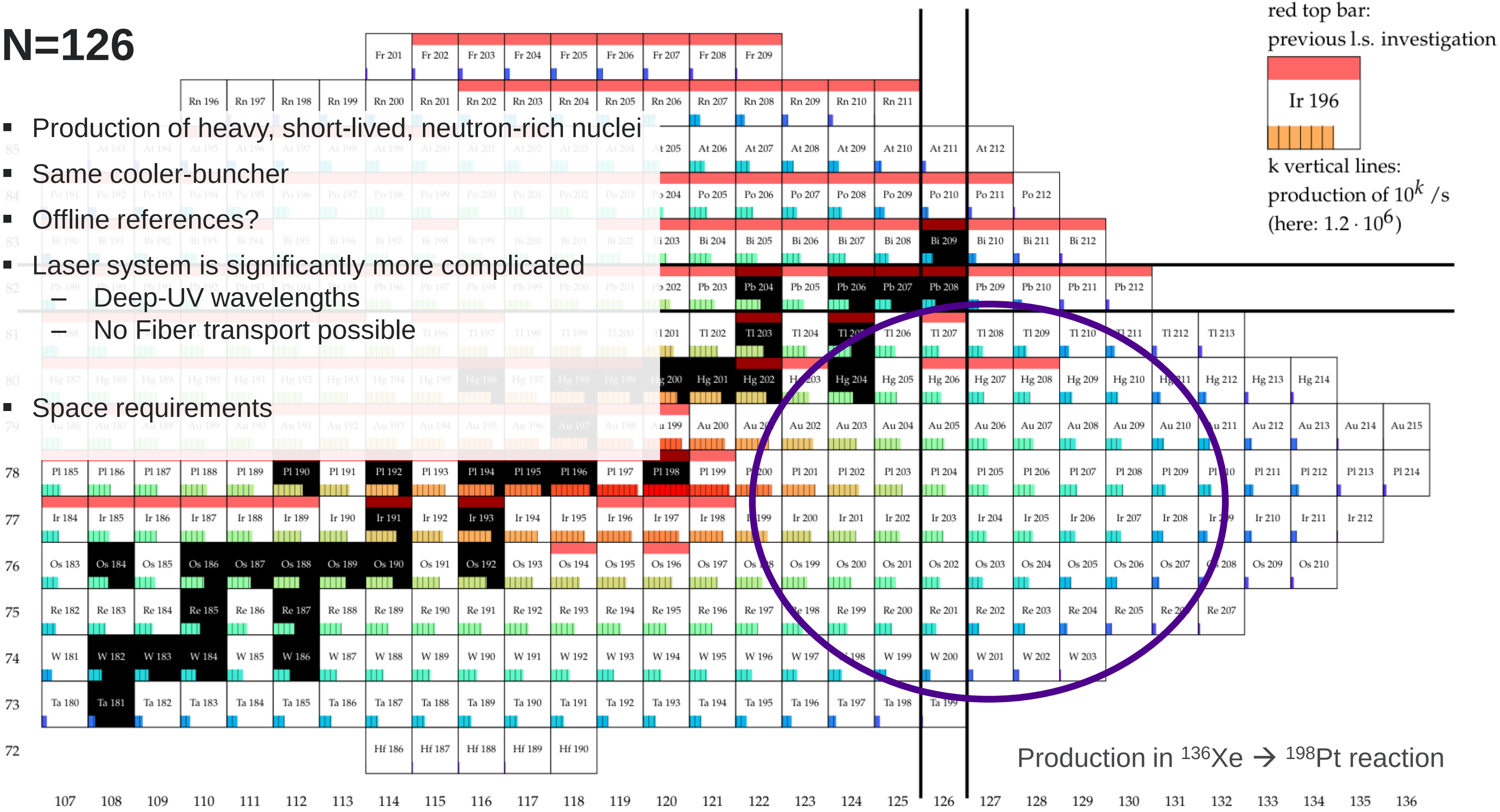
- Probed over 33 isotopes of 4 different elements in several weeks in in November 2022 & March 2023
- many radioactive isotopes that have never been investigated with LS before
- „Complete“ data sets for Ru & Pd and first hints of Rh & Tc
  - Rh, Tc are more difficult due to
    - Lack of stable references
    - Uneven nuclear spin (p uneven)



Palladium data is presented by Laura Renth / Poster

N=126

- Production of heavy, short-lived, neutron-rich nuclei
- Same cooler-buncher
- Offline references?
- Laser system is significantly more complicated
  - Deep-UV wavelengths
  - No Fiber transport possible
- Space requirements



Production in $^{136}Xe \rightarrow {}^{198}Pt$ reaction

ATLANTIS

Bernhard Maass[1], Alex Brinson[2,3], Daniel Burdette[1], Jason Clark[1], Adam Dockery[3], Max Horst[4,5], Phillip Imgram[4], Kristian König[4], Kei Minamisono[3], Patrick Müller[4], Peter Müller[1], Wilfried Nörtershäuser[4,5], Skyy Pineda[3], Simon Rausch[4,5], Laura Renth[4], Brooke Rickey[3], Daniel Santiago-Gonzalez[1], Guy Savard[1], Felix Sommer[4], Adrian Valverde[1,6]

[1]Physics Division, Argonne National Laboratory, Lemont, IL 60439, USA

[2]Massachusetts Institute of Technology, Cambridge, MA, USA

[3]Facility for Rare Isotope Beams, Michigan State University, East Lansing 48824, USA

[4]Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany

[5]Helmholtz Forschungsakademie Hessen für FAIR, Darmstadt, Germany

[6]Department of Physics & Astronomy, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada

Raffael / The School of Athens
1509-1511

Argonne **T**andem hall **LA**ser beamli**N**e for
a**T**om and **I**on **S**pectroscopy

The island of ATLANTIS was, according to Platon, plentiful in goods, especially gold, silver and brass, which he describes as fierily radiating (…) [Kritias 114e]

THANK YOU FOR YOUR ATTENTION!

ANALYZING THE HFS

- Interaction between electron angular momentum **J** and nuclear Spin **I** → Total angular momentum **F**

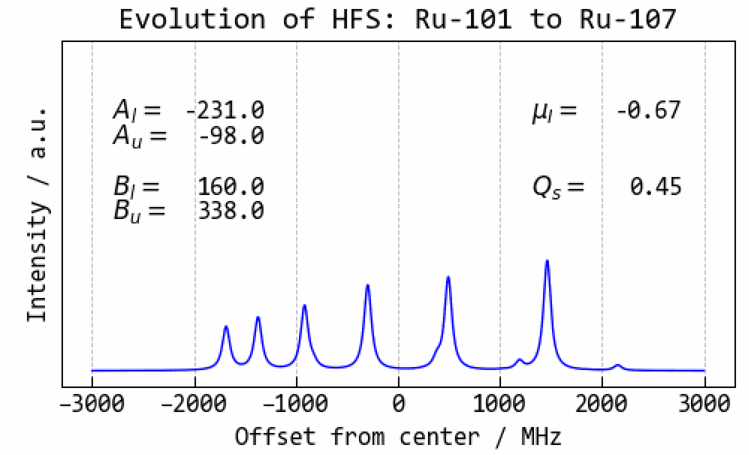
$$W_F = \frac{1}{2}AC + B\,\frac{\frac{3}{4}C(C+1) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}$$

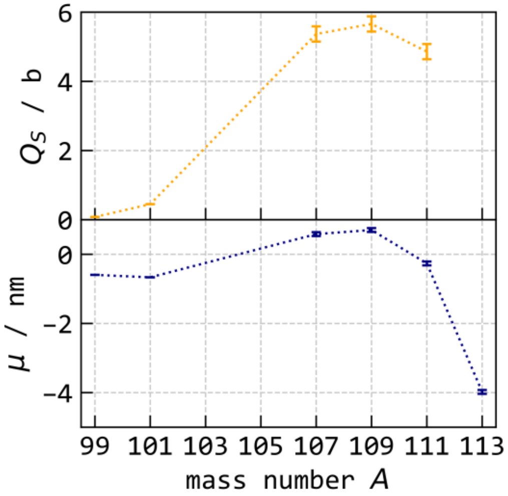
$$C = F(F+1) - I(I+1) - J(J+1).$$

Coupling constants

$$A = \mu_I B_e(0)/(IJ)$$

$$B = eQ_s V_{zz}(0)\,.$$ for I > 1/2





NUCLEAR MOMENTS OF RUTHENIUM

- Preliminary data for (spectroscopic) quadrupole moments and dipole moments of uneven isotopes

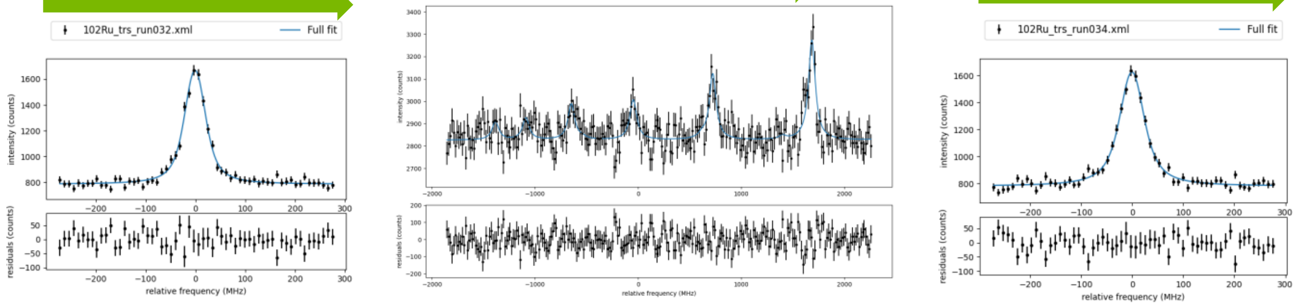
RECORDING SPECTRA

- Measurements are enframed in „bookends“ reference measurements
- In this time Laser, HV, beam intensity need to stay constant!

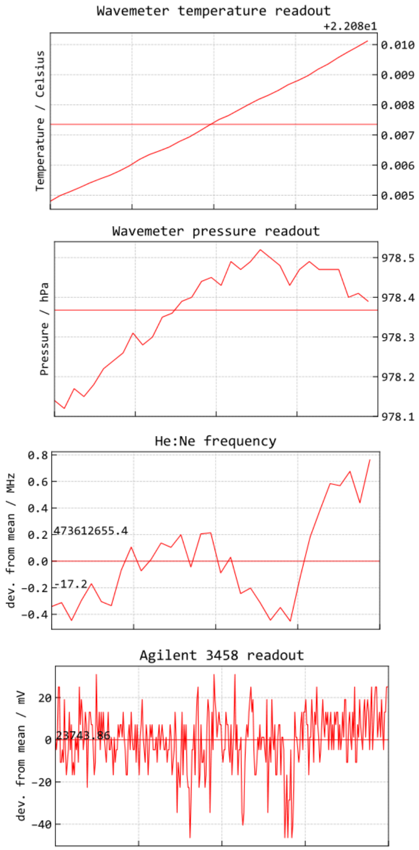
stable beam, < 20 mins

radioactive beam, hours

stable beam, < 20 mins



- Such a dataset triple allows to extract the isotope shift with good uncertainty
- Monitor the conditions „live“ with Grafana (backend MySQL database)



Grafana

ISOTOPE SHIFT MEASUREMENTS

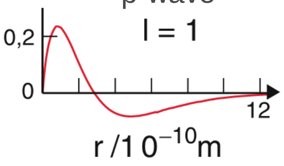
- It is impossible to *calculate* the atomic level energies to an accuracy to extract nuclear effects.
- In the isotope shift, all mass-independent terms cancel out.

$$E_{s/p} = E_0 + E(\mu) + \frac{2\pi}{3} Ze^2 |\psi(0)|^2 \langle r_c^2 \rangle$$

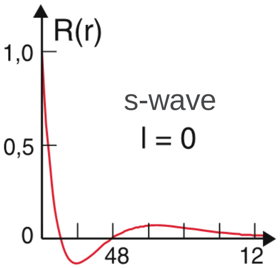
$$\hbar\nu_{s\to p} = \Delta_{sp} E_0 + \Delta_{sp} E(\mu) + \frac{2\pi}{3} Ze^2 \Delta_{sp} |\psi(0)|^2 \langle r_c^2 \rangle$$

$$\hbar\delta_{IS}\nu = \underbrace{\delta_{AA'} \Delta_{sp} E(\mu)}_{M_i} + \underbrace{\frac{2\pi}{3} Ze^2 \Delta_{sp} |\psi(0)|^2 \delta_{AA'} \langle r_c^2 \rangle}_{F_i}$$

$|\psi(0)|^2 = 0$



$|\psi(0)|^2 = 1$



<u>Isotope Shift:</u>

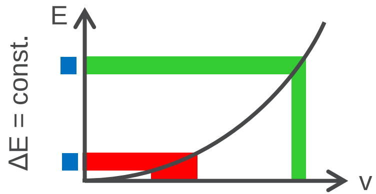
normal mass shift + specific mass shift
change in reduced mass + changing electron correlations

field shift
change in nuclear size

$$\hbar\nu_{s\to p} = \Delta_{sp} E_0 + \Delta_{sp} E(\mu) + \frac{2\pi}{3} Ze^2 \Delta_{sp} |\psi(0)|^2 \langle r_c^2 \rangle$$

COOLING THE BEAM

- Cooling the beam using a cooler/buncher at 23.7kV
  - adiabatic cooling in He buffer gas
  - Doppler compression

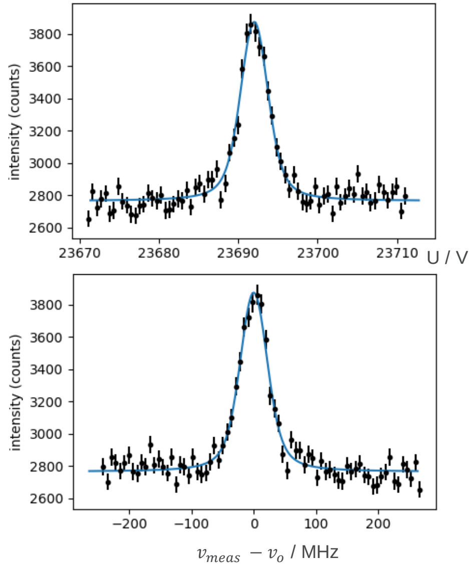


$$v_{observed} = v_0 \gamma (1 \pm \beta)$$

High-precision
voltage divider

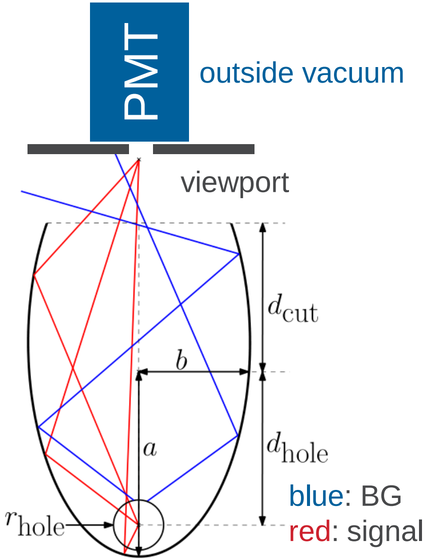
1V offset ≈ 12MHz
<100mV tolerable at 23kV → 5e-6
relative precision

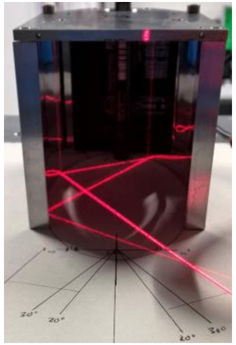
- Doppler tuning: Scanning the voltage applied to the detection system



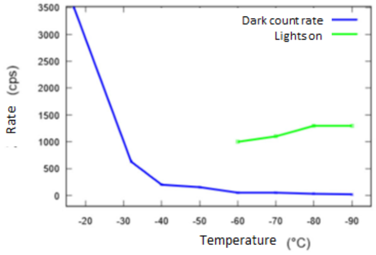
PHOTON DETECTION

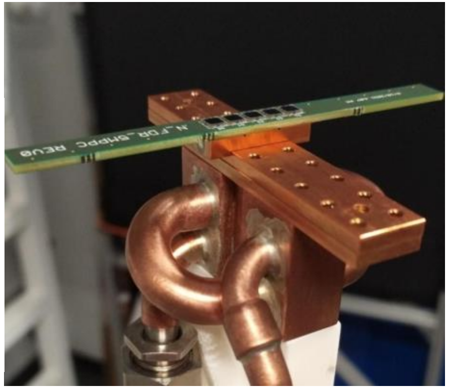
- Detect photons emitted by the overlapped beams
- Elliptical mirrors focus beam from one axis to the other
- Sources of background photons:
  - » Laser ~1M/s
  - » Ambient light ~100/s
  - » beam-induced ???

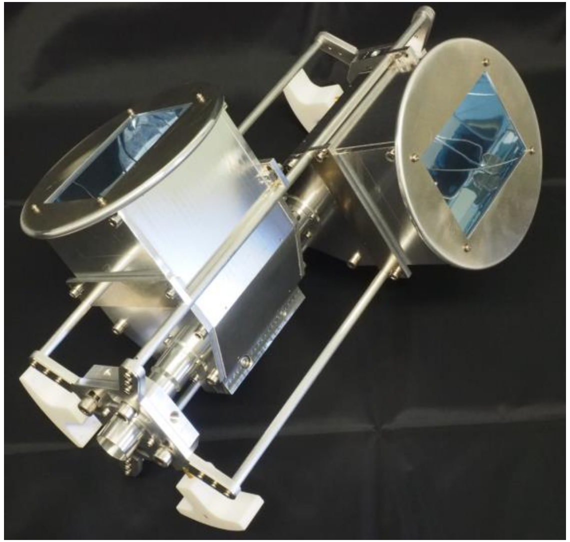




Future: with SiPMs?

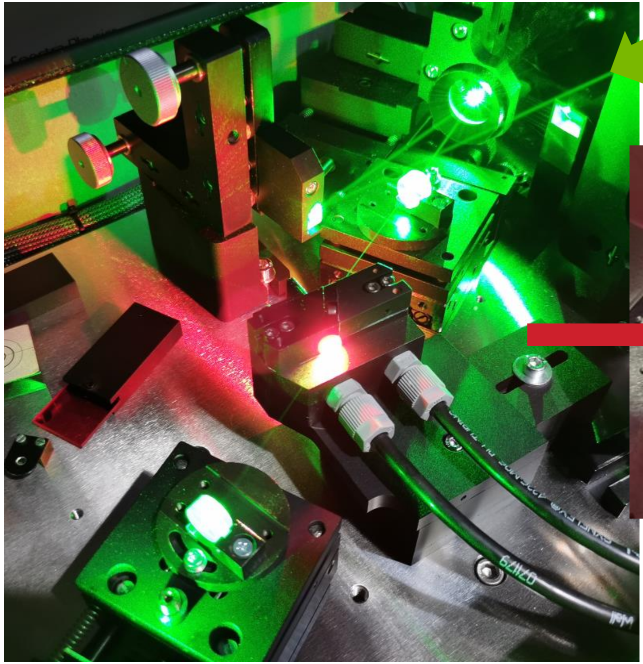




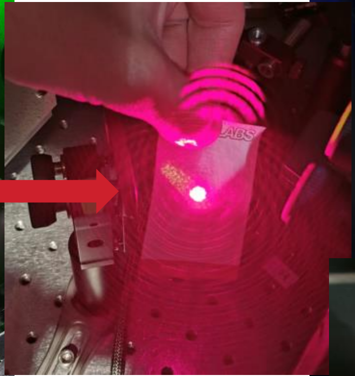


LASER SYSTEM

12W Diode-pumped cw Nd:YAGx2 532nm

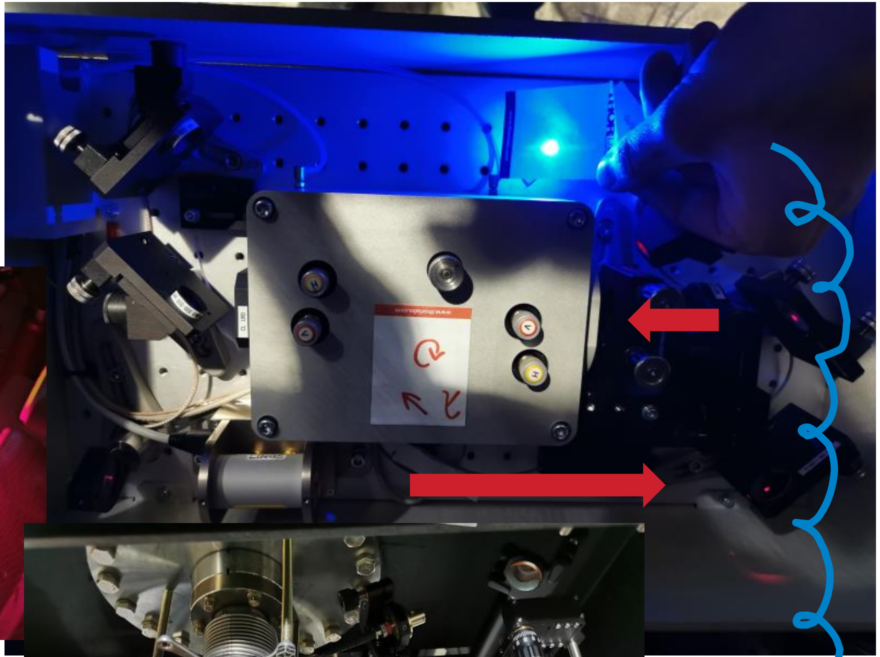


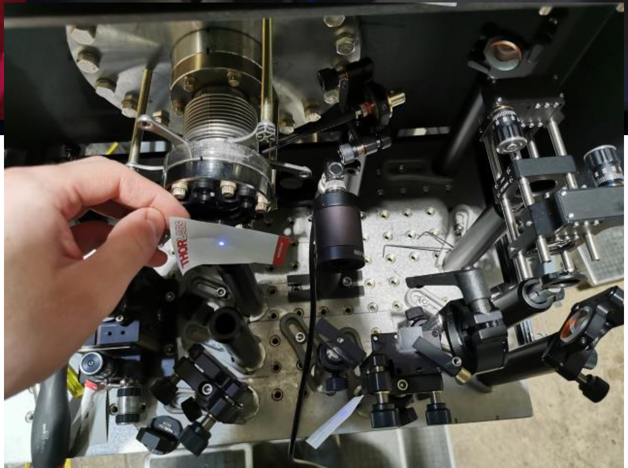
Ti:Sa crystal with focussed Nd:YAG for population inversion, inside ring cavity



3W (Infra)red output beam 880nm

100mW frequency-doubled in BBO crystal, 440nm





Fiber Link into beamline 300µW

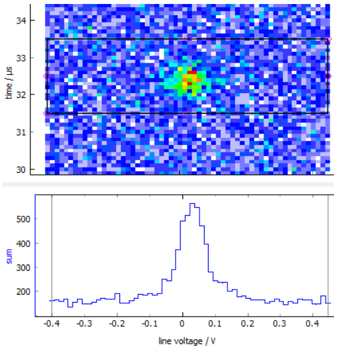
COLLINEAR – ANTI-COLLINEAR

- We don‘t know the actual transition frequency well
- We can‘t measure the absolute frequency well
- We don‘t know the actual high voltage well (HV platform + trap)!

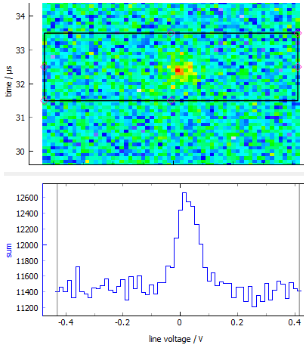
- Assume $\nu_0 = \nu_{lit} =$ 856 565 030 MHz (Ru-102)
  – COL: 857 170 240 MHz
  – ACOL: 855 960 100 MHz

Resonances appear ~ centered

Anticollinear peak appears at +1.163V



Collinear peak appears at +1.358V

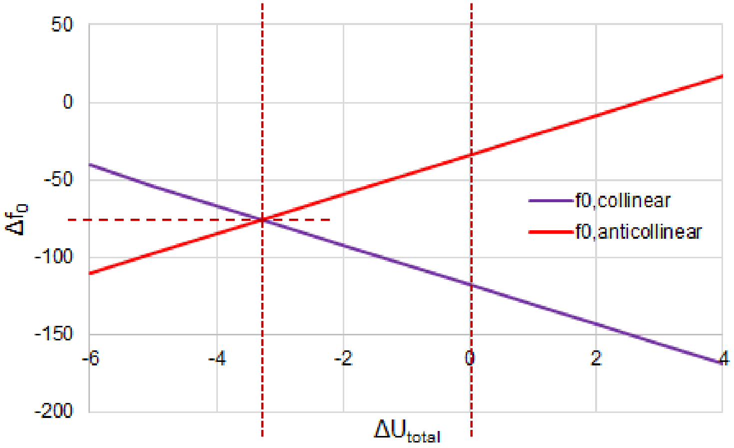


- Calculate $\nu_{0,coll}, \nu_{0,acoll}$

with $f_{Laser}, U_{tot} = U_{base} + U_{trap} + U_{scan}$

ν_0 differs when measured from opposite directions!

$\nu_{0,new}$ is offset from ν_{lit} by -74.9MHz



$\nu_{0,coll} = \nu_{0,acoll}$
for $U = U_{tot} + 3.29V$!

$\beta \sim \sqrt{U}$ with
$\Delta U \ll U_0$

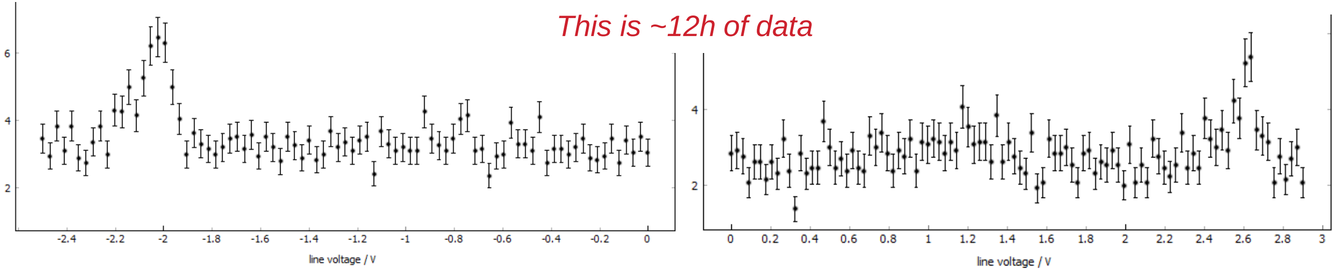
offset in U: trap, divider, voltmeter
offset in ν: wavemeter, literature value, overlap angle

THE CASE OF PD-115

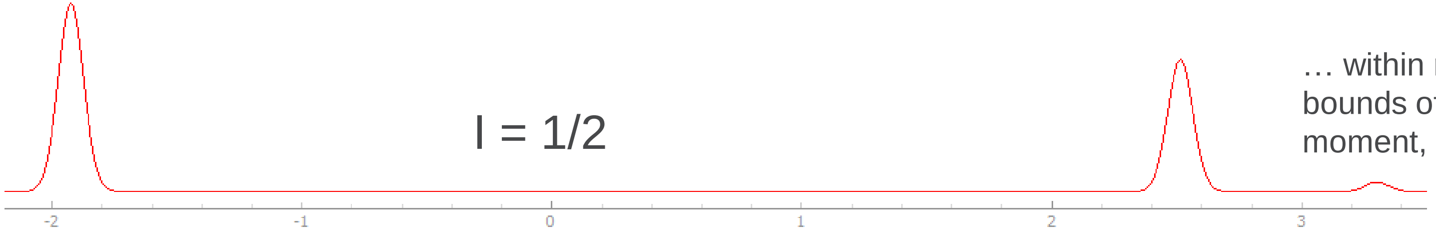
- Looking for the 5/2 HFS, we only found two peaks:

Ground and isomeric state information for $^{115}_{46}Pd$

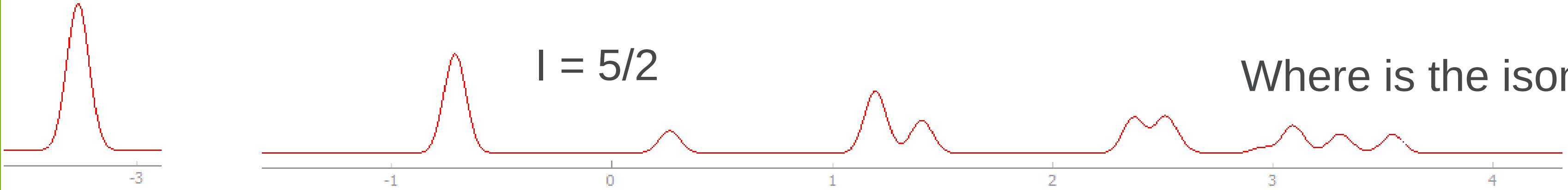
E(level) (MeV)	Jπ	Mass Excess (keV)	$T_{1/2}$	Decay Modes	252Cf FY
0.0	(5/2+)	-80426 *14*	25 s 2	β^- = 100.00%	0.017 5
0.0892	(11/2-)	-80337 *14*	50 s 3	β^- = 92.00% IT = 8.00%	



… + more data excluding more peaks on this significance level



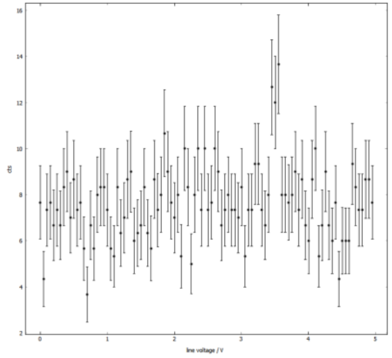
… within reasonable bounds of magnetic moment, this is a I=1/2!



Where is the isomer?

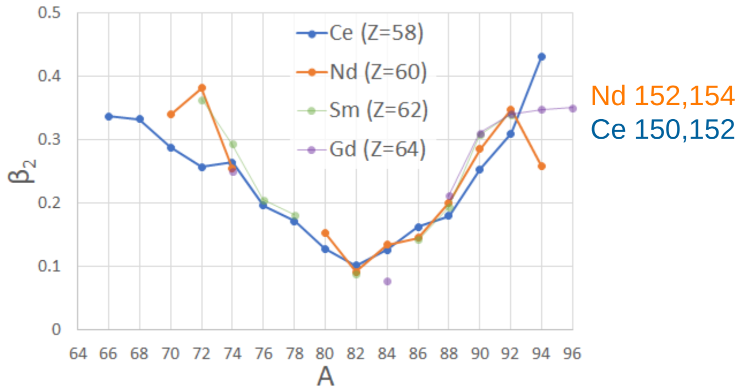
NuCARIBU

- Laser Spectroscopy on Technetium isotopes



Tc-107 HFS Peak

→ charge exchange work
→ transition is accessible
→ *no* stable reference



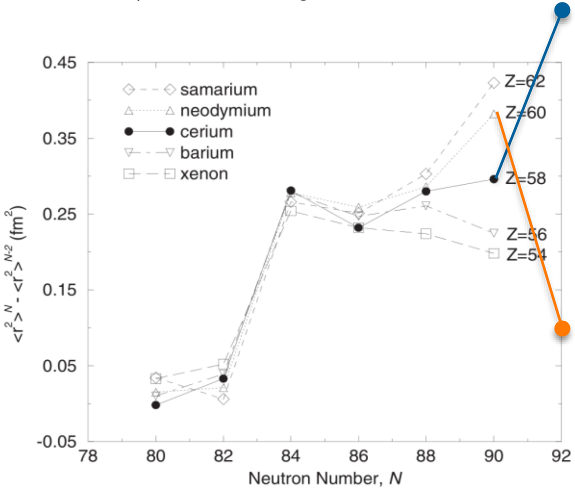
National Nuclear Data Center, Brookhaven National Laboratory, URL https://www. nndc.bnl.gov/nudat3/, 2022

- Laser Spectroscopy on Nd + Ce

$$\delta\langle r^2\rangle = \delta\langle r^2\rangle_{sph} + \langle r^2\rangle_{sph}\frac{5}{4\pi}\sum_i \delta\langle\beta_i^2\rangle$$

- $B(E2)$ value is proportional to $\langle\beta_2^2\rangle$
- Comparison of LS and NS

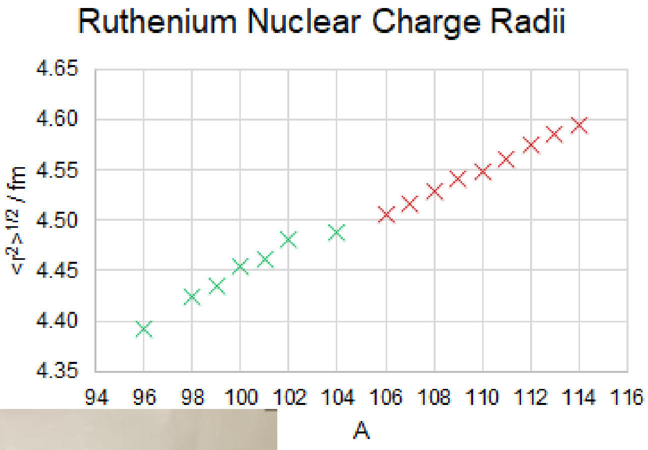
(see also: Cakirli et al, PRC **82**, 061306, 2010)



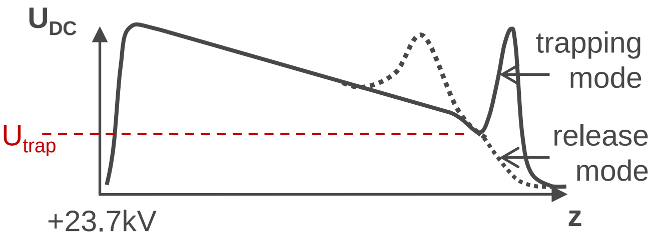
Cheal et al., J. Phys. G **29**, 2479, 2003

OUTLINE

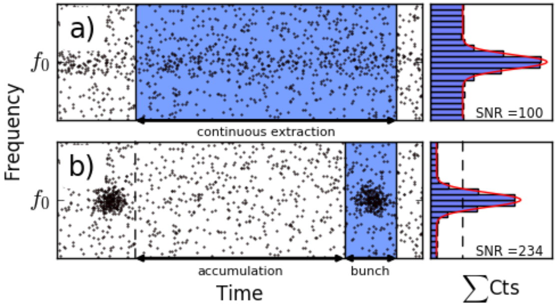

May 2019


Ruthenium Nuclear Charge Radii
4.65
4.60
4.55
4.50
4.45
4.40
4.35
<r2>1/2 / fm
94 96 98 100 102 104 106 108 110 112 114 116
A

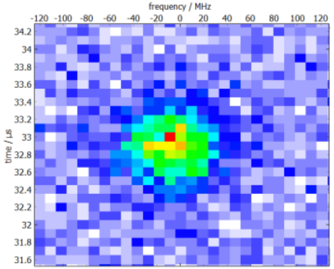
BUNCHING THE BEAM



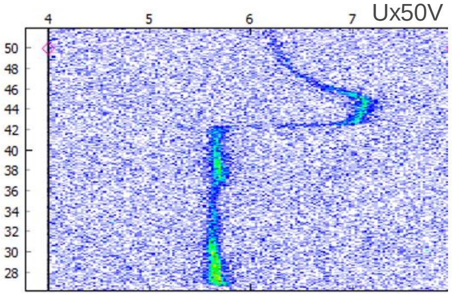
- Bunching compresses the beam into a short time window



  - time focussing:
    - make the bunch as short as possible
  - ion stacking
    - collect as many ions as possible in one bunch



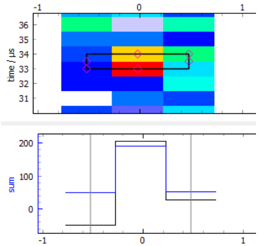
$\Delta t < 1\mu s$
$\Delta E < 40MHz\ (3V)$

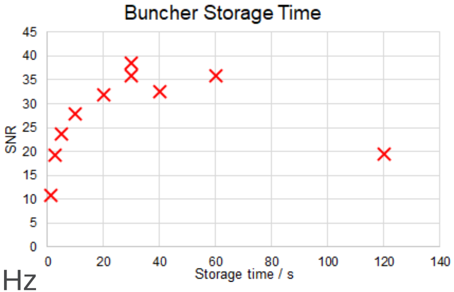


overfill + bad time focus

- Ideal storage time: 1.7x half-life

  - What is the buncher ion life time?
  - Measurement series with Pd-112 (21h)





CARIBU: 20 Hz
Ideal bunching settings: ~30s (600 bunches)
$> t_{1/2}$ for difficult isotopes

ATLANTIS

Argonne **T**andem hall **LA**ser beamli**N**e for a**T**om and **I**on **S**pectroscopy

Raffael / The School of Athens 1509-1511

The island of ATLANTIS was, according to Platon, plentiful in goods, especially gold, silver and brass, which he describes as fierily radiating (…) [Kritias 114e]