Mass spectrometry and a study of Ag isotopes at the IGISOL facility

Lecture 5

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Outline of lecture 5

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- The IGISOL facility
- Ion manipulation: cooling and bunching
- The MR-TOF and Penning trap devices
- The study of silver – combining all our tools so far!*

*Links to the discussion paper: Reponen *et al.*, Nature Comm. 12 (2021) 4596

The IGISOL radioactive beam facility

Primary beam from K130 cyclotron

Offline ion sources

Electrostatic switchyard

RFQ Cooler-buncher

Collinear laser spec. beamline

RAPTOR

Pulsed laser beam transport

Mass separator dipole magnet

MR-TOF

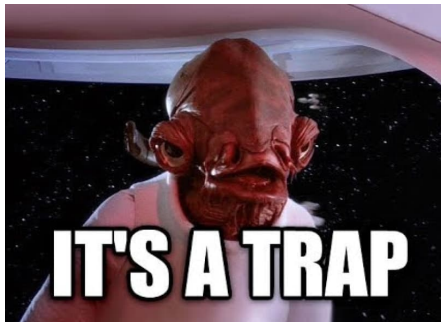
JYFLTRAP Penning trap

Post-trap decay spectroscopy

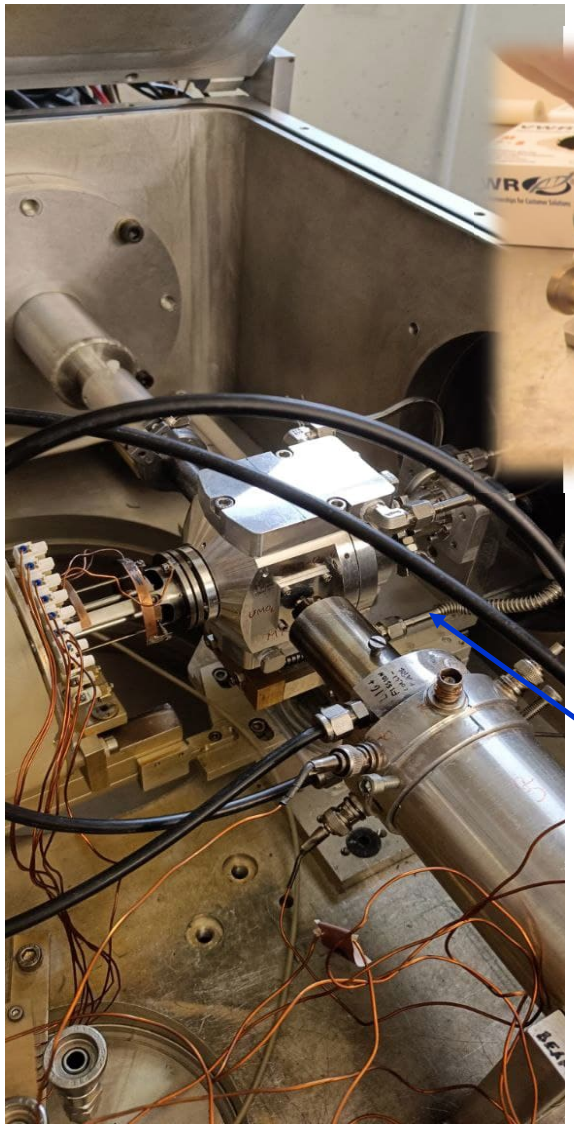
Target chamber (RIB production via different reactions)

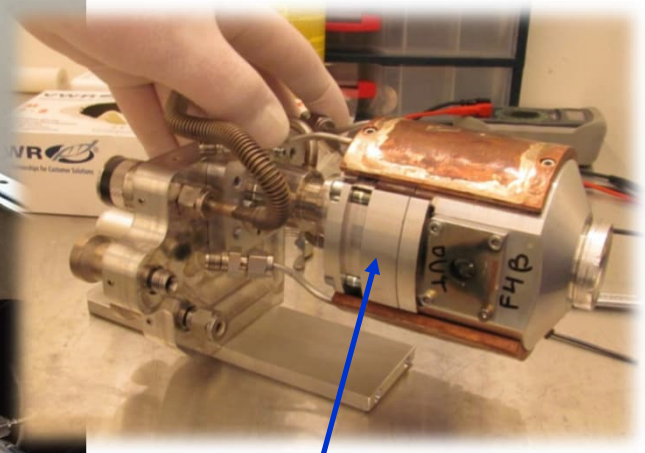
The ion guide method

- Chemical independence
- Extraction times *can be* < 1ms
- Relatively low efficiency



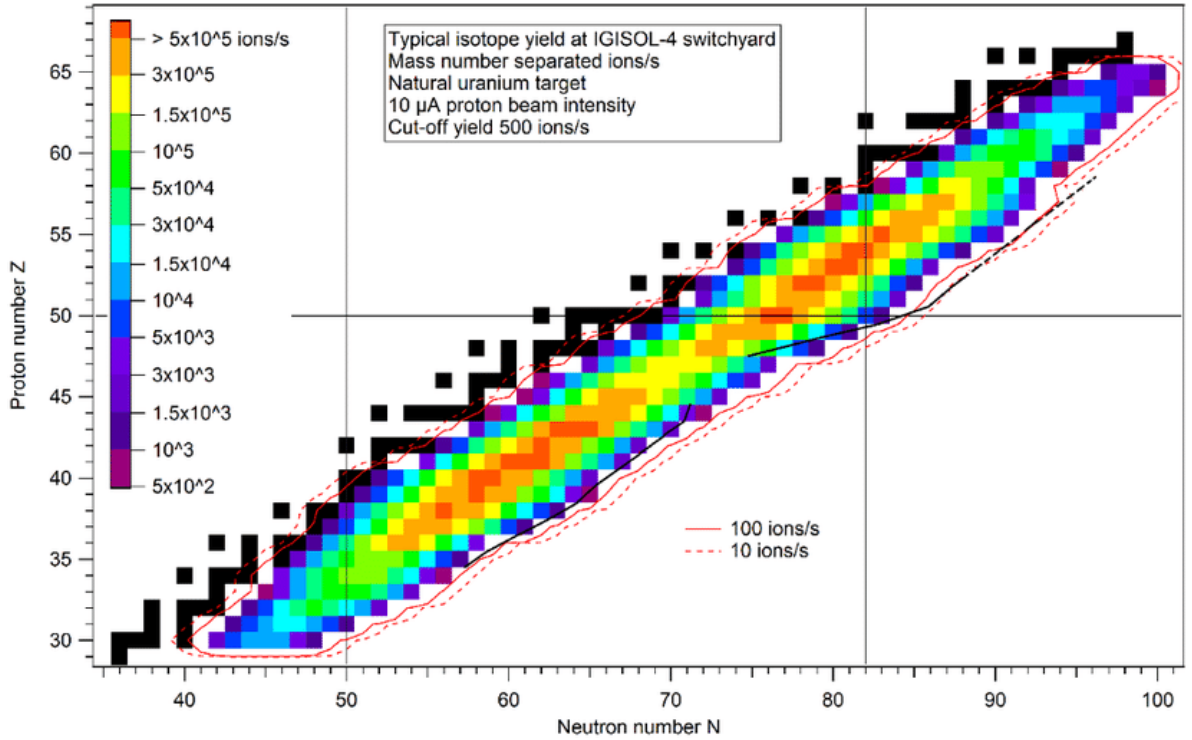
Production of neutron-rich isotopes





U/Th target inside gas cell

Gas cell installed into ``target chamber´´



- Protons, deuterons on U/Th targets (~15 mg/cm^2)
- Typical cross section ~1-1.5 barn @ 30 MeV – note, this is a huge cross section!!
- 1 μA of protons (primary beam) leads to 3×10^9 fissions/s (isotropically distributed)
- Fission ion guide efficiency ~0.1% (limited by stopping of fission fragments)

Extraction and acceleration of ions

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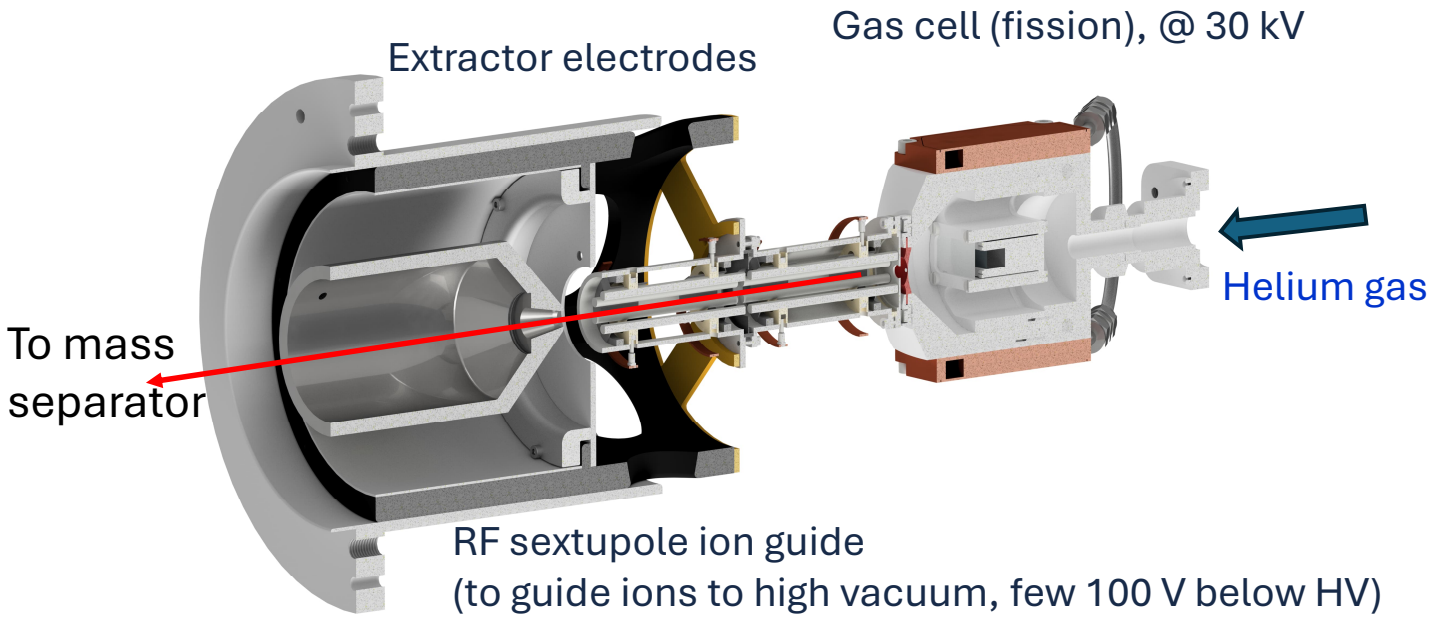
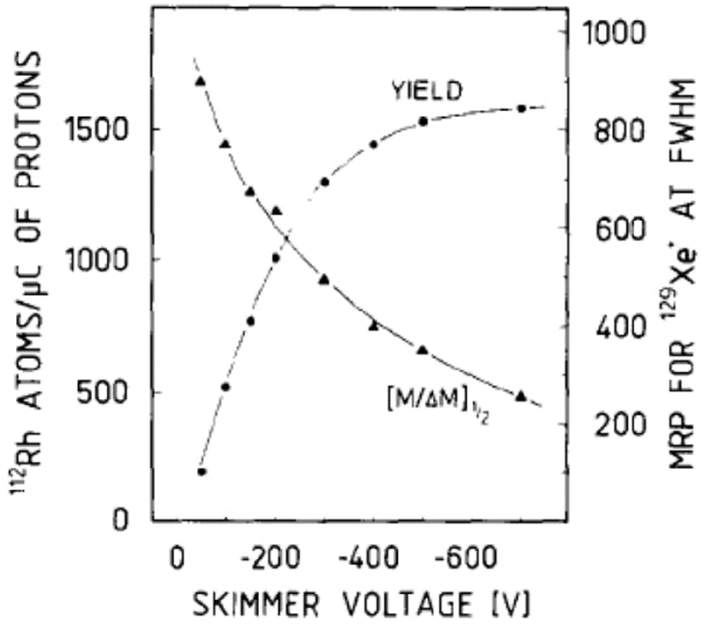
Typical ` ` low-energy ´ ´ ISOL/IGISOL beams are accelerated to 30-60 keV energy.

- *Too high energy requires high/ultrahigh vacuum; discharging, inconvenient!*
- *Too low energy, more difficult to transport ion beam with electrostatic elements.*
- *Too low energy: typical dipole magnets suffer from poor mass resolution.*





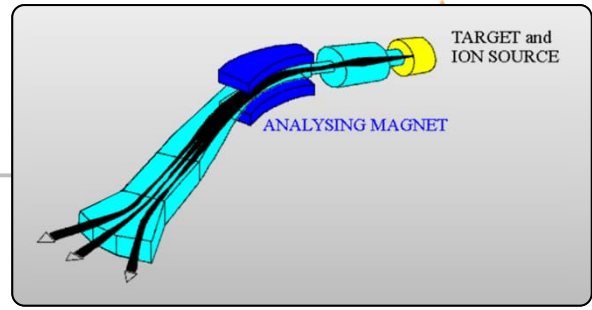
P. Taskinen et al., NIMA 281 (1989) 539

- Mass resolving power & yield were seen to depend sensitively on V_{sk}
- This led to an ion beam energy spread (10 – 150 eV).

High vacuum region (~10^{-6} mbar)

Poor vacuum (~$10^{-2,-1}$ mbar)

First stage of mass separation



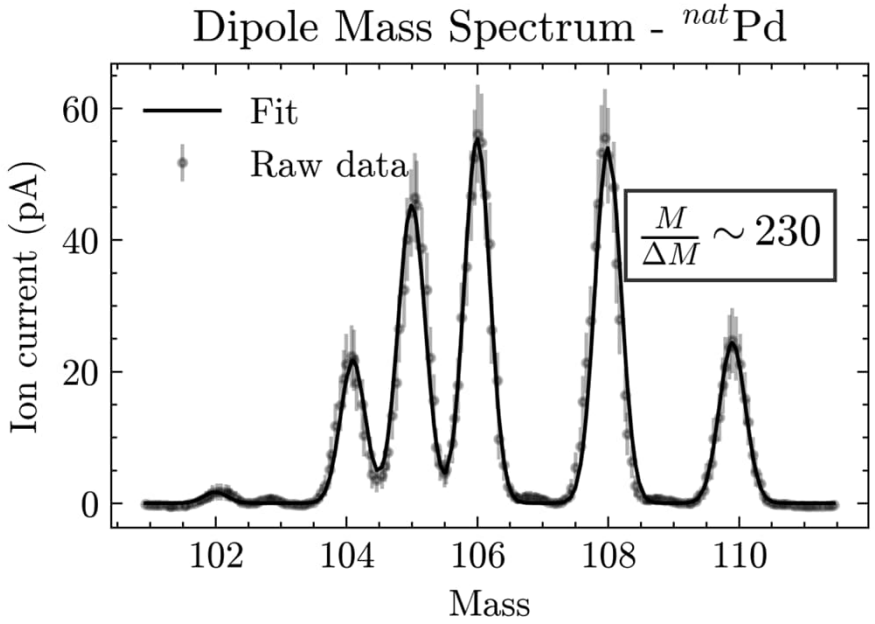
We saw that in Lecture 2, radioactive beams are often severely contaminanted!!

Most ISOL facilities will have an isotope separator. At IGISOL, after acceleration of the ion beam we pass through a dipole sector magnet. Other facilities may use two (e.g., ISOLDE…)

Mass Resolving Power

$$R = \frac{M}{\Delta M}$$ (at full-width half-maximum)

The bigger the number the better!



The experimental mass resolving power is affected by the energy spread and emittance (or quality) of the ion beam.

Note: isotopic abundance of ^{102}Pd ~1%

Limitations with the dipole mass separator

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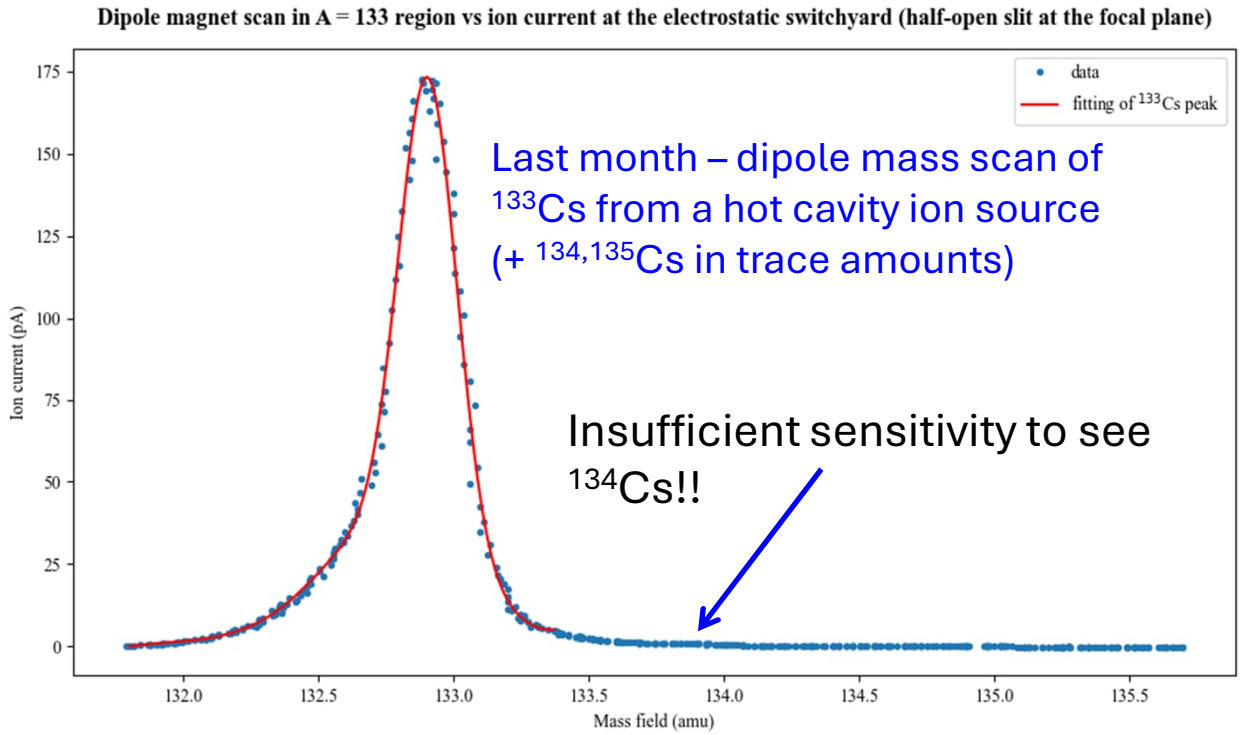
Well, obviously the mass resolving power!

^{106}Cd	^{107}Cd	^{108}Cd	^{109}Cd
^{105}Ag	^{106}Ag	^{107}Ag	^{108}Ag
^{104}Pd	^{105}Pd	^{106}Pd	^{107}Pd
^{103}Rh	^{104}Rh	^{105}Rh	^{106}Rh



Isotopes – MRP required to separate (^{105}Pd, ^{106}Pd) ~ 100
Isobars – MRP required to separate (^{106}Ag, ^{106}Pd) ~33000
Isomers – MRP required to separate (^{106}Ag, ^{106m}Ag) ~ 110000

- Mass peak tailing towards lower masses – could be effect of energy spread
- If we move to single-ion counting detector, we start to saturate due to the tail of ^{133}Cs

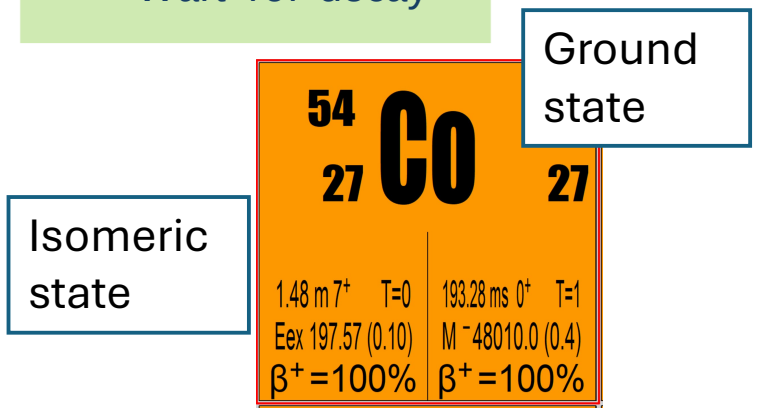
Why would we wish to bunch an ion beam?

Our ``low-energy´´ ISOL/IGISOL beams are typically continuous (unless we apply some form of bunched release at the source). Many experiments however require cooled and bunched beams.

- Low energy spread:
  - Collinear laser spectroscopy
  - Velocity spread -> Doppler broadening

- Low temporal spread
  - Multi-Reflection Time-of-Flight Mass Spectrometer (MR-TOF)

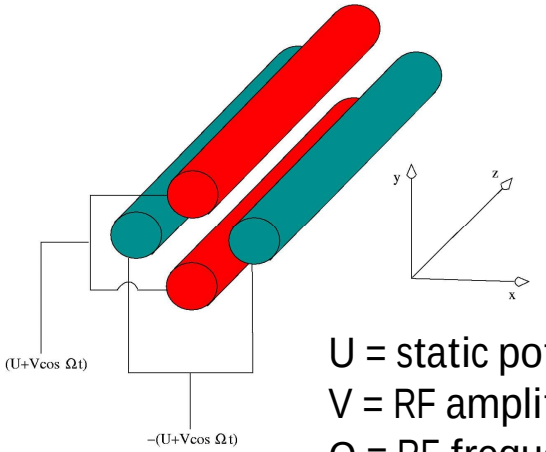
- Simply storing:
  - Wait for decay



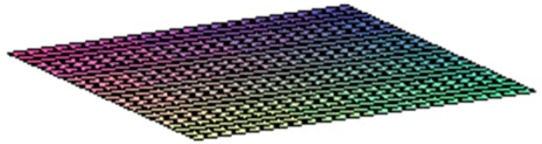
- Bunched beam
  - Transfer to other experiments that have no cooling possibility or low continuous beam capture efficiency
    - Penning traps
    - Electron beam ion traps
    - Pulsed drift tubes
    - Decay spectroscopy requiring clear *t=0*
  - Collinear laser spectroscopy
    - Signal-to-background improvement > 10^4 (seen in Lecture 3)

The radiofrequency quadrupole / Paul trap

Three-dimensional confinement of ions can be achieved in a linear RF quadrupole structure by segmenting four rods and applying appropriate dc potentials to the segments.



U = static potential
V = RF amplitude
Ω = RF frequency



- Equations of motion (Mathieu equations) can be found in textbooks
- Radiofrequency, time-varying electric field required to confine ions. Time-average force towards the central axis.
- ~1 MHz, 500 Vpp

Buffer gas / collisional cooling

- The most versatile and important method in eV range
- Neutral gas molecules collide with ions (He, Ne, Ar...)
- The cooling limit is the buffer gas temperature (often at room temperature). Thermal motion remains.

Cooling of the ions means to reduce their motional amplitudes.

- Overall: beam emittance reduction
- Emittance: transverse phase space “size”, unit: π mm mrad at kinetic energy X
- Many other methods of cooling (radiative, resistive, evaporative, laser...)

Many excellent reviews discuss these aspects in detail:

K. Blaum, High accuracy mass spectrometry with ions, Phys. Rep. 425 (2006) 1

The JYFL gas-filled RFQ

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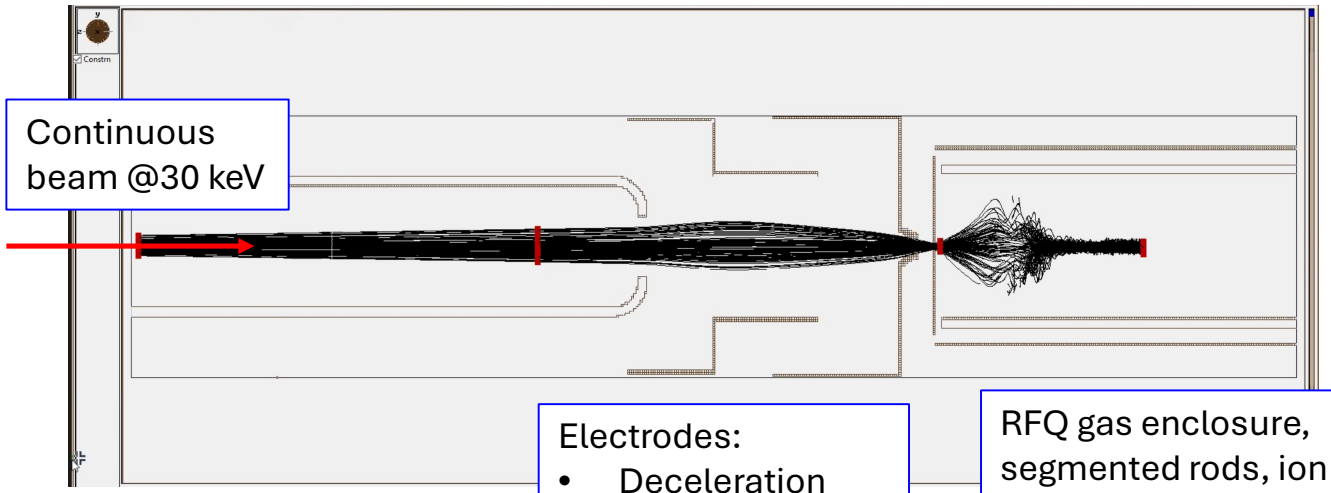
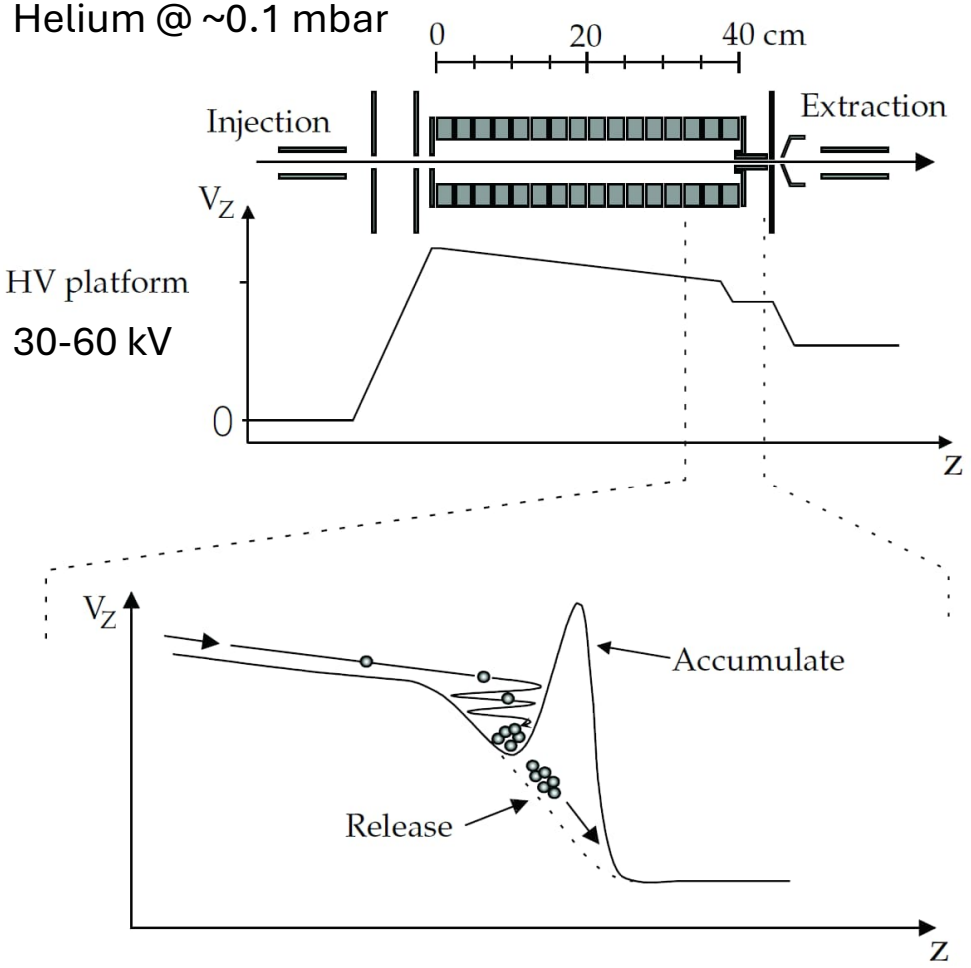
Injection of ions into the RFQ



Helium @ ~0.1 mbar



- Incoming beam:
  - ~10 eV energy spread
  - 15π mm mrad
  - Continuous beam

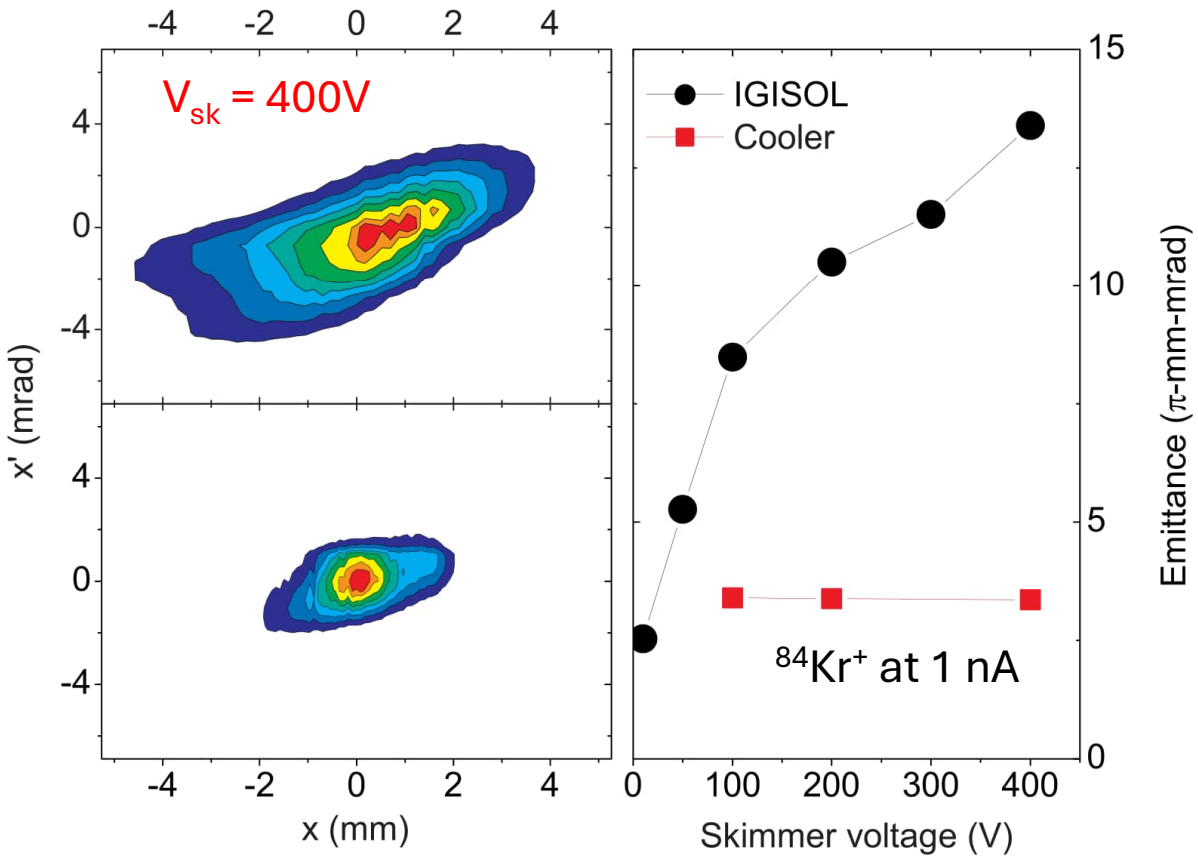
Outgoing beam:

- ~1 eV energy spread
- 3π mm mrad (at 30 keV)
- Bunched beam $\Delta t \sim 5\ \mu s$
- Transmission ~60-70%

A. Nieminen et al., Nucl. Instr. and Meth. A 469 (2001) 244

Benefits: the beam has its memory erased ☺

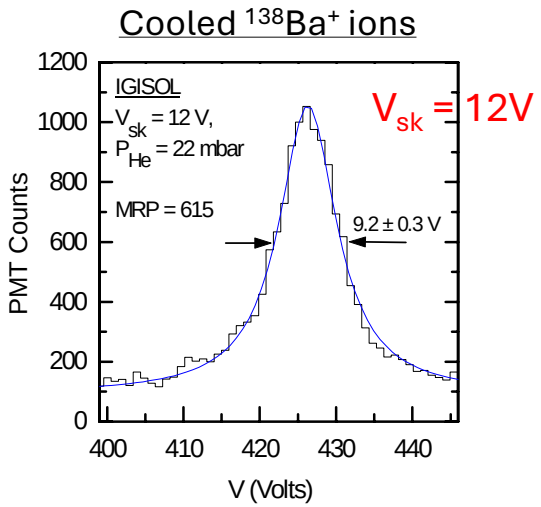
Beam emittance (quality of the beam) before and after the cooler-buncher

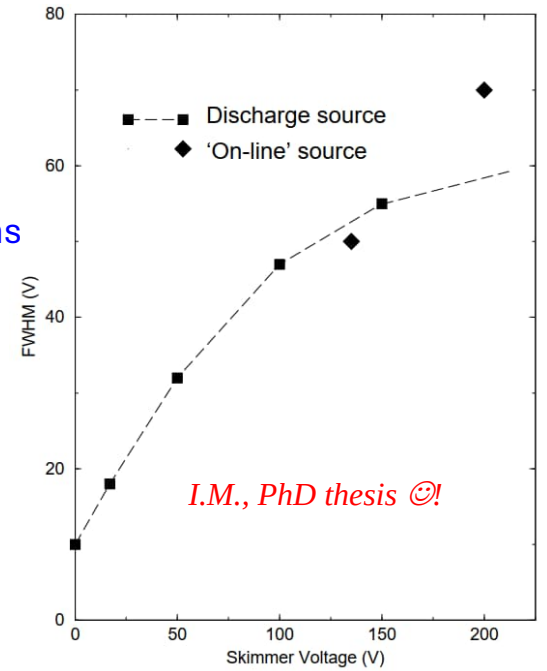


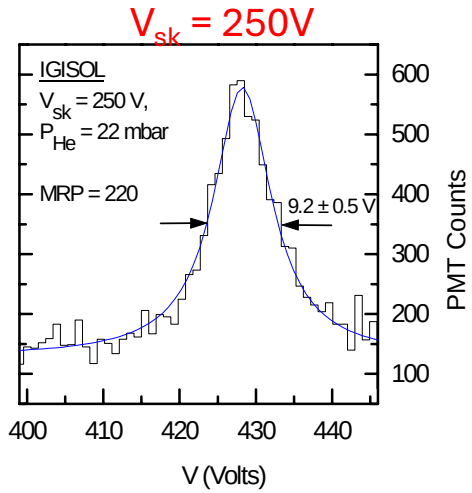
A. Nieminen et al., Nucl. Instr. and Meth. B 204 (2003) 563

Recall, as V_{sk} increases, the energy spread ΔE also increases!

Laser resonance of Ar^+ ions as a function of V_{sk}



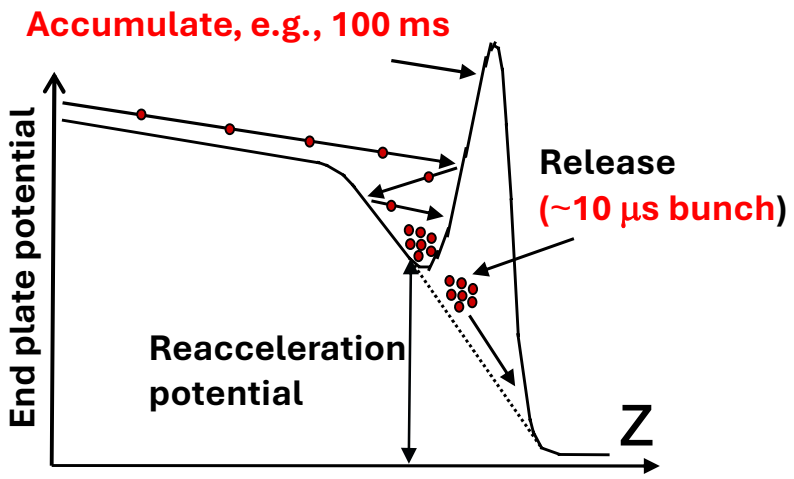


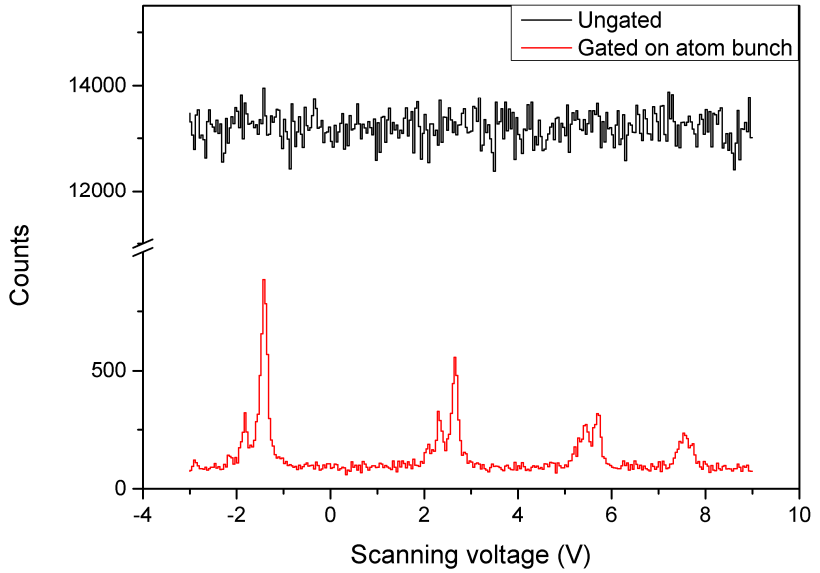


- Two skimmer voltages used
- Post-cooler, no change in spectral line profile seen.

Towards time-focused bunching

Recall from Lecture 3: application of bunching for laser spectroscopy.





- Typical bunched widths from ~1 – 10 µs
- Bunching times: 1 ms to >100 ms depending on experimental requirements

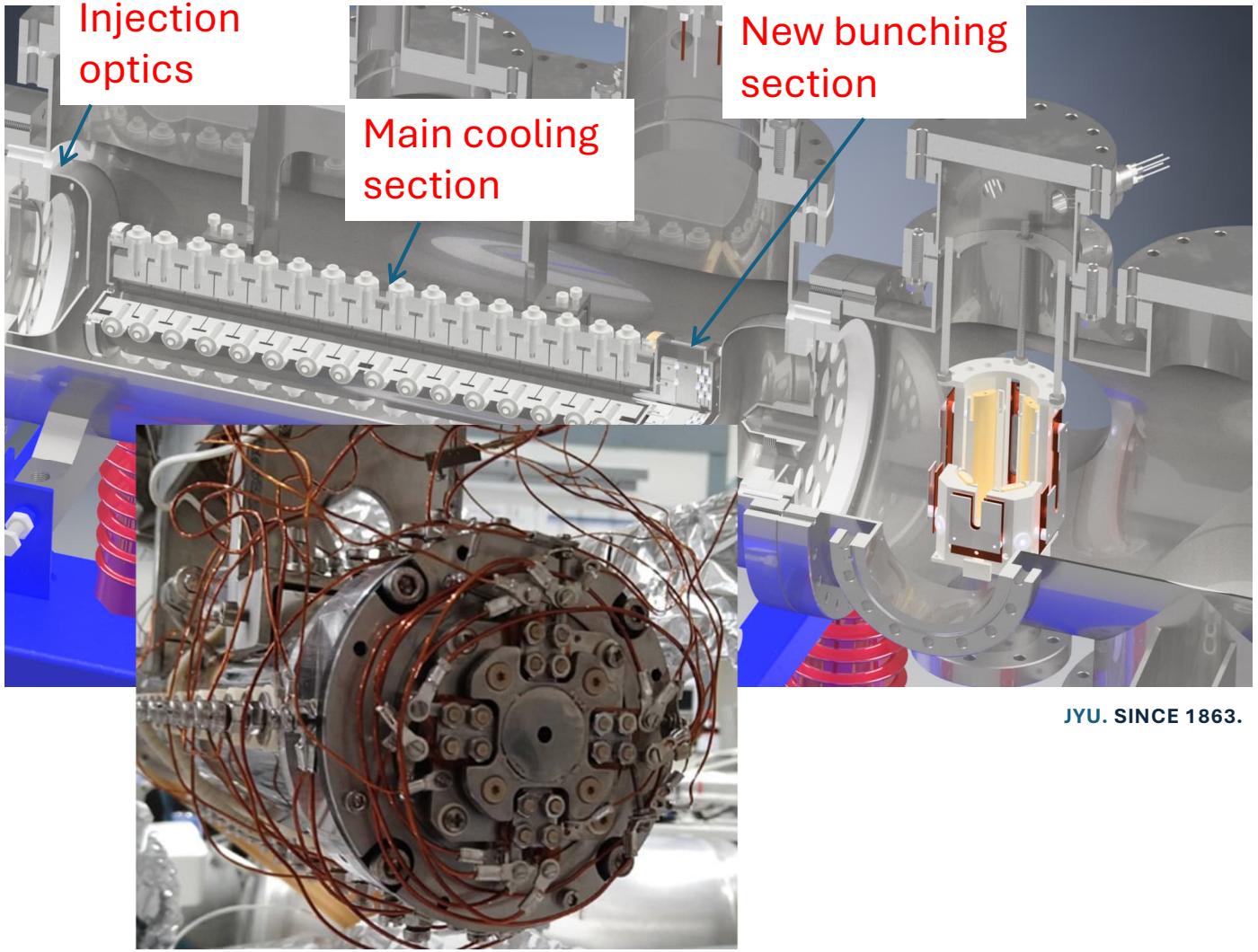
*P. Campbell et al., PRL **89** (2002) 082501*

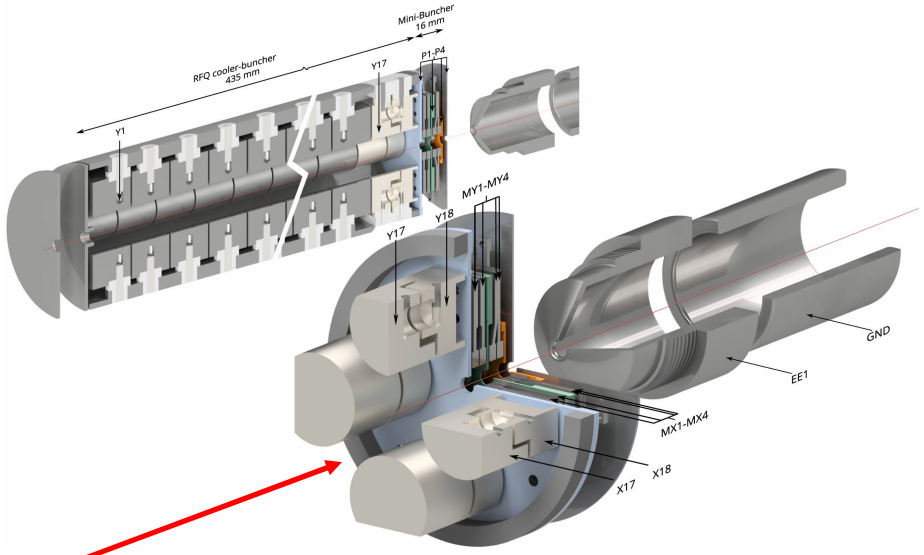
$$\text{Background suppression} = \frac{\text{e.g., 100ms accumulation}}{\text{10µs gate width}} \sim 10^4$$

For some applications, e.g., an MR-TOF mass spectrometer, the mass resolving power is determined by the minimum width of an ion bunch from the RFQ. Typically the demand is for <100 ns bunches.

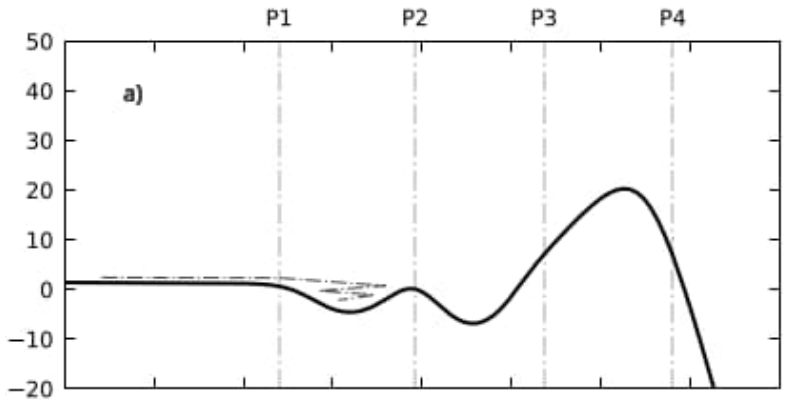
$$R = \frac{M}{\Delta M} = \frac{t_{tof}}{2\Delta t_{tof}}$$

A mini-buncher extension to the RFQ



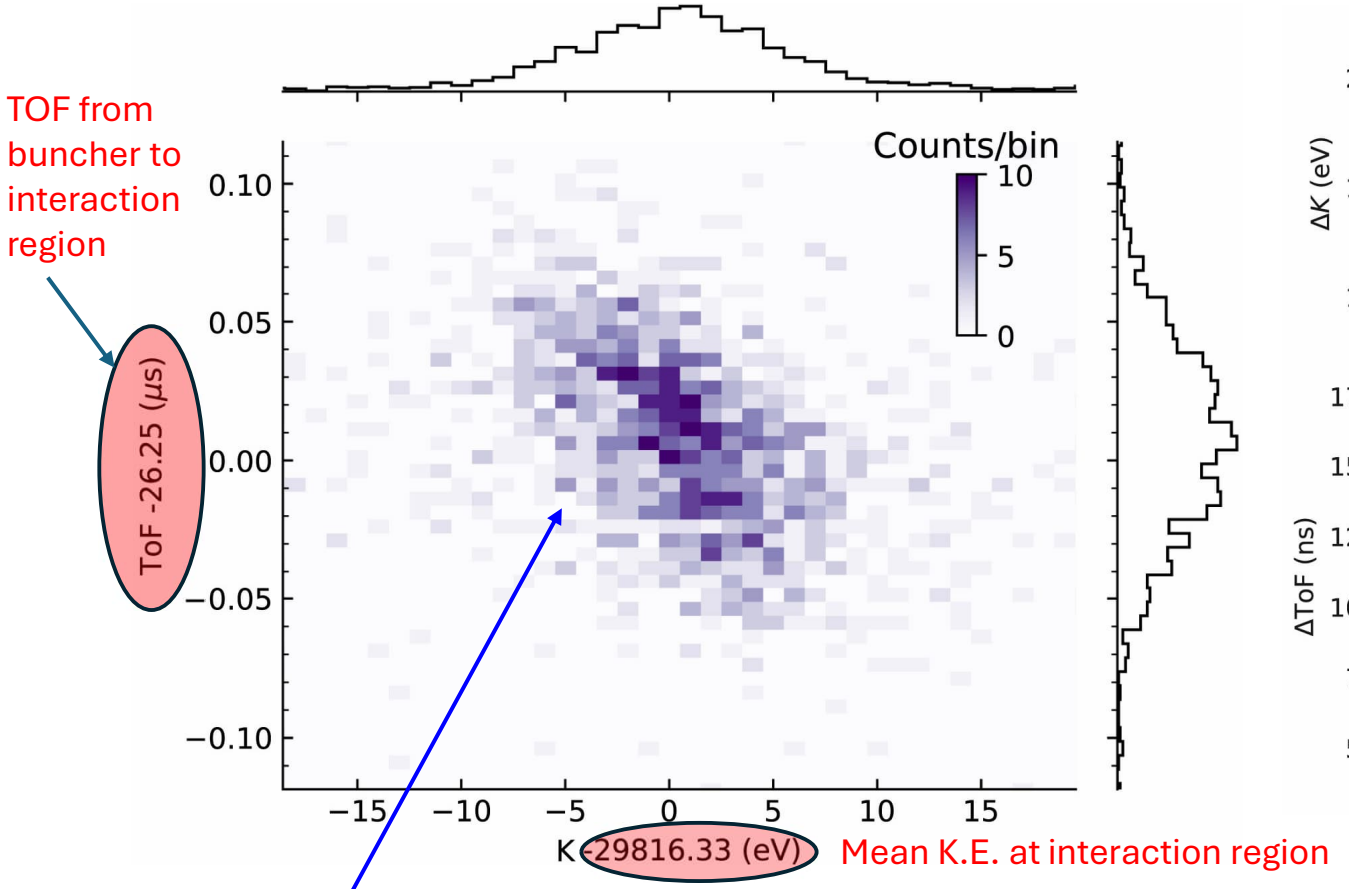


Beam from main RFQ

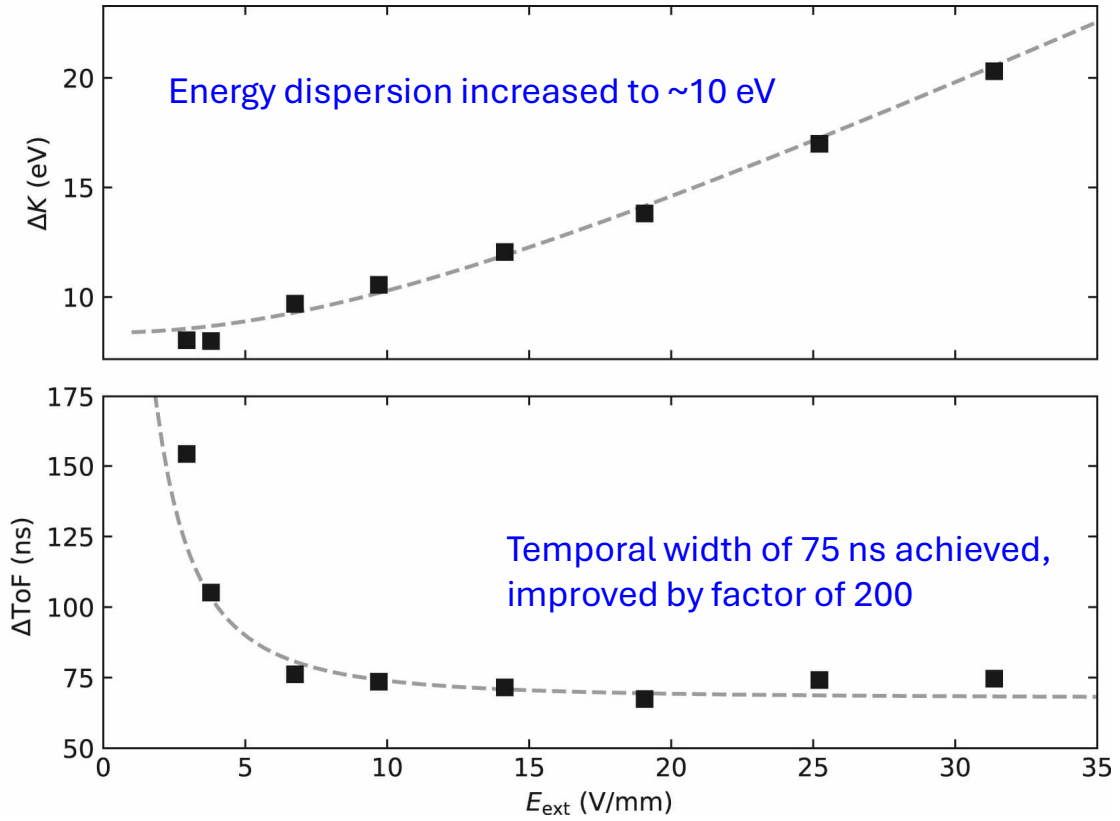


Determination of energy and temporal spread

Collinear laser spectroscopy of Sc^+ ions for different extraction fields from the mini-buncher.



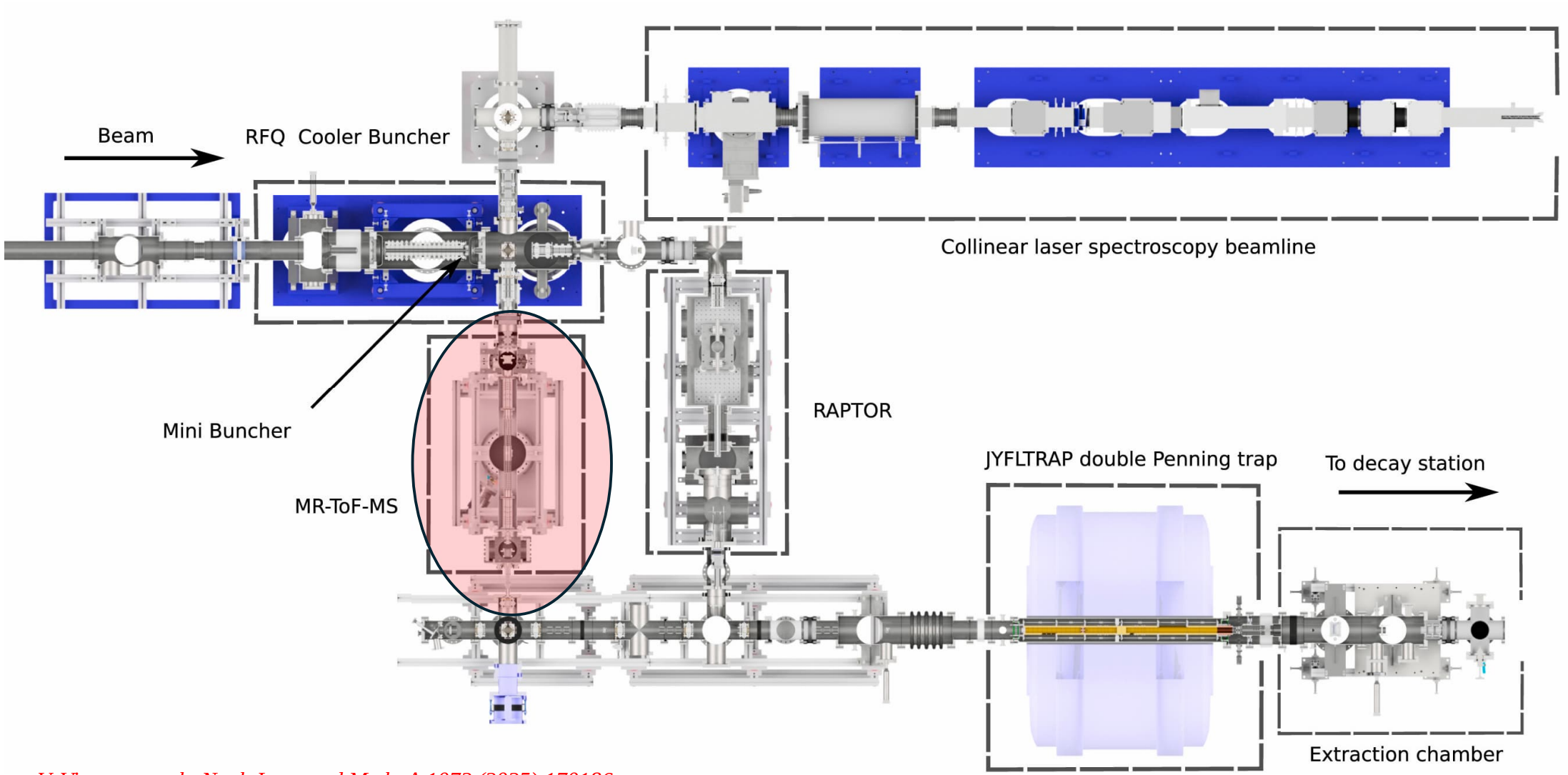
- Ellipse indicates the bunch has passed its time focus



- Decreasing the time disperson of the bunch increases the energy spread.

V. Virtanen et al., Nucl. Instr. and Meth. A 1072 (2025) 170186.

A brief refresher of our experimental stations



V. Virtanen et al., Nucl. Instr. and Meth. A 1072 (2025) 170186.

The MR-TOF mass spectrometer

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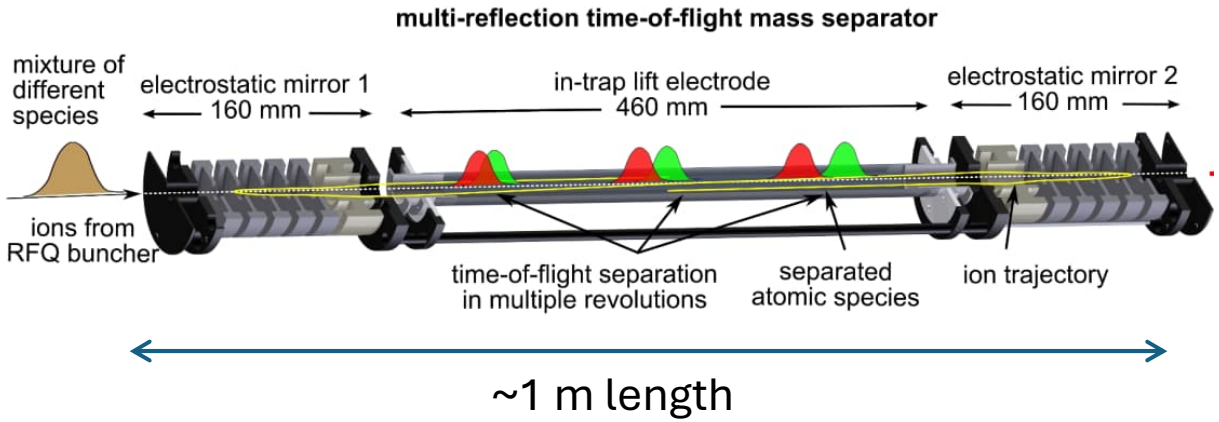
Multi-reflection time-of-flight mass spectrometry

- Inject a bunch of ions into a device confined by electrostatic mirrors
- All ions have the same start time and kinetic energy (ideally)
- Let the ions bounce back and forth
- Separation with mass/charge ratio via time-of-flight (all ions move in a set potential)
- More revolutions = bigger time difference = better separation (= better resolving power)
- Extract ions towards a detector for time-of-flight measurement. Mass separator or mass spectrometer.

$$R = \frac{M}{\Delta M} = \frac{t_{tof}}{2\Delta t_{tof}}$$

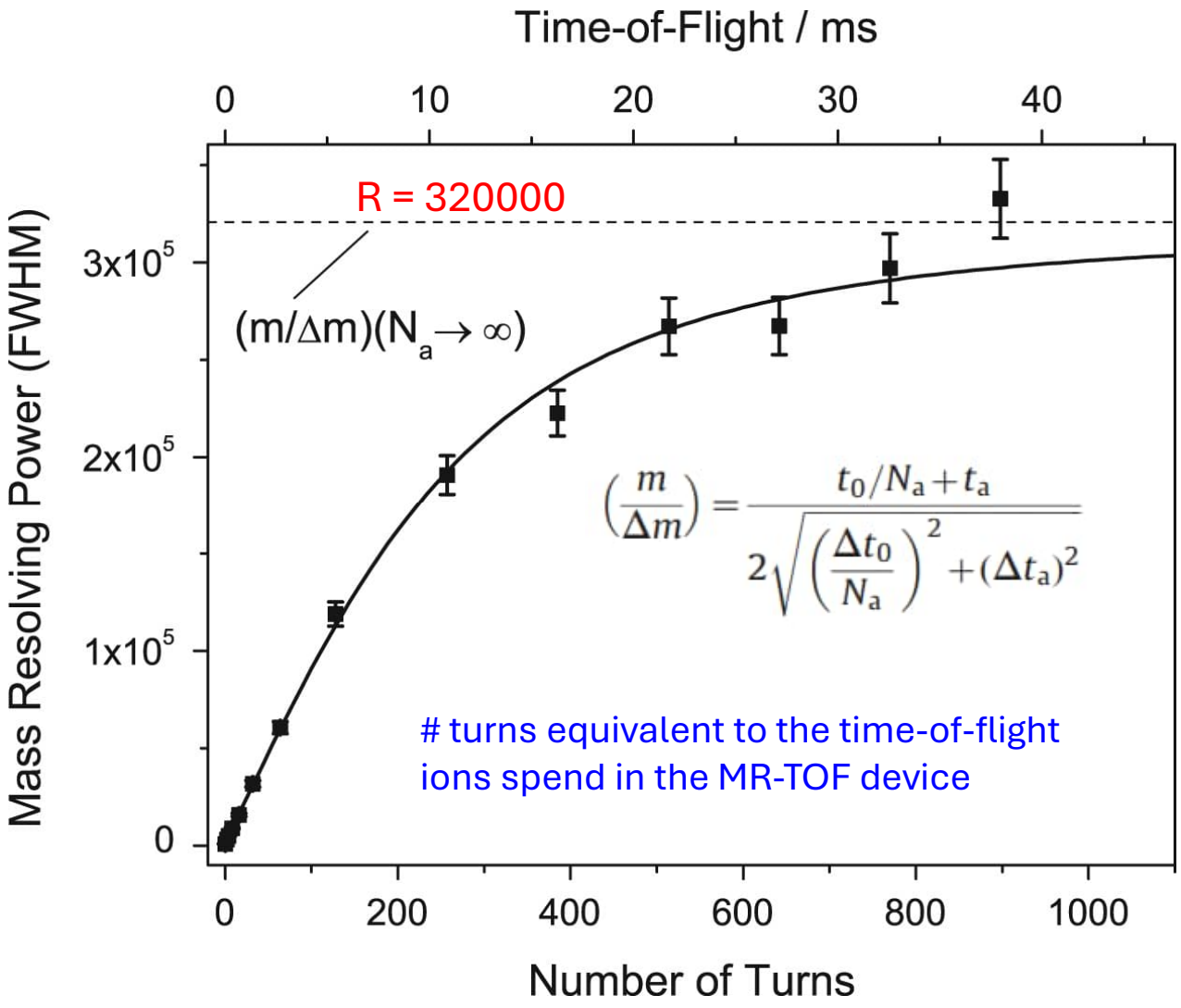


- 100…10000x single TOF, up to ~100 ms, up to few km of flight path
- For nuclei with…

  Short half-life (~ tens of ms)
  Low production

- Non-scanning (this is a good thing!): measures the full mass spectrum simultaneously

Example of the mass resolving power



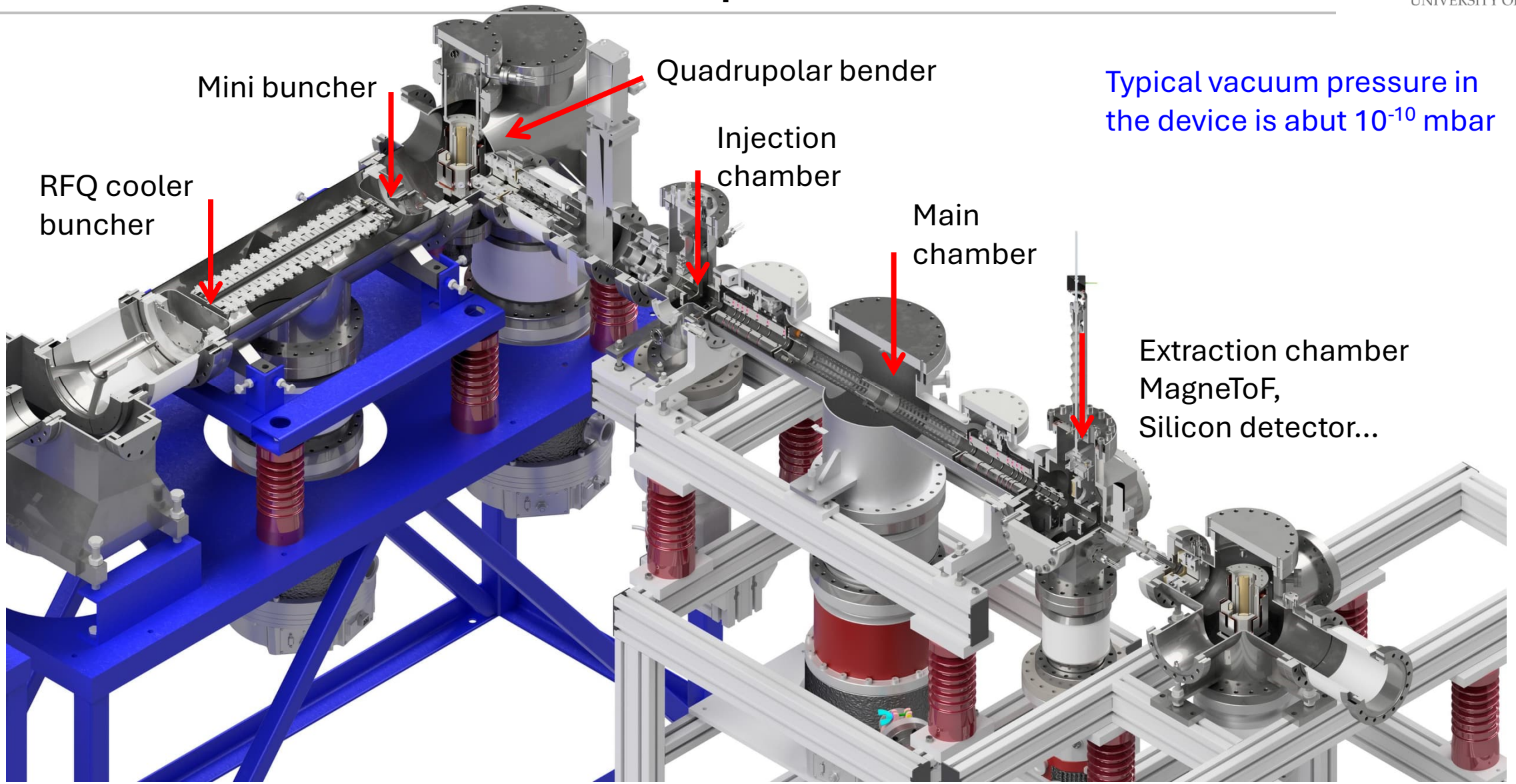
Example of MRP measured for $^{133}Cs^+$ with an MR-TOF-MS

- t_0 = TOF from start position to detector without any flight path extension
- t_a is the TOF for a single turn
- N_a is the number of passes in the device

$$R = \frac{M}{\Delta M} = \frac{t_a}{2\Delta t_a} \quad \text{... as } N_a \to \infty$$

T. Dickel et al., Nucl. Instr. and Meth. A 777 (2015) 172

The IGISOL MR-TOF mass spectrometer



Typical vacuum pressure in the device is abut 10^{-10} mbar

Exploiting the MR-TOF to identify $^{134,135}Cs^{+}$ ions

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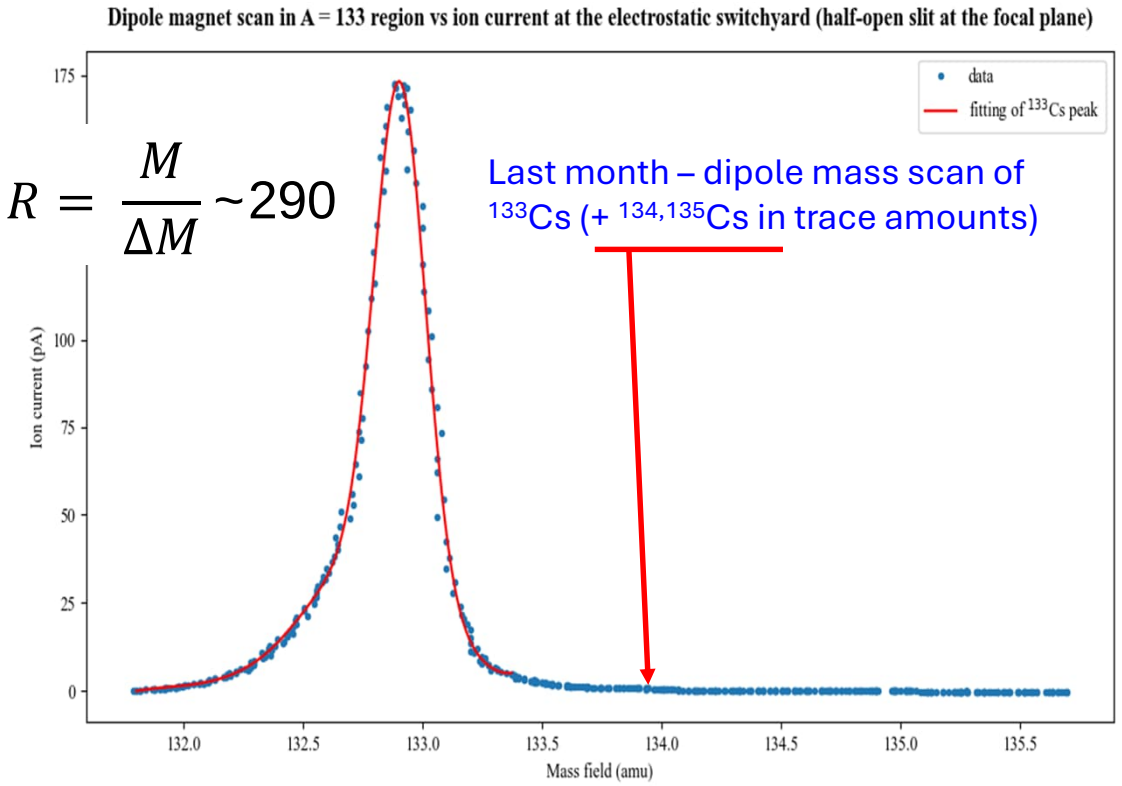
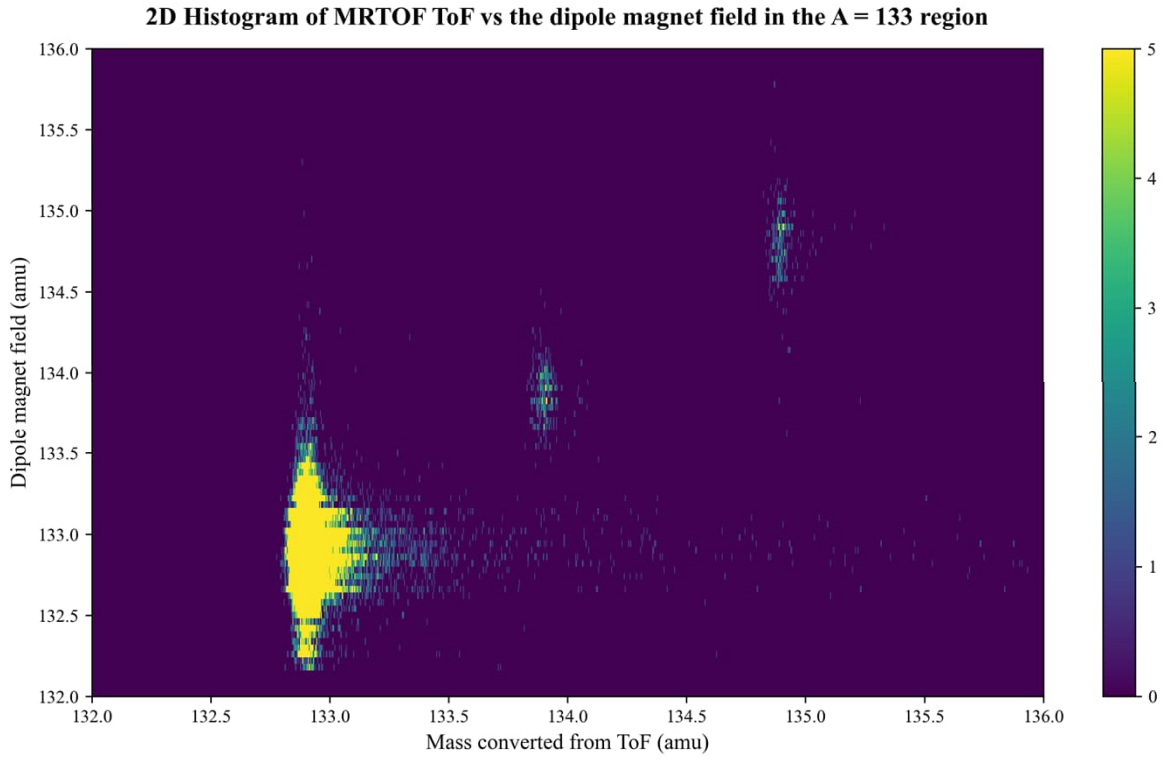
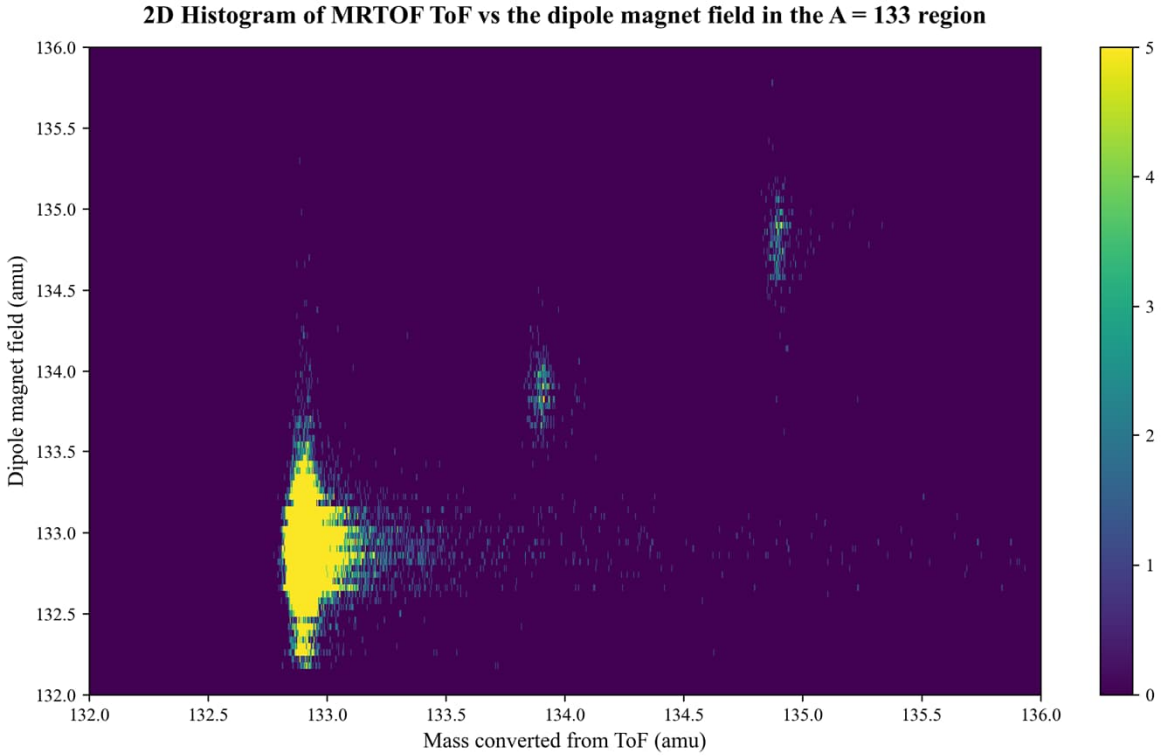
Remember I said we had insufficient sensitivity to see $^{134}Cs^{+}$...

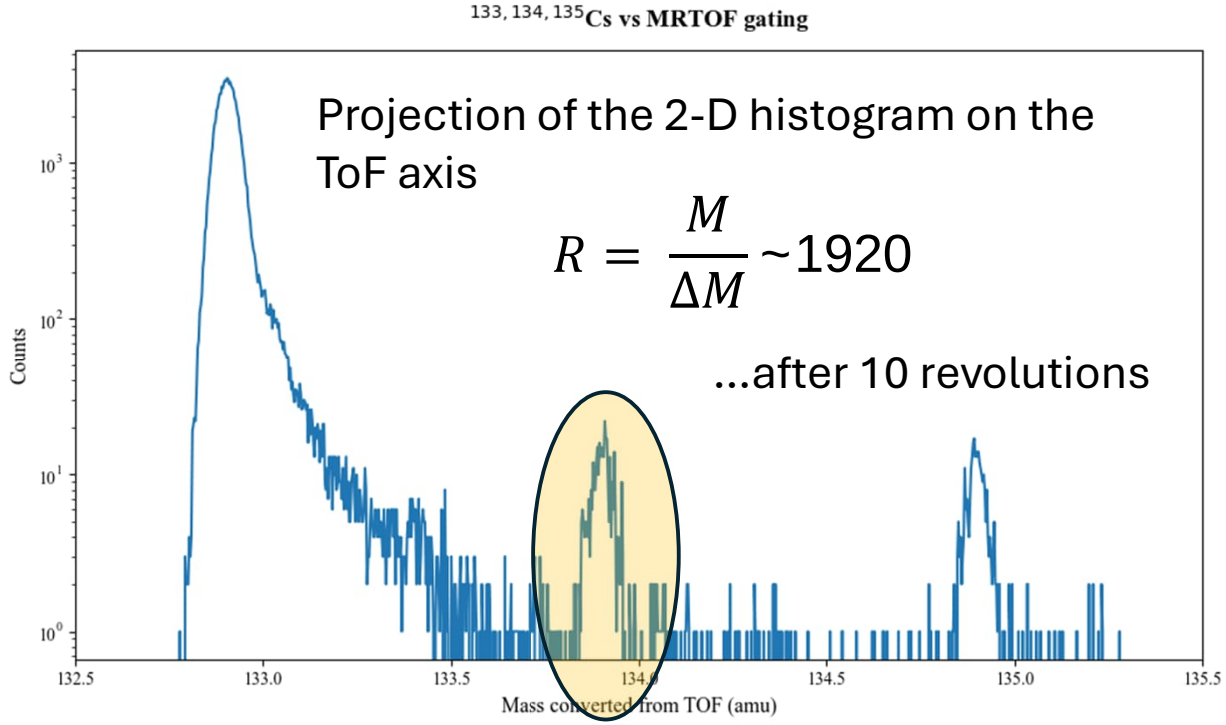




- After only 10 revolutions in the MR-TOF we could clearly separate out ^{133}Cs, ^{134}Cs and ^{135}Cs
- The only thing being scanned here is the magnetic field of the dipole magnet.

Exploiting the MR-TOF to identify $^{134,135}Cs^{+}$ ions

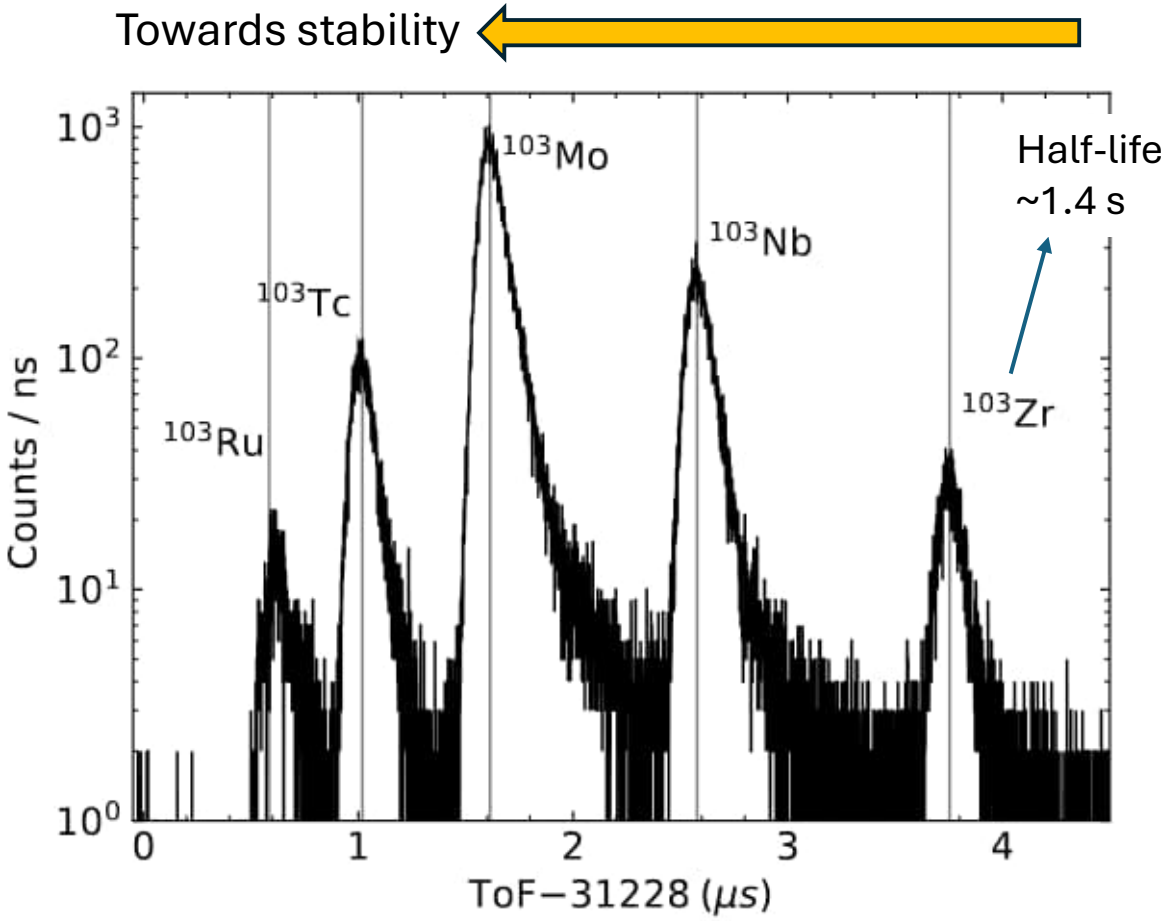




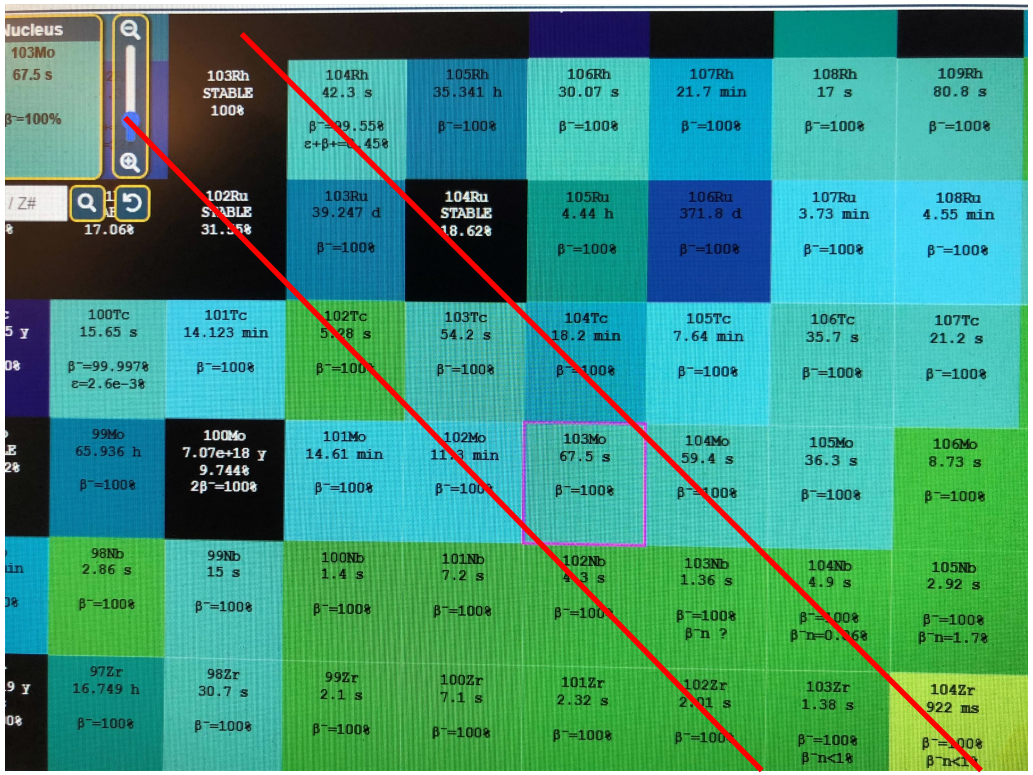
Atomic mass of ^{134}Cs: 133.9067185 u

- By projecting the two-dimensional ion counts on the ToF axis, the peaks could be integrated to get the abundance ratio.
- Combine this ratio with gamma spectroscopy of ^{134}Cs we can estimate the activity when the sample was created.

MR-ToF: On-line mass spectra of fission fragments



$$R = \frac{t_a}{2\Delta t_a} \sim 10^5$$



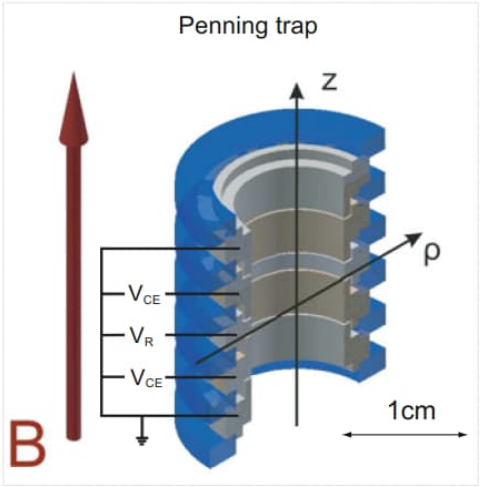
- Non-scanning method: stable & radioactive ions detected simultaneously

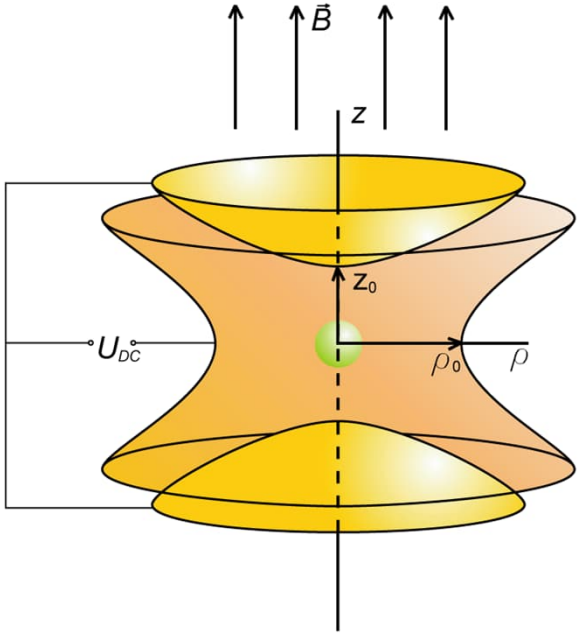
Typical mass precision: $\frac{\delta m}{m} \propto \frac{1}{R\sqrt{N}}$ ~10 …100 keV/c^2

Penning trap mass spectrometry (PTMS)

As soon as masses of nuclides with half-lives longer than a few hundred ms have to be determined with a fractional uncertainty smaller than 10^{-7} – there is only one choice – Penning-trap mass spectrometry!

- Trapping of particle via motion in electro-magnetic field
- Strong homogeneous magnetic field in the *z* direction
- An ion with ratio *q*/*m* experiences a Lorentz force $\vec{F}_L = q\vec{v} \times \vec{B}$
- Weak quadrupole (harmonic) electrostatic potential $\phi(z,r) = \frac{U_{DC}}{2d^2}\left(z^2 - \frac{1}{2}\rho^2\right)$





$$d^2 = \frac{1}{2}\left(z_0^2 + \frac{\rho_0^2}{2}\right)$$

Typical size a few cm

Ion motions in the Penning trap

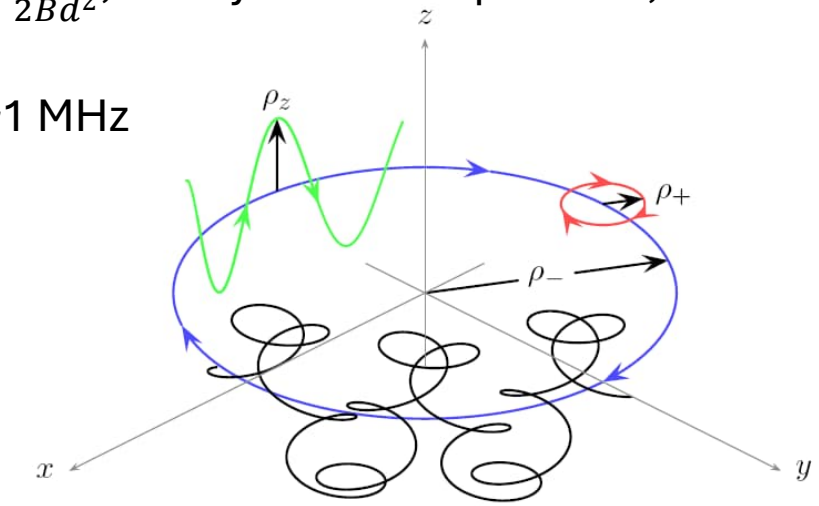
The trapped ion undergoes three motions – cyclotron, magnetron and axial, with frequencies ν_+, ν_- and ν_z, respectively, which are uniquely determined by the trap parameters (B field, trapping potential and the trap dimension.

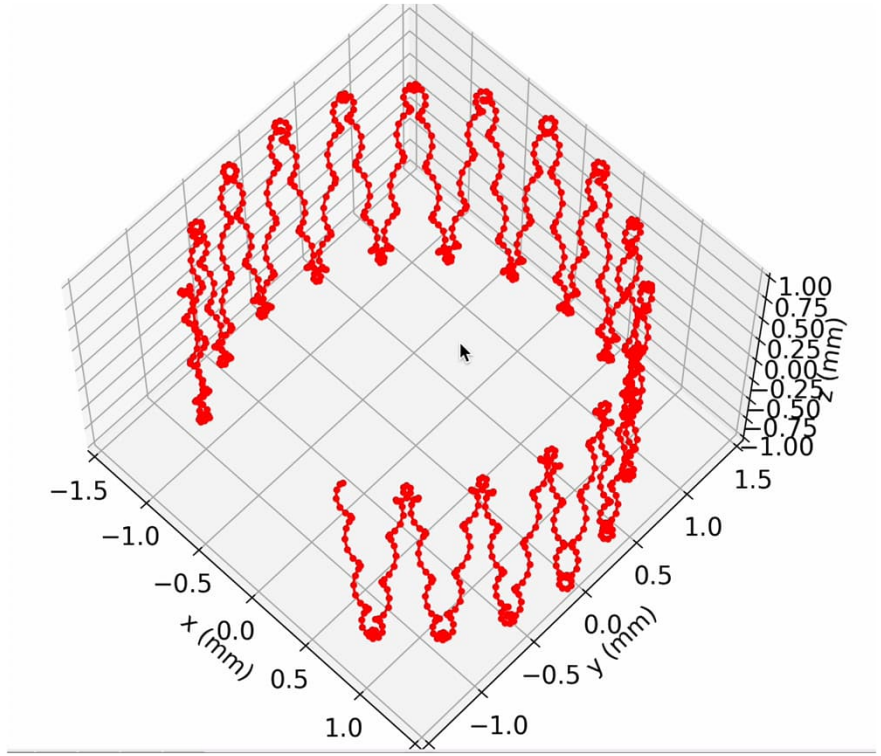
- Typical magnetic field for Penning traps for radioactive ions ~7T

$\upsilon_z = \frac{1}{2\pi}\sqrt{\frac{qV_0}{md^2}}$, harmonic oscillator, ~20 kHz

$\upsilon_- = \frac{1}{4\pi}\left(\upsilon_c - \sqrt{\nu_c^2 - 2\nu_z^2}\right) \approx \frac{U}{2Bd^2}$, nearly mass independent, ~1 kHz

$\upsilon_+ = \frac{1}{4\pi}\left(\upsilon_c + \sqrt{\nu_c^2 - 2\nu_z^2}\right)$, ~1 MHz





Penning trap ion manipulation techniques

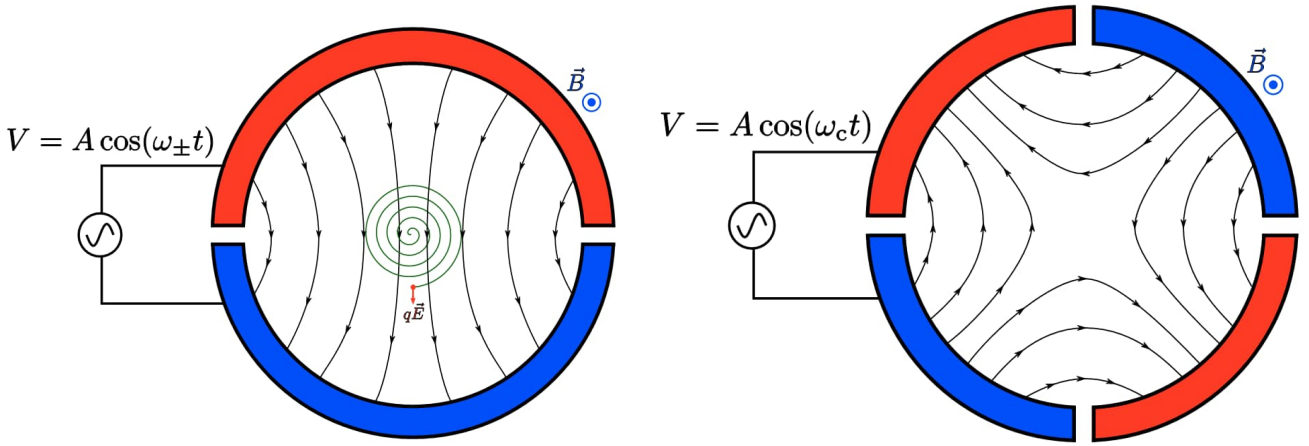
Here I will be extremely brief – sorry any trappers!! But there is a wealth of beautiful literature you can gorge yourselves on if you wish the juicy details!

- We are interested in obtaining the atomic mass…the quantity for mass determination is:

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

- For exotic nuclides, we get access to the cyclotron frequency by measuring the sideband frequency $\nu_+ + \nu_- = \nu_c$ (no need to measure axial frequency)

Trap motion excitations



Dipole

Quadrupole

- The ring electrode is split allowing for RF excitations to excite the (radial) motion amplitudes
- Eigenmotion excitation (dipolar)
- Conversions, coupling etc (quadrupolar)

Time-of-Flight Ion Cyclotron Resonance method

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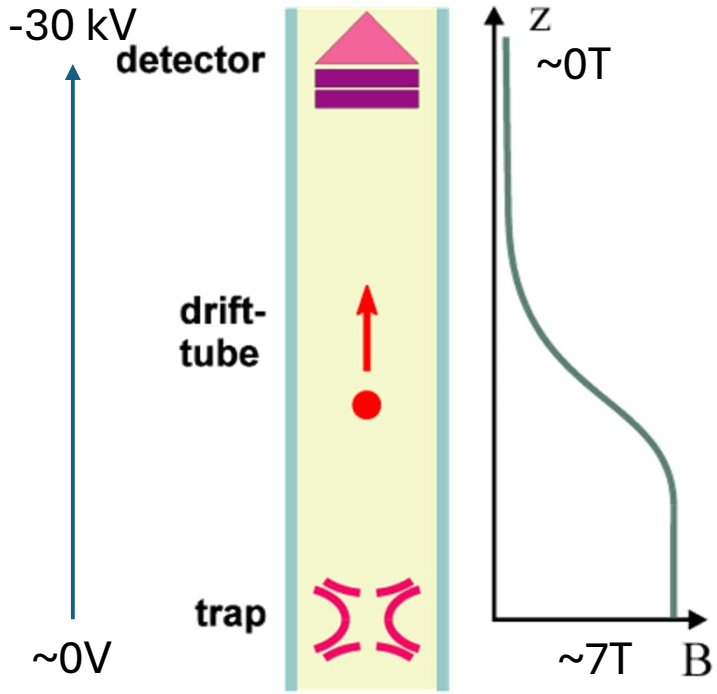
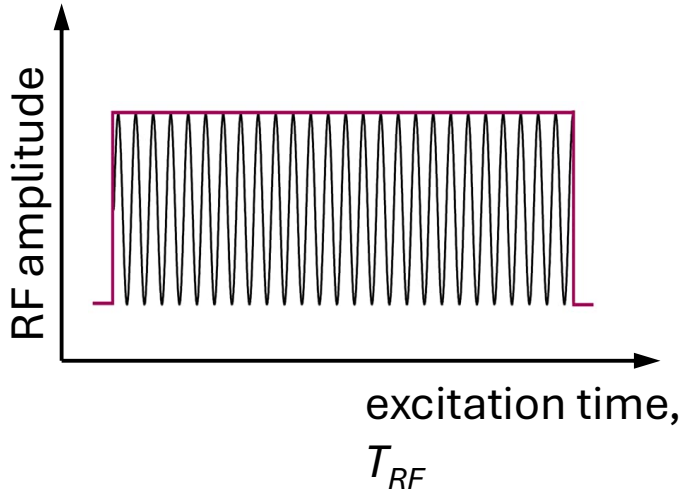
Basic idea

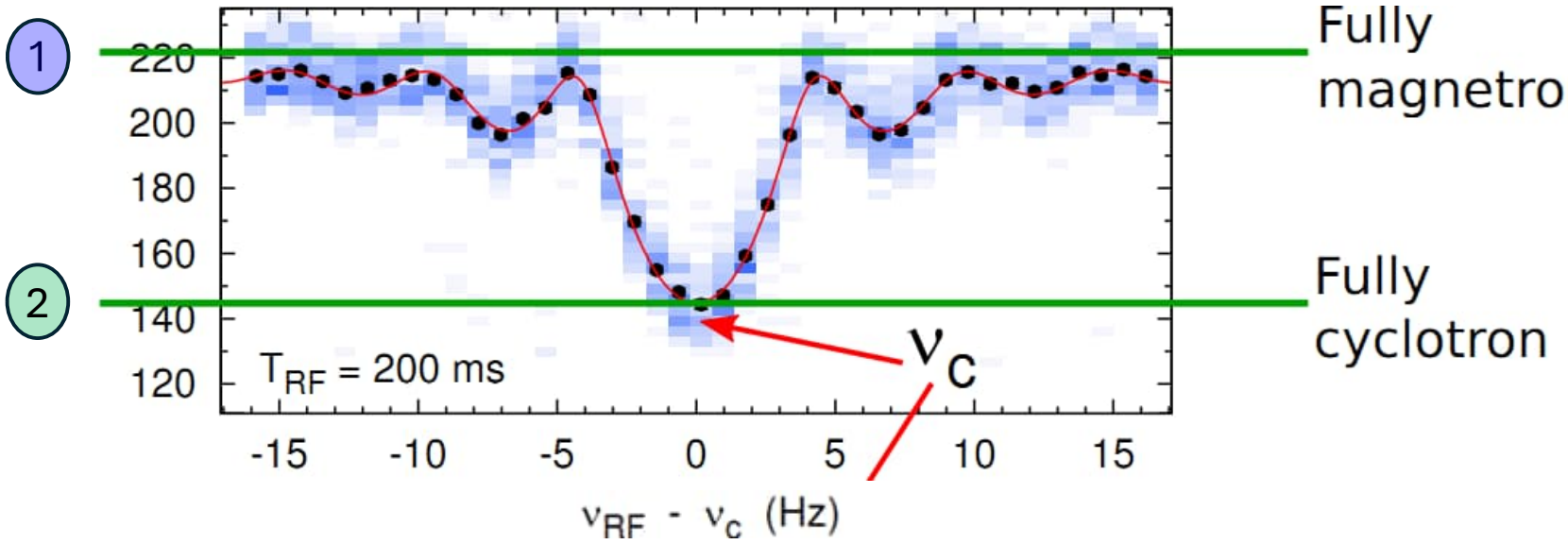
- Inject a bunch of ions into the trap, have them centred
- Excite ions to a well-defined radius of the magnetron motion (mass-independent)
- Apply a quadrupole excitation to convert the magnetron to the cyclotron motion (scan v_{RF} over ions v_c)
- Extract ions from the trap and record their TOF (start signal is ejection, ion's arrival is the stop signal)

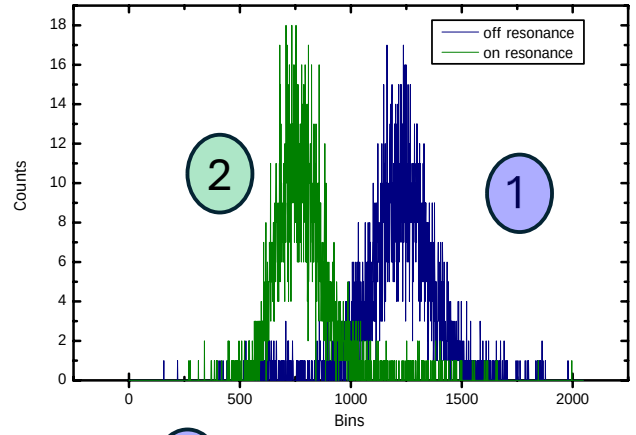




$$\vec{F} = -\vec{\mu}(\vec{\nabla}\vec{B}) = -\frac{E_r}{B}\frac{\partial B}{\partial z}\hat{z}$$

Time-of-Flight Ion Cyclotron Resonance method





1 = off resonance

2 = on resonance

- Scanning: frequency-by-frequency; several ion bunches per point
- Blue shaded pixels:
  - Ions with this TOF
  - Denser color- more ions
- Black points (with error bar): average TOF for this frequency

*M. König et al., Int. J. Mass Spec. Ion Process. 142 (1995) 95

- Solid line is theoretically expected lineshape, mainly determined by the Fourier transform of the RF excitation profile.
- The width and thus resolving power is Fourier limited by the duration of the quadrupole excitation.

$$R = \frac{m}{\Delta m} = \frac{\nu_c}{\Delta \upsilon_c} \approx \upsilon_c T_{RF}$$

Phase-Imaging Ion Cyclotron Resonance method

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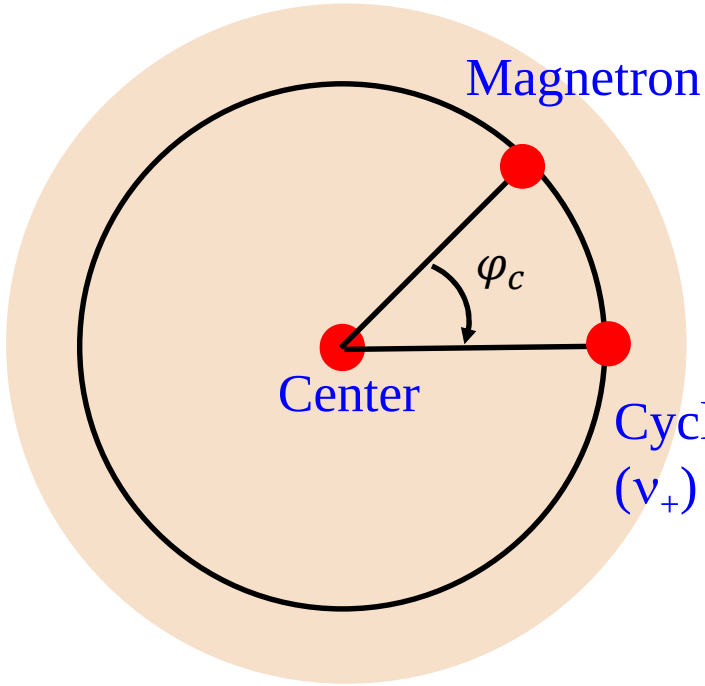
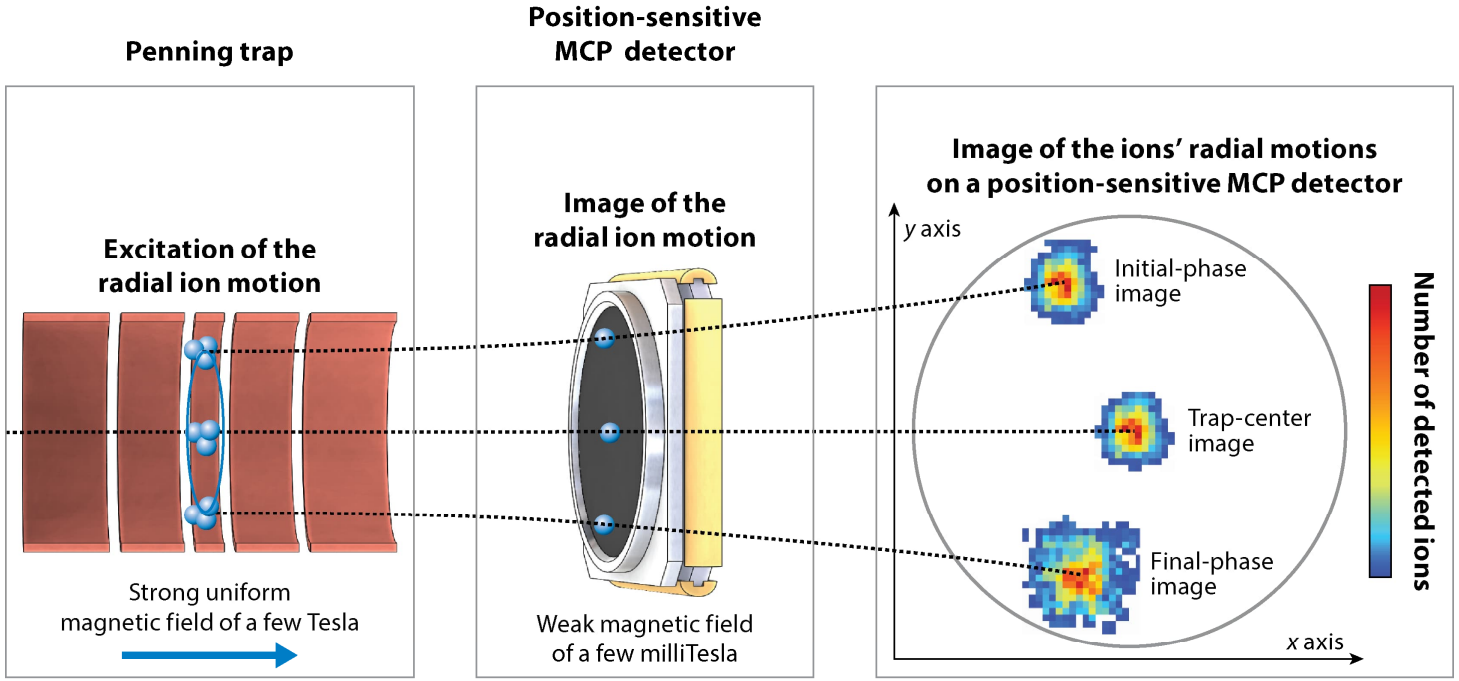
This is a method which has been developed in recent years...





Dilling J, et al. 2018.
Annu. Rev. Nucl. Part. Sci. 68:45–74

J. Dilling et al., Annu. Rev. Nucl. Part. Sci. 68 (2018) 45

$$\nu_c = \frac{\varphi_c + 2\pi n_c}{2\pi t}$$

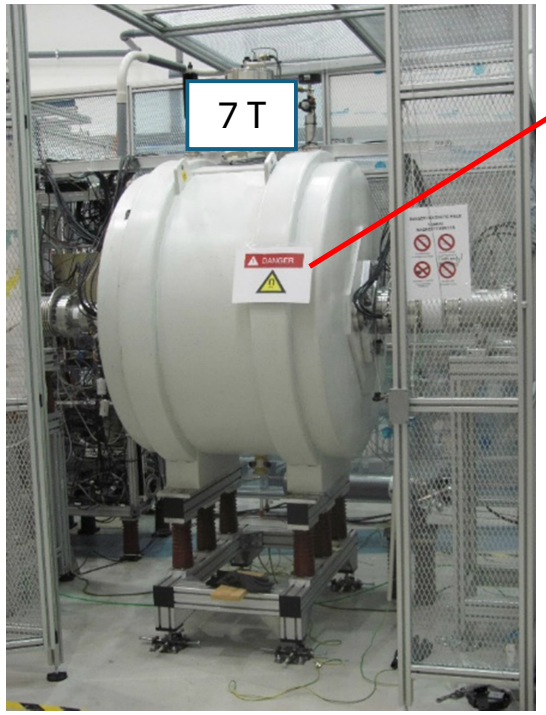
$n_\pm$ = number of turns
$\phi_\pm$ = phase of the radial frequency $\nu_\pm$
t = phase accumulation time

Offers a 5-fold gain in precision of the cyclotron-frequency determination, and 40-fold gain in resolving power.

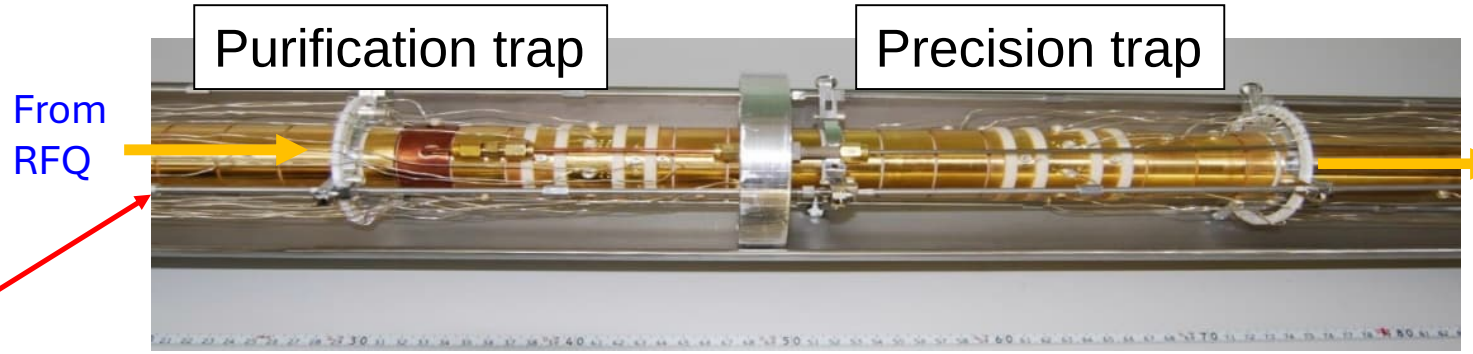
*S. Eliseev et al., Appl. Phys. B **114** (2014) 107*
D.A. Nesterenko et al., Eur. Phys. J. A 54 (2018) 154

The JYFLTRAP double Penning trap

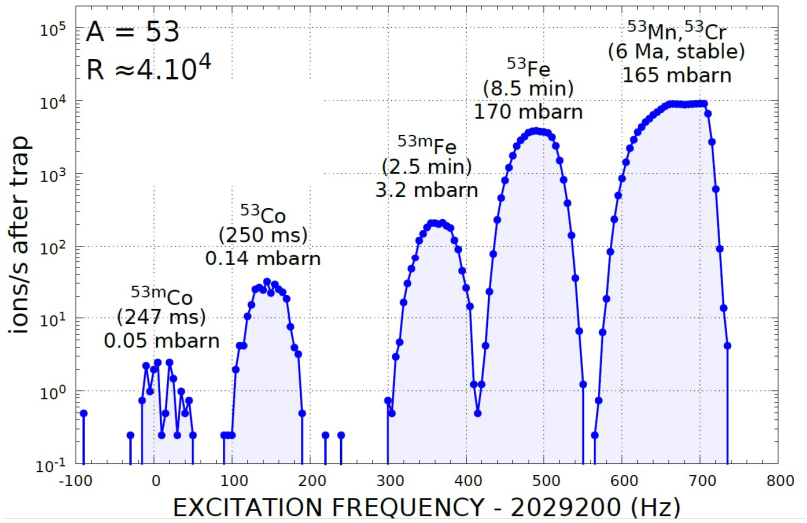
- Homogeneous 7T B field
- 100V deep quadrupole potential
- Cylindrical geometry



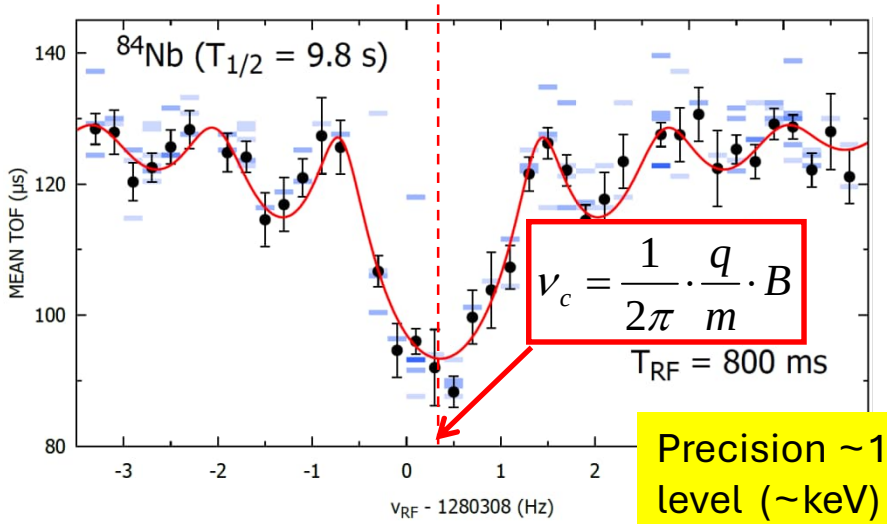
T. Eronen et al., Eur. Phys. J. A 48 (2012) 46



Mass-selective buffer gas cooling*

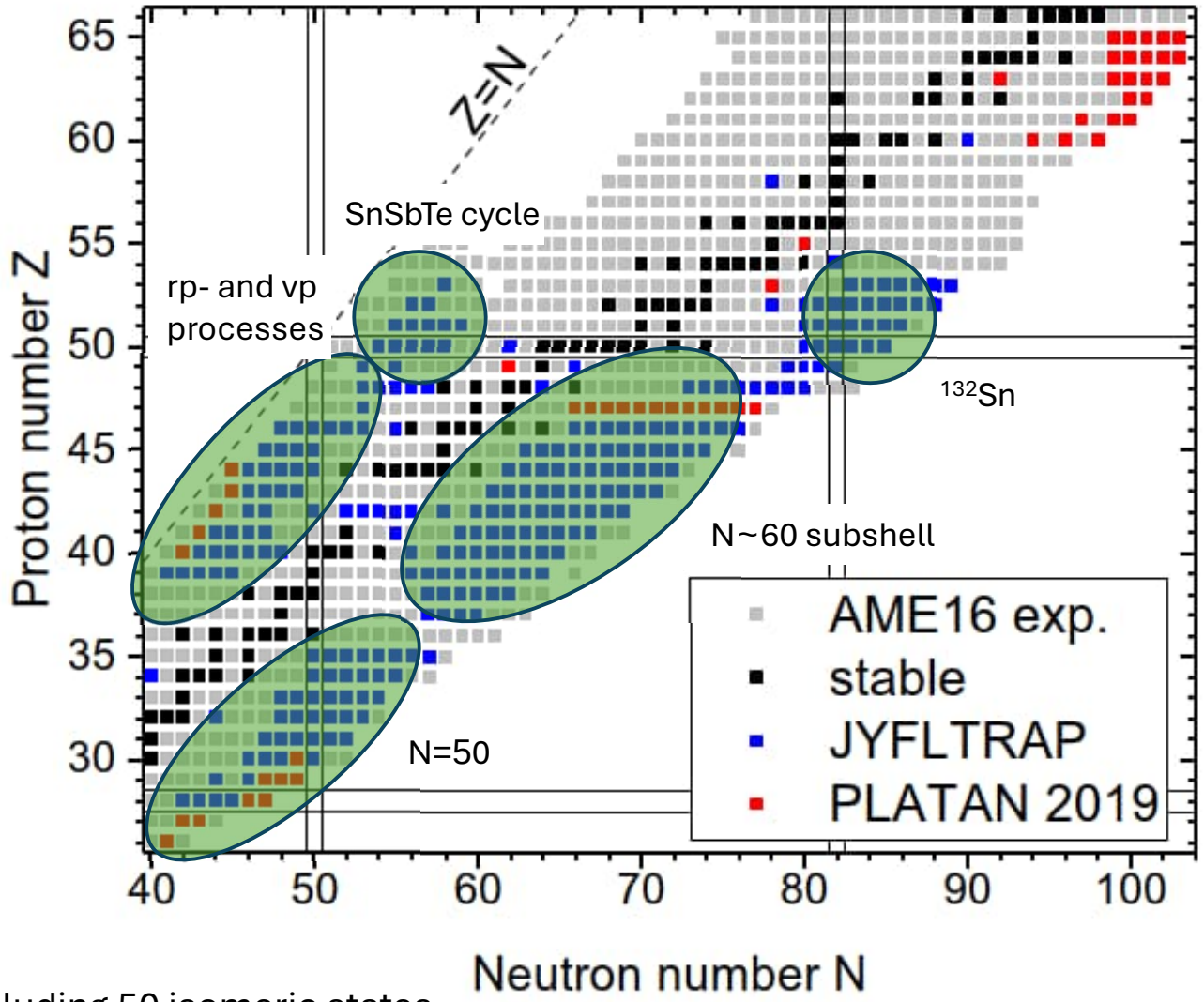


*Savard et al., Phys. Lett. A 158, 247 (1991)



Precision ~10^{-8} level (~keV)

Mass harvesting at JYFLTRAP



>400 masses measured including 50 isomeric states

A. Kankainen, Hyp. Int. 241 (2020) 43

Trap-assisted decay spectroscopy

Nowadays, almost 60% of all JYFLTRAP Penning trap experiments are not for mass measurements, but for mass purification. The nuclear decay spectroscopy community relish having pure beams, sometimes even isomerically purified!

A=111 fission fragments

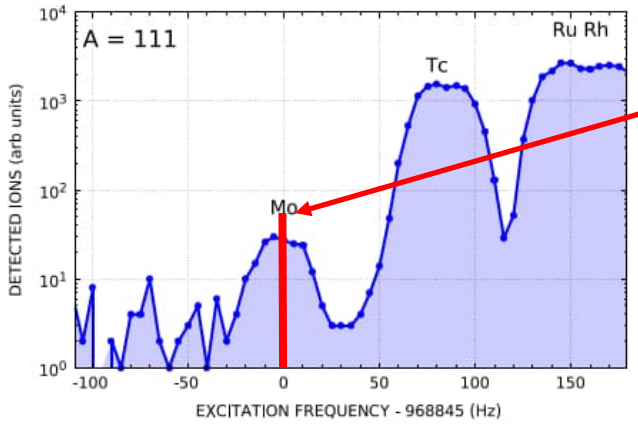
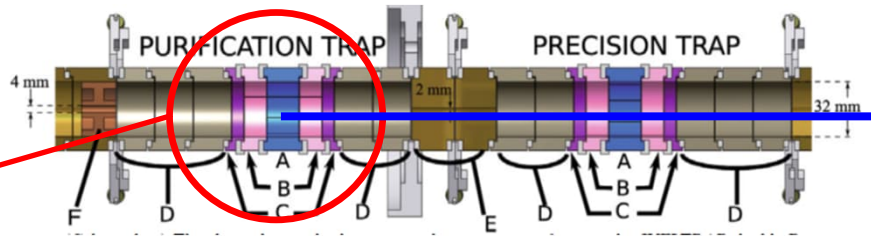
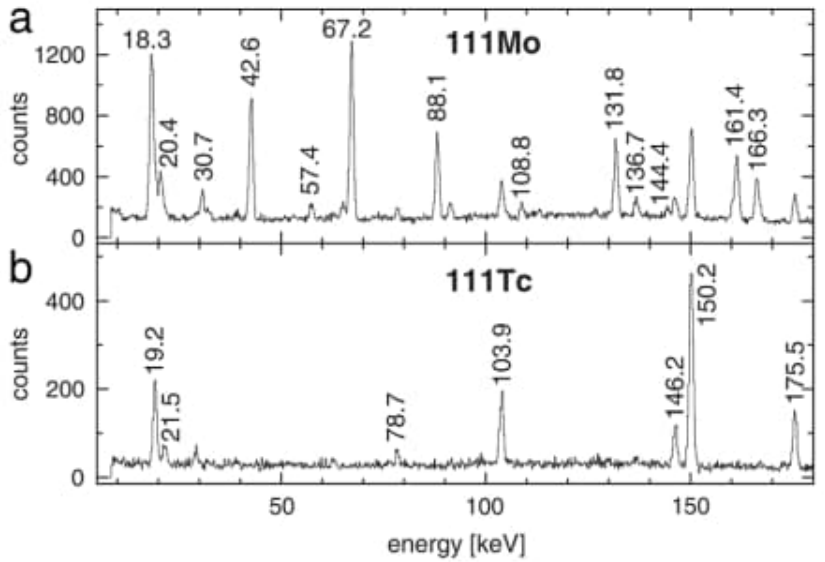
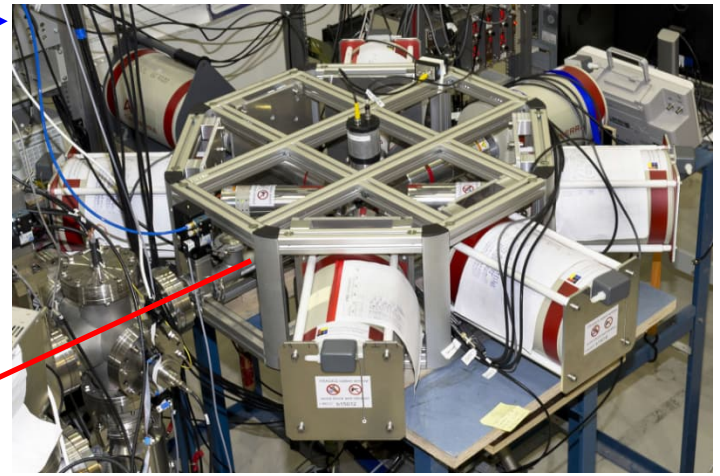


Fig. 24. Mass spectrum of $A = 111$ isobars.







Low-energy Ge array (U-Warsaw)

- Monoisotopic beam of ^{111}Mo delivered downstream for post-trap decay spectroscopy.

J. Kurpeta et al., Phys. Rev. C 84 (2011) 044304

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Once upon a time we wanted to study silver with lasers and traps

First we need some physics motivations

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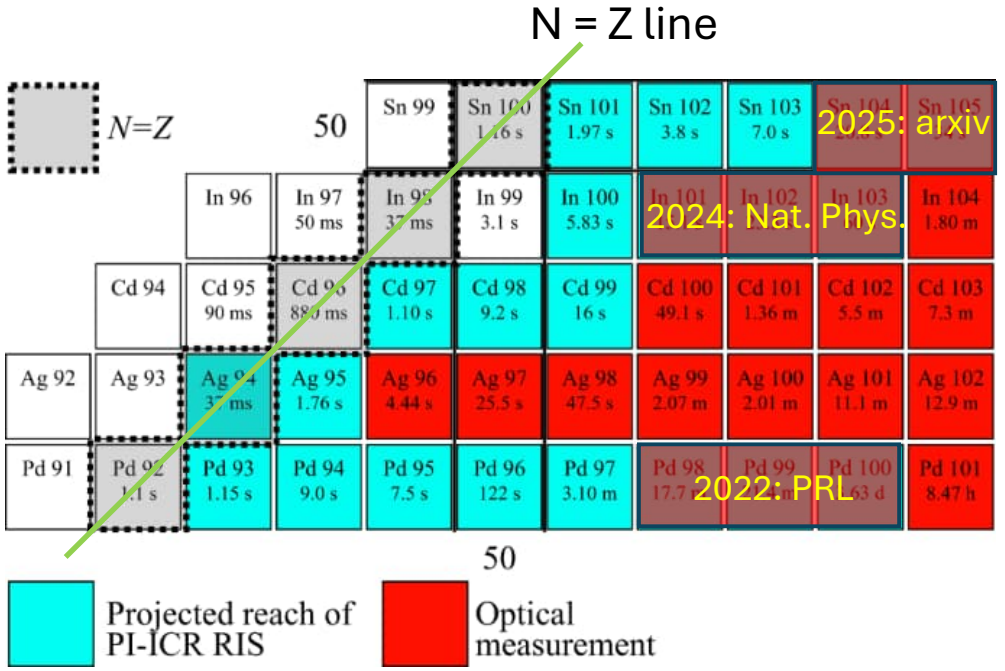
Nuclear structure trends

- Region below Sn (Z = 50) is of high interest – probing shell evolution below the closed proton shell (Z = 50) and between neutron shell closures at N = 50 and 82 (spanning 32 neutrons!)
- Data on neutron-rich odd-odd Ag isotopes is absent or incomplete
- Spin assignments are often tentative and in conflict due to experiments lacking isomeric or isobaric purification
- High precision mass and laser spectroscopy measurements can be combined with decay spectroscopy data to firmly establish spin and parity assignments, and level ordering.

M. Reponen, R.P de Groote,…IM, et al., Nature Comm. 12 (2021) 4596

Laser spectroscopy near ^{100}Sn



- Very neutron-poor isotopes are challenging to produce
- Reactions offer small cross section
- Often overwhelming contamination (same mass but closer to stability)

RIB methods to access the Ag isotopic chain

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$N=Z$ ^{94}Ag (gs): $T_{1/2}$ = 26 ms

Here we are going to focus on the neutron-deficient isotopes (as it makes a nicer story!!)

^{125}Ag:$T_{1/2}$ = 176 ms

Heavy-ion fusion-evaporation reactions

$^{92/nat}$Mo(^{14}N,2pxn)$^{104-96}$Ag
^{60}Ni(^{40}Ca,p3n)^{96,96m}Ag
^{58}Ni(^{40}Ca,pxn)^{95,94}Ag

Typical heavy-ion gas cell efficiency ~1%, few 100ms extraction time

Light-ion fusion-evaporation reactions

^{nat,110}Pd(p/d,xn/pxn)$^{110-102}$Ag

Light ion guide (gas cell)

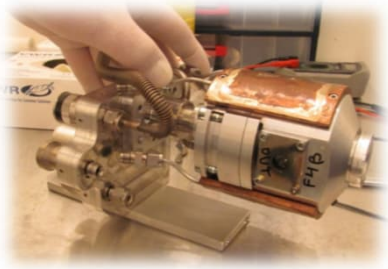
Efficiency 1-10%

Proton-induced fission of U

$^{113-125}$Ag

Fission ion guide (gas cell)

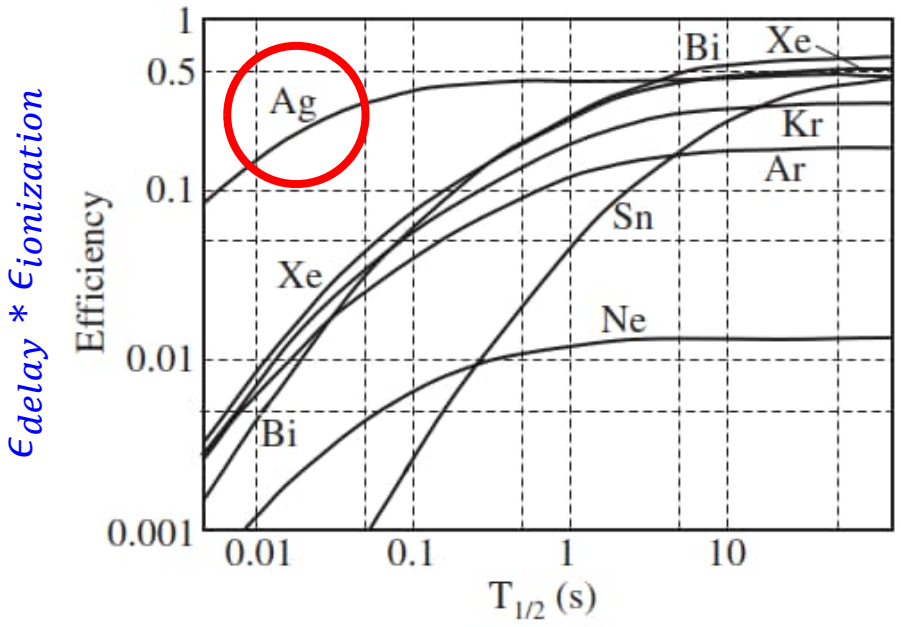
Typical efficiency 0.1%



Access to nuclei above A = 125 at ISOLDE; 1.4 GeV protons on UC_x target.

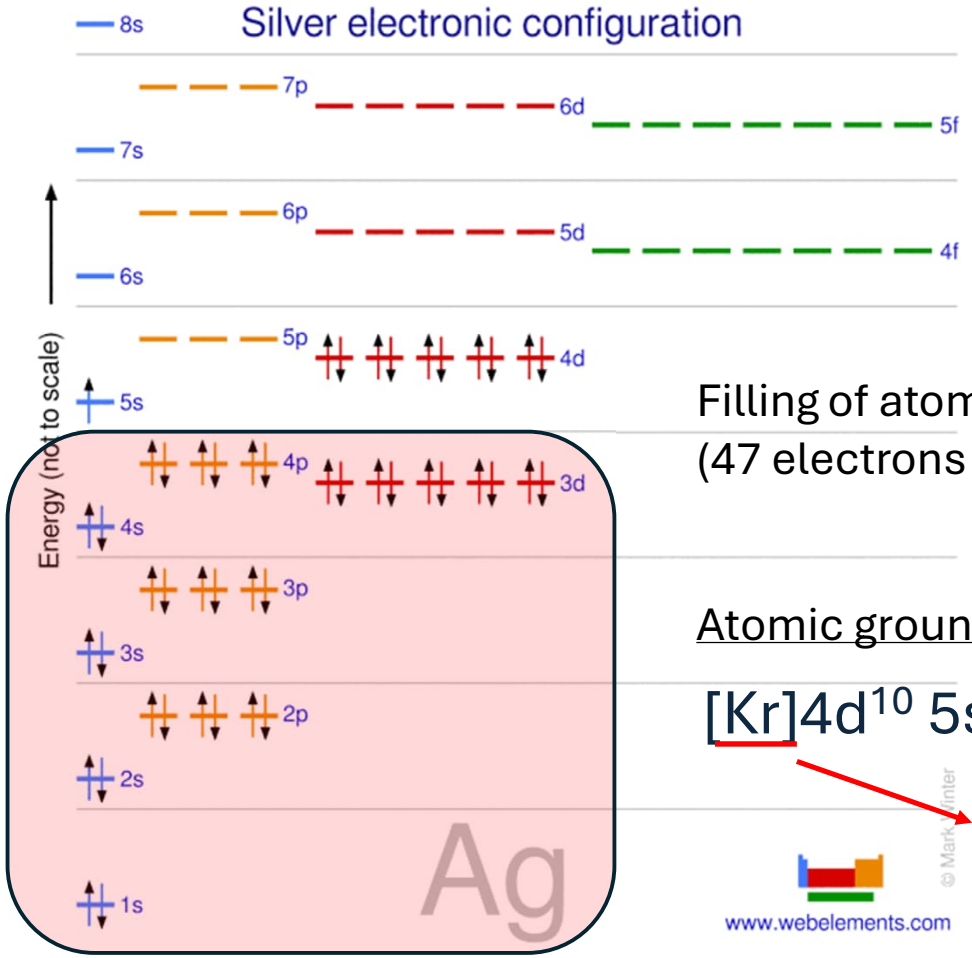
Recall from lecture 2 – FEBIAD ion source

- Alternative approach for the extraction of Ag was motivated by the FEBIAD ion source from the GSI on-line mass separator. Silver had an exceptional release from a graphite catcher, tens of ms timescale and close to 50% extraction efficiency.
- Selective and efficient laser ionization in a hot cavity.



R. Kirchner et al., NIMB 70 (1992) 186

Silver (Z = 47) has very suitable atomic properties



Filling of atomic orbitals (47 electrons – neutral)

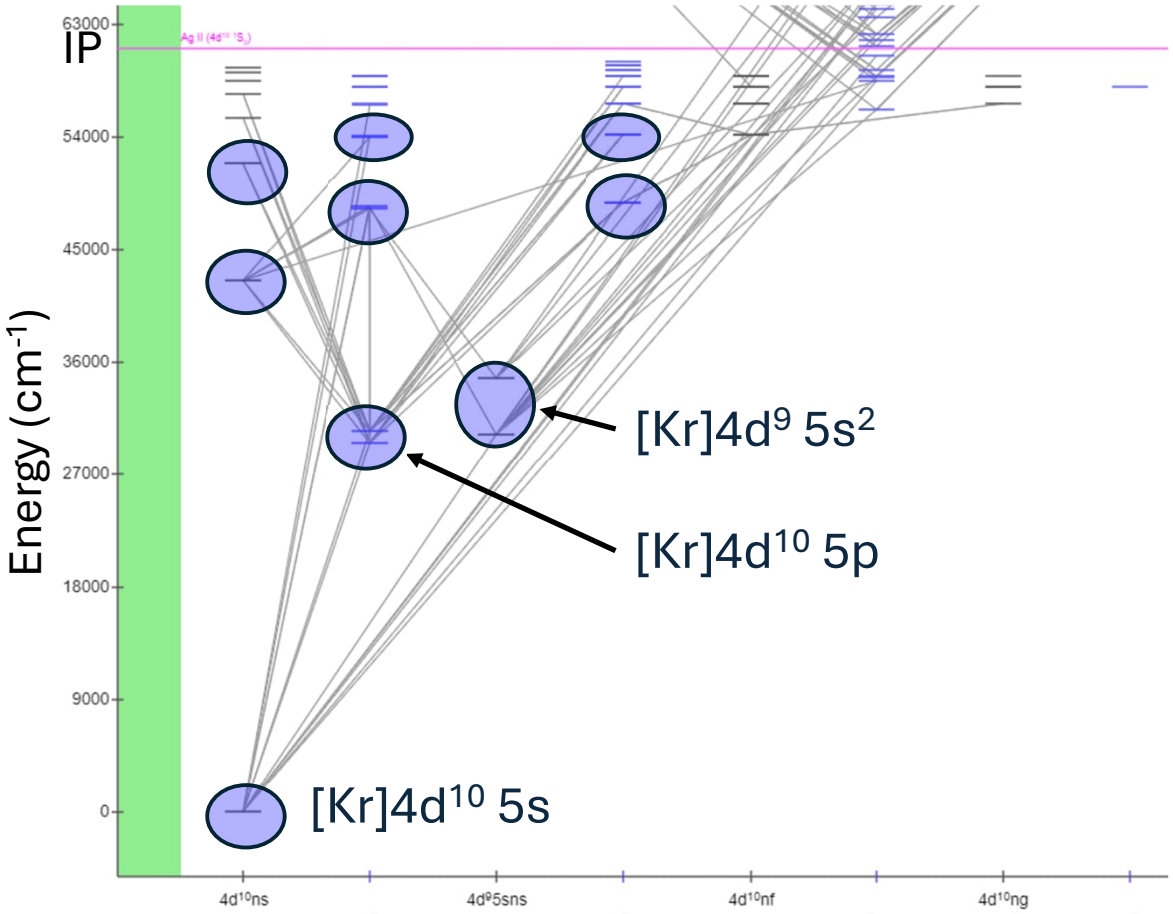
Atomic ground state:

$[Kr]4d^{10}\ 5s\ ^2S_{1/2}$

Z = 36

www.webelements.com

Lines and levels of neutral Ag (Ag I)

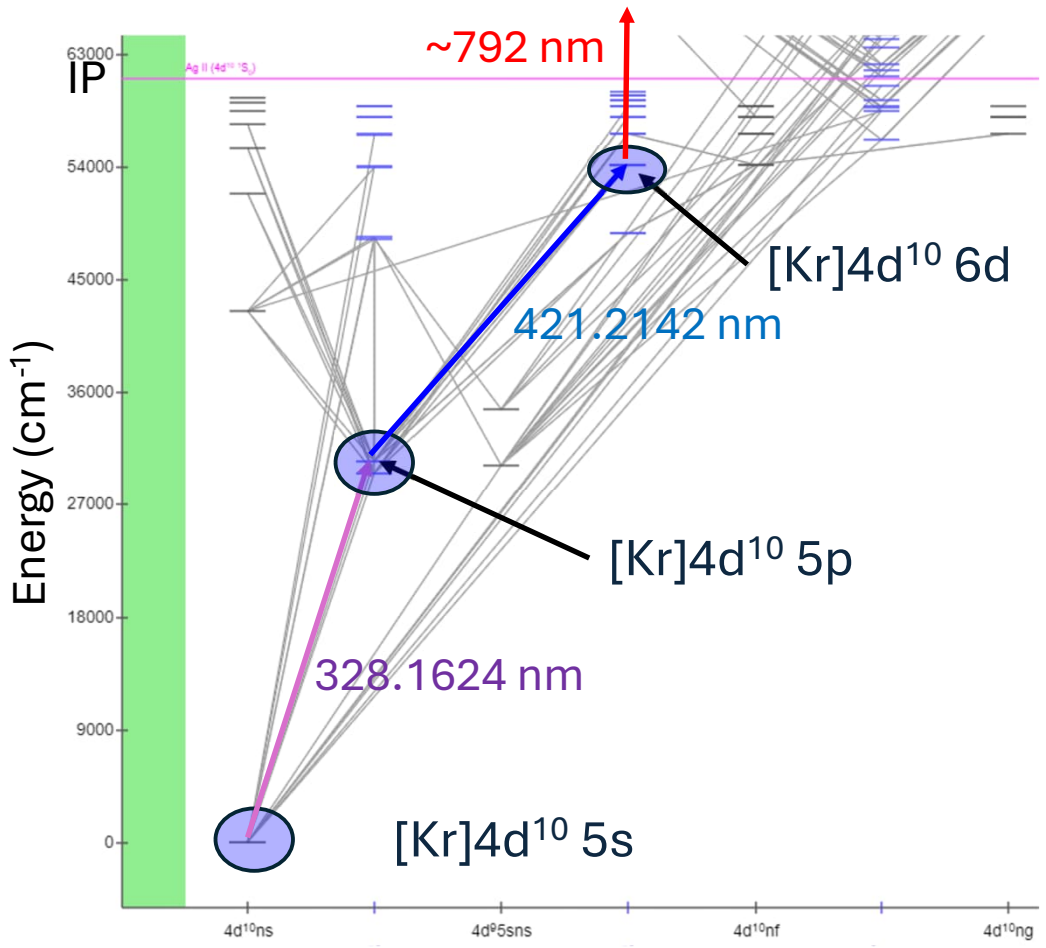


https://physics.nist.gov/PhysRefData/ASD/levels_form.html

Configuration	Term	J	Level (cm^{-1})	Uncertainty (cm^{-1})
$4d^{10}5s$	^{2}S	$^1/_2$	0.000000	0
$4d^{10}5p$	^{2}P°	$^1/_2$	29 552.05741	0.00014
		$^3/_2$	30 472.66516	0.00022
$4d^95s^2$	^{2}D	$^5/_2$	30 242.298349	0.000006
		$^3/_2$	34 714.22643	0.00010
$4d^{10}6s$	^{2}S	$^1/_2$	42 556.147	0.001
$4d^{10}6p$	^{2}P°	$^1/_2$	48 297.406	0.002
		$^3/_2$	48 500.8105	0.0004
$4d^{10}5d$	^{2}D	$^3/_2$	48 743.969	0.002
		$^5/_2$	48 764.219	0.002
$4d^{10}7s$	^{2}S	$^1/_2$	51 886.965	0.001
$4d^{10}7p$	^{2}P°	$^1/_2$	54 041.037	0.002
		$^3/_2$	54 121.108	0.001
$4d^{10}6d$	^{2}D	$^3/_2$	54 203.119	0.002
		$^5/_2$	54 213.564	0.003

- Filled atomic d shell
- Valence electron can be placed in 5s, 5p, 6s, 6p, … to form the lowest-energy atomic states

Resonance ionization scheme



Configuration	Term	J	Level (cm^{-1})	Uncertainty (cm^{-1})
$4d^{10}5s$	^2S	$^1/_2$	0.000000	0
$4d^{10}5p$	$^2P°$	$^1/_2$	29 552.05741	0.00014
		$^3/_2$	30 472.66516	0.00022
$4d^9 5s^2$	^2D	$^5/_2$	30 242.298349	0.000006
		$^3/_2$	34 714.22643	0.00010
$4d^{10}6s$	^2S	$^1/_2$	42 556.147	0.001
$4d^{10}6p$	$^2P°$	$^1/_2$	48 297.406	0.002
		$^3/_2$	48 500.8105	0.0004
$4d^{10}5d$	^2D	$^3/_2$	48 743.969	0.002
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$4d^{10}7s$	^2S	$^1/_2$	51 886.965	0.001
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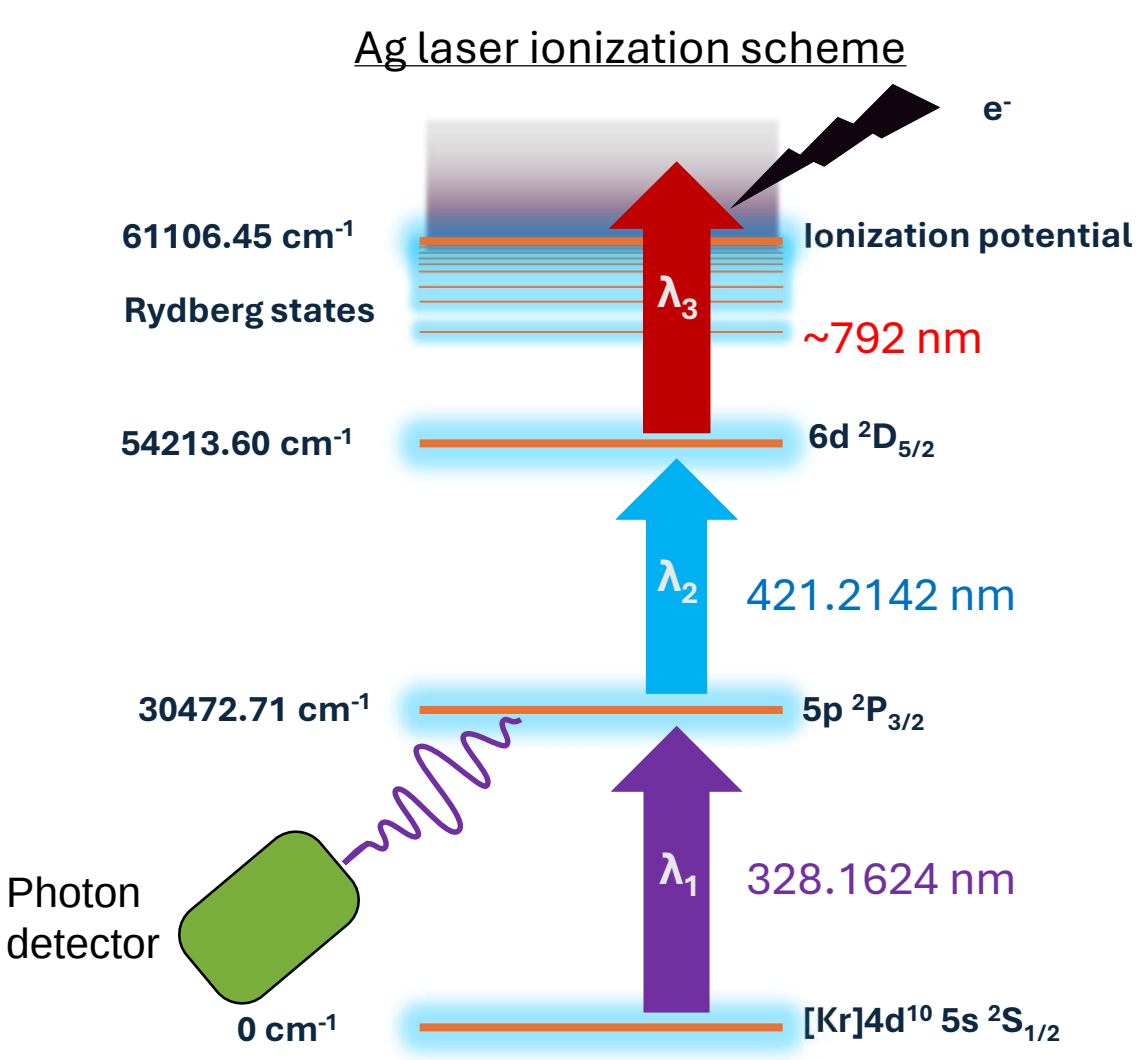
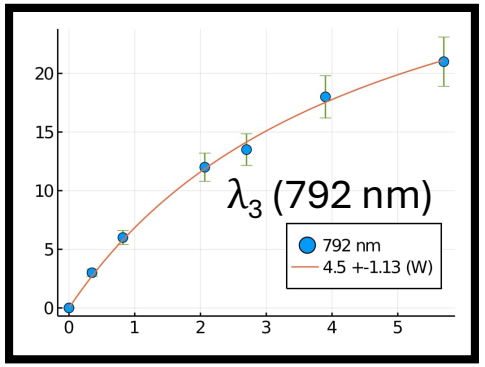
		$^3/_2$	54 121.108	0.001
$4d^{10}6d$	^2D	$^3/_2$	54 203.119	0.002
		$^5/_2$	54 213.564	0.003

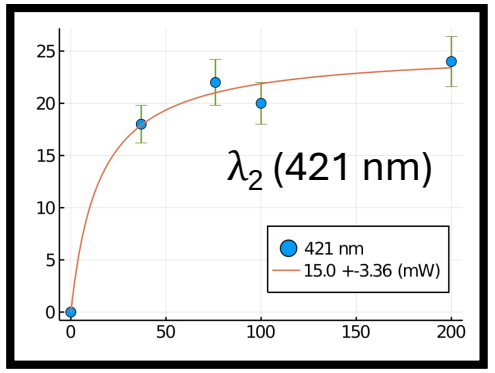
$$J_1 = \frac{1}{2} \rightarrow J_2 = \frac{3}{2} \rightarrow J_3 = \frac{5}{2}$$

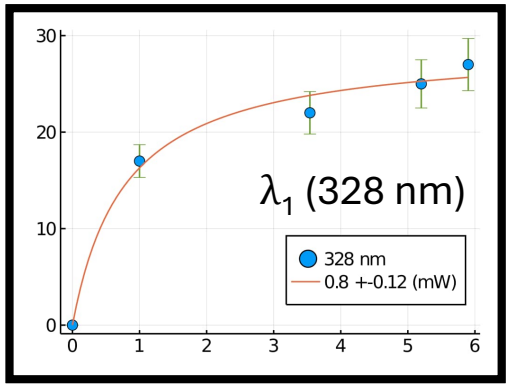
- Ground state with J = ½ has sensitivity to magnetic dipole moment
- Excited state with J = 3/2, additional sensitivity to Q_s

Checking the saturation of the scheme





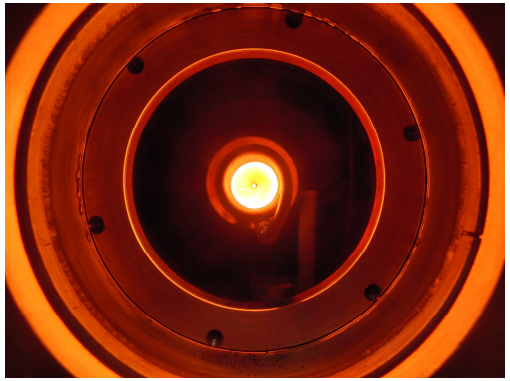




- We also measure the laser powers for each step at the end of the optical table and entering the transfer tube of the hot cavity.
- Typical transport efficiency (April 2025):
  - λ_1 = 50%
  - λ_2 = 30%
  - λ_3 = 60%
- We optimize the laser power with respect to ion count rate and spectral resolution (in-source)

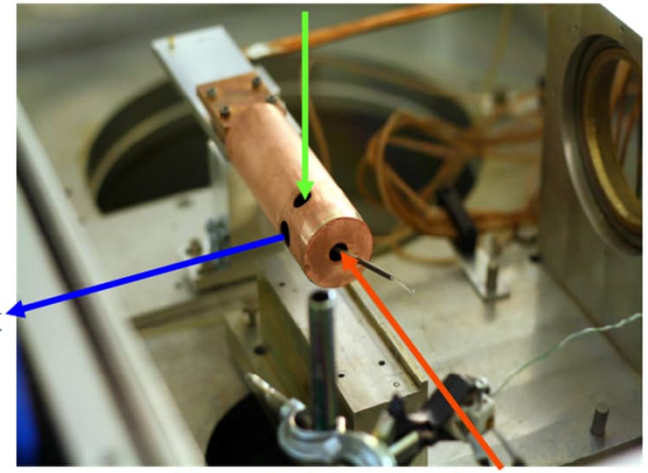
A few small iterations in the hot cavity design

- In fact version 0 started way back in 2007!!



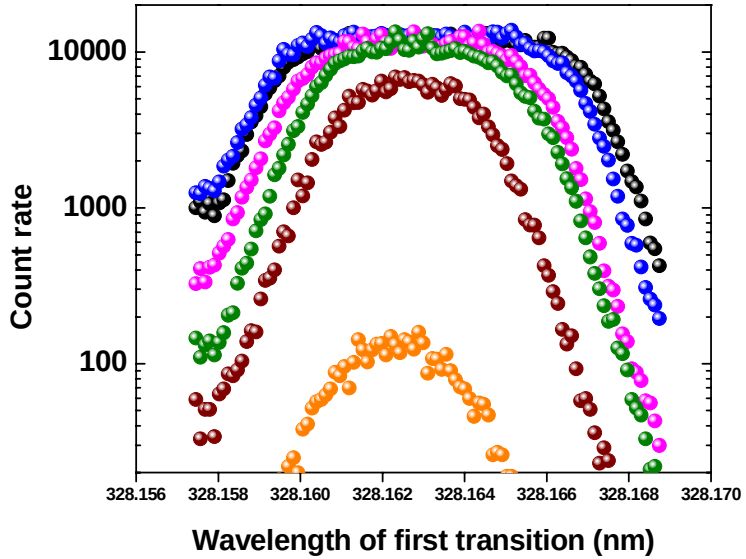
Version 1

- Two FEBIAD ion sources from GSI (2008-2009)
- Unstable operation
- Melted components
- First offline RIS results!



Test set-up for the hot cavity catcher

First step wavelength scan vs oven temp

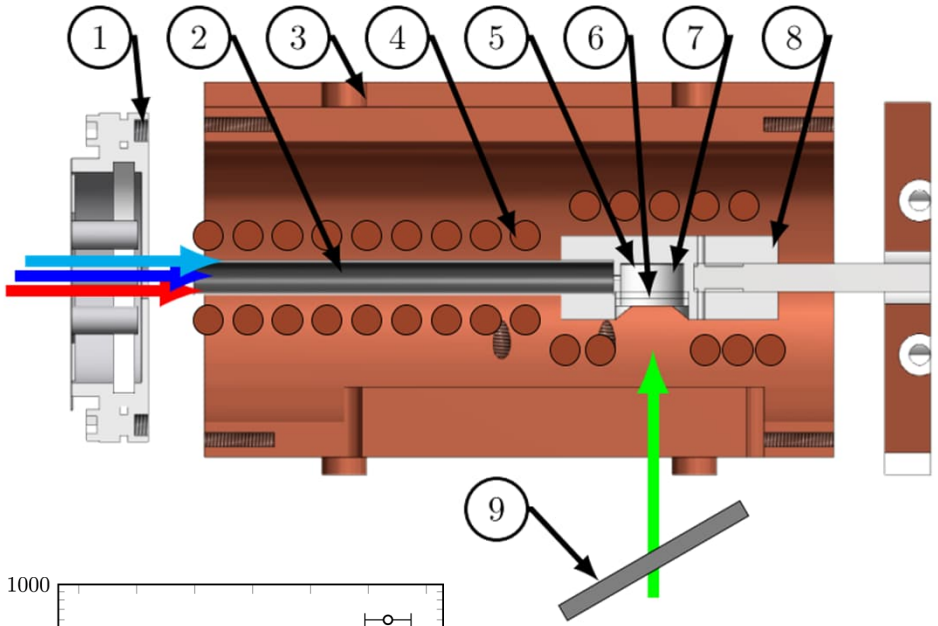


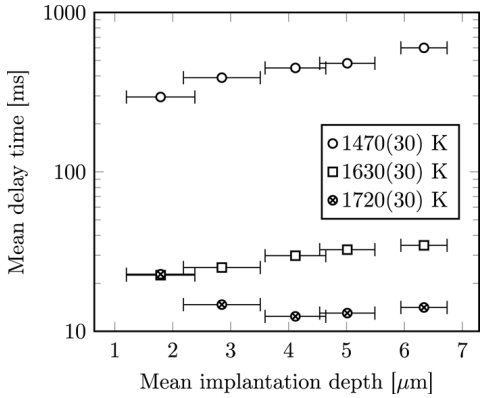
M. Reponen…IM et al., Eur. Phys. J A 42 (2009) 509

Version 2

- Development of RF heating mechanism with JYFL ECR ion source team
- No specific laser interaction region
- Huge energy spread
- Poor efficiency

A few small iterations in the hot cavity design





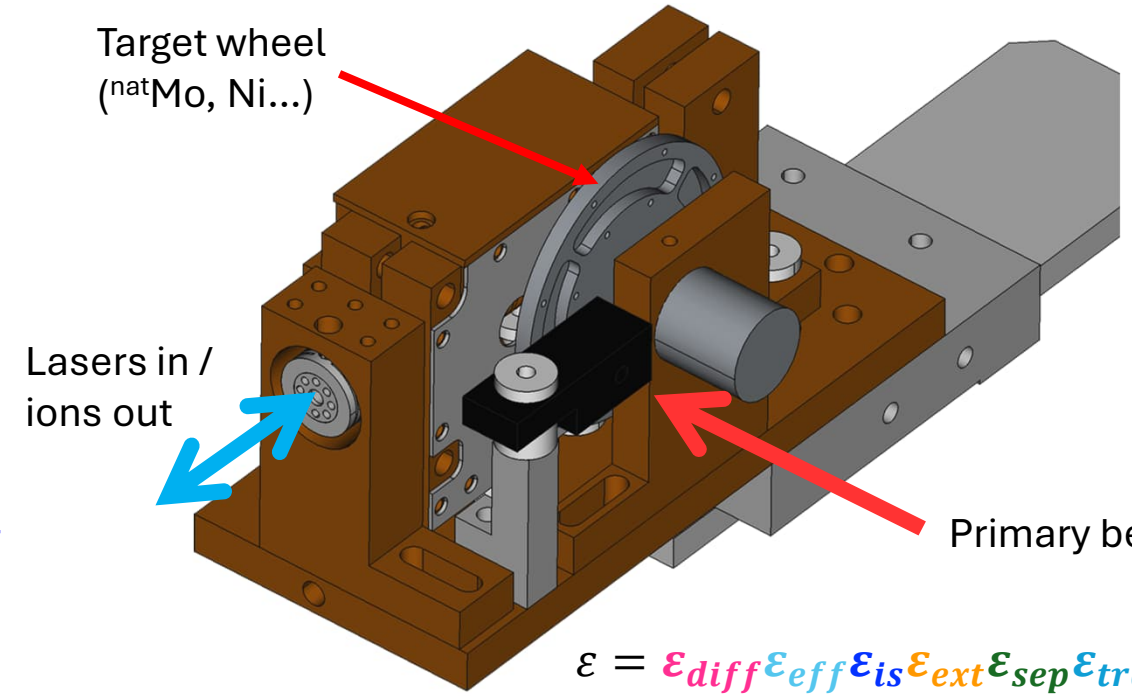
Version 3

- Included a transfer tube for laser ionization – inductively heated
- Demonstrated fast extraction of (implanted) silver

M. Reponen, I.M et al., Rev. Sci. Instrum. 86 (205) 123501

Version 4

- Separate heating mechanisms for the catcher & transfer tube
- Sigradur tubes (glassy carbon)
- First extraction of radioactive ^{99}Ag (half-life 124 s); γ-ray detection



$$\varepsilon = \varepsilon_{diff}\varepsilon_{eff}\varepsilon_{is}\varepsilon_{ext}\varepsilon_{sep}\varepsilon_{trans}$$

~10%

…and then we worked on improving the ion detection…

Penning trap-assisted in-source spectroscopy

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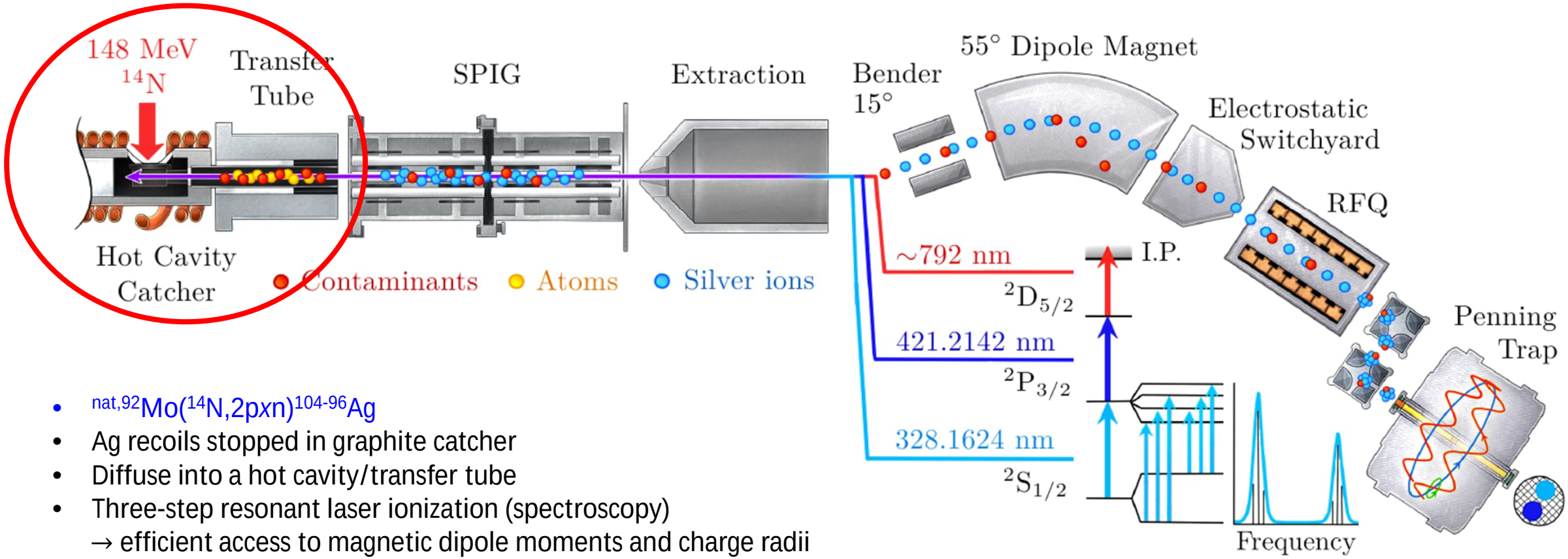
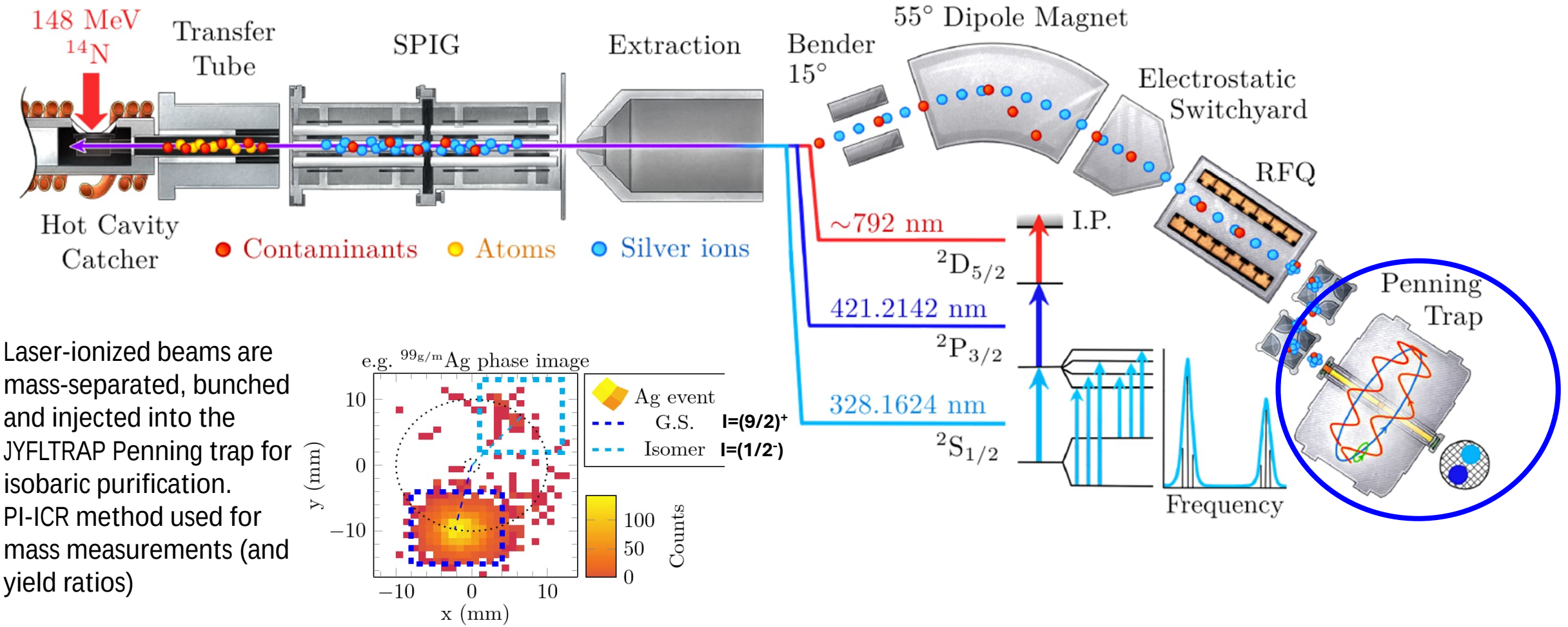
Recent efforts combining methods from ion manipulation and trapping techniques with laser resonance ionization have enabled almost a complete suppression of background, opening a window to the most exotic nuclei.



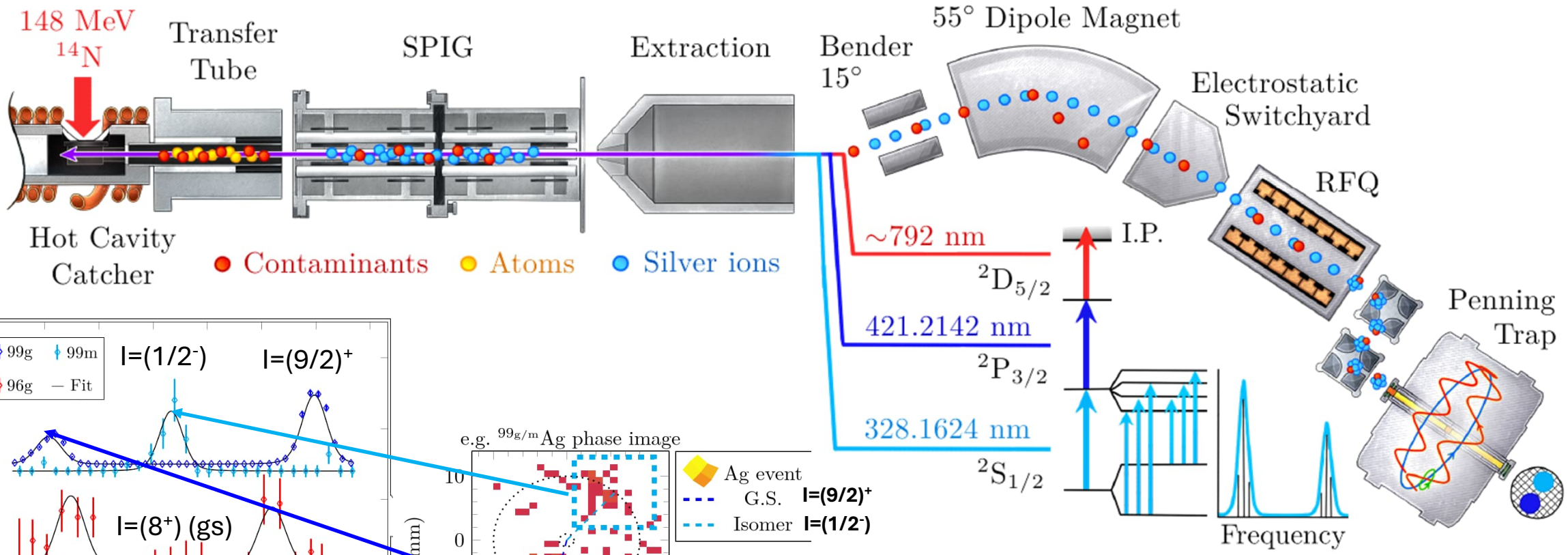
- ^{nat,92}Mo(^{14}N,2pxn)$^{104-96}$Ag
- Ag recoils stopped in graphite catcher
- Diffuse into a hot cavity/transfer tube
- Three-step resonant laser ionization (spectroscopy)
  → efficient access to magnetic dipole moments and charge radii

Penning trap-assisted in-source spectroscopy



- Laser-ionized beams are mass-separated, bunched and injected into the JYFLTRAP Penning trap for isobaric purification.
- PI-ICR method used for mass measurements (and yield ratios)

Penning trap-assisted in-source spectroscopy



- Count ions as a function of laser frequency
- Different gates on detector select different nuclear state
- ^{96}Ag “on resonance” 1 ion per 5 mins.
- Further improvement of ^{96}Ag yield to 1 ion per 25 seconds

M. Reponen et al., Nature Comm. 12 (2021) 4596

Evolution of charge radii across $N = 50$

Recall Lecture 1:

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

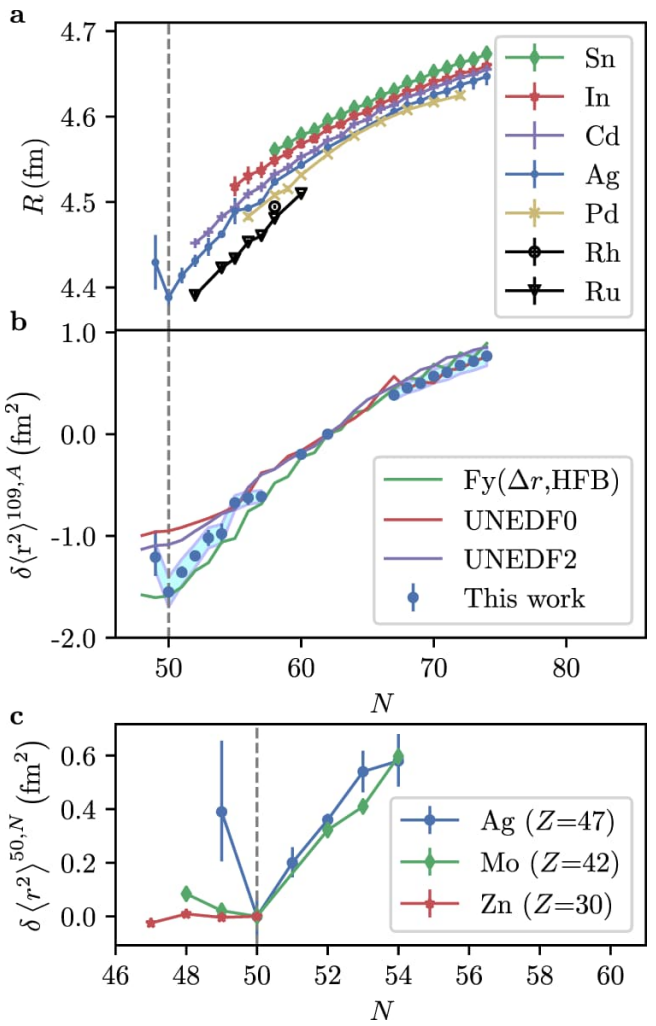
Mass shift — Field shift

THEORY

- A King plot evaluation would be possible if independent radius data (for Ag) is available for at least three different isotopes.
- Ag has only two stable isotopes (A = 107, 109)

Atomic factors *F* and *M* from empirical estimation:

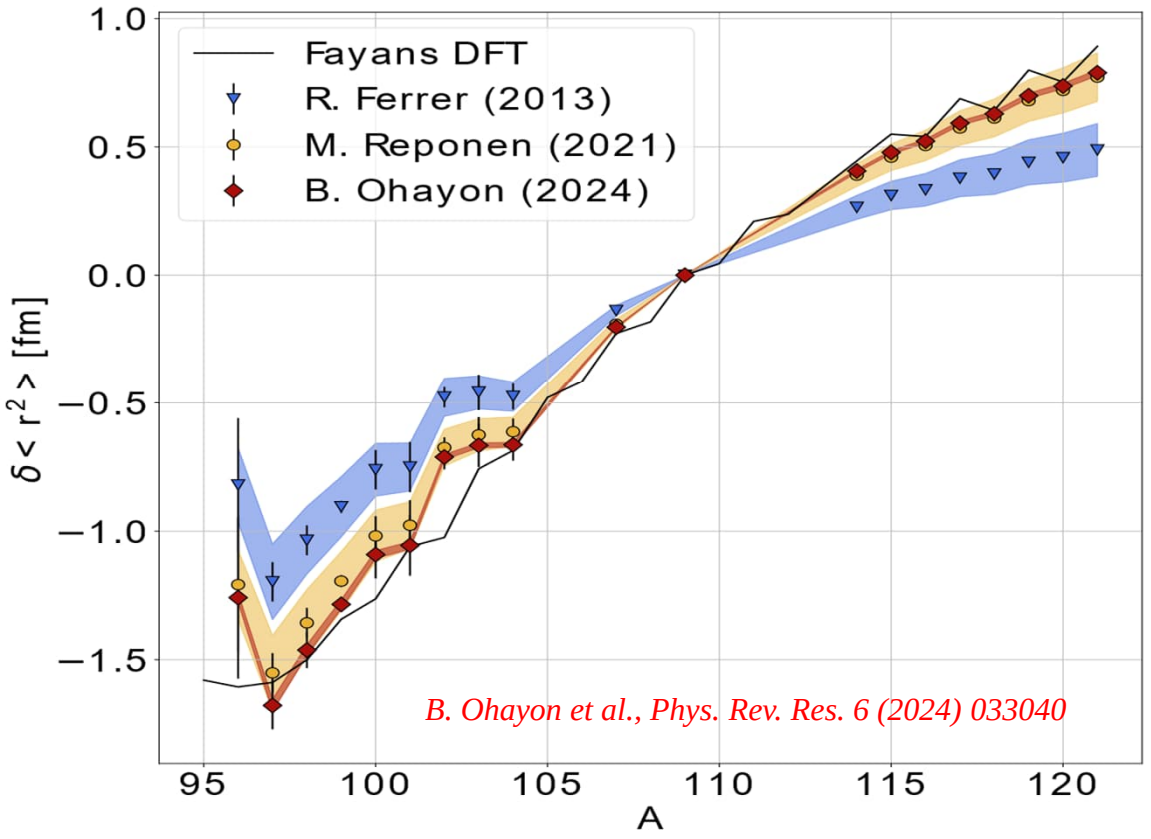
F = -4300(300) MHz fm^{-2}, *M* = 1956(360) GHz u



M. Reponen et al., Nature Comm. 12 (2021) 4596

- Measurements cross *N*=50 shell closure in the region of ^{100}Sn for the first time.
- Energy density functionals (UNEDF) predict a rather smooth behaviour; Fayans EDF better reproduces local variations.
- None of the models reproduces the remarkably sharp increase in crossing *N*=50.

Implication of recent *ab initio* calculations

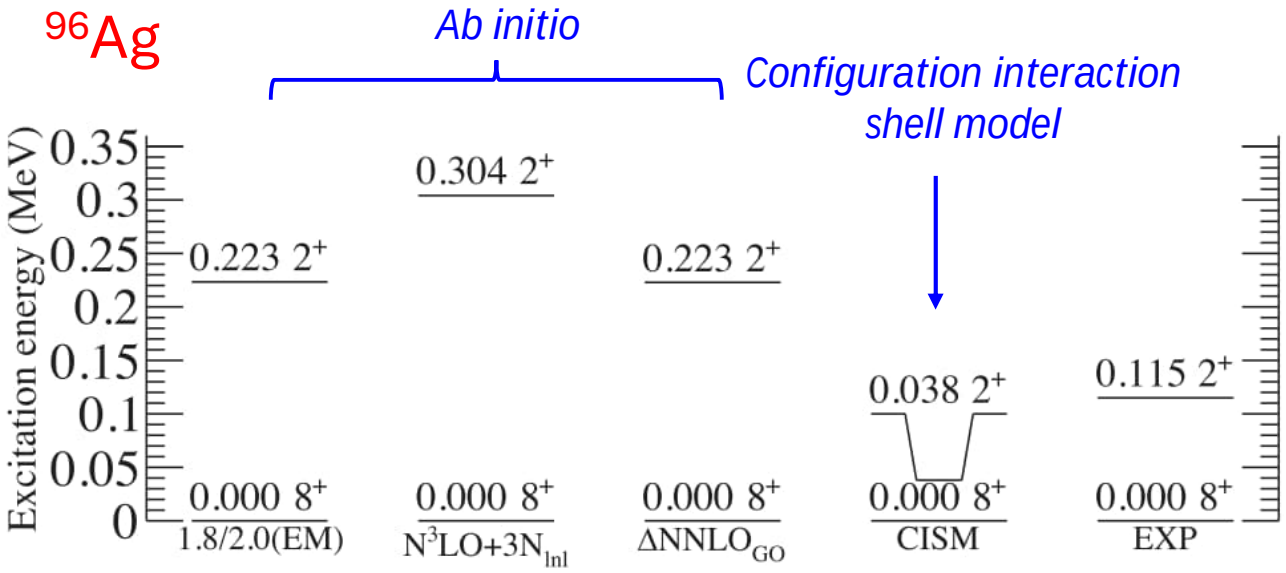


Note the improvement in the uncertainties of the atomic factors (often dominating the extracted charge radii).

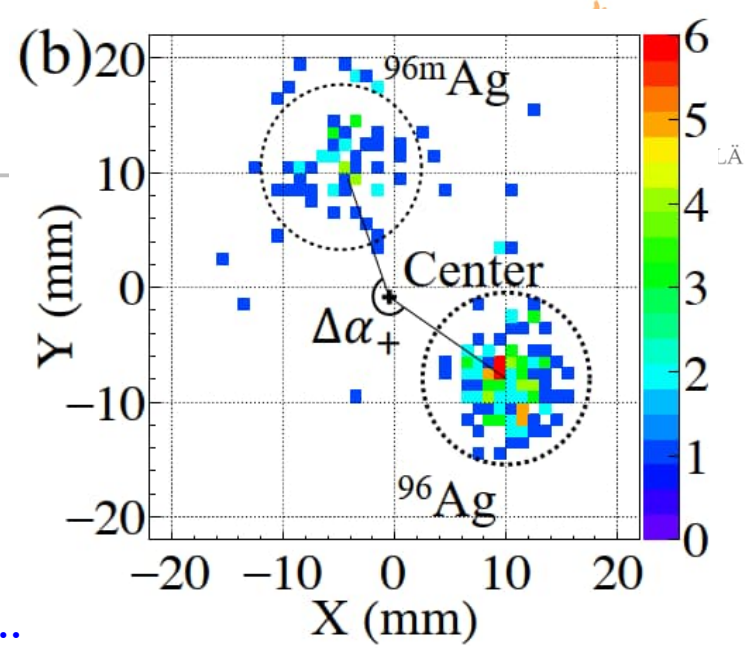
- Ferrer (2013); in-gas cell RIS of Ag on 328-nm line. Atomic factors *F* and *M* from empirical estimation:
- *F* = -4300(300) MHz fm^{-2}, *M* = 821(450) GHz u
- Reponen (2021); in-source hot cavity on 328 nm line Atomic factors *F* and *M* from empirical estimation:
- *F* = -4300(300) MHz fm^{-2}, *M* = 1956(360) GHz u
- Ohayon (2024); analytical response relativistic coupled cluster theory
- F = -3557(49) MHz fm^{-2}, *M* = 1479(14) GHz u
- Skripnikov (2025); somewhat similar calculations to Ohayon
- F = -3634(44) MHz fm^{-2}, *M* = 1318(46) GHz u

Mass measurements beyond $N = 50$

- Probing the robustness of the $N = 50$ shell closure via changes in the slope of S_{2n} (two-neutron empirical shell gap)
- Atomic masses of two β-decaying states identified in ^{96}Ag and measured for the first time
- Atomic mass of ^{95}Ag measured for the first time



Z. Ge et al., Phys. Rev. Lett. 133 (2024) 132503

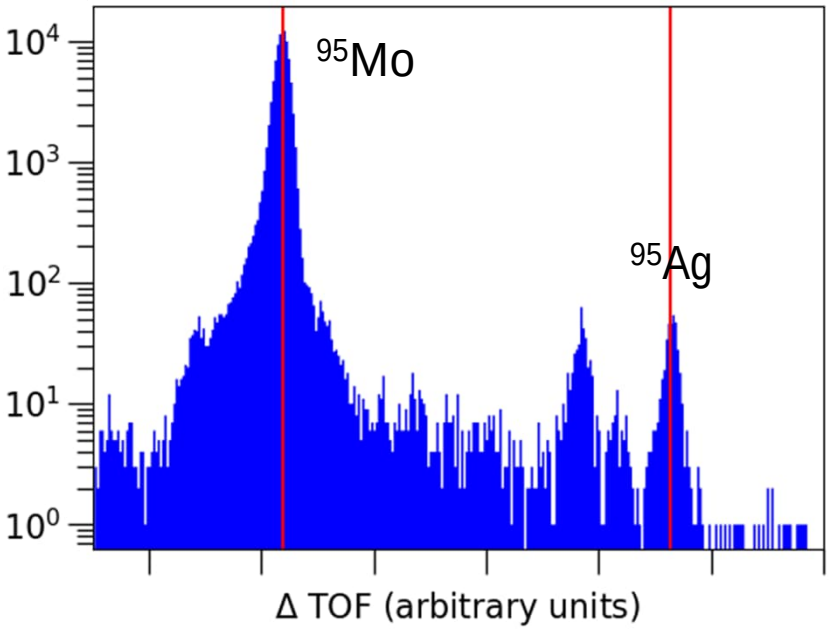


...and in 2023...

MR-TOF Mass Spectrometry of $N = Z$ ^{94}Ag

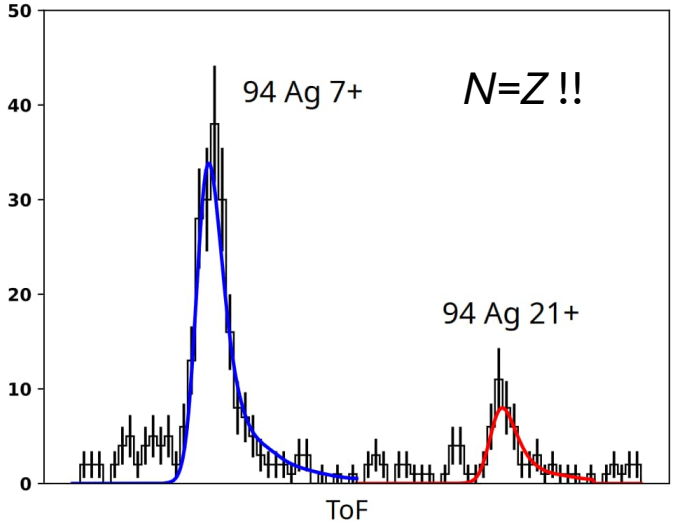
- The reliability of the MR-TOF method was verified with ^{94}Zr and ^{95}Ag (the latter measured at JYFLTRAP to 1.4 keV)
- We also measured the mass of ^{93}Pd* (as well as $N = Z$ ^{92}Pd!!)

*also measured with the FRS Ion Catcher at GSI



Mass precision of ^{95}Ag ~10 keV

V. Virtanen et al., to be submitted to Nature

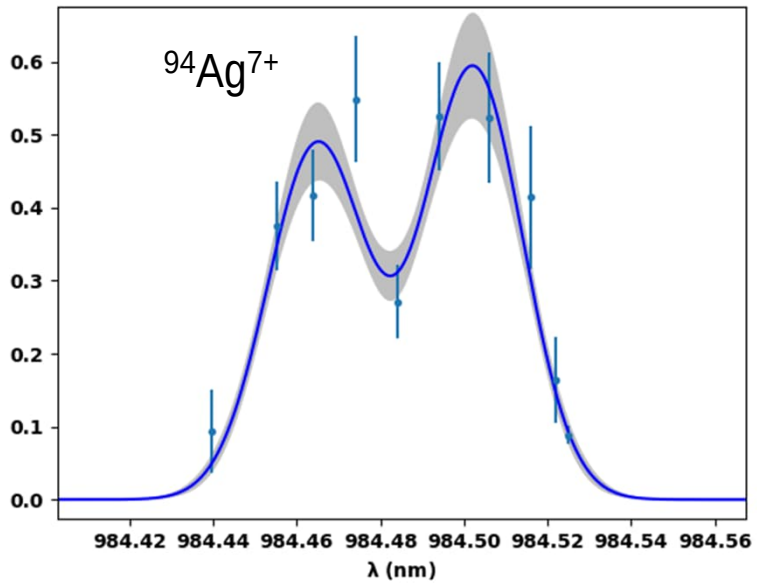


Ion rates

- (7^+) = 0.55 ions/min
- (21^+) = 0.15 ions/min

Mass precision of ^{94}Ag^{21+} ~90 keV

Laser frequency scan



Take home messages and summary

- Many experiments require cooled and bunched beams. RF cooler-bunchers are a staple diet of almost all RIB facilities.

- Mass spectrometry can take many forms, from MR-TOF devices, to Penning traps and also storage rings (the latter not discussed). There is no single ``magic´´ technique that can be considered optimal for the entire range of mass measurement uncertainties and nuclide half-lives.

- Nowadays, the most versatile and powerful techniques for the study of exotic nuclear ground state structure (masses, charge radii, moments & spins) combines all the methods we have been discussing. Selectivity, sensitivity and efficiency....we are now performing mesurements at the extremes of exoticity. And these tools can also be combined with decay spectroscopy stations for laser-assisted, trap-assisted decay spectroscopy ☺.

- The experimental results go hand-in-hand with benchmarking theoretical methods.