JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Mass Measurements of N~Z Nuclei

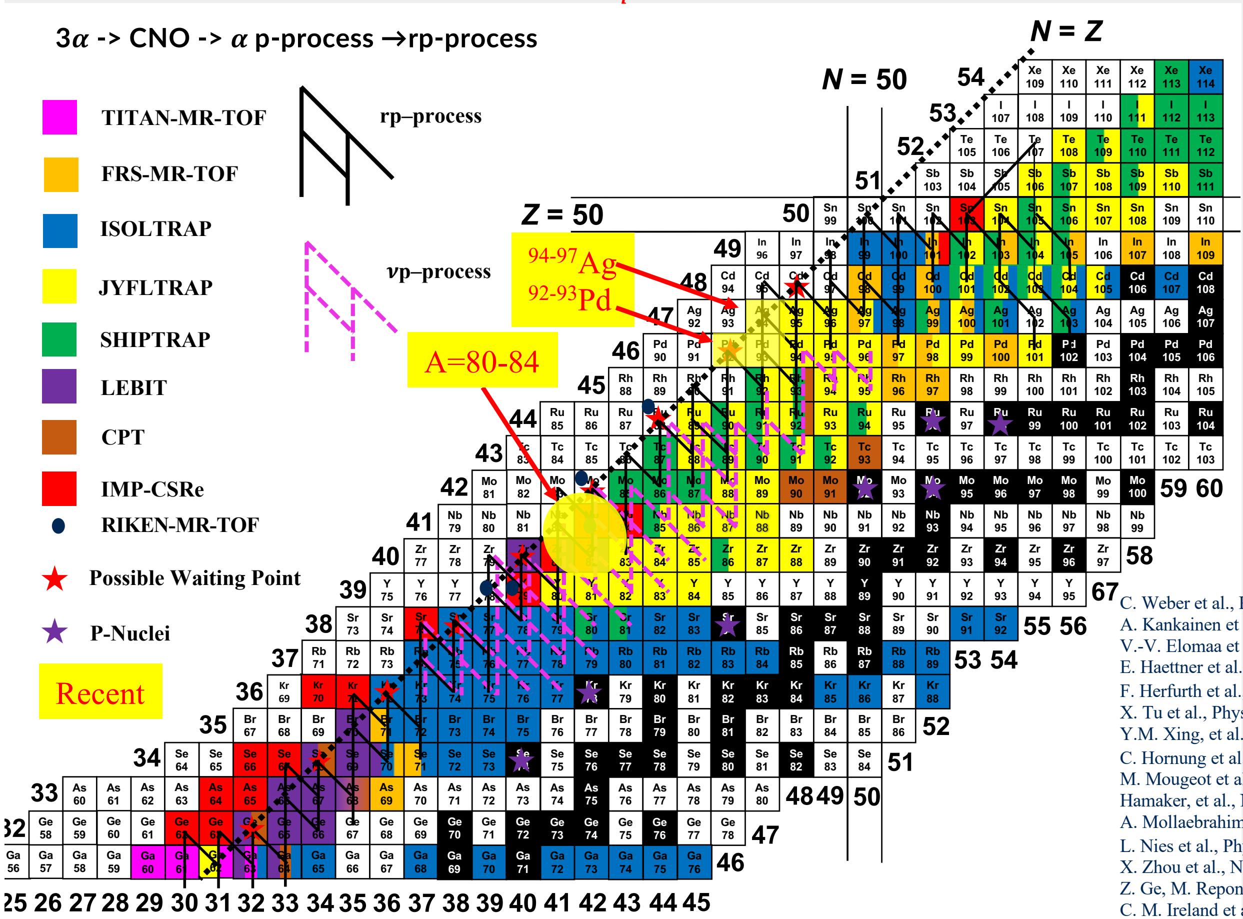
Zhuang Ge

University of Jyväskylä

Motivation

Nuclear mass ↔ nuclear binding energy:

$$M(N,Z) = Z \cdot m_p + N \cdot m_n - B(N,Z)/c^2$$



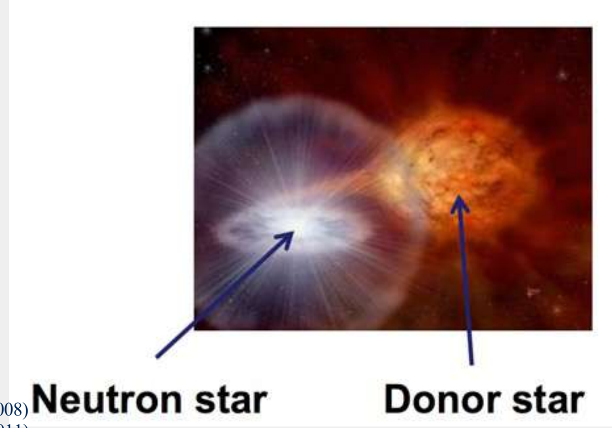
Nuclear Astrophysics

vp-, rp-process
(waiting point, Zr-Nr cycle)
abundance of P-nuclei
($^{92;94}$Mo and $^{96;98}$Ru,^{84}Sr isotopes)

H. Schatz, International Journal of Mass Spectrometry, 251(2–3), 293–299 (2006).

Measurement techniques:

Penning trap
MR-TOF
Storage ring



C. Weber et al., Phys. Rev. C 78, 054310 (2008)
A. Kankainen et al., Phys. Rev. Lett. 101, 142503 (2008)
V.-V. Elomaa et al., Phys. Rev. Lett. 102, 252501 (2011)
E. Haettner et al., Phys. Rev. Lett. 106, 122501 (2011)
F. Herfurth et al., Eur. Phys. J. A, 47,75 (2011)
X. Tu et al., Phys. Rev. Lett. 106, 112501 (2011)
Y.M. Xing, et al., Physics Letters B 781 358–363 (2018)
C. Hornung et al., Physics Letters B 802, 135200 (2020)
M. Mougeot et al., Nature Physics 17, 1099 (2021)
Hamaker, et al., Nat. Phys. 17, 1408–1412 (2021).
A. Mollaebrahimi et al., Physics Letters B 839, 137833 (2023)
L. Nies et al., Phys. Rev. Lett. 131, 022502 (2023)
X. Zhou et al., Nature Physics 19, 1091–1097 (2023)
Z. Ge, M. Reponen, et al., Phys. Rev. Lett. 133, 132503 (2024)
C. M. Ireland et al.,Phys. Rev. C 111, 014314 (2025)
L. Nies et al., Phys. Rev. C 111, 014315 (2025)
S. Kimura et al., arXiv:2504.12639v1
V. Virtanen, M. Reponen, et al. to be submitted

time−scale $\propto e^{(Q/kT)}$ / $A(Q)$
isotope production$\propto A(Q) \cdot e^{(Q/kT)}$
energy production $\propto A(Q) \cdot Q \cdot e^{(Q/kT)}$
Common parameter:
Q (mass difference)

Mass Measurement Techniques of Exotic N~Z Nuclei

Storage Rings

Isochronous MS

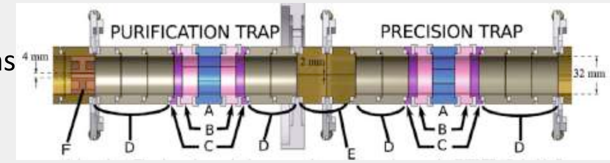
t_{meas} ~ 100 μs
$m/\Delta m = 2{\cdot}10^5$
$\delta m/m \sim 10^{-6}$
broadband
~ 10-200 keV

1. RIKEN/Rare RI Ring

Penning Trap MS (TOF-ICR and PI-ICR-MS)

TOF-ICR MS

t_{meas} ~ 100-1000 ms
$m/\Delta m = 10^6\text{-}10^7$
$\delta m/m < 10^{-7}$
scanning



PI-ICR MS

t_{meas} ~ 100-1000 ms
$m/\Delta m \sim 10^7$
$\delta m/m < 10^{-8}$
broadband

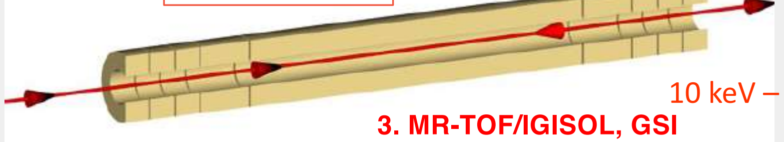
10s eV – 10 keV

2. IGISOL/JYFLTRAP

Multiple-Reflection Time-of-Flight MS (MR-TOF-MS)

t_{meas} ~ 10 ms
$m/\Delta m$ >10^5
$\delta m/m < 10^{-6}$
Broadband

Ville,Timo´ talks

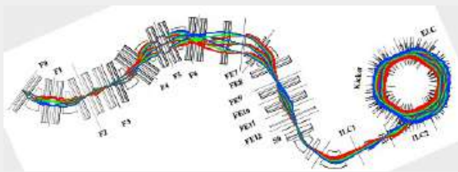


10 keV – 100 keV

3. MR-TOF/IGISOL, GSI

Magnetic-rigidity Time-of-Flight MS

t_{meas} < 1 us
$m/\Delta m \sim 10^4$
$\delta m/m > 10^{-6}$
Broadband



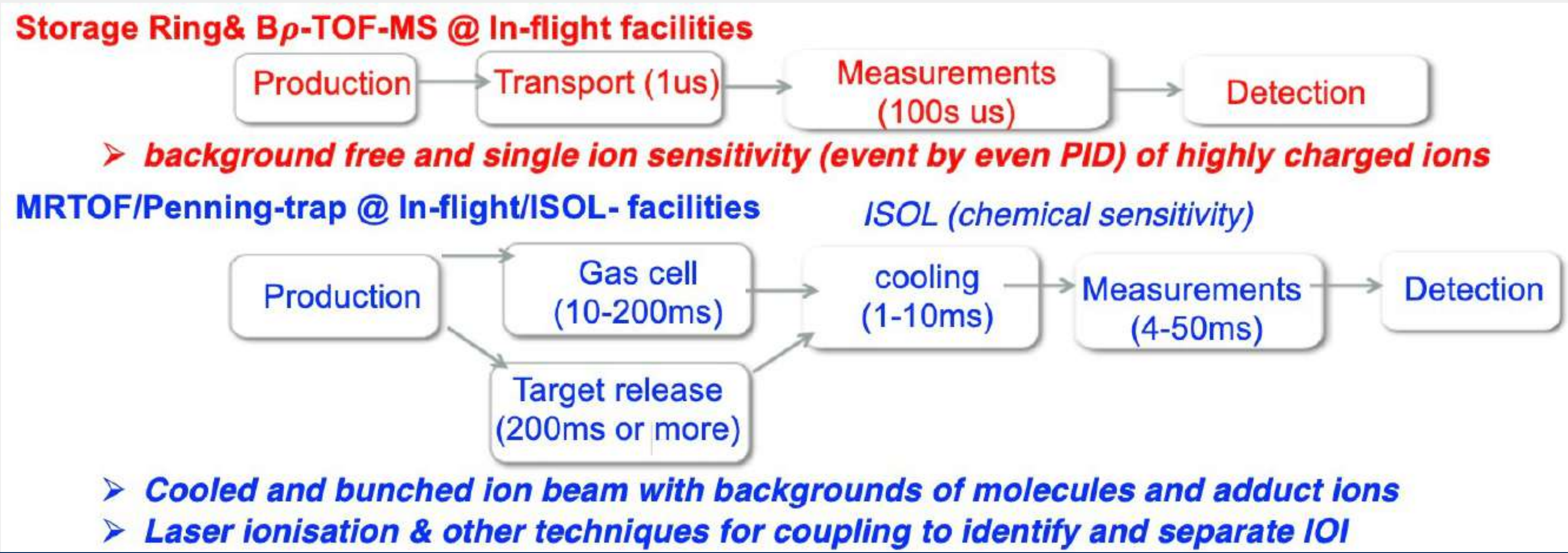
100 keV – 1000 keV

1. RIKEN/BigRIPS-OEDO-SHARAQ

Mass Measurement Techniques of Exotic N~Z Nuclei

Mass spectrometry	time	Precision	m/Δm	Precision	Device example
IMS (Storage Ring)	~100s μs	10^{-6}-10^{-7}	~3×10^{5}	10-200 keV	IMP/RIKEN
Penning Trap (TOF-ICR)	>50 ms	<10^{-7}	~10^{6}	10s eV-few keV	IGISOL/JYFLTRAP
Penning Trap (PI-ICR)	>50 ms	<10^{-8}	~10^{6}-10^{7}	10s eV-few keV	IGISOL/JYFLTRAP
MR-TOF-MS	~10 ms	<10^{-6}	>10^{5}	10-100 keV	IGISOL, GSI
Bρ-TOF-MS	<1 μs	>10^{-6}	~10^{4}	100-1000 keV	RIKEN/BigRIPS-OEDO-SHARAQ

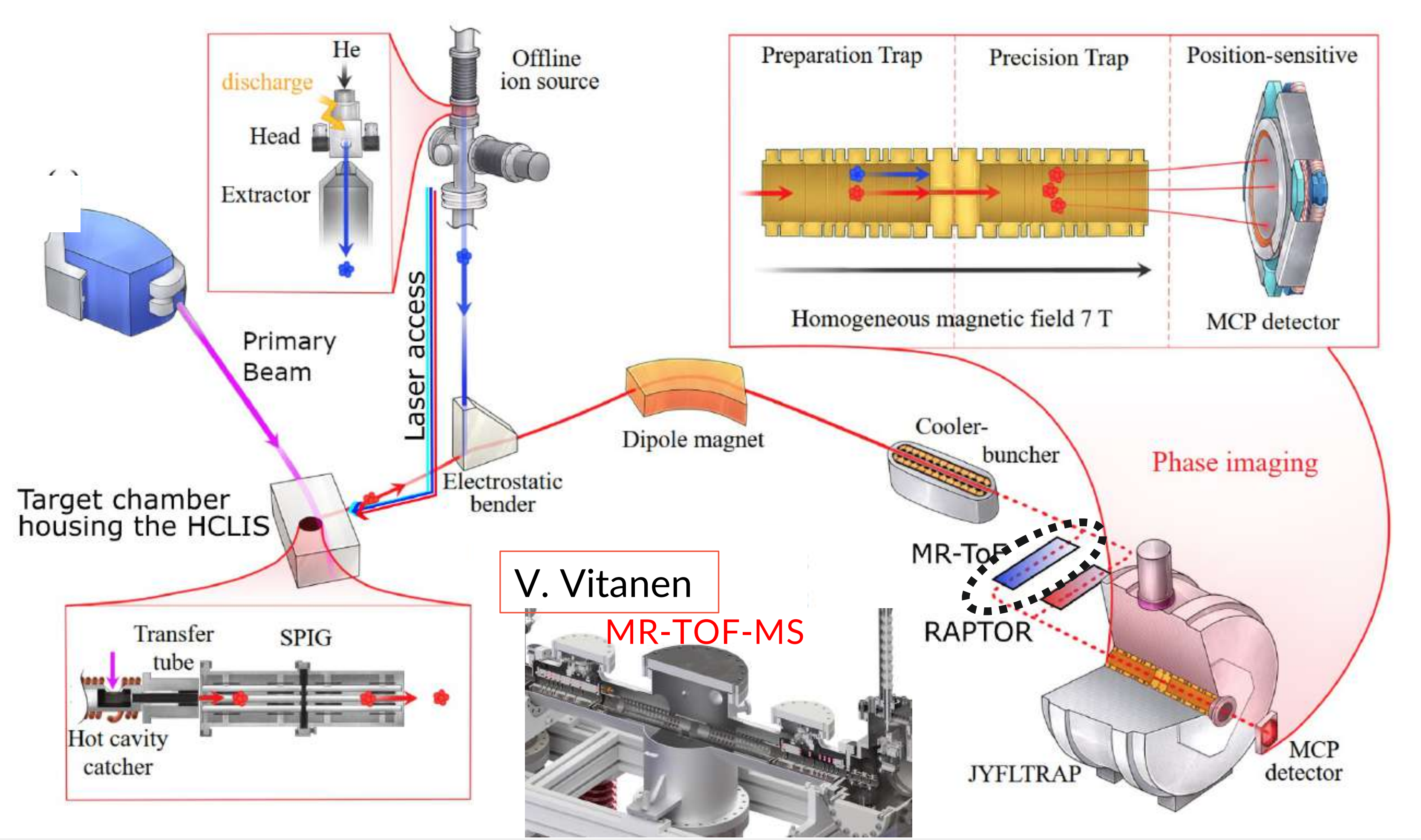
Measurement Schemes



Penning trap and MR-TOF mass spectrometer at IGISOL

T. Eronen et al., EPJA 48 (2012) 46
A. Kankainen et al., Hyperfine Interactions (2020) 241:43

Anu, Arthur`s talk



- Production of N=Z nuclei and the vicinity:
  - Heavy ion induced fusion-evaporation
  - MNT
- Extraction technique:
  - HIGISOL gas cell
  - MNT gas cell
  - Hot cavity

- Production of reference nucleus:
  - Co-produced in Target chamber
  - Sparking ion source
  - Surface ion source
  - Laser ablation ion source

Schematic of PI-ICR for 95Ag mass measurements

Hot cavity& in source Laser ionization
Identification/measurement with PI-ICR

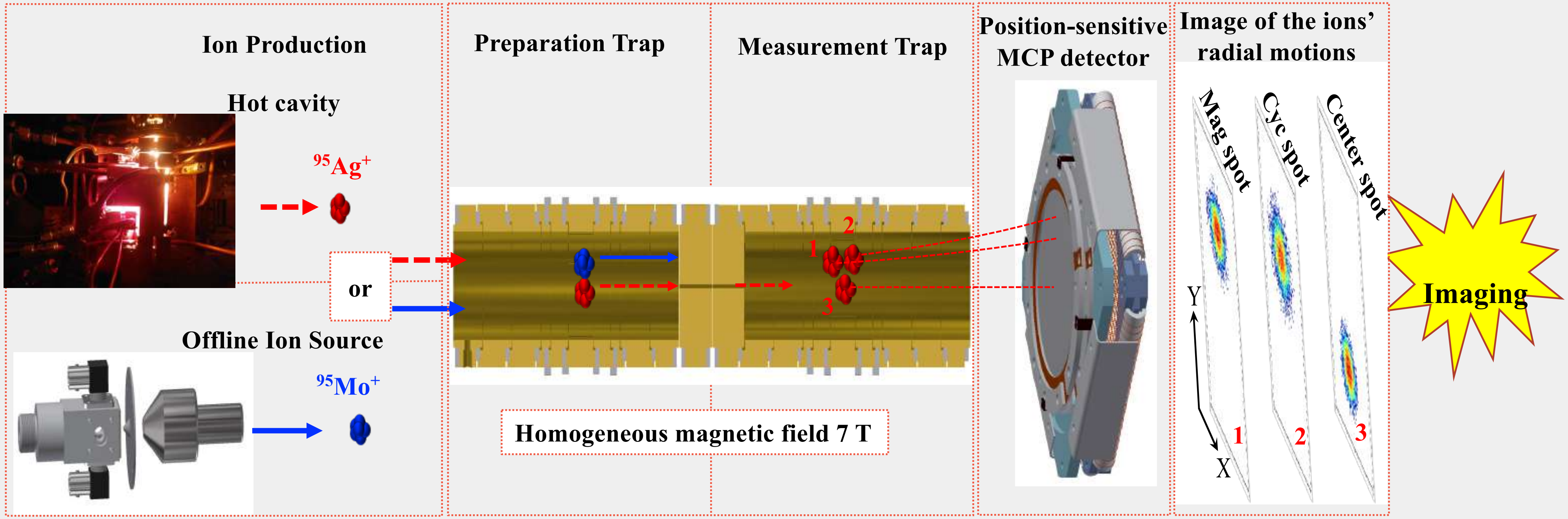
Traps ❤️ Lasers

Angle difference between cyclotron and magnetron motion phases:

$$\alpha_c = \alpha_- + \alpha_+$$

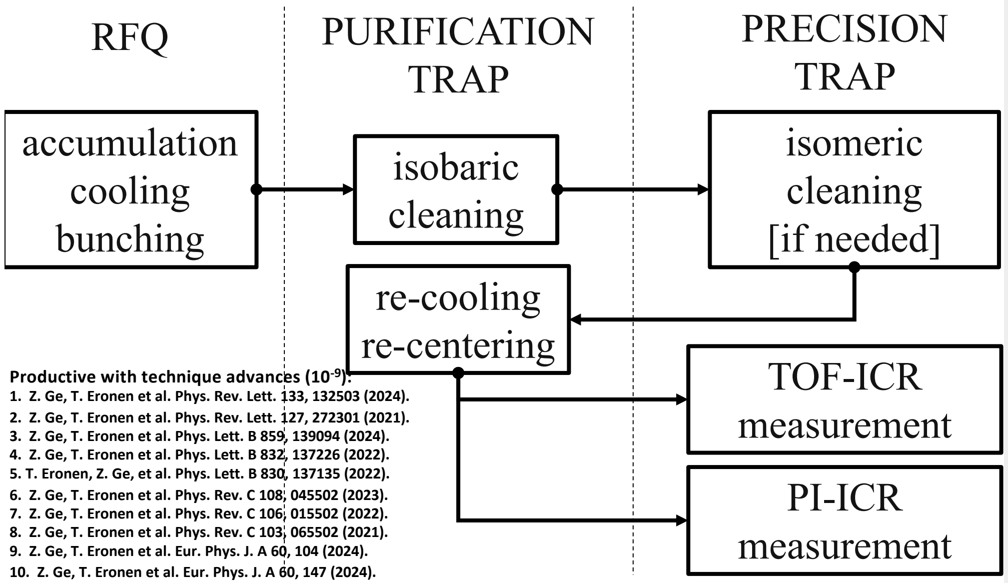
cyclotron frequency:

$$\nu_c = \nu_+ + \nu_- = \frac{\alpha_c + 2\pi n}{2\pi t}$$



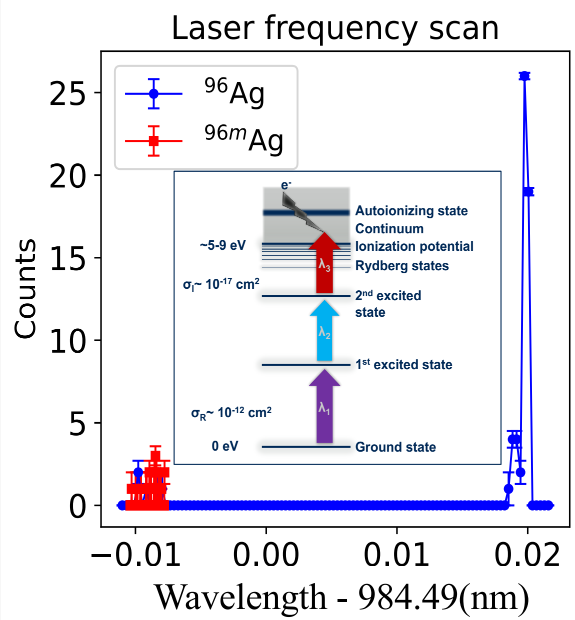
State-of-the-art trap method for purfication of isomers

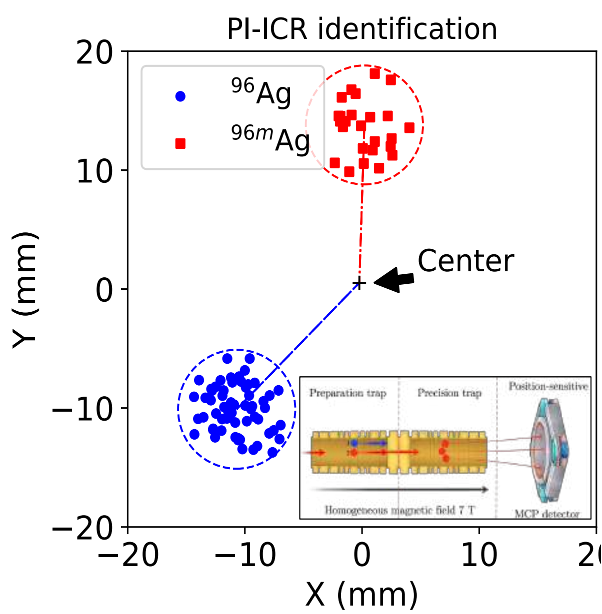
T. Eronen et al., EPJA 48 (2012) 46
Z. Ge, T. Eronen, A. de Roubin et al., Phys. Rev. C 108, 045502 (2023)
Z. Ge, M. Reponen, T. Eronen et al., Phys. Rev. LETTERS 133, 132503 (2024)



Productive with technique advances (10^{-9}):

1. Z. Ge, T. Eronen et al. Phys. Rev. Lett. 133, 132503 (2024).
2. Z. Ge, T. Eronen et al. Phys. Rev. Lett. 127, 272301 (2021).
3. Z. Ge, T. Eronen et al. Phys. Lett. B 859, 139094 (2024).
4. Z. Ge, T. Eronen et al. Phys. Lett. B 832, 137226 (2022).
5. T. Eronen, Z. Ge, et al. Phys. Lett. B 830, 137135 (2022).
6. Z. Ge, T. Eronen et al. Phys. Rev. C 108, 045502 (2023).
7. Z. Ge, T. Eronen et al. Phys. Rev. C 106, 015502 (2022).
8. Z. Ge, T. Eronen et al. Phys. Rev. C 103, 065502 (2021).
9. Z. Ge, T. Eronen et al. Eur. Phys. J. A 60, 104 (2024).
10. Z. Ge, T. Eronen et al. Eur. Phys. J. A 60, 147 (2024).
11. M. Ramalho, Z. Ge, T. Eronen et al. Phys. Rev. C 106, 015501 (2022).





Conatminant-free ion sample preparation (especially isomers):

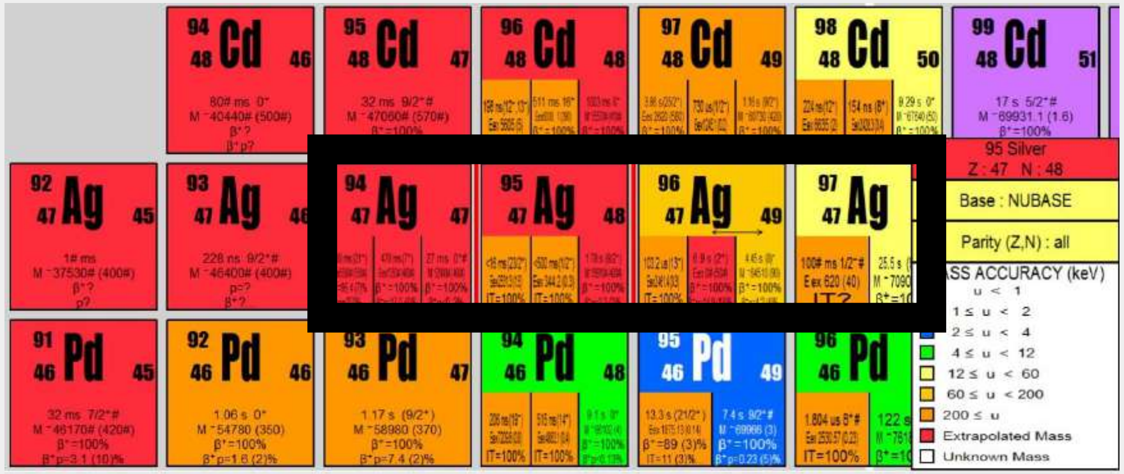
Coupling of Ramsey cleaning&Buffer gas cleaning&laser frequency scan and PI-ICR method for unambiguous cleaning (to reach 10^{-9} precision for exotic cases)

contaminants of <u>90 keV</u> (A =136) away from ion of interest easy to clean, more than 10^6 resolving power to clean 2 or more closely lying contaminants

$^{94\text{-}97}$Ag mass measurements at IGISOL

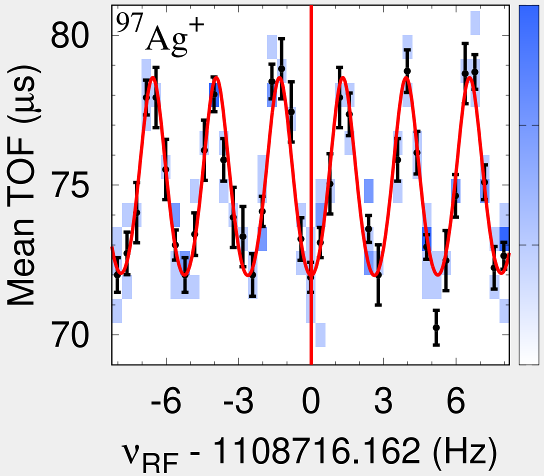
Z. Ge, M. Reponen, et al., Phys. Rev. Lett. 133, 132503 (2024)
T. Eronen et al., EPJA 48 (2012) 46

^{94}Ag:
with MR-TOF
(Ville´ talk)

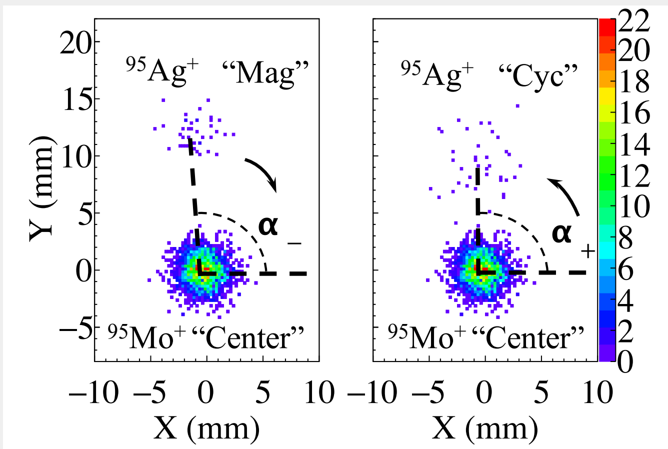


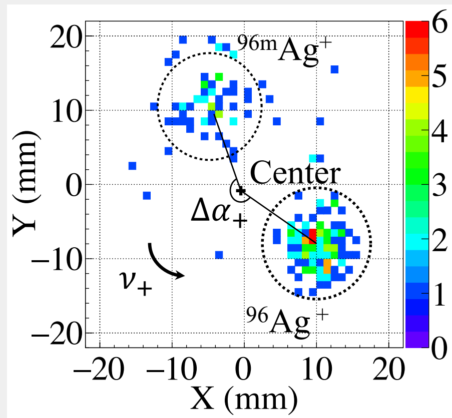
Uncertainty of around 1 keV with Penning Trap

Time-of-Flight Ion-Cyclotron-Resonance (TOF-ICR)



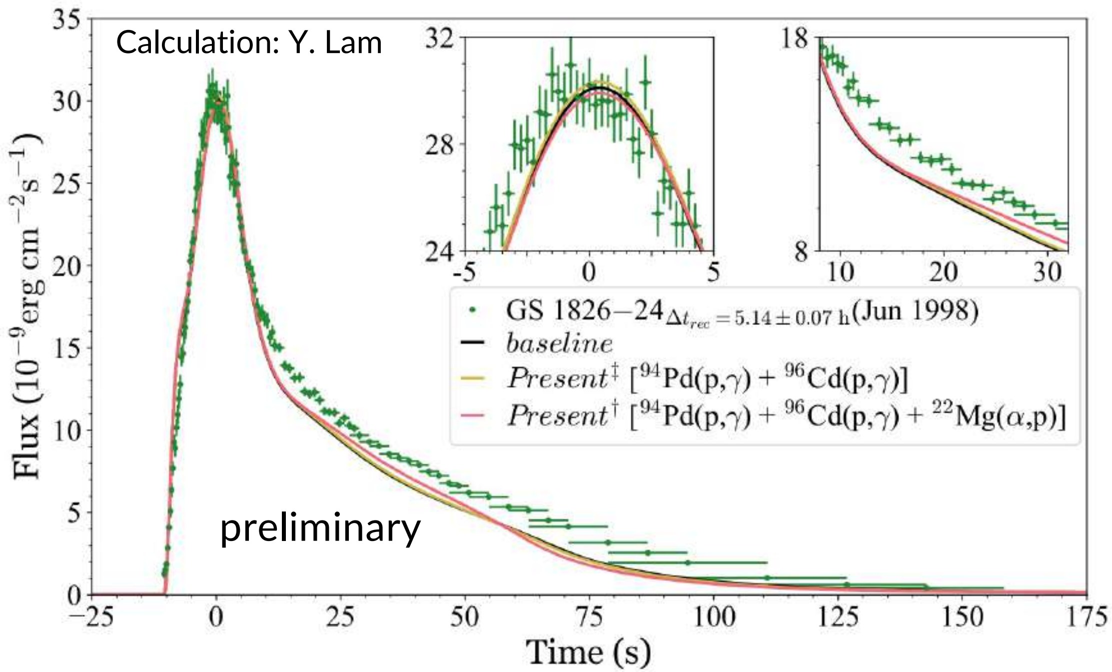
Phase-imaging Ion-Cyclotron-Resonance (PI-ICR)

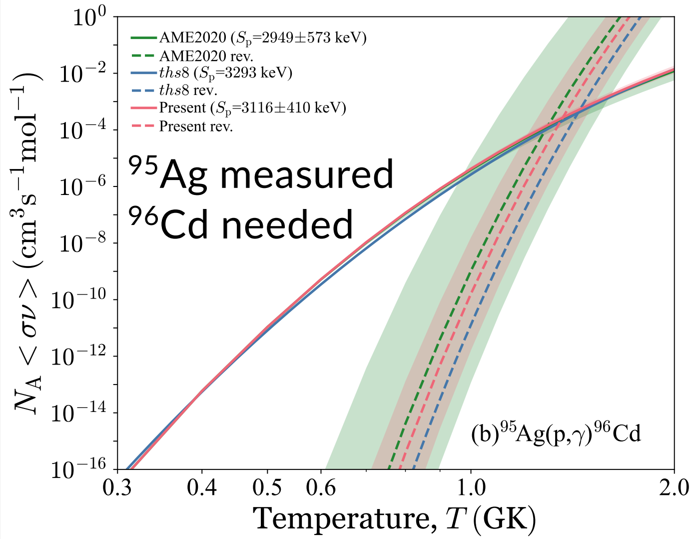


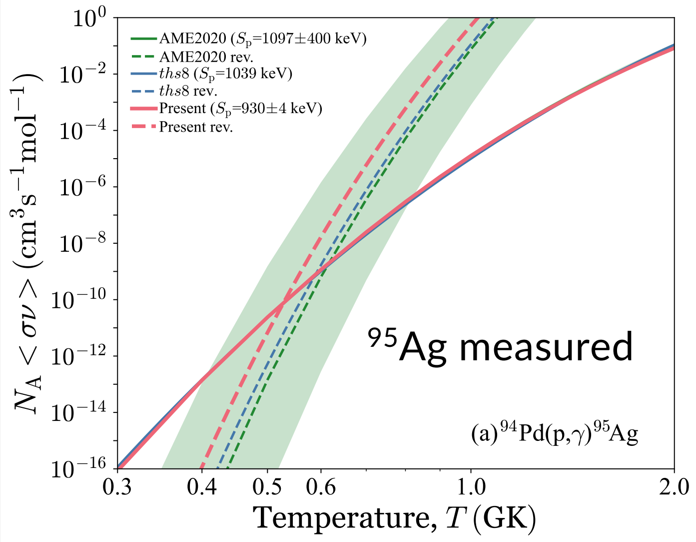


Impacts on the X-ray burst

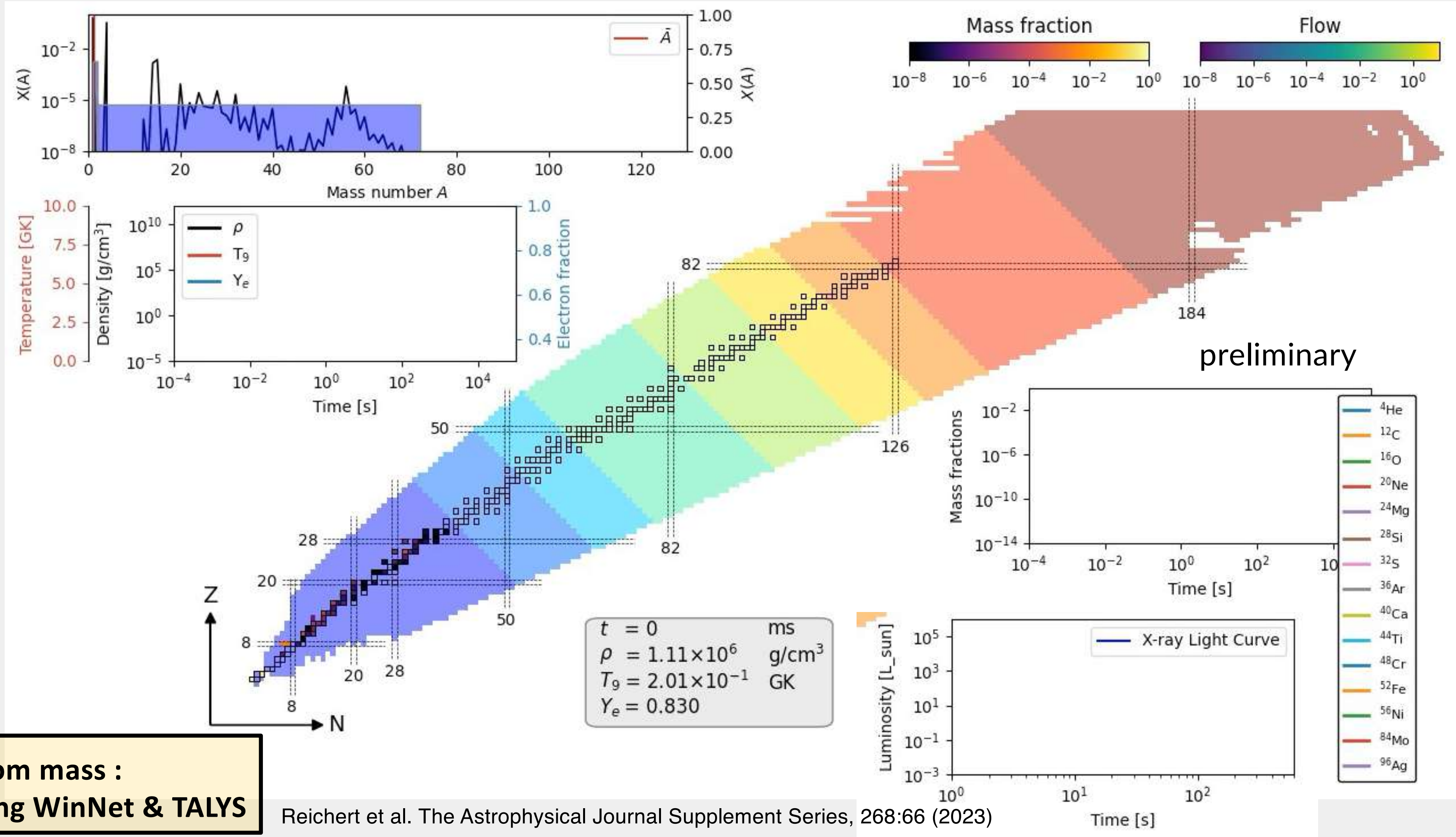
Timescale, isotope&energy production:
Exponential dependence on masses!







rp-process network calculations



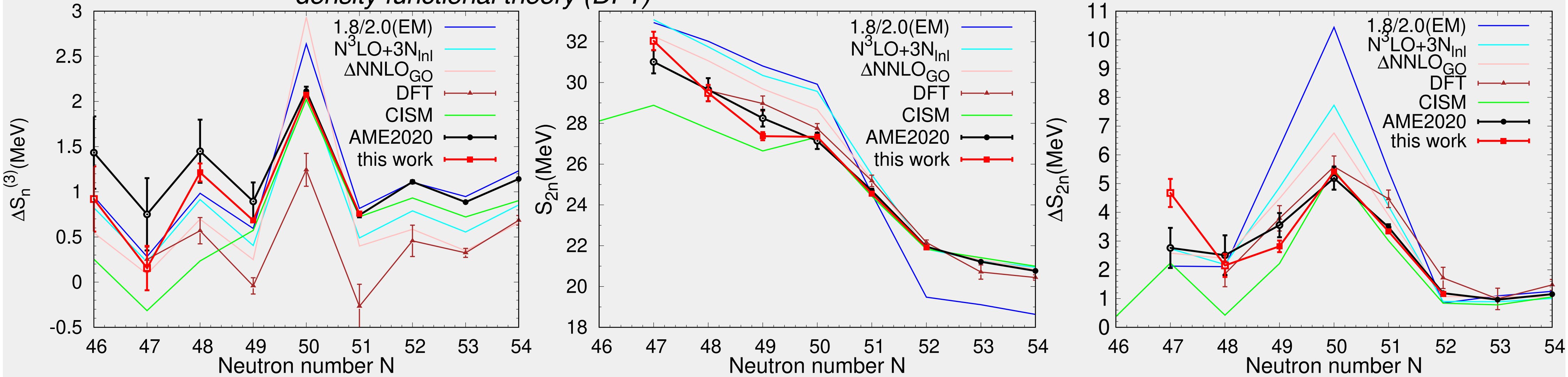
Reichert et al. The Astrophysical Journal Supplement Series, 268:66 (2023)

Impact study from mass :
Calculations using WinNet & TALYS

Benchmark theoretical models and isomer as *"astromer"*

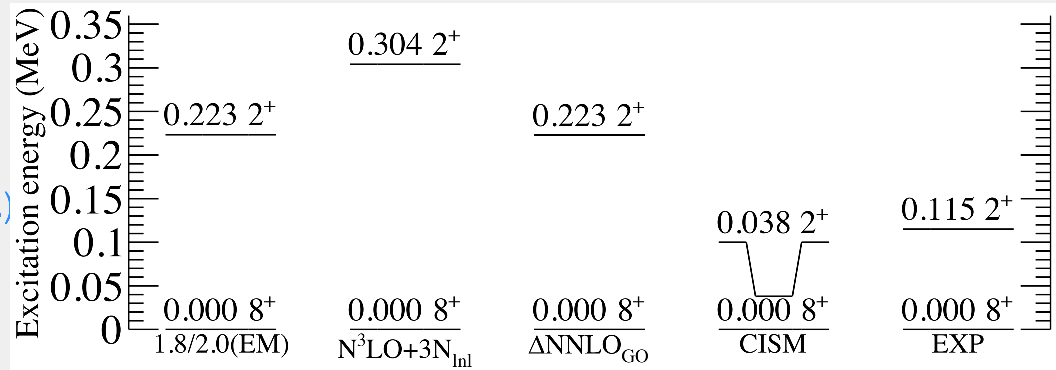
Theory: *ab initio,*
configuration-interaction shell-model (CISM)
density functional theory (DFT)

Z. Ge, M. Reponen, T. Eronen et al., PRL 133, 132503 (2024)
G.W. Misch et al., Eur. Phys. J. Spec. Top. 233, 1075 (2024).



Miikka´s talk ***Possible, astrophysical nuclear isomer, "astromer"***

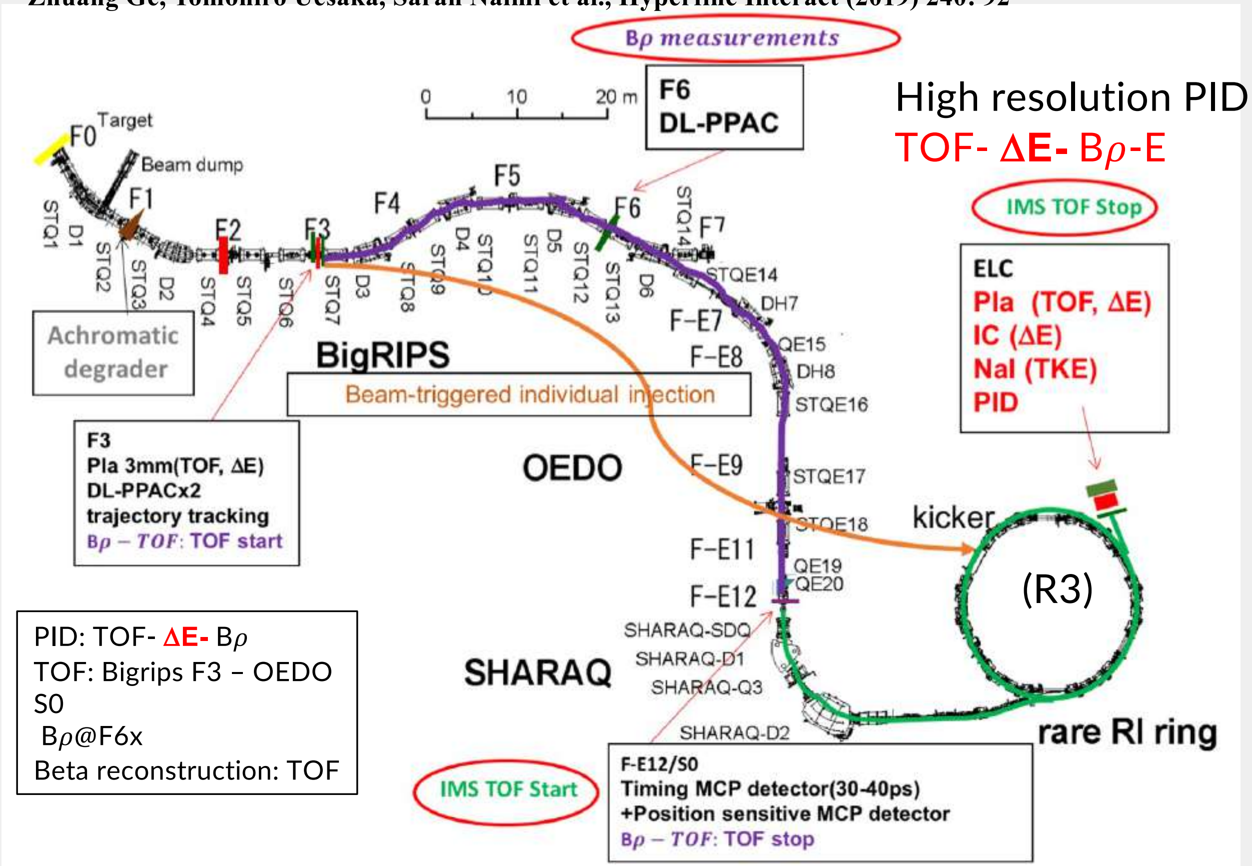
- Identification of **nuclear isomer of ^{96m}Ag,** *"astromer"*
- understanding of the **nuclear structure at N=50 shell**
- **Benchmark** nuclear models and shell model calculations
- **Solve the ^{94}Ag(21^+) 2p/p decay puzzle----in process** (Ville, Mikael et al.)
- **Wigner energy, np-pairing--- other N=Z masses**

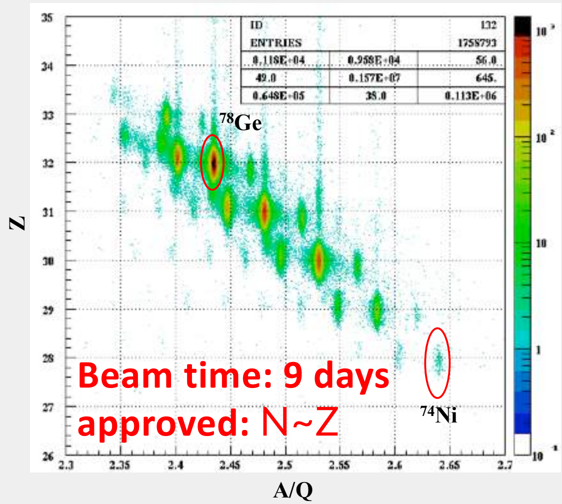


energy level of ^{96}Ag isomeric state

Setup for Mass measurements by Bρ − *TOF* & *IMS* (Isochronous mass spectrometry)

Zhuang Ge, Tomohiro Uesaka, Sarah Naimi et al., Hyperfine Interact (2019) 240: 92





Mass measurements of all N=Z nuclei in one run **(100Sn. 98In, 96Cd….and 93Ag)**
--- ~30 masses in one run

F3-S0 (100s ns):
Efficiency 70-90%
Momentum acceptance ±0.5%
Rare-RI Ring (100s us):
Efficiency 1 %
Momentum acceptance ±0.3%

IMS **(Isochronous mass spectrometry) method.**
Revolution time Correction by beta/ Bρ measurements:

$$\left(\frac{m}{q}\right)_1 = \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-\left(\frac{T_1}{T_0}\beta_1\right)^2}}$$

Mass measurements by **Bρ −** ***TOF*** **, TOF (F3-S0) and Bρ measurements at F6/F5:**

$$\frac{m_0}{q} = \frac{B\rho}{\gamma L/t} = B\rho\sqrt{\left(\frac{t}{L}\right)^2 - \left(\frac{1}{c}\right)^2}$$

Ion optics design (beam-line and storage ring)

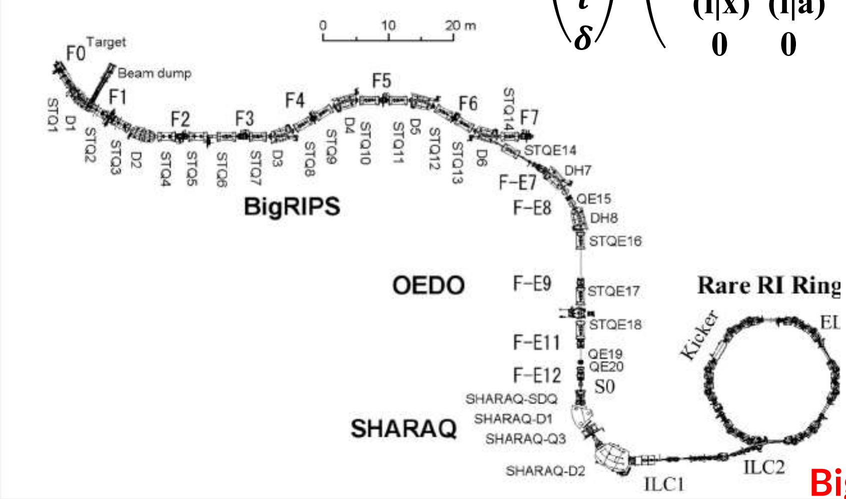
Zhuang Ge et al., Nuclear Physics Review, 2019, 36(3): 294-304 (2019)

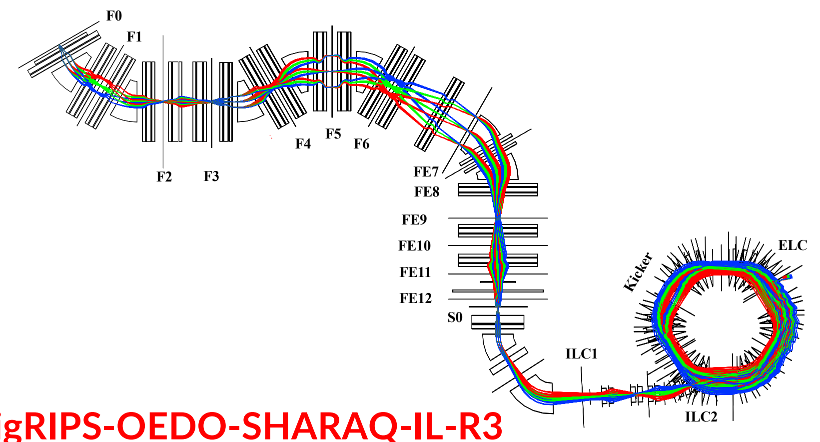
	(x|x)	(x|a)	(a|x)	(a|a)	(y|y)	(y|b)	(b|y)	(b|b)	(x|dp)	(a|dp)	(l|dp)	L|dEk
F3F4	-0.966	0	0	-1.03	-3.88	0	-0.04	-0.26	-1.86	-1.89	4.04	2.187439
F3F5	-0.01	-9.6	0.1	0	1.298	0	-0.06	0.77	0.108	0.505	8.81	4.771546
F3F6	0.965	0	0	1.036	-3.88	0	0	-0.257	7.54	0.368	11.62	6.296793
F3FE7	-0.394	9.7	-0.1	0.016	1.17	-2.386	0.438	-0.039	0.316	-0.803	17.21	9.323857
F3FE9	-0.854	0	-0.14	-0.527	2.67	0	-0.55	0.373	0	0.297	26.94	14.59592
F3S0	2.18	0	0.58	0.46	-2.27	0	0	-0.44	0	0.258	36.09	19.54942
F3ILC1	1.38	-0.58	1.87	-0.06	3.34	0.02	0.76	0.304	-4.15	0.66	44.26	23.98
F3ILC2	-6.18	0	0.83	-0.16	-2.6	0.48	0.476	-0.465	-5.78	-0.66	54.08	29.2974
F3KC	-9.1	1.04	-0.3	-0.07	-2.53	3.71	-0.42	0.22	-7	0	58.43	31.65375

Transfer matrix:

$$\begin{pmatrix} x \\ a \\ y \\ b \\ l \\ \delta \end{pmatrix} = \begin{pmatrix} (x|x) & (x|a) & 0 & 0 & 0 & (x|\delta) \\ (a|x) & (a|a) & 0 & 0 & 0 & (a|\delta) \\ 0 & 0 & (y|y) & (y|b) & 0 & 0 \\ 0 & 0 & (b|y) & (b|b) & 0 & 0 \\ (l|x) & (l|a) & 0 & 0 & 1 & (l|\delta) \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ a_0 \\ y_0 \\ b_0 \\ l_0 \\ \delta_0 \end{pmatrix}$$

Dispersion matching technique





BigRIPS-OEDO-SHARAQ-IL-R3

Isochronous design for all N=Z nuclei

Zhuang Ge, Tomohiro Uesaka et al., Hyperfine Interact (2019) 240: 92

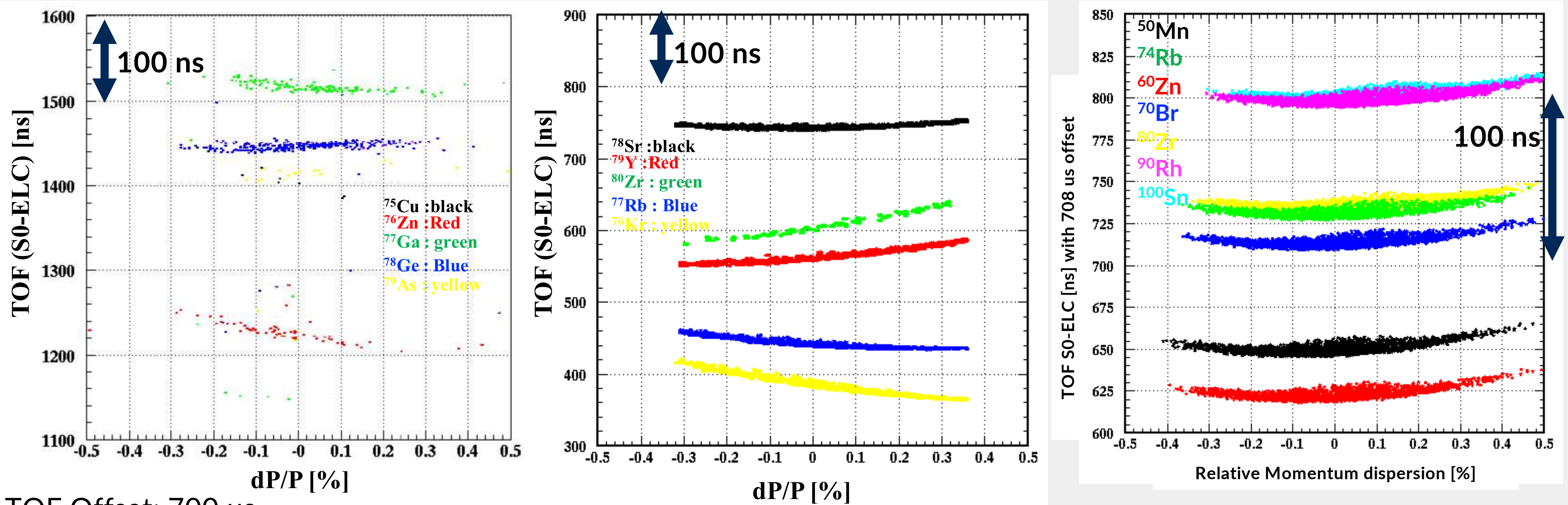
Isochronous optics not on N=Z nuclei

Online

simulation

Isochronous on N=Z nuclei

simulation



TOF Offset: 700 us

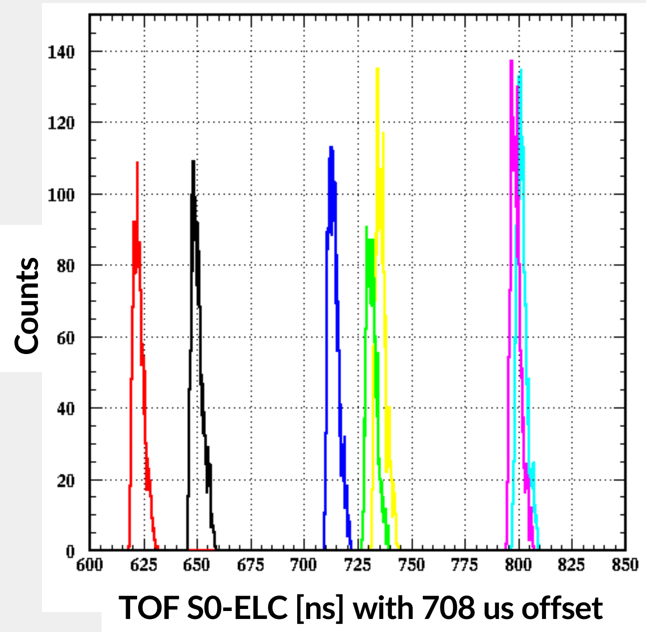
Only One ion species has isochronous condition

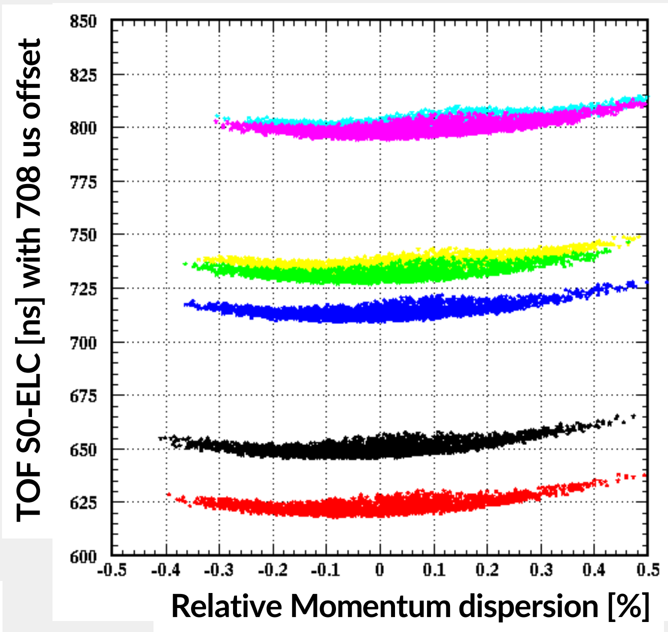
All N=Z nuclei ion species has isochronous condition

N=Z simulation (Z=25-50): all in isochronous in same setting

Varying the Dipole and degrader settings only,
Keeping settings from F3 to ELC
All N=Z is in isochronous condition

Simulation starting from F3





^{50}Mn
^{74}Rb
^{60}Zn
^{70}Br
^{80}Zr
^{90}Rh
^{100}Sn

Mass measurements of all N=Z nuclei <u>in one run</u> **(100Sn. 98In, 96Cd….and 93Ag)----approved proposal at RIKEN RIBF**

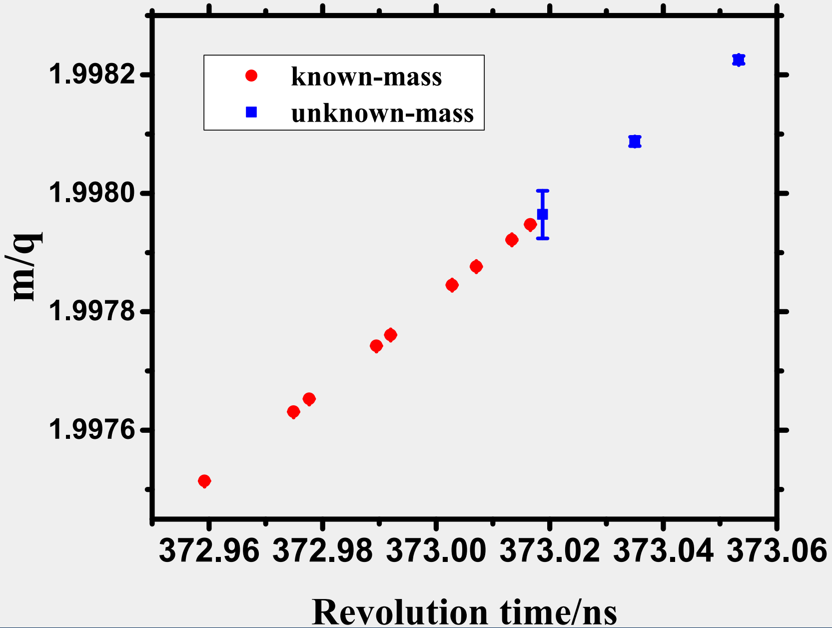
Mass Determination

1. Masses of bare ions

$$m = m_a - Zm_e + B_e(Z)$$

$$B_e(Z) = 14.4381 Z^{2.39} + 1.55468 \times 10^{-6} Z^{5.35} [eV]$$

2. Mass Calibration



Polynomial Fit:

$$\frac{m}{q}(T) = \sum_{i=0}^{k} a_i T^i.$$

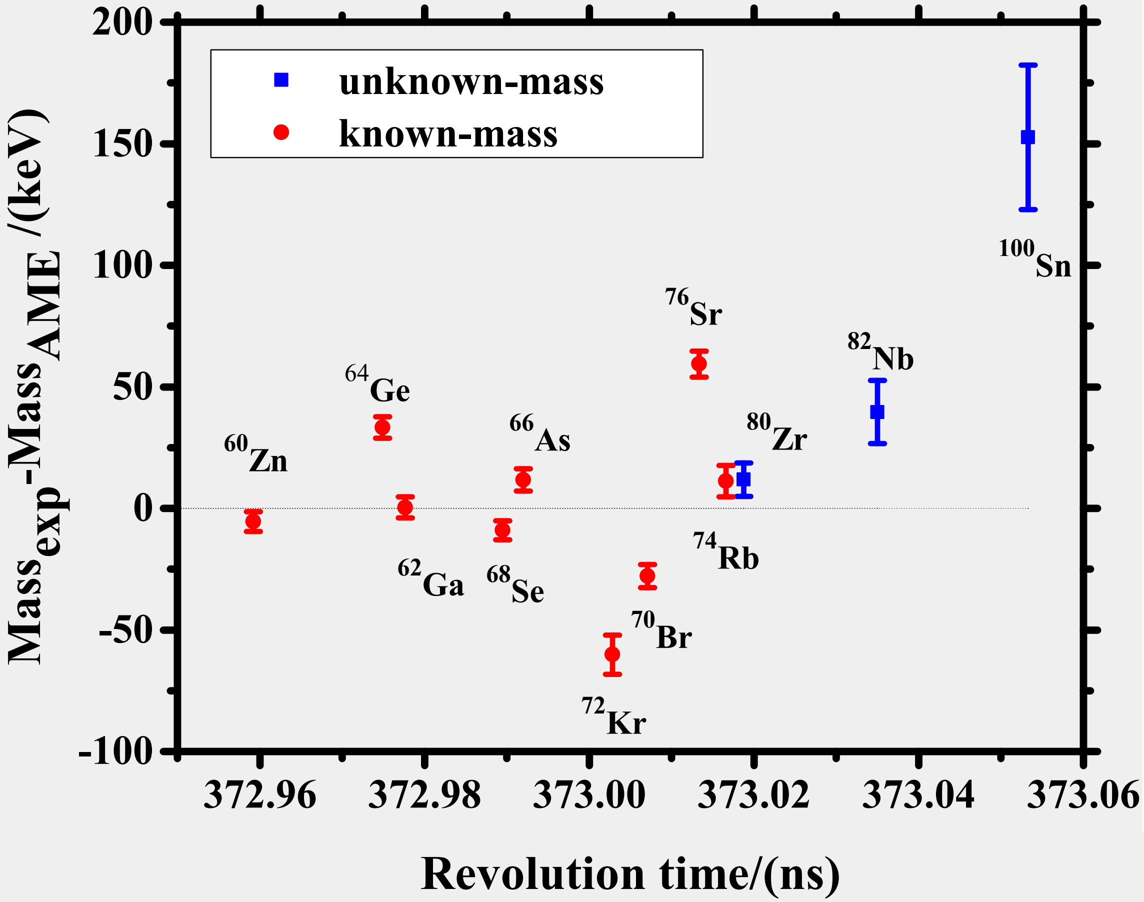
Least square method:

$$\chi^2 = \sum_{i=1}^{n} \frac{\left[\left(\frac{m}{q}\right)_i - \sum_{j=0}^{k} a_j T_i^j\right]^2}{\sigma_i^2\left(\frac{m}{q}\right) + \sigma_{meas,i}^2\left(\frac{m}{q}\right)}$$

$$\boxed{\mathcal{A} = (\mathcal{T}^t \mathcal{P} \mathcal{T})^{-1} \mathcal{T}^t \mathcal{P} \mathcal{M}}$$

Mass calibration results

employ the Hyper-EMG method to improve



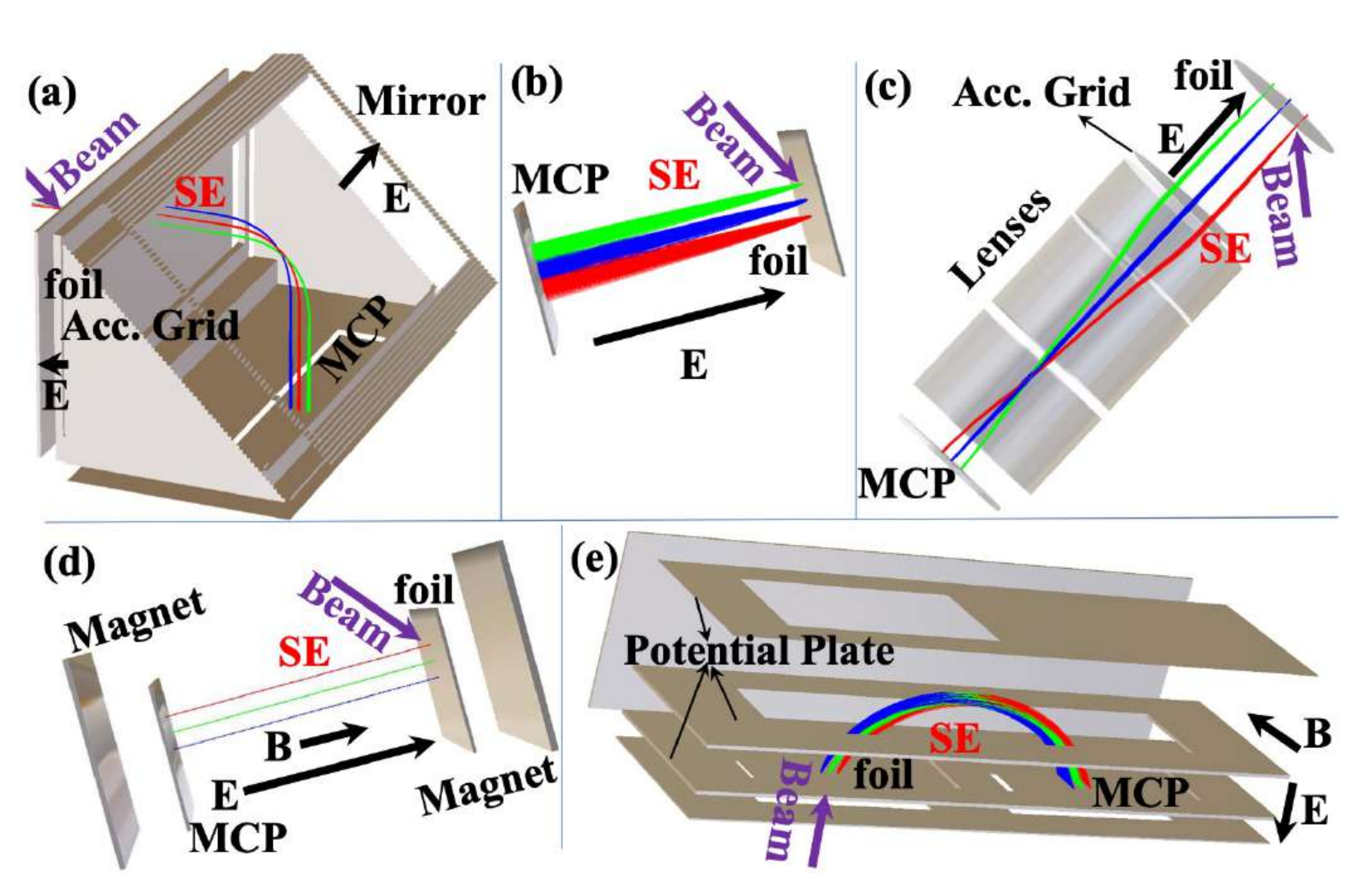
Nuclide	ME(exp-AME) (keV)	ME(exp) (keV)	Error(exp) (keV)	Error(AME) (keV)
^{60}Zn	-5.363	-54179	4.040	0.6
^{70}Br	-28.157	-51453	4.749	14.9
^{74}Rb	11.067	-51905	6.510	3.0
^{72}Kr	-60.596	-54001	8.022	8.0
^{76}Sr	59.119	-54189	5.331	34.5
^{62}Ga	0.077	-51986	4.359	0.7
^{64}Ge	32.909	-54283	4.424	3.7
^{66}As	14.322	-52011	4.557	5.7
^{68}Se	-9.476	-54199	3.965	0.5
^{80}Zr*	11.772	-55505	6.858	1490.4
^{82}Nb*	40.336	-52160	12.989	298.0
^{100}Sn*	155.250	-57127	29.737	301.5

Foil-MCP detectors for mass measurements

Designed for $B\rho - \mathrm{TOF}$ at beam line & $B\rho - \textit{IMS technique with one detector}$ for storage ring

Ge, Z. Sensors 24, 7261 (2024)

~1mm x-y 2D position resolution, ~50 ps timing resolution

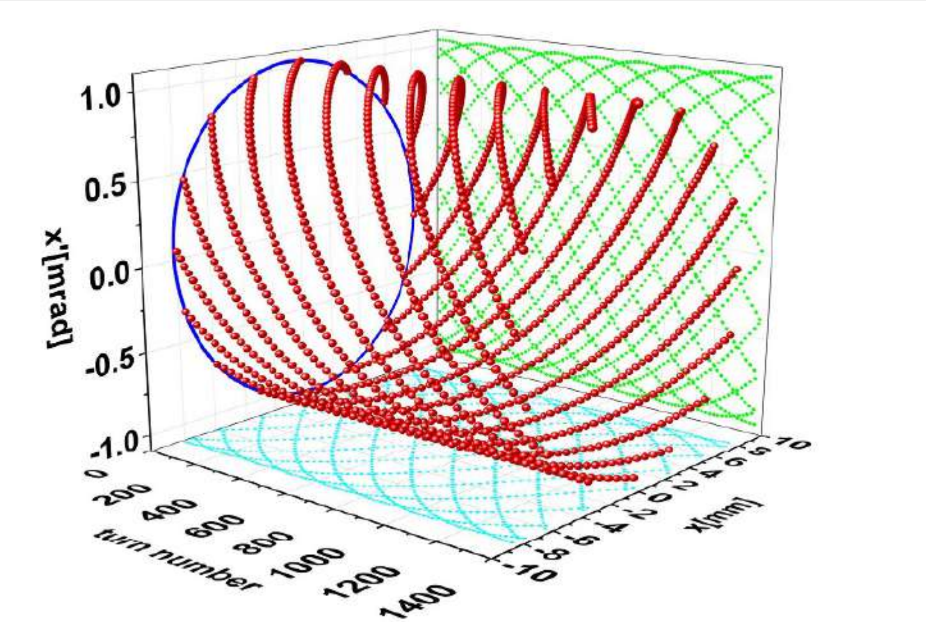


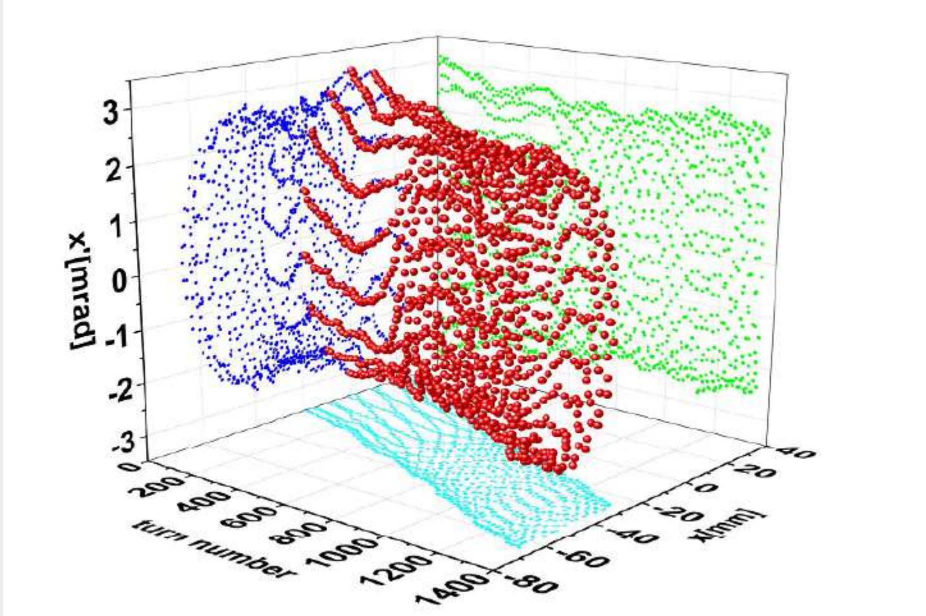
Schematic overview of the foil-MCP detectors:
(a) Mirror-type electrostatic
(b) Direct projection electrostatic
(c) Electrostatic-lens
(d) Magnetic field and electrostatic field parallelly arranged
(e) Magnetic field and electrostatic field crossly arranged
The trajectory of the SEs are from simulations

To improve efficiency and resolving power: employed for MR-TOF and Penning Trap

Simulation of detection of ions circulating in Ring
(phase space of XX' as a function of turn number)

$B\rho - IMS\ technique\ with\ one\ detector$ for storage ring





- *No energy loss detector in ring (like Position-sensitive Schottky)*
- *40 µg/cm² carbon foil MCP detector (matter angular and energy staggling in)*

Monitoring of ion's lateral position and angular distribution by in-ring detector with/without energy loss

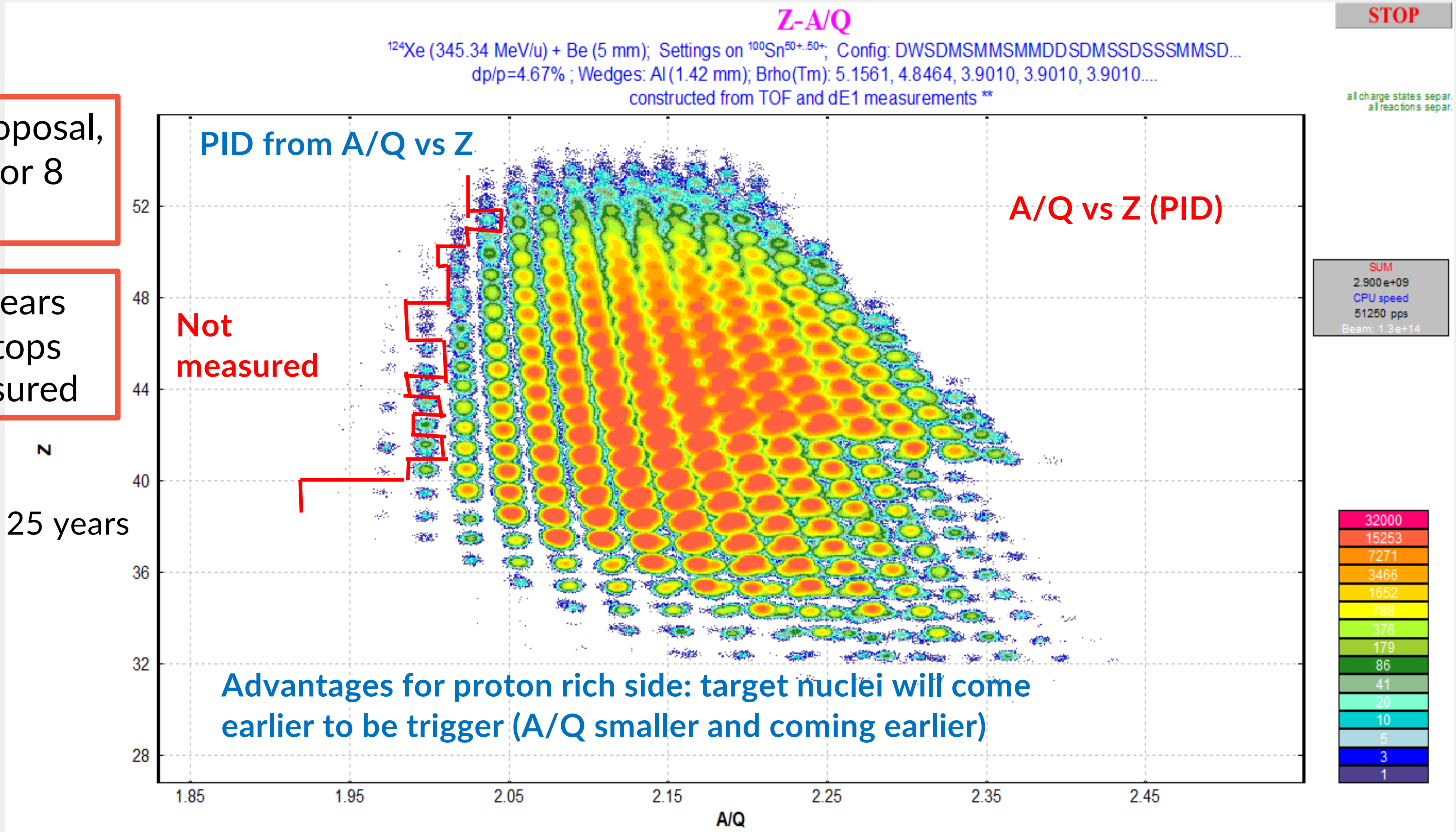
Scanning the chart of nuclides for mass measurements

Measure all N=Z with IMS & $B\rho - \boldsymbol{TOF}$ methods in one exp run

Approed proposal, Pending for 8 years

In last 8 years many isotops were measured

Plans for next 25 years



N~Z mass measurements outlook

- Mass measurements with **hot cavity + MR-TOF/Penning trap (published)**
  - ✓ Mass measurements of ground states and isomers of other N~Z nuclei: $^{95\text{-}97}Ag$, ^{96m}Ag
- Mass measurements with **hot cavity + MR-TOF/Penning trap**
  - ✓ Mass measurements of ground states and isomers of other N=Z nuclei by fusion evaporation reactions at IGISOL with MR-TOF:
    - ^{94}**Ag 21^{+} and 7^{+}** isomeric states, $^{92\text{-}93}$**Pd** (Ville, Mikael et al.)
- Mass measurements with HIGISOL gas cell + MR-TOF: **A=80-84** Area (measured by RIKEN)
  - ✓ **N~Z A=80-84** Area (try again with Penning Trap later)
- Mass measurements with HIGISOL/MNT gas cell + Penning Trap, approved proposals
- Mass measurements with Rare RI Ring and BigRISP-OEDO-SHARAQ @ RIKEN (8 years pending, next 25 years´ plan)
- Other collaboration efforts: FRS ion catcher @ GSI
- **Further combine the measurements to study the Influence of masses on rp-process and νp-process**

✓ Published

✓ Recent campaigns

Plans

Collaboration

Z. Ge,[1,2,*] Mikael Reponen,[1,†] T. Eronen,[1] Y. H. Lam,[3,4] B. S. Hu,[5] S. Nikas,[1] D. A. Nesterenko,[1] A. Kankainen,[1] O. Beliuskina,[1] L. Cañete,[1,6] R. de Groote,[1,7] C. Delafosse,[1,8] P. Delahaye,[9] T. Dickel,[2,10] A. de Roubin,[7] S. Geldhof,[1,7] W. Gins,[1] A. Heger,[11,12,13,14] J. D. Holt,[5,15] M. Hukkanen,[1,8] A. Jaries,[1] A. Jokinen,[1] Á. Koszorús,[16,17] G. Kripko-Koncz,[10] S. Kujanpää,[1] I. D. Moore,[1] A. Ortiz-Cortes,[1] H. Penttilä,[1] D. Pitman-Weymouth,[1] W. Plaß,[2,10] A. Raggio,[1] S. Rinta-Antila,[1] J. Romero,[1] M. Stryjczyk,[1] M. Vilen,[1,17] V. Virtanen,[1] X. F. Yang,[18] C. X. Yuan,[19] and A. Zadvornaya[1]

[1] *Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014, Jyväskylä, Finland*
[2] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[3] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China*
[4] *School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
[5] *TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada*
[6] *University of Surrey, Department of Physics, Guildford GU2 7XH, United Kingdom*
[7] *KU Leuven, Instituut voor Kern- en Stralingsfysica, B-3001 Leuven, Belgium*
[8] *Centre d'Etudes Nucléaires de Bordeaux Gradignan, UMR 5797 CNRS/IN2P3 - Université de Bordeaux, 19 Chemin du Solarium, CS 10120, F-33175 Gradignan Cedex, France*
[9] *GANIL, CEA/DSM-CNRS/IN2P3, Bd Henri Becquerel, 14000 Caen, France*
[10] *II. Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Gießen, Germany*
[11] *School of Physics and Astronomy, Monash University, Vic 3800, Australia*
[12] *OzGrav-Monash - Monash Centre for Astrophysics, School of Physics and Astronomy, Monash University, Vic 3800, Australia*
[13] *Center of Excellence for Astrophysics in Three Dimensions (ASTRO-3D), School of Physics and Astronomy, Monash University, Vic 3800, Australia*
[14] *Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, MI 48824, USA*
[15] *Department of Physics, McGill University, Montréal, QC H3A 2T8, Canada*
[16] *Oliver Lodge Laboratory, Oxford Street, University of Liverpool, Liverpool, L69 7ZE, United Kingdom*
[17] *Experimental Physics Department, CERN, CH-1211 Geneva 23, Switzerland*
[18] *School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[19] *Sino-French Institute of Nuclear Engineering and Technology,*

IGISOL Group

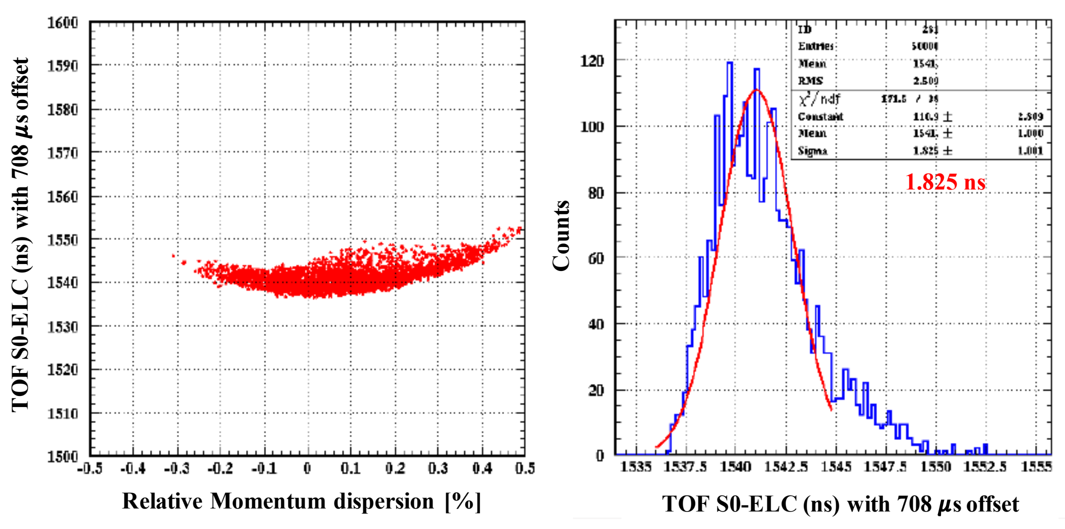
Thank you

for your attention

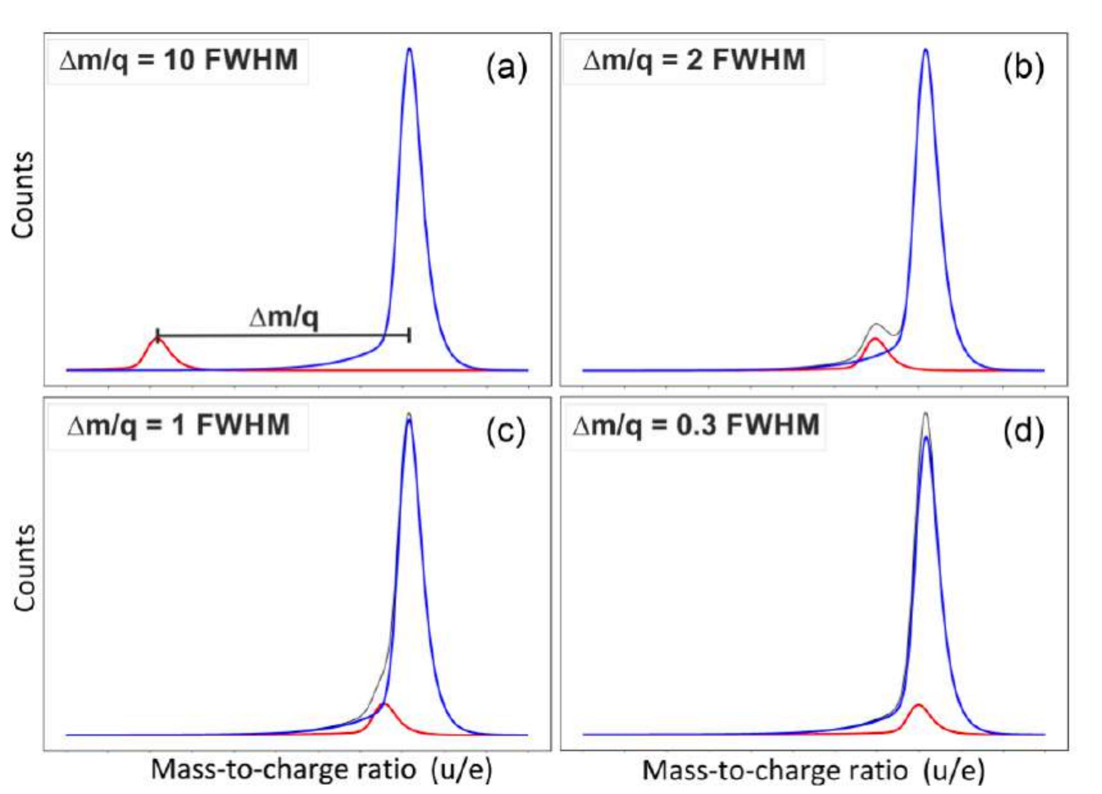
Thank you for your attention

Technique development for analysis

S. Ayet et al., Physical Review C 99, 064313 (2019)



Designed isochronism: ~2.5×10^{-6}



Will employ the Hyper-EMG method developed for GSI MR-TOF
to addressing
higher order optics effect and close-lying isomeric states

Advantages of combining the two TOF methods (Bρ-TOF and IMS) for direct mass measurements of N=Z and the vicinity:

(a). By combining two complementary methods to make full use of the beam time. When measuring masses with high precision with R3, the Bρ-TOF method by the beam-line can simultaneously accept nuclei with relatively larger momentum dispersion to reach a larger range of chart of nuclides at the proton rich side. We can measure the most exotic nuclei (proton unbound, like ^{93}Ag, ^{89}Rh) even with a half-lives of ~1 *us*.

(b). By taking full advantages of the Isochronous condition, it will be the first time to realize mass measurements in isochronous condition for all the target and reference nuclei (N=Z) in storage ring, of which the in-ring TOF are all independent of momentum dispersion.

(c). As all the N=Z nuclei are independent of momentum dispersion in-ring, we do not need Bρ/velocity correction for N=Z nuclei, thus making full liberation of the beam-line for the Bρ-TOF measurements and we can use more detectors in beam-line for trajectory reconstruction, which in return will help with the beam monitoring for in-ring mass measurements.

(d). We can achieve ever good resolution even with few counts for N=Z nuclei all in Isochronous mode. Besides, we can resolve most of the N=Z isomeric states due to the high resolving power for N=Z nuclei.

(e). More isochronous nuclei with precise known mass can be used as reference in the IMS method. We can use the mass measured in-ring directly for the mass calibration for the Bρ-TOF method to avoid far away extrapolation.

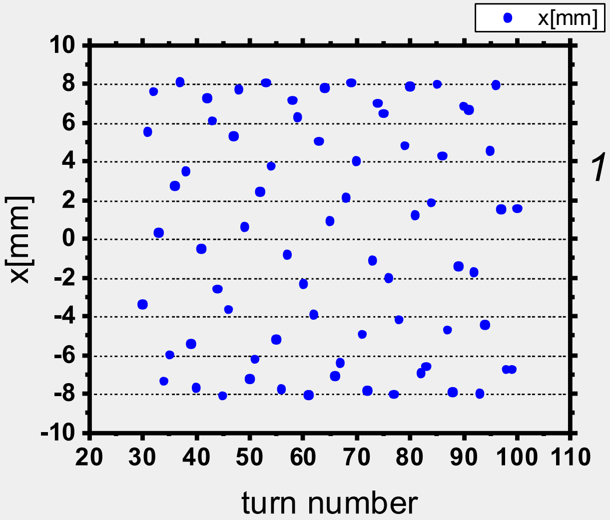
(f). R3 condition can be kept for the same for all reference and target N=Z nuclei in one same IMS setting (extraction time difference to the reference nuclei in 100 ns after 700 μs), thus saving a large amount of beam turning time.

(g). As we measure the proton rich ions possessing the smallest m/q, which corresponds to the shortest TOF from F0 to F3 compared to other produced secondary ions in the same run, the target nuclei will arrive earlier than other secondary ions to be trigger signals. For this reason, we can largely open the slits at F1, F2 to accept more nuclei for the IMS and Bρ-TOF mass measurements.

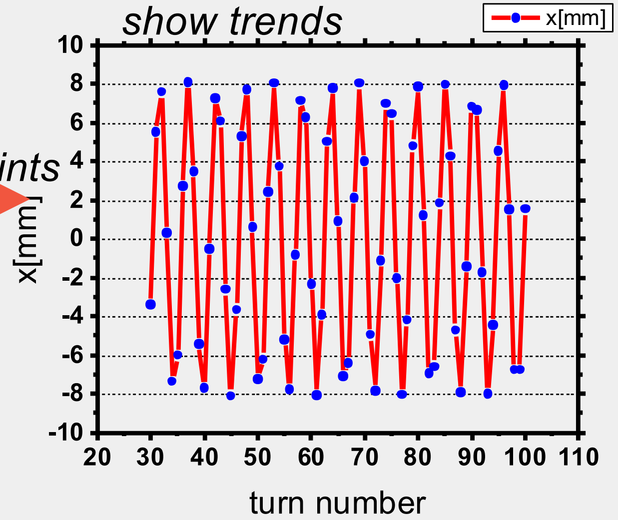
(h). It will be a good way to minimize systematic errors for measuring the N=Z lines, as the reference nuclei from the extra reference runs can cover a large range of Z. During the reference runs we can also pick up un-measured nuclei beyond N=Z line by the beam-lines to deduce the masses by the Bρ-TOF method.

No energy loss: X-position as a function of turn number

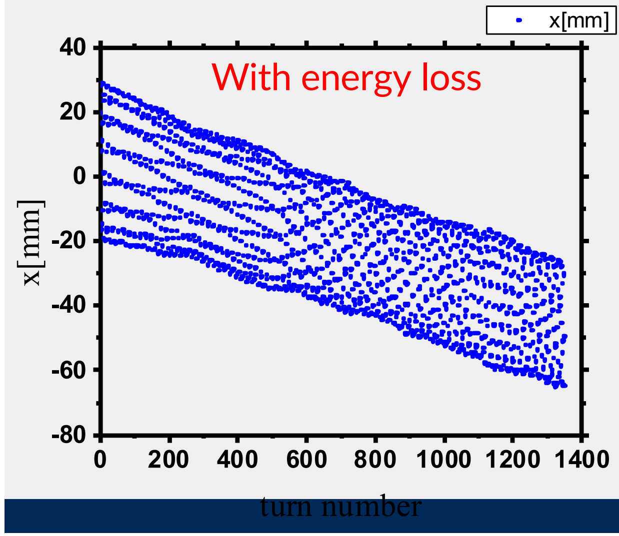
Red lines for connection to show trends

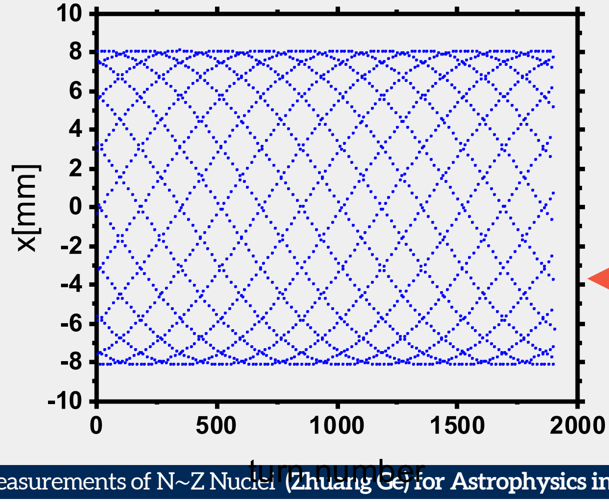


100 turns in blue points



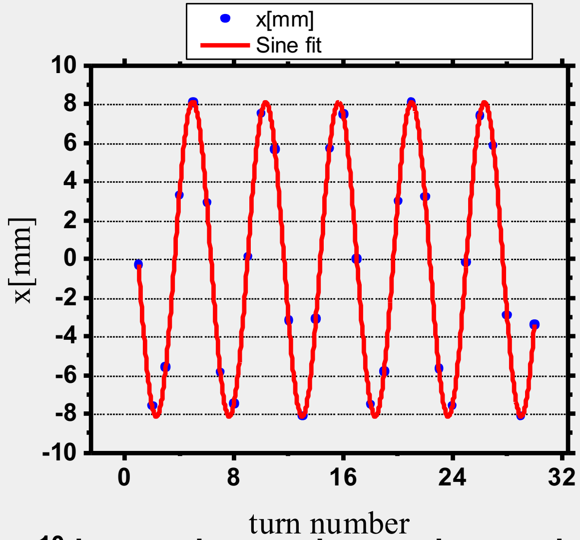
(^{38}K)

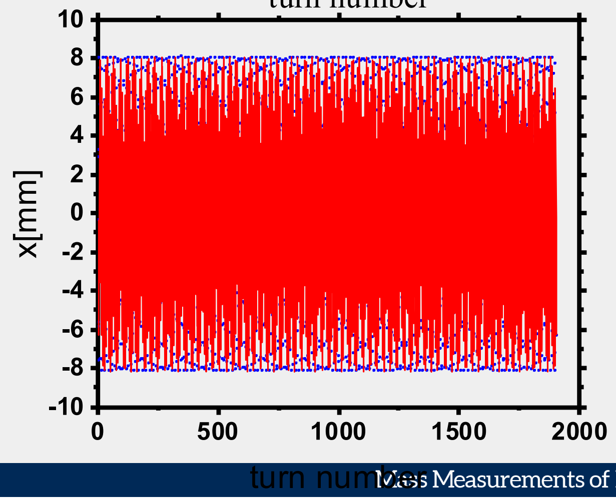




1900 turns in blue points

Fitting with betatron function

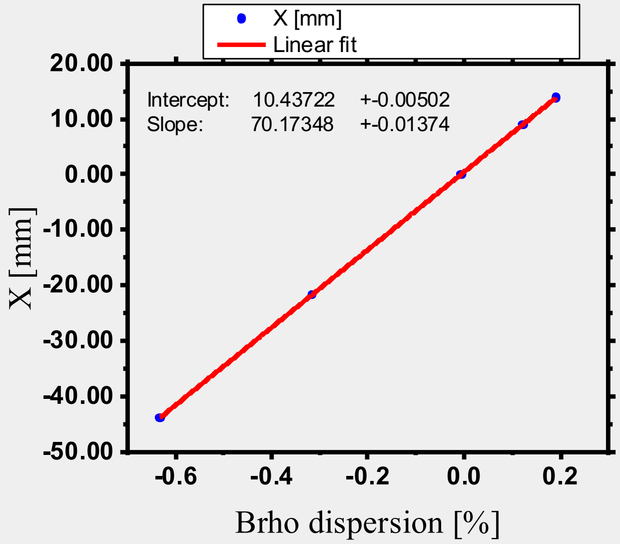


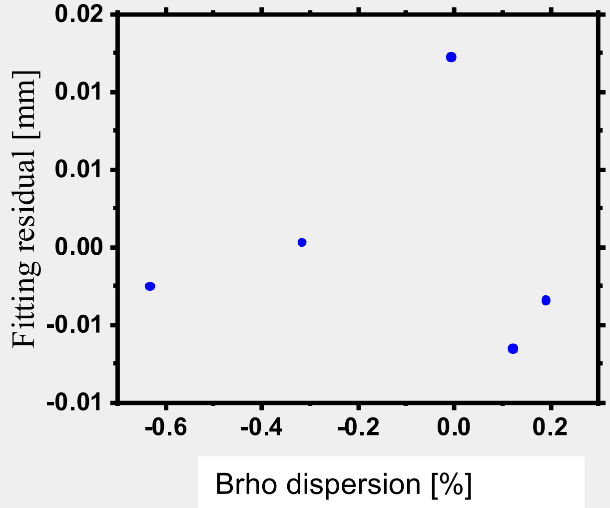


$$
\begin{aligned}
X_i &= X_0 + \sqrt{\beta_i \varepsilon}\ \cos(2\pi Qn+\mu_i) \\
&= X_0 + \sqrt{\beta_i \varepsilon}\ \sin(2\pi Qn+\mu_i+0.5\ \pi\ ) \\
&= X_0 + \sqrt{\beta_i \varepsilon}\ \sin[\pi(2Qn-(-\mu_i/\pi-0.5\ )\ ) \\
&= X_0 + \sqrt{\beta_i \varepsilon}\ \sin[2Q\pi(n-(-\mu_i/\pi-0.5\ )/2Q\ )
\end{aligned}
$$

$$
\left.
\begin{aligned}
&Xc = (-\mu_i/\pi-0.5\ )/2Q \\
&Y0 = X_0 \\
&W = 1/2Q \\
&X = n \\
&A = \sqrt{\beta_i \varepsilon}
\end{aligned}
\right\} \textit{Parameters}
$$

Dispersion function deduction and momentum measurements





After getting the a, b parameters, we can use the function: x=1/b(y-b) for momentum deduction from position measurements

*Equation: y = a + b*x*

Weight No Weighting

Residual Sum of Squares 1.5E-4

x: momentum dispersion; y:position

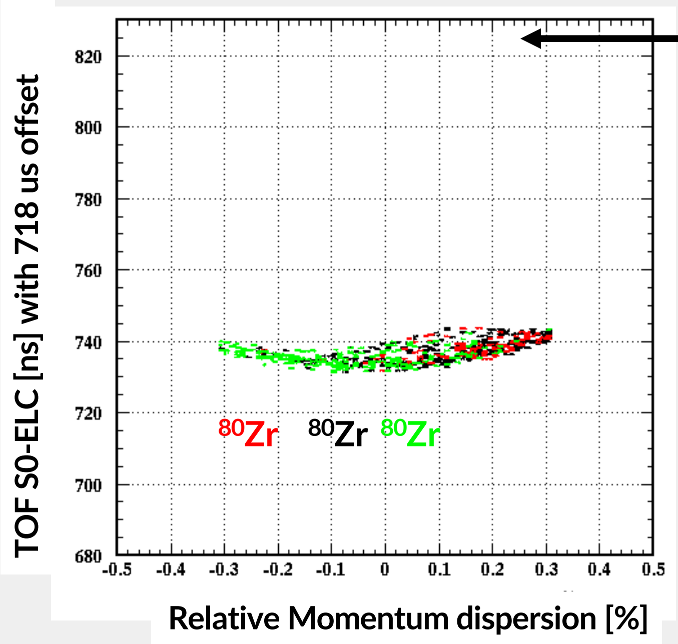
	Value	*Standard Error*
Intercept	*10.43722*	*0.00502*
Slope	*70.17348*	*0.01374*

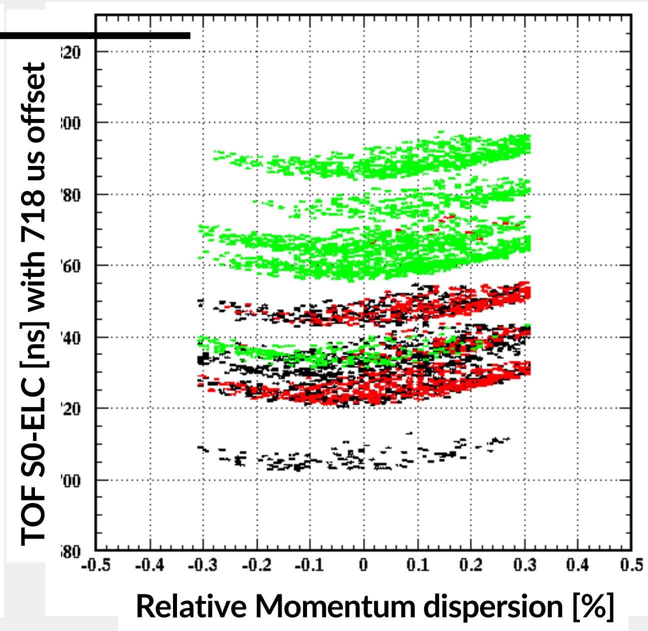
Designed: ~70 mm/%

Isochronous condition confirmation

Isochronous condition confirmation can be done by:
Check same species of ion at different settings

primary beam ^{124}Xe
Simulation starting from F0





Setting on 76Sr:

Setting on 80Zr:

Setting on 84Mo:

Only change variable degrader thickness and varying Dipole before F3

Emittance-dependent Isochronism

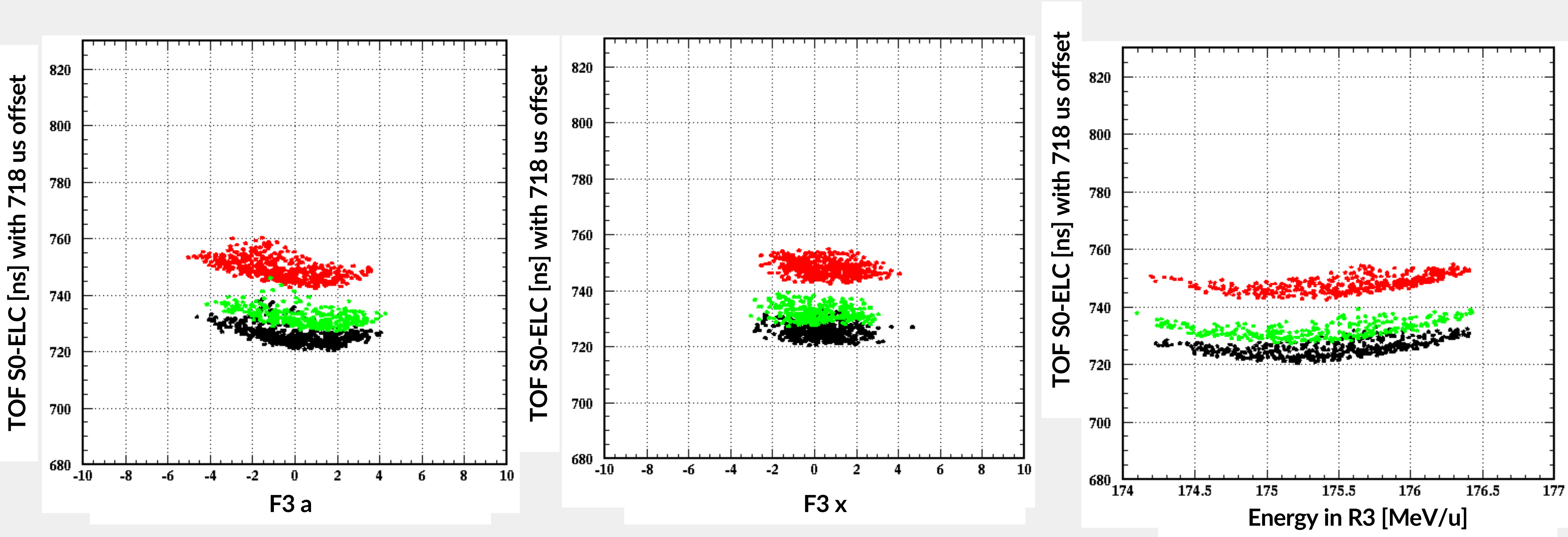
^{76}Sr: black
^{78}Y :Red
^{74}Rb: green

F3 Pla: 1mm^{t}
F3 IC in
F3 PPAC in

primary beam ^{124}Xe (345MeV/u)
Target: 8mm^{t} ^{9}Be
Simulation starting from F0

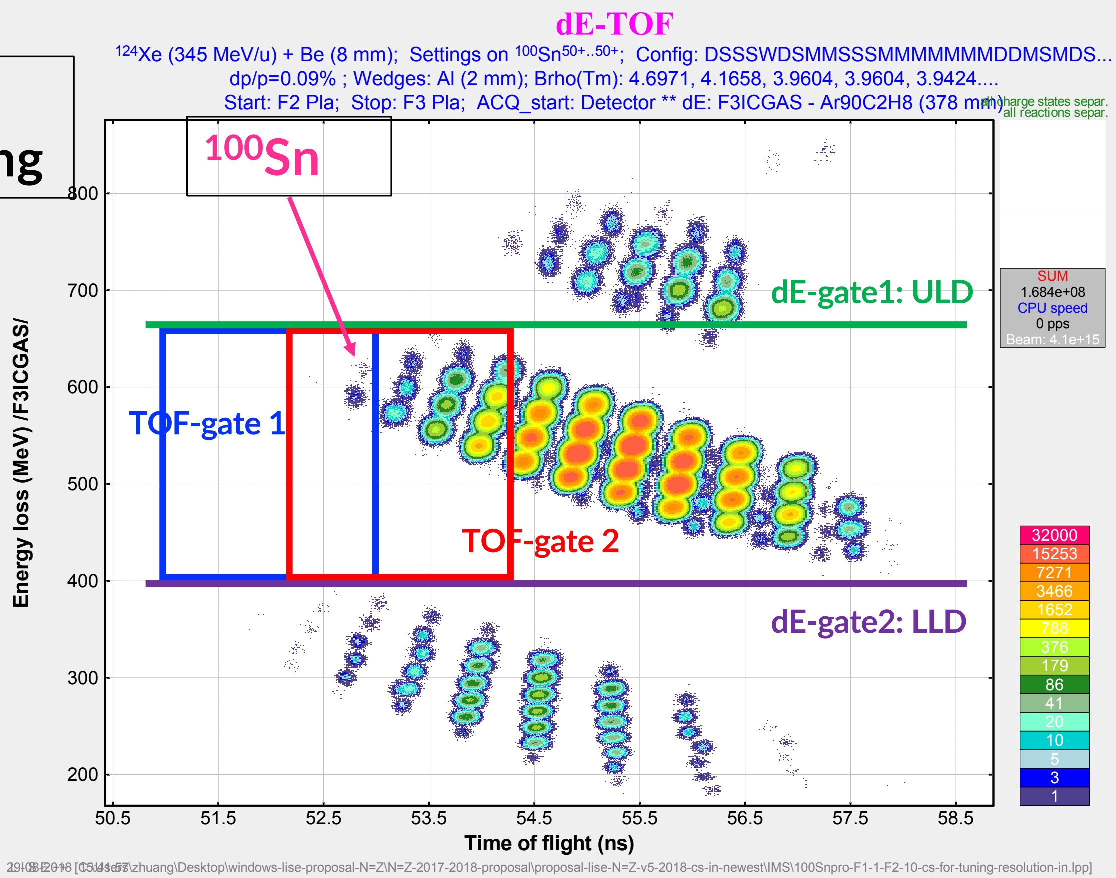
Setting on 76Sr:
Brho centering

1900 turns circulation in R3



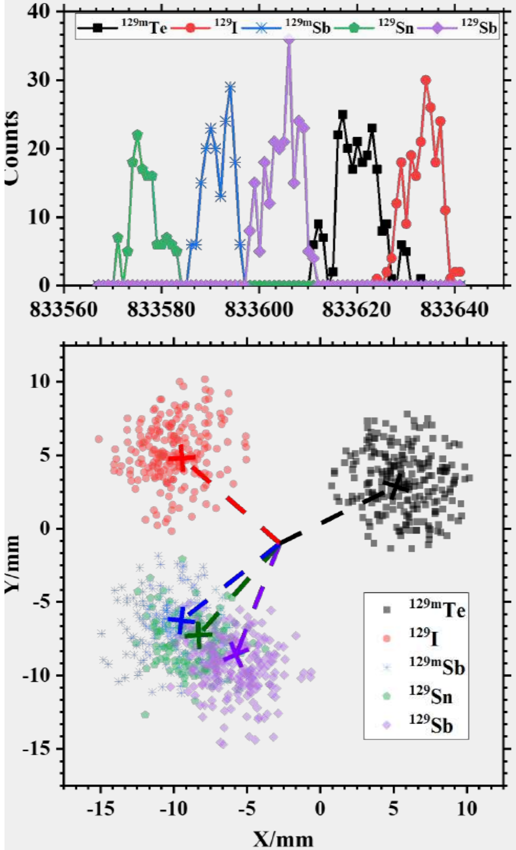
TOF-dE gate selection

^{100}Sn setting

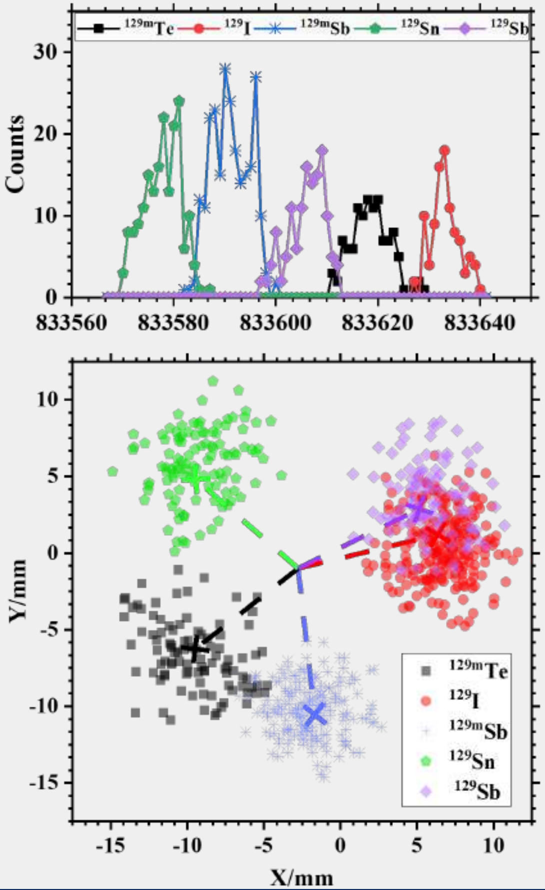


Tuning setting:
F1 slit:
+- 1 mm
F2 slit:
+- 10mm

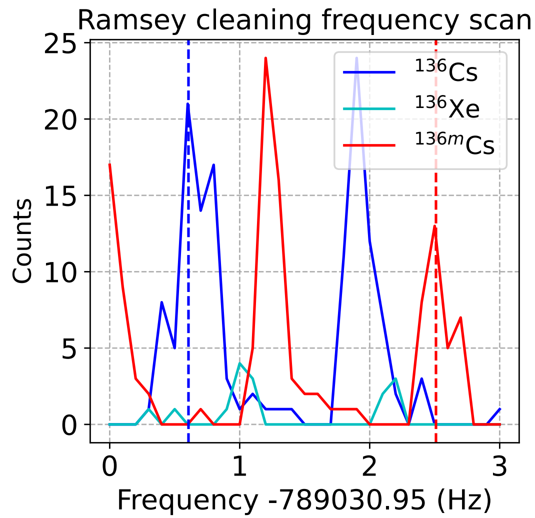
Setting TOF-grate1 and TOF-gate2 rates ratio to be 4:1
The two TOF gates set in 'or'logic (for example, 'N=Z and more exotic area'for TOF-gate 1 in 80 Hz
and
additional reference in TOF-gate 2
to be 20 Hz)



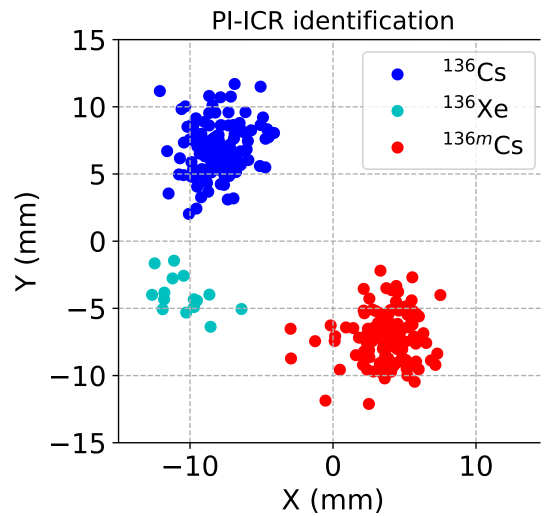
^{129m}Te ^{129}I ^{129m}Sb ^{129}Sn ^{129}Sb
Counts
833560 833580 833600 833620 833640
Y/mm
X/mm
^{129m}Te
^{129}I
^{129m}Sb
^{129}Sn
^{129}Sb



^{129m}Te ^{129}I ^{129m}Sb ^{129}Sn ^{129}Sb
Counts
833560 833580 833600 833620 833640
Y/mm
X/mm
^{129m}Te
^{129}I
^{129m}Sb
^{129}Sn
^{129}Sb



Ramsey cleaning frequency scan
^{136}Cs
^{136}Xe
^{136m}Cs
Counts
Frequency -789030.95 (Hz)



PI-ICR identification
^{136}Cs
^{136}Xe
^{136m}Cs
Y (mm)
X (mm)