Complementary mass measurements of N~Z isotopes at IGISOL and RIKEN

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Outline

- Motivation
- Mass measurements at RIBF/RIKEN
- Mass measurements at IGISOL/JYU
- Summary and Outlook

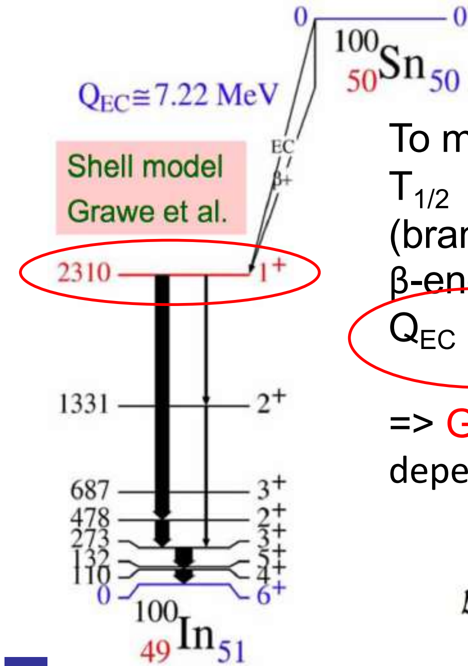
Motivation for mass measurements of N ~ Z nuclei

nuclear structure&fundamental physics

1. Wigner energy/ np pairing
2. Mapping proton drip-line
3. Isospin symmetry breaking
4. Deformation/Doubly-magic (N=Z=40, 50)
5. Test of mass models
6. Shell closures and evolution
7. New isomers
8. Standard model tests (CVC)

Nuclear Astrophysics

Modelling vp-, rp-processes



^{100}In Level scheme unknown

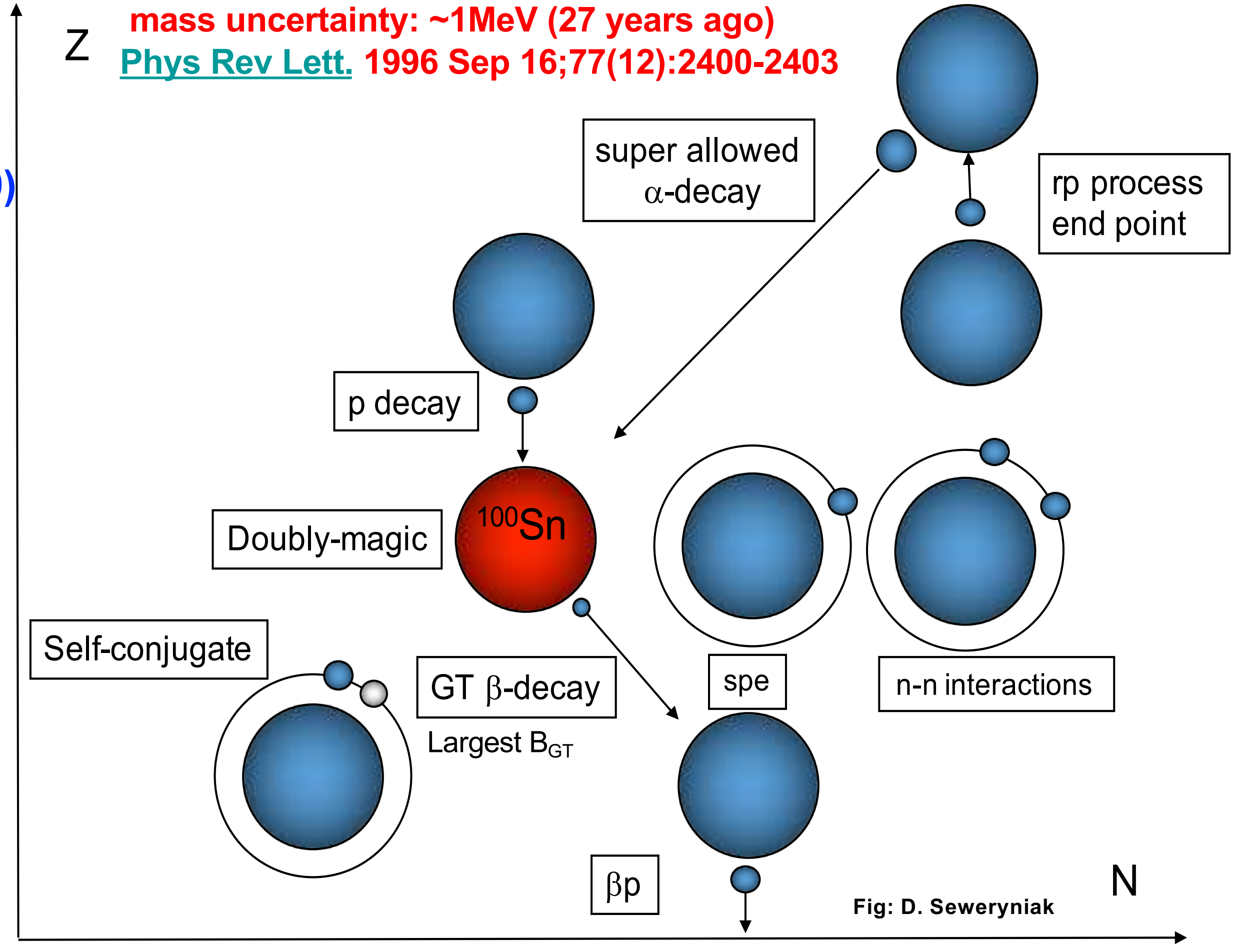
To measure:
$T_{1/2}$
(branching)
β-endpoint energy
Q_{EC} (Mass)

=> GT-strength B_{GT} :
depends on the 5th power of Q_{EC}

$$B_{GT} = \frac{3811.5 \text{ s}}{f(Z, Q_\beta) \cdot T_{1/2}}$$

^{100}Sn physics

mass uncertainty: ~1MeV (27 years ago)
Phys Rev Lett. **1996 Sep 16;77(12):2400-2403**



Discrepency of Q_{EC} from GSI and RIKEN 450 keV

C. B. Hinke et al., Nature 486, 341 (2012).
D. Lubos et al., Phys. Rev. Lett. 122, 222502 (2019).

Motivation for mass measurements of N ~ Z nuclei

Mass excess

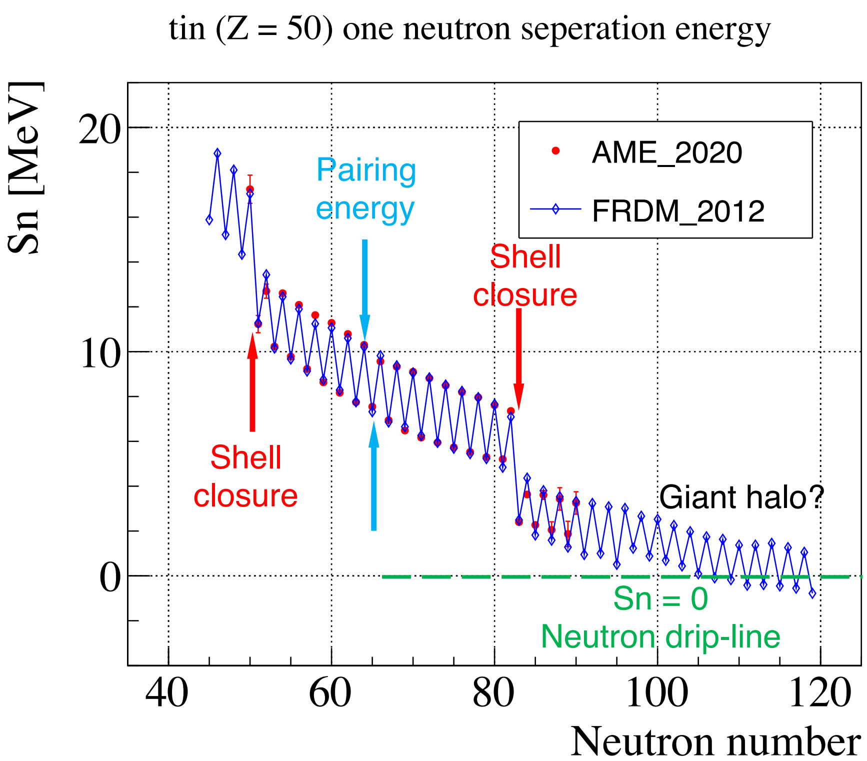
Nuclear mass ↔ nuclear binding energy:

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

Several masses ↔ Binding energy derivatives, such as S_n, S_{2n}….:

$$S_n(N,Z) = M(N-1,Z) + m_n - M(N,Z) = B(N,Z)/c^2 - B(N-1,Z)/c^2$$

Nuclear structure



Nuclear astrophysics

For example: rp process

X-ray burst

J. Grindlay et al., Astrophys. J. 205 (1976) L127.

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)

Final Composition (rp process):

X-ray burst model uncertainty: Q values

Exponential dependence on masses!

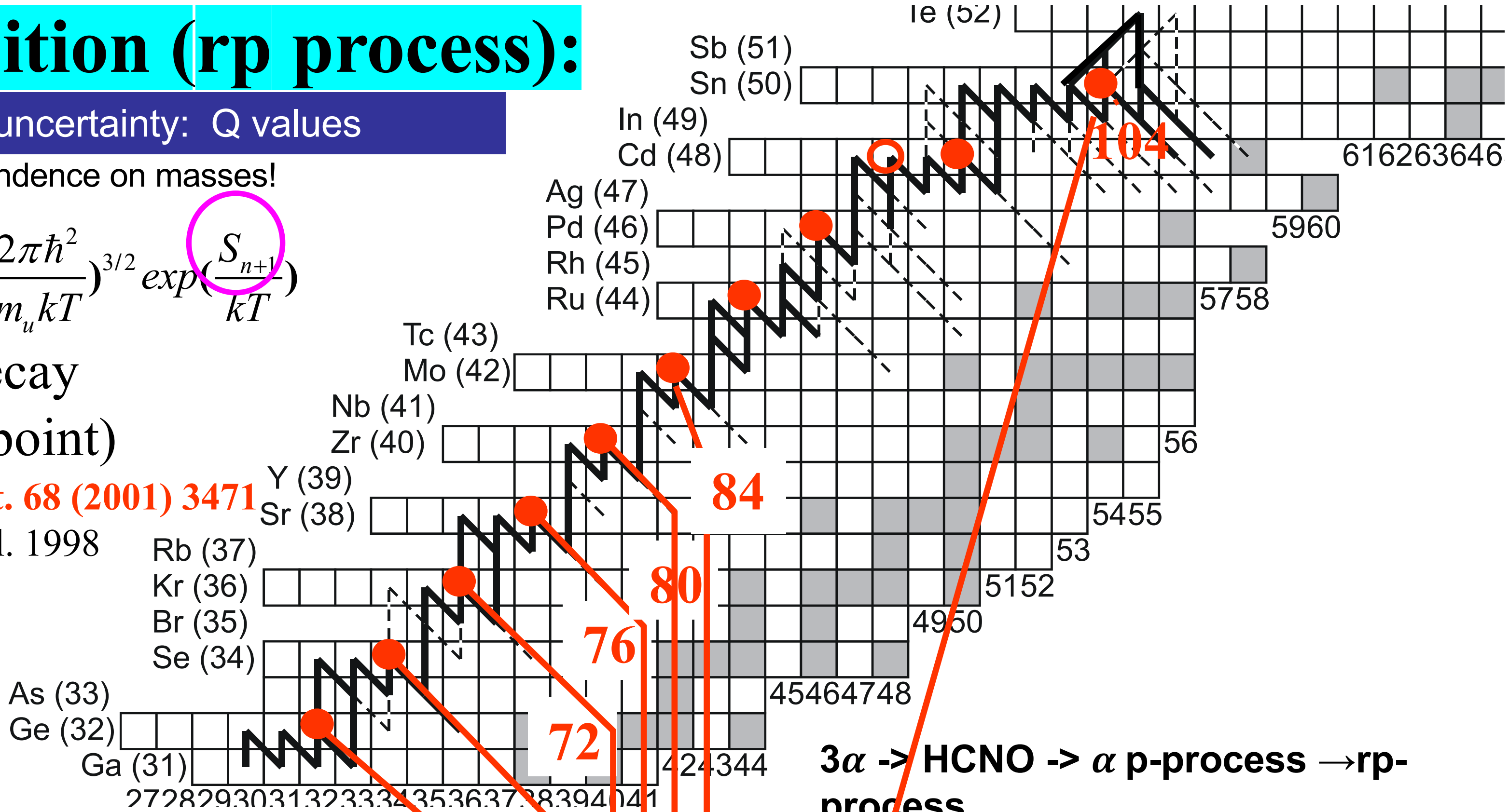
$$\frac{Y_{\mathrm{n+1}}}{Y_{\mathrm{n}}} = \rho_{\mathrm{n}} \frac{G_{n+1}}{2G_n} \left(\frac{A_{n+1}}{A_n} \frac{2\pi\hbar^2}{m_u kT}\right)^{3/2} exp\left(\frac{S_{n+1}}{kT}\right)$$

slow β decay

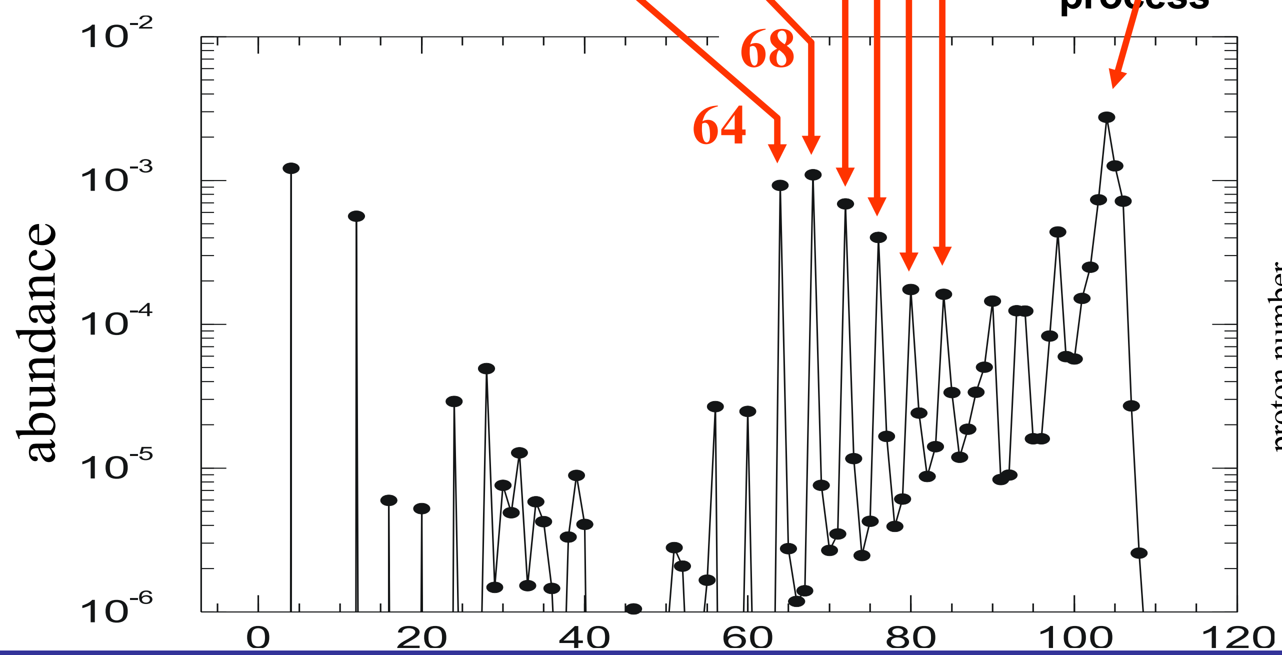
● (waiting point)

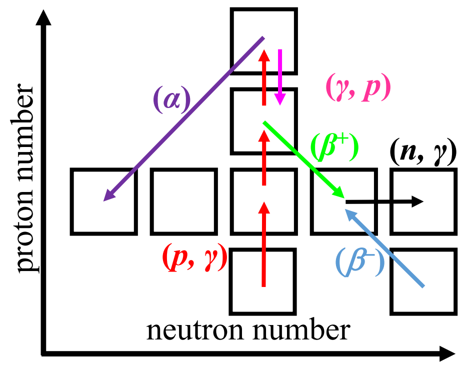
Schatz et al. Phys. Rev. Lett. 68 (2001) 3471

Schatz et al. 1998



3α -> HCNO -> α p-process →rp-process

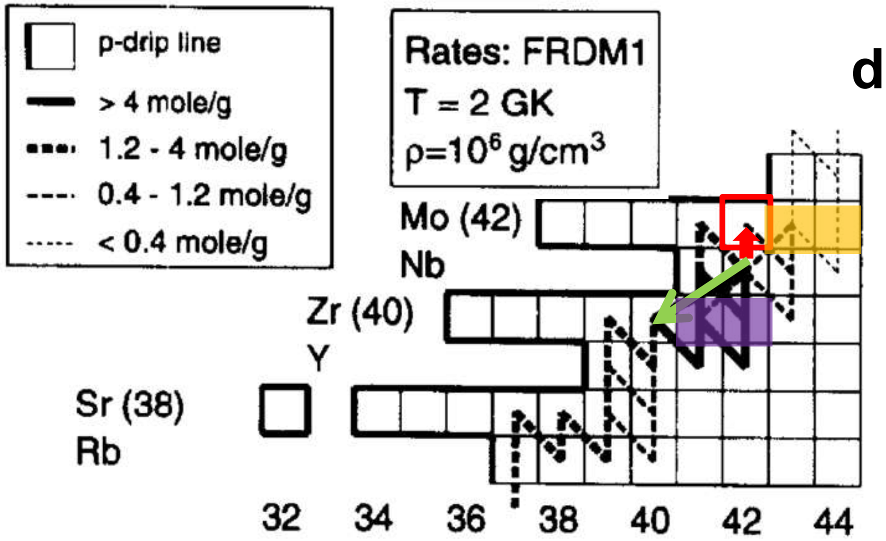




Mass number

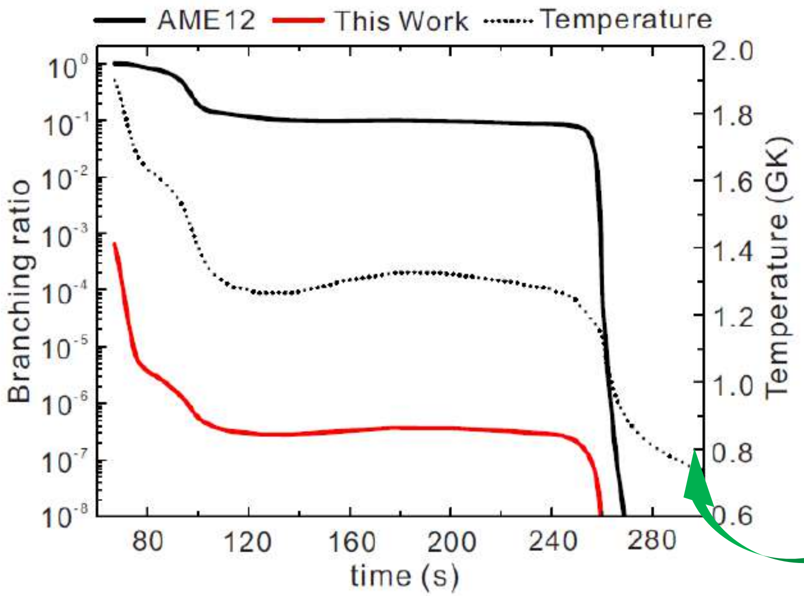
Impact on rp-process

H. Schatz et al. / Physics Reports 294 (1998) 167–263

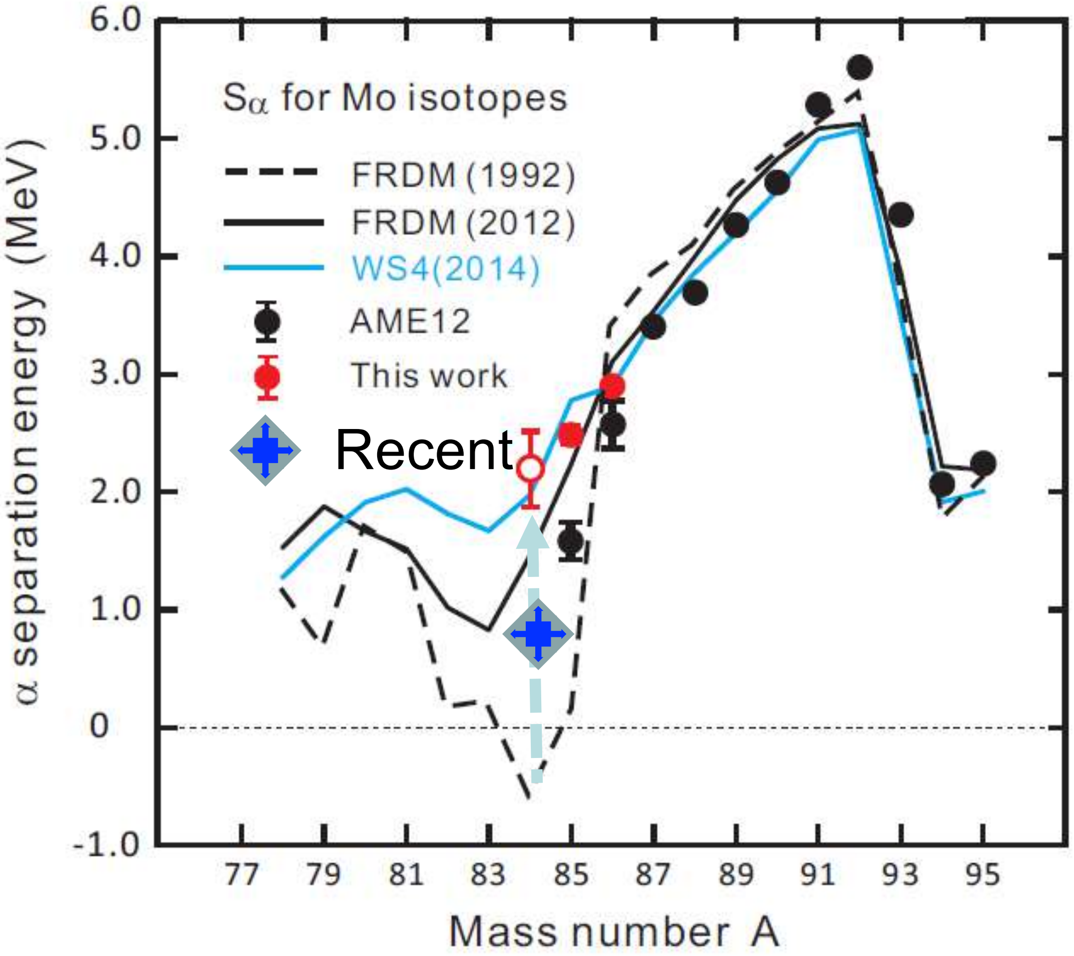


Zr-Nb cycle:

^{83}Nb(p, α) ^{80}Zr(β^{+}) ^{80}Y(p, γ) ^{81}Zr $\left\{ \begin{matrix} (\beta^{+})^{81}\text{Y}(p,\gamma) \\ (p,\gamma)^{82}\text{Nb}(\beta+) \end{matrix} \right\}$ ^{82}Zr(p, γ)^{83}Nb



Mass of ^{84}Mo needed for determination of α separation energy of ^{84}Mo

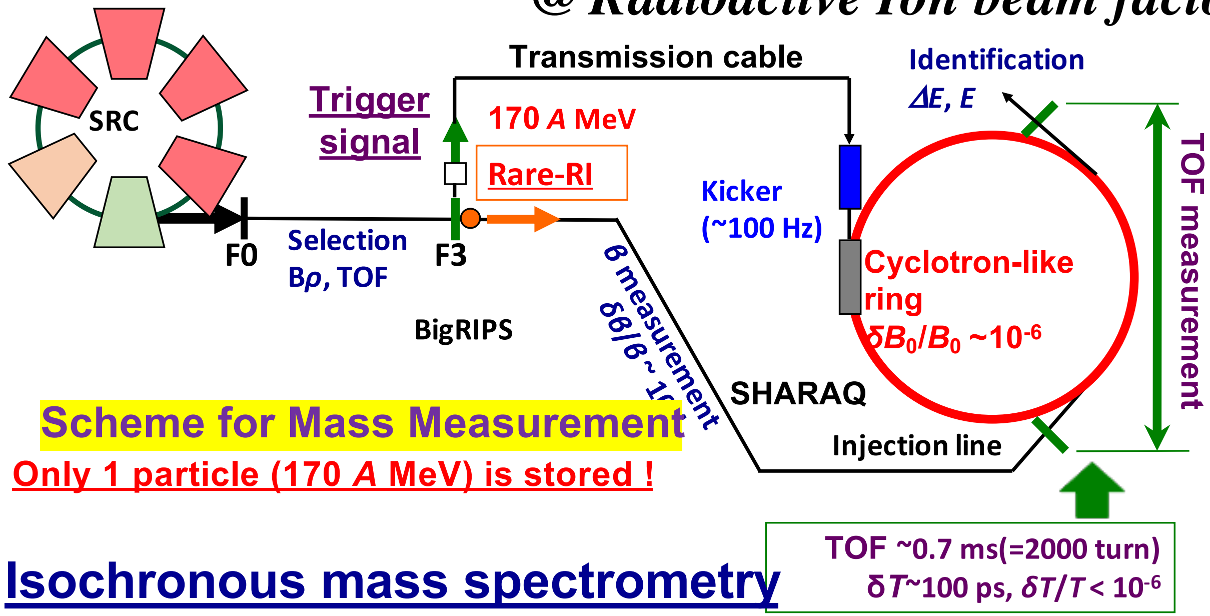


Y.M. Xing et al., PLB 781, 358 (2018)

masses of ^{83,84}Mo, ^{82}Nb, ^{83}Nb, would redefine fraction of the reaction flow branching into the Zr–Nb cycle

Scheme for Mass Measurement and location of Rare-RI Ring (R3)

@ Radioactive Ion beam factory (RIBF)



Scheme for Mass Measurement

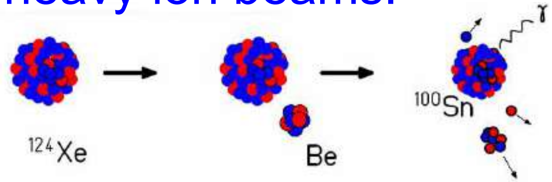
Only 1 particle (170 A MeV) is stored !

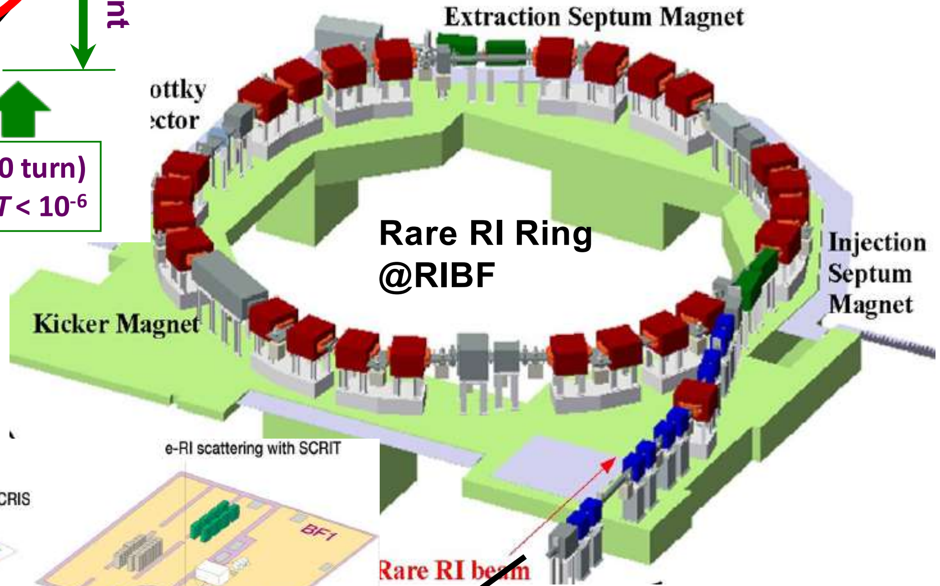
Isochronous mass spectrometry

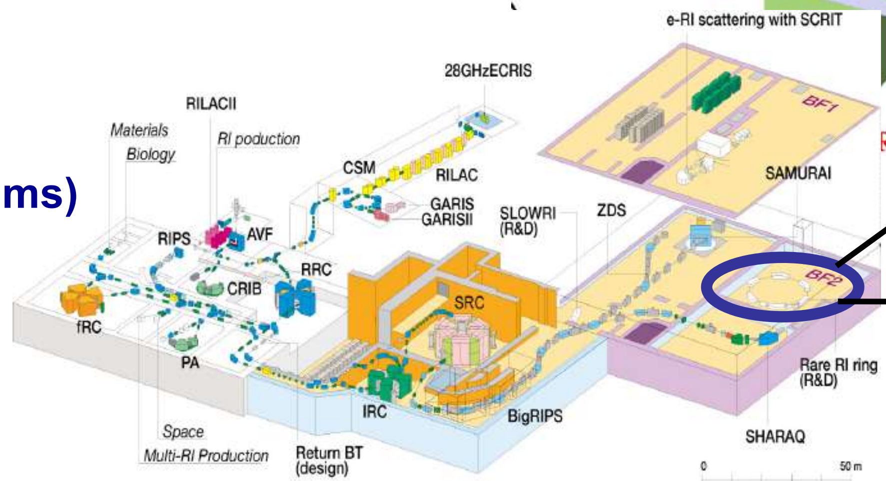
- Isochronous field ~10^{-6}
- Beam-triggered individual injection

Short measurement time (<1 ms)
Good resolution (~10^{-6})
High efficiency (~100%)

Projectile fragmentation of heavy ion beams:







Location of Rare-RI Ring at RIKEN RIBF

Particle identification scheme at BigRIPS-HA

TOF-Bρ-ΔE method with track reconstruction → Improve Bρ and TOF resolution

Measure TOF, Bρ, ΔE @ 2nd stage

↓ + isomeric γ-rays

Z, A/Q

$$Z \leftarrow -dE/dx = f(Z,\beta)$$

$$A/Q = \frac{B\rho}{\gamma\beta m_u}$$

Two-stage separator

1st stage: F0-F2

2nd stage: F3-S0

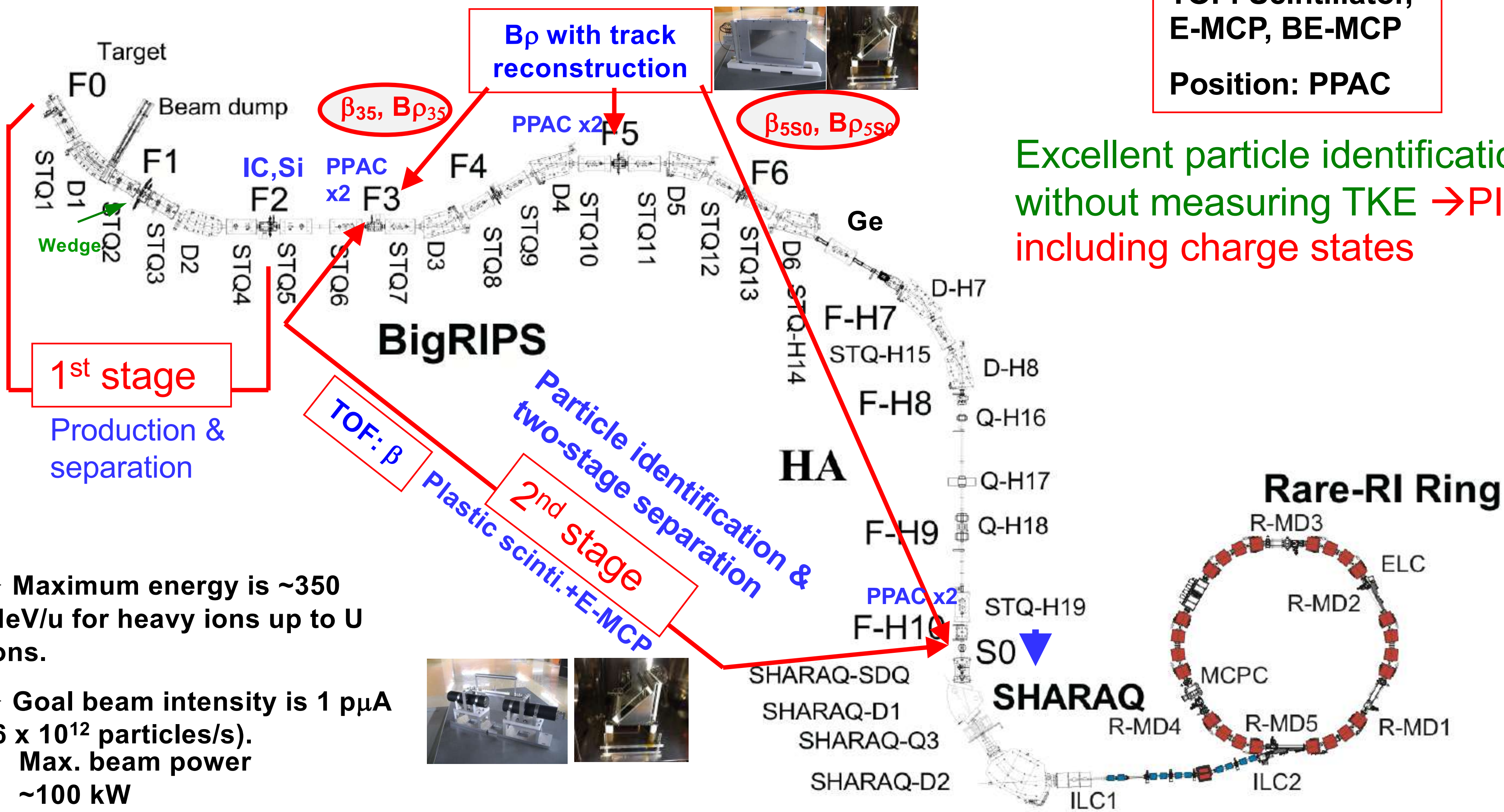
ΔE: IC, Si

Isomer γ-ray: Ge

TOF: Scintillator, E-MCP, BE-MCP

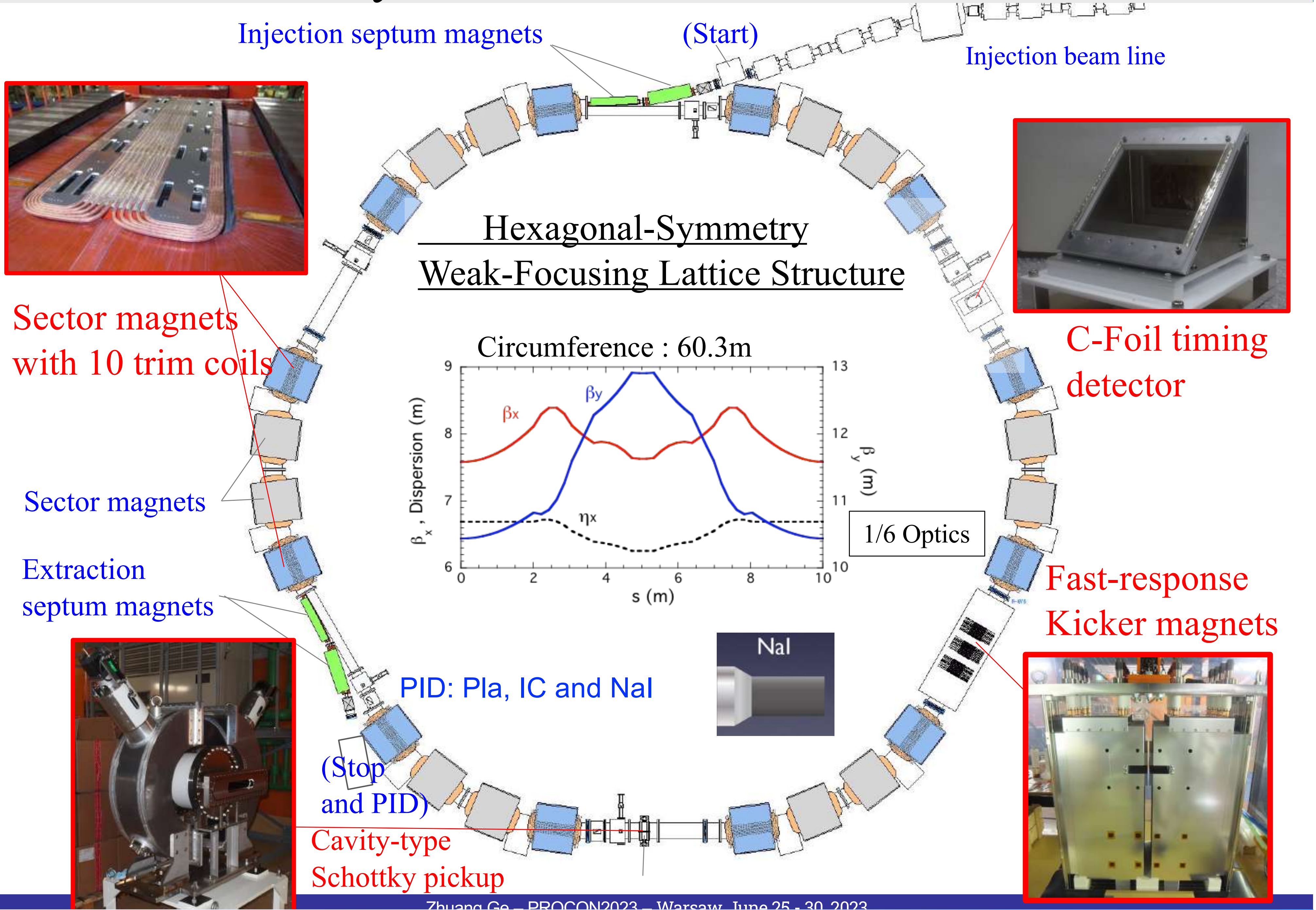
Position: PPAC

Excellent particle identification without measuring TKE →PID including charge states

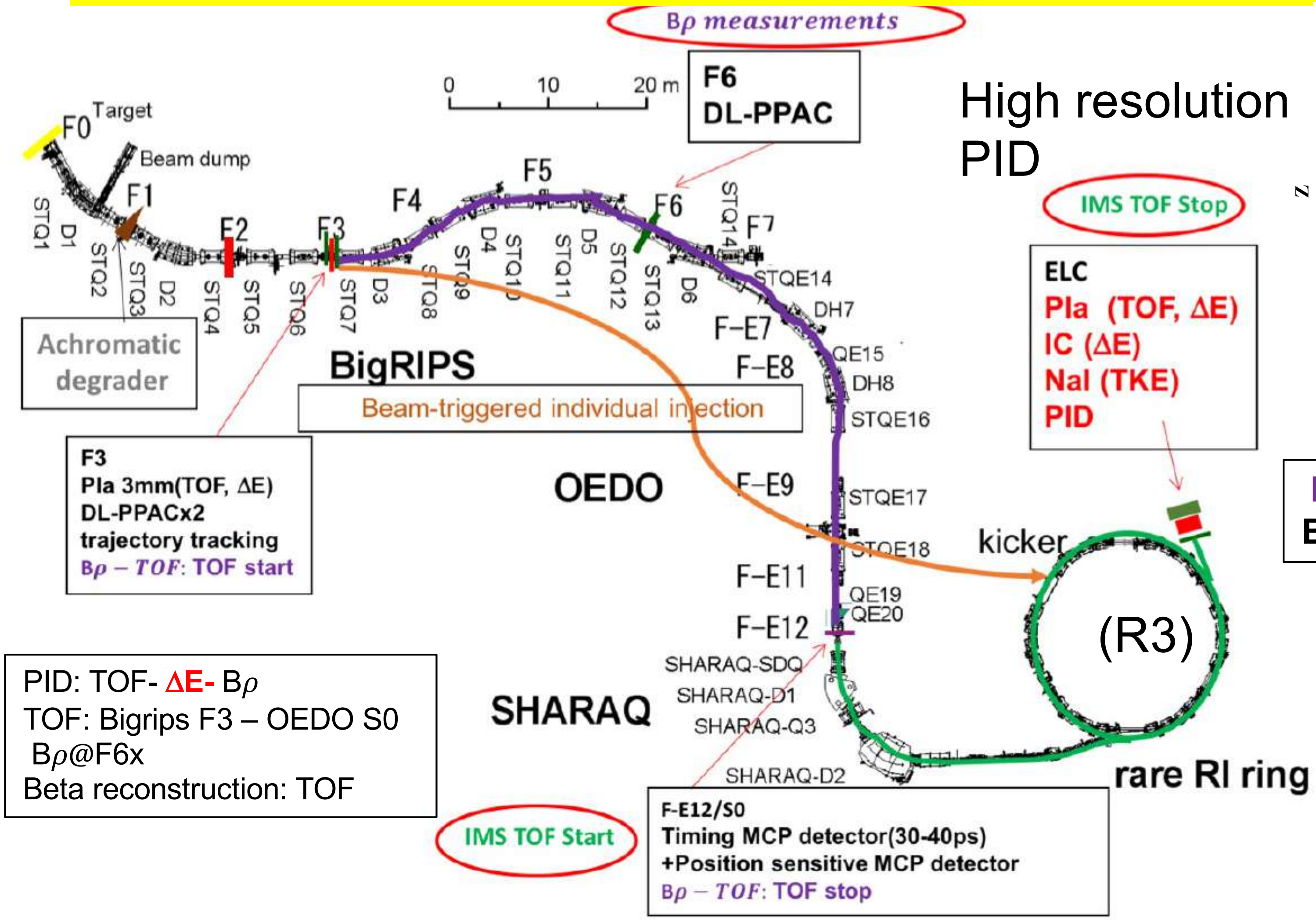


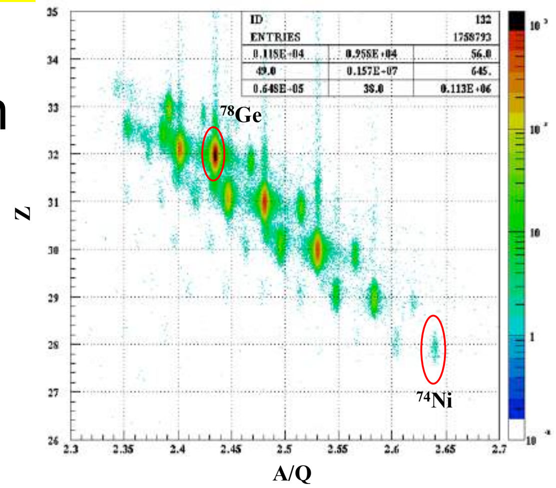
- **Maximum energy is ~350 MeV/u for heavy ions up to U ions.**
- **Goal beam intensity is 1 pμA (6 x 10^{12} particles/s).**
  Max. beam power ~100 kW

R3: Cyclotron-like Lattice Structure



Setup for Mass measurements by Bρ – *TOF* & *IMS* (Isochronous mass spectrometry) @RIKEN





Bρ – *TOF* mass is By-product part of IMS runs

PID: TOF- ΔE- Bρ
TOF: Bigrips F3 – OEDO S0
Bρ@F6x
Beta reconstruction: TOF

F3-S0:
Efficiency 70-90%
Momentum acceptance $\pm$0.5%

Rare-RI Ring:
Efficiency 1 %
Momentum acceptance $\pm$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:

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

Zhuang Ge, Tomohiro Uesaka et al., Hyperfine Interact (2019) 240: 92; Zhuang Ge, PhD thesis (2018)

Principle of Mass Measurement at the Rare-RI Ring

cyclotron frequency $f_c = \frac{1}{2\pi}\frac{qB}{m}$

Isochronous optics $B = B_0\gamma$

m/q **: charge-to-mass ratio**
T **: revolution time**
Index
0 : reference ion
1 : ion of interest

$$\begin{cases} \frac{m_0}{q_0}\gamma_0\beta_0 = \frac{m_1}{q_1}\gamma_1\beta_1 \\ \beta_0 T_0 = \beta_1 T_1 \end{cases}$$

$$T_0 = 2\pi\frac{m_0}{q}\frac{1}{B}\gamma_0 = 2\pi\frac{m_0}{q}\frac{1}{B_0}$$

For $m_1/q = m_0/q + \Delta(m_0/q)$

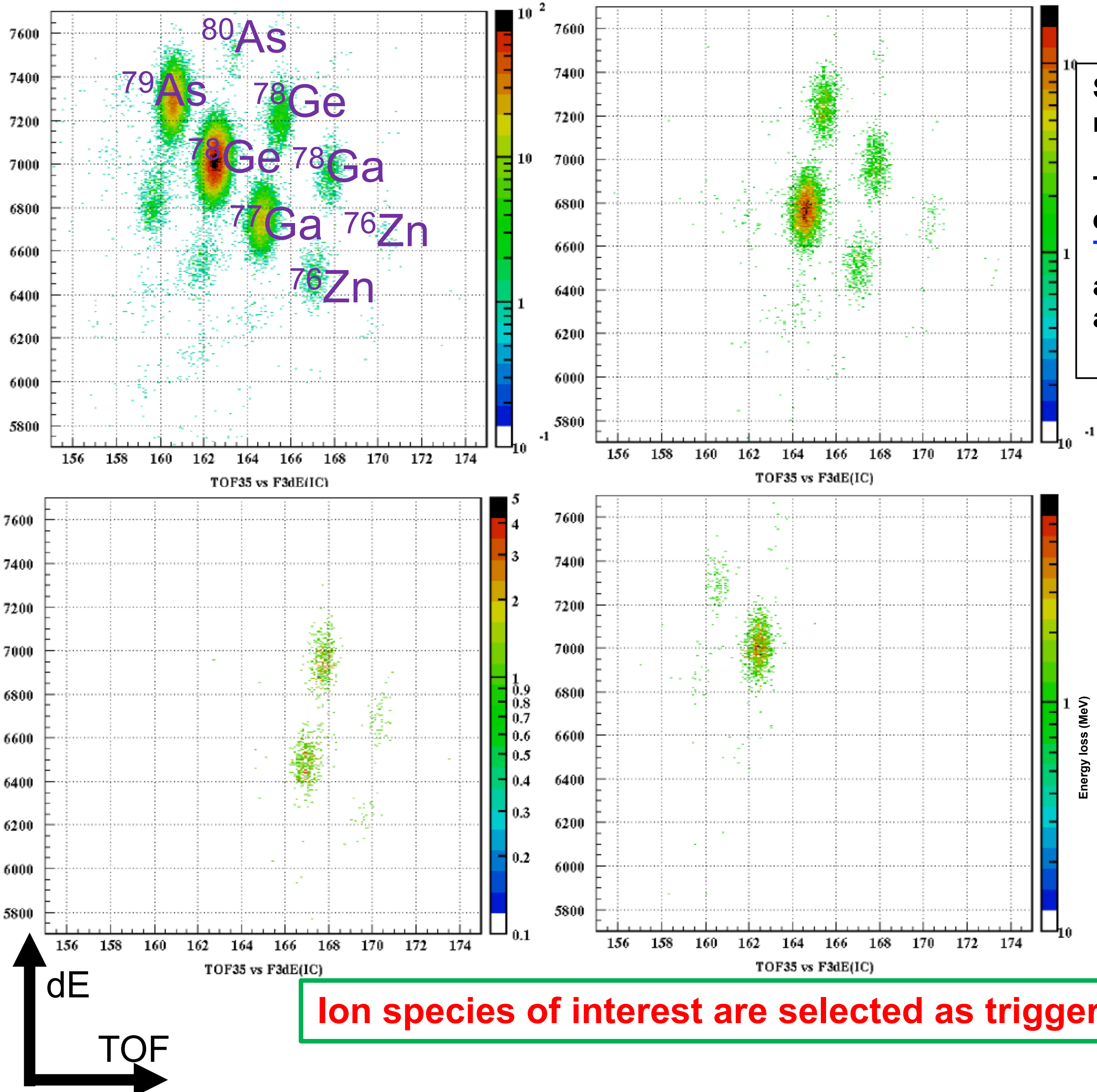
$$\frac{m_1}{q} = \left(\frac{m_0}{q}\right)\frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \left(\frac{m_0}{q}\right)\frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-\left(\frac{T_1}{T_0}\beta_1\right)^2}}$$

→ Need to measure velocity precisely

$$\left(\frac{m}{q}\right)_1 = \left(\frac{m}{q}\right)_0\frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \left(\frac{m}{q}\right)_0\frac{T_1}{T_0}\sqrt{\frac{1-(\frac{T_0}{T_1})^2}{\left(\frac{(m/q)_0}{(B\rho)_0}c\right)^2}+1}$$

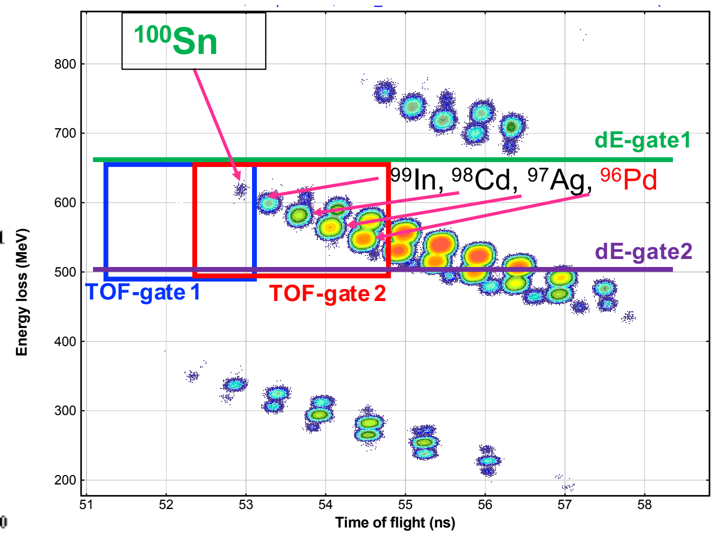
$B\rho$ **measurement is important here!**

dE-TOF gate Selection method



Setting TOF-gate1 and TOF-gate2 rates ratio to be 9:1

The two TOF gates set in 'or' logic (for example, 'N=Z and more exotic area'for **TOF-gate 1** in 90 Hz
and
additional reference in **TOF-gate 2** to be 10 Hz)



Ion species of interest are selected as triggering ions for injection to R3

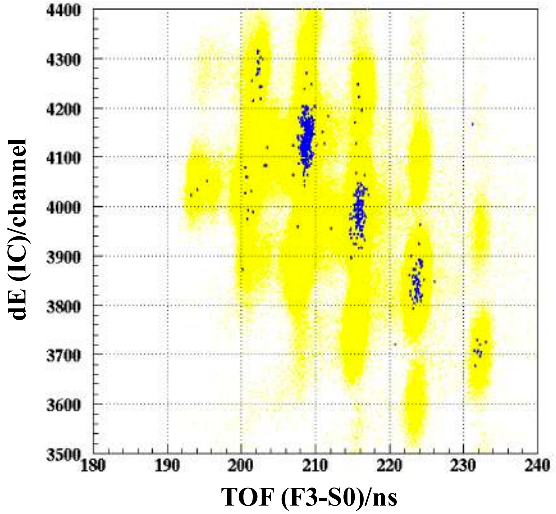
Event-by-event PID with **TOF(beamline)-Bρ-dE-E-TOF(in-Ring)**

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

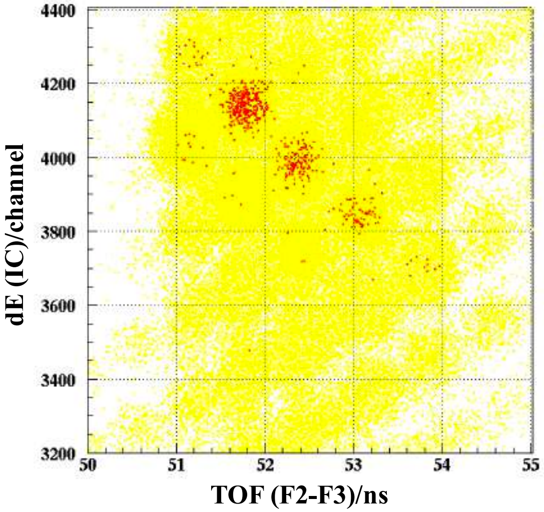
Unambiguously identification with single ion sensitivity

TOF: beamline (**F2-F3 and F3-S0**), dE: beamline IC

dE-TOF1



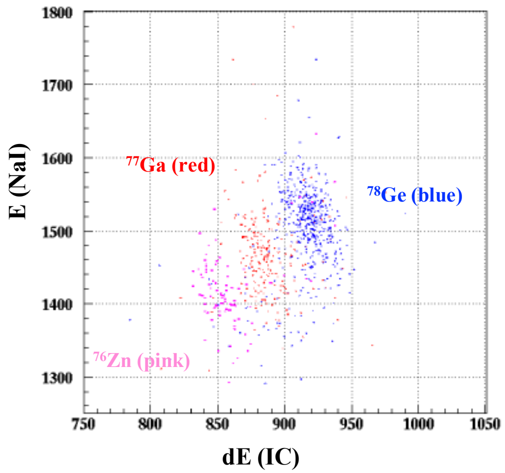
dE-TOF2



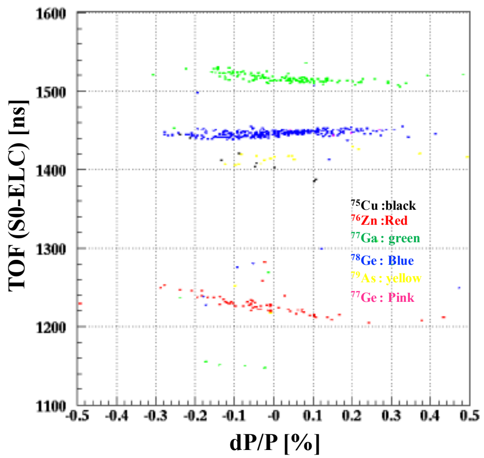
Yellow: all ions detected at S0
Blue: extracted from R3

Yellow: all ions detected at F3
Blue: extracted from R3

dE-E



In-ring TOF- Bρ



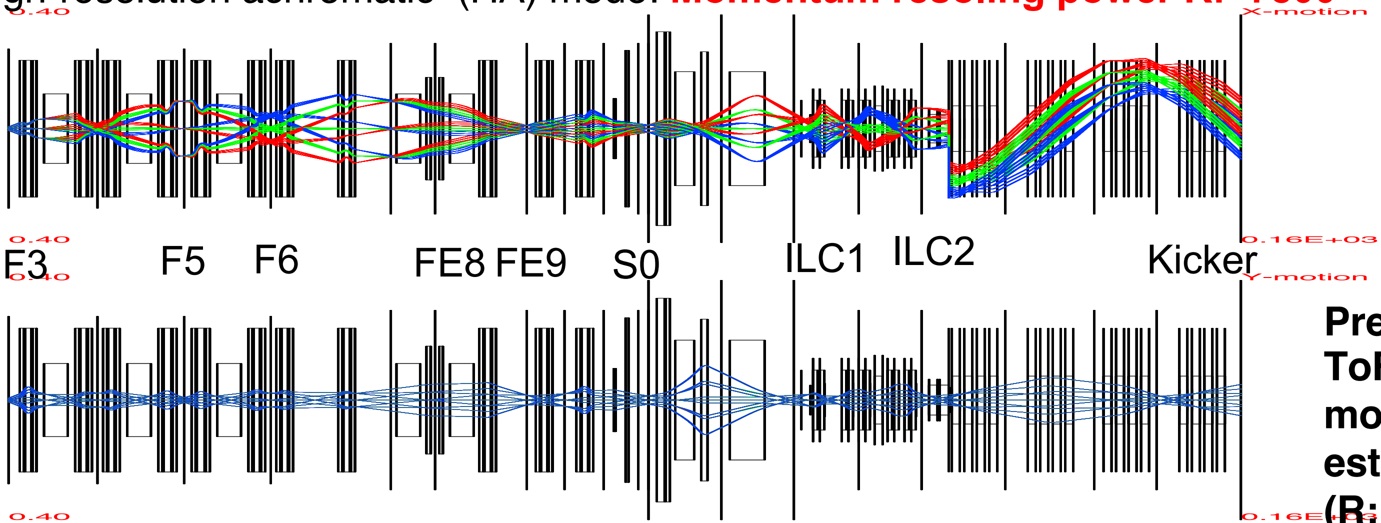
dE: IC, E: ring-extraction NaI

Bρ: beamline, TOF: in ring

Optics design with high momentum resolving power and ion transportation simulation

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

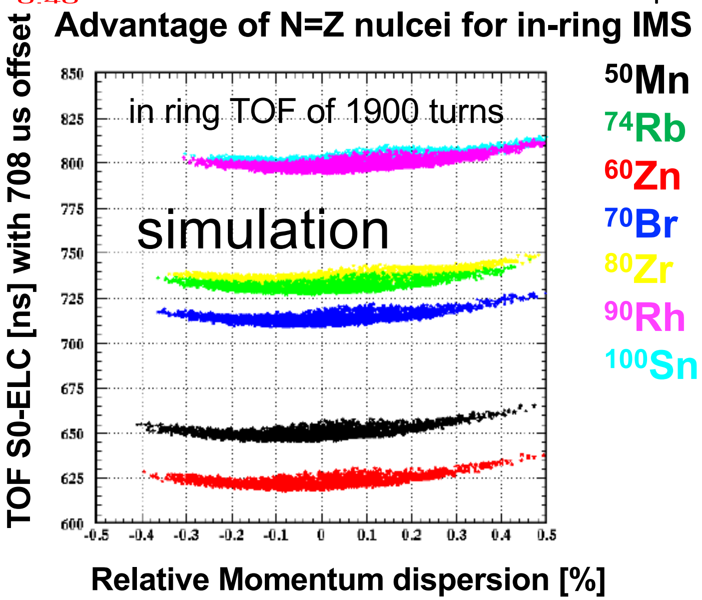
high-resolution achromatic (HA) mode: **Momentum resoling power R:~7800**



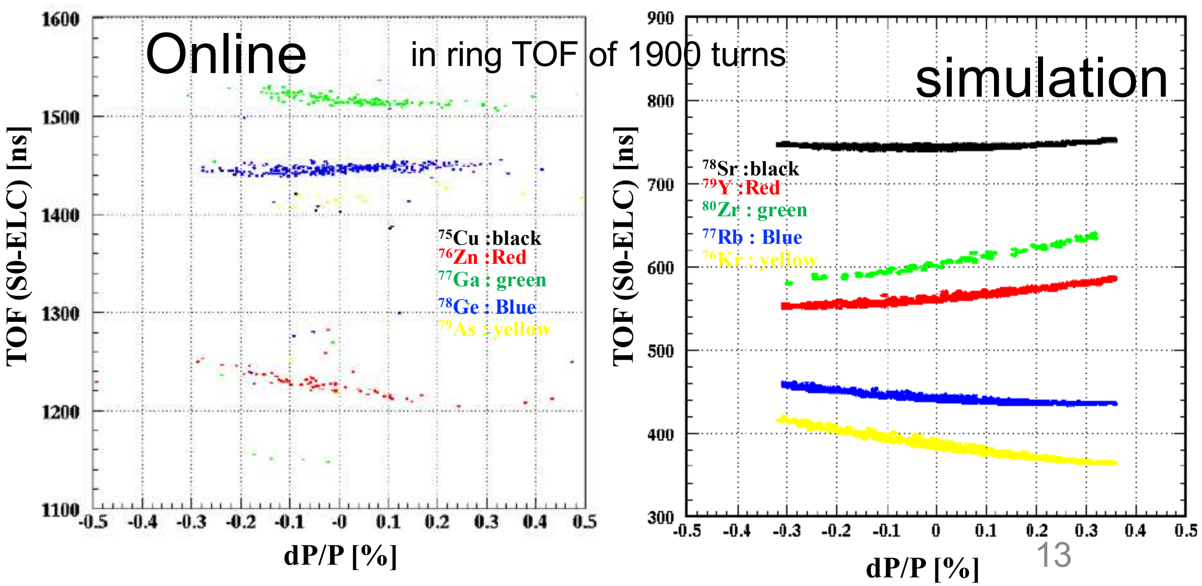
Dispersion matching is considered: no influence on the Bρ-ToF method precision if the settings are optimized for the storage ring operating as IMS

Precision (1.5×10^{-5}-2×10^{-6}) of Bρ-ToF is estimated based on nomal mode (R: 3300) for a save estimation. We will use HA mode (R: 7800)

Advantage of N=Z nulcei for in-ring IMS



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



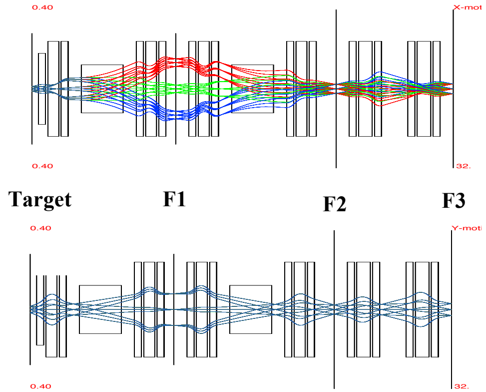
N=Z simulation (Z=25-50): all nuclei in isochronous In a same setting from F3 to R3, all with high resolving power

Ion optics design (beam-line and storage ring)

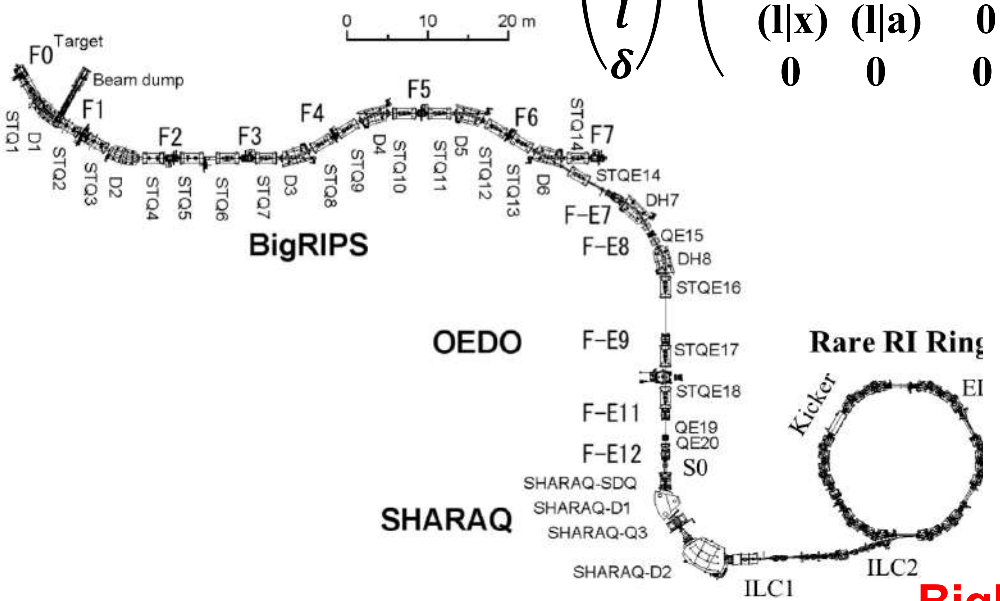
	(x|x)	(x|a)	(a|x)	(a|a)	(y|y)	(y|b)	(b|y)	(b|b)	(x|dp)	(a|dp)	(l|dp)	L|dEk
F3F4	-0.966	0	0	-1.03	-3.88	0	-0.04	-0.26	-1.86	-1.89	4.04	2.187439
F3F5	-0.01	-9.6	0.1	0	1.298	0	-0.06	0.77	0.108	0.505	8.81	4.771546
F3F6	0.965	0	0	1.036	-3.88	0	0	-0.257	7.54	0.368	11.62	6.296793
F3FE7	-0.394	9.7	-0.1	0.016	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

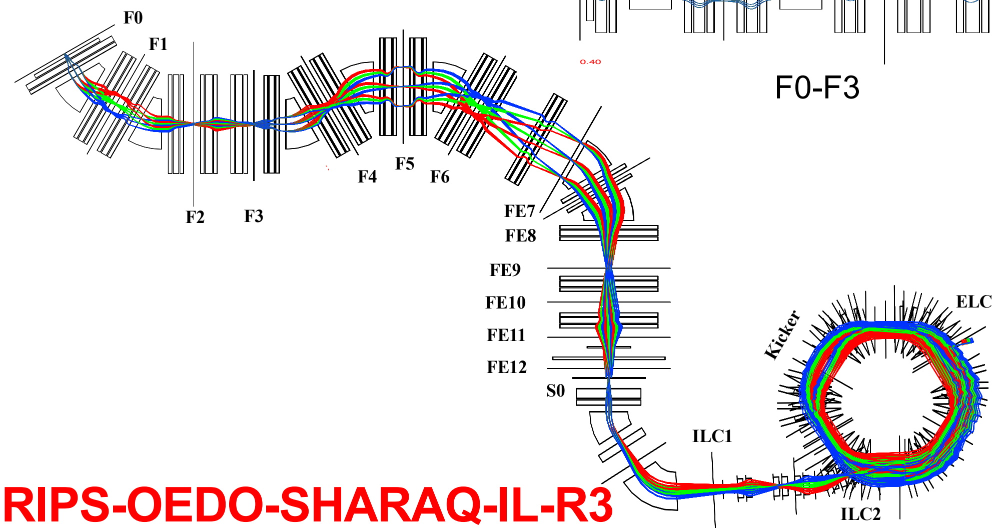
Transfer matrix :

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



F0-F3





BigRIPS-OEDO-SHARAQ-IL-R3

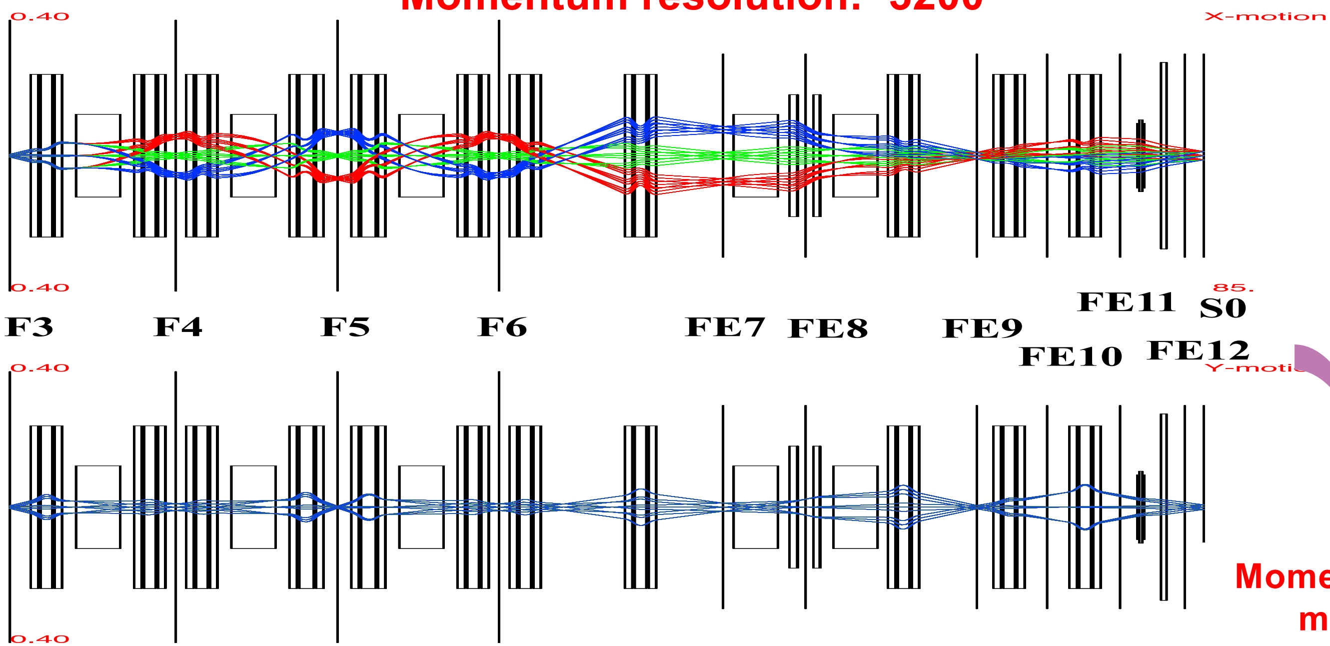
Optics Design of beam-line

Standard mode

Largest Dispersion function @F5

(x|dp)~3.3m/%
(x|x)~1.02
@F5x
Dispersive focus:
X: F4,F5,F6,FE7; Y: F4,F5,F6,FE7
double achromatic focus:
F3, FE9, S0

Momentum resolution:~3200



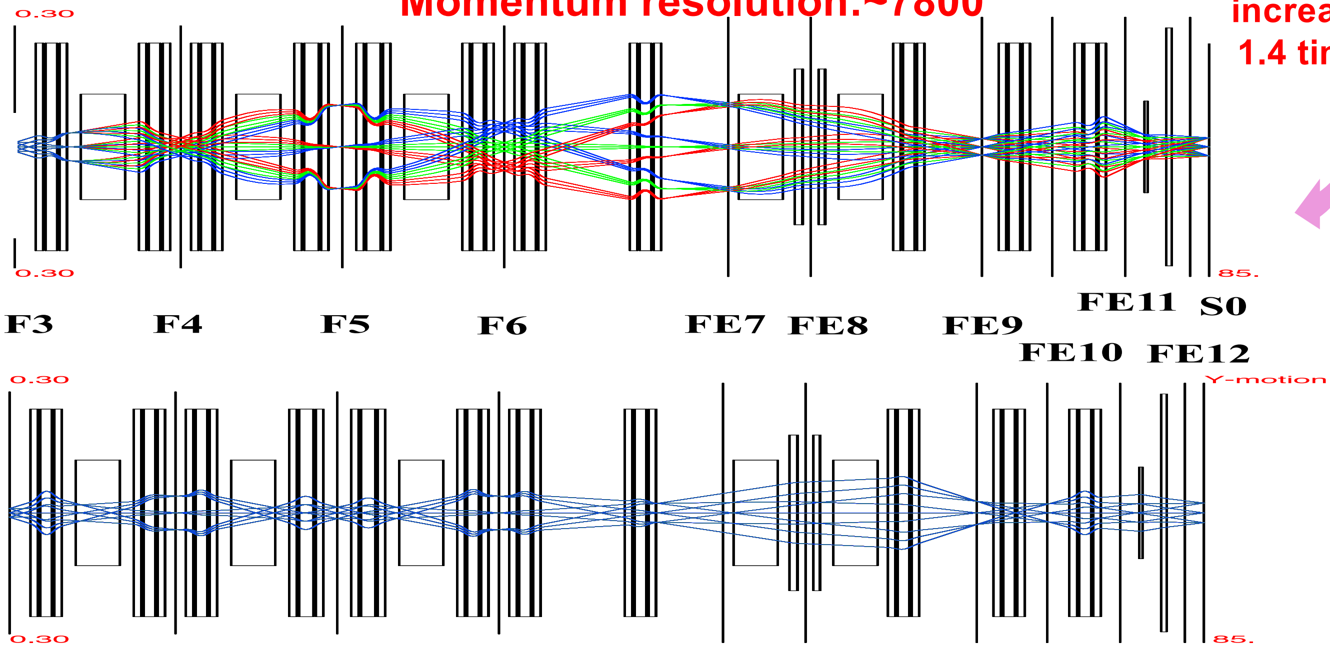
Momentum resolution increases 1.4 times

High-resolution (HA) mode

Largest Dispersion function @F6

(x|dp)~7.6m/%
(x|x)~0.9
@F6x
Dispersive focus:
X: F4,F6; Y: F4,F5,F6
double achromatic focus:
F3,FE9, S0

Momentum resolution:~7800

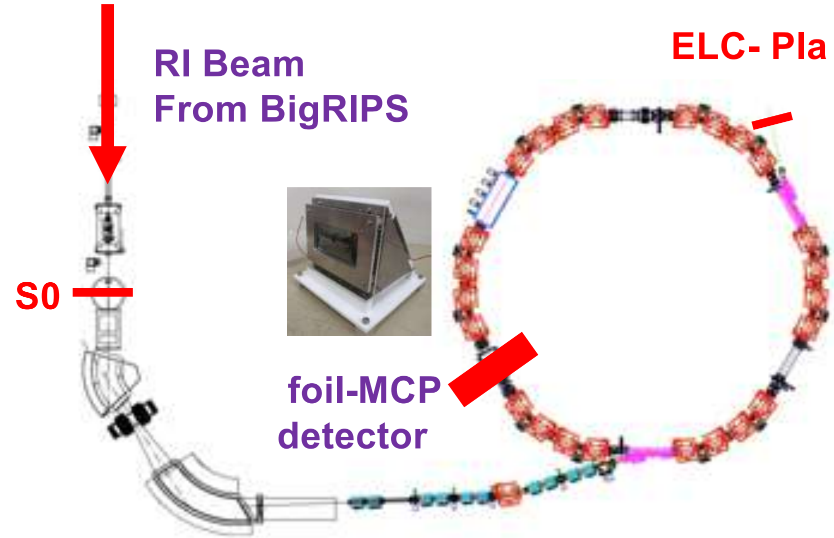


Revolution time determination

Circulation of turn number for each ion can be calculated from the Total TOF(s0->ELC) subtract the double kicker TOF over the MCP measured evolution time

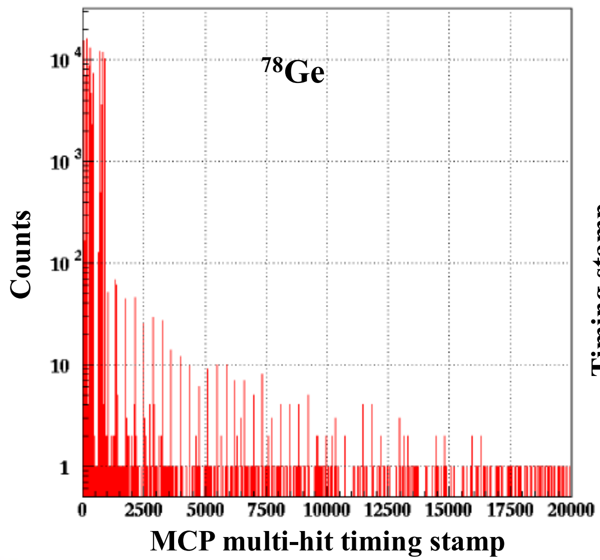
$$N = \frac{TOF^{total}_{(S0\rightarrow ELC)} - TOF^{doublekicker}_{(S0\rightarrow ELC)}}{T}$$

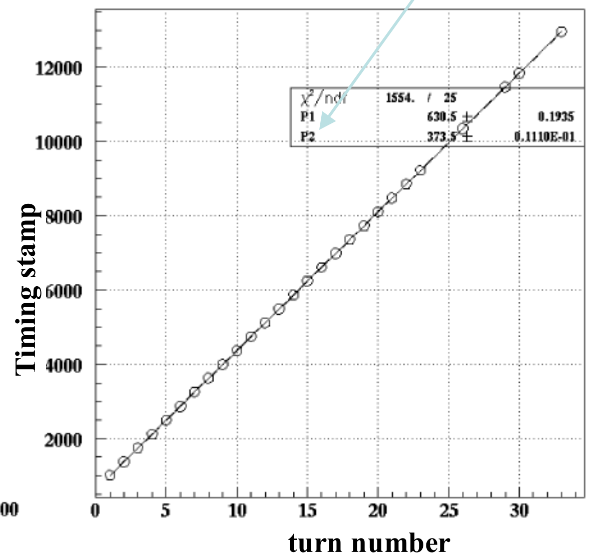
To remove the non-isochronous TOF from S0 to kicker center and kicker center to ELC



Multi-hit *time stamp*: $t = P2 * N + P1$

Revolution time: $T = P2$

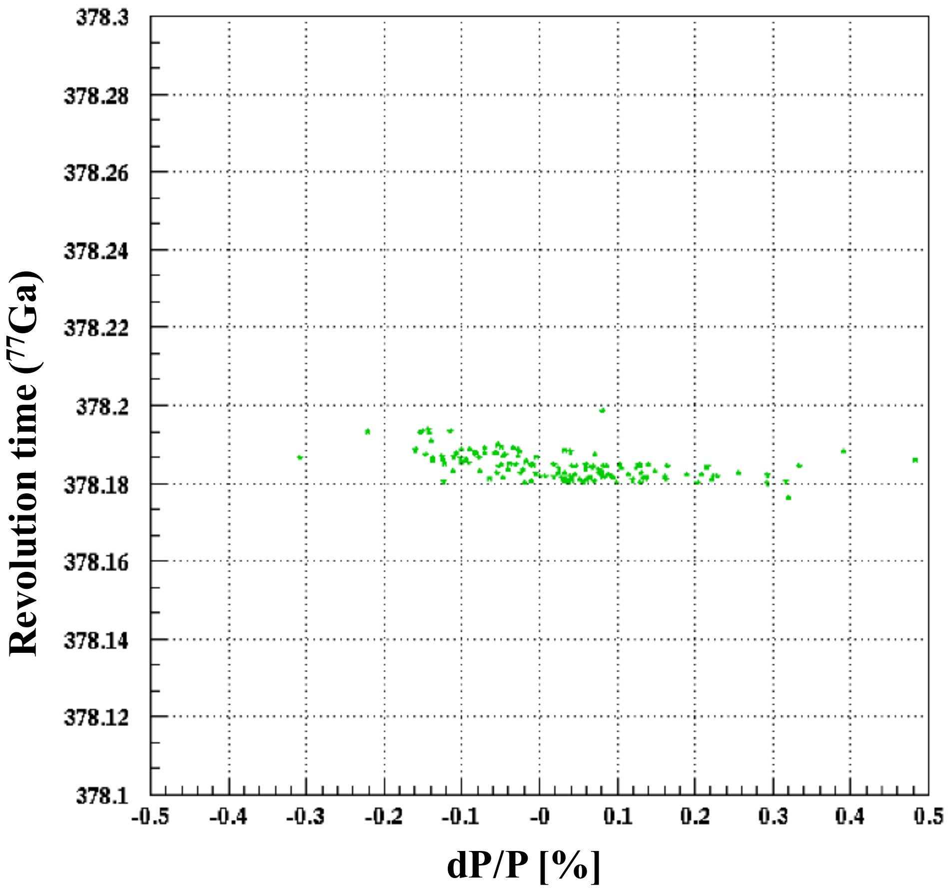


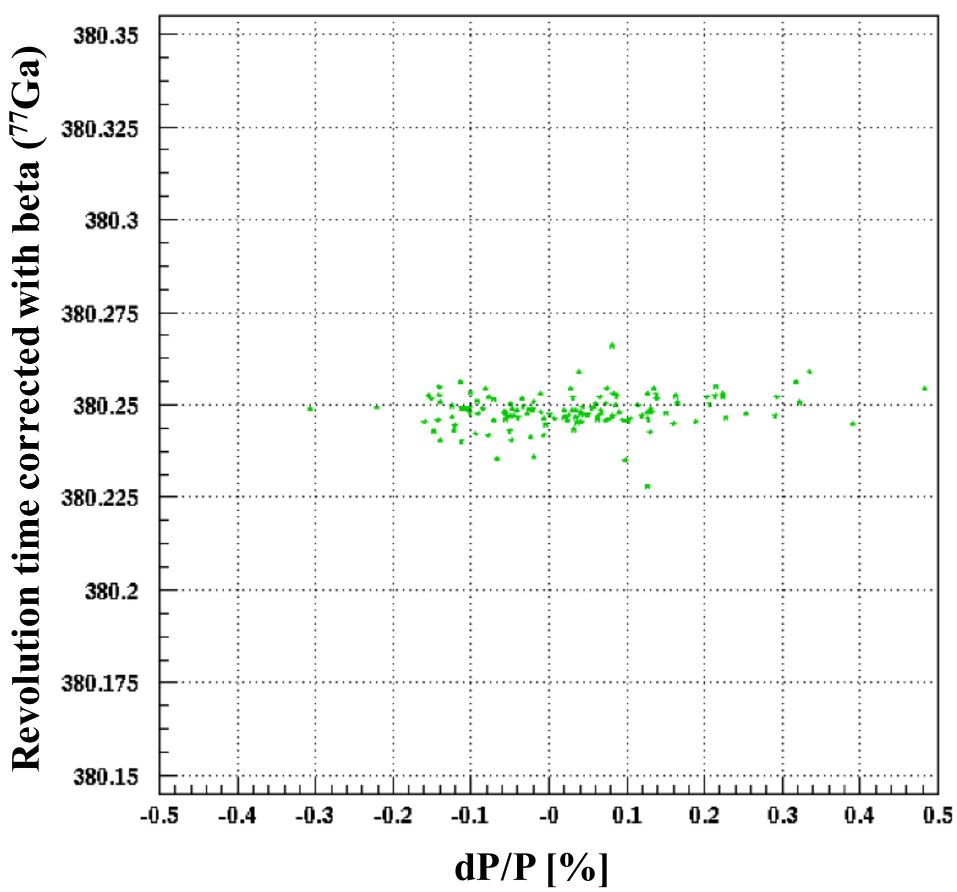


other particle's revolution time can be deduced from the relationship (assuming passing the same orbit):

$$\beta_0 T_0 = \beta_1 T_1$$

Mass measurements by IMS method





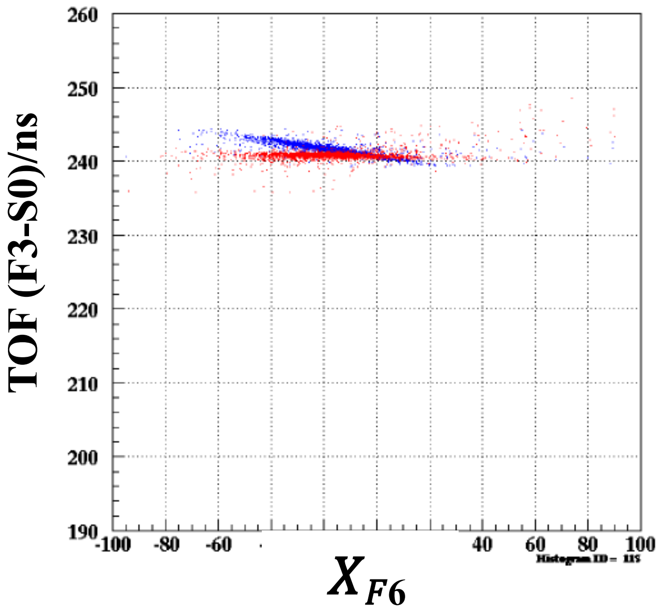
$$\left(\frac{m}{q}\right)_1 = \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-\left(\frac{T_1}{T_0}\beta_1\right)^2}}$$

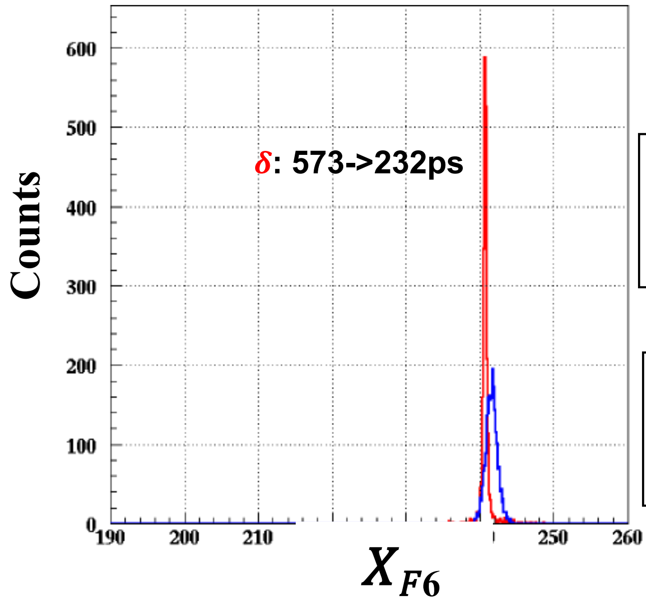
Mass accuracy: ~10^{-6}

Revolution time Correction by velocity measurements,
Velocity is deduced from TOF (F3-S0):

Mass measurements by B$\rho - TOF$ method

TOF determination with magnetic rigidity correction





X_{F6} : Proportional to momentum of ions

Mass measurements by B$\rho - TOF$ method:

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

$$\frac{m_0}{\sigma_{m_0}} = 1/\sqrt{\frac{\sigma^2_{(B\rho)}}{(B\rho)^2} + \frac{1}{k^2}\left(\frac{\sigma_t^2}{t^2} + \frac{\sigma_L^2}{L^2}\right)}$$

$$k = 1-(L/(ct))^2$$

$$\chi^2 = \sum_{\text{calibrants}} \frac{((m/q)_{\text{lit}} - f(\tau,z))^2}{(\sigma_{\text{lit}})_i^2 + (\sigma_{\text{stat}})_i^2 + \sigma^2_{\text{sys}}}$$

$$(\sigma_{\text{stat}})_i^2 = \left(\frac{\partial f(\tau,z)}{\partial \tau}\right)^2 \times \sigma_i^2(\tau)$$

m/q = f(T,A/Z,Z,A) :
Calibration function to deduce mass

Beam-line resolution:~2x10^{-4}

Advantages of the accelerated beam

BigRIPS&Rare-RI Ring @RIBF

Production → Transport (≈1us) (600 ns: brho-TOF) → Measurements (700us or less: IMS) → Detection

- ***background free and single ion sensitivity (event by even PID) of highly charged ions***

MRTOF/Penning-trap @ In-flight/ISOL- facilities

Production → Gas cell (few ms-120ms) → cooling (1-100ms) → Measurements (4-50ms) → Detection

Production → Target release (200ms or more) → cooling (1-100ms)

ISOL (chemical sensitivity)

- ***Cooled and bunched ion beam with backgrounds of molecules and adduct ions***

Proposed cases in RIKEN (No. 2)

C. Weber *et al.*, Phys. Rev. C 78, 054310 (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)
A. Hamaker, et al., Nat. Phys. 17, 1408–1412 (2021).

got 9 days of beam time

Nuclear Astrophysics

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

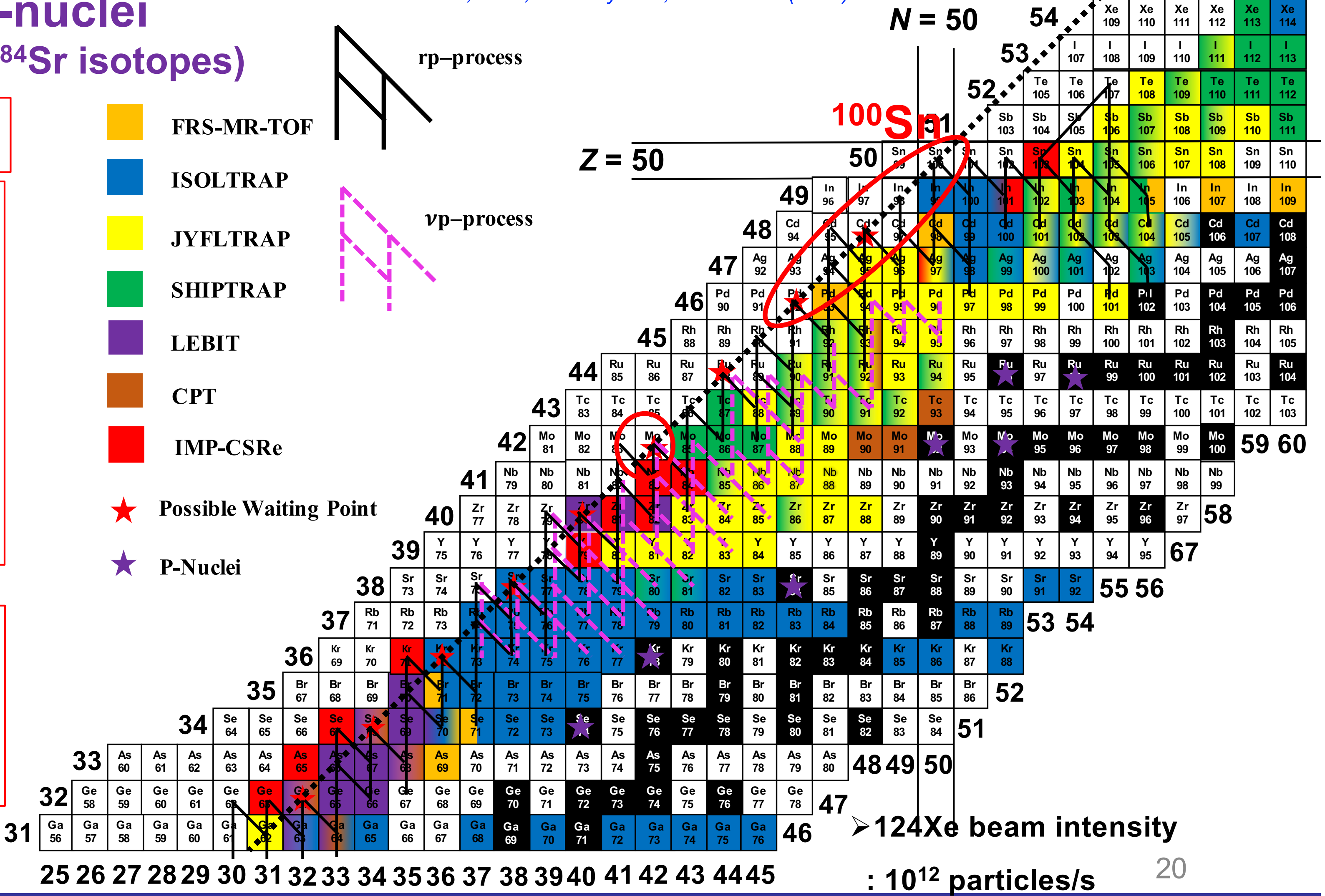
goals

Main settings: Isochronous mass spectrometry (IMS) By Rare-RI Ring

^{84}Mo, ^{83}Nb, ^{93}Pd, ^{92}Pd, ^{94}Ag, ^{96}Cd, ^{98}In, ^{100}Sn

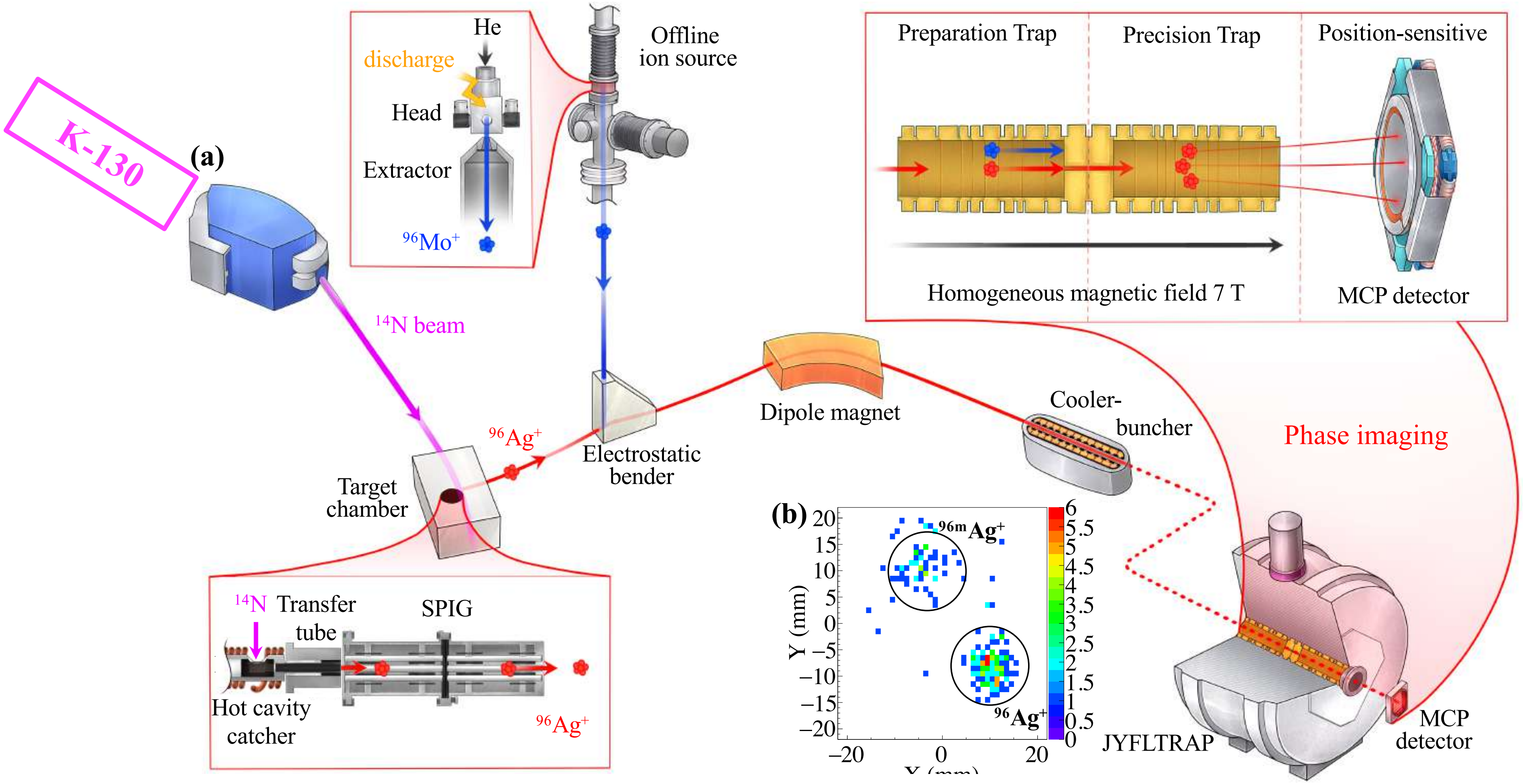
By-product: Magnetic-rigidity-time-of-flight (Bρ-TOF) With BigRIPS in conjunction with OEDO beam-line

^{90}Rh, ^{86}Tc, ^{83}Mo, ^{93}Ag



➢ ^{124}Xe beam intensity : 10^{12} particles/s

The Ion Guide Isotope Separator On-Line facility (IGISOL)

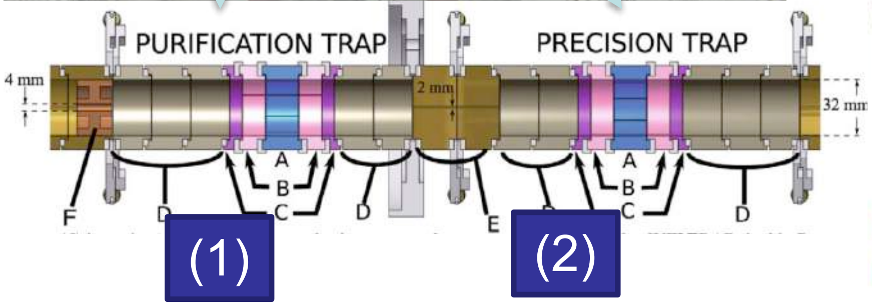


- **Production of ions of interest:**
  - **Proton beam of 5-65 MeV**
  - **Proton-induced fission**
  - **P/heavy ion-induced fusion-evaporation**
  - **Target**
    - **^{nat}U: 15mg/cm^2**
    - **natural-abundance/enriched target ~ few mg/cm^2**

- **Production of reference nucleus:**
  - **Co-produced from the Target chamber**
  - **Electrode of reference material installed in the spark source**

JYFLTRAP double Penning trap

JYFLTRAP double Penning trap



Eronen et al., EPJA 48 (2012) 46

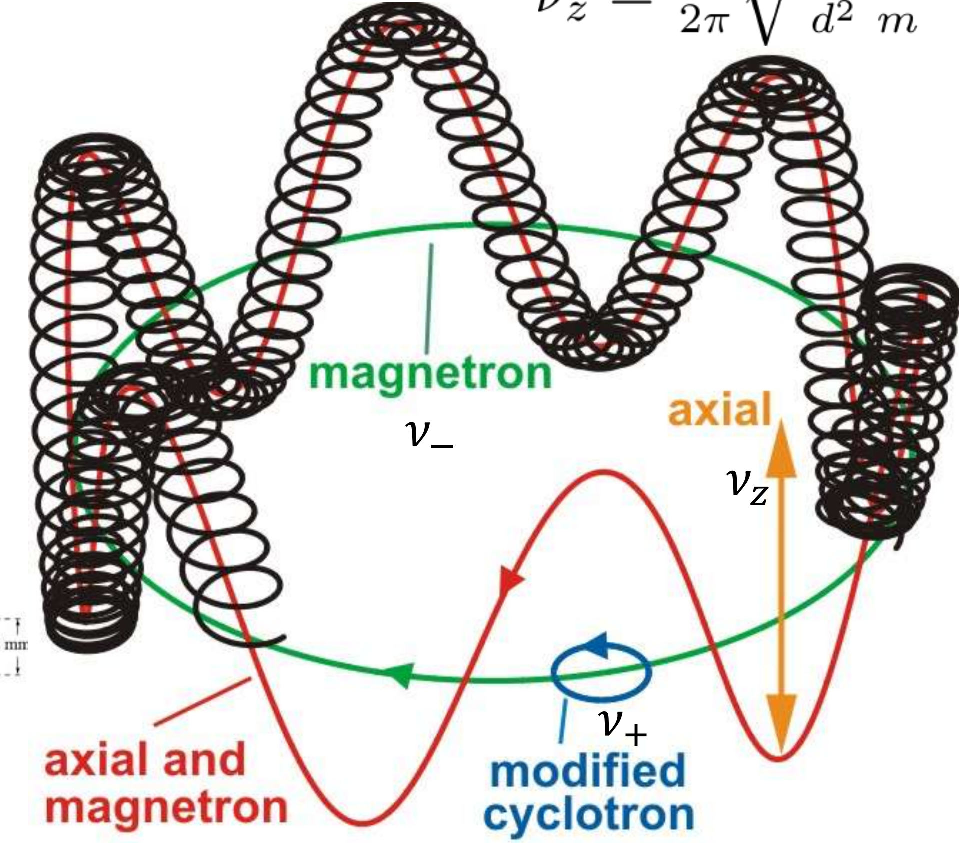
Cyclotron frequency

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

Penning trap eigenfrequencies:

$$\nu_\pm = \frac{1}{2}\left(\nu_c \pm \sqrt{\nu_c^2 - 2\nu_z^2}\right)$$

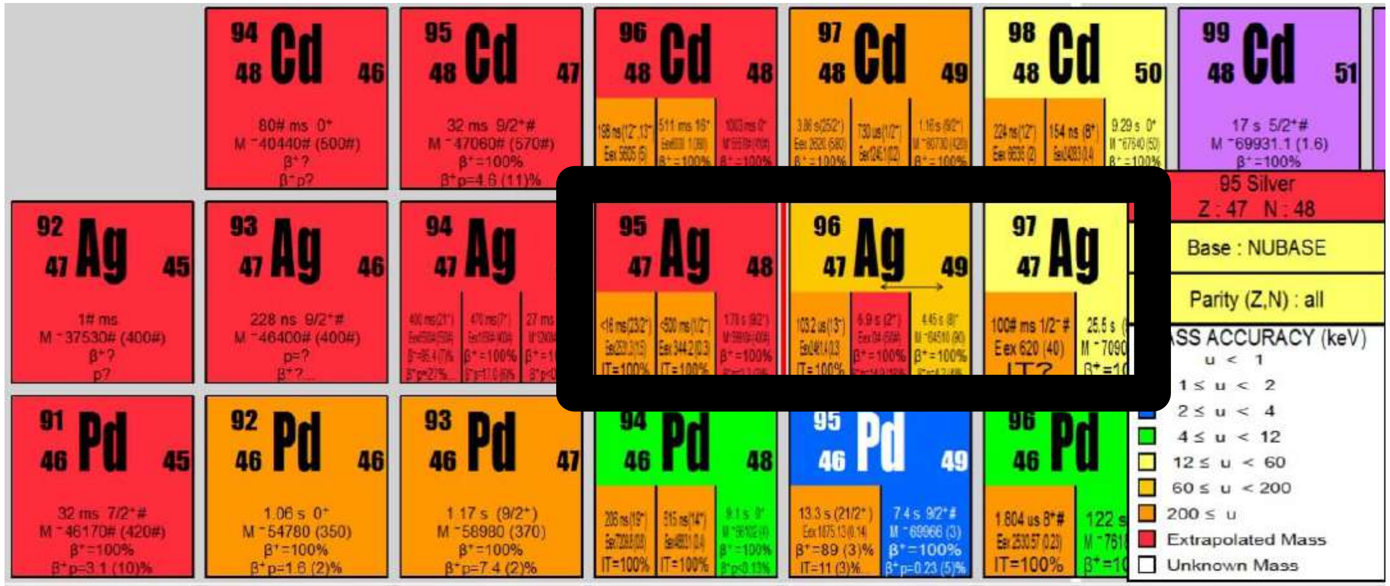
$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{U_0}{d^2}\frac{q}{m}}$$



Invariance theorem:

$$\nu_c^2 = \nu_-^2 + \nu_+^2 + \nu_z^2$$

95-97Ag mass measurements



Cyclotron frequency:

$$\nu_c = \nu_+ + \nu_- = \frac{qB}{2\pi m}$$

Frequency ratio *r*:

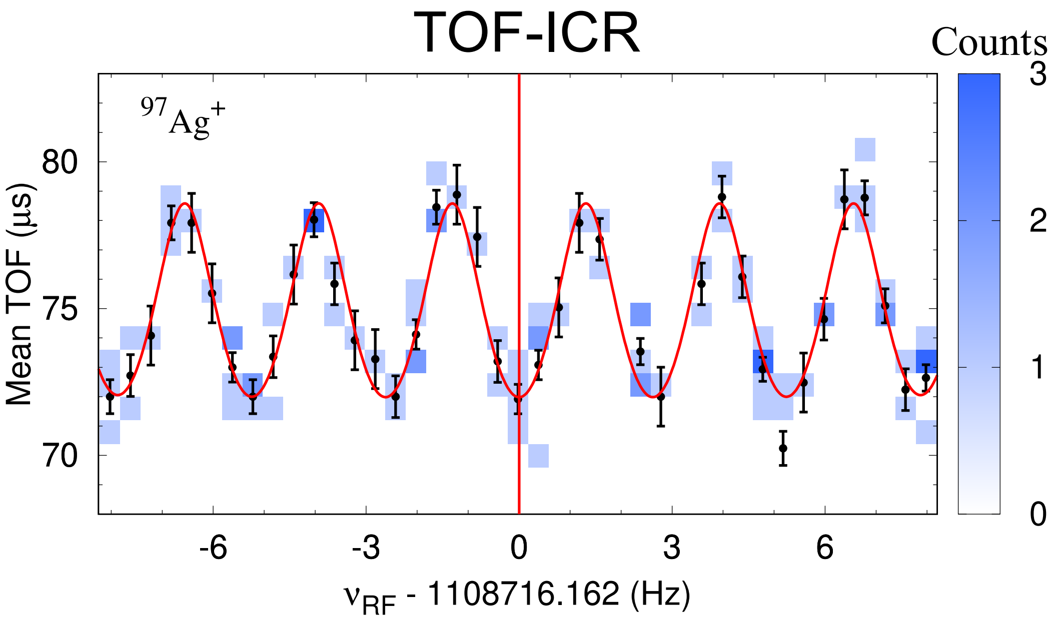
$$r = \frac{\nu_1}{\nu_2}$$

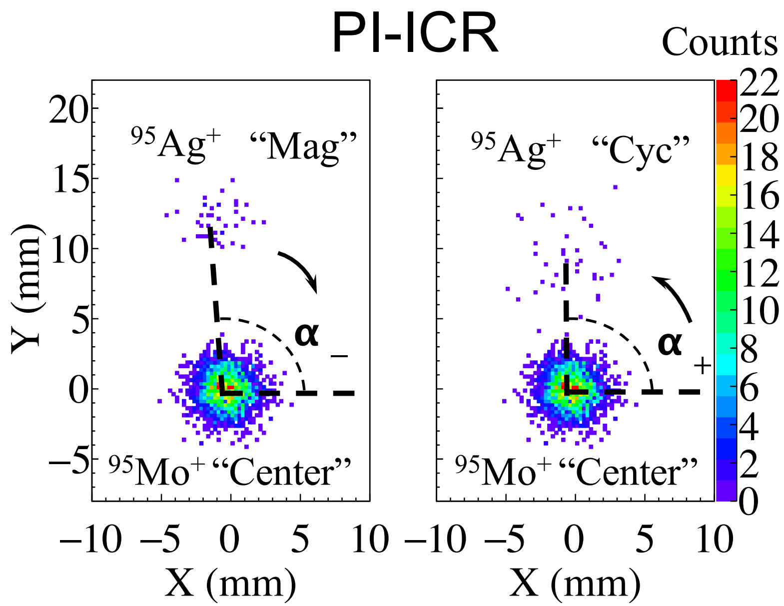
***Q*-value:**

$$Q = M_2 - M_1 = (r-1)(M_1 - m_e) + m_e$$

Mass:

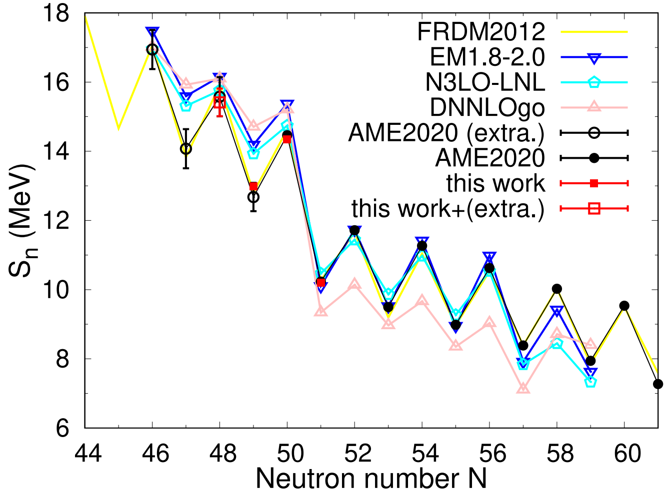
$$M_2 = r(M_1 - m_e) + m_e$$

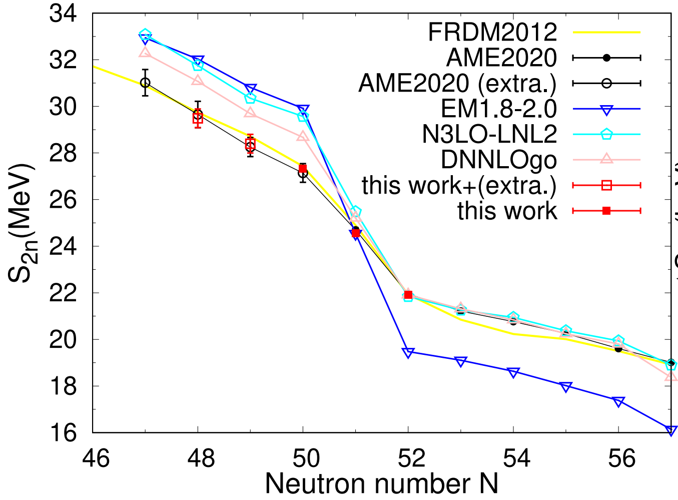


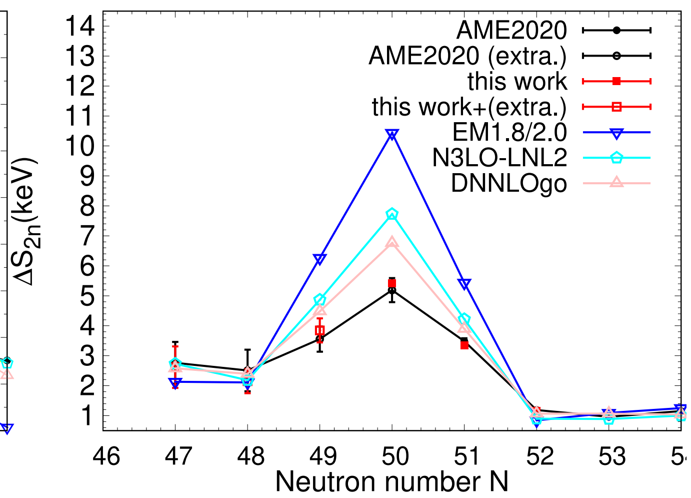


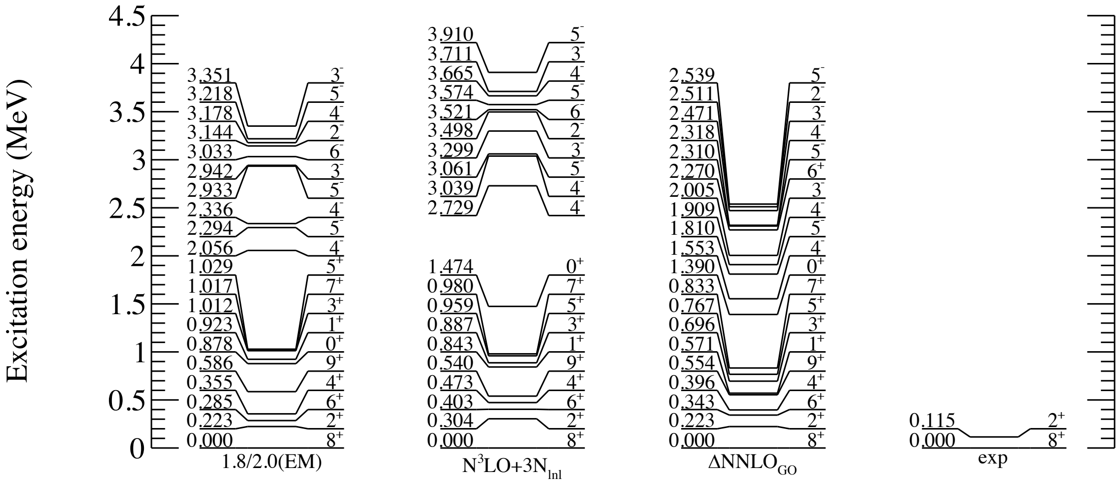
ab initio calculations

ab-initio calcluation crosswa the N=50 shell





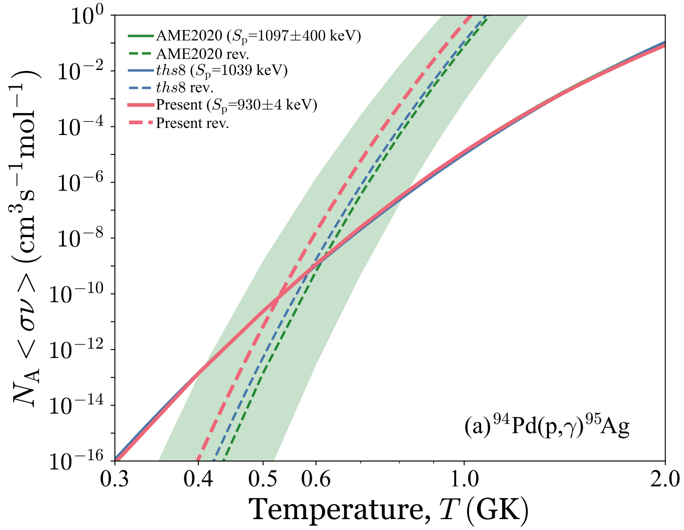


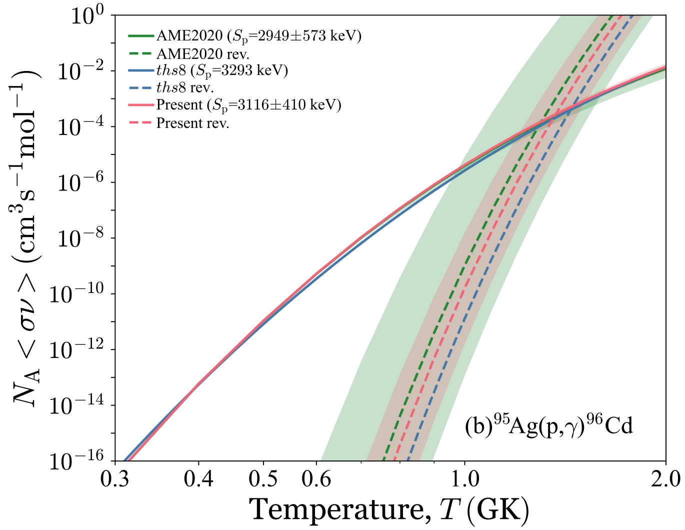


energy level of 96Ag isomeric state

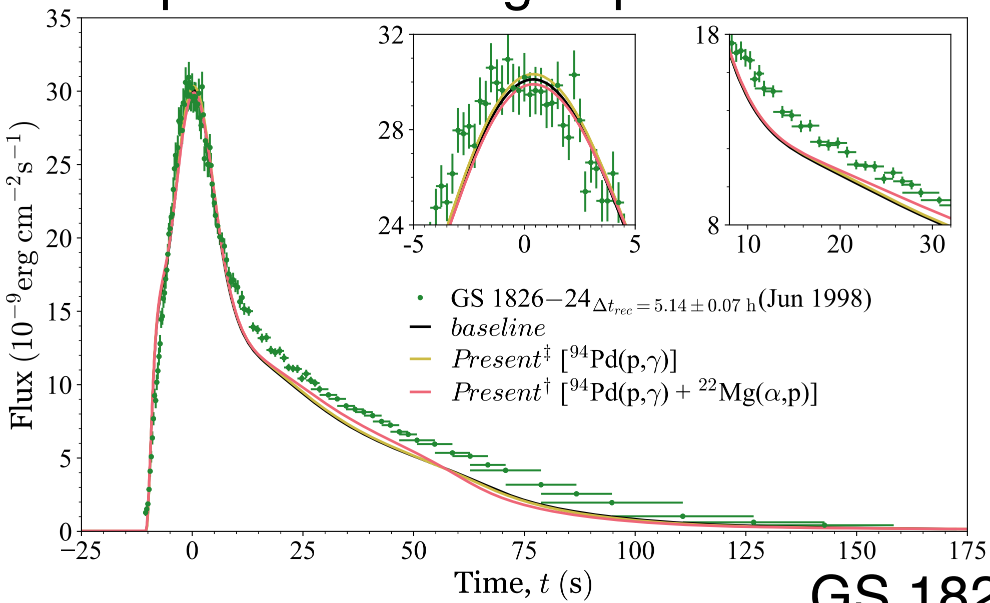
Impact on nuclear astrophysics

Influence on Forward and reverse thermonuclear reaction rates





Impact on averaged periodic burst light curves

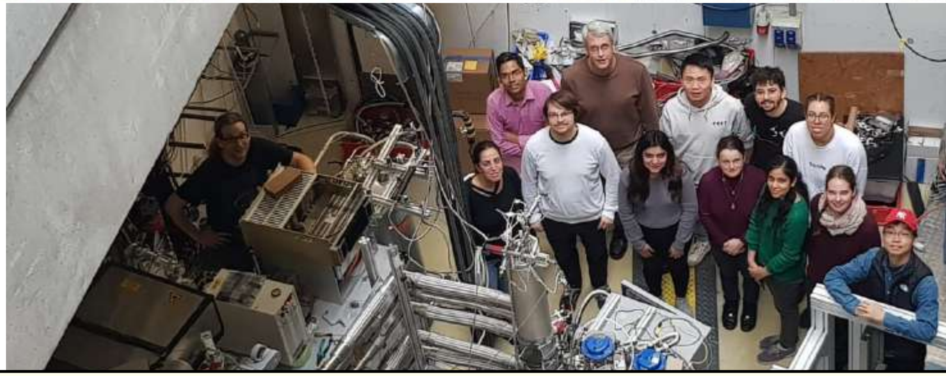


GS 1826–24 clocked burster

Summary and outlook

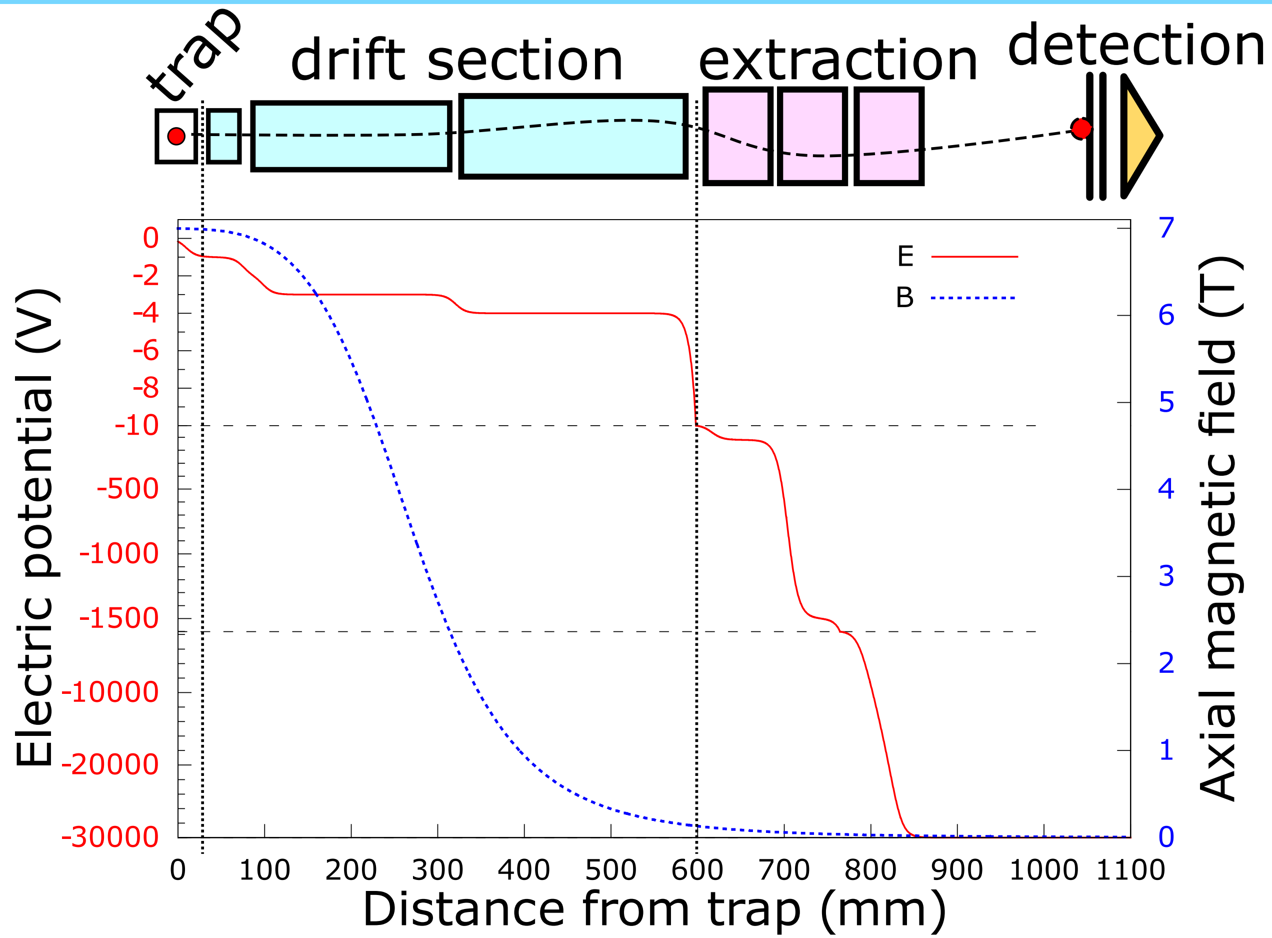
- Technique developments at R3 and Mass measurements with IMS and Brho-TOF method
  - Ion of interest selection and Particle identification
  - Optics design
  - mass measurement with IMS with R3
  - mass measurements with Brho-TOF method at the BigRIPS-OEDO beamline
  - Mass measurements with complementary methods at RIBF
- Mass measurements of ground states and isomers by fusion evaporation reactions at IGISOL with JYFLTRAP
  - mass measurements of ^{95}Ag for the first time
  - New direct mass measurement of $^{96-97}$Ag and first direct measurement of the isomer ^{96m}Ag
  - Ab-initio calculations of nuclear biding for the Ag isotopes and implications of N=50 shell
  - Impact on nuclear astrophysics
- **Outlook: towards more exotic nuclei for mass measurements of heavy *N=Z* nuclei up to ^{100}Sn @ IGISOL/RIKEN/GSI-FAIR**
  - **Mass measurement with IMS (storage ring), Brho-TOF (BigRIPS) at RIBF, JYFLTRAP, MRTOF at IGIOSL and collaboration with MR-TOF at GSI-FAIR**

Acknowledgements



Fundings: **Academy of Finland under the Finnish Centre of Excellence Programme** 2012-2017 (Nuclear and Accelerator Based Physics Research at JYFL) and projects No. 306980, 312544, 275389, 284516, 295207, 314733, 315179, 327629, 320062 and 345869. The support by the **EU Horizon 2020 research and innovation programme** under grant No. 771036 (ERC CoG MAIDEN) is acknowledged. This project has received funding from the **European Union's Horizon 2020 research and innovation programme** under grant agreement No. 861198-LISA-H2020-MSCA-ITN-2019.

TOF-ICR method



T. Eronen et al. / Progress in Particle and Nuclear Physics 91 (2016) 259–293

Flight-of-time (TOF) from trap to MCP detector:

$$T(\omega) = \int_0^{z'} \sqrt{\frac{m}{2(E_0 - qU(z) - \mu B(z))}} \mathrm{d}z$$

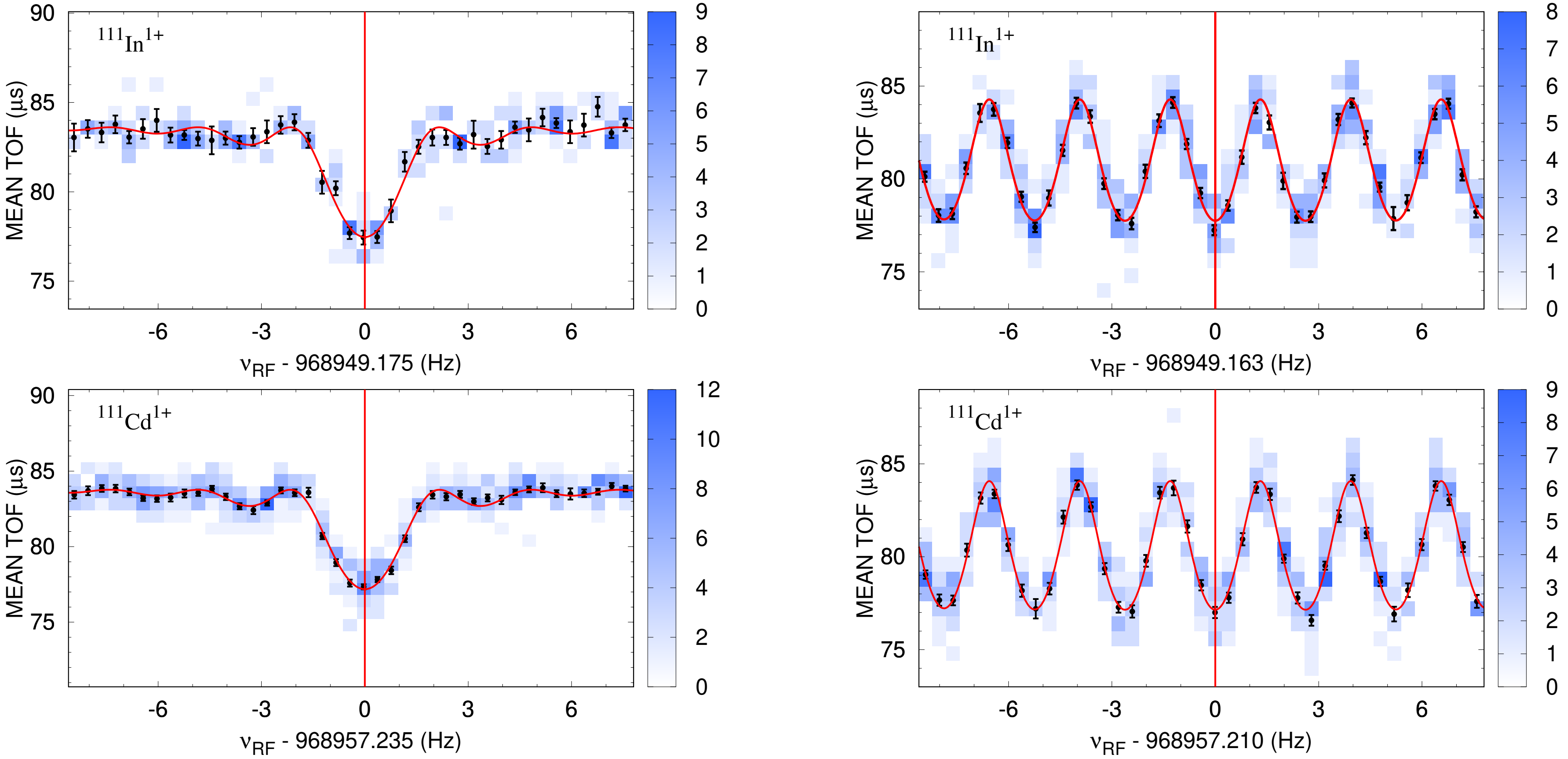
E_0: initial axial kinetic energy of the ion,
U(z): electrostatic potential and
B(z): the magnetic field along the flight path

Measurement procedure:
scanning the quadrupolar excitation frequency ν_{RF} around the cyclotron frequency ν_c and determining the frequency resulting in the shortest flight time from the trap to the MCP detector

TOF-ICR method

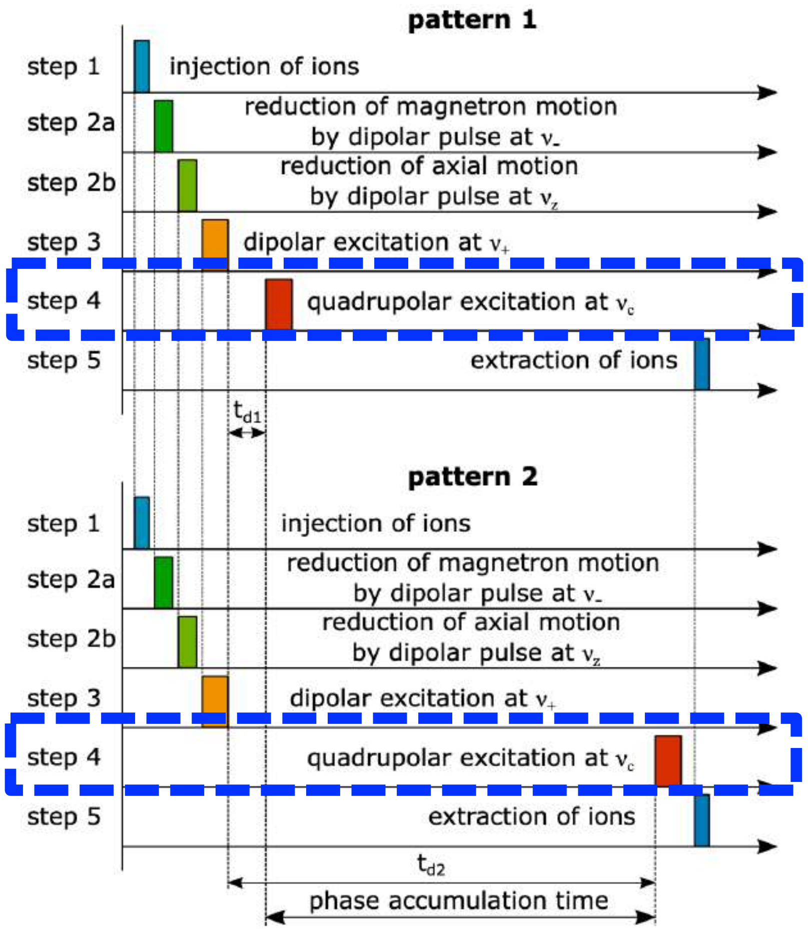
one-pulse radio-frequency (rf) field (400 ms)

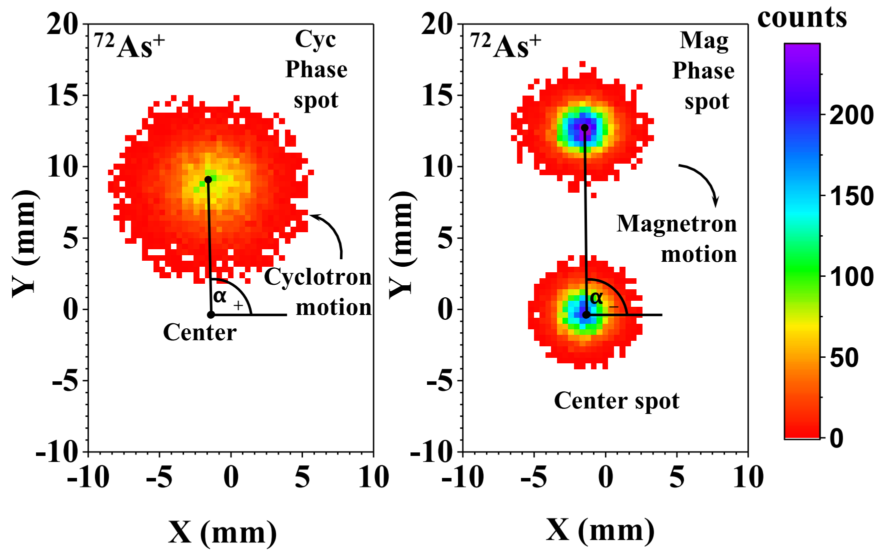
two-pulse rf field (25-350-25 ms)



Interleaved measurements of Ion-of-interest and reference (^{111}In and ^{111}Cd)

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





- Dipolar excitation at ν_+
  - Direct conversion to magnetron motion
    → Magnetron phase
  - Accumulation then conversion to magnetron motion
    → Modified cyclotron phase

- **Cyclotron frequency:**

$$\nu_c = \nu_+ + \nu_- = \frac{qB}{2\pi m}$$

- **Frequency ratio *r*:**

$$r = \frac{\nu_1}{\nu_2}$$

Determine

- ***Q*-value:**

$$Q = M_2 - M_1 = (r-1)(M_1 - m_e) + m_e$$

- **Mass:**

$$M_2 = r(M_1 - m_e) + m_e$$

methods

Eronen et al., EPJA 48 (2012) 46

1. TOF-ICR

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

G. Gräfft et al.,, Zeitschrift für Physik A: Atoms and Nuclei 297, 35 (1980).

a. Normal TOF-ICR

b. Ramsey TOF-ICR

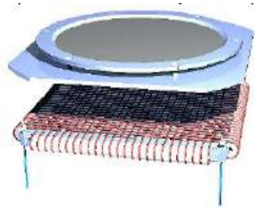
2. PI-ICR

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

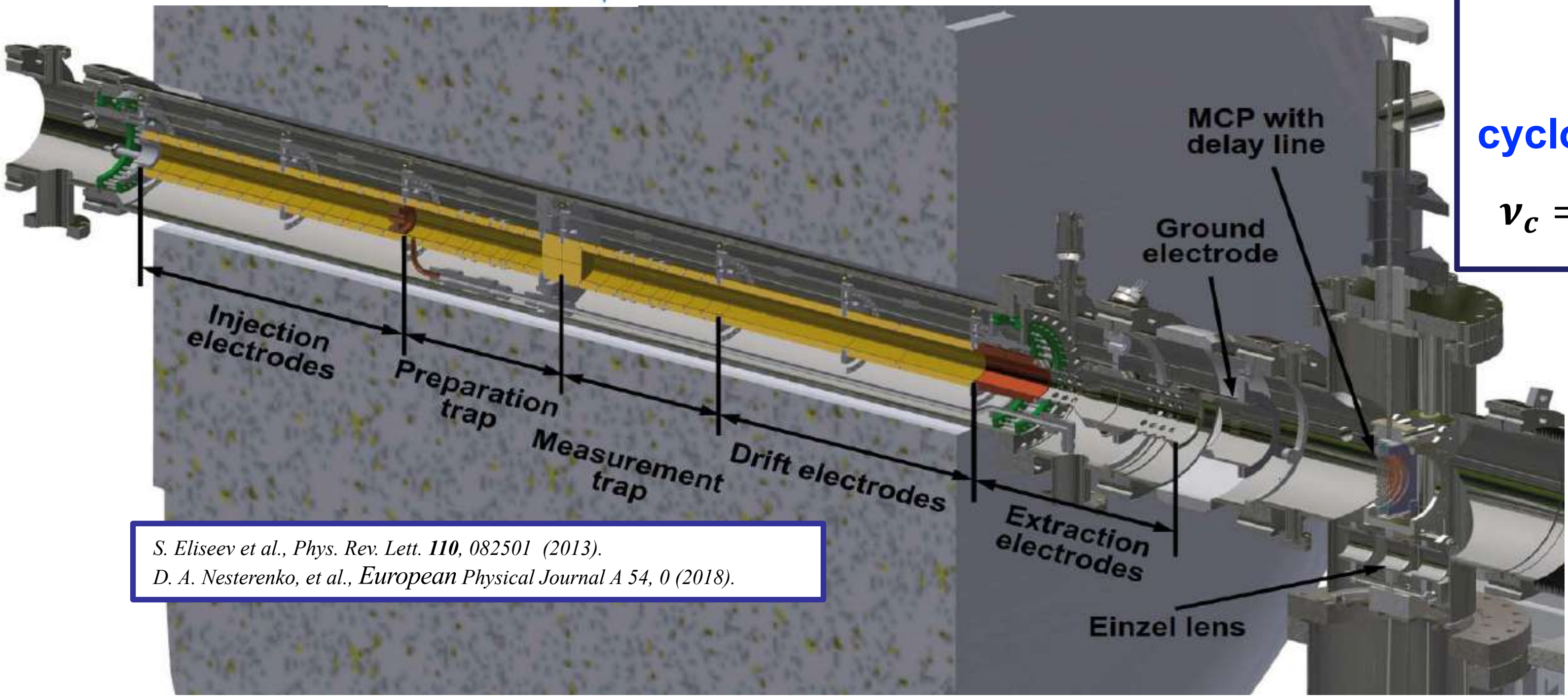
S. Eliseev et al., Phys. Rev. Lett. ***110****, 082501 (2013).*

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

Delay-Line Microchanel Channel Plate (MCP) Detector from Roentdek GmbH



Position sensitive detector



S. Eliseev et al., Phys. Rev. Lett. ***110****, 082501 (2013).*
D. A. Nesterenko, et al., European Physical Journal A 54, 0 (2018).

Angle between cyclotron and magnetron motion phases with respect to the center spot:

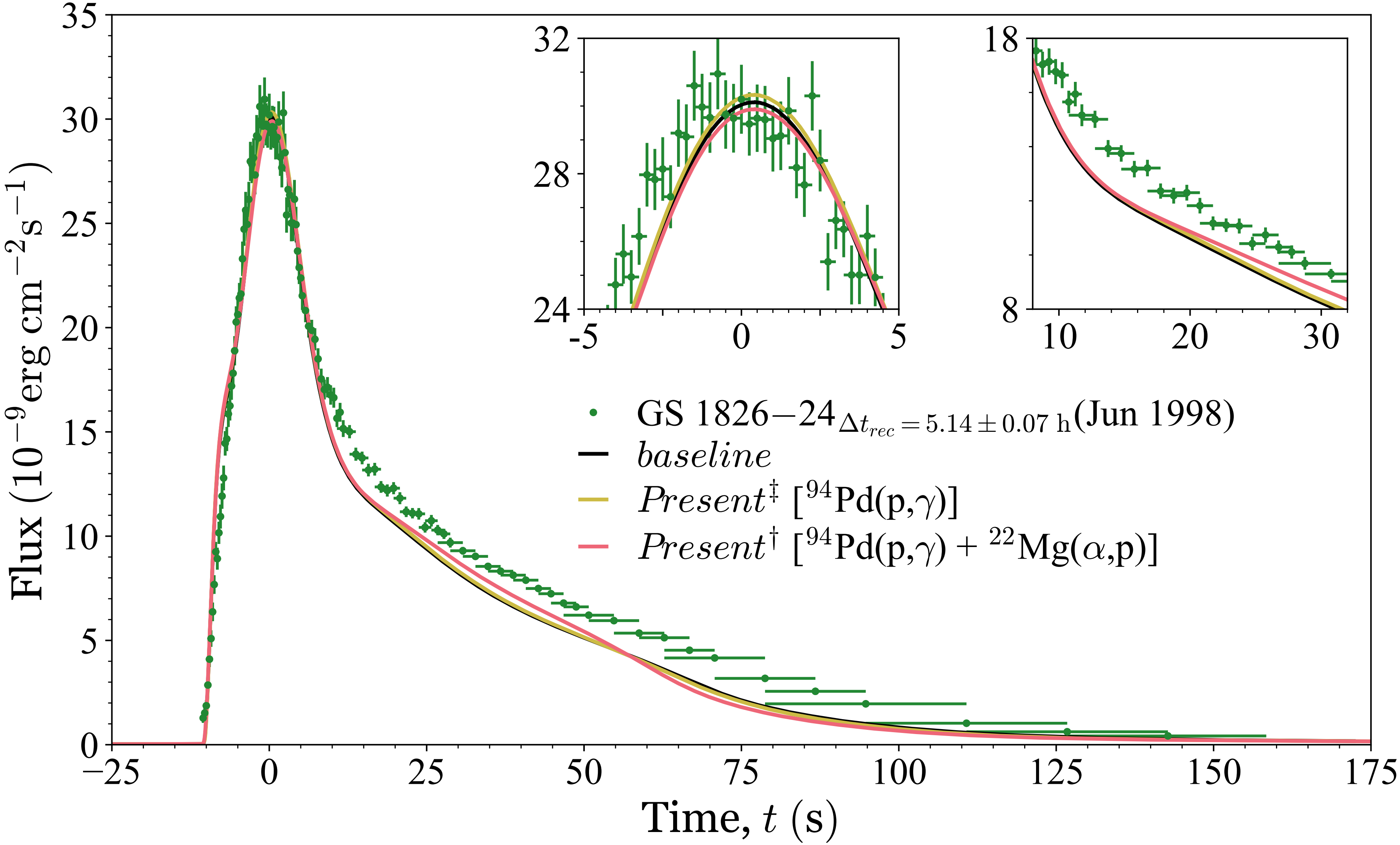
$$\alpha_c = \alpha_- + \alpha_+$$

cyclotron frequency:

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

Impact on averaged periodic burst light curves

GS 1826–24 clocked burster



Detectors at beam-line

- Standard beam-line detectors at BigRIPS for TOF, Bρ, ΔE measurement for PID
- Clover-type Ge detectors for isomer measurement

(1). Delay-line PPAC

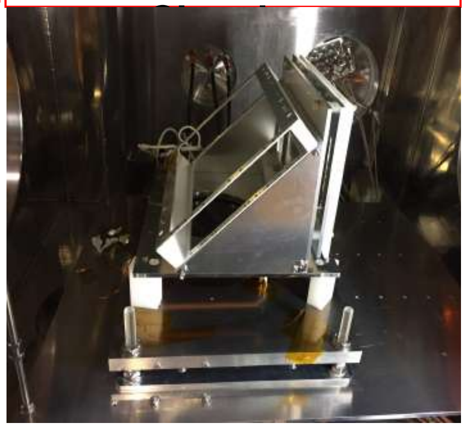
(2). Plastic Scintillator

(3). Ionization

(4). BE-MCP

(5). γ-ray (Ge) detector

(6). Si detector



(7). E-MCP

Function of detectors:

ΔE:

IC, Si

Isomer γ-ray:

Clover-Ge

TOF:

Scintillator, E-MCP, BE-MCP

Position:

DL-PPAC, CD-PPAC

Collaboration list

T. Eronen,[1] Z. Ge,[1] A. de Roubin,[2] D. A. Nesterenko,[1] M. Hukkanen,[1, 2] O. Beliuskina,[1] R. de Groote,[1] C. Delafosse,[1] S. Geldhof,[1], W. Gins,[1] A. Kankainen,[1] Á. Koszorús,[7] I. D. Moore,[1] H. Penttilä,[1] A. Raggio,[1] S. Rinta-Antila,[1] M. Stryjczyk,[1] V. Virtanen,[1] A. P. Weaver,[8] A. Zadvornaya,[1] A. Jokinen[1] and the IGISOL collaboration

Theory
experiment

K. S. Tyrin,[3] M. I. Krivoruchenko,[3,4] J. Kostensalo,[1] J. Kotila,[5,6] J. Suhonen,[1]

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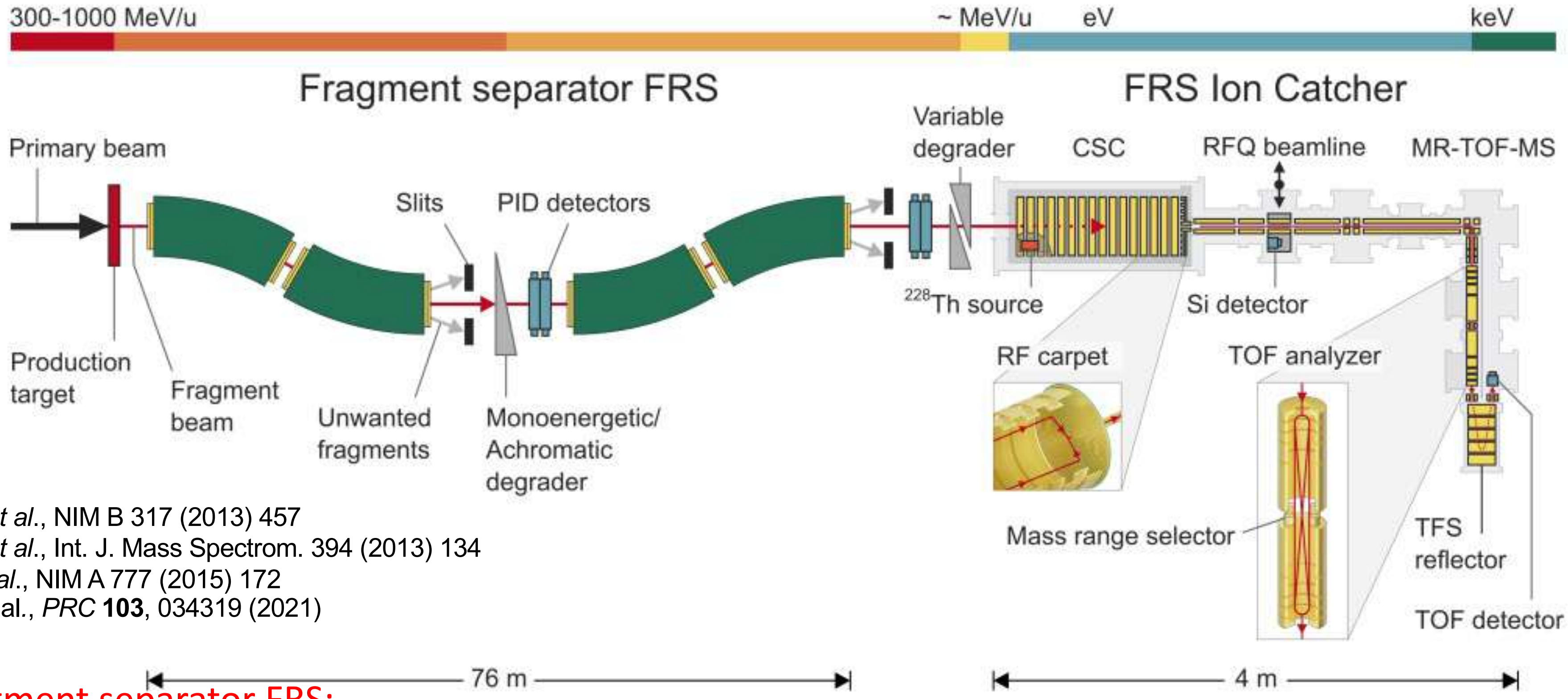
J. Jaatinen and R. Seppälä, for preparing the production target

The FRS Ion Catcher at GSI



W.R. Plaß *et al.*, NIM B 317 (2013) 457
W.R. Plaß *et al.*, Int. J. Mass Spectrom. 394 (2013) 134
T. Dickel *et al.*, NIM A 777 (2015) 172
I. Mardor et al., *PRC* **103**, 034319 (2021)

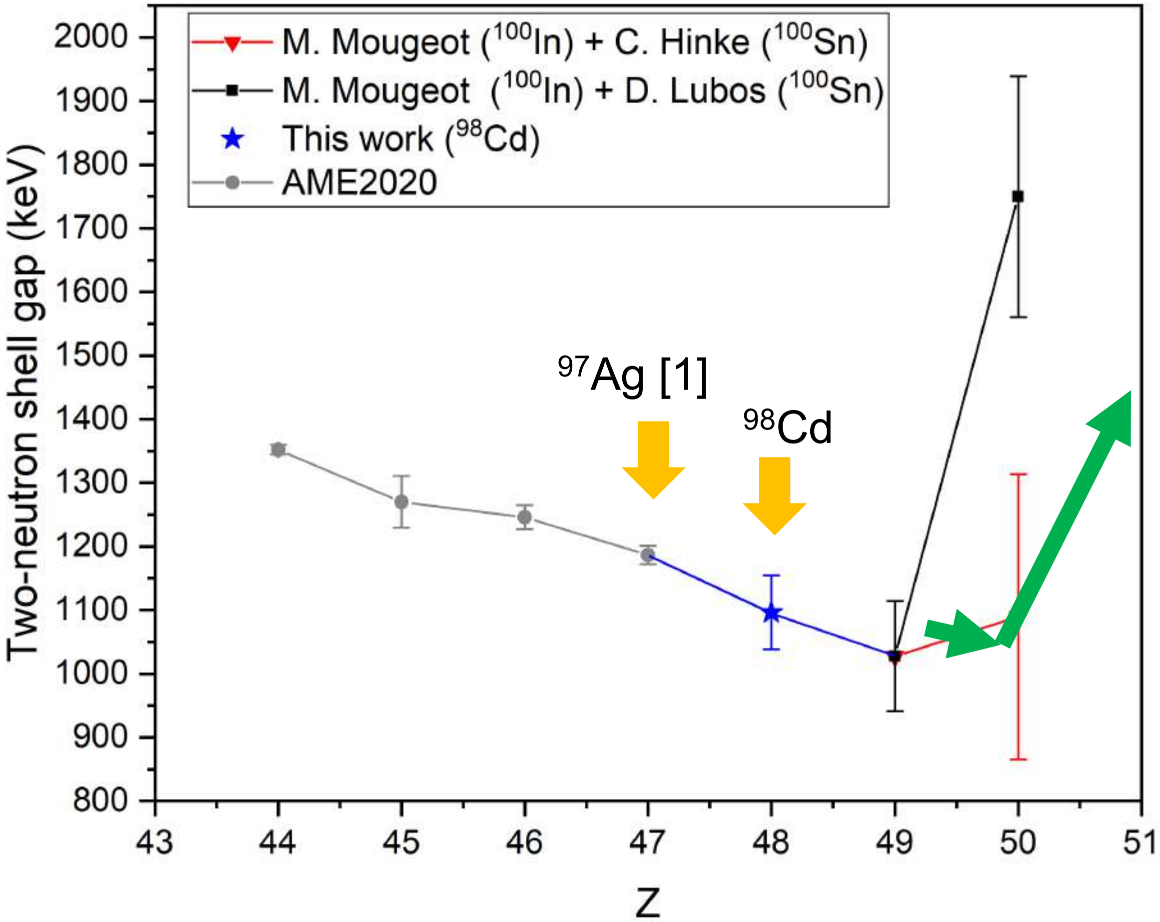
- Fragment separator FRS:
  - Production & separation of exotic nuclei via projectile fragmentation/fission
- Cryogenic Stopping cell (CSC):
  - universal, fast, efficient stopping and extraction

  cooled short-lived ($T_{1/2}$ ~ ms) exotic nuclei
- RF Quadrupole beamline:
  - for low-energy ion transport
  - Operate as a mass filter
  - Background Suppression (molecular and ions)

- MR-TOF-MS

fast, sensitive, broadband and non-scanning
- Resolving power: 1,000,000
- resolve isomers (hundreds of keV)
- Mass accuracy: 1.7×10^{-8}
- Sensitivity: a few detected ions
- Rate capacity: 10^6 ions/s
- Cycle times: a few ms

Two-neutron shell gap (shifted for *N*+2)



A. Mollaebrahimi et al., (*in preparation)*

$$\Delta_{2n}(Z,N+2) = ME(Z,N) - 2ME(Z,N+2) + ME(Z,N+4)$$

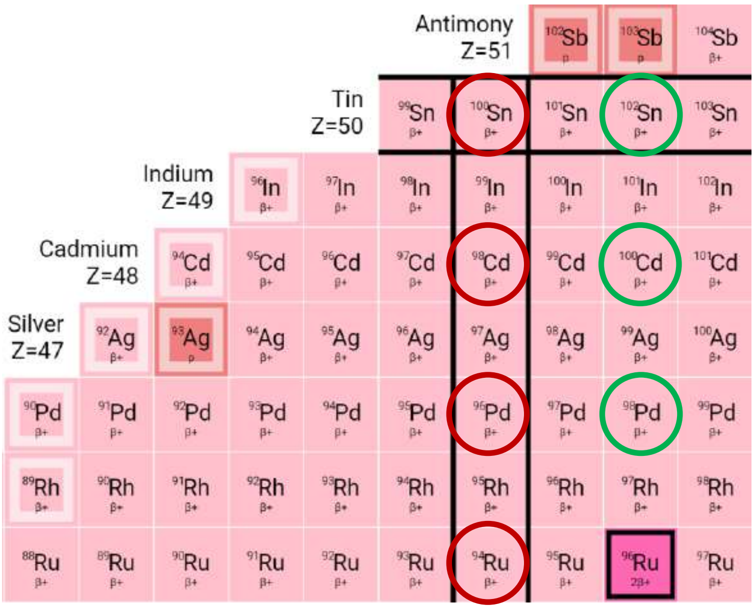
- The mass of ^{100}In is measured in [**M. Mougeot et al**] paper and then the mass of ^{100}Sn is derived by using two Q_{EC} values from [**C. Hinke et al.**] and [**D. Lubos et al.**]
- The Q_{EC} from **[D. Lubos et al.] was unfavorable** in comparison to ab-initio calculation done in [M. Mougeot et al.]

M. Mougeot et al., *Nature Physics* (2021)
C. Hinke et al., *Nature* **486** (2012)
D. Lubos at al., *Physical Review Letters* **122** (2019)
[1] C. Hornung et al., *Physics Letters B* **802** (2020)

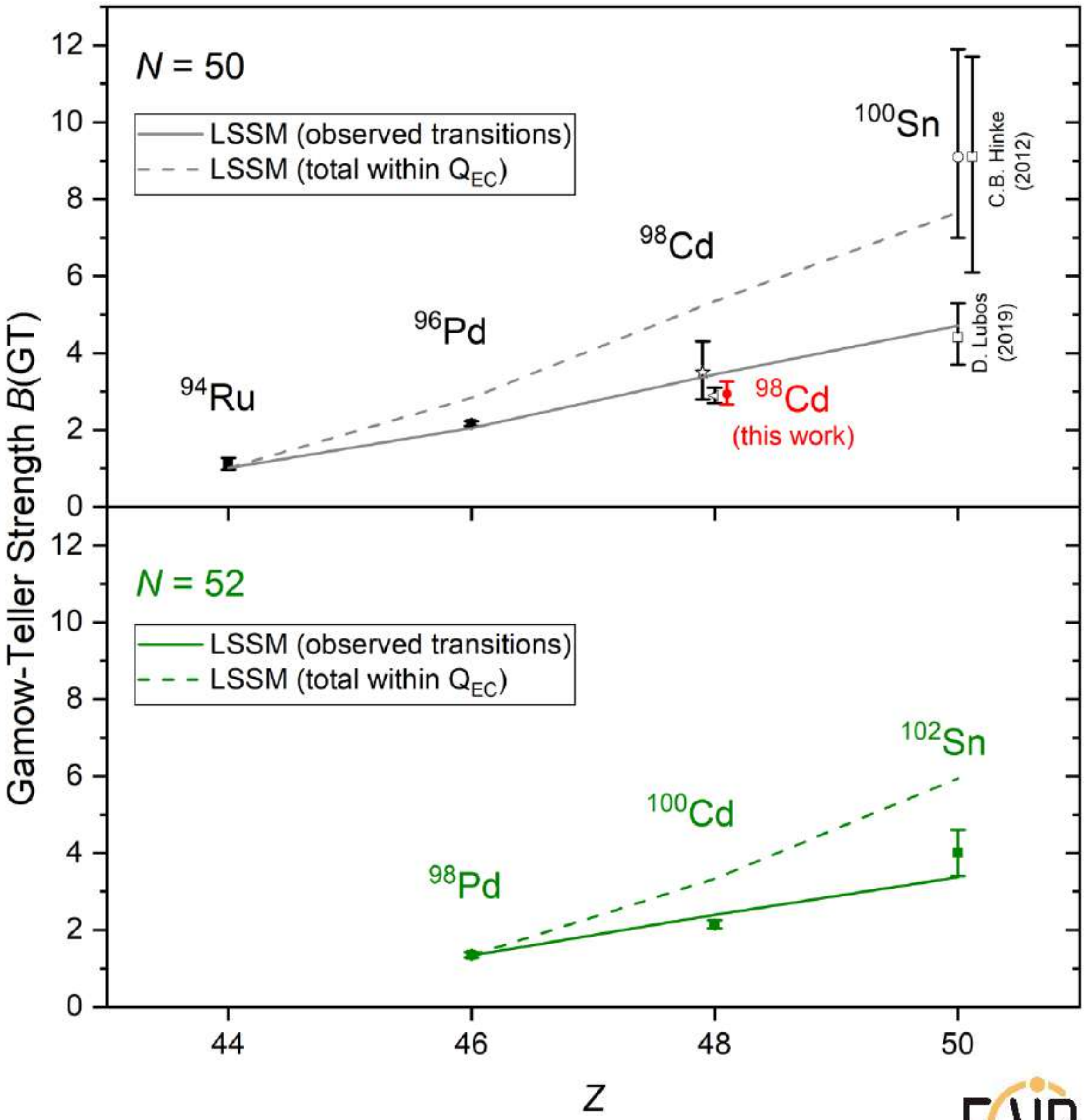
Gamow-Teller strength for even-even isotones at *N=50*

$$B(\mathrm{GT}) = \frac{2\pi^3\hbar^7 ln(2)}{m_e^2 c^4 G_F^2 V_{ud}^2 (G_A/G_V)^2 f t_{1/2}} = \frac{3885 \pm 14\,s}{f(z,\epsilon_0)t_{1/2}}$$

- Even-even isotones at *N=50* with 0^+ initial states
- Proton from shell $1g_{9/2}$ changes to neutron in shell $1g_{7/2}$
- B(*GT*) are calculated based on the latest ($Q_{EC}, t_{1/2}$ and decay scheme)



A. Mollaebrahimi et al.



A. Plochocki et al., *Zeitschrift fur Physik A* **342** (1992)
A. Stolz at al., *GSI Scientific Reports* **1** (2001)
A. Stolz at al., AIP conference proceeding **610** (2002)
C. Hinke et al., *Nature* **486** (2012)
D. Lubos at al., *Physical Review Letters* **122** (2019)