Mass measurements with modern techniques

---- Mass/Q-value measurements wtih
JYFLTRAP at IGISOL
&MR-TOF at GSI-FAIR
&Rare-RI Ring/Bigrips-OEDO at RIBF

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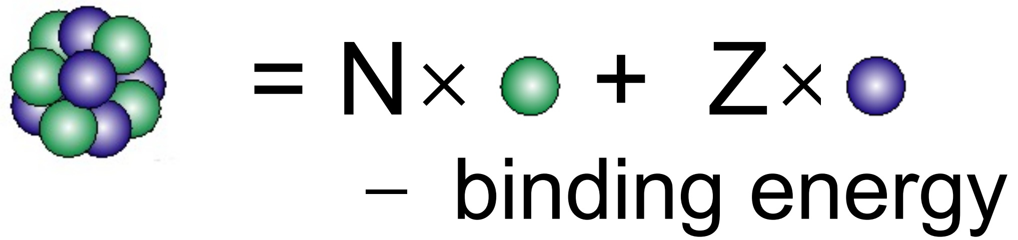
Motivation: why do we measure nuclear masses?

UNIVERSITY OF JYVÄSKYLÄ

Mass → binding energy → interaction



= N× ● + Z× ● − binding energy

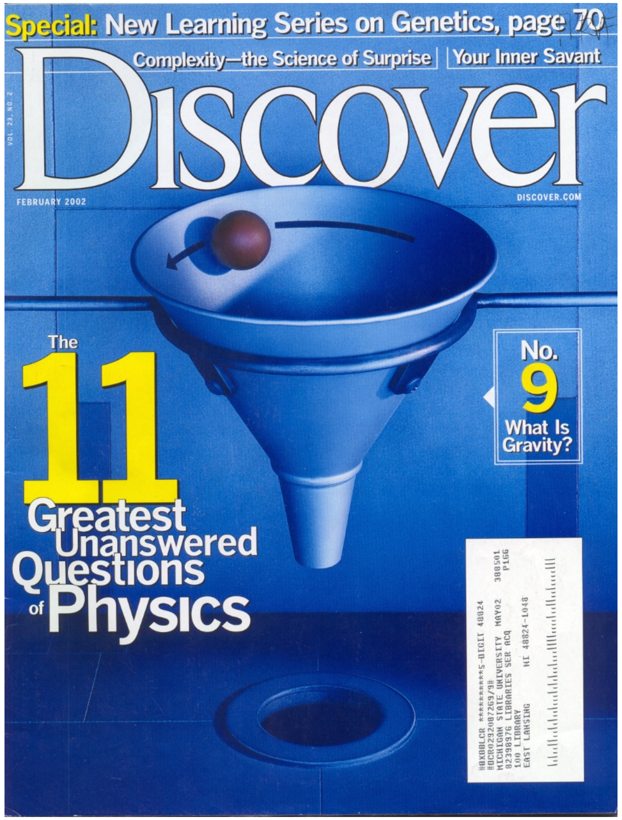
	Filed of application	Required uncertainty
	Chemistry: identification of molecules	10^{-5}–10^{-6}
Exotic nuclei	Nuclear physics: shells, sub-shells, pairing	10^{-6}
	Nuclear fine structure: deformation, halos	10^{-7}–10^{-8}
	Astrophysics: r-process, vp-, rp-process, waiting points	10^{-7}
	Nuclear models and formulas: IMME	10^{-7}–10^{-8}
	Weak interaction studies: CVC hypothesis, CKM unitarity	10^{-8}
	Atomic physics: binding energies, QED; neutrino physics	10^{-9}–10^{-11}
	Metrology: fundamental constants, CPT	10^{-10}

GSI

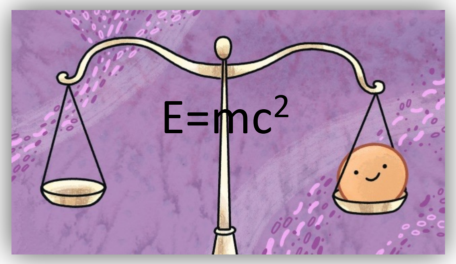
K. Blaum, Physics Reports 425 (2006) 1–78

Top 11 Greatest Unanswered Questions of Physics in this century

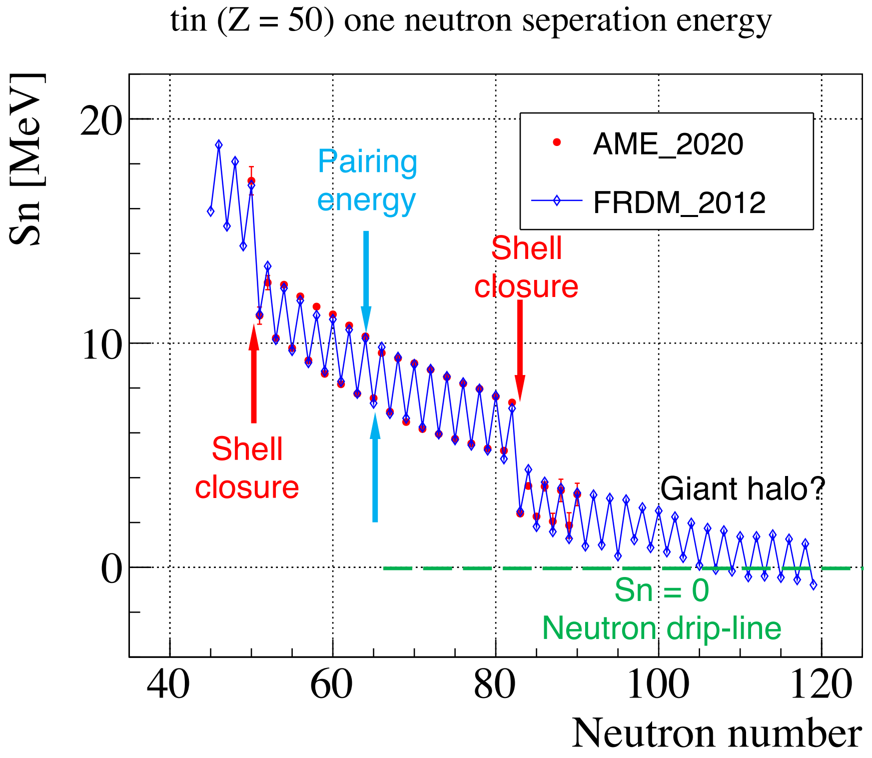
1. What is dark matter?
2. What is dark energy?
3. **How were the heavy elements from iron to uranium made?**
4. Do neutrinos have mass?
5. Where do ultrahigh-energy particles come from?
6. New light and matter theory needed at ultra-high energies?
7. New states of matter at ultrahigh temperatures and densities?
8. Are protons unstable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the universe begin?



Motivation for mass measurements



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)

Nuclear mass ↔ nuclear binding energy:

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

$$B(Z,N) = [N M_n + Z M_H - M_N(Z,N)]c^2$$

$$S_n(Z,N) = M(Z,N-1) + M_n - M(Z,N) = BE(N,Z) - BE(N-1,Z)$$

Mass Measurement Techniques of Exotic/stable Nuclei

Storage Rings

Isochronous MS

t_{meas} ~ 100 μs
$m/\Delta m = 2\cdot10^5$
$\delta m/m \sim 10^{-6}$
broadband

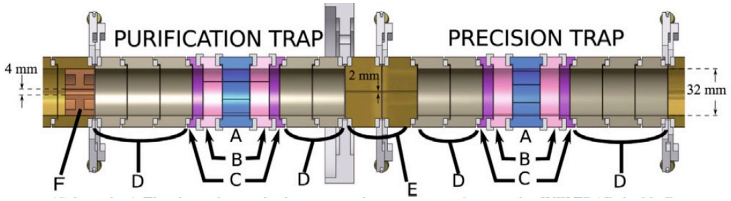
~ 10-200 keV

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

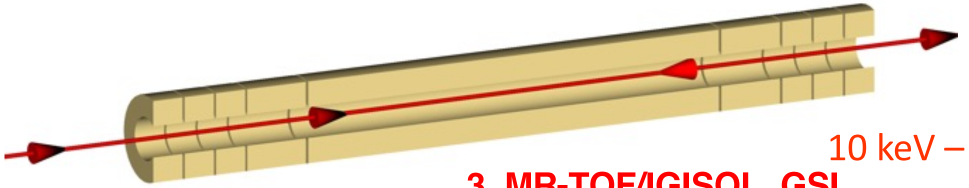
t_{meas} ~ 100-1000 ms
$m/\Delta m \sim 10^7$
$\delta m/m < 10^{-8}$
broadband

1 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

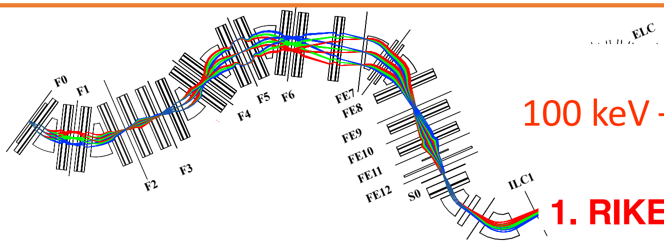


10 keV – 100 keV

3. MR-TOF/IGISOL, GSI

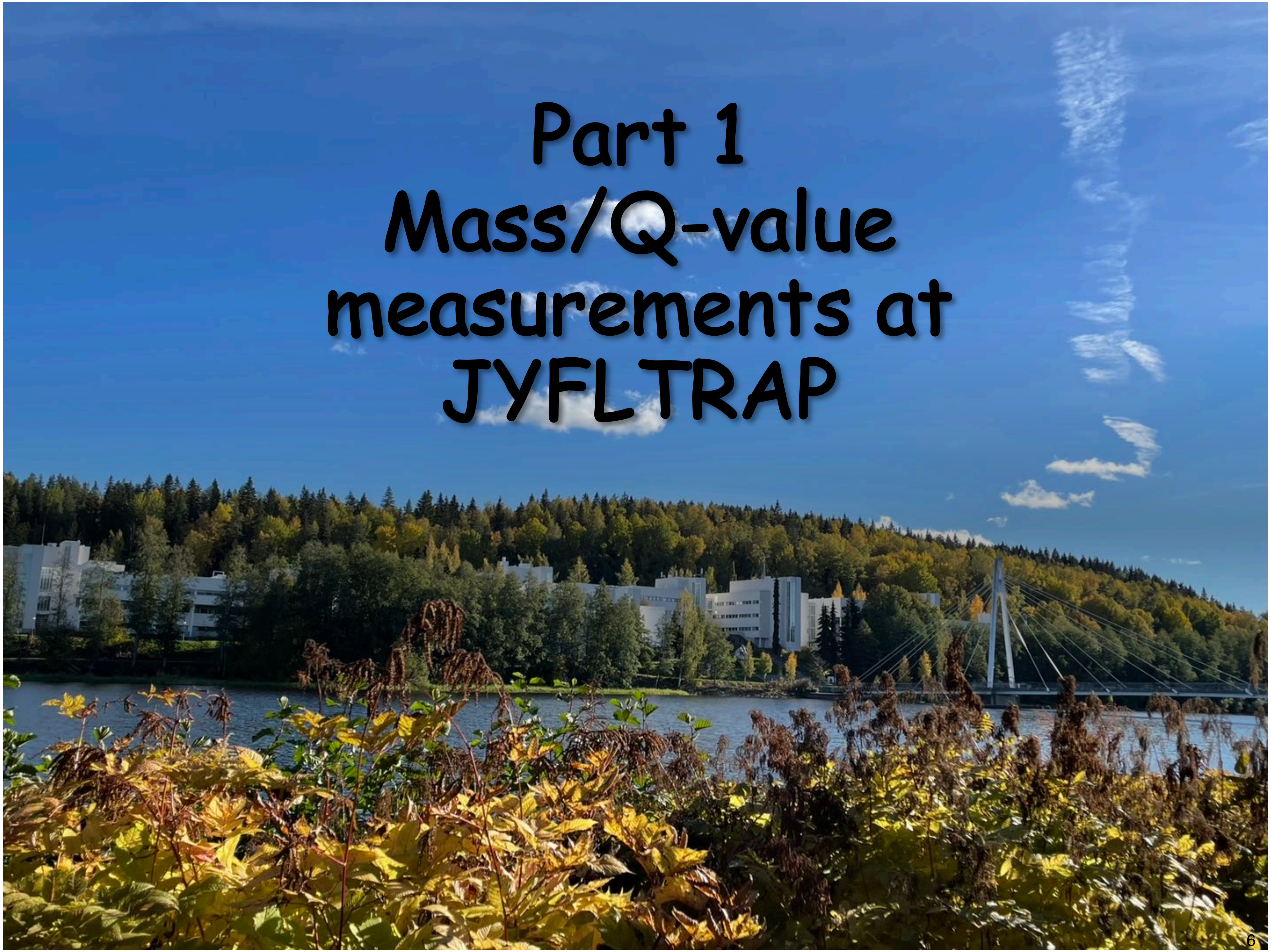
Magnetic-rigidity Time-of-Flight MS

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

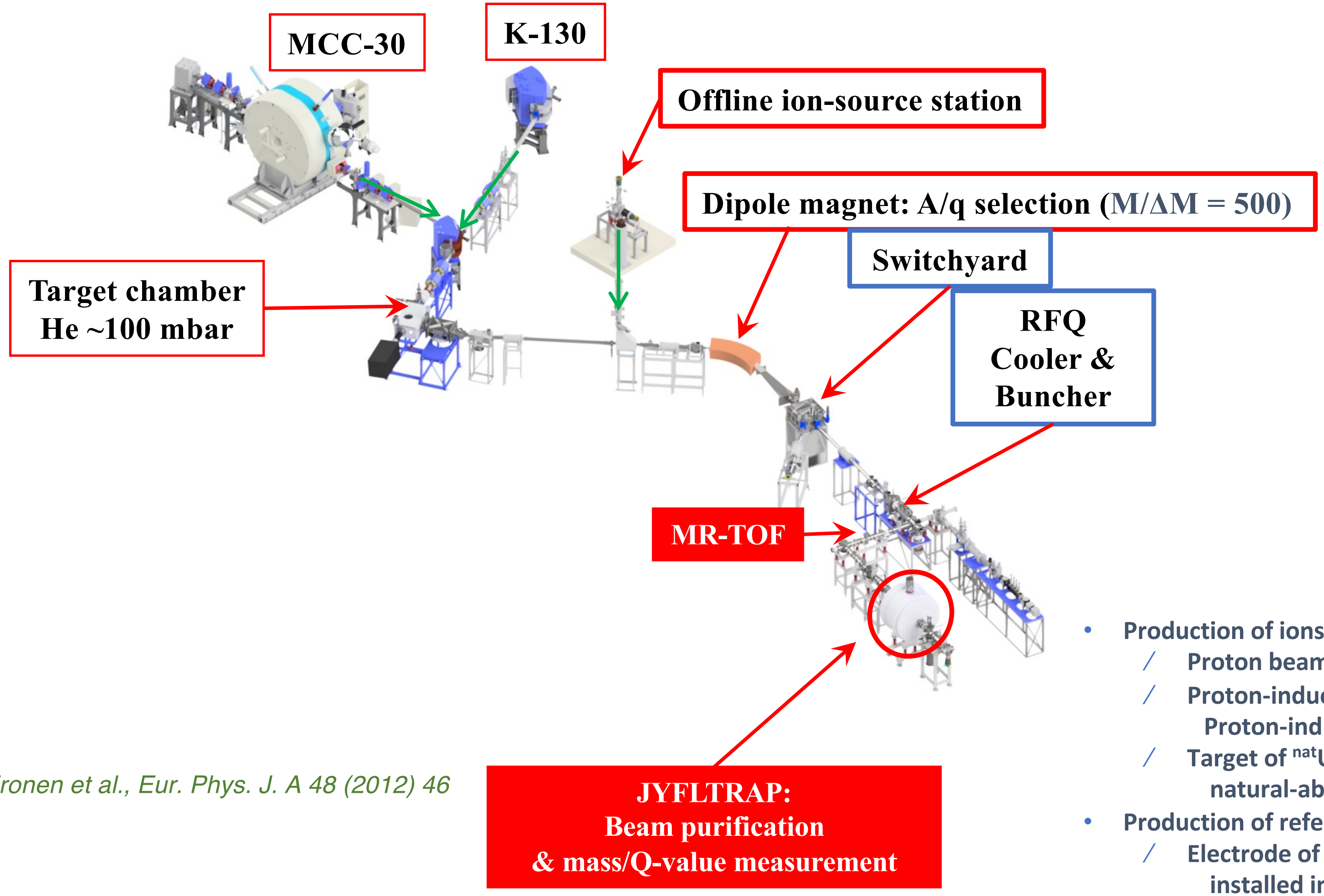


Part 1
Mass/Q-value measurements at JYFLTRAP

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

J. Ärje, J. Äystö et al., PRL 54 (1985) 99

A fast and universal method to produce radioactive beams



MCC-30

K-130

Offline ion-source station

Dipole magnet: A/q selection (M/ΔM = 500)

Switchyard

RFQ Cooler & Buncher

Target chamber He ~100 mbar

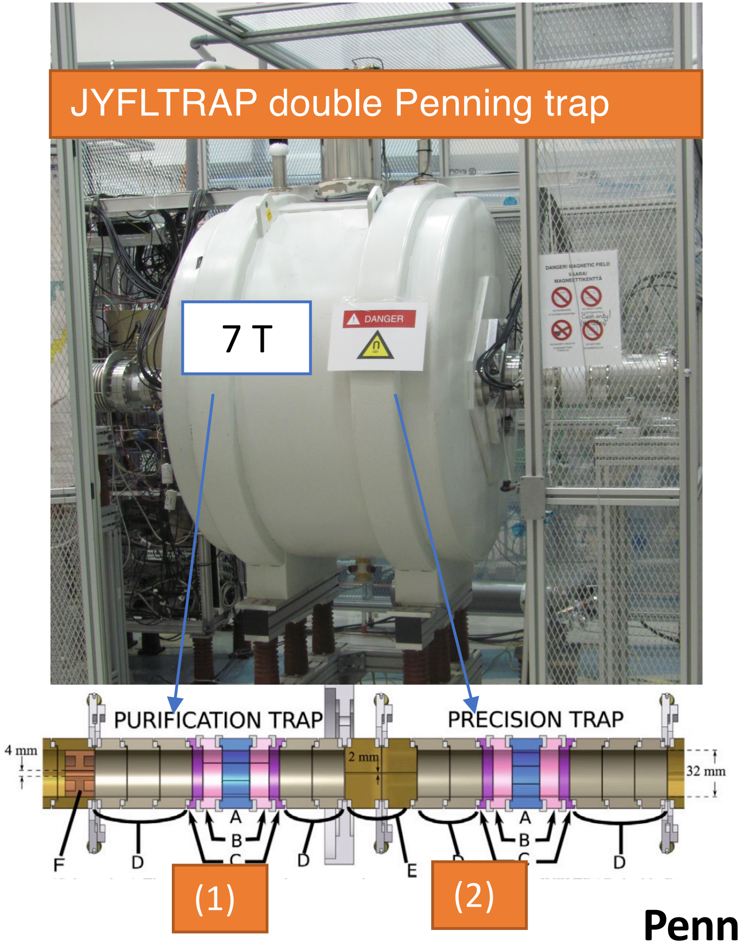
MR-TOF

JYFLTRAP: Beam purification & mass/Q-value measurement

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

- Production of ions of interest:
  - Proton beam of 5-65 MeV
  - Proton-induced fission
    Proton-induced fusion-evaporation
  - Target of ^{nat}U: 15mg/cm^2
    natural-abundance target ~2mg/cm^2
- Production of reference nucleus:
  - Electrode of reference material installed in the spark source

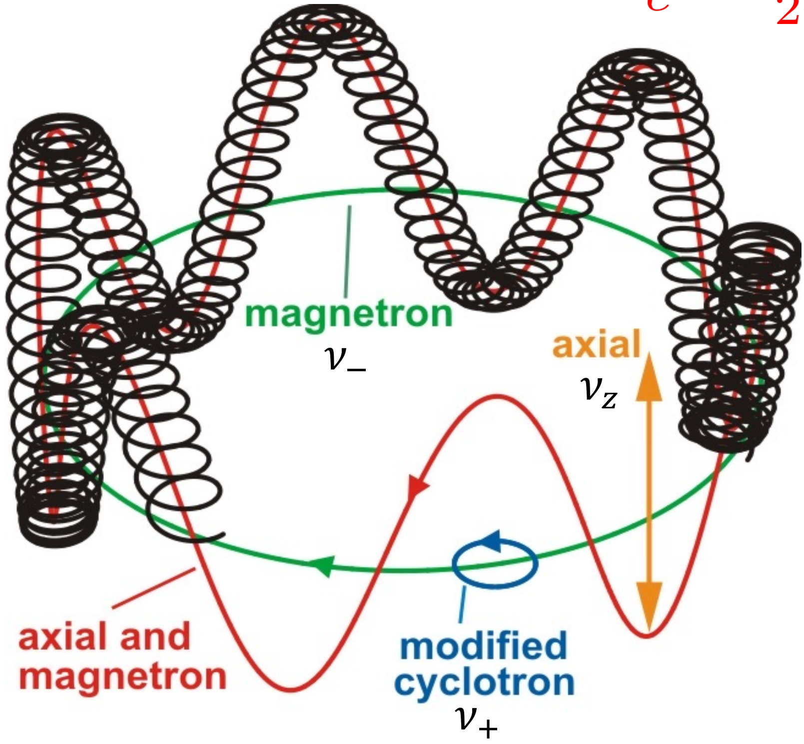
JYFLTRAP double Penning trap

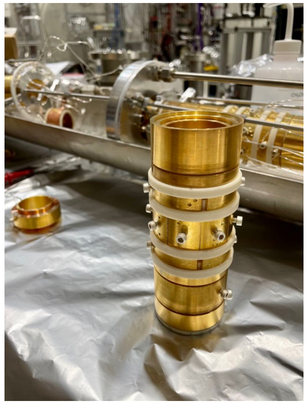


Eronen et al., EPJA 48 (2012) 46

Cyclotron frequency

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





Penning trap eigenfrequencies:

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

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

Invariance theorem:

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

Q-value and mass measurements

Eronen et al., EPJA 48 (2012) 46

- **Cyclotron frequency:**

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

- **Frequency ratio *r*:**

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

methods

Determine

- ***Q*-value:**

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

- **Mass:**

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

1. TOF-ICR

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

Eronen et al., EPJA 48 (2012) 46

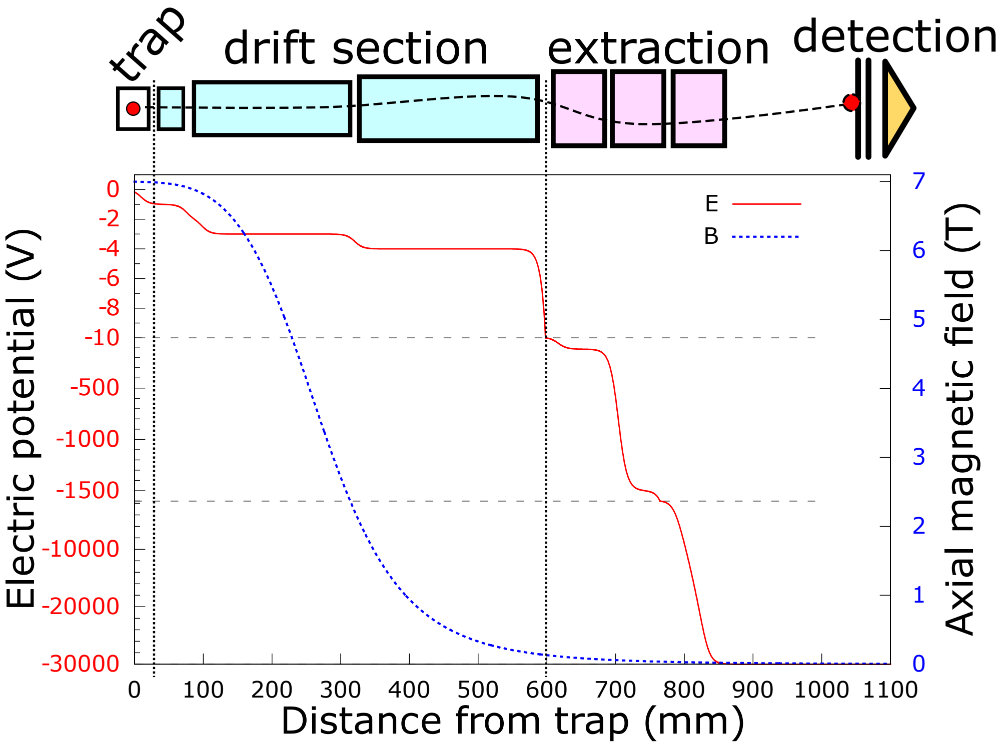
a. Normal TOF-ICR
b. Ramsey TOF-ICR

2. PI-ICR

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

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

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:

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

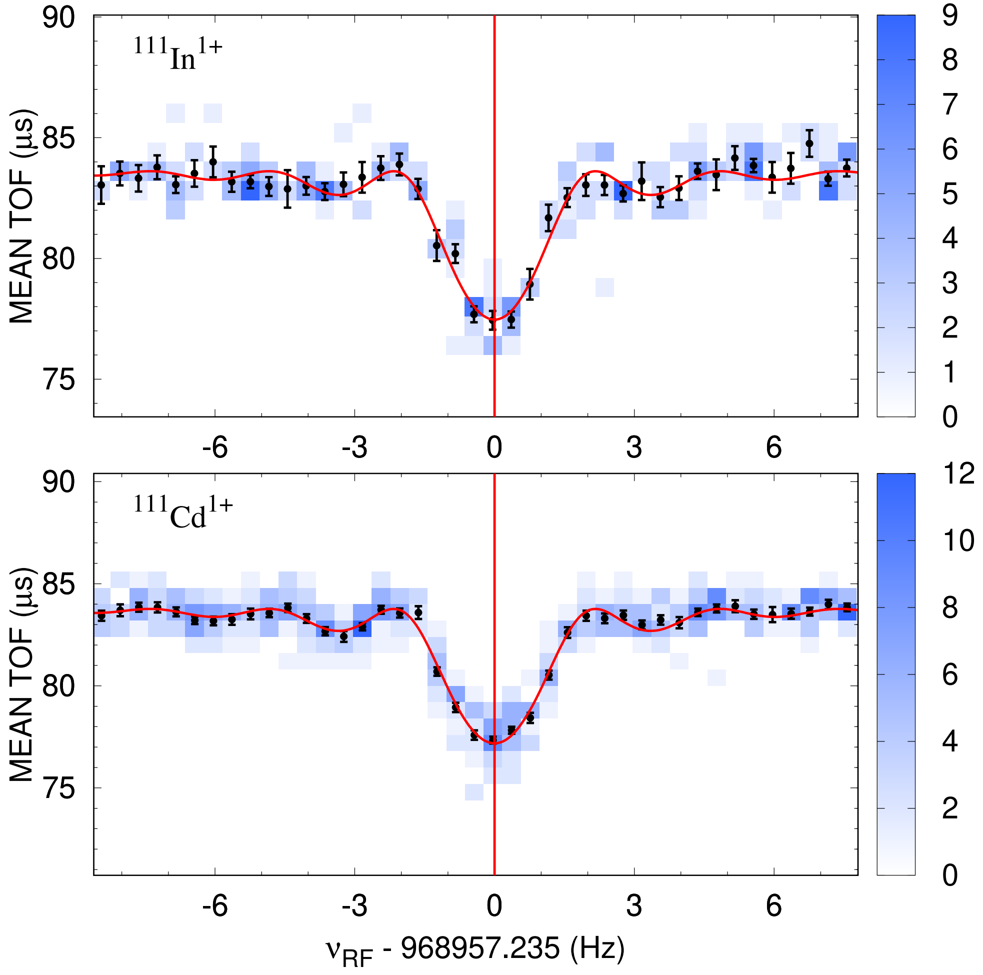
E_0: initial axial kinetic energy of the ion,
U(z): electrostatic potential,
B(z): the magnetic field along the flight path

Measurement procedure:

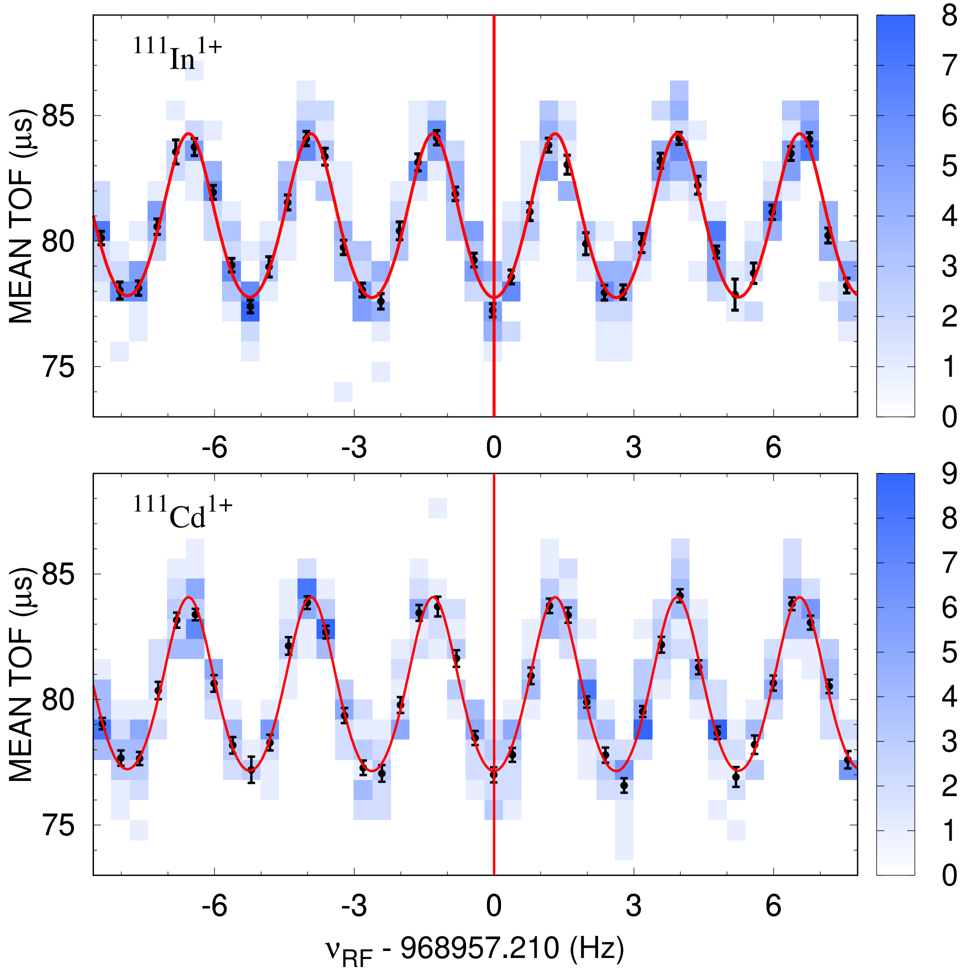
scanning the quadrupolar excitation frequency ν_{RF} around the cyclotron frequency ν_c and determining the frequency resulting in the shortest flight time from the trap to the MCP detector

TOF-ICR method

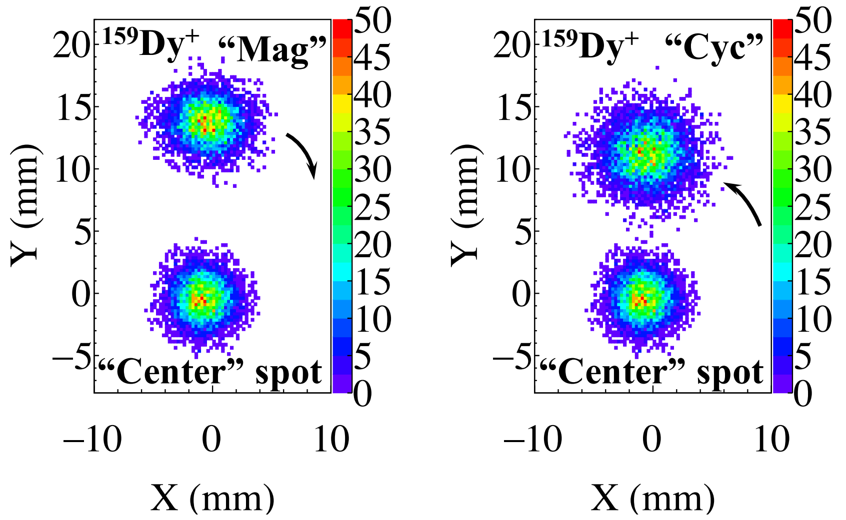
one-pulse radio-frequency (rf) field (400 ms)



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



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

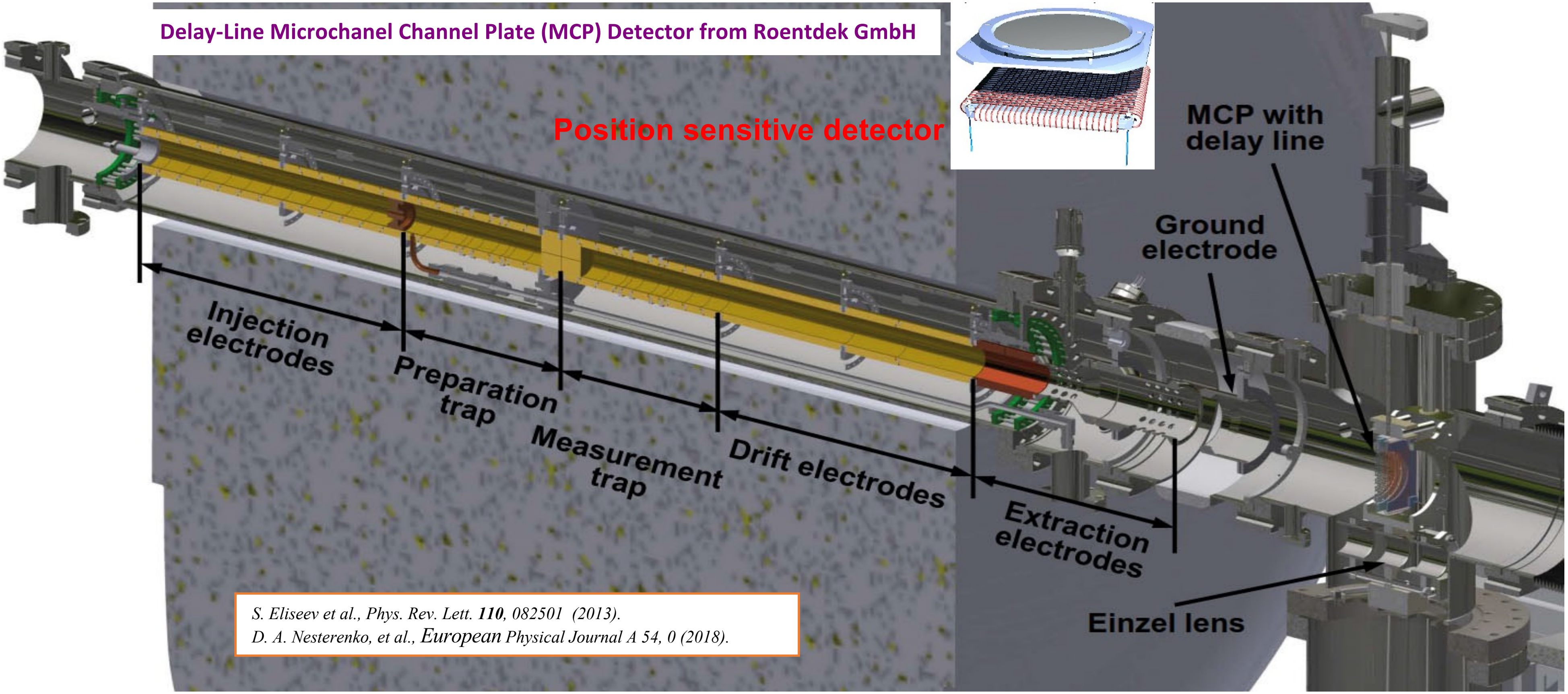


Angle between cyclotron and magnetron motion phases with respect to the center spot:

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

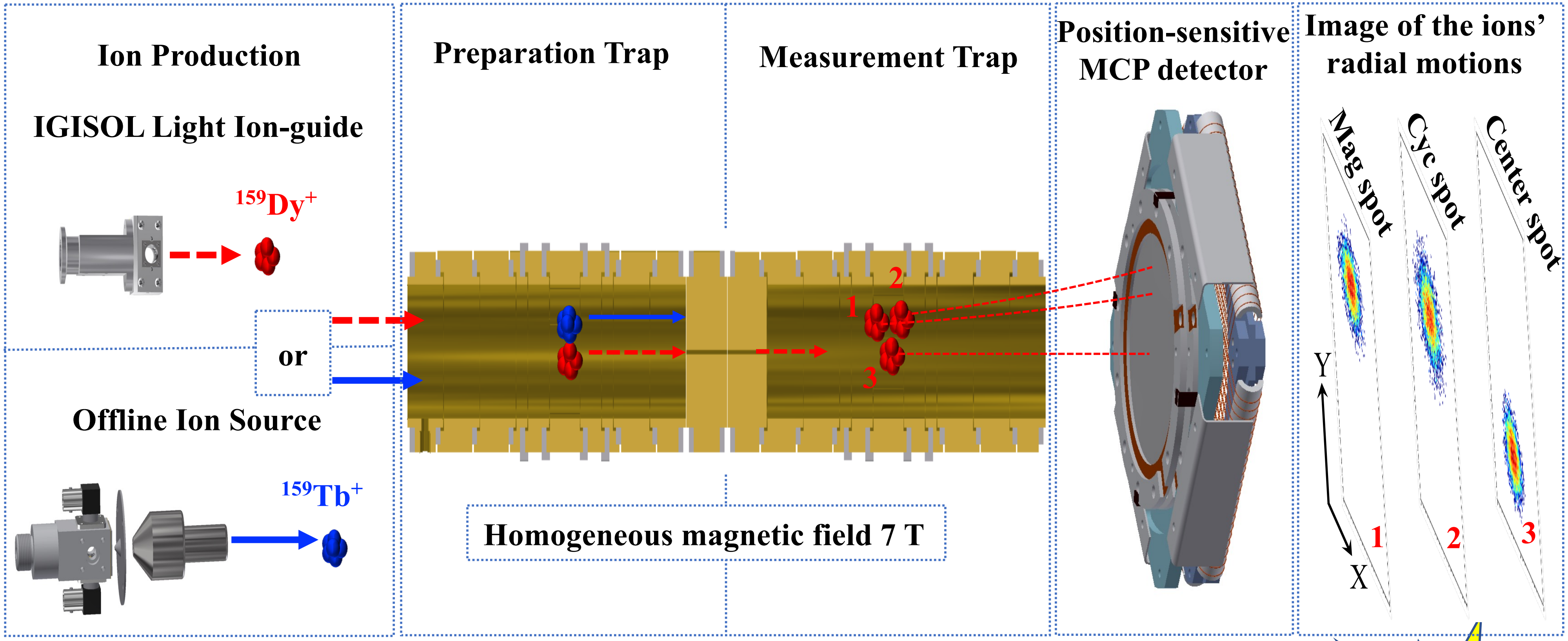
cyclotron frequency:

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



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

Schematic of PI-ICR for 159Dy-159Tb Q-value measurements



Ion Production

IGISOL Light Ion-guide

Offline Ion Source

Preparation Trap

Measurement Trap

Position-sensitive MCP detector

Image of the ions' radial motions

Homogeneous magnetic field 7 T

Imaging

D. A. Nesterenko, T. Eronen, Z. Ge, et al., Eur. Phys. J. A 57, 302 (2021).
https://doi.org/10.1140/epja/s10050-021-00608-3;
M. Ramalho, Z. Ge, T. Eronen et al., Phys. Rev. C 00, 005500 (2022) DOI: 10.1103/PhysRevC.00.005500

Determination of neutrino mass from single β±/EC decay

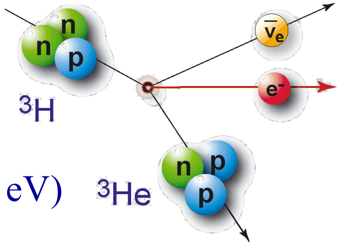
Current direct neutrino mass probes: Ground-state to ground-state (gs-to-gs) decays
(β⁻ :Tritium, ^{187}Re; EC: ^{163}Ho)

- Lower Q-value, higher sensitivity to neutrino mass
- Model independent method

Our Purpose: Search for low Q-value decays

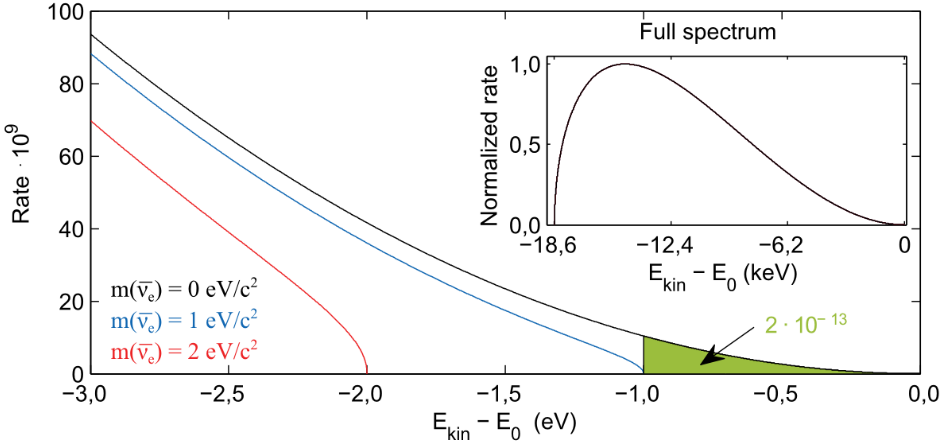
Q → 0, and Q < 1 keV (ultra-low)

Tritium (β⁻decay)



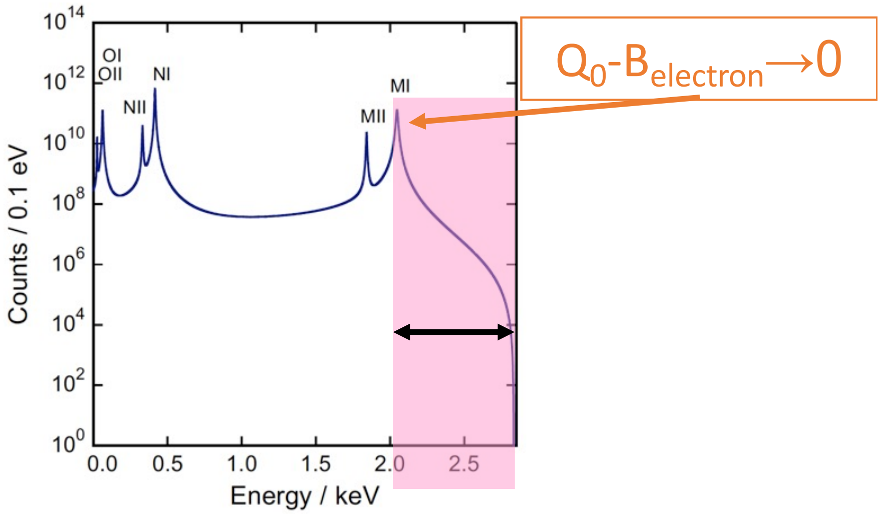
$E_0 = Q_0 - E_{rec}$ (recoil corrections: 1.72 eV)

Endpoint energy E_0 ~18.57 keV



^{163}Ho (Electron Capture)

Q_0 ~2.83 keV



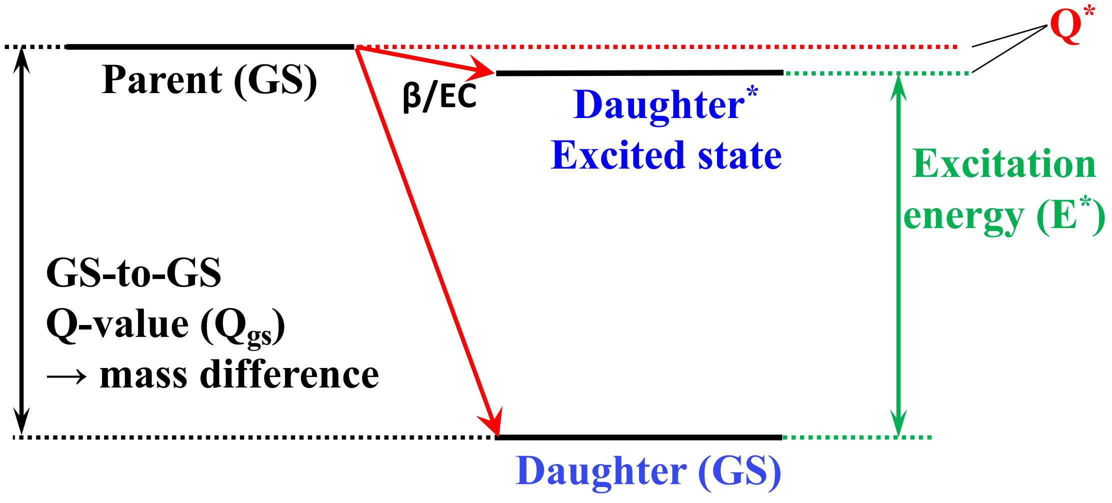
$Q_0 - B_{electron} \rightarrow 0$

Low Q-value decays for neutrino mass determination

J. Suhonen, Phys. Scr. 89, 054032 (2014)
N. D. Gamage et al., Hyp. Int. ***240****, 43 (2019)*

We search for low Q-value ground state to nuclear excited state decays.

- **Low Q-value (Q^*): < 1 keV**



Q^*

Parent (GS)

β/EC

Daughter*
Excited state

Excitation energy (E^*)

GS-to-GS
Q-value (Q_{gs})
→ mass difference

Daughter (GS)

$$\boxed{Q^* = Q_{gs} - E^*}$$

E^* From gamma spectroscopy

- **Typical uncertainty ~100 eV**
- **Potentially ~10 eV**

1. β-decay of $^{115}In(9/2^+) \rightarrow {}^{115}Sn^*(9/2^+)$: Q^*-value = 0.147(10) keV
E^* improvement: ***V. A. Zheltonozhsky et al. 2018 EPL 121 12001***

2. β-decay of $^{135}Cs(7/2^-) \rightarrow {}^{135}Ba^*(11/2^+)$: Q^*-value = 0.44(31) keV
Q_{gs} improvement: ***A. De Roubin, J. Kostensalo, T. Eronen et al., Phys. Rev. Lett., 124 (22), 222503.***

Our work: Q_{gs} measurements

- Penning trap mass spectrometry (JYFLTRAP)
- Q_{gs} through $E = mc^2$

Nuclear theory:

- Partial half-life based on Q^*

Summary of measured Q-values of potential candidates at JYFLTRAP

- List of measured promising low Q-value decay candidates for neutrino mass determination

Parent	T1/2	Daughter	E* (keV)	decay type	Q* (keV)	Decay	Q_0 (keV)	dQ_0 (keV)
146Pm(3−)	5.53(5) y	146Nd(2+)	1470.63(6)	1st FNU	1.3(4.2)	EC	1472.000	4.000
149Gd(7/2−)	9.28(10) dy	149Eu(5/2+)	1312(4)	1st FNU	2(6.4)	EC	1314.100	4.000
155Tb(3/2+)	5.32(6) dy	155Gd{3/2+}	815.731(3)	Allowed{?}	4.2(10.1)	EC	820.000	10.000
159Dy(3/2−)	144.4(2) dy	159Tb(5/2−)	363.5449(14)	Allowed	1.7(1.2)	EC	365.200	1.200
		159Tb(11/2+)	362.050(40)	3rd FU	3.2(1.2)	EC	365.200	1.200
161Ho(5/2−)	18.479(4) hr	161Dy{7/2+}	858.502(7)	1st FNU	1.0(2.2)	EC	858.500	2.200
		161Dy{3/2-}	858.7919(18)	Allowed	−0.3(2.2)	EC	858.500	2.200
72As(2−)	26.0(1)h	72Ge{1}	4358.7(3)	Allowed{?}	−2.8(4.0)	EC	4356.000	4.000
		72Ge(3−)	3325.01(3)	Allowed	8.9(4.0)	β+	4356.000	4.000
		72Ge(2+)	3327(3)	1st FNU	6.9(5.0)	β+	4356.000	4.000
		72Ge{1+}	3338.0(3)	1st FNU{?}	−4.1(4.0)	β+	4356.000	4.000
		72Ge{2−}	3341.76(4)	Allowed{?}	−7.9(4.0)	β+	4356.000	4.000
159Gd(3/2−)	26.24(9) h	159Tb{1/2+}	971	1st FNU{?}	0.0(1.8)	β-	970.900	0.800
77As(3/2−)	38.79(5) h	77Se(5/2+)	680.1035(17)	1st FNU	3.1(1.7)	β-	683.200	1.700
76As(2−)	26.24(9) h	76Se{2−}	2968.4(7)	Allowed{?}	−7.8(1.1)	β-	2960.600	0.900
153Tb(5/2+)	2.34(1)dy	153Gd(5/2−)	548.7645(18)	1st FNU	−1.2(4.0)	β+	1569.000	4.000
		153Gd{5/2}	551.092(19)	Allowed{?}	−3.5(4.0)	β+	1569.000	4.000
111In(9/2+)	3dy	111Cd(3/2+)	864.8(3)	2nd FU	−6.6(3.0)	EC	860.2	3.4
		111Cd(3/2+)	864.8(3)	2nd FU	−4.6(3.0)	EC	860.2	3.4
		111Cd(3/2+)	855.6(1.0)	2nd FU	4.6(3.2)	EC	860.2	3.4
		111Cd(7/2+)	853.94(7)	Allowed	6.3(3.0)	EC	860.2	3.4
131I(7/2+)	8dy	131Xe{9/2+}	971.22(13)	Allowed{?}	−0.42(0.61)	β-	970.80	0.60
		131Xe(7/2+)	973.11(14)	Allowed	−2.31(0.62)	β-	970.80	0.60
155Eu(5/2+)	5yr	155Gd(9/2−)	251.7056(10)	1st FU	0.1(1.8)	β-	252.00	2.40

Z. Ge, T. Eronen et al., PHYSICAL REVIEW Letter

Z. Ge, T. Eronen et al., PHYSICAL REVIEW C 103, 065502 (2021)

Z. Ge, T. Eronen, et al., PRC

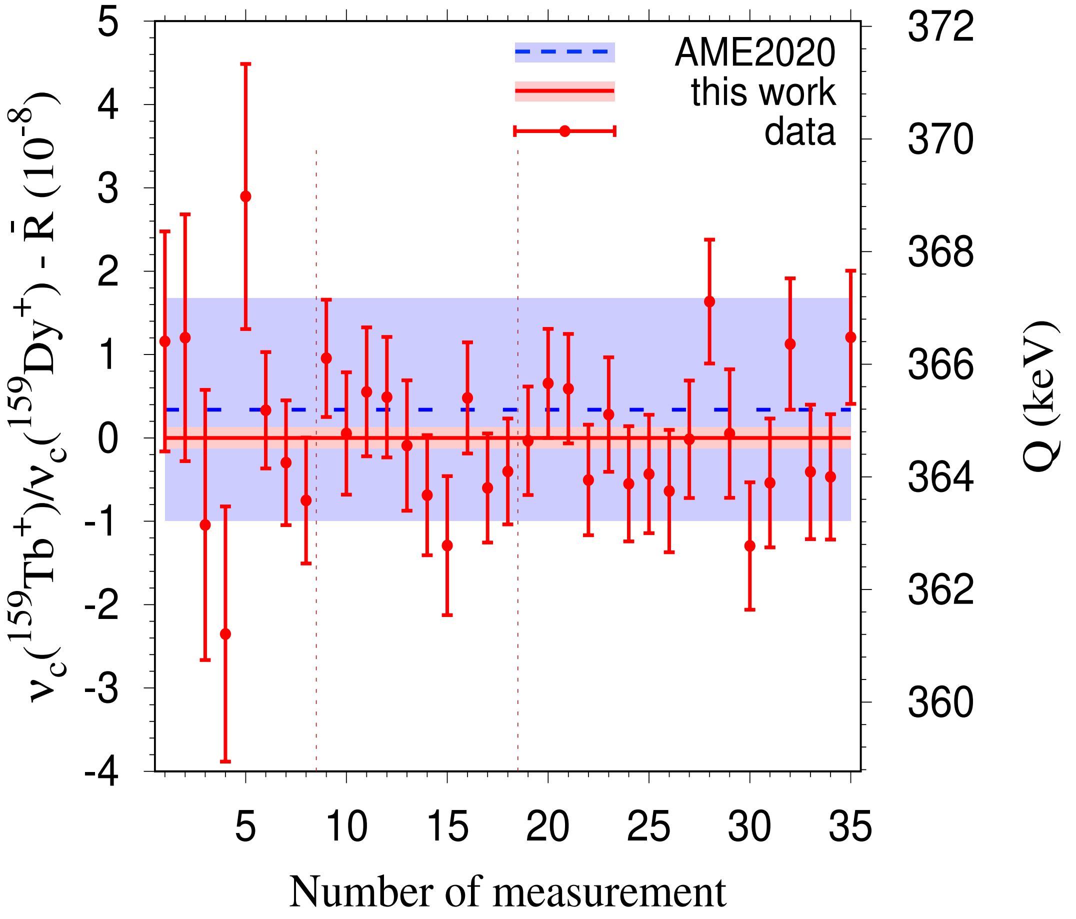
M. Ramalho, Z. Ge, T. Eronen et al., Phys. Rev. C

Z. Ge, T. Eronen ,et al., PLB

T. Eronen , Z. Ge, et al., PLB

Q_0 from: *M. Wang et al. , Chinese Physics C 45, 030003 (2021)*
E^* from: *National nuclear data center, Available at https://www.nndc.bnl.gov*

Q-value measurement of ^{159}Dy



Gs-to-GS Q value (Q_{EC}^{gs})

Obtained frequency ratio ***r*** with a precision of **1.3 ×10^{-9}**

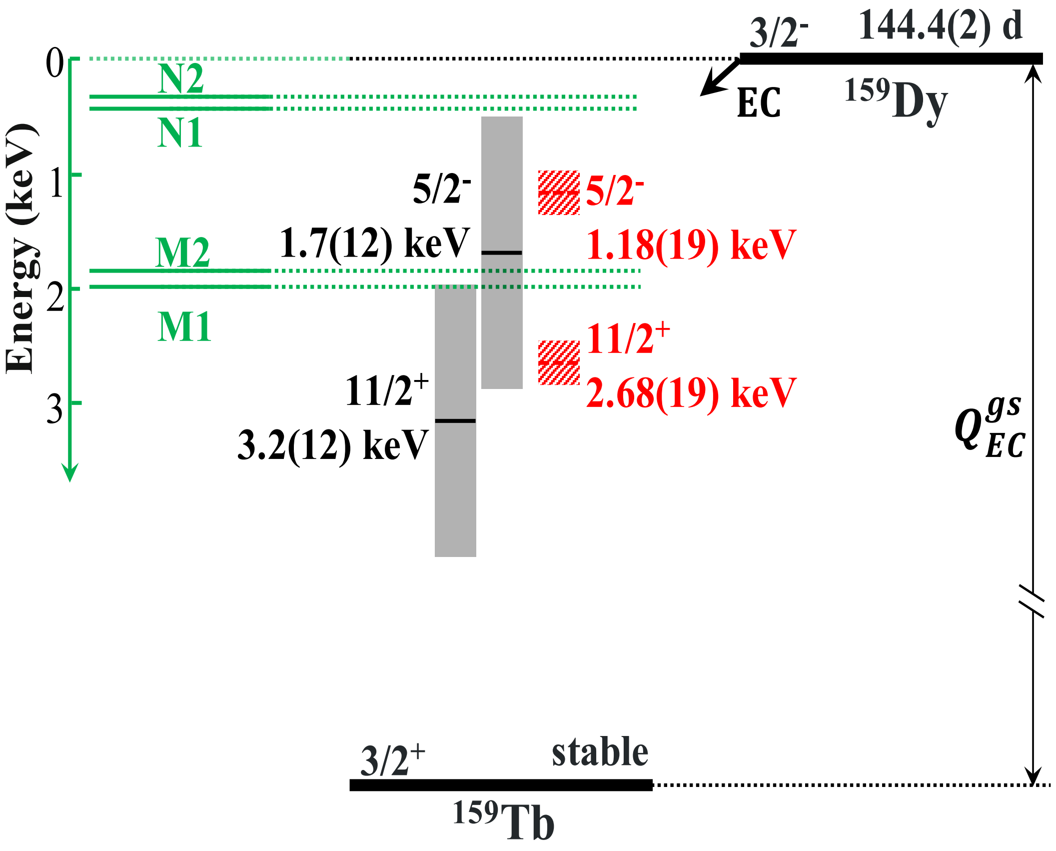
→

Q-value precision: **190 eV**

now **6.3 times** more precise and 0.47 keV smaller than liturature value

Z. Ge et al., Phys. Rev. Lett. 127, 272301 (2021) DOI: 10.1103/PhysRevLett.127.272301;

Level scheme of ^{159}Dy with refined Q-value



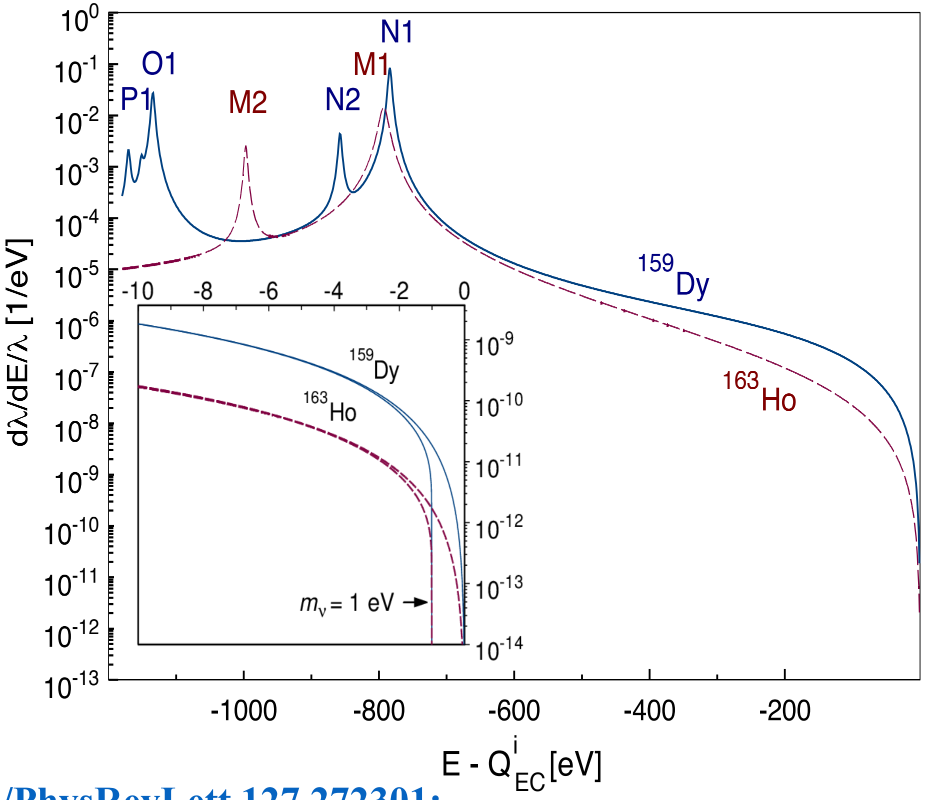
Gs-to-GS Q value (Q_{EC}^{gs})

E_i^*

$5/2^-$ 363.5449(14)
$11/2^+$362.050(40)

+

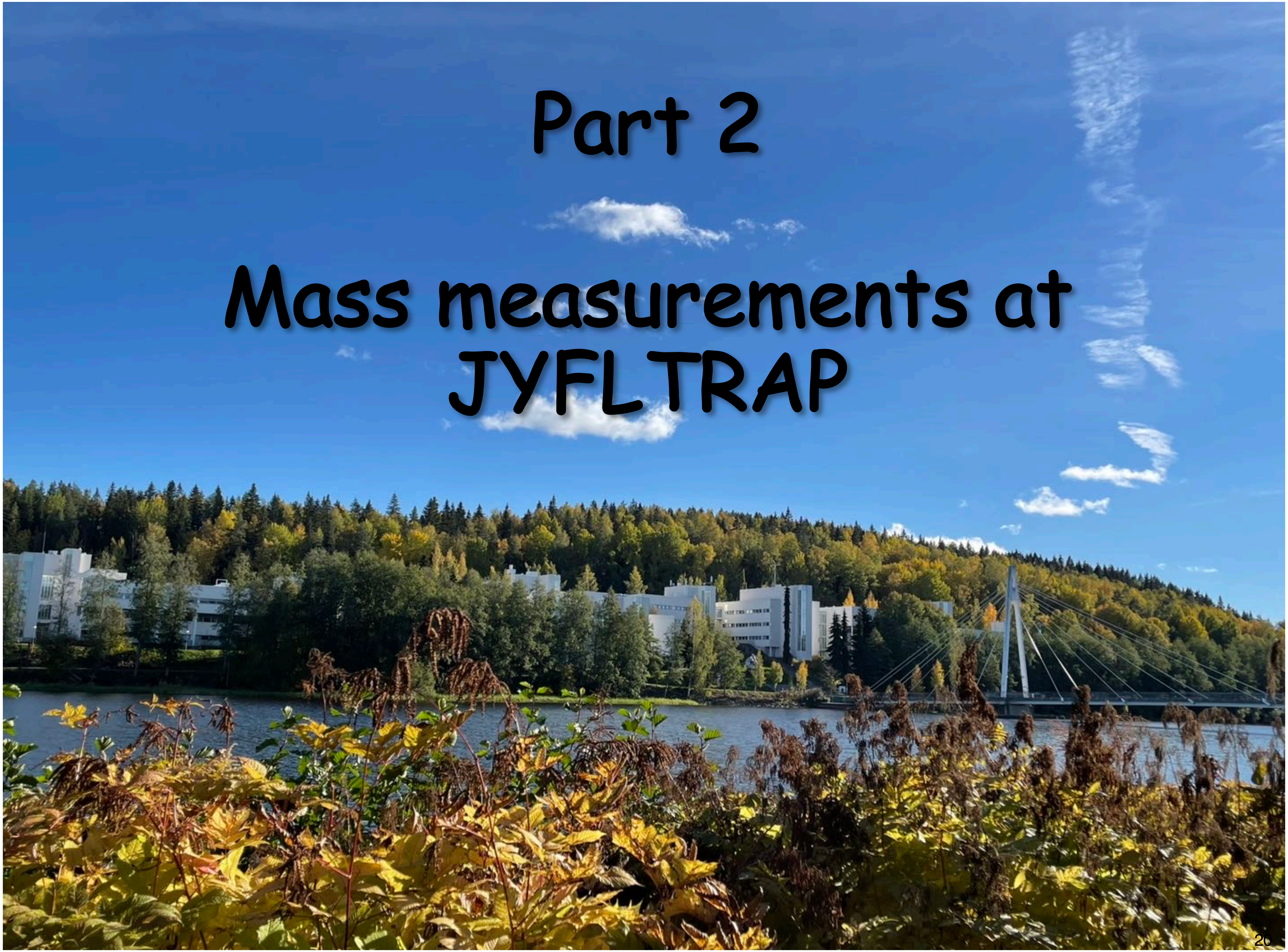
Binding energy e_x (allowed atomic shell x of the EC)



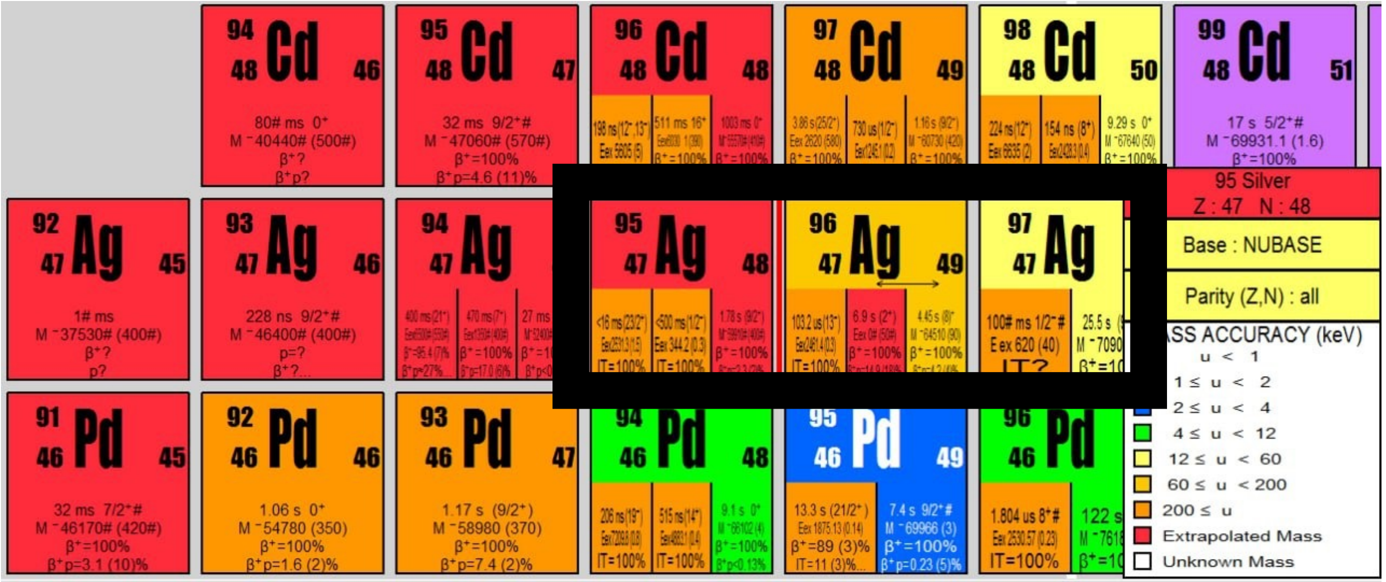
Z. Ge et al., Phys. Rev. Lett. 127, 272301 (2021) DOI: 10.1103/PhysRevLett.127.272301;

Part 2

Mass measurements at JYFLTRAP



Mass measurements of $^{95\text{-}97}$Ag mass data



Cyclotron frequency:

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

Frequency ratio r:

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

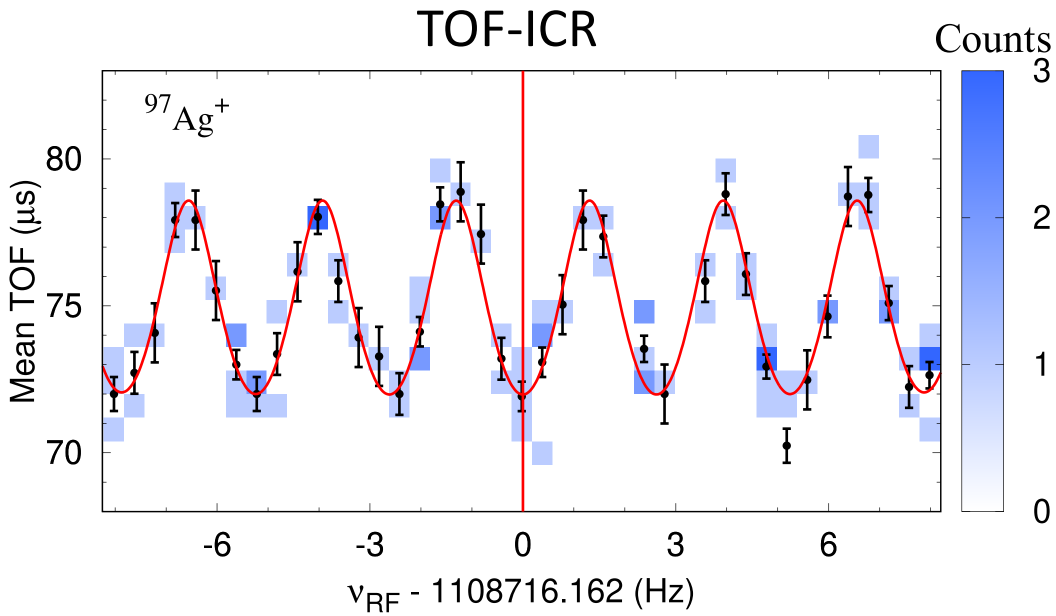
***Q*-value:**

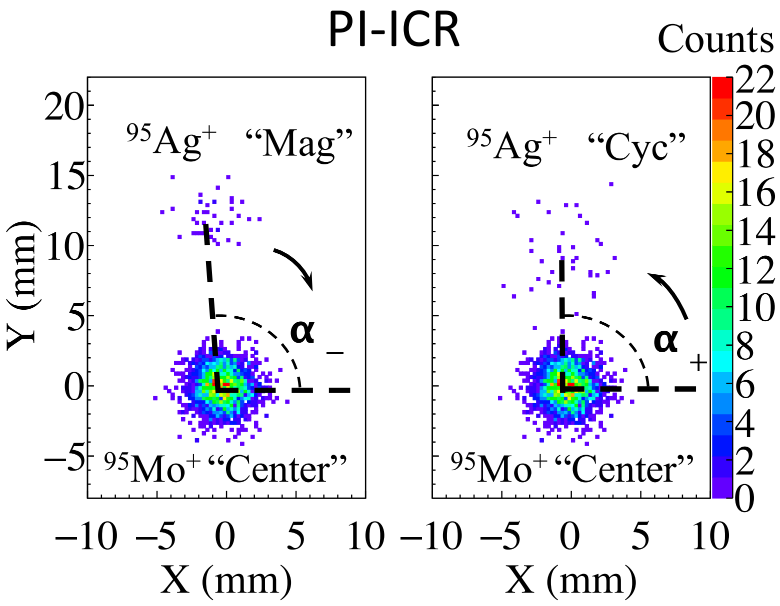
$$Q = M_2 - M_1 = (r-1)(M_1 - m_e) + m_e$$

Mass:

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

Z. Ge, M. Reponen, T. Eronen et al., in preparation (IGISOL collaboration)

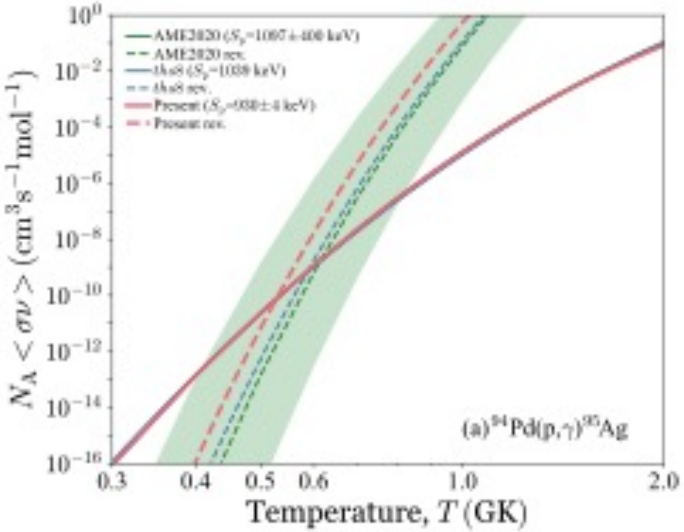


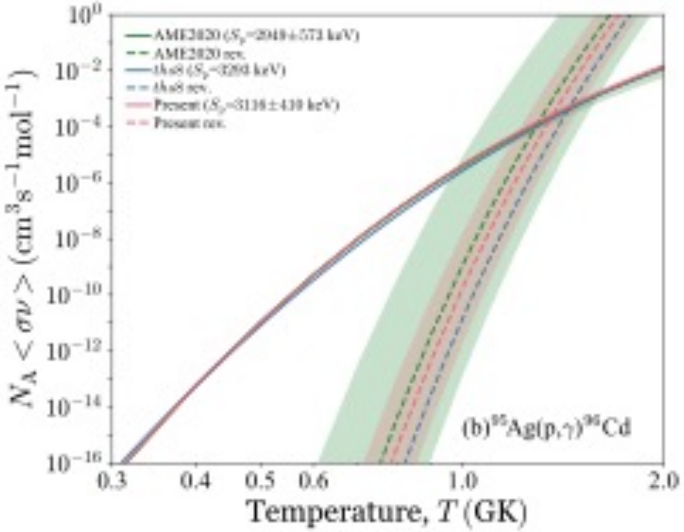


Impact on nuclear astrophysics

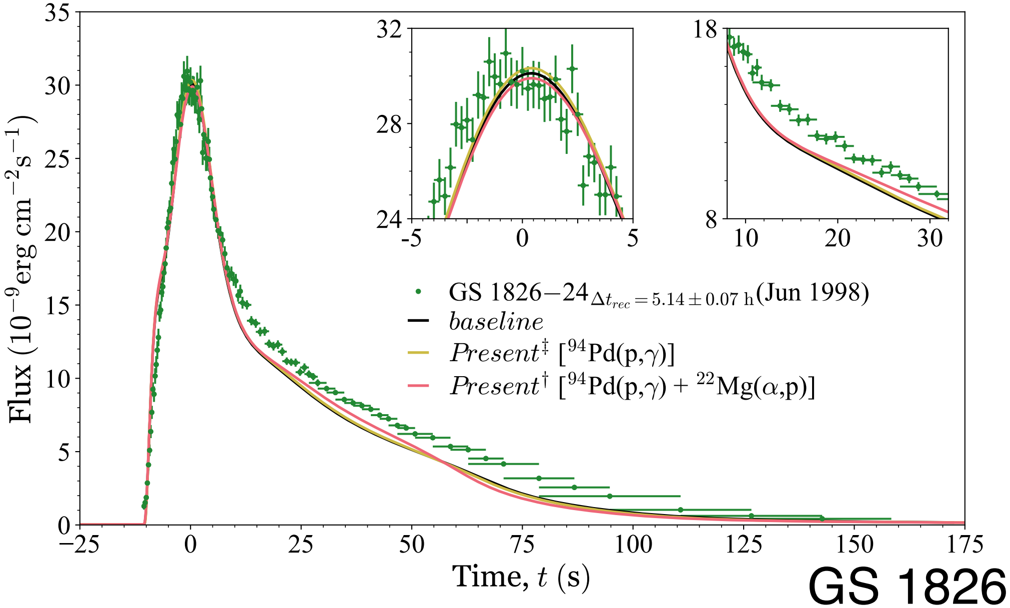
Influence on Forward and reverse thermonuclear reaction rates

Y. Lam et al.,





Impact on averaged periodic burst light curves



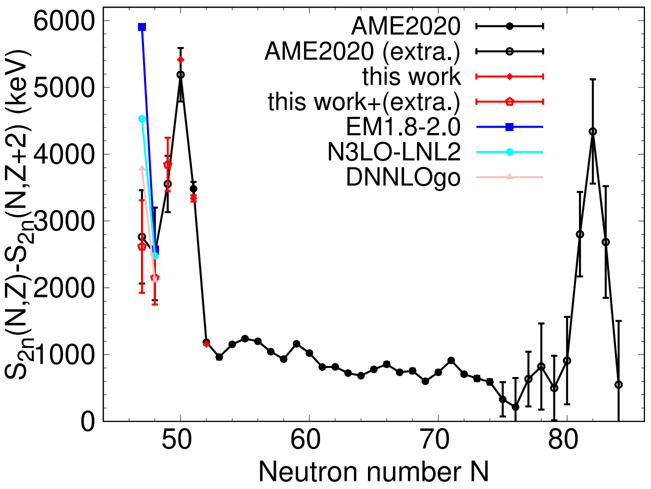
GS 1826−24 clocked burster

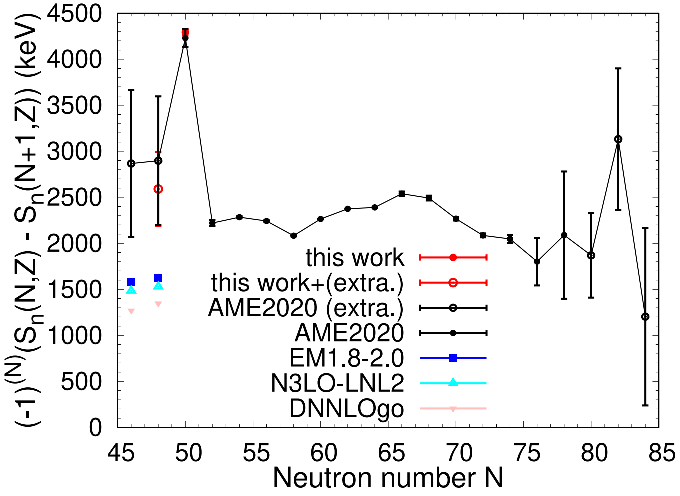
Z. Ge, M. Reponen, T. Eronen et al., in preparation (IGISOL collaboration)

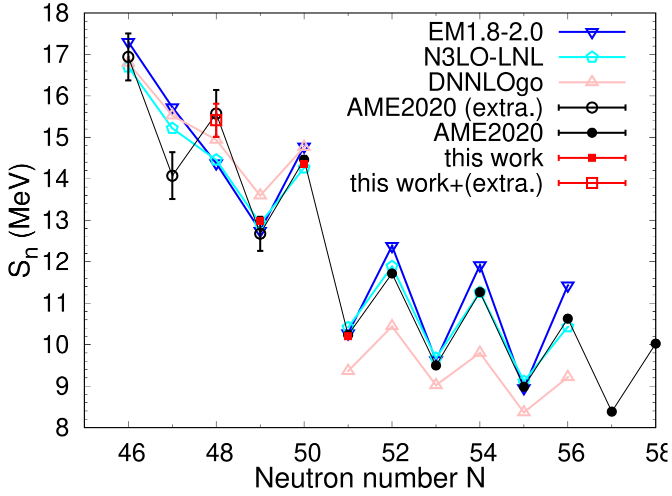
Nuclear structure study

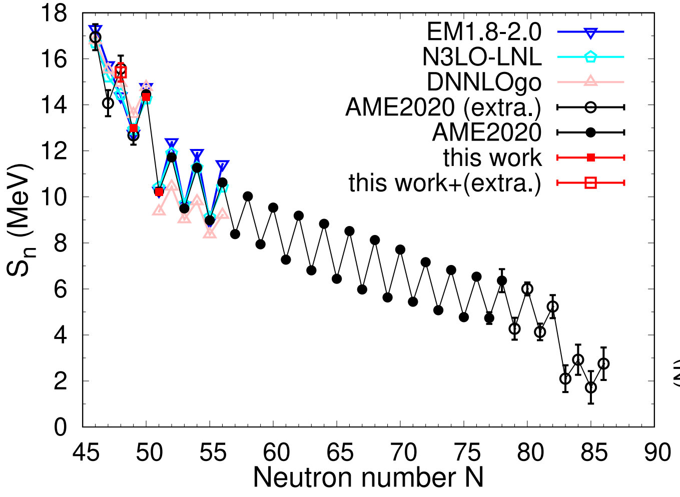
Ab-initio calculation compared to experiemental data&extrapolation

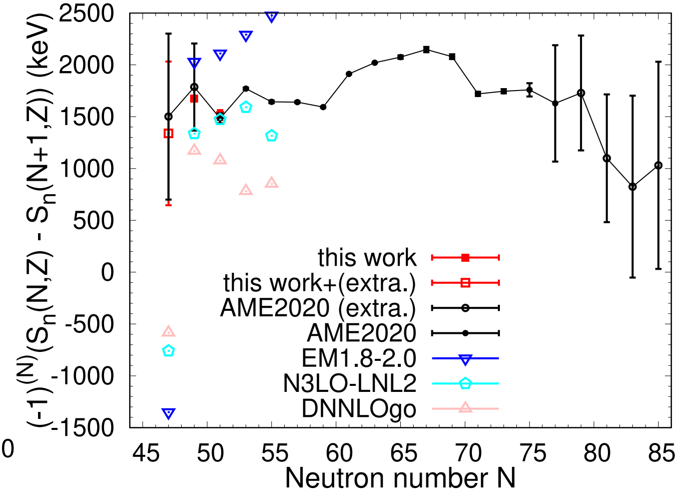
B, Hu, J Halt et al.

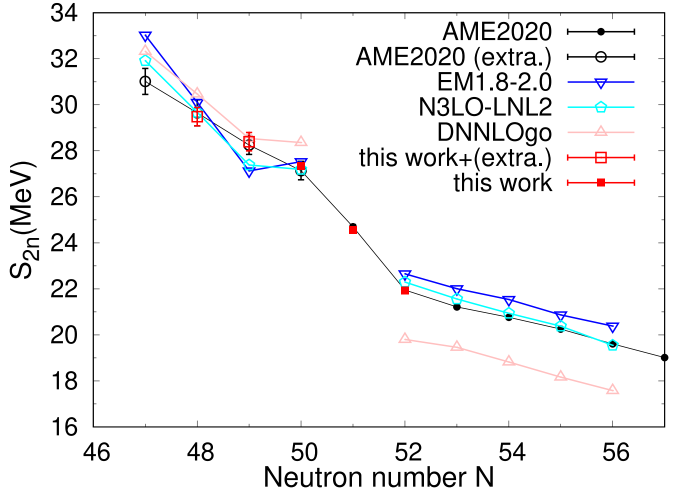








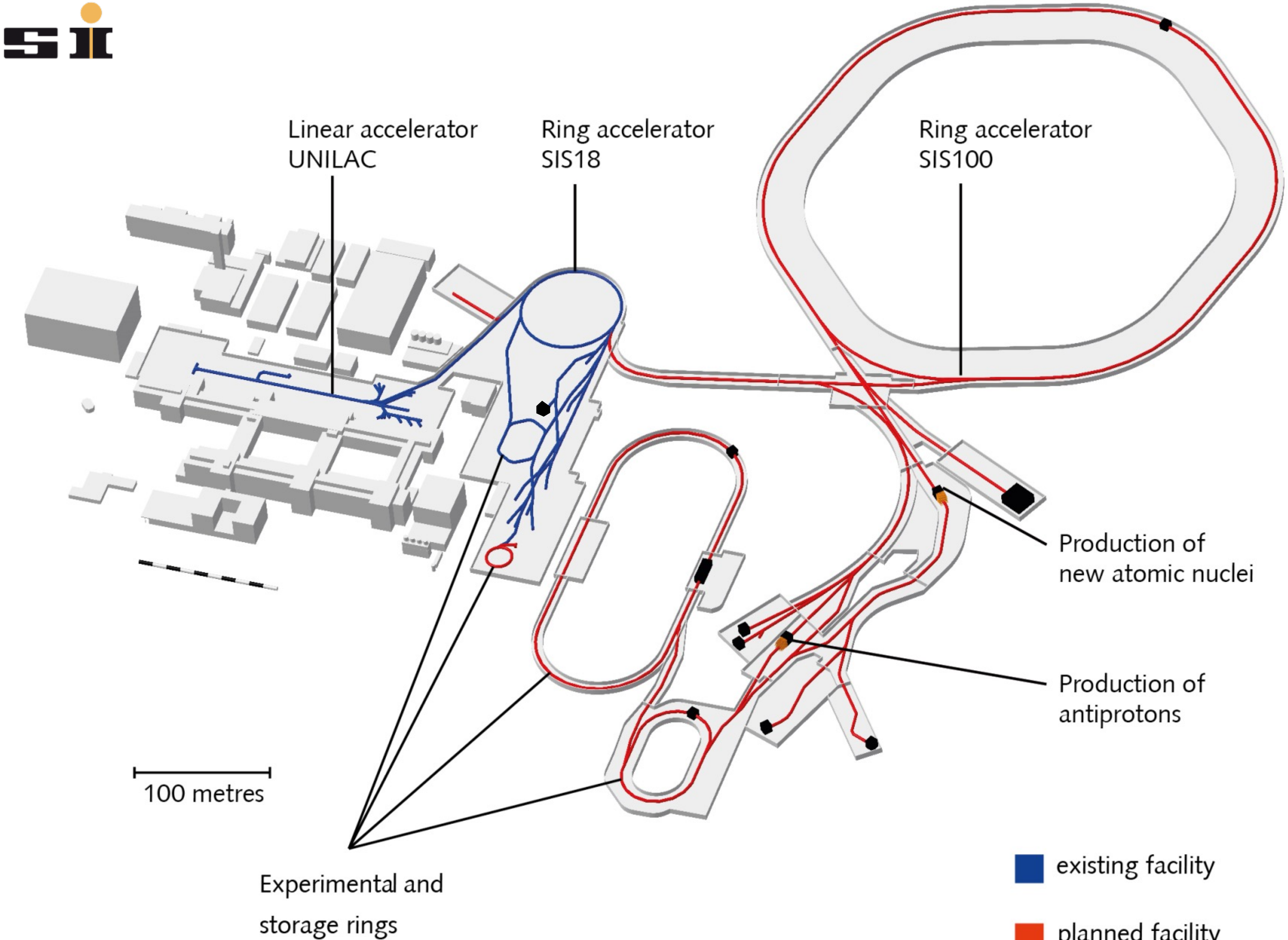




Part 3

Mass measurements with the MR-TOF MS at FRS/FAIR after Ion-Catcher

The FRS Ion Catcher at GSI/FAIR



Linear accelerator
UNILAC

Ring accelerator
SIS18

Ring accelerator
SIS100

Production of
new atomic nuclei

Production of
antiprotons

100 metres

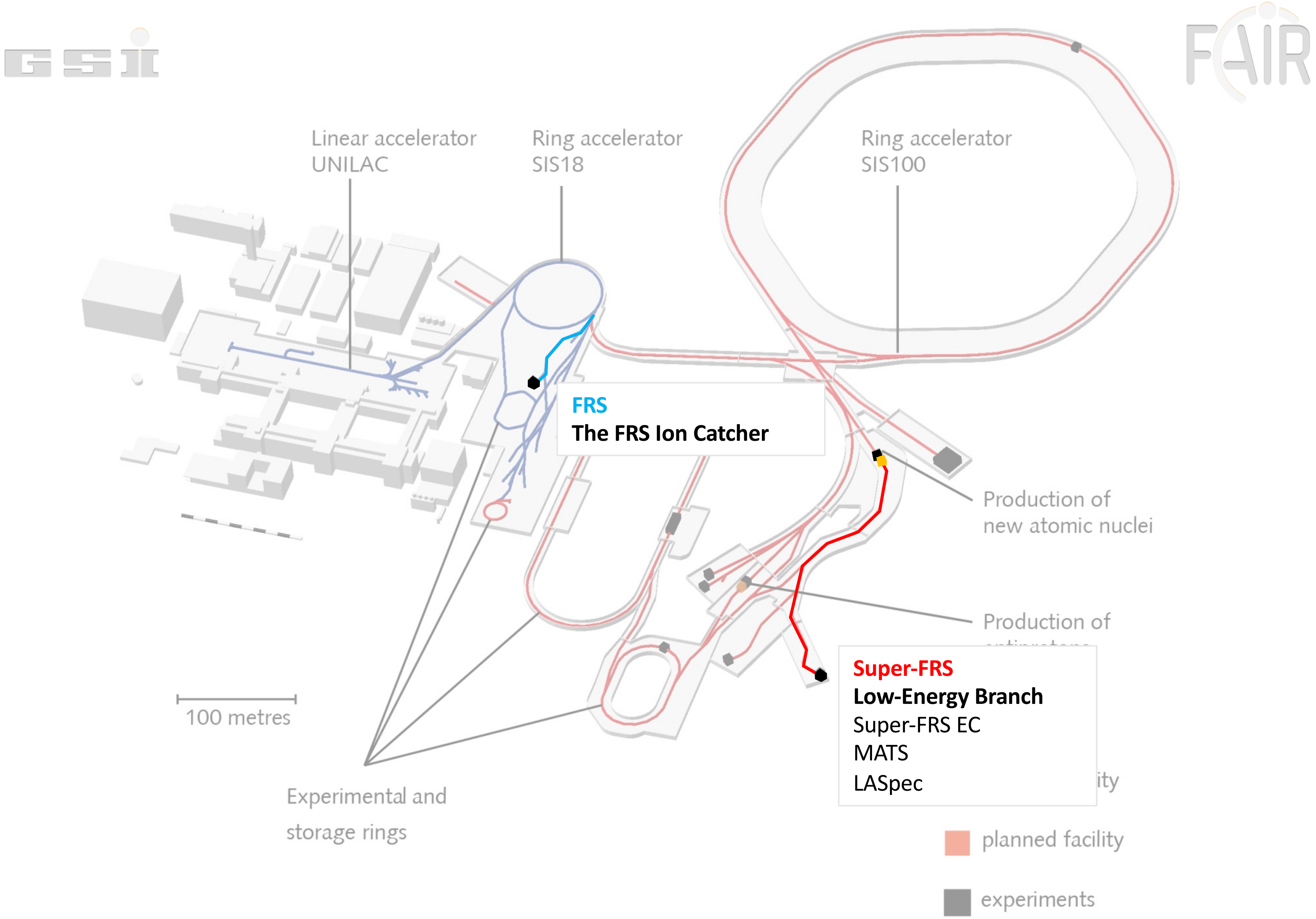
Experimental and
storage rings

🟦 existing facility

🟥 planned facility

⬛ experiments

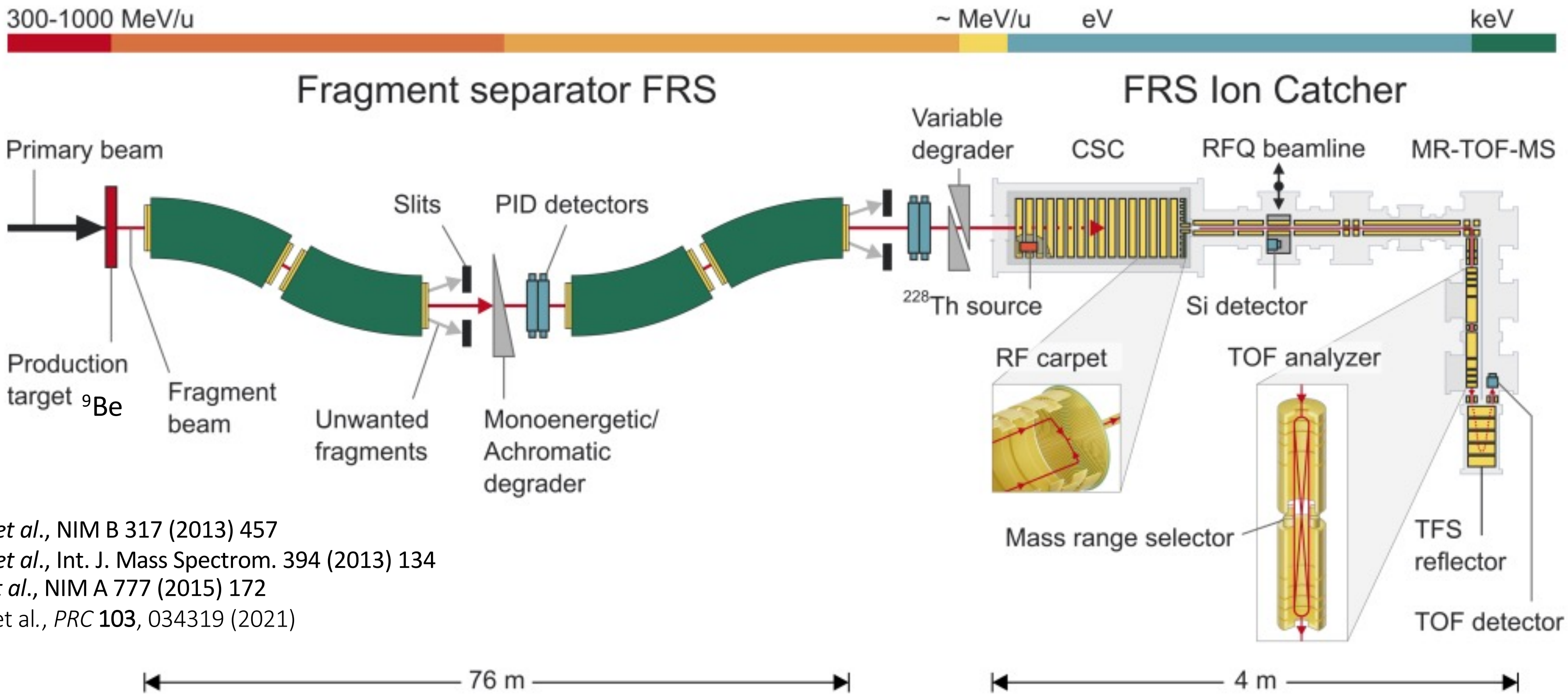
The FRS Ion Catcher at GSI/FAIR



FRS
The FRS Ion Catcher

Super-FRS
Low-Energy Branch
Super-FRS EC
MATS
LASpec

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

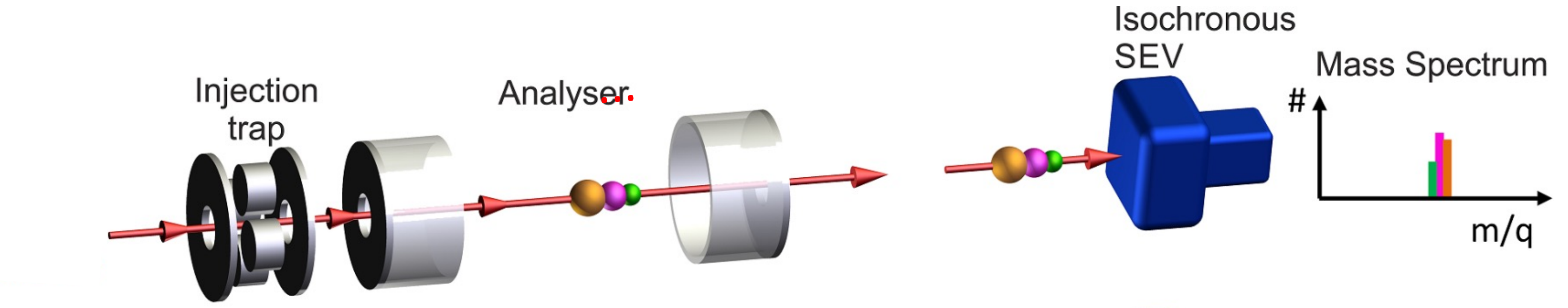
fast, sensitive, broadband and non-scanning

- Resolving power: up to 1,000,000
- resolve isomers (hundreds of keV)
- Best mass accuracy: 1.7×10^{-8}
- Sensitivity: a few detected ions
- Rate capacity: 10^6 ions/s
- Cycle times: a few ms

Concept: MR-TOF-MS

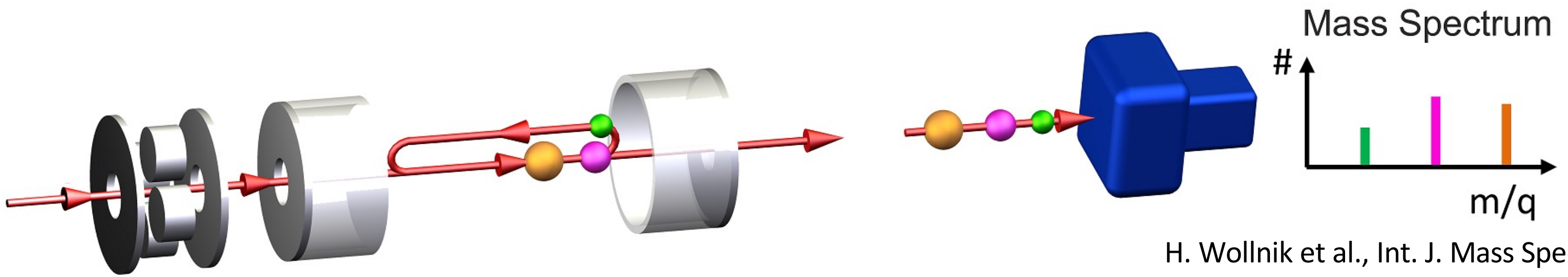
Enables high performance

- Fast → access to very short-lived ions ($T_{1/2}$ ~ ms)
- Sensitive, broadband, non-scanning → efficient, access to rare ions



To achieve high mass resolving power and accuracy:

Multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS)

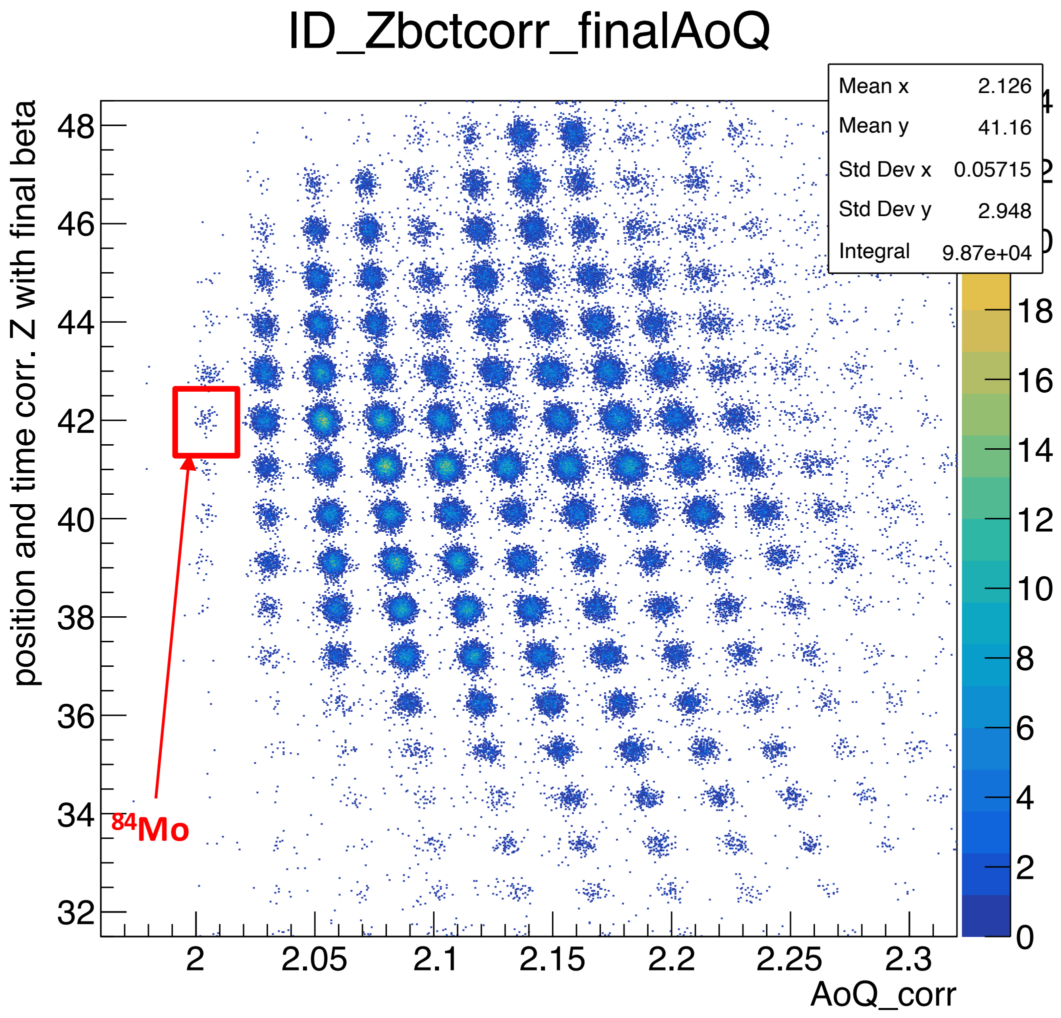


H. Wollnik et al., Int. J. Mass Spectrom. Ion Processes 96 (1990) 267

Applications

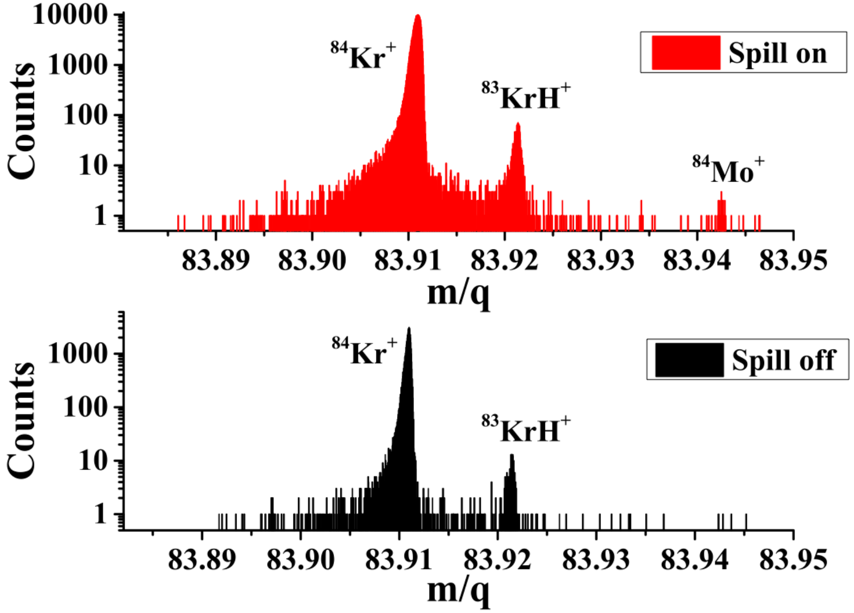
- Diagnostics measurements: monitor production, separation and low-energy beam preparation of exotic nuclei — W.R. Plaß et al., Int. J. Mass Spectrom. 394 (2013) 134
- Direct mass measurements of exotic nuclei — C. Scheidenberger et al., Hyperfine Interact. 132 (2001) 531
- High-resolution mass separator — W.R. Plaß et al., NIM B 266 (2008) 4560

Partical identification



AqQ-vs-Z spectrum

Z. Ge , in preparation



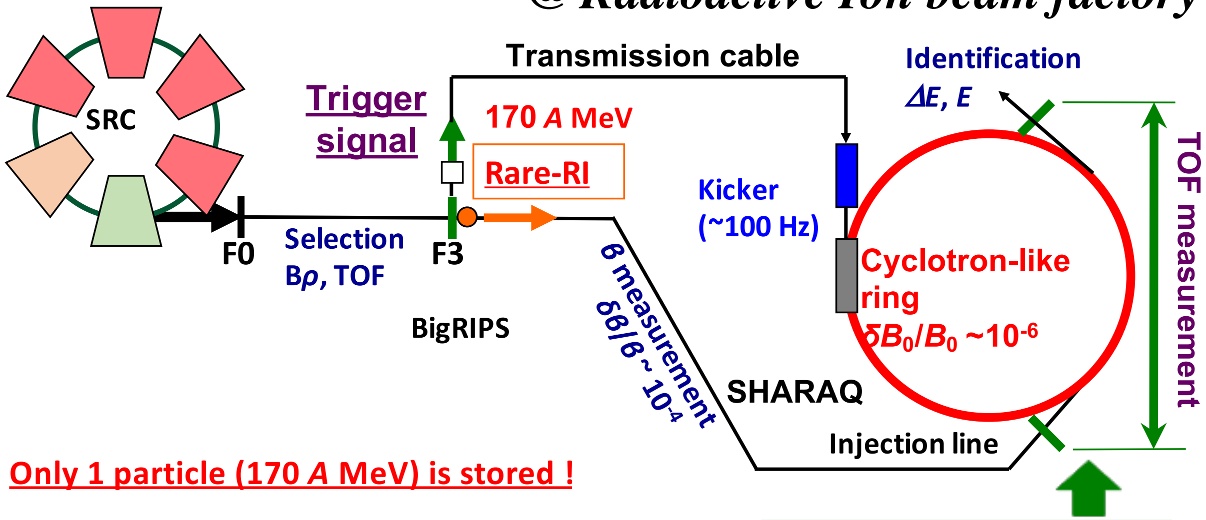
TOF spectrum

Part 4

Mass measurements with the Rare-RI Ring at RIBF

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

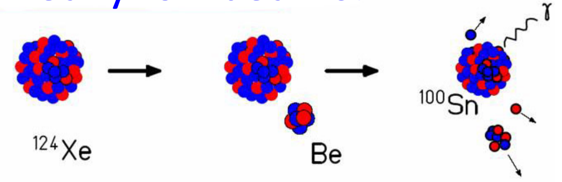
@ Radioactive Ion beam factory (RIBF)



TOF ~0.7 ms(=2000 turn)
δT~100 ps, $\delta T/T < 10^{-6}$

Only 1 particle (170 *A* MeV) is stored !

Projectile fragmentation of heavy ion beams:



Isochronous mass spectrometry

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

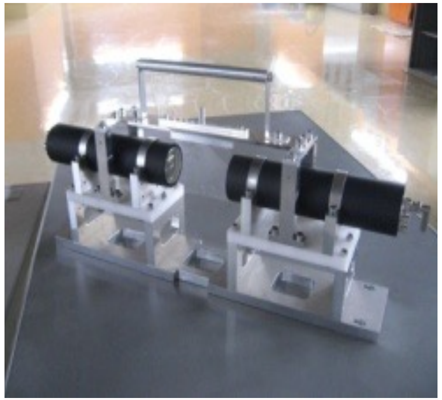
Short measurement time (<1 ms)
Good resolution (~10^{-6})
High efficiency (~100%)

Location of
Rare-RI Ring
at RIKEN RIBF

Detectors at beam-line

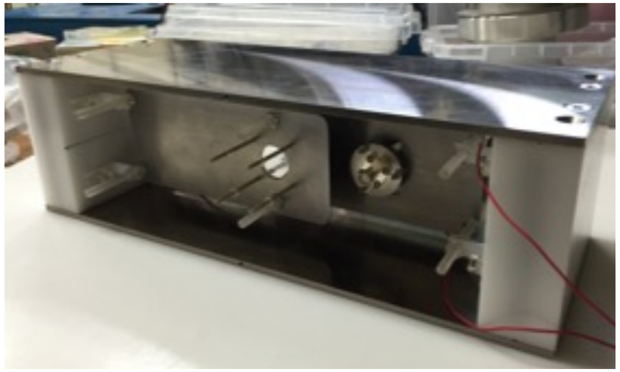
- Standard beam-line detectors at BigRIPS for TOF, Bρ, ΔE measurement for PID
- Clover-type Ge detectors for isomer measurement

(1). Delay-line PPAC



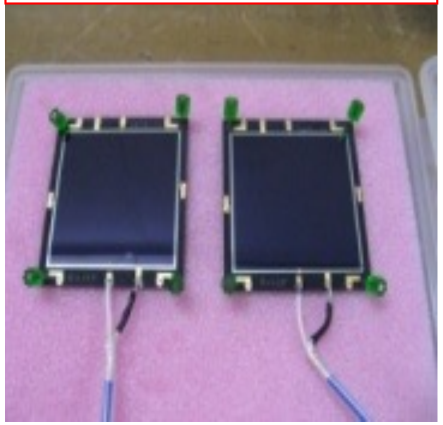
(2). Plastic Scintillator

(3). Ionization Chamber

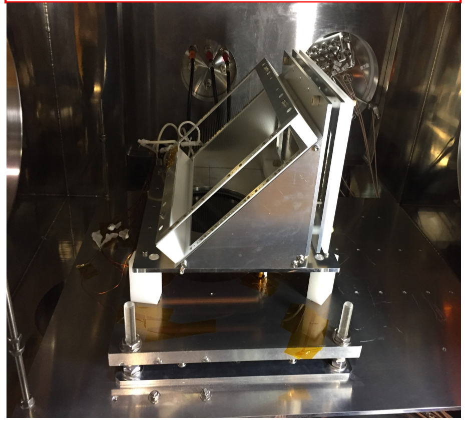


(4). BE-MCP

(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

Selection&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

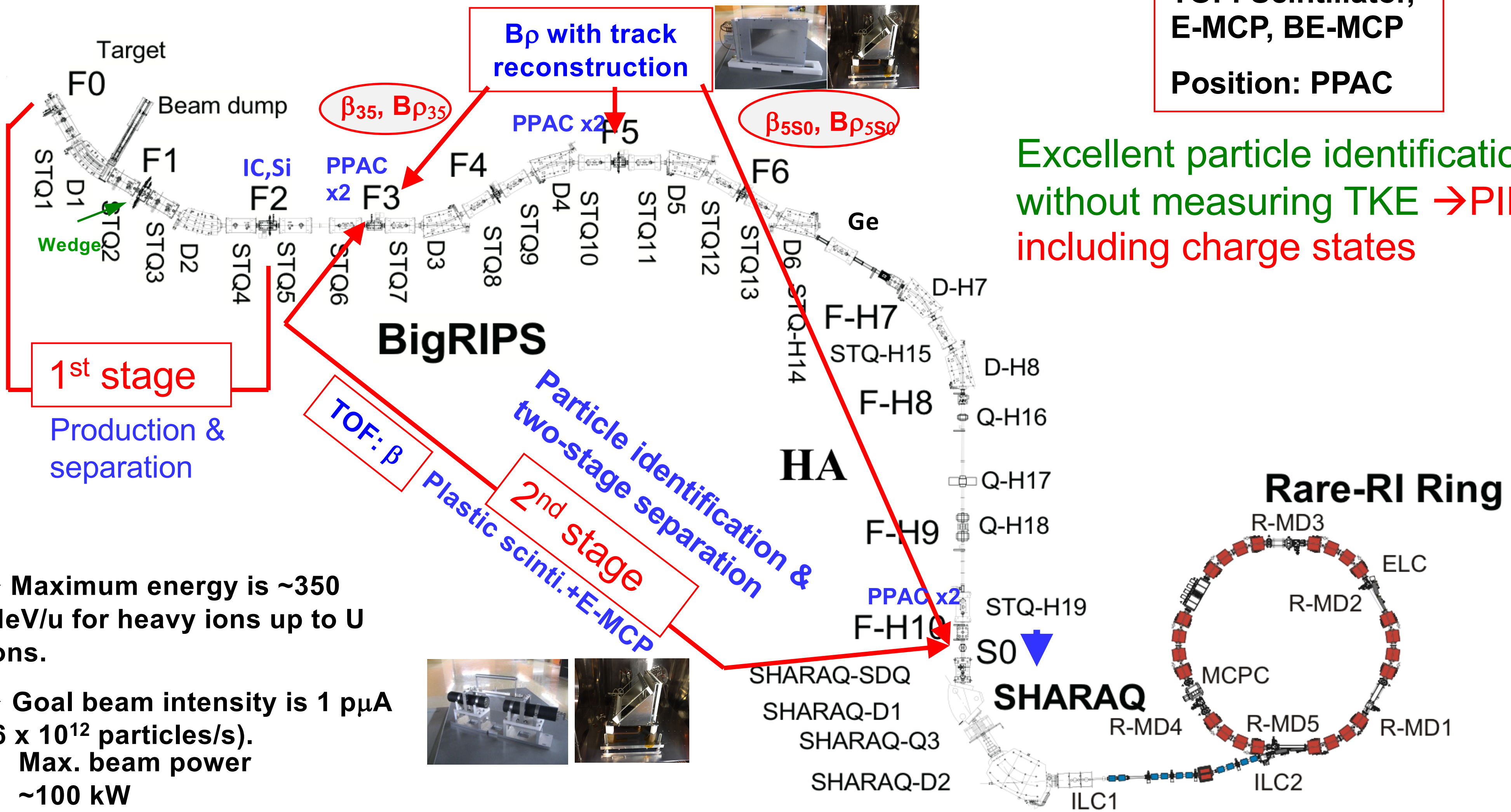
ΔE: IC, Si

Isomer γ-ray: Ge

TOF: Scintillator, E-MCP, BE-MCP

Position: PPAC

Excellent particle identification without measuring TKE →PID including charge states



Bρ with track reconstruction

1st stage

Production & separation

TOF: β

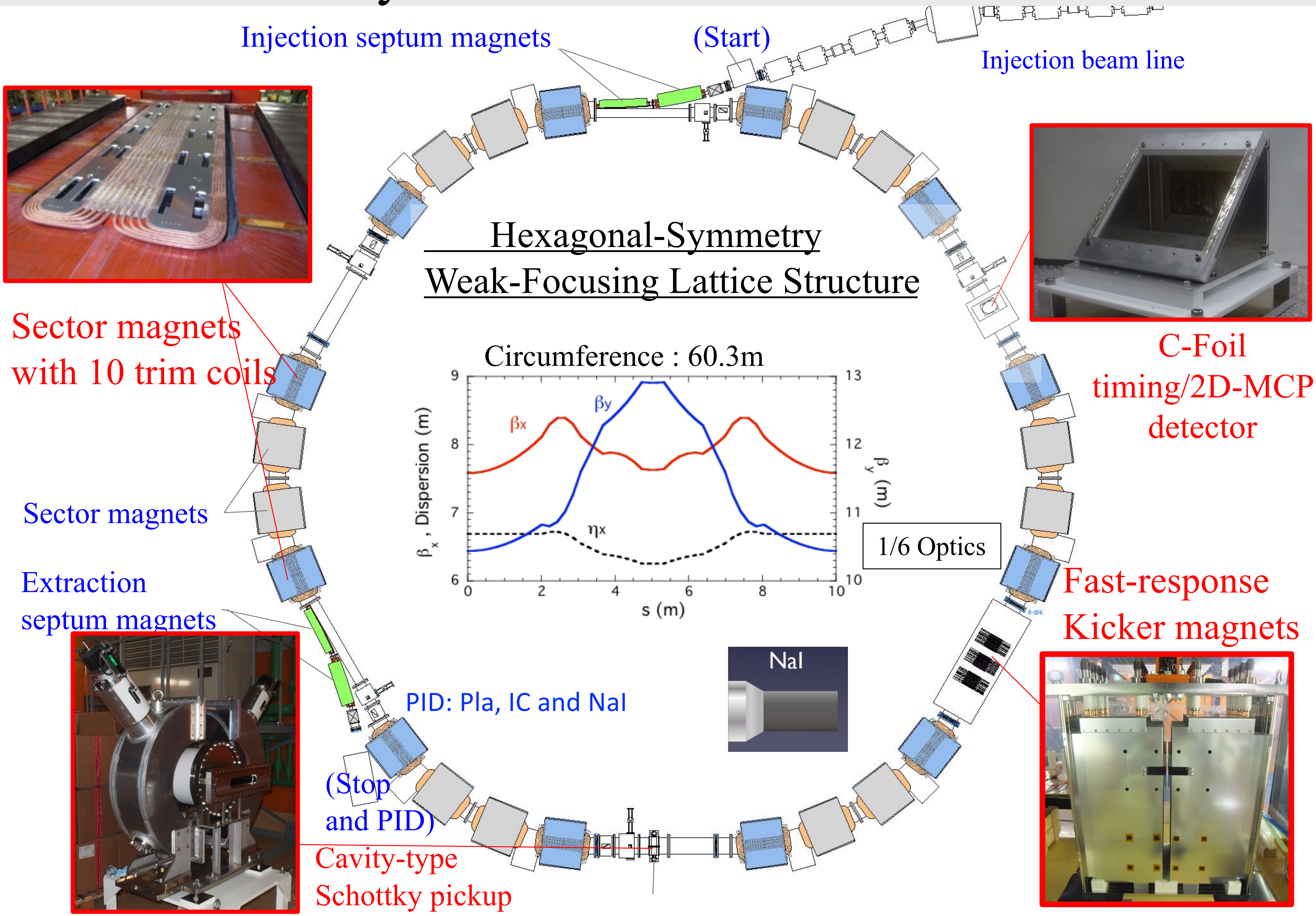
Plastic scinti.+E-MCP

2nd stage

Particle identification & two-stage separation

- **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



Injection septum magnets

(Start)

Injection beam line

Hexagonal-Symmetry
Weak-Focusing Lattice Structure

Circumference : 60.3m

1/6 Optics

Sector magnets
with 10 trim coils

Sector magnets

Extraction
septum magnets

PID: Pla, IC and NaI

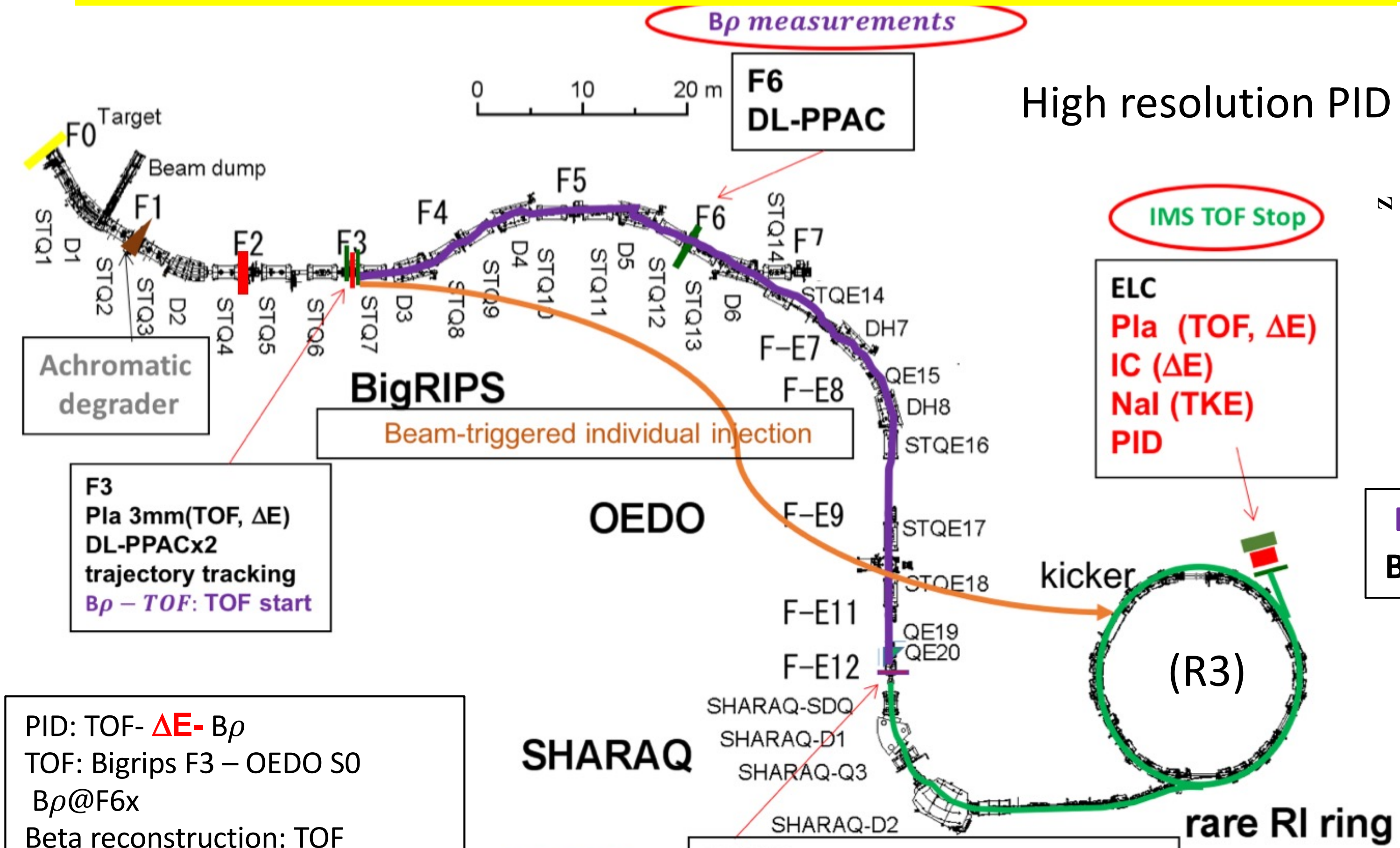
(Stop
and PID)

Cavity-type
Schottky pickup

C-Foil
timing/2D-MCP
detector

Fast-response
Kicker magnets

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



Bρ measurements

F6
DL-PPAC

Achromatic degrader

Beam-triggered individual injection

IMS TOF Stop

ELC
Pla (TOF, ΔE)
IC (ΔE)
NaI (TKE)
PID

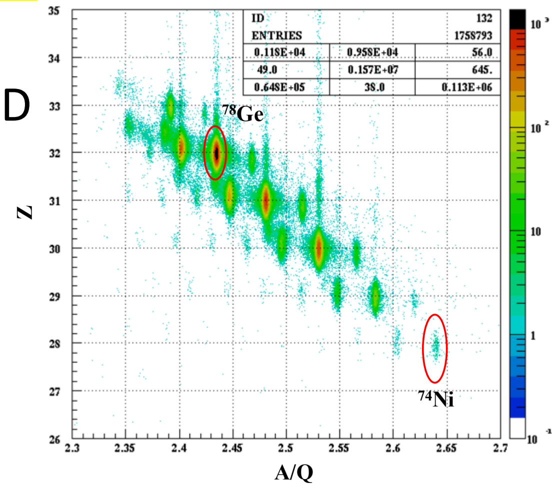
F3
Pla 3mm(TOF, ΔE)
DL-PPACx2
trajectory tracking
Bρ – *TOF*: TOF start

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

IMS TOF Start

F-E12/S0
Timing MCP detector(30-40ps)
+Position sensitive MCP detector
Bρ – *TOF*: TOF stop

High resolution PID



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

F3-S0:
Efficiency 70-90%
Momentum acceptance
±0.5%
Rare-RI Ring:
Efficiency 1 %
Momentum acceptance
±0.3%

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

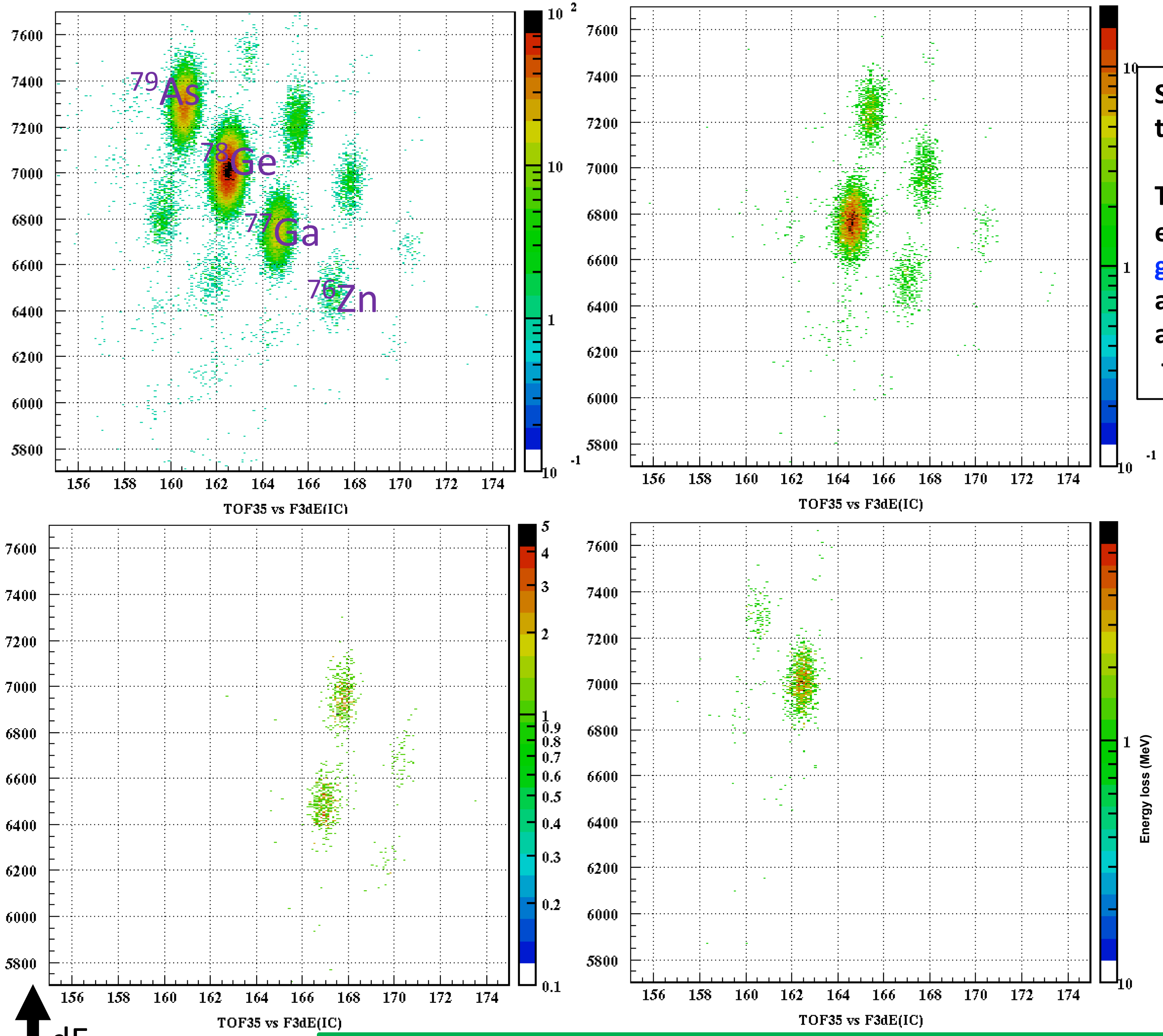
$$\left(\frac{m}{q}\right)_1 = \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-\left(\frac{T_1}{T_0}\beta_1\right)^2}}$$

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

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

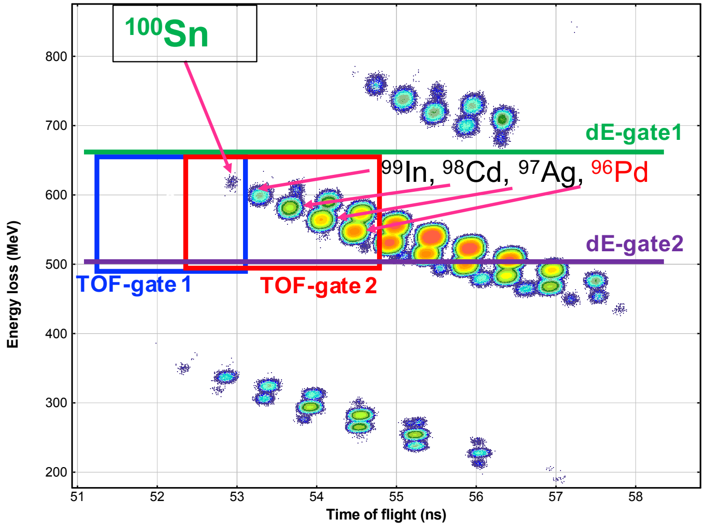
Zhuang Ge, Tomohiro Uesaka et al., Hyperfine Interact (2019) 240: 92; Zhuang Ge, PhD thesis (2018)

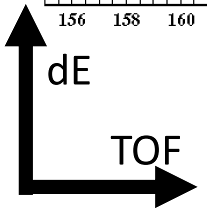
dE-TOF gate Selection method



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

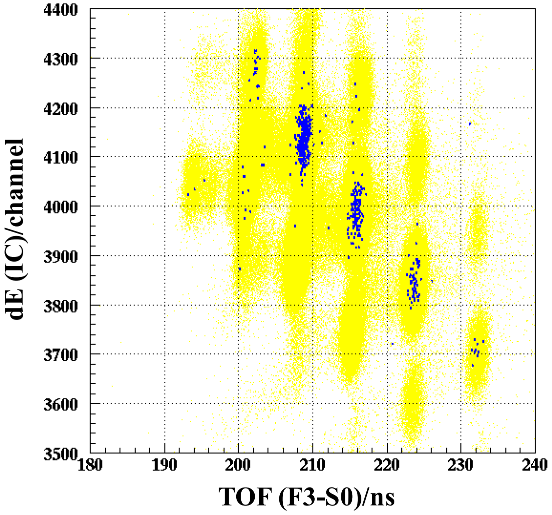
Event-by-event PID with TOF(beamline)-Bρ-dE-E-TOF(in-Ring)

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

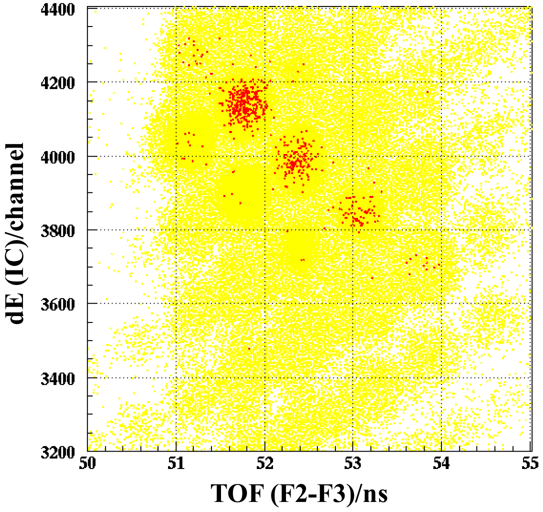
Unambiguously identification with single ion sensitivity

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

dE-TOF1



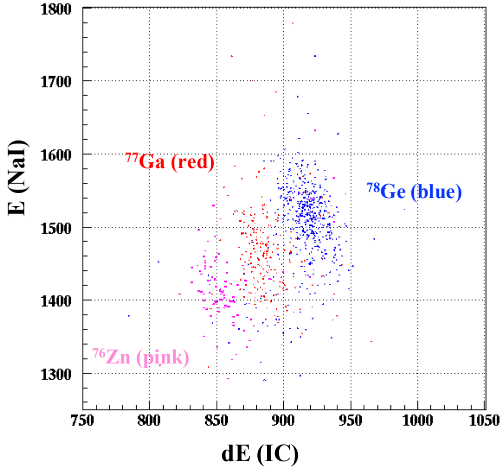
dE-TOF2



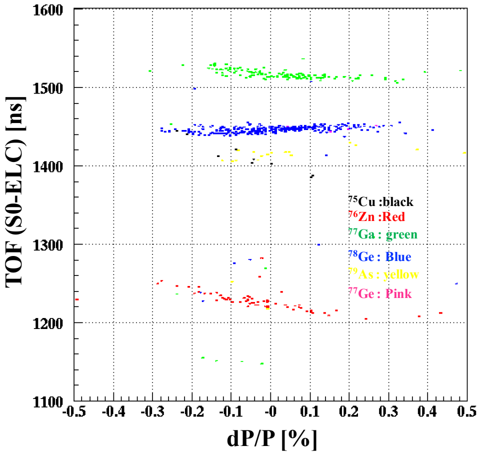
Yellow: all ions detected at S0
Blue: extracted from R3

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

dE-E



In-ring TOF- Bρ



dE: IC, E: ring-extraction NaI

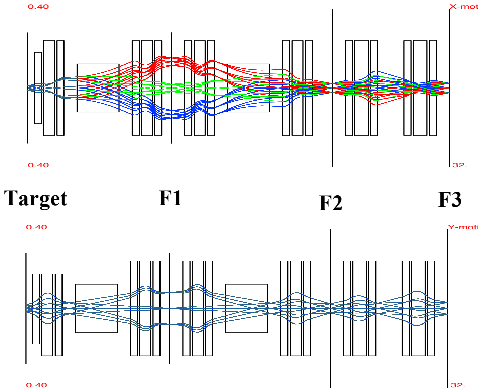
Bρ: beamline, TOF: in ring

Ion optics design (beam-line and storage ring)

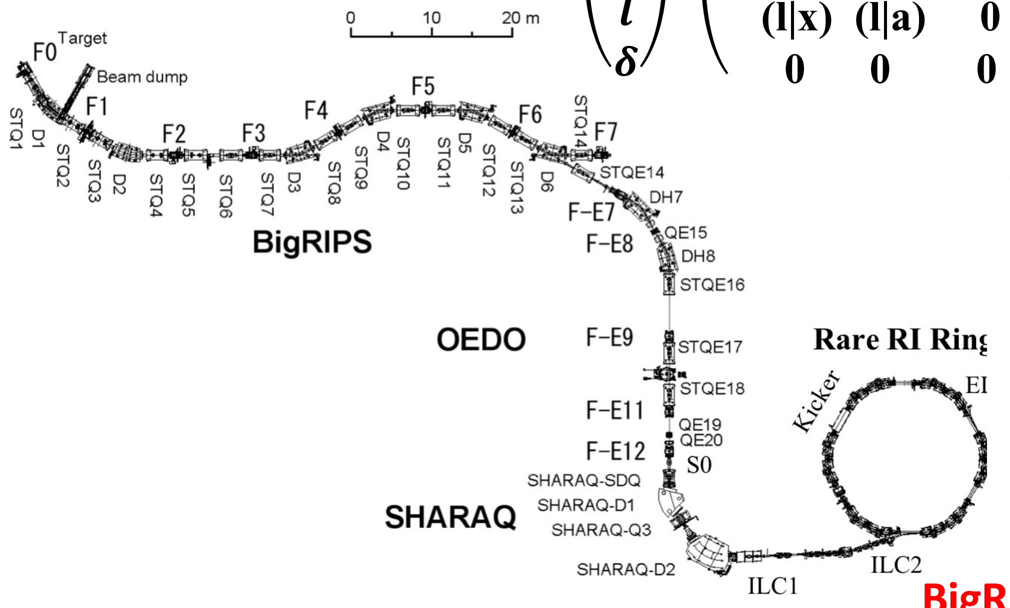
	(x|x)	(x|a)	(a|x)	(a|a)	(y|y)	(y|b)	(b|y)	(b|b)	(x|dp)	(a|dp)	(l|dp)	L|dEk
F3F4	-0.966	0	0	-1.03	-3.88	0	-0.04	-0.26	-1.86	-1.89	4.04	2.187439
F3F5	-0.01	-9.6	0.1	0	1.298	0	-0.06	0.77	0.108	0.505	8.81	4.771546
F3F6	0.965	0	0	1.036	-3.88	0	0	-0.257	7.54	0.368	11.62	6.296793
F3FE7	-0.394	9.7	-0.1	0.016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

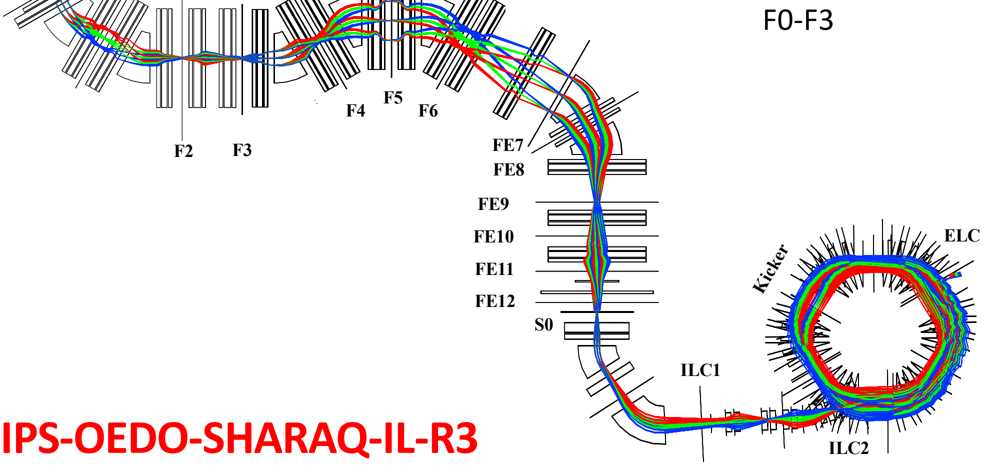
Transfer matrix :

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



F0-F3

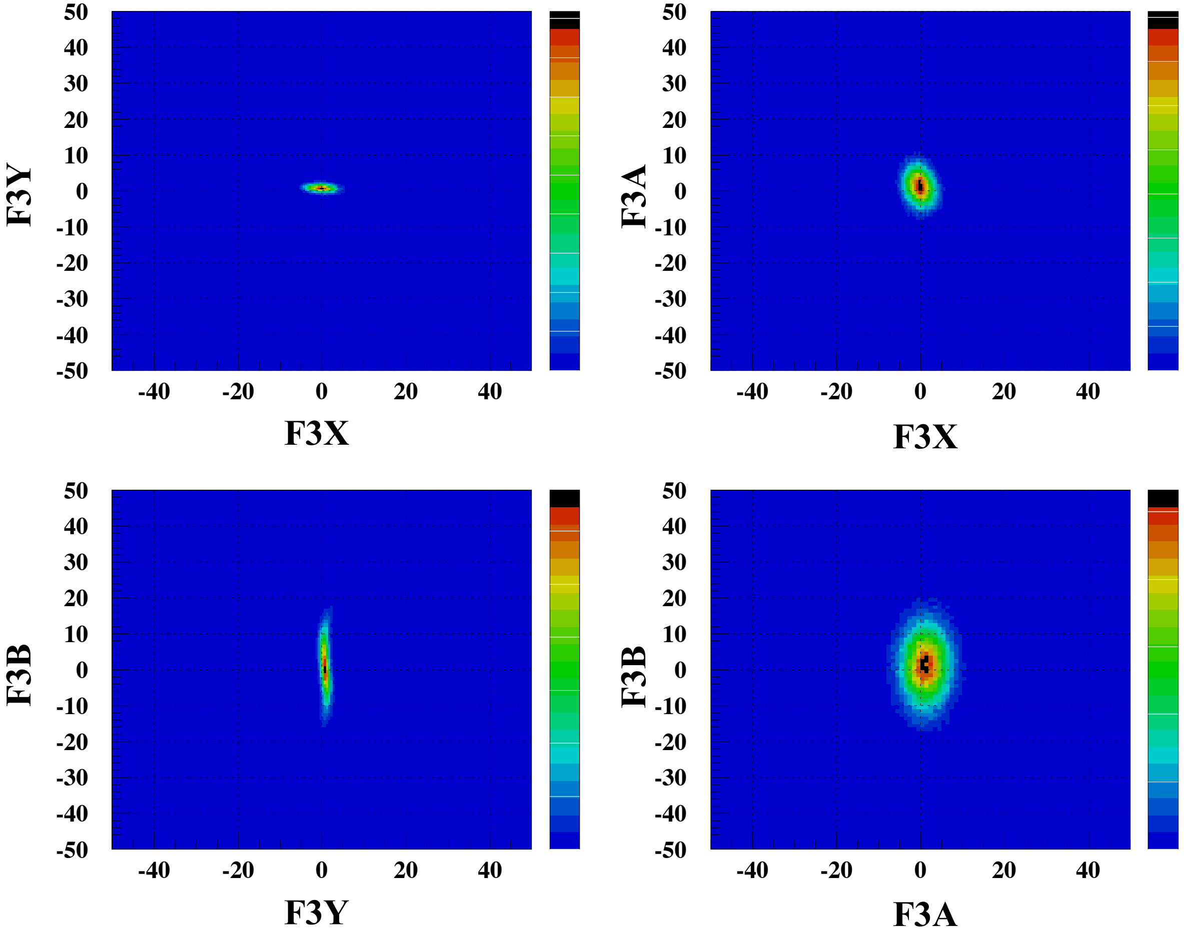




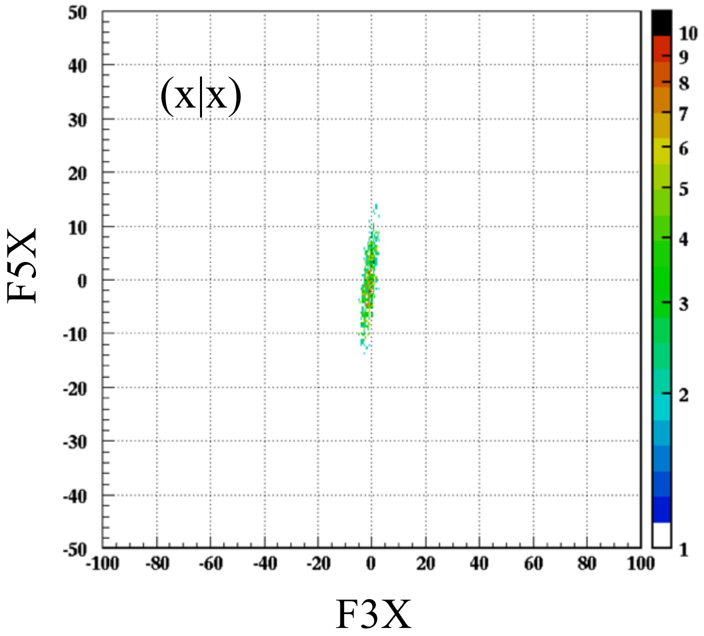
BigRIPS-OEDO-SHARAQ-IL-R3

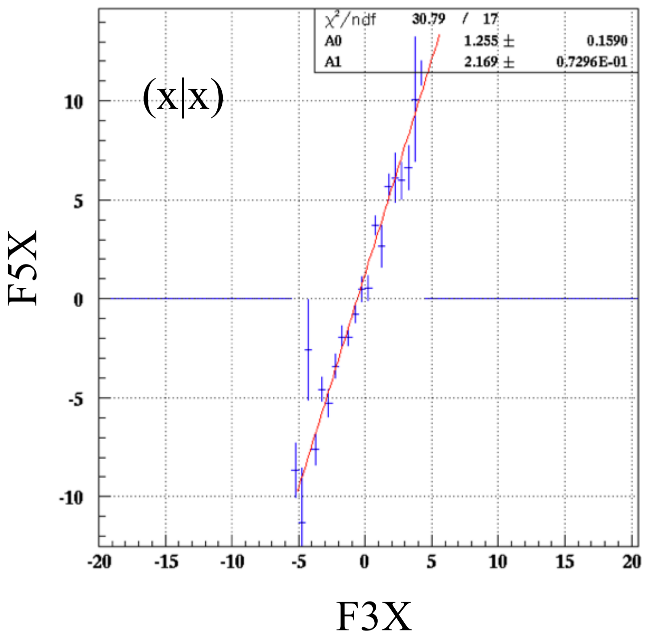
Optical matrix element reconstruction

Emittance



F3-F5 (X|X) measurement

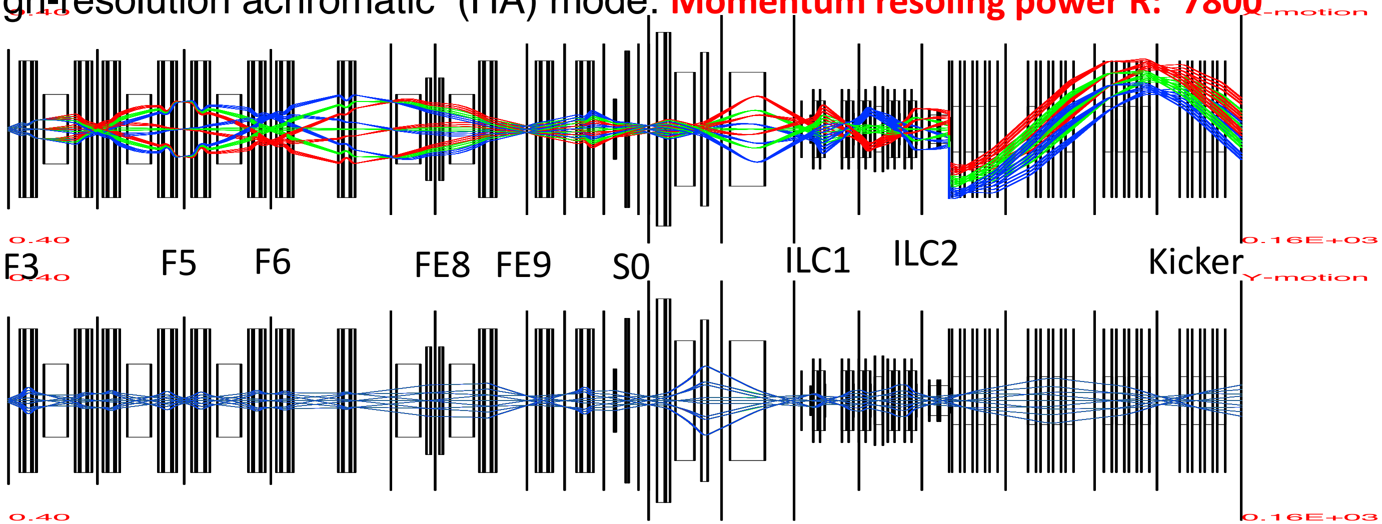




PPACs: position and angle

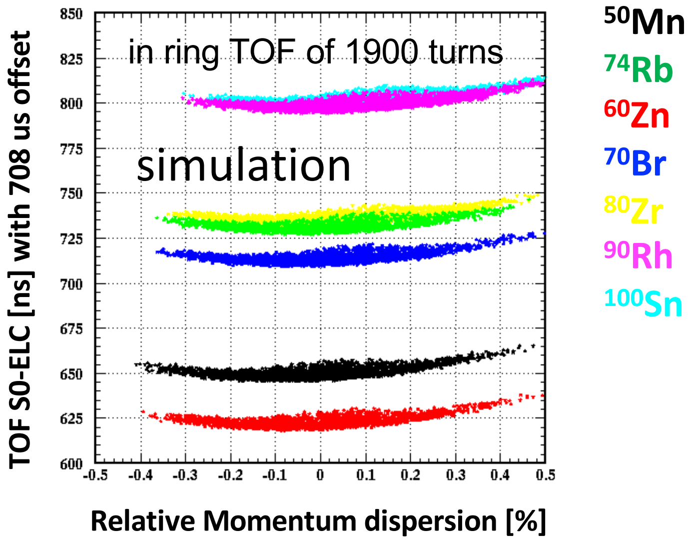
Optics design with high momentum resolving power and ion transportation simulation

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

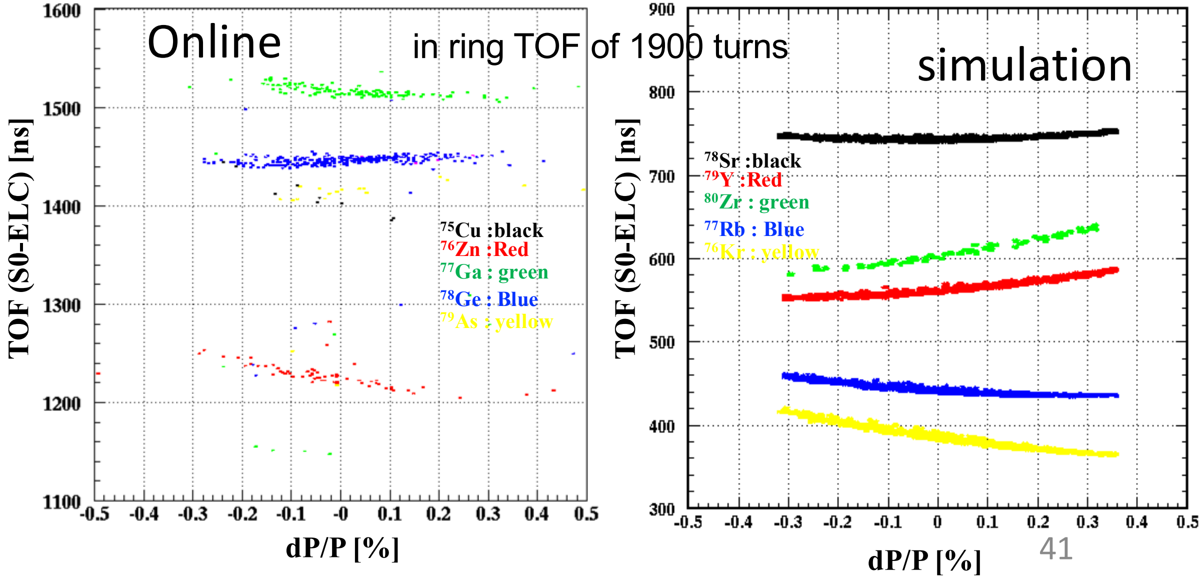


Zhuang Ge et al., Nuclear Physics Review, 2019, 36(3): 294-304 (2019)

Advantage of N=Z nulcei for in-ring IMS



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

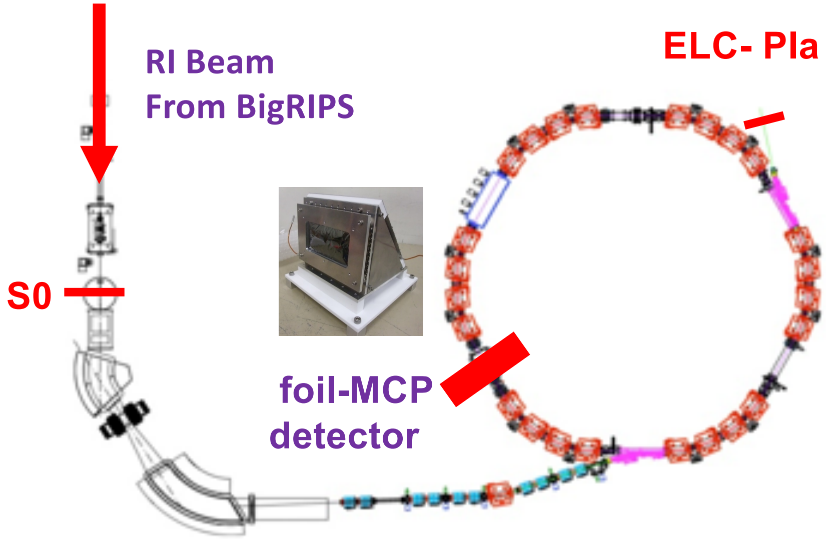


Revolution time determination

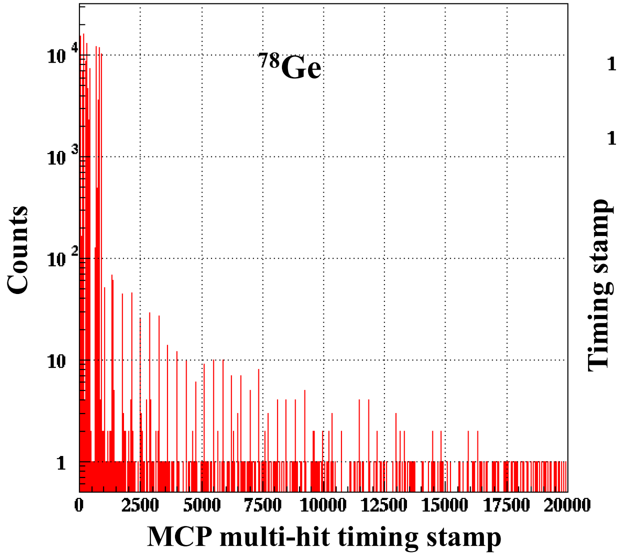
Circulation of turn number for each ion can be calculated from the Total TOF(s0->ELC) subtract the double kicker TOF over the MCP measured evolution time

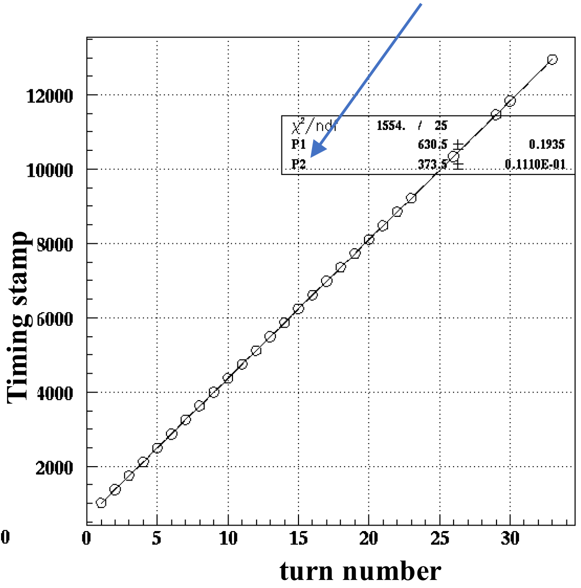
$$N = \frac{TOF^{total}_{(S0\rightarrow ELC)} - TOF^{doublekicker}_{(S0\rightarrow ELC)}}{T}$$

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: $T = P2$

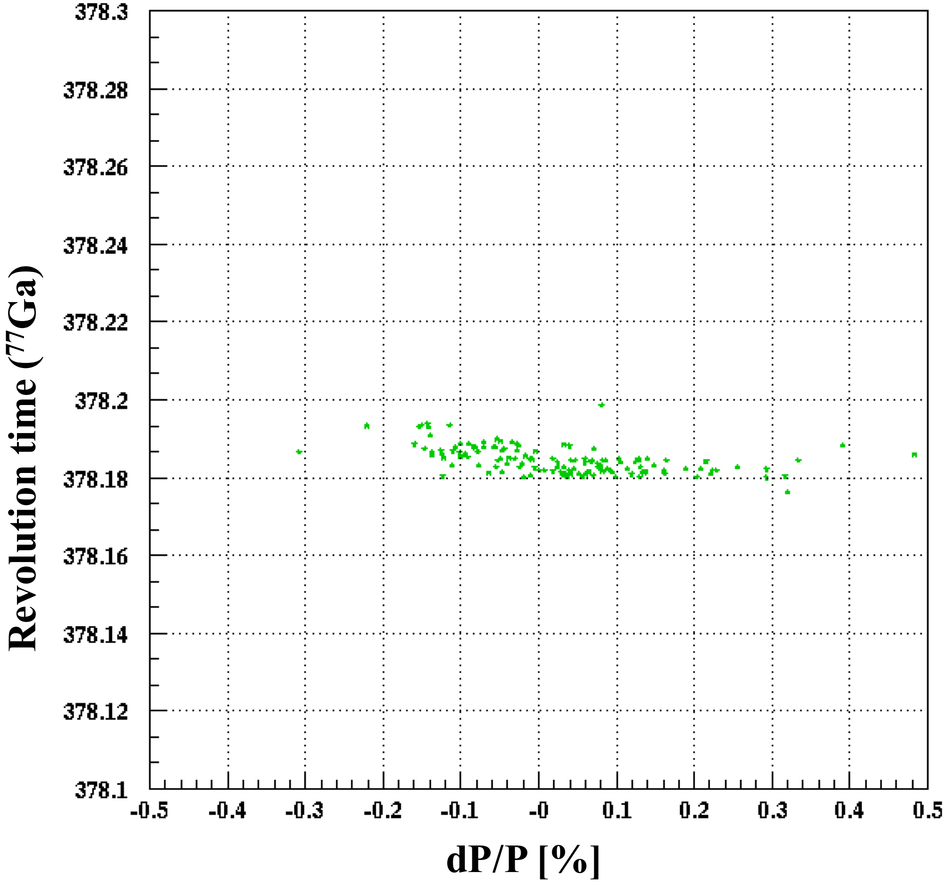


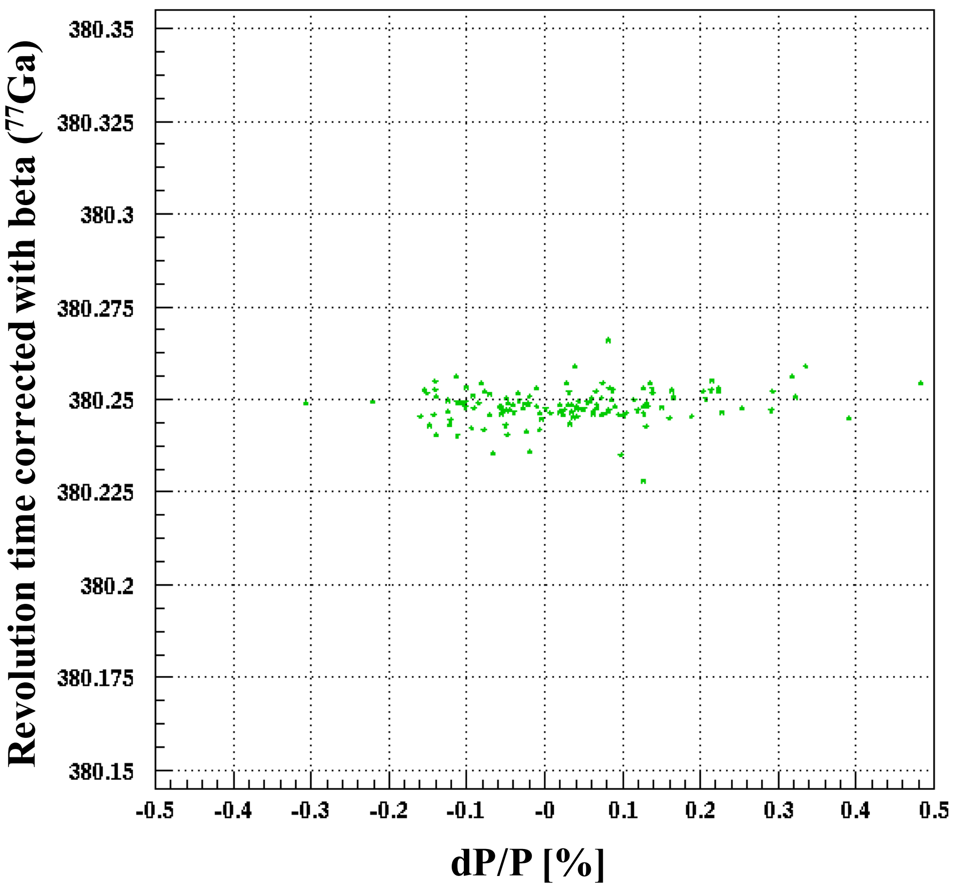


other particle's revolution time can be deduced from the relationship (assuming passing the same orbit):

$$\beta_0 T_0 = \beta_1 T_1$$

Mass measurements by IMS method





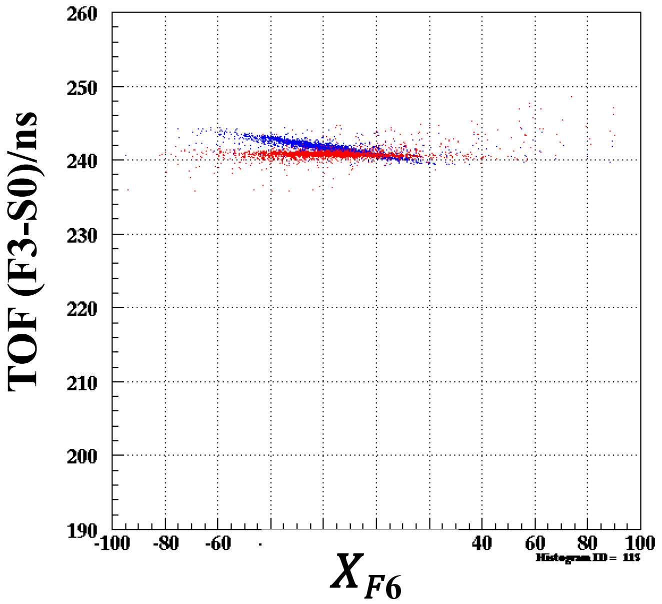
$$\left(\frac{m}{q}\right)_1 = \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-\left(\frac{T_1}{T_0}\beta_1\right)^2}}$$

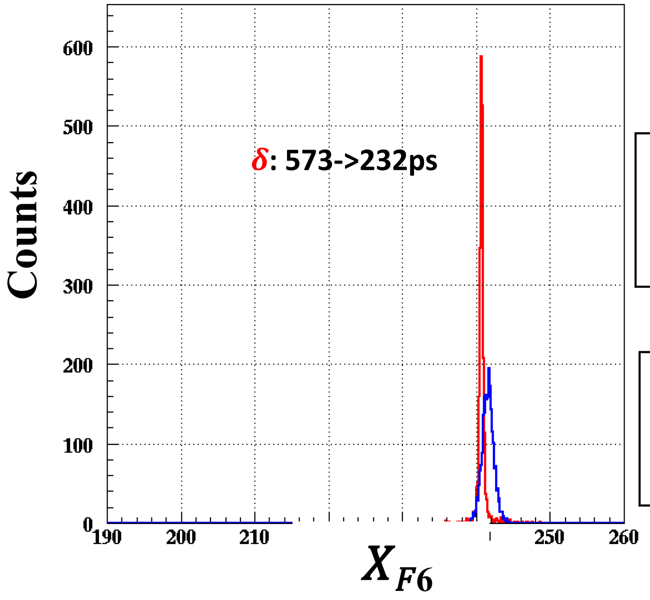
Mass accuracy: ~10^{-6}

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





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

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

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

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

X_{F6} : Proportional to momentum of ions

40ps MCP detector:

Ge, Z.: the Rare-RI Ring Collaboration: RIKEN Accelerator Progress Report 51,152 (2018)

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

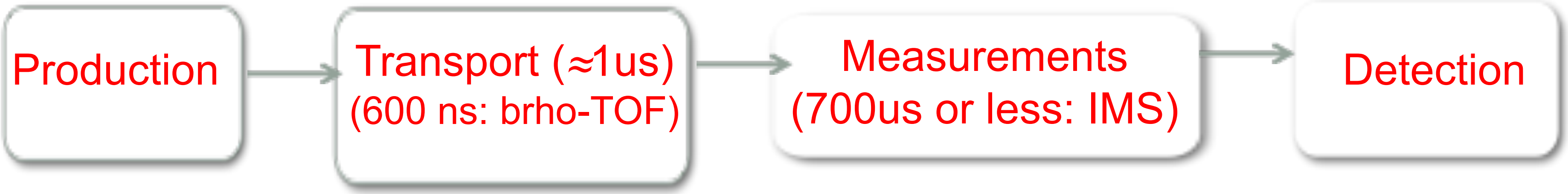
$$(\sigma_{\text{stat}})_i^2 = \left(\frac{\partial f(\tau,z)}{\partial\tau}\right)^2 \times \sigma_i^2(\tau)$$

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

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

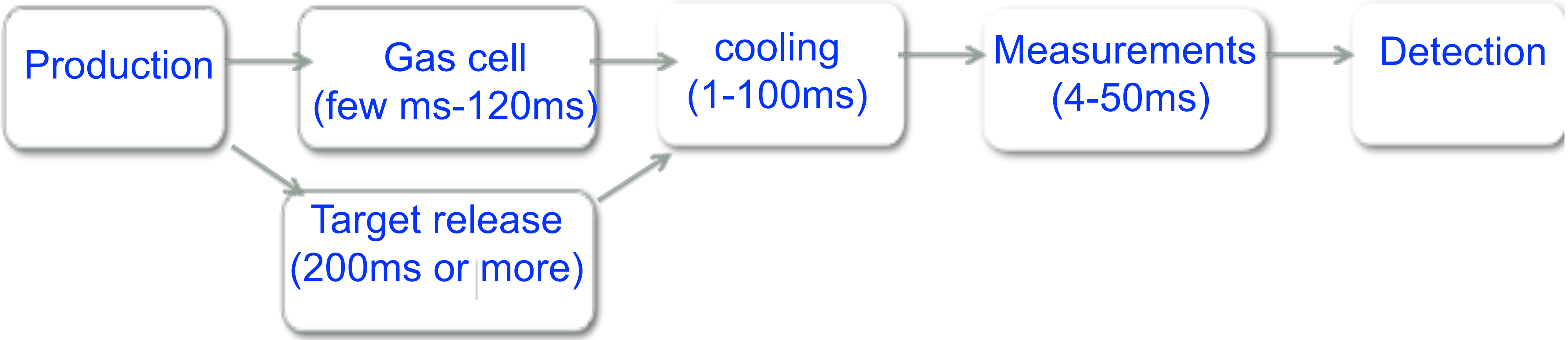
Low energy beam VS accelerated beam

BigRIPS&Rare-RI Ring @RIBF



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

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



ISOL (chemical sensitivity)

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

Acknowledgements

FRS Ion Catcher and IGISOL Collaborations

D. Amanbayev, B. Ashrafkhani, O. Aviv, S. Ayet San Andrés, J. Äystö, S. Bagchi, D. Balabanski, S. Beck, J. Bergmann, A. Blazhev, Z. Brencic, S. Cannarozzo, O. Charviakova, P. Constantin, D. Curien, D. Das, I. Dedes, M. Dehghan, T. Dickel, J. Dobaczewski, J. Dudek, T. Eronen, T. Fowler-Davis, Z. Gao, Z. Ge, H. Geissel, S. Glöckner, M. Górska, T. Grahn, F. Greiner, L. Gröf, M. Gupta, E. Haettner, O. Hall, M. Harakeh, B. S. Hu, C. Hornung, J.-P. Hucka, Y. Ito, A. Jokinen, B. Kaizer, N. Kalantar-Nayestanaki, A. Kankainen, A. Karpov, Y. Kehat, L. Kilmartin, D. Kostyleva, G. Kripkó-Koncz, D. Kumar, A. N. Kuzminchuk, Y. H. Lam, K. Mahajan, I. Mardor, A.A. Mehmandoost-Khajeh-Dad, N. Minkov, A. Mollaebrahimi, D. Morrissey, I. Moore, I. Mukha, G. Münzenberg, T. Murböck, M. Narang, D. Nichita, S. Nikas, D. A. Nesterenko, Z. Patyk, A. Perry, S. Pietri, A. Pikhtelev, W.R. Plaß, Pohjalainen, S. Pomp, S. Purushothaman, M.P. Reiter, M. Reponen, S. Rinta-Antila, H. Rösch, A. Rotaru, C. Scheidenberger, T. Schellhaas, P. Schury, A. Shrayer, S.K. Singh, A. Solders, A. Spataru, A. State, Y. Tanaka, P. Thirolf, N. Tortorelli, E.Vardaci, L. Varga, M. Vencelj, V. Virtanen, M. Wada, M. Wasserheß, H. Weick, M. Wieser, M. Will, H. Wilsenach, O. Yaghi, M.I. Yavor, X. Yang, J. Yu, A. Zadvornaya, J. Zhao

The results from GSI presented here are based on the experiment S459+, which was performed at the FRS at the GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt (Germany) in the context of FAIR Phase-0. The IGISOL experiment is carried out at the Accelerator Laboratory of University of Jyväskylä (JYFL-ACCLAB).

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.

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招收博士后，联合培养学生

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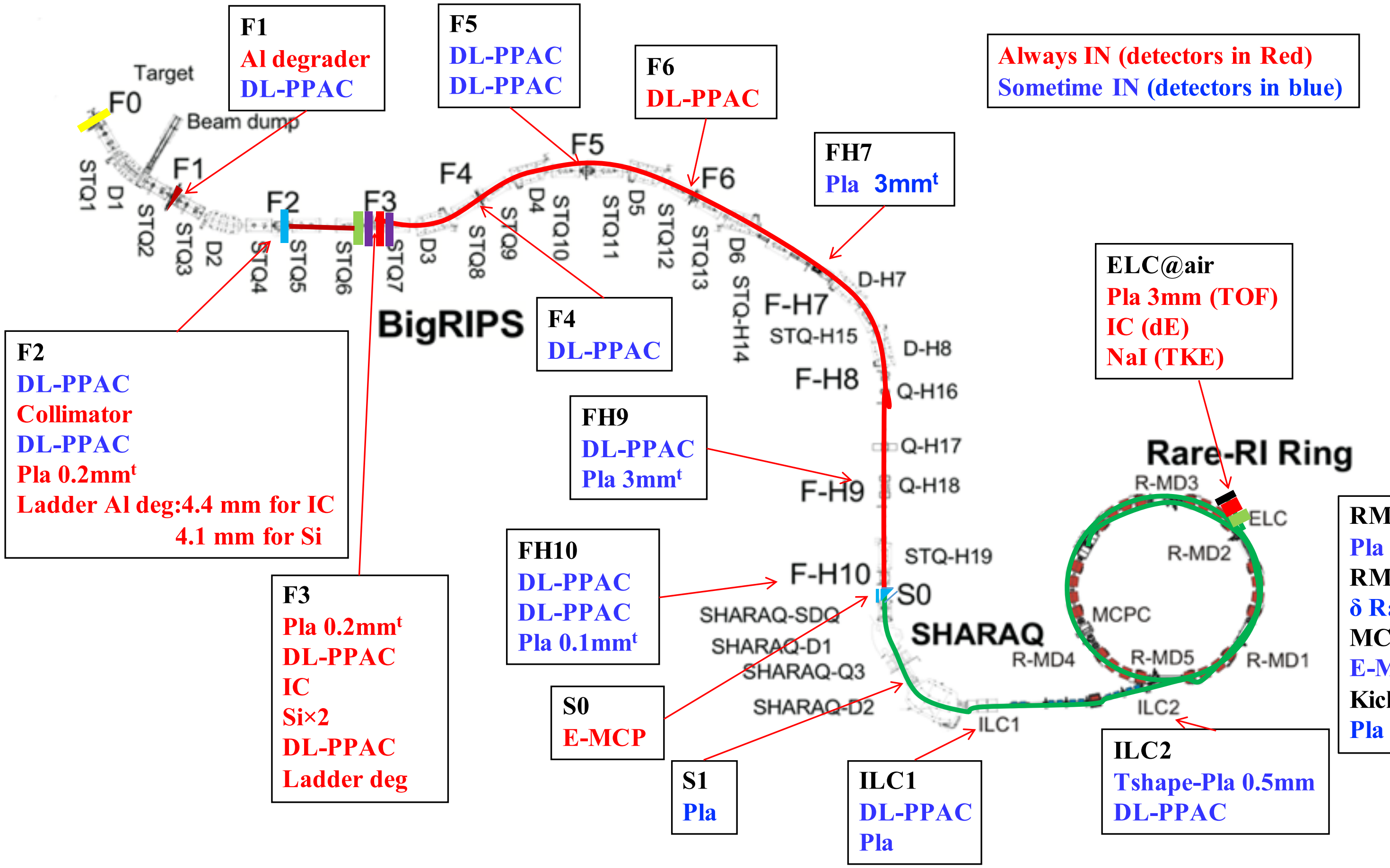
Thank you

for your attention

Experimental setup

In four years' time, to conduct the experiment.

$$B\rho = P/q = mv\gamma/q = A\,c\mu\gamma\beta/(qe)$$



F1
Al degrader
DL-PPAC

F5
DL-PPAC
DL-PPAC

F6
DL-PPAC

FH7
Pla 3mm^t

Always IN (detectors in Red)
Sometime IN (detectors in blue)

ELC@air
Pla 3mm (TOF)
IC (dE)
NaI (TKE)

F2
DL-PPAC
Collimator
DL-PPAC
Pla 0.2mm^t
Ladder Al deg:4.4 mm for IC
4.1 mm for Si

F4
DL-PPAC

FH9
DL-PPAC
Pla 3mm^t

FH10
DL-PPAC
DL-PPAC
Pla 0.1mm^t

F3
Pla 0.2mm^t
DL-PPAC
IC
Si×2
DL-PPAC
Ladder deg

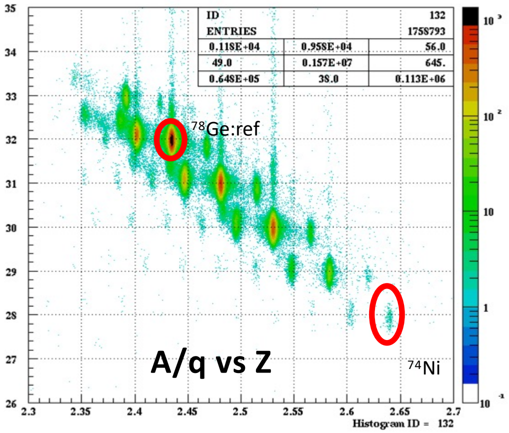
S0
E-MCP

S1
Pla

ILC1
DL-PPAC
Pla

ILC2
Tshape-Pla 0.5mm
DL-PPAC

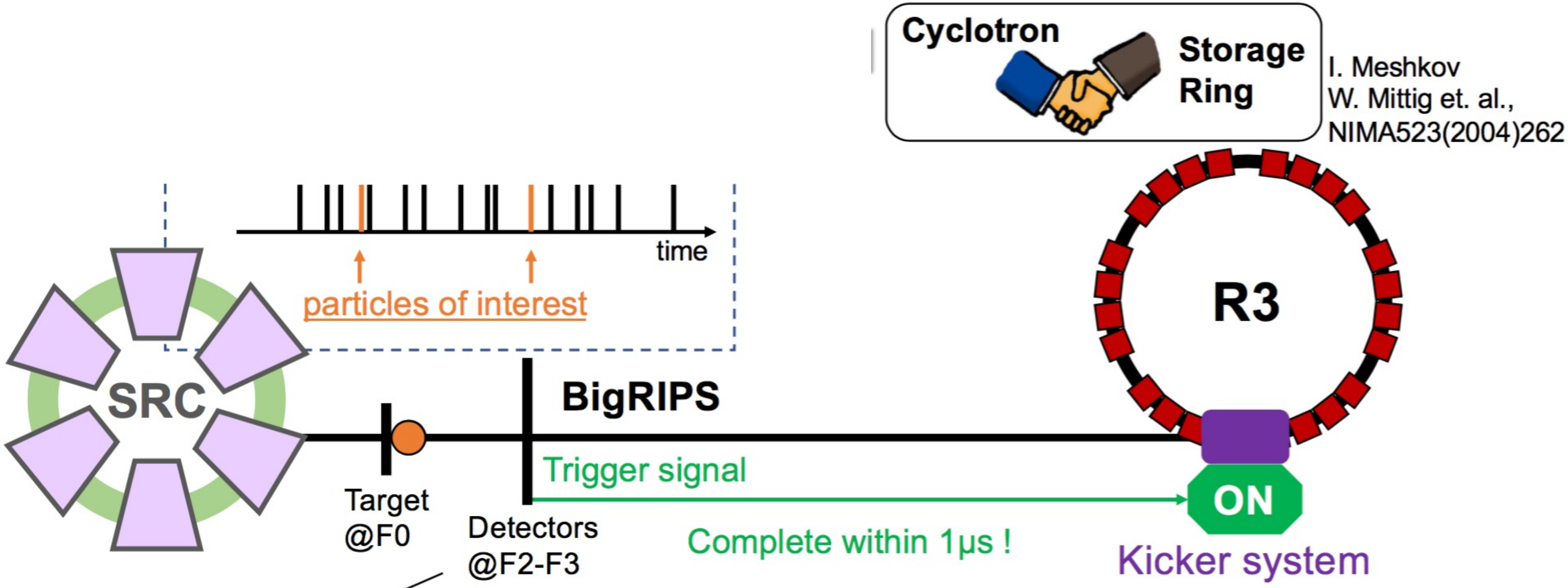
RMD 1-4
Pla 5mm^t
RMD 5
δ Ray-detector
MCPC
E-MCP
Kicker
Pla



F2-F3: PID and selection
dE-TOF PID
F3-S0: PID and Bρ−TOF
mass measurements
velocity/momentum
measurements
dE-TOF PID
A/q-Z PID
S0-ELC: PID and in-ring
mass measurements
dE-E PID

$$\Delta E \propto E \propto (Z/v)^2$$

Self-triggered injection method



Cyclotron

Storage Ring

I. Meshkov
W. Mittig et. al.,
NIMA523(2004)262

time

particles of interest

SRC

Target
@F0

Detectors
@F2-F3

BigRIPS

Trigger signal

Complete within 1μs !

R3

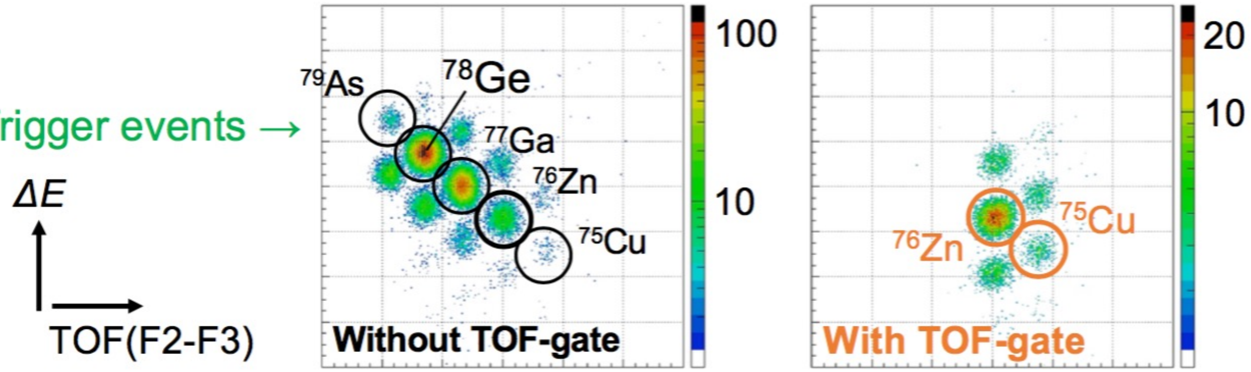
ON

Kicker system

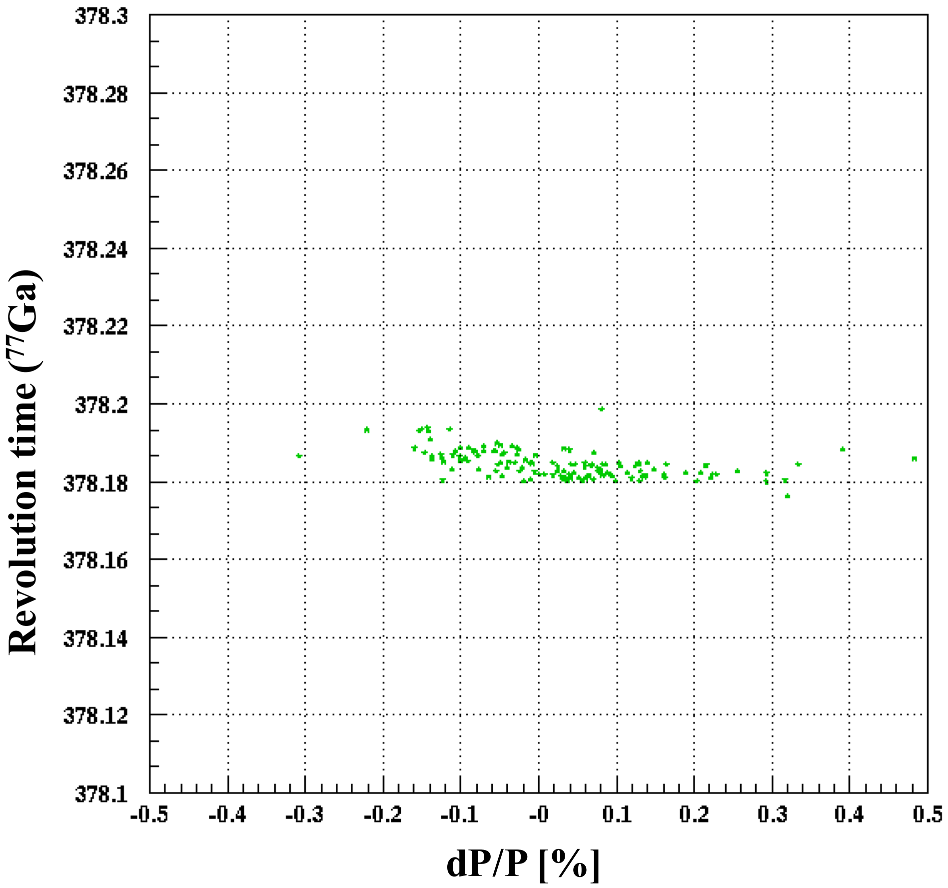
Isotope selection
for trigger signal generation using "TOF-gate".

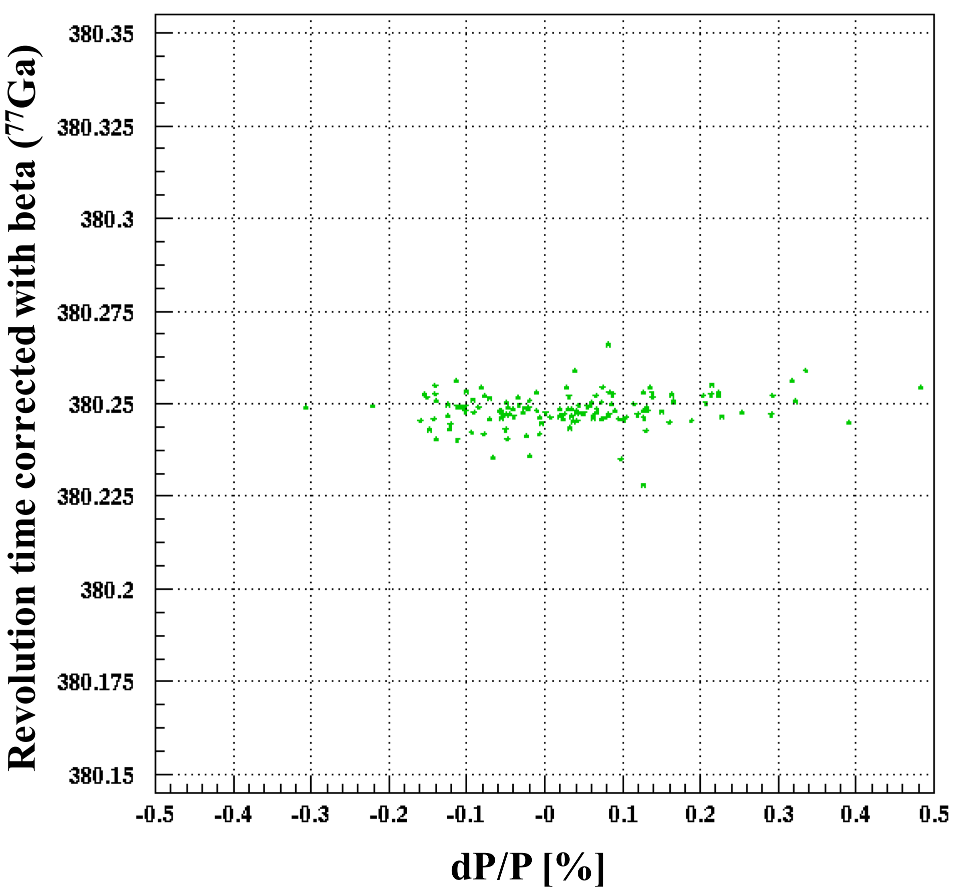
(TOF-gate: veto signal using reference RF-signal)

Trigger events →



Mass measurements by IMS method





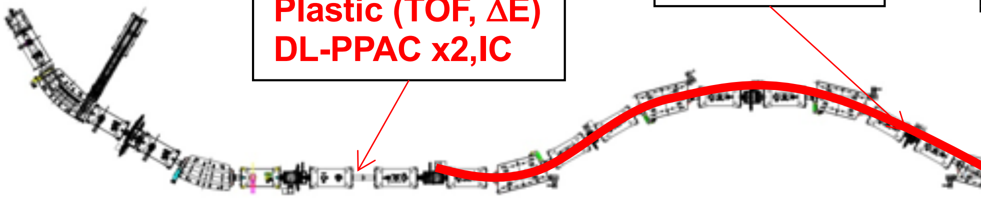
$$\left(\frac{m}{q}\right)_1 = \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-\left(\frac{T_1}{T_0}\beta_1\right)^2}}$$

Mass accuracy: ~10^{-6}

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

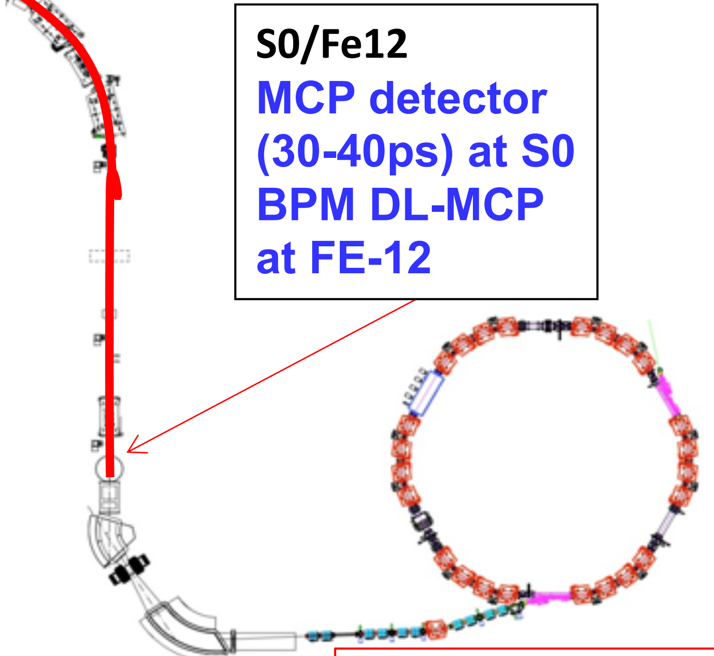
Brho(@F6 or F5)-TOF (f3-S0) mass measurements

MS03 machine study



F3
Plastic (TOF, ΔE)
DL-PPAC x2,IC

F6
DL-PPAC
Brho meas.

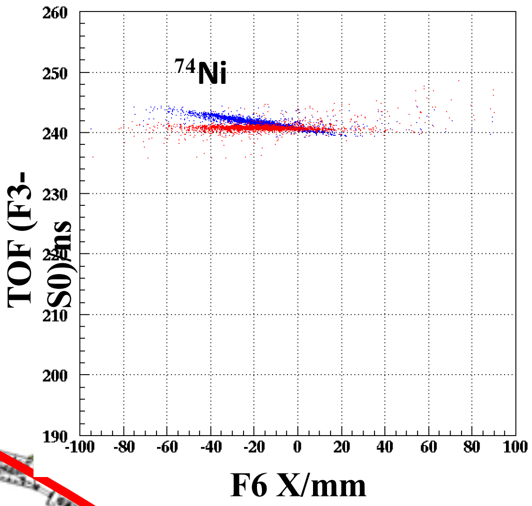


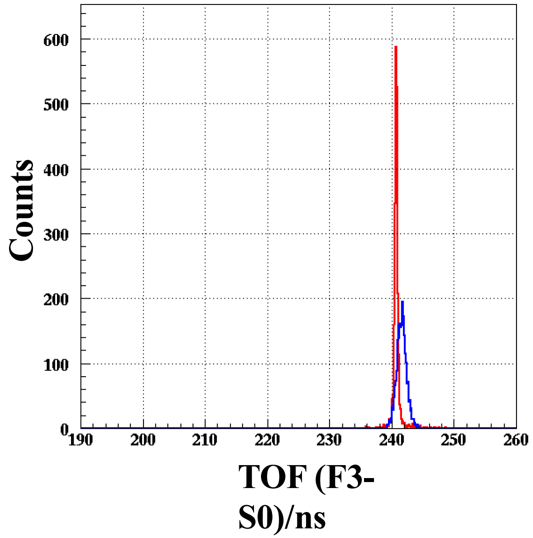
S0/Fe12
MCP detector (30-40ps) at S0
BPM DL-MCP at FE-12

Momentum resolving power(MS03):~7500/0.9~8333
δBρ/Bρ =0.007%

$$\delta m = \frac{m}{\boldsymbol{R\sqrt{N}}}$$

R~2x10^{-4}(TOF resolution 50ps)
200keV-1MeV: 10000-400 conts

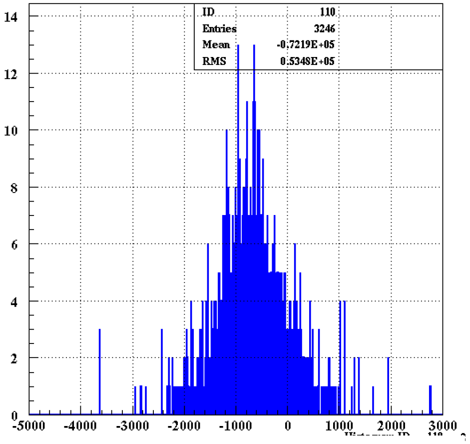




$$\frac{m_0}{q} = \frac{B\rho}{\gamma L/t} = B\rho\sqrt{\left(\frac{t}{L}\right)^2 - \left(\frac{1}{c}\right)^2}$$

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

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



Mass excess of 74Ni

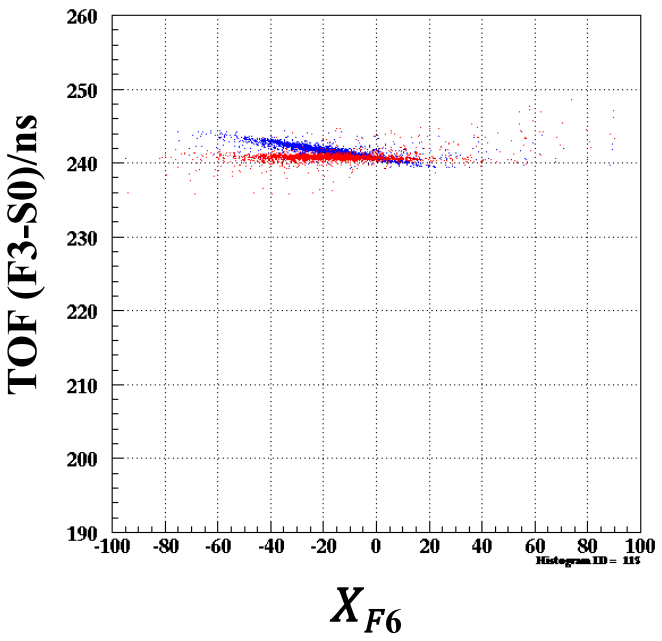
Equation to get mass

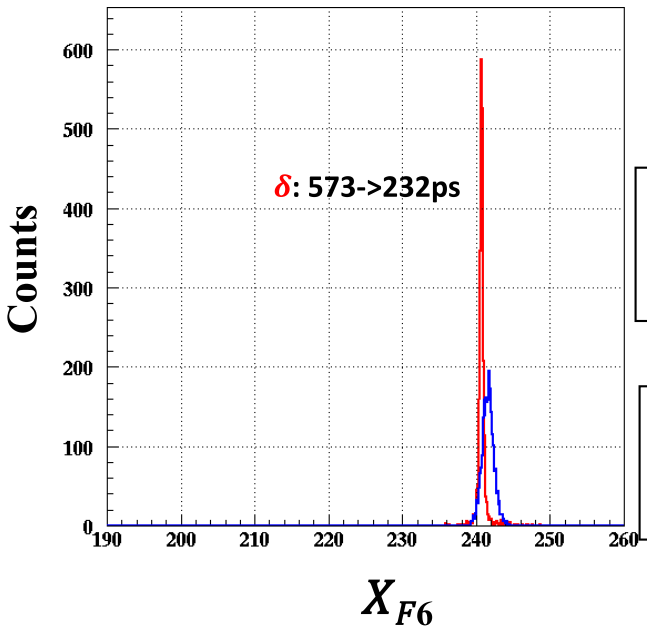
$$m/q = f(\tau,z)$$

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

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

Mass measurements by $B\rho - TOF$ method





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

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

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

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

X_{F6} **: Proportional to momentum of ions**

TOF determination with magnetic rigidity correction

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

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

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

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