Development of new ionization chamber specialized in high-Z beam

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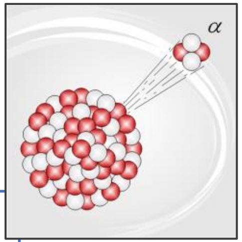
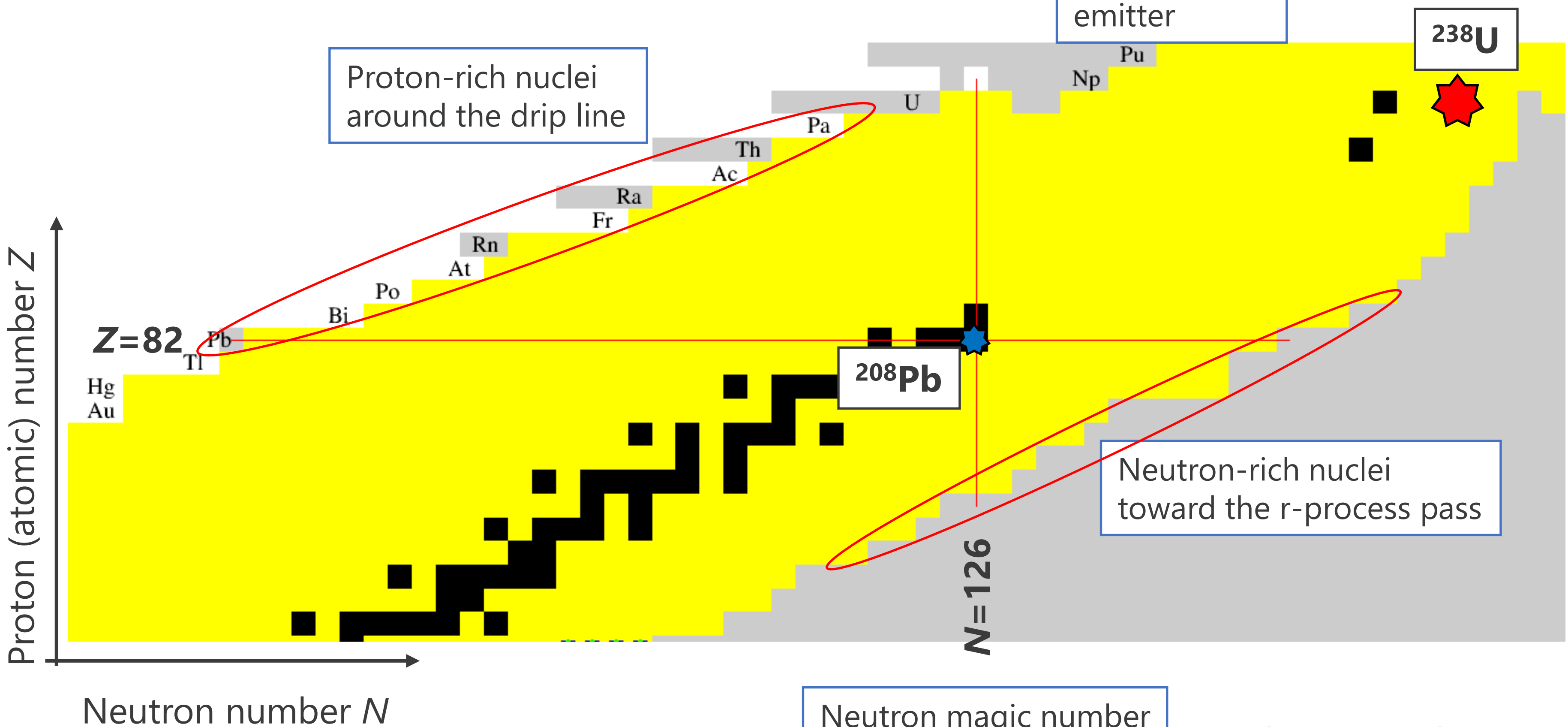
Motivation for high-*Z* beam @ RIBF

Requests for Higher-*Z* beams production are increasing,
based on the success of BigRIPS in delivering RI beams
Z<70 at 200-300 MeV/u.



Alpha particle emitter



Neutron magic number
N=126

There must be more…

BigRIPS separator & in-flight PID

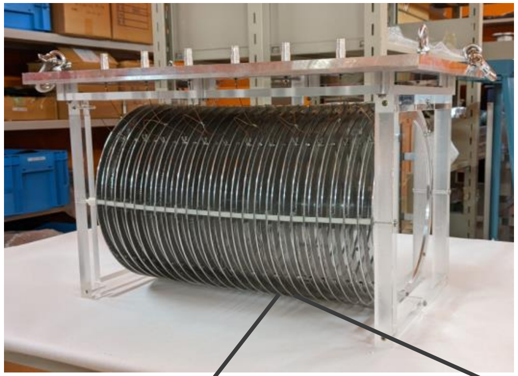
TOF-$B\rho$-ΔE method

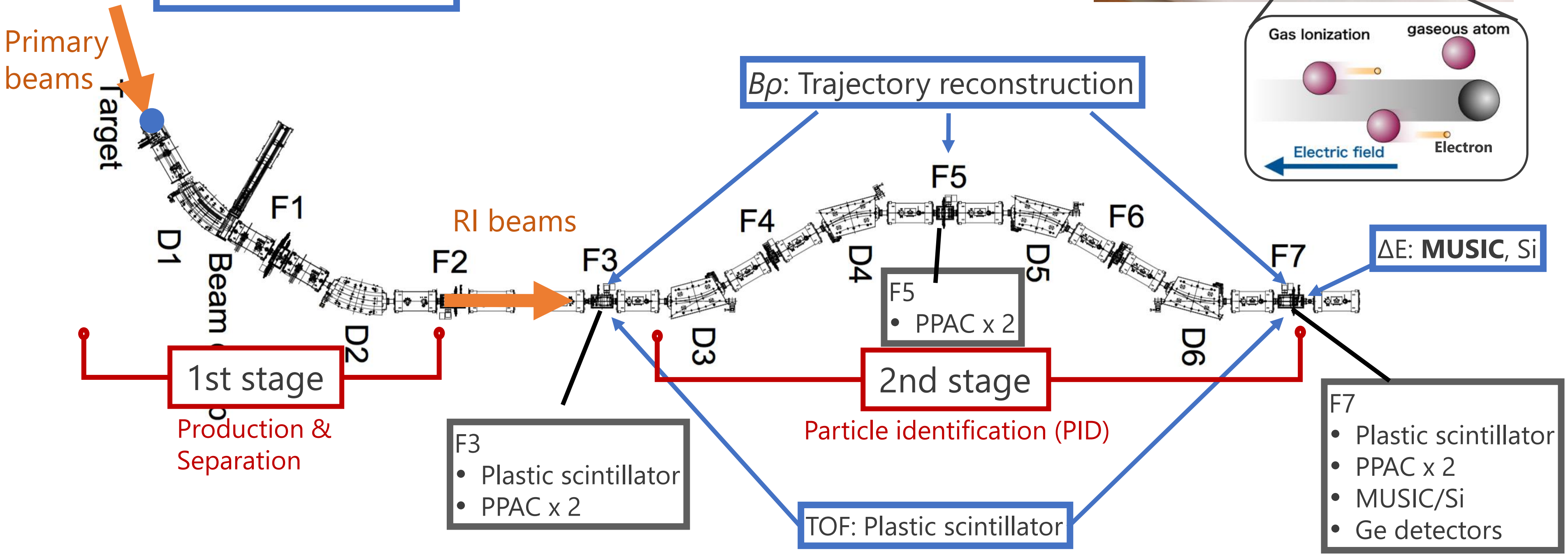
$$\frac{A}{Q} = \frac{B\rho c}{\beta\gamma m_u}$$

$$Z \leftarrow \Delta E = f(Z, \beta)$$

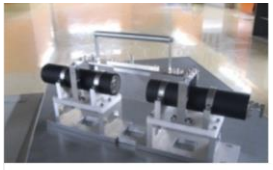
$B\rho$: magnetic rigidity
TOF: time of flight
ΔE : energy loss

MUSIC: Multi-Sampling Ionization chamber





Parallel Plate Avalanche Counter (PPAC)

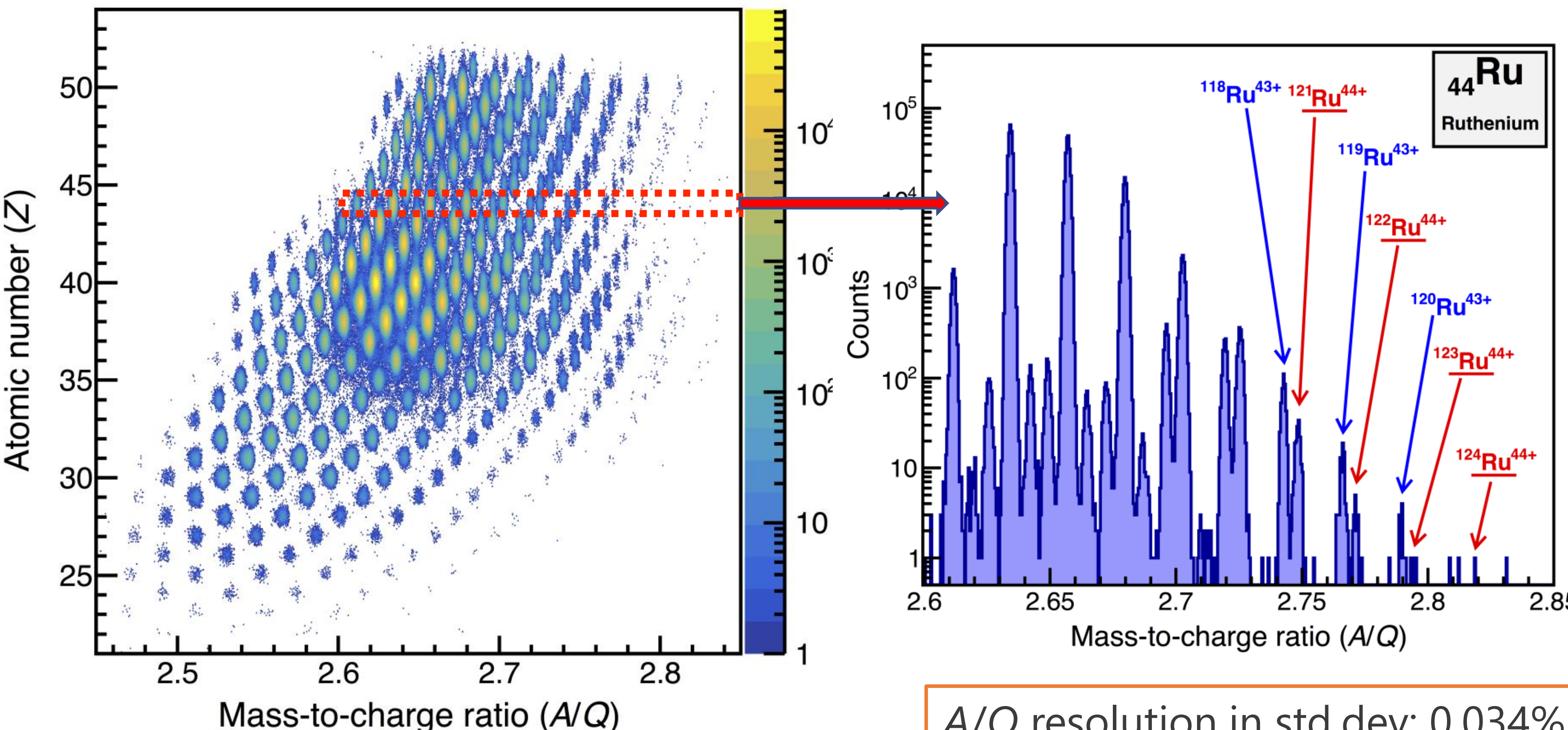


Plastic scintillation counter

Previous studies on MUSIC
W. B. Christie, *et al.* NIM A **255**, 466–476 (1987).
M. Pfützner, *et al.* NIM B **86**, 213–218 (1994).
K. Kimura, *et al.* NIM A **538**, 608–614 (2005).
Y. Sato, *et al.* Jpn. J. Appl. Phys. **53**, 016401 (2014).

BigRIPS separator & in-flight PID

^{238}U (345 MeV/u) + Be (2.9 mm^{t}), $B\rho$ = 7.990 Tm



A/Q resolution in std.dev: 0.034%
→ 6.1σ separation

N.Fukuda *et al.*, Nucl. Instrum. Meth. B 317, 323 (2013)

Issues for high-Z beam

Poor Z resolution of ionization chamber at F7 in high-Z region at 200-300 MeV/u* has been a major problem so far.

Why is the Z resolution so poor for the high-Z beams at this energy?

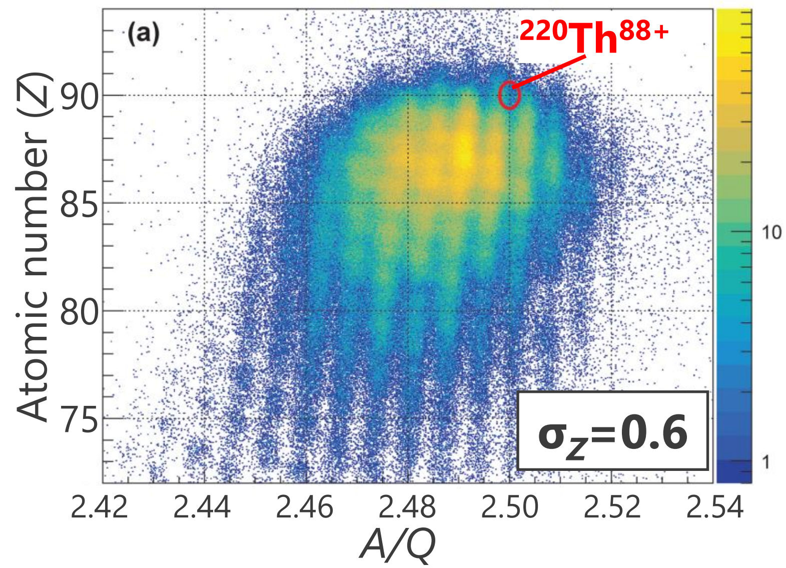
→ Charge-state (Q) fluctuation

- Electron capture and electron stripping occurs in material with heavy ions
- Changing effective Z in IC changes ΔE
- H. Weick, *et al.* Phys. Rev. Lett. **85**, 2725 (2000).

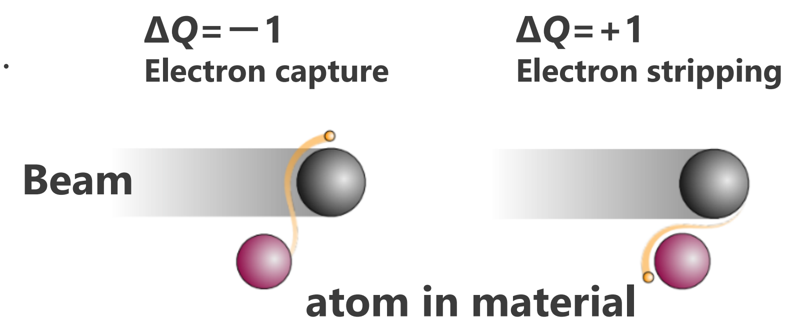
Z considering Q fluctuation

$$\Delta E \propto \frac{{Z_{eff}}^2}{\beta^2}\left[\ln\frac{2m_e(\beta c)^2}{I} - \ln\left(1-\beta^2\right) - \beta^2\right]$$

High-energy high-Z beam production
^{216}Th and ^{220}Th (Z=90) ≥250 MeV/u



^{238}U primary beam, Be 1mm target, No degraders
RIKEN Accel. Prog. Rep. 54 (2021)



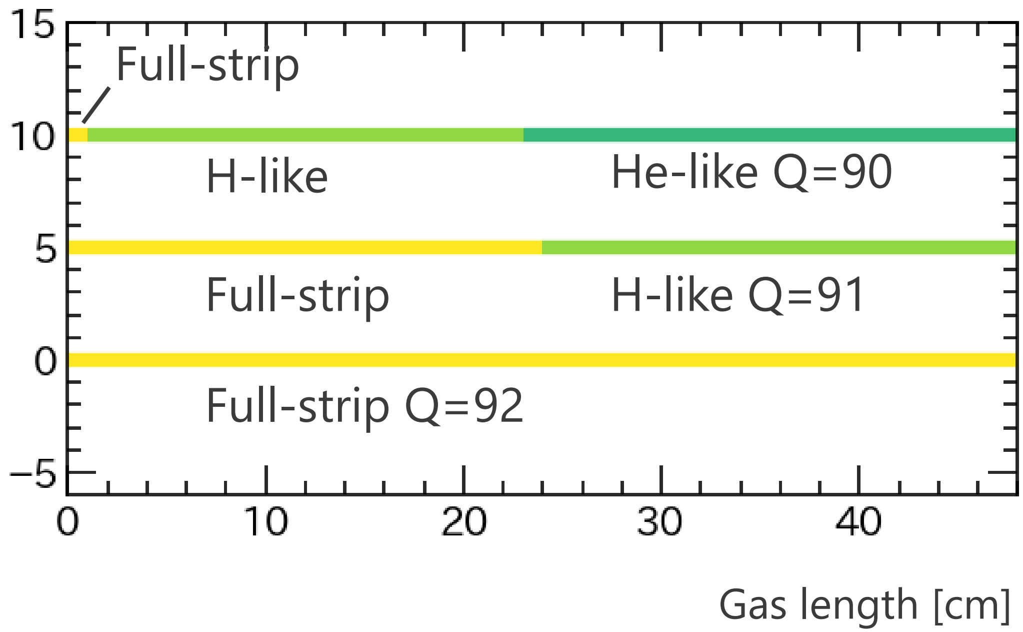
* Results for other energy and charge states
σZ=0.24 @Z=92 500 MeV/u F. Farinon, PhD thesis, Justus Liebig University Giessen (2011).
σZ=0.4 @Z=88 180 MeV/u T. Sumikama, *et al.* NIM B **463**, 237 (2020).

Charge-state fluctuation

$$\bar{Z}_{eff} = \frac{\overbrace{Q_0 \sum L_{Q_0}}^{\text{Full-strip}} + \overbrace{Q_1 \sum L_{Q_1}}^{\text{H-like}} + \overbrace{Q_2 \sum L_{Q_2}}^{\text{He-like}}}{Gas\ length}$$

in ionization chamber

$_{92}U^{92+}$ Full-strip



$\bar{Z}_{eff}$ = 91.0

$\bar{Z}_{eff}$ = 91.5

$\bar{Z}_{eff}$ = 92.0

Ref: GLOBAL code
C. Scheidenberger, *et al.* NIM B **142**, 441 (1998).

Charge-state fluctuation

P10 gas
Argon 90%
Methane 10%
0.8 atom,
Total L=48cm

300 MeV/u
Full-strip

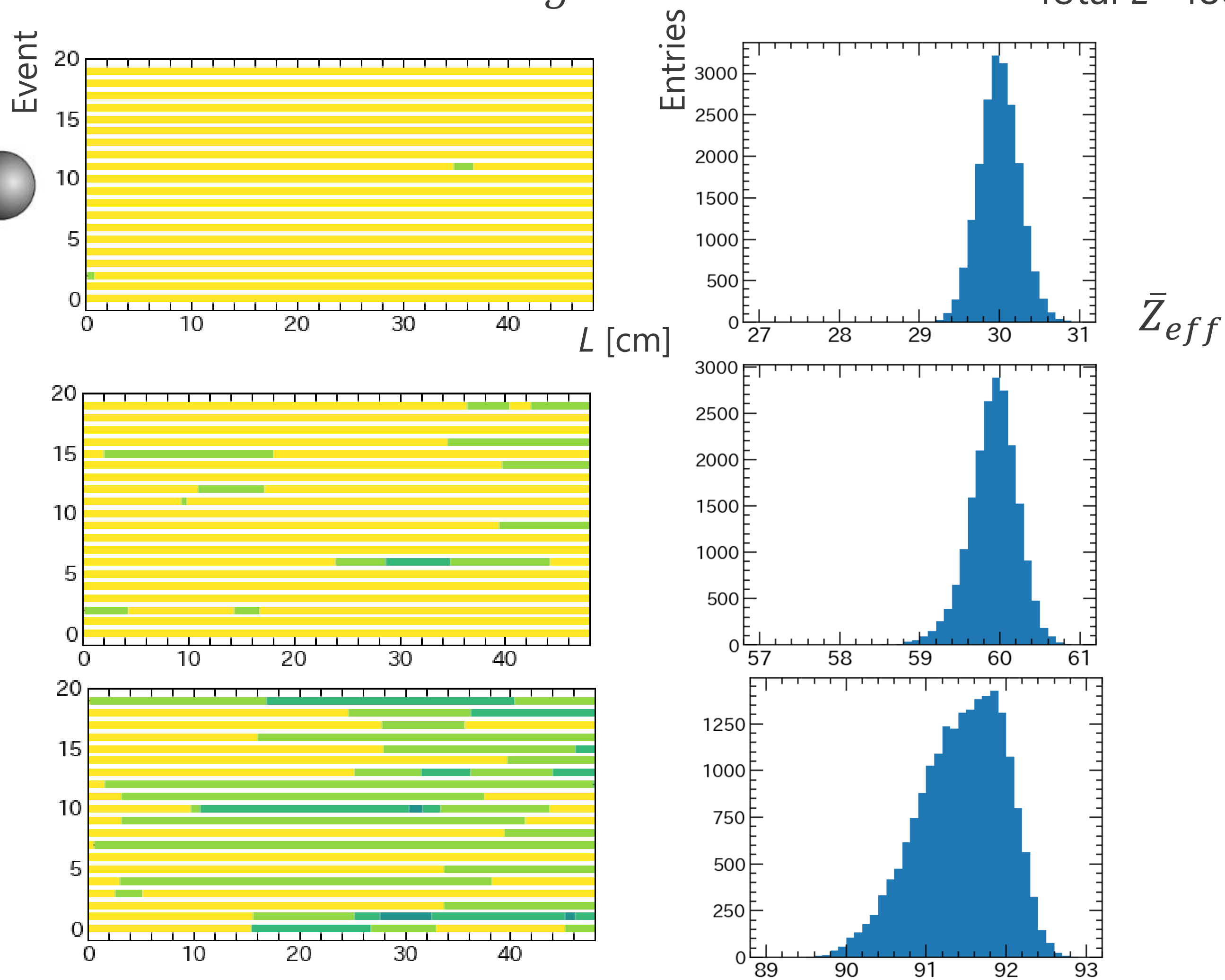
Full-strip H-like He-like

$$\bar{Z}_{eff} = \frac{Q_0 \sum L_{Q_0} + Q_1 \sum L_{Q_1} + Q_2 \sum L_{Q_2}}{Gas\ length}$$

Zn (Z=30)

Nd (Z=60)

U (Z=92)



Ref: GLOBAL code
C. Scheidenberger, *et al.* NIM B **142**, 441 (1998).

Charge-state fluctuation

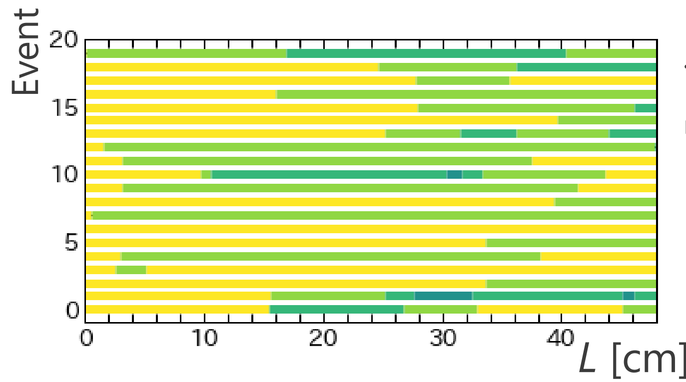
300 MeV/u
Full-strip

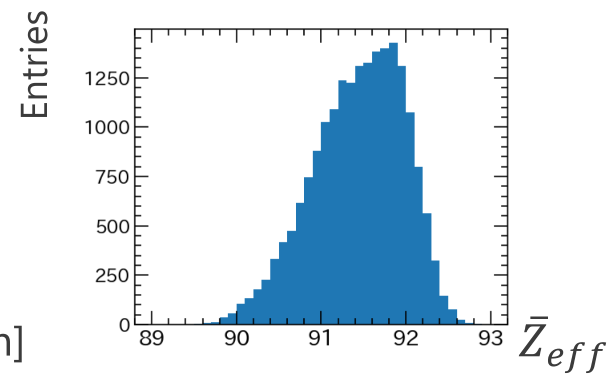
U (Z=92) beam

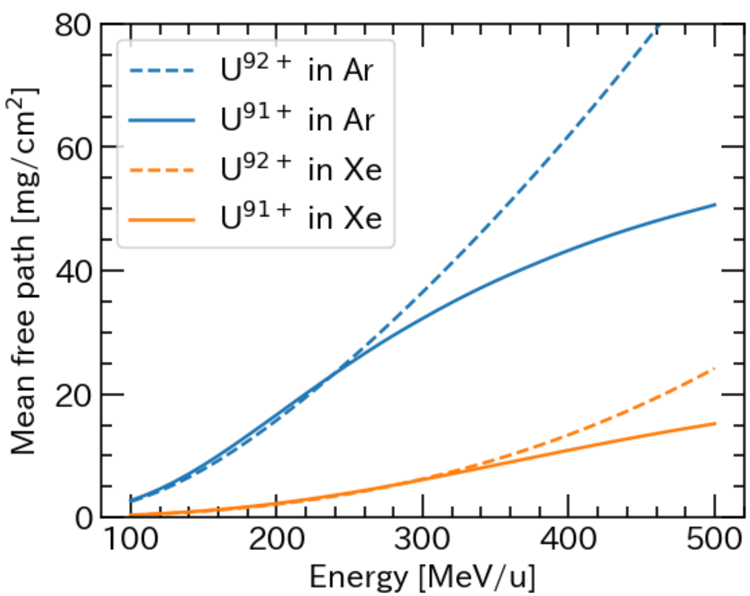
P10 gas

Full-strip H-like He-like

$$\bar{Z}_{eff} = \frac{Q_0 \sum L_{Q_0} + Q_1 \sum L_{Q_1} + Q_2 \sum L_{Q_2}}{Gas\ length}$$







Argon

1/5

Xenon

Ref: GLOBAL code
C. Scheidenberger, *et al.* NIM B **142**, 441 (1998).

Charge-state fluctuation

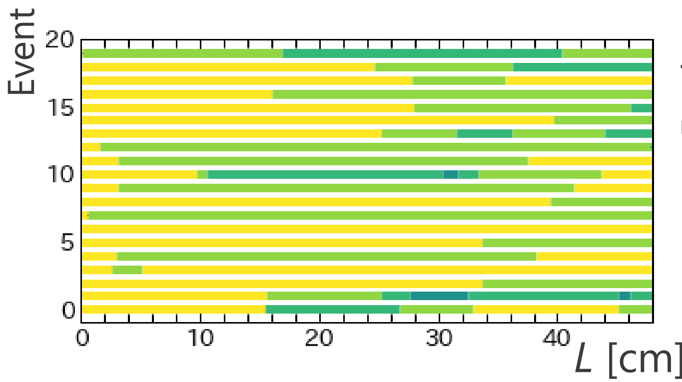
300 MeV/u
Full-strip

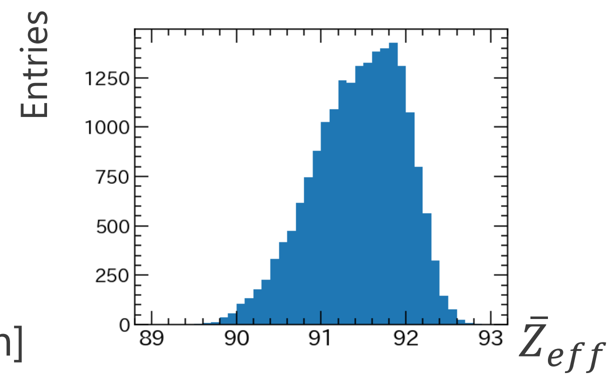
U (Z=92) beam

Full-strip H-like He-like

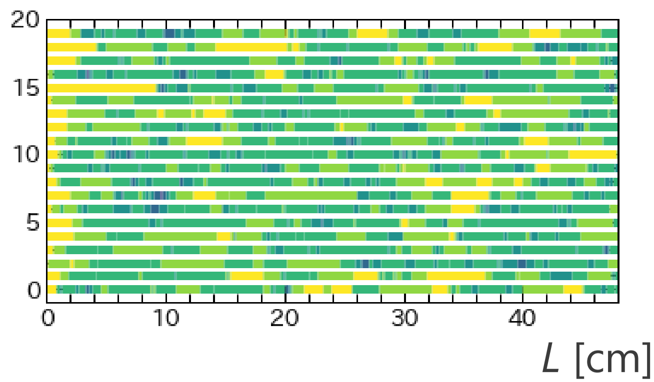
$$\bar{Z}_{eff} = \frac{Q_0 \sum L_{Q_0} + Q_1 \sum L_{Q_1} + Q_2 \sum L_{Q_2}}{Gas\ length}$$

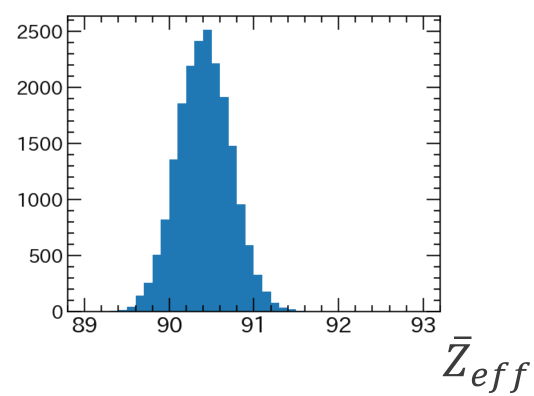
P10 gas





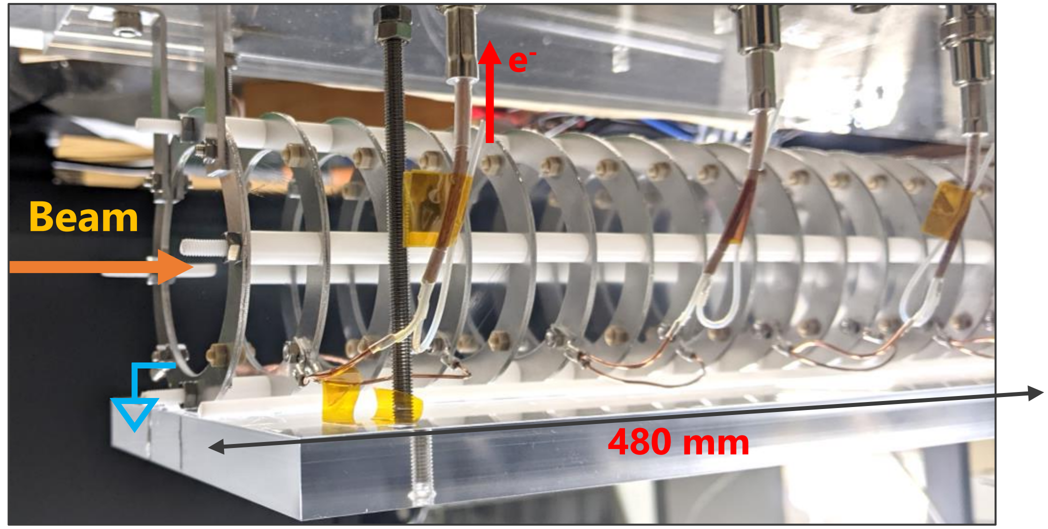
Xenon gas





Xenon gas is promising for ionization chamber for high-*Z* beam.

Xenon gas IC



Electrode: ϕ60 mm x25
placed at 2cm intervals

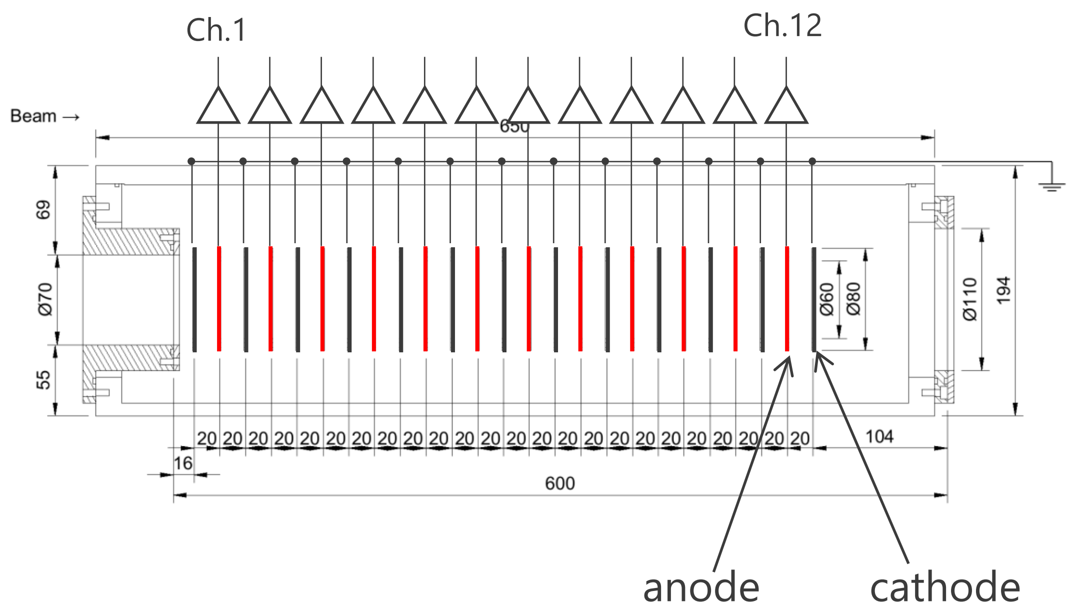
IC type	Argon-based (P10)	Xenon-based
Mixture	**Argon 90%** CH_4 10%	**Xenon 70%** CH_4 30%
High voltage [V]	400	800
Electron drift velocity *W* [cm/μs]	**4.9**	**3.5**
	Computed with Garfield++	
Gas flow	Yes	No
Pressure [Torr]	620	620
Total gas thickness [mg/cm^2]	76.5	198

Mixed methane to increase electron drift velocity

Xenon is expensive, so IC was operated in containment.

This increase corresponds to Be 0.4 mm^t.

IC data acquisition



Electronics

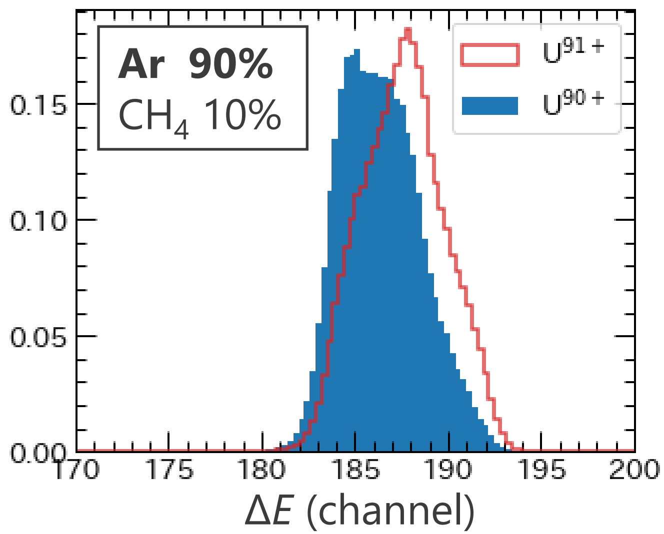
1. Pre amp.
   Mesytec MPRT-16-HV
   Decay time 7 µs
2. Shaping amp.
   Mesytec MSCF-16
   Shaping time 1 µs
3. ADC
   Technoland T-CM405

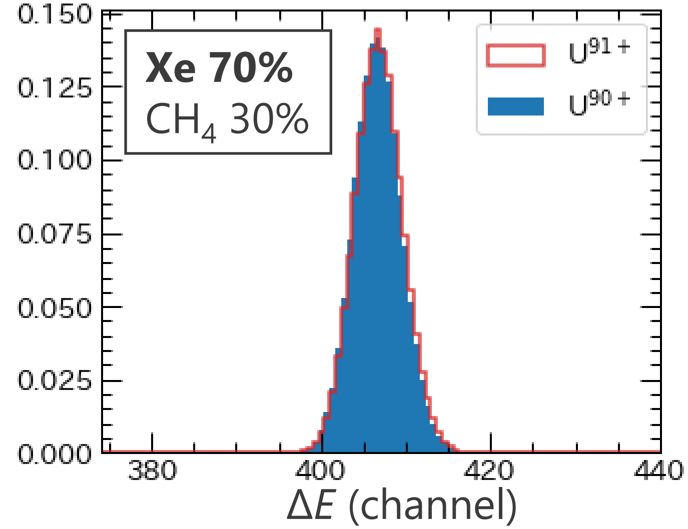
Data processing

4. Pedestal and gain correction
5. Geometric mean $\sqrt[12]{\Pi\, ADC_{Ch.}}$
6. IC positional correction
7. Velocity β correction with simple Bethe formula and empirical correction.

Primary beam

He-, H-like
$^{238}U^{90+,91+}$ 344 MeV/u beam
σ_E: less than 0.1%





Q=91+ 187.5 ± 2.1 (**1.13%**)
90+ 186.5 ± 2.0 (**1.09%**)

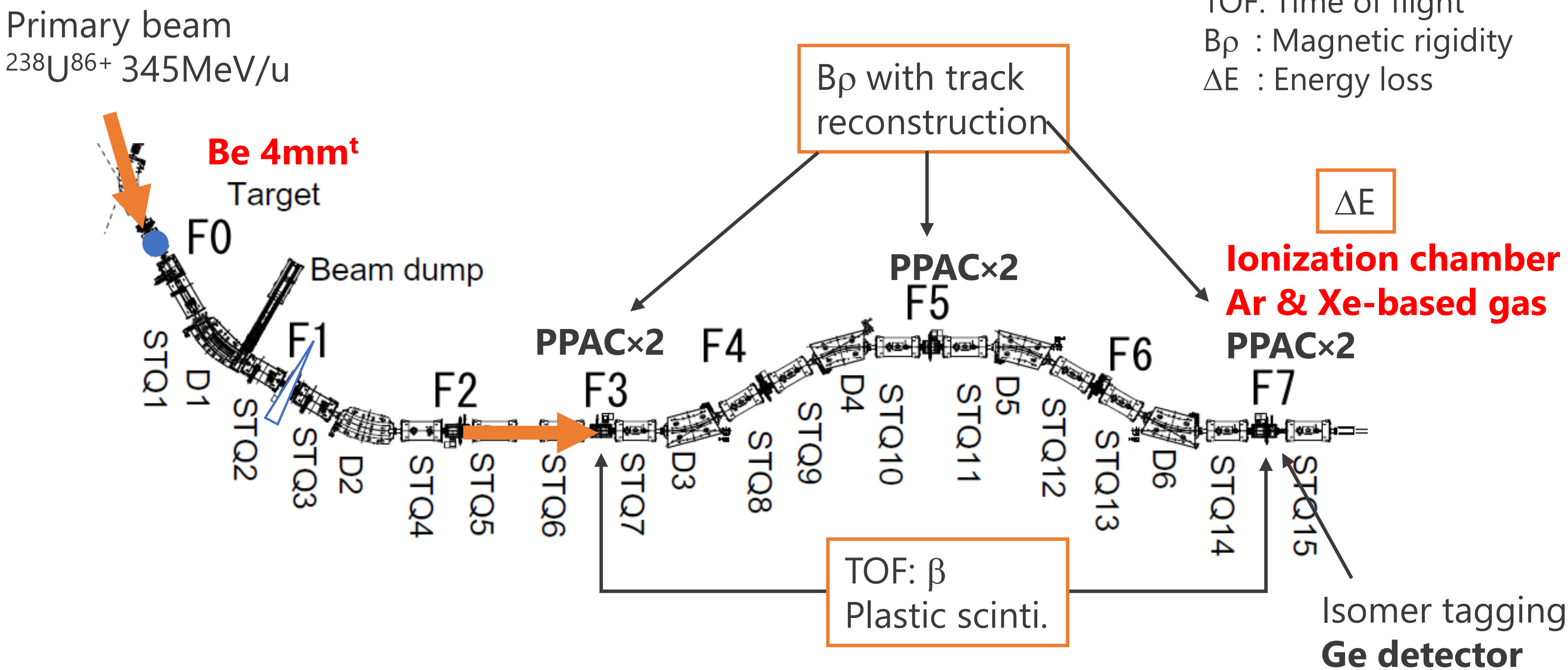
Q=91+ 406.8 ± 2.8 (**0.69%**)
90+ 406.7 ± 2.8 (**0.69%**)

No charge-state dependence and narrow ΔE distribution was confirmed with the Xe gas IC.

Secondary beam

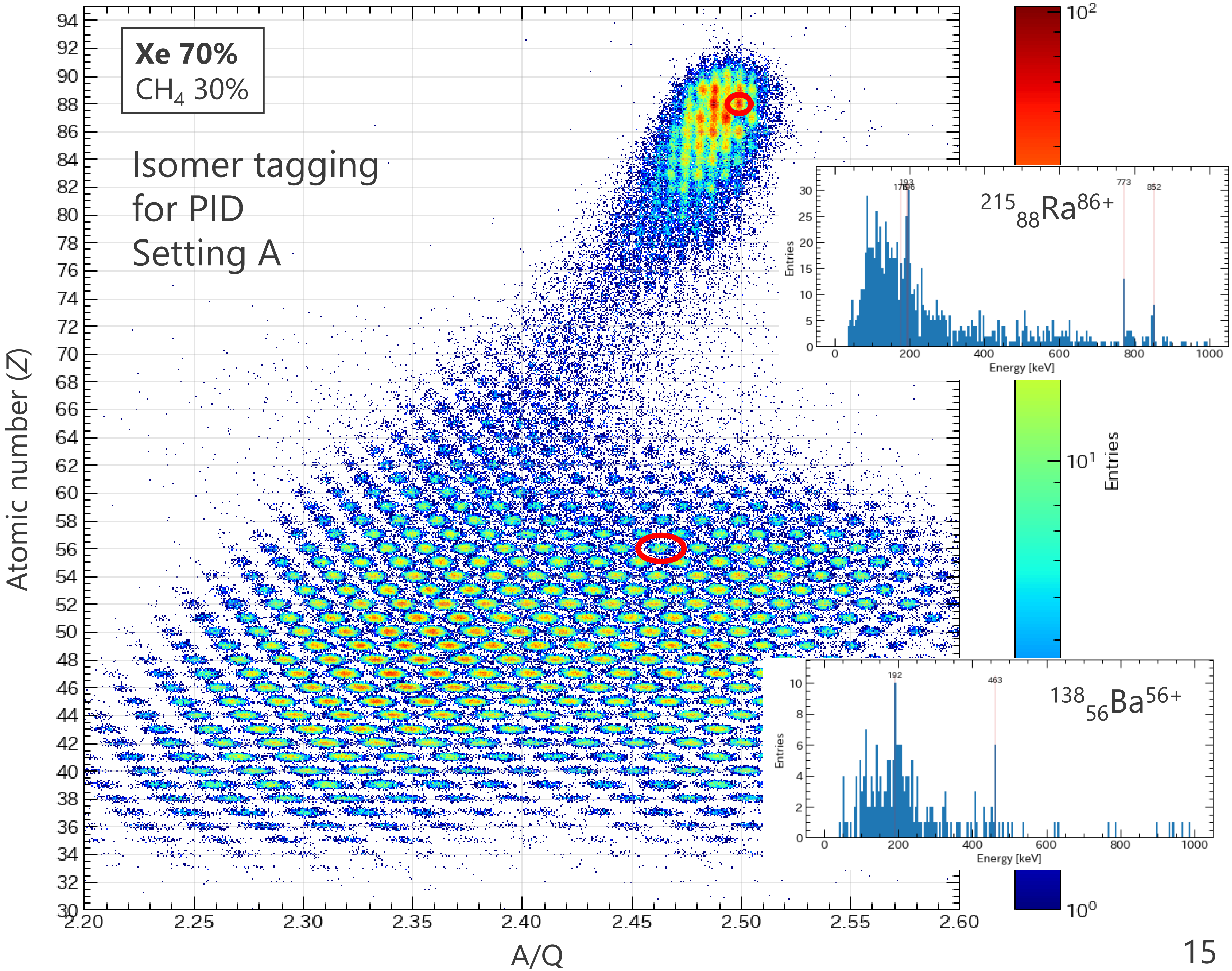
TOF-Bρ-ΔE method

TOF: Time of flight
Bρ : Magnetic rigidity
ΔE : Energy loss

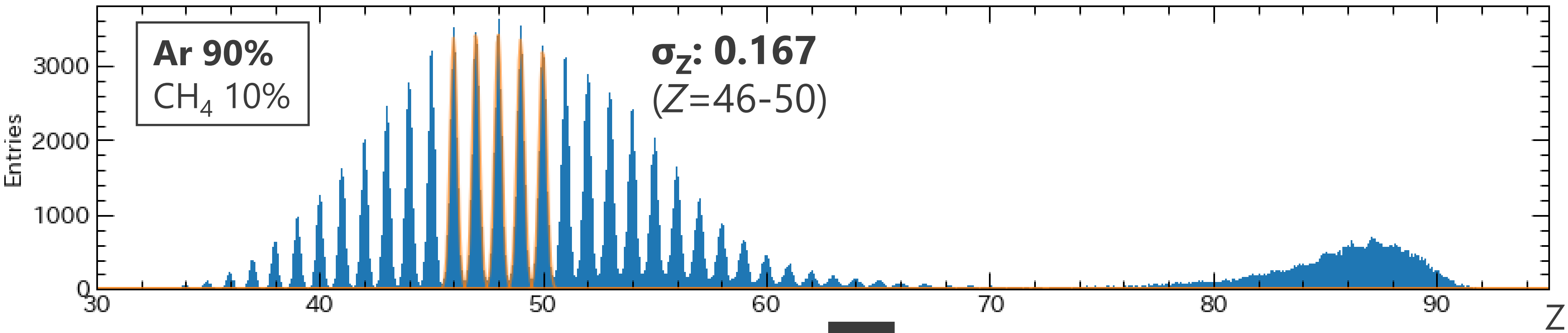


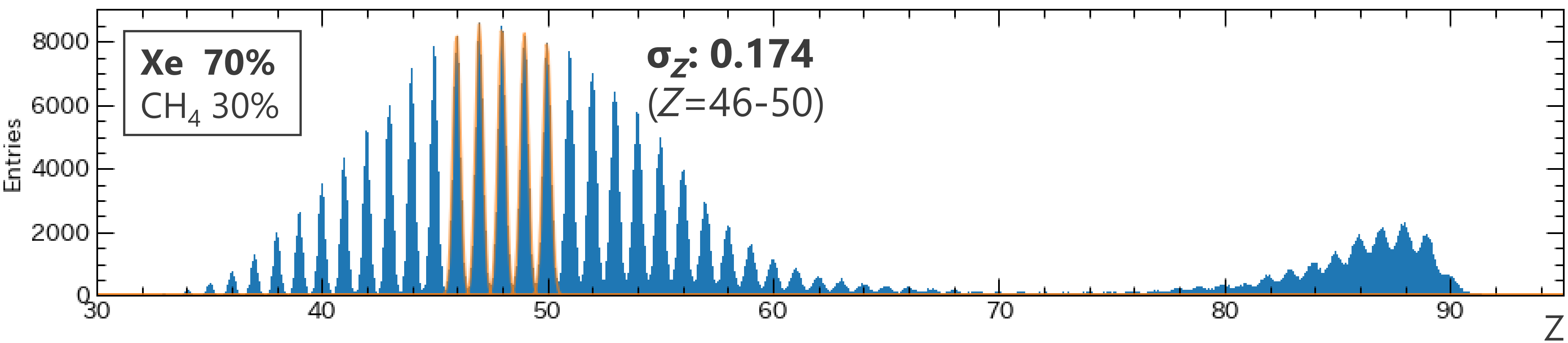
	Setting A	Setting B
Energy @F7	280 MeV/u @ Z=50 **260 MeV/u @ Z=85**	240 MeV/u @ Z=50 **200 MeV/u @ Z=85**
D1	6.3 Tm	6.1712 Tm
F1	No degrader	Al 2mm degrader **for Z separation**

Beam intensity:
1 kcps @F7


Xe 70%
CH4 30%
Isomer tagging
for PID
Setting A
Atomic number (Z)
A/Q
Entries
215 88 Ra 86+
138 56 Ba 56+
Energy [keV]
193
773
852
192
463

Setting A
280 MeV/u @ Z=50
260 MeV/u @ Z=85



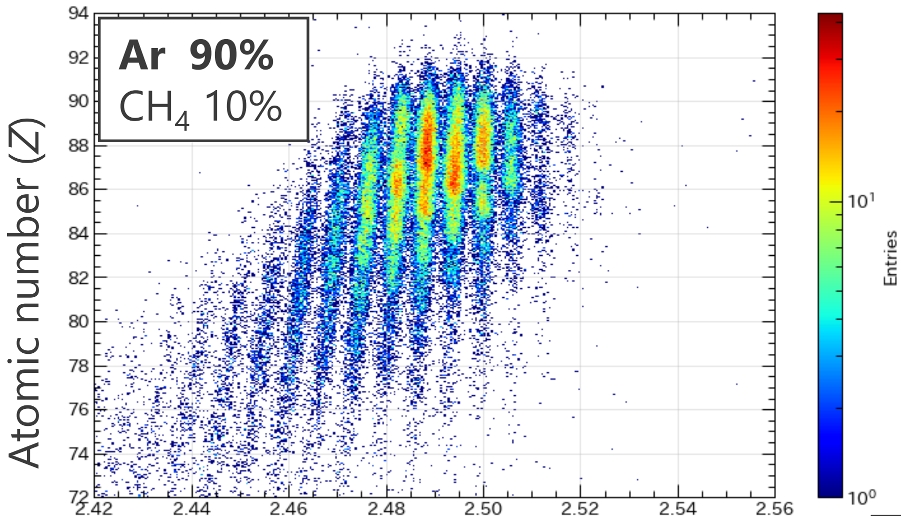


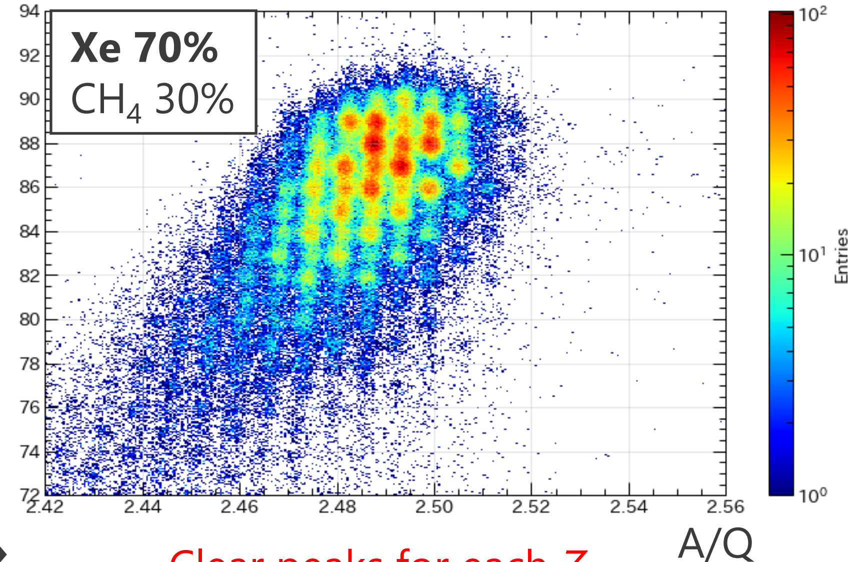
No difference in Z resolution at Z=30-60 between Ar and Xe gas ICs.

Big difference at Z>80.
Z is not separated in Ar gas IC, whereas separated in Xe gas IC.

Setting A
260 MeV/u @ Z=85

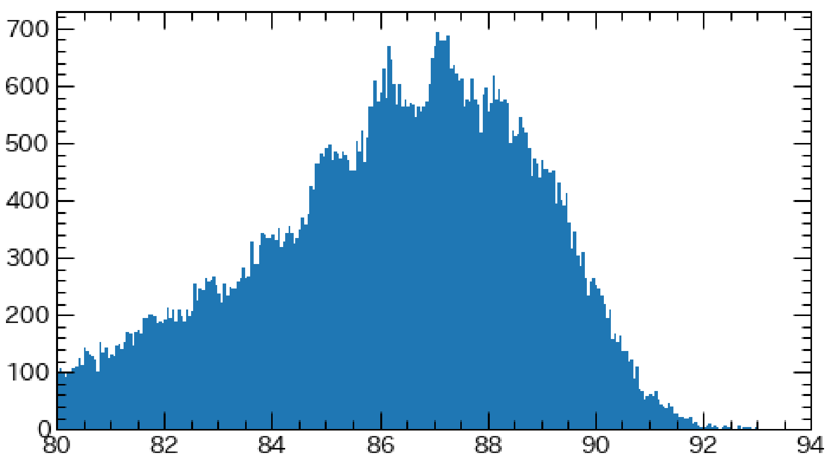
In the Z>80 region, **H-like** and **He-like** are transported, so the blobs of the ions are dense.

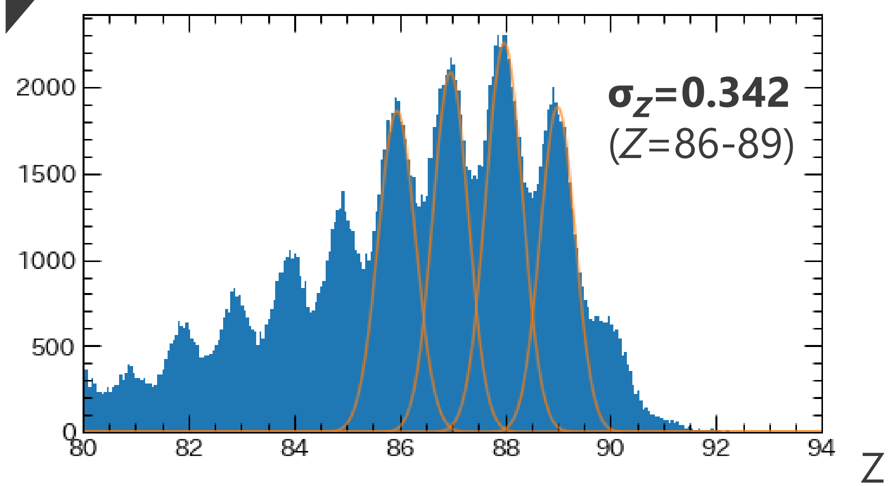




Particle (Z) identification is difficult.

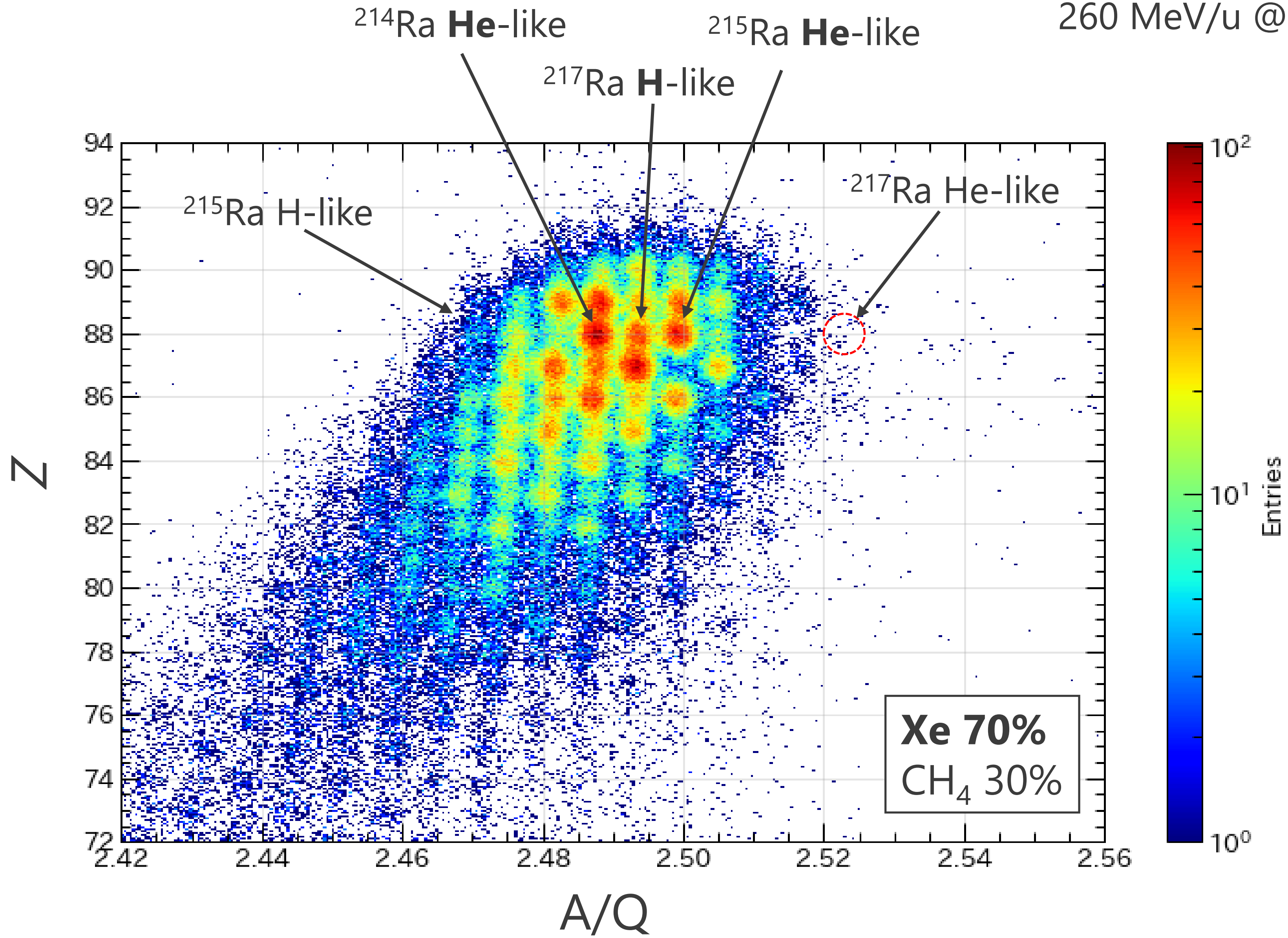
Clear peaks for each Z



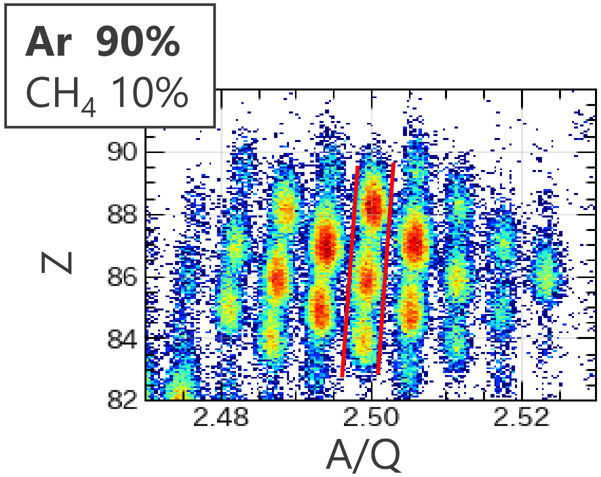


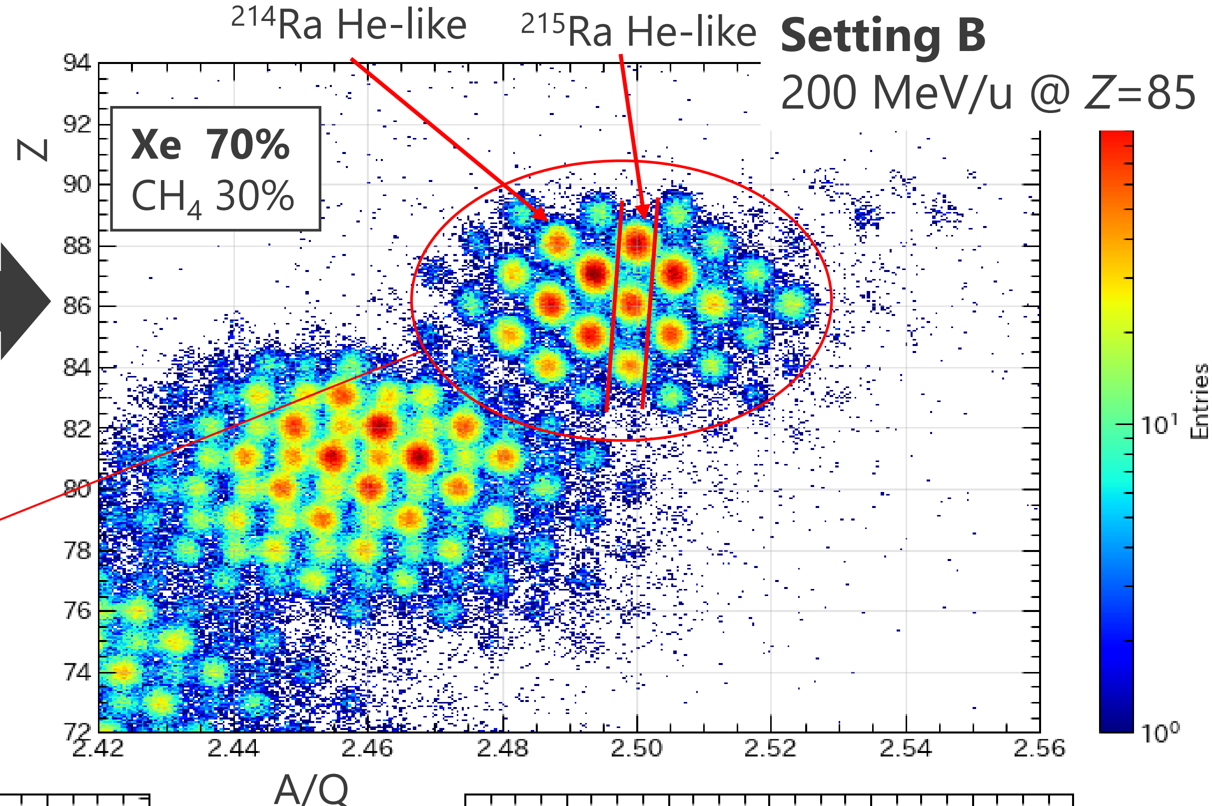
The particle (Z) identification is possible with the Xe gas IC, even though the two charge states are transported.

Setting A
260 MeV/u @ Z=85

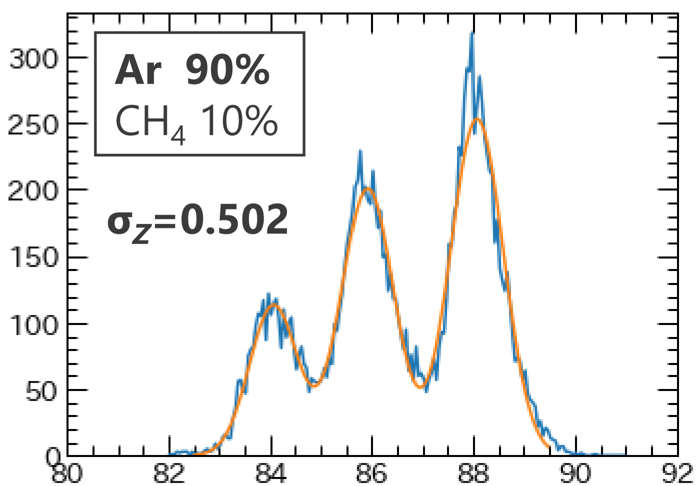


Setting B
200 MeV/u @ Z=85

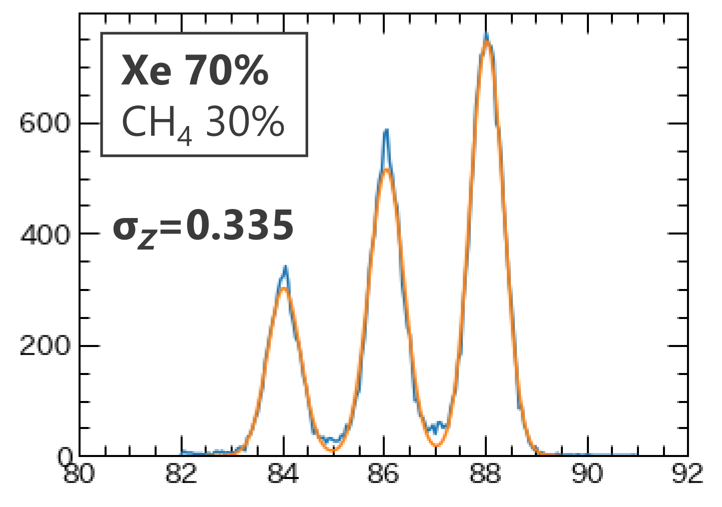




He-like is dominant in the group in the setting B, so PID is possible even with Ar gas IC.



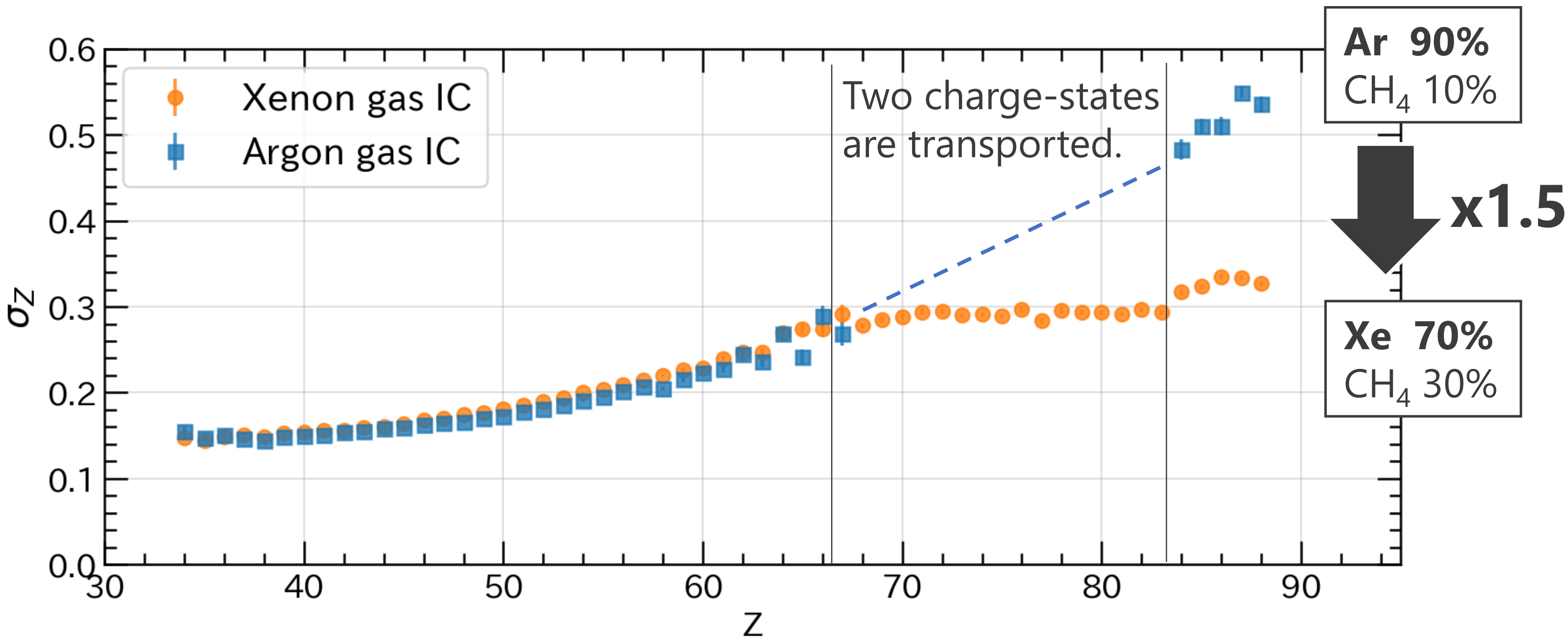
x1.5



Xe gas IC dramatically improved Z resolution in the high-Z (Z>80) region.

Z resolution of Xe and Ar gas IC

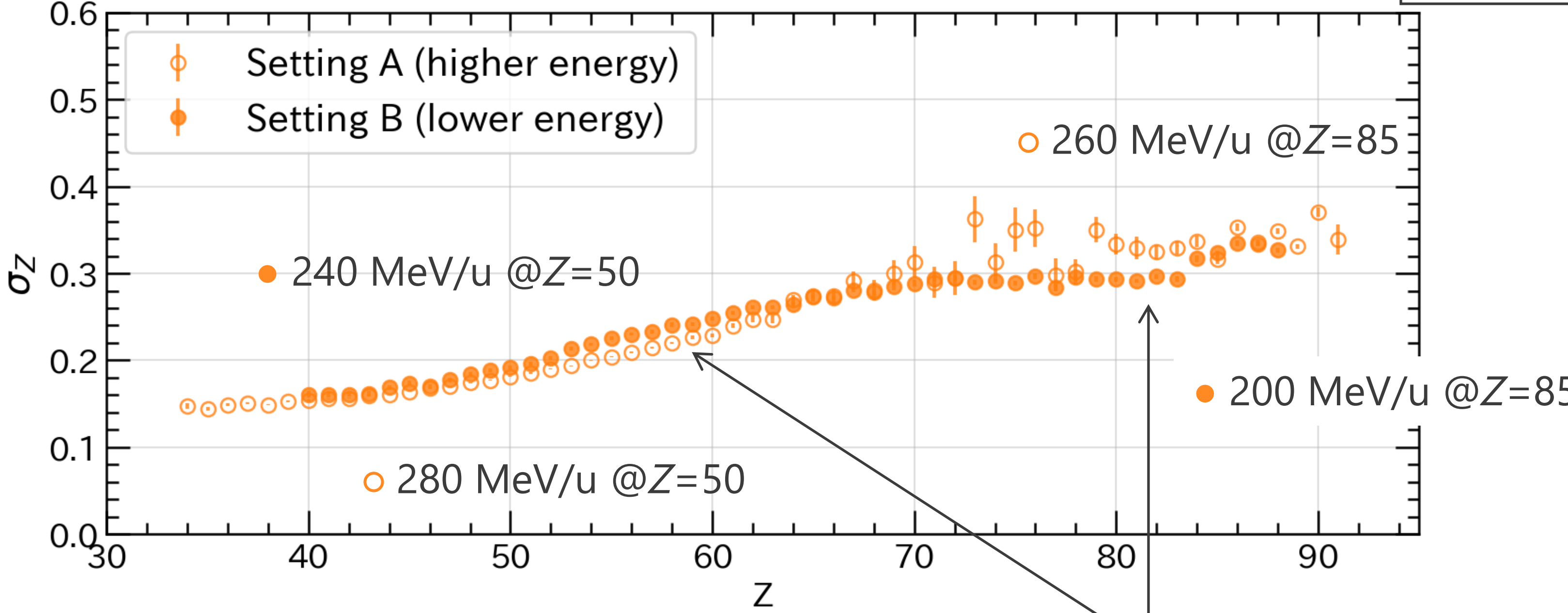
Setting B
240 MeV/u @Z=50
200 MeV/u @Z=85



Xe gas IC improves the Z resolution for Z>70.

Z resolution of Xe gas IC

Xe 70%
CH_4 30%



The slight energy dependence can be caused by δ-ray effect, charge-state fluctuation, IC position dependence, and β correction.

Almost no energy dependence was found in practical use.
>3σ separation is achieved in the energy and *Z* regions.

Summary

- Higher-Z beams will be provided with the ^{238}U 345 MeV/u primary beam at RIBF, and many experiments are waiting to be explored.

- A new **xenon-based gas** (Xe70%+$CH_4$30%) **ionization chamber** (IC) has solved the PID problem at 200-300 MeV/u for the high-Z beam (Z>70).
  - **PID is possible** in the ***Z*>70** region even when **different charge states** are transported.
  - *Z* resolution for ***Z*>80** is improved by **1.5 times** compared to the P10 gas IC.
  - **>3σ separation** is achieved in the ***Z*=30-90** & **200-280 MeV/u** regions.
  - Energy loss of the Xe gas IC is slightly increased, but the advantages are much greater.