Ion Optics Development at BigRIPS 1
--- High resolution mode ---

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BigRIPS team, RIKEN Nishina Center

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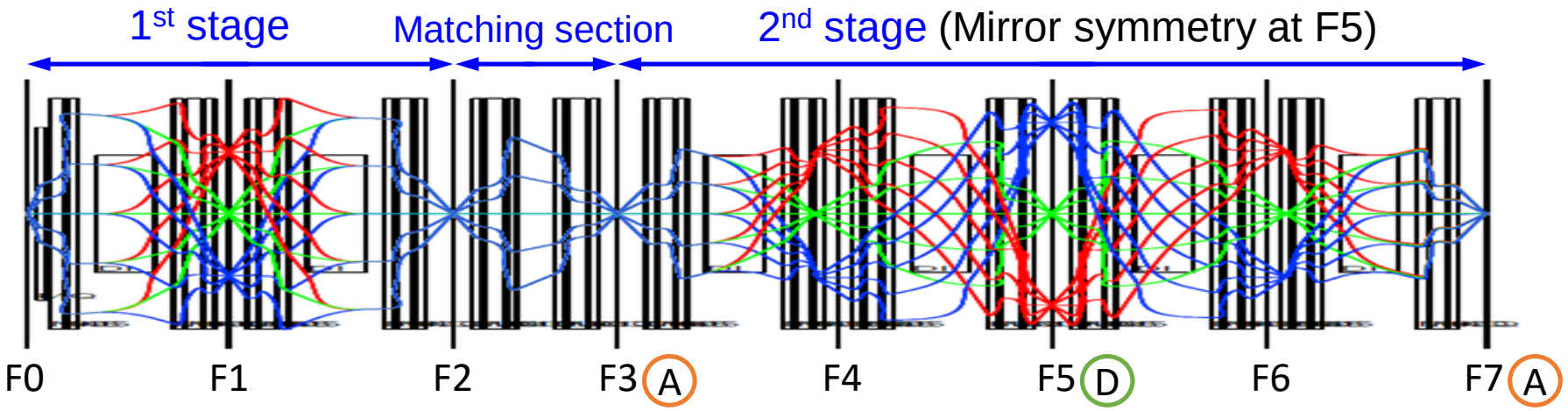
Amway Grand Plaza Hotel, Grand Rapids, USA

Outline

- My talk (Suzuki)
  - High-resolution mode
    - Introduction of the high-resolution modes
      - D-double mode
      - M-half mode
    - Momentum and angular acceptances
      - Comparison with spreads of secondary beams
    - Experiments
      - ^{136}Sn test experiment (F3-F5-F7: 2nd stage)
      - ^{136}Sn test experiment (F3-F5-F11: 2nd stage + ZeroDegree)
      - ^{87}Zn mass measurement experiment
      - High-*Z* ($^{208}_{88}Rn^{86+}$) test experiment
    - Summary

- Takeda -san's talk (just after my talk)
  - Additive and subtractive modes
- Sumikama-san's talk (9/1 morning)
  - Energy-degraded RI beams (Momentum compression mode)

Ion Optics of the BigRIPS



$P/\Delta P$ = 1260 (1st stage)
3420 (2nd stage)
(Object size = 1 mm)

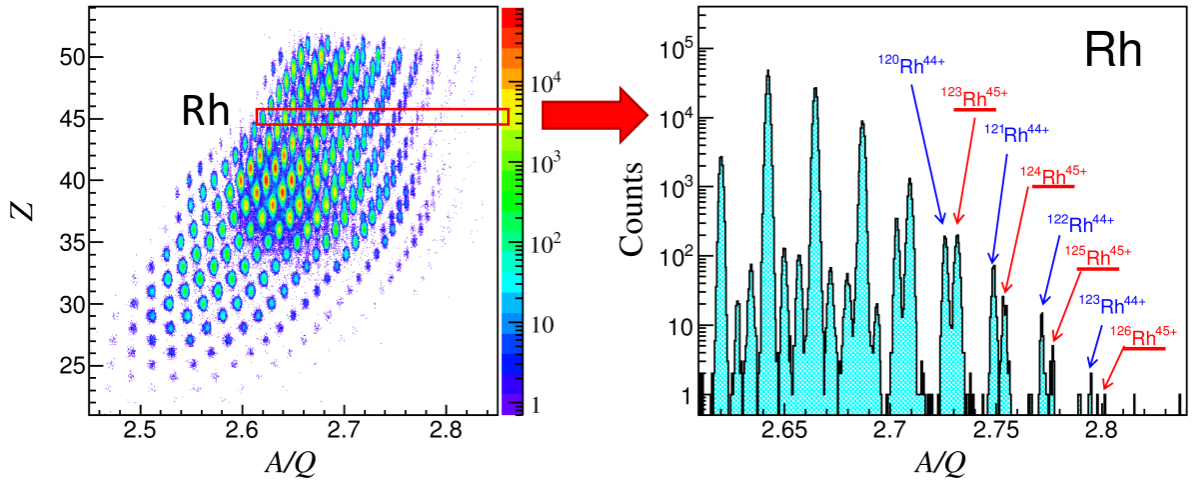
F3-F5

$(x|x)$=0.92, $(x|a)$=0,
$(y|y)$=1.06, $(y|b)$=0,
$(x|\delta)$=31.7 mm/%, $(a|\delta)$=0

F7-F5
Mirror symmetry
of F3-F5
in the standard optics

A Achromatic foci

D Dispersive foci



Best value of
A/Q resolution:
0.034%

Development of High-resolution modes

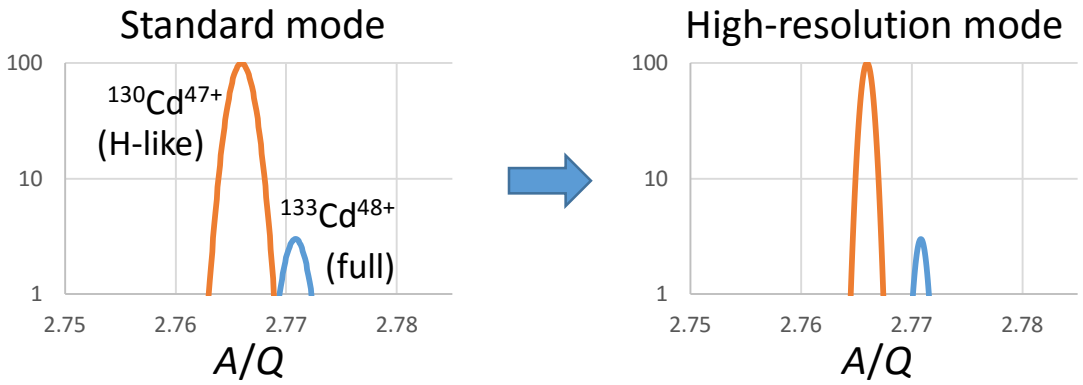
- Purpose: To improve the momentum resolution at the 2nd stage
  - Mass-measurement experiment
  - Separation of mid-heavy very-neutron-rich nuclei
    - A/Q values of fully-stripped $^{A}Z^{Z+}$ nuclide and hydrogen-like $^{A-3}Z^{(Z-1)+}$ contaminants are close, where A/Z value is close to 3.
  - High-Z region (Z ~ 70,80,…)
    - Many charge states (full, H-like, He-like, Li-like, …) are produced.

Resolution: $R \propto \frac{D}{M \cdot \Delta x}$ (D: dispersion, M: magnification)

→ To increase the D/M value.

→In the high-resolution modes, the D/M values are doubled.
($P/\Delta P$ = 3420 → 6840)

Ex) Separation of $^{A}Z^{Z+}$ and $^{A-3}Z^{(Z-1)+}$

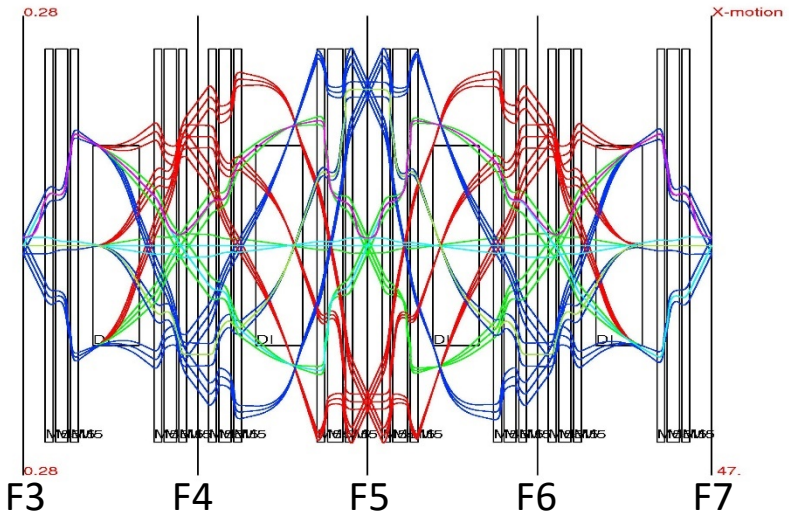


High-resolution D-double mode

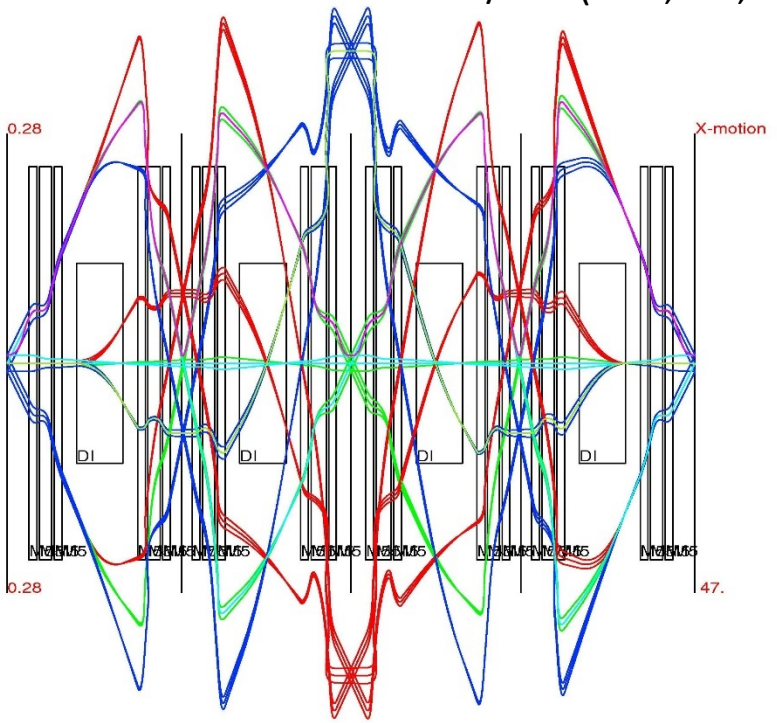
- $M_{35} = (x|x)_{35}$ remains.
- $D_{35} = (x|\delta)_{35}$ is doubled.

→ D_{35}/M_{35} is doubled from the Standard mode.

x: +/-5 mm
a: +/-18.4 mrad
δ: +/-3% (+3%, 0%, -3%)



(*x* direction)



Standard mode

High-resolution D-double mode

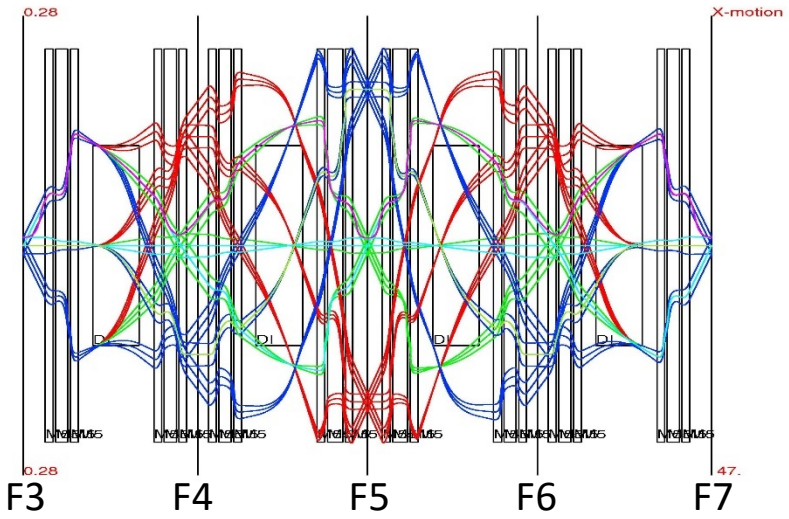
$$\begin{pmatrix} \underline{(x|x)} & (x|a) & \underline{(x|\delta)} \\ (a|x) & (a|a) & (a|\delta) \\ (\delta|x) & (\delta|a) & (\delta|\delta) \end{pmatrix}_{35} = \begin{pmatrix} \underline{0.9206} & 0 & \underline{31.687} \\ -0.0243 & 1.0863 & 0 \\ 0 & 0 & 1 \end{pmatrix}_{\text{Standard}} \begin{pmatrix} \underline{0.9206} & 0 & \underline{63.374} \\ 0.0388 & 1.0863 & 0 \\ 0 & 0 & 1 \end{pmatrix}_{\text{D-double}}$$

High-resolution M-half mode

- $M_{35} = (x|x)_{35}$ is halved.
- $D_{35} = (x|\delta)_{35}$ remains.

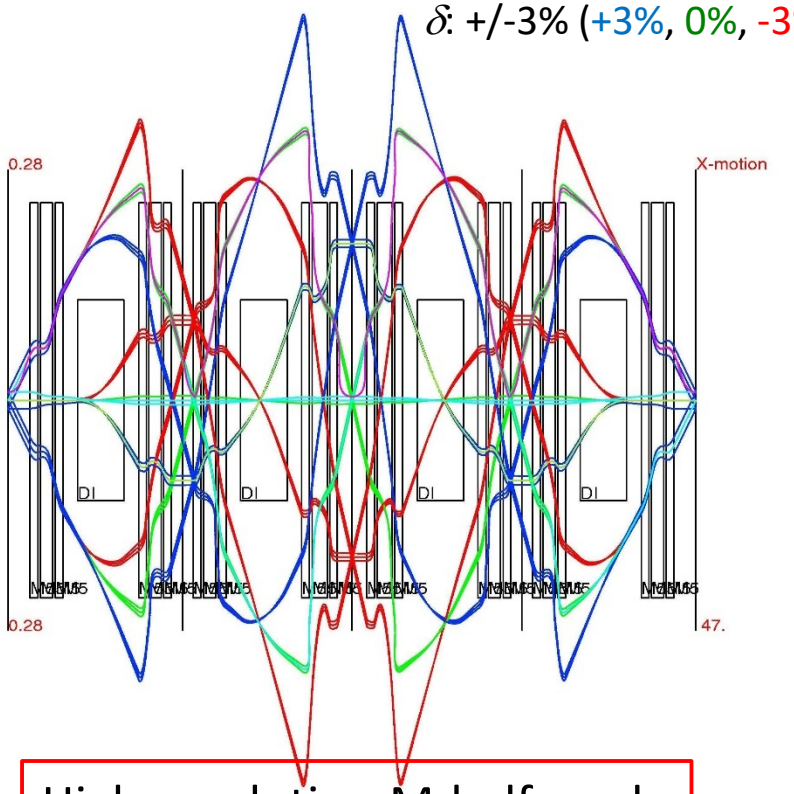
→ D_{35}/M_{35} is doubled from the Standard mode.

x: +/-5 mm
a: +/-18.4 mrad
δ: +/-3% (+3%, 0%, -3%)



Standard mode

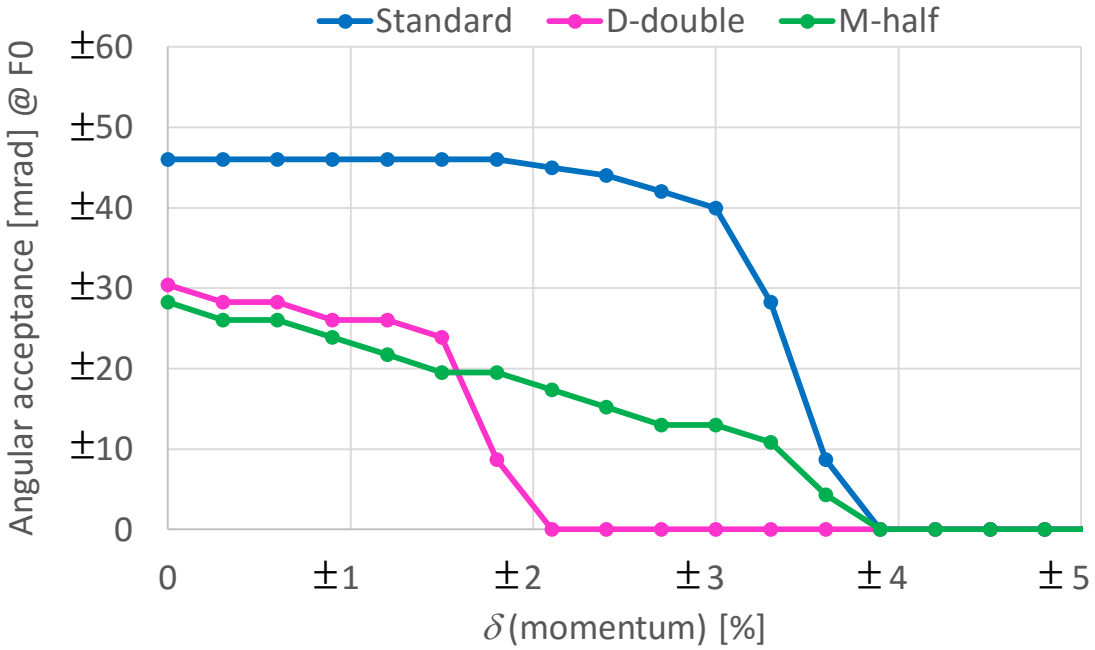
(x direction)



High-resolution M-half mode

$$\begin{pmatrix} \underline{(x|x)} & (x|a) & \underline{(x|\delta)} \\ (a|x) & (a|a) & (a|\delta) \\ (\delta|x) & (\delta|a) & (\delta|\delta) \end{pmatrix}_{35} = \begin{pmatrix} \underline{0.9206} & 0 & \underline{31.687} \\ -0.0243 & \underline{1.0863} & 0 \\ 0 & 0 & 1 \end{pmatrix}_{\text{Standard}} \begin{pmatrix} \underline{0.4603} & 0 & \underline{31.687} \\ -0.0137 & \underline{2.1725} & 0 \\ 0 & 0 & 1 \end{pmatrix}_{\text{M-half}}$$

Acceptance of each mode (calculation)



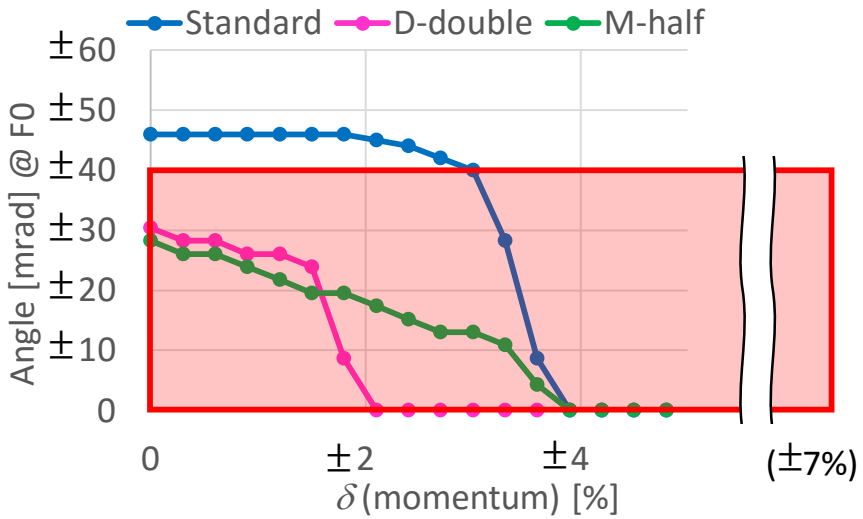
- Standard mode (blue data)
  - δ: +/-3%, α: +/-40 mrad
    - +/-0~3%: angular acceptance is cut in the 1st stage
    - +/-3~4%: cut in the 2nd stage
- D-double mode (magenta data)
  - δ: +/-1.5%, α: +/-25 mrad
    - Dispersion is doubled. → Momentum acceptance is halved.
- M-half mode (green data)
  - δ: +/-2.5%, α: +/-20 mrad
    - The angular magnification is doubled. → Angular acceptance becomes small.

Spreads of secondary beams

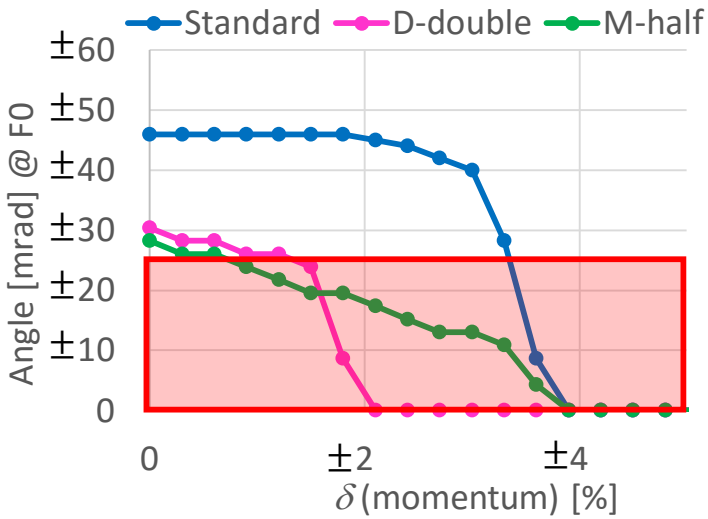
Comparison between the acceptances and the spreads of secondary beams

Projectile energy: 345 MeV/u

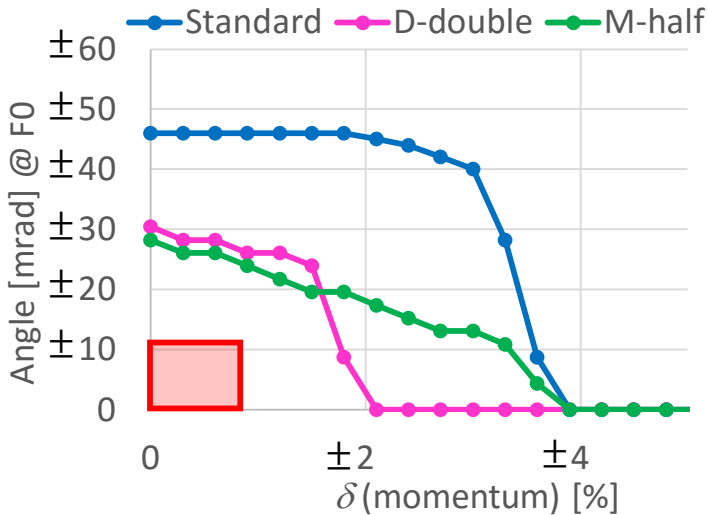
- $^{238}U \rightarrow {}^{132}_{50}Sn$ (4-mm Be) fission



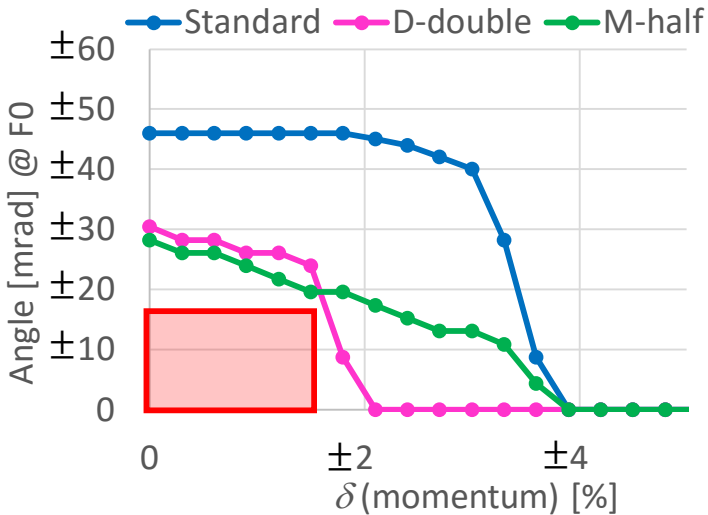
- $^{238}U \rightarrow {}^{171}_{66}Dy$ (5-mm Be) fission



- $^{238}U \rightarrow {}^{208}_{88}Ra$ (3-mm Be) frag. (+fission)



- $^{124}Xe \rightarrow {}^{100}_{50}Sn^{50+}$ (4-mm Be) fragmentation



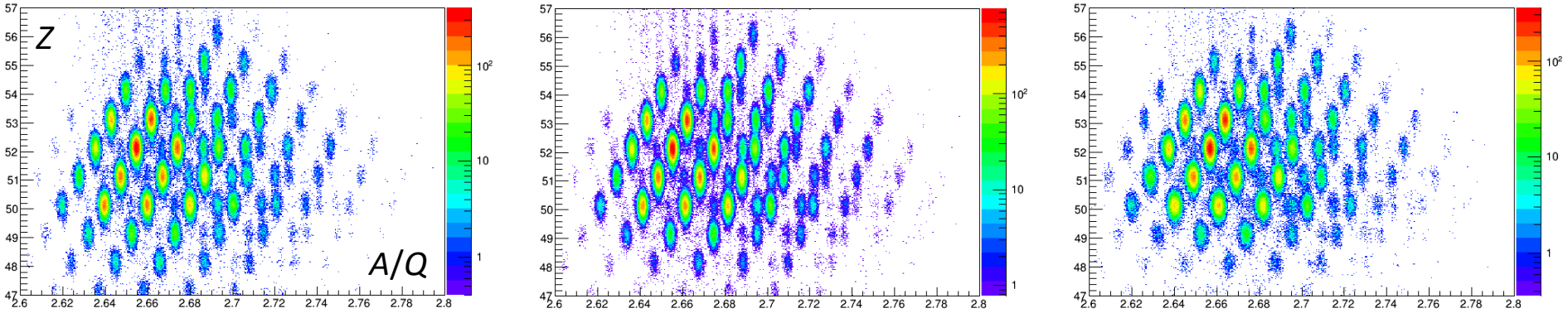
Experiments

- Case 1. ^{136}Sn test experiment (F3-F5-F7: 2nd stage)
  - Standard, D-double, M-half
  - Achieved *A*/*Q* resolution
  - Momentum and angular acceptance
- Case 2. ^{136}Sn test experiment (F3-F5-F11: 2nd stage + ZD)
  - D-double mode
  - Flight path length of F3-F11 is double of the 2nd stage (F3-F7)
- Case 3. ^{87}Zn mass measurement experiment
  - The first physics experiment with high-resolution mode (D-double mode)
- Case 4. High-*Z* ($^{208}_{88}Rn^{86+}$) test experiment

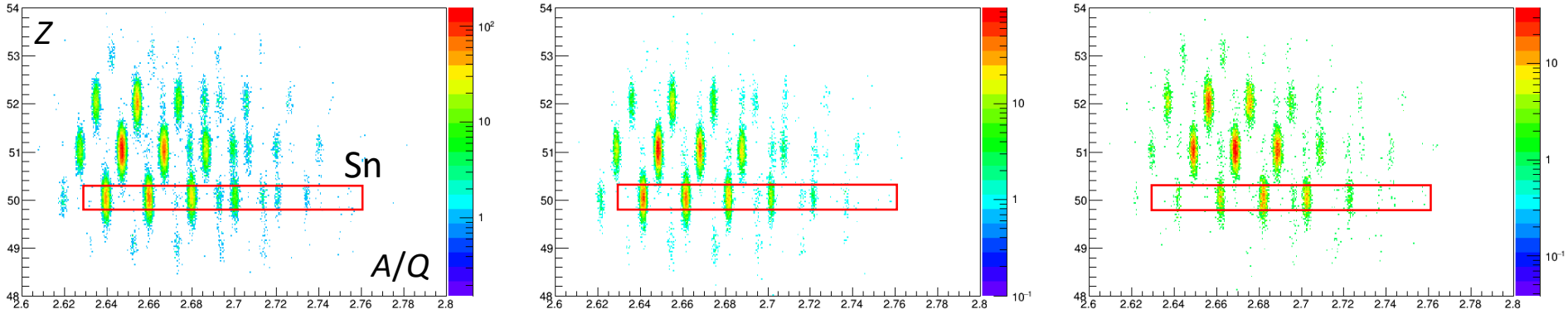
Case 1. ^{136}Sn test experiment (F3-F5-F7)

- Settings
  - Central particle: $^{136}Sn^{49+,50+,\ldots}$
  - Target: 2 mm, F1deg: 2 mm, F5deg: none
  - Bρ01: 8.004 Tm, Bρ12: 7.463 Tm, Bρ35: 7.435 Tm, Bρ57: 7.424 Tm
  - F1: -2/+3%, F2: +/-2 mm, F5: fully opened, F7: +/-18 mm → δ: +/-1% cut by analysis

Standard | D-double | M-half



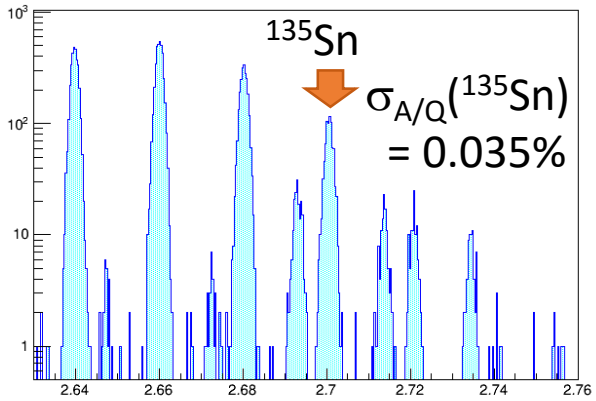
Gated on F3Pla and F7Pla's analogues to remove the slewing effect



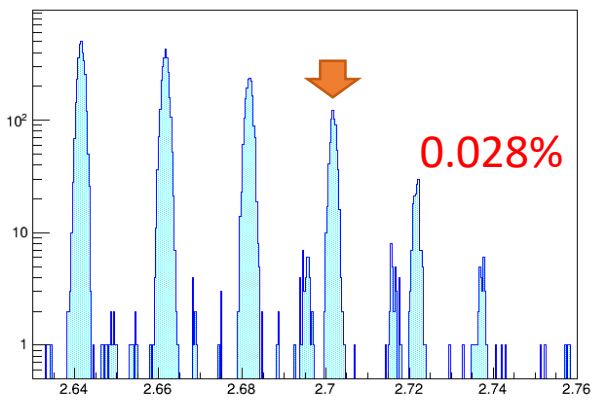
The *A*/*Q* distribution of Sn isotopes are shown in the next page.

A/Q resolution of each optics mode

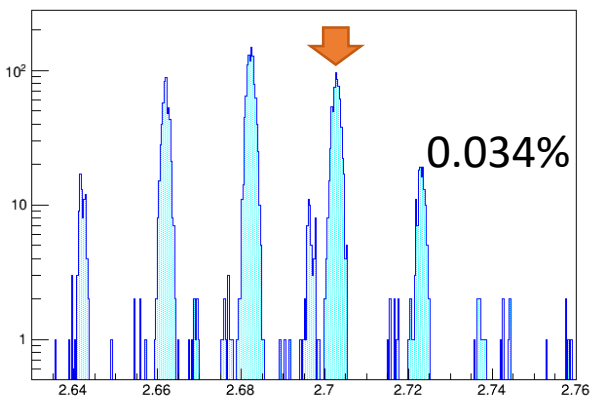
Standard



D-double



M-half



- Resolution of the D-double mode improved from the standard mode. However, it was not halved.
- In the M-half mode, the resolution was not improved.

→ A/Q resolution is affected by $B\rho$ resolution and β (TOF) resolution.

→ $B\rho$ resolution is affected by the position resolution at F3 and F5.

$$\begin{cases} A/Q = \dfrac{B\rho}{\beta\gamma}\dfrac{c}{m_u} \\ TOF = \dfrac{L}{\beta c} \end{cases} \Rightarrow \left(\frac{\Delta A/Q}{A/Q}\right) = \sqrt{\left(\frac{\Delta B\rho}{B\rho}\right)^2 + \left(\gamma^2\frac{\Delta\beta}{\beta}\right)^2}$$

$$\left(\frac{\Delta B\rho}{B\rho}\right) = \Delta\delta = \sqrt{\left(\frac{\Delta x_5}{D}\right)^2 + \left(\frac{M\Delta x_3}{D}\right)^2}$$

A/Q reso. estimated from detectors

- Position resolution (PPAC)
  ~0.8 mm

- Position resolution (F3, F5)
  ~0.6 mm (F3)
  ~0.4 mm (F5)

- $B\rho$ resolution (=$\Delta\delta$)

$$\Delta\delta = \sqrt{\left(\frac{\Delta x_5}{D}\right)^2 + \left(\frac{M\Delta x_3}{D}\right)^2}$$

	Sta.	D-d.	M-h.
D [mm/%]	31.7	63.4	31.7
M	0.92	0.92	0.46
Resolution	0.021%	0.010%	0.015%

- TOF resolution
  TOF: ~235 ns
  ΔTOF: ~35 ps

- β resolution

$$\frac{\Delta\beta}{\beta} = \frac{\Delta TOF}{TOF}$$

$$\gamma^2\frac{\Delta\beta}{\beta} \approx 0.027\%$$

- A/Q resolution

$$\left(\frac{\Delta A/Q}{A/Q}\right)^2 = \left(\frac{\Delta B\rho}{B\rho}\right)^2 + \left(\gamma^2\frac{\Delta\beta}{\beta}\right)^2$$

	Standard	D-double	M-half
$B\rho$ resolution	0.021%	0.010%	0.015%
β resolution (x γ^2)	0.027%	0.027%	0.027%
A/Q reso. (est.)	0.034%	0.029%	0.031%
A/Q reso. (exp.)	0.035%	0.028%	0.034%

Consistent!

Matrices (experiment & design value)

- Experiment

Standard

$$M_{35} = \begin{pmatrix} 0.8859 & -0.4418 & 30.83 \\ 0.0058 & 1.125 & 0.465 \\ 0 & 0 & 1 \end{pmatrix}$$

det.=0.9992

$$M_{75} = \begin{pmatrix} 1.1659 & -0.2885 & 30.56 \\ -0.0050 & 0.9229 & 1.263 \\ 0 & 0 & 1 \end{pmatrix}$$

det.=1.0746

D-double

$$M_{35} = \begin{pmatrix} 1.135 & -0.297 & 60.21 \\ -0.0246 & 1.102 & 1.583 \\ 0 & 0 & 1 \end{pmatrix}$$

det.=1.243

$$M_{75} = \begin{pmatrix} 1.4281 & -0.2662 & 61.13 \\ -0.0183 & 0.7598 & 0.7592 \\ 0 & 0 & 1 \end{pmatrix}$$

det.=1.080

M-half

$$M_{35} = \begin{pmatrix} 0.4985 & 0.116 & 31.78 \\ 0.0132 & 2.381 & 0.7700 \\ 0 & 0 & 1 \end{pmatrix}$$

det.=1.185

$$M_{75} = \begin{pmatrix} 0.4078 & 0.0413 & 31.97 \\ -0.0146 & 2.128 & 0.5127 \\ 0 & 0 & 1 \end{pmatrix}$$

det.=0.868

- Design

Standard

$$M_{35} = \begin{pmatrix} 0.9206 & 0 & 31.687 \\ -0.0243 & 1.0863 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

D-double

$$M_{35} = \begin{pmatrix} 0.9206 & 0 & 63.374 \\ 0.0388 & 1.0863 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

M-half

$$M_{35} = \begin{pmatrix} 0.4603 & 0 & 31.687 \\ -0.0137 & 2.1725 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

(Reference)

- COSY calculation (folded method for Enge function, FR5 for fringe mode)

Standard

$$M_{35} = \begin{pmatrix} 0.8189 & -0.3434 & 31.34 \\ 0.0180 & 1.213 & -0.296 \\ 0 & 0 & 1 \end{pmatrix}$$

$$M_{75} = \begin{pmatrix} 0.9690 & -0.4652 & 31.30 \\ 0.0567 & 1.0046 & 0.330 \\ 0 & 0 & 1 \end{pmatrix}$$

D-double

$$M_{35} = \begin{pmatrix} 0.8893 & -0.0729 & 62.91 \\ 0.0185 & 1.112 & -0.400 \\ 0 & 0 & 1 \end{pmatrix}$$

$$M_{75} = \begin{pmatrix} 1.131 & -0.4188 & 62.95 \\ 0.1712 & 0.8201 & 0.463 \\ 0 & 0 & 1 \end{pmatrix}$$

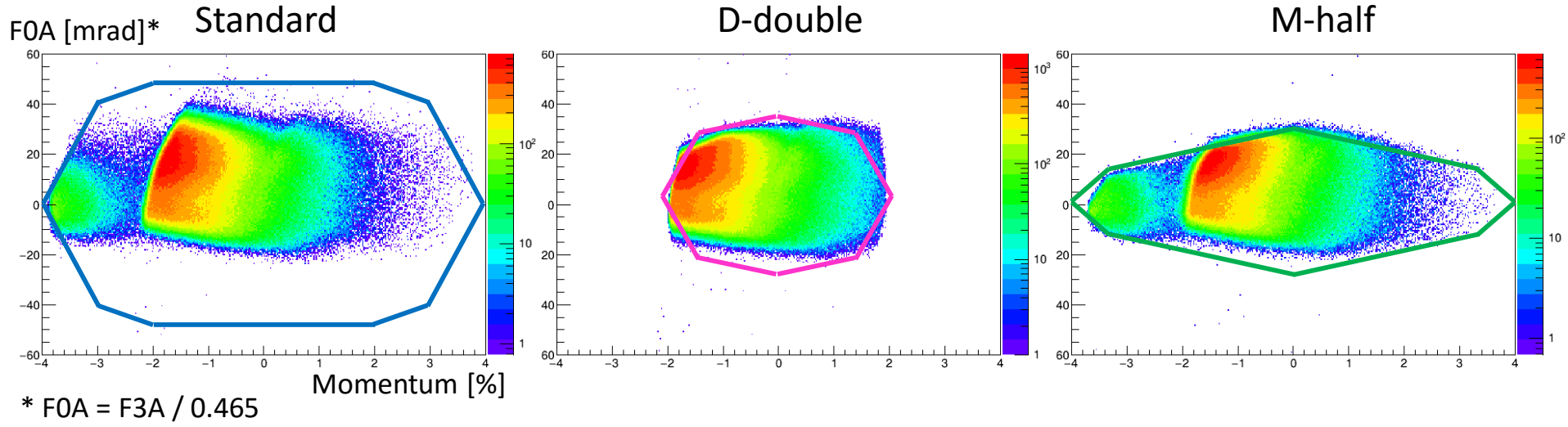
M-half

$$M_{35} = \begin{pmatrix} 0.4233 & 0.165 & 30.95 \\ 0.0421 & 2.378 & -0.325 \\ 0 & 0 & 1 \end{pmatrix}$$

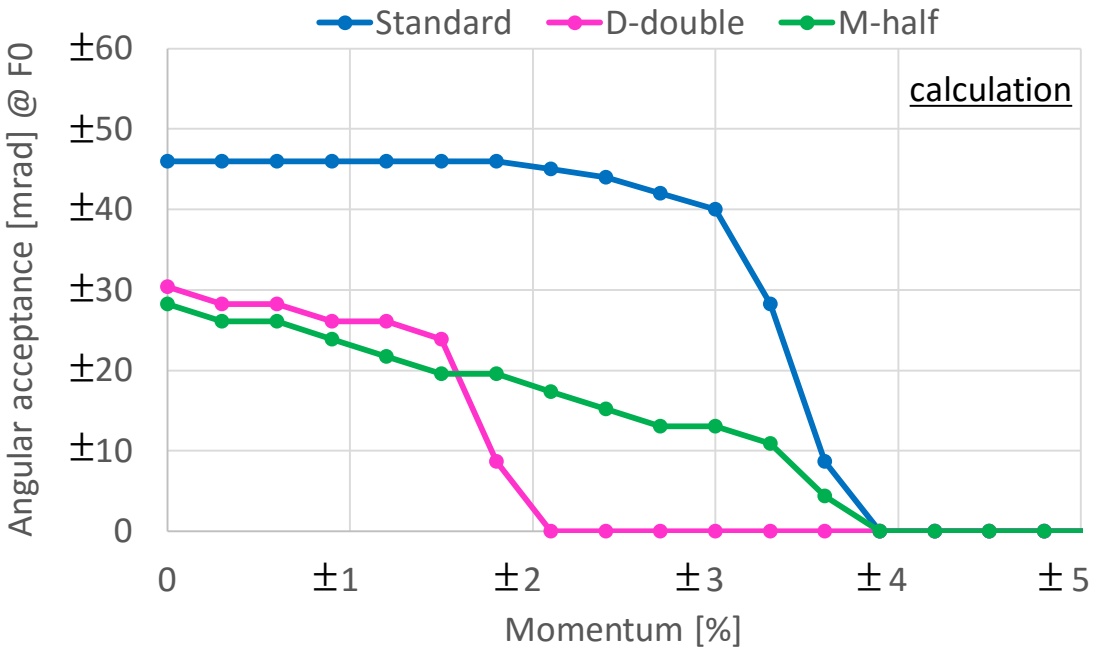
$$M_{75} = \begin{pmatrix} 0.4483 & -0.125 & 30.94 \\ 0.1341 & 2.192 & 0.351 \\ 0 & 0 & 1 \end{pmatrix}$$

Momentum and angular acceptance

- Beam spreads are cut by the acceptances of each mode (Z = 48-54 nuclei)

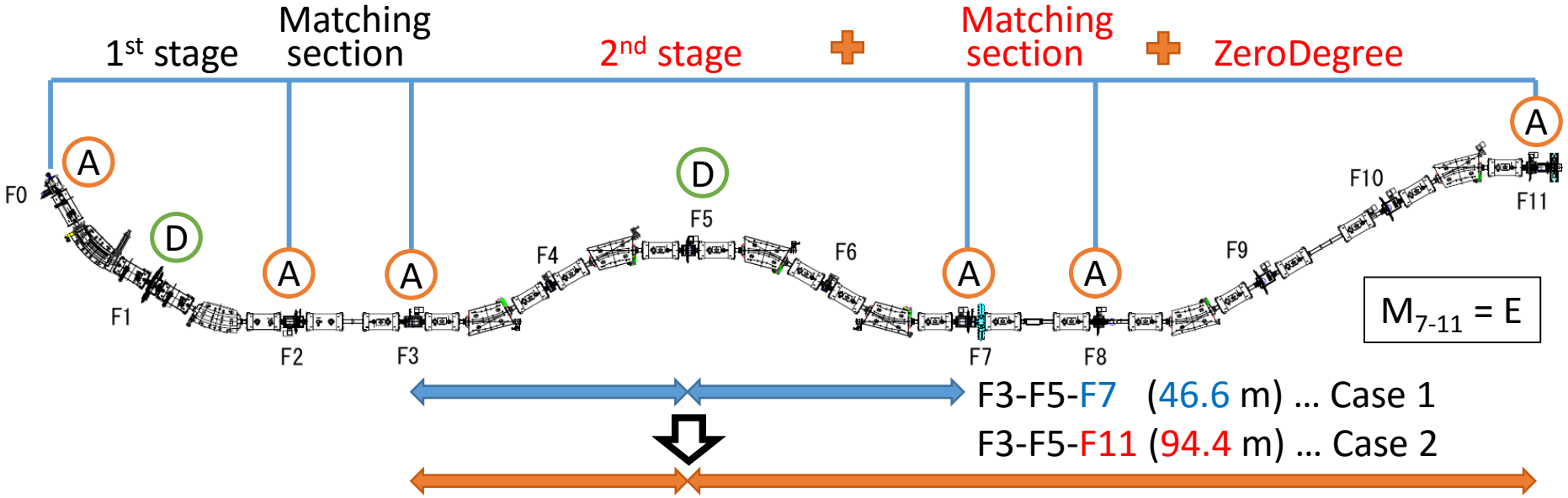


* F0A = F3A / 0.465



- Consistent with the calculation.
- Standard mode
  - Both momentum and angular acceptances are wide.
- D-double mode
  - Both acceptances are cut.
- M-half mode
  - Angular acceptance is small. Momentum acceptance is relatively wide.

Case 2. ^{136}Sn test experiment (F3-F5-F11)



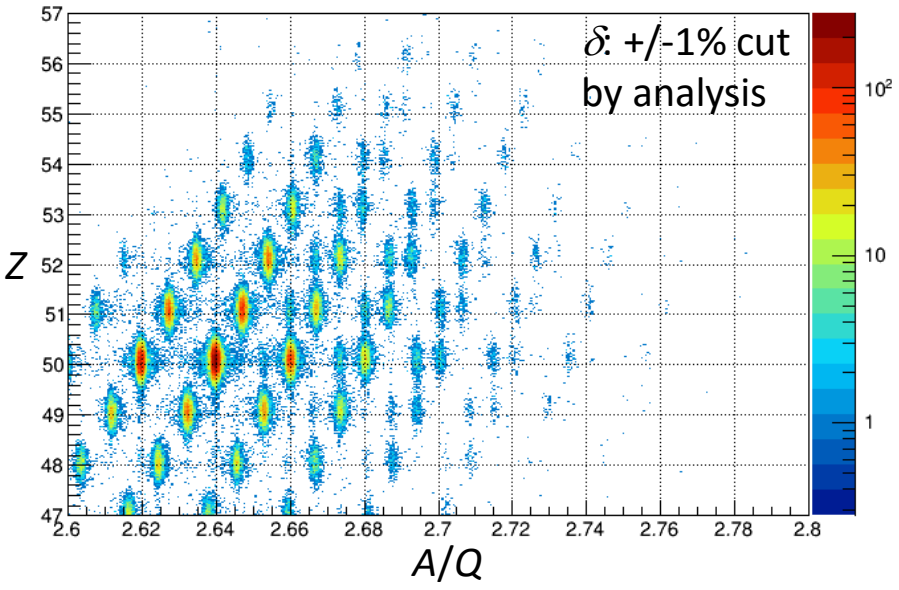
$$\left(\frac{\Delta A/Q}{A/Q}\right)^2 = \left(\frac{\Delta B\rho}{B\rho}\right)^2 + \left(\gamma^2\frac{\Delta\beta}{\beta}\right)^2$$

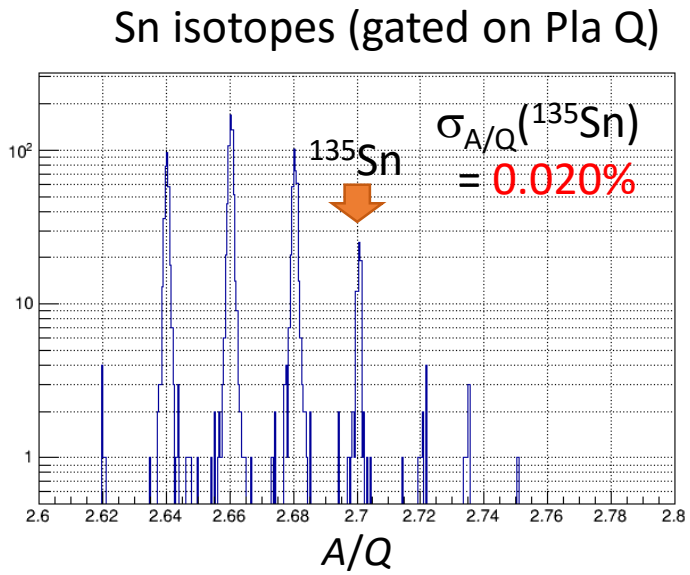
	Case 1 Standard F3-F5-F7	Case 1 D-double F3-F5-F7	Case 2 D-double F3-F7-F11
$B\rho$ resolution	0.021%	0.010%	0.010%
β resolution (x γ^2)	0.027%	0.027% →	0.013%
A/Q reso. (est.)	0.034%	0.029%	0.017%
A/Q reso. (exp.)	0.035%	0.028%	???

Expected to be half!!

- D-double mode was used.
- The flight-path for the PID was F3 to F11. → The TOF resolution is doubled.
- The transfer matrix from F7 to F11 is identity matrix.
- The BigRIPS settings were the same with the case 1 except the F7 slit (+/-18 → +/-50 mm).

PID and *A*/*Q* resolution





	Standard (F3-F5-F7)	D-double (F3-F5-F7)	D-double (F3-F5-F11)
A/*Q* resolution	0.035%	0.028%	0.020%

- The *A*/*Q* resolution of the D-double mode in F3-F11 was 0.020%.
- Potentially, the resolution of this mode should be about 0.017% which is the half of the one of the standard mode in F3-F7.
- Higher terms of the transfer matrices may affect to the resolution.

Case 3. ^{87}Zn exp. for mass measurement

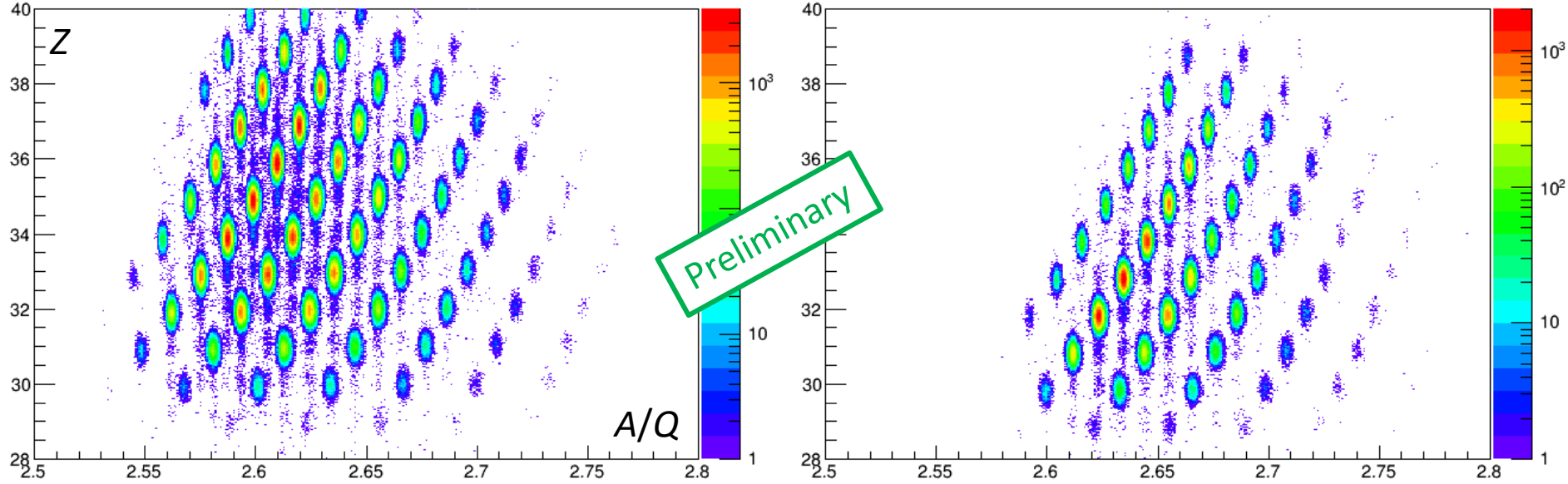
- Physics motivation of the experiment (proposed by A. Estrade)
  - Mass (and beta-decay spectroscopy) of Zn to Kr isotopes, around N = 56.
  - This region corresponds to the *r*-process flows through mass A ~ 90.

- Settings
  - Central particle: $^{87}Zn^{30+}$
  - Bρ01: 7.880 Tm, Bρ12: 7.777 Tm, Bρ35: 7.757 Tm, Bρ57: 7.749 Tm
  - F1deg: 1 mm, F5deg: none
  - Target: 2 mm
  - F1: -0.61/+1.54%, F2: +/-7 mm,
    F5: -0.48/+1.44%, F7: +/-12 mm

  <u>For reference setting (stable side)</u>

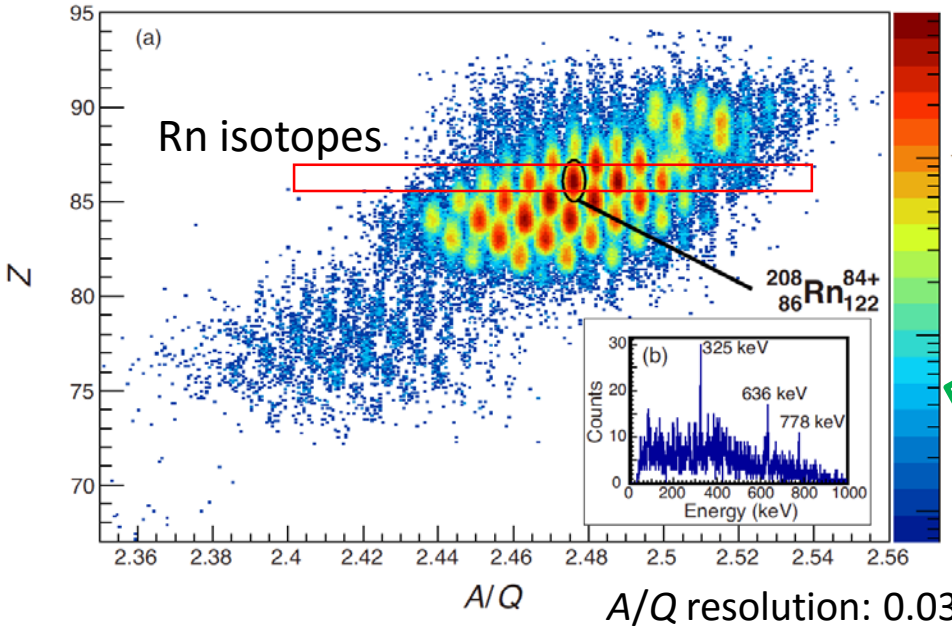
  - Target: 4 mm
  - F1: -0.23/+0.42%, F2: +/-7 mm,
    F5: -0.19/+0.36%, F7: +/-12 mm

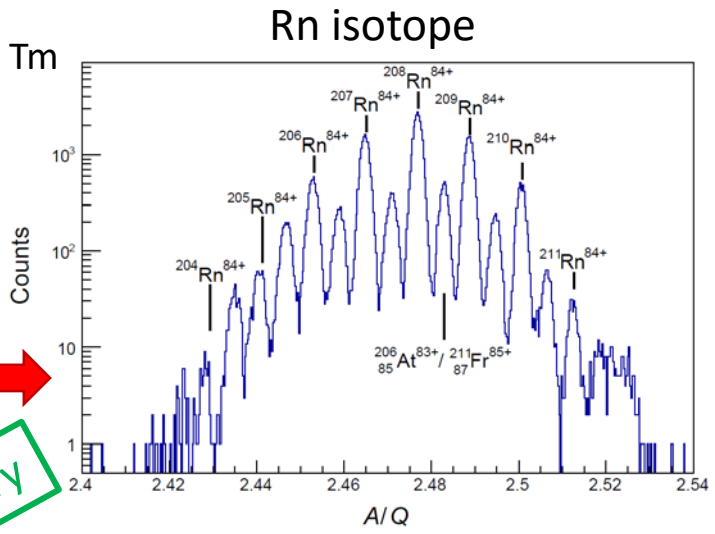
  <u>For neutron-rich setting</u>



Case 4. High-*Z* test experiment

- Settings
  - Center particle: $^{208}_{86}Rn^{84+,86+,84+,84+}$
  - Target: 3 mm, F1deg: 2 mm, F5deg: 1 mm
  - Bρ01: 6.475 Tm, Bρ12: 5.571 Tm, Bρ35: 5.634 Tm, Bρ57: 5.083 Tm
  - F1: +/-0.70%, F2: +/-10 mm, F5: +/-0.63%, F7: +/-30 mm



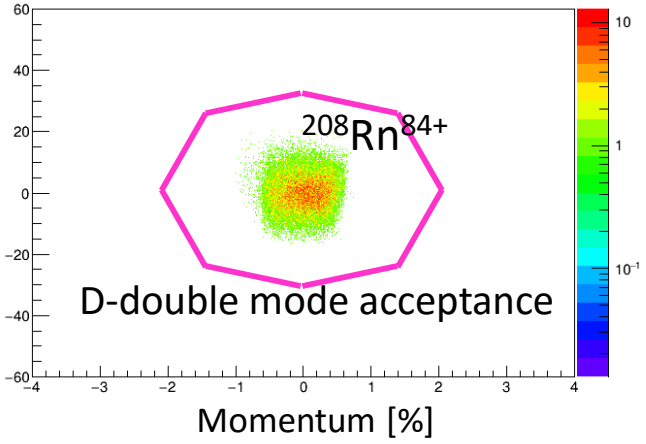


Preliminary

A/*Q* resolution: 0.038%

Z resolution: 0.7%

T. Sumikama et al., Accel. Prog. Rep. **49** (in printing)



- Many charge states are observed. The D-double mode helps the separation of nuclei.

Summary

- Two high -resolution modes were made.
  - High-resolution D-double mode : M_{35} remains, D_{35} is doubled.
  - High-resolution M-half mode : D_{35} remains, M_{35} is halved.
  - Mass measurement, Separation of isotopes around $A/Q = 3$, high-Z region, etc…
- Momentum and angular acceptances of the high-resolution modes are smaller than the ones of the standard mode.
  - Standard mode : +/-3%, +/-40 mrad
  - D-double mode : +/-1.5%, +/-25 mrad
  - M-half mode : +/-2.5%, +/-20 mrad
- Experiments
  - ^{136}Sn test experiment in F3 to F7 (Standard, D-double, M-half)
  - ^{136}Sn test experiment in F3 to F11 (D-double)
  - ^{87}Zn experiment for mass measurement in F3 to F11 (D-double)
  - High-Z ($^{208}_{88}Ra^{86+}$)test experiment in F3 to F7
- Achieved A/Q resolutions (experiment) are
  - 0.035% for the Standard mode (F3-F5-F7).
  - 0.028% for the D-double mode (F3-F5-F7).
  - 0.020% for the D-double mode (F3-F5-F11).
- D-double mode is suitable for heavy-nuclei ($Z > 70$) secondary beam from ^{238}U, because the beam has small spreads in momentum and angle.