Identification and Separation of RI Beams by BigRIPS Separator at RIKEN RI Beam Factory

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1. Brief overview of the BigRIPS in-flight separator
2. Particle identification
3. Two-stage separation
4. Summary

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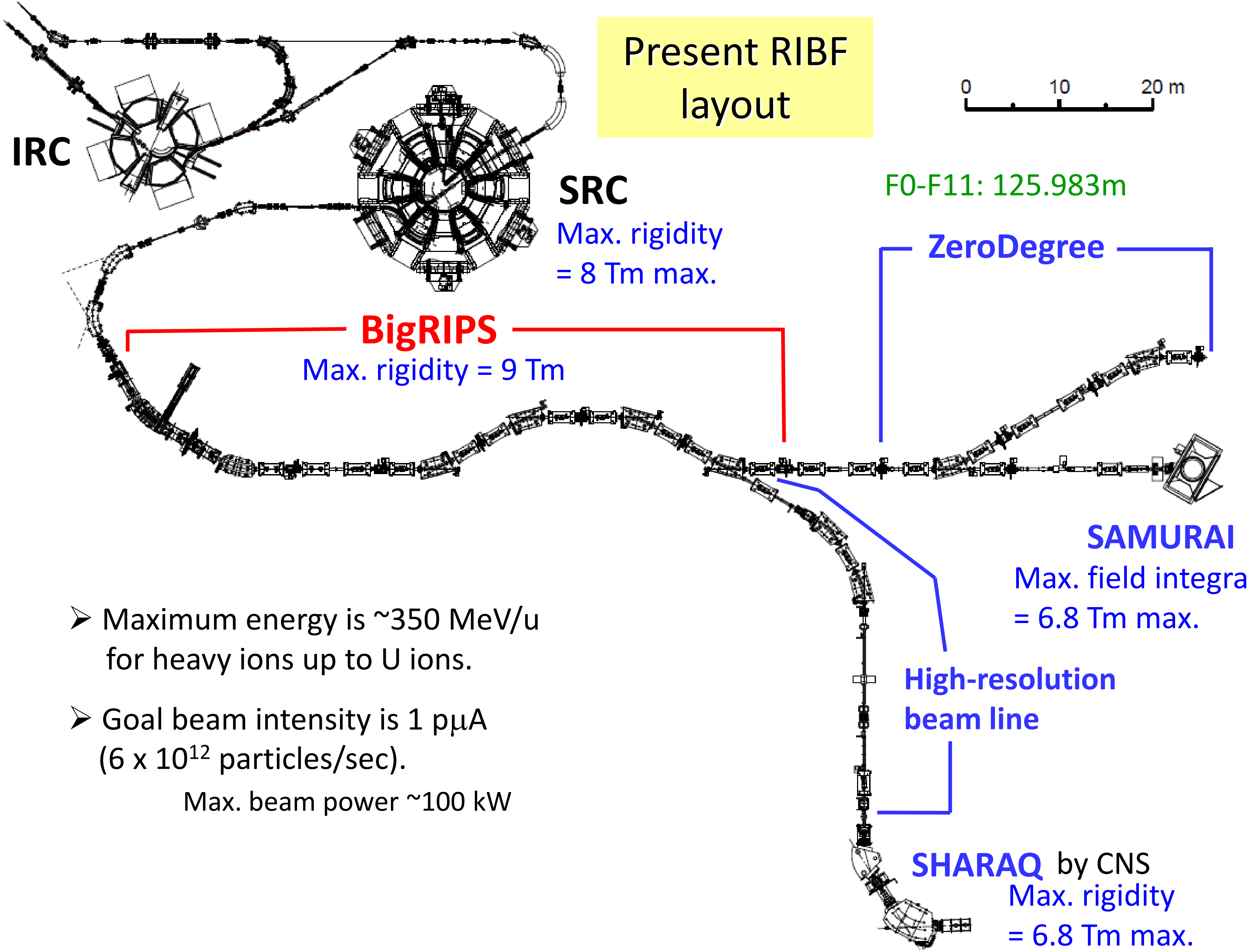
Present RIBF layout



- Maximum energy is ~350 MeV/u for heavy ions up to U ions.
- Goal beam intensity is 1 pμA (6×10^{12} particles/sec).

Max. beam power ~100 kW

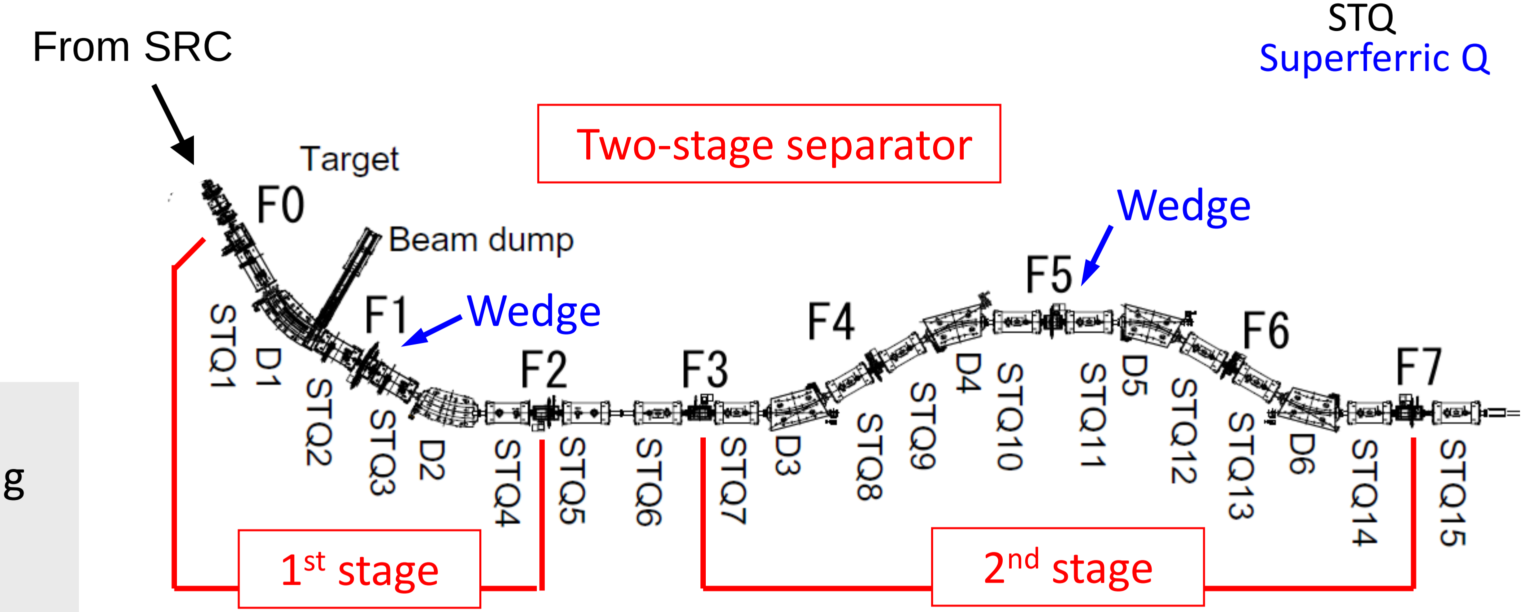
Layout and major features of BigRIPS Separator

- Large acceptances
  - Comparable with spreads of in-flight fission at RIBF energies: ±50 mr, ±5%
- Superconducting quadrupoles having a large aperture
  - Pole-tip radius = 17 cm, pole tip field = 2.4—2.5 T
- Two-stage separator scheme
- 2nd stage with high resolution
  - Particle identification without measuring TKE ← charge states

STQ
Superferric Q

Parameters:
$\Delta\theta$ = ±40 mr
$\Delta\phi$ = ±50 mr
$\Delta p/p$ = ±3 %
$B\rho$ = 9 Tm
L = 78.2 m

STQ1—14: Superconducting Q triplets
D1—D6: Dipoles (30 deg.)
F1—F7: Focuses



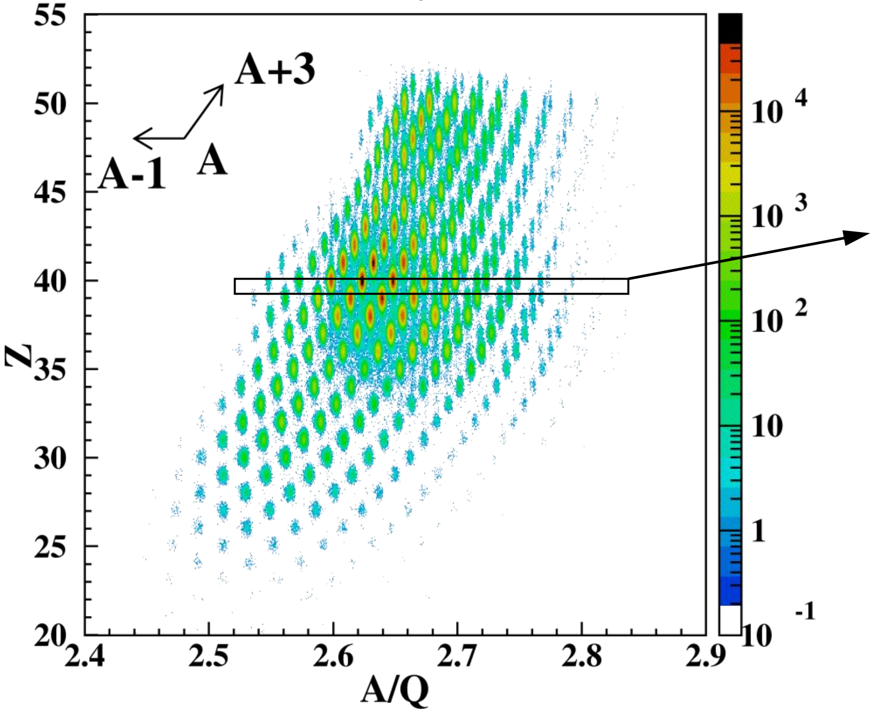
Production & separation

Particle identification & two-stage separation

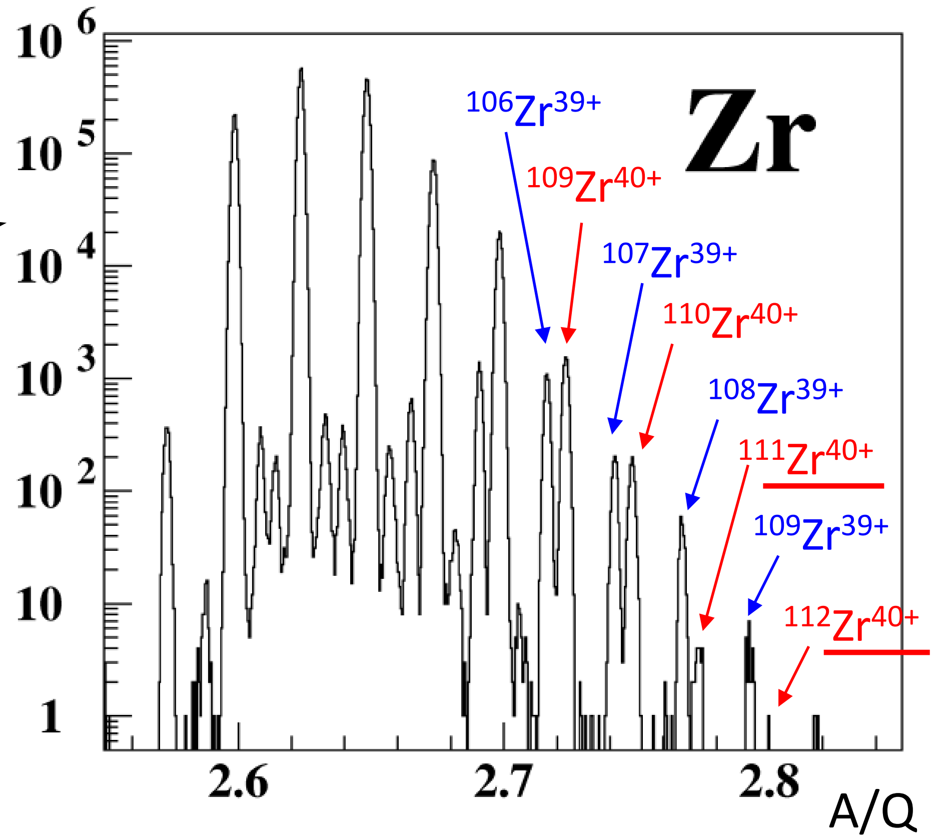
PID power for fission fragment

High enough to well identify charge states
thanks to the track reconstruction!

Z vs. *A/Q* plot



A/Q spectrum for Zr isotopes (*Z*=40)



U+Be 2.9 mm Br 01 = 7.990 Tm
F1 deg Al 2.18mm $\Delta p/p = \pm 3\%$
G2 setting in J. Phys. Soc. Jpn. 79 (2010) 073201.

r.m.s. *A/Q* resolution: 0.035 %

Particle identification (PID) scheme at BigRIPS

TOF-$B\rho$-ΔE method with track reconstruction → Improve $B\rho$ and TOF resolution

Measure TOF, $B\rho$, ΔE @ 2nd stage

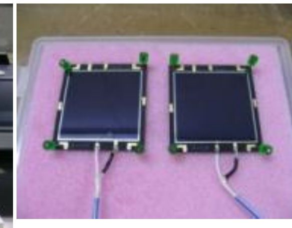
+ isomeric γ-rays

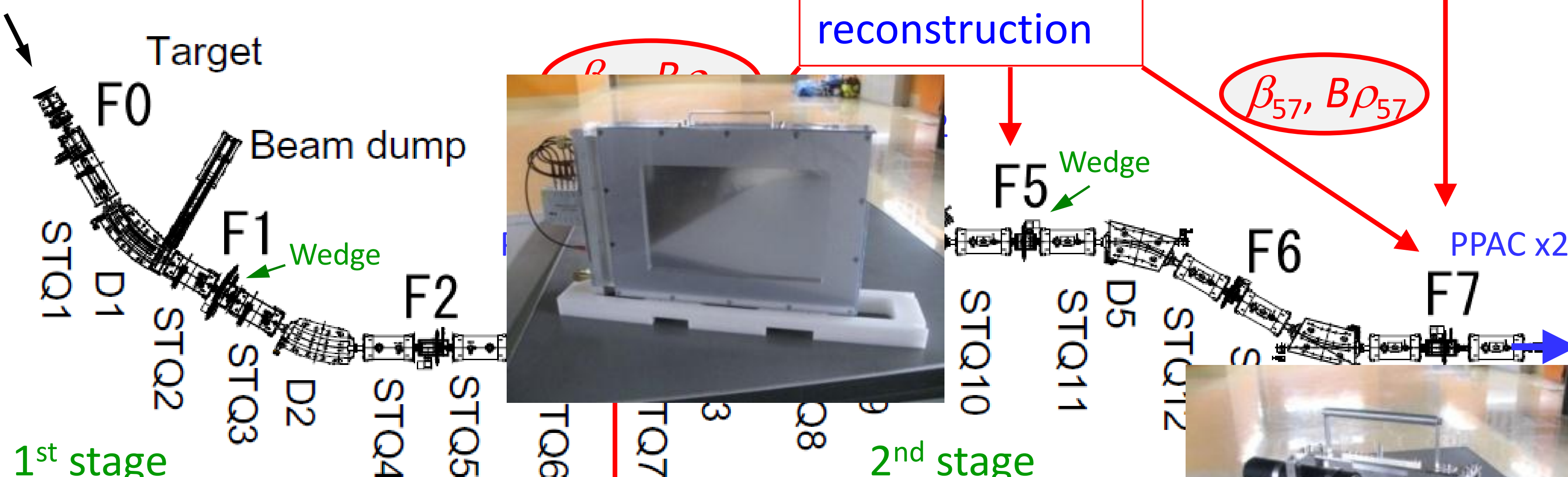
↓

Z, A/Q

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

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

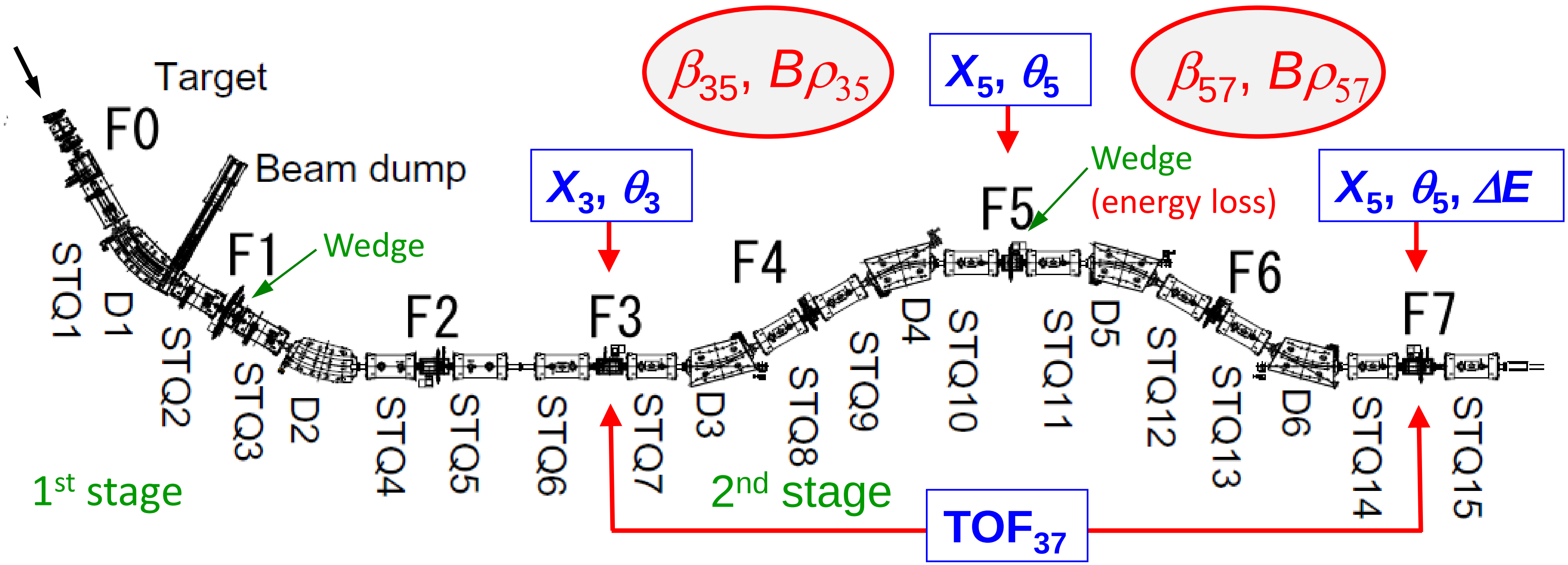




PID without measuring TKE

Particle identification

TOF, trajectories ($B\rho$), $\Delta E \rightarrow Z, A/Q$



$B\rho$ determination by track reconstruction

Ion optics

1st half: X_3, θ_3 & X_5, θ_5 → $B\rho_{35}$

2nd half: X_5, θ_5 & X_7, θ_7 → $B\rho_{57}$

β determination by the simultaneous equations

$TOF_{37} = L_{35}/\beta_{35}c + L_{57}/\beta_{57}c$

$B\rho_{35}/B\rho_{57} = (\beta\gamma)_{35}/(\beta\gamma)_{57}$

→ β_{35} (1st half), β_{57} (2nd half)

Trajectory reconstruction (F3-F5 case)

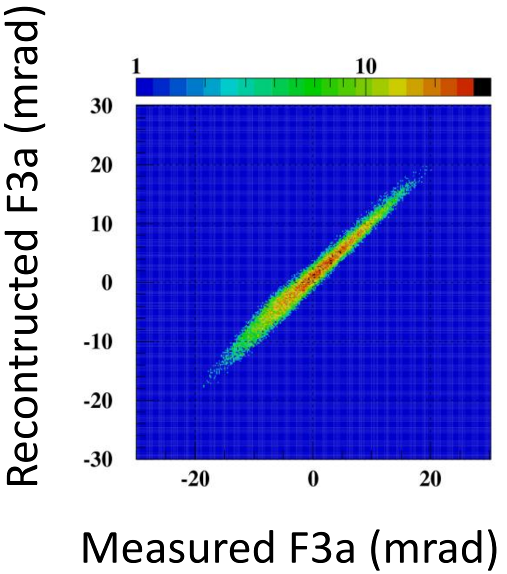
$F5x = (x|x)F3x + (x|a)F3a + (x|\delta)\delta$

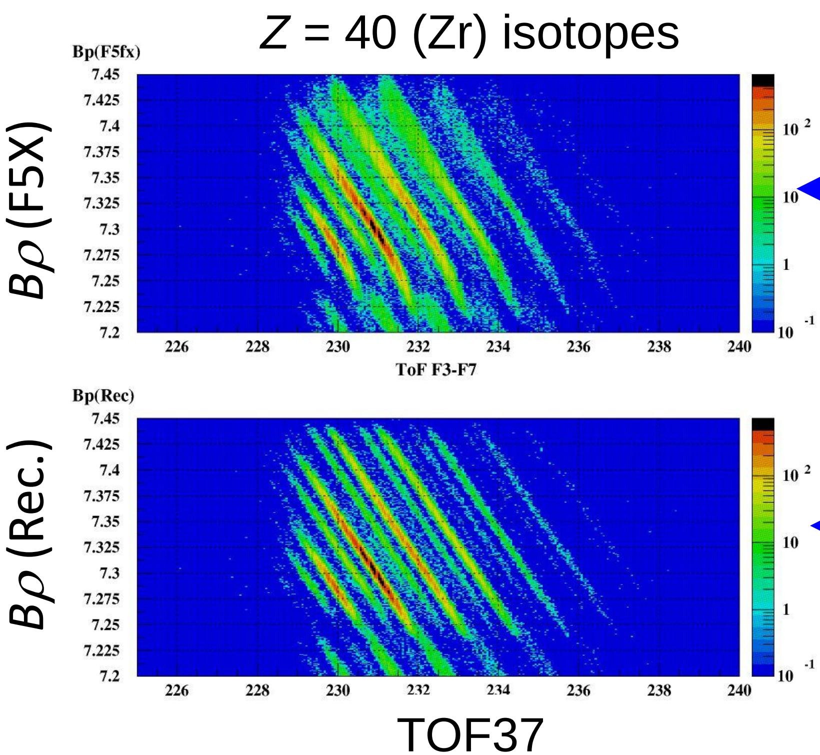
$F5a = (a|x)F3x + (a|a)F3a + (a|\delta)\delta$

$a = \theta$: angle

Measured *F5x*, *F5a*, *F3x*
Transfer matrix $(x|x)$, $(x|a)$, …
→ deduce δ, *F3a*

$B\rho = B\rho_0(1+\delta)$





Without track reconstruction
(from the position at dispersive focus)

With track reconstruction

For *Z* = 40 isotopes produced by in-flight fission of a ^{238}U beam at 345 MeV/u

Our goal for trajectory reconstruction

Final goal is to perform the trajectory reconstruction only with the COSY calculation.

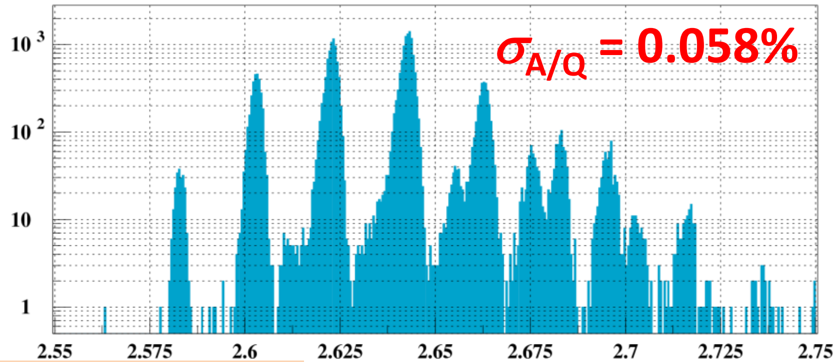
- Higher resolution in an online PID
- Accurate and efficient delivery of RI beams

A/Q resolution with COSY matrices

In-flight fission of a ^{238}U beam at 345 MeV/u. $\Delta p/p$ = 6%

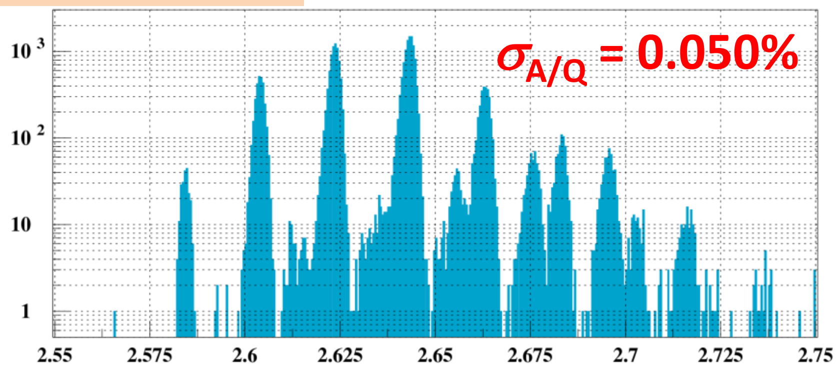
Sn isotopes

Only 1st order



A/Q

Up to 3rd order



A/Q

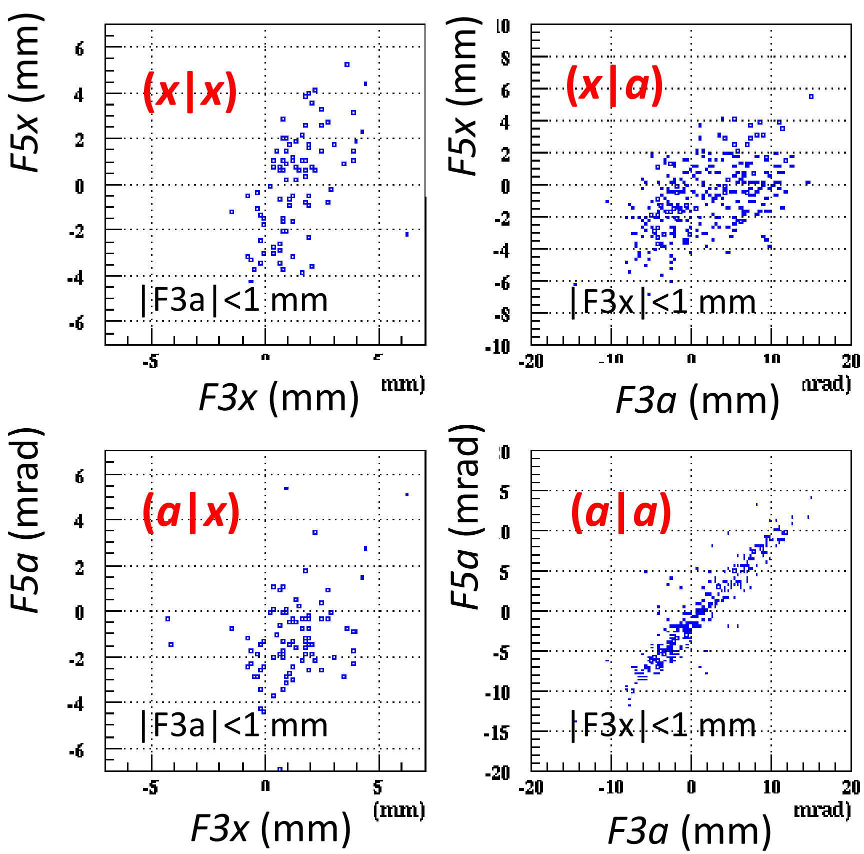
Ideal $\sigma_{A/Q}$ = 0.03%
estimated by the detector resolutions.
(Poster session by D. Kameda)

The present COSY calculation does not reproduce sufficiently the actual matrix.

Experimental determination of transfer matrices

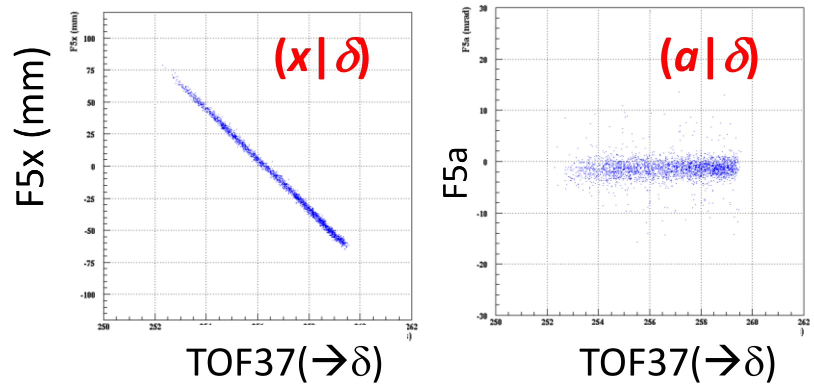
$F5x = (x|x)F3x + (x|a)F3a + (x|\delta)\delta$

$F5a = (a|x)F3x + (a|a)F3a + (a|\delta)\delta$



1st order matrix elements from F3 to F5

|F3x| < 1 mm, |F3a| < 1 mrad

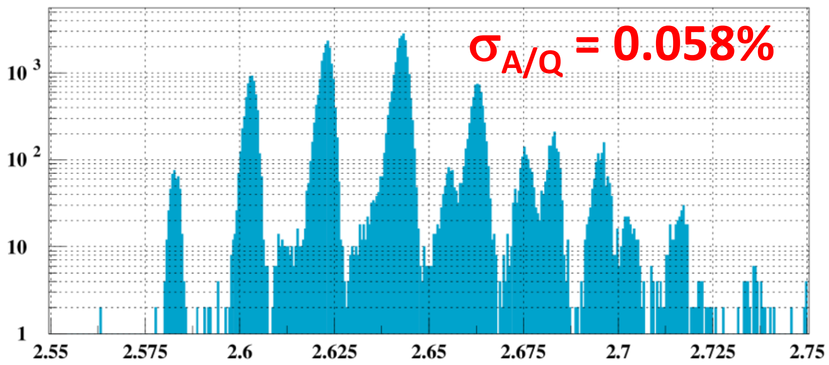


	Experiment	COSY	
$(x\|x)$	1.020±0.103	0.9266	
$(x\|a)$	**0.219±0.043**	-0.0047	mm/mrad
$(a\|x)$	0.333±0.200	-0.0197	mrad/mm
$(a\|a)$	1.018±0.036	1.0793	
$(x\|\delta)$	30.80±0.50	31.67	mm/%
$(a\|\delta)$	-0.004±0.001	0.015	mrad/%
Det.	0.966	1.000	

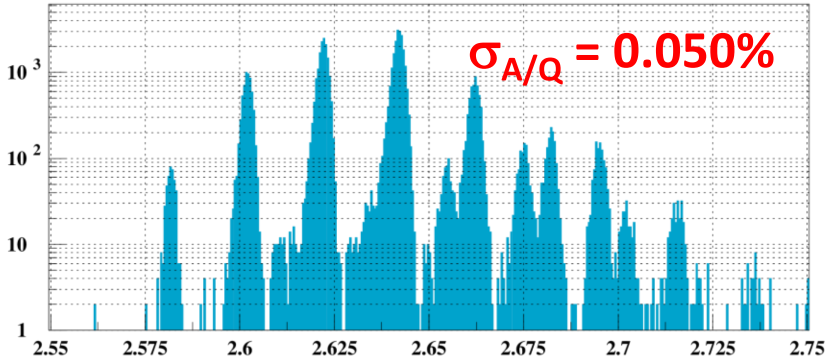
Improvement in A/Q resolution

In-flight fission of a ^{238}U beam at 345 MeV/u. $\Delta p/p$ = 6%

Sn isotopes



COSY 1st order matrices



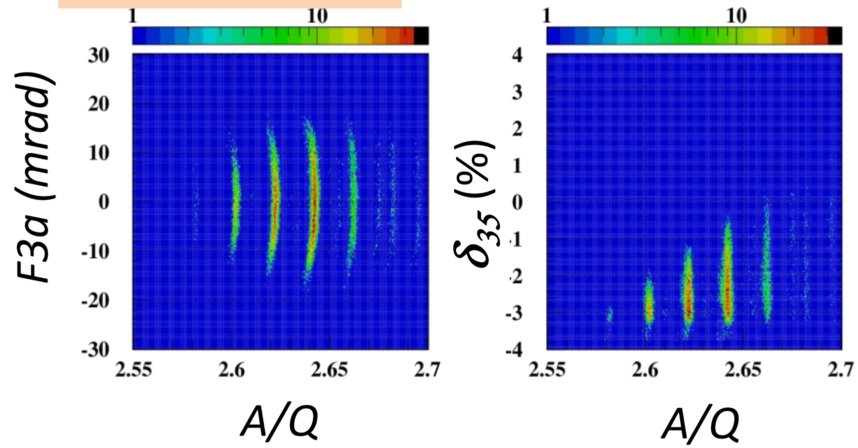
Experimentally determined 1st order matrices

Empirical determination of transfer map

To determine higher-order transfer matrix

For $Z = 50$ isotopes produced by in-flight fission of a ^{238}U beam at 345 MeV/u.

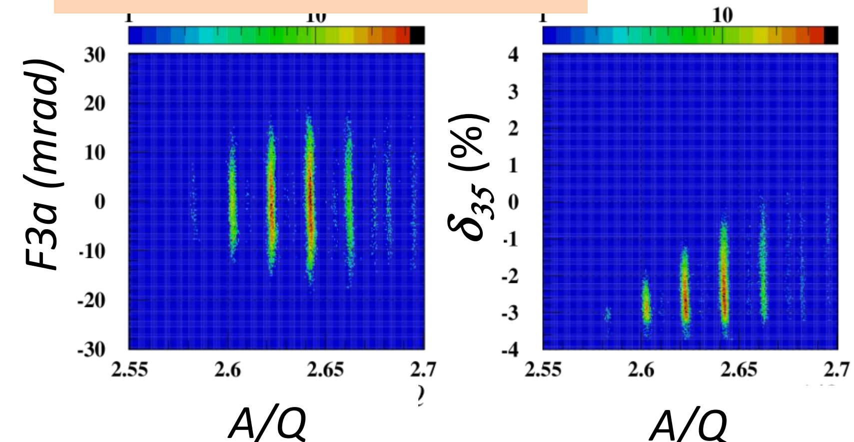
Only 1st order



Higher-order terms

Cancel out dependence of *A/Q* on *F3a* and δ_{35}

Including higher order

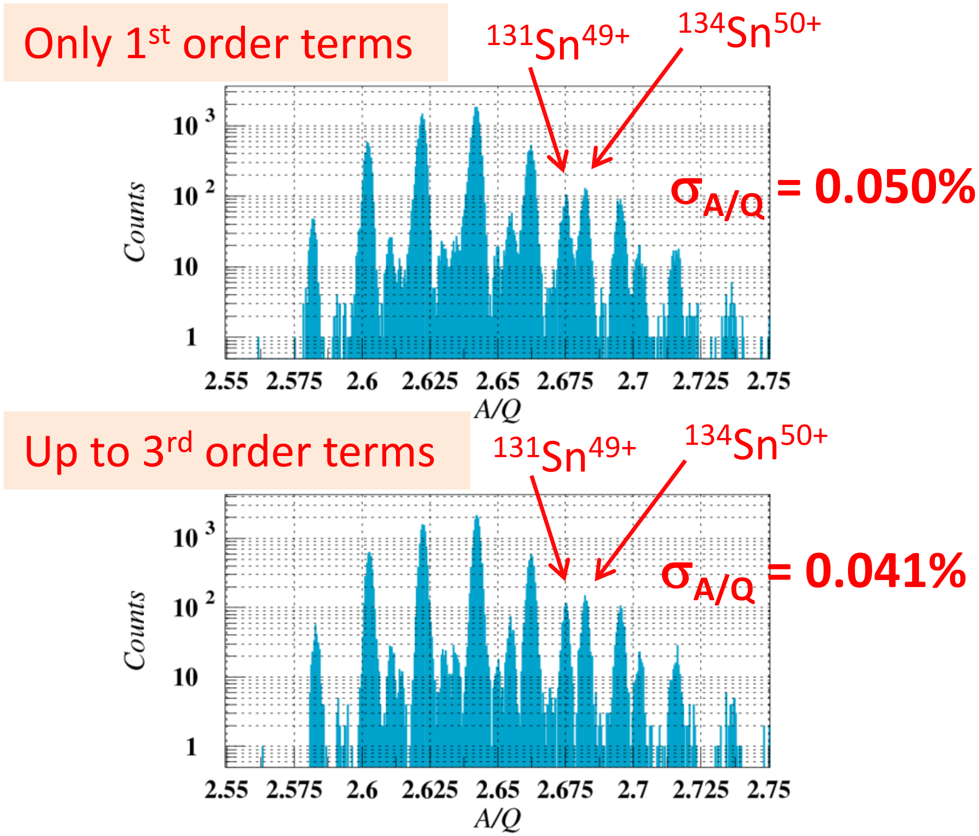


$$F5x = F5x_{1st} + (x|x\delta)F3x \cdot \delta + (x|a\delta)F3a \cdot \delta$$
$$+ (x|y^2)F3y^2 + (x|b^2)F3b^2 + (x|\delta^2)\delta^2$$
$$+ (x|a^3)F3a^3 + (x|a^2\delta)F3a^2 \cdot \delta$$
$$F5a = F5a_{1st} + (a|\delta^2)\delta^2 + (a|a\delta^2)F3a \cdot \delta^2$$

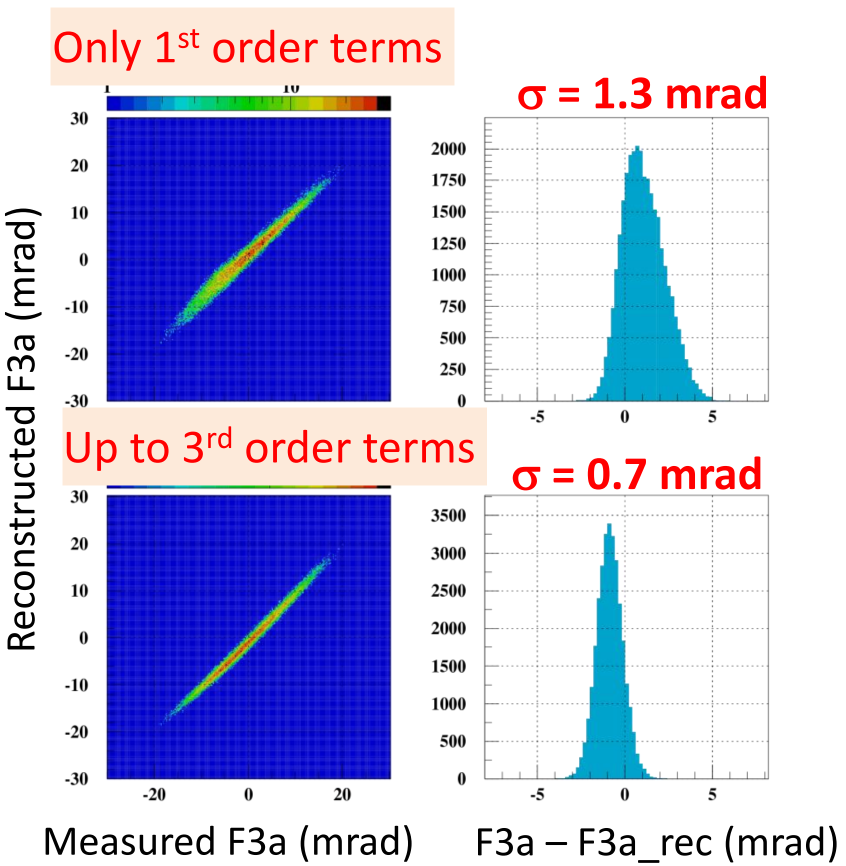
solved by Newton-Raphson method.

Achievement in *A/Q* resolution

Sn isotopes

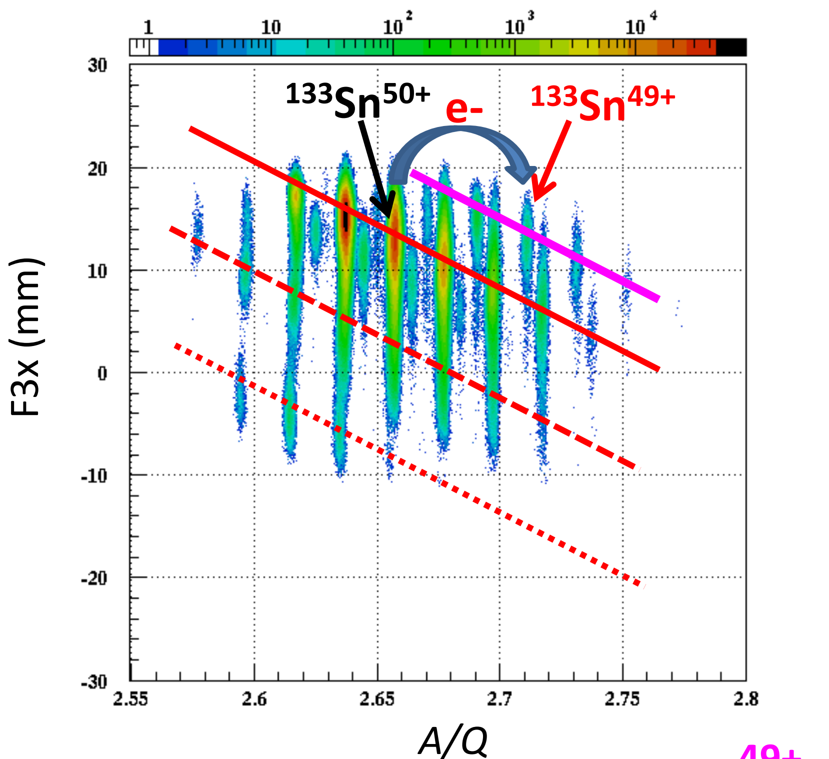


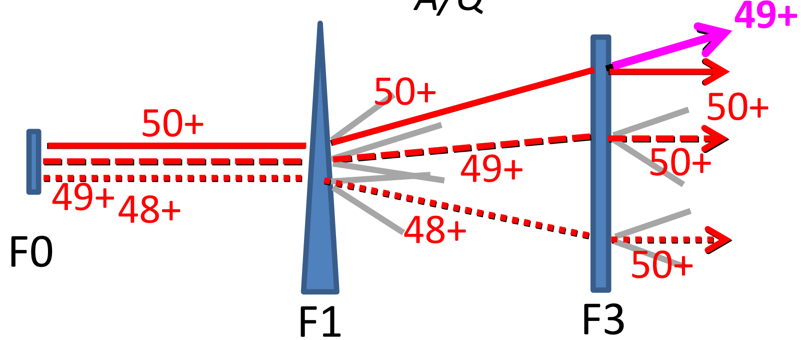
F3a deduced from track reconstruction



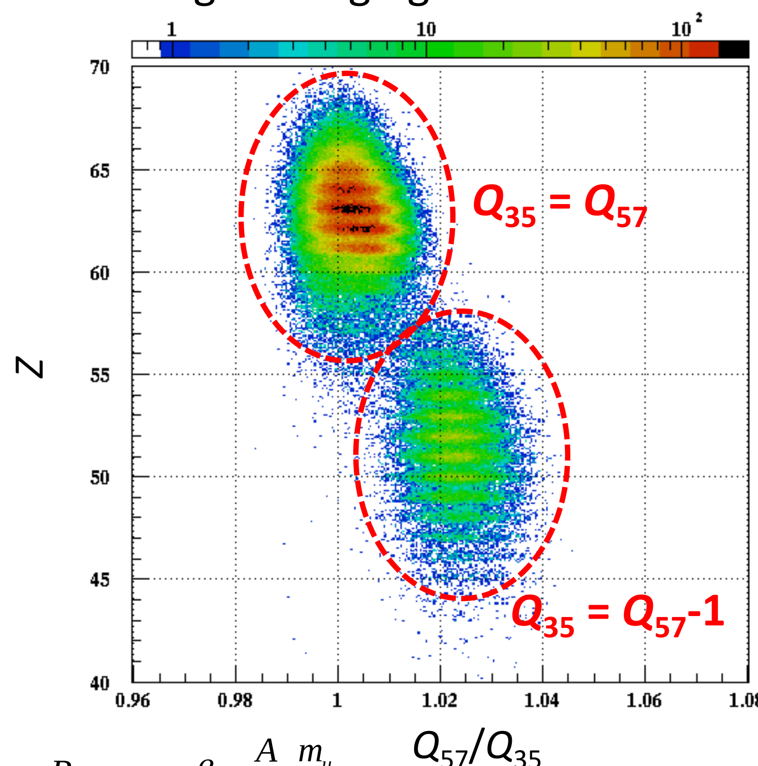
History of charge-changing at F1, F3 and F5

Charge-changing at materials at F1 and F3





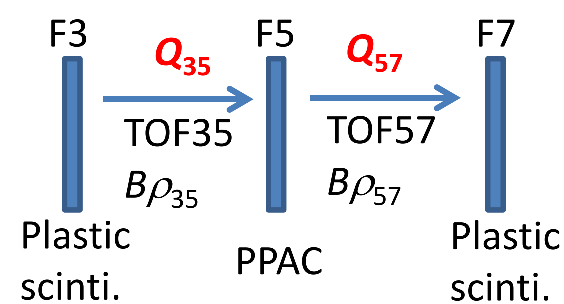
Charge-changing at materials at F5



$$B\rho_{35} = \gamma_{35}\beta_{35}\frac{A}{Q_{35}}\frac{m_u}{c}$$

$$B\rho_{57} = \gamma_{57}\beta_{57}\frac{A}{Q_{57}}\frac{m_u}{c}$$

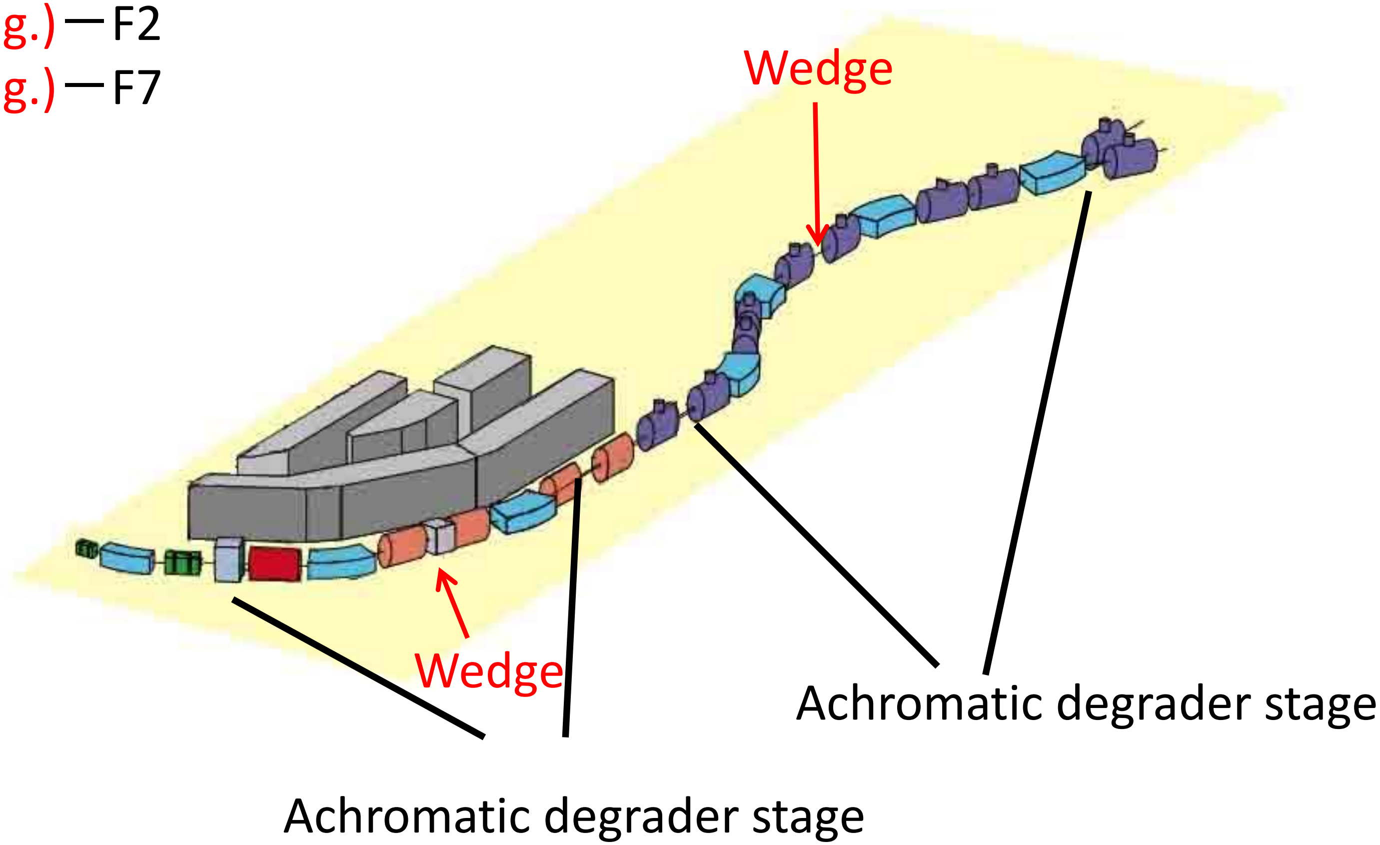
$$\frac{Q_{57}}{Q_{35}} = \frac{B\rho_{35}/\gamma_{35}\beta_{35}}{B\rho_{57}/\gamma_{57}\beta_{57}}$$



Two-stage separation

- **Two achromatic degrader stage**

Ⅰ : F0 — F1(deg.) — F2
Ⅱ : F3 — F5(deg.) — F7



Two-stage separation: example-1

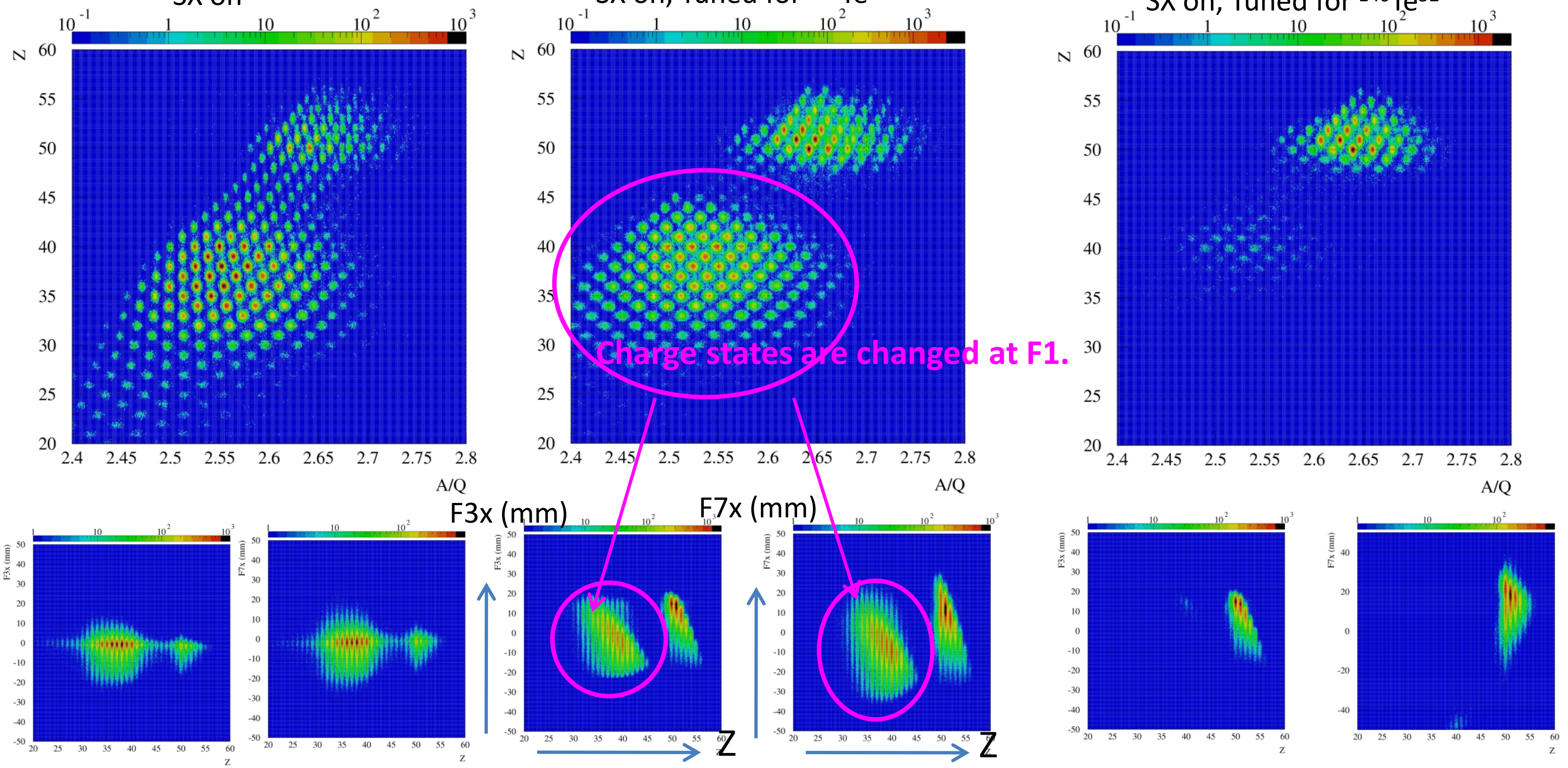
Remove charge state events.

^{238}U 345 MeV/u + Pb 1.5 mm, $B\rho_{01}$ = 7.3940 Tm
F1 slit +-63 mm, F2 slit +-15 mm, F7 slit +-120 mm

No degrader
SX on

F1 Al 3 mm (Wedge)
SX on, Tuned for $^{140}Te^{52+}$

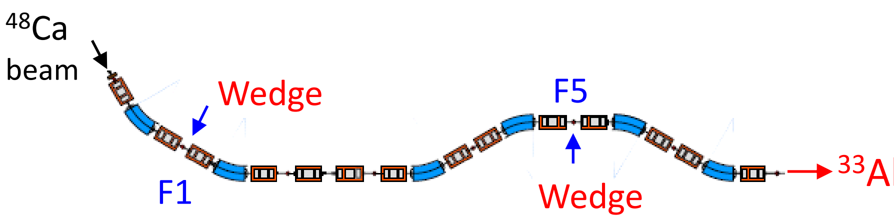
F1 Al 3 mm (Wedge)
F5 Al 1.8 mm (Profile)
SX on, Tuned for $^{140}Te^{52+}$

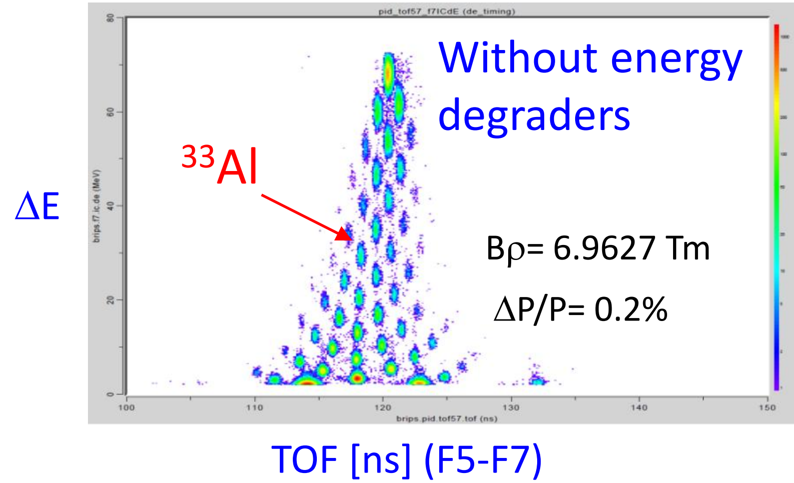


Two-stage separation: example-2

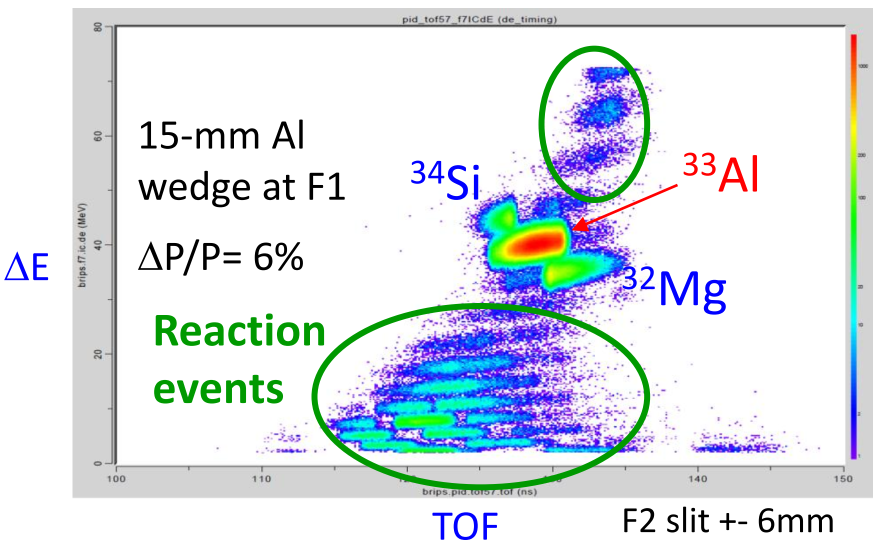
Remove secondary reaction events.

Example: production of ^{33}Al using a ^{48}Ca beam at 345 MeV/u (with a 10-mm Be target)

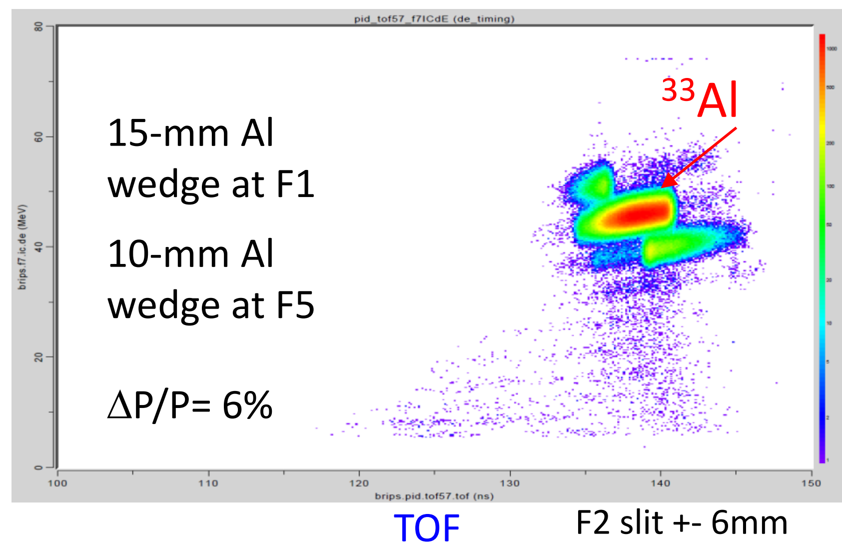




Wedge degrader at the first stage only



Wedge degrader at both stages



Summary

- The performance of particle identification of RI beam by BigRIPS was presented.
  The trajectory reconstruction improves the *A/Q* resolution significantly, which provides unambiguous particle identification including charge-states.

- The examples that demonstrates two-stage isotope separation were presented.
  The contaminant events are well removed by the two-stage separation.

Thank you for your kind attention.