BigRIPS Workshop
--- Ion Optics of BigRIPS Separator---

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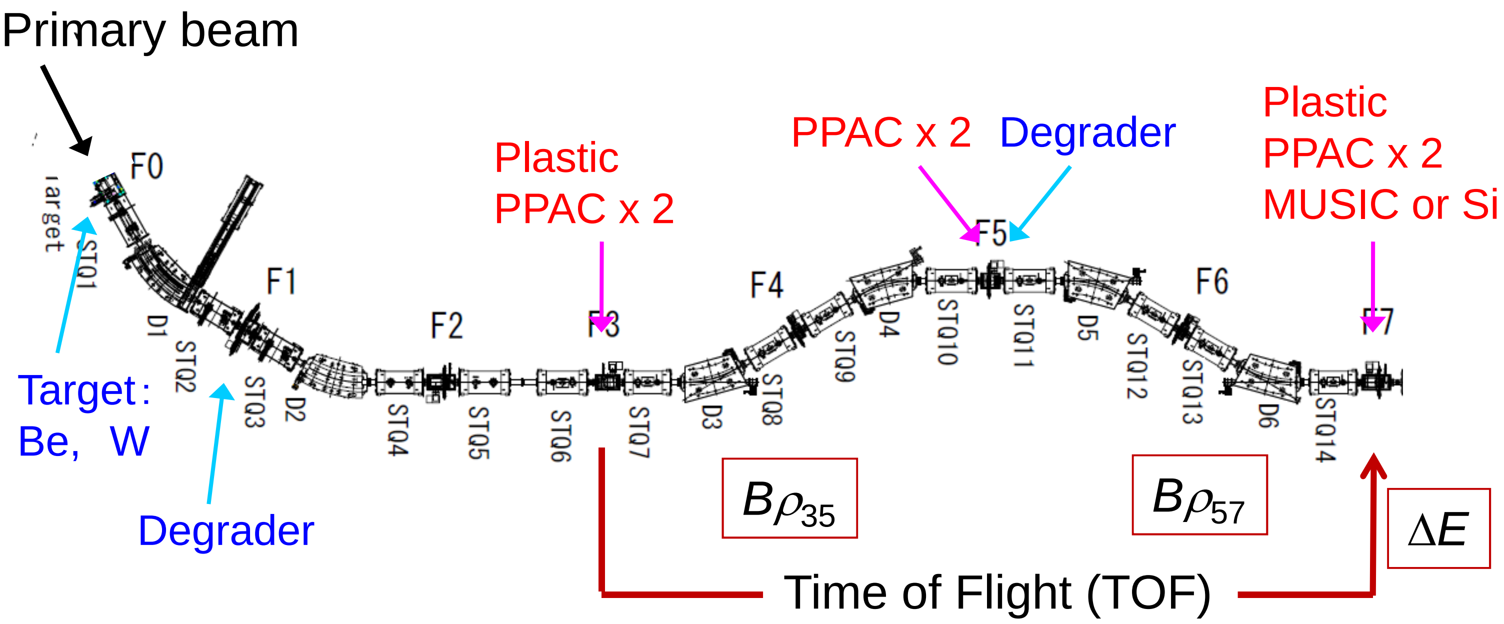
Outline of My Talk

- Introduction
  - Standard ion optics of the BigRIPS
- Procedure of focus tune
  - Focusing terms (x|a), (y|b) tune by quadrupoles
  - Higher order terms tune by sextupoles
  - Setting for the matrix elements
- New optics for the BigRIPS separator
  - D double mode
- Optics for the SAMURAI beam line
- Summary

BigRIPS Separator



RI production & separation: F0-F2	PID (A/Q): F3-F7	PID (Z): F7
	$B\rho_{35}$, $B\rho_{57}$, TOF	ΔE

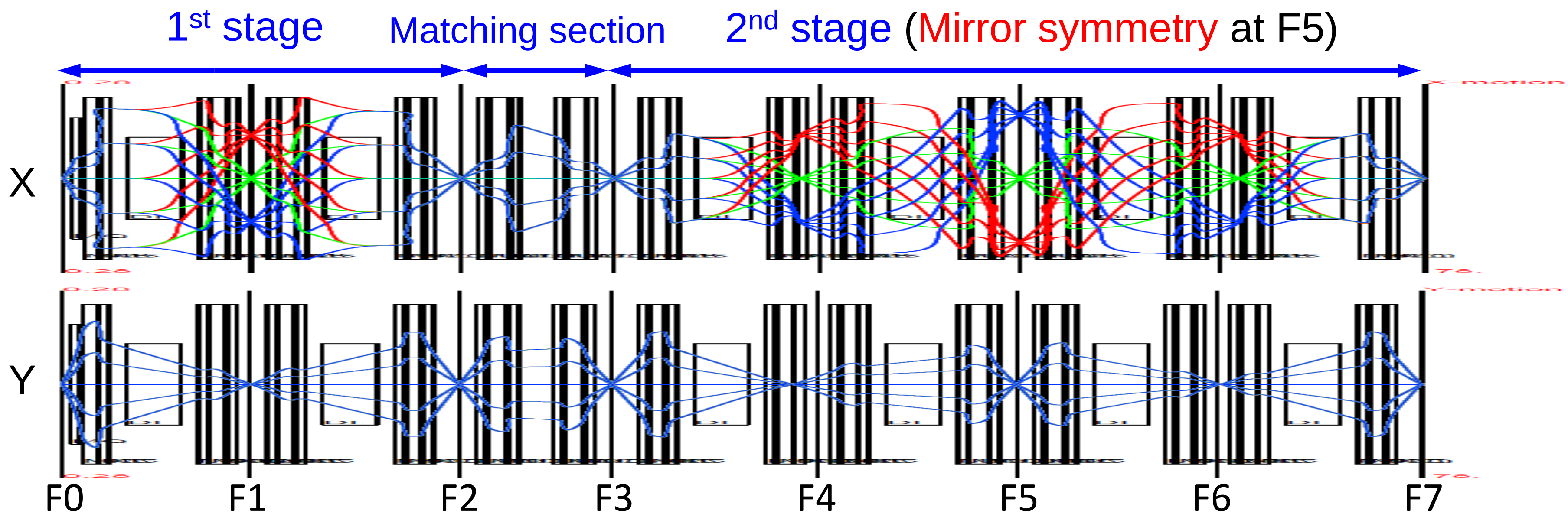
- Projectile fragments
- Separation using A/Q and R(range) of Ris
- Two stage separation with the degraders at F1 & F5

- $B\rho_{35}$, $B\rho_{57}$, TOF → A/Q

$$TOF_{37} = L_{35}/\beta_{35}c + L_{57}/\beta_{57}c$$
$$A/Q = B\rho_{35} / c\beta_{35}\gamma_{35}$$
$$A/Q = B\rho_{57} / c\beta_{57}\gamma_{57}$$

- ΔE → Z

Standard Ion Optics of BigRIPS



→ F0F1

(x|x)=-1.7, (x|a)=0,
(y|y)=-5.0, (y|b)=0,
(x|δ)=-21.4 mm/%, (a|δ)=0

→ F0F2

(x|x)=2.0, (x|a)=0,
(y|y)=1.6, (y|b)=0,
(x|δ)=0 mm/%, (a|δ)=0

→ F2F3

(x|x)=-1.08, (y|y)=-1.18,
(x|a)=(y|b)=(a|x)=(b|y)=0

→ F3F4

(x|x)=-1.40, (x|a)=-0.791,
(y|y)=-3.45, (y|b)=-0.272,
(x|δ)=-22.1 mm/%, (a|δ)=0

→ F3F5

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

P/ΔP =
1260 (1st stage)
3420 (2nd stage)

Mirror symmetry
of F3-F5

F7F6 ←

F7F5 ←

Procedure of Focus Tune

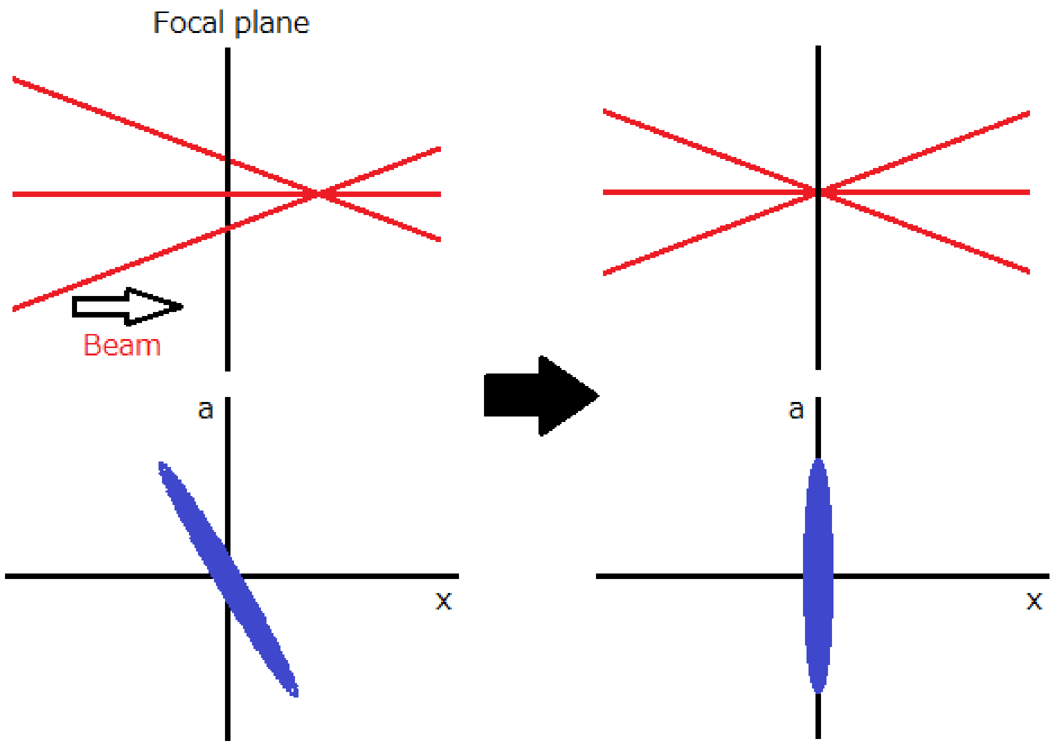
Procedure for Making BigRIPS Settings (Ion Optics Only)

- 1. Set the $B\rho$ value of each section
- 2. Focus tune by adjusting the quadrupoles
- 3. Higher order tune by the sextupoles
- 4. Optics settings for deducing the matrix elements in the 2nd stage

2. Focus Tune by Quadrupoles

- After setting the Bρ value, the focusing is not sufficient.
- Focusing is essential especially for the separation of the nuclei at the achromatic focal planes.

- First, we tune focusing terms (x|a), (y|b) by the quadrupoles.
- Procedure of focusing at each focal plane
  - Close the F1 momentum slit (+/-0.1%)
  - For focusing, make the emittance-ellipse vertically.



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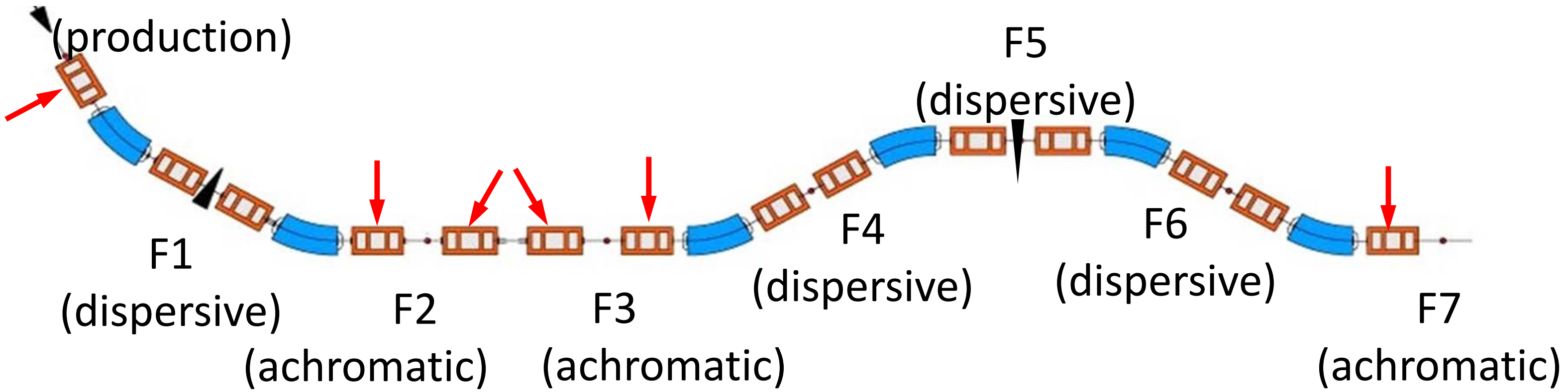
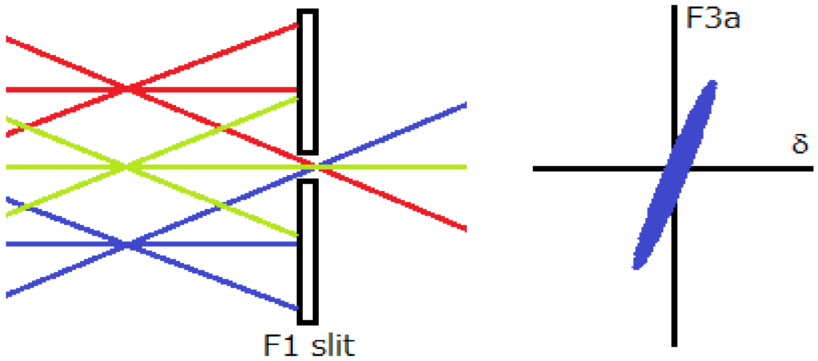
Focus Tune by Quadrupoles

- Deduce the displacement of the focus position from the slope of the emittance ellipse.
- The relation between the focal-position displacement and the magnetic field adjustment are calculated already.
- Using these relations, the displacement is corrected.

- In the focus tuning, STQs in the achromatic section is used. ex) F3-F5: STQ07
- The focusing in x and y directions are independently.
- In most of cases, the adjustment is in less than a few %.



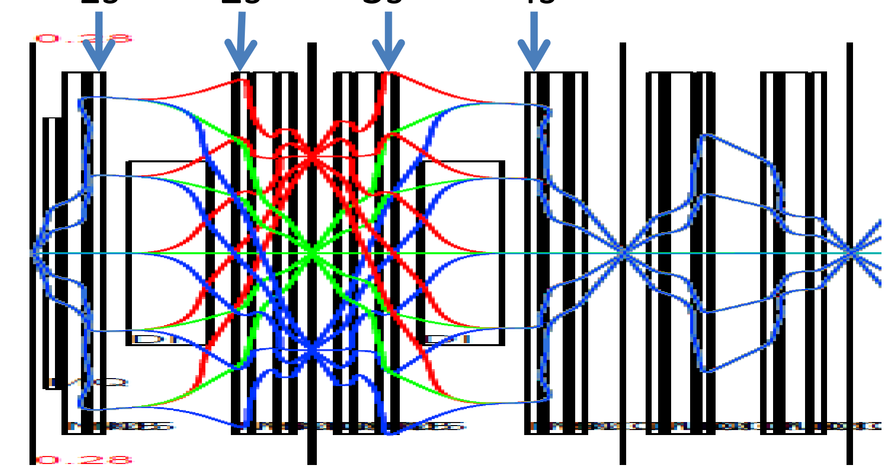
- Repeat these procedures for each plane.
- For F1, F3a vs δ is used.
  Here, assuming F3a ~ F1a



3. Sextupole tune

- Sextupole: tune for the higher order terms. (x|aa), (x|aδ), (x|aaa), etc…
- 2^{nd} stage: For F3-F5 (F7-F5 is mirror symmetry at F5)
  - F3-F4: Minimize $\{(x|ad)*0.04*0.03\}^2 + \{(y|ab)*0.04*0.04\}^2$
  - F3-F5: Min. $\{(x|ad)*0.04*0.03\}^2 + \{(x|aa)*0.04^2\}^2 + \{(x|bb)*0.05^2\}^2 + \{(y|ab)*0.04*0.05\}^2$

- 1^{st} stage: 2 sextupoles in each section → 2 conditions each.
  - STQ2s, 3s: Cancel the chromatic aberration.
  - STQ1s, 4s: Cancel the angular aberration caused by 2s and 3s.



BigRIPS 1^{st} stage

- 4 settings (next page)
- ^{90}Sr setting (primary beam: ^{238}U)

  0.1-mmt Be, F1: 7 mm, F5: 5 mm

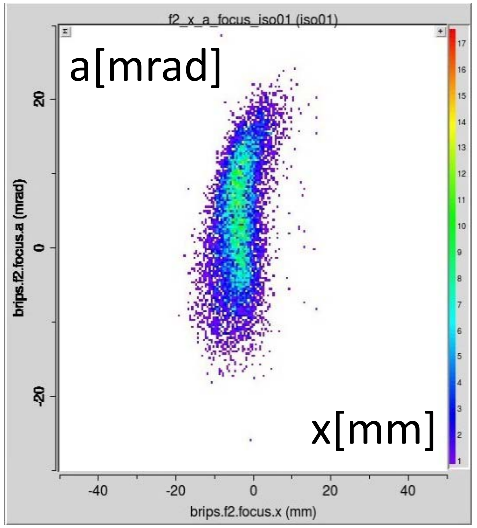
  Bρ01: 7.25, Bρ12: 6.30, Bρ35: 6.28, Bρ57: 5.43 Tm

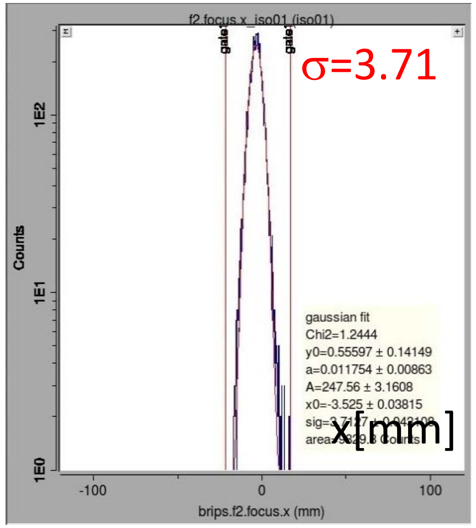
  F1: +/-64.2, F2: +/-20, F5: +/-120, F7: +/-50 mm
- Image at F2 of ^{90}Sr
- Angular distribution
  - 11 mrad @ F0 (1σ)
  - +/-30 mrad @ F0 (total width)
- Momentum distribtion
  - +/-3%

1st Stage: Sextupole Optics 1 & 2

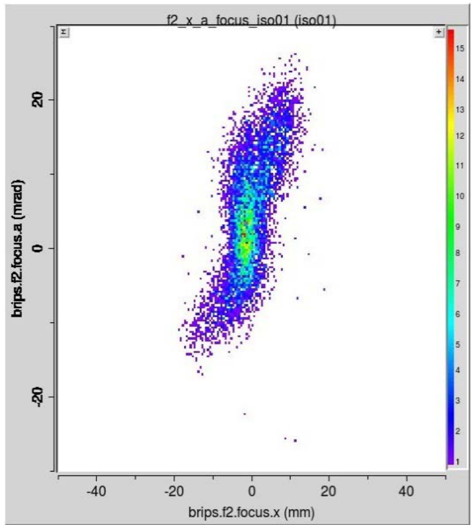
F2 images, ^{90}Sr, F1:+/-64.2 mm

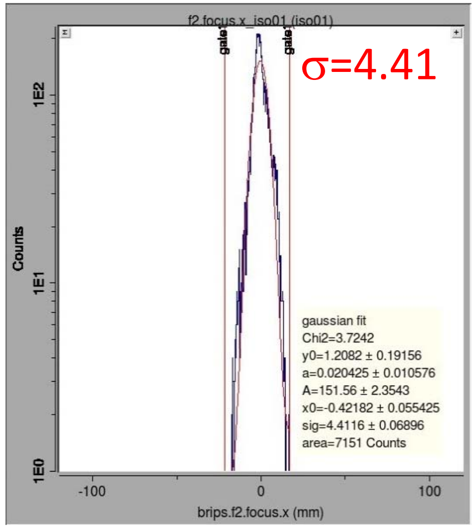
- SH optics 1: Usual optics
  - F0-F1
    - $(x|a\delta) = 0$
    - $\{(x|aa)*40^2\}^2 = \{(x|bb)*50^2\}^2$
  - F0-F2
    - $(x|a\delta) = 0$
    - Minimize $(x|a\delta)_{02}^2 + (x|a\delta)_{03}^2$





- SH optics 2: All Sextupoles OFF

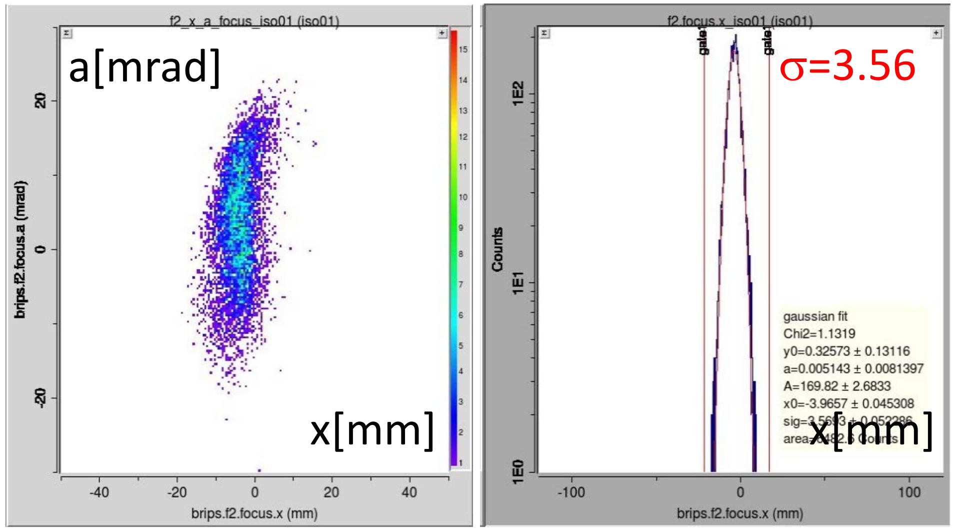




1st Stage: Sextupole Optics 3 & 4

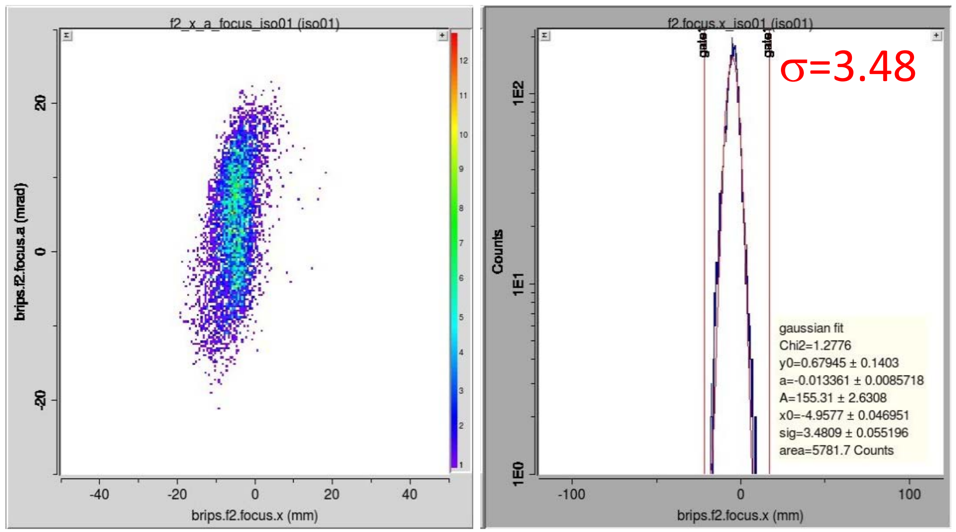
F2 images, ^{90}Sr, F1:+/-64.2 mm

- SH optics 3: Original optics
  - F0-F1
    - $(x|a\delta) = 0$
    - $(x|aa) = 0$
  - F0-F2
    - $(x|a\delta) = 0$
    - $(x|aa) = 0$



- SH optics 4:
  - F0-F1
    - $(x|a\delta) = 0$
    - Minimize $\{(x|aa)*40^2\}^2 + \{(x|aaa)*40^3\}^2$
  - F0-F2
    - $(x|a\delta) = 0$
    - Minimize $\{(x|aa)*40^2\}^2 + \{(x|aaa)*40^3\}^2$

40 mrad: Angular acceptance

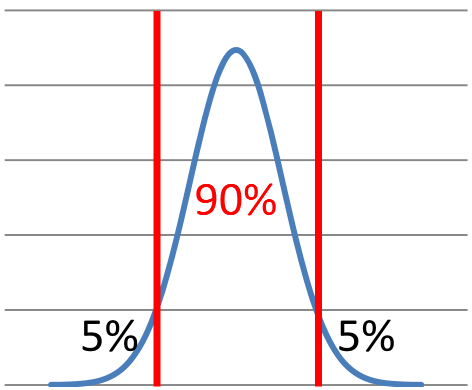


Width at F2 (1σ)

	SH optics 1 Usual	SH optics 2 All SH OFF	SH optics 3 Original	SH optics 4 New
F1 = +/-2 mm	2.28 mm	2.34 mm	2.26 mm	2.19 mm
F1 = +/-64.2	3.71 mm	4.41 mm	3.56 mm	3.48 mm

- The width of the image are narrowest in the case of SH optics 4.
- Room for the improvement of the separation.

- Purity
  - Set the F2 slit on the analysis, and deduced the purity for these 4 settings.
  - The position of the slits were decided as the figure.



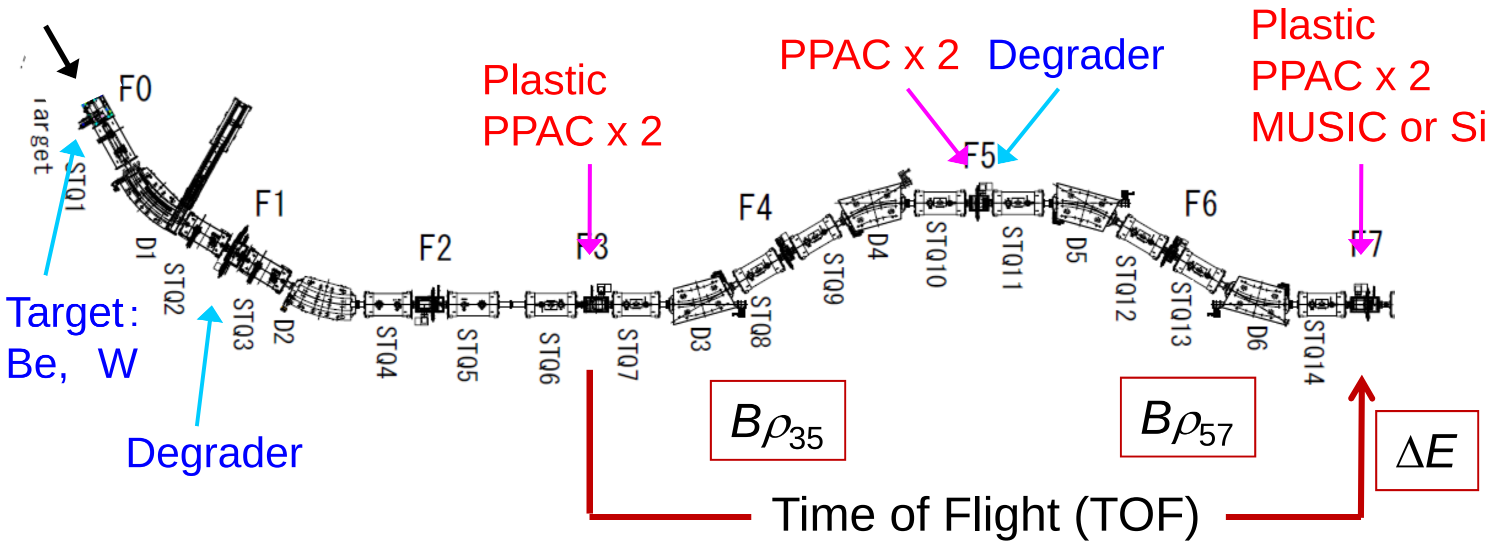
Purity	12.8%	8.6%	13.5%	13.6%

(F1 slit: +/-64.2 mm)

- The purities are almost the same in the case of ^{90}Sr beam.

4. Optics Setting for the Matrices

- Derivation of A/Q



- A/Q is deduced from $B\rho_{35}$, $B\rho_{57}$, and TOF_{37}

$$A/Q = B\rho_{35} / c\beta_{35}\gamma_{35}$$
$$A/Q = B\rho_{57} / c\beta_{57}\gamma_{57}$$
$$TOF_{37} = L_{35}/\beta_{35}c + L_{57}/\beta_{57}c$$

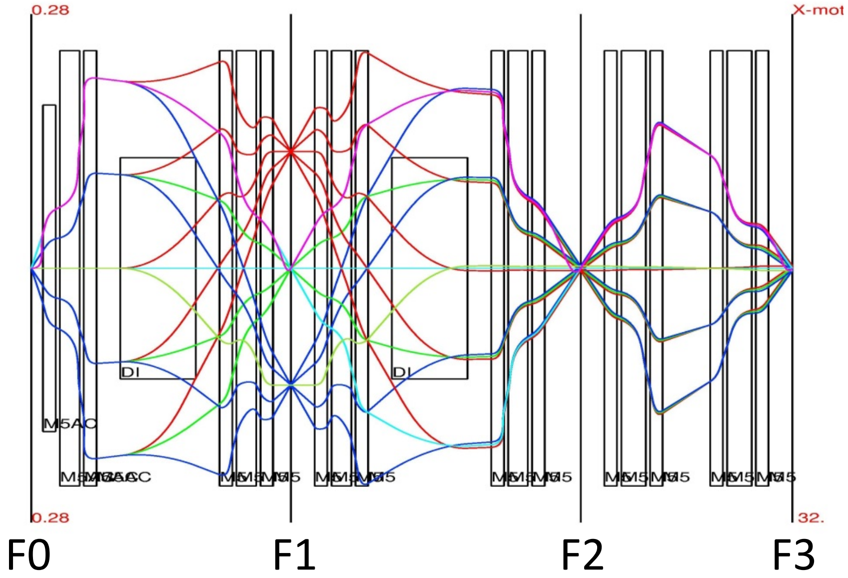
- $B\rho_{35} = B\rho_{35\_0} * (1+\delta_{35})$
  $B\rho_{57} = B\rho_{57\_0} * (1+\delta_{57})$
- δ_{35} and δ_{57} are deduced by the track reconstruction

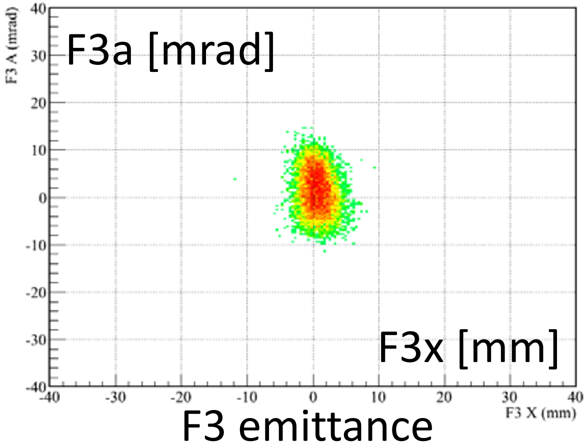
$$F5x = (x|x)_{35}*F3x + (x|a)_{35}*F3a + (x|d)_{35}*\delta_{35}$$
$$F5a = (a|x)_{35}*F3x + (a|a)_{35}*F3a + (a|d)_{35}*\delta_{35}$$

4. Optics Setting for the Matrices

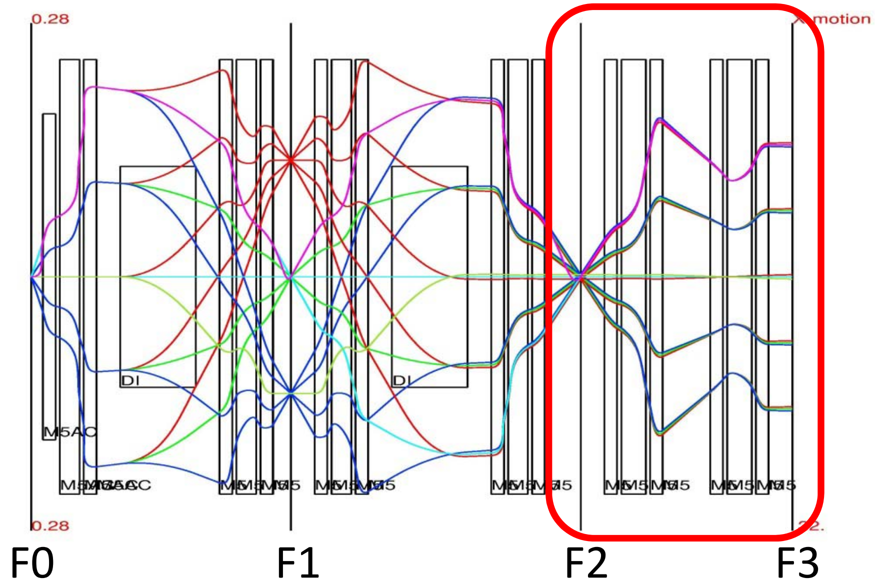
- For deducing the matrix elements of (x|x) and (a|x), F3 parallel mode was developed.

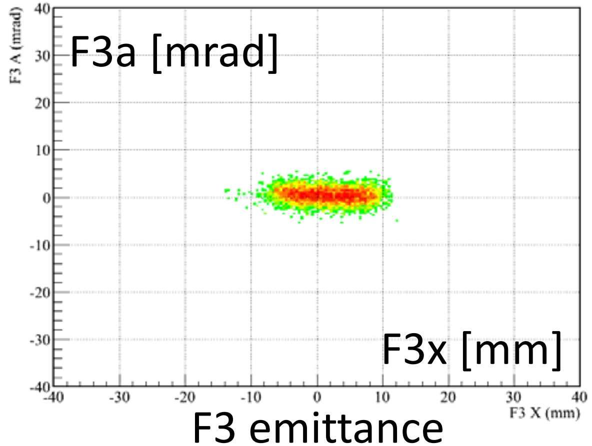
F3 focus mode (standard)





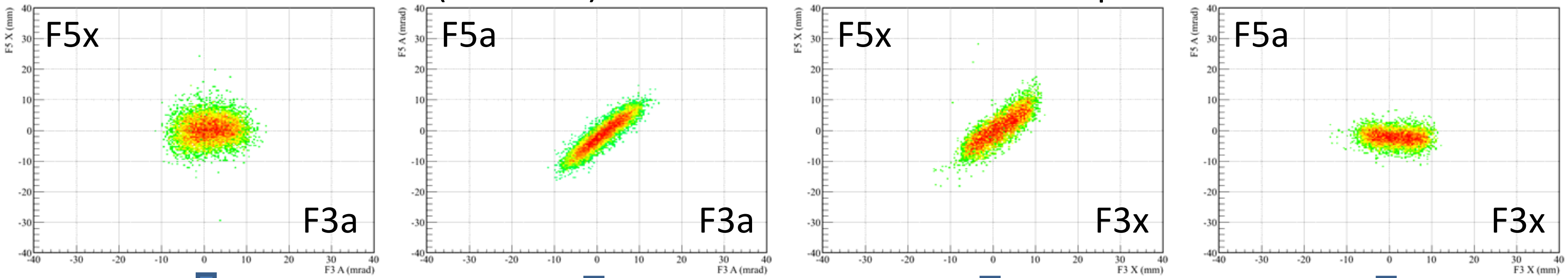
F3 parallel mode





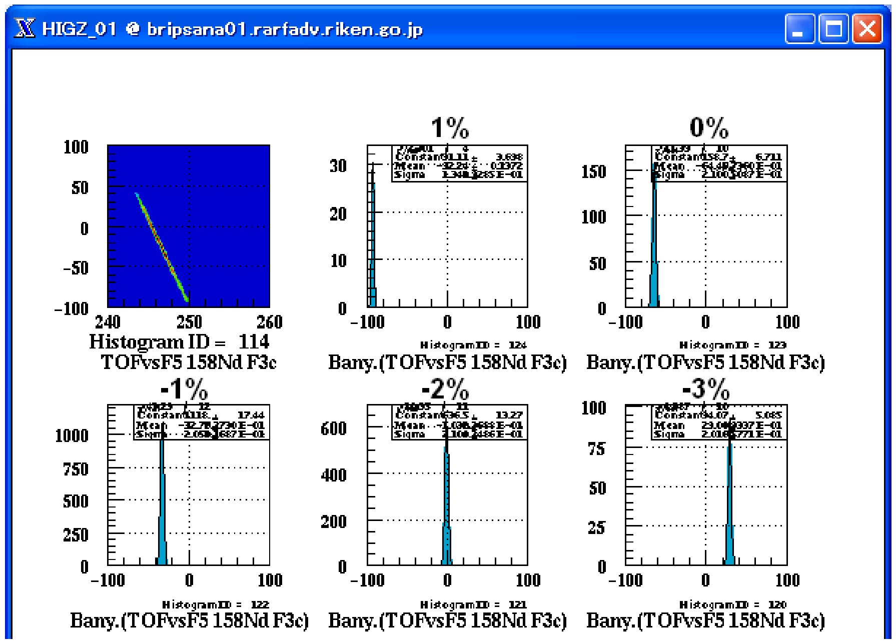
Derivation of Matrix Elements

F3 focus mode (standard) | F3 parallel mode



$(x|a)_{35}$ $(a|a)_{35}$ $(x|x)_{35}$ $(a|x)_{35}$

- For $(x|\delta)_{35}$ and $(a|\delta)_{35}$
  - Choose the events at the center at F3 and F7.
  - From the relation between F5x and TOF_{37}, $(x|\delta)$ is deduced.
  - TOF is calculated from δ.
  - Here, we assume that the $(l|\delta)$ term is 0.



New Optics for BigRIPS
(D double mode)

High Resolution D-double Mode

- Purpose: to double the *A/Q* resolution in the 2nd stage (standard mode: ~3300).

  → Make the D/M value double.

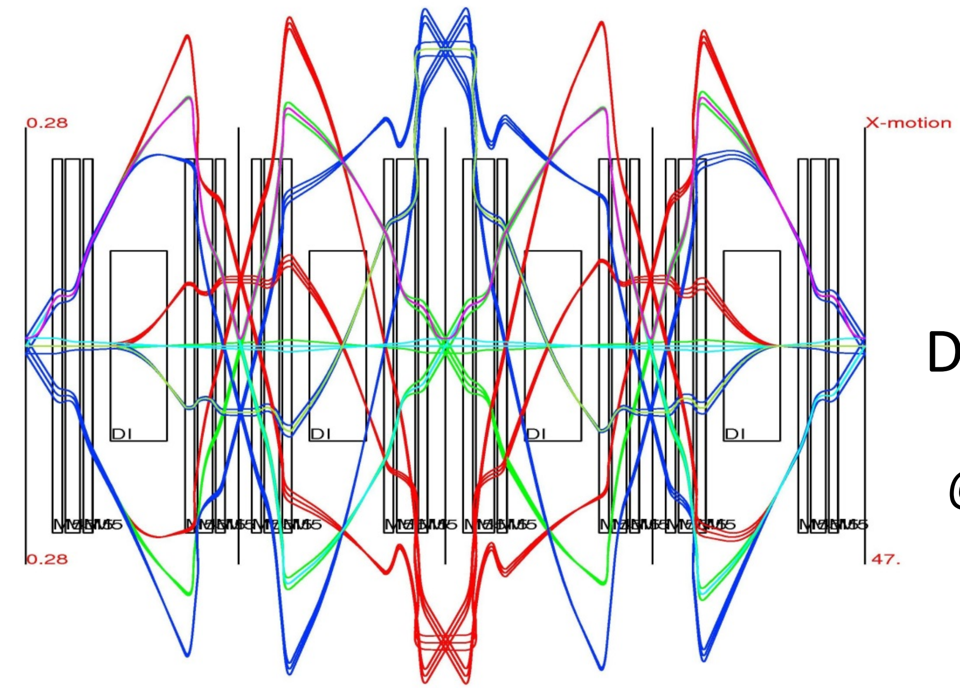
  (D: Dispersion)

  (M: Magnification)

- So, we developed “D-double” mode.
  - The Dispersion is doubled, while the Magnification is not changed.

- Matrix elements @ F3-F5 (@ F7-F5: mirror symmetry)
  - $(x|a) = (y|b) = 0$ (focusing terms).
  - $(a|\delta) = 0$ (angular dispersion).
  - $(x|x)$ term (M) keeps the original value (0.92).
  - $(x|\delta)$ term (D) is set to be doubled (31.7 → 63.4 mm/%).
  - $(a|x)$, $(b|y)$ are less than 0.1 (In the standard mode, these values are around 0.1 or more.)

Envelopes



D double mode

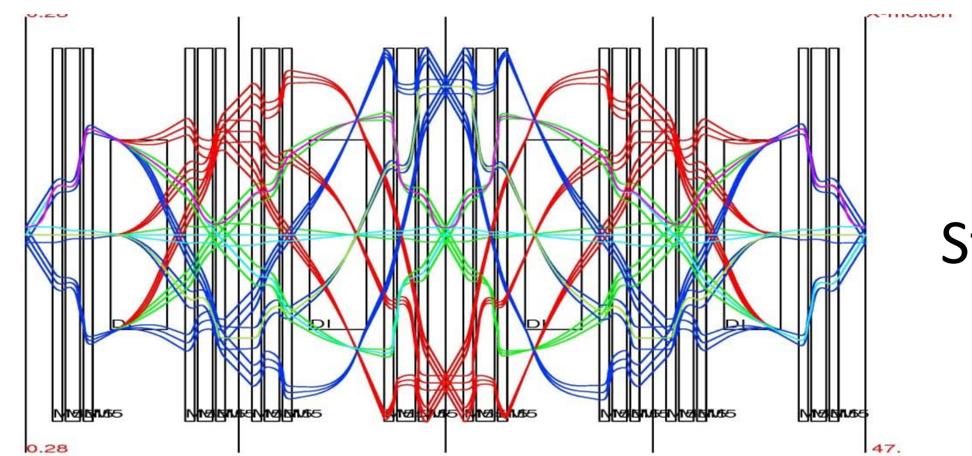
@F3

x: +/-5 mm

a: +/-18.4 mrad (+/-40 mrad @ F0)

δ: +/-3% (+3%, 0%, -3%)

F3 F4 F5 F6 F7



Standard mode

$Matrix_{35}$ of D-double Mode

D-double mode

- Design
- Experiment

Design	Experiment	
(x|x) = 0.9206	1.14 +/- 0.04	
(a|a) = 1.0863	1.10 +/- 0.01	
(x|d) = 63.374	60.2 +/- 0.1	D/M = 52.8

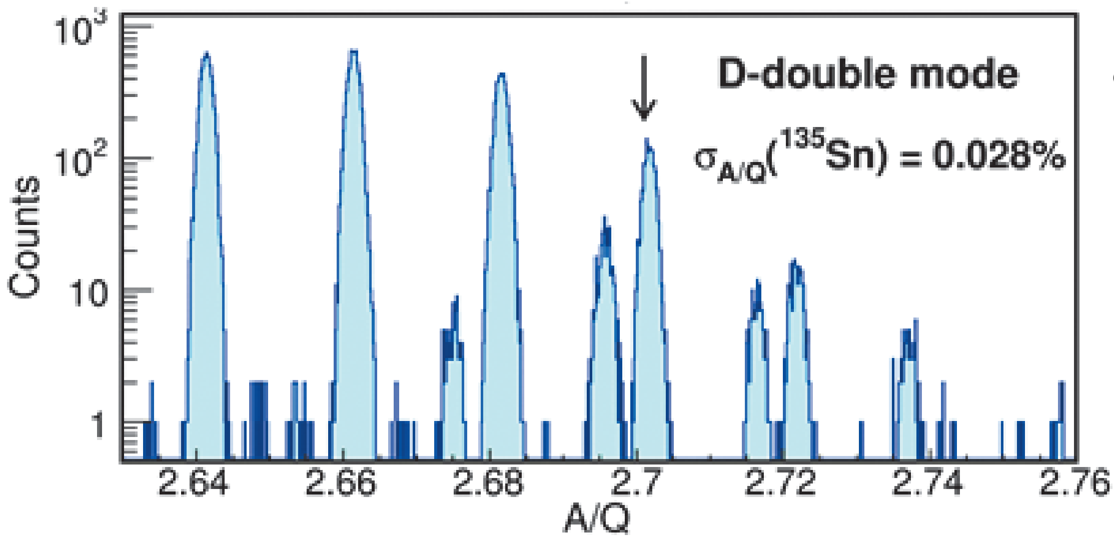
x ~1.5

Standard mode

- Design
- Experiment

Design	Experiment	
(x|x) = 0.9206	0.886 +/- 0.0115	
(a|a) = 1.0863	1.13 +/- 0.01	
(x|d) = 31.687	30.8 +/- 0.1	D/M = 34.8

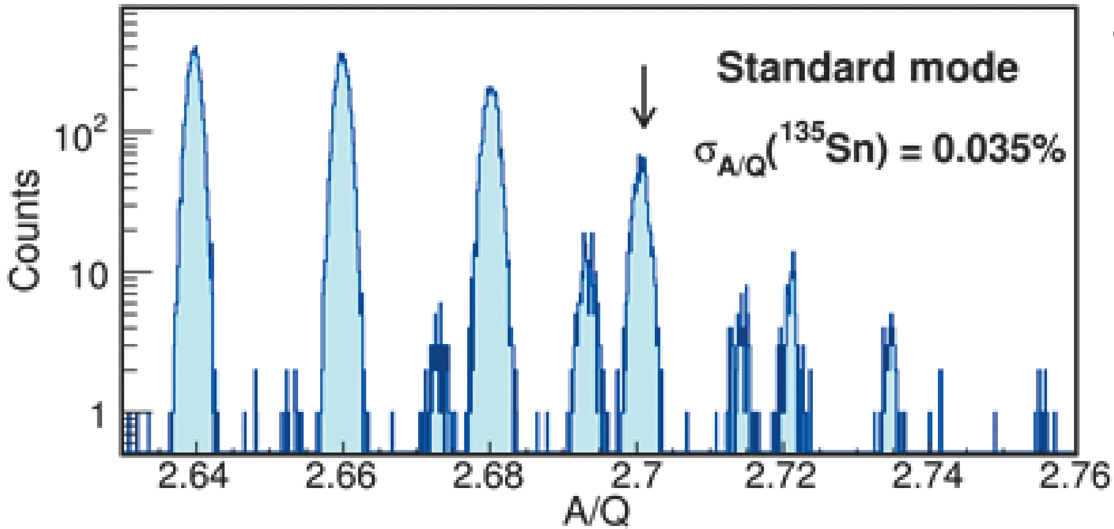
A/Q Separation (Sn Isotopes)



- D double mode

  $\sigma_{A/Q}(^{135}Sn)$

  $= 0.028\ \%$

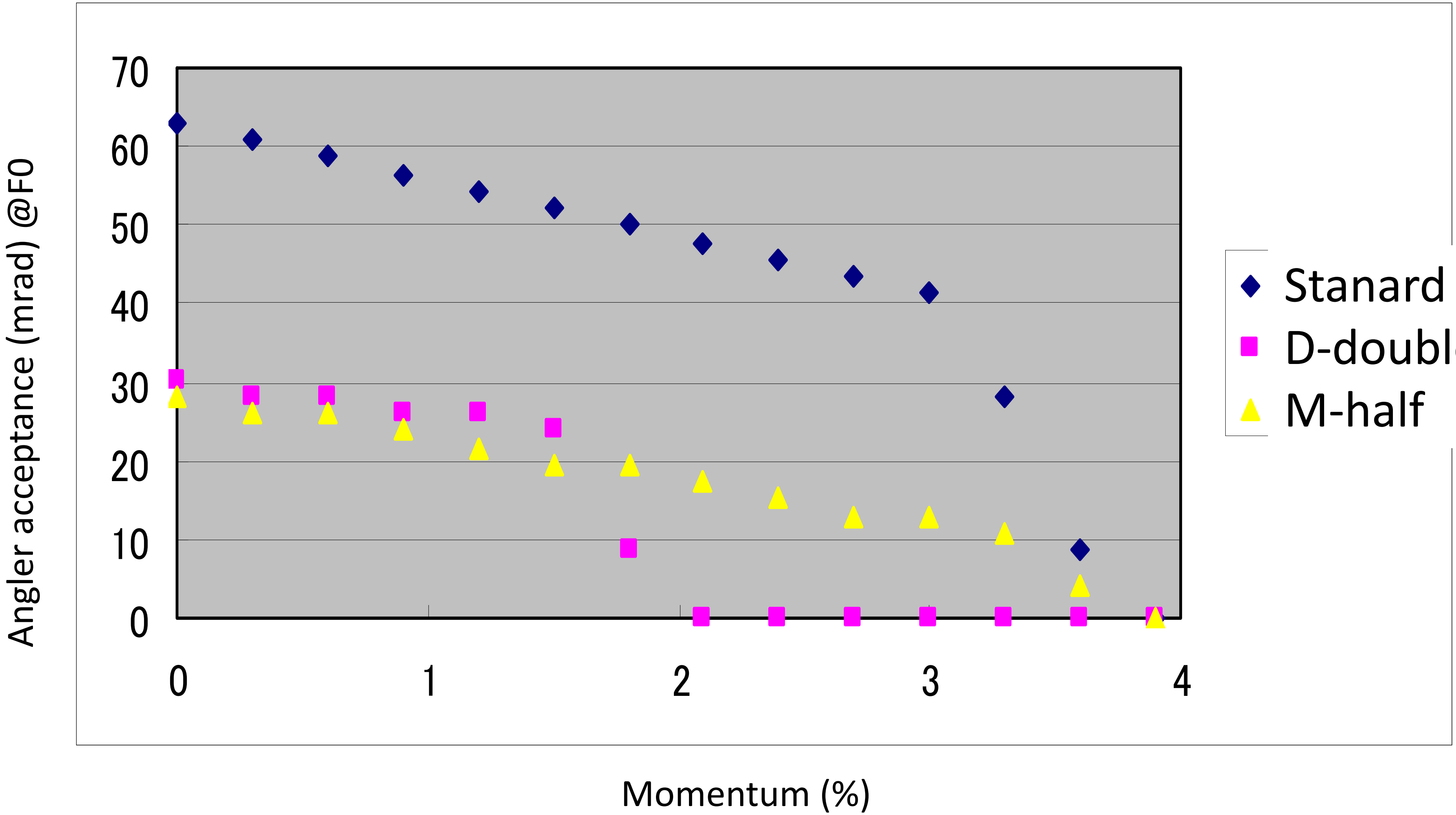


- Standard mode

  $\sigma_{A/Q}(^{135}Sn)$

  $= 0.035\ \%$

Angular Acceptance vs Momentum (Simulation)



SAMURAI Beam Line Optics

SAMURAI Beam Line

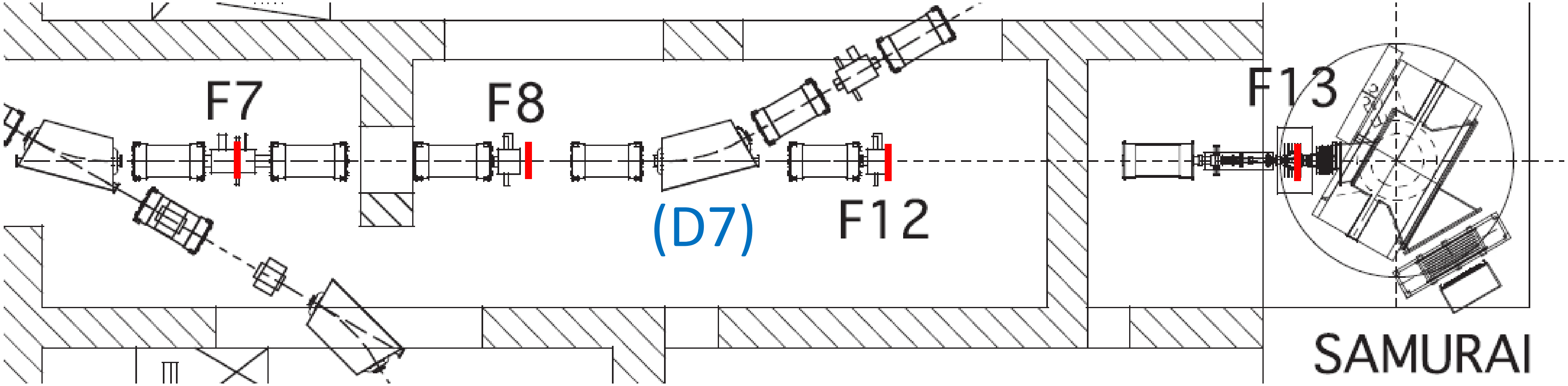


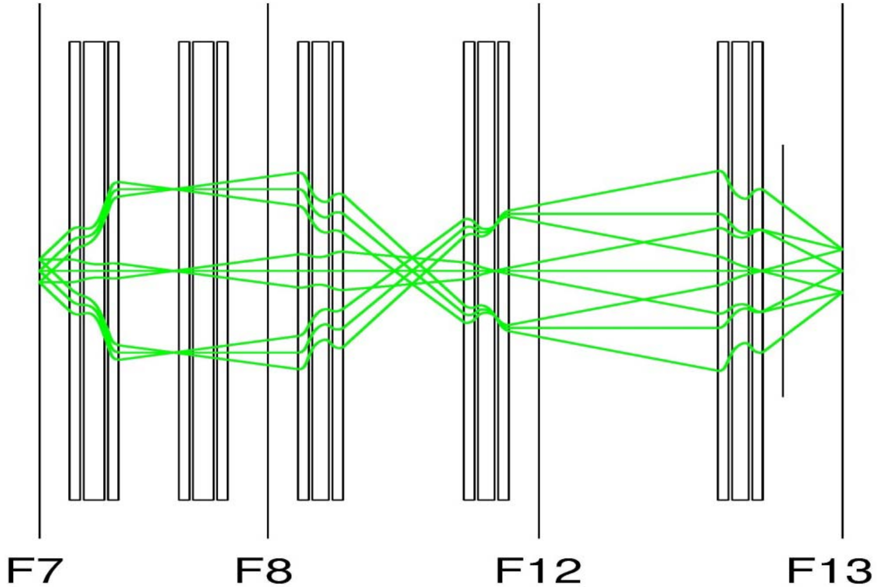
Figure: T. Kobayashi et al.: NIMB 317, 294 (2013)

- Size of the duct
  - Beam duct : ϕ240 mm
  - Beam blocker between F7 and F8 : +/-78 mm (y)
  - Gap of D7 dipole : +/-61 mm (y)
  - F13 duct : ϕ132 mm

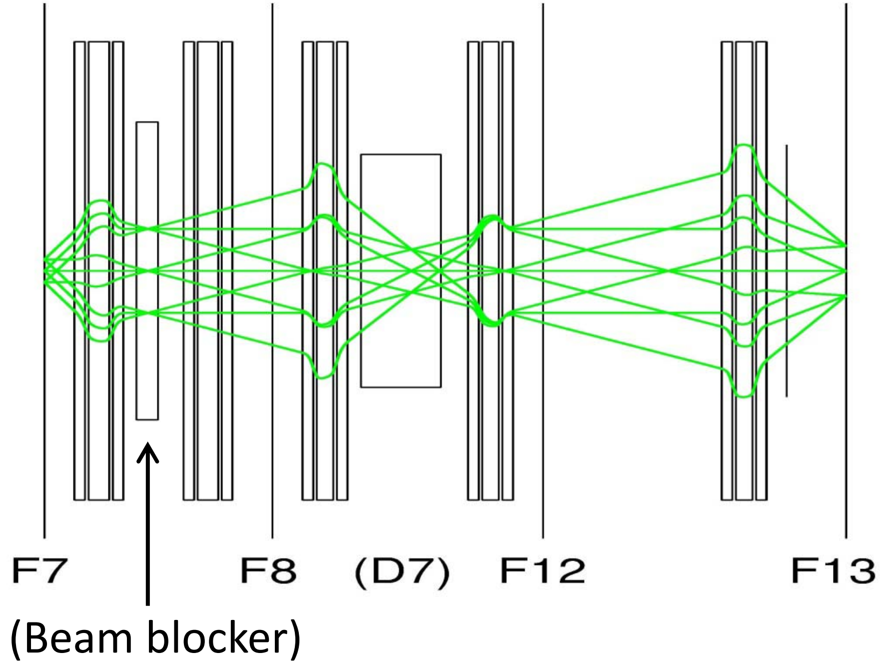
- Problems
  - Only one STQ between F12 and F13.
  - The gap of the D7 dipole is +/-61 mm.

Ion Optics in SAMURAI Beam Line

x direction



y direction



x,y: +/-6 mm @F7
a,b: +/-10 mrad @F7
(~1/2 of the BigRIPS acceptance)

$M_{7\rightarrow13}$: ~2

- Focus the beam inside D7 dipole magnet instead of F8 or F12.
- At F8 and F12, the beam is set to parallel.
  → This makes it easier to diagnose the beam optics using the PPAC detectors.

Summary

- Procedure of focus tune
  - Set the Bρ value of each section.
  - Focus tune with quadrupoles.
  - Focus tune with sextupoles.
  - F3 parallel mode (for deducing the matrix elements)
- D double mode (BigRIPS)
  - To obtain the better *A*/*Q* resolution, D double mode was developed.
  - The Dispersion is doubled, while the Magnification is not changed.
  - *A*/*Q* resolution: 0.035% → 0.028%.
- SAMURAI beam line optics
  - The beam is focused in D7 dipole magnet.
  - The beam is parallel at F8 and F12 to diagnose the beam optics