



# **Ion optical developments at BigRIPS**

## **- Additive and Subtractive Modes -**

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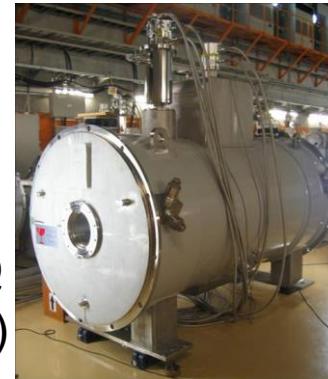
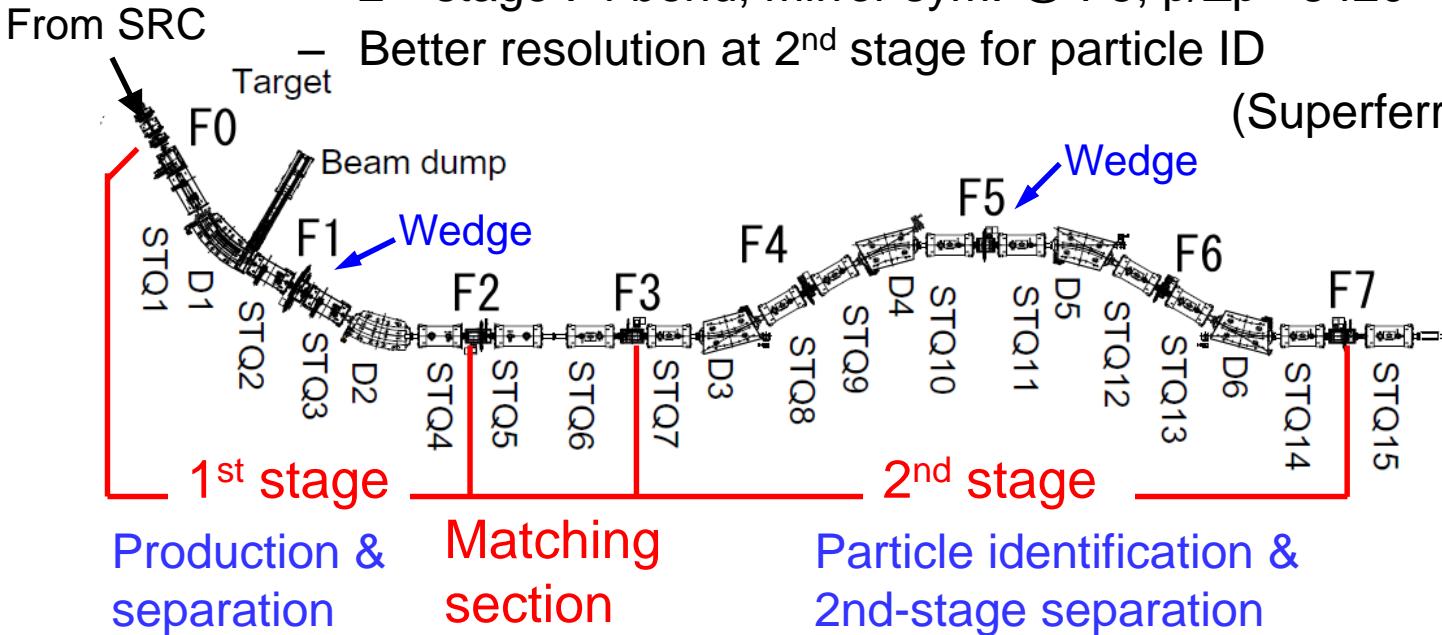


# Features of BigRIPS separator

- 1) Large acceptances
  - Comparable with angular / momentum spreads of **in-flight fission** at RIBF energy (+/-50 mrad, +/-5%)
- 2) Superconducting quads with a **large aperture**, and **strong field** → high magnetic rigidity
  - Pole tip radius: 170 mm
  - Max. pole tip field: 2.4 T
- 3) **Two-stage** separator scheme
  - 1<sup>st</sup> stage : 2 bend,  $p/\Delta p=1260$
  - 2<sup>nd</sup> stage : 4 bend, mirror sym. @ F5,  $p/\Delta p= 3420$
  - Better resolution at 2<sup>nd</sup> stage for particle ID

Parameters:

$\Delta a = +/-40$  mrad  
 $\Delta b = +/-50$  mrad  
 $\Delta p/p = +/-3$  %  
 $B_p = 9$  Tm  
 $L \sim 78$  m



**STQ1-14:**  
 Superconducting quad. triplets

**D1-6:** Room temp. dipoles (30 deg)

**F1-F7:** focuses

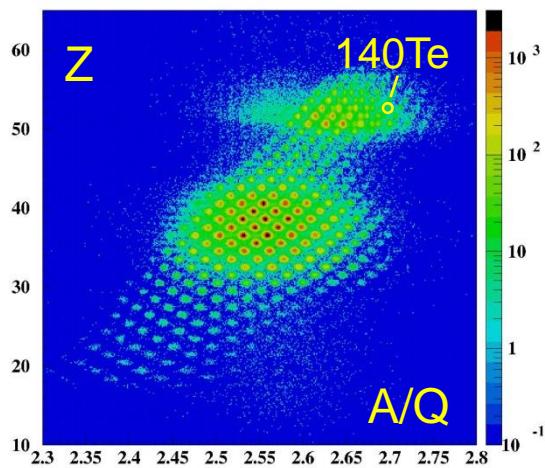


# Example of two-stage separation

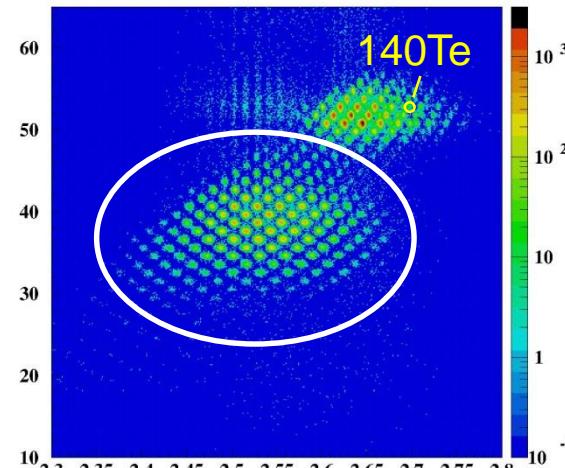
$^{238}\text{U}^{86+} + \text{Pb}(1.5\text{mm}), 345 \text{ MeV/u}$   $B_P = 7.394 \text{ Tm}$

F1 slit:  $\pm 63\text{mm}$ , F2 slit  $= \pm 15\text{mm}$ ,  
F7 gate  $= \pm 15\text{mm}$

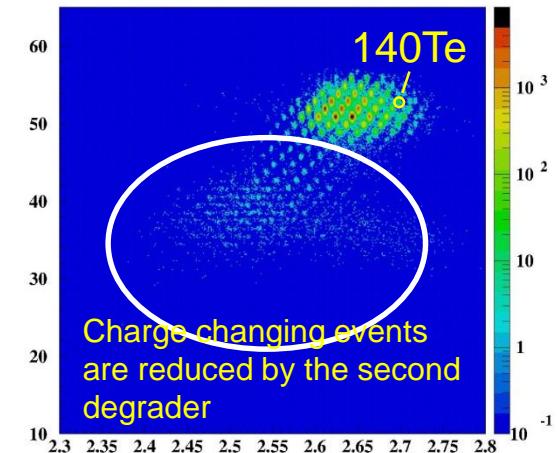
Tuned for  $^{140}\text{Te}$



No degraders



With F1 deg. (Al 3mm)



With F1 deg. (Al 3mm)  
and F5 (Al 1.8mm)



# 1st stage separation

F0F2 is an achromatic spectrometer with an intermediate dispersive focus F1.  
1st order transfer matrices are:

First half (F0F1)

$$R_{01} = \begin{pmatrix} (x|x)_{01} & 0 & (x|\delta)_{01} & 0 & 0 \\ 0 & 1/(x|x)_{01} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Second half (F1F2)

$$R_{12} = \begin{pmatrix} (x|x)_{12} & 0 & (x|\delta)_{12} & 0 & 0 \\ 0 & 1/(x|x)_{12} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Total matrix (without degrader)

$$R_{12}R_{01} = \begin{pmatrix} (x|x)_{01}(x|x)_{12} & 0 & \underline{(x|x)_{12}(x|\delta)_{01} + (x|\delta)_{12}} & 0 & 0 \\ 0 & 1/(x|x)_{01}(x|x)_{12} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Achromatic condition:

$$(x|x)_{12}(x|\delta)_{01} + (x|\delta)_{12} = 0$$



# Wedge-shaped degrader at intermediate dispersive focus

Degrader matrix can be expressed as

$$\text{Deg}_1 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ (\delta|x)_1 & (\delta|a)_1 & (\delta|\delta)_1 & (\delta|m)_1 & (\delta|z)_1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

where

$$(\delta|x) = -\frac{K}{\gamma} \frac{d_0/R_0}{1-d_0/R_0}$$

$$(\delta|a) = -\frac{K}{\gamma} d_0 \frac{d_0/R_0}{1-d_0/R_0}$$

$$(\delta|\delta) = \frac{1}{1-d_0/R_0}$$

$$(\delta|m) = \frac{1-\gamma}{\gamma} \frac{d_0/R_0}{1-d_0/R_0}$$

$$(\delta|z) = -\frac{2}{\gamma} \frac{d_0/R_0}{1-d_0/R_0}$$

$$d(x) = d_0(1 + Kx) \quad \text{Wedge shape}$$

$$R_0 = k \frac{A^{1-\gamma}}{Z^2} E^\gamma \quad \text{Range}$$

$$\gamma=1.75 \text{ (AI)}$$

(from Kubo-memo.)



# Total matrix with degrader

$$R_{12}\text{Deg}_1 R_{01} = \begin{pmatrix} (x|x)_{01}(x|x)_{12} + (\delta|x)_1(x|\delta)_{12}(x|x)_{01} & (\delta|a)_1(x|\delta)_{12}/(x|x)_{01} & ((\delta|x)_1(x|\delta)_{01} + (\delta|\delta)_1 - 1)(x|\delta)_{12} & (\delta|m)_1(x|\delta)_{12} & (\delta|z)_1(x|\delta)_{12} \\ 0 & 1/(x|x)_{01}(x|x)_{12} & 0 & 0 & 0 \\ (\delta|x)_1(x|x)_{01} & (\delta|a)_1/(x|x)_{01} & (\delta|x)_1(x|\delta)_{01} + (\delta|\delta)_1 & (\delta|m)_1 & (\delta|z)_1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Achromatic degrader condition:

$$(\delta|x)_1(x|\delta)_{01} + (\delta|\delta)_1 - 1 = 0 \quad \rightarrow \text{slope of wedge } K = \frac{\gamma}{(x|\delta)_{01}}$$

Rewrite the FOF2 total matrix with degrader as follows for simplicity

$$R_{02} = \begin{pmatrix} (x|x)_{02} & (x|a)_{02} & 0 & (x|m)_{02} & (x|z)_{02} \\ 0 & 1/(x|x)_{02} & 0 & 0 & 0 \\ (\delta|x)_{02} & (\delta|a)_{02} & (\delta|\delta)_{02} & (\delta|m)_{02} & (\delta|z)_{02} \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \cdot \frac{1-\gamma}{\gamma} \cdot \frac{d_1/R_1}{1-d_1/R_1}$$

where

mass dispersion:  $(x|m)_{02} = (\delta|m)_1(x|\delta)_{12} = -\frac{1}{1-d_1/R_1} (x|x)_{12}(x|\delta)_{01} (\delta|m)_1$

magnification:  $(x|x)_{02} = (x|x)_{01}(x|x)_{12} + (\delta|x)_1(x|\delta)_{12}(x|x)_{01} = (x|x)_{01}(x|x)_{12} (\delta|\delta)_1$

mass resolving power  $\sim \frac{(x|m)_{02}}{(x|x)_{02}\Delta x_0} = -\frac{(x|\delta)_{01}}{(x|x)_{01}\Delta x_0} \cdot \frac{(\delta|m)_1}{(\delta|\delta)_1} = \frac{1-\gamma}{\gamma} \cdot \frac{d_1}{R_1}$



# Two-stage separation

Similar expression can be applied to the second stage (F3-F5-F7)

$$R_{37} = \begin{pmatrix} (x|x)_{37} & (x|a)_{37} & 0 & (x|m)_{37} & (x|z)_{37} \\ 0 & 1/(x|x)_{37} & 0 & 0 & 0 \\ (\delta|x)_{37} & (\delta|a)_{37} & (\delta|\delta)_{37} & (\delta|m)_{37} & (\delta|z)_{37} \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad \begin{aligned} (x|m)_{37} &= -(x|x)_{57}(x|\delta)_{35}(\delta|m)_5 \\ (x|x)_{37} &= (x|x)_{35}(x|x)_{57}(\delta|\delta)_5 \end{aligned}$$

We have a matching section F2F3 between two stages.

$$R_{23} = \begin{pmatrix} (x|x)_{23} & 0 & 0 & 0 & 0 \\ 0 & 1/(x|x)_{23} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Total mass dispersion and magnification at F7 can be obtained from  $R_{37}R_{23}R_{02}$ .

$$(x|x)_{07} = (x|x)_{02}(x|x)_{23}(x|x)_{37}$$

$$(x|m)_{07} = \underline{(x|x)_{23}(x|x)_{37}}(x|m)_{02} + (x|m)_{37}$$

Mass dispersions of the two stages  $(x|m)_{02}$  and  $(x|m)_{37}$  are added or subtracted according to the sign of  $(x|x)_{23}(x|x)_{37}$

BigRIPS standard mode:  $(x|x)_{23} = -1.1$ ,  $(x|x)_{37} = +1.0 \rightarrow$  subtracted mode



# Resolving power of two-stage separation

F0F7 mass dispersion and magnification can also be expressed explicitly with degrader matrix elements...

$$\begin{aligned}(x|m)_{07} &= (x|x)_{23}(x|x)_{37}(x|m)_{02} + (x|m)_{37} \\ &= -(x|x)_{12}(x|x)_{23}(x|x)_{35}(x|x)_{57}(x|\delta)_{01}(\delta|m)_1(\delta|\delta)_5 - (x|x)_{57}(x|\delta)_{35}(\delta|m)_5\end{aligned}$$

$$\begin{aligned}(x|x)_{07} &= (x|x)_{02}(x|x)_{23}(x|x)_{37} \\ &= (x|x)_{01}(x|x)_{12}(x|x)_{23}(x|x)_{35}(x|x)_{57}(\delta|\delta)_1(\delta|\delta)_5\end{aligned}$$

mass resolving power at F7

$$\sim \frac{(x|m)_{07}}{(x|x)_{07}\Delta x_0} = -\frac{(x|\delta)_{01}}{(x|x)_{01}\Delta x_0} \cdot \frac{(\delta|m)_1}{(\delta|\delta)_1} - \frac{(x|\delta)_{35}}{(x|x)_{01}(x|x)_{12}(x|x)_{23}(x|x)_{35}\Delta x_0} \cdot \frac{(\delta|m)_5}{(\delta|\delta)_1(\delta|\delta)_5}$$

$\frac{1-\gamma}{\gamma} \cdot \frac{d_1}{R_1}$        $\frac{1-\gamma}{\gamma} (1 - d_1/R_1) \cdot d_5/R_5$



# Possible merits of additive mode

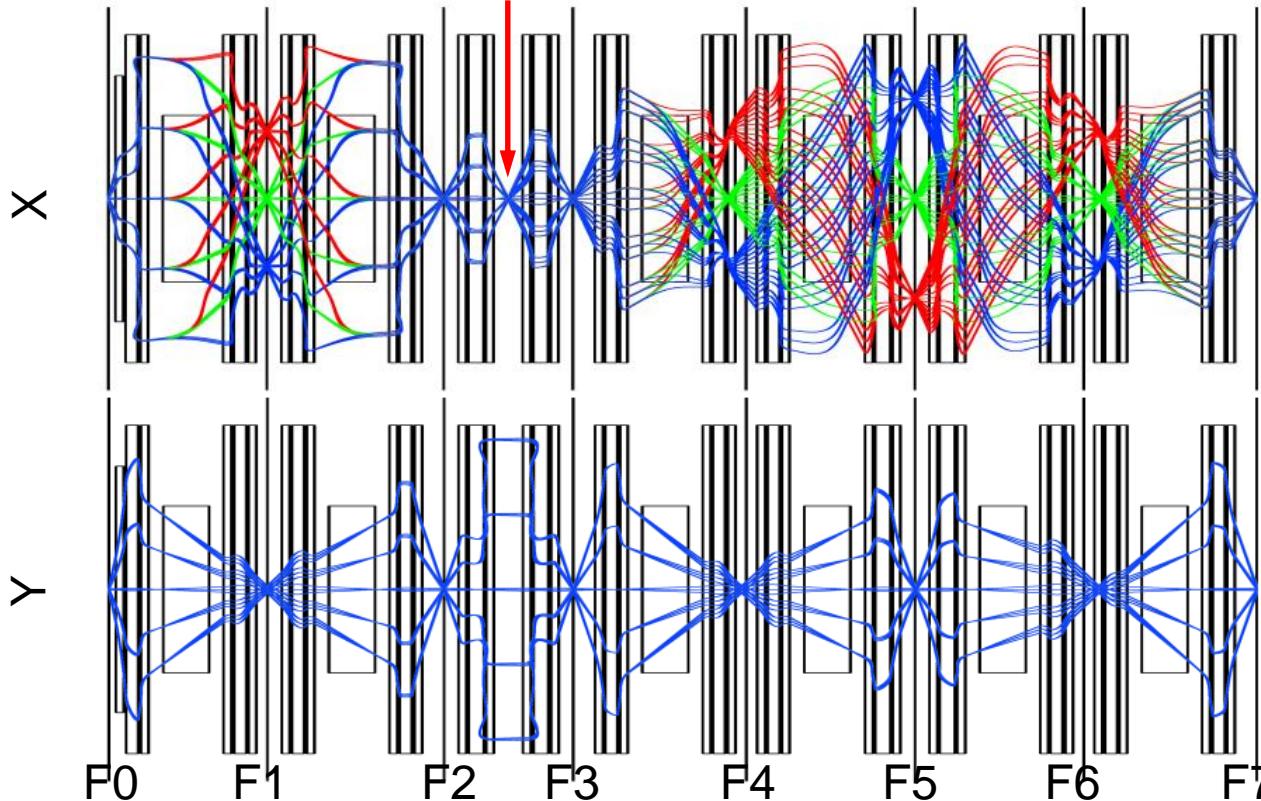
- Gain of mass dispersion
  - Purity of target isotope may be improved
  - Background reduction at F7, particular if F6 diagnostics and slits are implemented
  - ...



# Ion optical solution for additive mode

- Additive mode can be realized by changing sign of  $(x|x)_{23}$ 
  - For this purpose, we added one focus in X direction in between F2 and F3.
    - Optics of F0F2 and F3F7 are the same as the standard mode.
  - We needed to change polarities of STQs in F2F3 section to reduce excitation currents.

Additional focus at F2.5 (only in X direction)

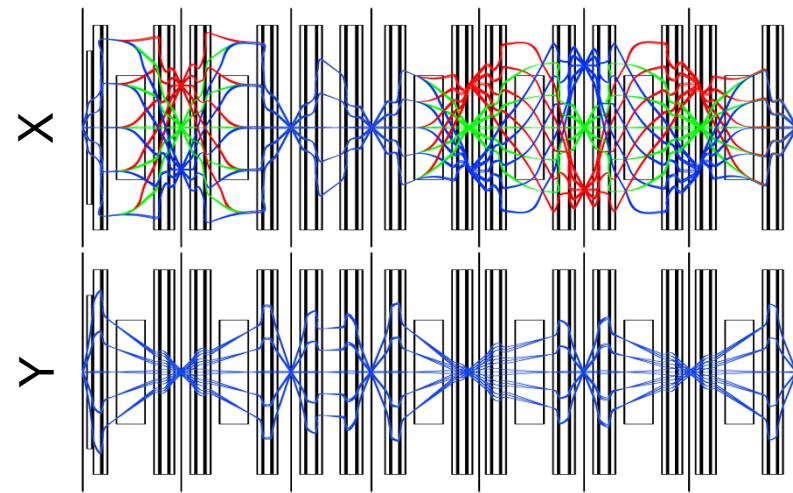


(H. Geissel,  
T. Kubo  
H. Takeda )

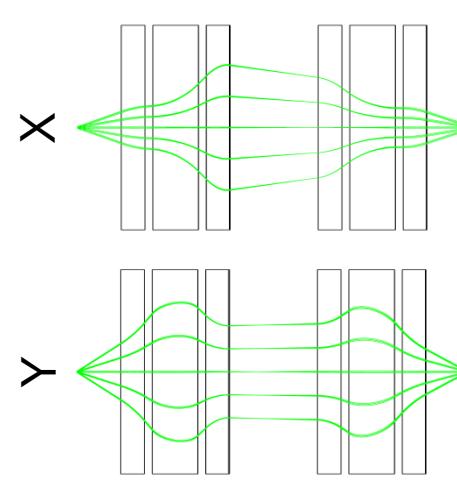
F2-F3 Max.B<sub>p</sub> ~ 8.7Tm  
(standard mode:  
9.25Tm For F2-F3,  
8.8Tm for F3-F7)

Subtractive mode  
(standard)

F0-F7

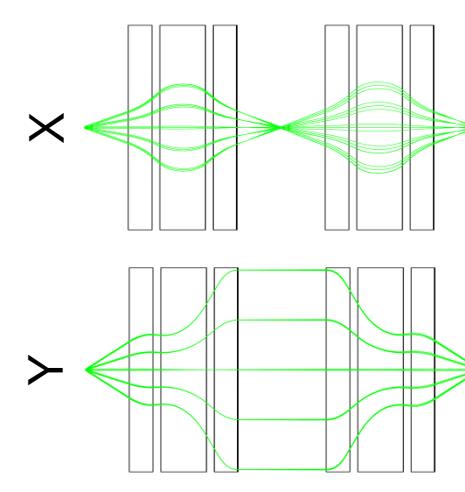
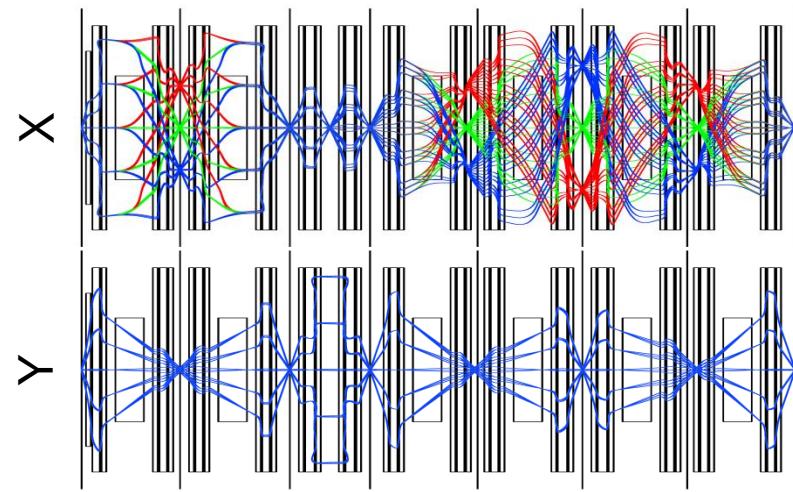


F2-F3



Additive mode

F0 F1 F2 F3 F4 F5 F6 F7



# • LISE++ simulation

$^{238}\text{U}$  345MeV/u + Be 5 mm

D1 7.100 Tm, D2 5.9924 Tm, D3D4 5.8830 Tm, D5D6 4.6288 Tm

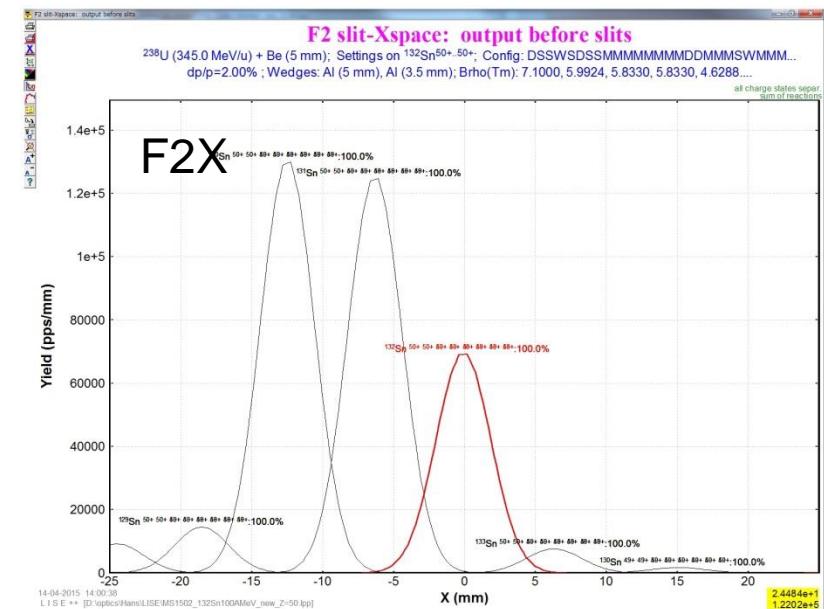
F1 deg. Al 5 mm ( $d/R=0.377$ ) / F5 deg. Al 3.5 mm ( $d/R=0.463$ )

F1 slit  $\pm 21.4$  mm

F2 slit  $\pm 6$  mm

F7 slit  $\pm 15$ mm

## Distribution of Z=50 (Sn) isotopes





# Measurements

- April 2015 (MS-EXP15-03)
  - Comparison of additive and subtractive modes with the same conditions of F0F2 and F3F7
- November 2015 (MS-EXP15-08)
  - Systematic study of subtractive mode with changing F5 degrader thickness
  - F1 degrader thickness was the same as Apr.2015

# RI beam setting

Primary beam:  $^{238}\text{U}$  345MeV/u

$^{132}\text{Sn}$  center

F0 target: Be 5 mm

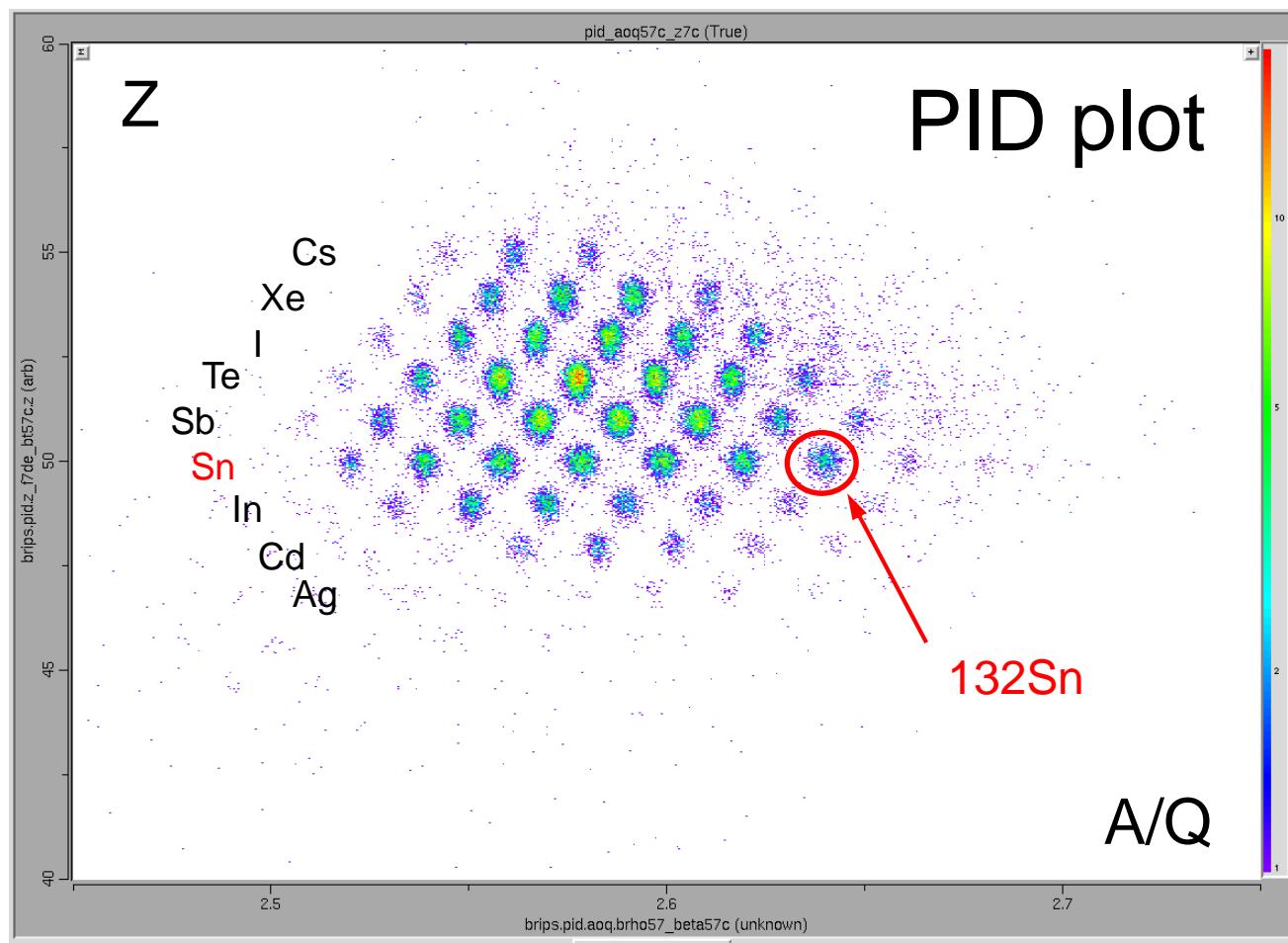
D1 7.100 Tm, D2 5.9924 Tm, D3D4 5.9535 Tm, D5D6 5.0525 Tm

F1 deg. Al 5 mm ( $d/R=0.377$ ) / F5 deg. Al 3 mm ( $d/R=0.372$ )

F1 slit  $\pm 2$ , 21.4, 64.2 mm

F2 slit  $\pm 120$  mm

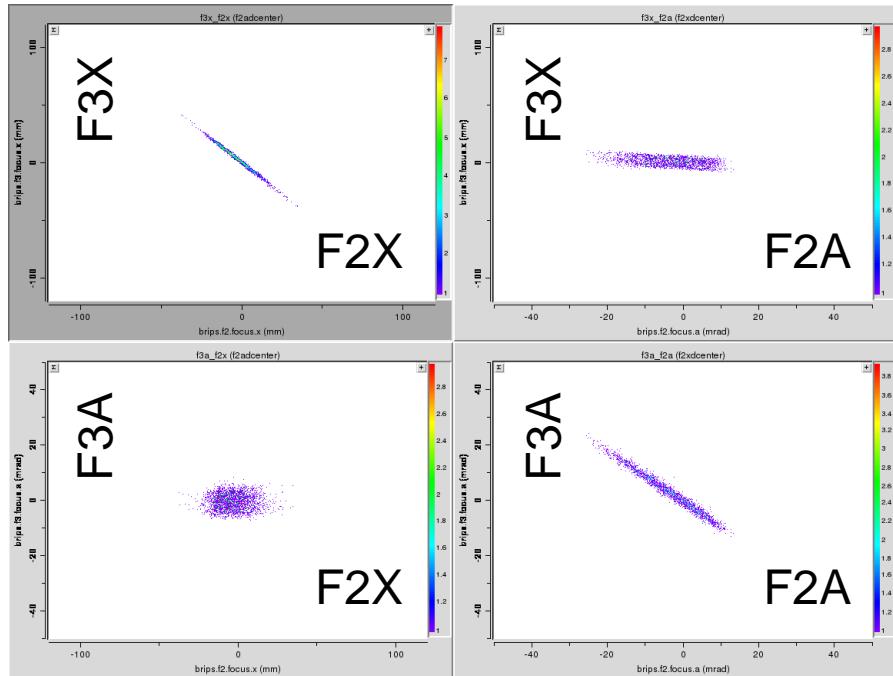
F7 slit  $\pm 120$  mm





# F2-F3 transfer matrix

Subtractive mode

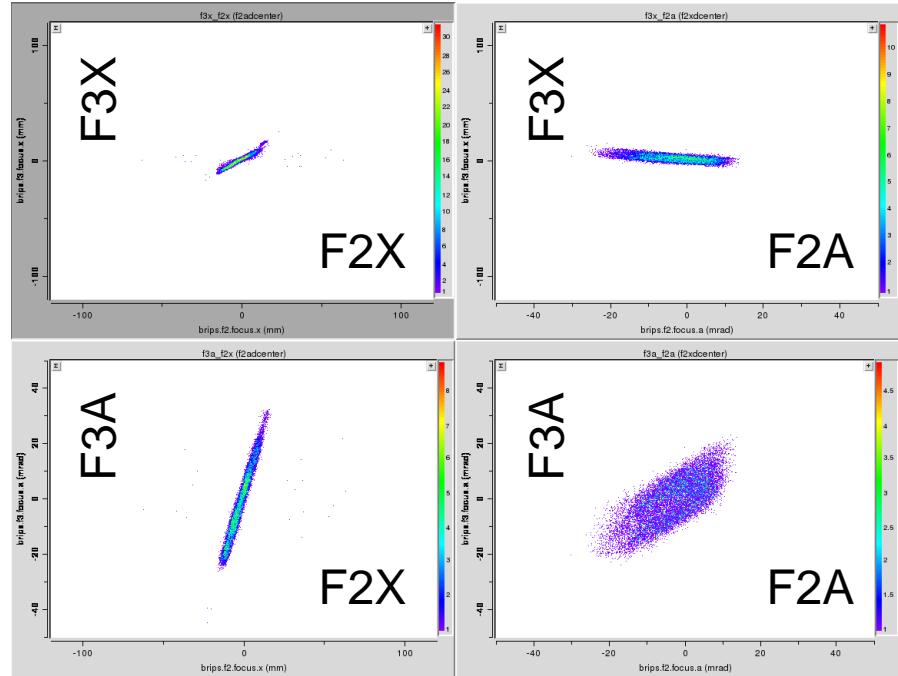


(unit: mm, mrad)

	$(x x)$	$(x a)$	$(a x)$	$(a a)$
Exp.	-1.10	-0.27	0.024	-0.94
COSY	-1.08	0.06	-0.004	-0.92

det.=1.04

Additive mode



(unit: mm, mrad)

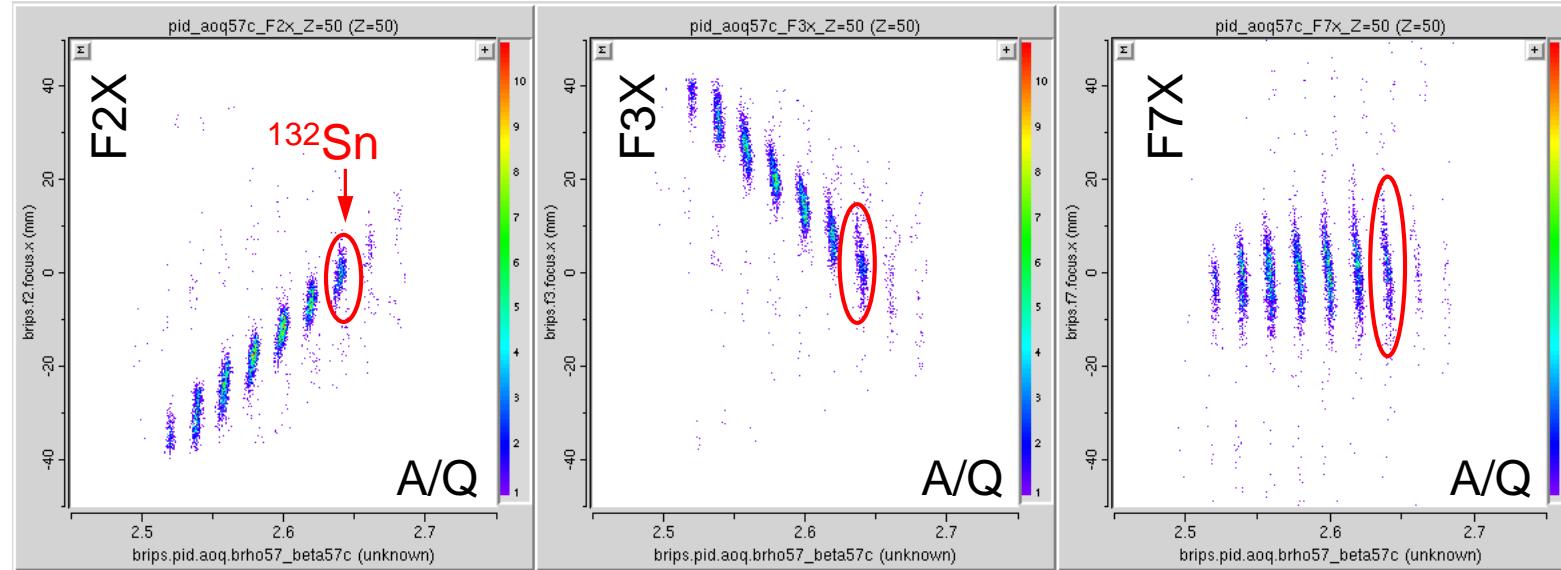
	$(x x)$	$(x a)$	$(a x)$	$(a a)$
Exp.	0.78	-0.28	1.89	0.92
COSY	1.01	0.002	2.14	1.00

det.=1.25

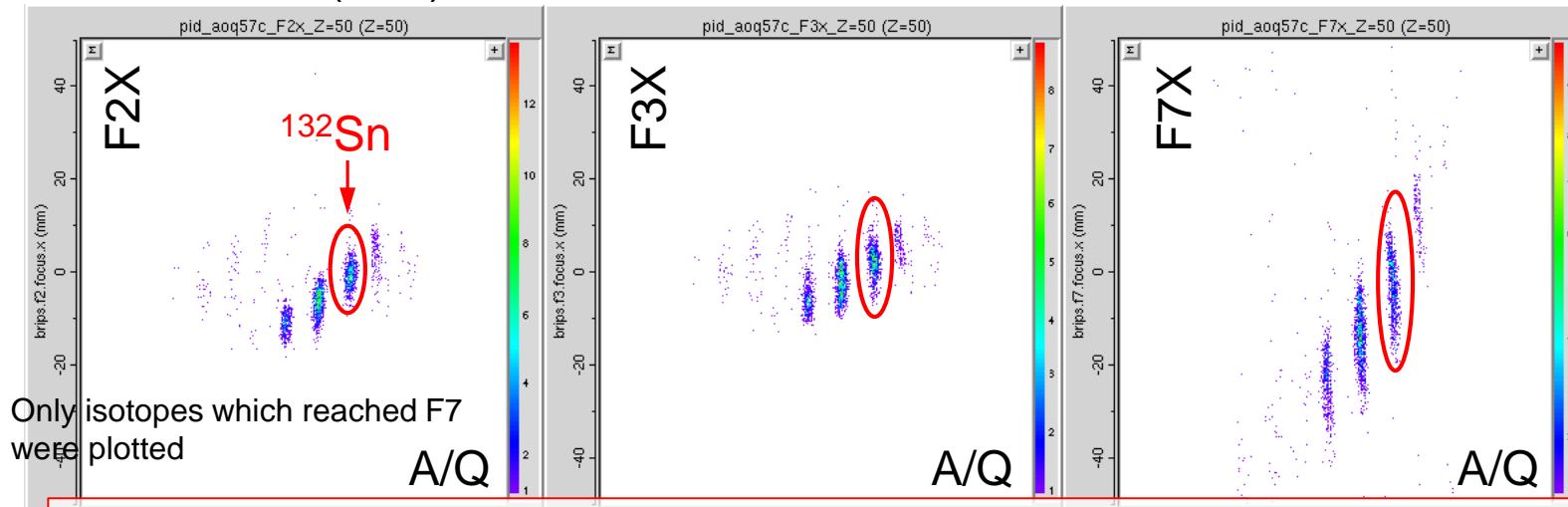
large  $(a|x)$  term adversely affects transmission, track reconstruction etc

# X distribution of Sn isotopes

Subtractive mode (standard)



Additive mode (new)

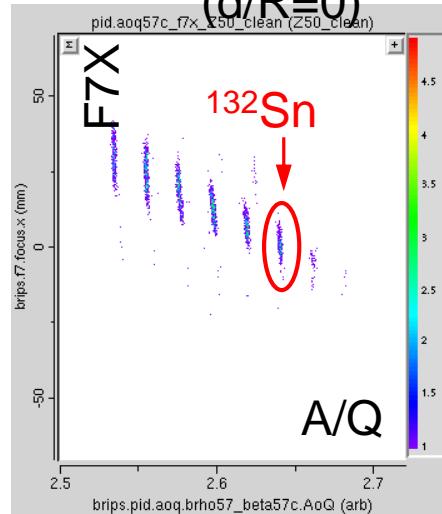


132Sn yield (normalized with beam intensity) in additive mode is about 70% of subtractive mode.  
(30% transmission loss even for the center particle?)

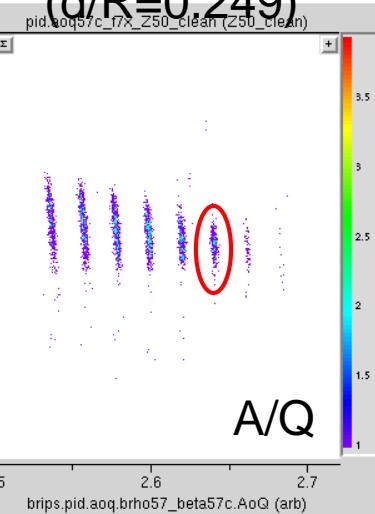
# Change of F7X positions of Z=50 isotopes and N=82 isotones due to the F5 degrader thickness

(subtractive mode only)

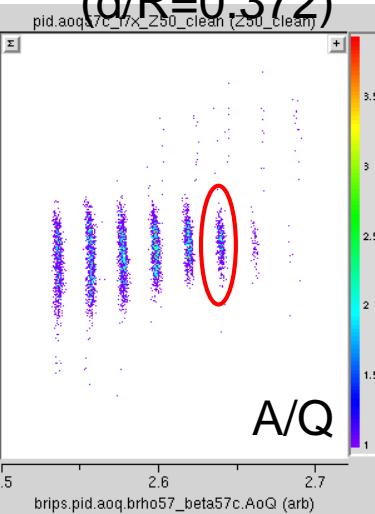
F5 deg. $\rightarrow$  Al 0 mm  
( $d/R=0$ )



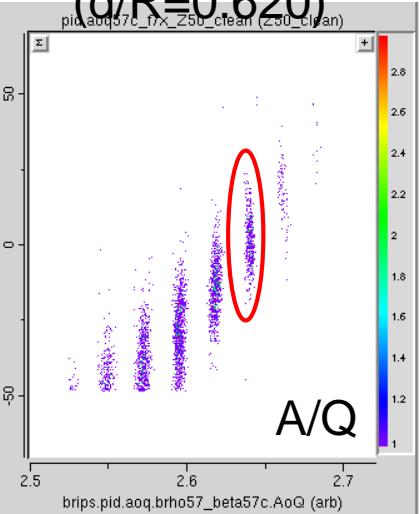
Al 2 mm  
( $d/R=0.249$ )



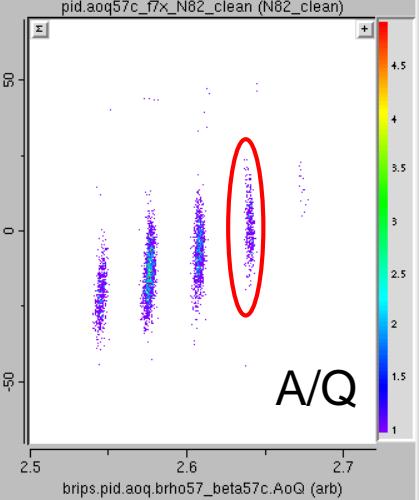
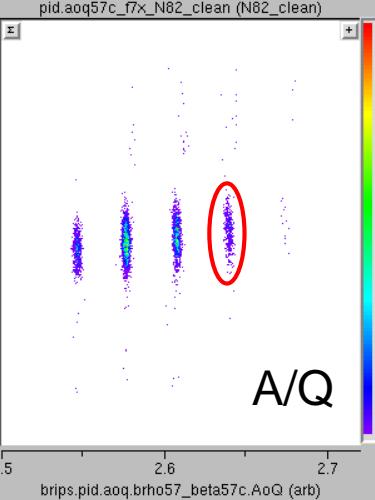
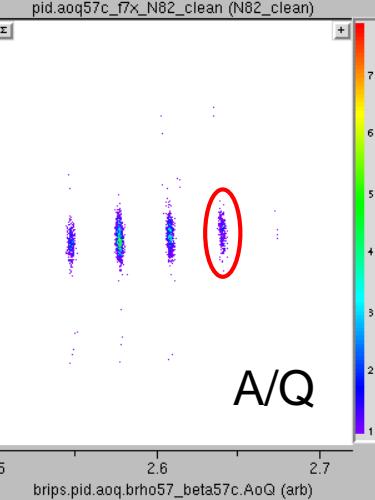
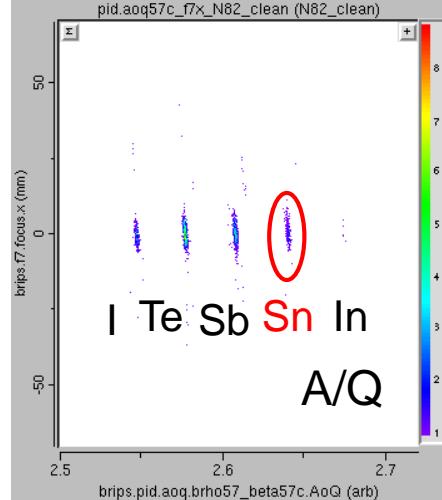
Al 3 mm  
( $d/R=0.372$ )



Al 5 mm  
( $d/R=0.620$ )

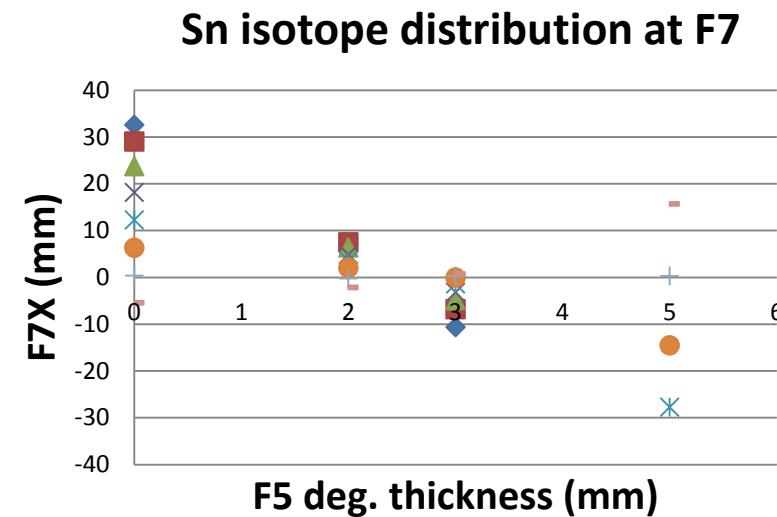


Z=50 isotope

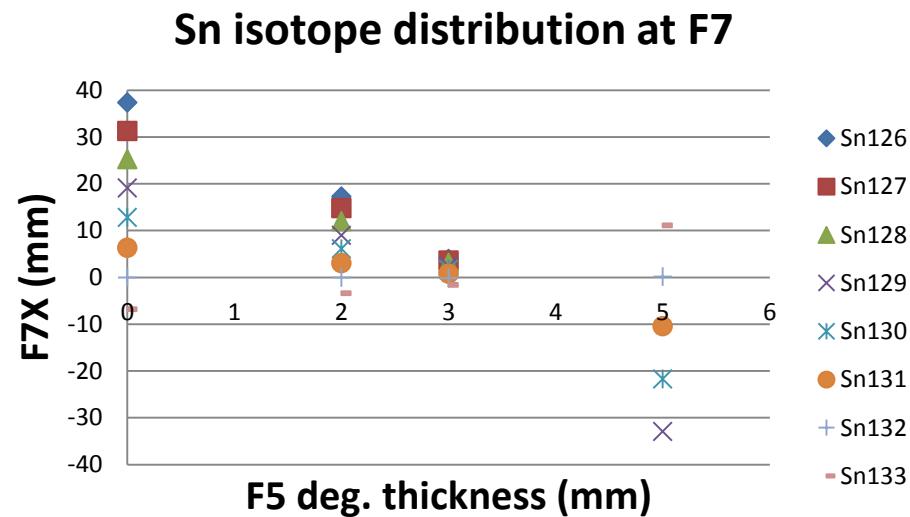


N=82 isotope

# Measured and LISE++ results of isotope separation at F7 (in subtractive mode)



measurement

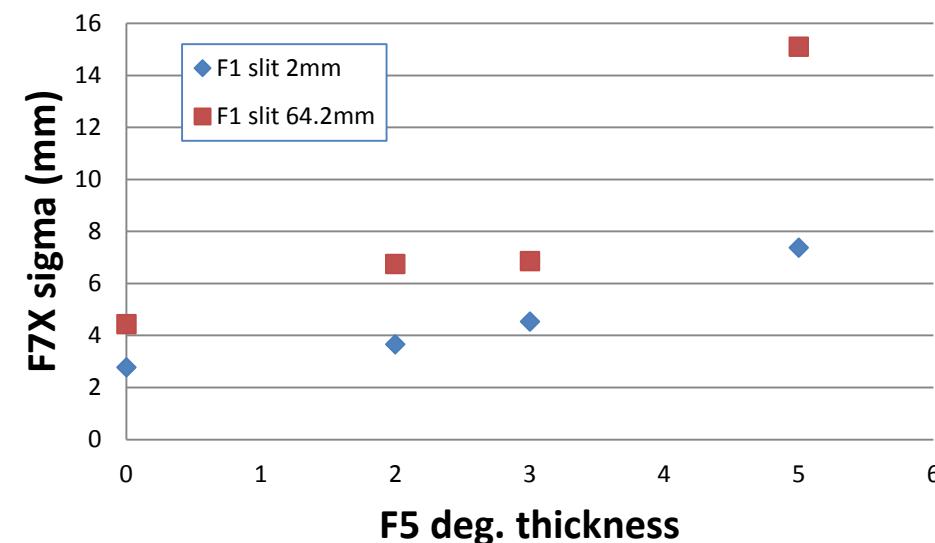


LISE ++

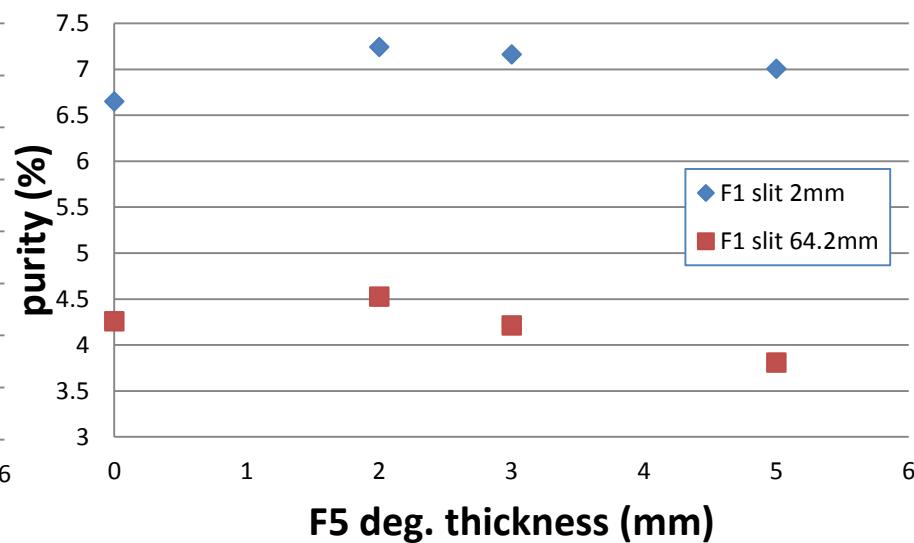
# Change of F7 positions image size and due to the F5 degrader thickness

(Subtractive mode only)

**132Sn image size @F7 ( $\sigma$ )**

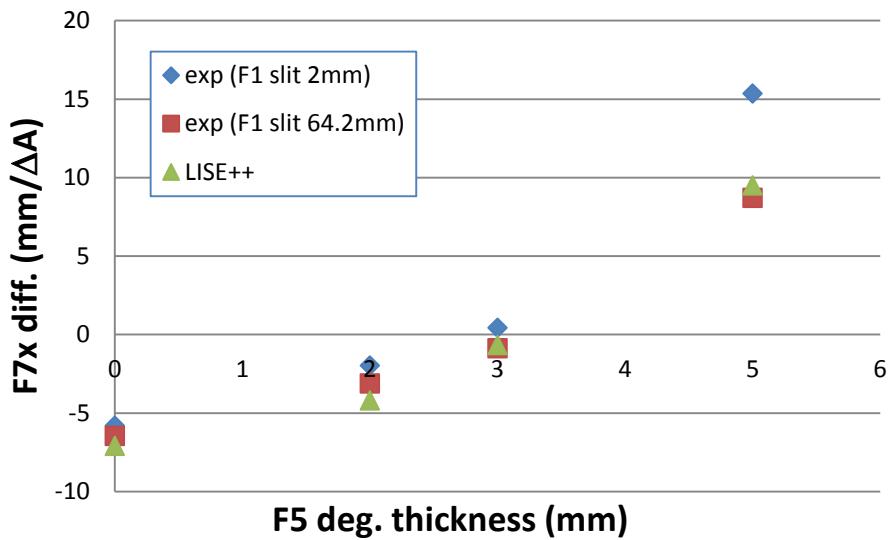


**132Sn purity**

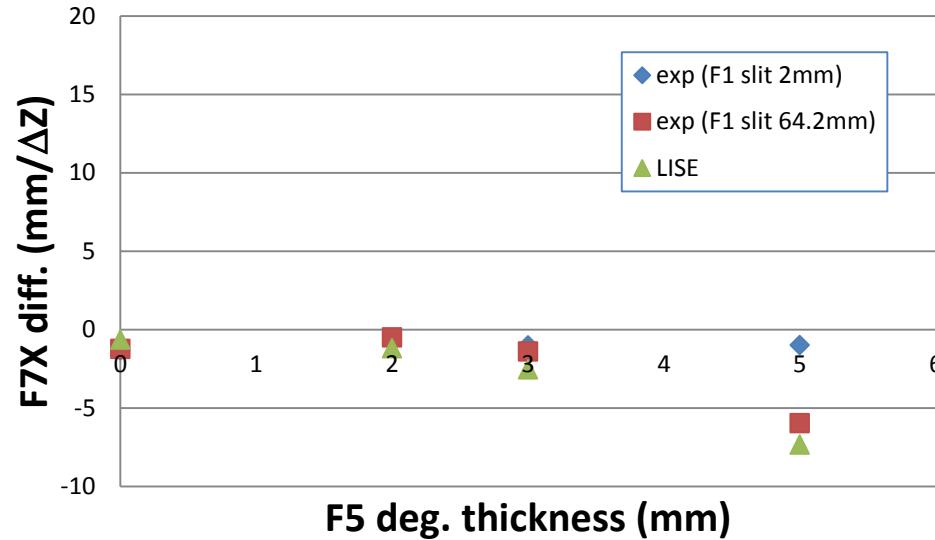


(with  $2\sigma$  gate for F2X, F7X)

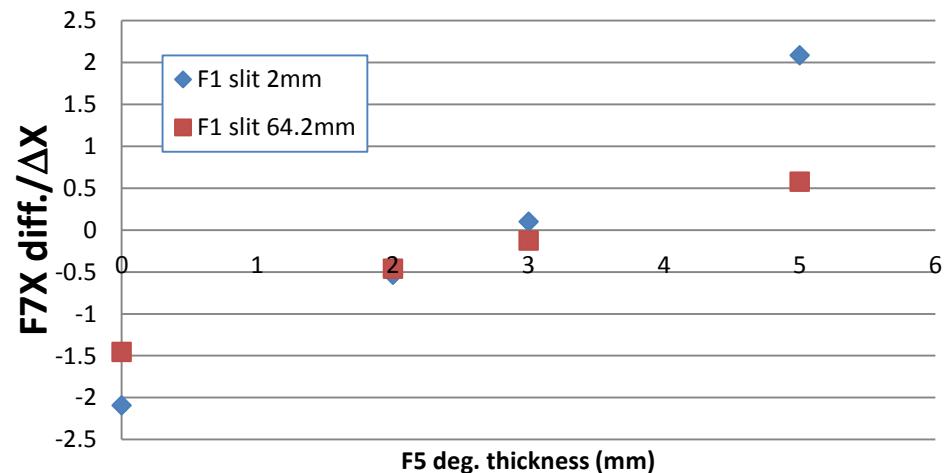
## Sn isotope separation at F7



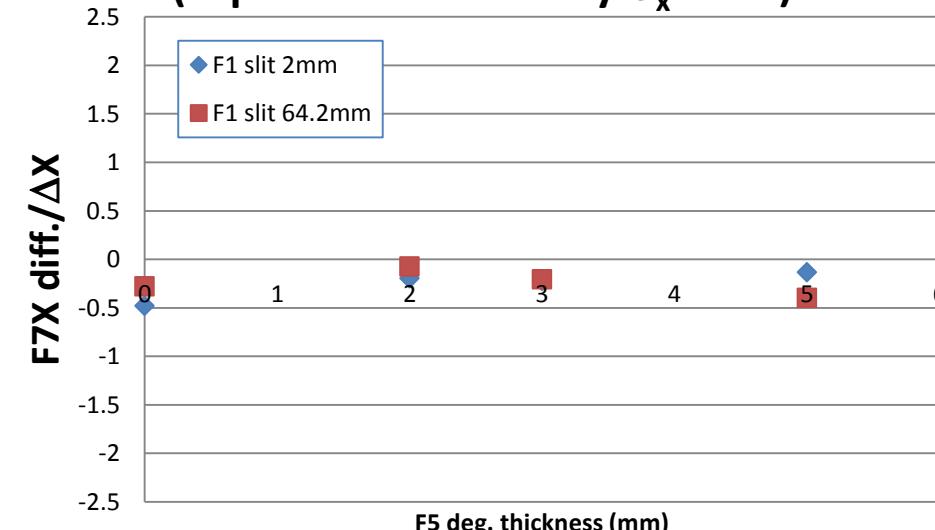
## N=82 isotone separation at F7



## Sn isotope separation power at F7 (separation divided by $\sigma_x$ at F7)



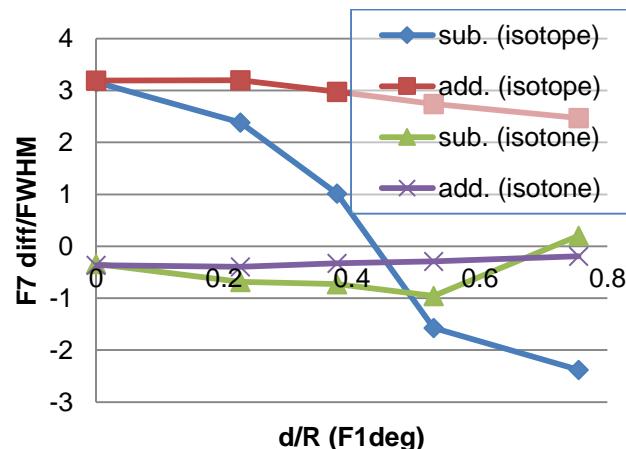
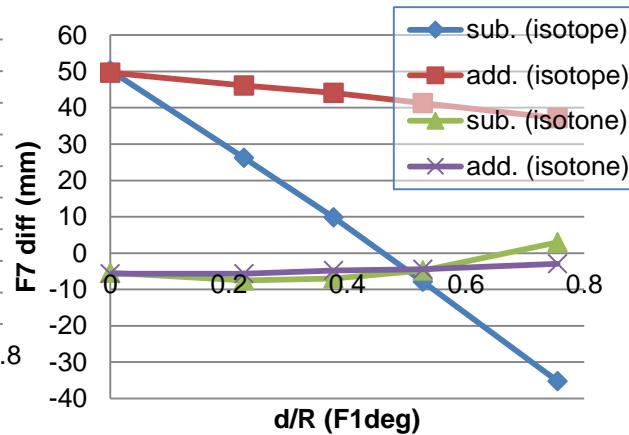
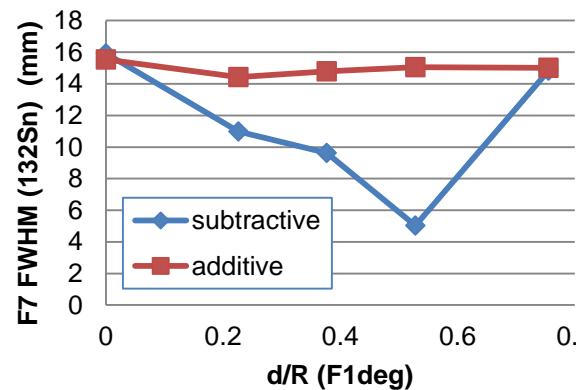
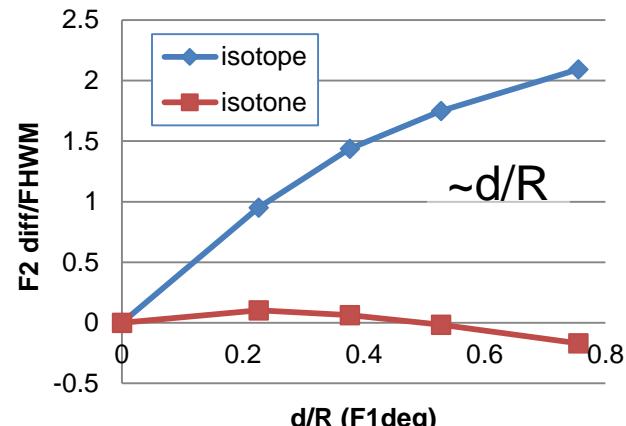
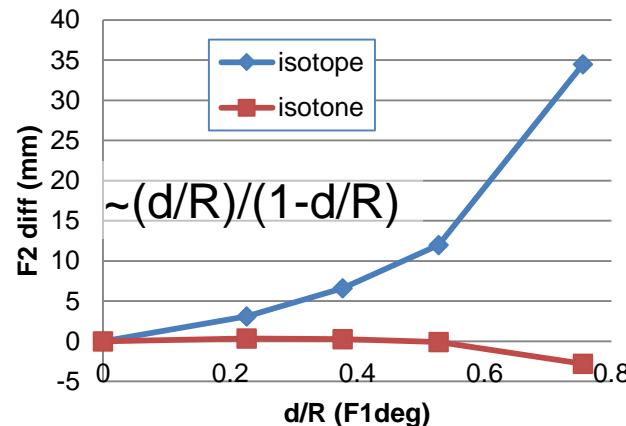
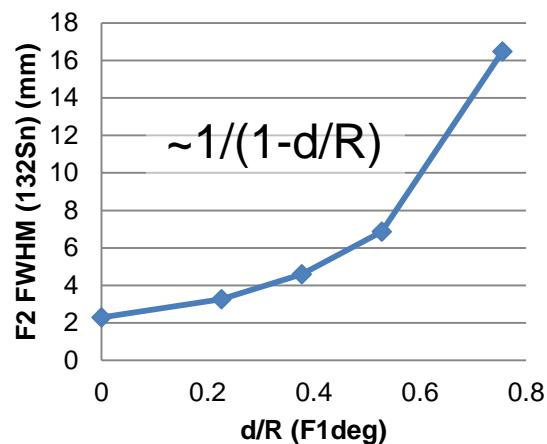
## N=82 isotone separation power at F7 (separation divided by $\sigma_x$ at F7)



# Simulations

$^{238}\text{U}$  345MeV/u, F0 Be 5mm,  $B_p01=7.1\text{Tm}$

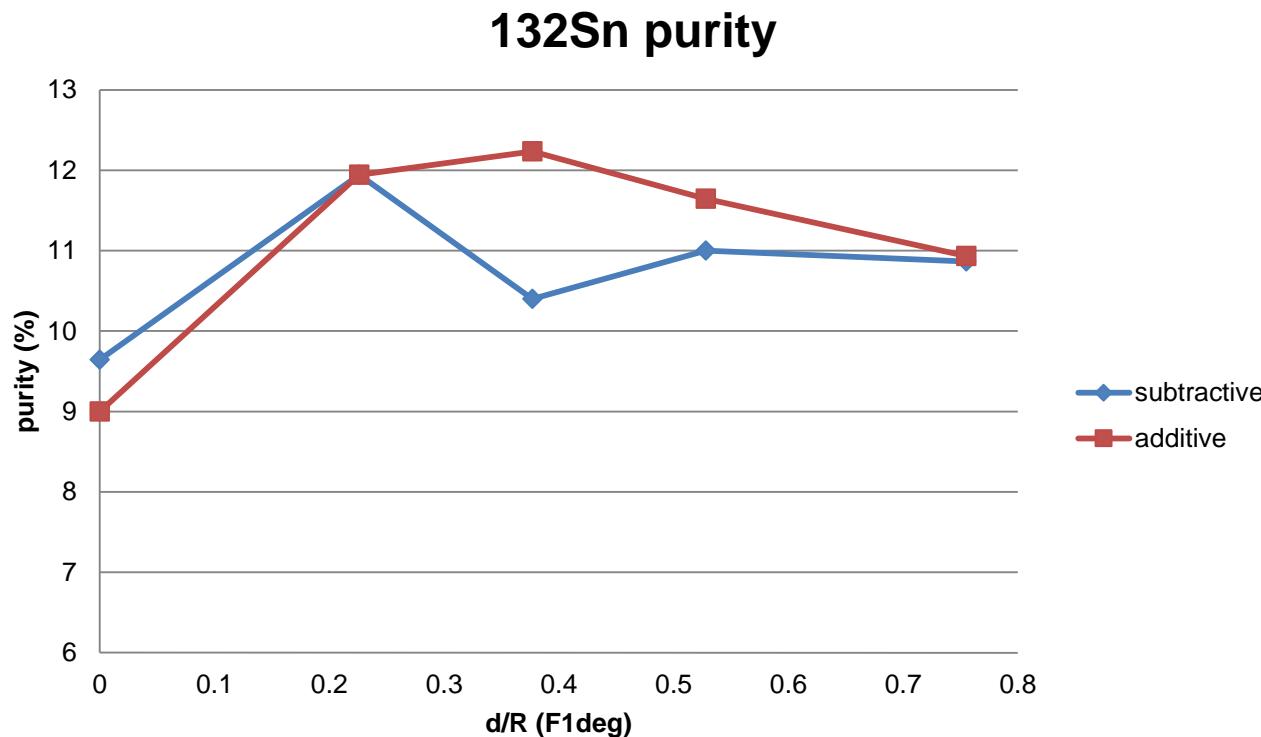
Isotope / isotone separations are examined by changing F1 and F5 degrader thicknesses with keeping F1+F5 total thickness (Al 10mm).



# Purity simulation

238U 345MeV/u, F0 Be 5mm,  $B_p01=7.1\text{Tm}$

Isotope / isotone separations are examined by changing F1 and F5 degrader thicknesses with keeping F1+F5 total thickness (Al 10mm).



F2, F7 slits were tuned for 132Sn  
No big difference between additive and subtractive modes  
due to contamination of isotones



# Summary

- BigRIPS has two stages which act independently as isotope separator.
- Separation powers of the two stages can be added or subtracted. In the BigRIPS standard mode, they are subtracted.
- Additive mode was developed by changing polarity of F2F3 magnification
- Machine study was performed. Additive mode was compared with subtractive mode
- Mass dispersions were well reproduced in both modes.
- Comparison between additive and subtractive mode
  - two-dimensional A/Q resolutions were almost the same
  - pure spatial separation is superior for the additive mode  
(in the test the contaminants were dominated by isotones)
  - Transmission of the additive mode has to be improved
  - (about 70% of subtractive mode due to large  $(a|x)$  term).



R37 R23 R02=

$$\begin{bmatrix} xx02 \ xx23 \ xx37 & xa02 \ xx23 \ xx37 + \frac{xa37}{xx02 \ xx23} & 0 & xm02 \ xx23 \ xx37 + xm37 & xz37 + xx23 \ xx37 \ xz02 \\ 0 & \frac{1}{xx02 \ xx23 \ xx37} & 0 & 0 & 0 \\ dx37 \ xx02 \ xx23 + dd37 \ dx02 & dx37 \ xa02 \ xx23 + \frac{da37}{xx02 \ xx23} + da02 \ dd37 & dd02 \ dd37 & dx37 \ xm02 \ xx23 + dm37 + dd37 \ dm02 & dx37 \ xx23 \ xz02 + dz37 + dd37 \ dz02 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$



# RI beam setting

Primary beam:  $^{238}\text{U}$  345MeV/u

$^{132}\text{Sn}$  center

F0 target: Be 5 mm

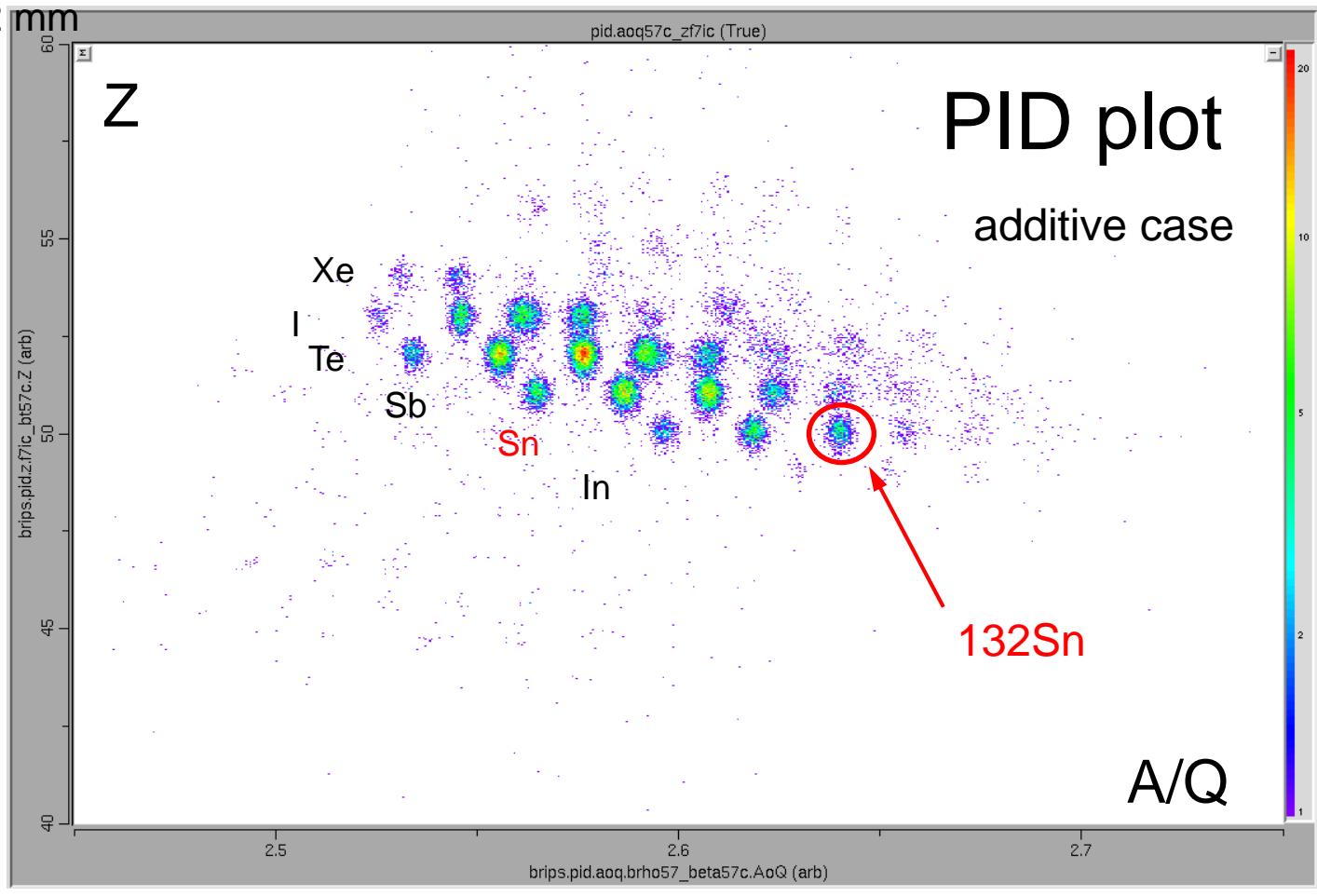
D1 7.100 Tm, D2 5.9924 Tm, D3D4 5.9535 Tm, D5D6 5.0525 Tm

F1 deg. Al 5 mm ( $d/R=0.377$ ) / F5 deg. Al 3 mm ( $d/R=0.372$ )

F1 slit  $\pm 2$ , 21.4, 64.2 mm

F2 slit  $\pm 120$  mm

F7 slit  $\pm 120$  mm



# • 132Sn 100MeV/u setting

238U 345MeV/u + Be 5 mm

D1 7.100 Tm, D2 5.9924 Tm, D3D4 5.8830 Tm, D5D6 4.6288 Tm

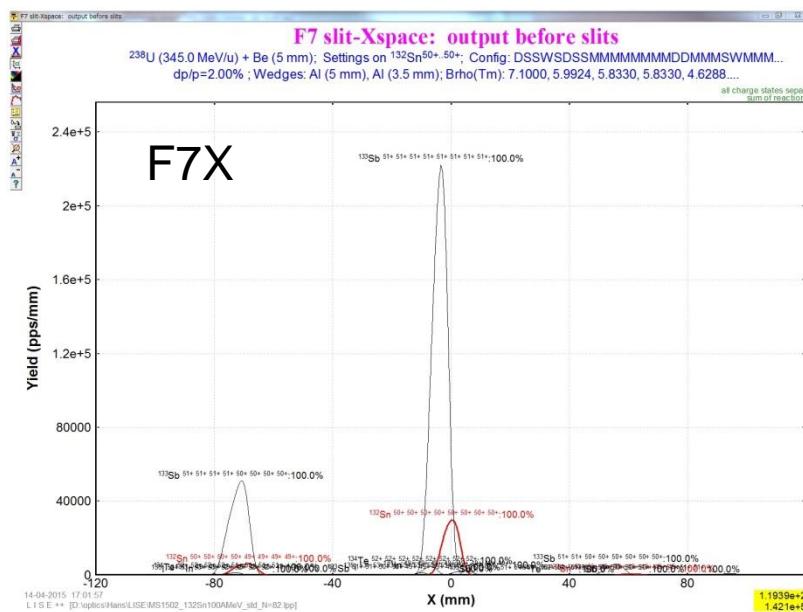
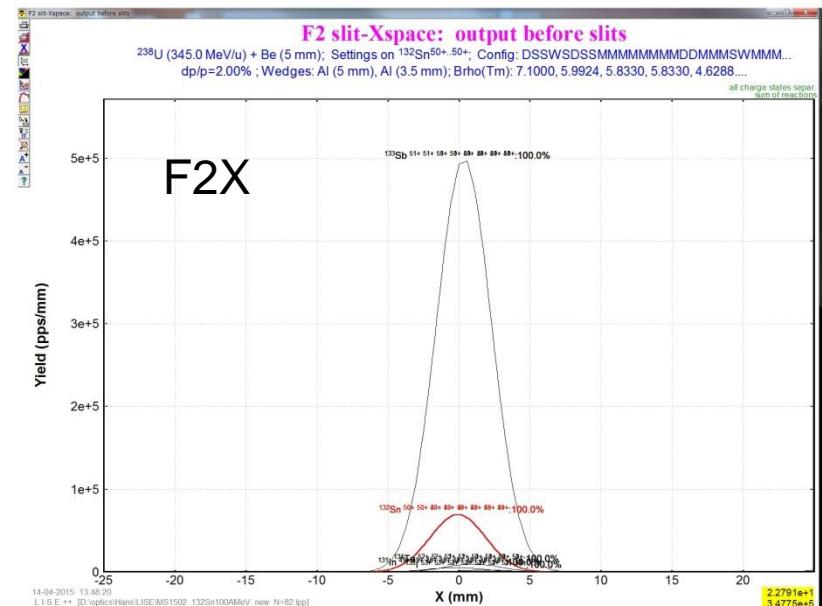
F1 deg. Al 5 mm ( $d/R=0.377$ ) / F5 deg. Al 3.5 mm ( $d/R=0.463$ )

F1 slit  $\pm 21.4$  mm

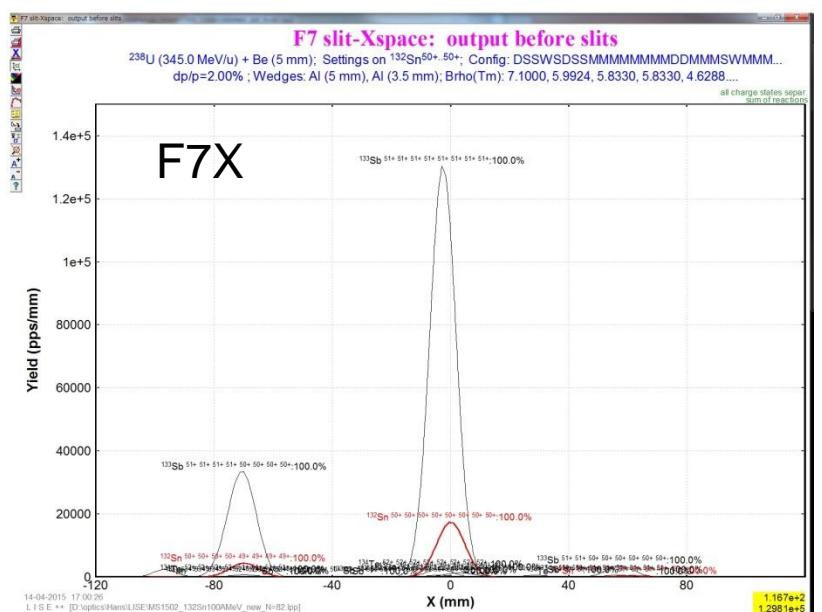
F2 slit  $\pm 6$  mm

F7 slit  $\pm 15$ mm

## Distribution of N=82 isotones



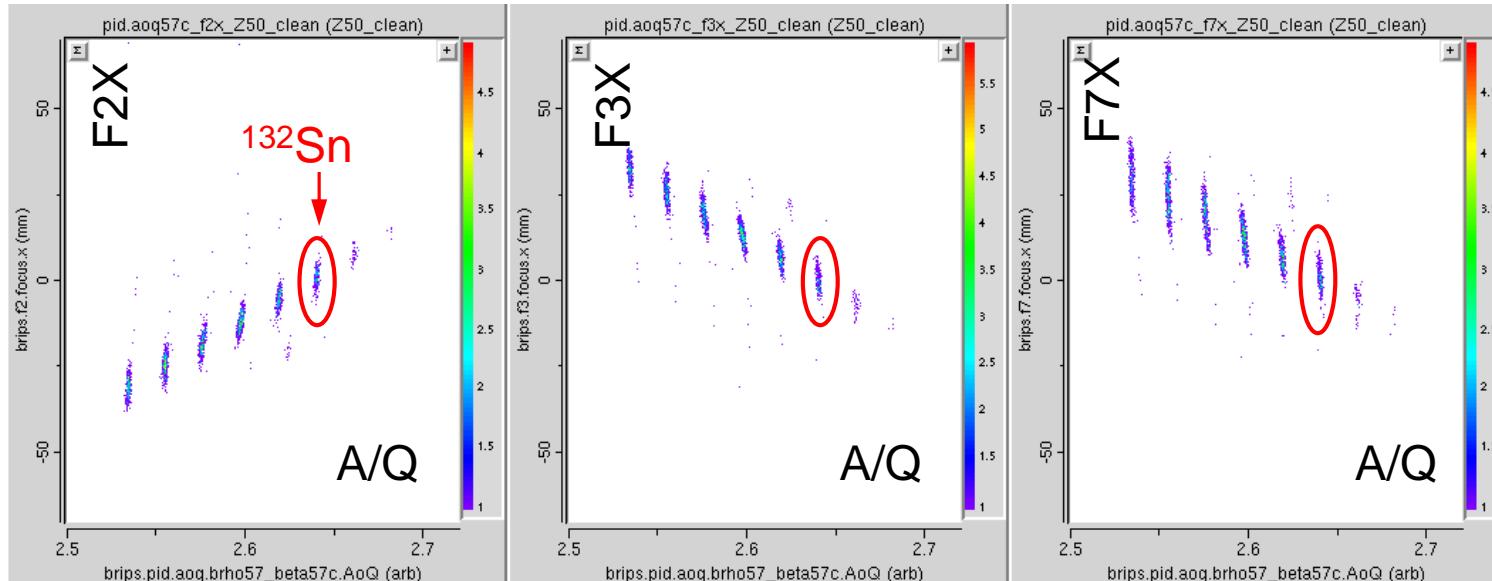
F2-F3 standard mode



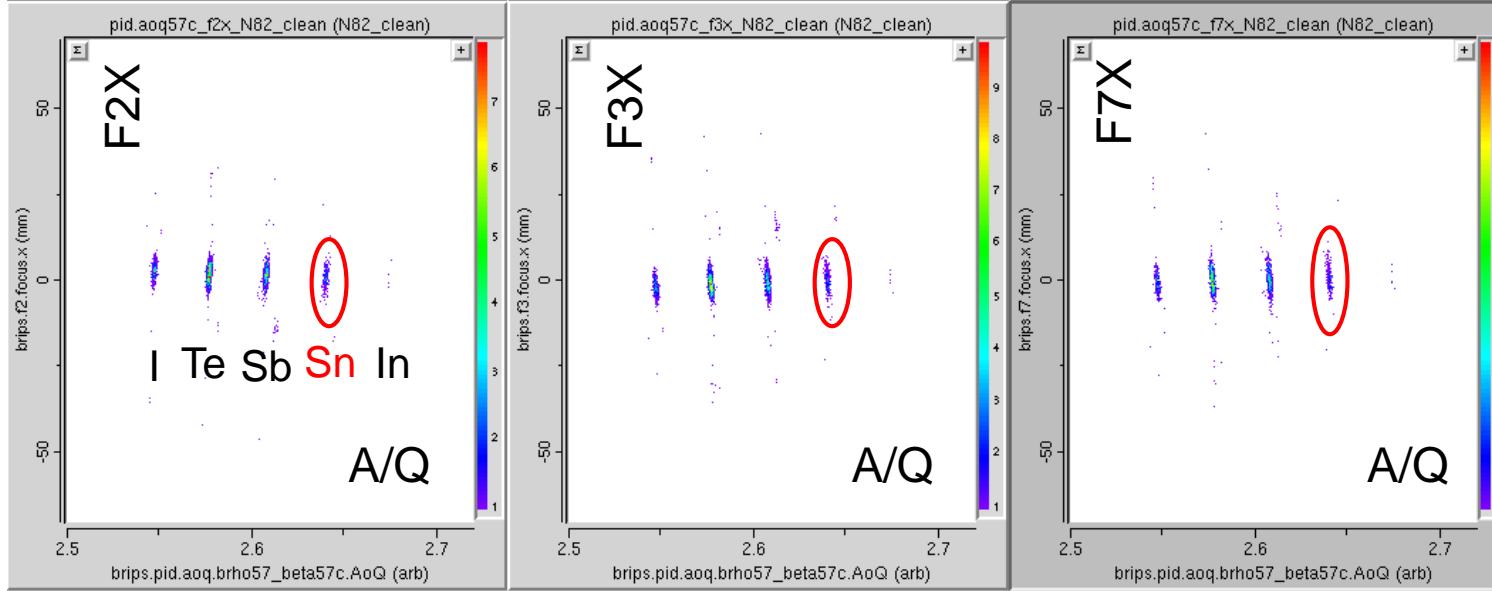
F2-F3 new mode

# Z=50 isotope および N=82 isotone の各焦点面での位置

Z=50 isotope



N=82 isotone



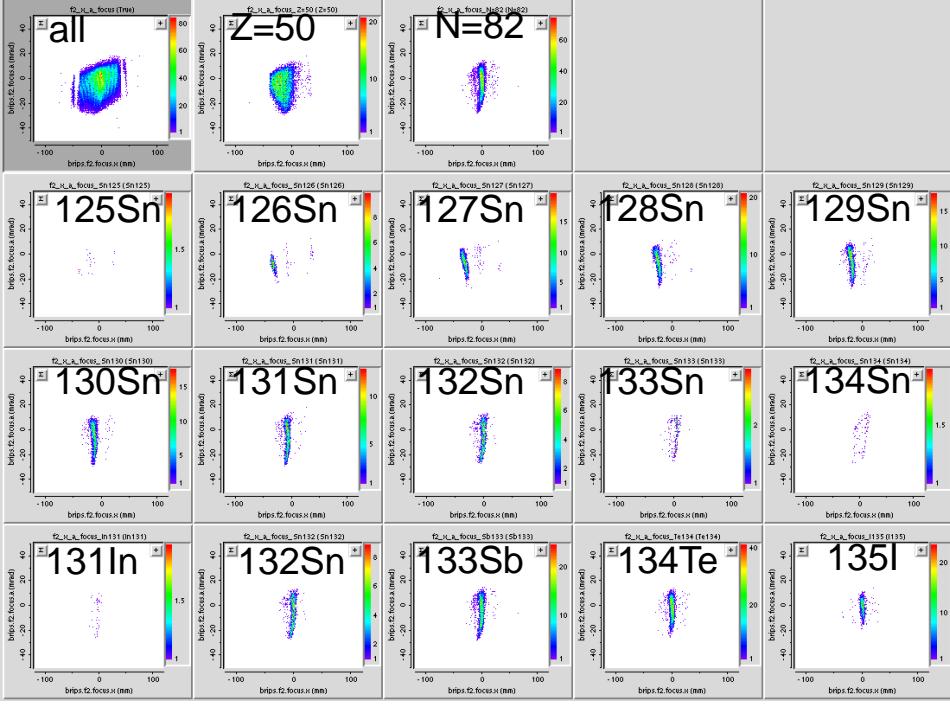
これはF5 deg.  
なしの例



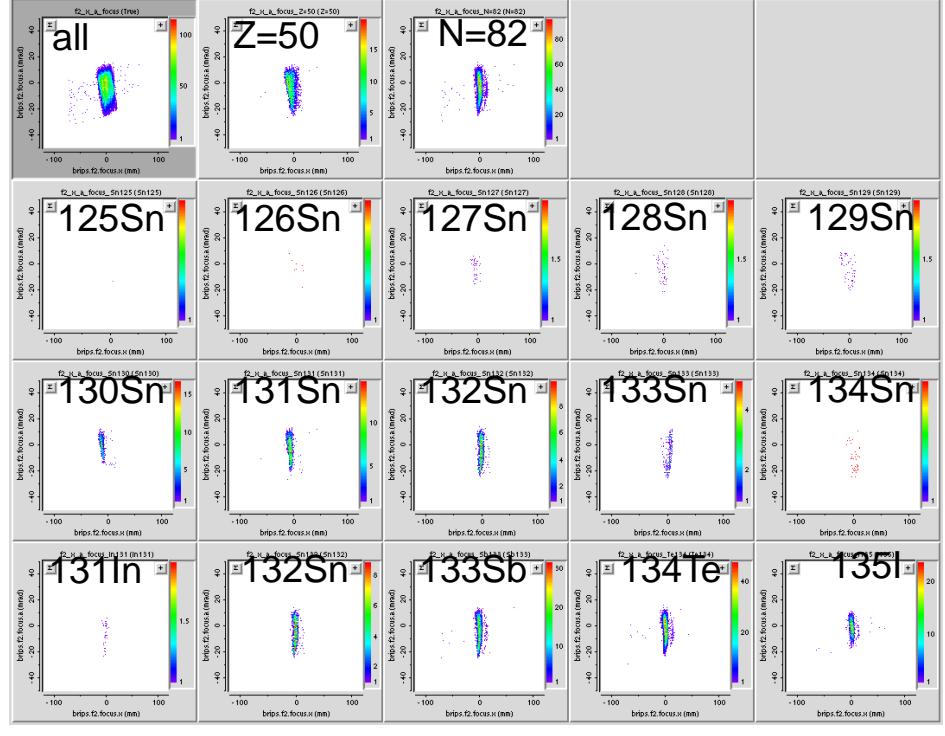
# Phase space (F2x, F2a)

(F7まで到達してPIできたものしかプロットされていない)

subtractive



additive

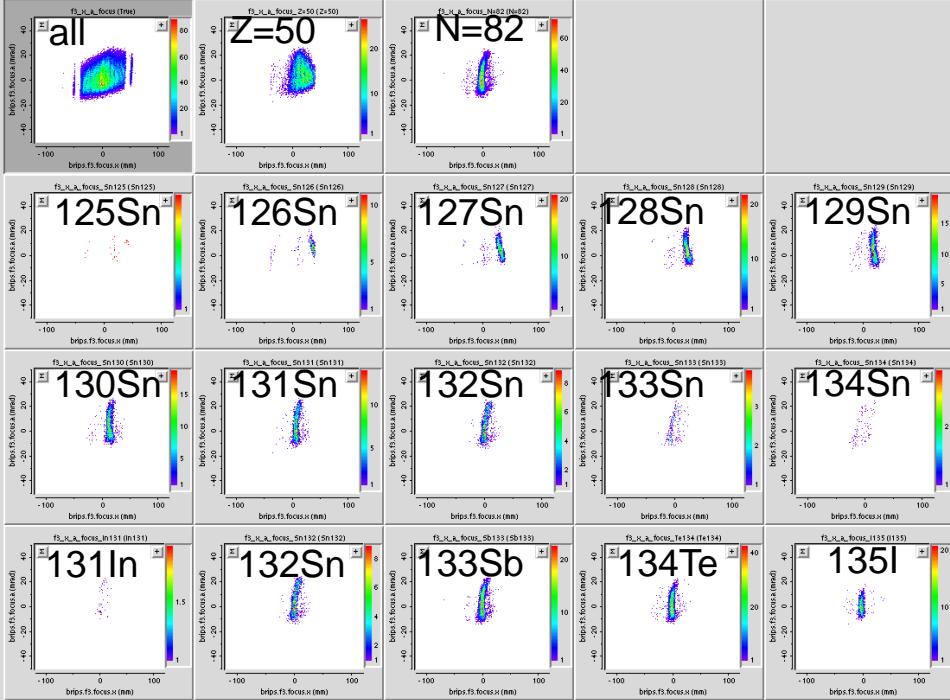




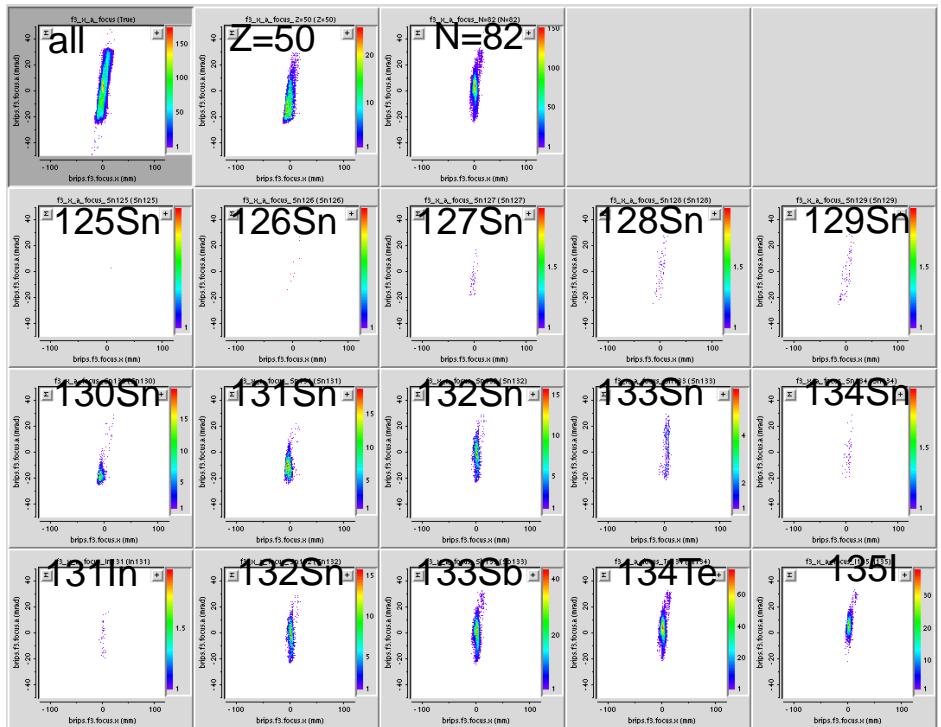
# Phase space (F3x, F3a)

(F7まで到達してPIできたものしかプロットされていない)

subtractive



additive

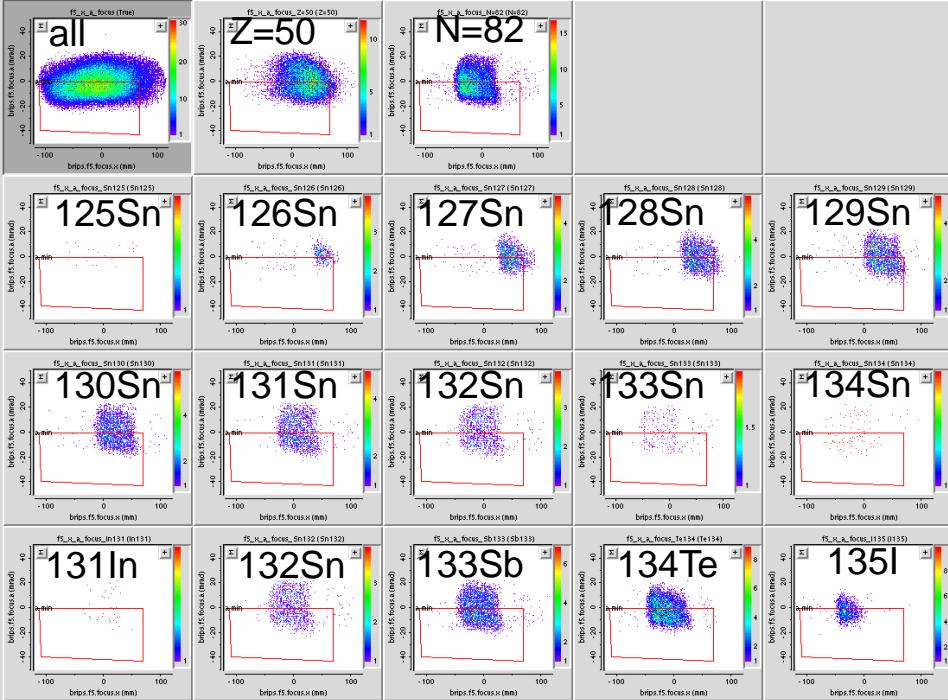




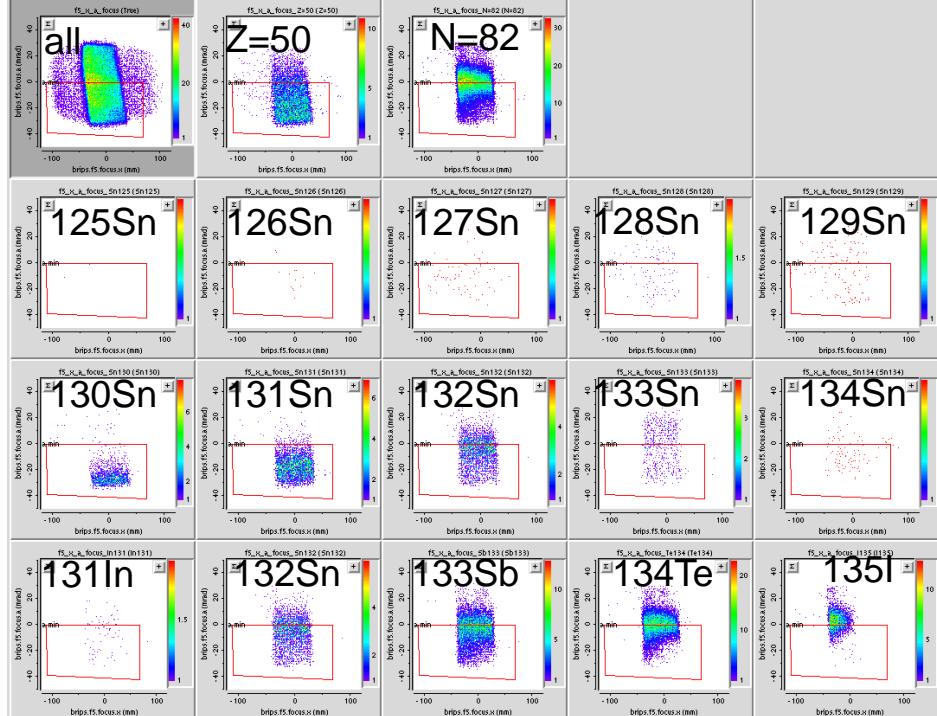
# Phase space (F5x, F5a)

(F7まで到達してPIできたものしかプロットされていない)

subtractive



additive

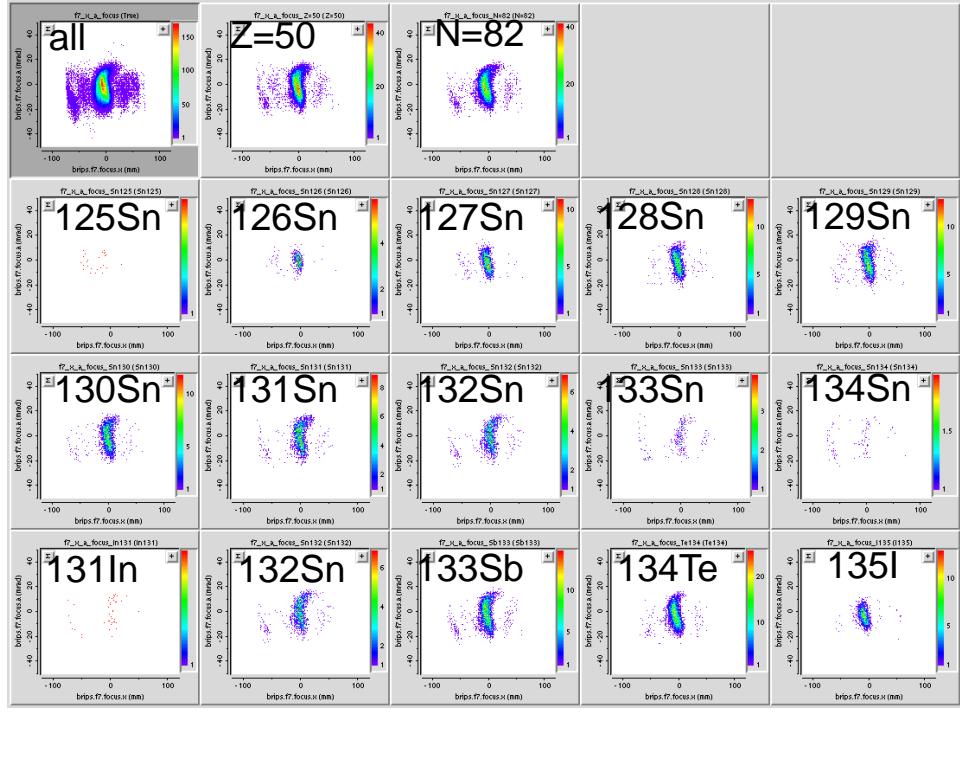




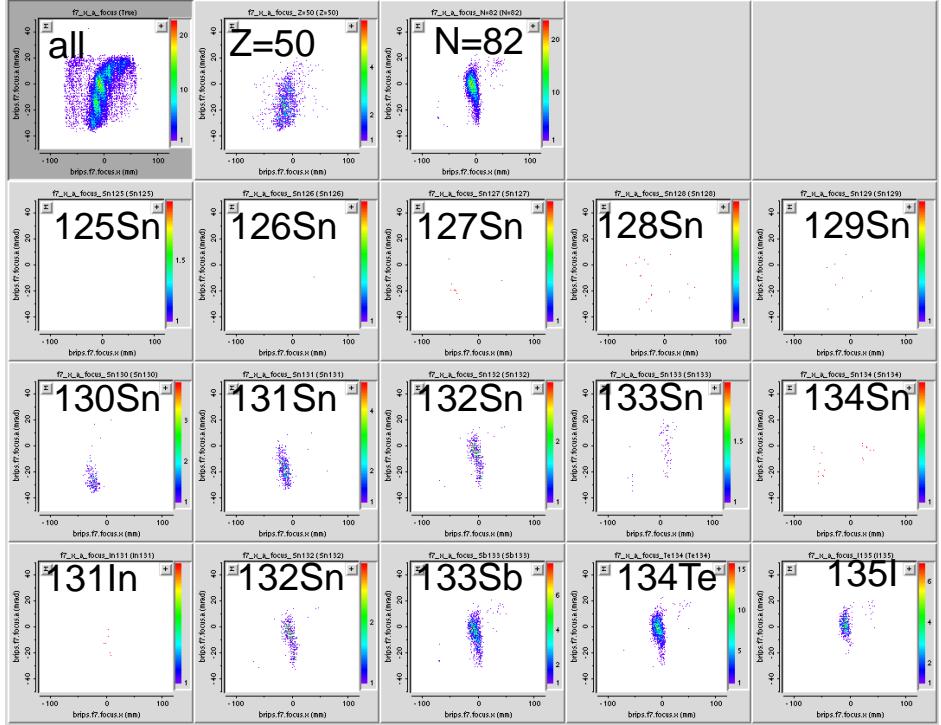
# Phase space (F7x, F7a)

(F7まで到達してPIできたものしかプロットされていない)

subtractive



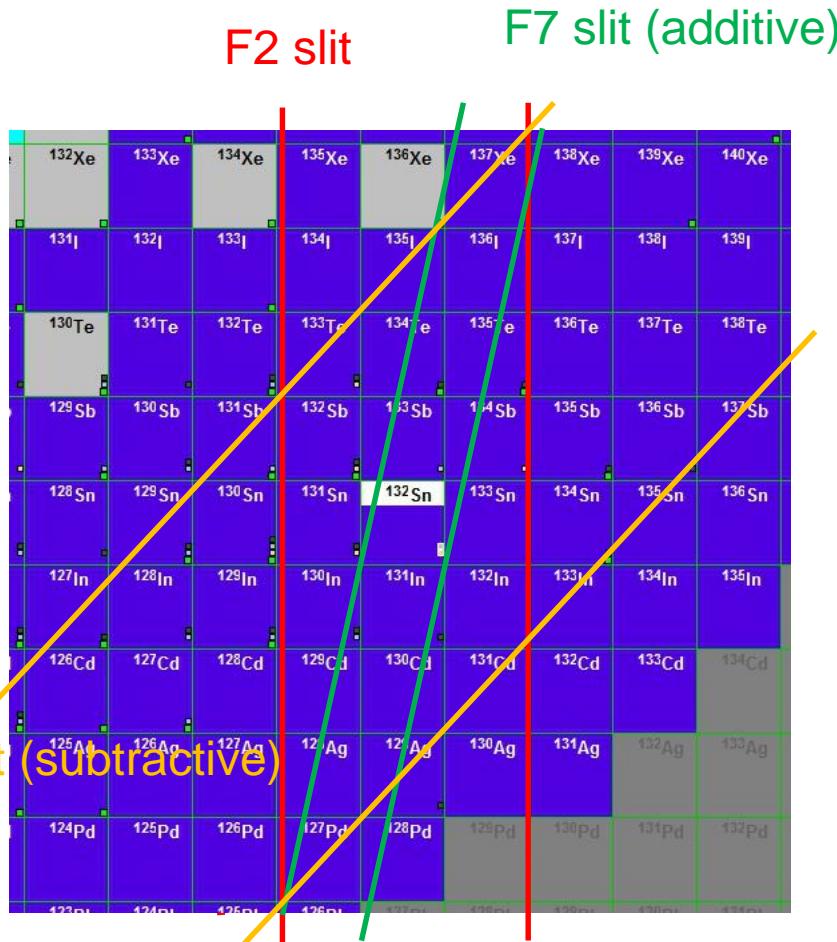
additive



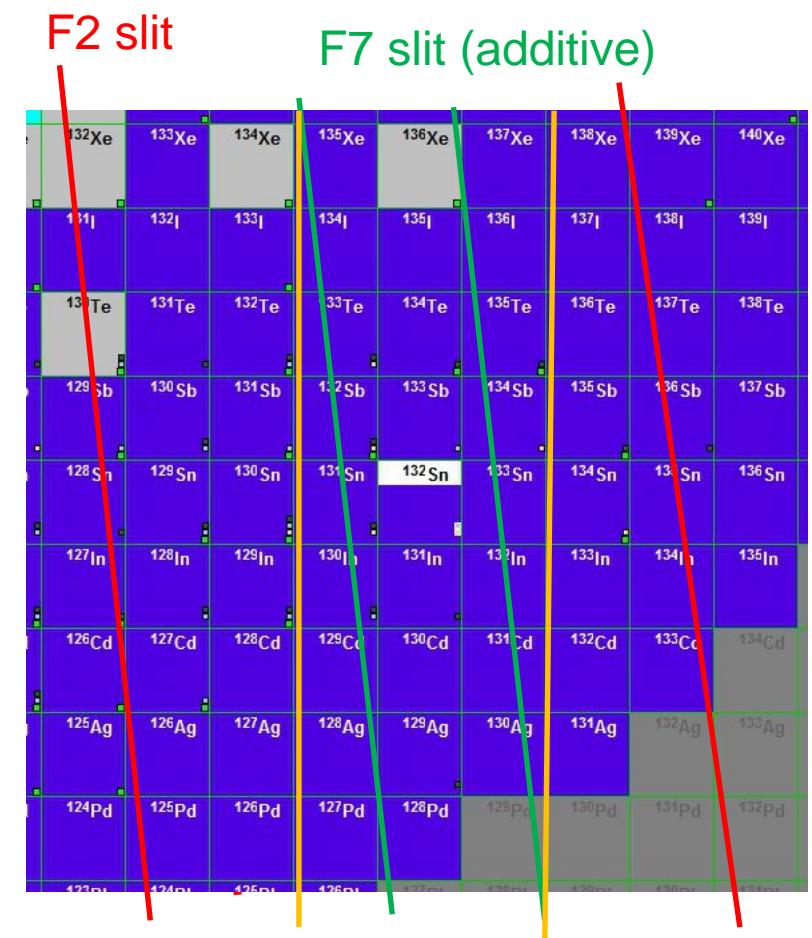
# • Slit selection



132Sn 100MeV/u setting

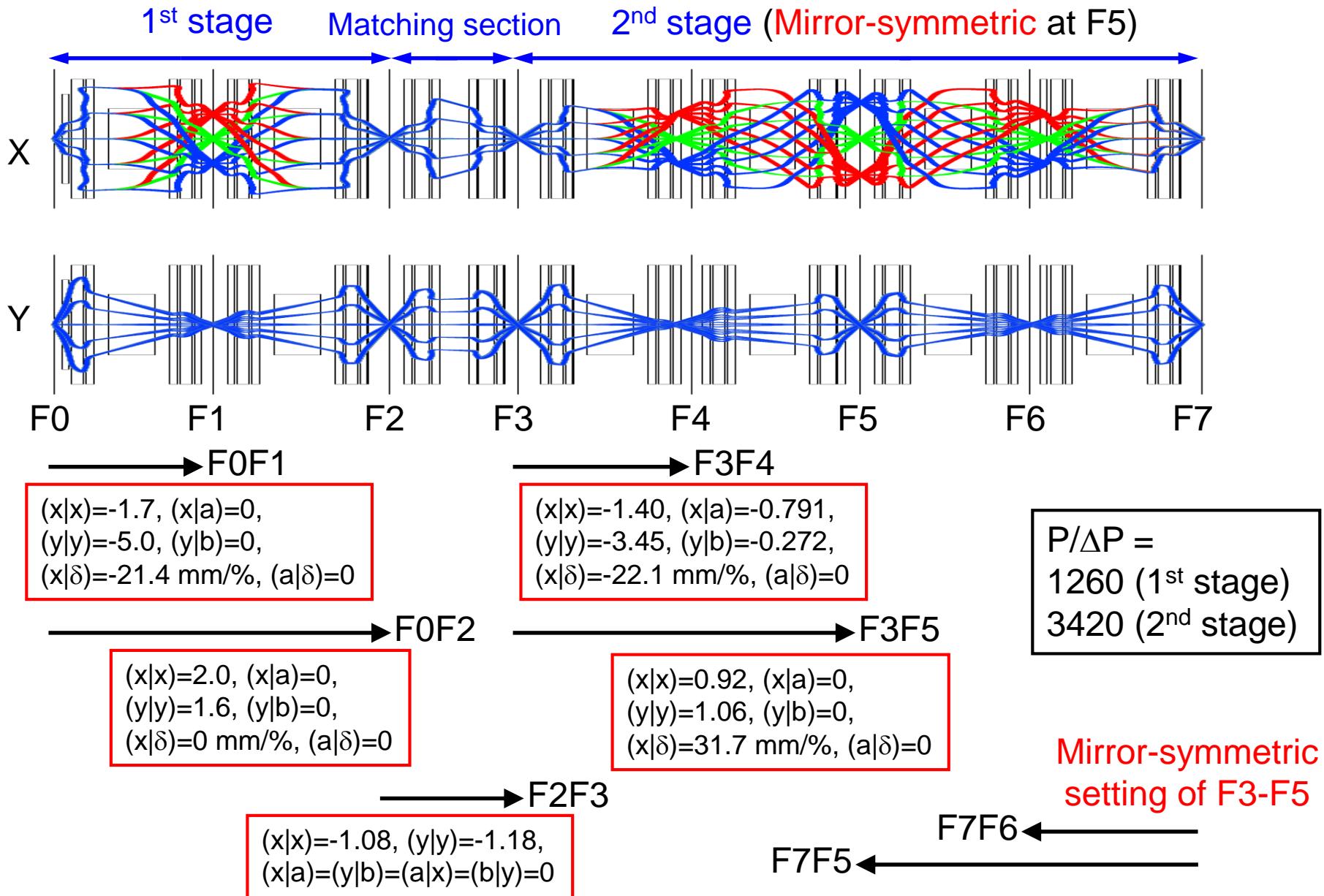


132Sn 200MeV/u setting



F7 slit (subtractive)

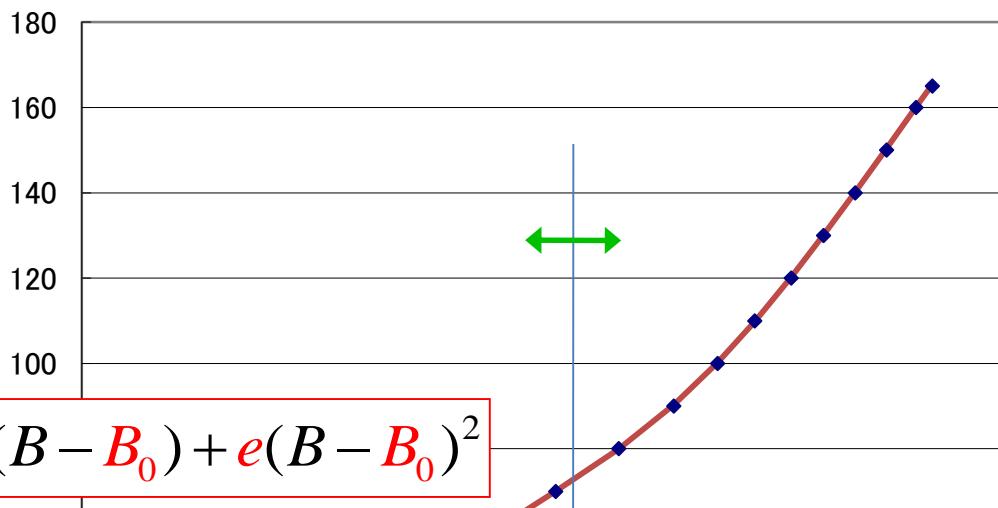
# Ion-optical setting of BigRIPS



# B-I curve

Q500

current (A)



$$I = I_0 + f(B - B_0) + e(B - B_0)^2$$

$$I = a \cdot B + \frac{b \cdot (B - c)}{1 + \exp[-d \cdot (B - c)]}$$

agree within 0.1% order

- same for other super-ferric quadrupoles and dipoles
- linear functions are used for air-core quads