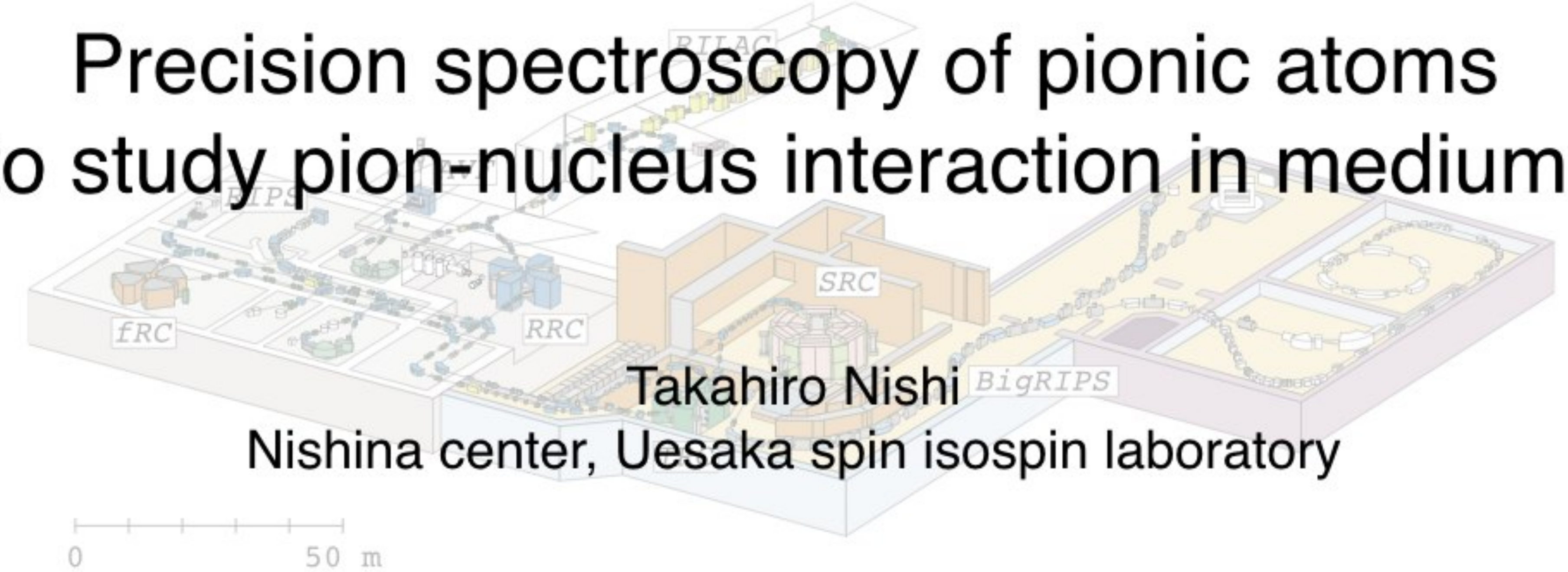
Precision spectroscopy of pionic atoms to study pion-nucleus interaction in medium

Takahiro Nishi
Nishina center, Uesaka spin isospin laboratory



Collaborators

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*spokesperson, ** co-spokesperson

University of Tokyo, RIKEN, Nishina Center, University of Notre Dame, Tohoku University, Kyoto University, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Nara Women's University, Osaka University, Stefan Meyer Institute

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(i) Motivation and prior research

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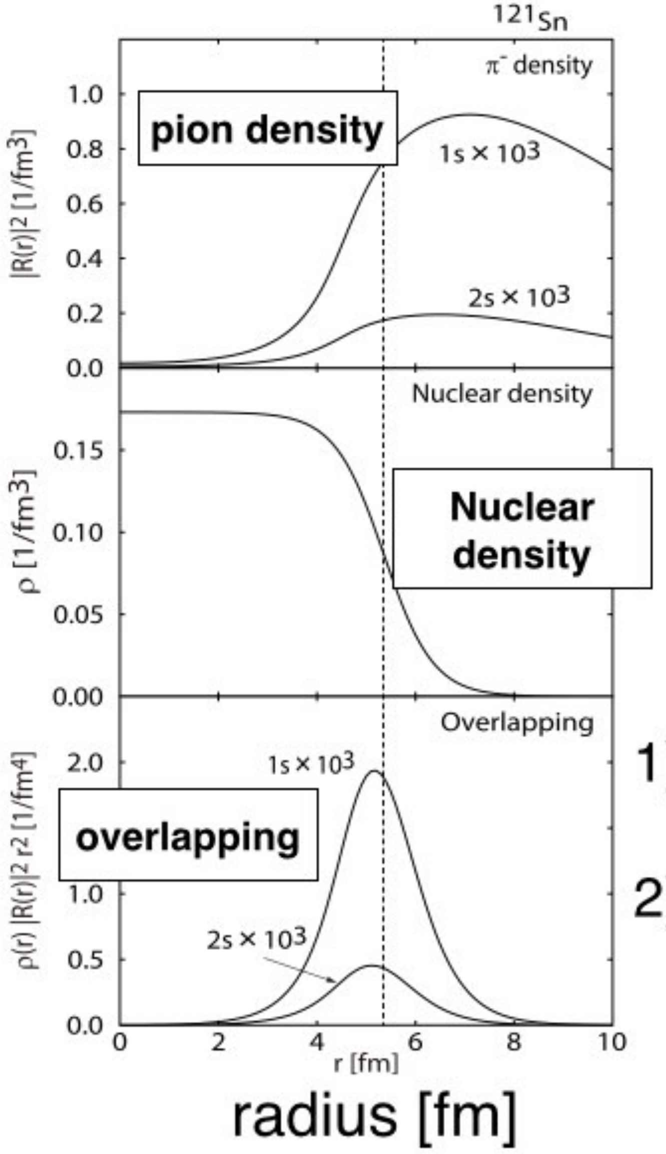
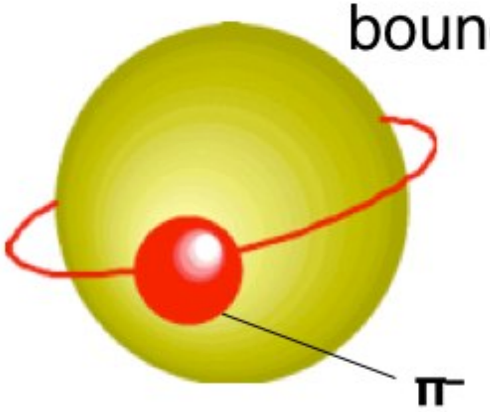
Deeply bound pionic atoms





bound system of π^- & nucleus

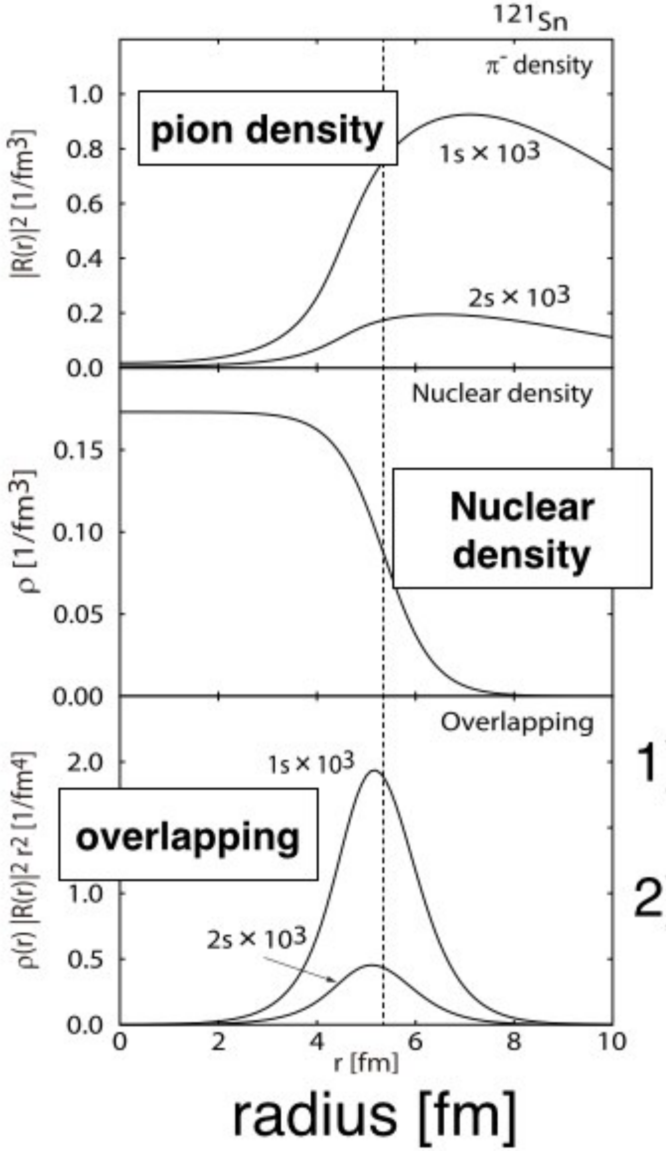
very unique objects in terms of

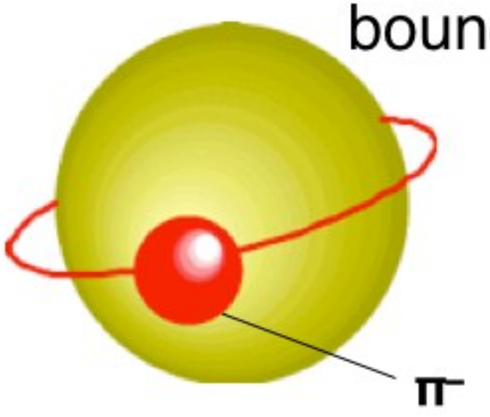
1) Bound system of meson-nucleus

2) Quasi-stable state

N. Ikeno *et al.*, PTP126(2011)483.

Deeply bound pionic atoms





bound system of π^- & nucleus

very unique objects in terms of

1) Bound system of meson-nucleus

No other “meson in nucleus” system established

2) Quasi-stable state

Quantitative evaluation of strong interaction in medium

N. Ikeno *et al.*, PTP126(2011)483.

Deeply bound pionic atoms

BE, Γ of 1*s* pionic state
⇔ strong interaction effect

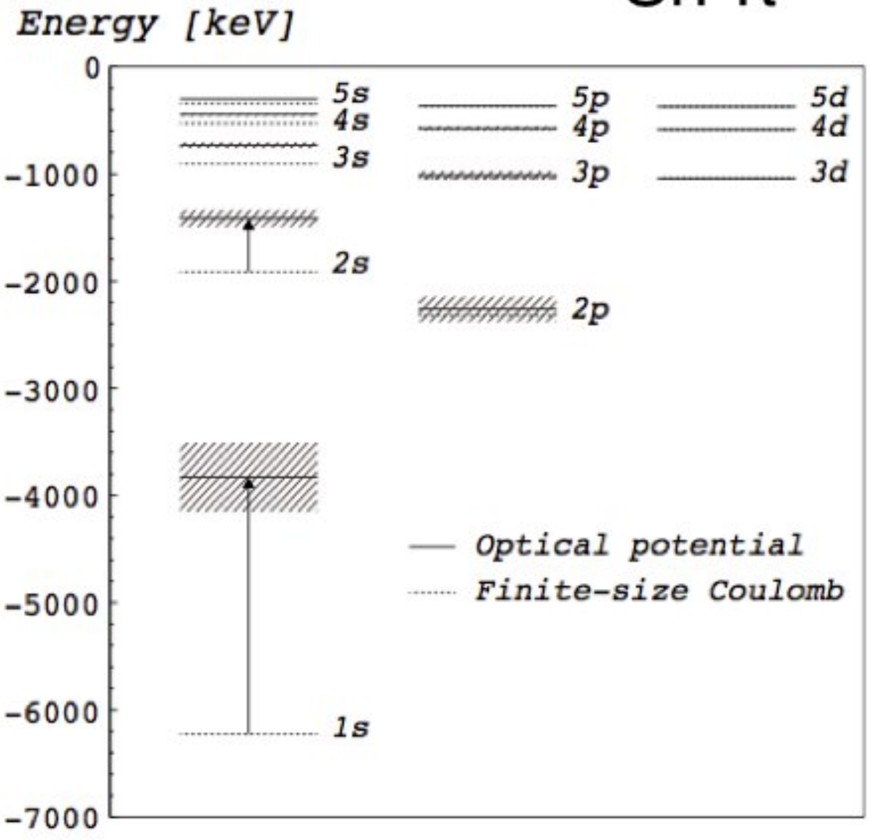
π-A s-wave optical potential (s-wave)

$$V_s(r) = -\frac{2\pi}{\mu}[\epsilon_1\{b_0\rho + b_1\delta\rho\} + \epsilon_2 B_0\rho^2]$$

$\rho = \rho_p + \rho_n$

$\delta\rho = \rho_p - \rho_n$

^{121}Sn-π$^-$



N. Ikeno et al., Prog. Theor. Phys. 126 (2011) 483.
S. Itoh, Doctoral Dissertation, Univ. of Tokyo (2011)

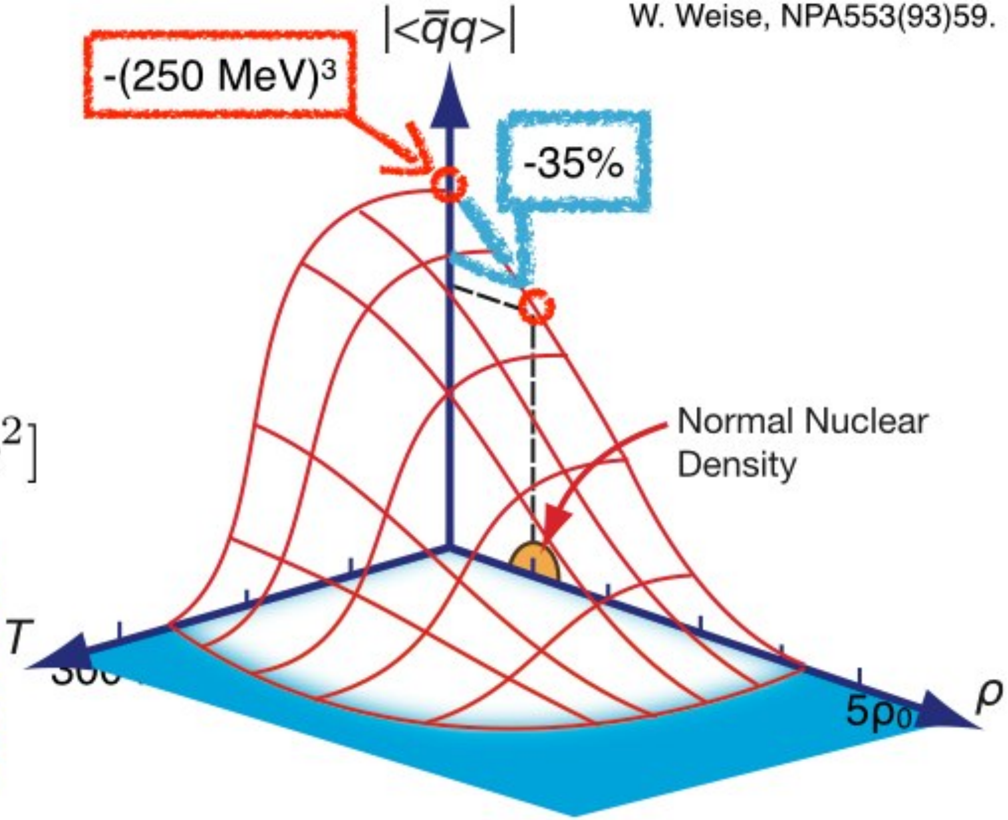
Deeply bound pionic atoms

BE, Γ of 1*s* pionic state
⇔ strong interaction effect

π-A s-wave optical potential (s-wave)

$$V_s(r) = -\frac{2\pi}{\mu}[\epsilon_1\{b_0\rho + \boxed{b_1}\delta\rho\} + \epsilon_2 B_0\rho^2]$$

$$\boxed{\frac{\langle\bar{q}q\rangle_{\rho=\rho_0}}{\langle\bar{q}q\rangle_{\rho=0}} \simeq \left(\frac{m_\pi^*}{m_\pi}\right)^2 \frac{\mathrm{b}_1(\rho=0)}{\mathrm{b}_1(\rho=\rho_0)}}$$

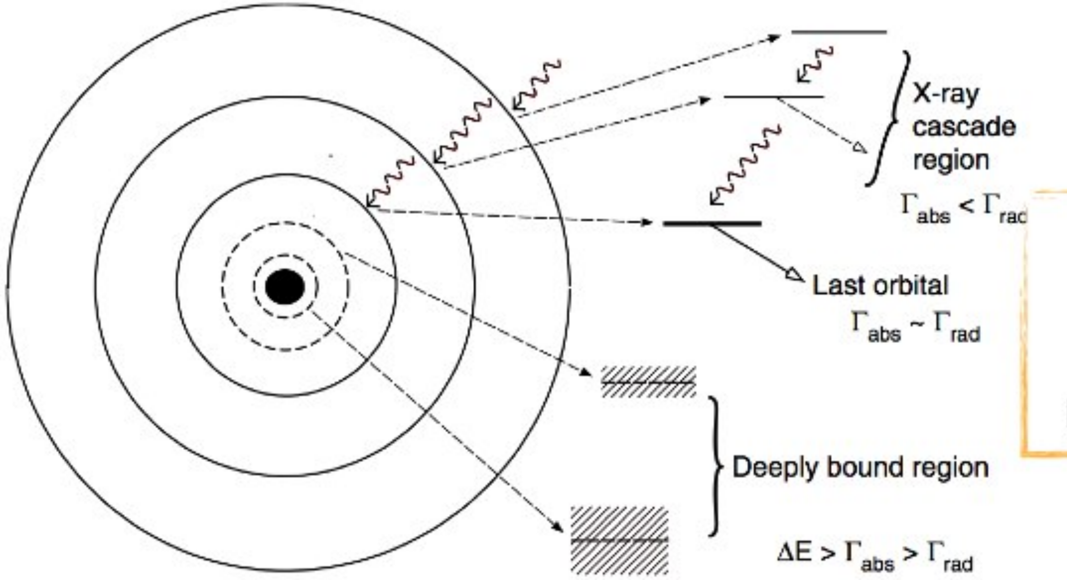


W. Weise, NPA553(93)59.

Quantitative evaluation of $\underline{\langle\bar{q}q\rangle}$

Order parameter of
chiral symmetry breaking

Conventional method: X-ray spectroscopy



Yamazaki *et al,* Phys. Rep. 514, 1(2012)

x rays during atomic cascade
→ higher orbits / light nuclei
(~ ^{24}Mg for 1s)

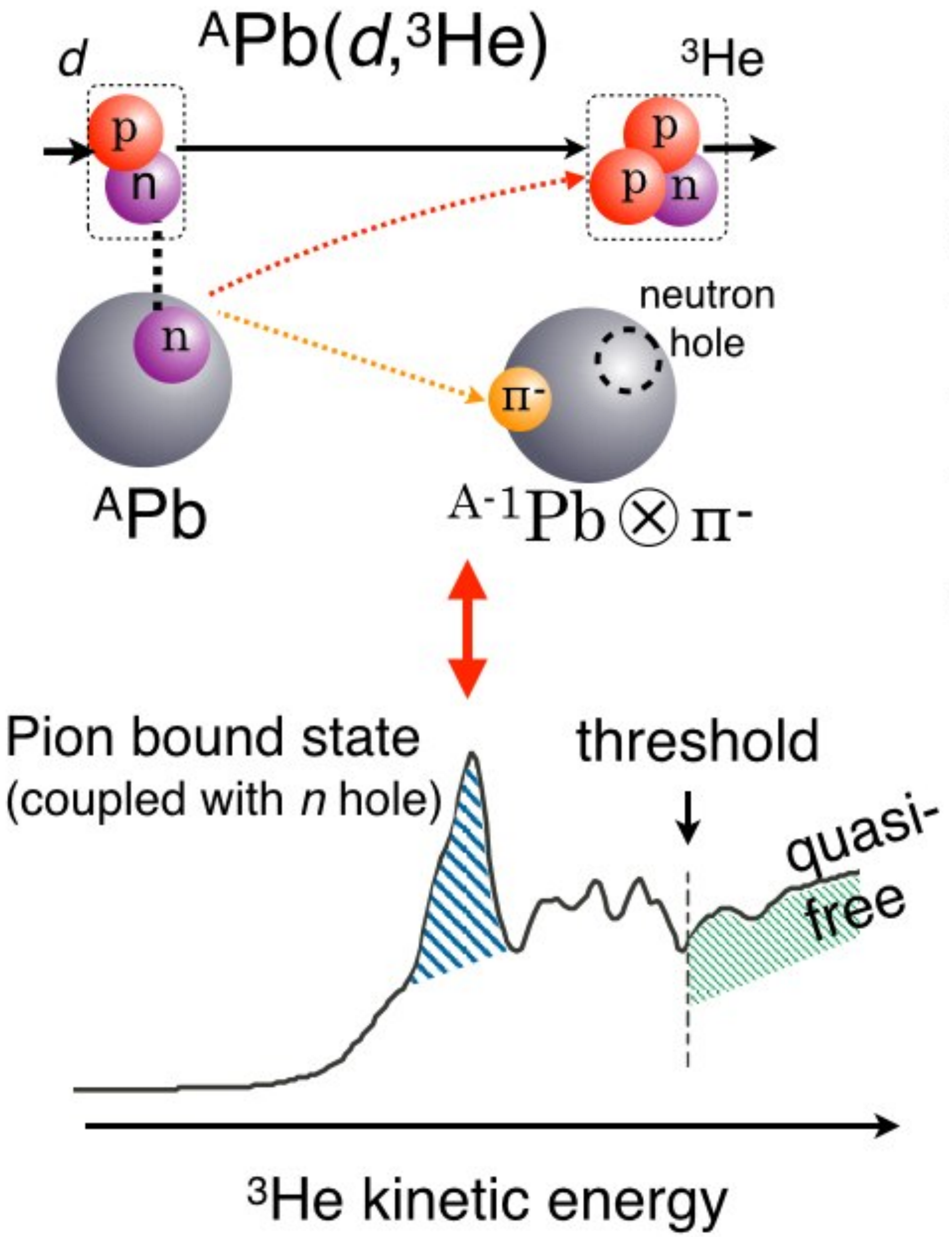
pionic 1s state in H
→ b_1 in vacuum

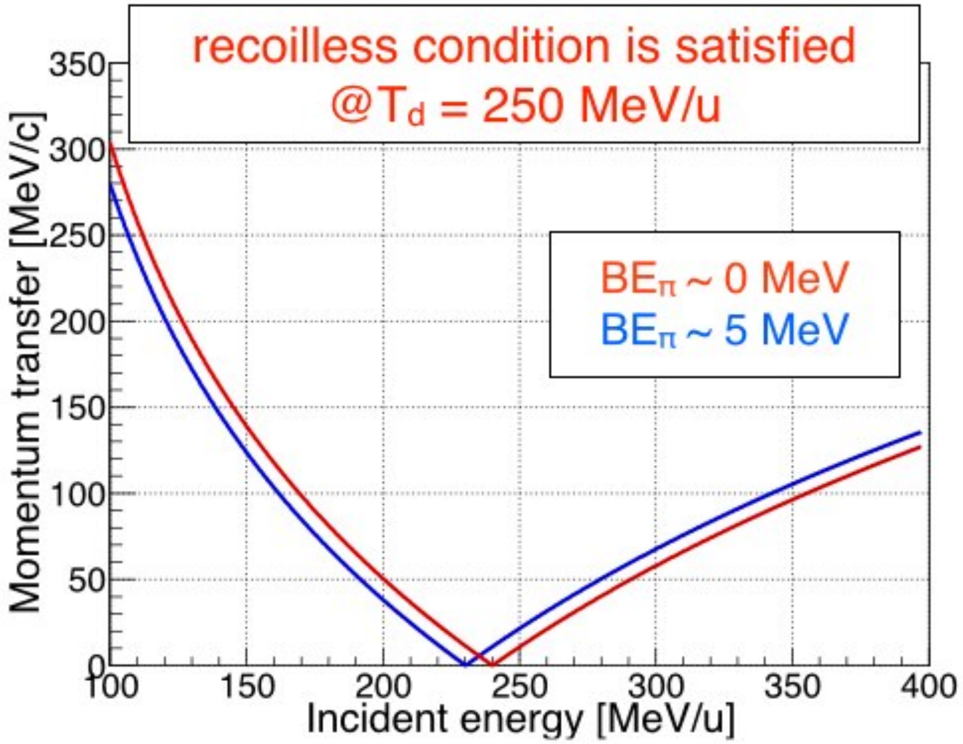
H. Schröder *et al.*, Eur. Phys. J. C 21, 473 (2001).

for deep orbit in heavy nuclei
absorption is faster

This method cannot produce “deeply-bound” pionic atom…

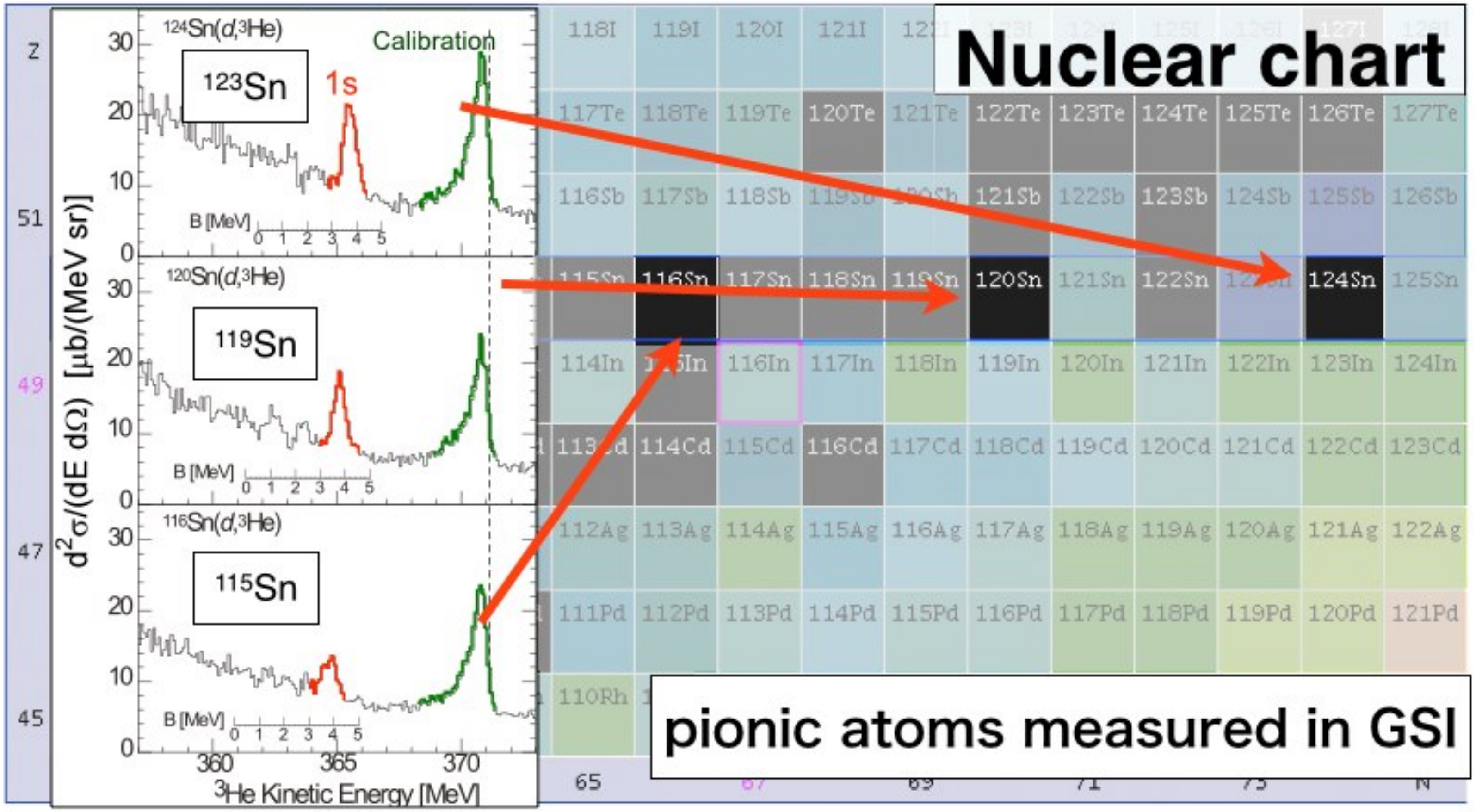
Our method: Missing mass spectroscopy




recoilless condition is satisfied
@T_d = 250 MeV/u

(i) Motivation and prior research

Prior research: Experiment at GSI



Nuclear chart

pionic atoms measured in GSI

K. Suzuki et al., PRL92 072302 (2004)

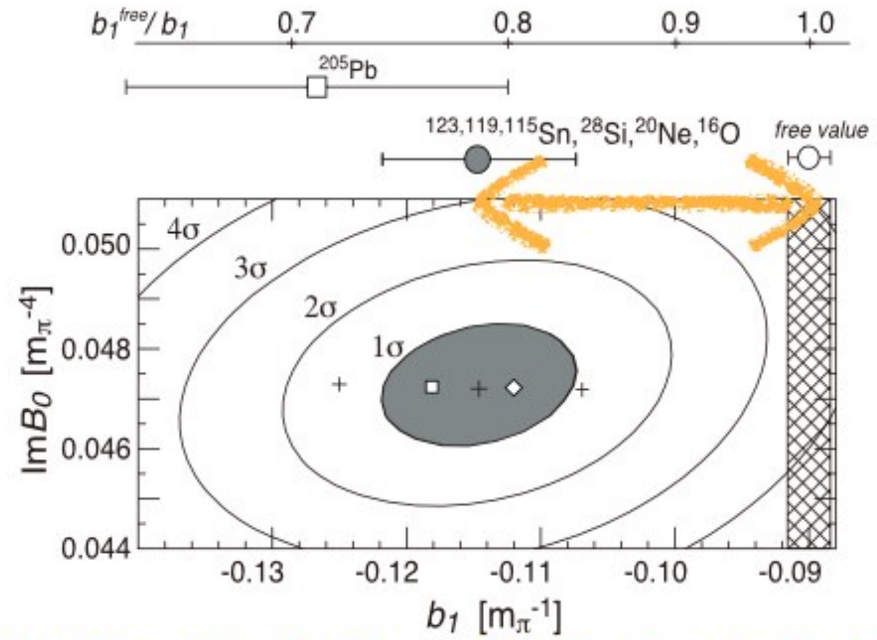
NuDat

Systematic study of pionic Sn isotopes

~ **3 month** measurement for 3 isotopes

Extract b_1 from experimental data at GSI

Contour plot of χ^2



$$\boxed{\frac{b_1^{\mathrm{free}}}{b_1} = 0.78 \pm 0.05} \longrightarrow \boxed{\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle} \approx 0.66 \pm 0.06}$$

cf. theoretical prediction ~ 0.65

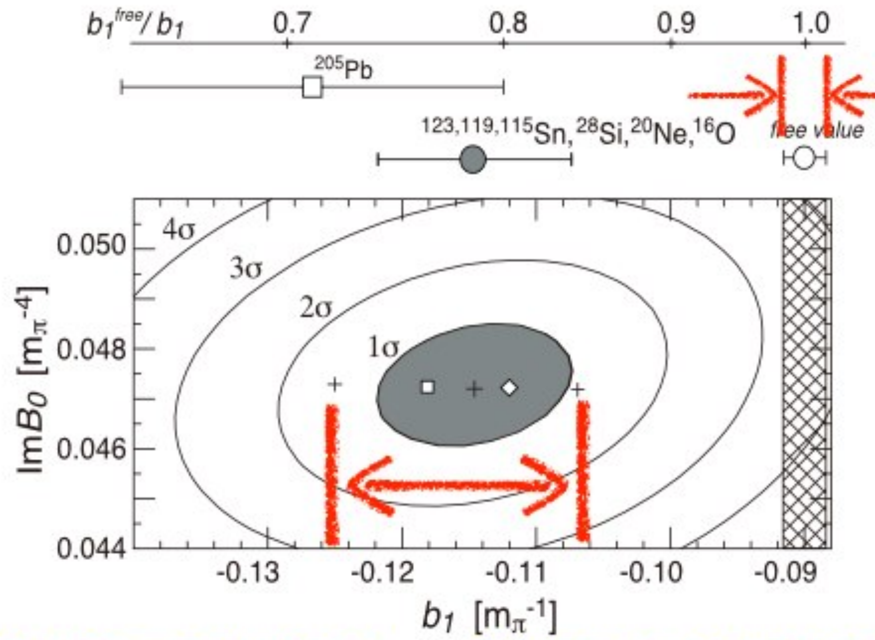
π-A s-wave optical potential

$$V_s(r) = -\frac{2\pi}{\mu}[\epsilon_1\{b_0\rho + b_1\delta\rho\} + \epsilon_2 B_0\rho^2]$$

※ b_0 , $\mathrm{Re}B_0$ are deduced from data of light / symmetric pionic atoms

Extract b_1 from experimental data at GSI

Contour plot of χ^2



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error of b_1 in medium is still large
compared with that in vacuum!!
two main sources are

- **experimental error**
- **neutron distribution ambiguities**

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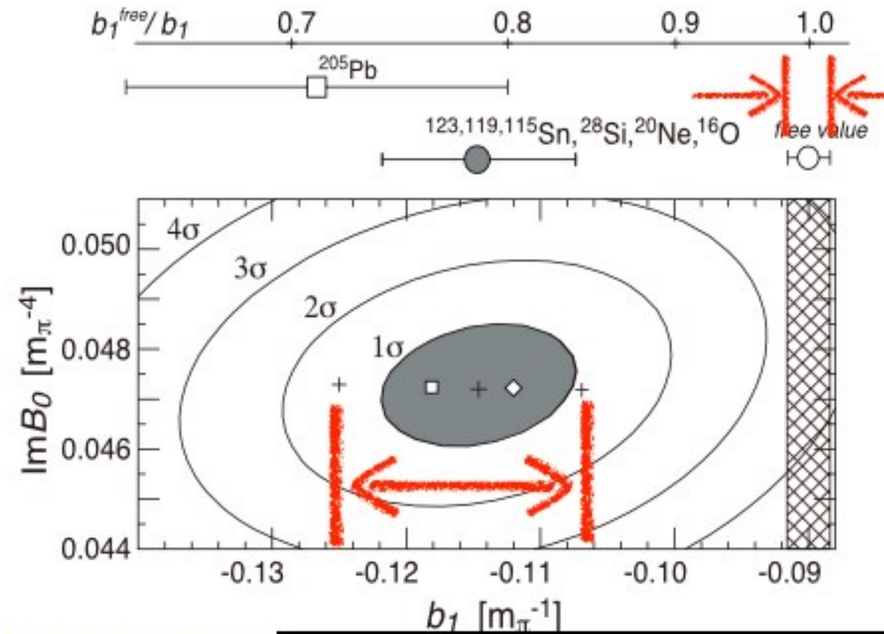

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- **neutron distribution ambiguities**

$$\frac{b_1^{\mathrm{free}}}{b_1} = 0.78 \pm$$

cf. theo

To extract b_1 with higher precision

improve resolution / calibration

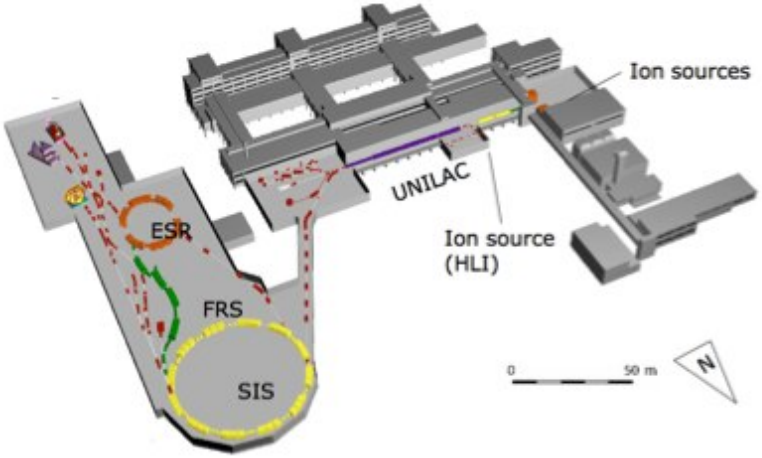
More isotopes

(ii) Experiment performed in 2014 at RIKEN

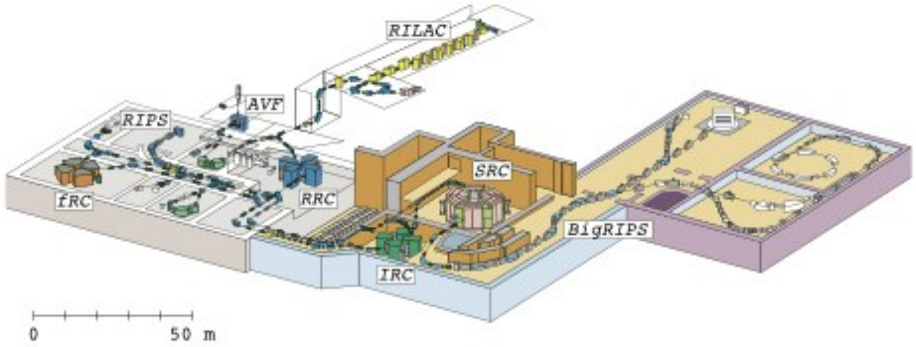
First production experiment in 2014 @ RIKEN (11 days)

Comparison between RIBF and GSI

GSI facilities



RIKEN facilities

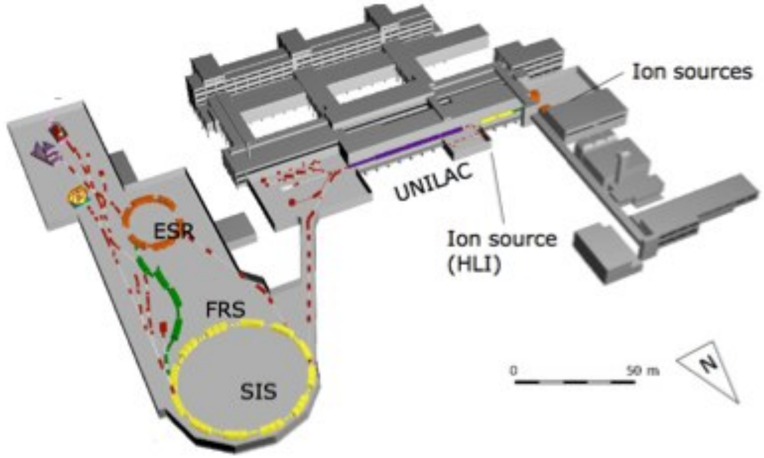


	GSI (FRS)	RIBF (BigRIPS)	Improvement
intensity	~ 10^{11}/ 6 s (1 spill)	~ 10^{12}/ s	**× 60**
angular acceptance (H / V)	15 / 10 mrad	40 / 60 mrad	×16
resolution (FWHM)	400 keV	**~ 600 keV**	↘ factor 1.5 ~ 2

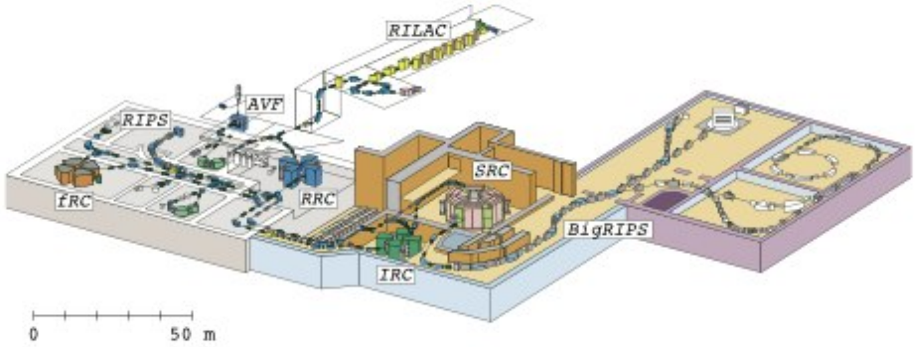
(ii) Experiment performed in 2014 at RIKEN

Comparison between RIBF and GSI

GSI facilities



RIKEN facilities

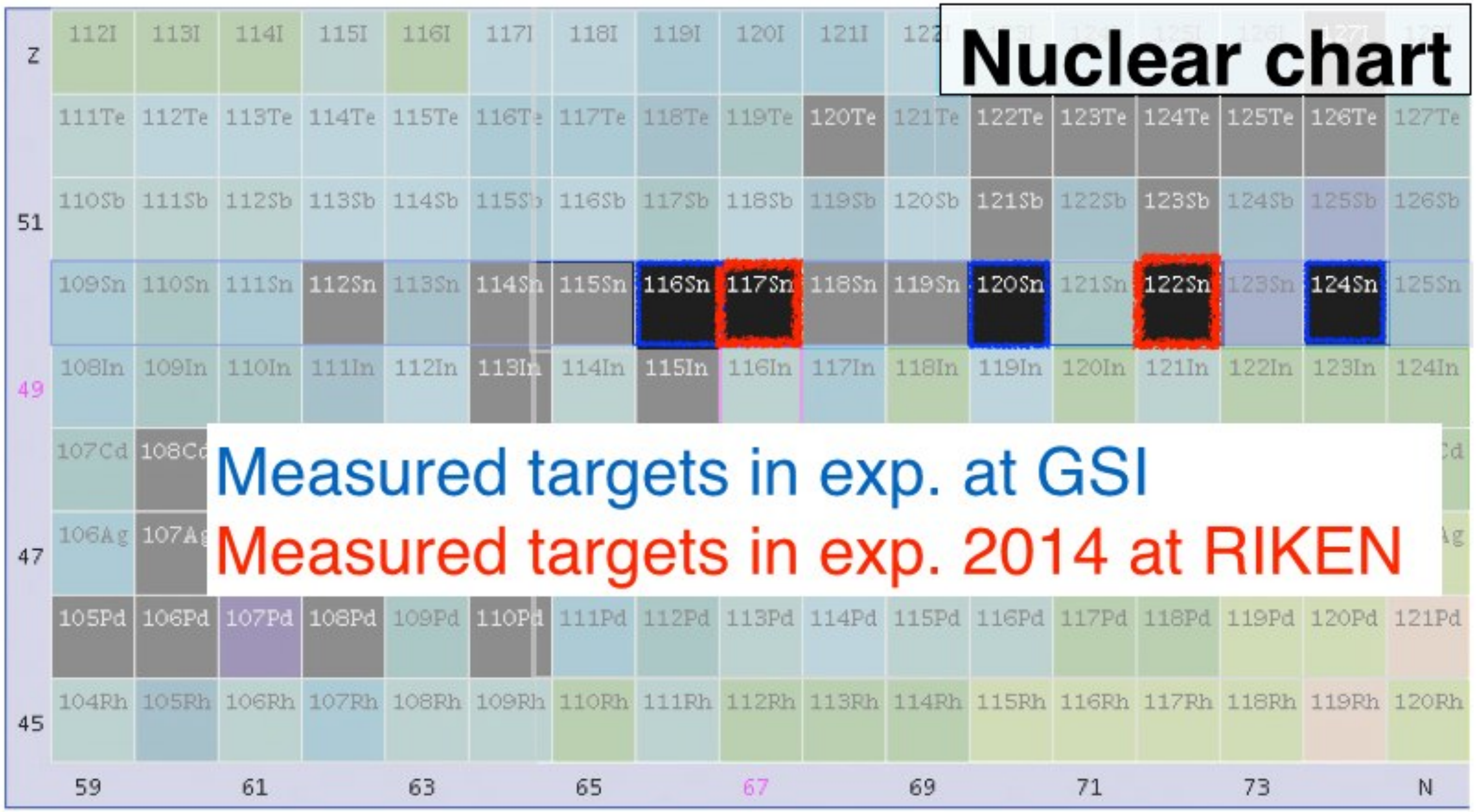


	GSI (FRS)	RIBF (BigRIPS)	Improvement
intensity	~ 10^{11}/ 6 s (1 spill)	~ 10^{12}/ s	**× 60**
angular acceptance (H / V)	15 / 10 mrad	40 / 60 mrad	×16
resolution (FWHM)	400 keV	**200 ~ 300 keV**	improve

by dispersion matching optics

Targets in the experiment at RIKEN

NuDat



Nuclear chart

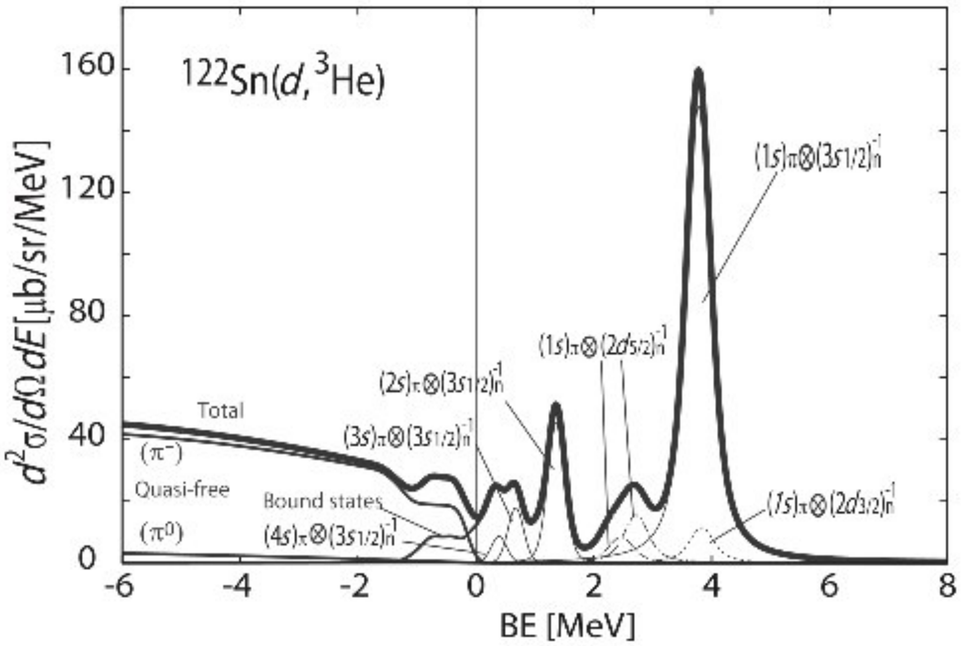
Z	112I	113I	114I	115I	116I	117I	118I	119I	120I	121I	122I	123I	124I	125I	126I	127I	128I
	111Te	112Te	113Te	114Te	115Te	116Te	117Te	118Te	119Te	120Te	121Te	122Te	123Te	124Te	125Te	126Te	127Te
51	110Sb	111Sb	112Sb	113Sb	114Sb	115Sb	116Sb	117Sb	118Sb	119Sb	120Sb	121Sb	122Sb	123Sb	124Sb	125Sb	126Sb
	109Sn	110Sn	111Sn	112Sn	113Sn	114Sn	115Sn	116Sn	117Sn	118Sn	119Sn	120Sn	121Sn	122Sn	123Sn	124Sn	125Sn
49	108In	109In	110In	111In	112In	113In	114In	115In	116In	117In	118In	119In	120In	121In	122In	123In	124In
	107Cd	108C															Cd
47	106Ag	107A															Ag
	105Pd	106Pd	107Pd	108Pd	109Pd	110Pd	111Pd	112Pd	113Pd	114Pd	115Pd	116Pd	117Pd	118Pd	119Pd	120Pd	121Pd
45	104Rh	105Rh	106Rh	107Rh	108Rh	109Rh	110Rh	111Rh	112Rh	113Rh	114Rh	115Rh	116Rh	117Rh	118Rh	119Rh	120Rh
	59		61		63		65		67		69		71		73		N

Measured targets in exp. at GSI

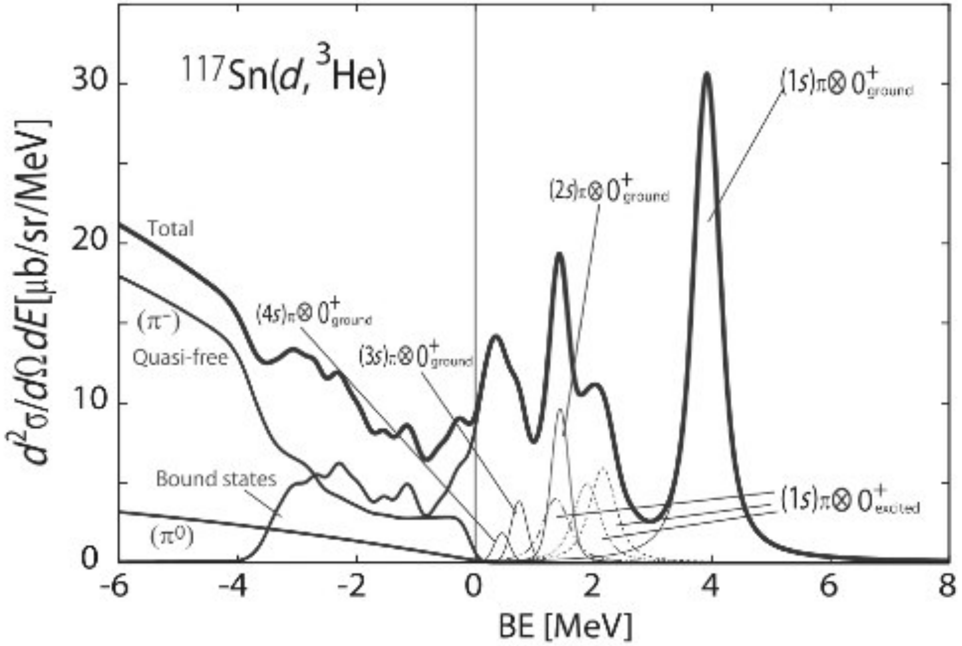
Measured targets in exp. 2014 at RIKEN

Expected excitation spectra

^{122}Sn: relatively large cross section



^{117}Sn: first odd-A target



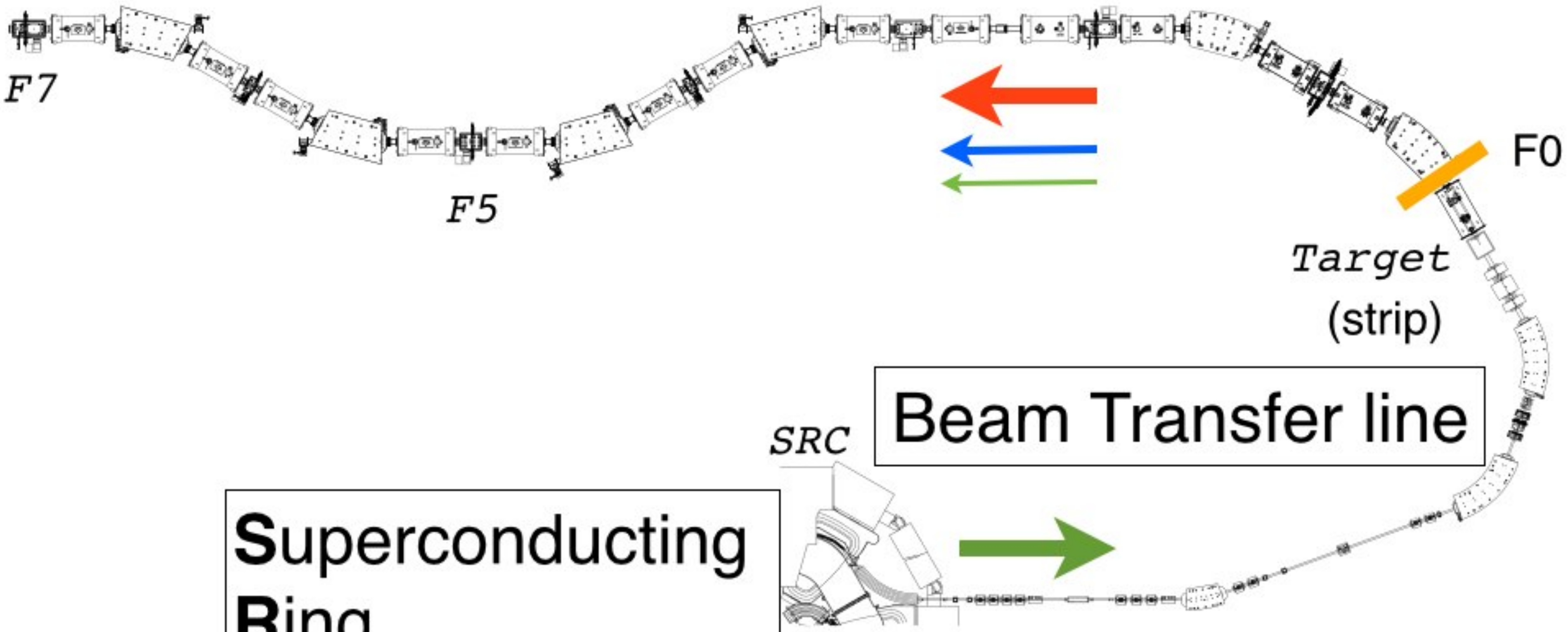
N. Ikeno et al., Prog. Theor. Exp. Phys. (2013) 2013 (6): 063D01.

Experimental setup

RIKEN Fragment Separator
BigRIPS

^{3}He ~ 10^2Hz
(signal)

p ~ 10^5 Hz
(break up/ background)



Beam Transfer line

Superconducting
Ring
Cyclotron

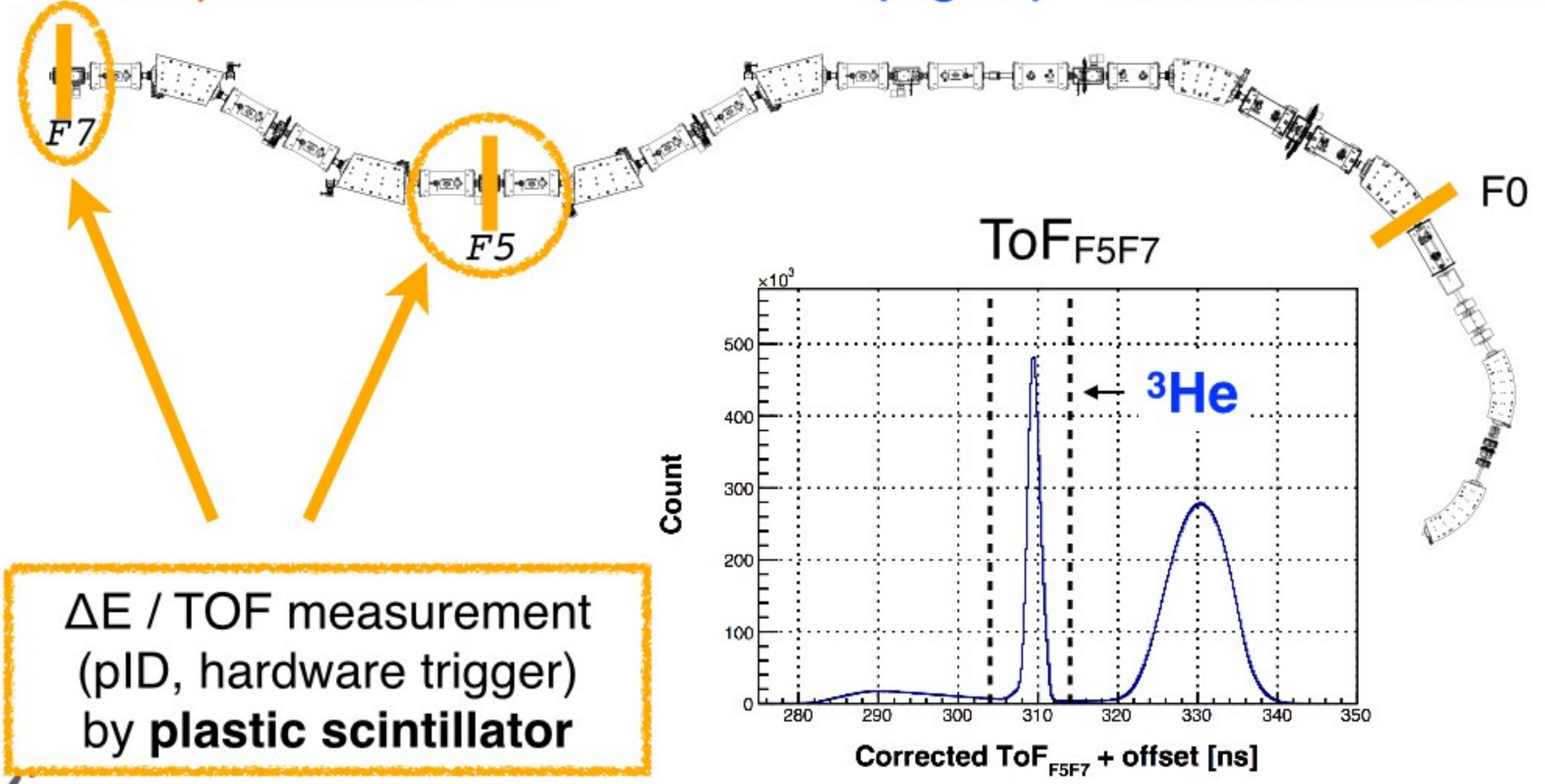
d beam 250 MeV/u
~ 10^{12} /s

Experimental setup

large part of *p*:
swept out in F5 - F7

^{3}He ~ 10^{2}Hz
(signal)

p ~ 10^{5} Hz
(break up/ background)



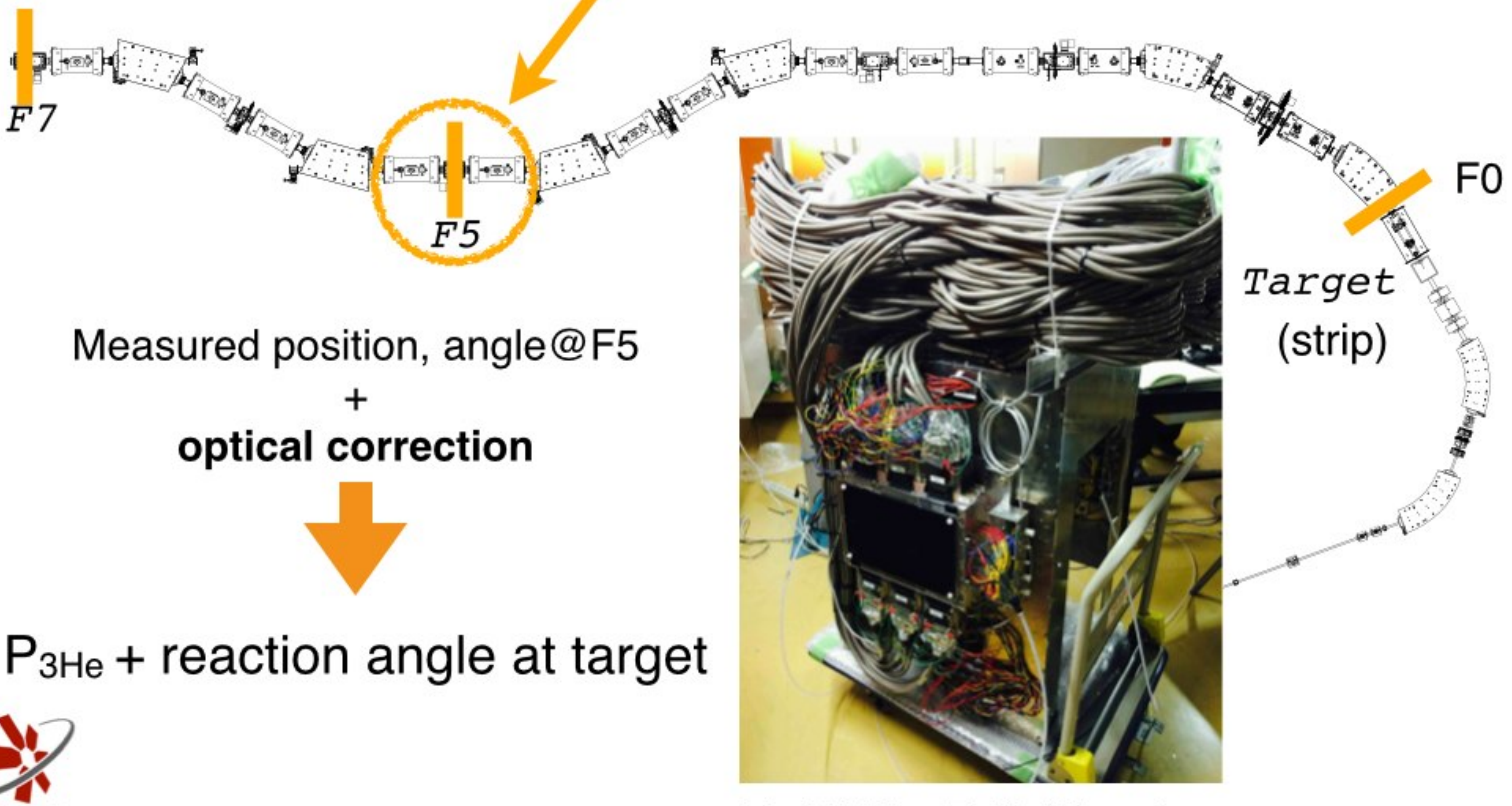
ΔE / TOF measurement
(pID, hardware trigger)
by **plastic scintillator**

Experimental setup

Tracking by **MWDC**

^{3}He ~ 10^{2}Hz
(signal)

p ~ 10^{5} Hz
(break up/ background)



Measured position, angle@F5
+
optical correction

P_{3He} + reaction angle at target

Multi Wire Drift Chamber

Ion optics (design)

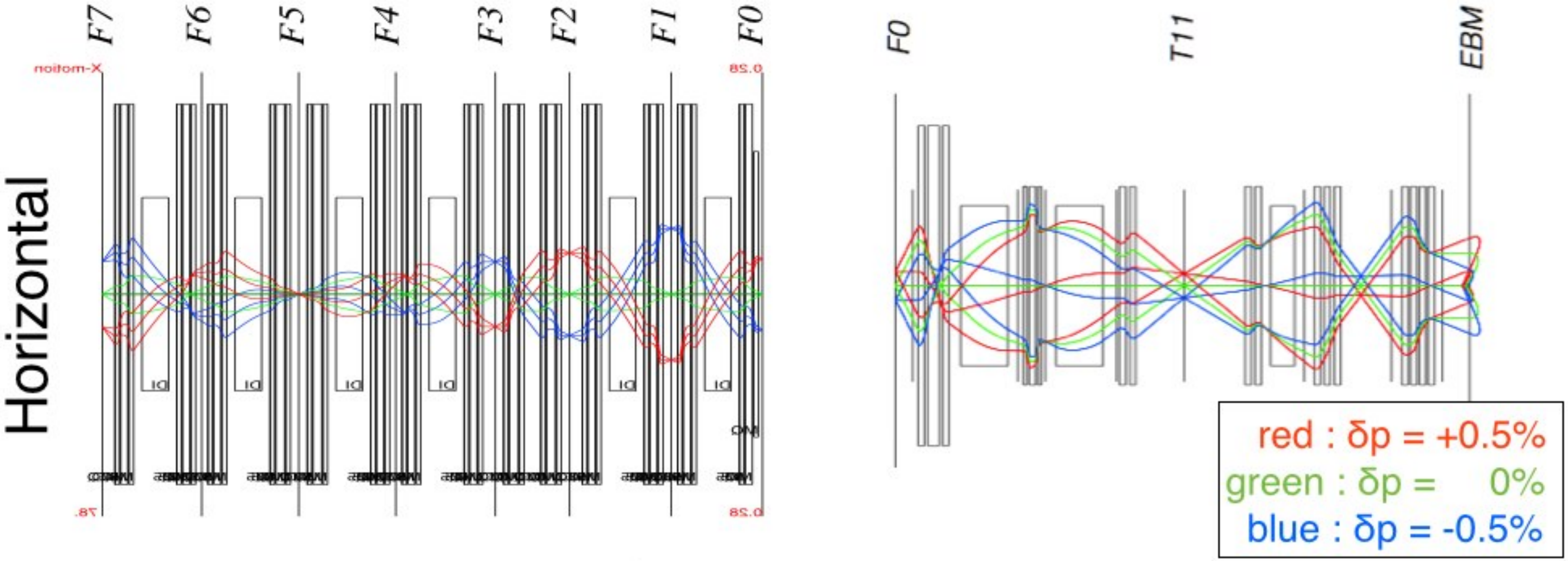
Dispersion matching:
Eliminate contribution of beam momentum spread

$$\underset{\text{F5}}{\begin{pmatrix} x_{fp} \\ \theta_{fp} \\ \delta p_{fp} \end{pmatrix}} = \overset{\boxed{\text{Spectrometer (BigRIPS)}}}{\begin{pmatrix} S_{11} & S_{12} & S_{16} \\ S_{21} & S_{22} & s_{26} \\ 0 & 0 & 1 \end{pmatrix}} \overset{\boxed{\text{reaction}}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & C \end{pmatrix}} \overset{\boxed{\text{Analyzer (Beam Transfer Line)}}}{\begin{pmatrix} A_{11} & A_{12} & A_{16} \\ A_{21} & A_{22} & A_{26} \\ 0 & 0 & 1 \end{pmatrix}} \underset{\text{inside SRC}}{\begin{pmatrix} x_0 \\ \theta_0 \\ \delta p_0 \end{pmatrix}}$$

*C: kinematical factor = 1.31

$$x_{fp} = \cdots + (\underline{S_{11}}\,\underline{A_{16}} + \underline{C}\,\underline{S_{16}})\underline{\underline{\delta p_0}}$$

Ion optics (design)



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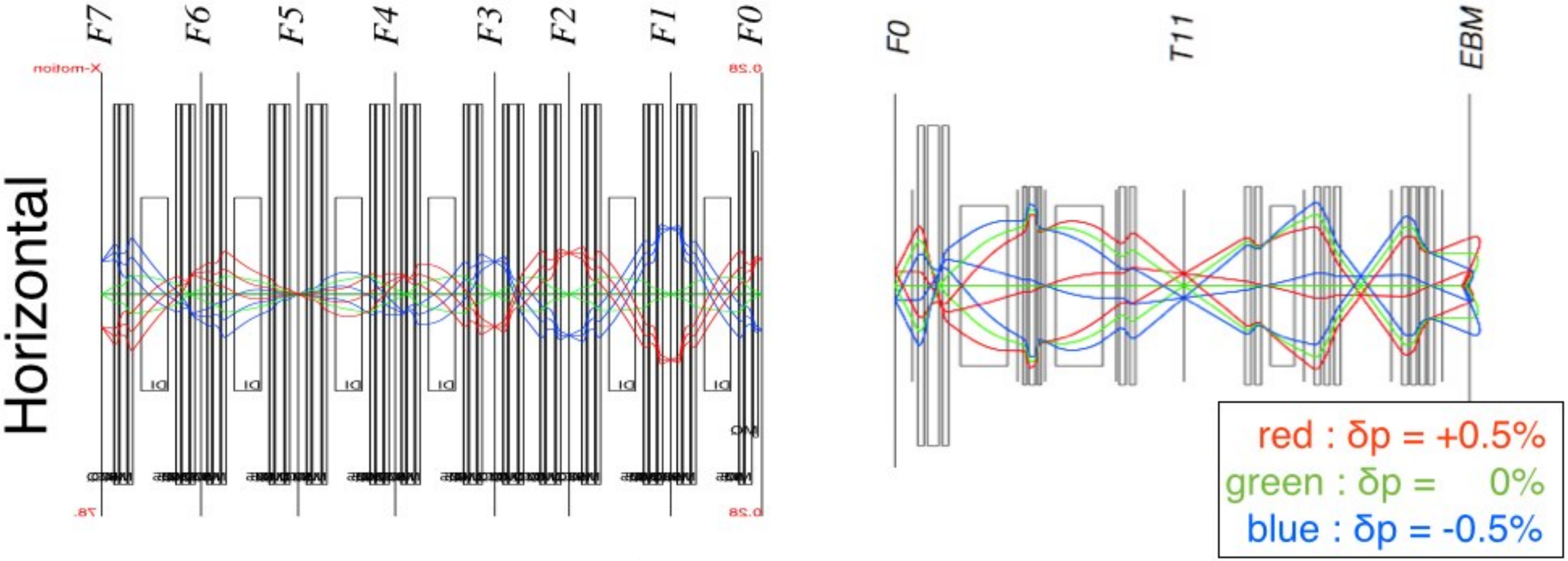
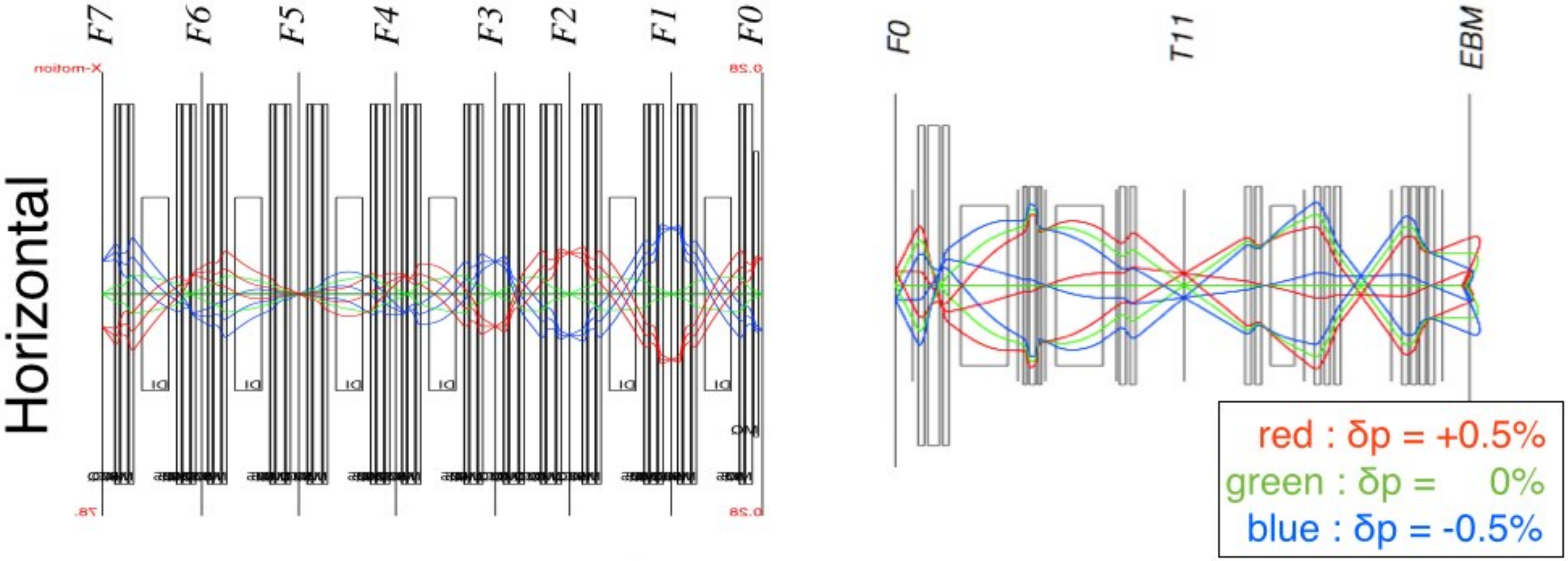


$$x_{fp} = \cdots + (\underline{S_{11}}\,\underline{A_{16}} + \underline{C}\,\underline{S_{16}})\underline{\delta p_0}$$

magnification of BigRIPS

position at F0

Ion optics (design)



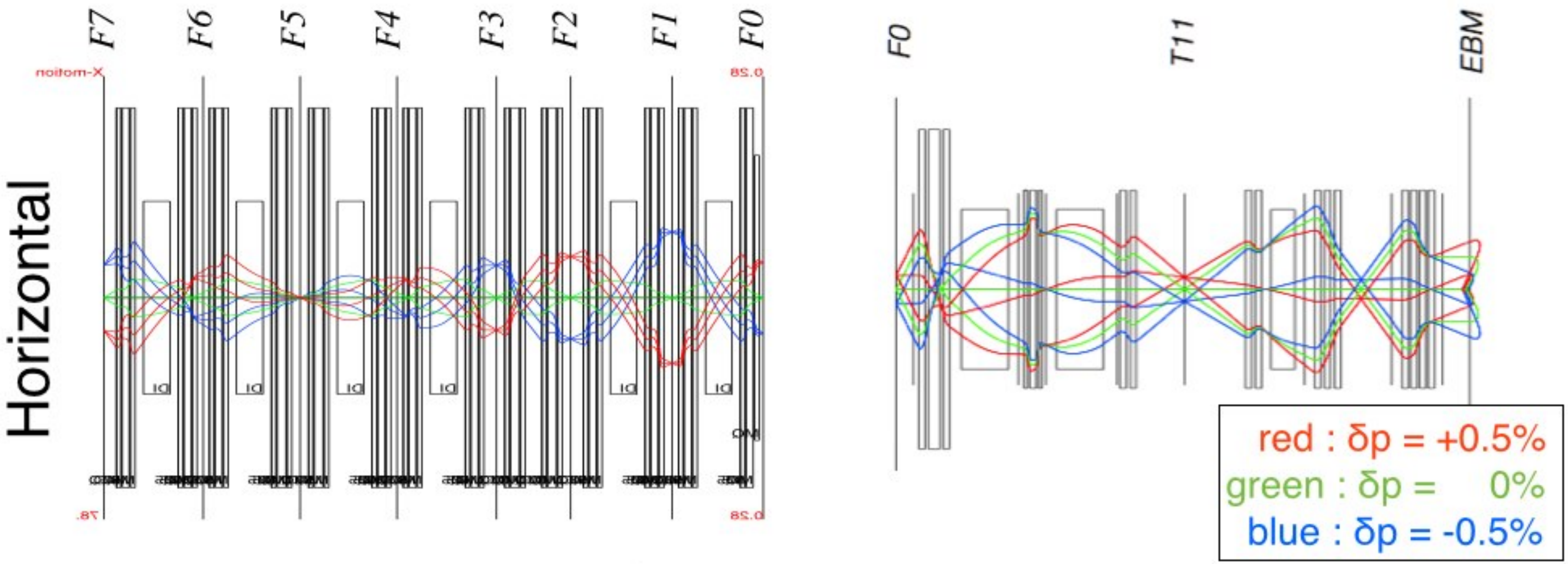
red : δp = +0.5%
green : δp = 0%
blue : δp = -0.5%

$$x_{fp} = \cdots + (\underline{S_{11}}\,\underline{A_{16}} + \underline{C}\,\underline{S_{16}})\underline{\underline{\delta p_0}}$$

δ at F0

dispersion of BigRIPS

Ion optics (design)



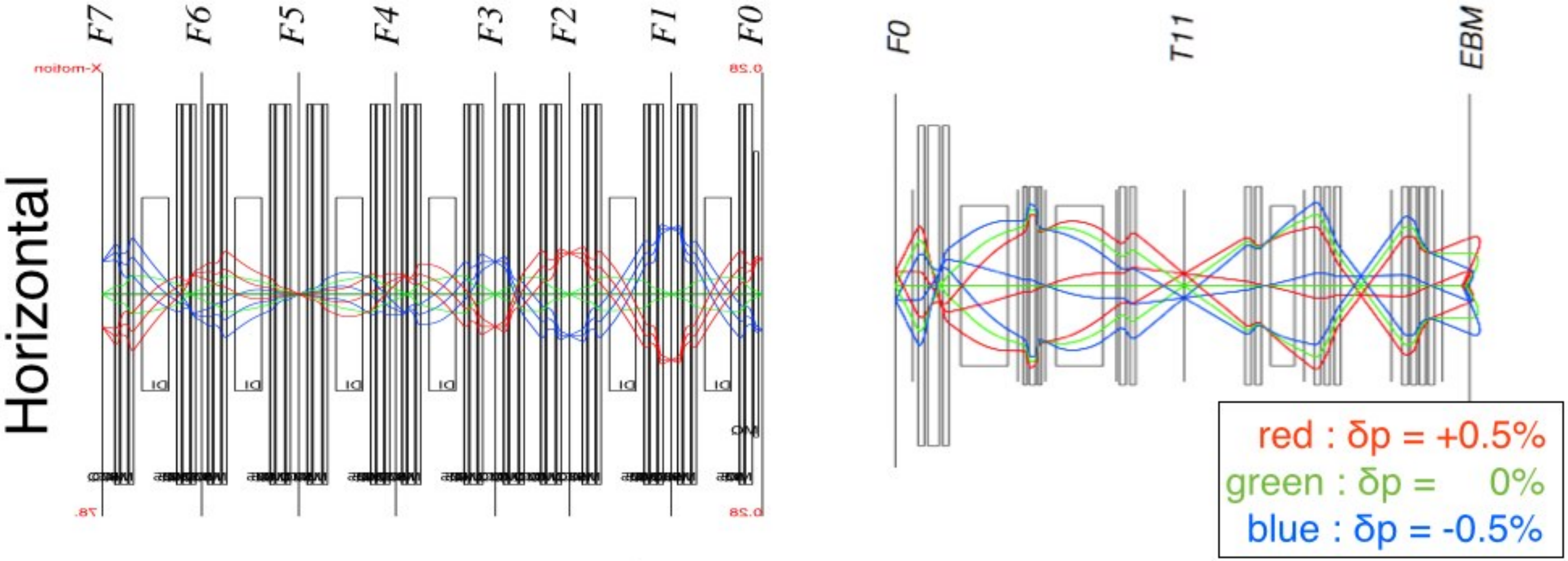
red : δp = +0.5%
green : δp = 0%
blue : δp = -0.5%

$$x_{fp} = \cdots + (\underline{S_{11}}\,\underline{A_{16}} + \underline{C}\,\underline{S_{16}})\underline{\underline{\delta p_0}}$$

← → **Cancel out**

same Q value
different primary beam Energy → same position at F5

Ion optics (design)



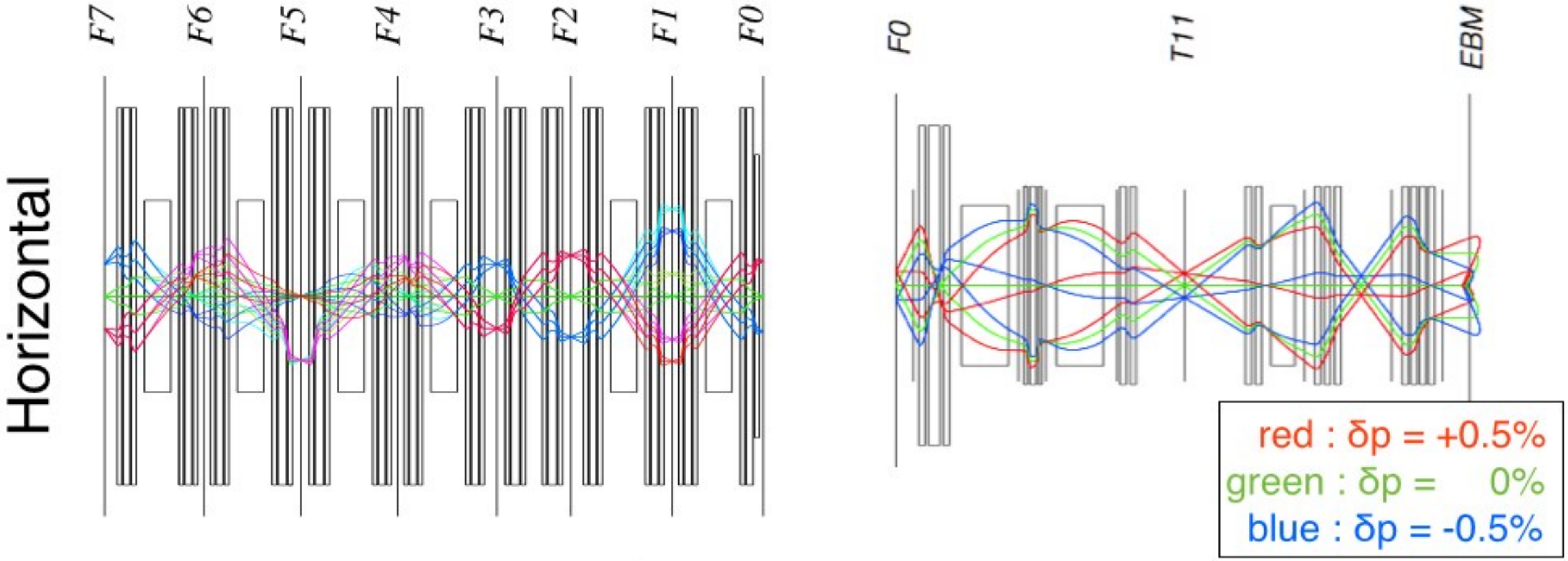
$$x_{fp} = \cdots + (\underline{S_{11}}\,\underline{A_{16}} + \underline{C}\,\underline{S_{16}})\underline{\underline{\delta p_0}}$$

Cancel out

design values: S_{11} = -1.8 **A_{16} = 44.6 mm/%**

C = 1.31 S_{16} = 62 mm/%

Ion optics (design)

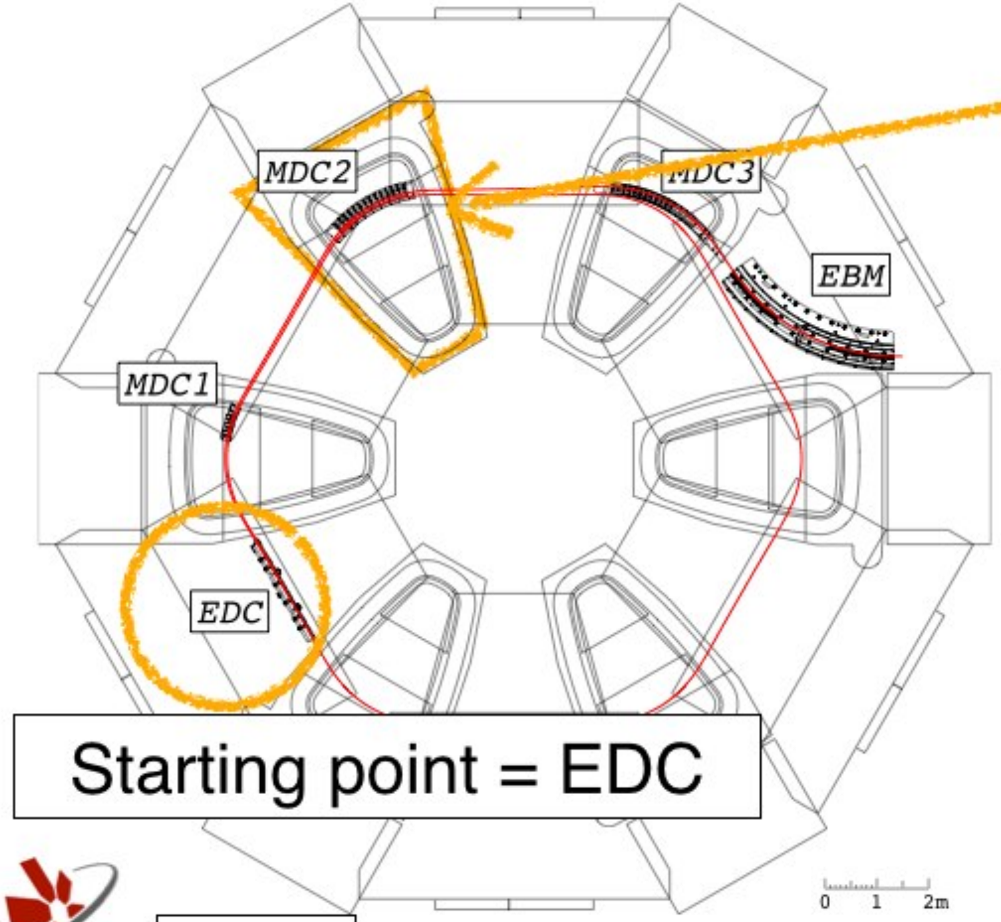


$$x_{fp} = \cdots + (\underline{S_{11}}\,\underline{A_{16}} + \underline{C}\,\underline{S_{16}})\underline{\underline{\delta p_0}}$$

different Q value → different position at F5

Ion Optics inside SRC (calc.)

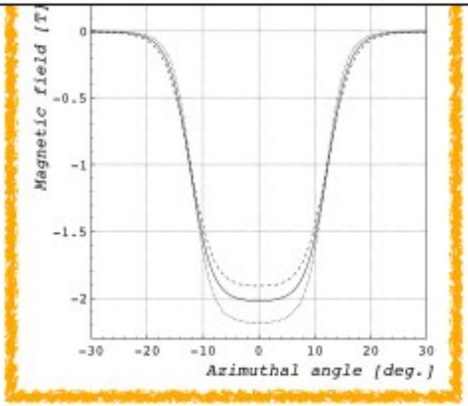
Dispersion matching using primary beam



Starting point = EDC

SRC

magnetic field in the magnet



calculate the transfer matrix using Runge-Kutta method

$$\begin{pmatrix} (x|x) & (x|a) & (x|y) & (x|b) & (x|\delta) \\ (a|x) & (a|a) & (a|y) & (a|b) & (a|\delta) \\ (y|x) & (y|a) & (y|y) & (y|b) & (y|\delta) \\ (b|x) & (b|a) & (b|y) & (b|b) & (b|\delta) \end{pmatrix}_{\mathrm{EDC}\rightarrow\mathrm{EBM}} = \begin{pmatrix} -1.00 & -3.35 & 0.0 & 0.0 & 76.9 \\ 0.30 & -0.01 & 0.0 & 0.0 & -25.4 \\ 0.0 & 0.0 & -1.03 & -1.75 & 0.0 \\ 0.0 & 0.0 & -0.09 & -1.12 & 0.0 \end{pmatrix}$$

Key points of the experiment for better resolution

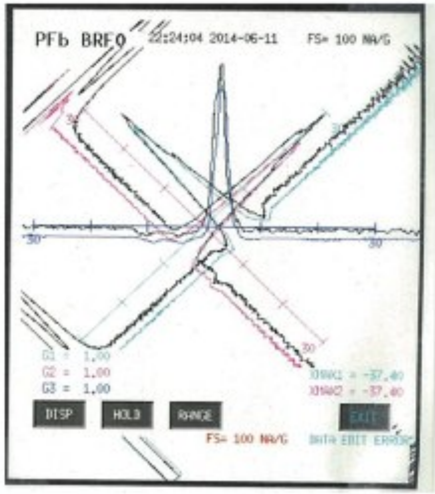
① Tuning of the beam transfer line optics
→ realize dispersion matching

② Reduce the primary beam emittance / δp

① × ② ⇒ contribution of δp on resolution

① Tuning of the beam transfer line optics

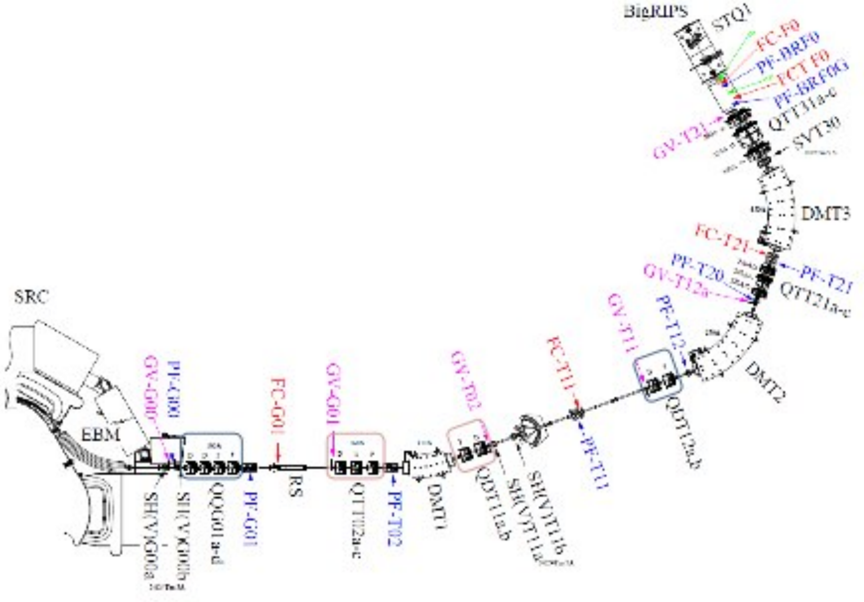
beam envelope measured by profile monitor



Diagnostics in BT line

- ~ 10 profile monitors (wires)
- **No tracker**

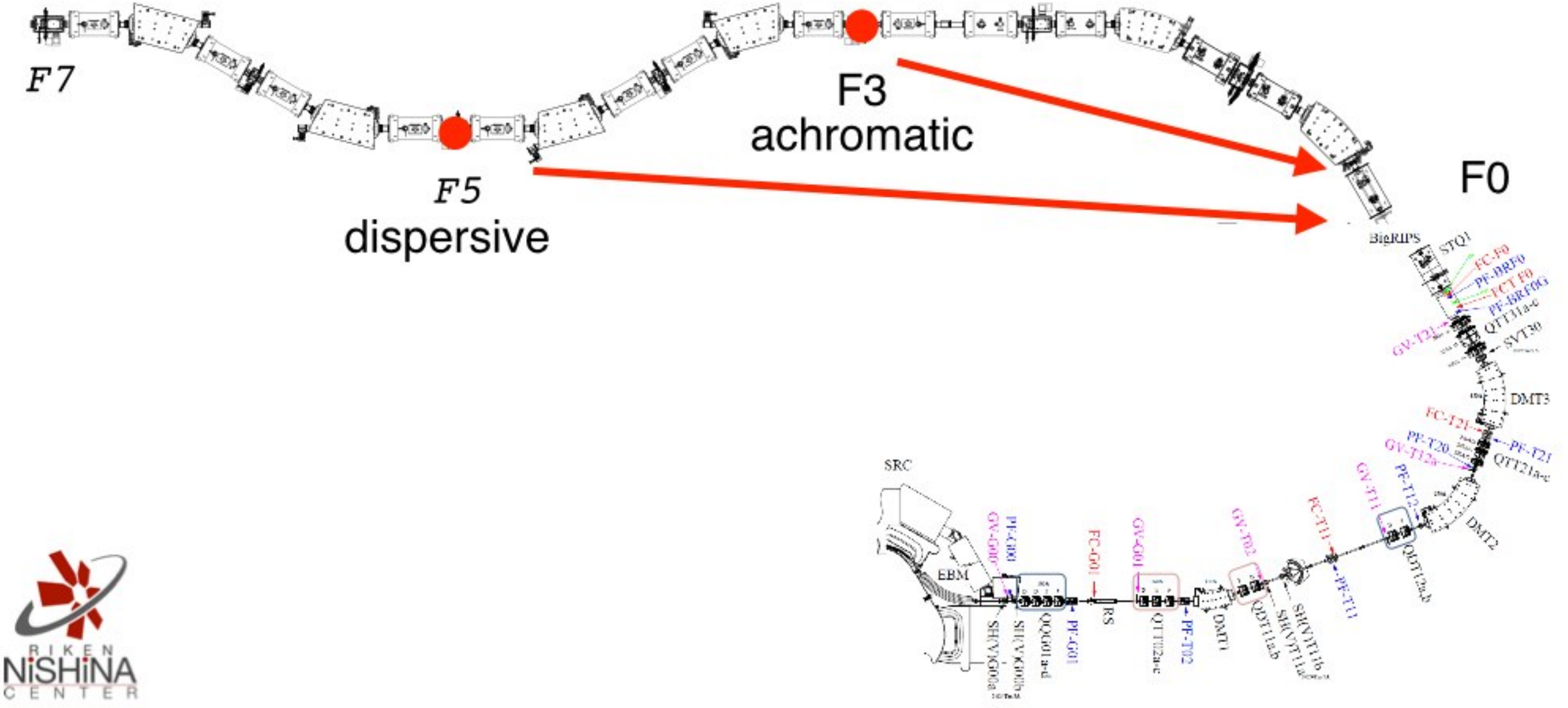
not enough to measure
dispersion / other transfer matrix



① Tuning of the beam transfer line optics

Use BigRIPS as a diagnostics of BT line

- measure the position / angle at F3 and F5 focal plane
- trace back to F0



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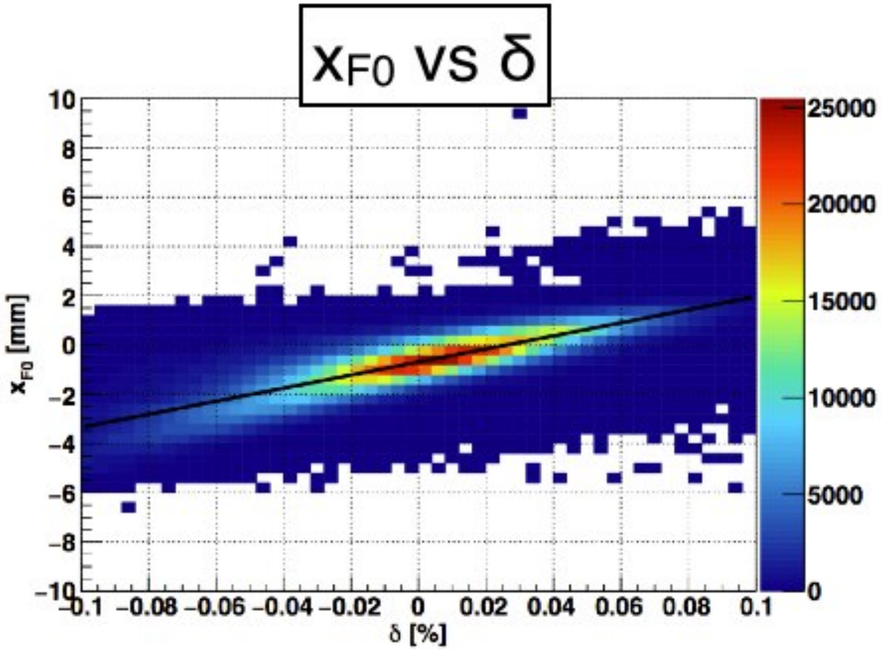


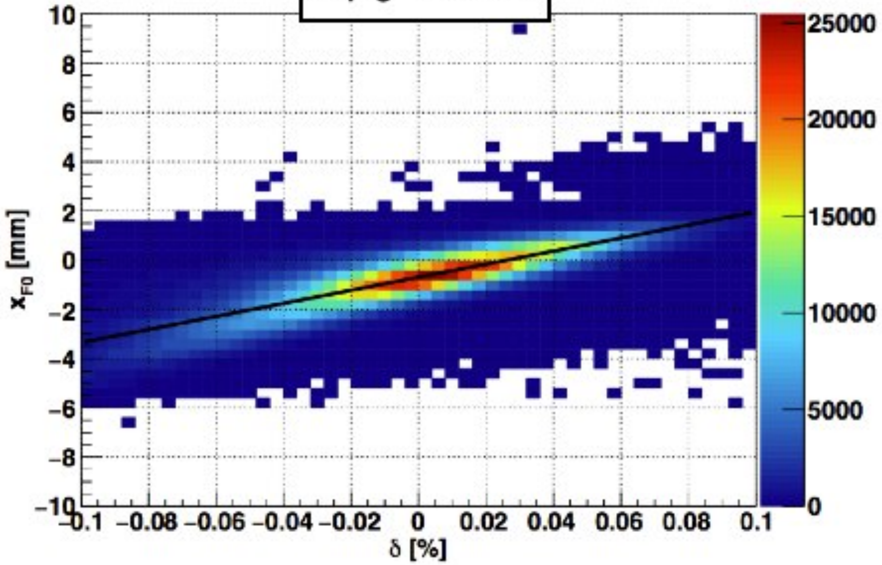
measured dispersion in BT line

① Tuning of the beam transfer line optics

Use BigRIPS as a diagnostics of BT line

- measure the position / angle at F3 and F5 focal plane
- trace back to F0

x_{F0} vs δ



measured dispersion in BT line

→ 24 mm/% !!!

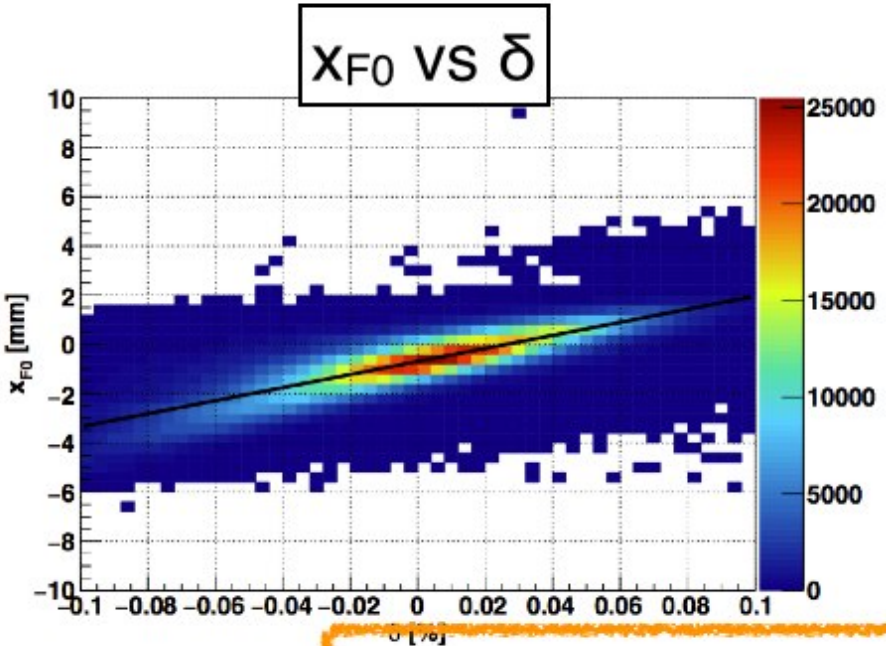
(cf. designed value: 44.6 mm/%)

The difference may be caused by the optics inside SRC

① Tuning of the beam transfer line optics

Use BigRIPS as a diagnostics of BT line

- measure the position / angle at F3 and F5 focal plane
- trace back to F0



measured dispersion in BT line
→ 24 mm/% !!!

(cf. designed value: 44.6 mm/%)

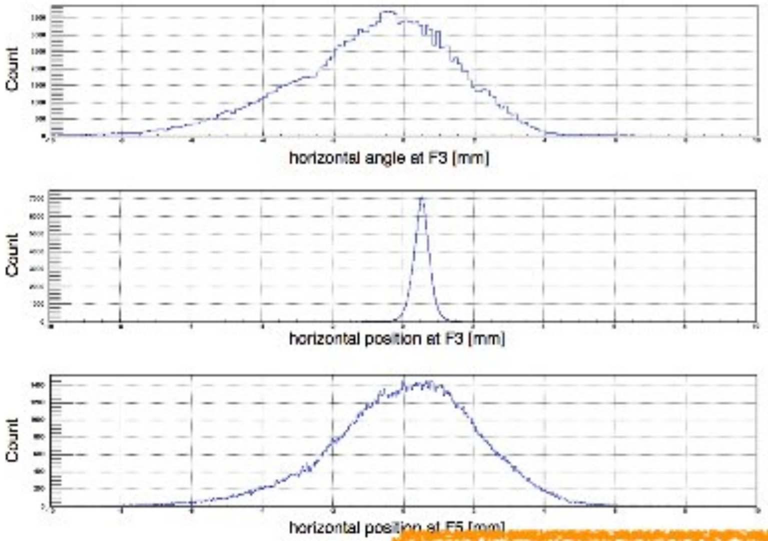
The difference may be caused by the optics inside SRC

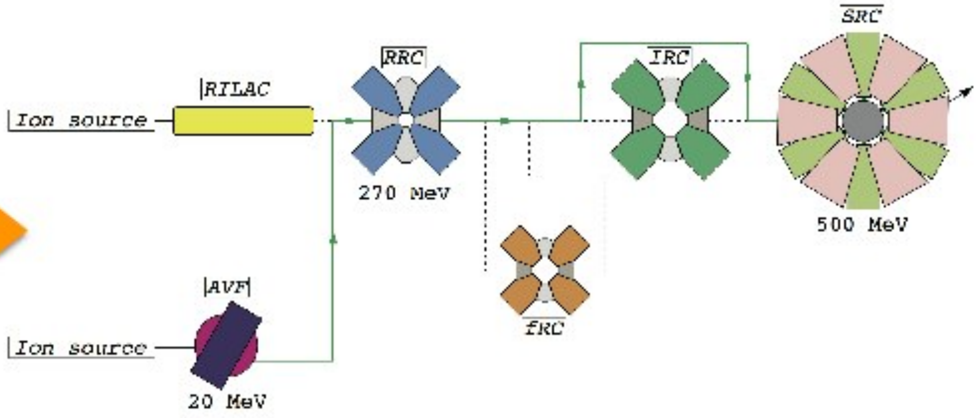
After phenomenological tuning,
dispersion is improved to be **28 mm/%**
⇔ reduce the contribution of δp by ~ 50%

② Reduce the primary beam emittance / δp

Use BigRIPS as a diagnostics of Primary beam

- position and angle distribution at achromatic focal plane (F3)
  → beam emittance
- position distribution at dispersive focal plane (F5)
  → δp





feedback to the accelerator team
to tune accelerator parameters / slit condition
achieve **0.2 × 2.0 mm・mrad / 0.03 % (RMS)**

Contribution of δp on resolution

① Tuning of the beam transfer line optics
→ dispersion 28 mm/% ⇔ reduce the contribution by ~ 50%

② Reduce the primary beam emittance / δp
→ achieve 0.2 × 2.0 mm・mrad / 0.03 % (RMS)

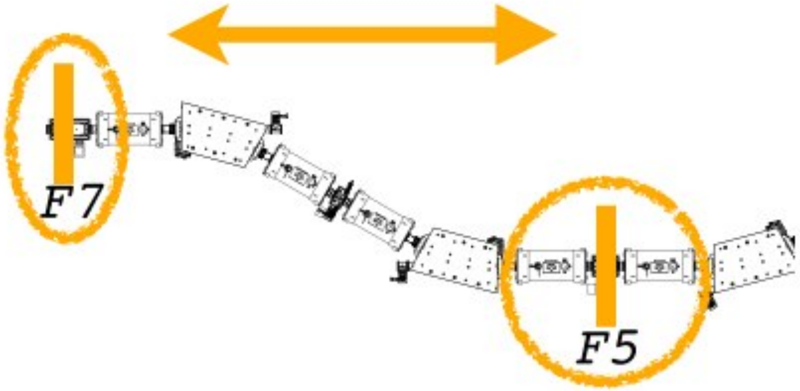
① × ② ⇒ **~ 220 keV (FWHM)**

acceptable compared with $\Gamma_{1s} \sim 300$ keV
※ With other contributions, resolution is estimated
to be 250 ~ 400 keV (position dependent)

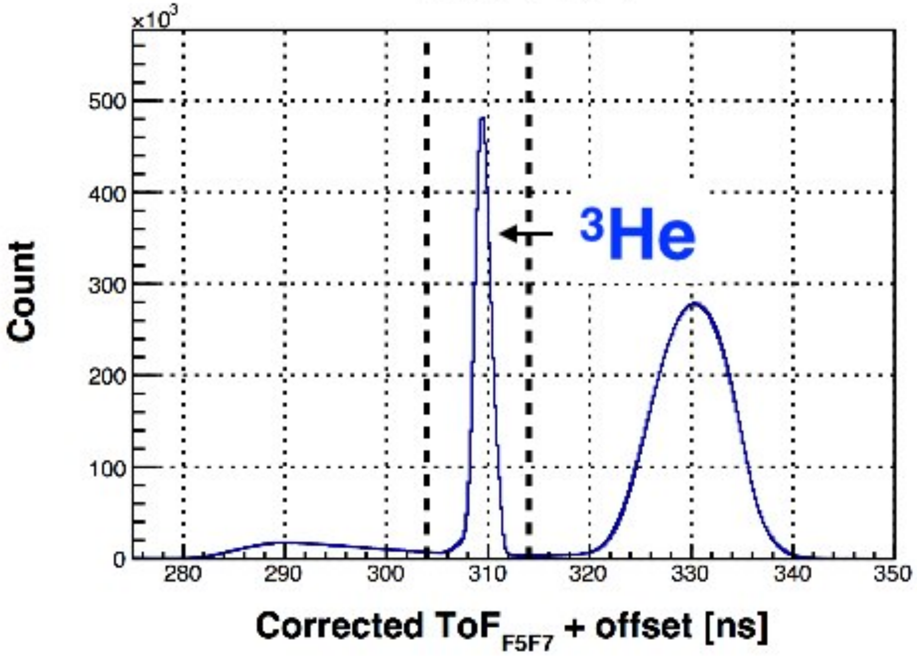
(iii) Data analysis (pID / optics / decomposition)

- Particle identification
- Optics analysis
- Decomposition of Eex spectra

Particle identification



ToF_{F5F7}



^{3}He is well separated only with ToF.
Using additional information of

- Eloss in MWDC (as ToT)
- relative timing with RF of SRC

We achieve

efficiency : ≧ **98 %**
purity : ≧ **99.5 %**

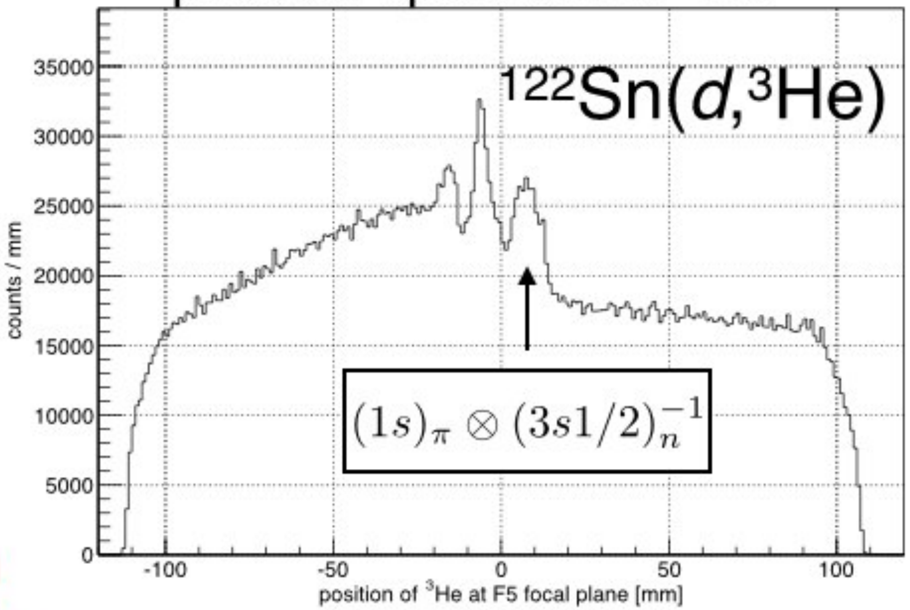
Optics analysis

To convert the position spectrum to Eex spectra, we should

① measure the **dispersion**

② correct the **optical higher order aberration**

position spectrum of ^{3}He



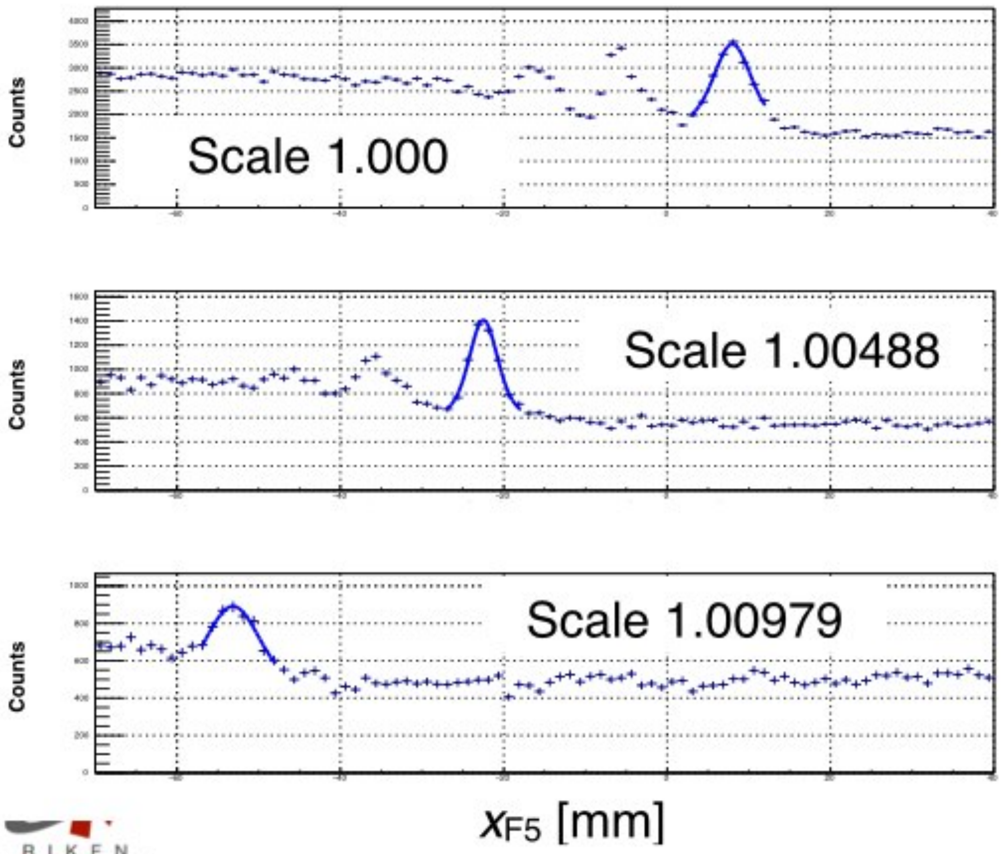
To analyze the optics,
we used the peak of $(1s)_\pi \otimes (3s1/2)_n^{-1}$

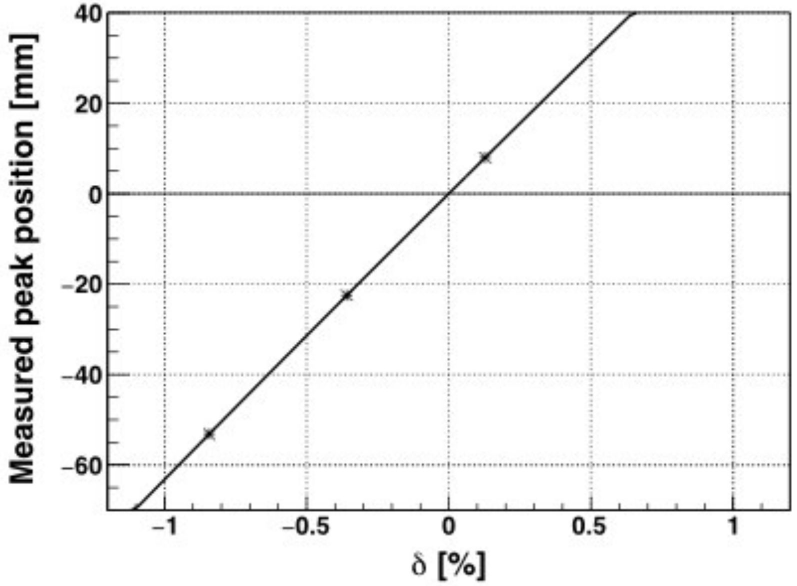
- sufficient strength in forward θ
- no angle dependence of Eex

① Dispersion of BigRIPS

$$\delta = (P^{1s}_{^3He} - P_{\text{BigRIPS}})/P_{\text{BigRIPS}} * 100.$$

scale BigRIPS by 1.000 (default), 1.00488, 1.00979

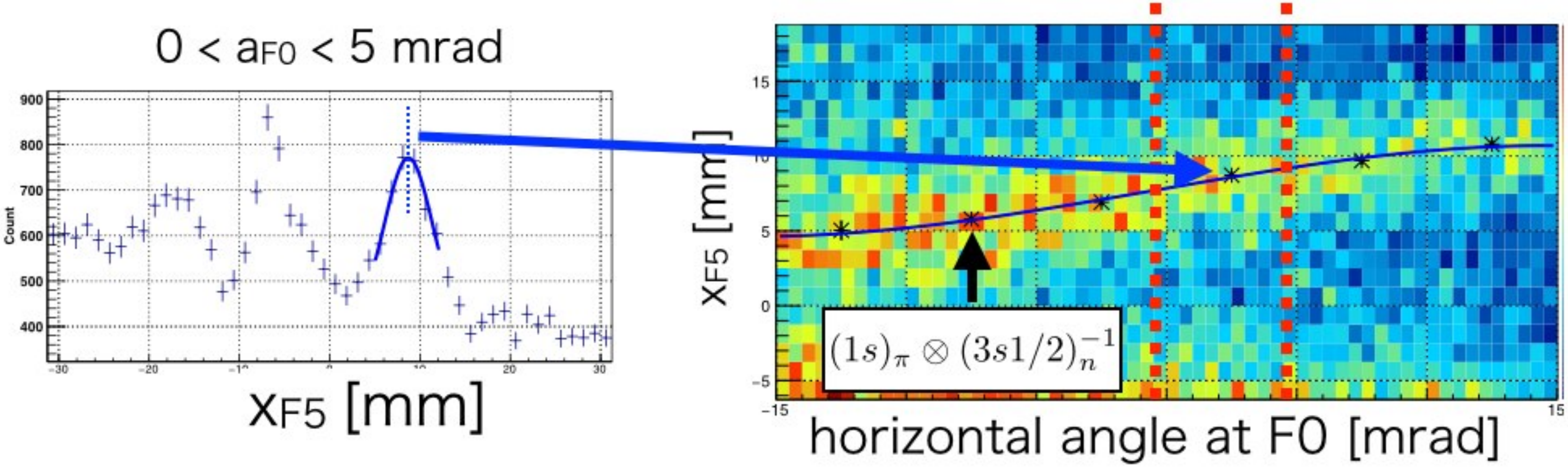




$$x_{F5} = \alpha\,\delta + \beta\,\delta^2$$

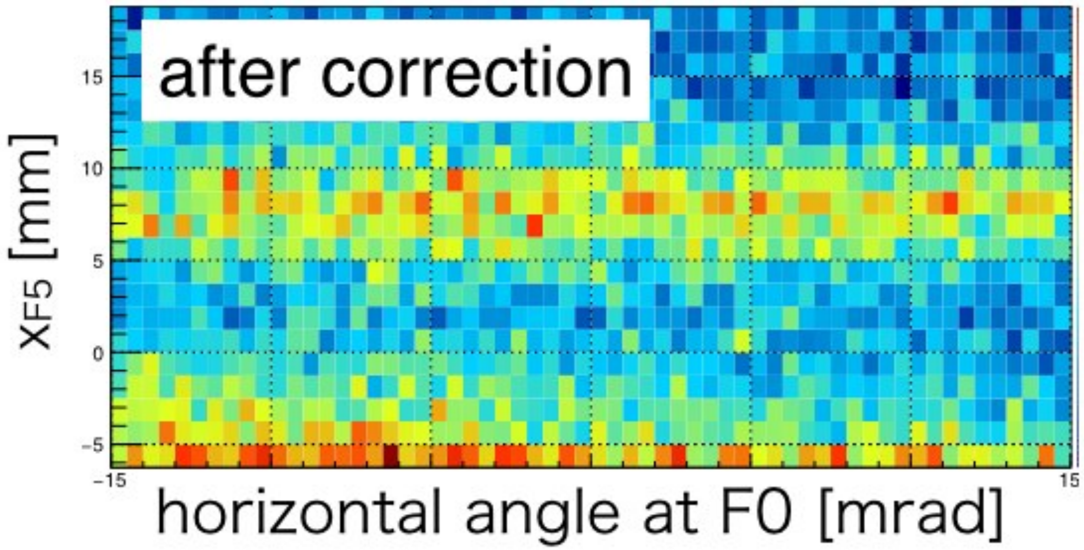
Dispersion

② Correct optical higher order aberration


$0 < a_{F0} < 5$ mrad

$(1s)_\pi \otimes (3s1/2)_n^{-1}$

vertical angular aberration is also corrected

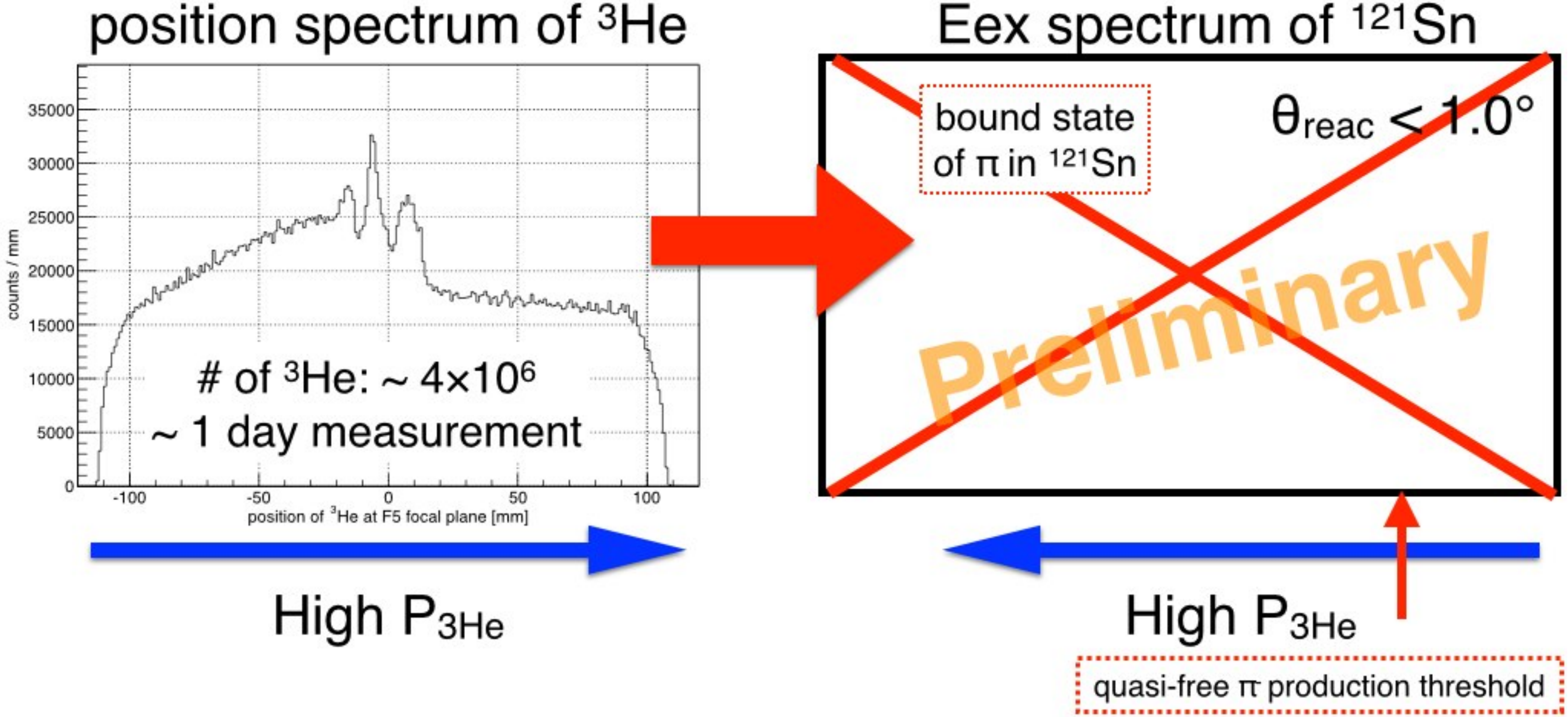

after correction

*data for the evaluation separated from the production run

Finally, we include 15 elements of transfer matrix for the analysis.

matrix element	deduced values from exp. data	calculated values
$(x_{\mathrm{F5}}\|a_{\mathrm{F0}})$ [mm/mrad]	$\mathbf{(+2.75 \pm 0.2) \times 10^{-1}}$	$+1.93 \times 10^{-1}$
$(x_{\mathrm{F5}}\|a^2_{\mathrm{F0}})$ [mm/mrad^2]	$\mathbf{(-9.44 \pm 8.0) \times 10^{-4}}$	-1.37×10^{-3}
$(x_{\mathrm{F5}}\|a^3_{\mathrm{F0}})$ [mm/mrad^3]	$\mathbf{(-4.41 \pm 0.9) \times 10^{-4}}$	-7.10×10^{-4}
$(x_{\mathrm{F5}}\|b_{\mathrm{F0}})$ [mm/mrad]	$\mathbf{(+4.87 \pm 6.1) \times 10^{-3}}$	0.00
$(x_{\mathrm{F5}}\|b^2_{\mathrm{F0}})$ [mm/mrad^2]	$\mathbf{(-8.45 \pm 4.0) \times 10^{-4}}$	-2.15×10^{-4}
$(x_{\mathrm{F5}}\|a_{\mathrm{F0}}b^2_{\mathrm{F0}})$ [mm/mrad^3]	$\mathbf{(-2.53 \pm 0.5) \times 10^{-4}}$	-3.01×10^{-4}
$(x_{\mathrm{F5}}\|a_{\mathrm{F0}}\delta)$ [mm/mrad/%]	$\mathbf{(+7.83 \pm 0.2) \times 10^{-1}}$	8.27×10^{-1}
$(x_{\mathrm{F5}}\|a^2_{\mathrm{F0}}\delta)$ [mm/mrad^2/%]	$\mathbf{(+6.74 \pm 1.9) \times 10^{-3}}$	$+1.28 \times 10^{-3}$
$(x_{\mathrm{F5}}\|\delta)$ [mm/%]	$\mathbf{+62.42 \pm 0.27}$	$+61.20$
$(x_{\mathrm{F5}}\|\delta^2)$ [mm/%^{2}]	$\mathbf{(-7.84 \pm 4.7) \times 10^{-1}}$	-8.34×10^{-1}
$(a_{\mathrm{F5}}\|a_{\mathrm{F0}})$[mrad/mrad]	$\mathbf{(-5.19 \pm 0.5) \times 10^{-1}}$	-5.48×10^{-1}
$(b_{\mathrm{F5}}\|b_{\mathrm{F0}})$[mrad/mrad]	$\mathbf{(-5.40 \pm 0.5) \times 10^{-1}}$	-6.39×10^{-1}
$(a_{\mathrm{F5}}\|a_{\mathrm{F0}}\delta)$[mrad/mrad/%]	–	$\mathbf{-3.72 \times 10^{-2}}$
$(b_{\mathrm{F5}}\|b_{\mathrm{F0}}\delta)$[mrad/mrad/%]	–	$\mathbf{-6.79 \times 10^{-2}}$
$(b_{\mathrm{F5}}\|b_{\mathrm{F0}}\delta^2)$[mrad/mrad/%^{2}]	–	$\mathbf{+5.29 \times 10^{-2}}$

Conversion from position to Eex



position spectrum of ^{3}He

of ^{3}He: ~ 4×10^{6}

~ 1 day measurement

High P_{3He}

Eex spectrum of ^{121}Sn

bound state of π in ^{121}Sn

$\theta_{reac} < 1.0°$

Preliminary

High P_{3He}

quasi-free π production threshold

The spectrum seems to achieve the best resolution among the past deeply-bound pionic atom experiment.

Decomposition of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.5°$

Preliminary

fit region

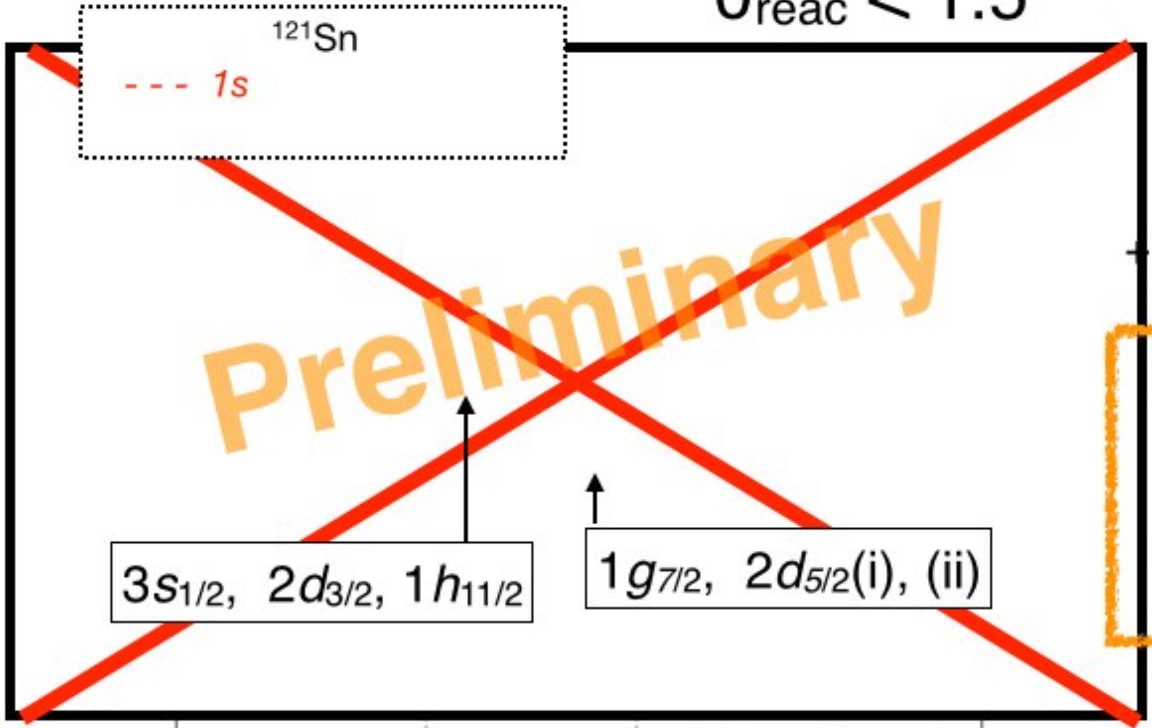
quasi-free π^- production threshold 139.57 MeV

green solid line : fit function with N_{eff} approach

The E_{ex} spectrum is fit by the function with several components
→ deduce binding energies and widths of pionic states

Decomposition of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.5°$



background (solid line / flat)

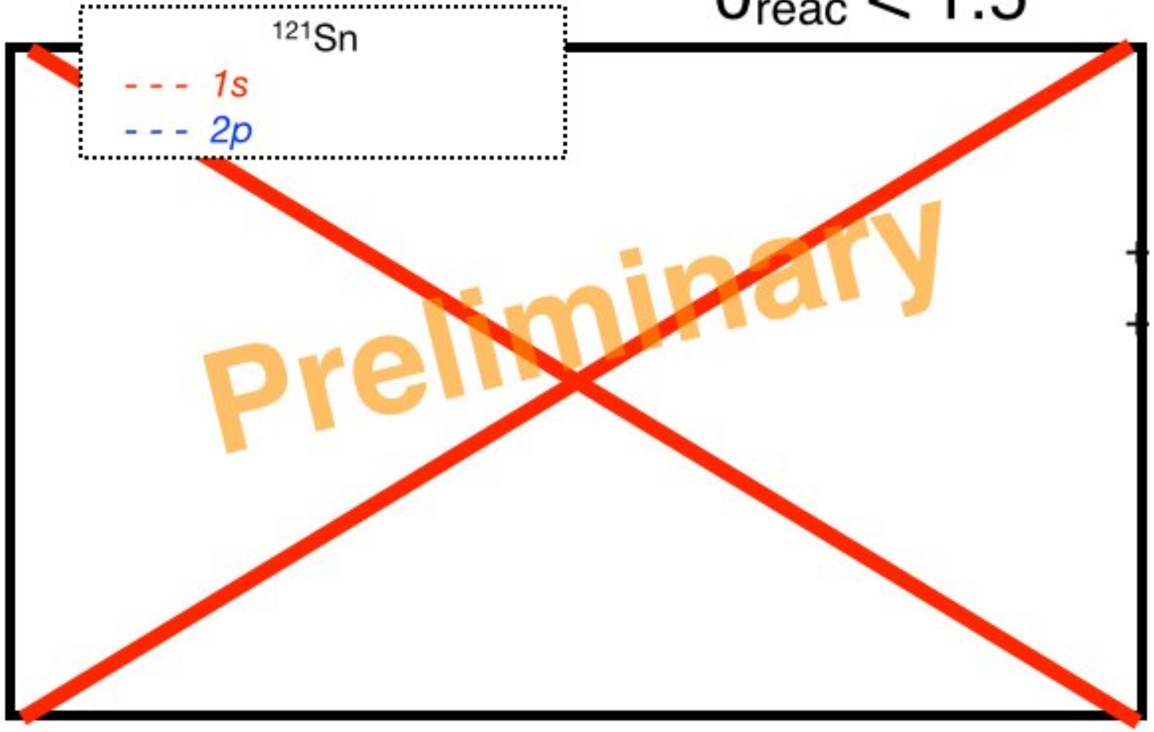
+ 1*s* pionic state (dashed line)

each pionic state
→ several configuration
with different neutron holes
each configuration
→ Voigtian / σ_{exp} is fixed

neutron hole	Eex [MeV]	relative strength for pionic 1*s* state
$2d_{3/2}$	0.000	0.09
$1h_{11/2}$	0.006	0.001
$3s_{1/2}$	0.060	**1**
$1g_{7/2}$	0.926	0.003
$2d_{5/2}$ (i)	1.121	0.12
$2d_{5/2}$ (ii)	1.403	0.06

Decomposition of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.5°$

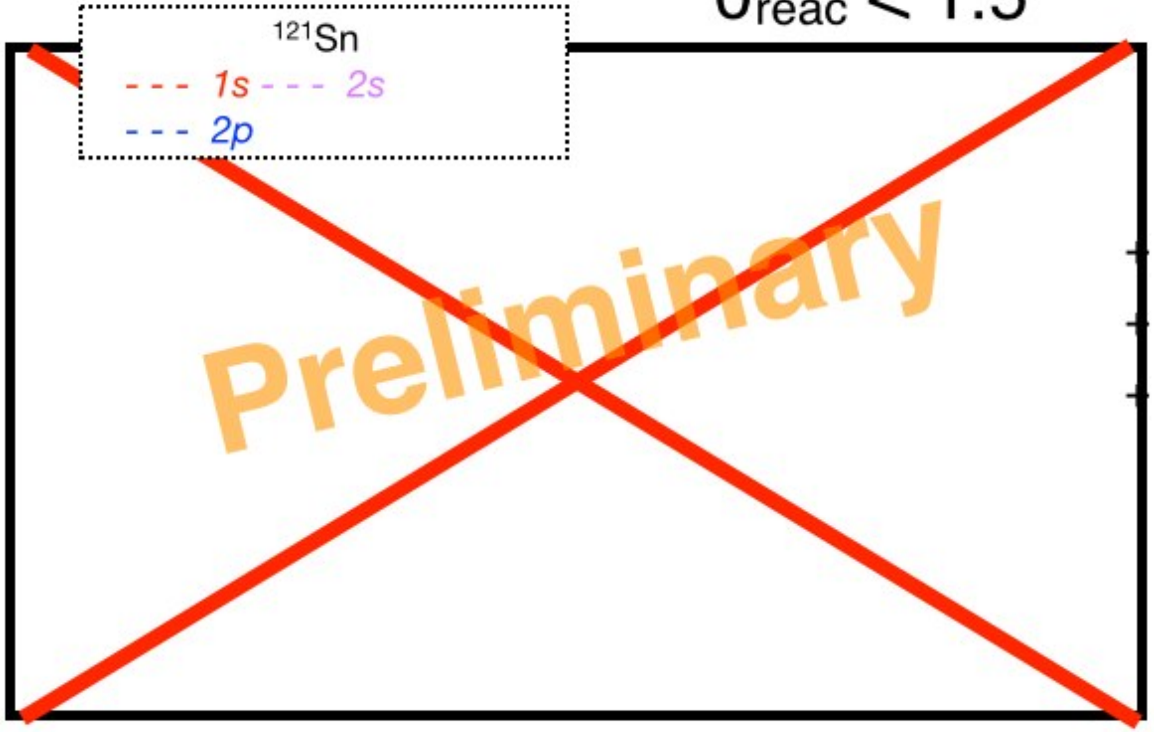


background (solid line / flat)

1*s* pionic state (dashed line)

2*p* pionic state (dashed line)

Decomposition of the E_{ex} spectrum : ^{122}Sn target



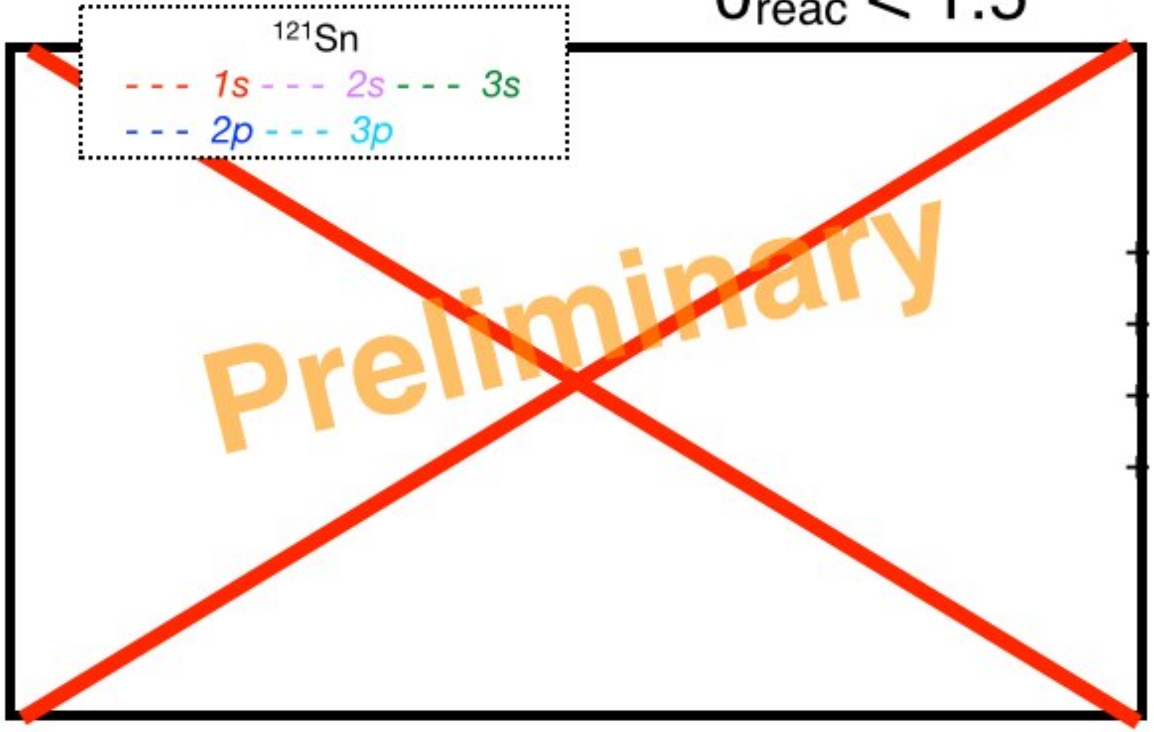
$\theta_{reac} < 1.5°$

background (solid line / flat)

1*s* pionic state (dashed line)
2*p* pionic state (dashed line)
2*s* pionic state (dashed line)

Decomposition of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.5°$



background (solid line / flat)

1*s* pionic state (dashed line)

2*p* pionic state (dashed line)

2*s* pionic state (dashed line)

3*p*, 3*s* state (dashed line)

Fitting parameter

- relative strength of each state
- BE_{1s}, BE_{2p}, BE_{2s}
- Γ_{1s}, Γ_{2p}

Fixed parameter

- BE_{3p}, BE_{3s}
- Γ_{2s}, Γ_{3p}, Γ_{3s}

Decomposition of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.5°$

quasi-free π^- production threshold 139.57 MeV

2p state → good calibration peak

Deduced B_{1s}, Γ_{1s}, **B_{2p}** in ^{121}Sn

(nl)	B_{nl} [MeV]	Γ_{nl} [MeV]
$1s$	XXX ± XXX (stat.)± XXX (sys.)	XXX ± XXX (stat.)± XXX (sys.)
$2p$	XXX ± XXX (stat.)± XXX (sys.)	XXX ± XXX (stat.)± XXX (sys.)
$1s$ - $2p$	**XXX ± XXX (stat.)± XXX (sys.)**	—

Decomposition of the E_{ex} spectrum : ^{117}Sn target

$\theta_{reac} < 1.5°$

fit region

quasi-free π^- production threshold 139.57 MeV

Deduced B_{1s} in ^{117}Sn

(nl)	B_{nl} [MeV]	Γ_{nl} [MeV]
1s	XXX ± XXX (stat.)± XXX (sys.)	—

Optical potential deduced from B_{1s}, Γ_{1s}, B_{2p} in ^{121}Sn

※$\Delta B = B_{1s} - B_{2p}$

Calculate likelihood for each b_1 and ImB_0
→ obtain best value

$$V_s(r) = -\frac{2\pi}{\mu}[\epsilon_1\{b_0\rho(r) + \boxed{b_1}\delta\rho(r)\} + \epsilon_2\boxed{B_0}\rho(r)^2\}].$$

※ b_0 , ReB_0 are deduced from data of light / symmetric pionic atoms

	b_1 [m_π^{-1}]	ImB_0 [m_π^{-4}]
This exp.	XXX ± XXX	XXX ± XXX
GSI	- 0.115 ± 0.007	0.0472 ± 0.0013
In vacuum	- 0.0868 ± 0.0014	–

Optical potential deduced from B_{1s}, Γ_{1s}, B_{2p} in ^{121}Sn

※$\Delta B = B_{1s} - B_{2p}$

Calculate likelihood for each b_1 and ImB_0
→ obtain best value

$$V_s(r) = -\frac{2\pi}{\mu}[\epsilon_1\{b_0\rho(r) + \boxed{b_1}\delta\rho(r)\} + \epsilon_2 \boxed{B_0}\rho(r)^2\}].$$

※ b_0 , ReB_0 are deduced from

ns

most precise evaluation the value of b_1 in medium
further evidence that chiral symmetry breaking is partially restored at finite densities.

This exp.	XXX ± XXX	XXX ± XXX
GSI	- 0.115 ± 0.007	0.0472 ± 0.0013
In vacuum	- 0.0868 ± 0.0014	–

Summary

- Deeply-bound pionic atom is good probe for QCD in finite density, especially for quark condensate via b_1 parameter in π - A potential.
- To determine the b_1 precisely, experiments of pionic Sn isotopes are on going at RIKEN.
- In the first exp. , we measured with the target of ^{122,116}Sn, and succeed in
  - improvement of the resolution,
  - observation of the pionic 1s, 2p and 2s states in $^{121,\ 116}$Sn,
- From the obtained binding energies and widths of pionic states, b_1 in medium is evaluated most precisely, which is consistent with the partial restoration of chiral symmetry breaking.

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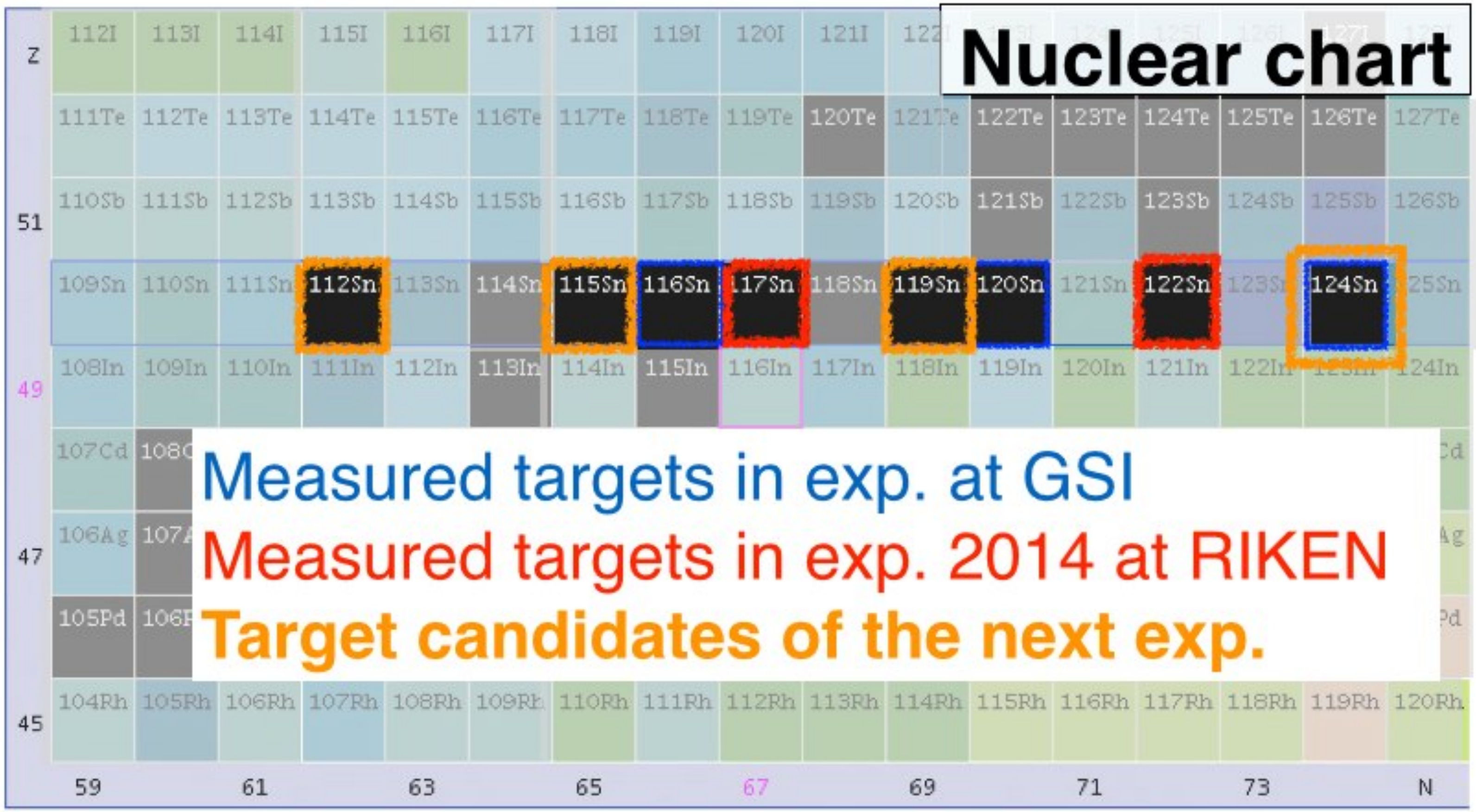
(Near) future works

NuDat



Nuclear chart

Z	112I	113I	114I	115I	116I	117I	118I	119I	120I	121I	122						
	111Te	112Te	113Te	114Te	115Te	116Te	117Te	118Te	119Te	120Te	121Te	122Te	123Te	124Te	125Te	126Te	127Te
51	110Sb	111Sb	112Sb	113Sb	114Sb	115Sb	116Sb	117Sb	118Sb	119Sb	120Sb	121Sb	122Sb	123Sb	124Sb	125Sb	126Sb
	109Sn	110Sn	111Sn	112Sn	113Sn	114Sn	115Sn	116Sn	117Sn	118Sn	119Sn	120Sn	121Sn	122Sn	123S	124Sn	25Sn
49	108In	109In	110In	111In	112In	113In	114In	115In	116In	117In	118In	119In	120In	121In	122In	123In	124In
	107Cd	108C															Cd
47	106Ag	107A															Ag
	105Pd	106P															Pd
45	104Rh	105Rh	106Rh	107Rh	108Rh	109Rh	110Rh	111Rh	112Rh	113Rh	114Rh	115Rh	116Rh	117Rh	118Rh	119Rh	120Rh
	59		61		63		65		67		69		71		73		N

Measured targets in exp. at GSI

Measured targets in exp. 2014 at RIKEN

Target candidates of the next exp.

The next exp. are already approved in PAC at RIKEN with wider range of isotopes.

The exp. will be performed in a few years.