SHARAQ Spectrometer: High-resolution Spectroscopy Using Exotic Beams and Reactions

Shin'ichiro Michimasa

Center for Nuclear Study, Univ. of Tokyo

Collaborators

S. Michimasa[1], S. Ota[1], M. Dozono[1], M. Takaki[1], K. Kisamori[1], H. Miya[1], M. Kobayashi[1], Y. Kiyokawa[1], H. Baba[2], N. Fukuda[2], N. Inabe[2], S. Kawase[3], T. Kubo[2], Y. Kubota[2], C.S. Lee[1], M. Matsushita[1], H. Sakai[2], A. Stolz[4], H. Tokieda[1], T. Uesaka[2], K. Yako[1], Y. Yanagisawa[2], R. Yokoyama[1], K. Yoshida[2], S. Shimoura[1]

[1]Center for Nuclear Study, the University of Tokyo
[2]RIKEN Nishina Center
[3]Kyushu University
[4]NSCL, Michigan State University

Contents

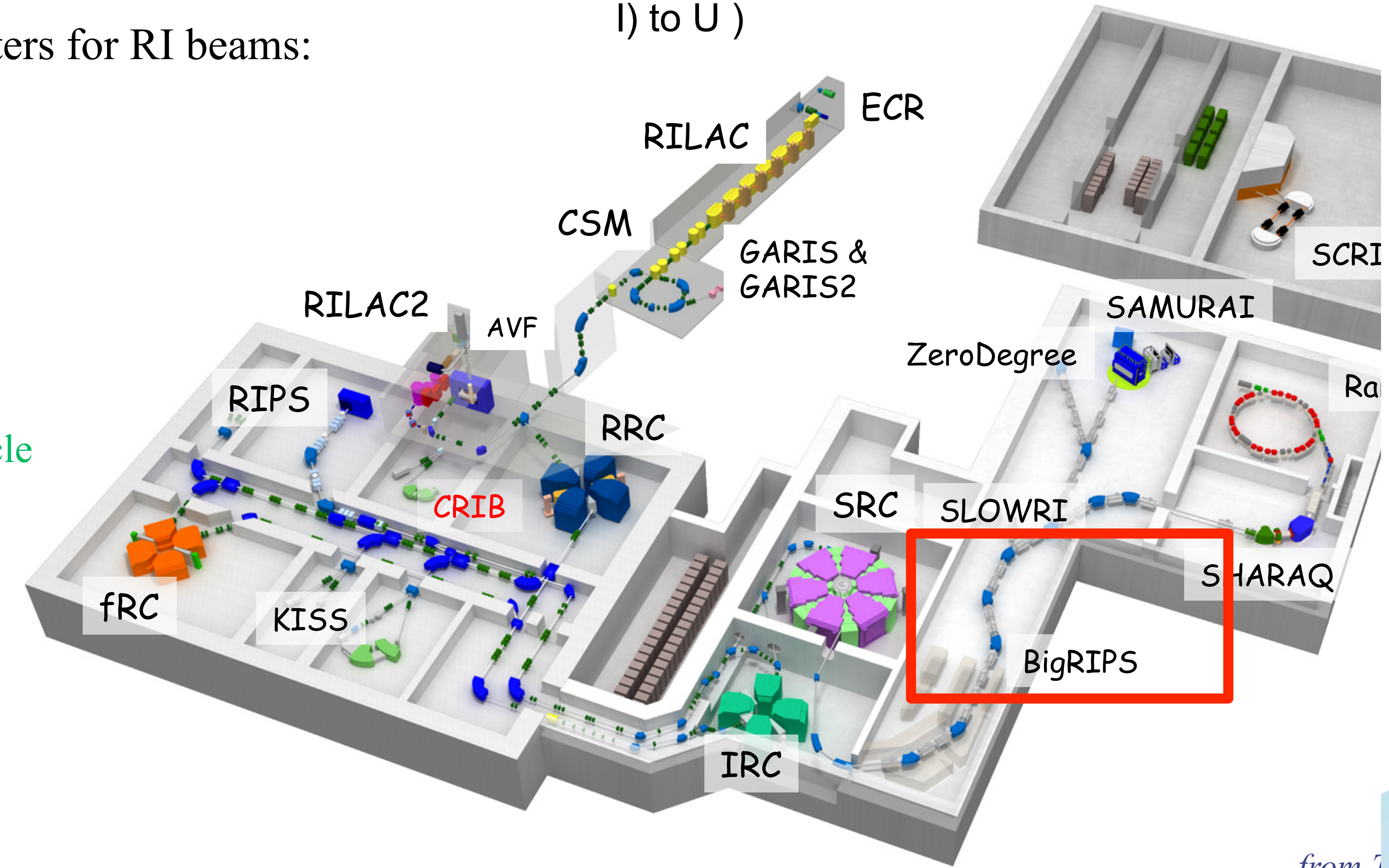
- **Status of performed experiments at SHARAQ**
  - Introduction of SHARAQ
  - Recent Achievements
    - **New probes using exotic reactions**:
      Search for Tetra-neutron state using (^{8}He,^{8}Be$\rightarrow$2α)
      Search for 0^{-} collectivity in ^{12}B using (^{16}O,^{16}F*[0^{-}]$\rightarrow$^{15}O+p)
    - **High-resolution analysis of exotic beams**:
      Mass measurement for n-rich ^{55,56}Ca isotopes
  - Summary

RIBF facility

l) to U)

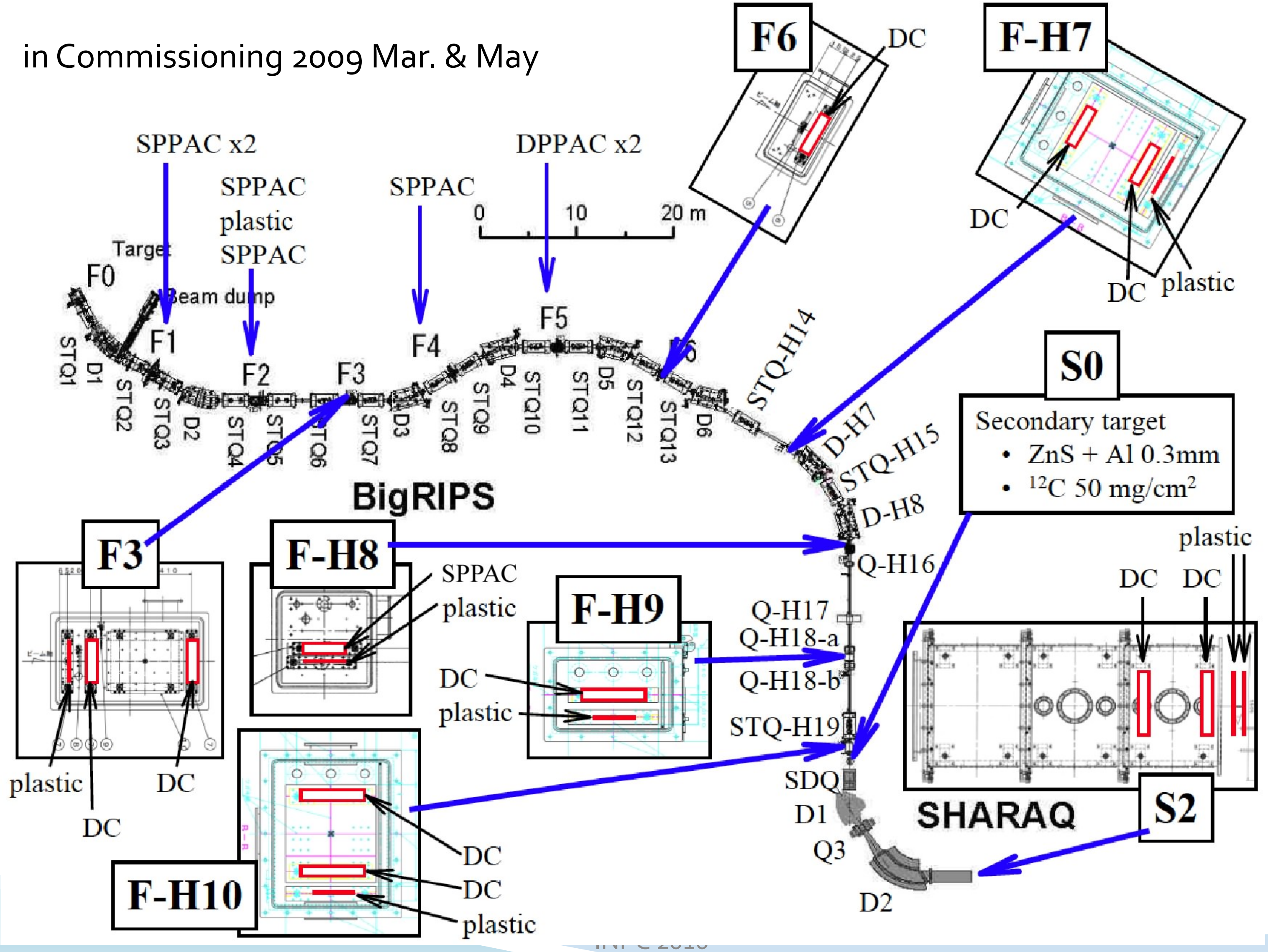
RIBF was equipped with 3 spectrometers for RI beams:

- ZeroDegree spectrometer
  (RIKEN)
  - multi-purpose for PID
  - completed in 2007
- SAMURAI spectrometer
  (Tohoku Univ.)
  - large acceptance, multi-particle
  - completed in 2011
- High resolution beamline
  +SHARAQ spectrometer
  (Univ. of Tokyo)
  - high resolution, rotatable
  - completed in 2009



Detector Setup in Beamline to SHARAQ

in Commissioning 2009 Mar. & May

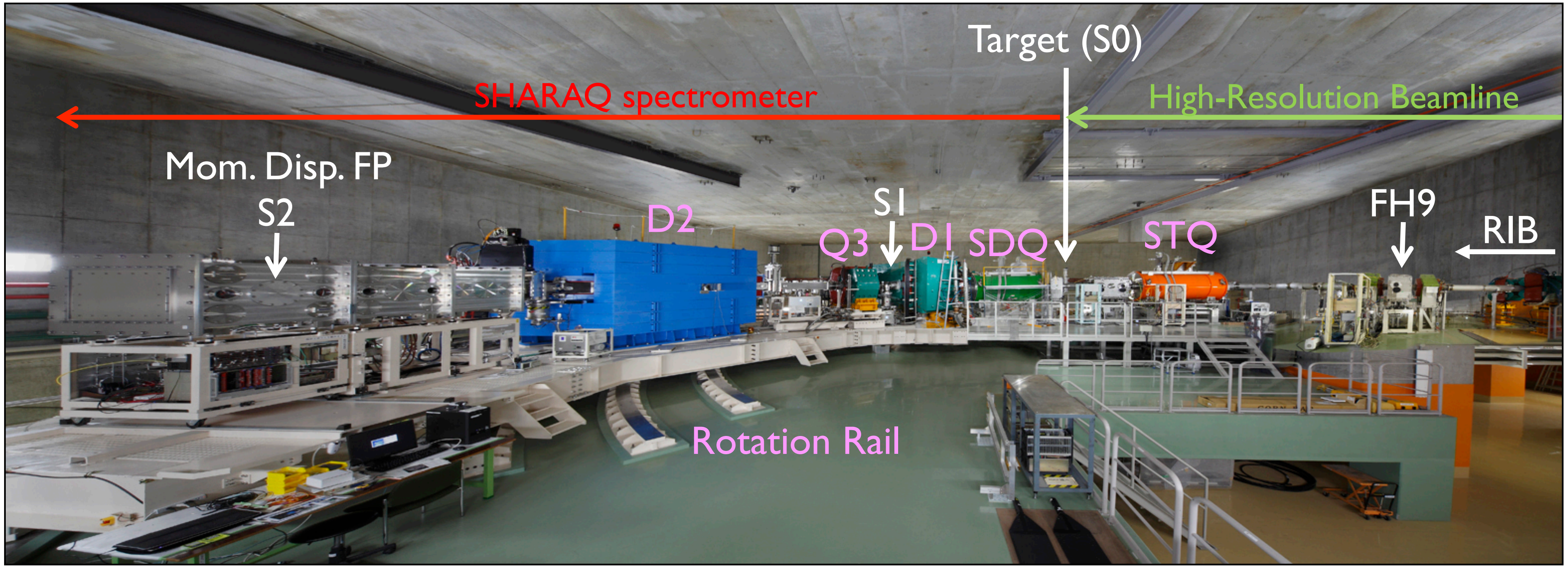


Transport Mode of HRBL

Mode	Dispersion Matching	High-resolution Achromatic	Large-Acceptance Achromatic
Acceptance			
$\Delta p/p$ (%)	±0.3	±1.0	±2
$\Delta\theta_x$ (mrad)	±10	±10	±20
$\Delta\theta_y$ (mrad)	±30	±30	±20
Maximum Dispersion	Target	F6	F5
Typical Spot size at target (mm)	100×10	20-30×10	20-30×10
Resolution $\Delta p/p$	1/14700	1/7500	1/3300

You can select beam transportation for your experiment.

SHARAQ spectrometer



- **QQDQD configuration**
  - good angular resolution and momentum resolution
- **Dipole Magnets**
  - Minimization of higher-order aberration by pole-edge curving
    - Easier tuning to dispersion matching conditions and data analysis
- **Superconducting doublet Q**
  - Higher resolution & Larger acceptance

Combine missing mass spectroscopy with invariant mass technique

2 alpha particles: K. Kisamori, S. Shimoura et al.
Different particles: M. Dozono et al.

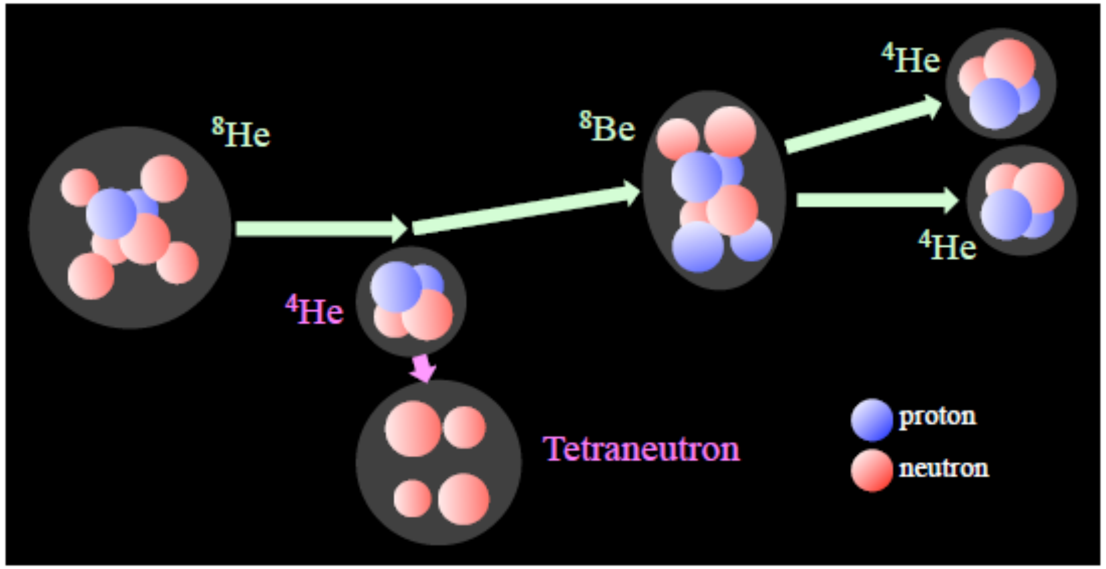
2 alpha detection

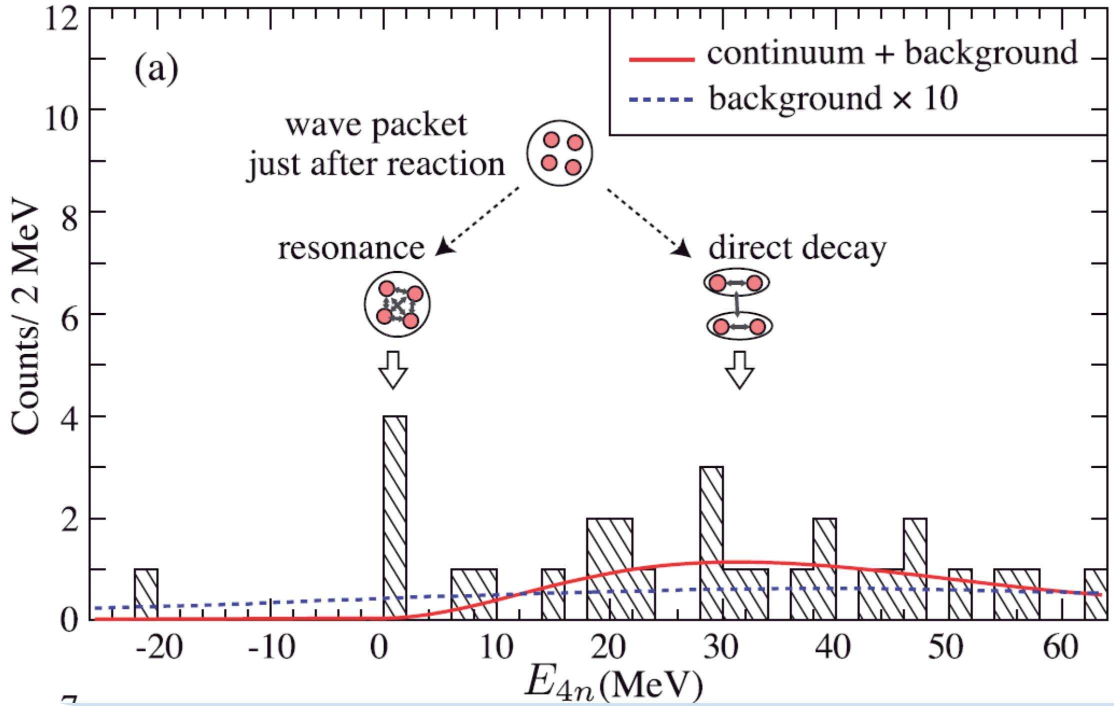
Sept. 12/ R5 15:40
by Shimoura

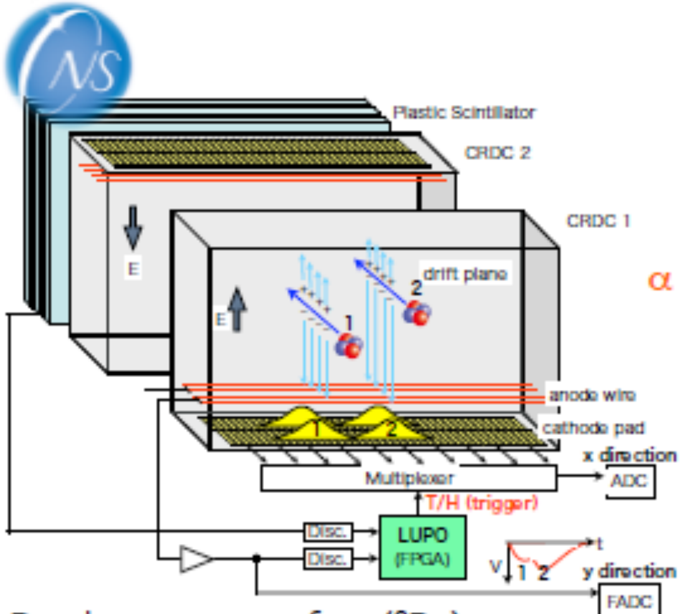
Selected for a Viewpoint in *Physics*
PRL **116,** 052501 (2016) PHYSICAL REVIEW LETTERS week ending 5 FEBRUARY 2016

Candidate Resonant Tetraneutron State Populated by the ^{4}He(^{8}He,^{8}Be) Reaction

K. Kisamori,[1,2] S. Shimoura,[1] H. Miya,[1,2] S. Michimasa,[1] S. Ota,[1] M. Assie,[3] H. Baba,[2] T. Baba,[4] D. Beaumel,[2,3] M. Dozono,[2] T. Fujii,[1,2] N. Fukuda,[2] S. Go,[1,2] F. Hammache,[3] E. Ideguchi,[5] N. Inabe,[2] M. Itoh,[6] D. Kameda,[2] S. Kawase,[1] T. Kawabata,[4] M. Kobayashi,[1] Y. Kondo,[7,2] T. Kubo,[2] Y. Kubota,[1,2] M. Kurata-Nishimura,[2] C. S. Lee,[1,2] Y. Maeda,[8] H. Matsubara,[12] K. Miki,[5] T. Nishi,[9,2] S. Noji,[10] S. Sakaguchi,[11,2] H. Sakai,[2] Y. Sasamoto,[1] M. Sasano,[2] H. Sato,[2] Y. Shimizu,[2] A. Stolz,[10] H. Suzuki,[2] M. Takaki,[1] H. Takeda,[2] S. Takeuchi,[2] A. Tamii,[5] L. Tang,[1] H. Tokieda,[1] M. Tsumura,[4] T. Uesaka,[2] K. Yako,[1] Y. Yanagisawa,[2] R. Yokoyama,[1] and K. Yoshida[2]



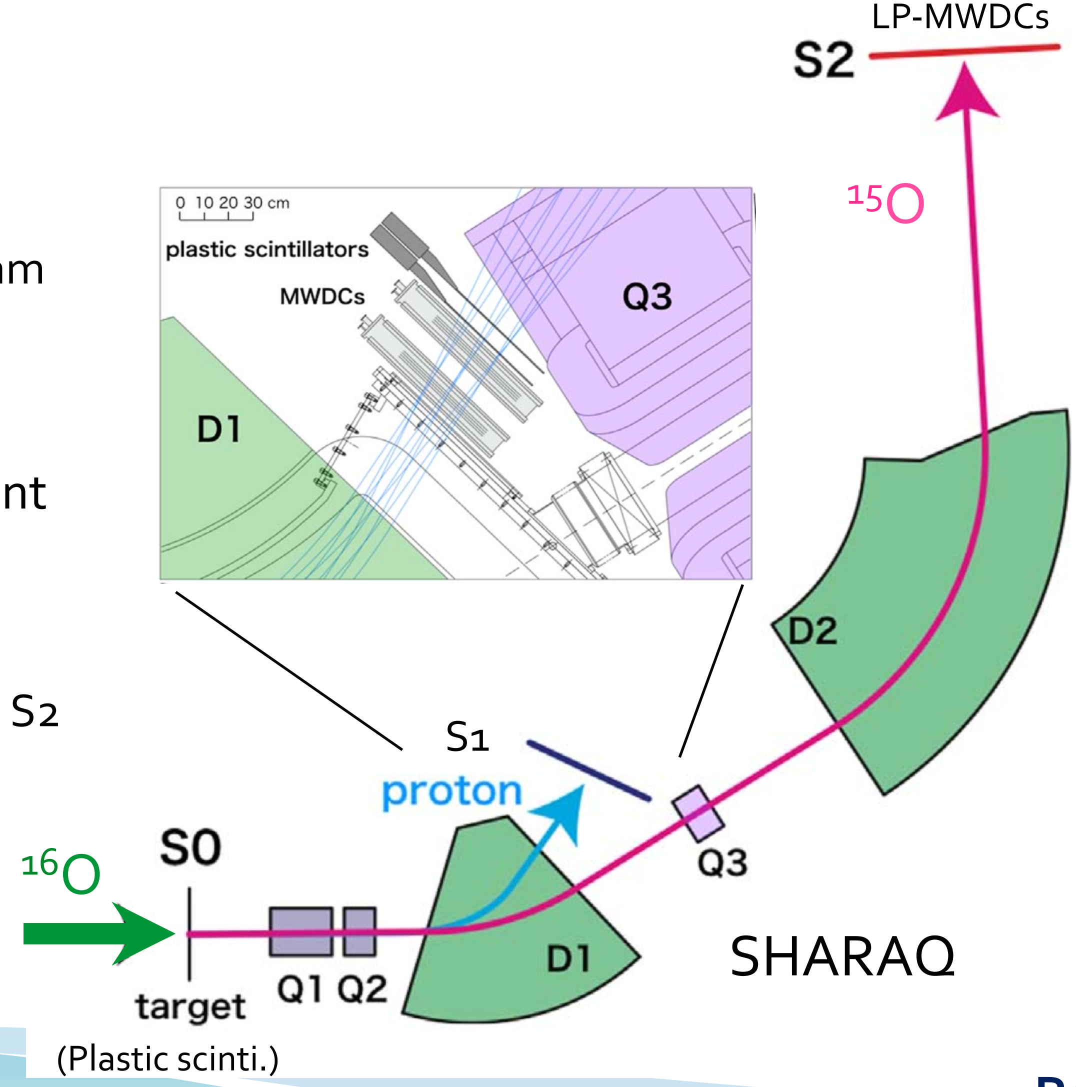




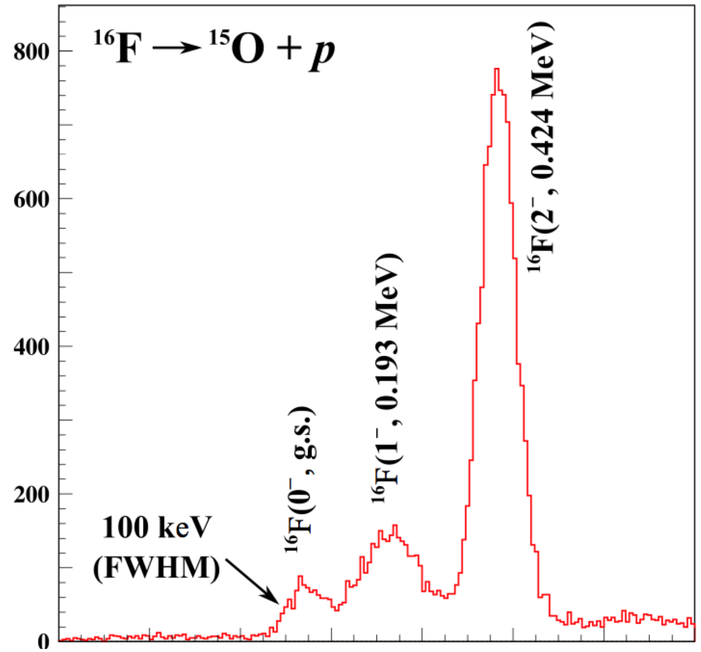
Readout system of 2α (^{8}Be)

$^{16}F \rightarrow ^{15}O+p$ decay determination

- Beam : Primary ^{16}O
  - 250 MeV/u, 10^7 pps
  - Dispersion matched beam
- Target : Plastic scinti.
  - 1 mm thickness
- Coincidence measurement of $^{16}F \rightarrow ^{15}O + p$
  - Separated flow mode
    - ^{15}O : 2 LP-MWDCs @ S2
    - p : 2 MWDCs @ S1

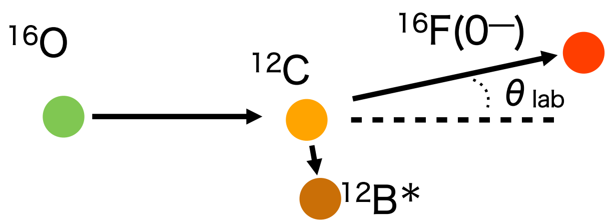


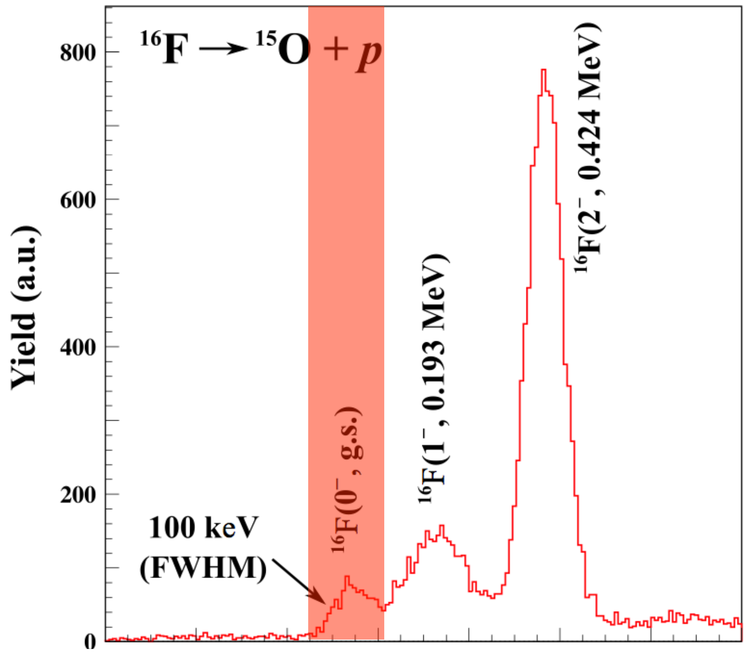
Invariant mass spectrum of $^{15}O + p$

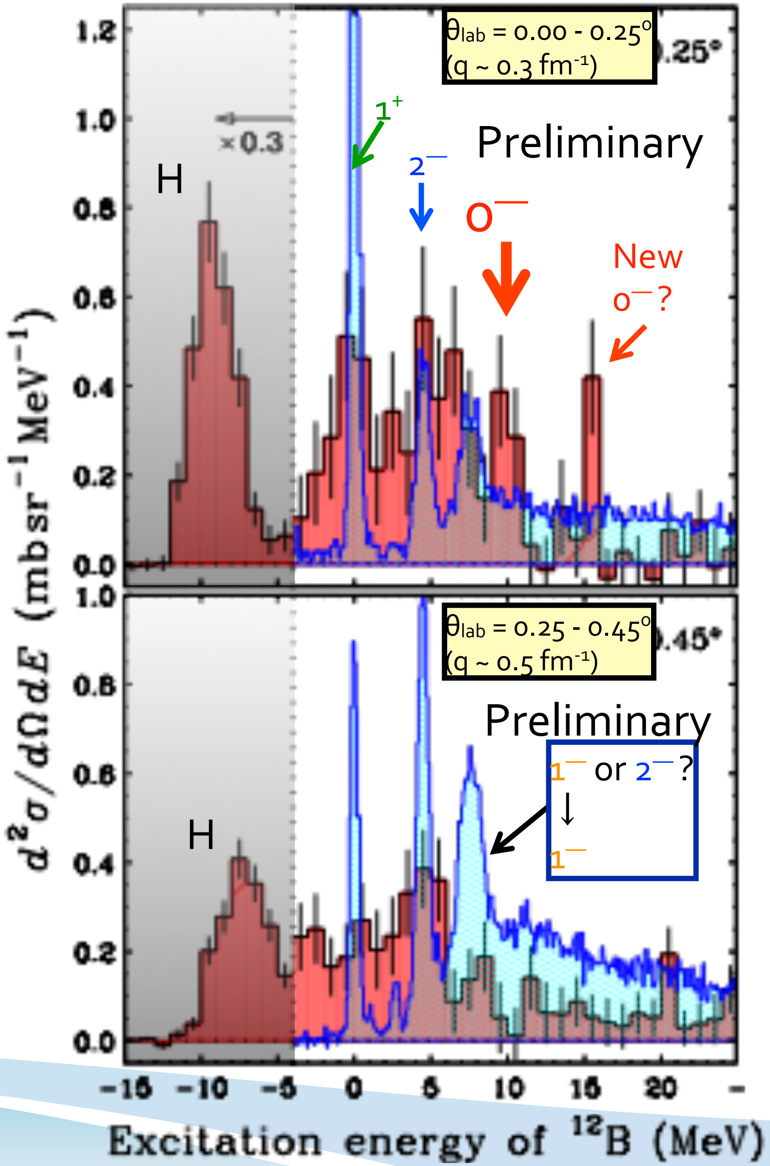


Ref: NIM A 830 233-242 (2016).

$^{12}C(^{16}O,^{16}F(0^-))^{12}B$ missing mass spectra







$(^{16}O,^{16}F(0^-))$ is
clean probe for SD(0^-) !

Cf. H. Okamura *et al*. PLB 345 (1995) 1.

Sept. 14/ L 16:20
by M. Kobayashi

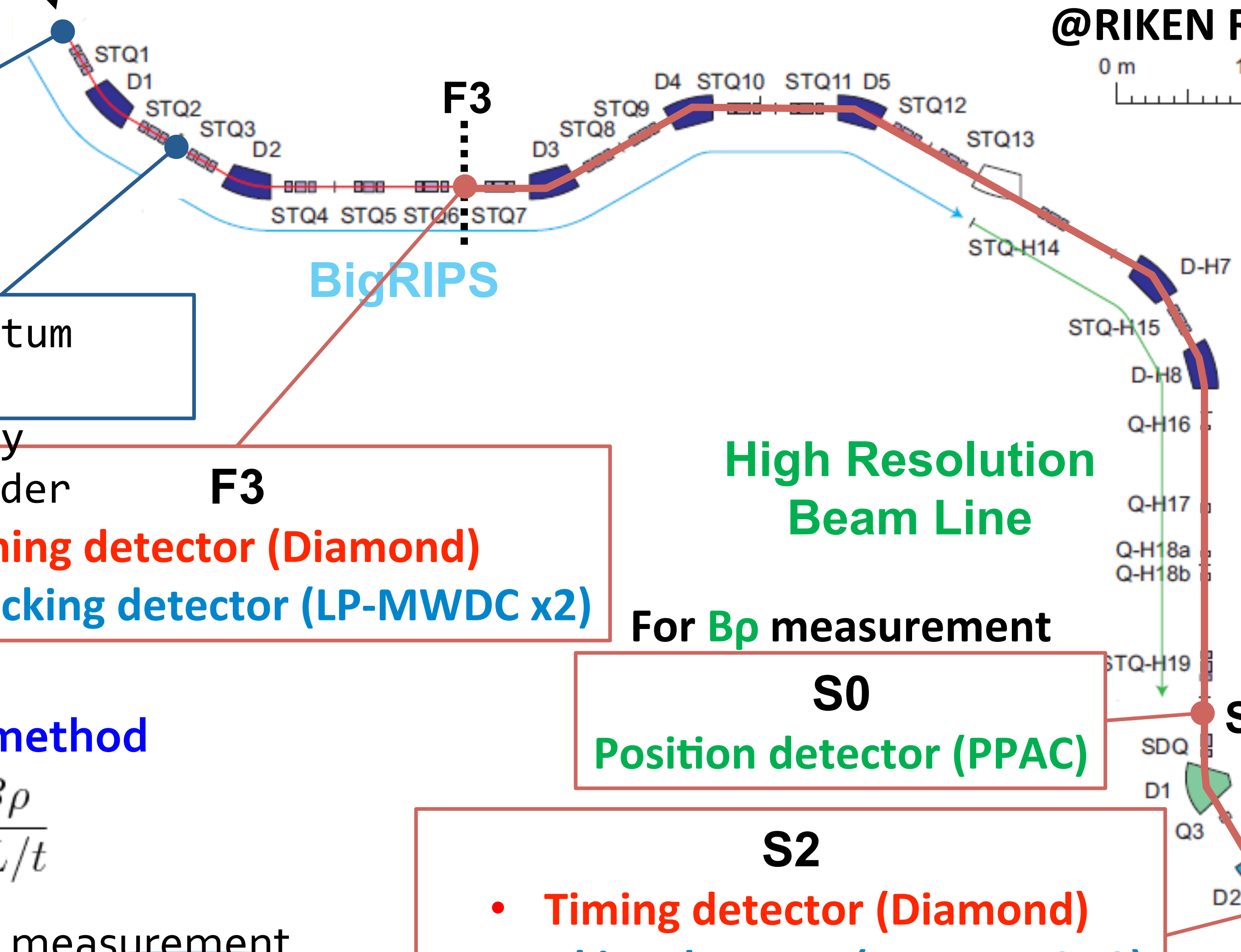
High-resolution performance

Mass measurement: M. Kobayashi, S. Michimasa et al.

Experimental setup

Primary beam:
^{70}Zn (345 MeV/u), I = 150 pnA

@RIKEN RI Beam Factory (RIBF) - SHARAQ



Production target (^{9}Be)

- Momentum slit
- Energy degrader

F3
- **Timing detector (Diamond)**
- **Tracking detector (LP-MWDC x2)**

Flight length (F3-S2)
105 m (~540 ns)

For Bρ measurement

S0
Position detector (PPAC)

For isomer tagging (confirm PID)

Gamma detectors

S2
- **Timing detector (Diamond)**
- **Tracking detector (LP-MWDC x2)**
- **ΔE detector (SSD x2)**

Dispersion matching mode (p/δp = 14700)

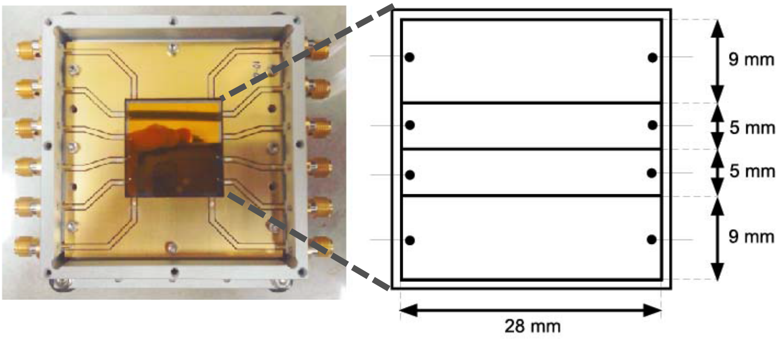
SHARAQ Spectrometer

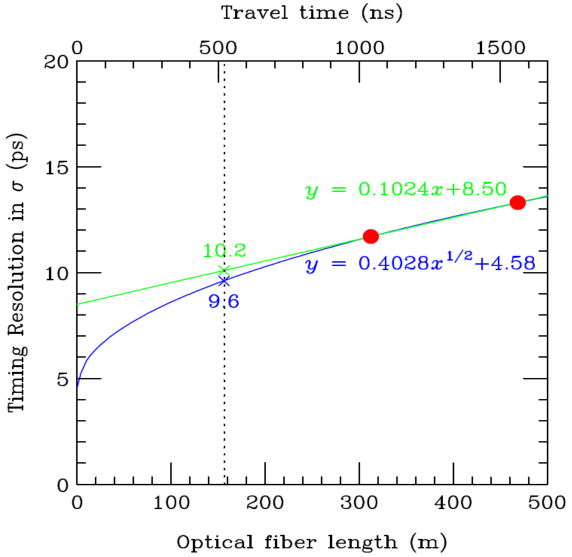
- **TOF-Bρ method**

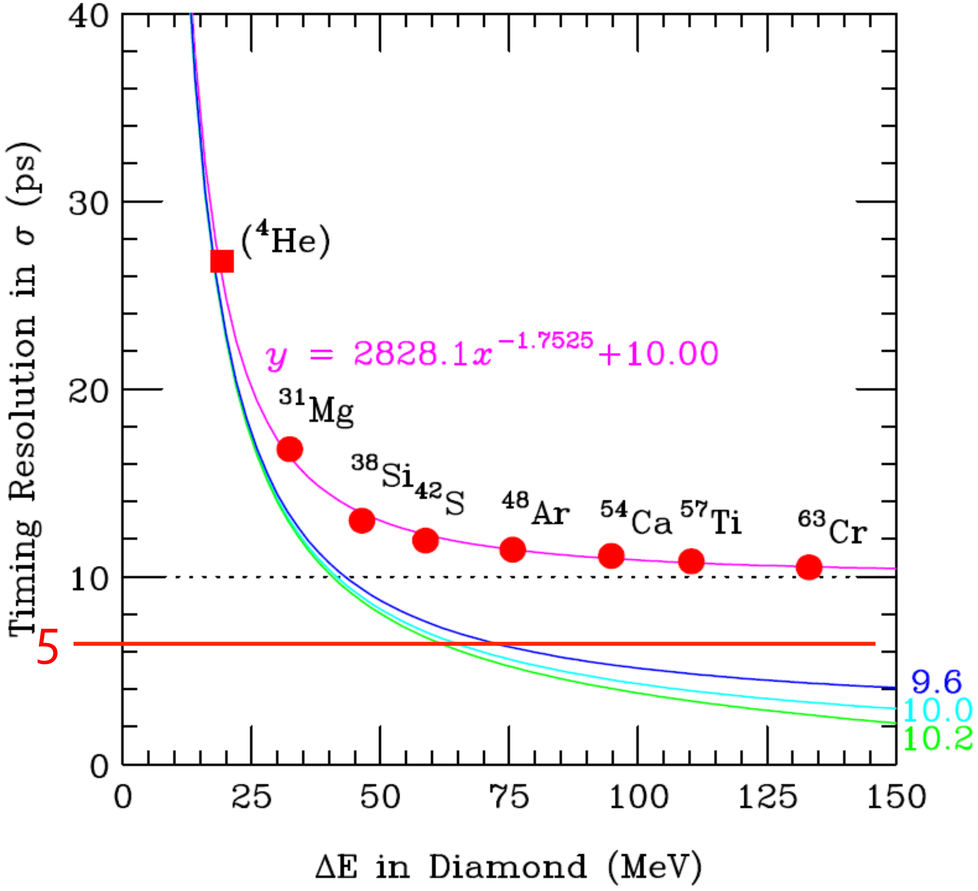
$$\frac{m_0}{q} = \frac{B\rho}{\gamma L/t}$$

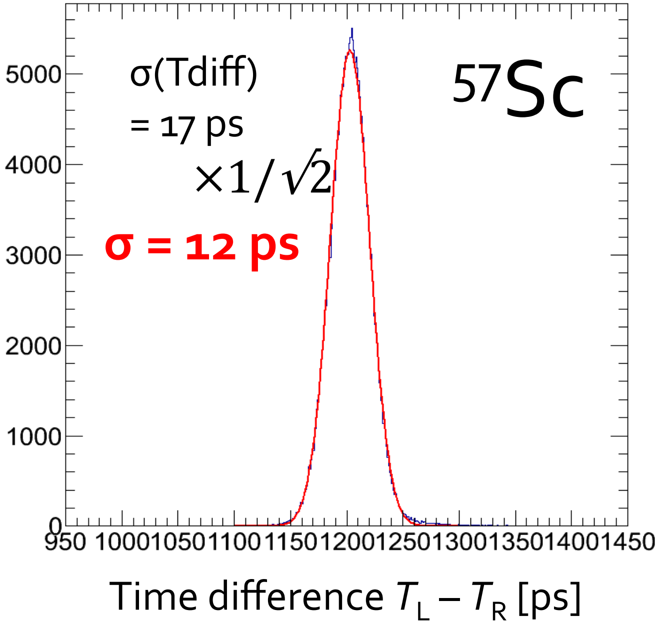
→ Precise measurement of TOF and Bρ

Time resolution of Diamond detector







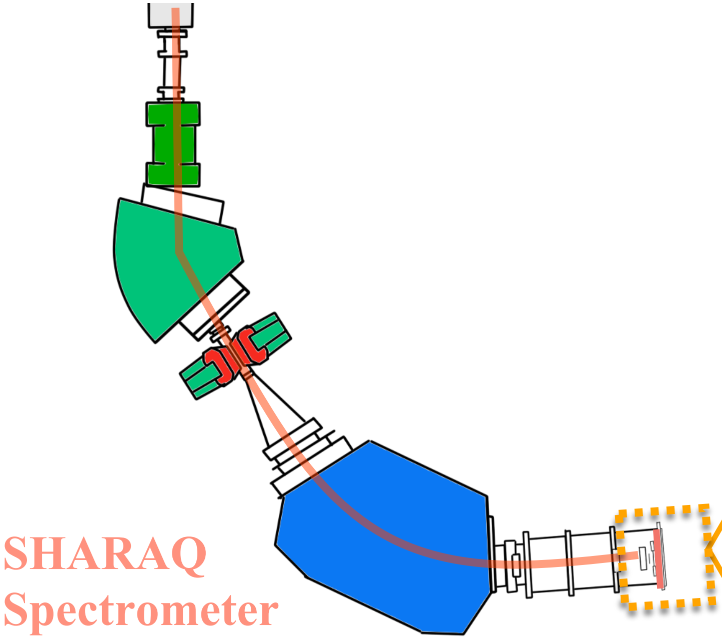


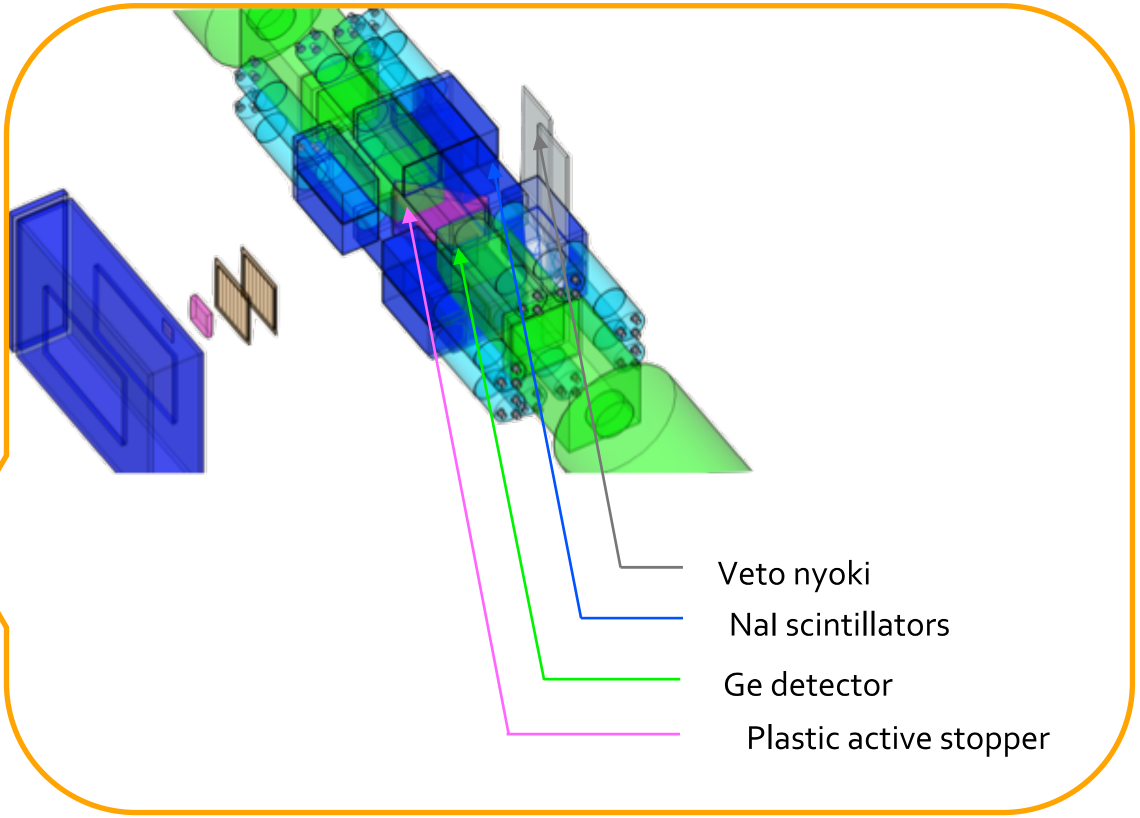
◎ Time resolution incl. DAQ system **～10ps(σ)**

⇒ Intrinsic resolution : **5 ps(σ) @ΔE=100MeV**

※ Signals travel in a 155-meter fiber in the experiment.

Gamma-ray detectors for PID





<u>Gamma-ray detector array</u>

- 2 clover-type Ge detectors
- 16 NaI scintillators
- Active stopper

<u>Downstream of array</u>

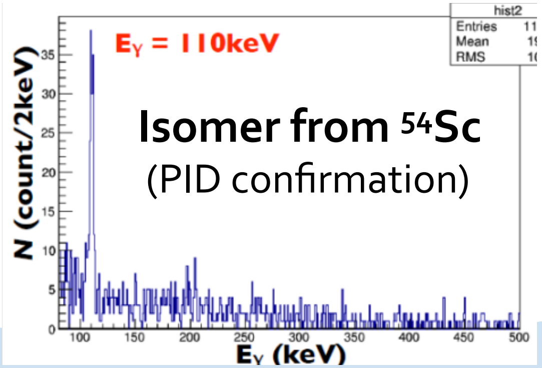
- veto scintillator

<u>Energy Resolution</u>

HPGe: 3.8 keV at 1333 keV

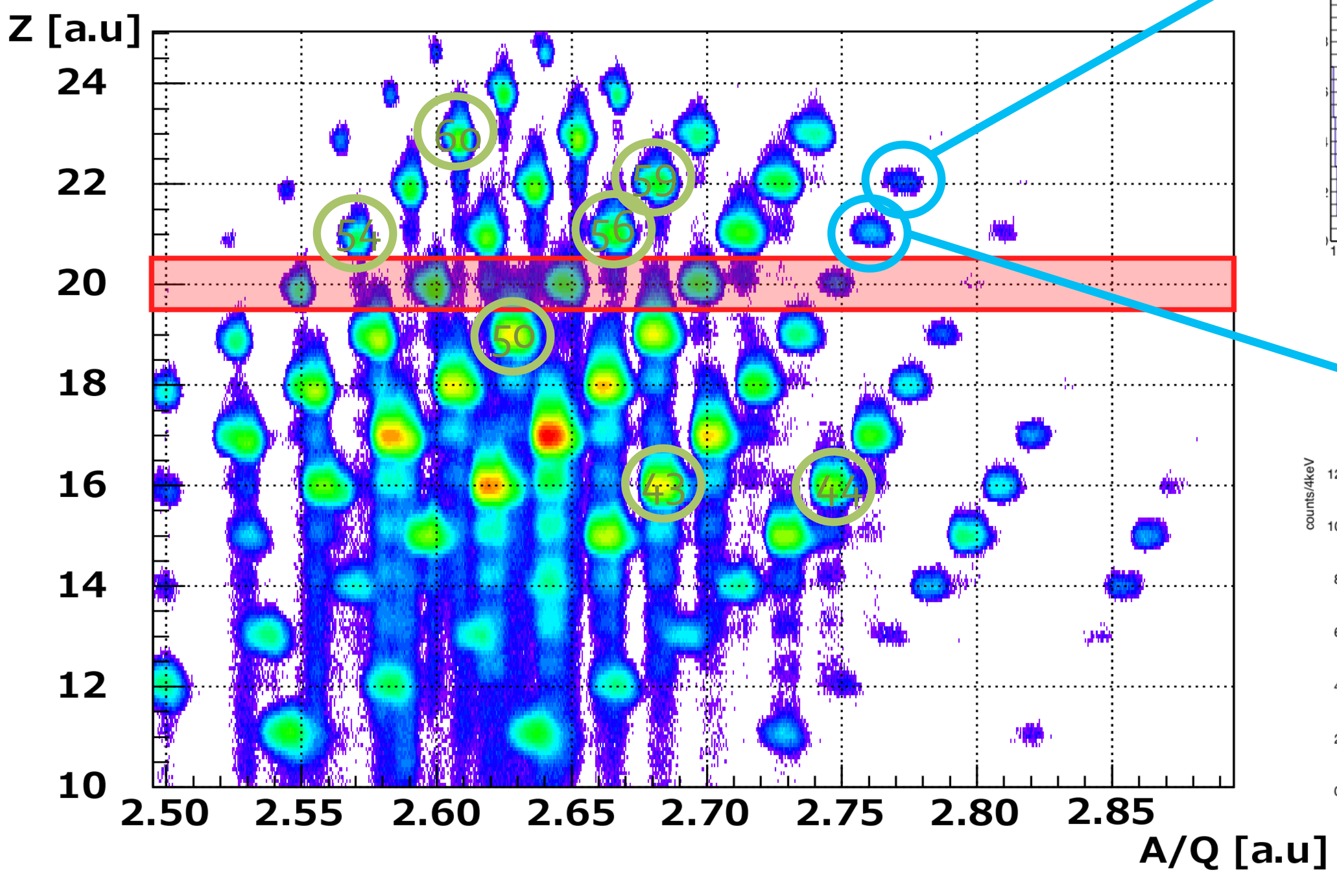
<u>Al degrader</u>

- Al plate 14-18mm

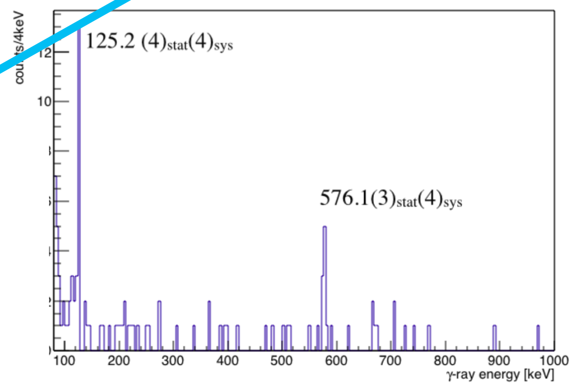


Property of Secondary Beam

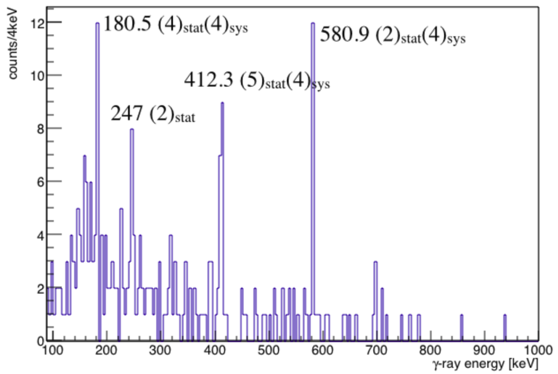
PID by BigRIPS F3-SHARAQ S2



^{61}Ti New



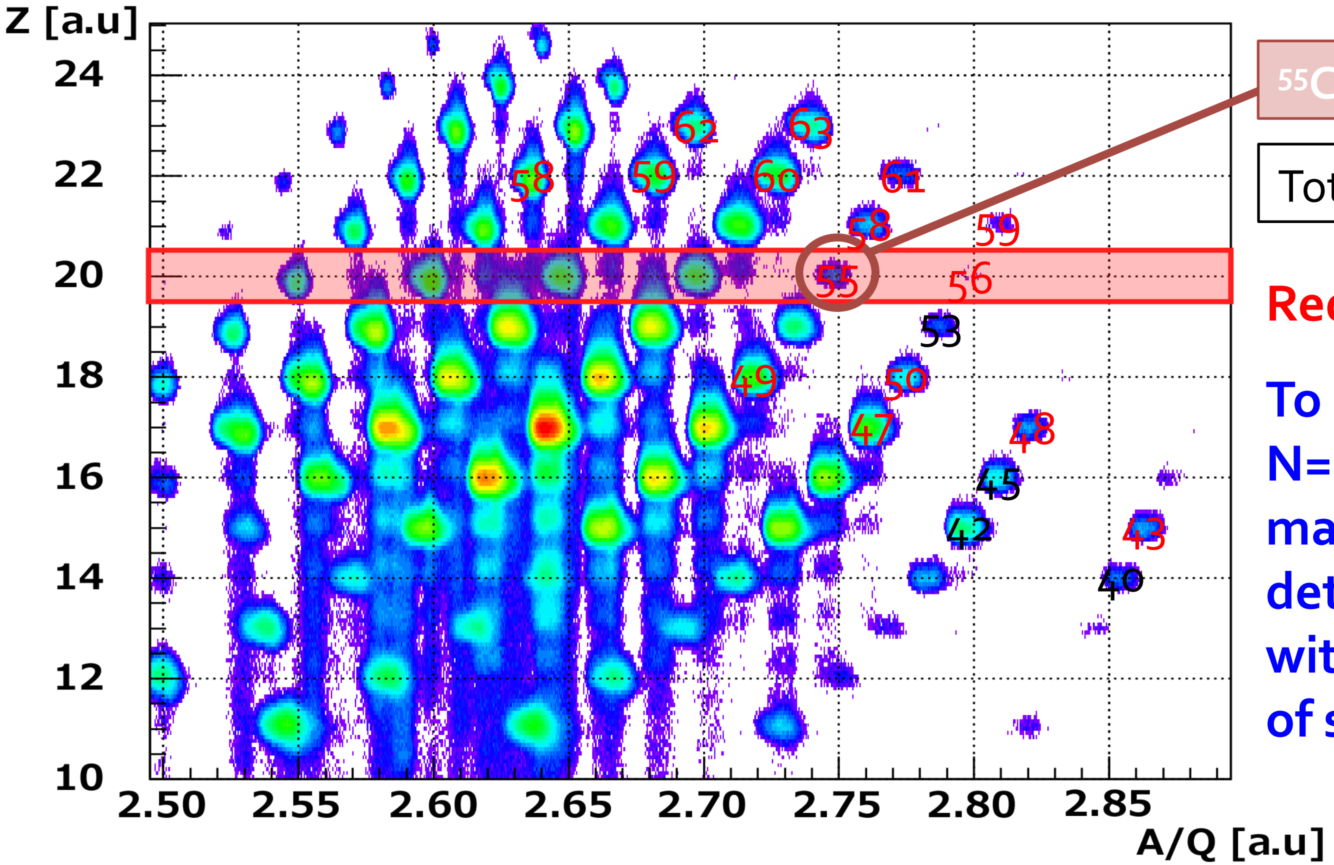
^{58}Sc New



Primary beam: ^{70}Zn (345 MeV/u), I = 130 pnA

Property of Secondary Beam

PID by BigRIPS F3-SHARAQ S2



^{55}Ca : ~ 10^{-2} cps

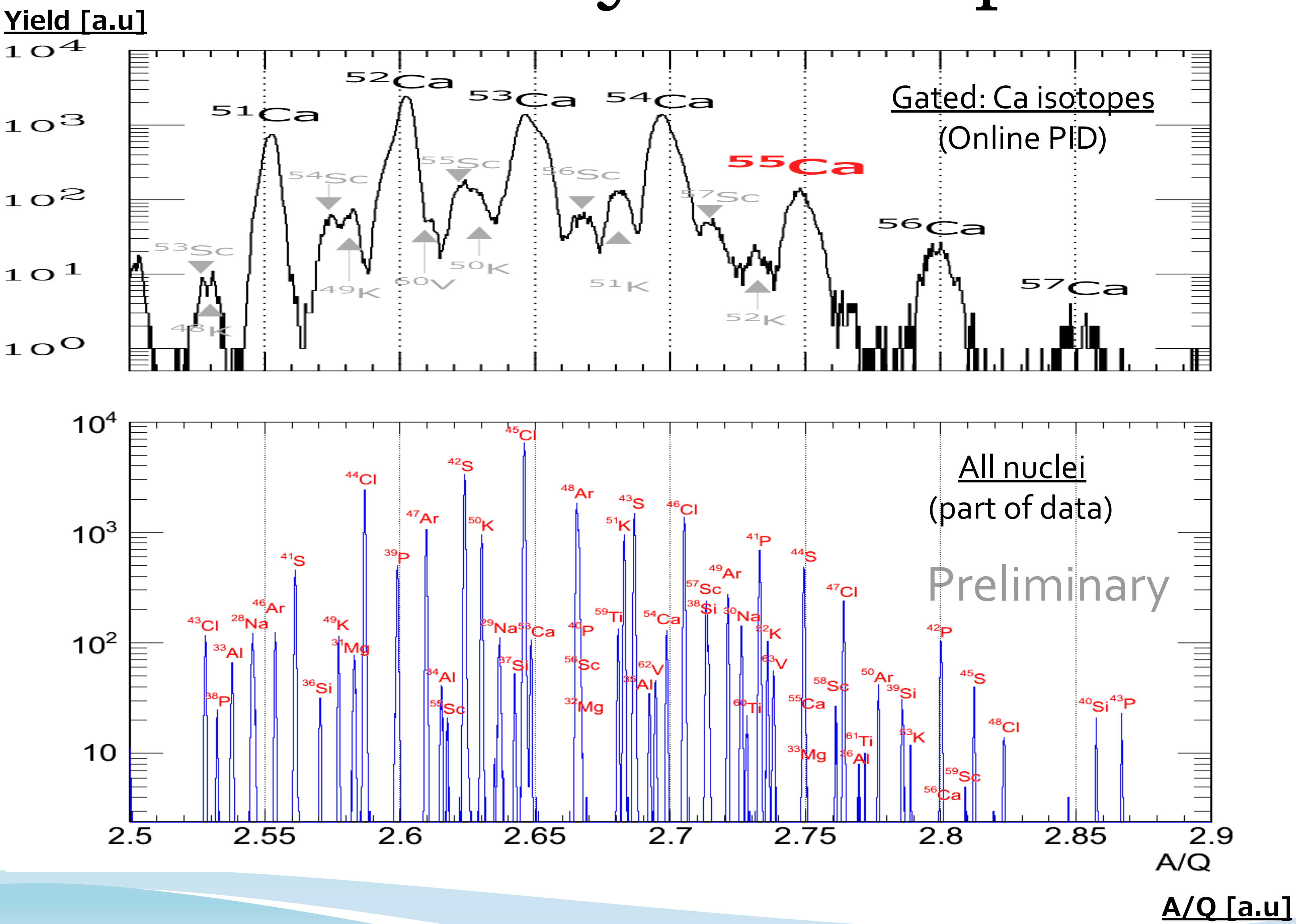
Total yield (^{55}Ca): ~3000

Red : unknown masses

To discuss magicity of N=32 and 34, masses must be determined with the precision of several hundreds keV

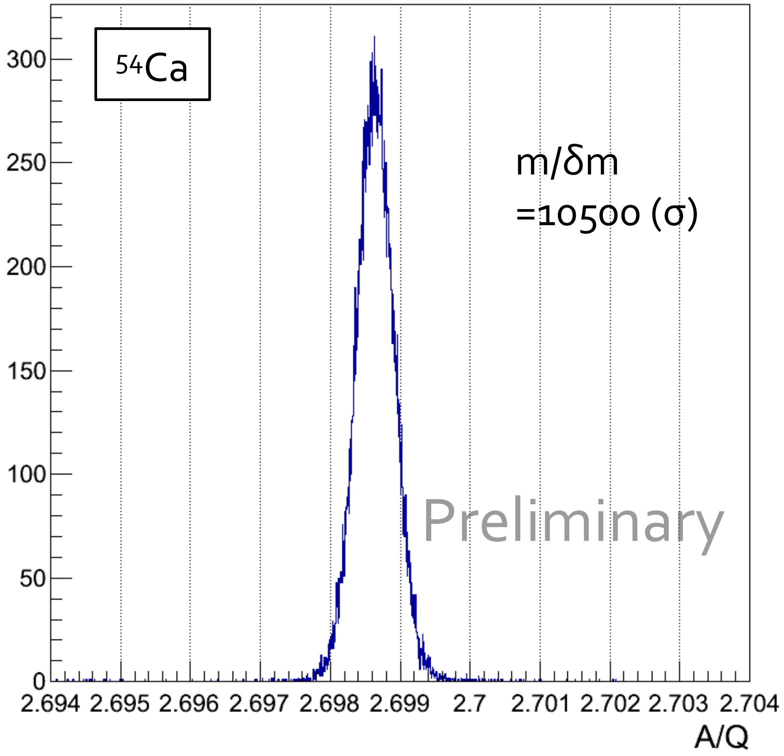
Primary beam: ^{70}Zn (345 MeV/u), I = 130 pnA

Preliminary Mass Spectra



Evaluation of Mass resolution

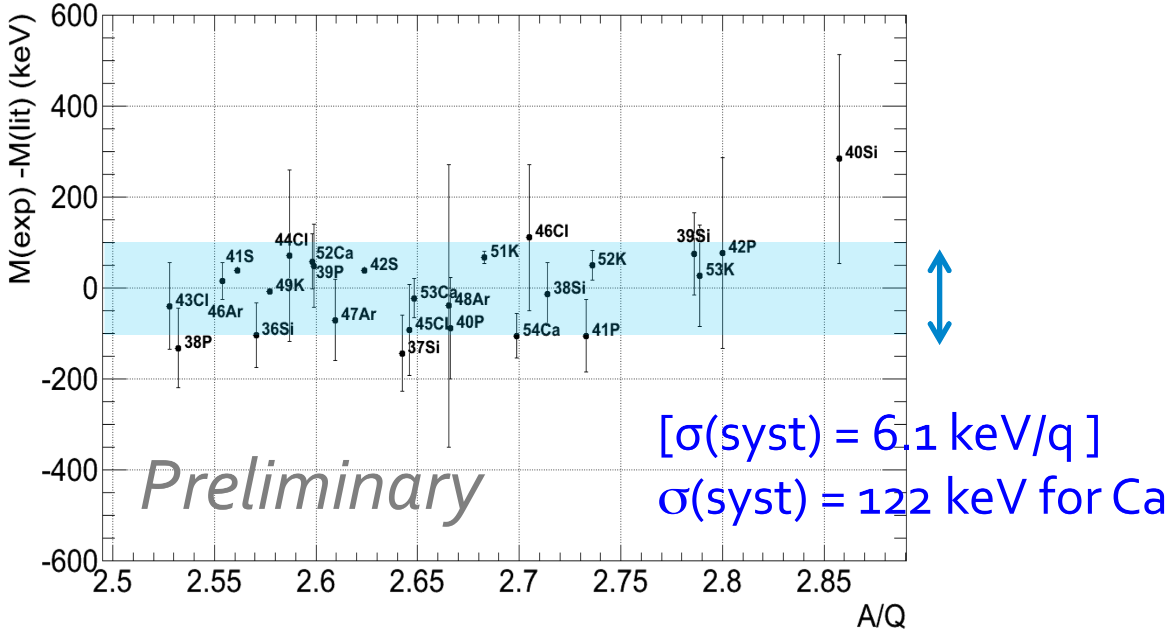
1. Statistical error



- **Mass resolution of 10500 (σ) has been achieved for Ca isotopes**
  - ^{55}Ca: σ(stat) = 90 keV (3000 events)
  - ^{56}Ca: σ(stat) = 200 keV (400 events).

2. Systematic error

(evaluated from known masses)

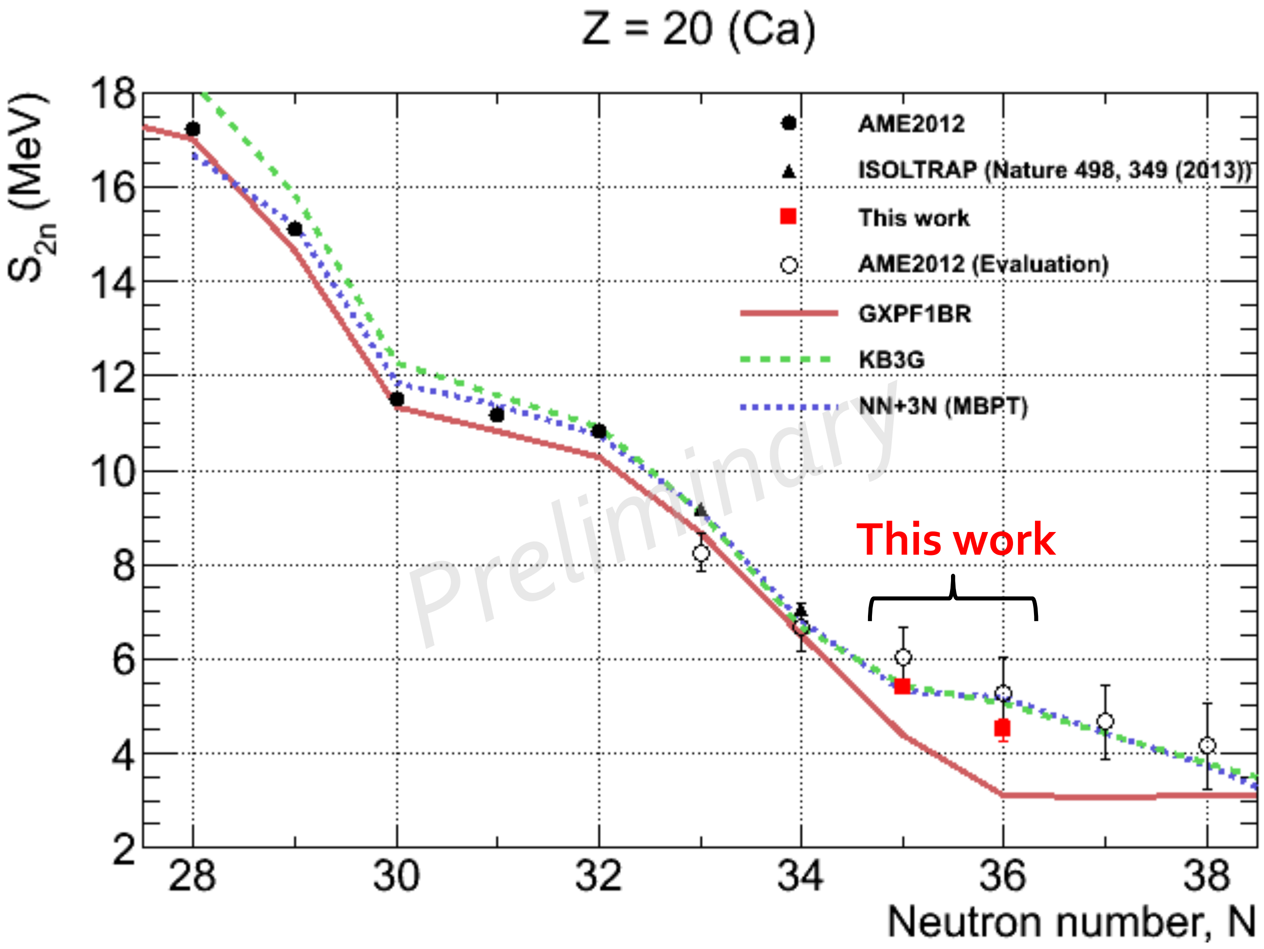


Achieved masses resolution:

σ(mass) ~ 150 keV for ^{55}Ca

~ 234 keV for ^{56}Ca

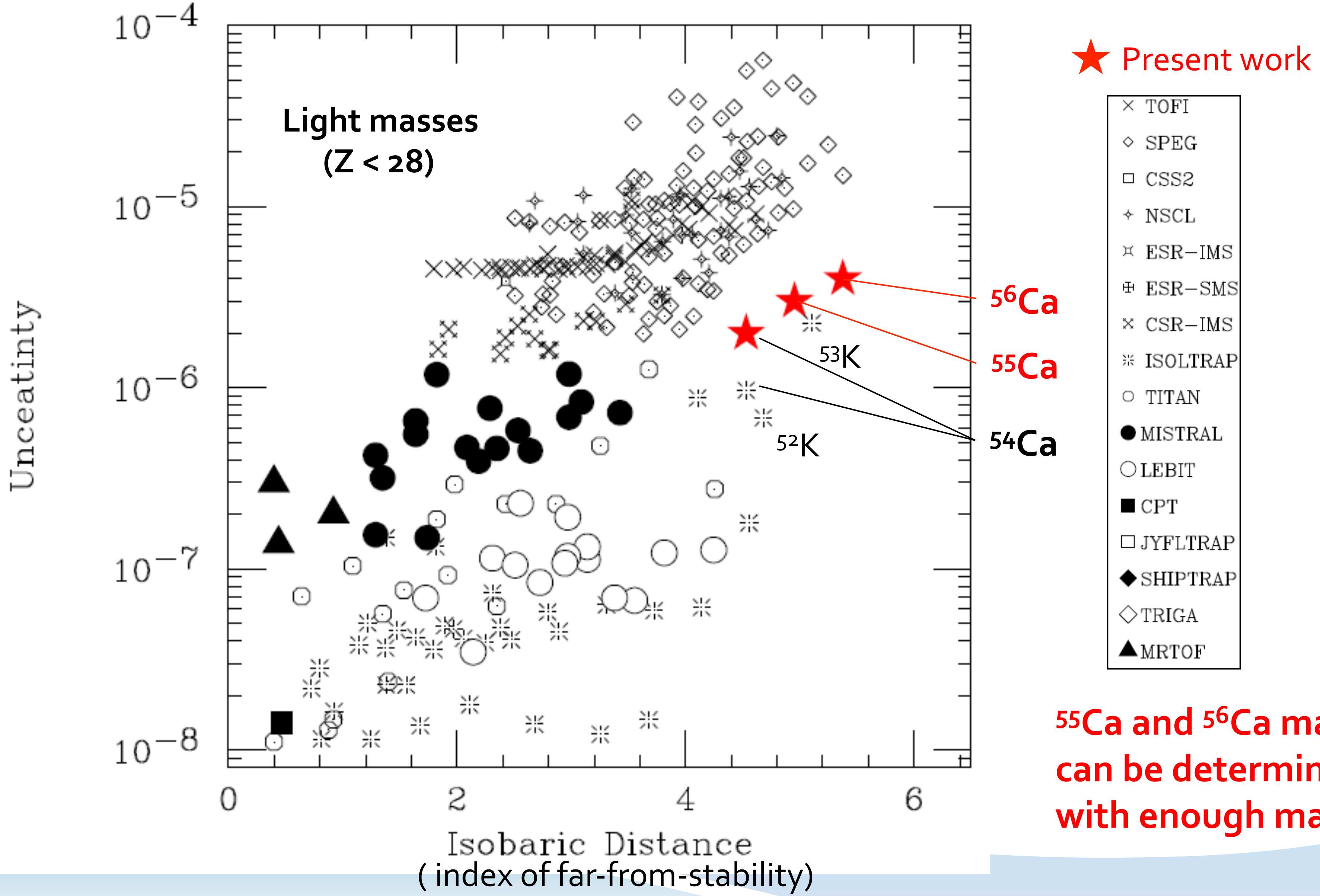
S_{2n} trend in Ca isotopes



$$S_{2n} = -M(A,Z) + M(A-2,Z) + 2M_n$$

^{55}Ca and ^{56}Ca masses can be determined with enough mass resolution!!

Mass Resolution for Exotic nuclei



^{55}Ca and ^{56}Ca masses can be determined with enough mass resolution!!

Summary

- **Recent development of SHARAQ spectrometer**
  - SHARAQ developed the missing spectroscopy combined with invariant mass technique.
    - We have obtained the tetra-neutron state for the first time.
    - Also successfully obtained a sensitive probe for 0- collectivity
  - SHARAQ continued to develop high-resolution performance.
    - Diamond detector excellent time resolution
      σ=12 ps(performance), 5 ps (intrinsic) for Sc isotopes.
    - For PID of heavy ions, isomer tagging system installed.
      New isomer states were found in ^{58}Sc and ^{61}Ti.
    - Mass resolution reaches 1/10000 (σ).
      → We can target nuclei far from stability of < 10^{-2} cps
      The ^{55,56}Ca masses can be determined with good resolution.

Backup

Basic Performance

Maximum rigidity	**6.8 Tm**
Dispersion (D)	**5.86m**
Horizontal magnification (M_x)	**0.40**
D/M_x	**14.7m**
Momentum resolution	**1/14700**
Vertical magnification (M_y)	**0.0**
Angular resolution	**< 1mrad**
Vertical acceptance	**± 3 deg**
Dispersion matching	**p & θ_x**

For spot size of 60mm(H)×10mm(V)
(*in dispersion matching operation*)

Horizontal acceptance	± 1 deg
Solid angle	2.7 mrad

For spot size of 10mm(H)×10mm(V)
(*in achromatic focus operation*)

Solid angle	4.8 mrad

Requirement of Tracking Detectors

- **for dispersion matching**
  - Little disturbing of the beam
  - Low Multiple Scattering: ~1 mrad (s)
    - Low Energy Straggling: thickness/L_R < 10^{-3}
  - Precise measurement of the beam trajectory
    - High Position Resolution: ~300 μm (FWHM)
      [30 cm*1 mrad ~ 300 mm]

- **for using RI Beam**
  - Overcoming of Low intensity
    - 100% Detection Efficiency for light particles

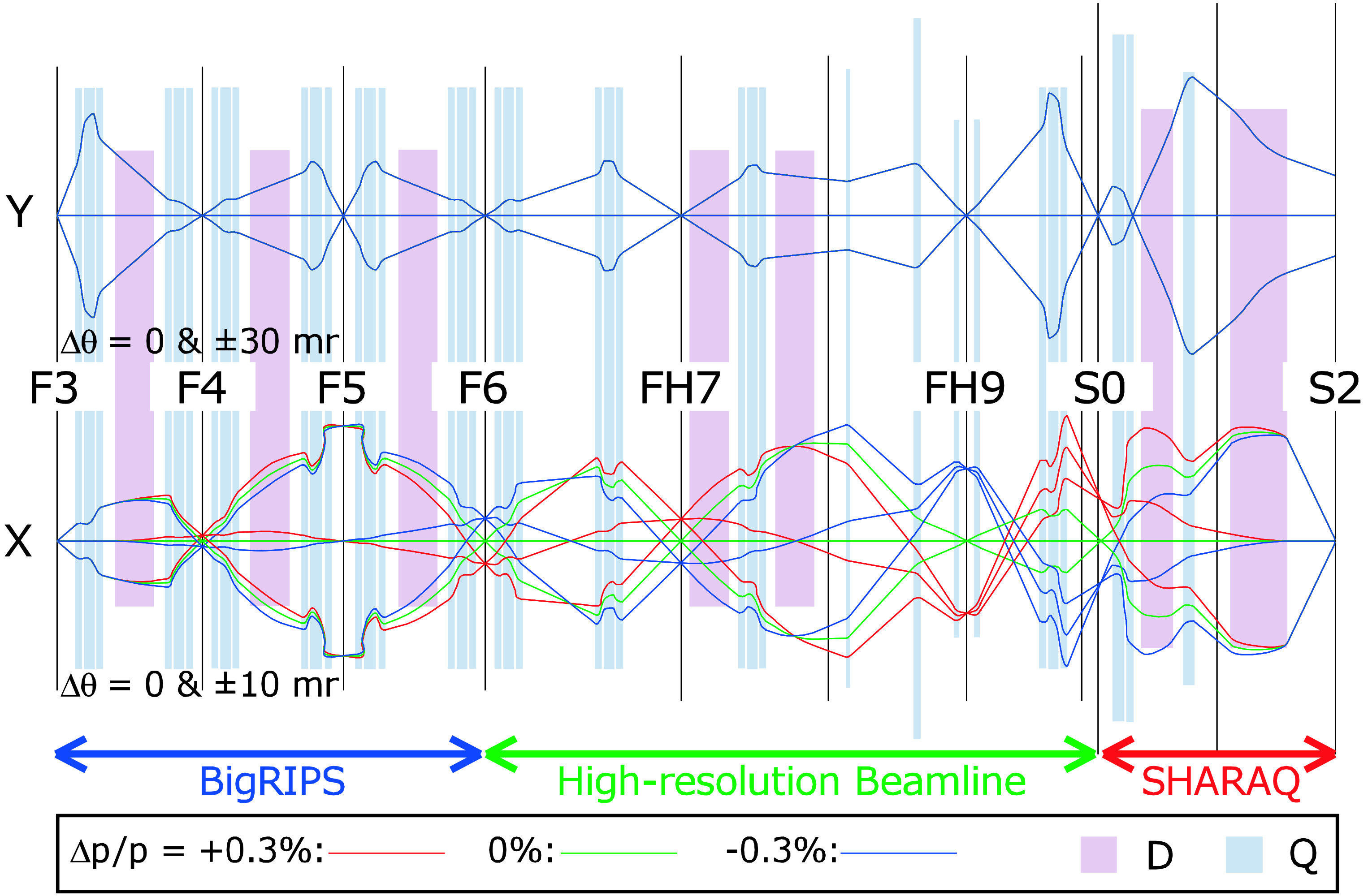
- **in Beam-line detectors, especially**
  - Operate under High Counting Rates
    - Goal : Over 1 MHz

What is SHARAQ

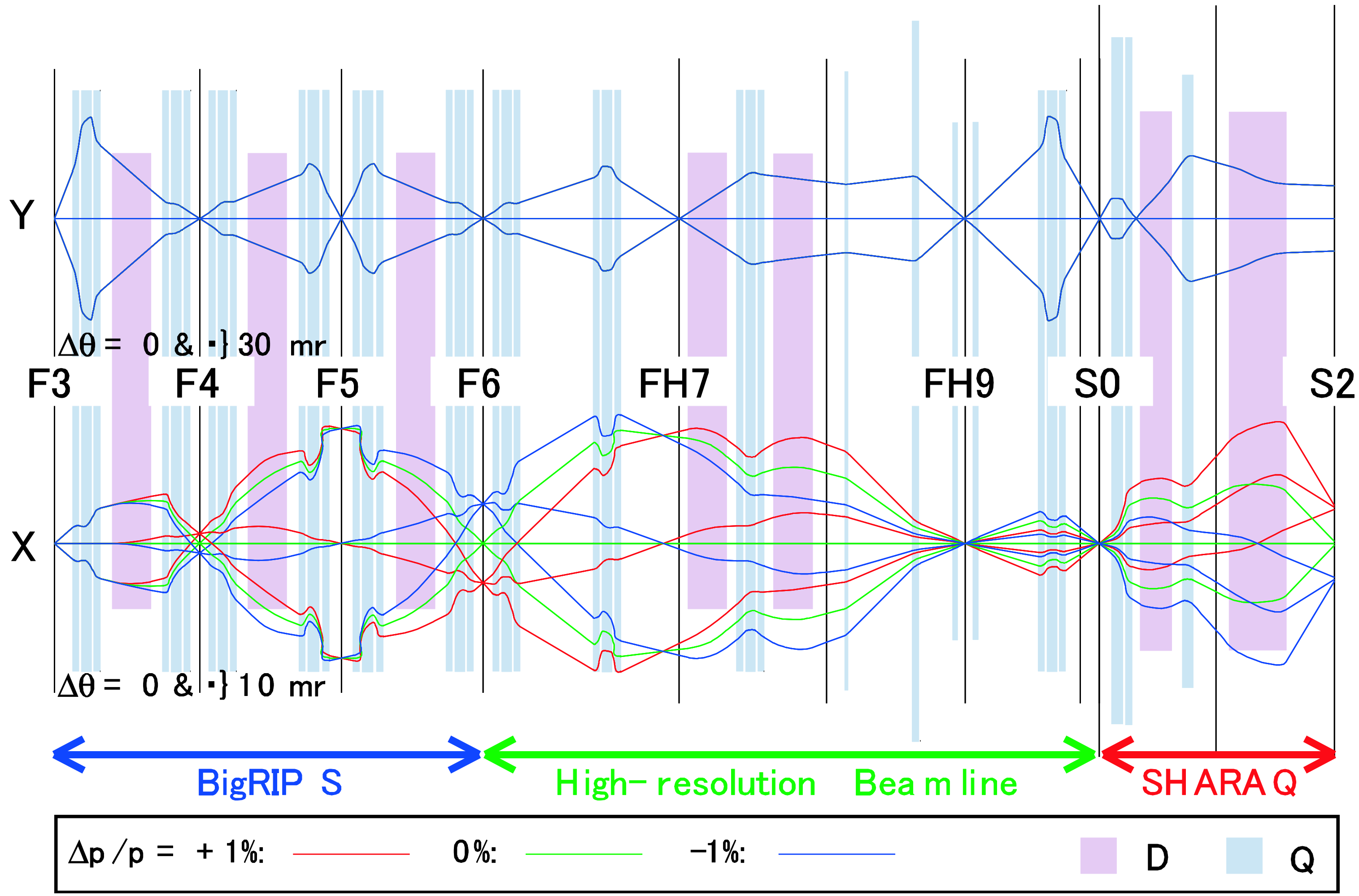
- SHARAQ
  = Spectroscopy with High-resolution Analyzer
  and RadioActive Quamtum beams

- BigRIPS × High-resolution beamline × SHARAQ spectrometer
  - BigRIPS
    provides High intense RI beam
  - High-Resolution beamline
    realizes dispersion-matching transport with SHARAQ spectrometer against large momentum spread of RI Beam
  - SHARAQ spectrometer
    analyzes momentum of reaction products with high resolution

Dispersion Matching



High-Resolution Achromatic



Experiment for confirmation (2016.6.16-25)

Better statistics and Better accuracy of energy than previous experiment (^{4}He(^{8}He,^{8}Be)4n @ 186 MeV/u)

4 events

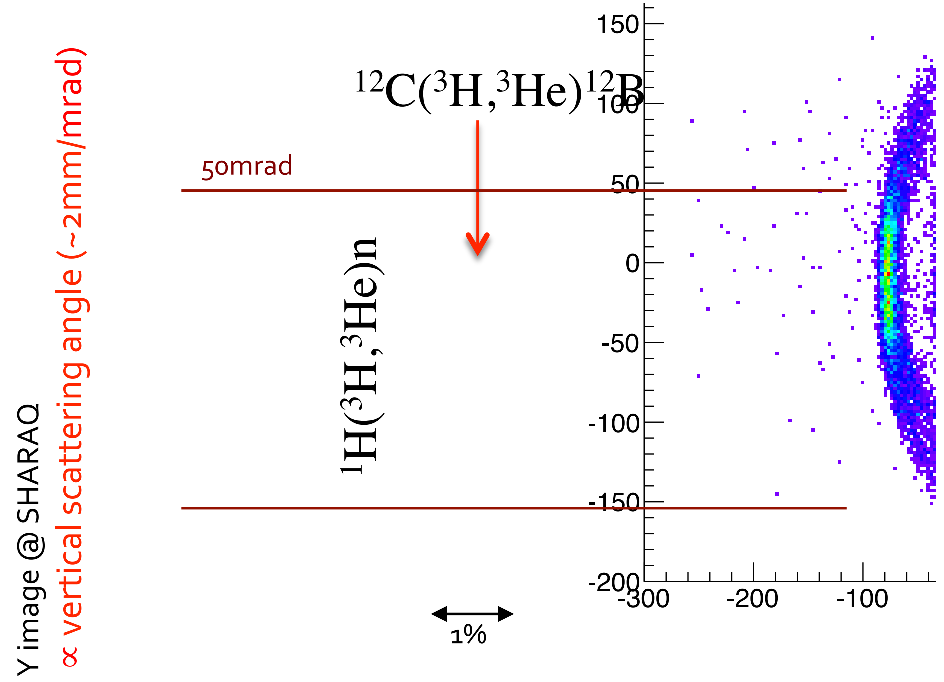
→ 5 times or more

Improve efficiencies (redundancy)

$E_{4n} = 0.83 \pm 0.65(\mathrm{stat.}) \pm 1.25(\mathrm{sys.})$ MeV

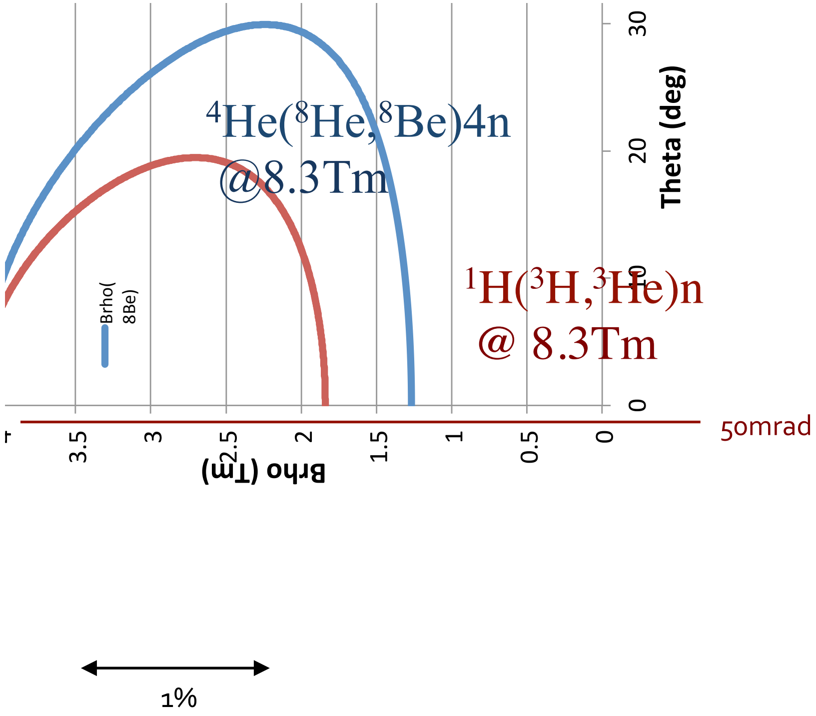
→ better than 0.3 MeV both for stat. and syst.

Calibration using ^{1}H(^{3}H,^{3}He)n with same rigidity ^{3}H beam (310 MeV/u) as ^{8}He



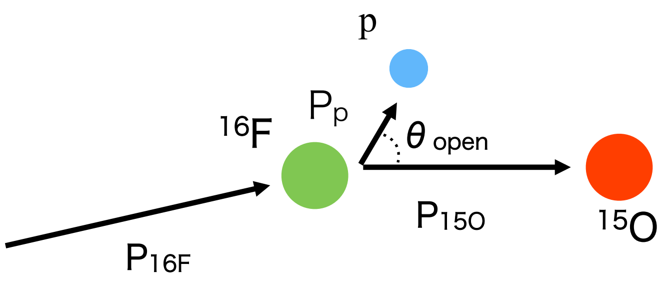
On-line X image @ SHARAQ corrected by beam momentum

∝ momentum (~60mm/%)

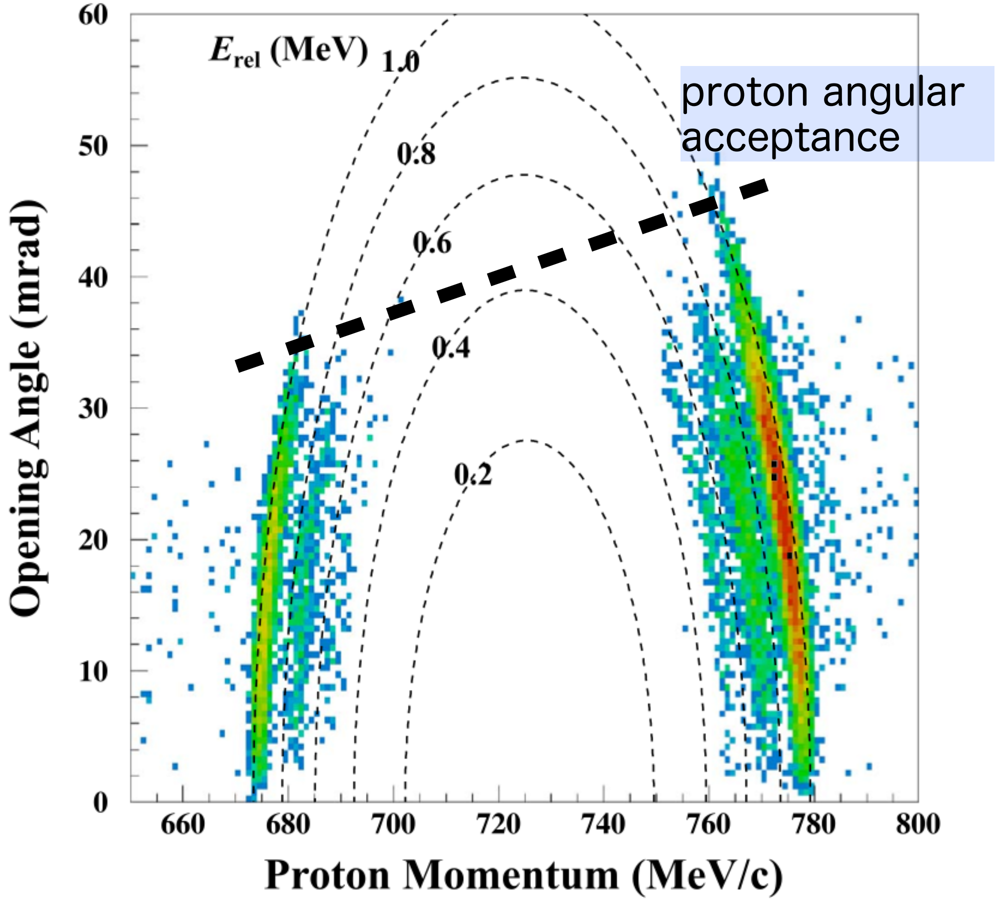


Resolution & Statistics are consistent with expected

$^{16}F \rightarrow ^{15}O+p$ decay



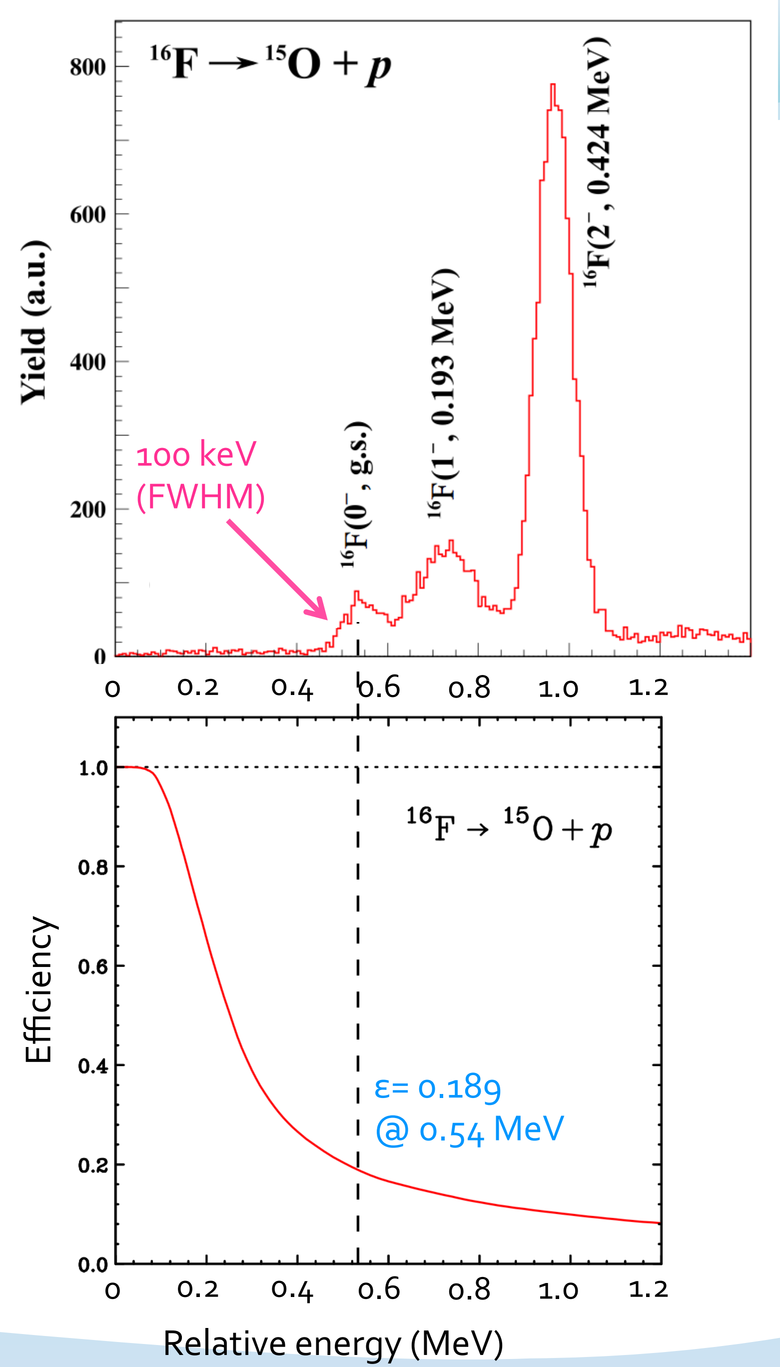
- Kinematics curves
  are clearly observed



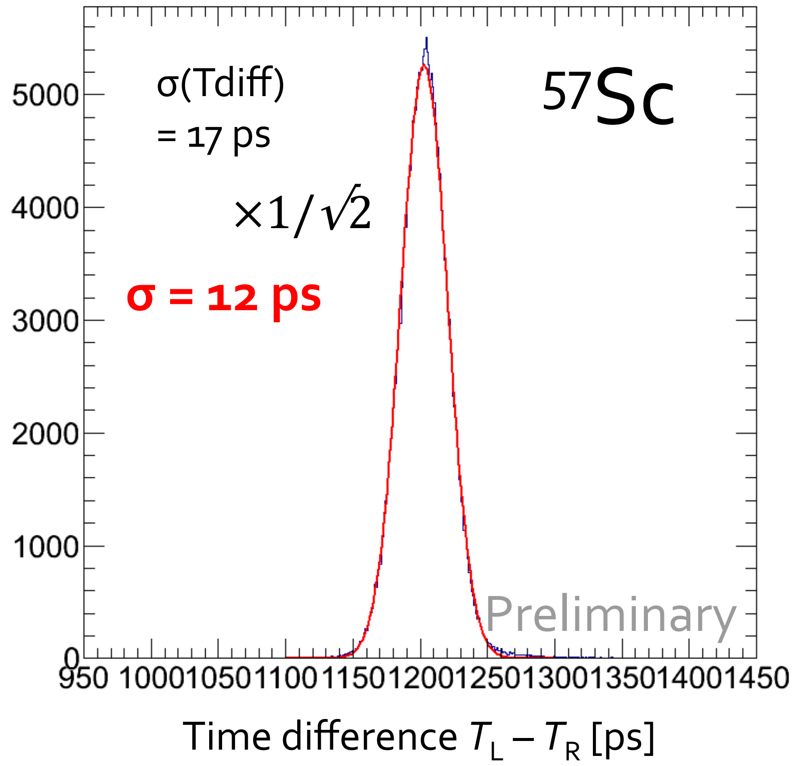
$^{16}F \rightarrow ^{15}O + p$ decay

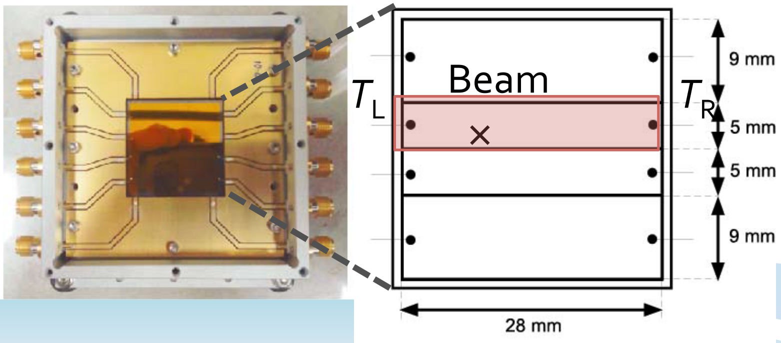
- Relative energy (E_{rel})
  - δE_{rel} = 100 keV (FWHM)
    @ E_{rel} = 0.54 MeV
    ⇒ Clear separation
    between $^{16}F(0^-, 1^-, 2^-)$!

- Detection efficiency (ε)
  (Monte Carlo simulation)
  - ε=0.189 @ E_{rel} = 0.54 MeV
  - Due to ang. accpt. for proton



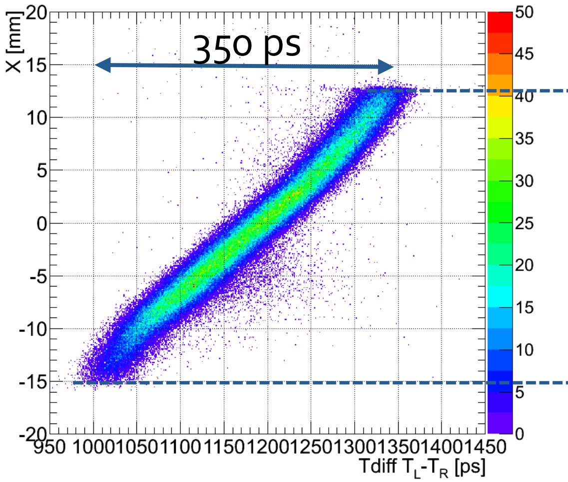
Time resolution for heavy ions





- Time difference between both edges of a strip in a diamond detector
- Corrected by hit position in the strip

cf. Time difference vs tracked position (before correction)



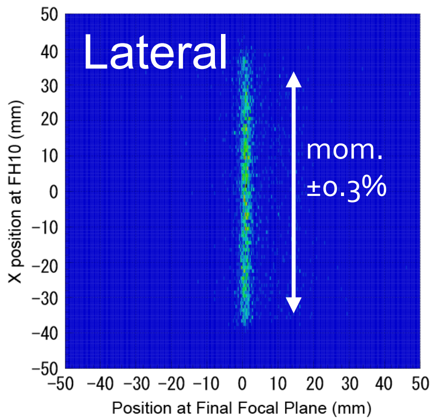
Position resolution : 200 μm(FWHM) by MWDC

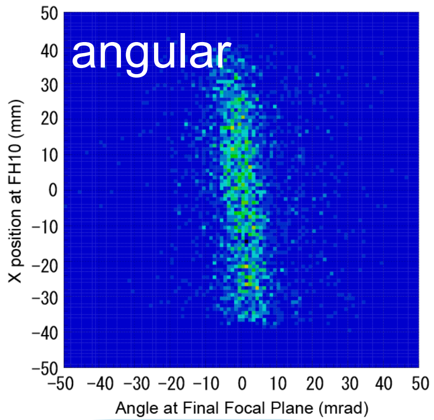
- **Timing resolution of the diamond detector is estimated to be σ = 12 ps**

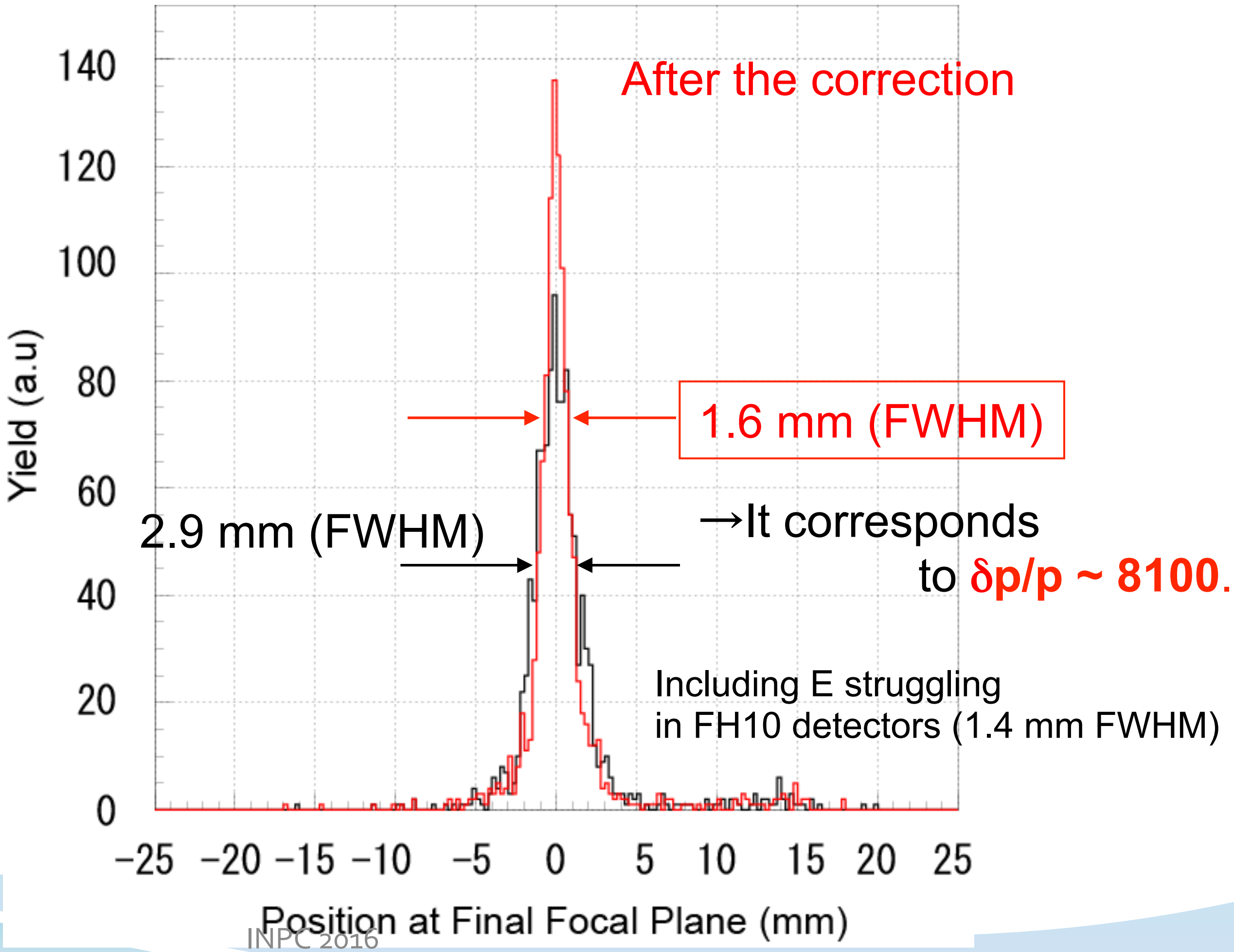
(cf. ^{4}He at 32 MeV → σ = 27 ps)

Dispersion matching transport

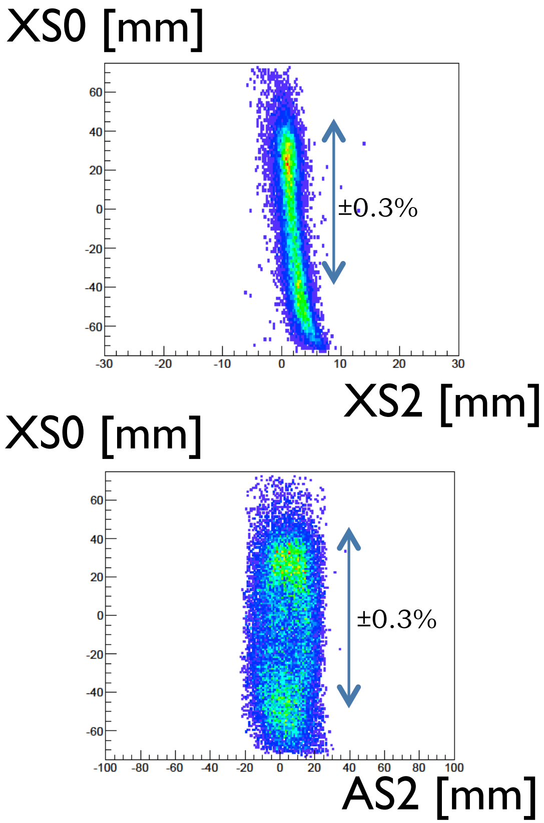
- Previous record for ^{14}N at 200 AMeV

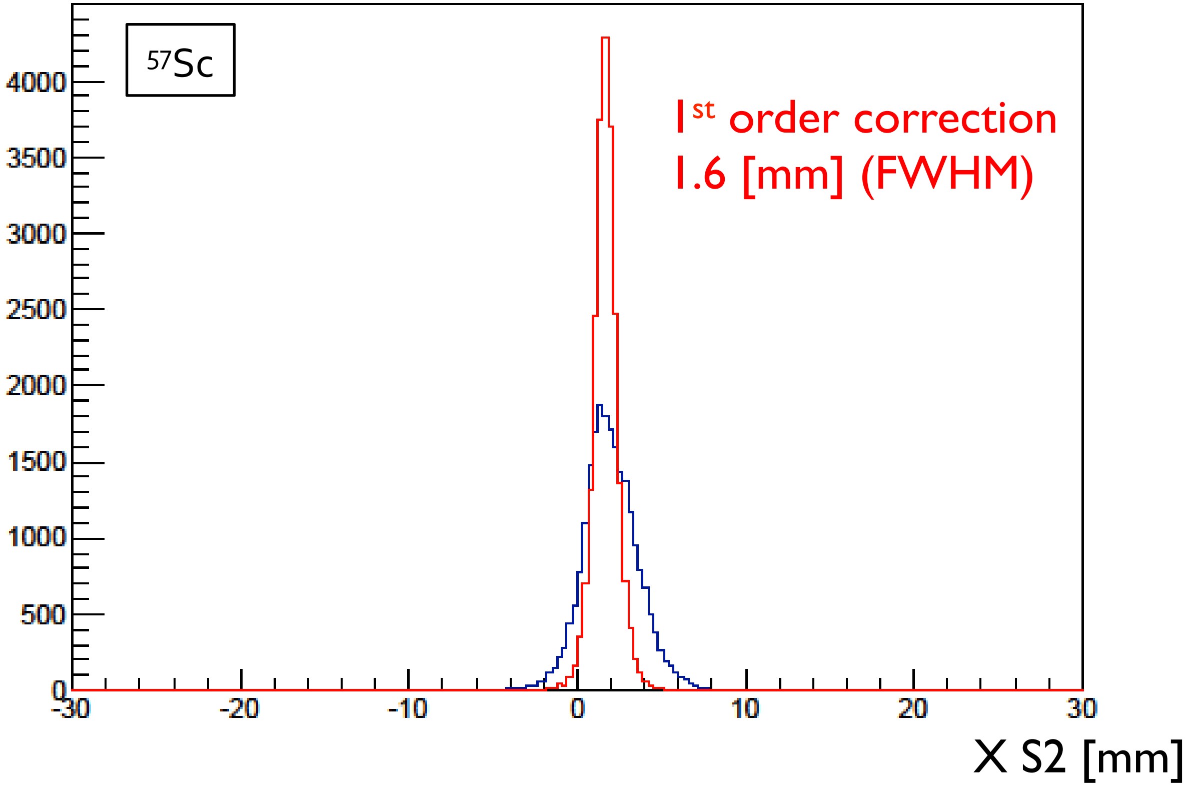






DM Optics Tuning and Correction in SHARAQ03





⇒ Due to low intense secondary beam (< 1 cps),

ion optical tuning was not sufficient…

⇒ 1.6 mm (FWHM) corresponds to $p/\Delta p \sim 7500$ (FWHM;)

We can do correction well using F3 (Starting) and S0 (dispersive) information.

Radiation Damage

◎ pCVD diamonds operate 10-days beam time

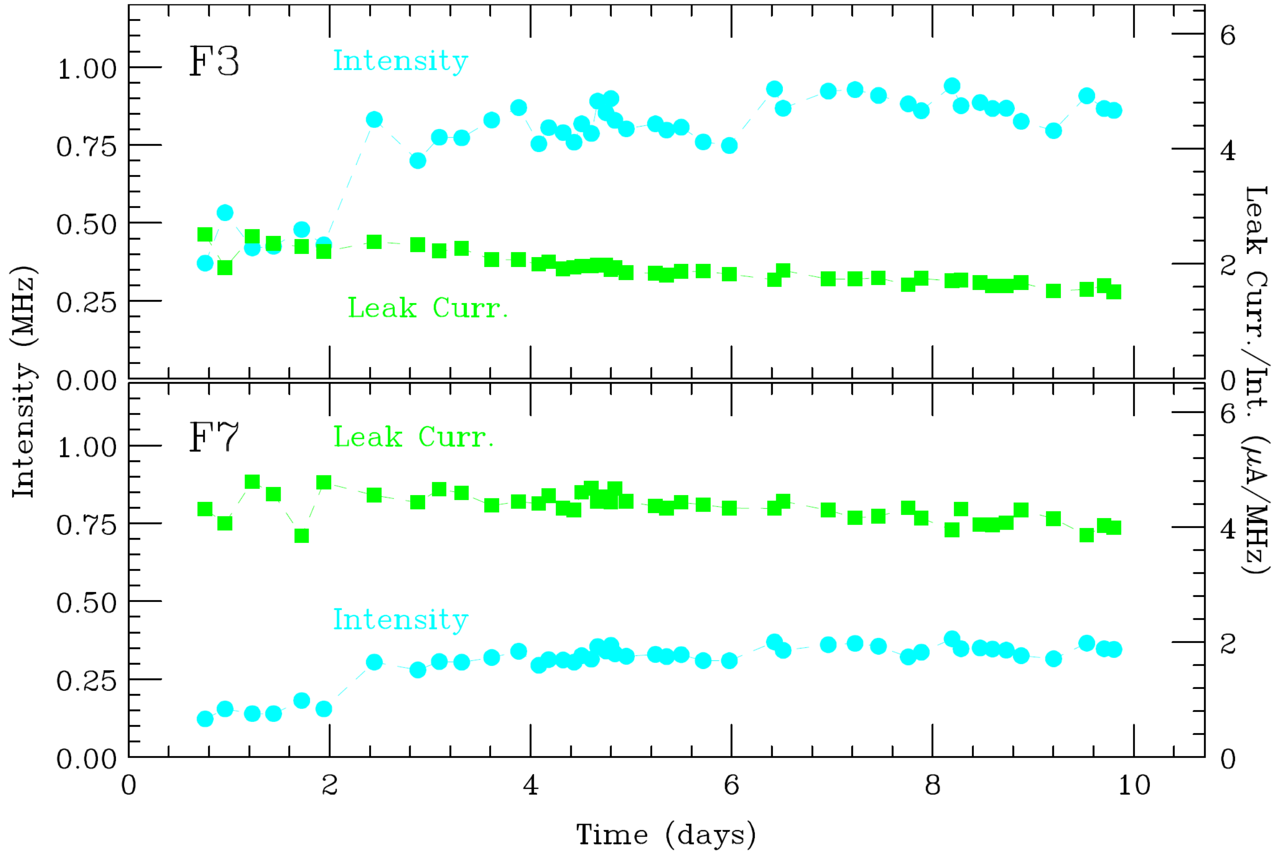
Setup: 2 diamonds were installed for (F3 and F7)
Beam: ^{132}Sn beam
    at F3 : 193 MeV/u, 850kHz (ΔE=464MeV)
    at F7 : 130 MeV/u, 300kHz (ΔE=581MeV)
Beam Time : 10 days

As Online Radiation Damage Monitor, we measured leak current ⇒ Stable (not increased) during MT.
We have not observe serious problems of detector signals

Details of radiation damage (in time resolution etc) are under analysis…

Radiation Damage

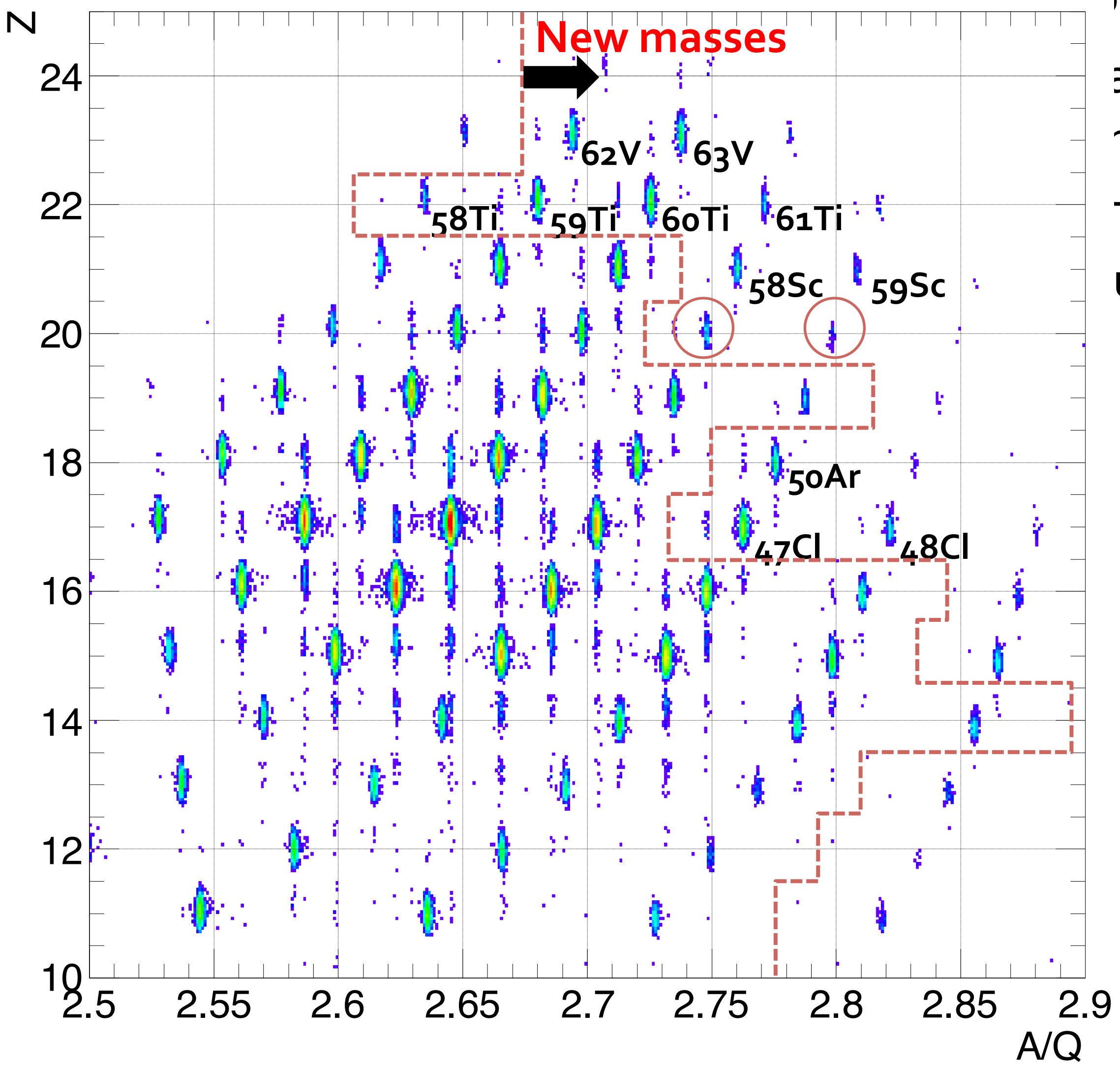
◎ pCVD diamonds operate 10-days beamtime



← crystal #001

← crystal #003

※ Initial values of leak current may be determined by the property of each crystal

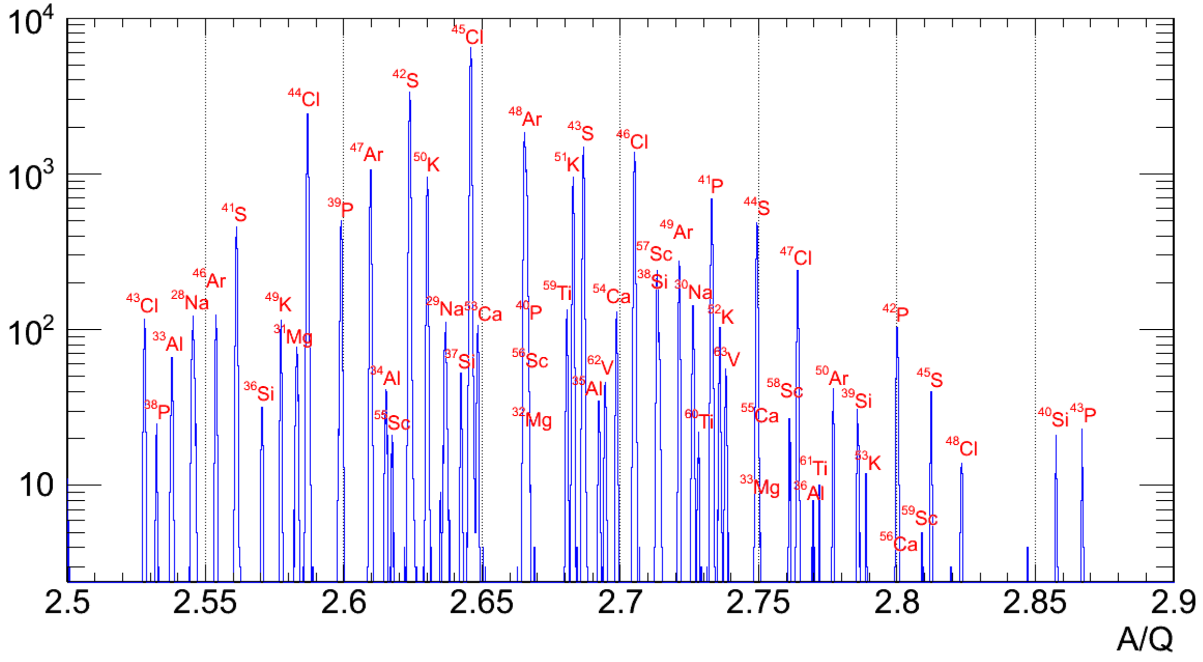


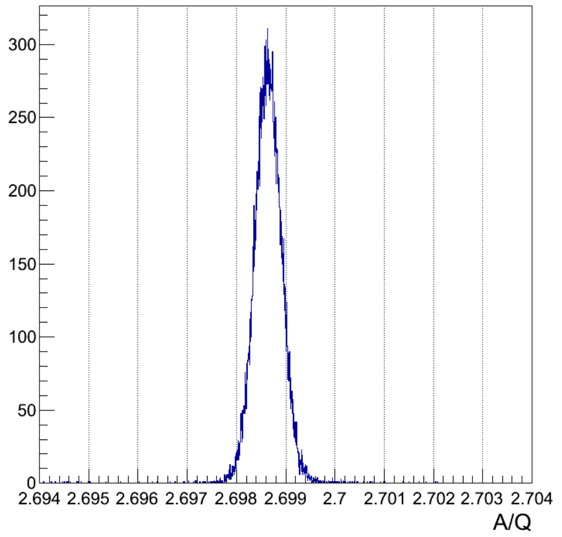
- **Total yield of 55Ca: several thousands**
- any species of reference nuclei over a broad nge of *A* and *Z* were observed.
  - These nuclei are used in the mass calibration.
- **uclei whose masses have not been measured:**

Z	Nuclei (Yield > 1000)
17	47Cl, 48Cl
18	50Ar
19	--
20	55Ca
21	58Sc, 59Sc
22	58Ti, 59Ti, 60Ti
23	62V, 63V

Masses of these nuclei will be determined with the precision of several hundreds keV

Mass spectra





- **Mass resolution of 10000 (σ) has been achieved for Z = 20 nuclei**
  - 55Ca: σ(stat) = 90 keV
  - 56Ca: σ(stat) = 200 keV
- **Masses of 55Ca and 56Ca are determined with precisions of a few hundreds keV**