SAMURAI Spectrometer for RI Beam Experiments

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representing
SAMURAI Construction team

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Project manager : K. Yoneda (RIKEN)

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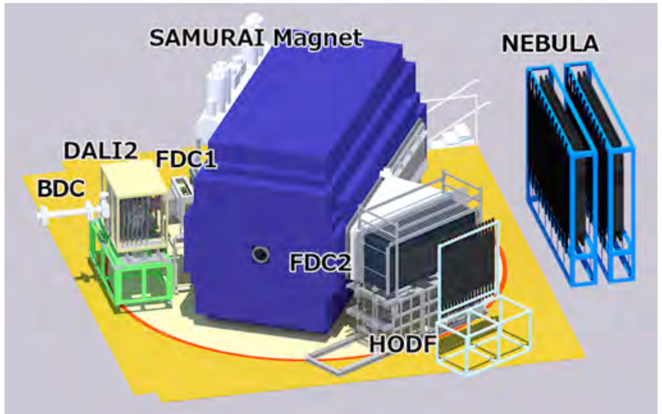
Vacuum system and Utilities: H. Otsu*, Y. Shimizu (RIKEN)
Heavy ion detectors: T. Kobayashi*, Y. Matsuda, N. Chiga (Tohoku Univ.), H. Otsu (RIKEN)
Neutron detectors: T. Nakamura*, Y. Kondo, Y. Kawada, T. Sako, R. Tanaka (Tokyo Tech), Y. Satou (Seoul National Univ.)
Proton detectors: K. Yoneda*, Y. Togano, M. Kurokawa, A. Taketani, H. Murakami, T. Motobayashi (RIKEN), K. Kurita (Rikkyo), T. Kobayashi (Tohoku), L. Trache (Texas A&M) and the TWL collaboration
Polarized deuteron exp. : K. Sekiguchi*, Y. Matsuda
Time projection chamber: T. Murakami* (Kyoto), T. Isobe, A. Taketani, S. Nishimura, Y. Nakai, H. Sakurai (RIKEN), W.G. Lynch (Michigan State) and SAMURAI TPC collaboration

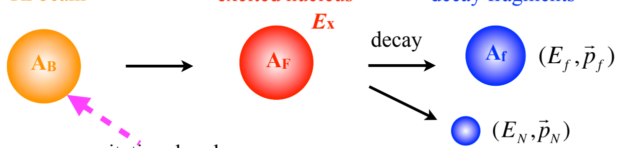
SAMURAI(7)

Superconducting Analyser for MUlti particles from RAdio Isotope Beams with 7 Tm of bending power

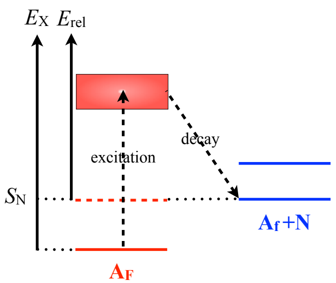
- designed/built primarily for kinematically complete experiments at RIKEN RIBF (invariant mass spectroscopy)
- Time line
  - Construction period : FY2008 ~ FY2011
  - SAMURAI magnet : ~ Jun-2011
  - Commissioning run : Mar-2012
  - 3 physics experiments : May-2012



Invariant mass spectroscopy



excitation, breakup
via
"γ" absorption (heavy target)
(p,p'), (p,n),
(p,pN), nucleon removal ...



∗ **Excitation energy E_X or relative energy E_{rel}**

$$E_X = \sqrt{(E_f + E_N)^2 - (\vec{p}_f + \vec{p}_N)^2} - (M_f + M_N) + S_N$$

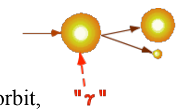
∗ Coulomb Breakup

$$\frac{d\sigma(E1)}{dE_x} \propto N_\gamma(E_x) \frac{dB(E1)}{dE_x}$$

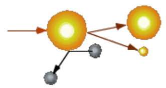
∗ Energy region : < 300 MeV/u

Physics Interest

- Coulomb breakup reaction : excitation via virtual photon ("γ")

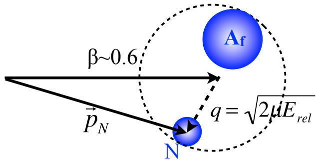


  - (γ,n)-type, neutron-rich nuclei
    - light-mass region : non-resonant excitation, single-particle orbit, halo neutron correlation — ^{19}B+Pb(γ) → ^{17}B+2n
    - heavy-mass region : collective excitation, Pygmy dipole resonance (PDR); neutron skin, Giant dipole resonance (GDR) — ^{76}Ni+Pb(γ) → ^{75}Ni+n, ^{74}Ni+2n
  - (γ,p)-type, proton-rich nuclei
    - inverse reaction of (p,γ) for astrophysics — ^{65}As+Pb(γ) → ^{64}Ge+p (?)
- Nucleon-removal / knockout reactions : unbound ground state beyond the drip line — ^{28}Ne+C → ^{26}O → ^{24}O+2n
- Direct reactions : (p,p'), (p,n), (p,pN) ... decay tagging with missing-mass method GTR, ... — ^{64}Ge(p,n)



Experimental requirements

- Acceptance for projectile-rapidity nucleon
  - angle : $\theta_N < \pm 6\ (11)°$
  - momentum : $\Delta p/p < \pm 13\ (24)$ %
  - for $E_{rel} = 3\ (10)$ MeV @250MeV/A
  - i.e. large angular/momentum acceptance for p or n



- Resolution for M_{inv}

$$\Delta E_{rel} \approx \sqrt{2\mu E_{rel}/m_u}\sqrt{E_{in}/A}\sqrt{(\Delta p_f/p_f)^2 + (\Delta p_N/p_N)^2 + \Delta\theta_{fN}^2}$$

$$\Delta E_{rel} \approx 0.2\sqrt{E_{rel}}\ [\text{MeV}] \quad \leftarrow \quad \text{rigidity(f)}\ \frac{\sigma_R}{R} \approx \frac{5}{1000} \quad \text{velocity(N)}\ \frac{\sigma_\beta}{\beta} \approx \frac{5}{1000} \quad \text{angle(N)}\ \sigma_\theta \approx \frac{5}{1000}$$

(σ_T~250psec σ_X~5cm @10m)

- Resolution for PID(f)

＊often limited by target thickness

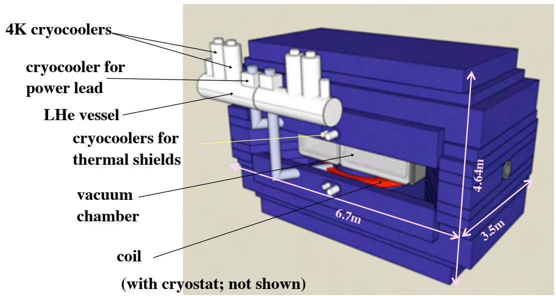
- rigidity(f) $\frac{\sigma_R}{R} \approx \frac{1}{700}$ $@R \sim 2.2$ GeV/c
- velocity(f) $\frac{\sigma_\beta}{\beta} \approx \frac{1}{1100}$ $@\ \beta \sim 0.6$ or • energy(f) $\frac{\sigma_E}{E} \approx \frac{1}{400}$ $@\ E \sim 30$ GeV

$\leftarrow \frac{\sigma_A}{A} \approx \frac{0.2}{100}$

Magnet Design Principles

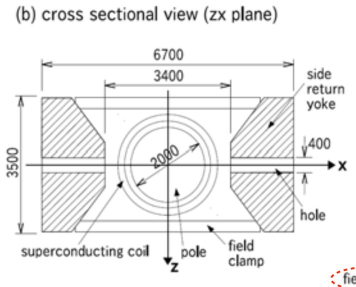
- Large field integral
  - good rigidity analysis, $\Delta R/R$~10^{-3},
  - charged-particle sweeper
    - ★ BL_{max}= 7.1 Tm (B_{max}= 3.1 T)
- Small fringe field
  - target detectors : B < 30G
    - ★ enough Iron
    - ★ Field cramp
- Large opening for neutrons
  - θ_H(n)~ ±10°, θ_V(n)~ ±5°
    - ★ Large pole gap (80cm)
    - ★ Shape of return yoke & vacuum chamber
- Flexibility
  - for various experiments
    - ★ Rotatable base : -5° ~ +95°
    - ★ Hole in the return yoke : 400 x 400 mm^2

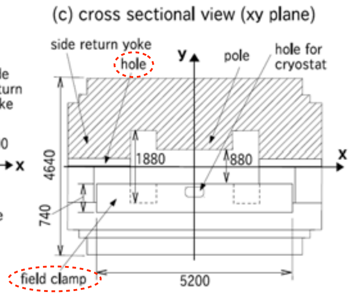
Superconducting Magnet ~ HISS @LBL



H-type superconducting magnet

pole :	diameter : 2 m
	gap : 0.8(0.88) m
max. Field :	3.1 T
BL :	7.1 Tm
M.M.Force :	1.9 MAT/coil
	3411 turns x 560A
stored energy :	33MJ
coil :	180 x 160 mm^2
current density:	66 A/mm^2 (NiTi/Cu)
weight:	600 (567+8x2+14) ton
company：	Toshiba





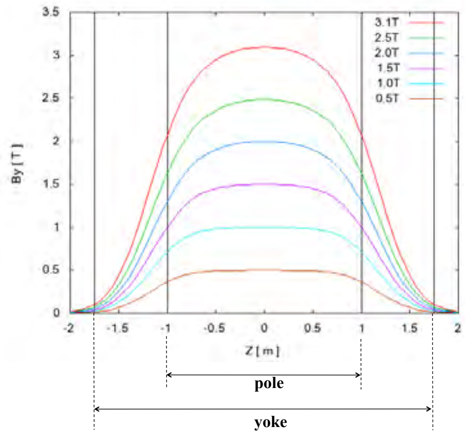
Cryocooler (x14)
@4.2, 20, 80K

on Rotating Base :
-5° ~ +95°

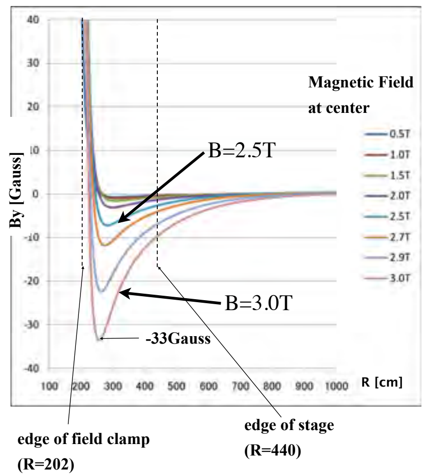
Magnetic Field

- Design principle : high magnetic field & low fringe field
  - use enough iron (~570 t)
  - add field cramp

Central field



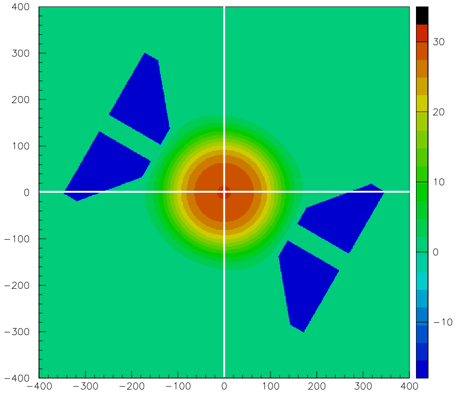
Fringing field (central axis)



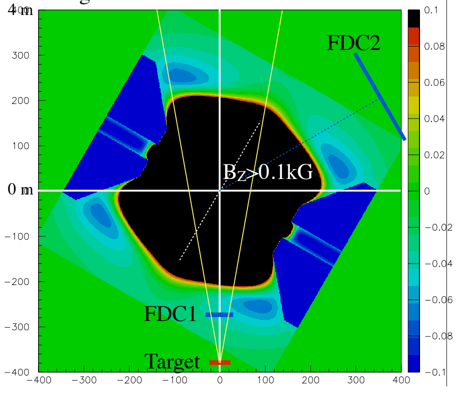
Magnetic Field - 2

- Magnetic field at target / target detectors

Central field : 0 ~ 30 kG



Fringe field : -0.1 kG ~ +0.1 kG

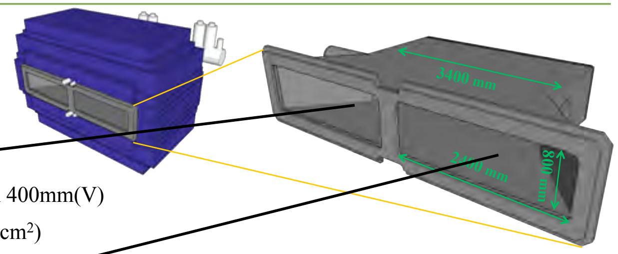


B~ -20±10 G @Target position ±1m

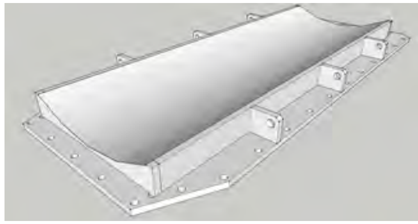
iron shield necessary
around NaI(Tl) γ detectors [DALI2]

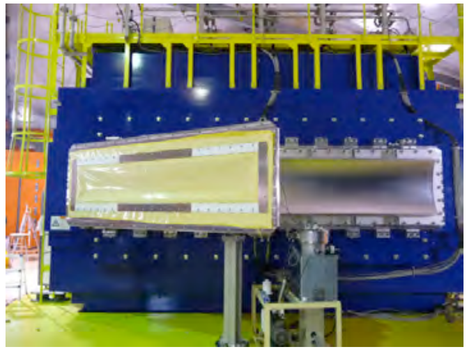
Vacuum Chamber & Exit Window

Poster : Shimizu Y.



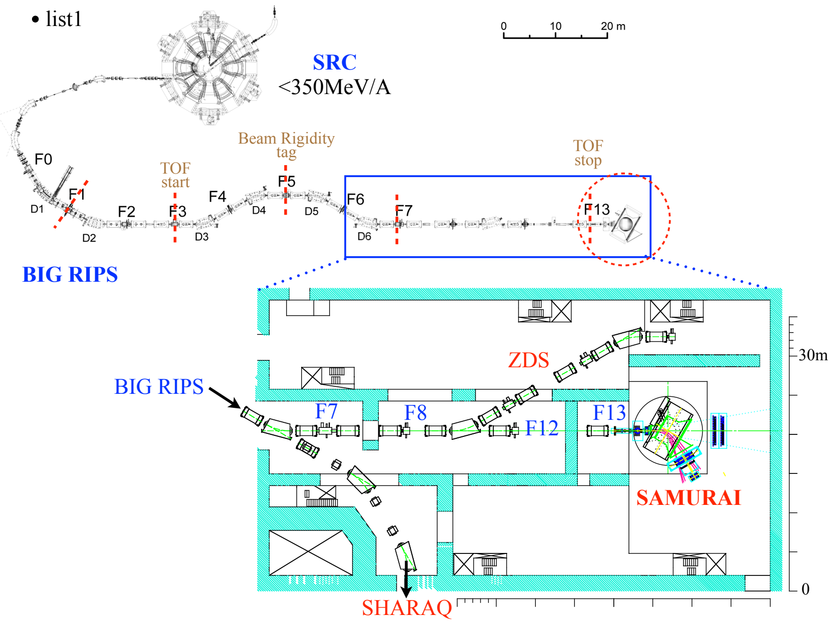
- Charged particles
  - opening : 2940mm(H) x 400mm(V)
  - 0.3mm^t Kevlar (~16mg/cm^2) + 75μm^t Mylar
- Neutrons
  - opening : 2400mm(H) x 800mm(V)
  - 3mm^t SUS





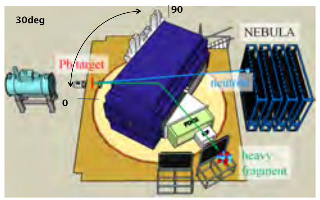
SAMURAI @RIKEN RIBF (RI Beam Factory)

- list1

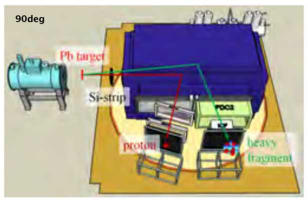


Experimental configuration

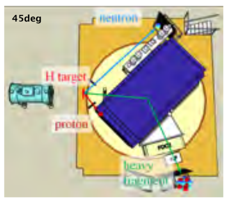
(γ, *n*) : neutron-rich side



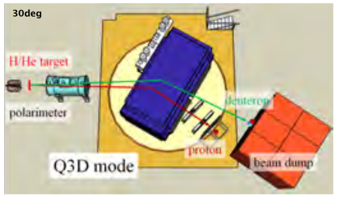
(γ, *p*) : proton-rich side



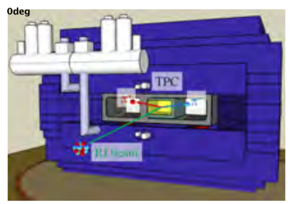
(*p,p'*), (*p,n*), (*p,pN*)



pol. *d*

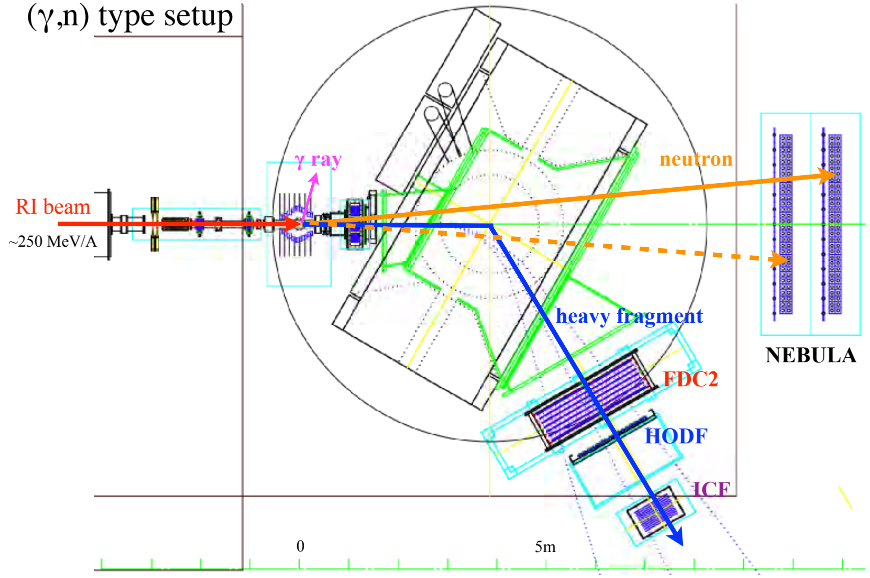


EOS

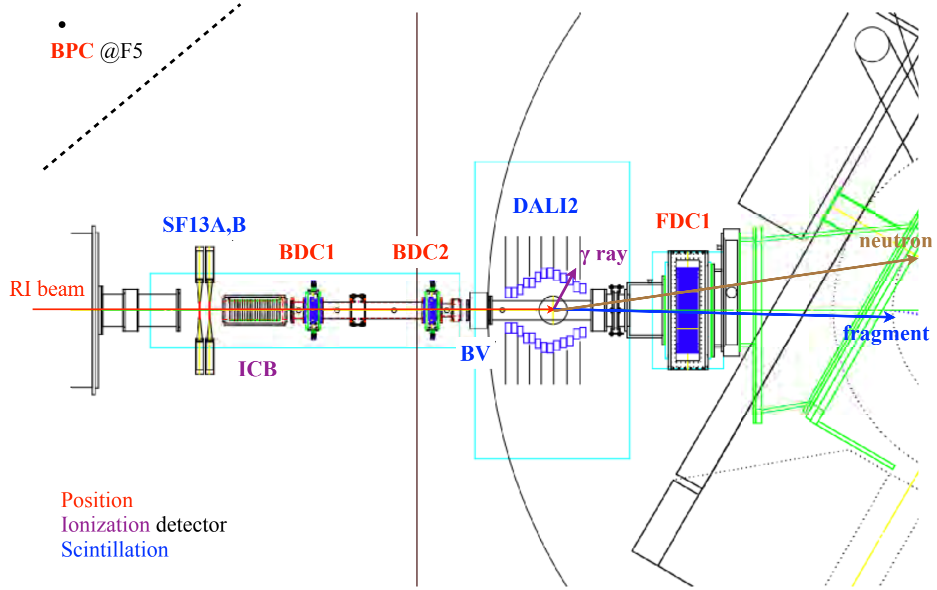


Experimental Setup @Mar/May-2012

(γ,n) type setup

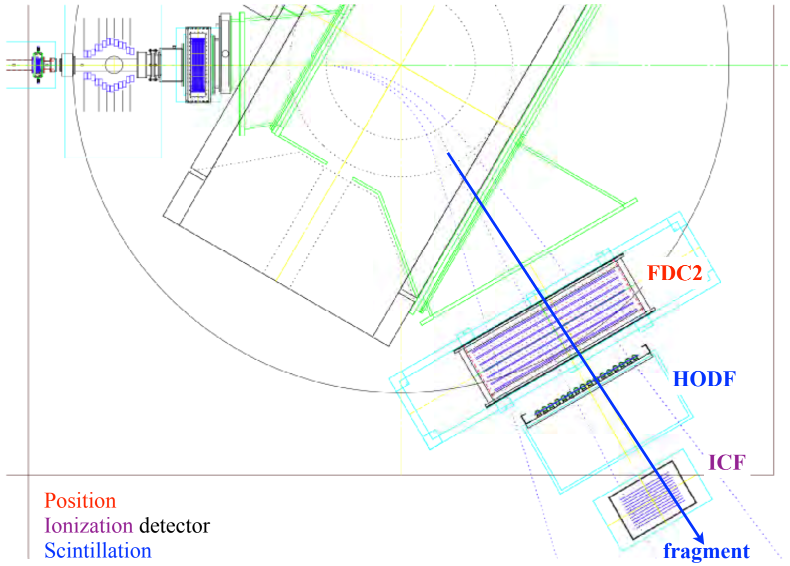


Setup : upstream



Poster on DALI2 by S. Takeuchi

Setup : downstream



Detectors

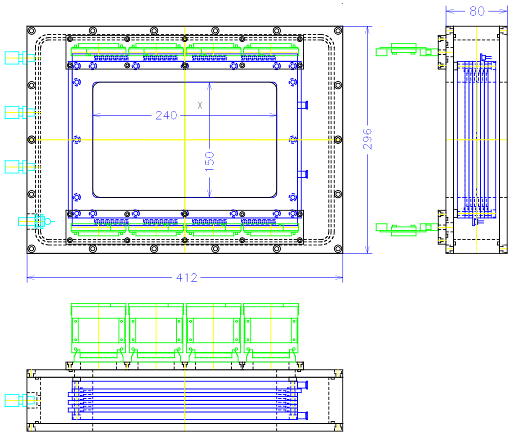
Position, Ionization, Scintillation detector

Name	Effective Area	configuration	#Readout ch	Data	gas
BPC	240 x 150	2x	128	T(2)	i-C_4H_{10} 50 torr
BDC1	80 x 80	4X 4Y	128	T(2)	i-C_4H_{10} 50 torr
BDC2	80 x 80	4X 4Y	128	T(2)	i-C_4H_{10} 50 torr
FDC1	310φ	6X 4U 4V	448	T(7)	i-C_4H_{10} 50 torr
FDC2	2200 x 800	6X 4U 4V	1568	T(25)	He+50%C_2H_6 1atm
ICB	140 x 140	10X	10	A(1)	P10, 1atm
ICF	750 x 400	12X	48	A(2)	P10, 1atm
HODF	1600 x 1200	16	32/32	T(1) / A(1)	10mm^t
HODP	1600 x 1200	16	32 / 32	T(1) / A(1)	10mm^t
SF13 A/B	120 x 120	2	4 / 4	T / A	0.5mm^t
SBV	100 x 100	1	2 / 2	T / A	10mm^t
NEBULA	3600 x 1800	120 (N)+ 24(V)	288 / 288	T(10) / A(10)	120mm^t
DALI2		13 rings	140	T / A	NaI(Tl) 40(45)x80x160

Beam Proportional Chamber (BPC)

* Momentum tagging
  @F5 momentum dispersive focul plane

Type : 4mm-spacing MWPC
Effective area : 240mm(H) x 150mm(V)
Configuration : xx
Anodes : 128ch= 2 x 64ch/plane
Gas : i-C_4H_{10} @50torr
in F5 vacuum chamber

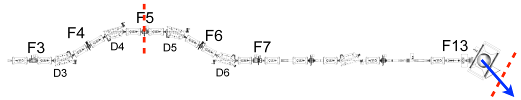


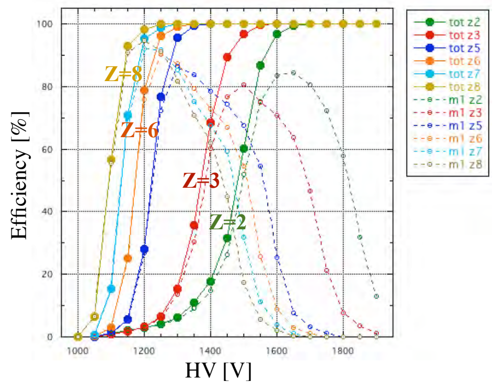
BPC - 2 : Response for Z=2~8

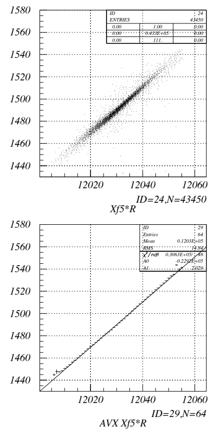
○ Pressure= 50 torr, E_b= 250 MeV/A, V_{th}=-0.4V

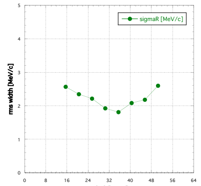
$$\frac{4[mm]}{\sqrt{12}}\frac{1}{33[mm/\%]} \approx 0.03\%$$

D~33mm/%







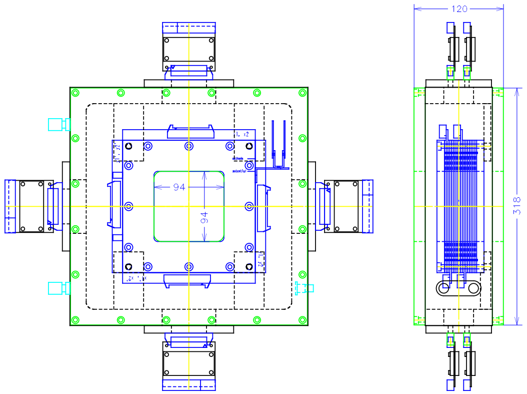


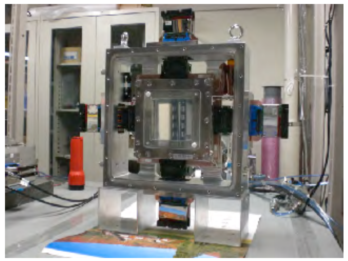
D(F5)~ 29.4 mm/%

Beam Drift Chamber (BDC1, BDC2)

* Beam Phase Space measurement

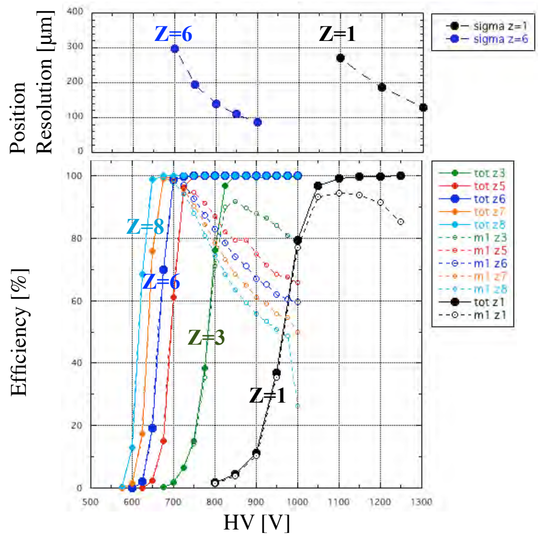
Drift distance : 2.5mm
Gap : 2.5mm
Effective area: 80mm x 80mm
Configuration: xx'yy'xx'yy' (8 planes)
Anode : 128ch / chamber
Gas : i-C_4H_{10} @25-100 torr
connected to beam pipe



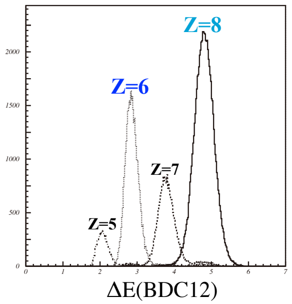


BDC - 2 : response for Z= 1~8

○ Pressure= 100 torr, E_b= ~200 MeV/A, V_{th}=-0.8V



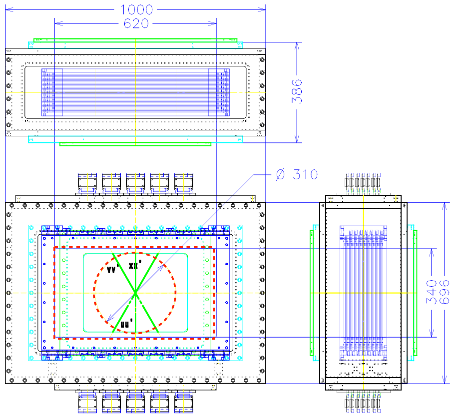
* Detection efficiency
  stable plateau, ε~100%
* Position resolution σ_x
  300 μm → < 200μm
* Tracking efficiency
  ε > 99.5%
* ΔE information
  16 planes averaged
  moderate Z resolution



Forward Drift Chamber 1 (FDC1)

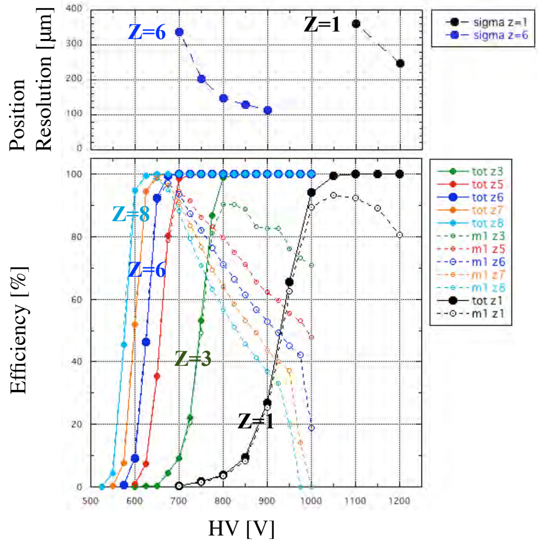
* Fragment Phase Space after target

Drift distance : 5mm
Gap : 5mm
Effective area: 310mmφ [620mm(H) x 340(V)]
Anode: 448 = 14 x 32ch/plane
Configuration: xx'uu'vv'xx'uu'vv'xx'(14 planes)
Gas: i-C_4H_{10} , P< 100 torr
connected to upstream/downstream vacuum

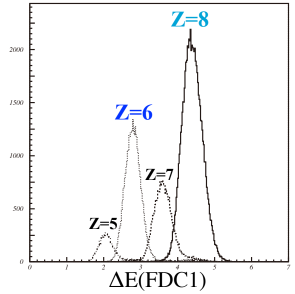


FDC1 - 2 : response for Z=1~8

o Pressure= 50 torr, E_b= 200 MeV/u, V_{th}=-0.4V



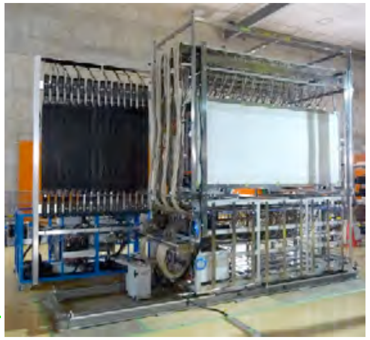
* Detection efficiency
  stable plateau, ε~100%
* Position resolution σ_x
  300 μm → < 200μm (z=6)
* Tracking efficiency
  ε > 99.5%
* ΔE information
  14 planes averaged
  moderate Z resolution

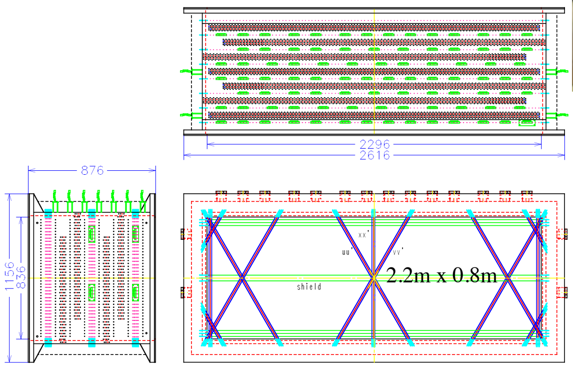


Forward Drift Chamber 2 (FDC2)

* Momentum reconstruction : after Samurai magnet

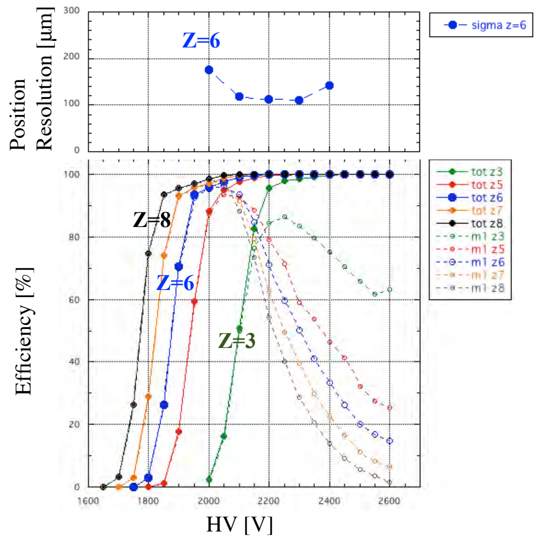
Drift distance : 10mm (hexagonal)
Configuration : xx'uu'vv'xx'uu'vv'xx'(14 planes)
Effective area : 2.2m(H) x 0.8m(V) x 0.8m(D)
Anode : 1568 ch (112 x 14)
Gas : He+50%C_2H_6 (or 60%CH_4) @1atm
L/Lr : 0.9 x 10^{-3}



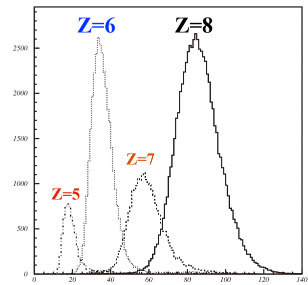


FDC2 - 3 : response for Z=3~8

o E_b= 200 MeV/u, V_{th}=-0.8V, Gas= He+50%C_2H_6

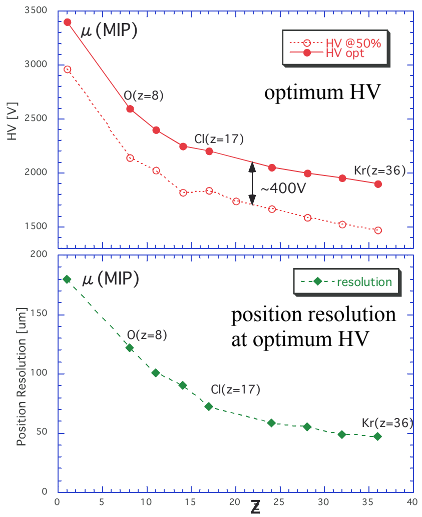


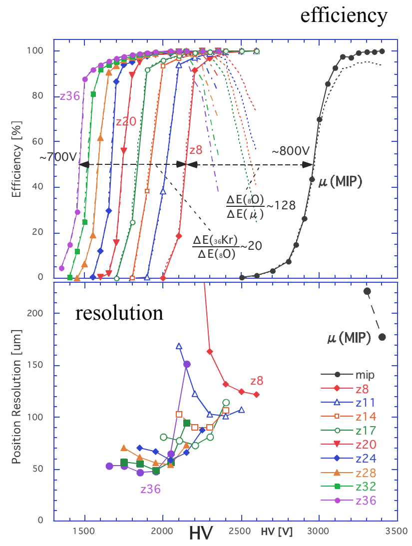
* Detection efficiency
  stable plateau, ε~100%
* Position resolution σ_x
  200 μm → ~100μm
* Tracking efficiency
  ε > 99.5%
* ΔE information
  14 planes average
  moderate Z resolution



FDC2 - 4 : response for high Z (8 ~ 36) @HIMAC

＊gas : He+60%CH4

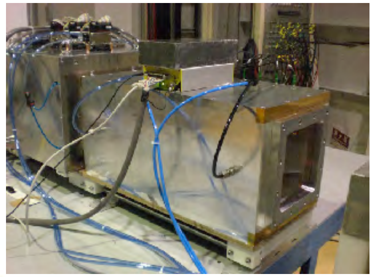


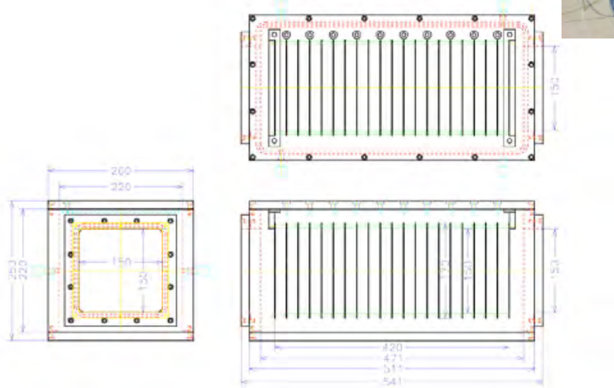


Ion Chamber for Beam (ICB)

＊Multi-Layer Ion Chamber : dE/dx (beam charge)

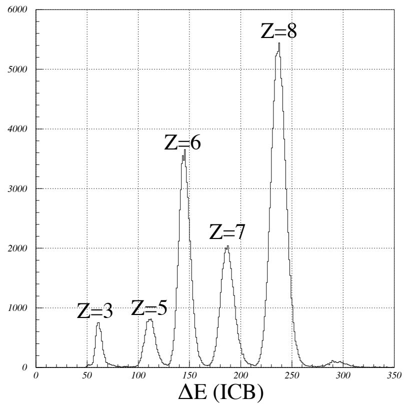
Configuration :	10 anodes+11 cathodes
Effective area:	140mm x 140mm x 420mm(D)
Gas:	P10 @1atm
Preamp :	τ_{decay}= 10 μs
Shaper :	τ= 0.25 μs, unipolar+active BLR



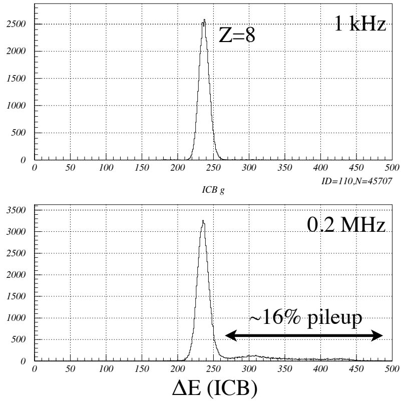


ICB - 2 : response

＊Z= 3~8 (A/Z=2) @250MeV/u

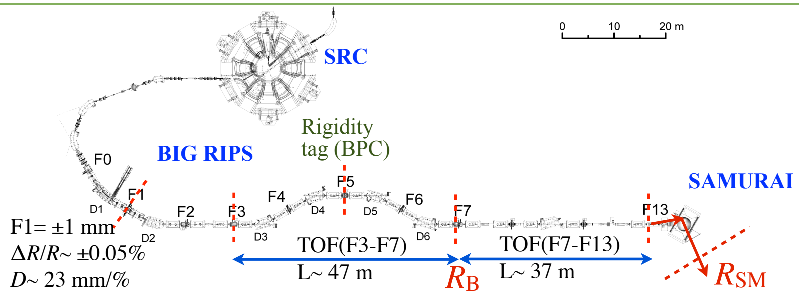


＊Rate dependence



better resolution than 2mm^t plastic

Bρ scan & Rigidity reconstruction



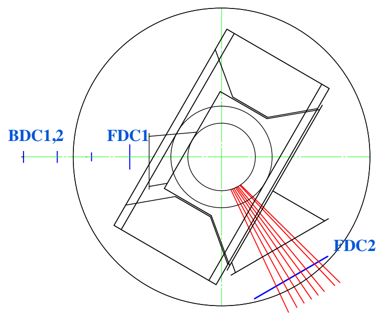
＊$\Delta R_B/R_B$ ~ ±0.05% (F1= ±1mm)

with TOF(F3-F7) & TOF(F7-F13)

B_{SM}= 2.0 T : ^{10,11,12,15}C R= 1347 MeV/c ±21%

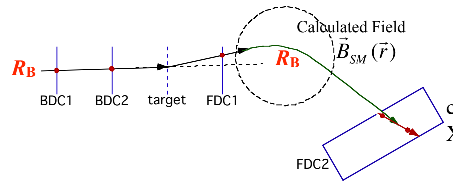
B_{SM}= 2.5 T : ^{12,15,16,17}C R= 1676 MeV/c ±18%

B_{SM}= 3.0 T : ^{10,11,12,14}Be R= 2011 MeV/c ±17%



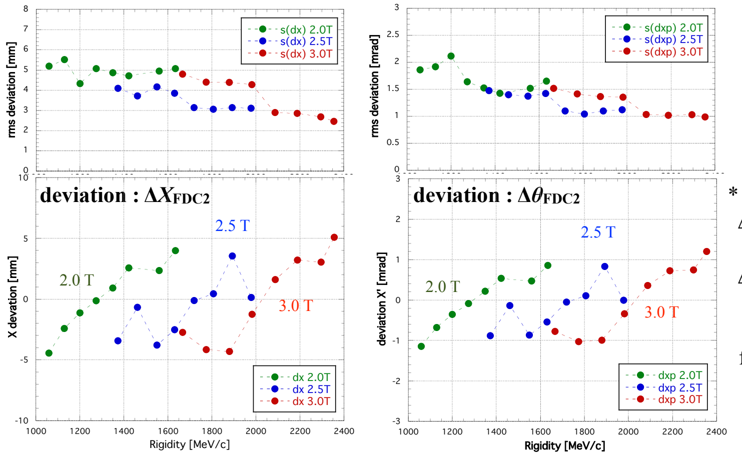
Magnetic Field & Detector Position

Poster : H. Otsu
Detector position meas.



＊Magnetic Field scaled

f(2.0T)= +0.45%
f(2.5T)= +0.35%
f(3.0T)= +0.10%



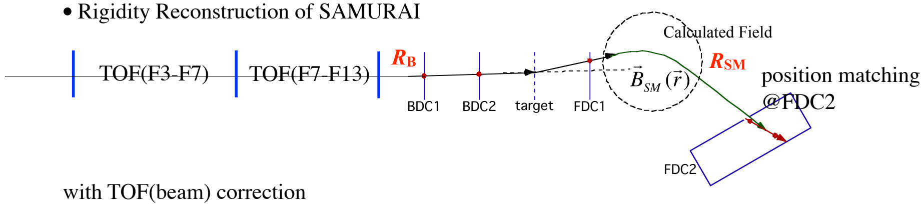
* Deviation
$\Delta x \sim \pm 5$ mm
$\sigma(\Delta x)$= 2~6 mm
$\Delta x' \sim \pm 1$ mrad
$\sigma(\Delta x')$= 1~2 mrad

for $\Delta R/R \sim \pm 20\%$

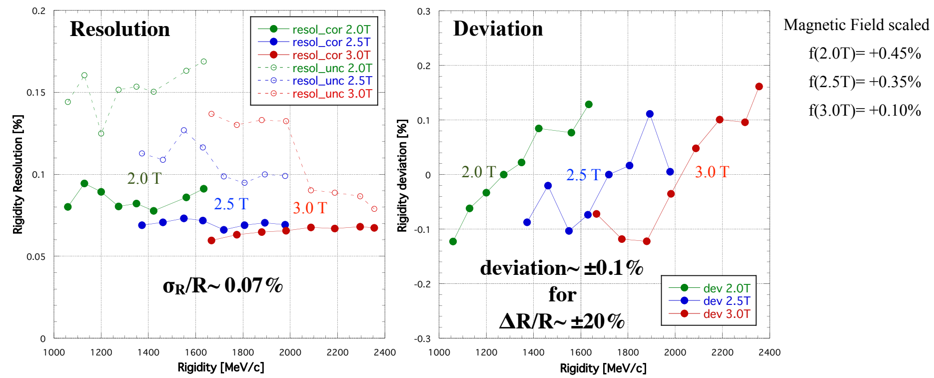
29

Rigidity Resolution (& deviation)

- Rigidity Reconstruction of SAMURAI



with TOF(beam) correction



Magnetic Field scaled
f(2.0T)= +0.45%
f(2.5T)= +0.35%
f(3.0T)= +0.10%

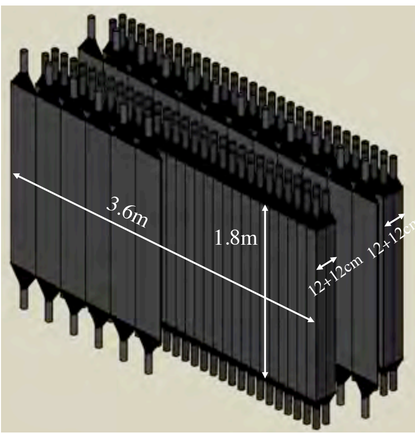
＊at least, inside the phase space tested

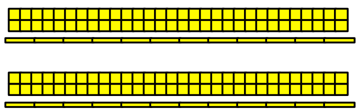
30

NEBULA : Large Area Neutron TOF Array

Slat(neutron) : 12cm(D) x 12cm(H) x 180cm(V), 30 slats/layer, 4 layers
Slat (veto) : 190cm(H) x 32cm(V) x 1cm(t), 12 slats/layer, 2 layers
Effective area : 3.6m(H) x 1.8m(V)
Total thickness : 48cm
Efficiency : ε(1n)~ 40%, ε(2n)~ 12%
Proportional tube for position calibration : 50φ x 4m, x16

- $L_{TOF} \sim 11$ m
- $\theta_H=\pm 10°$, $\theta_V=\pm 5°$





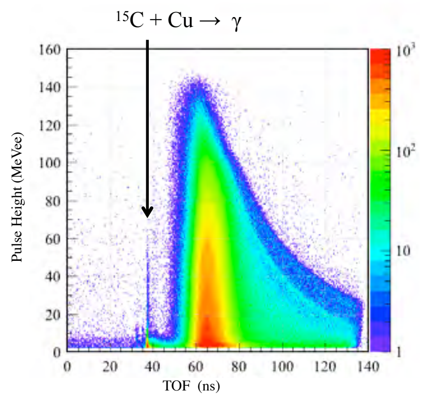
31

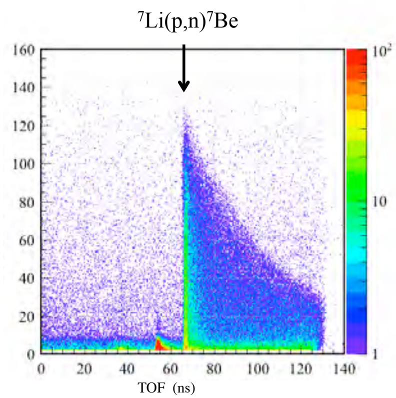
NEBULA - 3 : performance

by R.Tanaka (TIT)

○ Detection Efficiency, Energy Resolution
  ^{7}Li(p,n)^{7}Be(gs+0.43MeV) @Ep= 200, 250 MeV
○ TOF Time Zero
  C(^{15}C,γX) @E(^{15}C)= 240 MeV/A

＊TOF - Pulse height





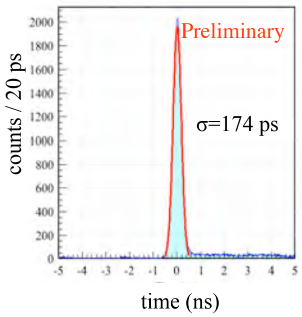
32

NEBULA - 4 : Time / Energy Resolution, Efficiency

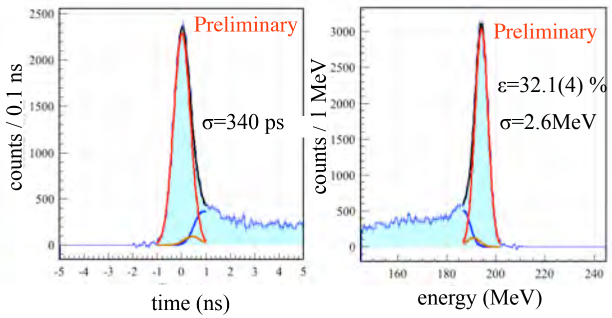
by R.Tanaka (TIT)

Preliminary

∗ γ ray from C(^{15}C,γX)



∗ ^{7}Li(p,n)^{7}Be 200MeV θ_{lab} < 40 mrad



V_{th}(soft)= 6 MeV_{ee}

Intrinsic resolution

γ ray : σ_t=171 ps

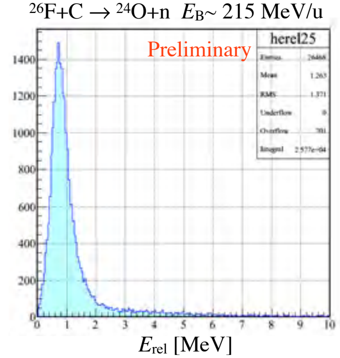
200 MeV neutron : σ_t=263 ps, σ_p/p = 0.57 %

Invariant-Mass Spectroscopy (check) - 1 : ^{25}O

by Y. Kondo (TIT)

- ^{26}F + C → ^{24}O + n
  - beam : E_B~ 215 MeV/u, I_B~ 2.5 kHz
  - target : 2 g/cm² C
- Relative energy distribution

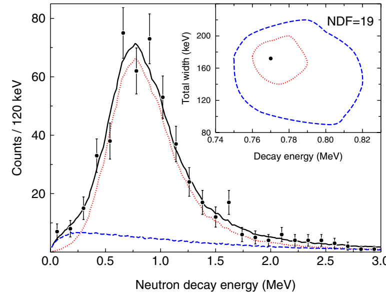
^{26}F+C → ^{24}O+n E_B~ 215 MeV/u



∗ no empty subtraction

- Previous data

^{26}F+Be → ^{24}O+n E_B= 85 MeV/u



C.R.Hoffman et al., PRL100, 152502 (2008)

$E(^{26}$F)= 85 MeV/u, I_B= 20Hz, @NSCL

Invariant-Mass Spectroscopy (check) - 2 : ^{14}Be

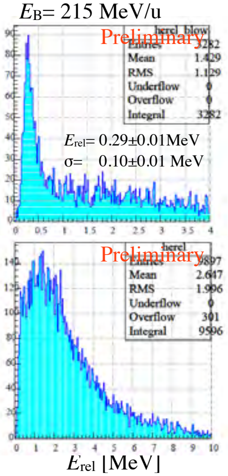
by R. Tanaka (TIT)

- ^{14}Be + Pb/C/emp → ^{12}Be + 2n
  - beam : E_B~ 215 MeV/u, I_B~ 50 kHz
  - target : ~2 g/cm² Pb, C
- Relative energy distribution (no empty subtraction)

E_B= 215 MeV/u

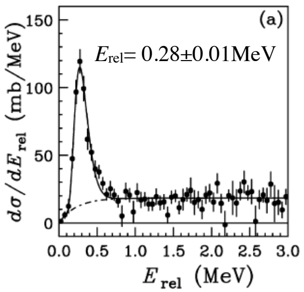
^{14}Be+C → ^{12}Be+2n

^{14}Be+Pb → ^{12}Be+2n



- Previous data

^{14}Be+C → ^{12}Be+2n E_B= 68 MeV/u



T. Sugimoto, et al., Phys. Lett. B 654 (2007) 160

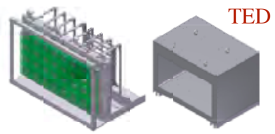
$\sigma(E_{rel}) \sim 0.19\sqrt{E_{rel}}$

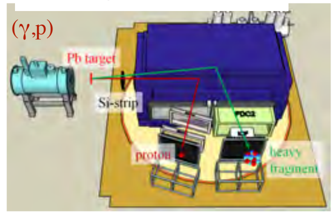
at both energies

Detectors to come

- PID of heavy fragment : ~FY2012
  - Total Energy Detector (TED)
  - Total Internal Reflection Cherenkov Detector (TIRC)

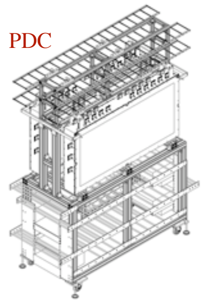
σ_A~0.2 for A<100





- (γ,p)-type experiment : ~FY2012
  - Si-strip telescope : col. w Texas A&M
  - Proton Drift Chamber (PDC) : 1.7m x 0.8m
- TPC : ~FY2013, col. w MSU

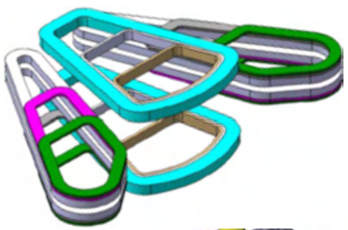
Poster : T. Isobe TPC

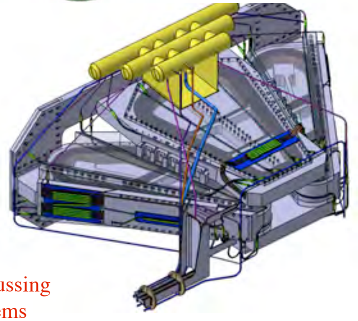


- High-efficiency γ detectors :
  - budget approved, in few years

R3B-GLAD Spectrometer @FAIR/GSI : comparison

- Superconducting magnet (SAMURAI)
  - B_{max} : 2.4 T (3.1T)
  - Field integral : 4.8 Tm (7.1Tm)
  - Stored energy : 24 MJ (33MJ)
  - I_{max} : 3700A (560A)
  - Total weight : 50 t (600t)
- No iron + active shielding (Iron+Field cramp)
  - tilted coil (parallel)
  - Fringe field @target: <200G (<30G)
- Resolution/ acceptance
  - Rigidity resolution : 0.1% (<0.1%)
  - Ang. acceptance : ±80mrad (±5°)
  - H/V angle resolution : 1 mrad (1 mrad)
- Tracking Detector
  - Diamond, Si-strip, fiber det : (gas det.)
- Beam energy
  - < 1.5 GeV/A (<340 MeV/A)





X less kinematic focussing
X charge state problems

Summary

- SAMURAI Spectrometer : construction finished in 4 years (FY2008-FY2011)
  - system tested in commissioning run (Mar-2012) : basic properties are reported
    - magnet : BL~ 7 Tm @B_{max}= 3T
      - high field for rigidity analysis & sweeper
      - low fringing field for target-area detectors
      - large opening (θ_H<10°, θ_V<5°) for projectile-rapidity neutrons
    - Tracking detectors :
      - more or less, conventional type : σ_X < 200 μm → σ_R/R < 0.1%, R<2.8 GeV/c
    - Neutron detector :
      - high efficiency & cross-talk rejection for multi-neutrons
    - Invariant-mass resolution : ~same compared with @60 MeV/u
  - 3 physics runs performed in May-2012
    - ^{19}B, ^{22}C, ^{26}O-region
    - combined with high-intensity primary beam from SRC/RIBF
      - gain > 1000 compared with previous facility

SAMURAI

- built primarily for kinematically complete experiments at RIKEN RIBF (invariant mass spectroscopy)
- Time line
  - Construction period : FY2008 ~ FY2011
  - SAMURAI magnet : ~ Mar-2011
  - Commissioning run : Mar-2012
  - 3 physics experiments : May-2012