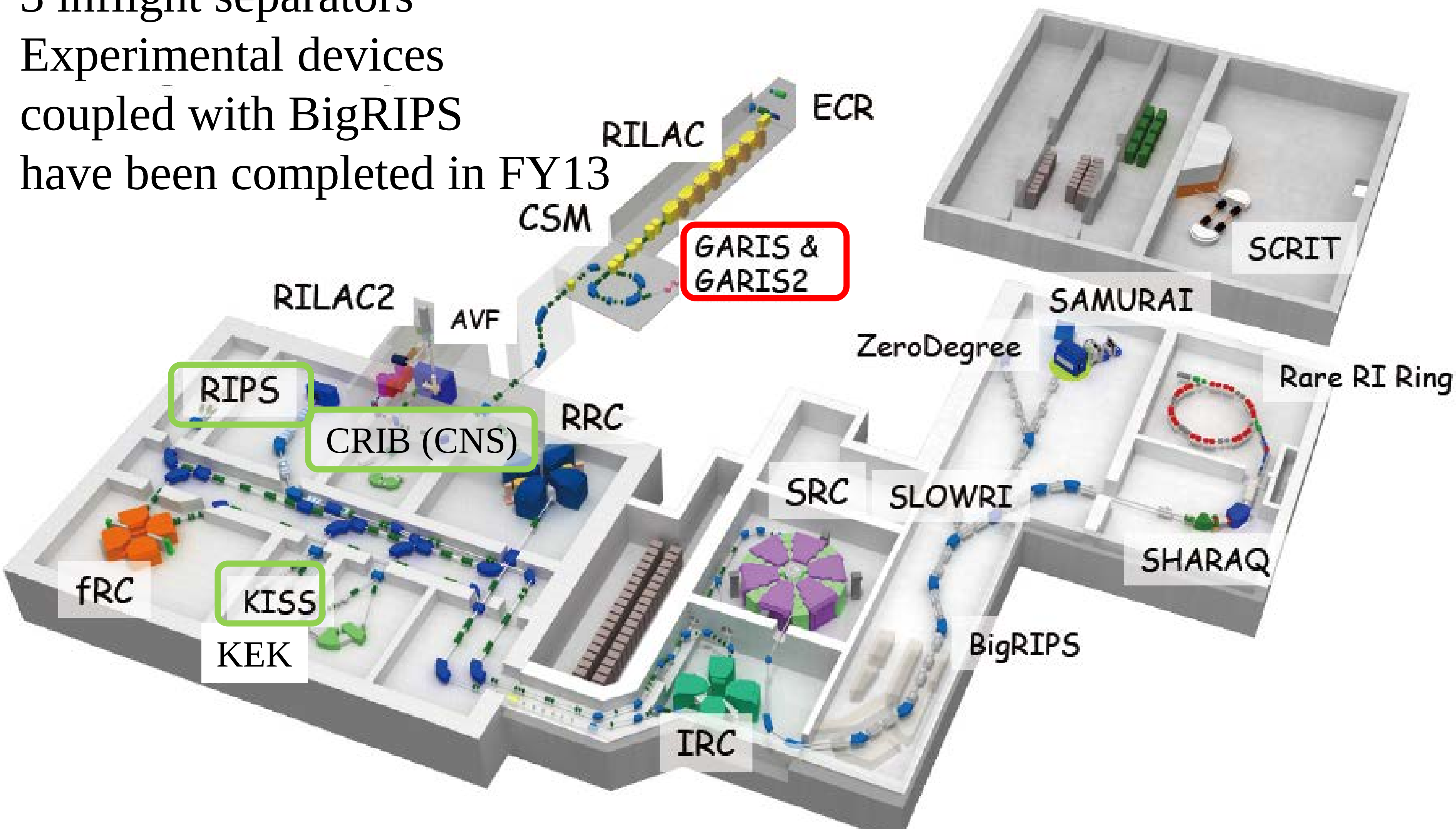
Current and future programs at RIBF

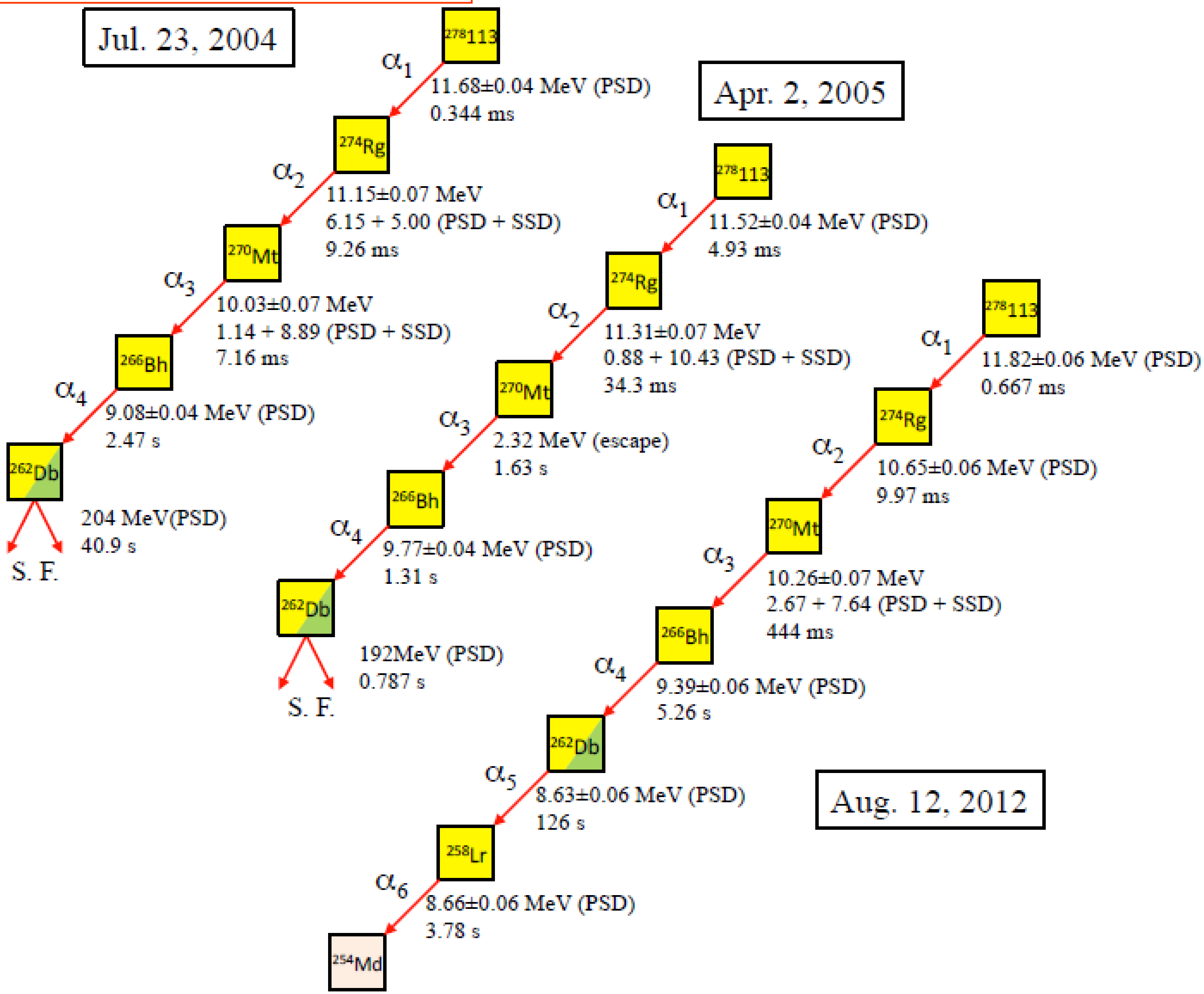
H. Sakurai
RIKEN Nishina Center/Dept of Phys., Univ. of Tokyo

RI Beam Factory

5 cyclotrons + 2 linacs
3 inflight separators
Experimental devices coupled with BigRIPS have been completed in FY13



Element 113th at GARIS



K. Morita et al., J. Phys. Soc. Jpn. 81 (2012) 103201

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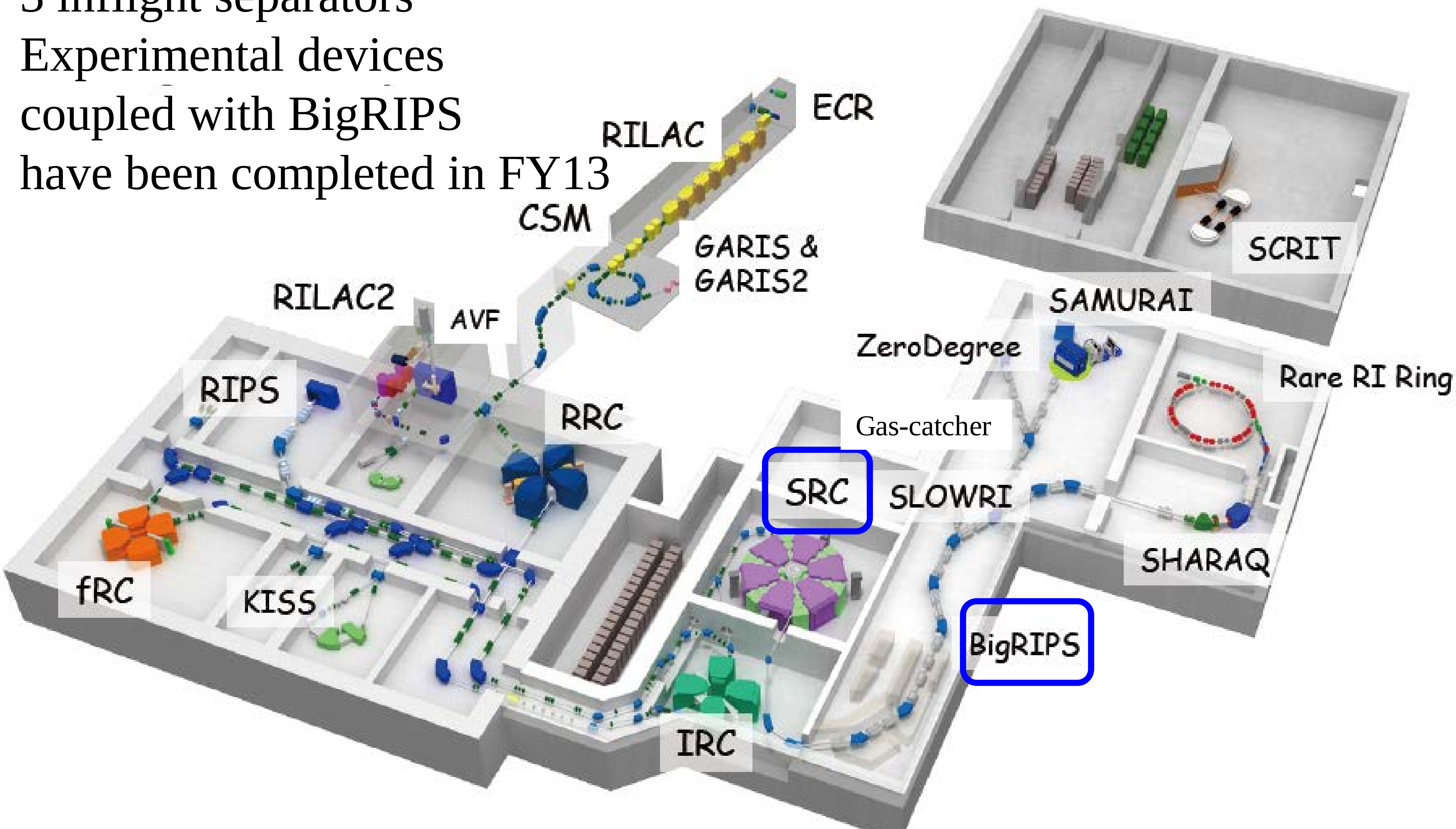
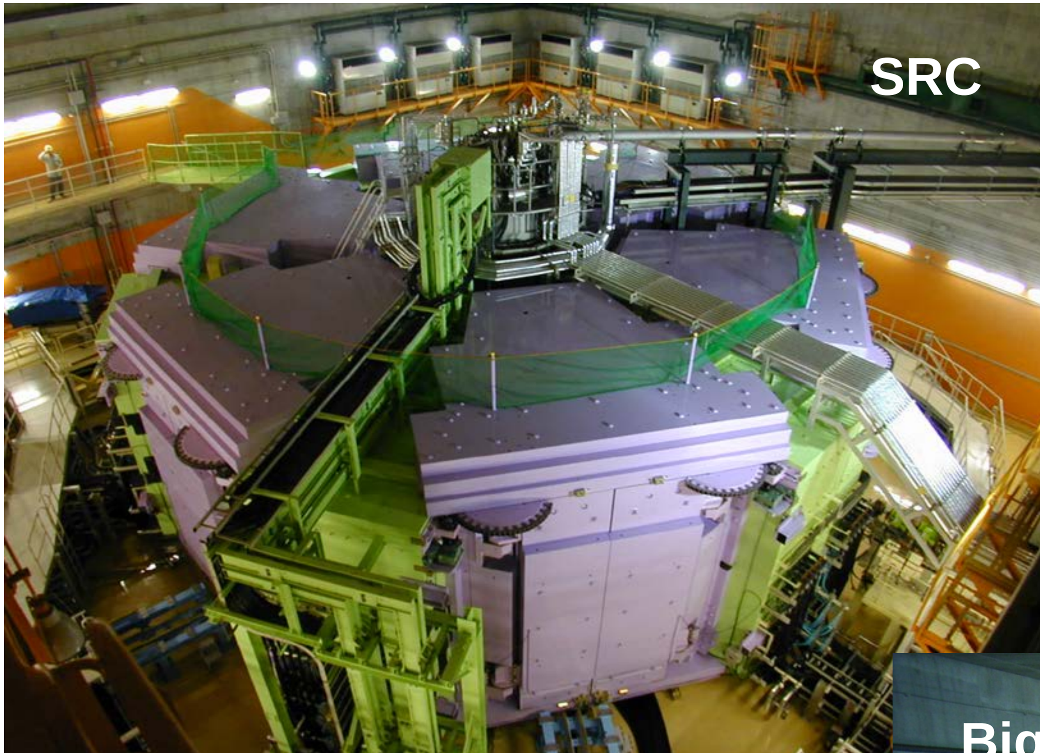




World's First and Strongest
K2600MeV
Superconducting Ring Cyclotron

400 MeV/u Light-ion beam
345 MeV/u Uranium beam

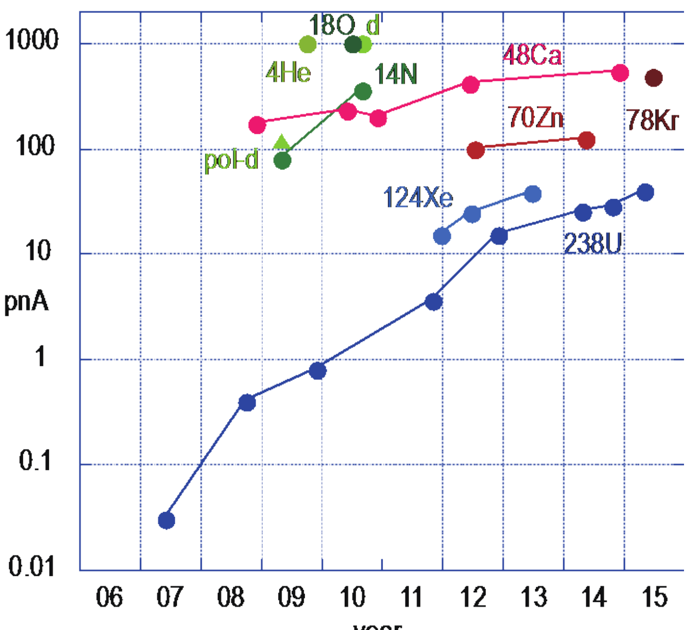
World's Largest Acceptance
9 Tm
Superconducting RI beam Separator

~250-300 MeV/nucleon RIB

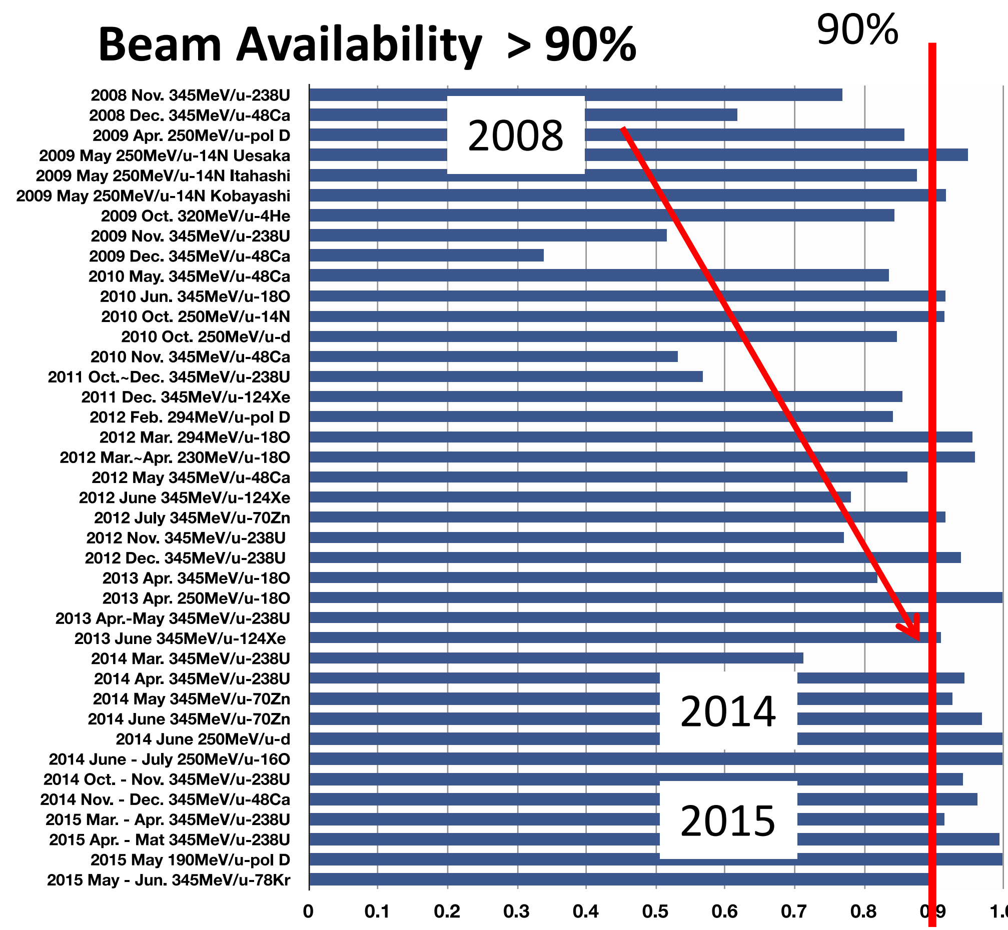
Primary Beam Status and Plan

345 MeV/u HI beams

Beam Particle	Maximum [pnA]	Expected [pnA]
^{18}O	1000	500
^{48}Ca	530	400
^{70}Zn	123	100
^{78}Kr	486	300
^{124}Xe	38	20
^{238}U	39.5	30



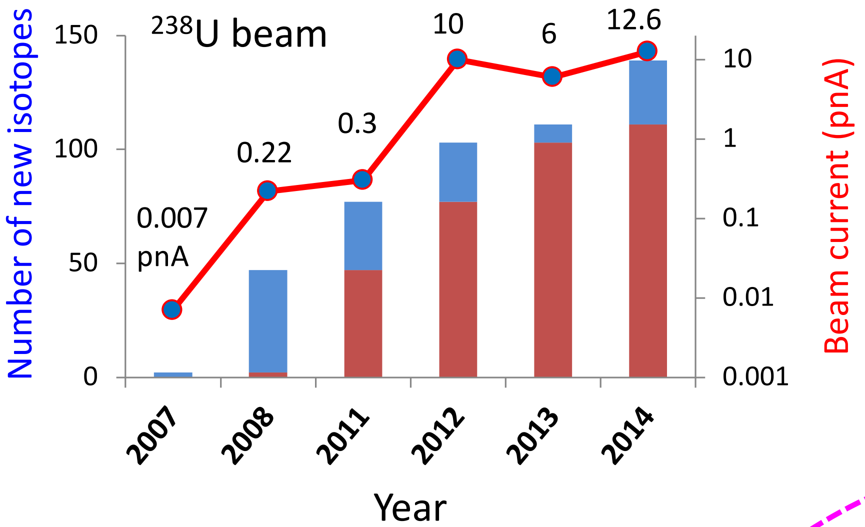
Beam Availability > 90%



Intensity goal 100pnA for U in 2017
RF cavity of RRC replaced by new one to increase a transmission efficiency

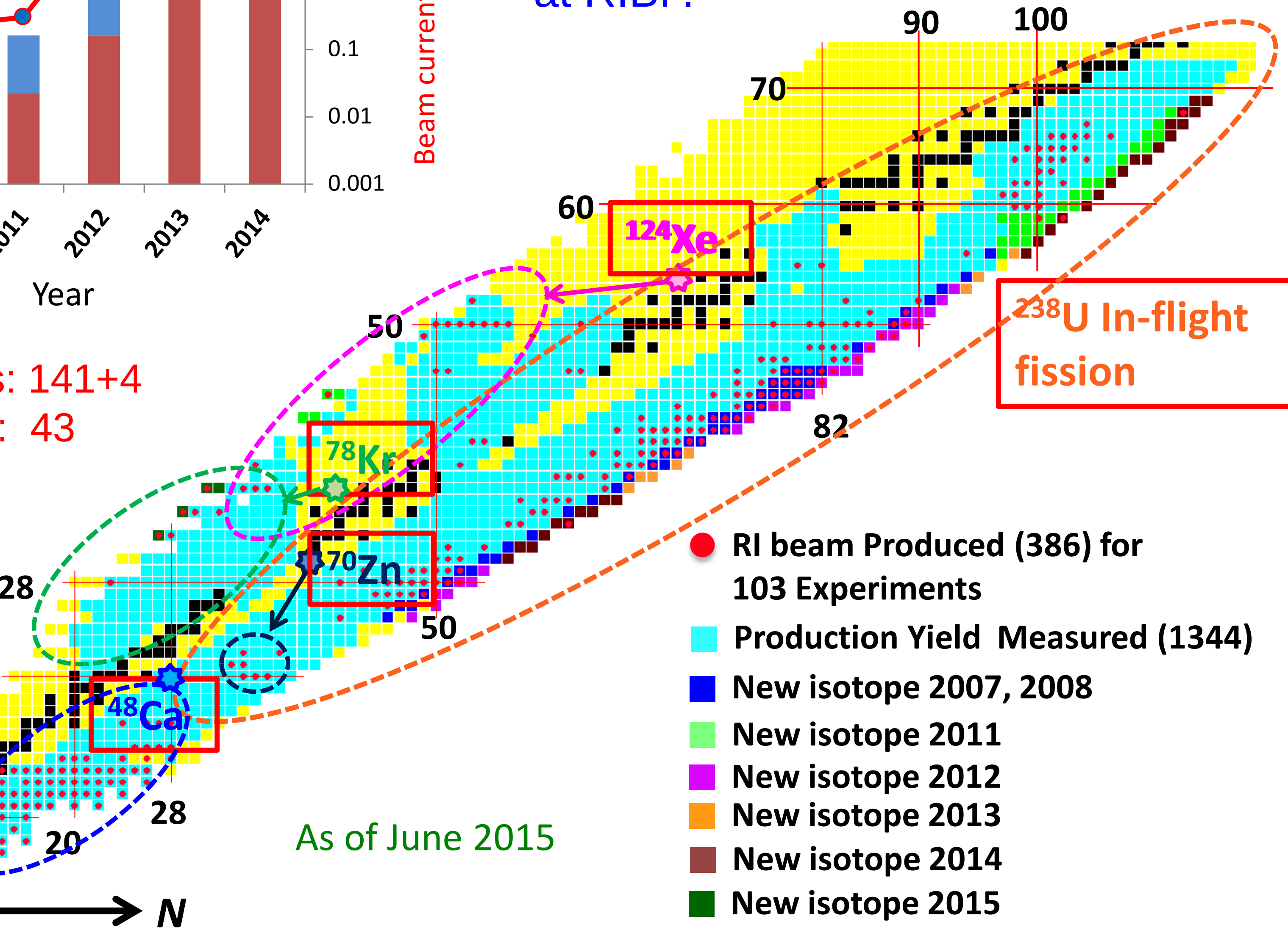
RI Beam Production at BigRIPS Since 2007

Kubo et al.



The frontiers of nuclear chart is expanding with the upgraded features at RIBF.

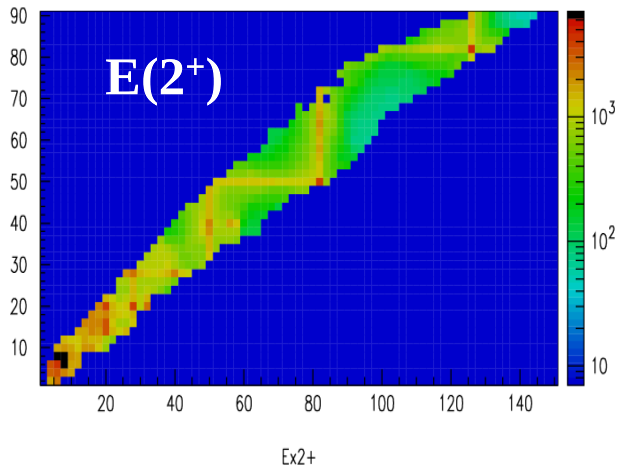
New isotopes: 141+4
New isomers: 43
(preliminary)



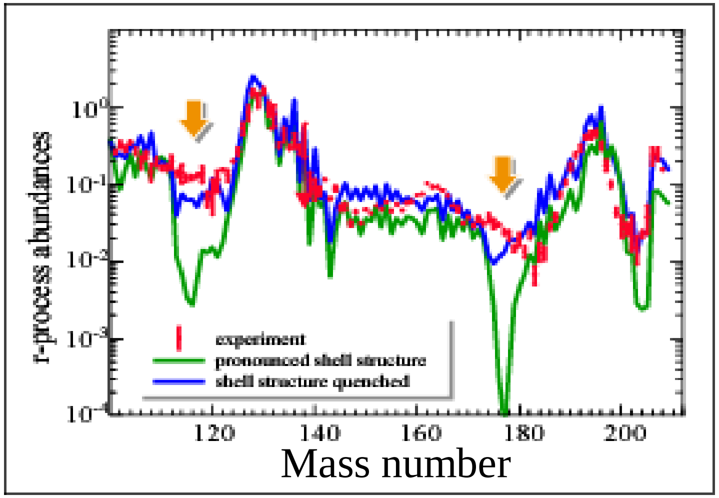
As of June 2015

Challenges at RIBF

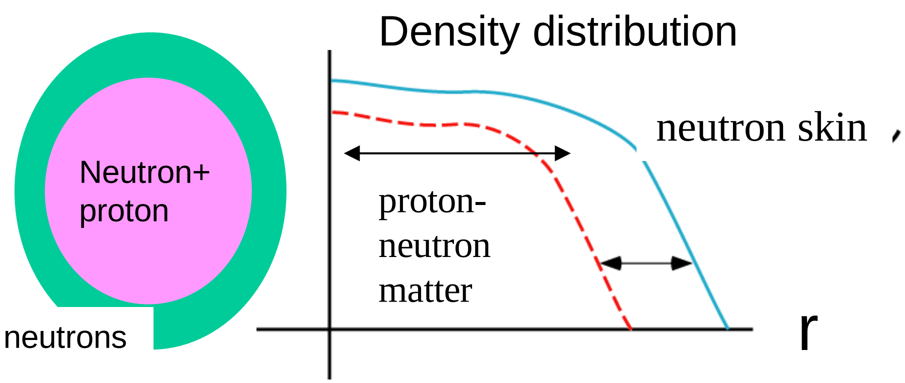
Shell Evolution : magicity loss and new magicity



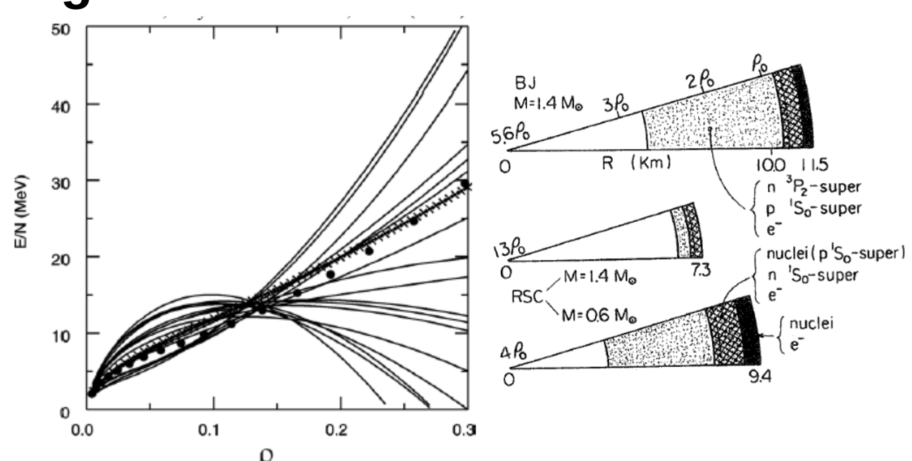
R-process path: Synthesis up to U



Dynamics of new "material" : Neutron-skin (halo)



EOS: asymmetric nuclear matter SN explosion, neutron-star, gravitational wave



RI Beam Factory

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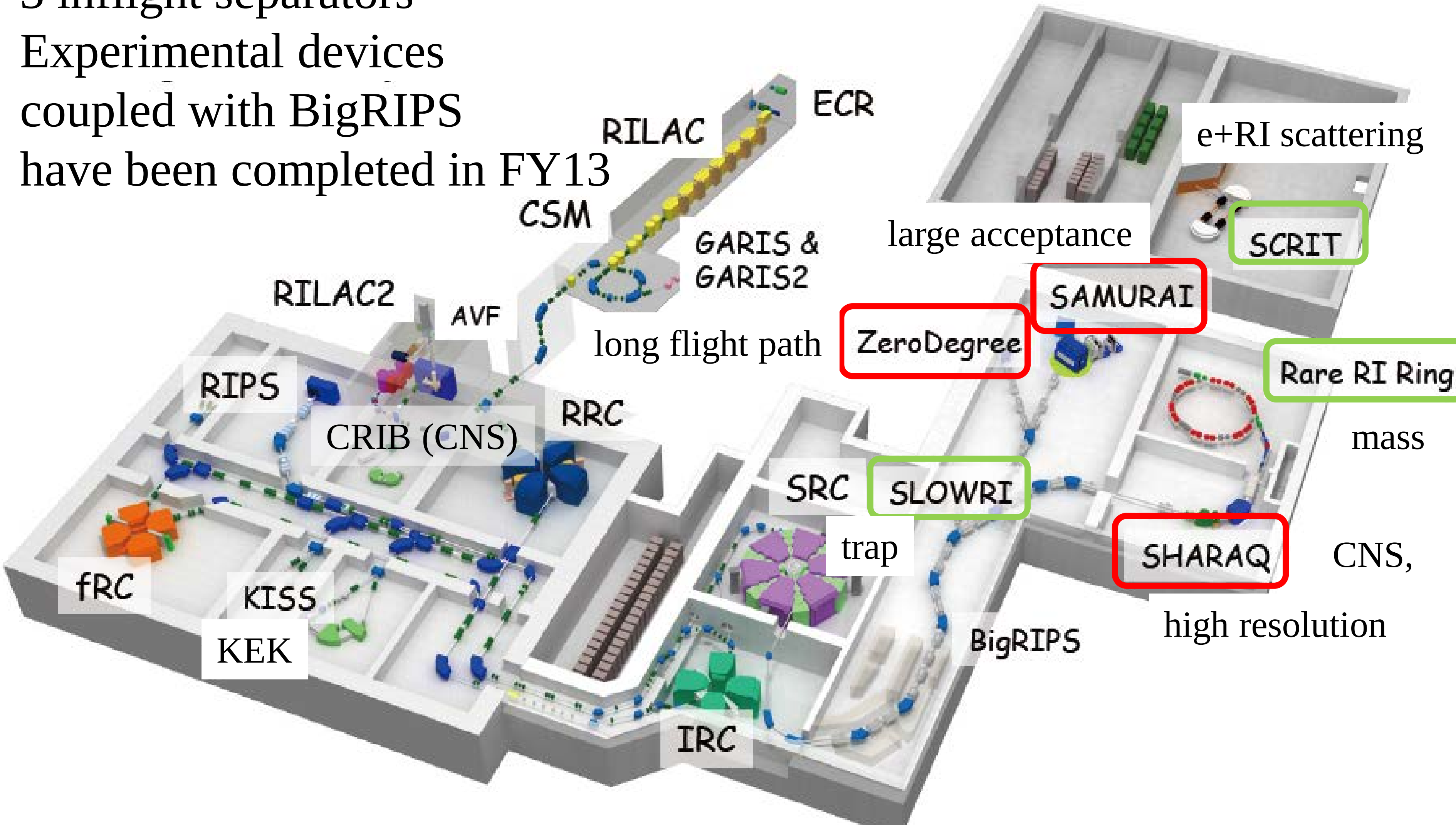
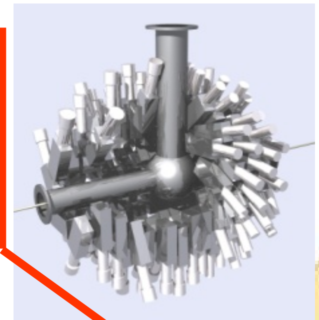


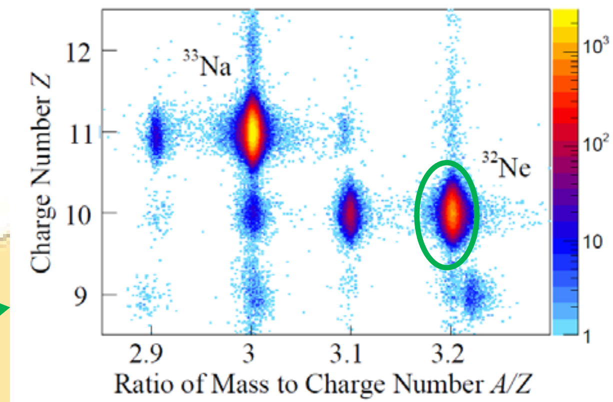
Spectroscopy via reactions with in-beam gamma method

Secondary target: H_2, Be, C, Pb….
Gamma-detectors : DALI2 NaI array to measure de-excited gamma rays

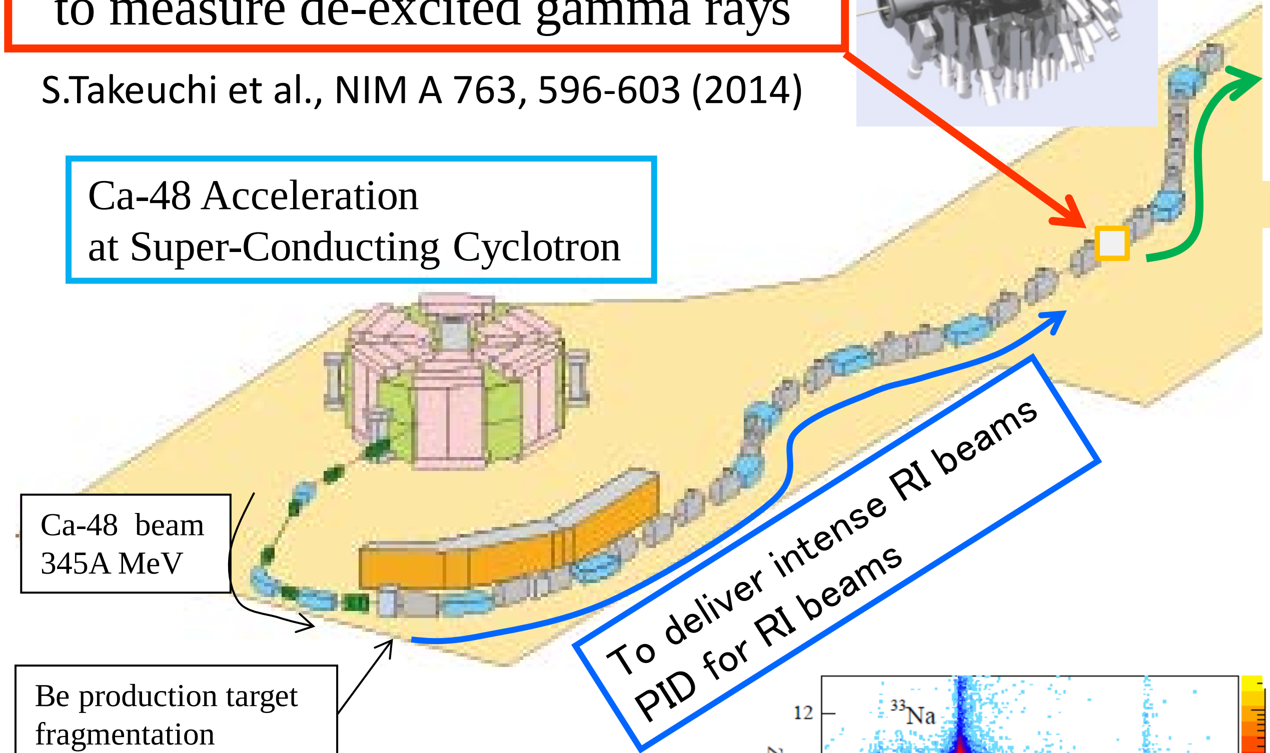
S.Takeuchi et al., NIM A 763, 596-603 (2014)

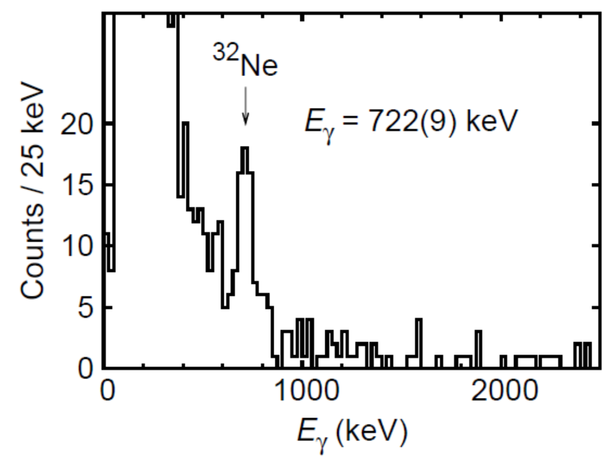


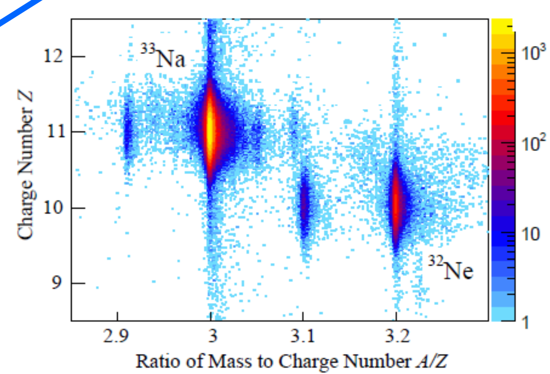
PID at ZeroDegree



Ca-48 Acceleration at Super-Conducting Cyclotron

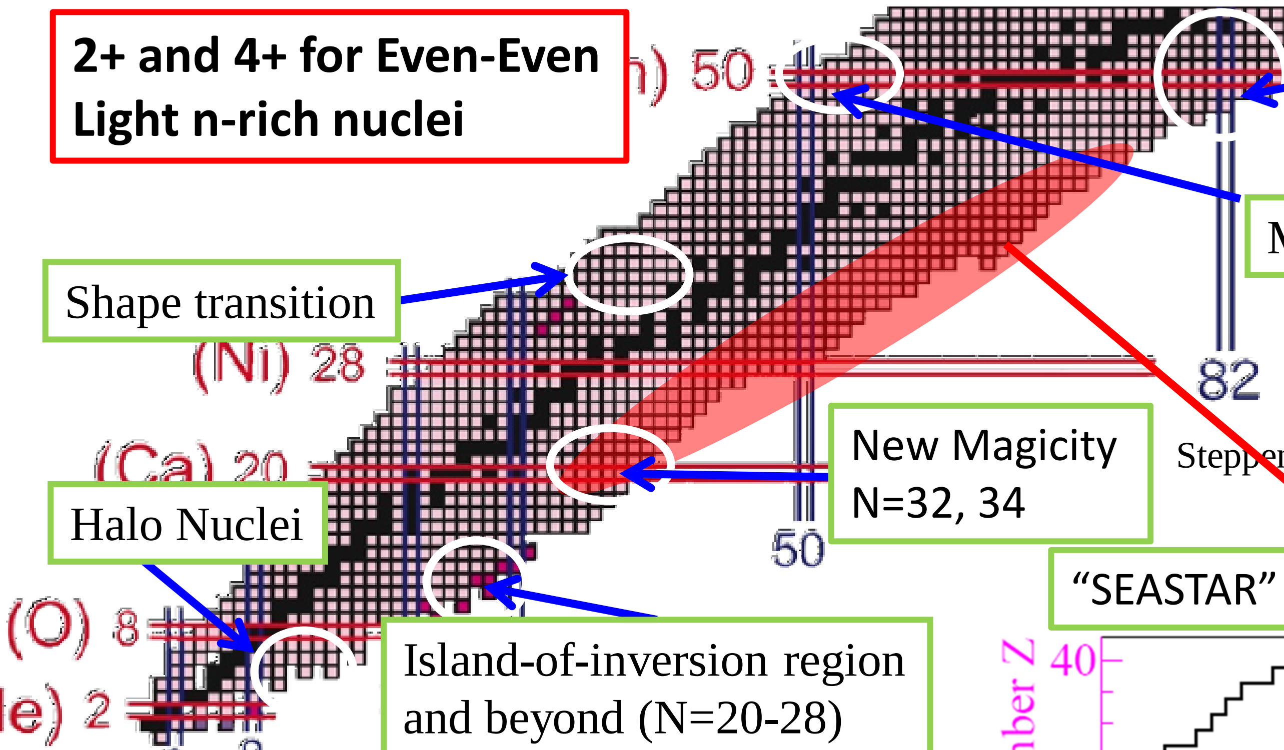






Doornenbal, Scheit et al. PRL 103, 032501 (2009)

Past and Current Programs with DALI2 at ZD



2+ and 4+ for Even-Even Light n-rich nuclei

Magicity at N=82 and Z=50?

^{126}Pd Wang, PRC 88 054318 (2013)
^{136}Sn Wang, PTEP 023D02 (2014)

Magicity at Z=50 and N=50?

^{104}Sn: Corsi, PLB 743, 451 (2015)
^{104}Sn: Doornenbal. PRC90, 061302 (2014)

Shape transition

New Magicity N=32, 34

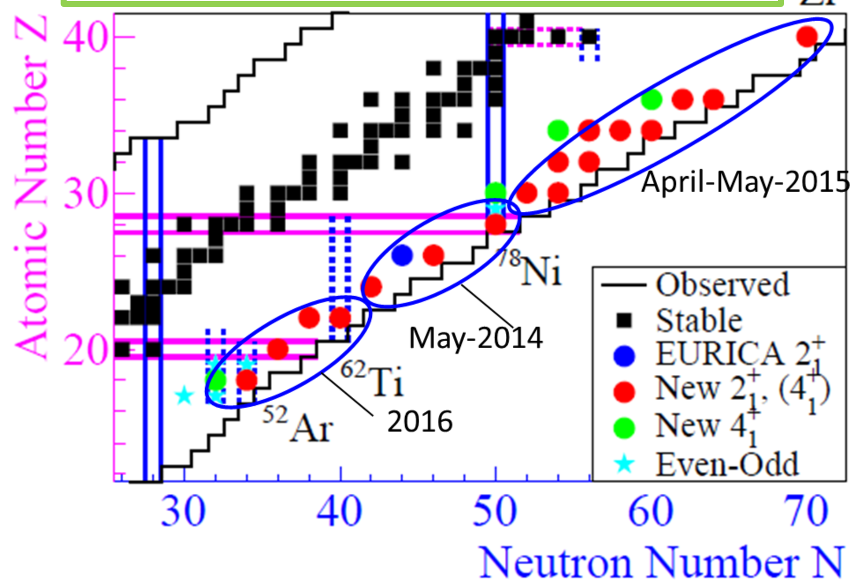
Steppenbeck , Nature 502, 207 (2013)
PRL 114, 252501 (2015)

Halo Nuclei

Island-of-inversion region and beyond (N=20-28)

^{32}Ne:: Doornenbal, PRL 103, 032501 (2009)
^{31,32,33}Na: Doornenbal, PRC 81, 041305R (2010)
^{33,34,35}Na: Doornenbal, PTEP 2014, 053D01 (2014)
^{36,38}Mg: Doornenbal, PRL111, 212502 (2013)
^{32}Mg: Li, PRC 92, 014608 (2015)
^{42}Si : Takeuchi PRL109, 182501 (2012)
^{40}Mg : Crawford PRC 89, 041303 (2014)
^{31}Ne: Nakamura, PRL 103, 262501 (2009), PRL, 112, 142501 (2014)
^{37}Mg: Kobayashi, PRL 112, 242501,(2014)

"SEASTAR" project (MINOS+DALI2)



New “Magicity” of N=34 in the Ca isotopes

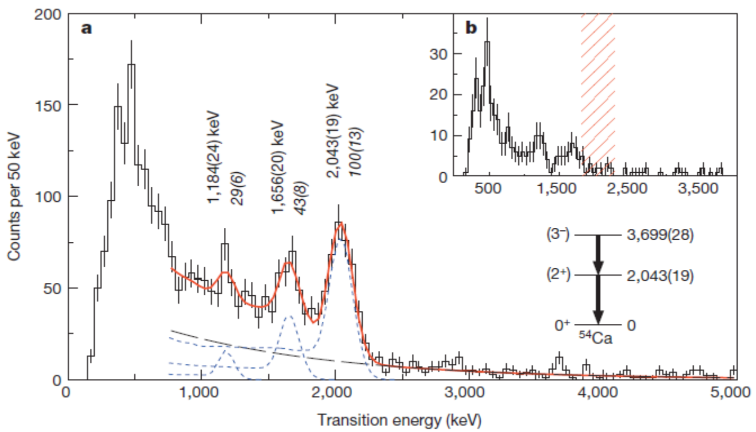
D. Steppenbeck et al., Nature 502

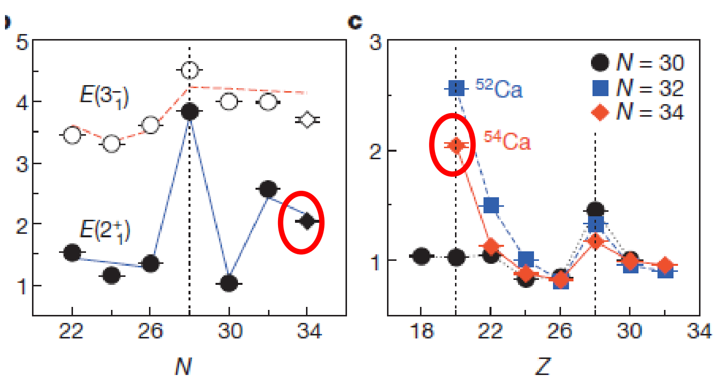
Zn-70 primary beam (100 pnA max)

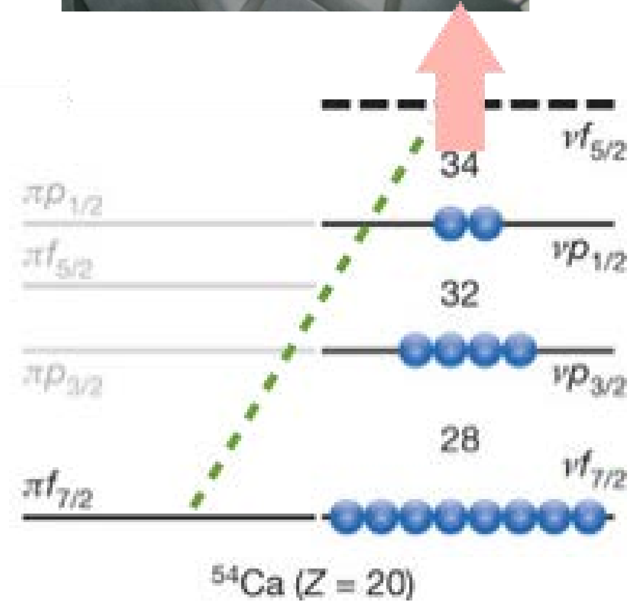
Ti-56 120 pps/pnA, Sc-55 12 pps/pnA

Zn-70 -> Ti-56, Sc-55

Ti-56, Sc-55 + Be -> Ca-54 + X



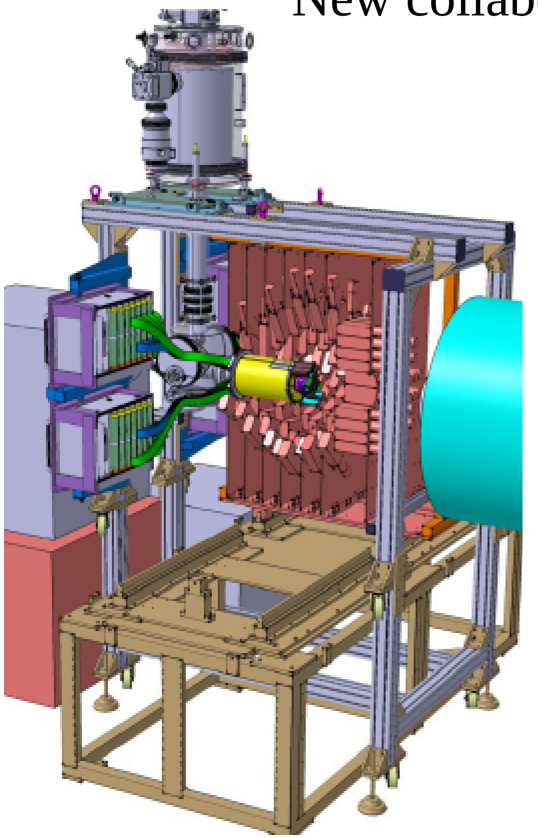


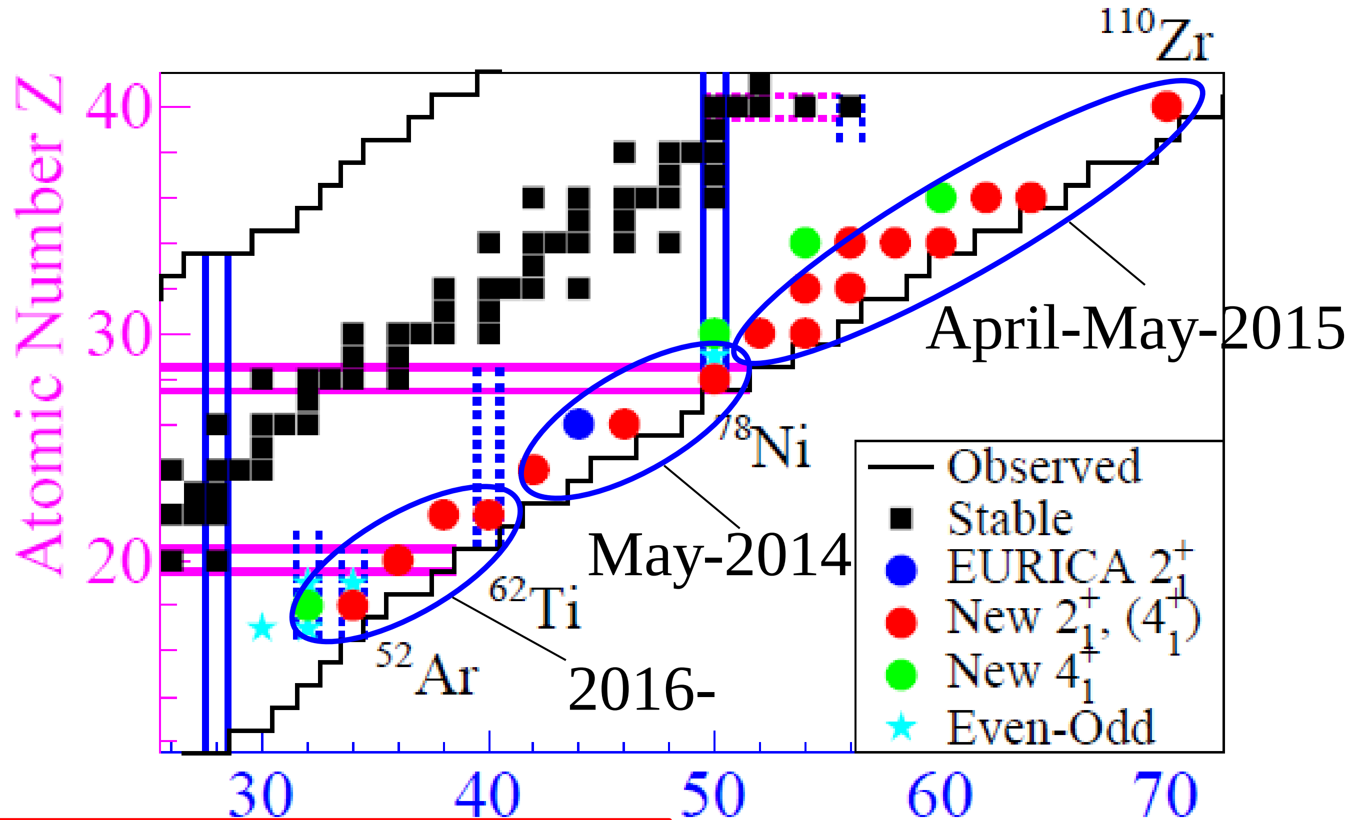


Shell Evolution And Search for Two-plus energies At the RIBF (SEASTAR) – a RIKEN Physics Program

Spokespersons: P. Doornenbal (RIKEN), A. Obertelli (CEA, RIKEN)

New collaboration scheme; Nuclear Physics News, 24 No2, 35





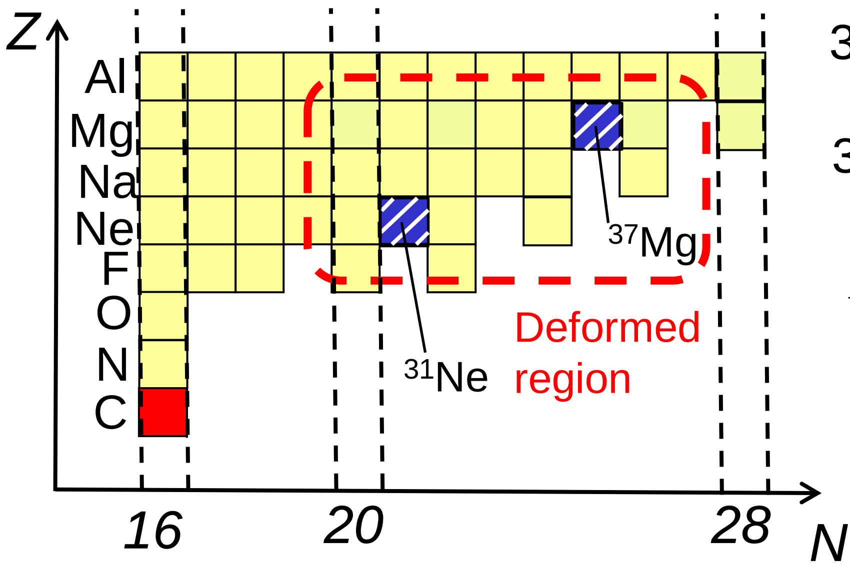
Cr-66, Fe-70,72 and Ni-78 results coming up soon

Primary beam ^{238}U at 345 MeV/nucleon, **mean intensity = 15 pnA!**

Secondary beams at 240 MeV/nucleon, 100-mm target, $\Delta\beta$ = 20%

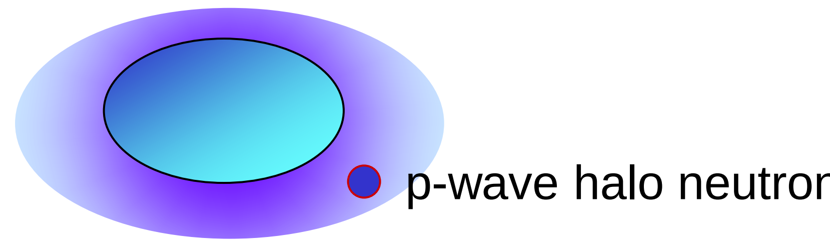
Not only gamma, but Interesting Ones

Deformed Halo Nuclei Ne-31 and Mg-37



^{31}Ne

^{37}Mg



Inclusive Coulomb and Nuclear Breakup at ZDS

T.Nakamura et al., Phys.Rev.Lett.**103**,262501 (2009).
N.Kobayashi et al., PRC **86**, 054604 (2012)
T.Nakamura,et al., Phys.Rev.Lett.**112**,142501 (2014).
N.Kobayashi et al., Phys. Rev. Lett. **112**, 242501 (2014)

Total Interaction Cross Section at BigRIPS

M. Takechi et al., Phys. Lett. B 707, 357 (2012)
M. Takechi et al., Phys. Rev. C 90, 061305(R) (2014)

PF-reaction-induced spin-aligned RI beams

(1) *Q*(^{43m}S) measurement

structure of *N* ~ 28 nuclei

R. Chevrier *et al*., Phys. Rev. Lett. **108**, 162501 (2012)

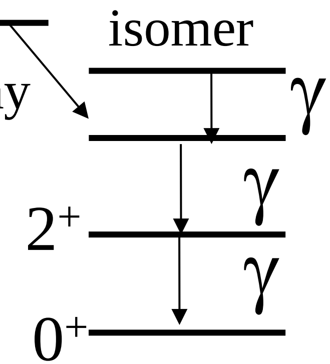
(2) New method for high spin alignment

Two-step PF + dispersion matching

Y. Ichikawa, H. Ueno *et al*., Nature Phys. **8**, 918 (2012)

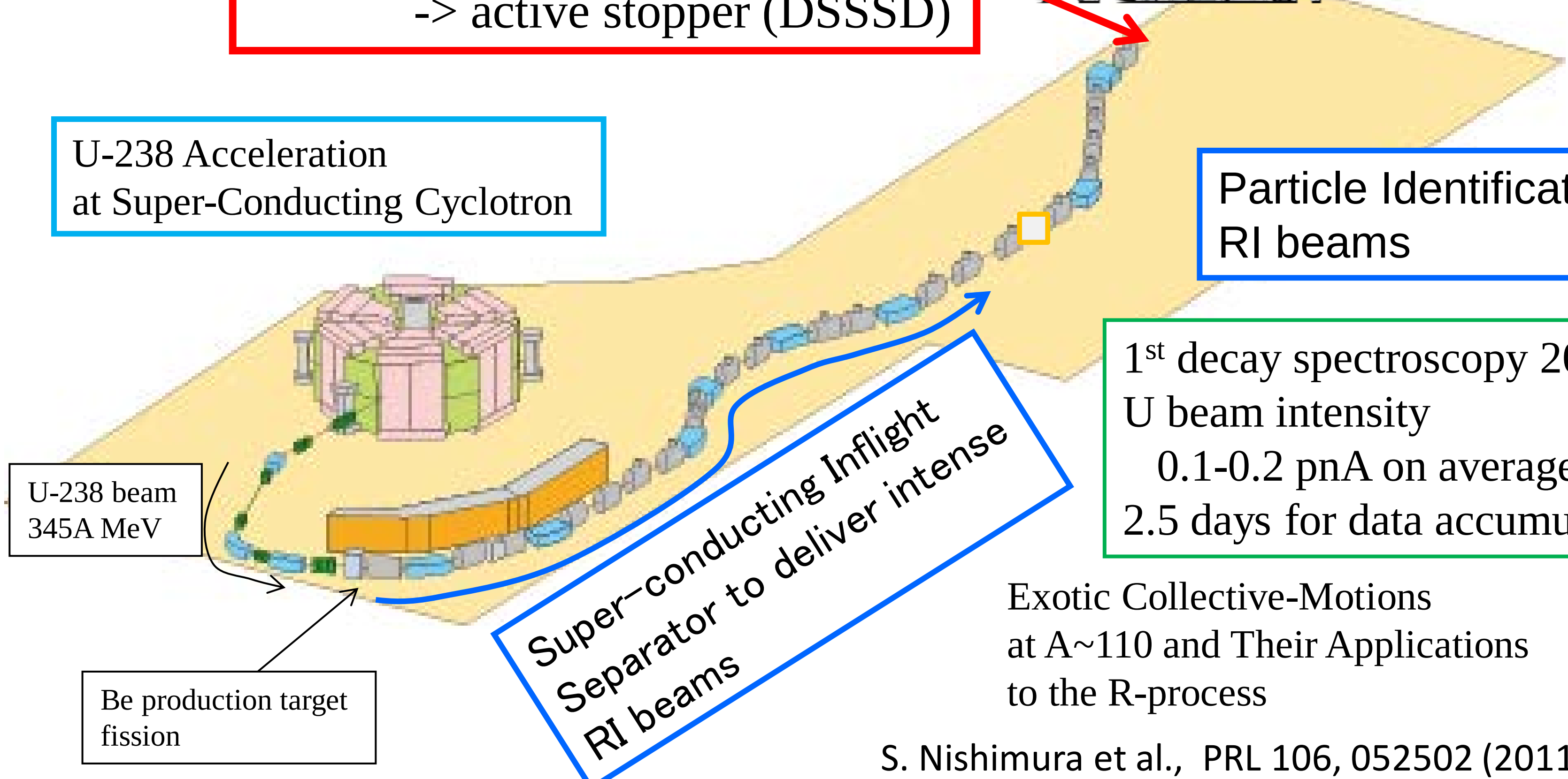
Decay Spectroscopy Setup

Beta-delayed gamma
-> Ge detectors
HI implanted and beta-rays
-> active stopper (DSSSD)



U-238 Acceleration
at Super-Conducting Cyclotron

Particle Identification of RI beams



1^{st} decay spectroscopy 2009 Dec.
U beam intensity
0.1-0.2 pnA on average
2.5 days for data accumulation

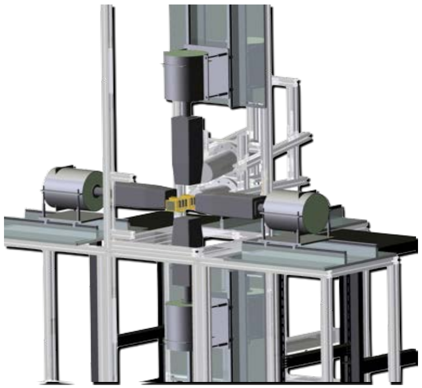
Exotic Collective-Motions
at A~110 and Their Applications
to the R-process

S. Nishimura et al., PRL 106, 052502 (2011)
T. Sumikama et al., PRL 106, 202501 (2011)
H. Watanabe et al., Phys.Lett.B 704,270-275(2011)
H. Watanabe et al., Phys. Lett. B 696, 186-190 (2011)

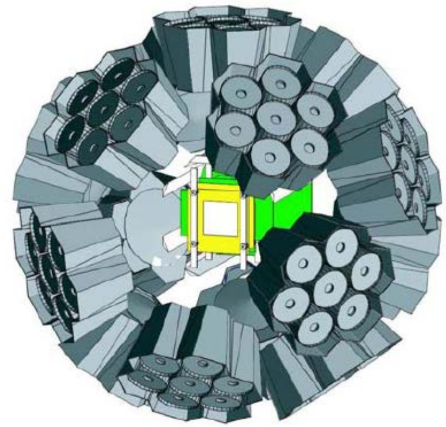
RIKEN NiSHiNA CENTER

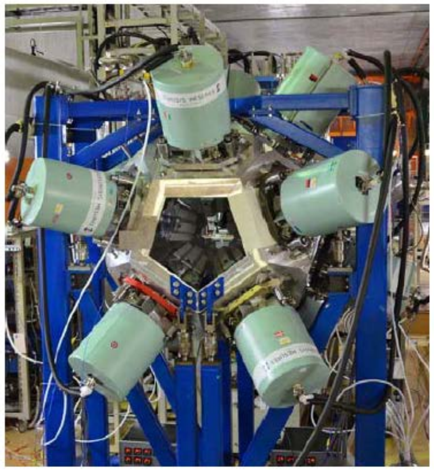
Decay Spectroscopy at RIBF

First decay spectroscopy in 2009



EURICA setup





EUroball-RIKEN Cluster Array

U-beam intensity ... x 50 times
- 0.2 pnA → 10 pnA

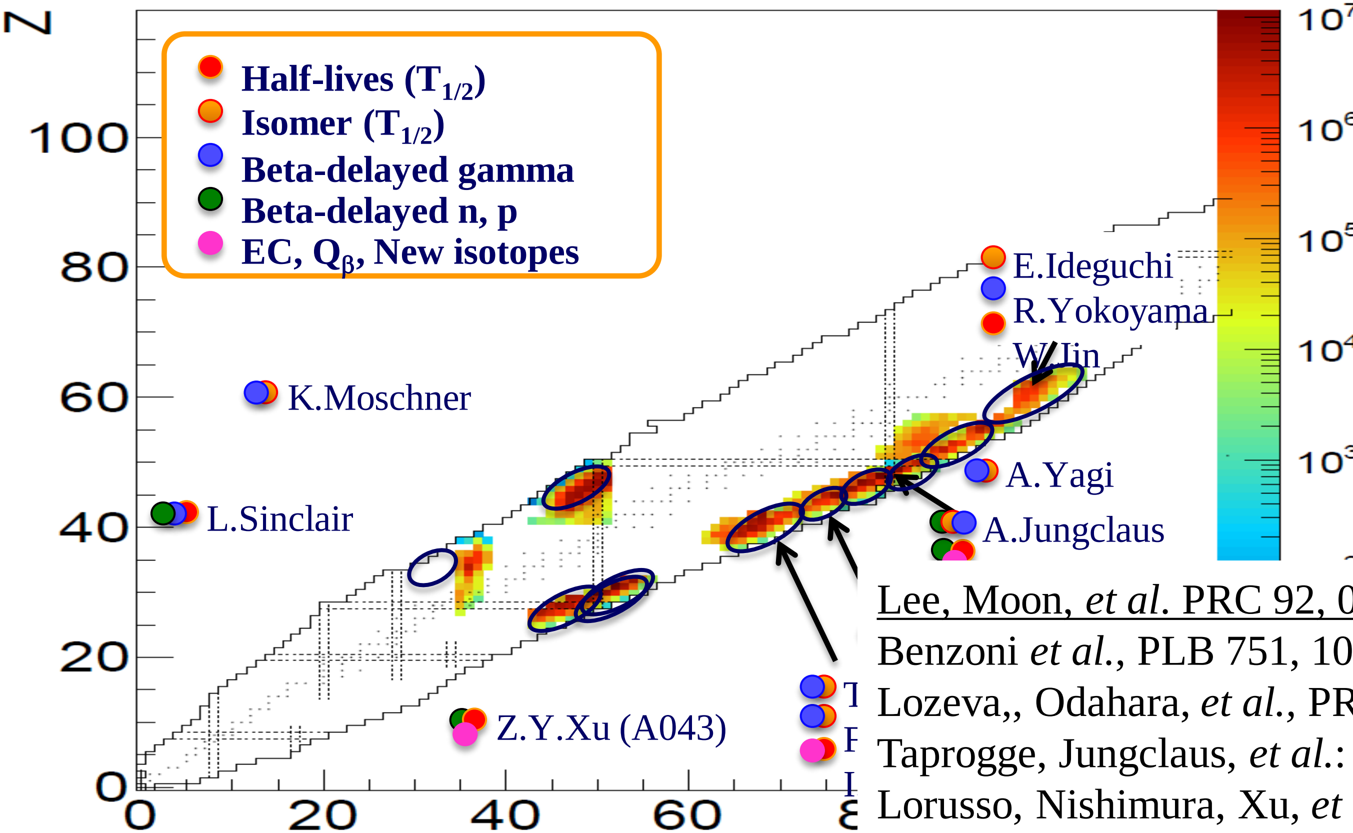
EURICA Collaboration

Si-strip: IBS-RIKEN

Gamma-ray efficiency ... x 10 times
- 4 Clover detectors (Det. Effi. ~1.5% at 0.662 MeV)
→ 12 Cluster detectors (Det. Eff. ~ 15 % at 0.662MeV)

Beam time x 40 times
- 2.5 days (4 papers) → 100 days ... (160 papers)

Past and Current Programs via Decay Spectroscopy

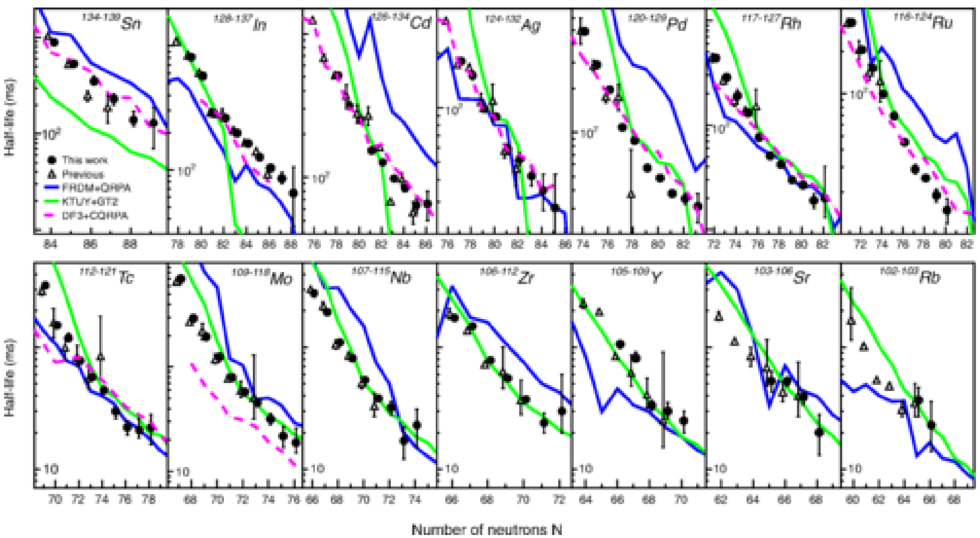


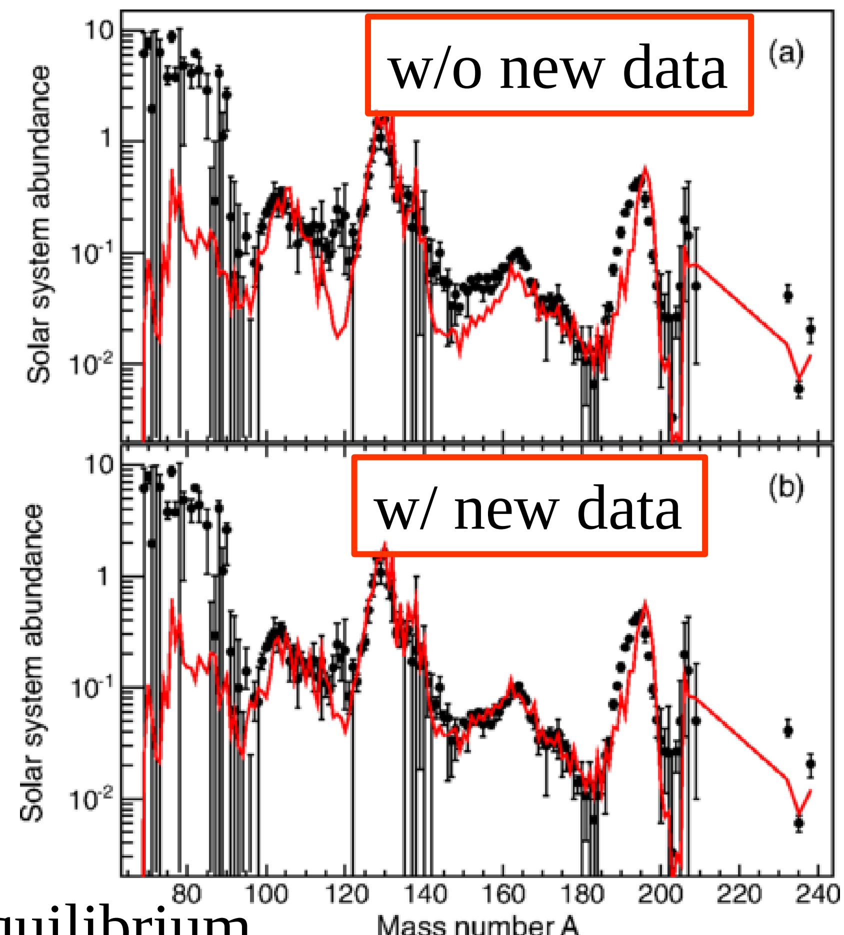
So far…
7 PRL's, 3 PLB's, 4 PRC's

<u>Lee, Moon, *et al*. PRC 92, 044320 (2015)</u>
Benzoni *et al*., PLB 751, 107 (2015)
Lozeva,, Odahara, *et al*., PRC 92, 024304 (2015)
Taprogge, Jungclaus, *et al*.: PRC 91, 054324 (2015)
Lorusso, Nishimura, Xu, *et al*.: PRL 114, 192501 (2015)
Patel, Söderström, *et al*.: PRL 113, 262502 (2014)
Taprogge, Jungclaus, *et al*.: PLB 738, 223 (2014)
Simpson, Gey, *et al*.: PRL 113, 132502 (2014)
Watanabe, Lorusso, *et al*.: PRL 113, 042502 (2014)
Xu, Nishimura, *et al*.: PRL 113, 032505 (2014)
Taprogge, Jungclaus, *et al*.: PRL 112, 132501 (2014)
Watanabe, Lorusso, *et al*.: PRL 111, 152501 (2013)
Söderström, *et al*.: PRC 88, 024301 (2013)

beta-decay Half-Lives of 110 Neutron-Rich Nuclei across the N=82 Shell Gap: Implications for the Mechanism and Universality of the Astrophysical **r** Process

G. Lorusso *et al.* Phys. Rev. Lett. 114, 192501 (2015)

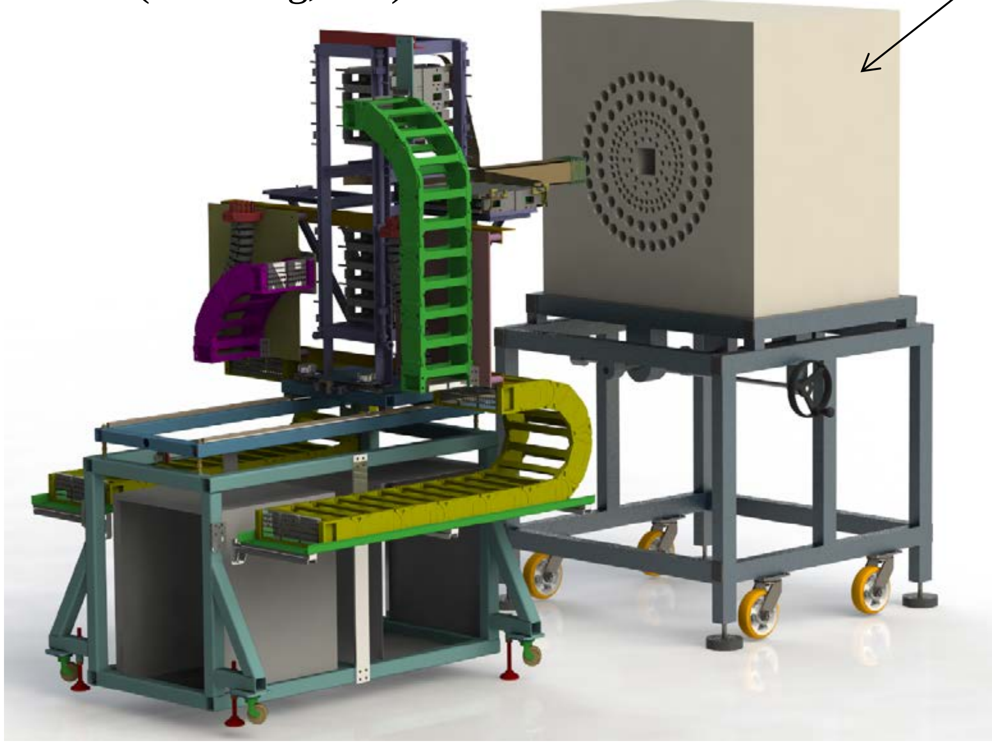




40 new half-lives
The second and
the rare-earth-element abundance
peaks may result
from the freeze-out of an n-gamma equilibrium

BRIKEN: beta-delayed neutron detection (He-3)

AIDA (Edinburg, UK)

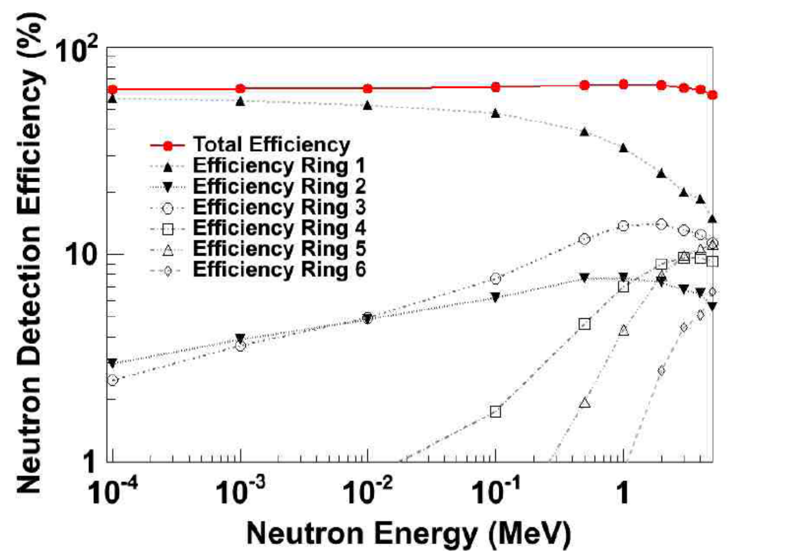


He-3 detector system

ORNL-JINR-GSI-UPC-RIKEN
182 counters

Table 1: ^{3}He tubes available within the BRIKEN Collaboration.

Owner	Pressure (atm)	Size Diameter (inch/cm)	Size Eff. Length (inch/mm)	Number of Counters
GSI	10	1 / 2.54	23.62 / 600	10
JINR	4	1.18 / 3.0	19.69/500	20
ORNL	10	2 / 5.08	24/609.6	67
ORNL	10	1 / 2.54	24/609.6	17
RIKEN	5.13	1 / 2.54	118.1/300	26
UPC	8	1 / 2.54	23.62/600	42
		Total		182

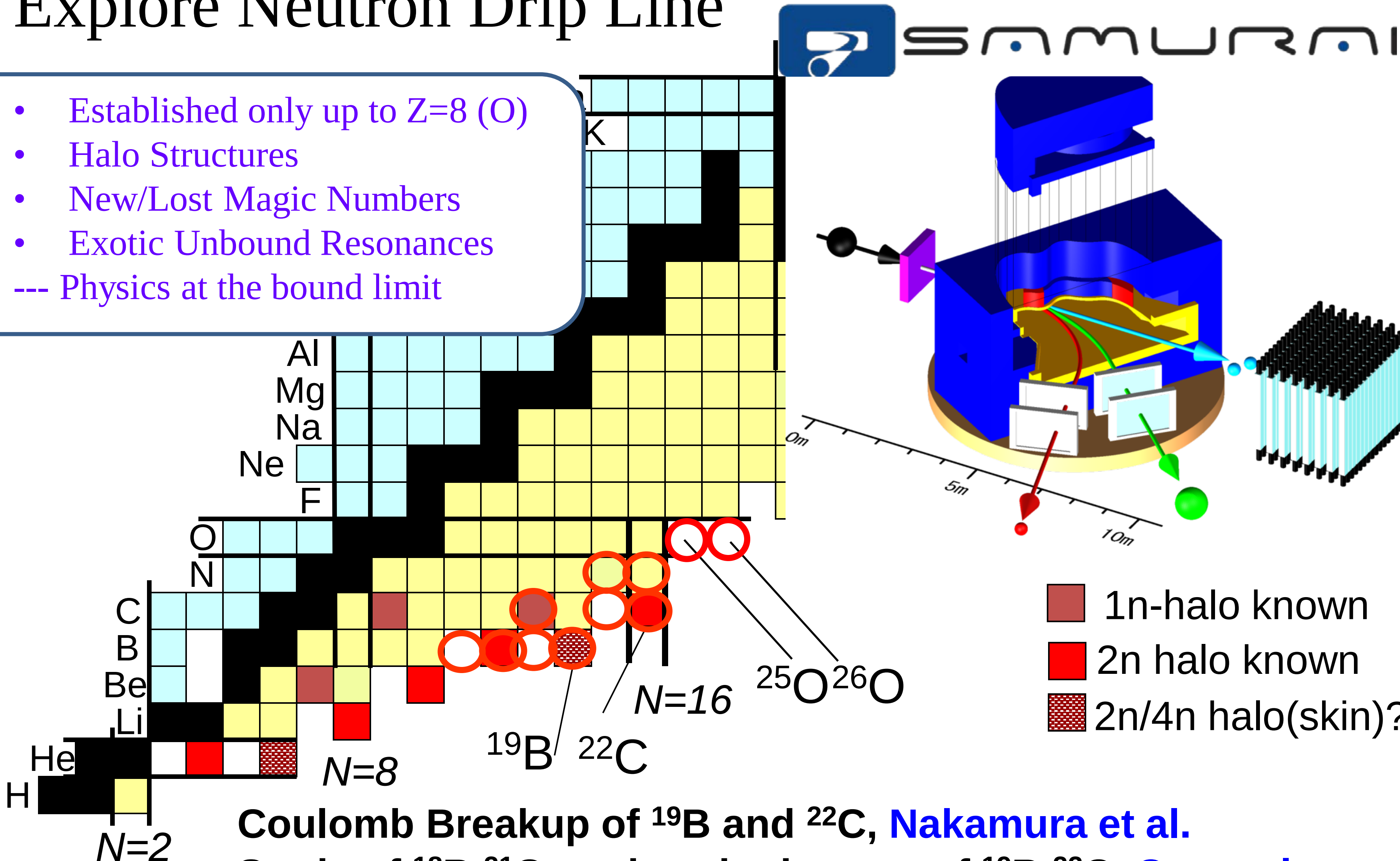


Very high efficiency neutron detector →
Survey of beta-delayed multi-neutron & T1/2
2016-

Day-One Campaign Experiments at SAMURAI: Explore Neutron Drip Line

- Established only up to Z=8 (O)
- Halo Structures
- New/Lost Magic Numbers
- Exotic Unbound Resonances

--- Physics at the bound limit



Coulomb Breakup of ^{19}B and ^{22}C, Nakamura et al.

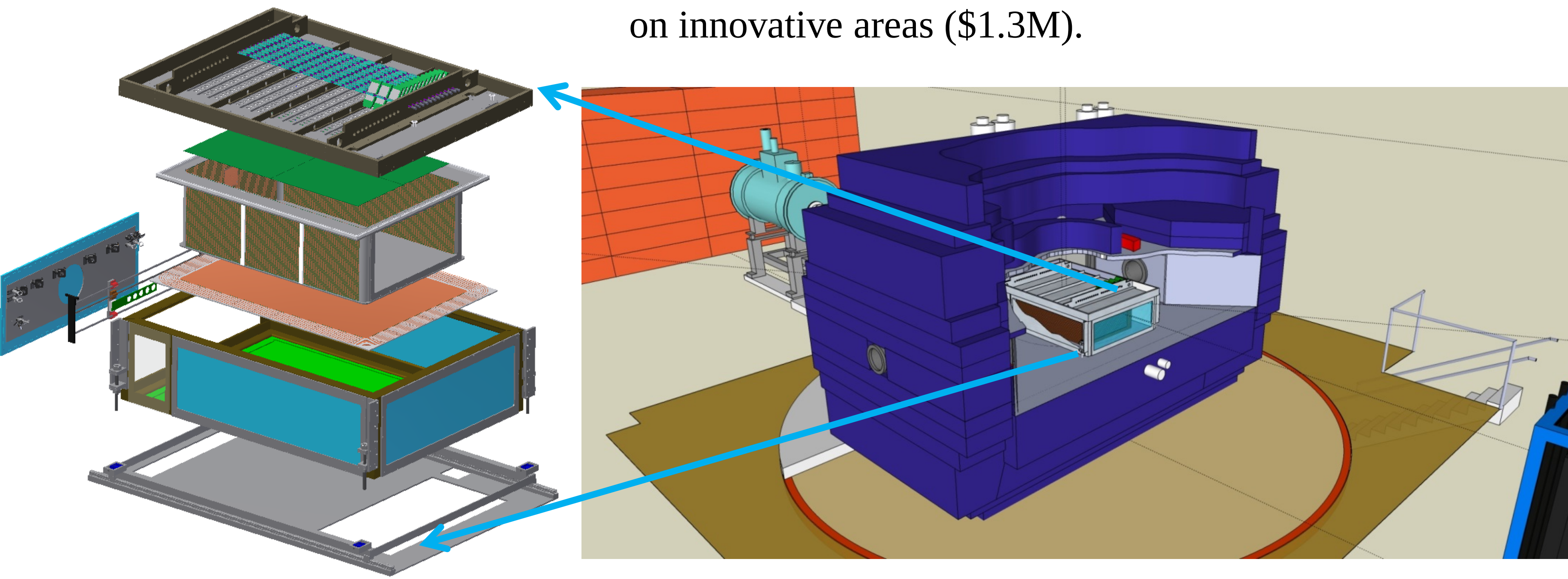
Study of ^{18}B,^{21}C, and excited states of ^{19}B,^{22}C, Orr et al.

Structure of Unbound Oxygen Isotopes ^{25}O,^{26}O, Kondo et al.

US-Japan Initiatives for EOS at $\rho \sim 2\rho_0$

Time Projection Chamber installed in the SAMURAI magnet to detect pions, charged particles at $\rho \sim 2\rho_0$

Supported by USA DoE funding ($1.2M), and Japanese Grant-in-Aid for Scientific Research on innovative areas ($1.3M).



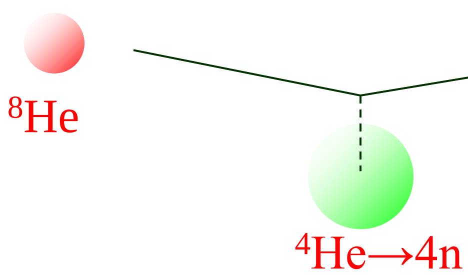
Exothermic double-charge exchange reaction

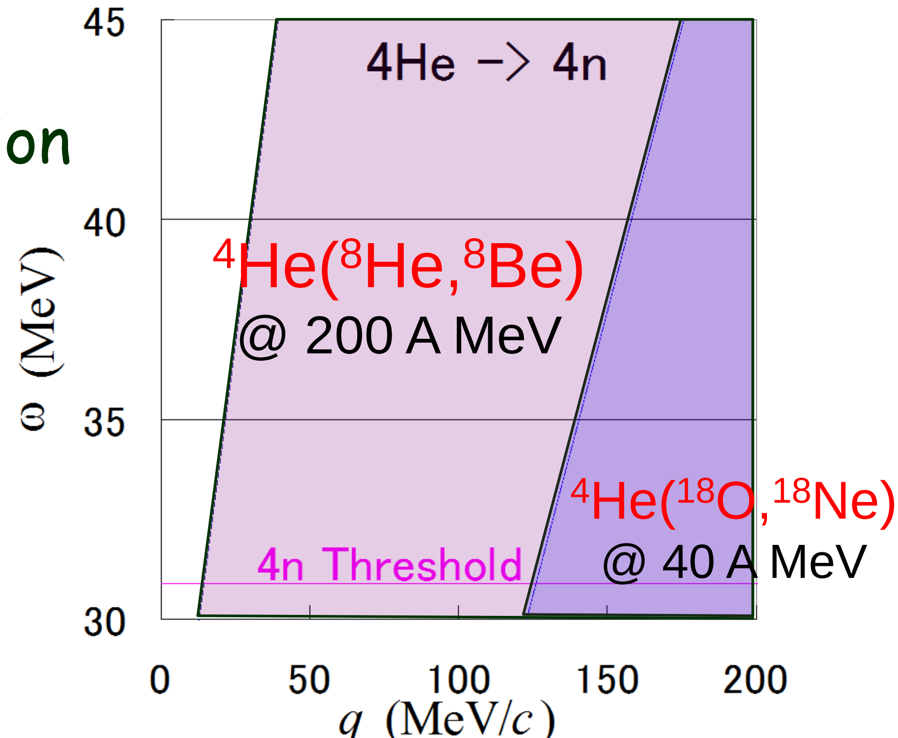
^{4}n production with ^{4}He(^{8}He,^{8}Be)

Small q <- exothermic reaction

Double-Charge ~200nb/sr

^{8}He :2x10^6/s at 190A MeV





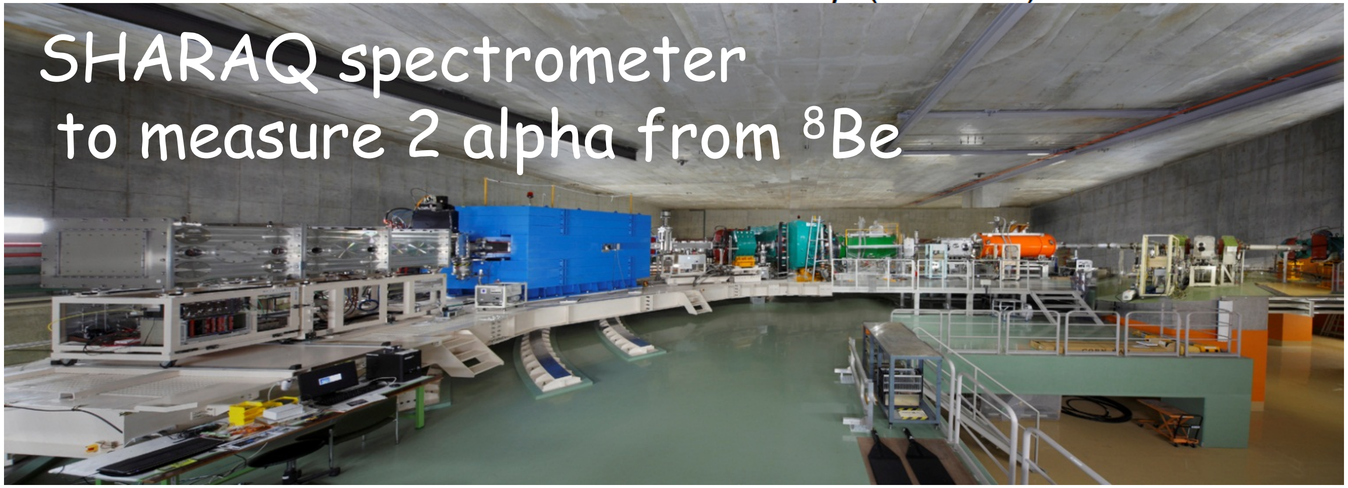
T. Uesaka et al.,
NIMB B **266** (2008) 4218.

Momentum resolution

d*p*/*p* = 1/14700

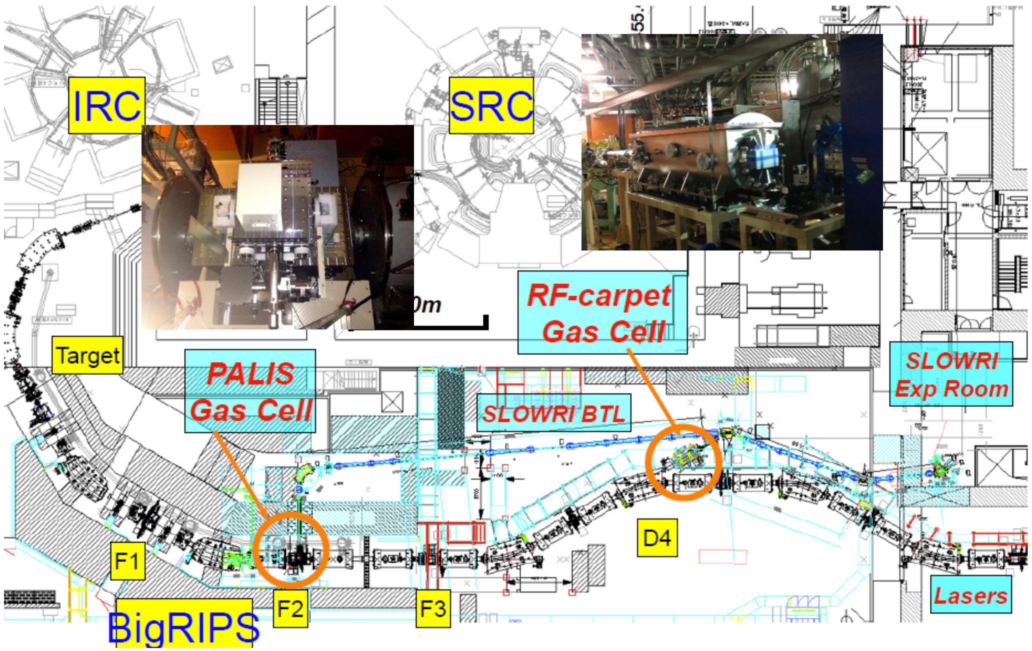
Angular resolution

~ 1 mrad

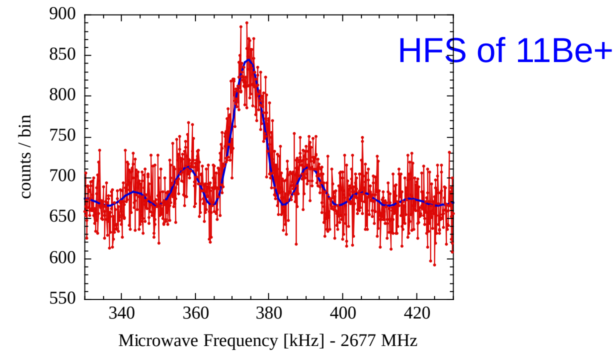


SLOWRI Device for Trap Experiments

Wada, Sonoda et al.

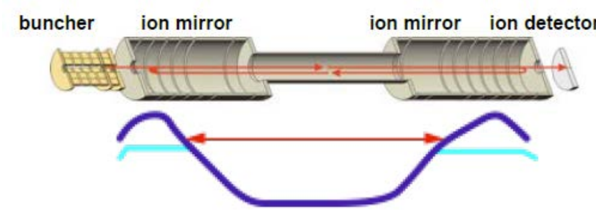


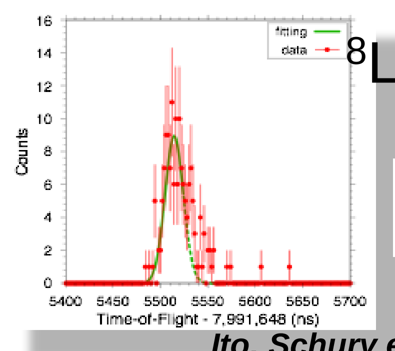
1)Optical spectroscopy



Takamine et al, PRL 112(2014)162502

2)Mass measurements of short-lived nuclei





^{8}Li ToF spectrum

ToF = 7,994,989.2(8) ns
R_m ~ 173,000

Ito, Schury et al, PRC 88(2013)011306R

3)Resonance Ionization Spectroscopy

Parasitic RI beam production, spin, moments, radii..

Mass spectroscopy at "Rare RI Ring" 2015-

Construction started in April 2012!
Ozawa, Wakasugi, Uesaka et al.

Dedicated to mass measurements
r-process nuclei
Low production rate (~1/day)
Short life time (<50ms)

Key technologies:
Isochronous ring
$\Delta T/T < 10^{-6}$ for $\delta p/p = \pm 0.5\%$
Individual injection triggered by
a detector at BigRIPS
efficiency ~ 100%
even for a "cyclotron" beam

Schedule:
2015 Commissioning run
2016~ Mass measurements of RI

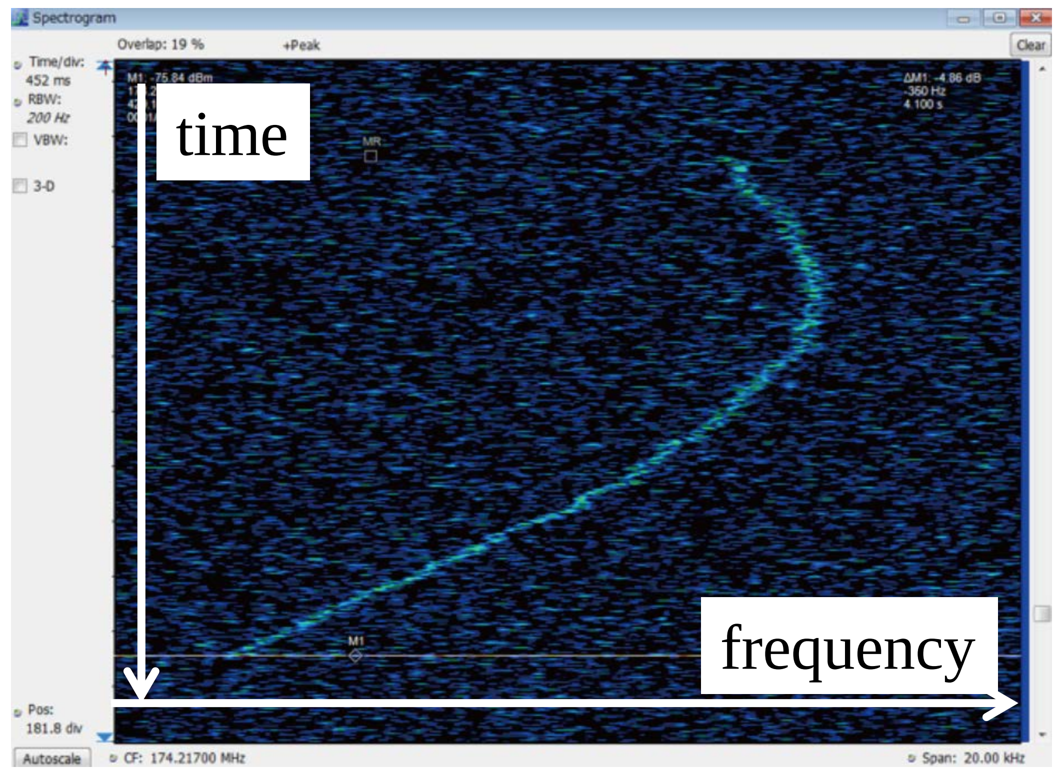
Commissioning for “Rare RI Ring” June 2015

Commissioning run with a primary beam of Kr-78

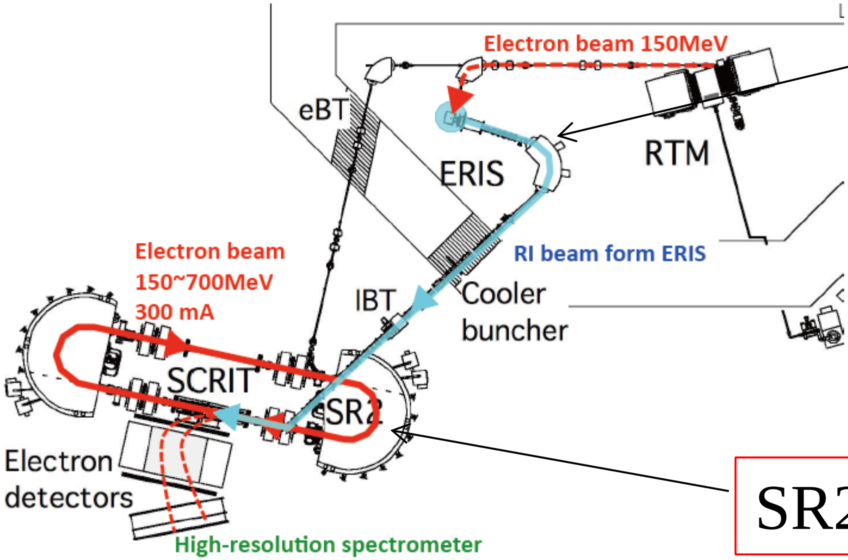
Single particle injection and extraction scheme was confirmed.

Schottky frequency spectrum was successfully obtained for a single ion.

A single ion was observed to be accumulated for ~ 4 seconds.



SCRIT Facility for e+RI scattering

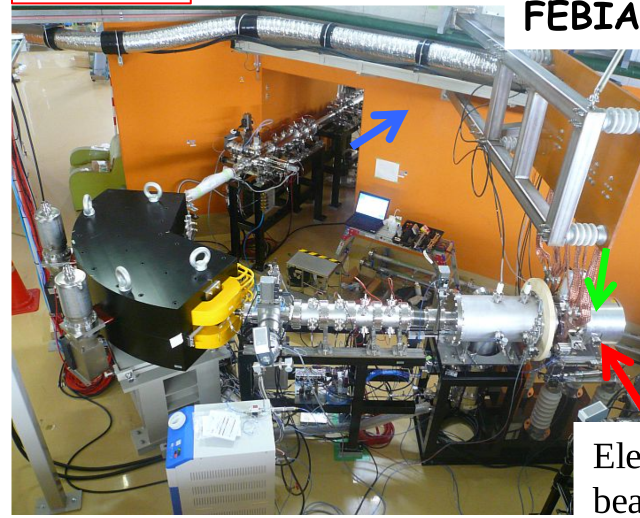


SR2

ERIS

UCx Target in
FEBIAD ion source

～2000℃



Electron
beam

SR2 (SCRIT-equipped RIKEN Storage Ring)	
Energy	100 – 700 MeV
Stored current	300 mA (current operation)
Lifetime	~ 1 AH
Circumference	21.946 m
Tunes	1.62 / 1.58
β-max	10.36 / 4.09 m

Luminosity of $10^{27}/(cm^2 s)$ was achieved at the e-beam current of 250mA.

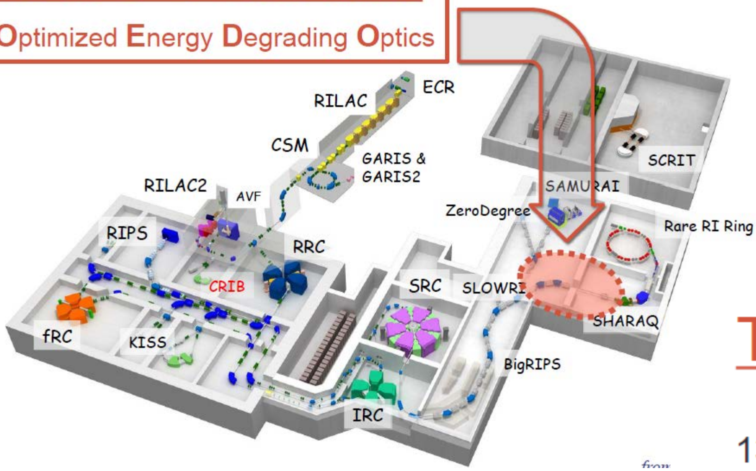
Efficiency improvement
More high power beam 10W->1kW
-> $10^{29}/cm^2/s$

CNS-RIKEN: OEDO Project

Shimoura et al

OEDO Beam-line

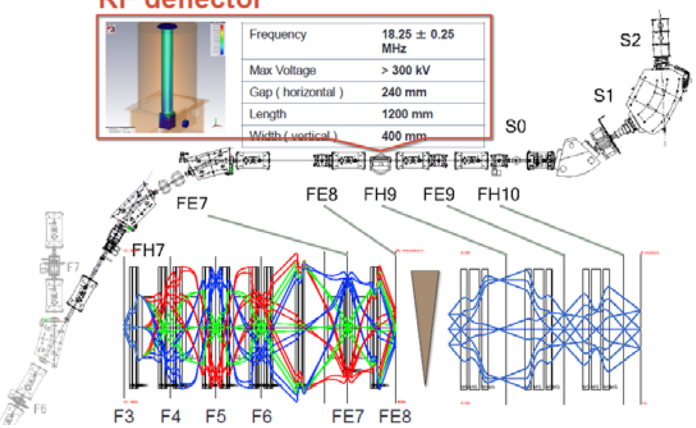
Optimized Energy Degrading Optics



- Nucleon transfer reactions (10A – 50A MeV)
- Pair transfer / Cluster transfer (10A – 20A MeV)
- Deep inelastic collisions (incomplete fusion) (5A – 30A MeV)
- Fusion reaction (~ 5A MeV)
- Coulomb excitation reactions for low-energy gamma rays (~ 50A MeV)

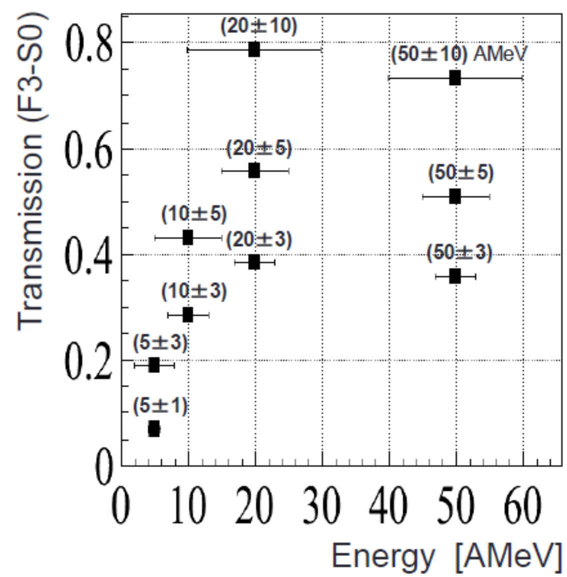
Magnet configuration and optical condition

RF deflector



Transmission and intensity

^{132}Sn



Transmission (F3 - S0)
×
Intensity @ F3
||
Intensity @ OEDO (S0)

Typical example of ^{132}Sn

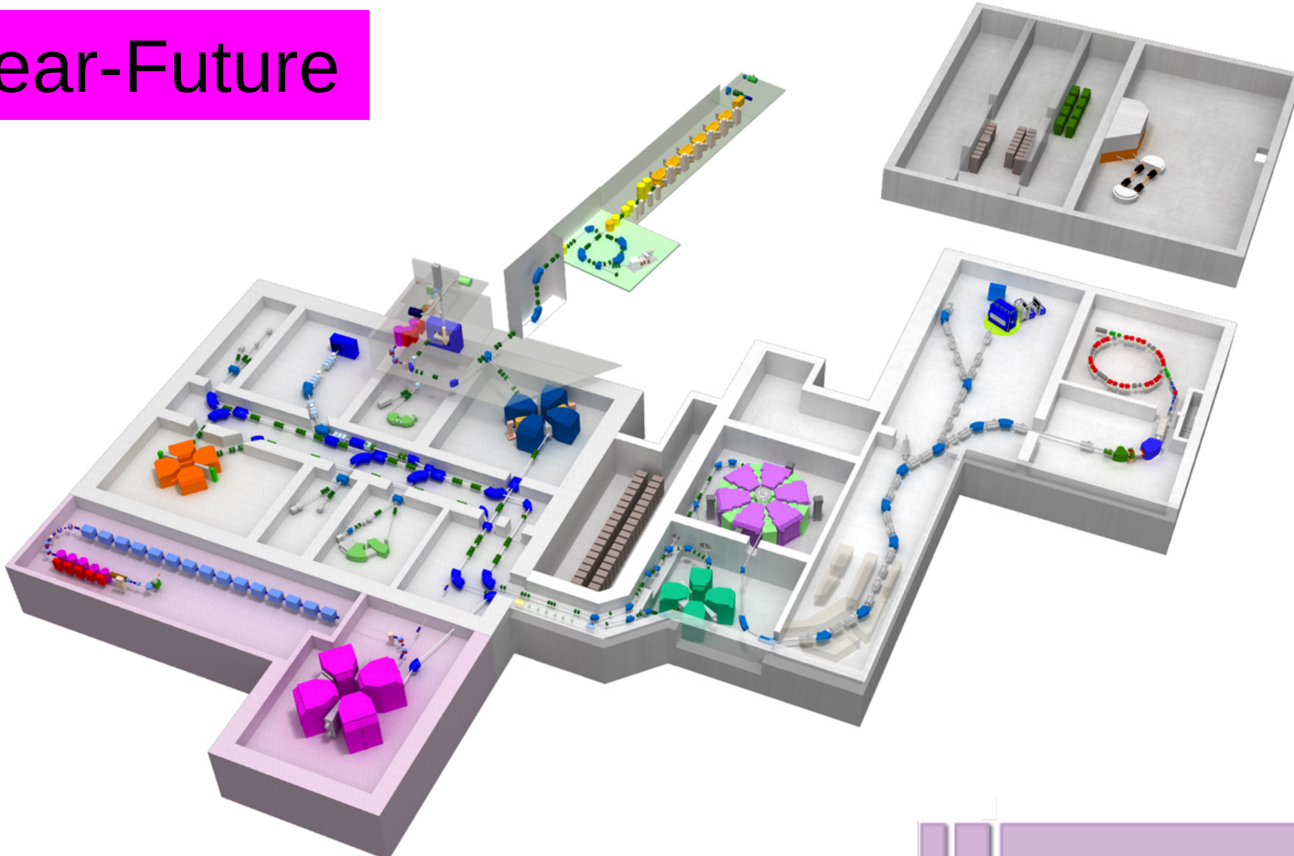
based on actual intensity in experiment by using 345 AMeV 30pnA U primary beam (Apr. 2015)

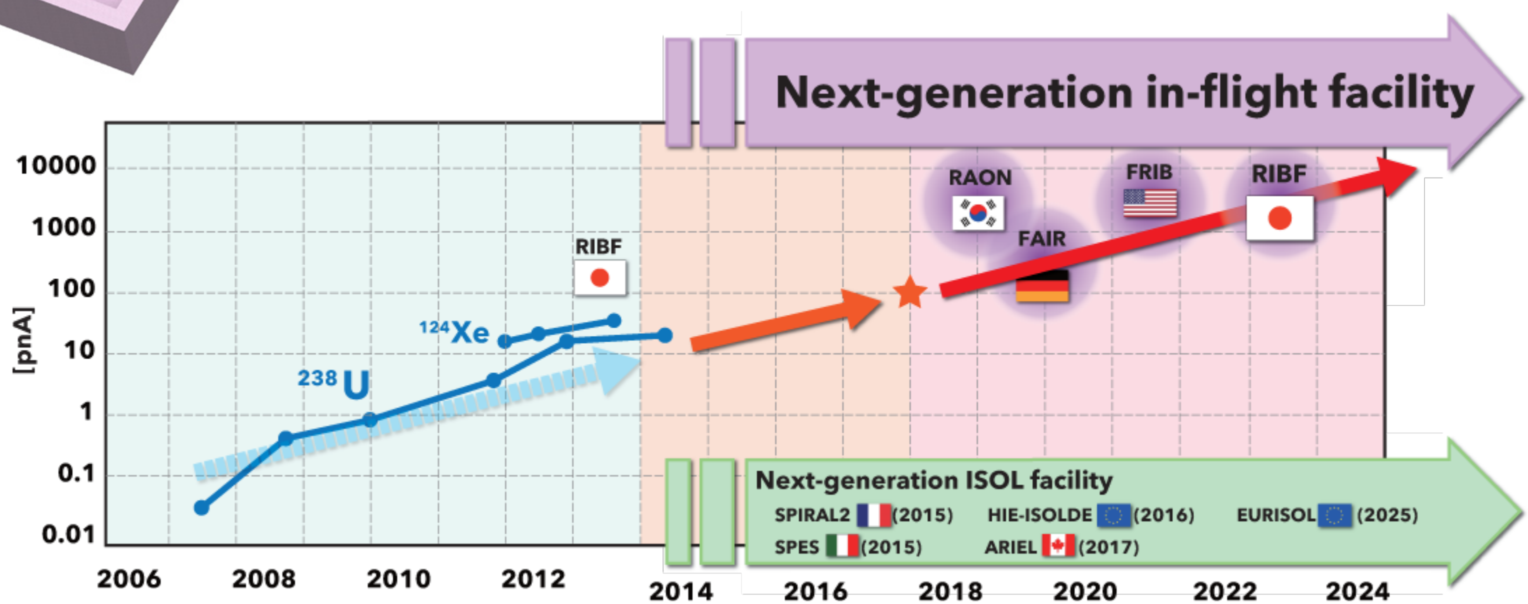
Intensity @ F3 (Apr. 2015)	2.5×10^6 [pps]
50 ± 5 AMeV @ S0	1.3×10^6
20 ± 3 AMeV @ S0	9.5×10^5
10 ± 3 AMeV @ S0	7.5×10^5
5 ± 1 AMeV @ S0	1.7×10^5

cf. 1.4×10^4 pps ^{132}Sn in CARIBU proposal

Operation will start in 2017

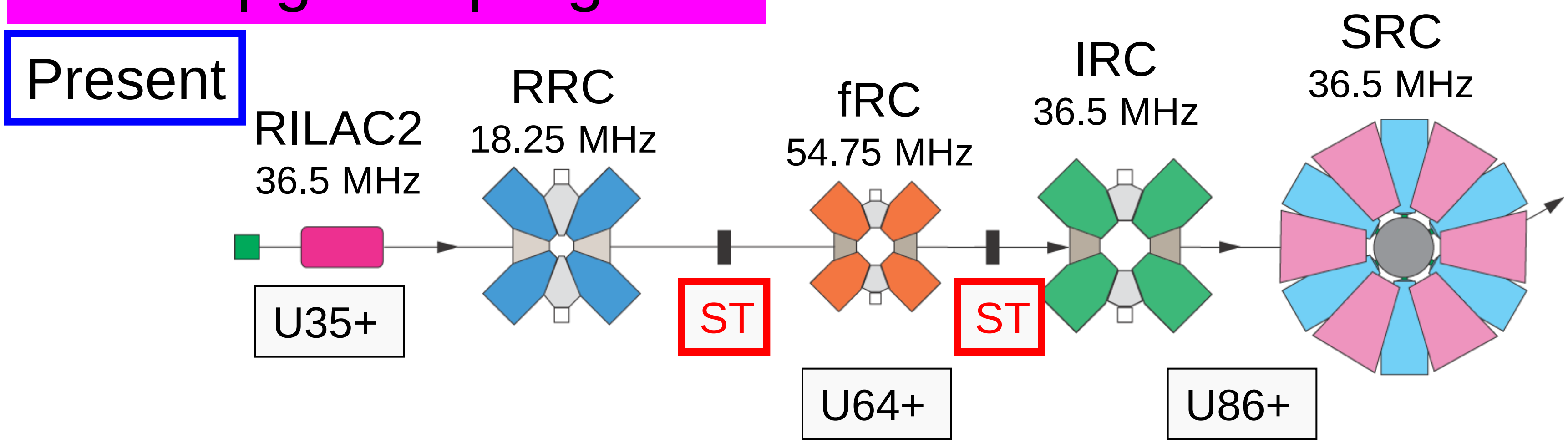
Near-Future





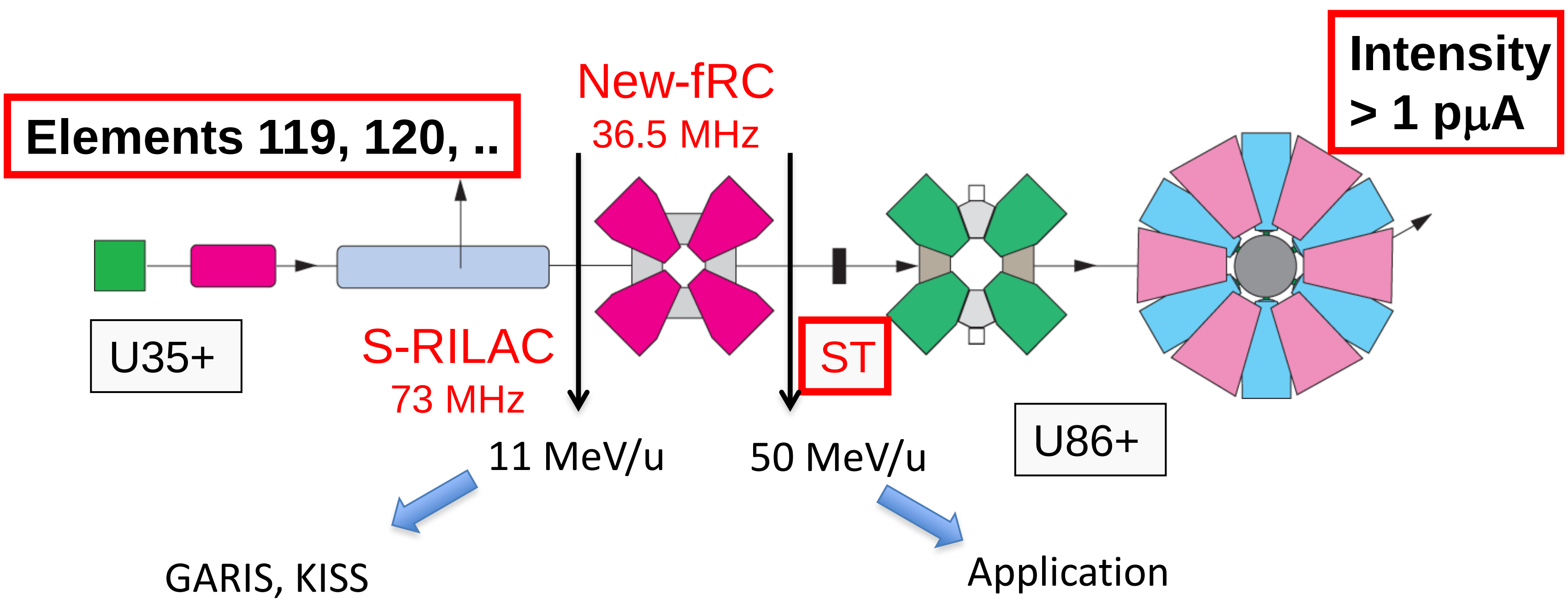
Next-generation in-flight facility
RAON
FRIB
RIBF
FAIR
RIBF
[pnA]
10000
1000
100
10
1
0.1
0.01
^{124}Xe
^{238}U
2006
2008
2010
2012
2014
2016
2018
2020
2022
2024
Next-generation ISOL facility
SPIRAL2 (2015)
HIE-ISOLDE (2016)
EURISOL (2025)
SPES (2015)
ARIEL (2017)

RIBF upgrade program



Upgrade plan

- Single stripping stage => New fRC
- Supercondcuting linac injector



Summary

- RIBF has started delivering intense RI beams since 2007.
- All of experimental devices have been completed.
- Bunch of data are being produced for nuclear structure study as well as nuclear reactions.
- Before FRIB, FAIR and RISP starting, RIBF has made efforts to access exotic nuclei as many as possible.
- The OEDO project will start to deliver decelerated in-flight beams in 2017 to promote science with low-E beams.
- The accelerator upgrade plan has been discussed to compete with FRIB, FAIR and RISP.