RIKEN RI Beam Factory (RIBF) : Status and Plans

T. Kubo, RIKEN Nishina Center

Focusing on the major experimental facilities at RIBF

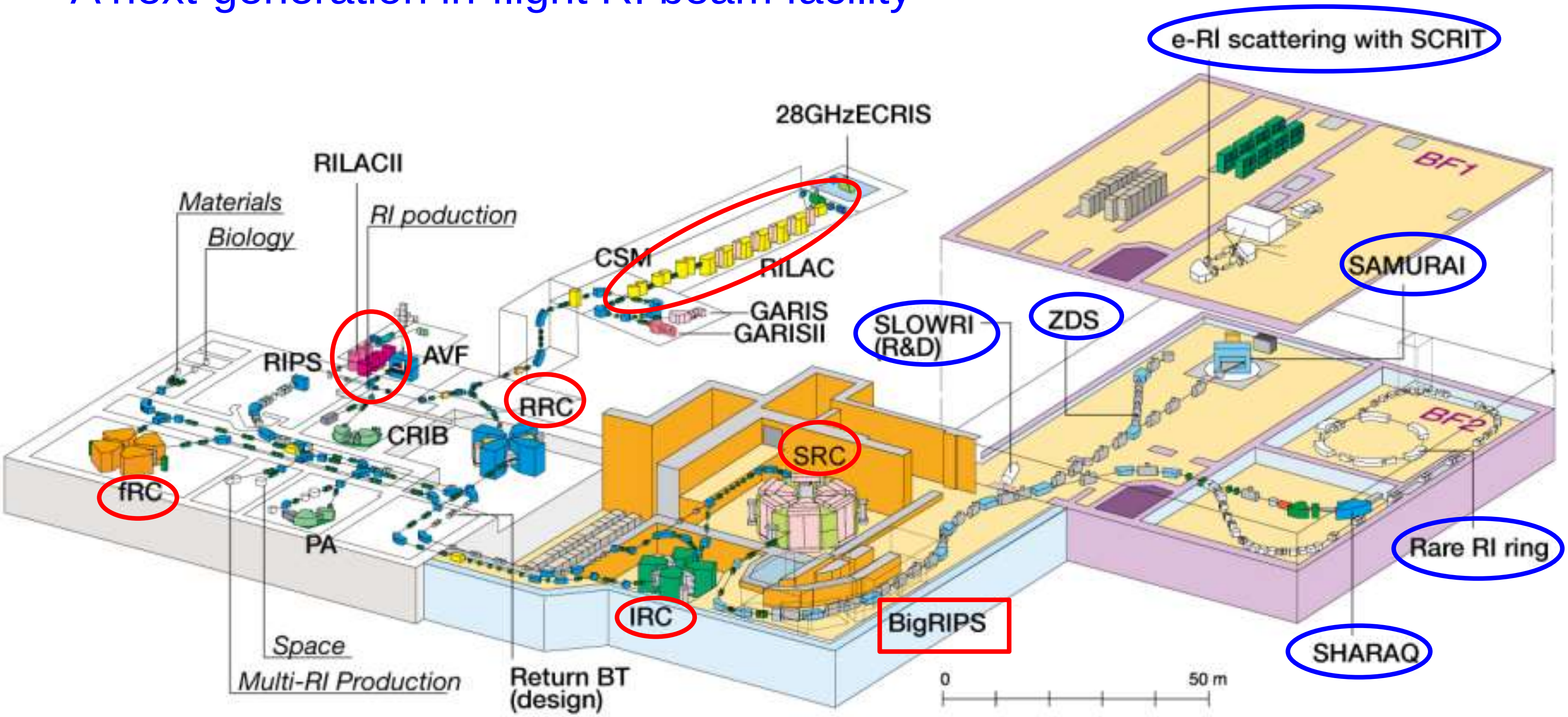
Outline of my talk

- Brief introduction
- Overview of BigRIPS separator and RI-beam production at RIBF
- Overview and status of experimental facilities at RIBF
- Accelerator upgrade plan
- Summary

Presented on Oct 16, 2014 @ FAIR2014 conference, Worms, Germany, Oct 13-17,2014

RI Beam Factory (RIBF) at RIKEN

A next-generation in-flight RI beam facility



- RIBF accelerator system consists of linacs and cyclotrons.
- Maximum energy is ~350 MeV/u for heavy ions up to U ions.
- Goal beam intensity is 1 pμA (6 x 10^{12} particles/sec).

RRC, fRC, IRC & SRC cyclotrons

- BigRIPS separator: used for RI-beam production
- Major experimental facilities

BigRIPS separator (since March 2007)

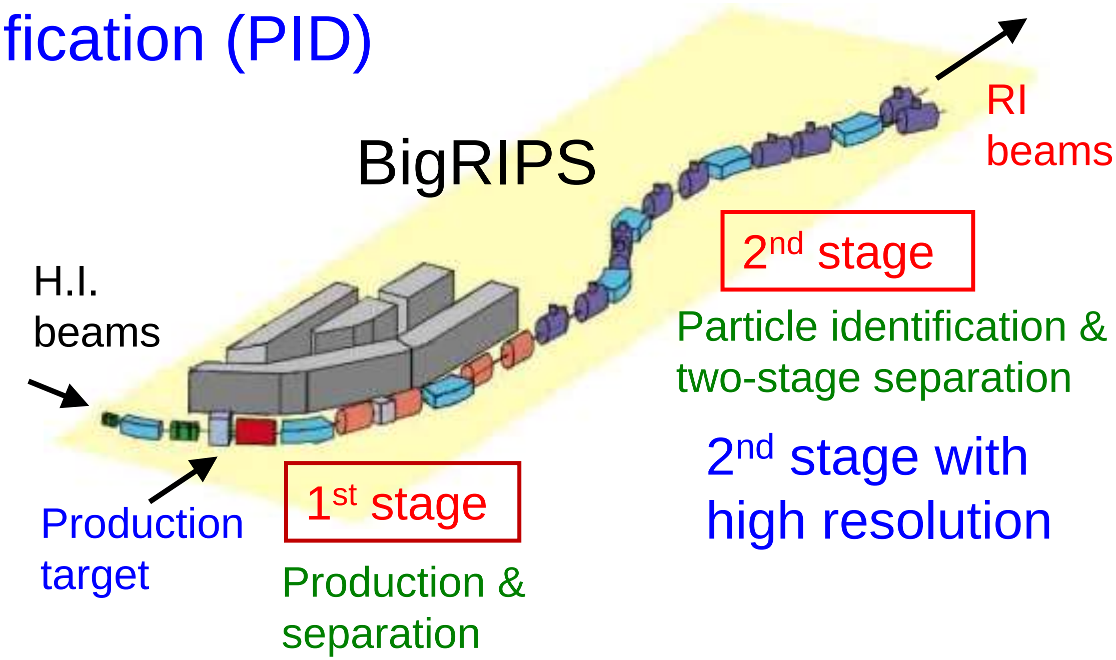
- **Large acceptances**

  Comparable with spreads of in-flight fission of U beam at RIBF energies, allowing efficient production of RI beams

$\Delta\theta$ = 80 mr
$\Delta\phi$ = 100 mr
$\Delta p/p$ = 6 %
$B\rho$ = 9 Tm
L = 78.2 m

- **Two-stage separator scheme with excellent particle identification (PID)**


BigRIPS 2nd stage

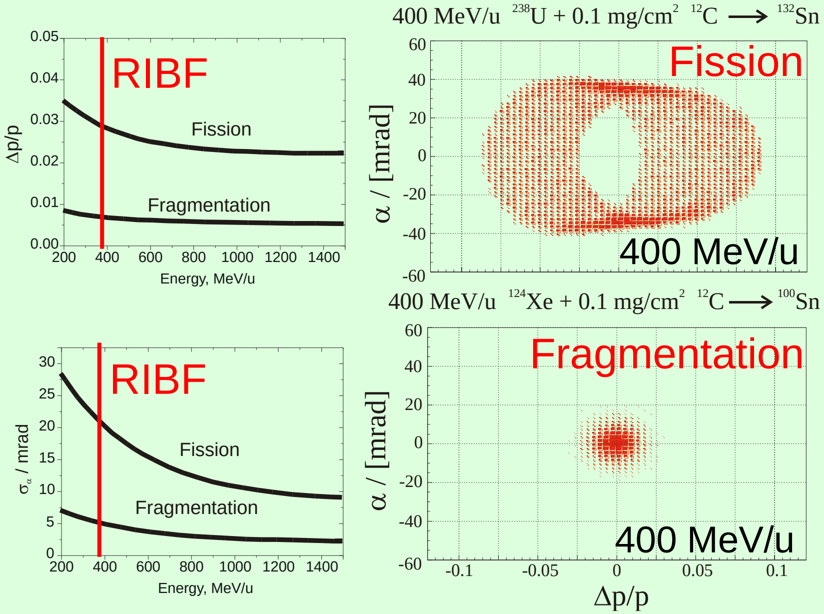


- PID scheme based on TOF-$B\rho$-ΔE method with track reconstruction → Z and A/Q
- A/Q resolution is high enough to identify charge state events without measuring TKE

Angle and momentum spreads (reaction kinematics) and large collection efficiency of fragments at BigRIPS

Momentum spread

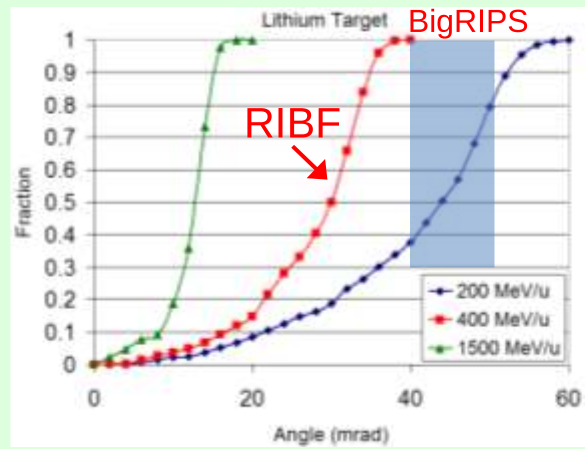
Angular spread



^{132}Sn

From Hans Geissel

Fraction of ^{132}Sn contained in a cone of the respective angle

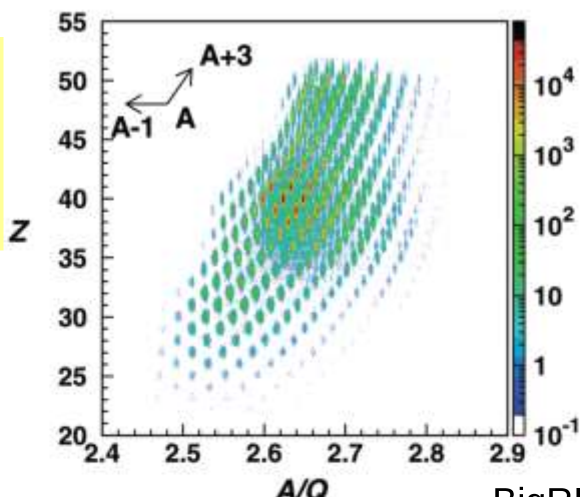


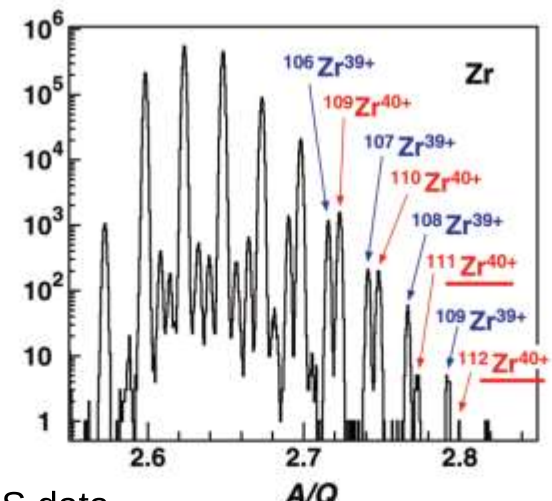
Fission

From Jerry Nolen

Excellent PID for fission fragments

^{238}U+Be at 345 MeV/u

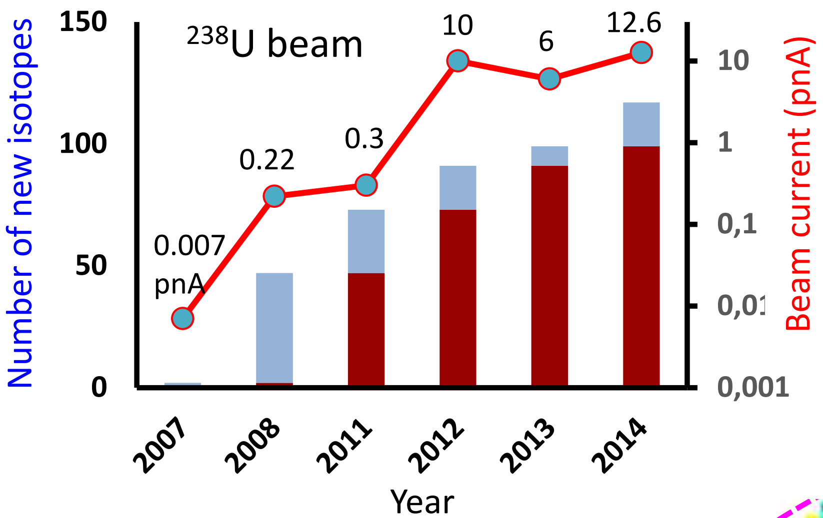




BigRIPS data

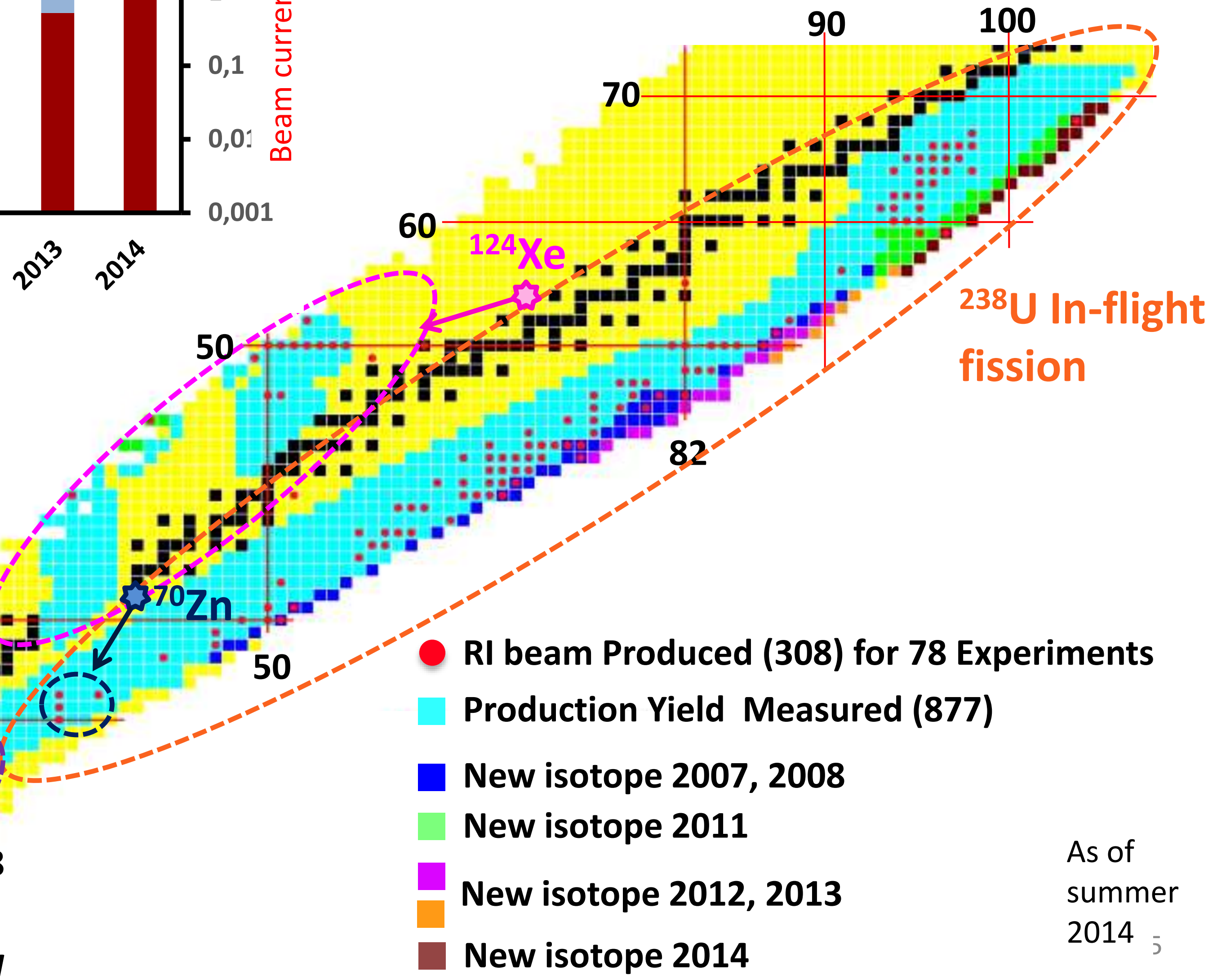
Fully-stripped and hydrogen-like peaks clearly identified

RI beams produced at BigRIPS (May 2007 – June 2014)

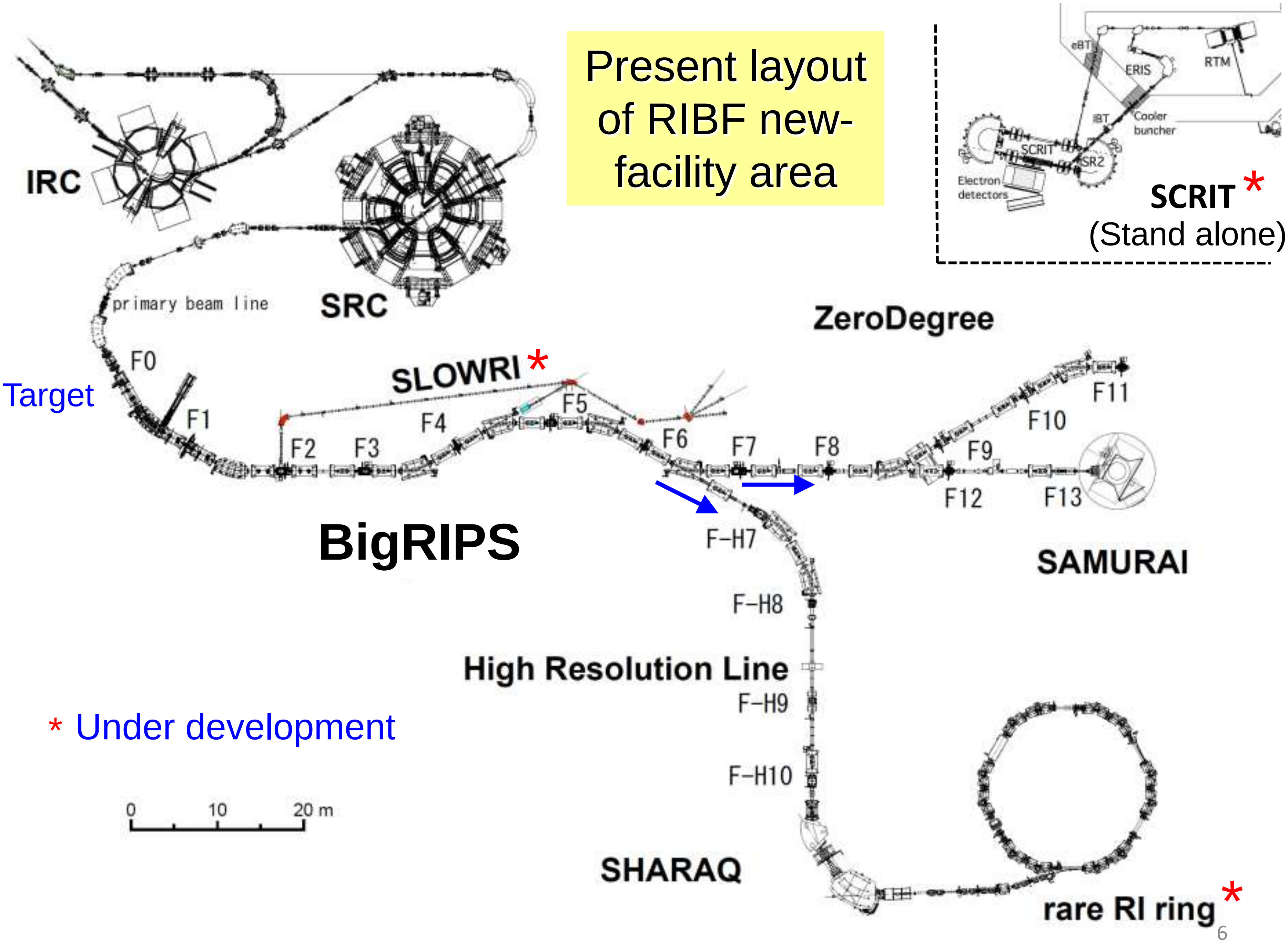


New isotopes: 120
New isomers: 43

Produced reactions:
- In-flight fission of ^{238}U
- Projectile fragmentation of ^{14}N, ^{18}O, ^{48}Ca, ^{70}Zn, ^{124}Xe



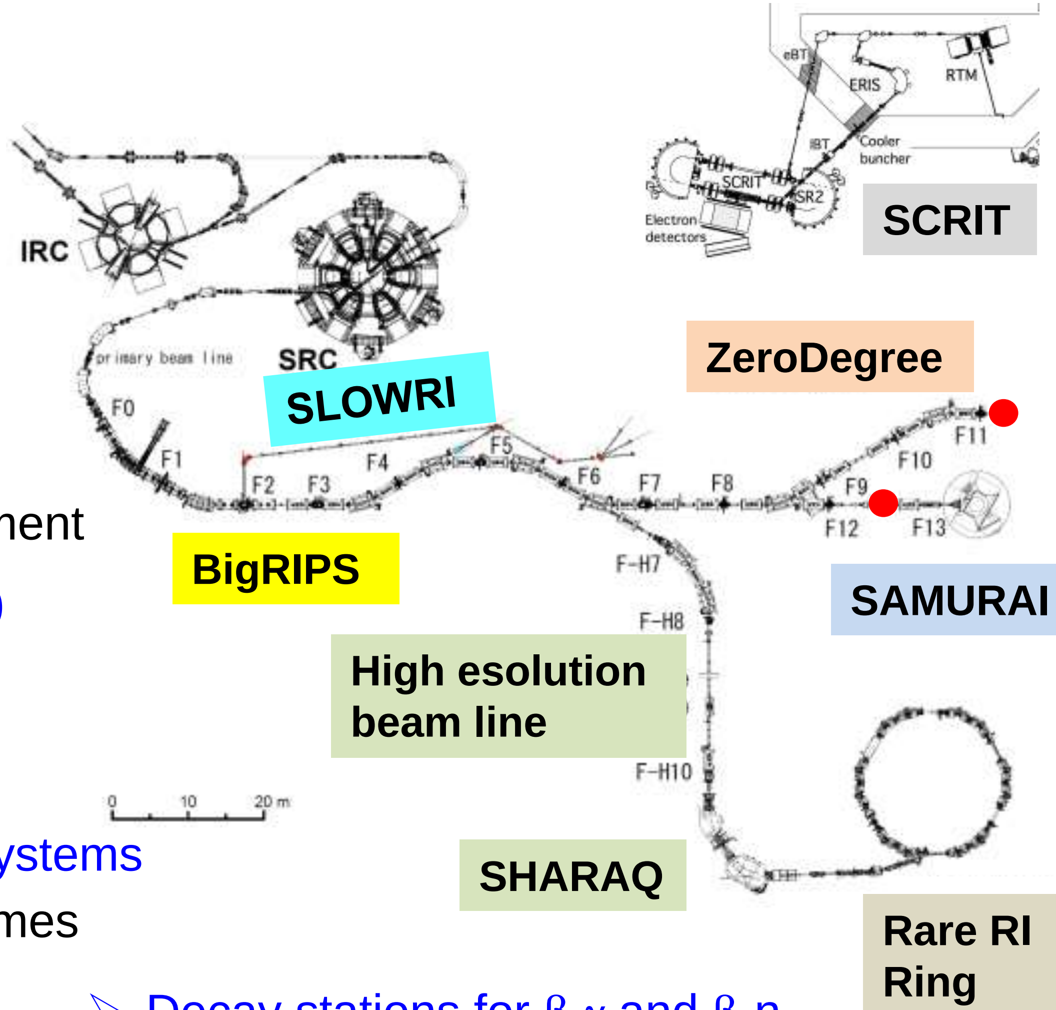
Present layout of RIBF new-facility area



* Under development

Major experimental facilities and devices at RIBF

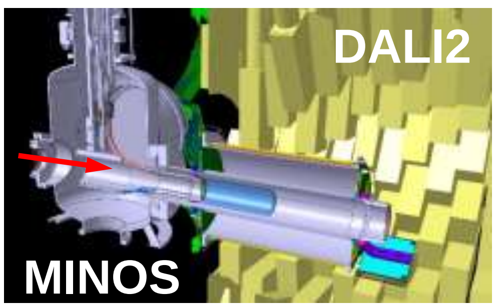
- **BigRIPS separator**
  Also used as a spectrometer
- **ZeroDegree spectrometer: ZDS**
  Forward spectrometer fixed at 0 degrees and nice PID
- **SAMURAI spectrometer**
  Very large acceptances and kinematically complete measurement
- **SHARAQ spectrometer (by CNS) and high-resolution beam line**
  High-resolution measurement by momentum dispersion matching
- **SLOWRI & PALIS: gas catcher systems**
  Combine in-flight and ISOL schemes
- **Rare RI Ring : isochronous ring**
  TOF mass measurement (~ppm)
- **SCRIT (Self-Confining RI target)**
  Electron-RI scattering using electron storage ring

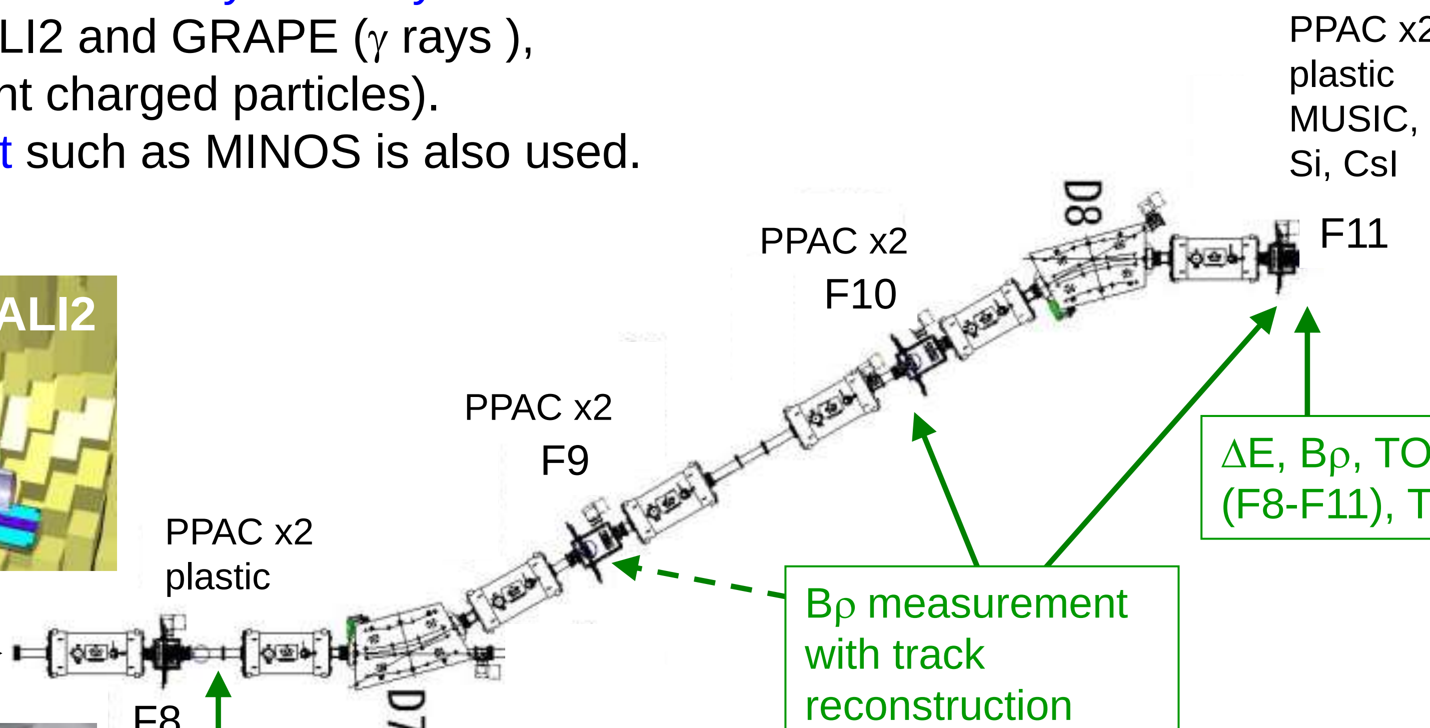


- **Decay stations for β-γ and β-n measurements** : EURICA, BRIKEN
- **Large-scale detectors** : DALI2, GRAPE, EUROBALL, ESPRI, MUST2, MINOS, SAMURAI TPC, …

ZeroDegree: ZDS (since Oct 2008)

- Analyze and identify projectile reaction residues in coincidence with γ rays or light charged particles, which are emitted in reactions in inverse kinematics, such as COULEX, (p, p'), transfer reactions, nucleon removal reactions.
- Target is surrounded by an array detector
  such as DALI2 and GRAPE (γ rays),
  MUST2 (light charged particles).
- Active target such as MINOS is also used.





ΔE, Bρ, TOF (F8-F11), TKE

Bρ measurement with track reconstruction

Target & γ-ray array detector (or charged particle detector)

DALI2, GRAPE, MUST2, MINOS

PID: TOF-Bρ-ΔE method with track reconstruction, also TKE

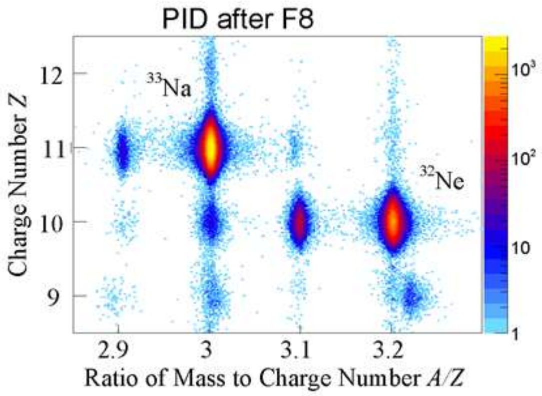
An example of experiments with ZeroDegree and DALI2

In-beam γ ray spectroscopy of ^{32}Ne

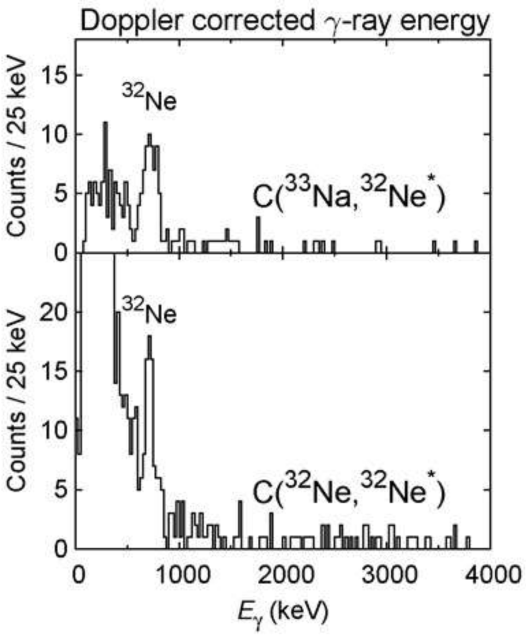
Inelastic and knock-out reactions were measured with γ rays to study ^{32}Ne

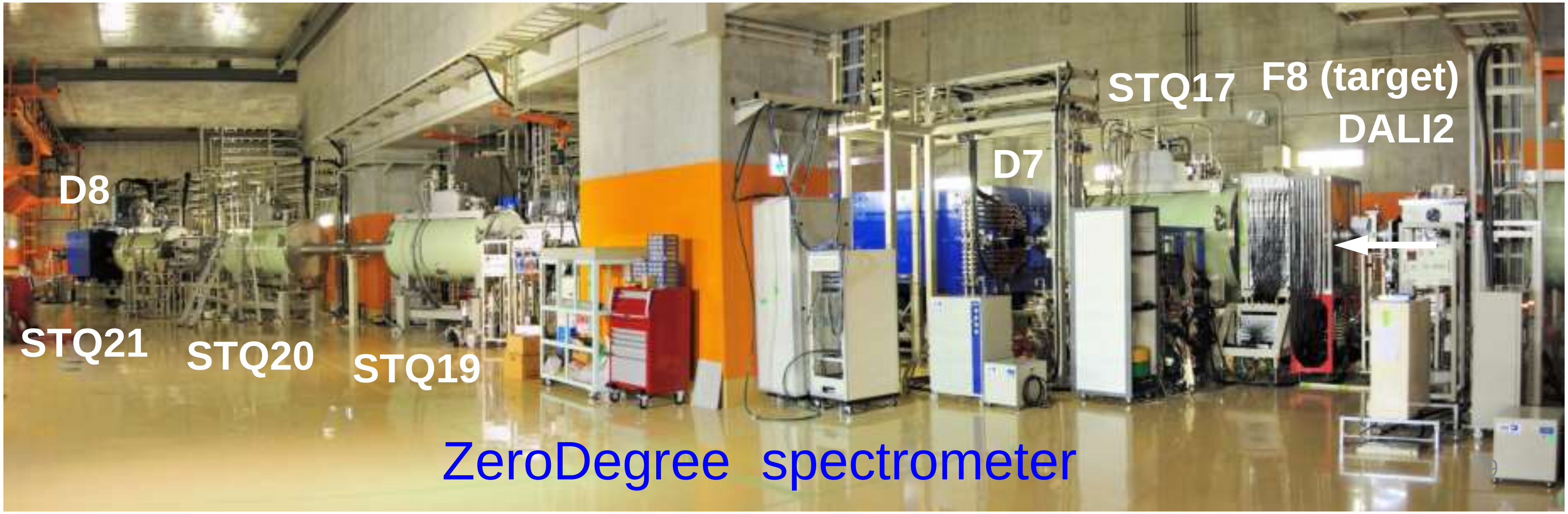
C(^{32}Ne, ^{32}Ne*(γ)),
C(^{33}Na, ^{32}Ne*(γ))

Island of inversion



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





In-beam γ ray experiments at ZeroDegree 2008-2014

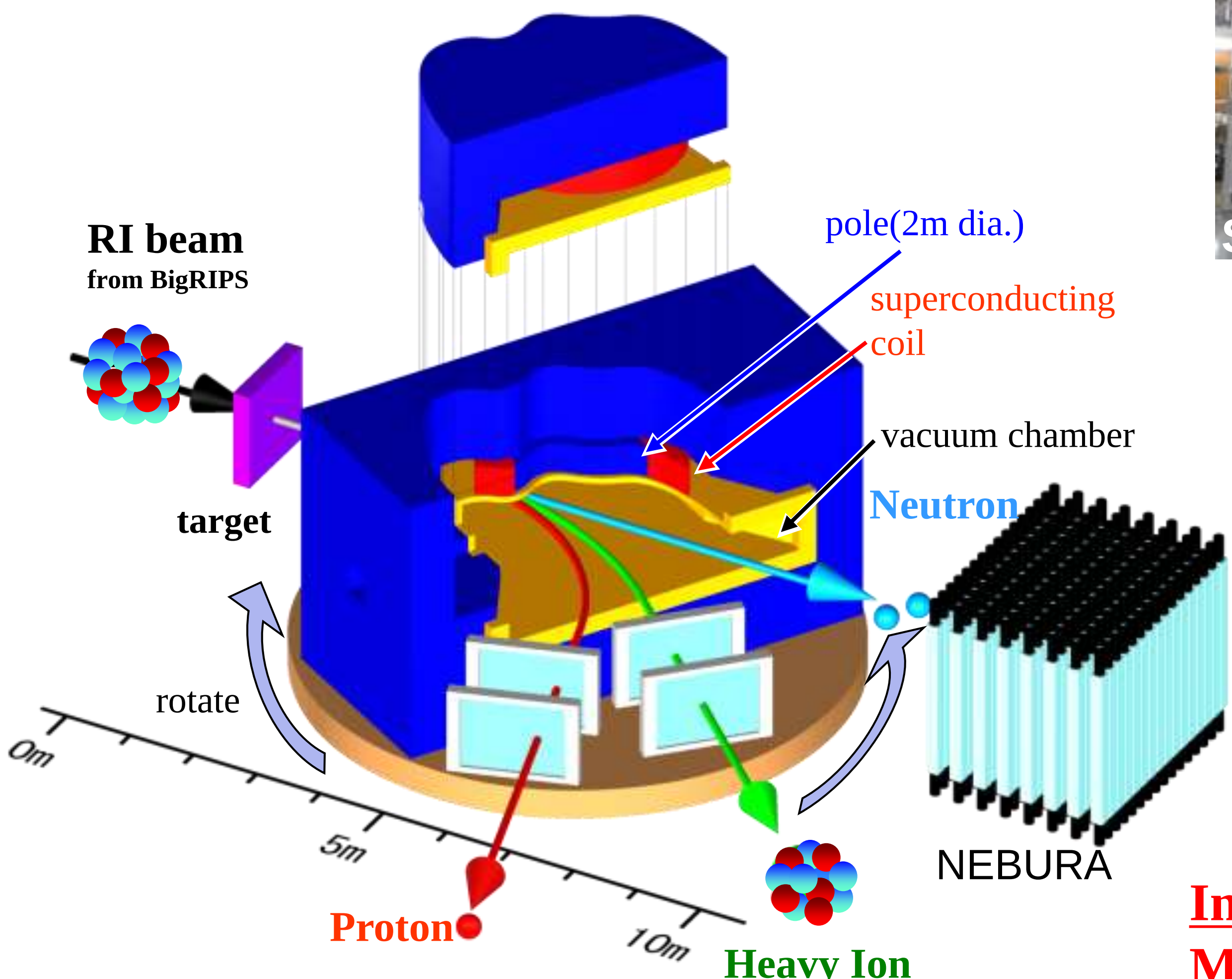
From H. Sakurai

2008	Day-One experiment	
	32Ne, 31,33Na	H. Scheit, P. Doornenbal
2009	Test with U (0.3-0.6 pnA)	
	~132Sn	H. Wang, N. Aoi
	Test with 48Ca beam	
	32Mg etc.	K.Li, H.Scheit
2010	48Ca campaign	
	38,40,42Si	S.Takeuchi, M.Matsushita
	A>36Mg	P. Doornenbal, H. Scheit
	F isotopes	P. Doornenbal, H. Scheit
	~Al, P	D. Steppenbeck
	33Mg	D. Bazin
	40Mg test	P. Fallon
2011	U beam campaign	
	78Ni	K. Yoneda, D. Steppenbeck
	~132Sn	H. Wang, N. Aoi
2012	124Xe and 70Zn beam campaign	
	10xSn	A. Obertelli, P. Doornenbal
	54Ca	D. Steppenbeck, S. Takeuchi
2013	U beam campaign	
2014	SEASTAR campaign with 238U (2+ search)	
	N-rich Z ~24-28	P. Doornenbal, A. Obertelli

New magic number N=34 in Ca isotopes

SAMURAI spectrometer (since March 2012)

Large-acceptance spectrometer
Kinematically complete measurements



T. Kobayashi et al.

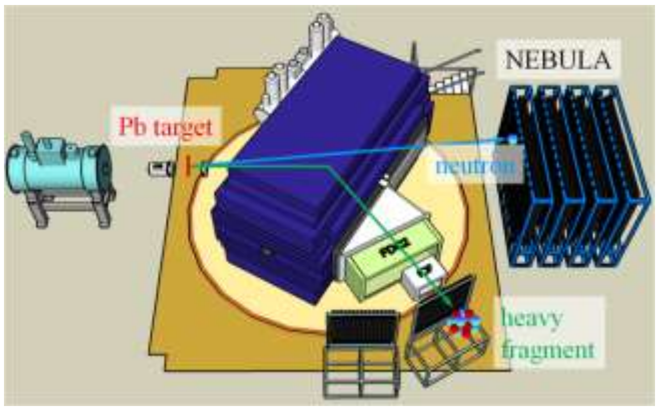
- Superconducting dipole magnet (a max. field of 3T, a field integral of 7 Tm and a pole gap of 88 cm)
- Heavy Ion Detectors
- Neutron Detectors
- Proton Detectors
- Large Vacuum Chamber
- Rotational Stage
- Designed resolution 700

Invariant Mass Measurement
Missing Mass Measurement

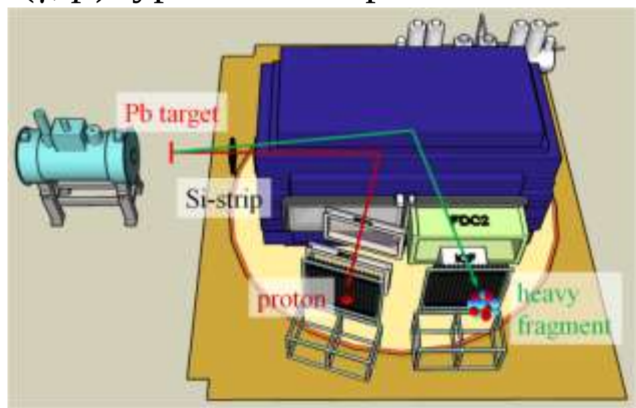
Various Configuration is possible by rotating the magnet!

allows versatile usage of SAMURAI spectrometer

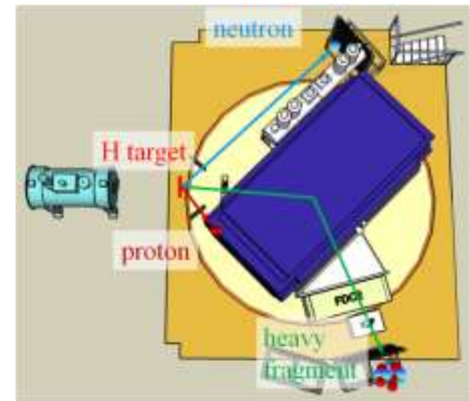
Breakup reaction
(γ, n) type reaction: neutron-rich side



Breakup reaction
(γ, p) type reaction: proton-rich side

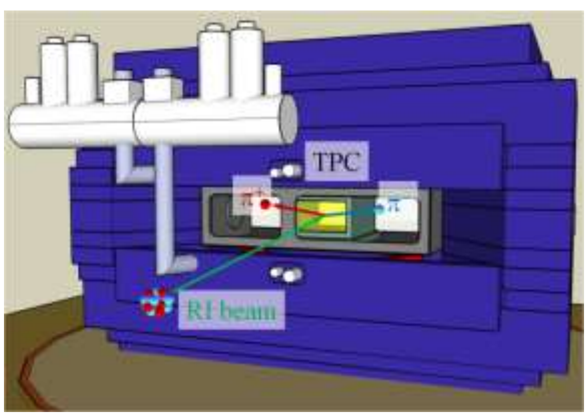


Missing mass measurement
(p,p'), (p,$2p$), (p,pn), …

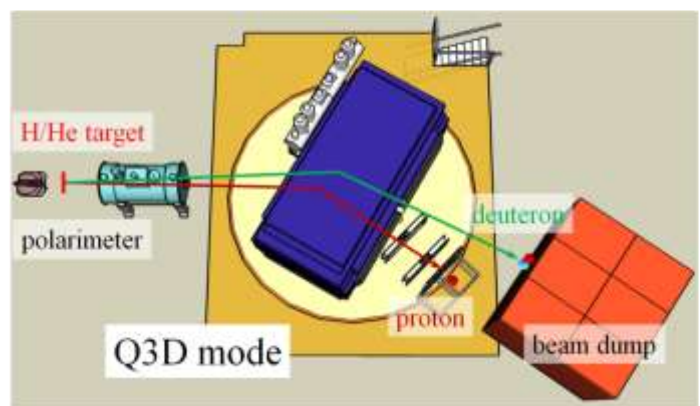


EOS measurement using TPC

SπRIT



pol. d-induced reaction using Q3D mode



A variety of physics programs are covered with SAMURAI

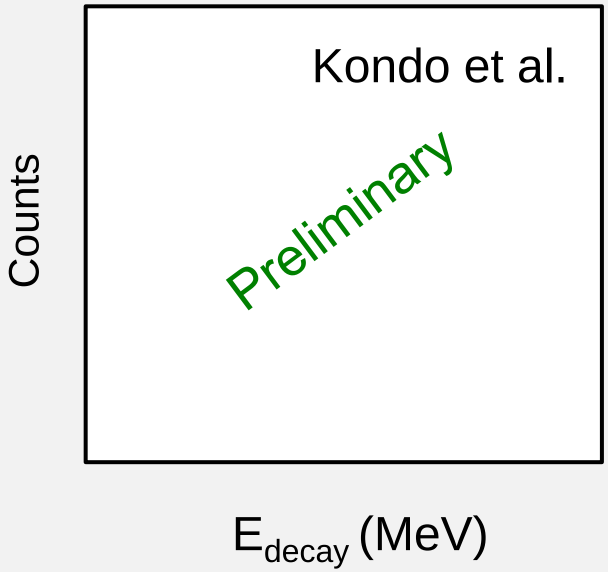
SAMURAI experiments performed so far

- NP1106-SAMURAI02 (Kondo et al.): Spectroscopy of unbound oxygen isotopes
- NP1106-SAMURAI04 (Orr & Gibelin et al.): Structure of ^{18,19}B and ^{21,22}C
- NP1106-SAMURAI03 (Nakamura et al.): Exclusive Coulomb Breakup of neutron drip-line Nuclei
- NP1112-SAMURAI08R1 (Otsu et al.): Exploration of cluster states on neutron rich isotopes by means of broadband magnetic spectrometer SAMURAI
- NP1206-SAMURAI10 (Lee et al.): Study of neutron-proton correlation & 3N-force in *N*=*Z* nuclei
- NP1306-SAMURAI17 (Sasano & Zegers et al.): Study of Gamow-Teller and spin-dipole transitions from ^{132}Sn via the (*p*,*n*) reaction at 270 MeV/u
- NP1306-SAMURAI14 (Muecher): Fission barrier studies of neutron-rich nuclei via the (*p*, 2*p*) reaction (*just started*)

Example

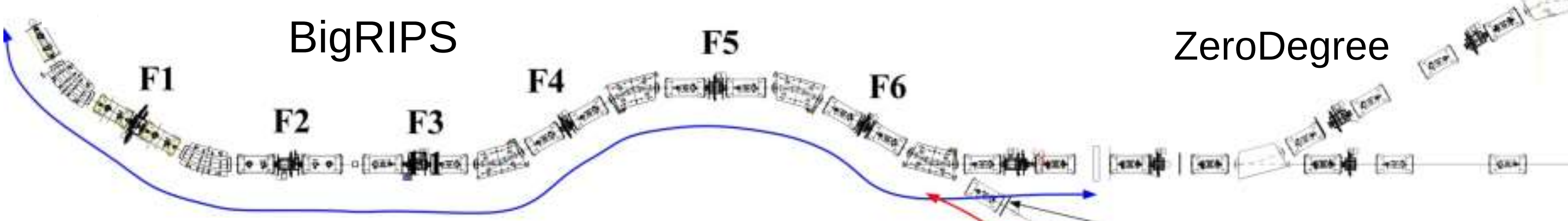
Spectroscopy of unbound oxygen isotopes

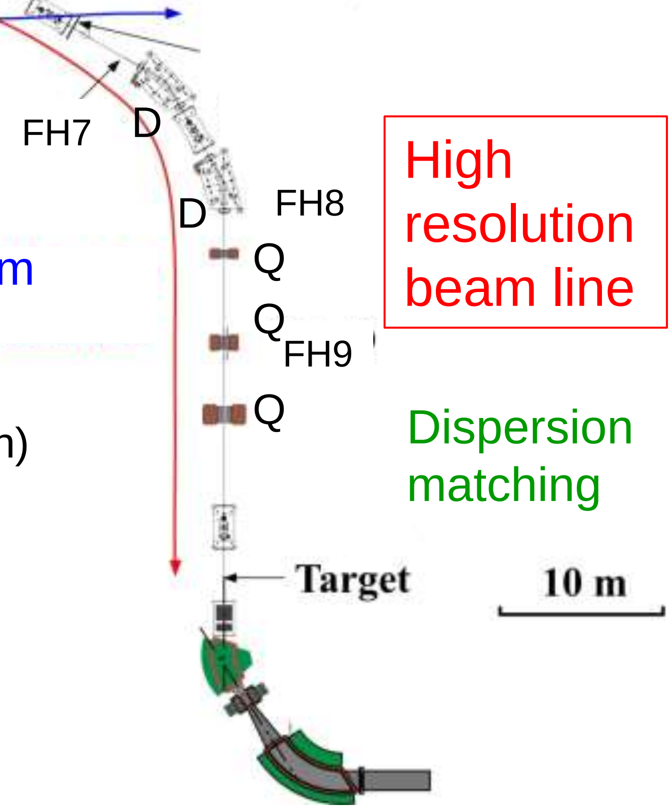
^{27}F+C → ^{26}O* → ^{24}O+2n



High-resolution spectrometer SHARAQ (since March 2009)

Uesaka et al.





High resolution beam line

Dispersion matching

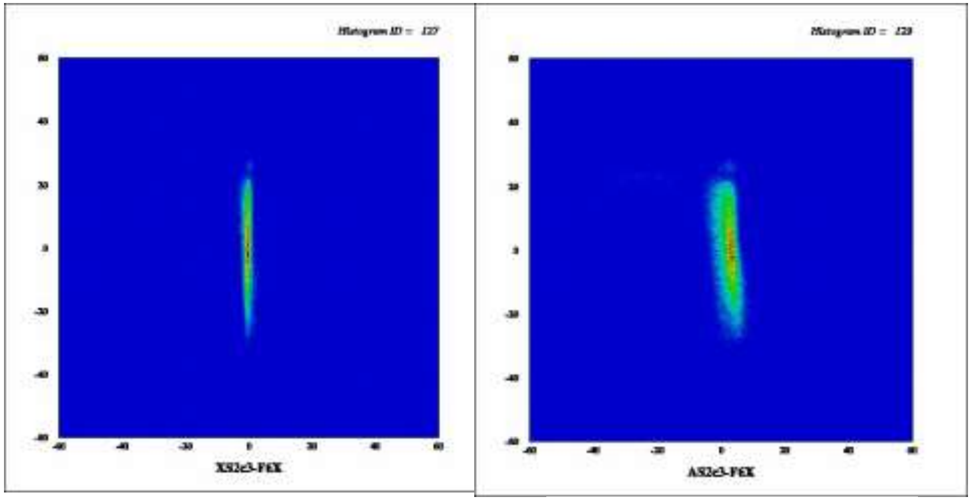
SHARAQ

- Consists of high-resolution beam line and spectrometer, and dispersion matching is used to achieve high resolution: p/Δp =14700
- Used for spectroscopy of target nuclei with RI-beam induced charge exchange reactions in normal kinematics, e.g. (t,^{3}He), (^{12}C,^{12}N), (^{10}C,^{10}B), (^{8}He,^{8}Be)
- Also for reactions in inverse kinematics, e.g.^{12}Be(p,n)

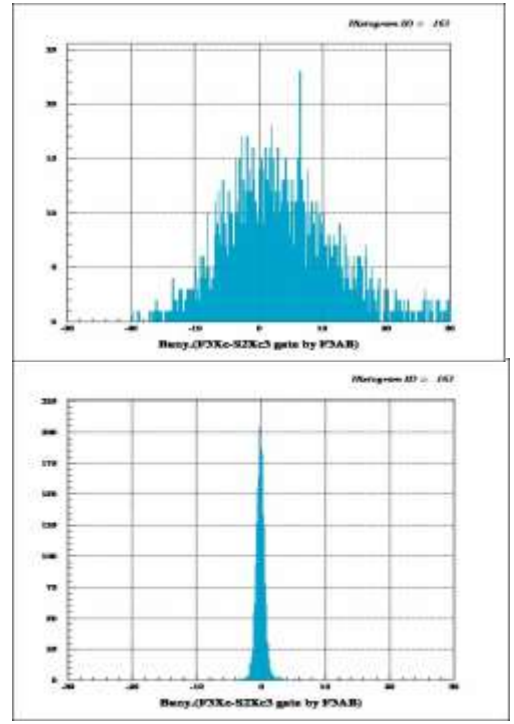
Demonstration of dispersion matching

for a secondary ^{10}C beam

Beam momentum



Position at FP [mm] Angle at FP [mm]



Position at FP [mm]

Without dispersion matching

Achromatic transport

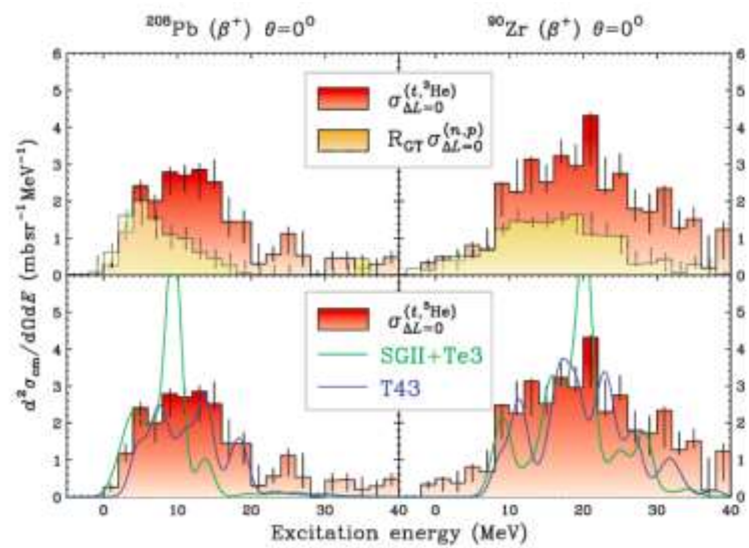
With dispersion matching

Dispersion matched!

Example of SHARAQ experiments

Observation of isovector spin monopole resonances by ^{208}Pb, ^{90}Zr (t,^{3}He) at 300 MeV/u

K. Miki et al., PRL **108**, 262503 (2012)



Multipole Decomposition Analysis to extract ΔL=0 amplitudes

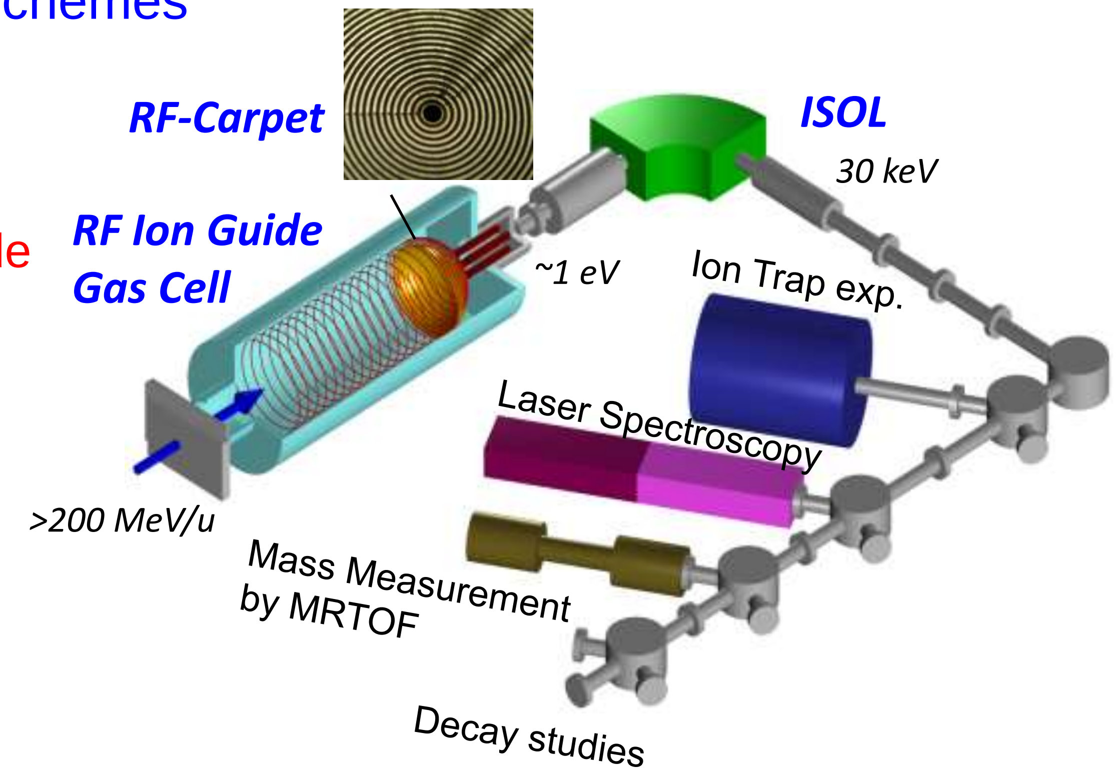
SLOWRI/PALIS (under development)

Wada et al.

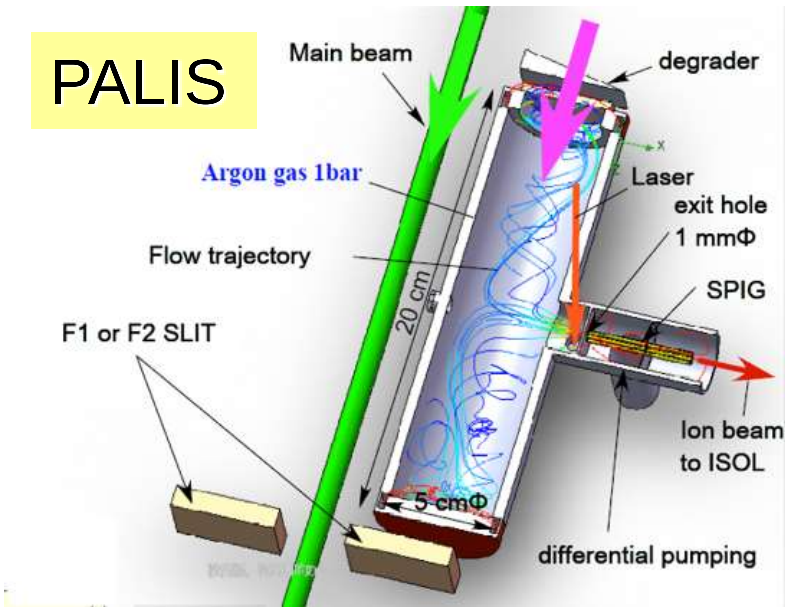
Gas catcher systems which are aimed at production of slow RI beams by combining in-flight with ISOL schemes

SLOWRI

- Uses a gas cell with RF ion guide
- Allows universal production of slow RI beams regardless of chemical properties.



PALIS



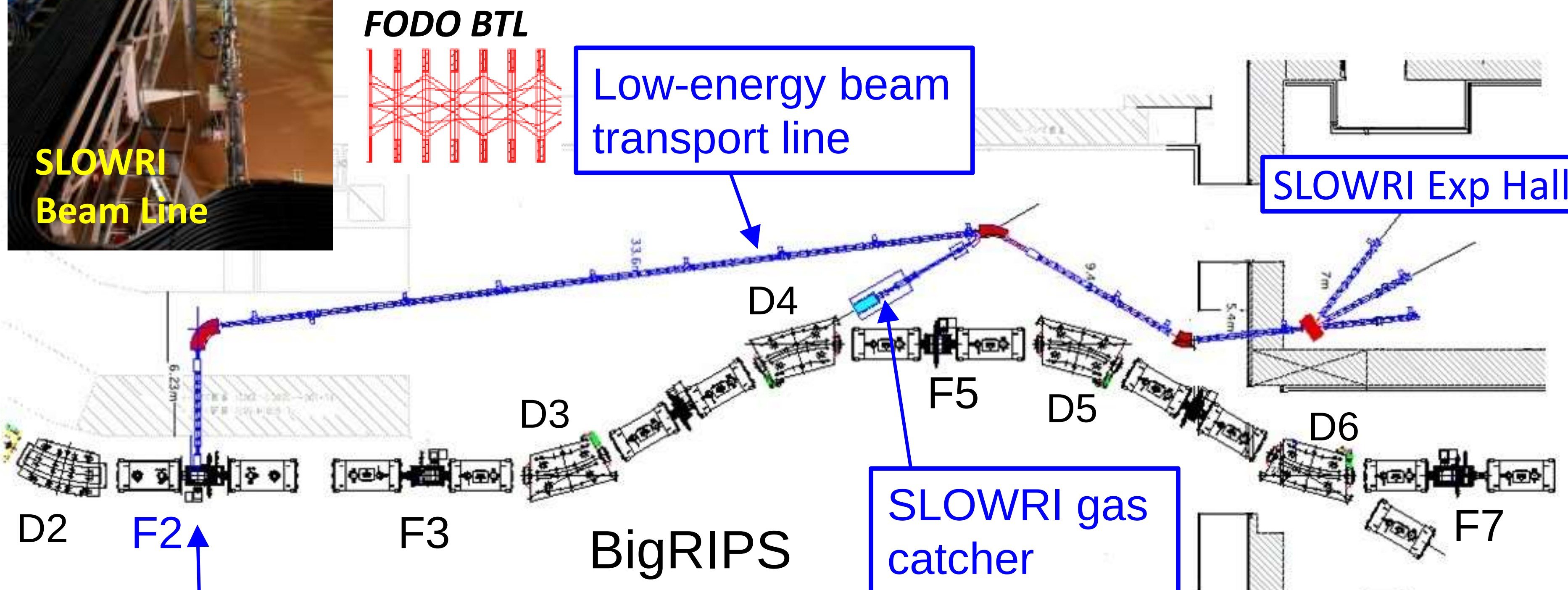
- PALIS (PArasitic slow RI-beam with gas catcher Laser Ion Source) uses a gas catcher laser ion source
- Placed at the first stage of BigRIPS separator to parasitically harvest unused RI beams

Status of SLOWRI/PALIS facility

Wada et al.

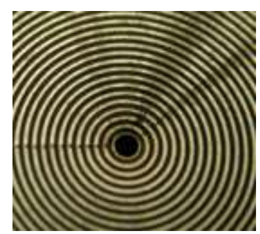
Layout and photos

Day-one experiment is planned in 2015.



PALIS gas catcher

Parasitic harvest of RI beams

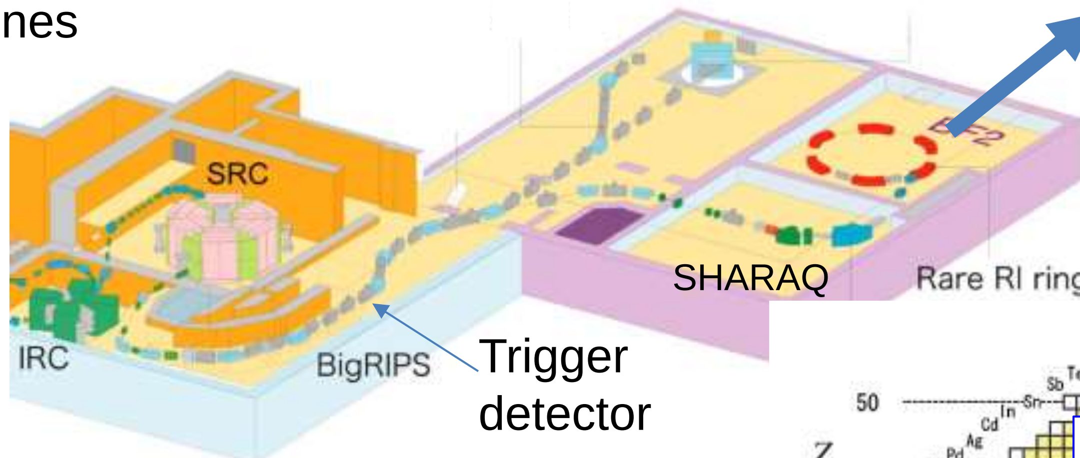


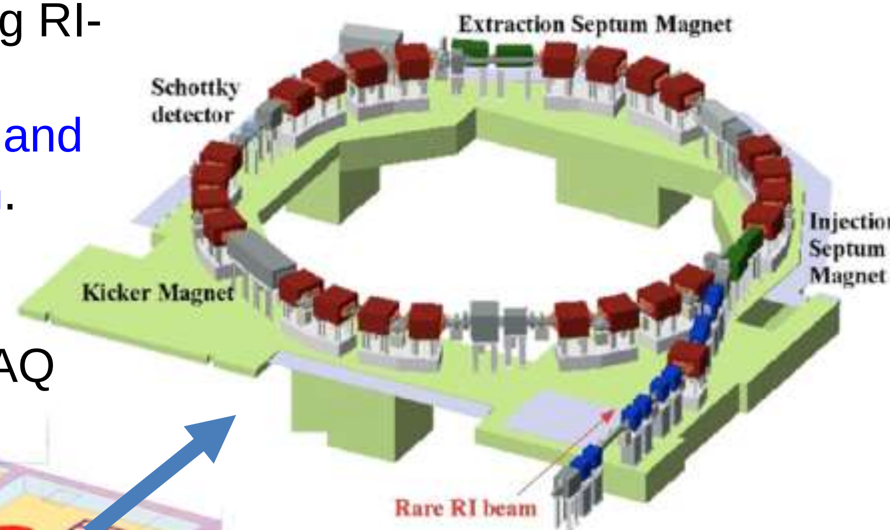
RF-Carpet Gas Cell

Rare RI Ring (R3) (under development)

Ozawa et al.

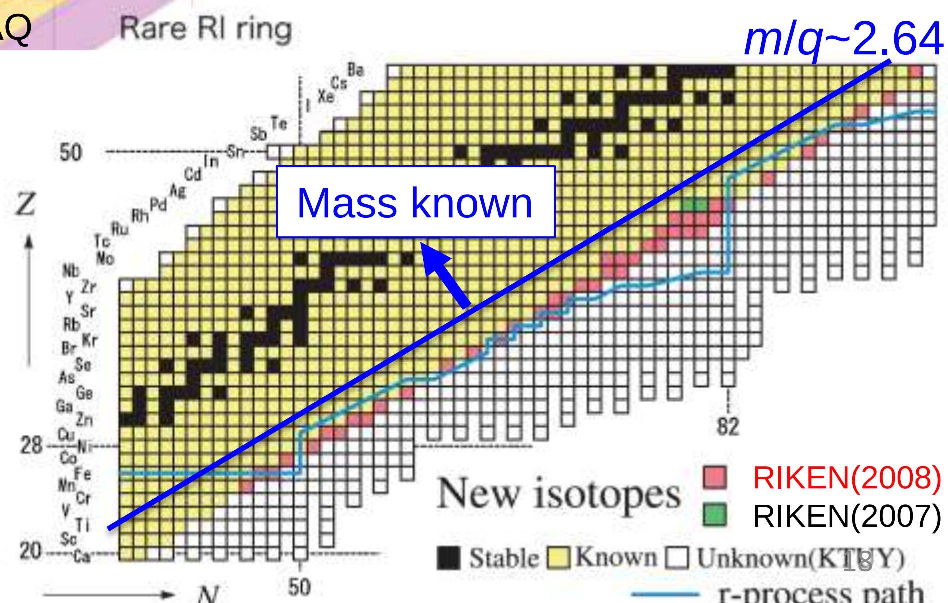
- Consists of an isochronous ring and a long RI-beam transport line, allowing TOF mass measurement with individual ion injection and velocity measurement before the injection.
- A kicker magnet is used for individual injection and extraction
- Velocity measurement: BigRIPS + SHARAQ lines





Rare RI Ring

- Mass measurement is planned for neutron-rich exotic nuclei around astrophysical r-process path.



Status of Rare RI Ring facility

Wakasugi et al.

Trim coils for isochronous tuning

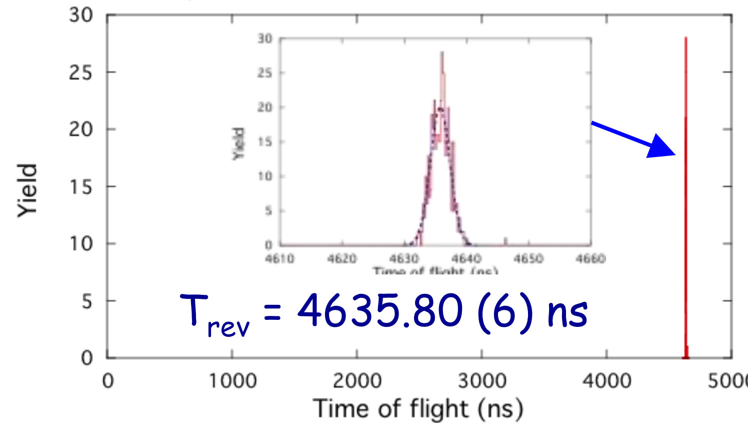
Hexagonal Symmetry
Weak-Focusing Lattice Structure

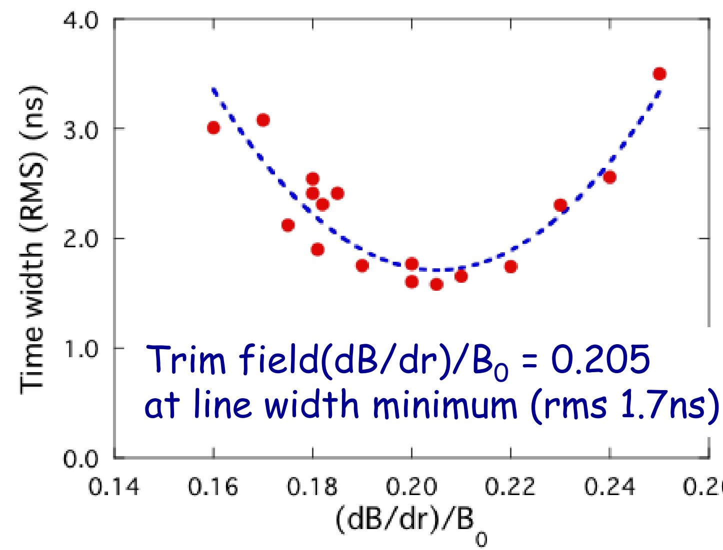
Energy	**200 MeV/u**
Circumference	**60.3 m**
Tunes	**1.21 / 0.84**
Acceptance	**$\Delta p/p \pm 0.5\%$**
Emittance	**20π / 10π mm mrad**

The first mass measurement is planned for the ^{78}Ni region (day-one experiment).

Testing of isochronous condition was made using α-particles from an α-source

TOF Spectrum for 1 revolution

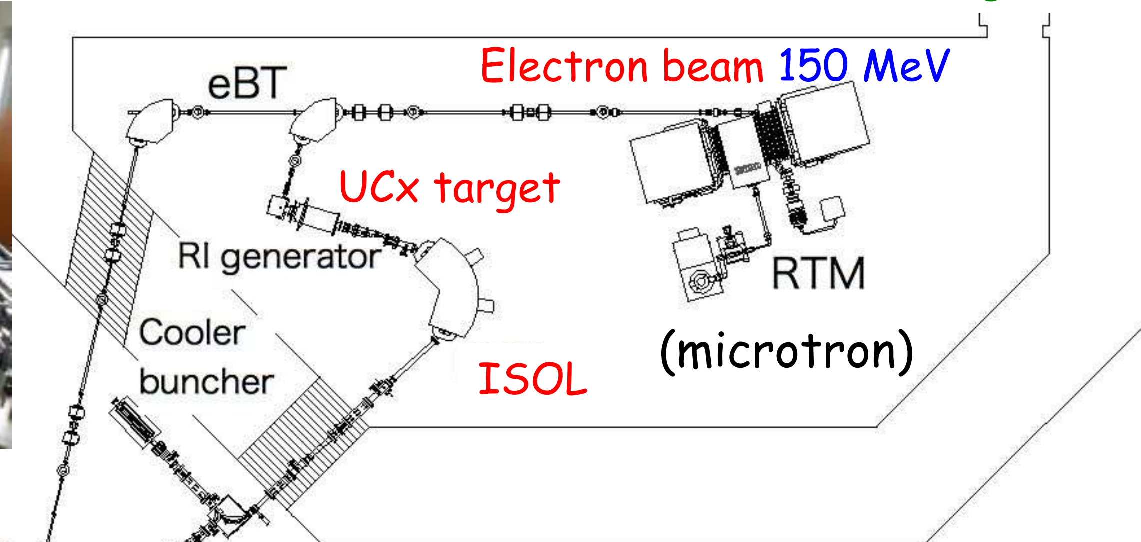


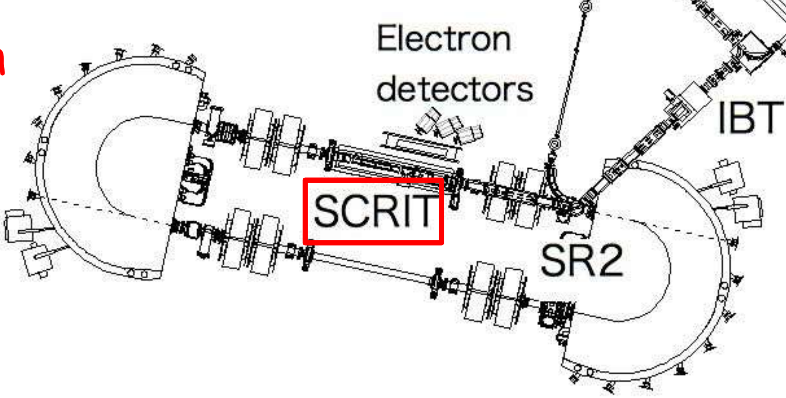


SCRIT electron scattering facility (under development)

- Consists of an electron storage ring, SCRIT (Self-Confining Rare Isotope Target) system and an ISOL RI production system using photo-fission of ^{238}U.
- Aimed at measurement of electron scattering on rare isotopes to determine charge distribution of exotic nuclei, such as ^{132}Sn.

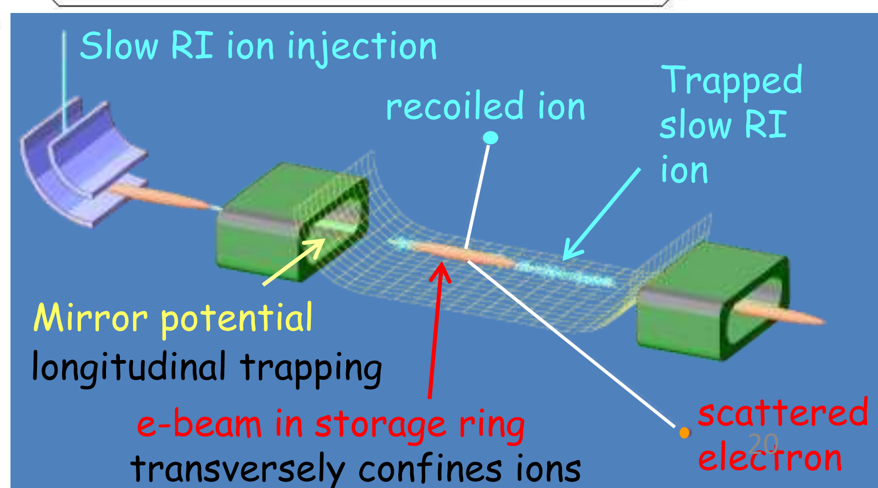
Wakasugi et al.





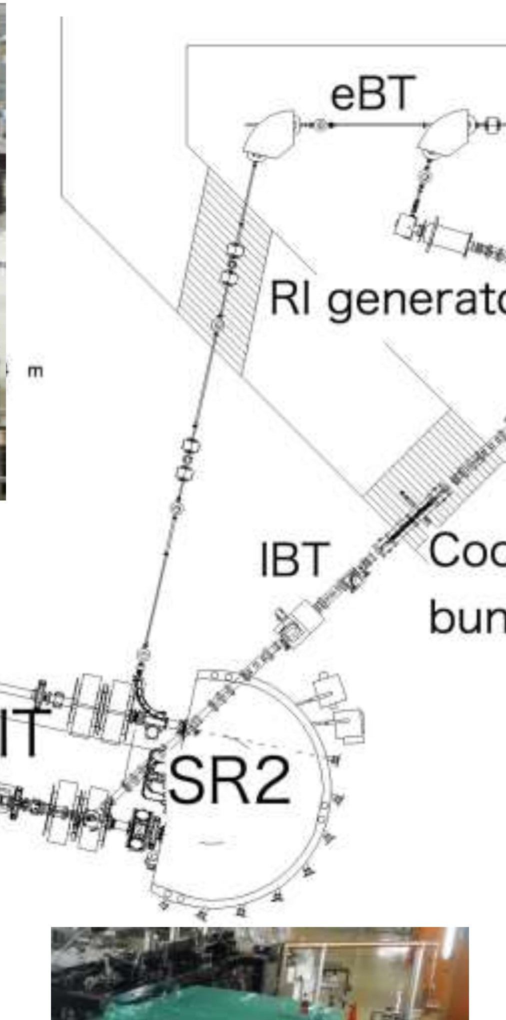
Electron storage ring 15~700 MeV

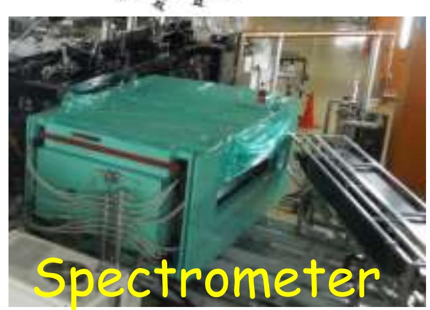
Principle of SCRIT: RI ions are trapped on electron beam orbit in electron storage ring and electron scattering is measured.



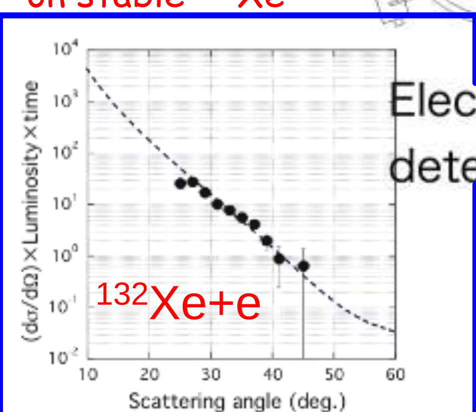
Status of SCRIT facility

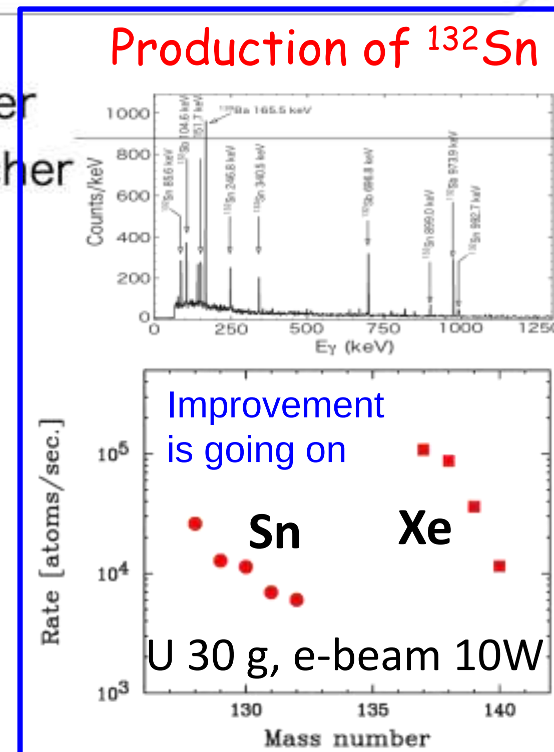
Wakasugi et al.





Elastic scattering on stable ^{132}Xe

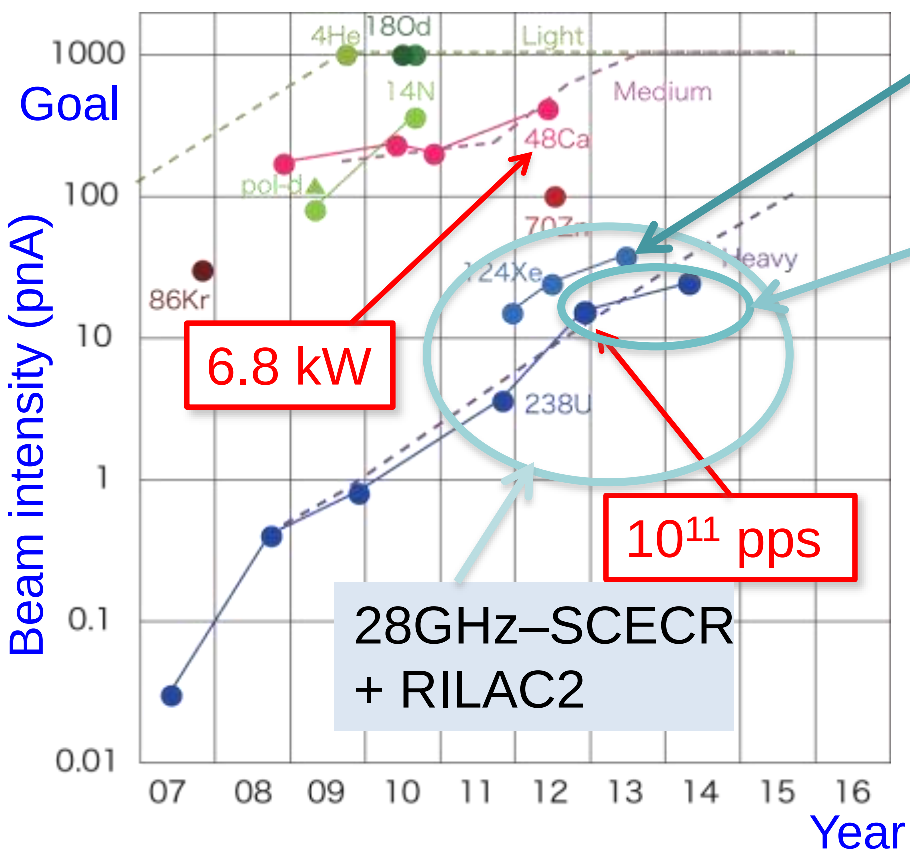




Status of RIBF accelerators and upgrade plan

Status of primary beams and planned schedule of intensity upgrade

From O. Kamigaito



Present beam list (RIBF website)

	E/A(MeV)	Beam current (pnA) Maximum record	Expected ¶	Injector
d	250	1000	200	AVF
d(pol.)	250	120	30	AVF
^{4}He	320	1000	1000	AVF
^{14}N	250	400	400	RILAC
^{18}O	345	1000	500	RILAC
^{48}Ca	345	415	150	RILAC
^{70}Zn	345	123	100	RILAC
^{76}Ge	345	not tested	N/A	RILAC
^{78}Kr	345	under development	50	RILAC
^{86}Kr	345	30	50	RILAC
^{136}Xe	345	not tested	20	RILAC2
^{124}Xe	345	38	20	RILAC2
^{238}U	345	25	15	RILAC2

¶ Some intensities are limited by shielding requirements

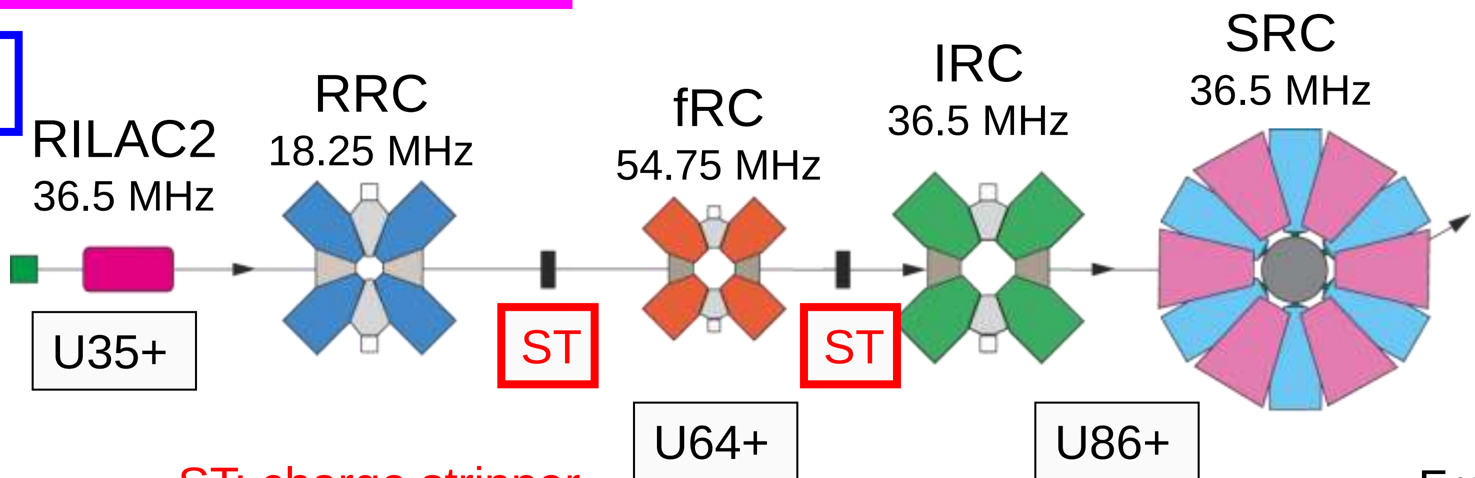
Accelerator upgrades made so far:

- Construction of 28GHz SC-ECR and new injector RILAC2
- Development of gas charge strippers
- Upgrade of fRC max. Brho value

RIBF upgrade program

To further increase the beam intensity

Present

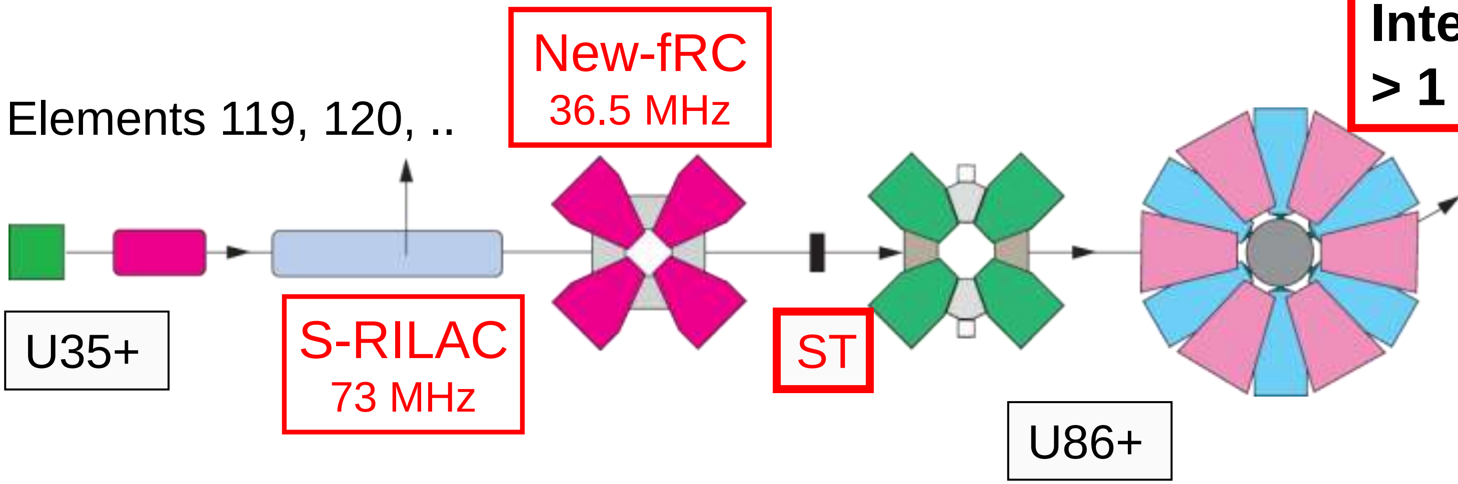


ST: charge stripper

From O. Kamigaito

Upgrade plan

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

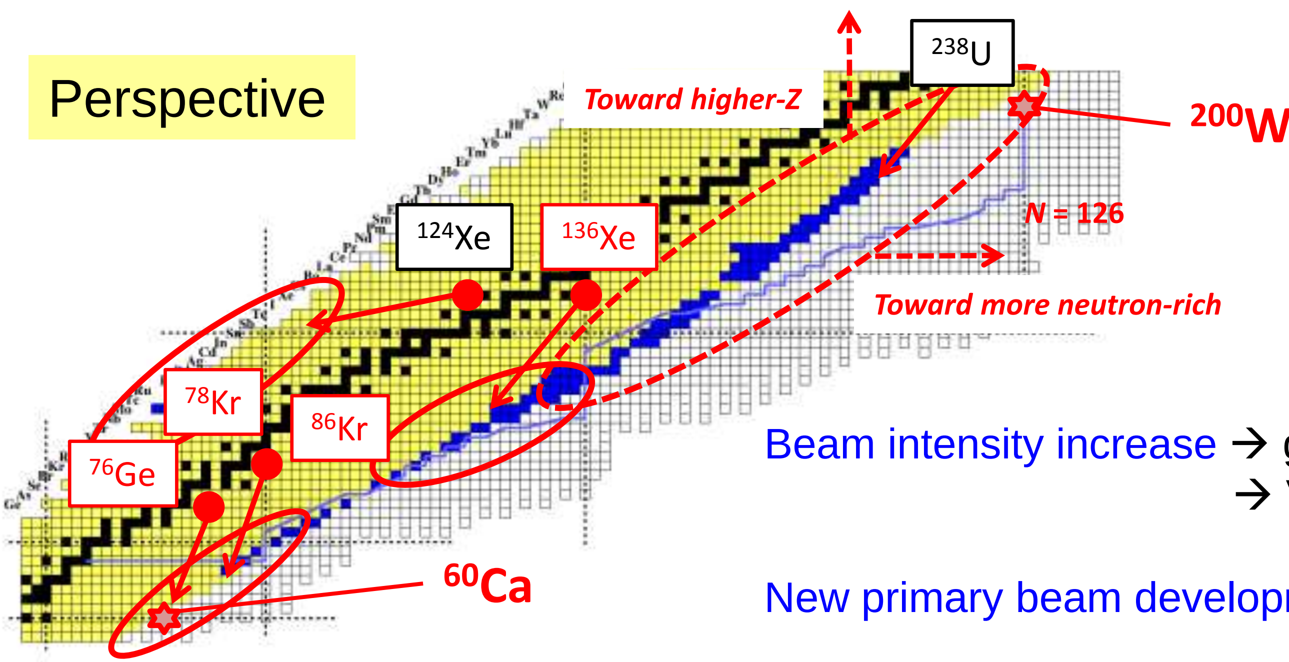


Intensity > 1 pμA

Summary and perspective

- Overview and status of major experimental facilities at RIKEN RIBF have been presented: BigRIPS, ZeroDegree, SAMURAI, SHARAQ, SLOWI/PALIS, Rare RI Ring, SCRIT and so on.
- The region of accessible rare isotopes is expanding with upgraded features at RIBF, which is a next-generation in-flight RI beam facility.
- A large variety of experiments using the major experimental facilities at RIBF have been/being carried out for a wide range of rare isotopes, significantly promoting studies on exotic nuclei far from stability.

Perspective



Beam intensity increase → go further from stability
→ Various types of experiments
(Decay → Reaction)

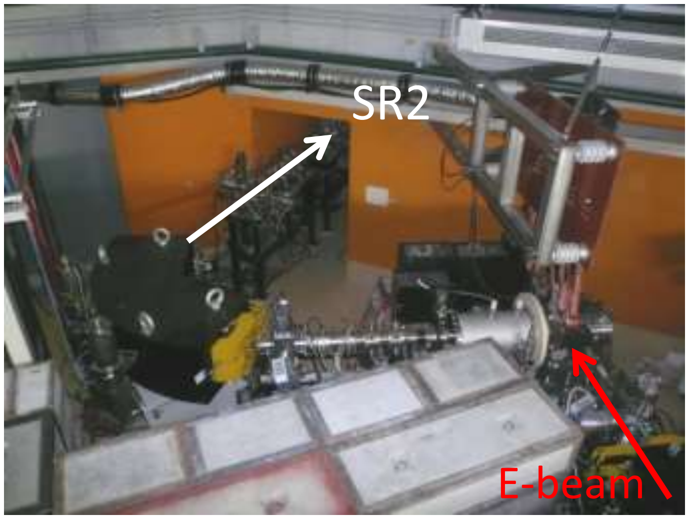
New primary beam development → Variety of RI beams

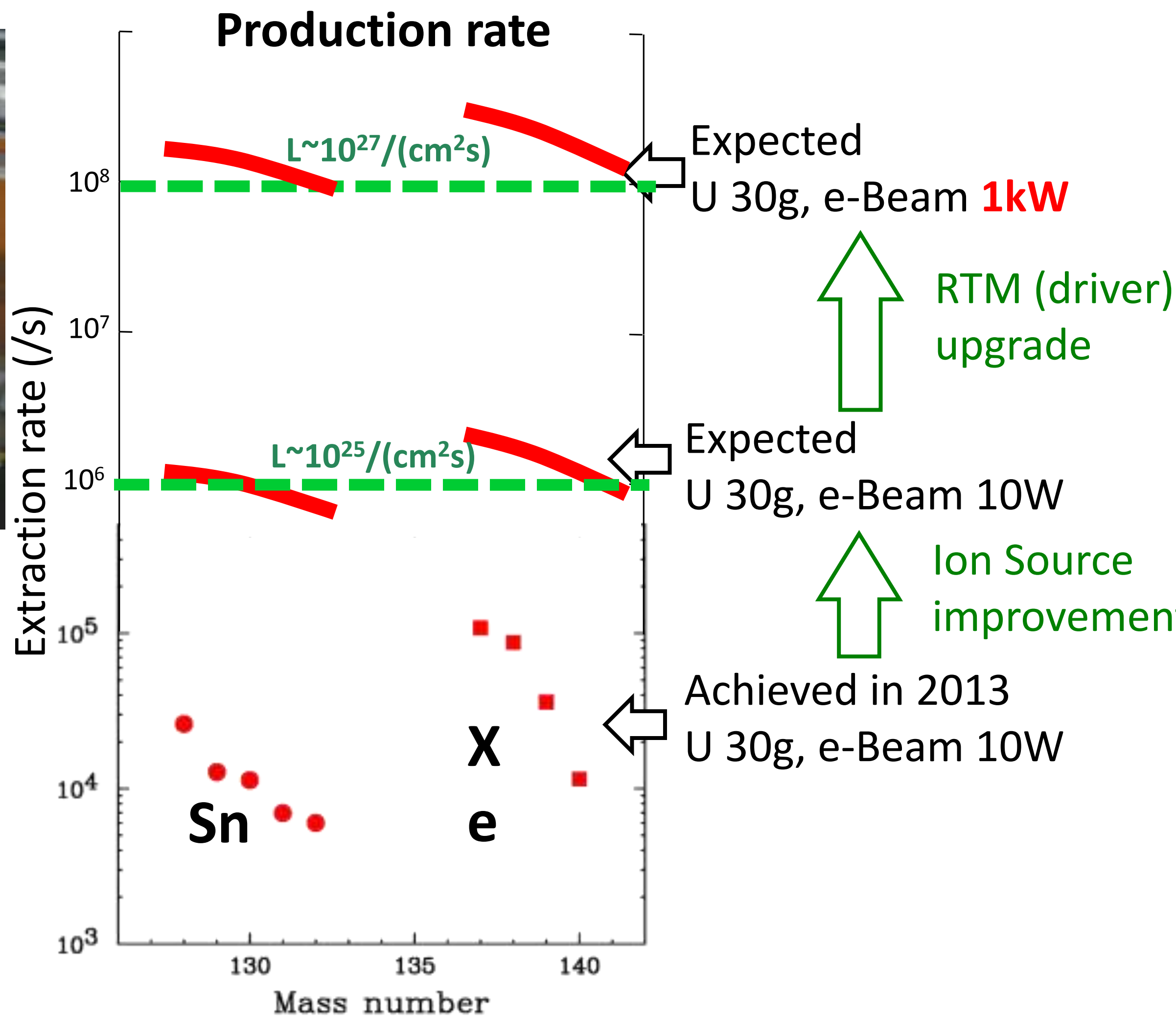
Thank you for your attention.

Backup slides

ISOL (ERIS) Construction in the SCRIT Facility

^{238}U photo-fission driven by 150-MeV e-Beam from RTM





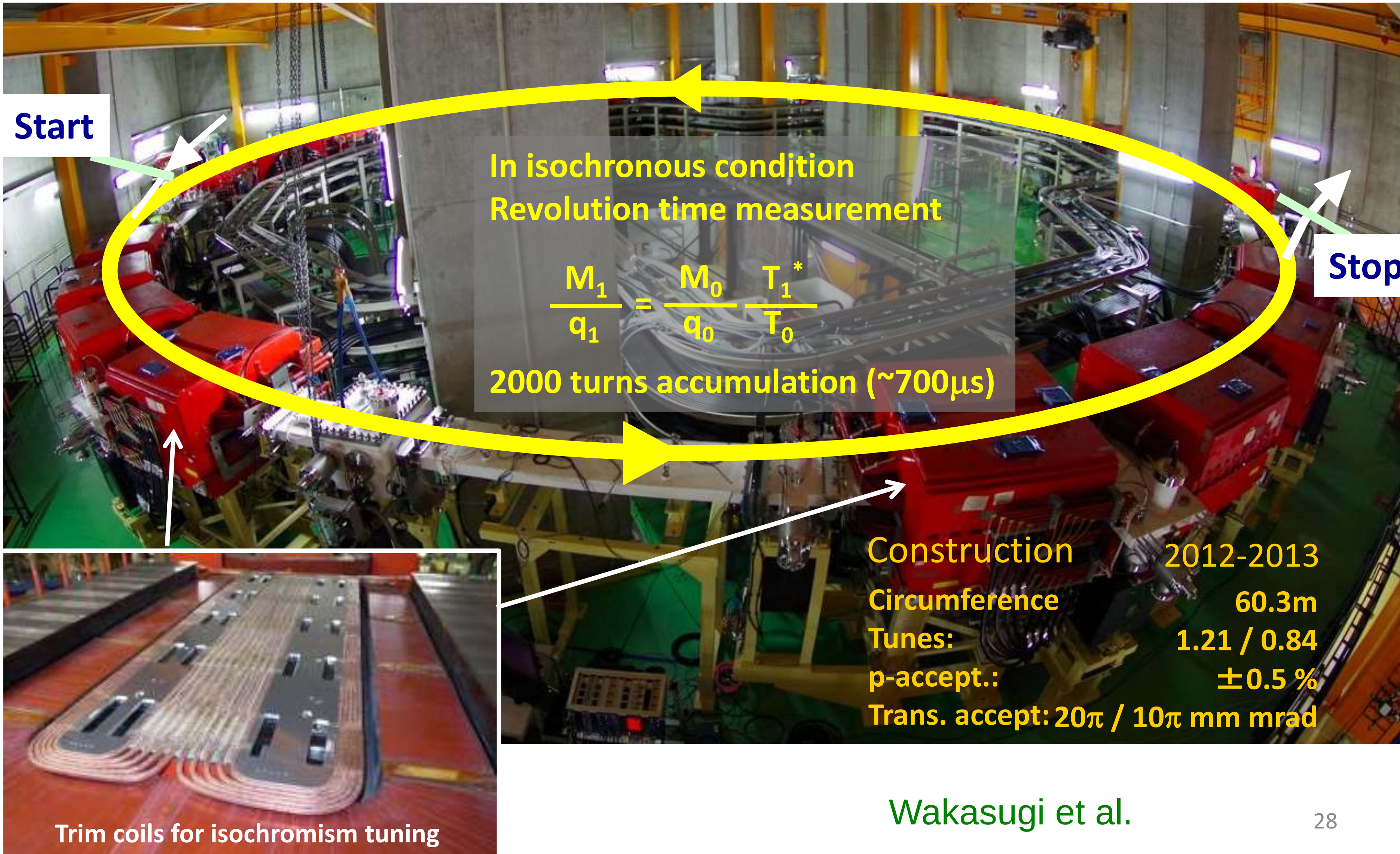
2011-2012 Construction
2012 ERIS commissioning
2013 RI production start

Wakasugi et al.

Rare RI Ring Construction and Operation

Isochronous Storage Ring

Precision (~ppm) mass measurement for isotopes around r-process pass

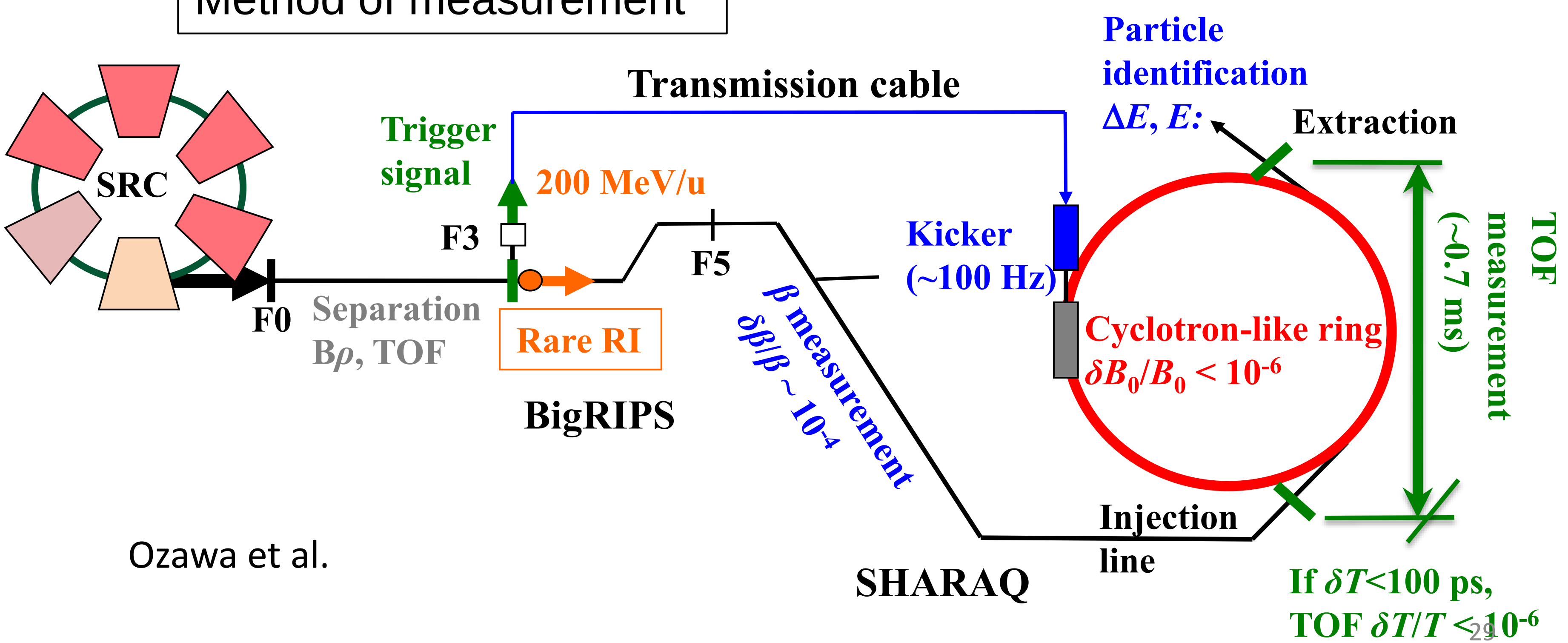


Wakasugi et al.

Features & method of TOF mass measurement at Rare-RI Ring

- Individual injection by a kicker: storage of one single particle
- Isochronous mass spectrometry with short measurement time (< 1 ms)
- Velocity measurement (β) before injection to improve accuracy
- Highly isochronous field by cyclotron-like storage ring: goal of mass-resolution 10^{-6}

Method of measurement



Ozawa et al.

Principle of measurement

Ozawa et al.

Isochronous optics $T_0 = 2\pi \frac{m_0}{q} \frac{1}{B} \gamma_0 = 2\pi \frac{m_0}{q} \frac{1}{B_0}$

- TOF depends only on m/q.
- But the isochronous conditions are no longer fulfilled for other m/q such as $m_1/q = m_0/q + \Delta(m_0/q)$
- m_1/q can be expressed as

$$\frac{m_1}{q} = \left(\frac{m_0}{q}\right)\frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \left(\frac{m_0}{q}\right)\frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-\left(\frac{T_1}{T_0}\beta_1\right)^2}}$$

- Measurement of β_1 before the injection allows more accurate mass determination.

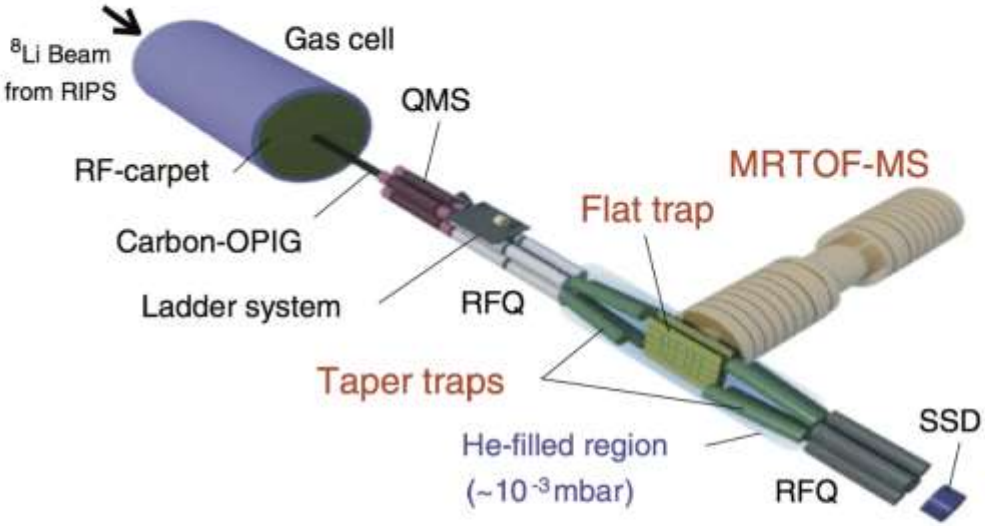
$\longrightarrow$ Measurement of β (or $B\rho$) is indispensable

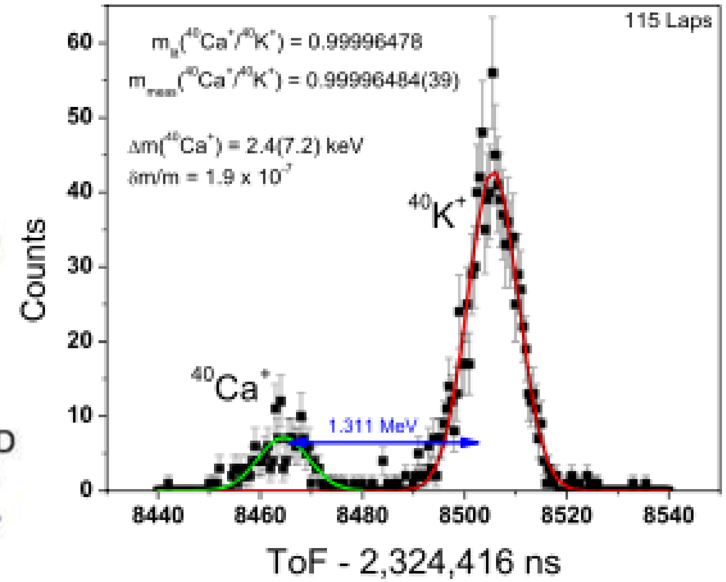
$\delta\beta/\beta \sim 10^{-4} \longrightarrow \delta(m_1/q)/(m_1/q) \sim 10^{-5}$ for 10% m/q difference

Experiments prepared at SLOWRI Facility

Wada et al.

Precision Mass Measurement by MRTOF





Charge and Magnetization Radii from Atomic Transition Measurement