Overview of the RI Beam Facility (RIBF)

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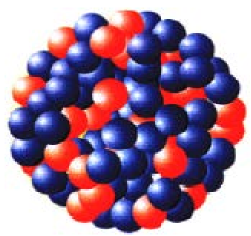
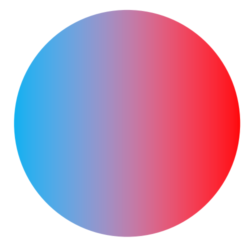
CNS Summer School 2019 (CNSSS19)

August 21 - 27, 2019 Nishina Hall, Riken, Wako

Nucleus: many body system composed of protons and neutrons

- Many-body quantum-system with spontaneous order and self organization
  - Shell structure without inner core
- Two aspects: microscopic and macroscopic
- Superposition of single state nucleon ←→ bulk matter





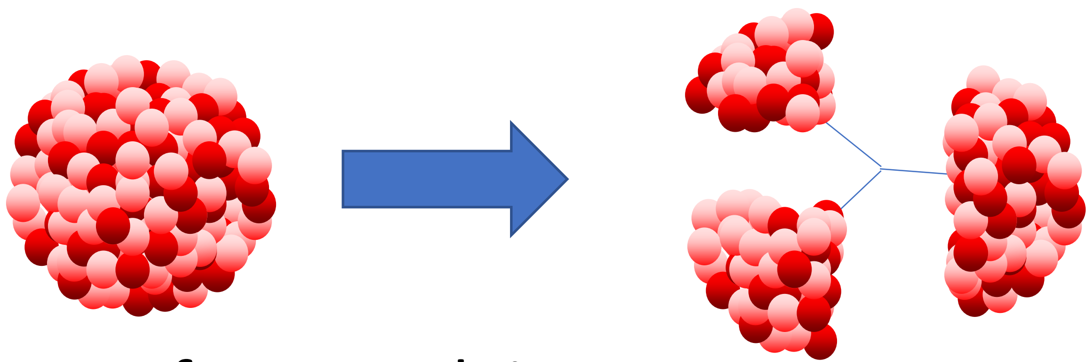
- ~1990 study with stable (N~Z) nuclei
- 1990~ study with unstable (N≠Z) nuclei
  - Now we can control one of the quantum number in laboratory.

RI=Radioactive Isotope B=Beam F=Factory

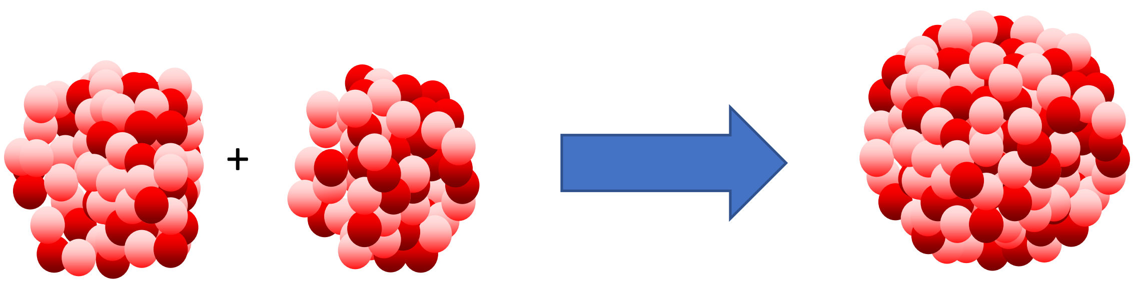
Mass production of radioactive isotopes as secondary beams

How to produce new nucleus

- Breaking large nucleus



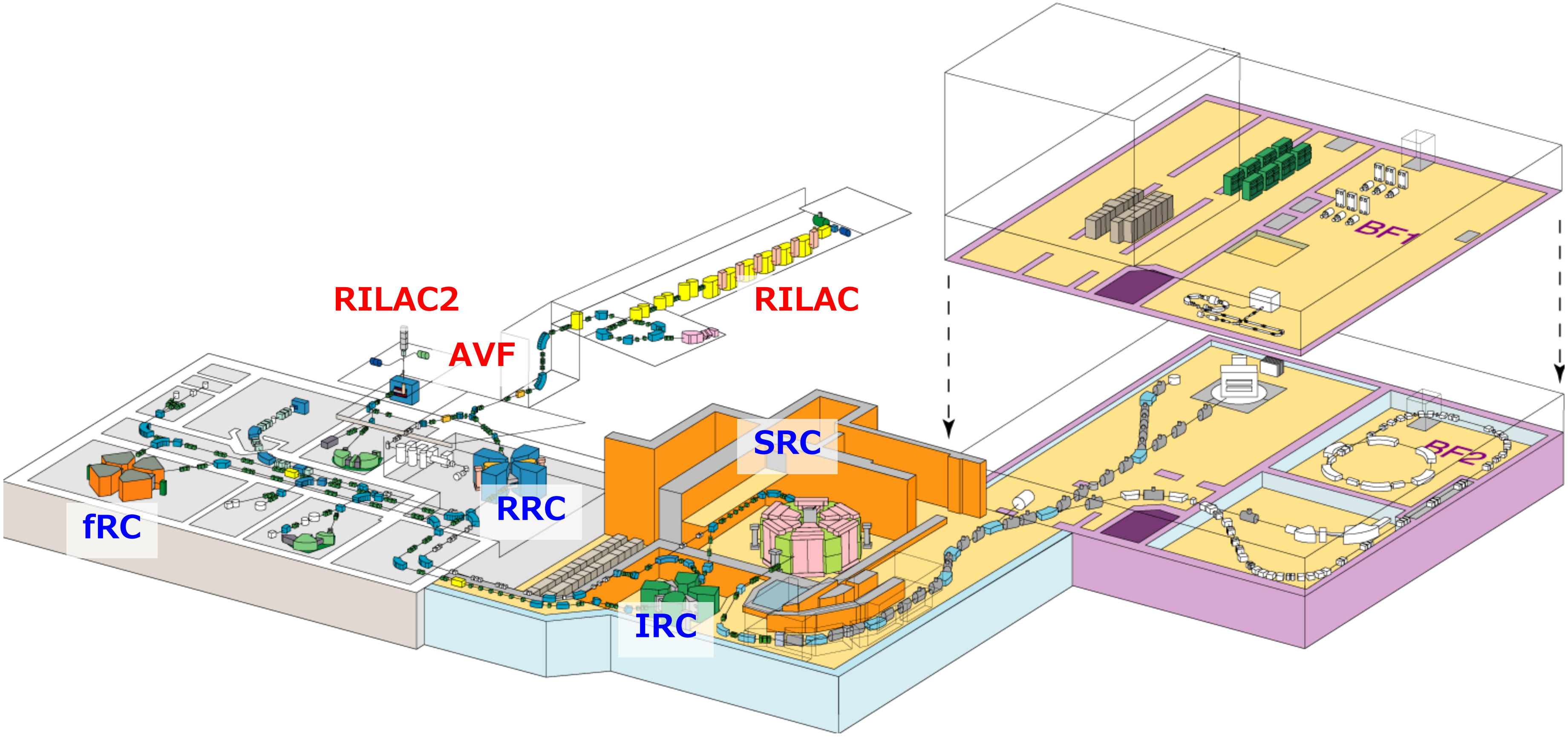
- Coalescence of two nuclei



Do you think which way is easier??

RIBF (Radioactive Isotope Beam Factory)

- Both way to produce new nucleus is possible
- 3 injectors + 4 cyclotrons
- A variety of primary beam up to U
- Energy up to 345 MeV/nucleon



How to accelerate?
RILAC (RIKEN heavy Ion LINAC)

- Total Accel. Voltage: 16MV
- Total length: 40m

- Accelerator used for 113 search.
- 1st accelerator drive nuclei to following accelerators.

How to accelerate?
SRC (Superconducting Ring Cyclotron)

Diameter : 18.4m
Weight : 8,300 tons

- K2500MeV
  - 345 MeV/nucleon for U beam
  - 400 MeV/nucleon for Light-ion beam
- Self magnetic shield
  - Up to 8 Tm

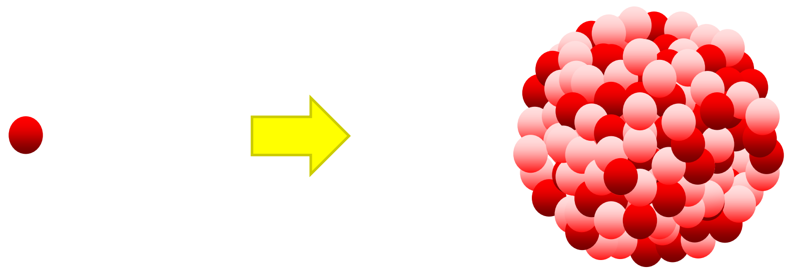
Which accelerator do you like?

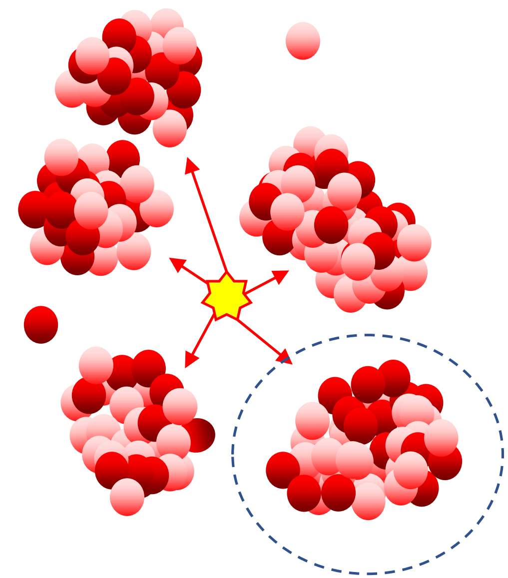
Two ways of RI beam production by breaking large nucleus

Hit small particle against large target

light beam
(e.g., proton)

heavy target
(e.g., Uranium)

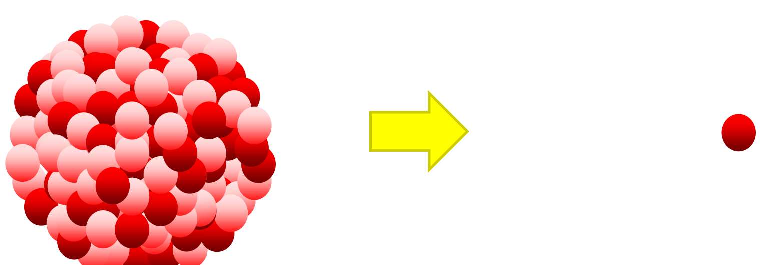




Hit large particle against small target

heavy beam
(e.g., Uranium)

thin target
(e.g., proton)

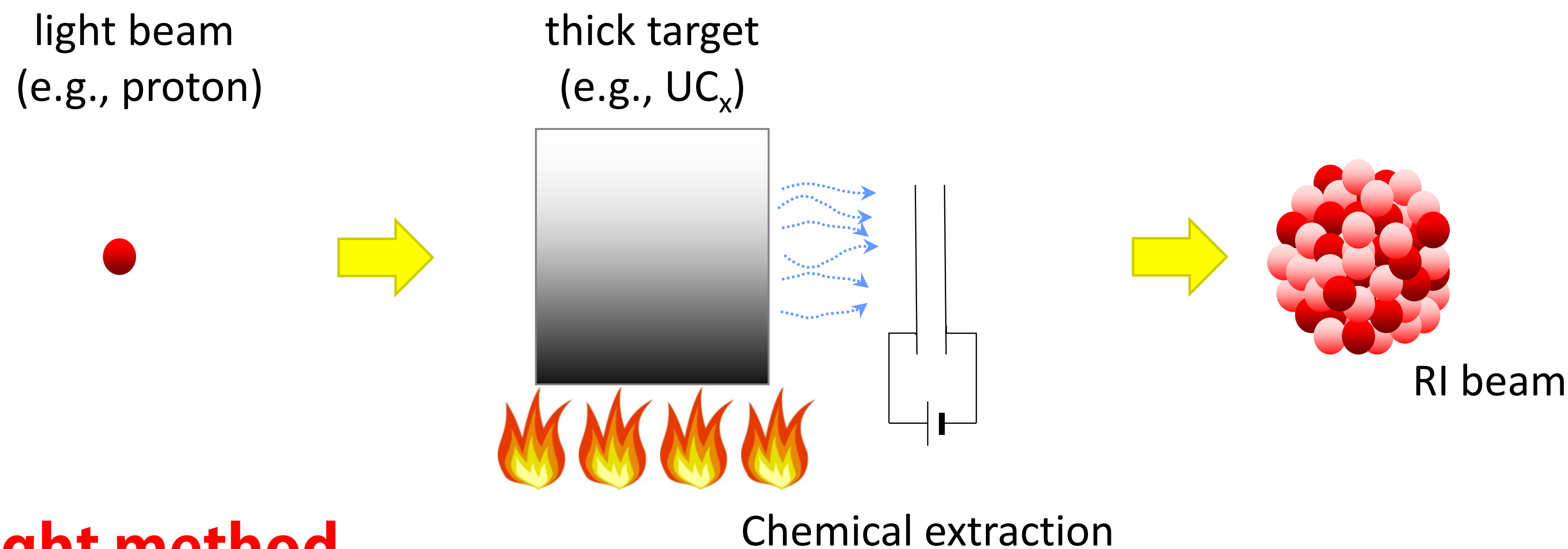


Pick up nucleus you want

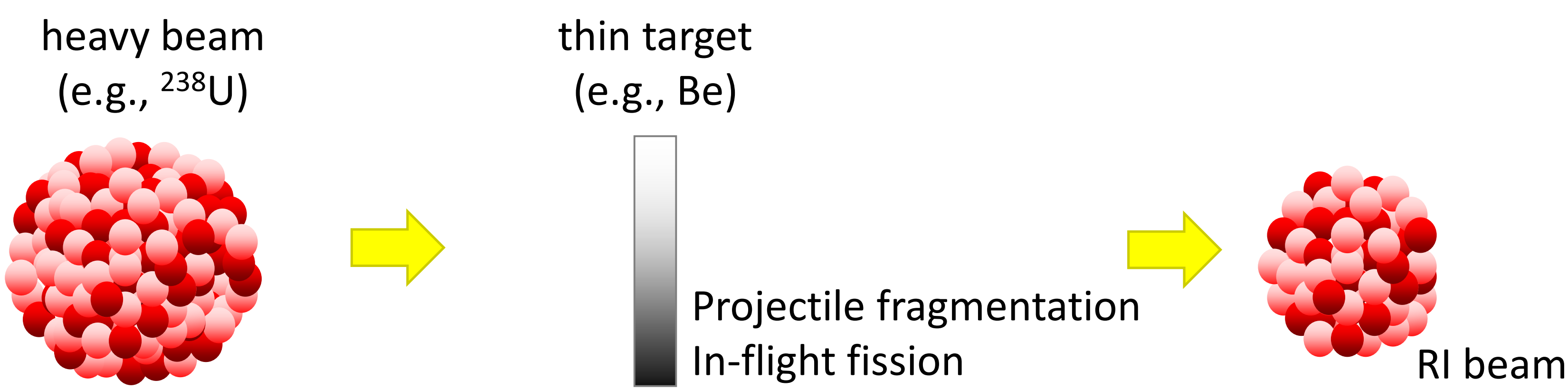
Do you think which way is easier??

Two ways of RI beam production

ISOL method (Isotope Separation On-Line)



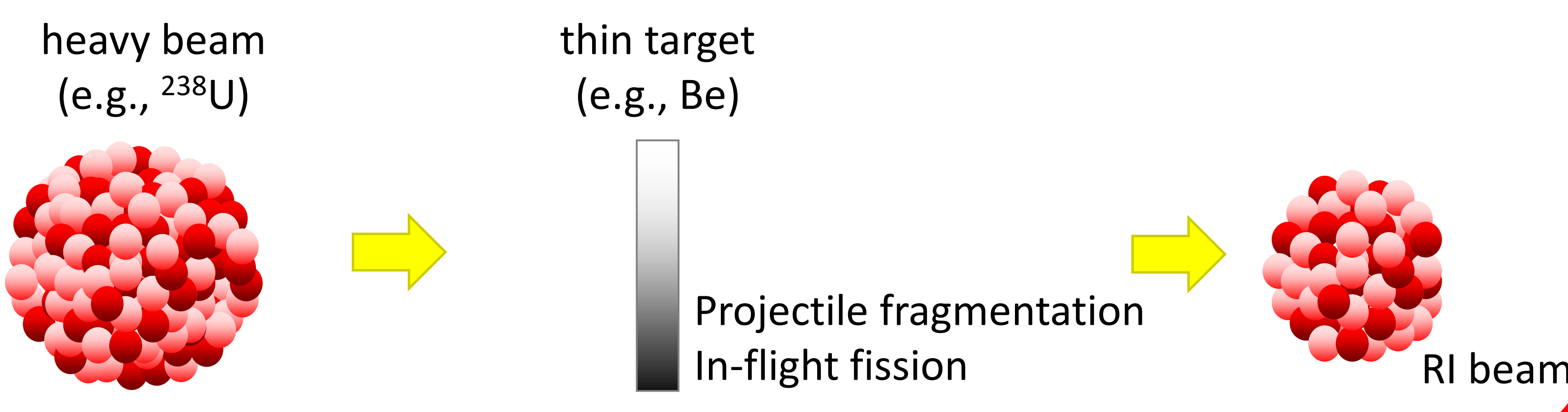
In-flight method



Two ways of RI beam production

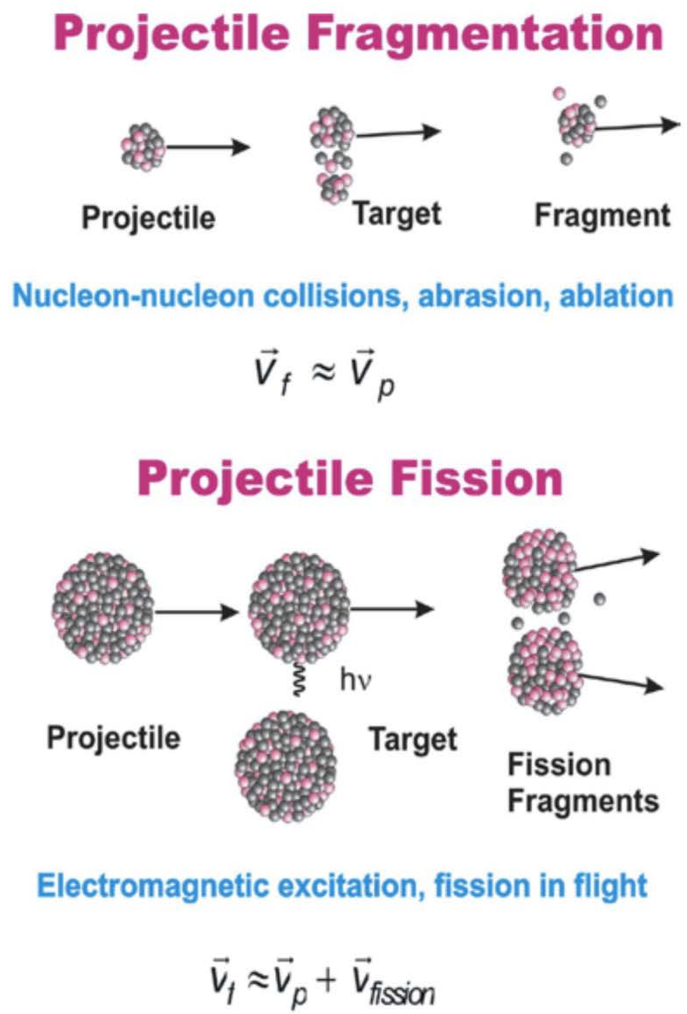
Method employed at RIBF

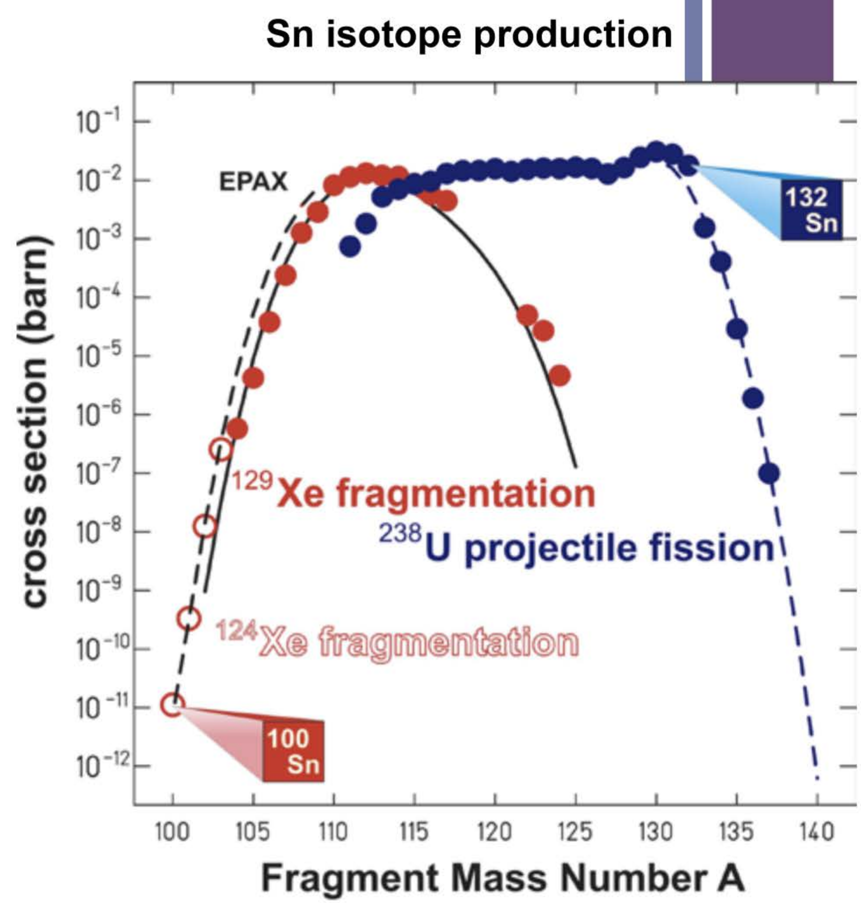
In-flight method



Two types of physics processes for projectile fragmentation

Production of exotic nuclei at relativistic energies

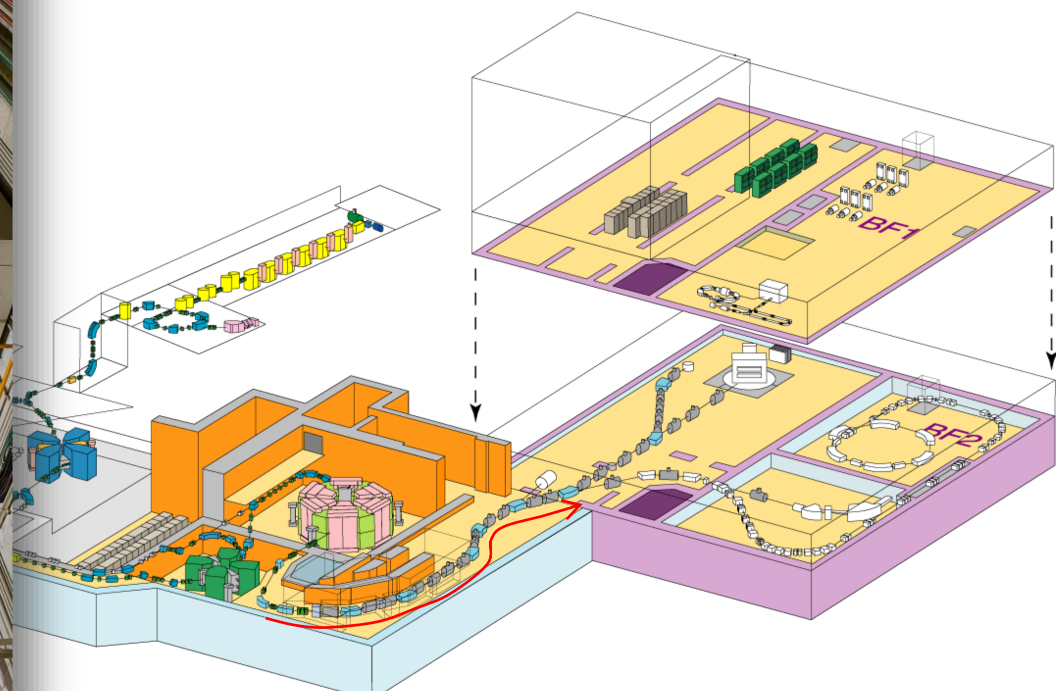




K.Sümmerer

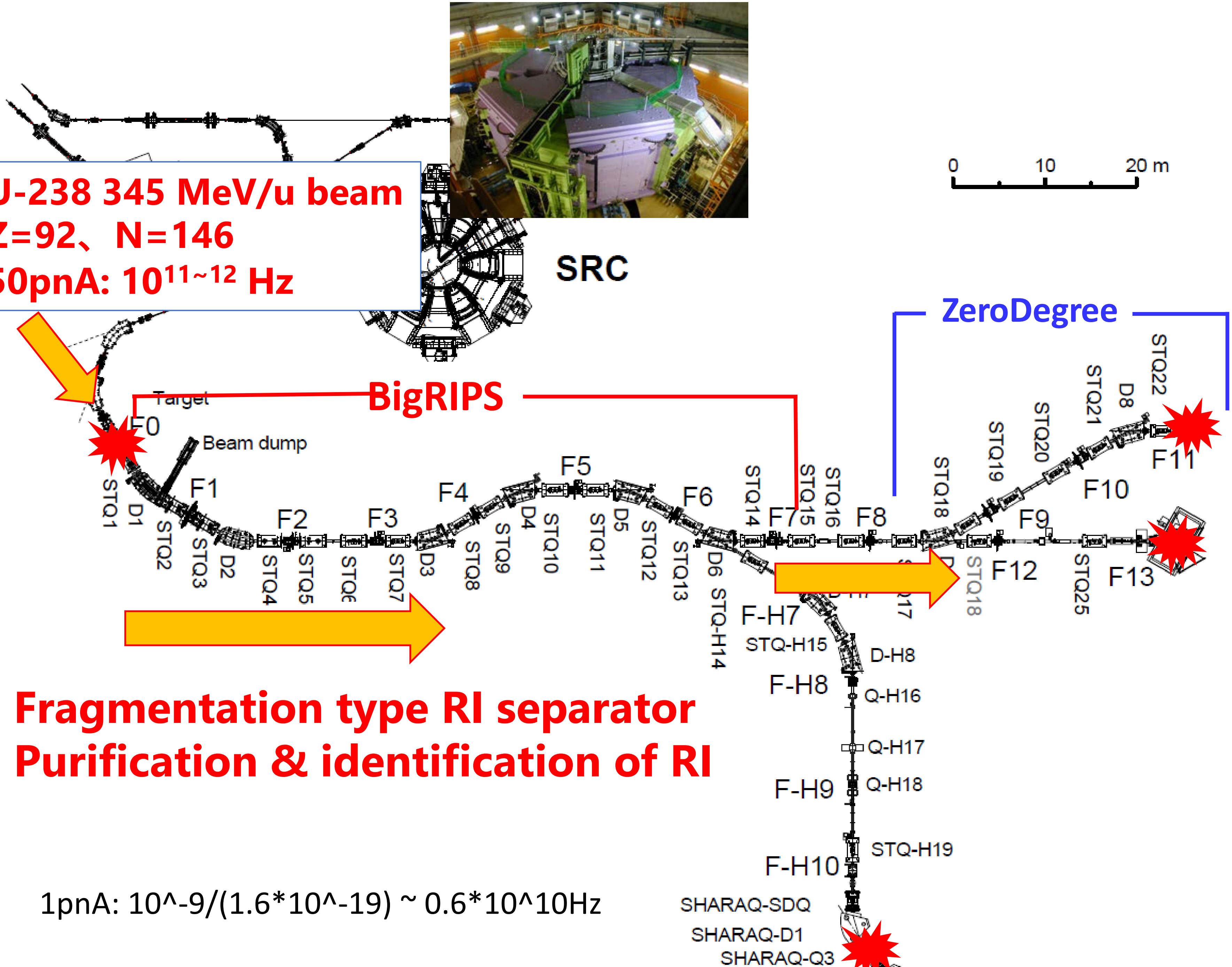
BigRIPS: Spectrometer to choose RI you want

- In-flight separator
- Largest acceptance up to 9 Tm



BigRips: T. Kubo, Nucl. Instr. Meth. B 204, 97 ('03)

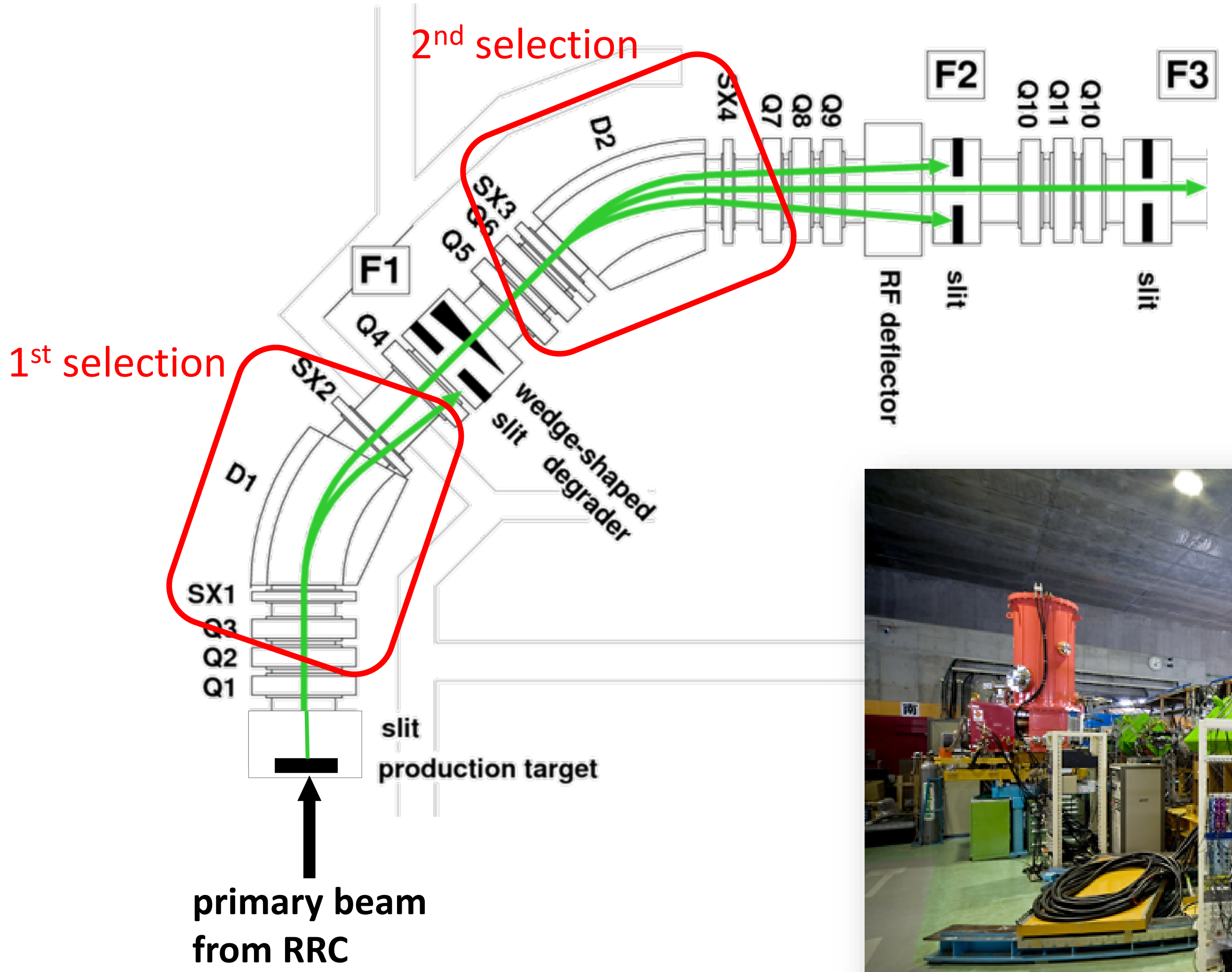
U-238 345 MeV/u beam
Z=92、N=146
50pnA: $10^{11\sim12}$ Hz



Fragmentation type RI separator
Purification & identification of RI

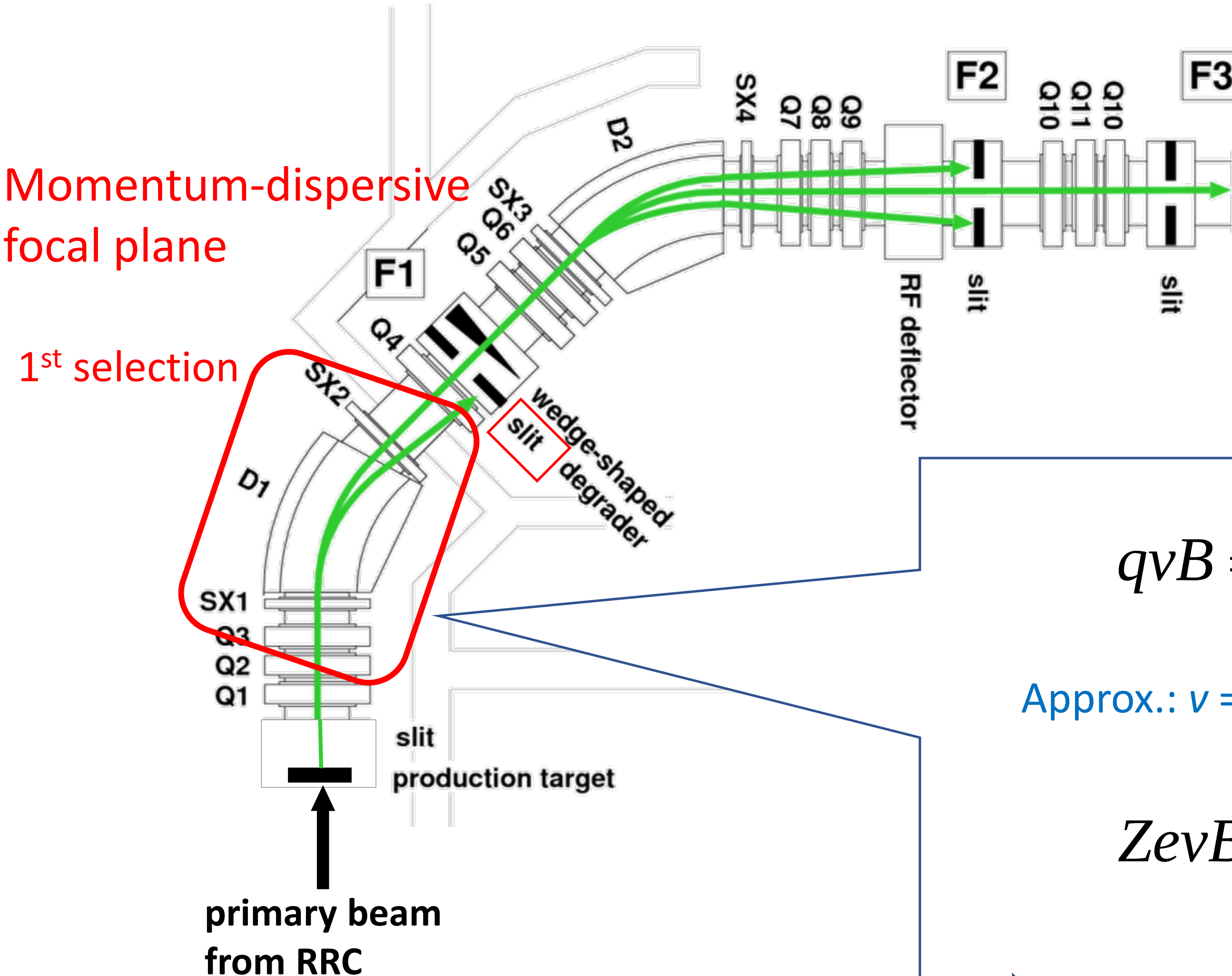
1pnA: 10^-9/(1.6*10^-19) ~ 0.6*10^10Hz

RIPS: precursor of BigRIPS



RIPS: T. Kubo *et al.*, Nucl. Instr. Meth. B 70, 309 ('92)

1^{st} stage selection



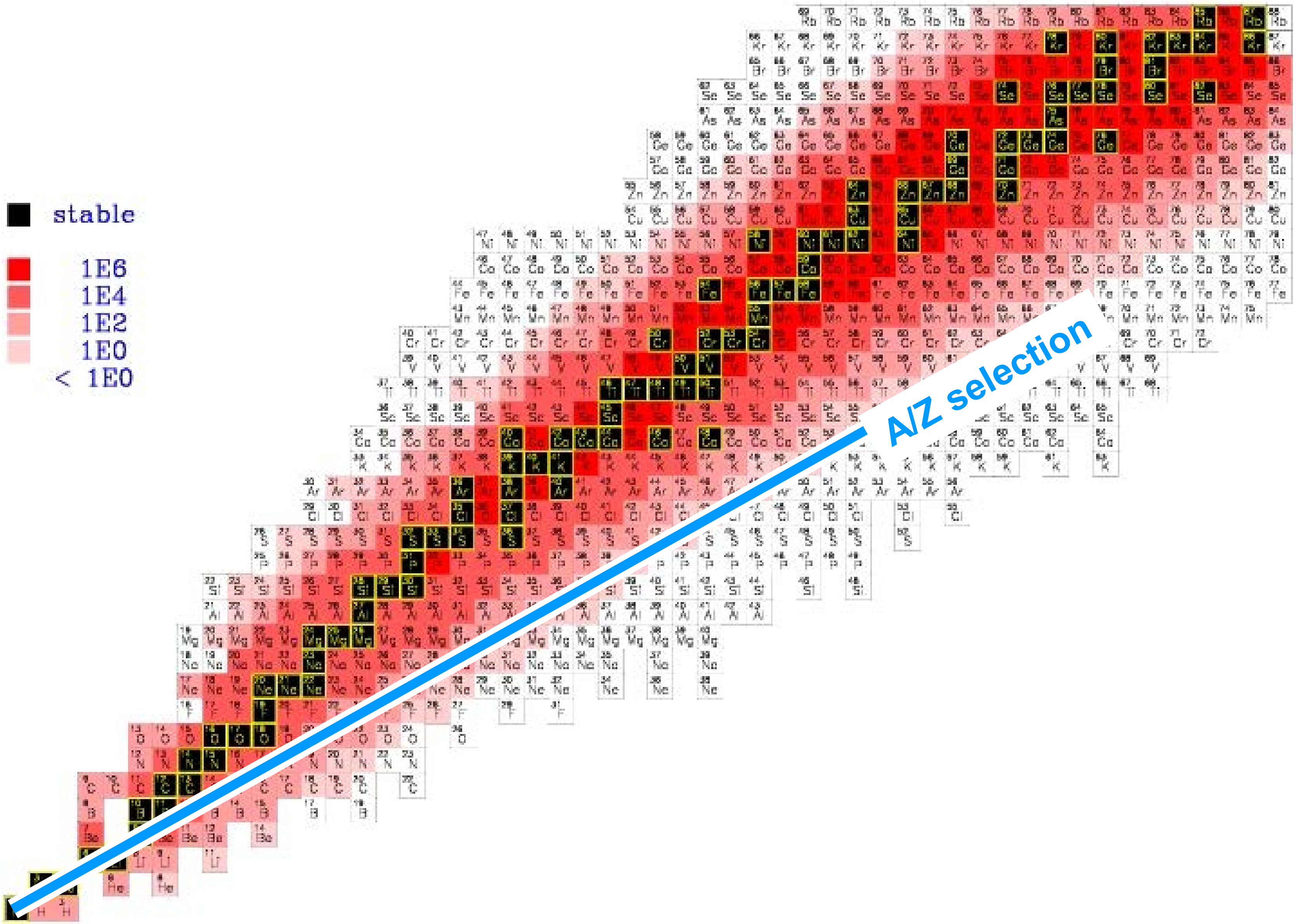
$$qvB = m\frac{v^2}{\rho}$$

Approx.: $v = v_{beam}$ for all fragments

$$ZevB = Am_{nucl}\frac{v^2}{\rho}$$

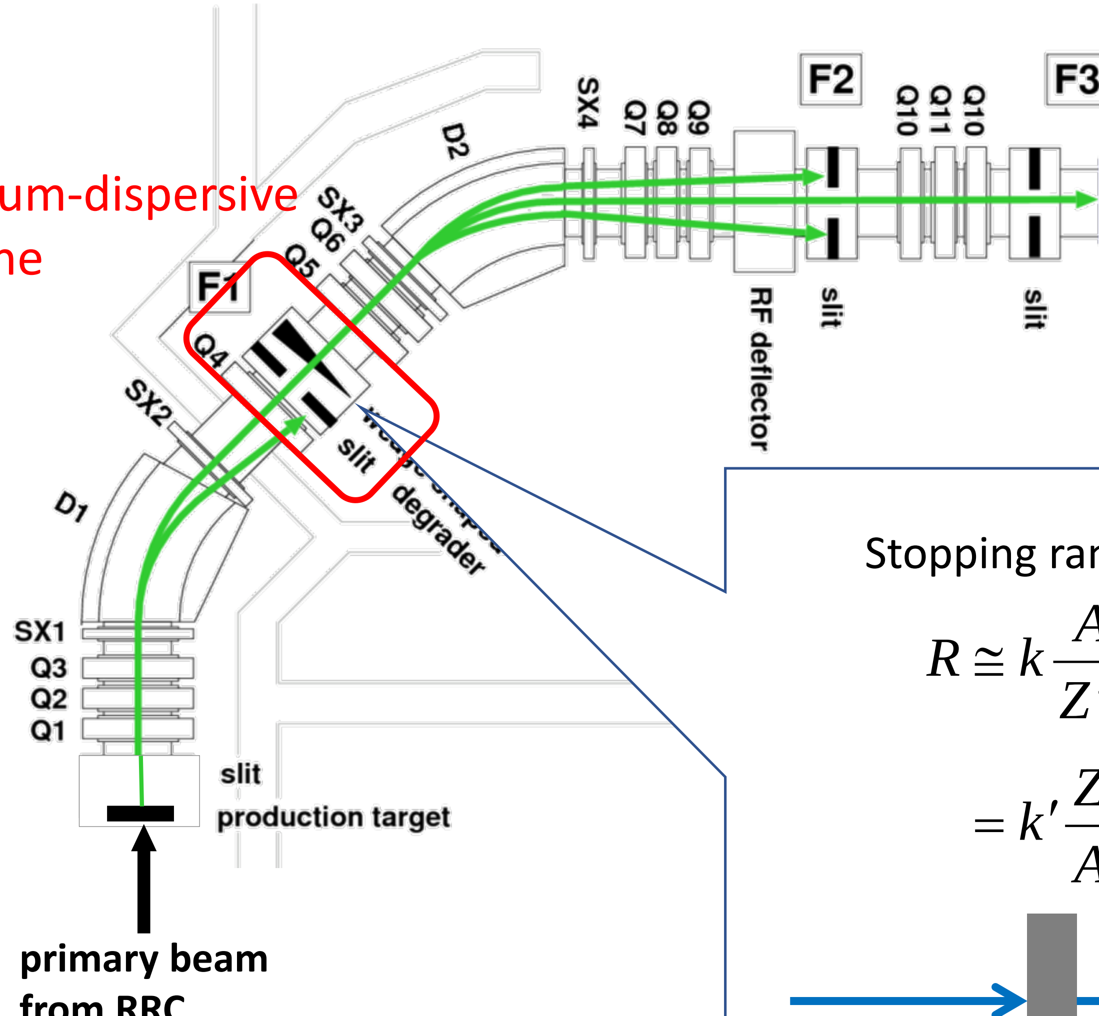
$$B\rho = \frac{A}{Z}\frac{p_{nucl}}{e}$$

Isotope separation (stage1)



Between 1st and 2nd selections

Momentum-dispersive focal plane

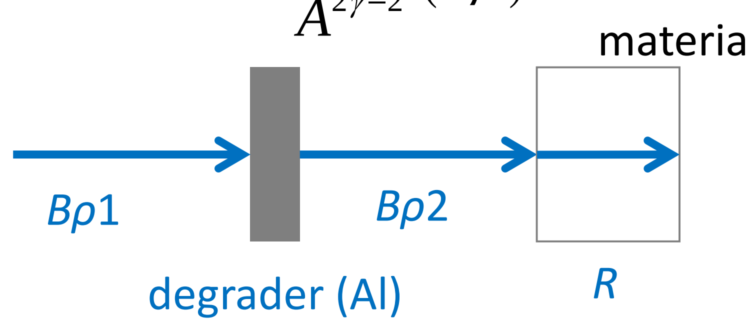


Stopping range

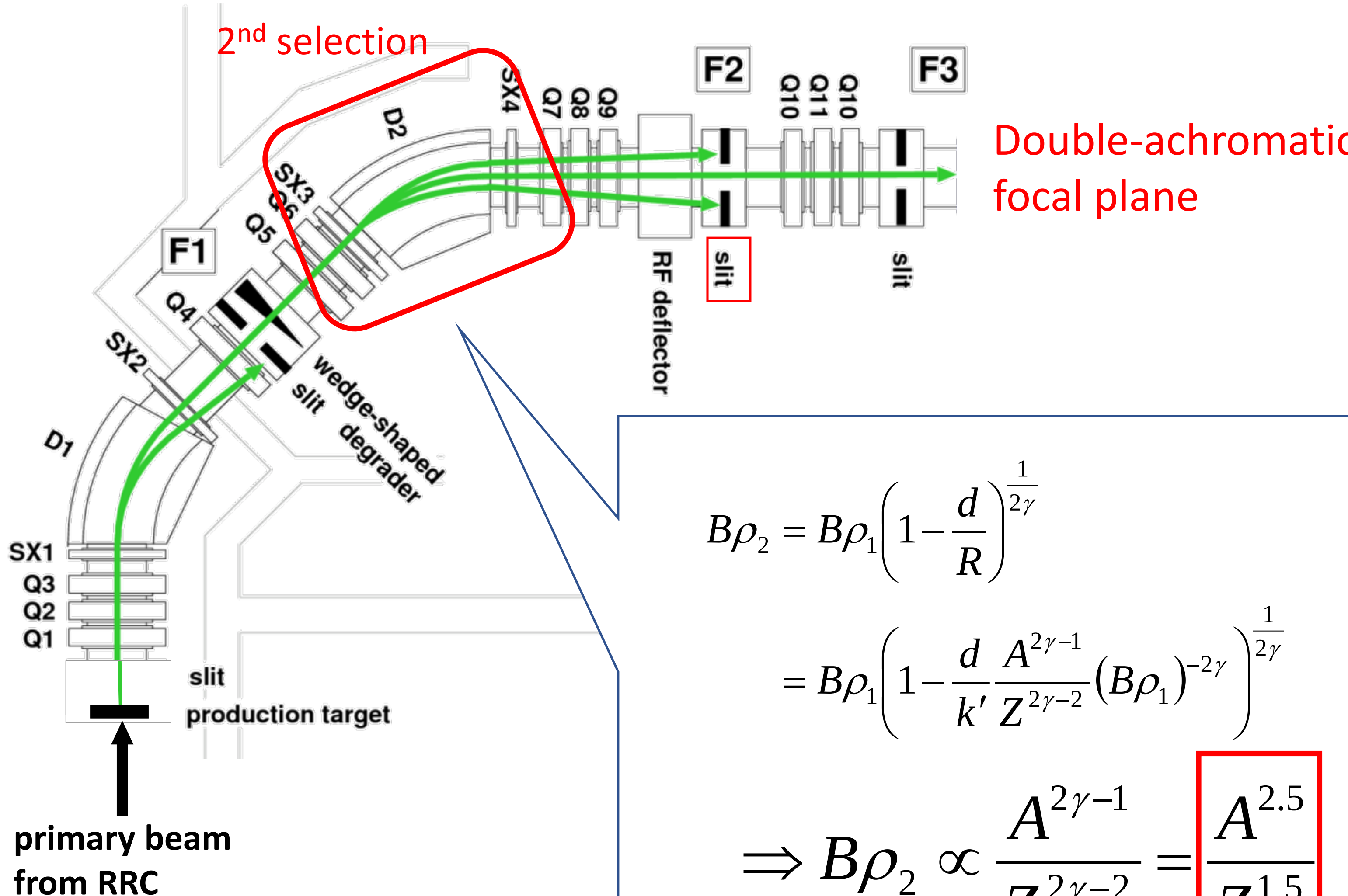
$$R \cong k \frac{A}{Z^2}\left(\frac{E}{A}\right)^{\gamma}$$

γ =1.75
(at intermediate beam energies)

$$= k' \frac{Z^{2\gamma-1}}{A^{2\gamma-2}}(B\rho)^{2\gamma}$$



2^{nd} stage selection

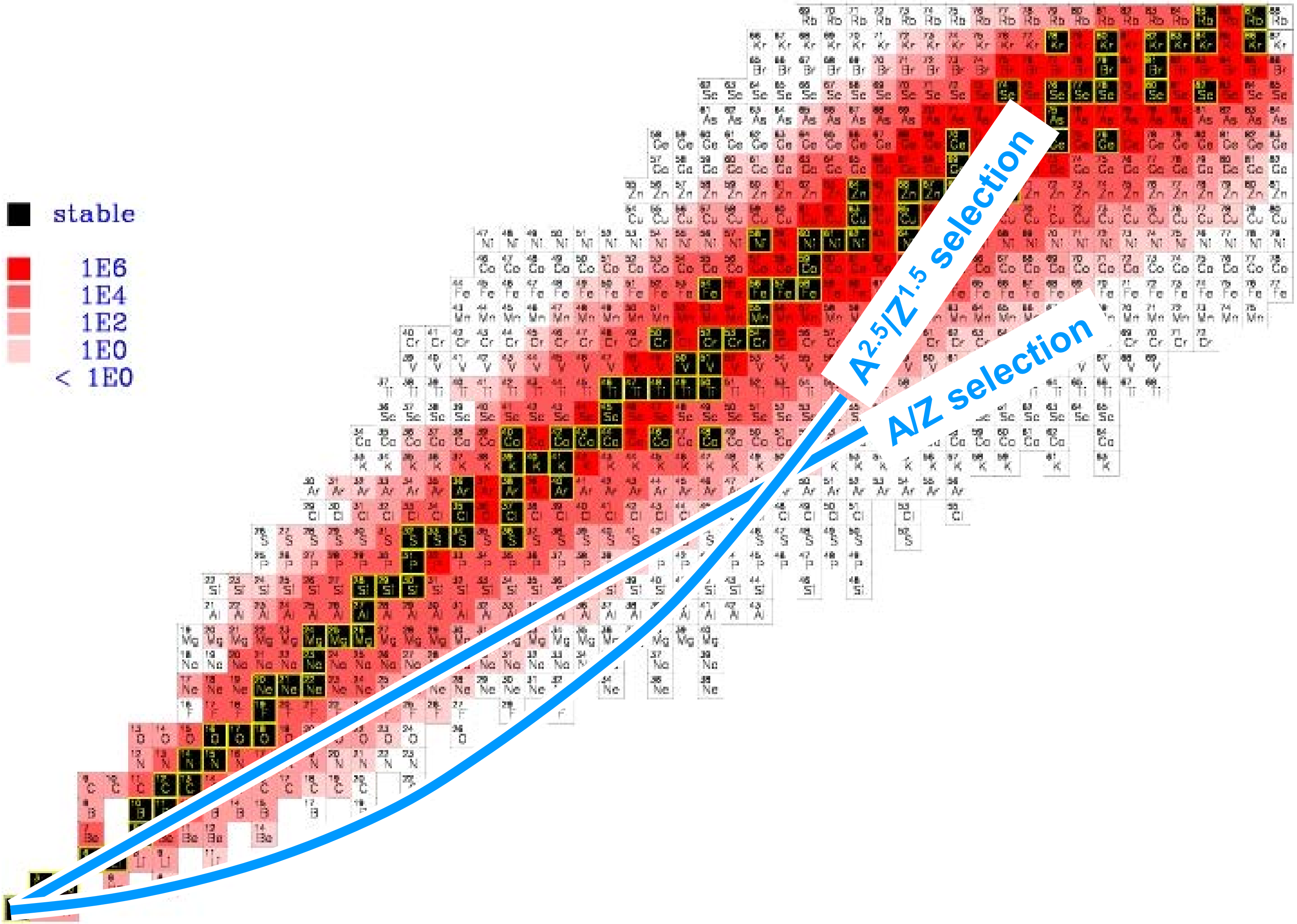


$$B\rho_2 = B\rho_1\left(1-\frac{d}{R}\right)^{\frac{1}{2\gamma}}$$

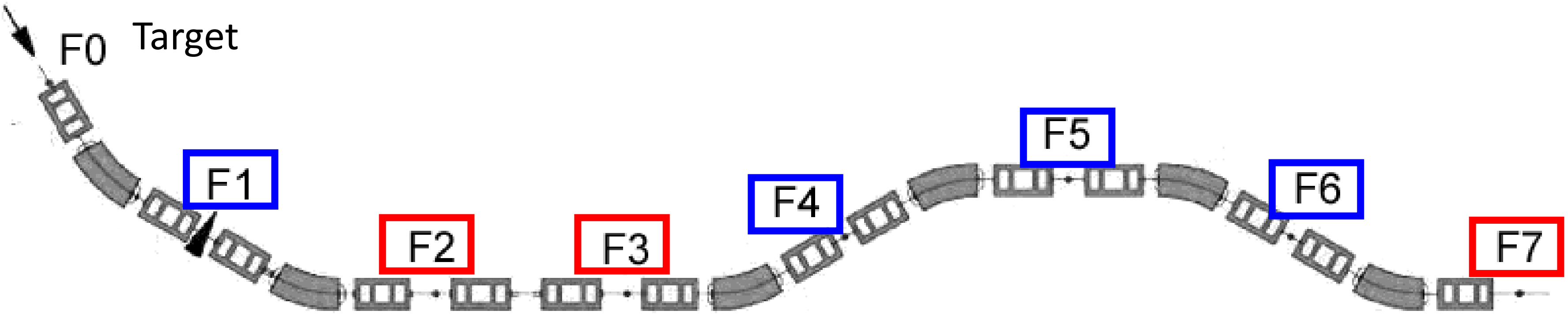
$$= B\rho_1\left(1-\frac{d}{k'}\frac{A^{2\gamma-1}}{Z^{2\gamma-2}}(B\rho_1)^{-2\gamma}\right)^{\frac{1}{2\gamma}}$$

$$\Rightarrow B\rho_2 \propto \frac{A^{2\gamma-1}}{Z^{2\gamma-2}} = \boxed{\frac{A^{2.5}}{Z^{1.5}}}$$

Isotope separation (stage2)



BigRIPS configuration



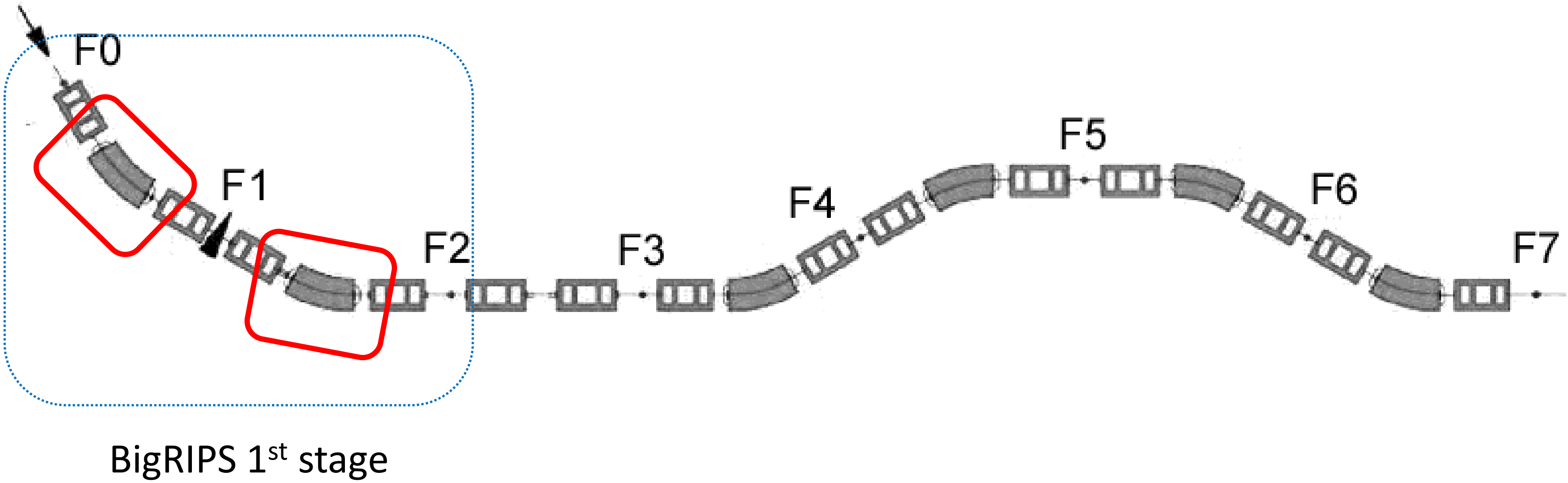
Momentum-dispersive focal planes

- Hit position depends on its momentum
- Same Bρ: same hit position

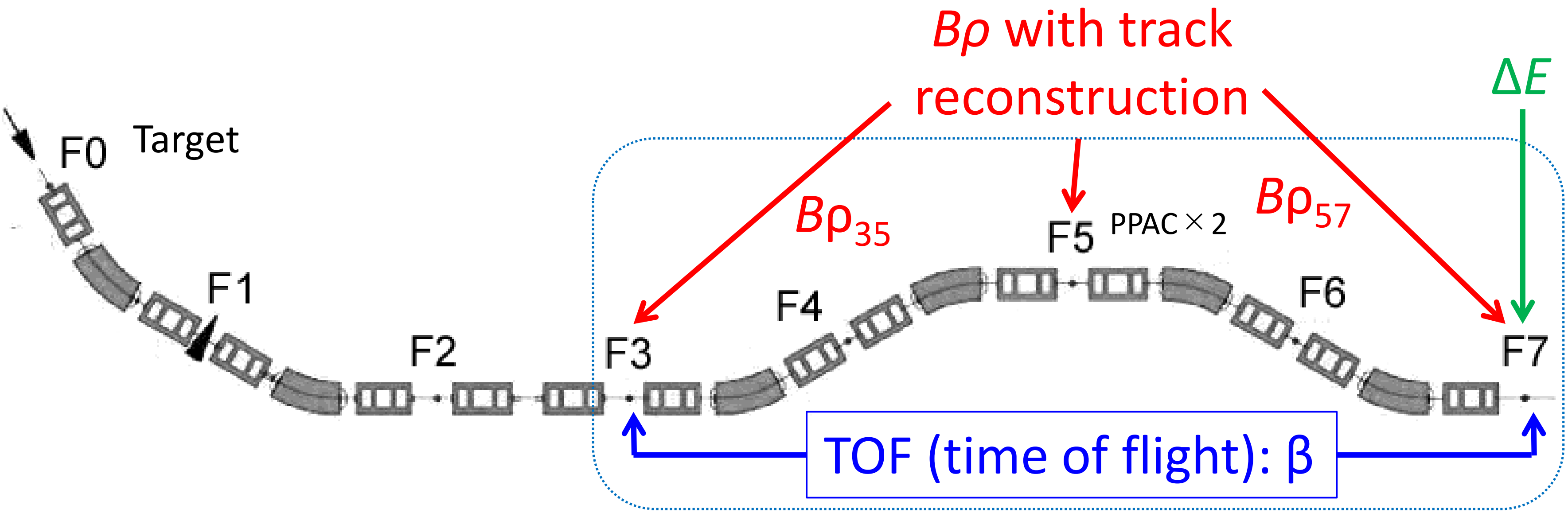
Double-achromatic focal planes

- Beam is focused

Isotope separation



Particle identification



BigRIPS 2nd stage

TOF-$B\rho$-ΔE method

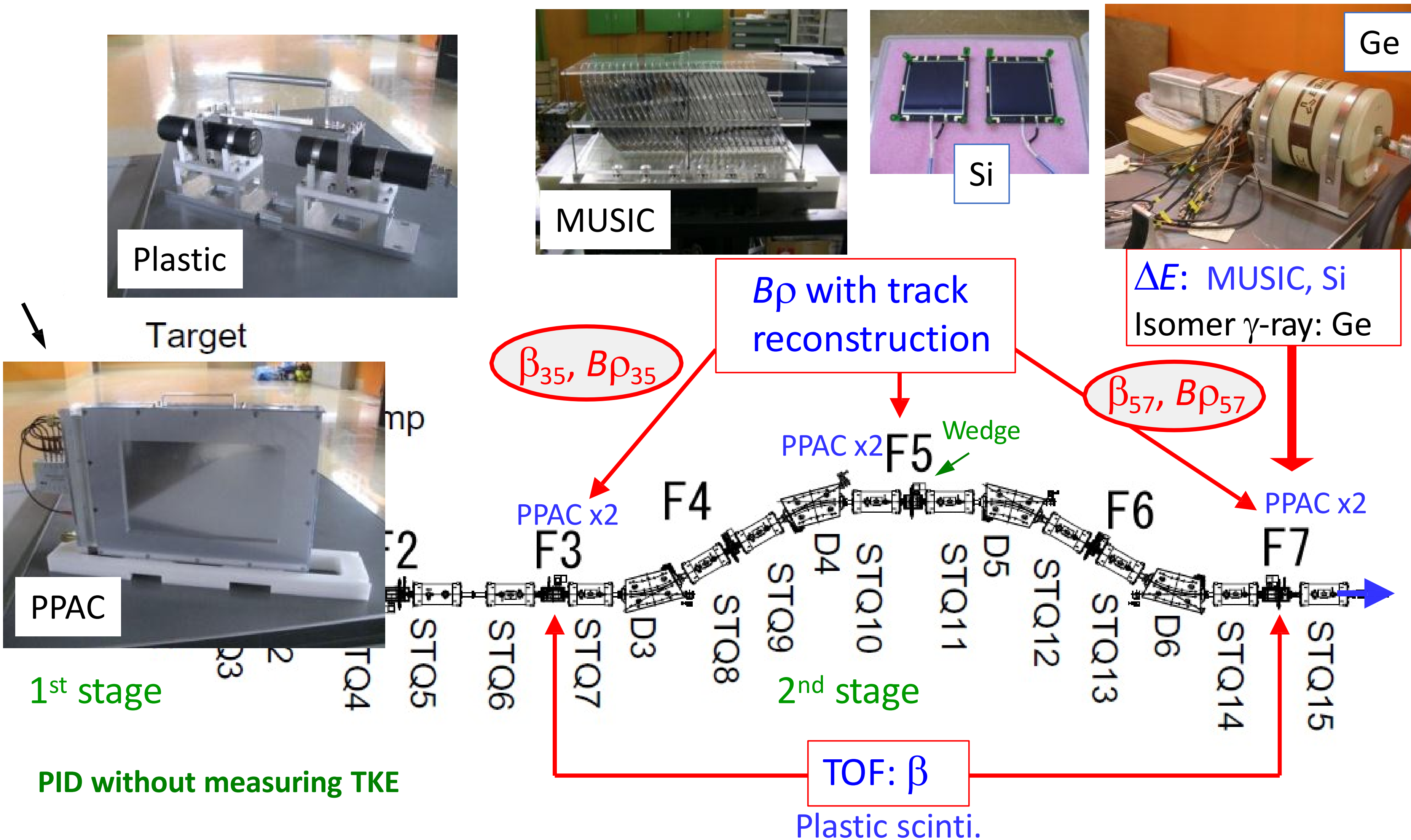
$$\frac{A}{Q} = \frac{B\rho}{\gamma\beta}\frac{c}{m_{\mathrm{nucl}}}$$

$$Z \leftarrow \Delta E = f(Z, \beta)$$

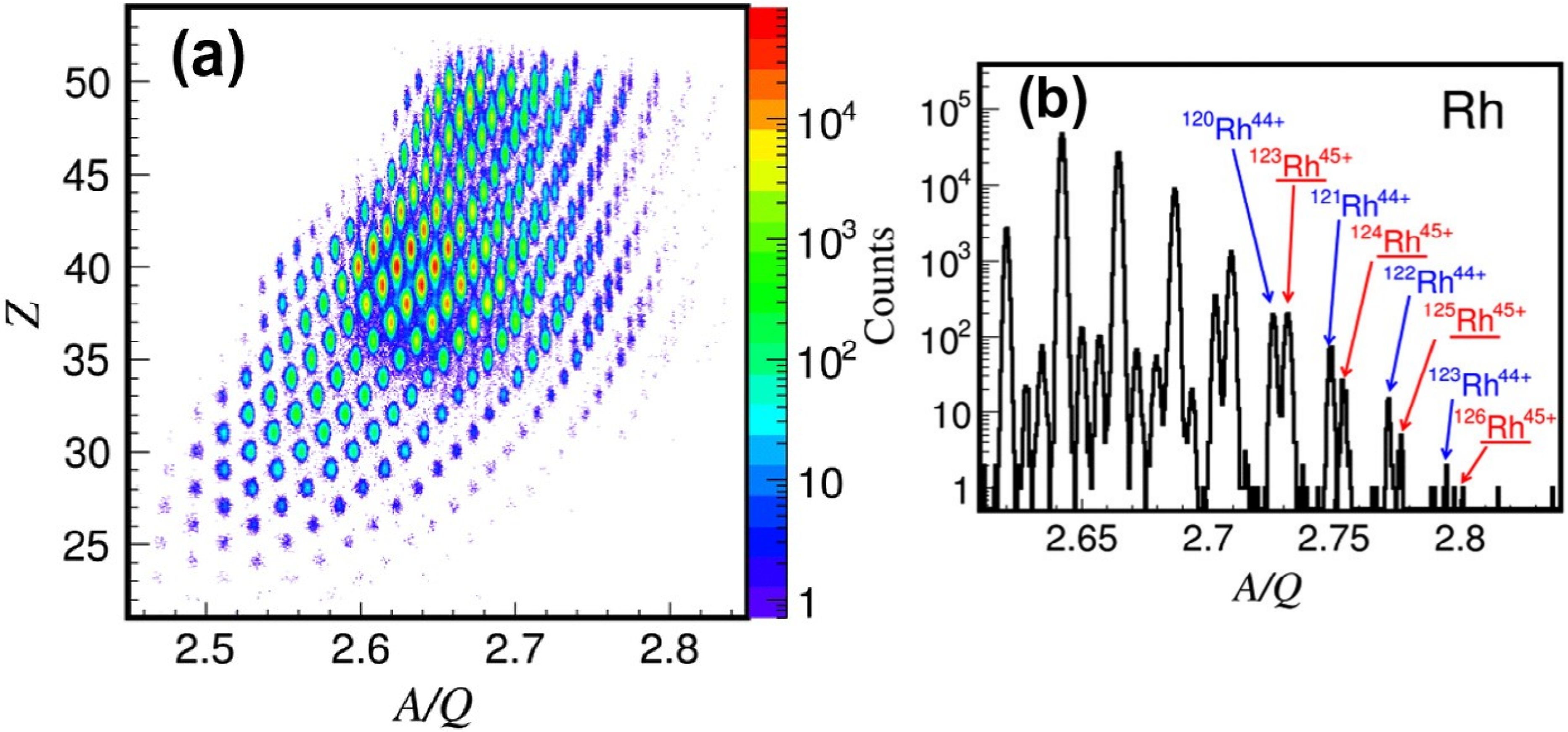
Bethe-Bloch formula

Particle identification (PID) detectors at BigRIPS

TOF-$B\rho$-ΔE method with track reconstruction → Improve $B\rho$ and TOF resolution



Example of PID plot

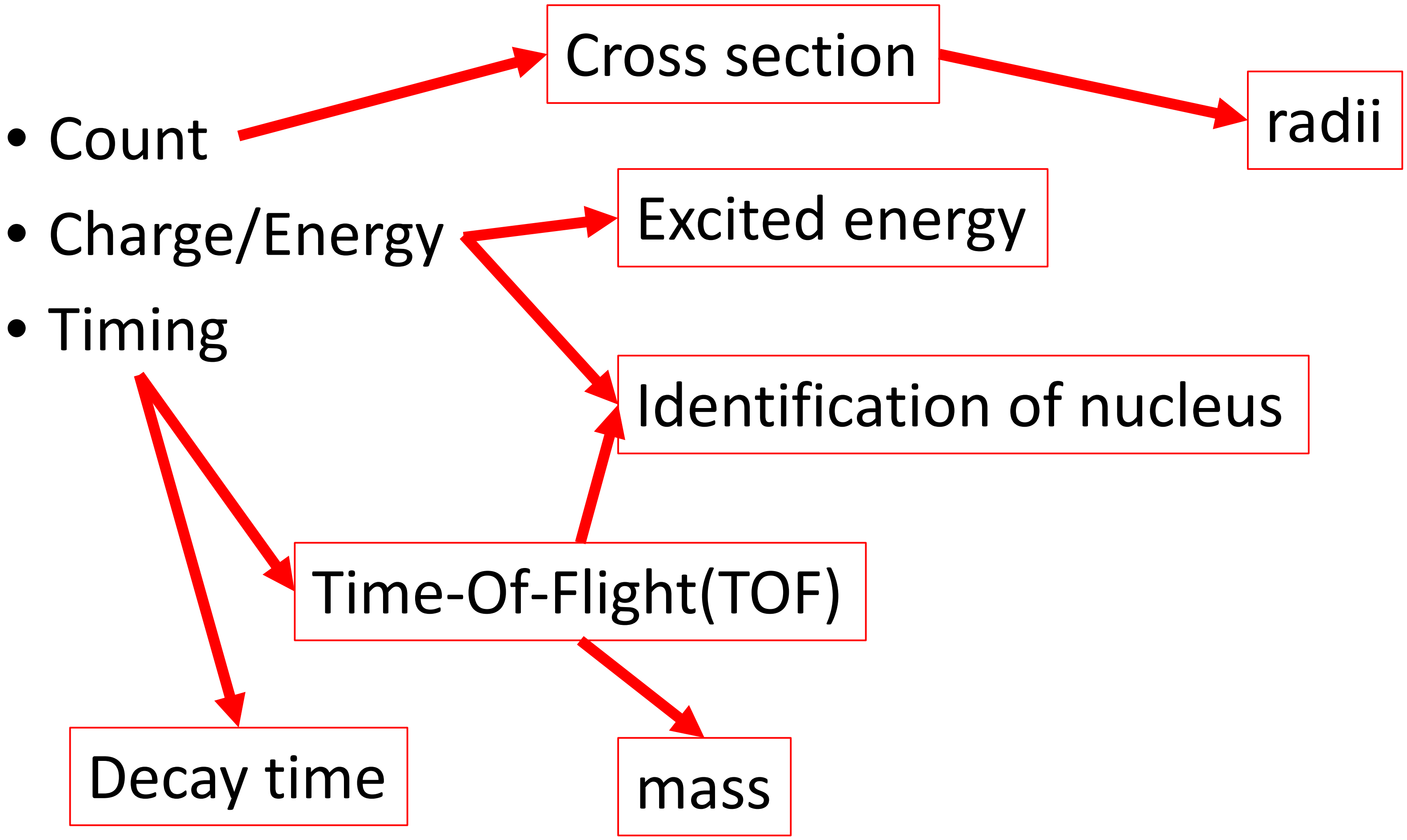


Fukuda et. al, NIM B317 (2013) 323

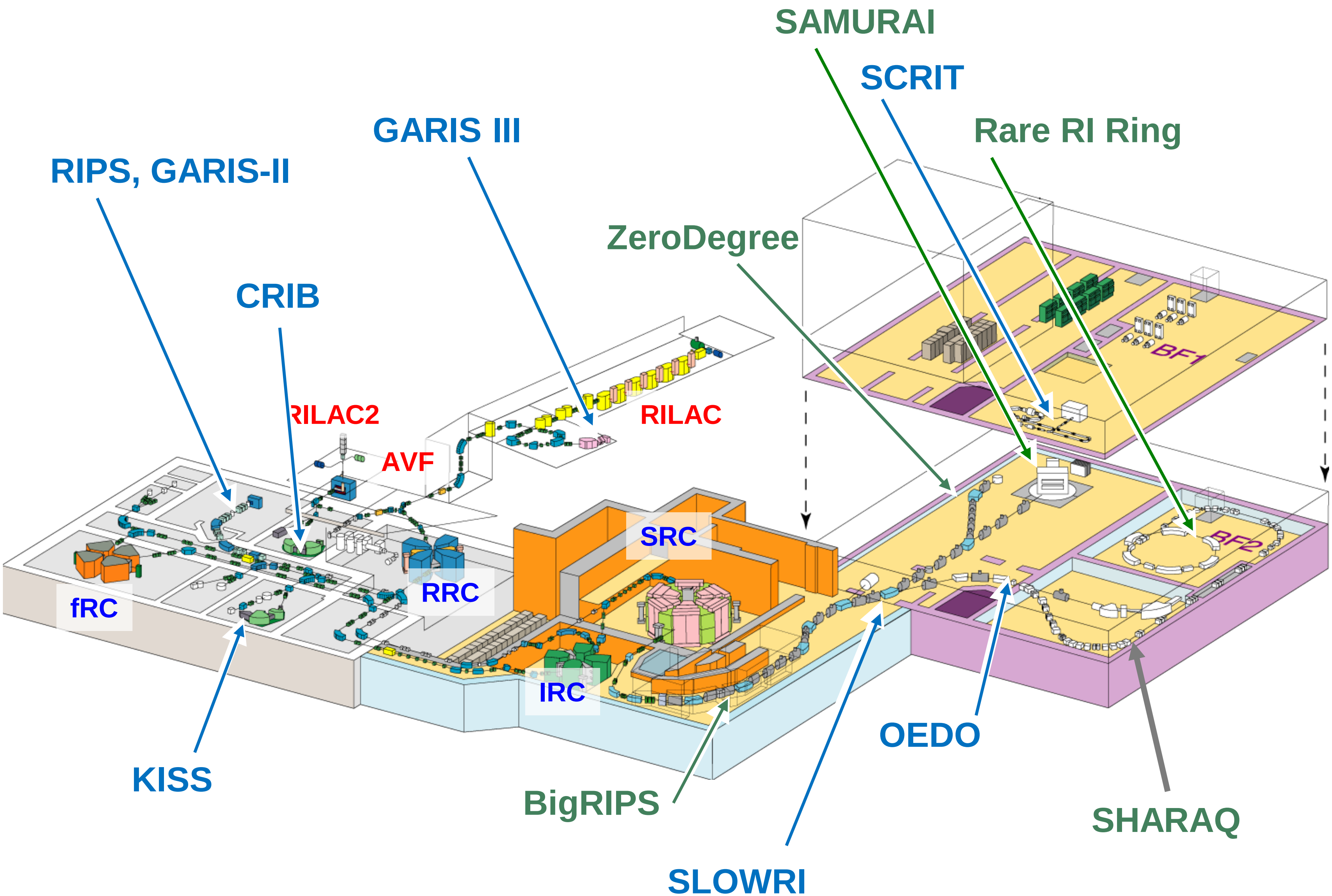
OK. RI beam which you want is provided. What do you want to measure?

- **Mass?**
- **Half-life?**
- **Excited states?**
- **Deformation?**
- **Charge radii?**
- **Matter radii?**
- **Charge distribution?**
- **Matter distribution?**
- **EM moments?**
- **Single particle states?**
- **Astrophysical reactions?**
- **Giant resonances?**
- **Exotic modes?**
- **Equation of state?**

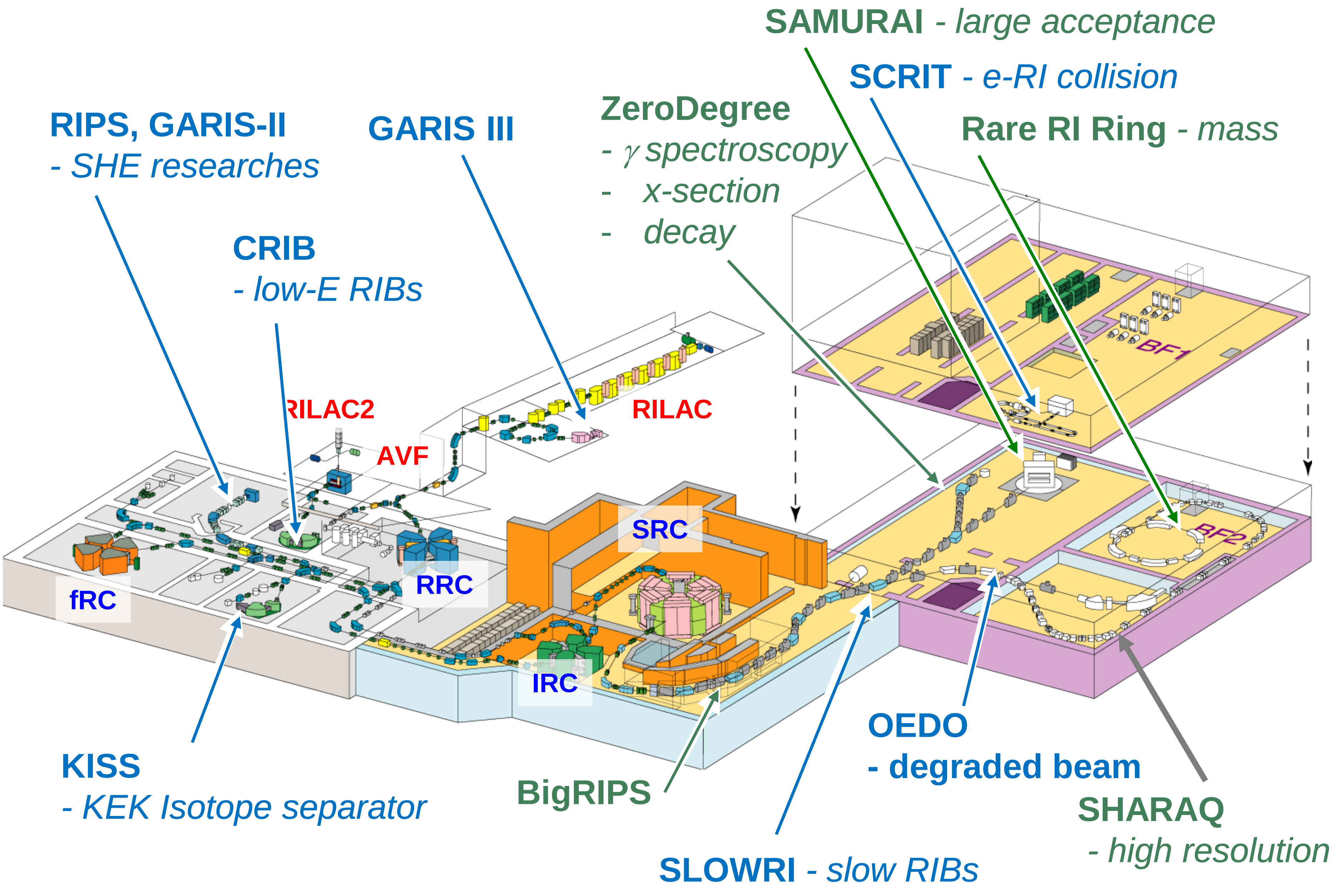
What we can measure is quite limited. Need to combine detector information.



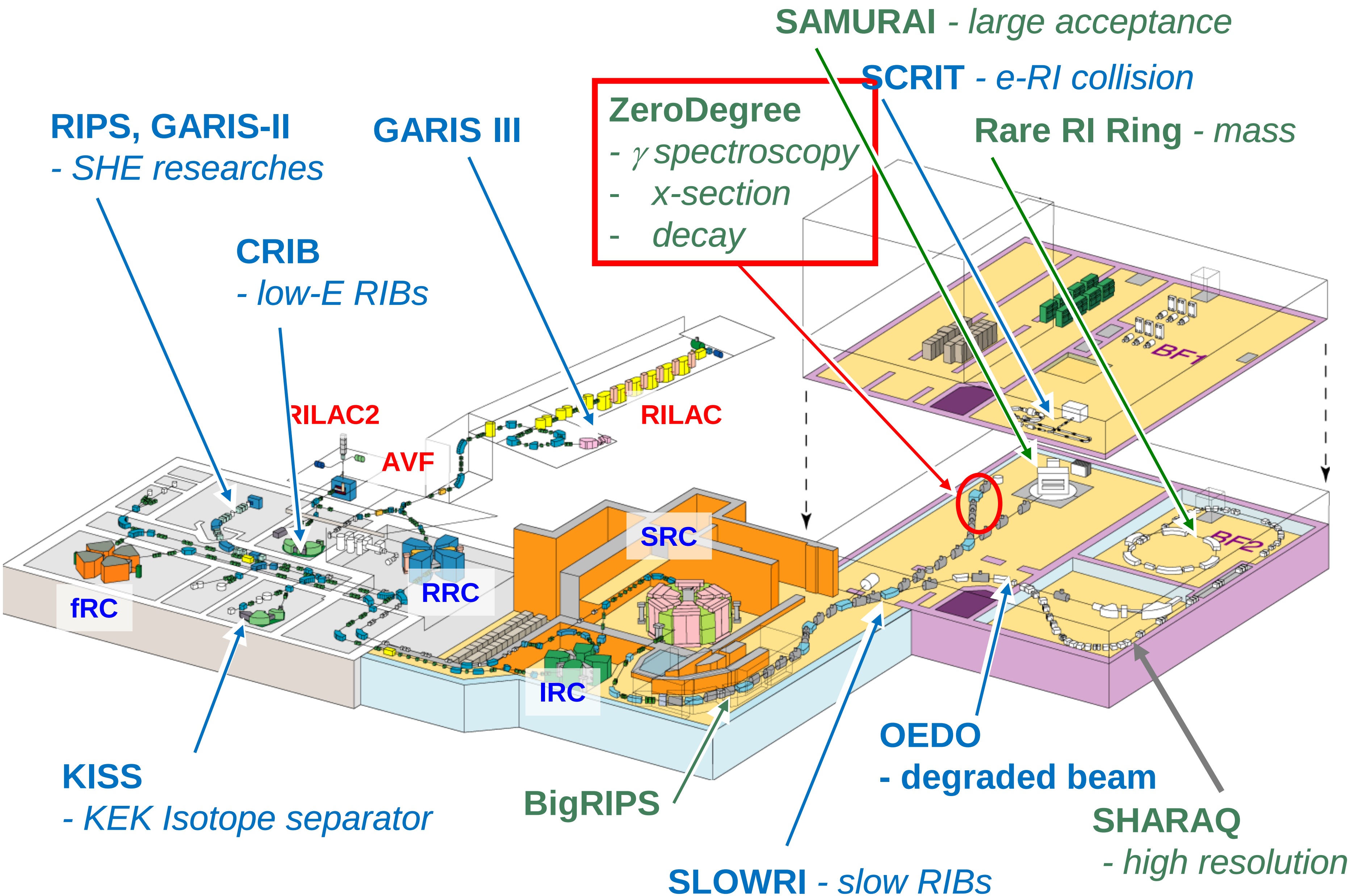
Devices for the measurement of physics observables: small and large



Versatile devices for the measurement of physics observables

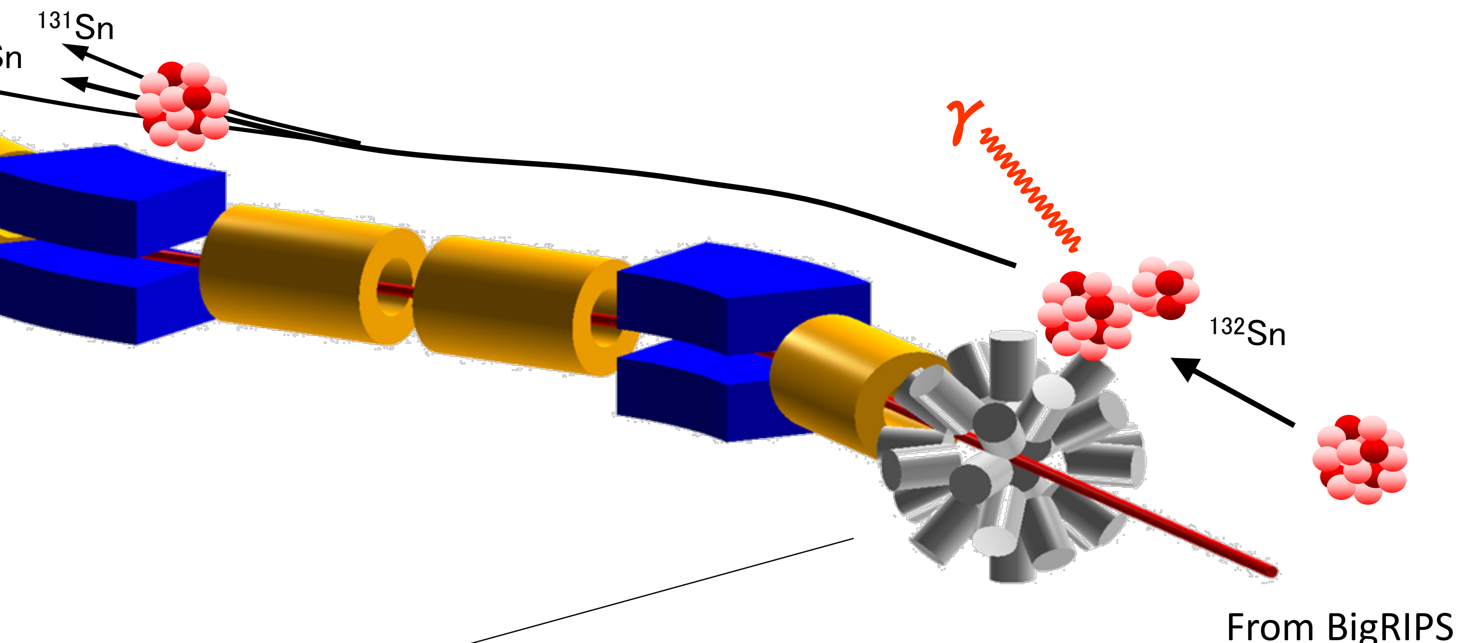


ZDS(Zero-degree spectrometer)



ZDS(Zero-degree spectrometer)

Spectrometer for in-beam gamma-ray measurement



DALI2 (NaI scintillators): S. Takeuchi *et al.*, Nucl. Instr. Meth. B 763, 596 ('14)

ZDS(Zero-degree spectrometer)

Magicity of ^{78}Ni

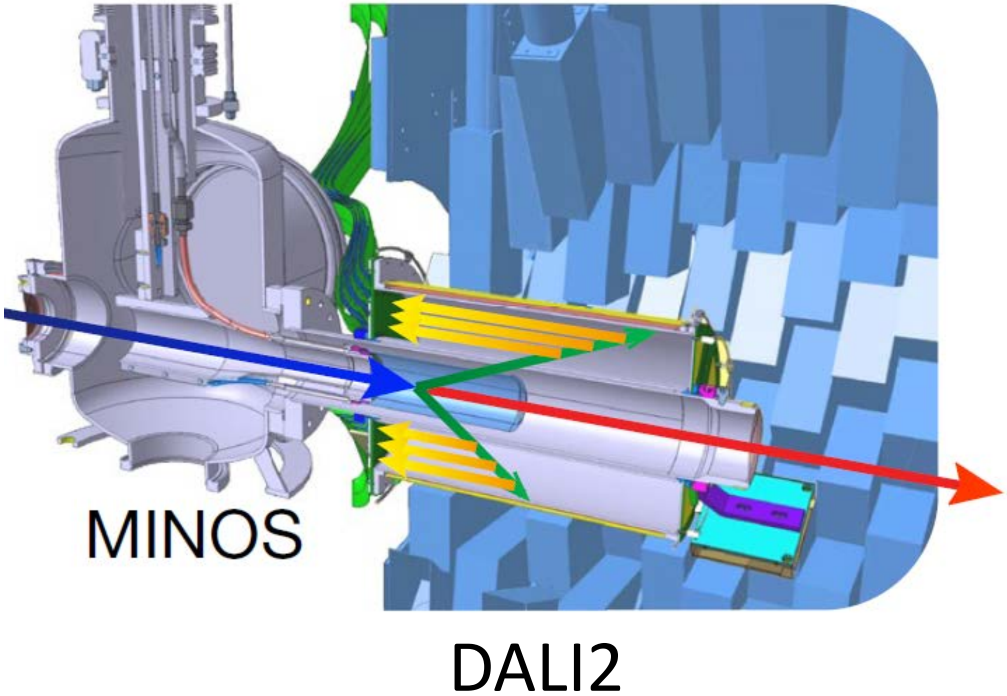
ARTICLE

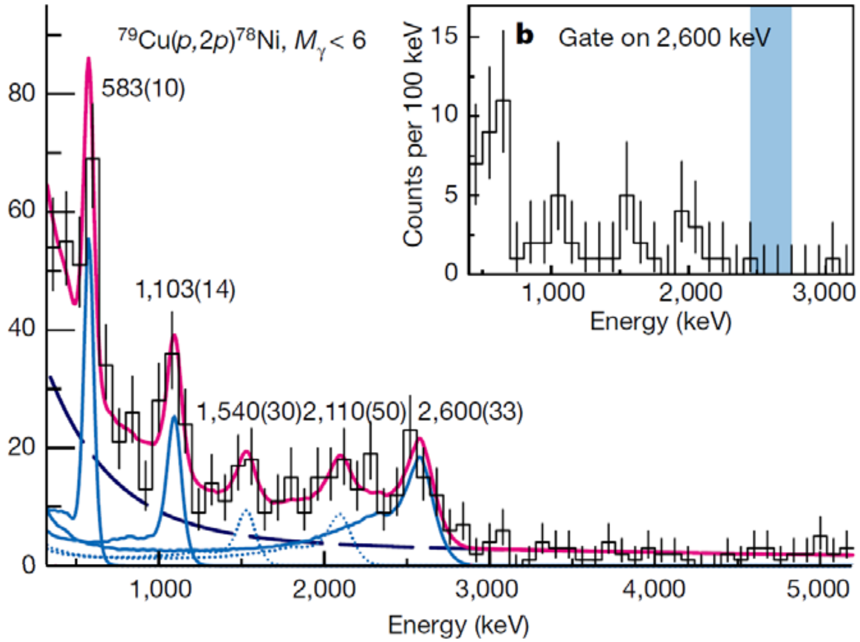
Nature 2019

https://doi.org/10.1038/s41586-019-1155-x

^{78}Ni revealed as a doubly magic stronghold against nuclear deformation

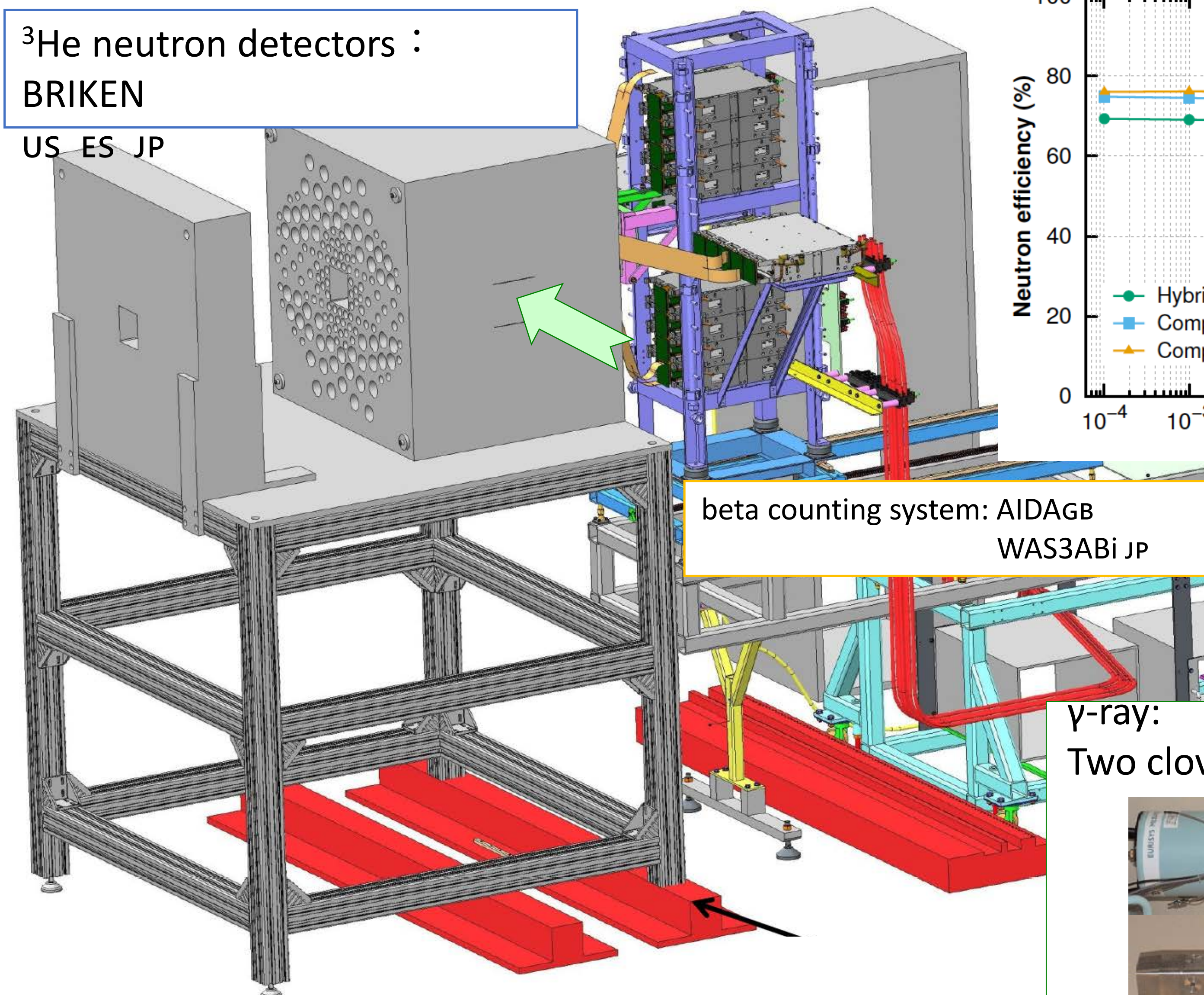
R. Taniuchi[1,2], C. Santamaria[2,3], P. Doornenbal[2*], A. Obertelli[2,3,4], K. Yoneda[2], G. Authelet[3], H. Baba[2], D. Calvet[3], F. Château[3], A. Corsi[3], A. Delbart[3], J.-M. Gheller[3], A. Gillibert[3], J. D. Holt[5], T. Isobe[2], V. Lapoux[3], M. Matsushita[6], J. Menéndez[6], et al.

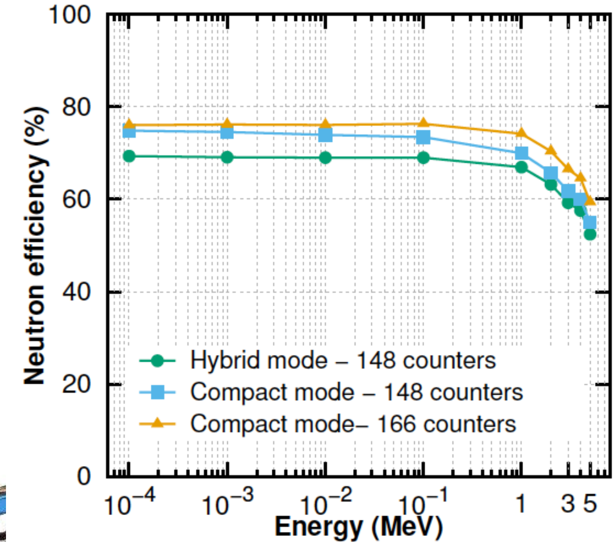




BRIKEN at ZDS (2016 ~)

^{3}He neutron detectors：
BRIKEN
US ES JP



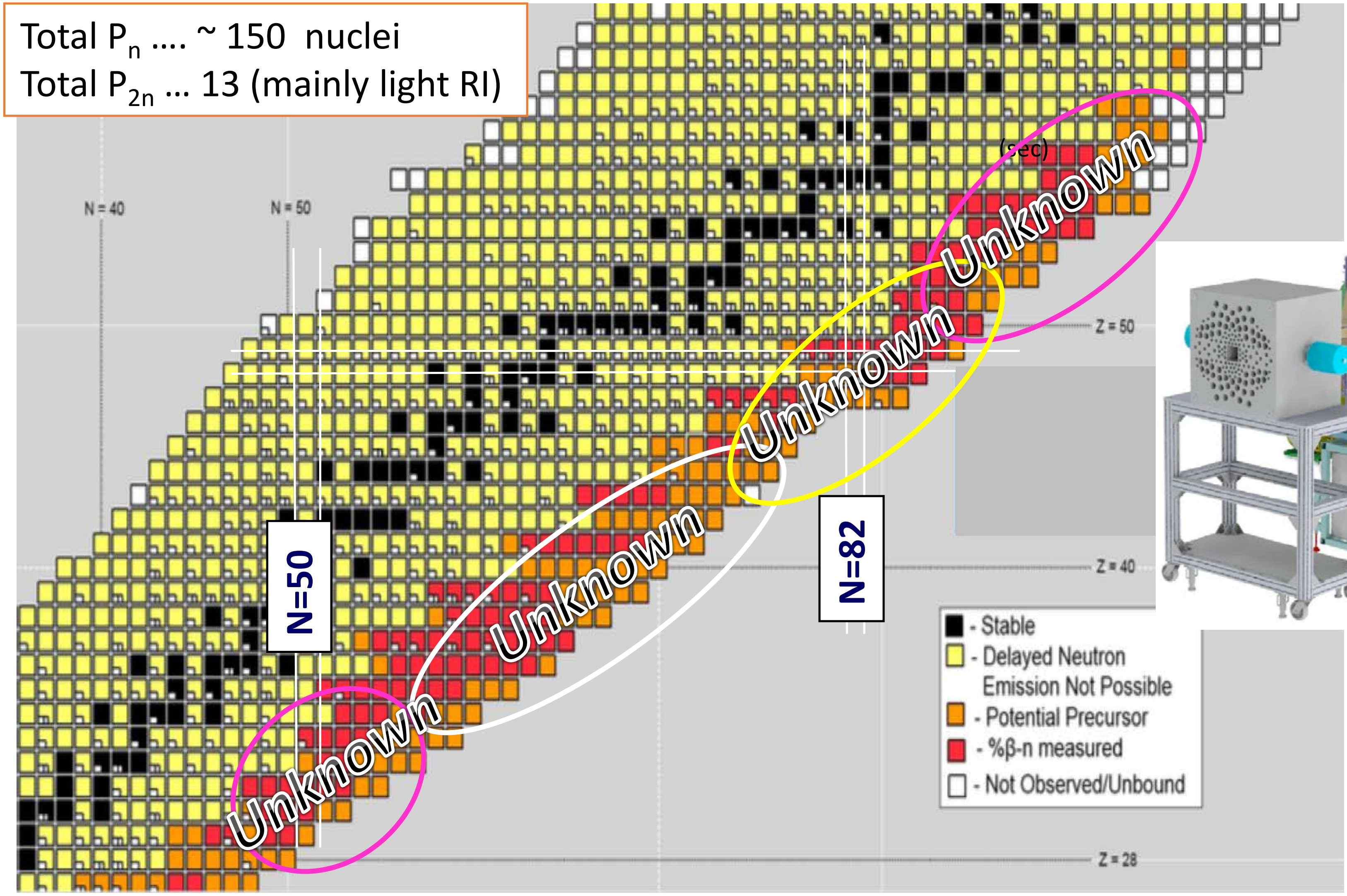


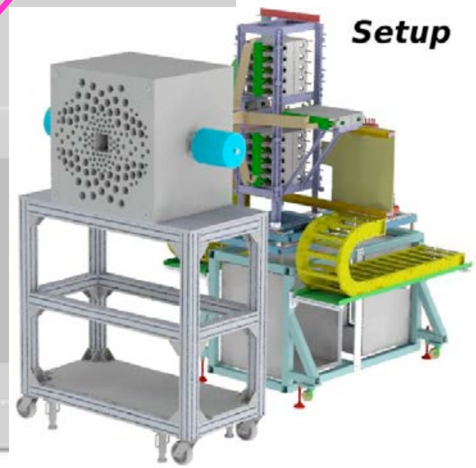
beta counting system: AIDA GB
WAS3ABi JP

γ-ray:
Two clover Ge detectors US

Beta-delayed neutron emission probabilities

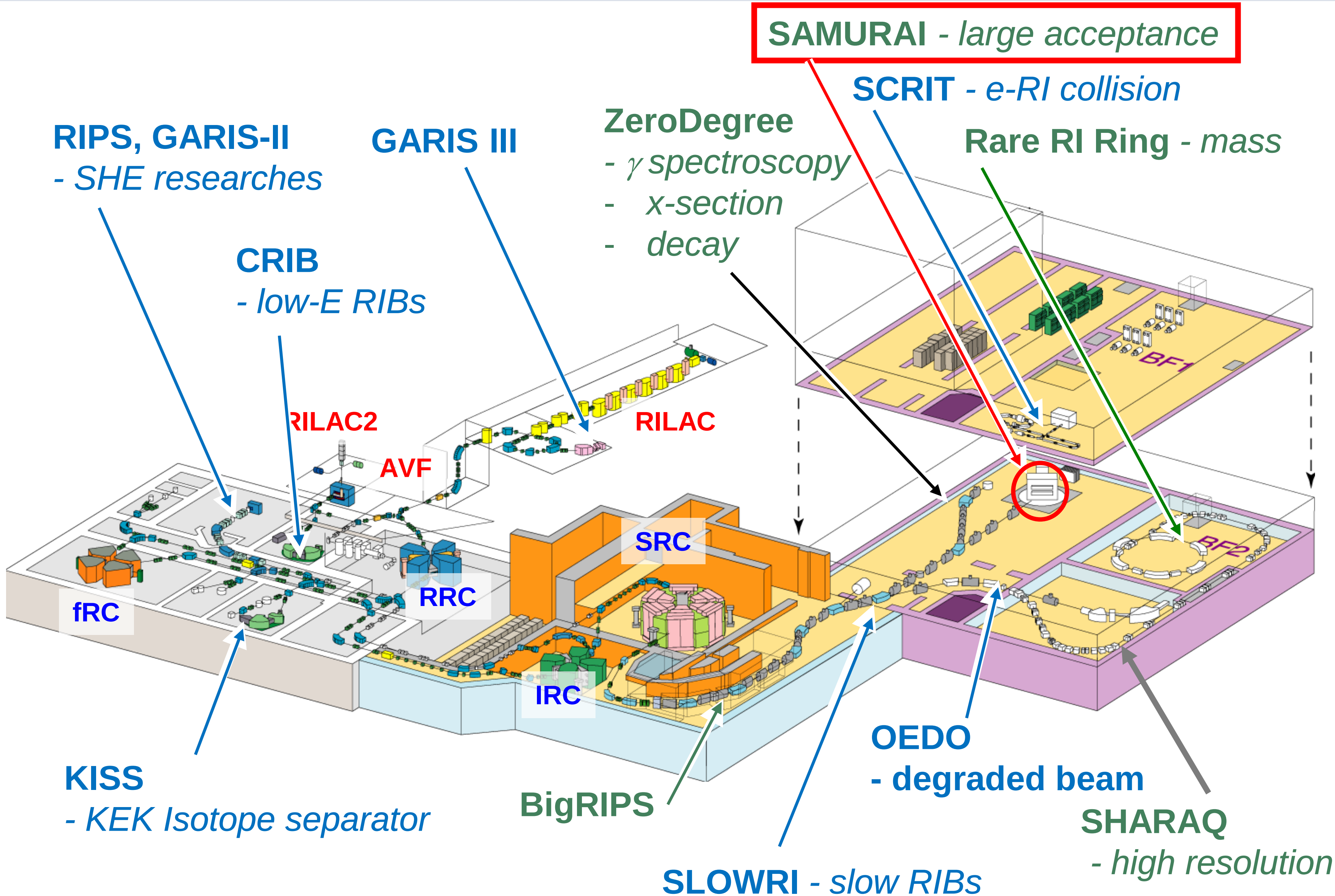
Total P_n …. ~ 150 nuclei
Total P_{2n} … 13 (mainly light RI)





Several hundreads of beta-delayed neutron emission P_n (n)
together with $T_{1/2}$ (β) & level scheme (γ)

SAMURAI

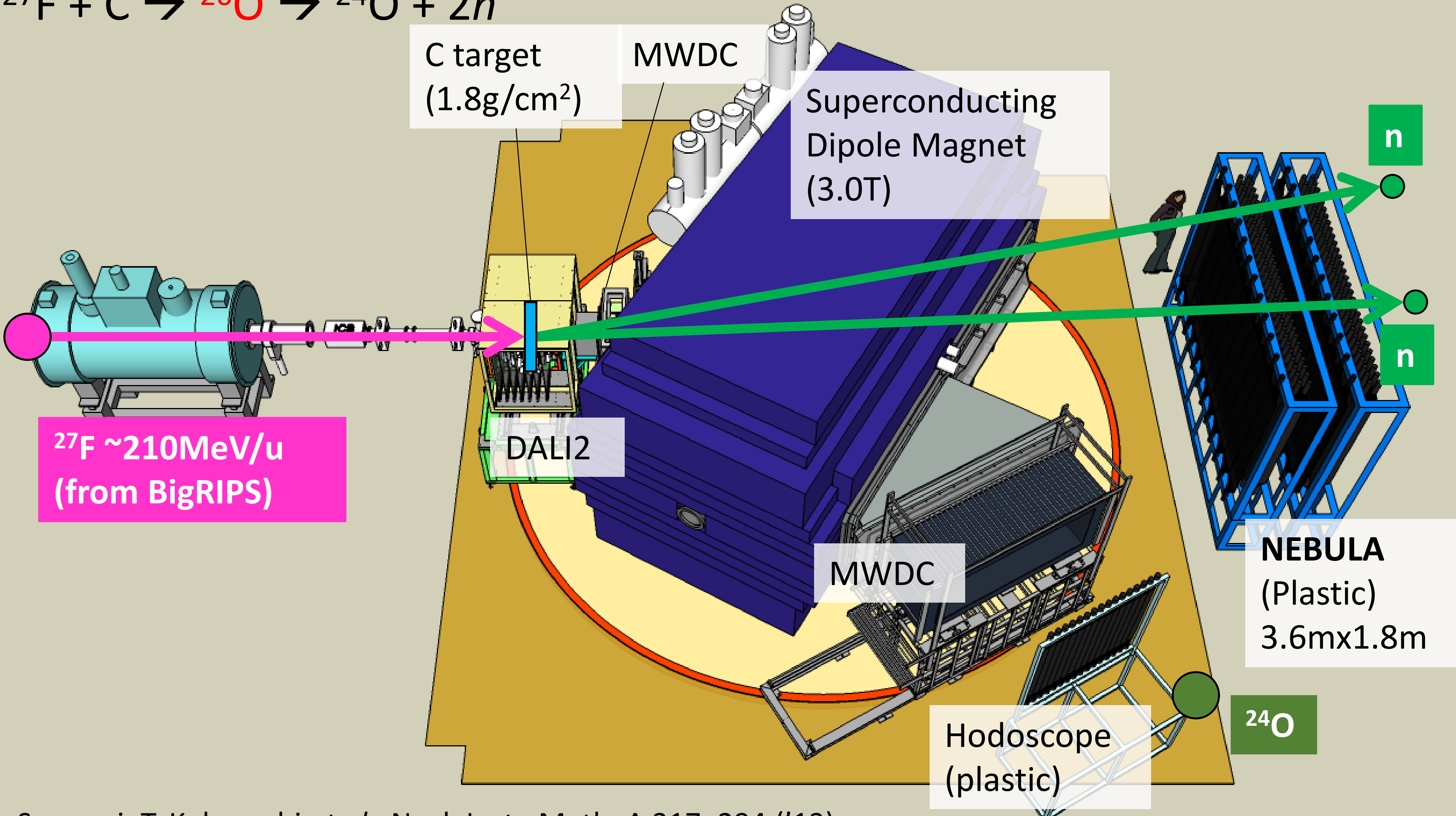


SAMURAI - large acceptance
SCRIT - e-RI collision
Rare RI Ring - mass
ZeroDegree
- γ spectroscopy
- x-section
- decay
RIPS, GARIS-II
- SHE researches
GARIS III
CRIB
- low-E RIBs
RILAC2
RILAC
AVF
SRC
RRC
fRC
IRC
BF1
BF2
KISS
- KEK Isotope separator
BigRIPS
SLOWRI - slow RIBs
OEDO
- degraded beam
SHARAQ
- high resolution

SAMURAI

Superconducting **A**nalyzer for **MU**lti-particle from **RA**dio**I**sotope beams

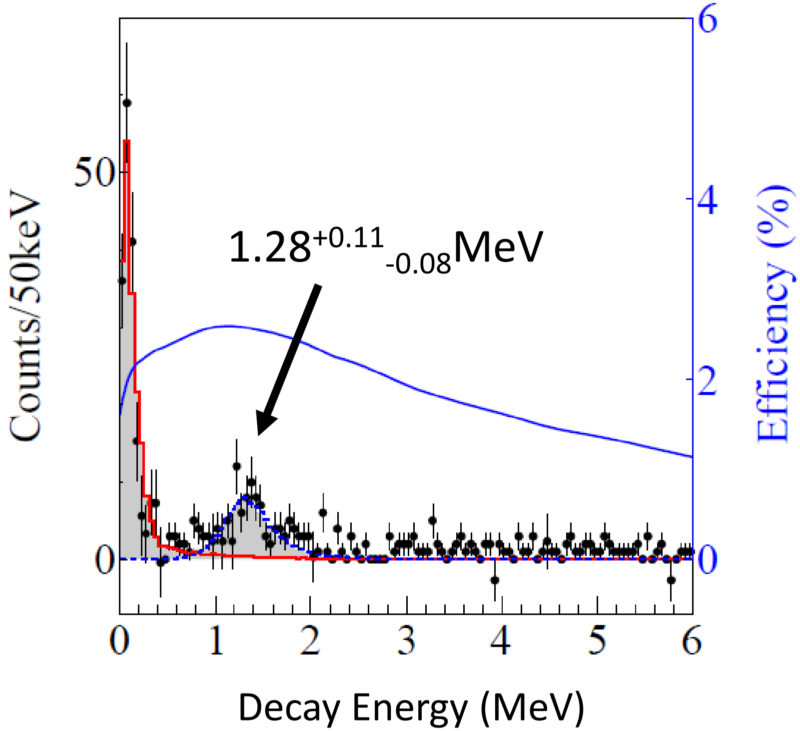
$^{27}F + C \rightarrow {}^{26}O \rightarrow {}^{24}O + 2n$

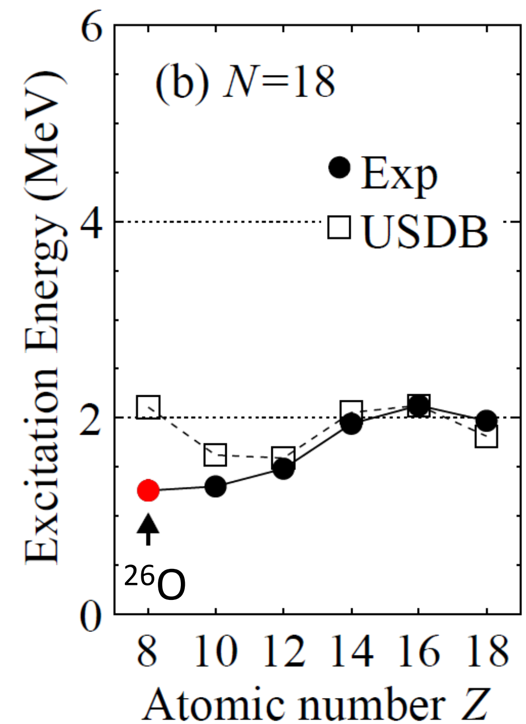


Samurai: T. Kobayashi *et al.*, Nucl. Instr. Meth. A 317, 294 ('13)

SAMURAI

First 2^+ state of unbound ^{26}O



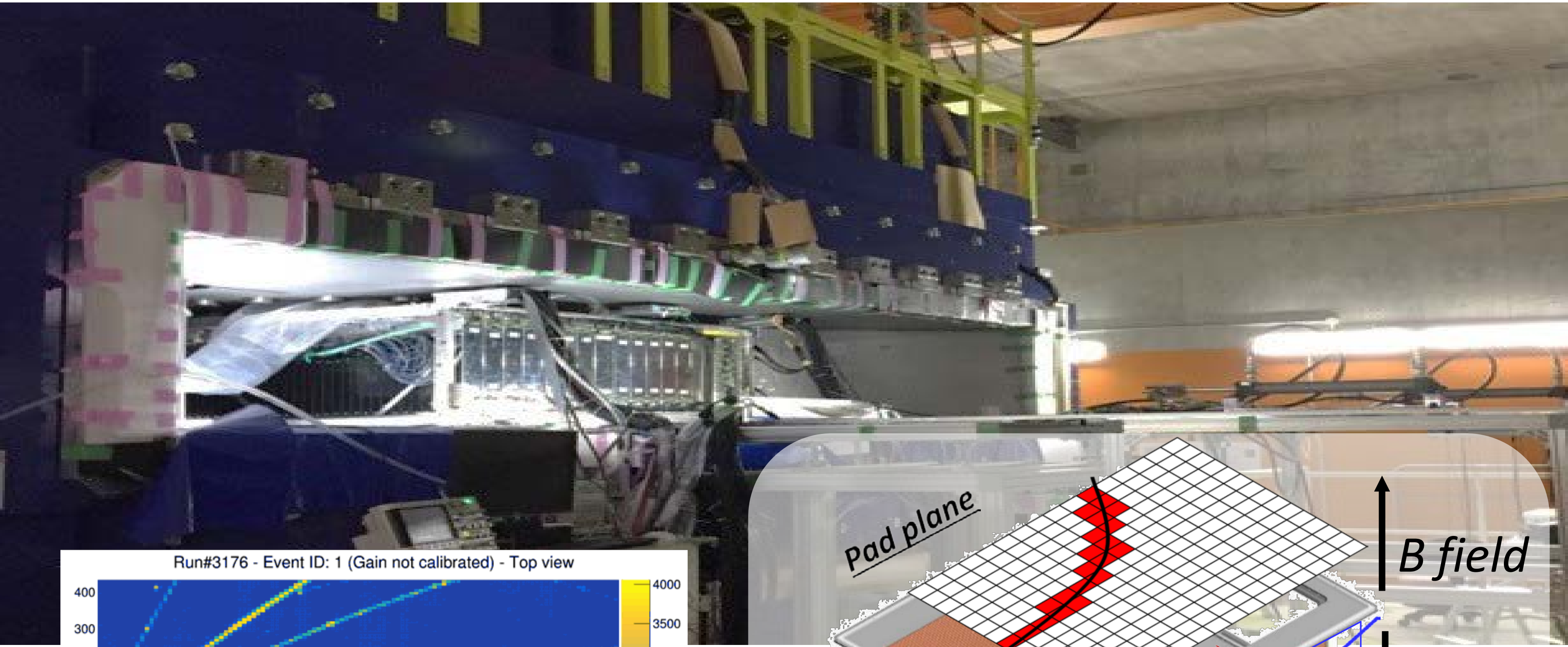


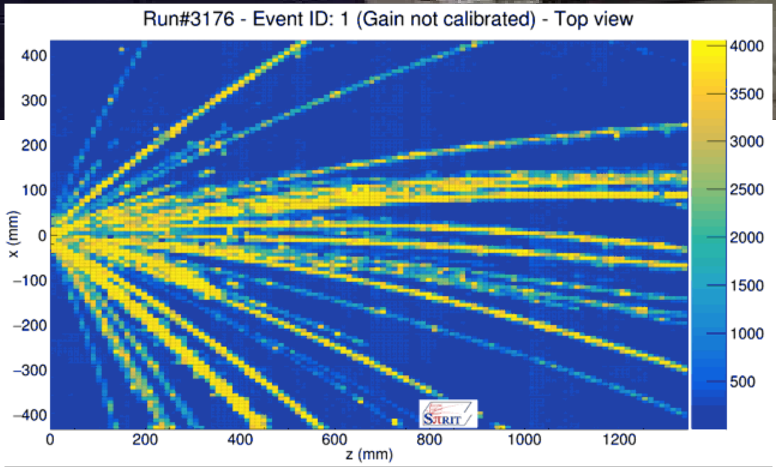
- USDB cannot reproduce the 2^+ energy of ^{26}O
- Effect of *pf* shell? and/or continuum? Or other effects (such as 3N forces, 2n correlation)
- Further studies are desired to pin down the various effects quantitatively. (Experiment was done for ^{27}O and ^{28}O.)

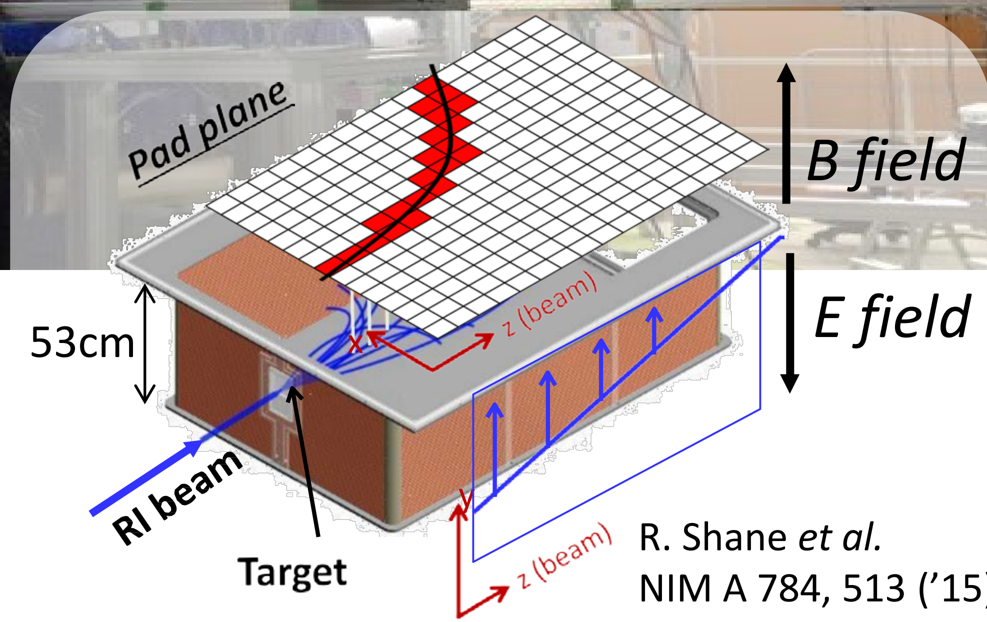
Y. Kondo *et al.*, Phys. Rev. Lett. 116, 102503 ('16)

SPiRIT
(SAMURAI Pion Reconstruction and Ion Tracker)

Nuclear equation of state via π^+/π^- production ratio in heavy RI collision

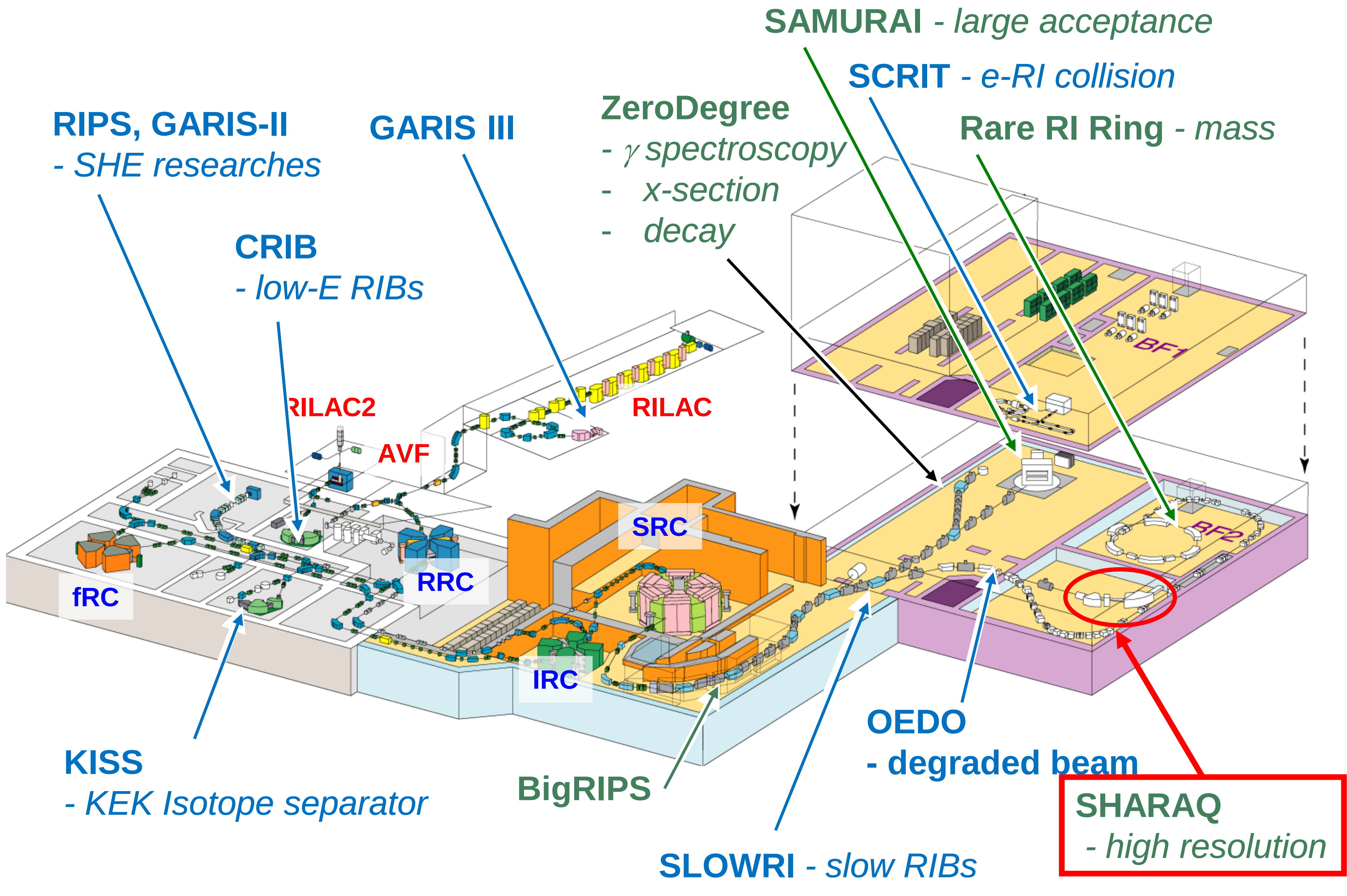






R. Shane *et al.*
NIM A 784, 513 ('15)

SHARAQ


SAMURAI - large acceptance
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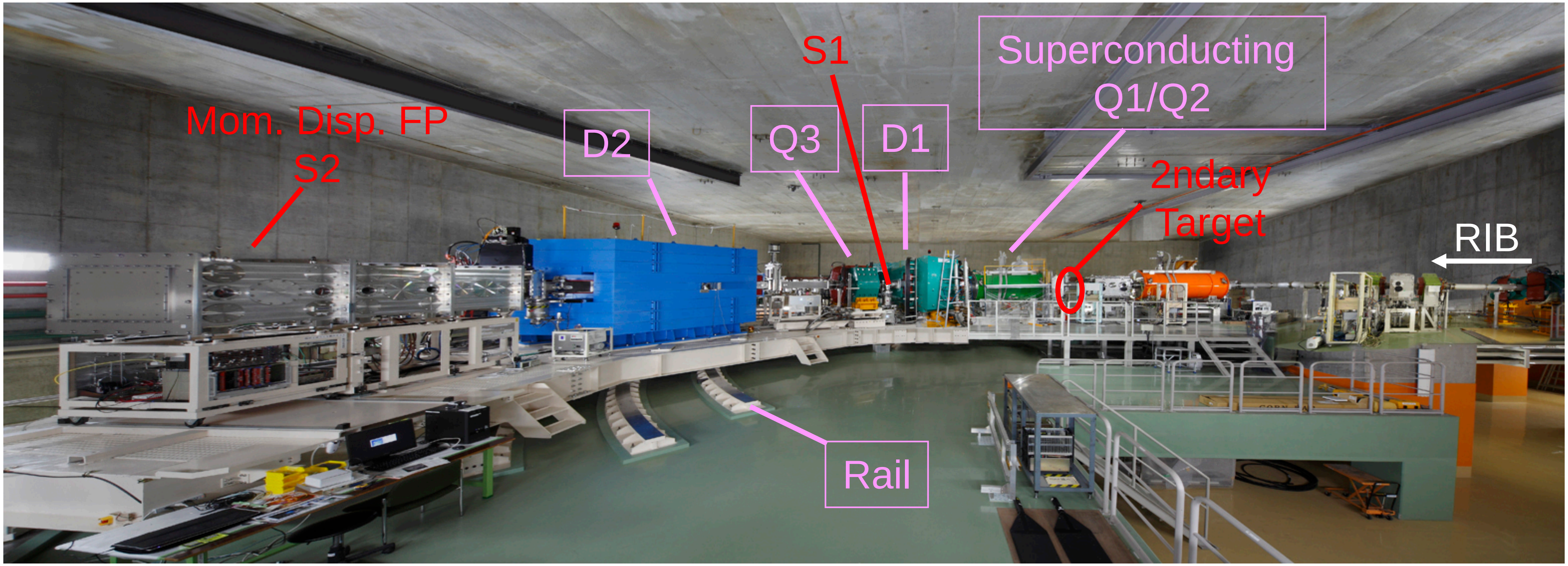
RIPS, GARIS-II
- SHE researches
GARIS III
CRIB
- low-E RIBs
RILAC2
RILAC
AVF
SRC
RRC
fRC
IRC
BF1
BF2
KISS
- KEK Isotope separator
BigRIPS
OEDO
- degraded beam
SLOWRI - slow RIBs
SHARAQ
- high resolution

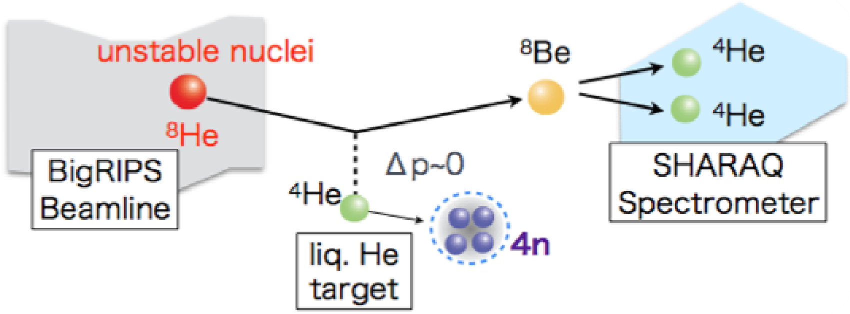
SHARAQ

Spectroscopy using RI beam as a reaction probe

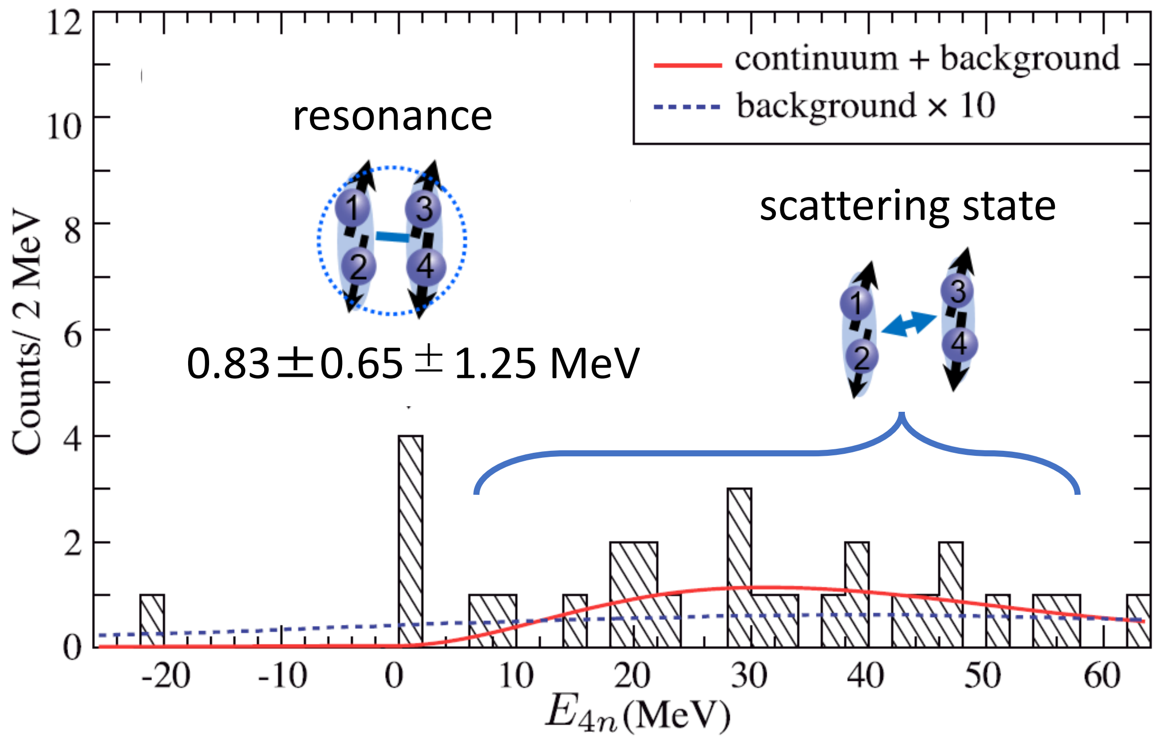


T. Uesaka *et al.*, Nucl. Instr. Meth. B 266, 4218 ('08)
T. Uesaka, S. Shimoura, and H. Sakai, Prog. Theor. Exp. Phys. 03C007 ('12)

Neutral nucleus ‘tetraneutron’ candidate

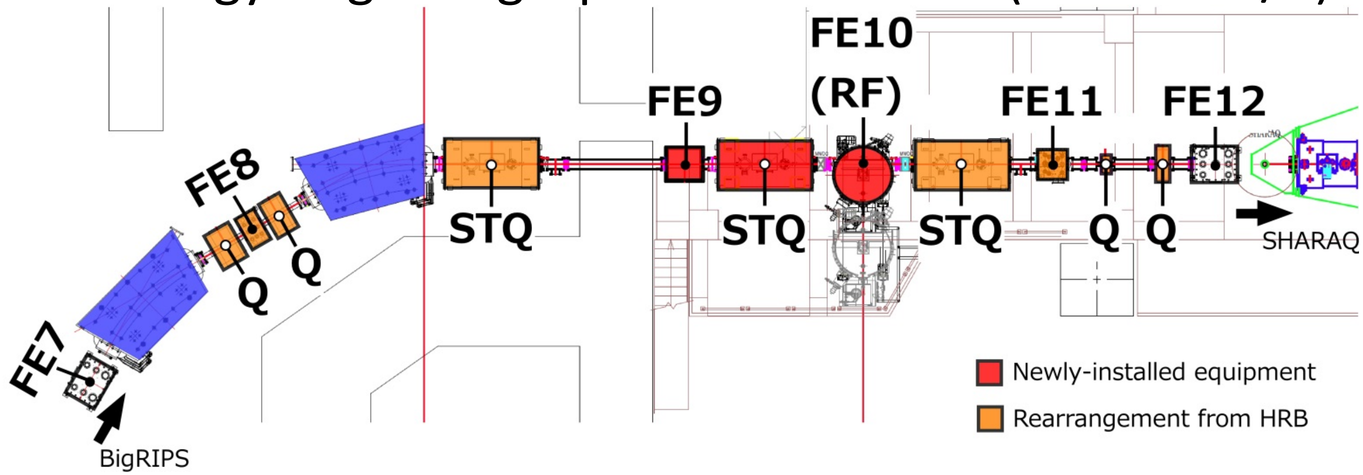


Kisamori *et al.*,
Phys. Rev. Lett. 116, 052501 (’16)

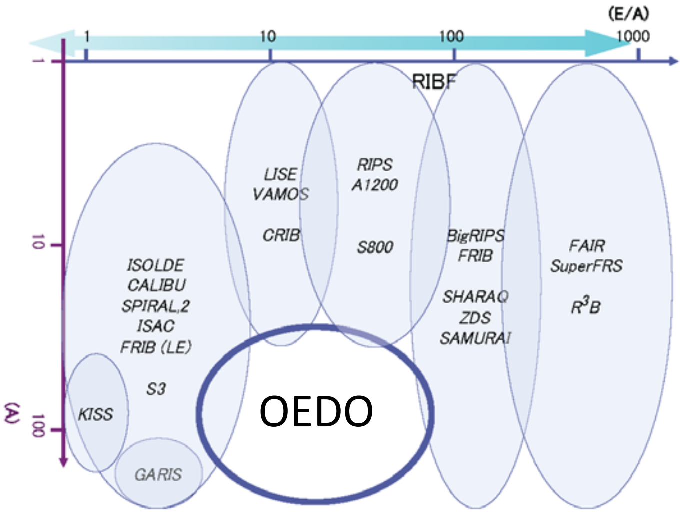


OEDO

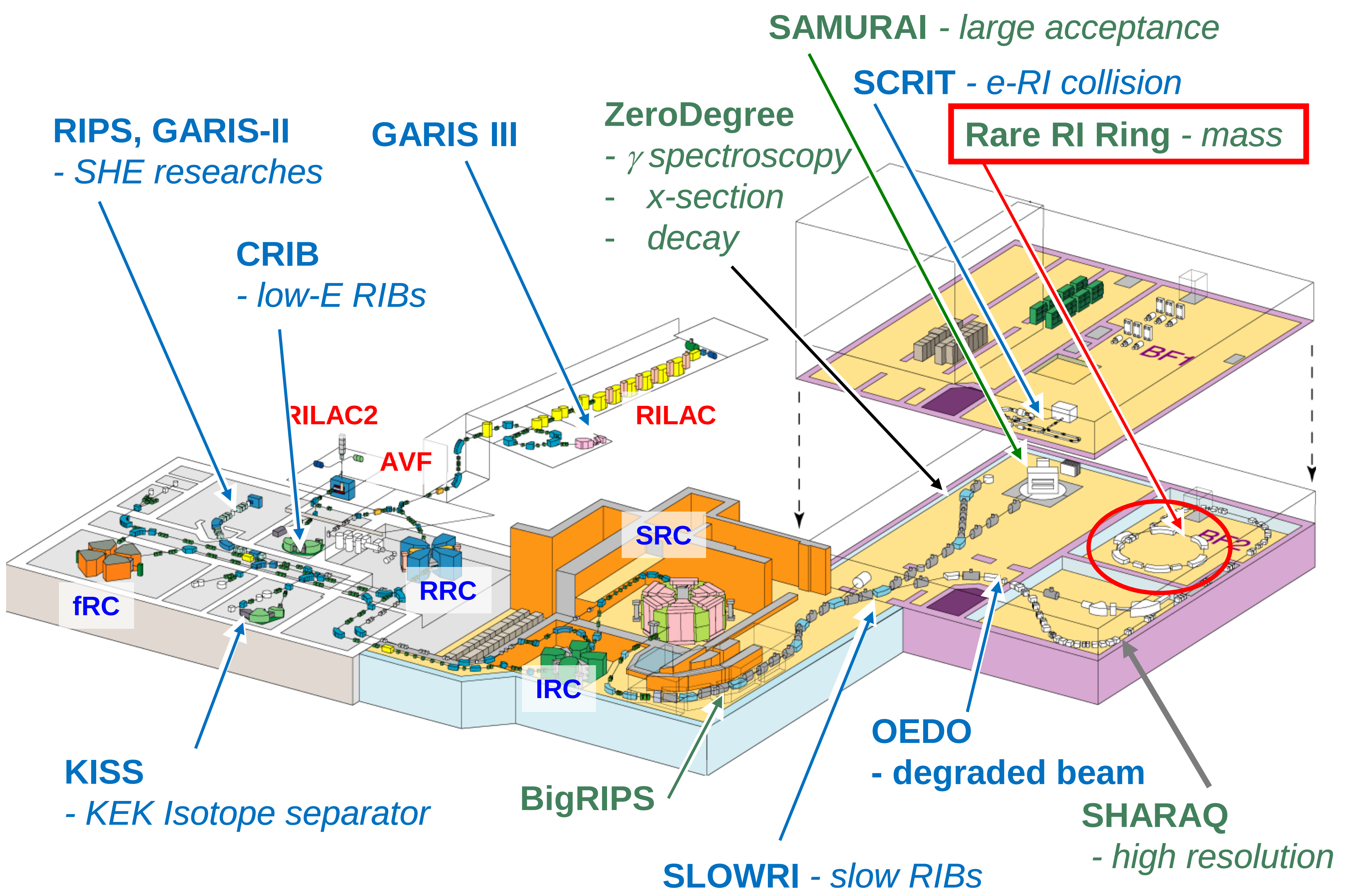
Optimized Energy Degrading Optics for RI beam (< 50 MeV/u)



Commissioning using ^{79}Se and ^{107}Pd was successfully done in FY**2017**.
^{79}Se : 170 → 45 MeV/u
^{107}Pd : 180 → 33 MeV/u
Beam spot size is reduced to ~20 mm after RF deflector is on.

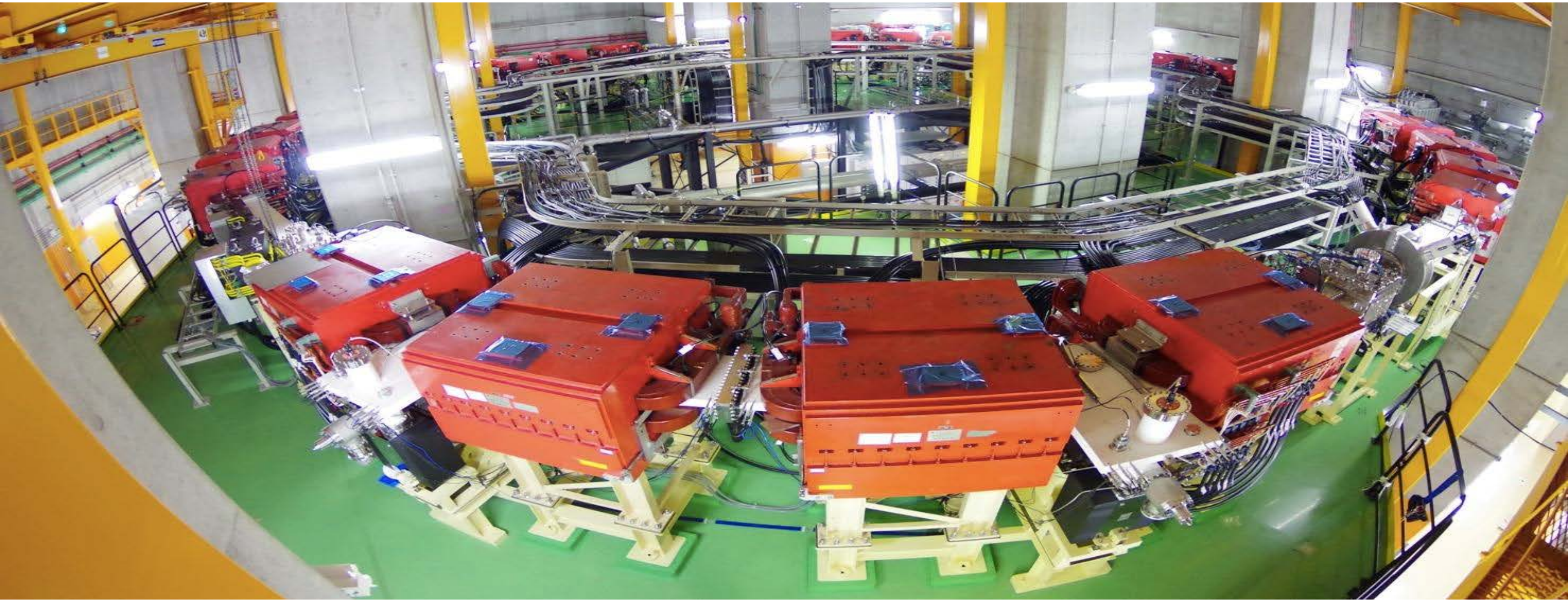


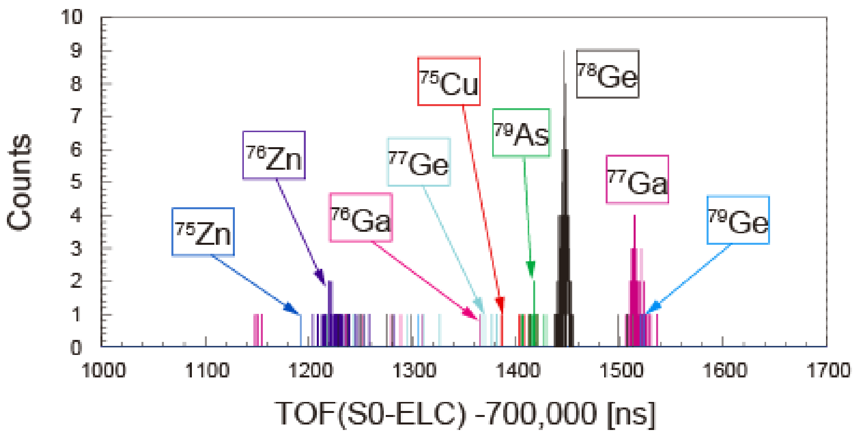
Rare RI Ring (R3)



Rare RI Ring (R3)

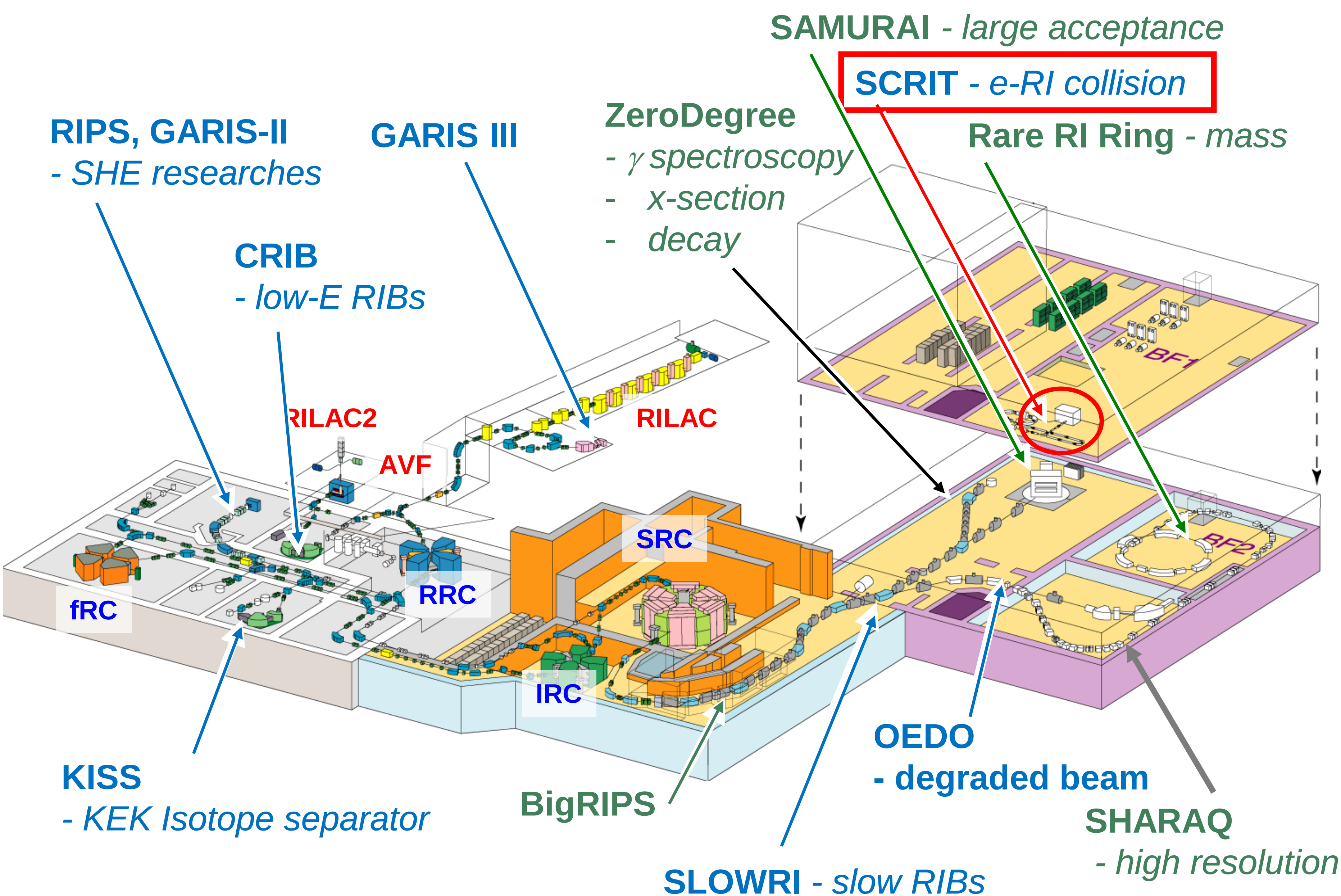
Mass measurement in an 'isochronous' storage ring





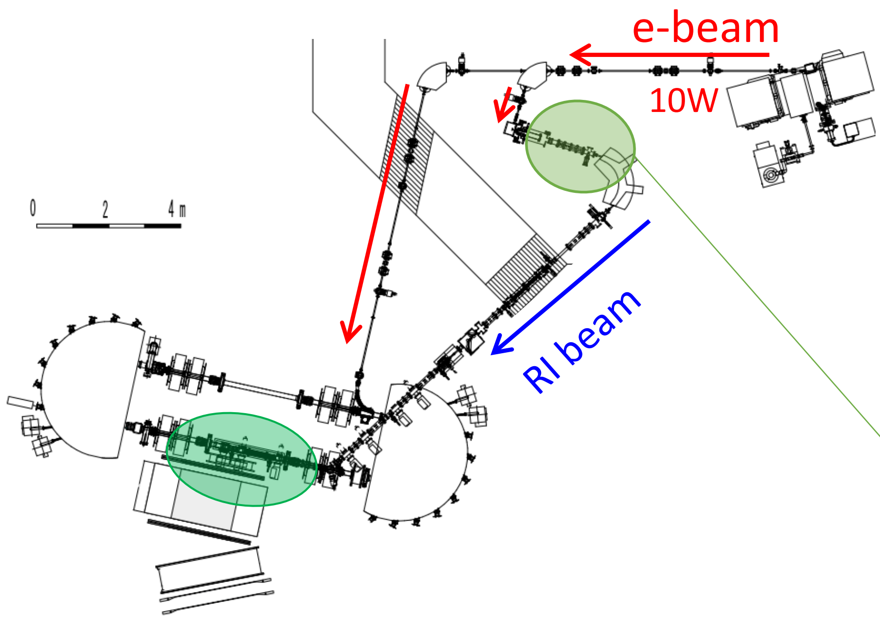
$$f_c = \frac{1}{2\pi}\frac{qB}{m}$$

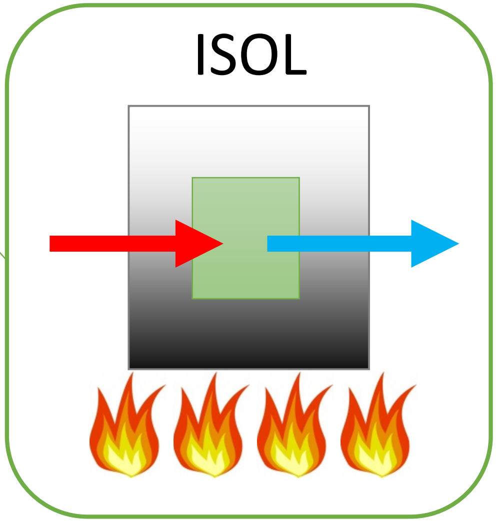
SCRIT (Self Confining RI Ion Target)

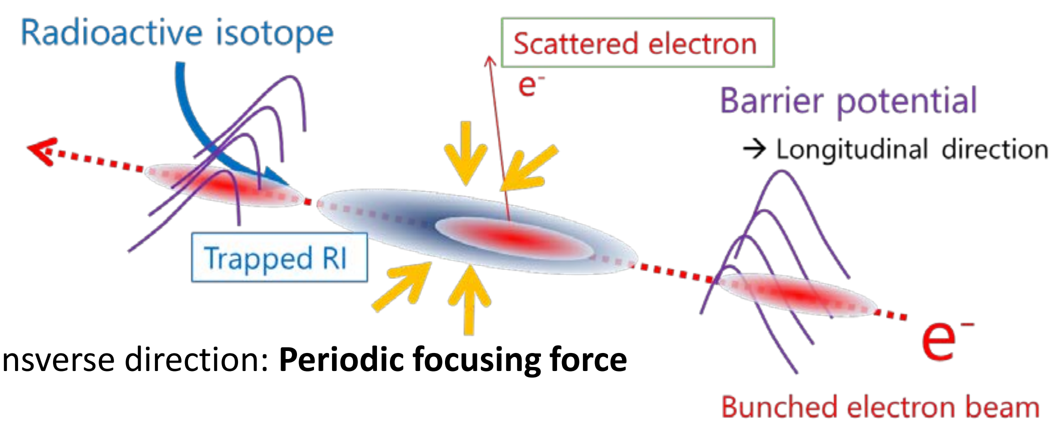


SCRIT (Self Confining RI Ion Target)

Electron scattering off RI beam





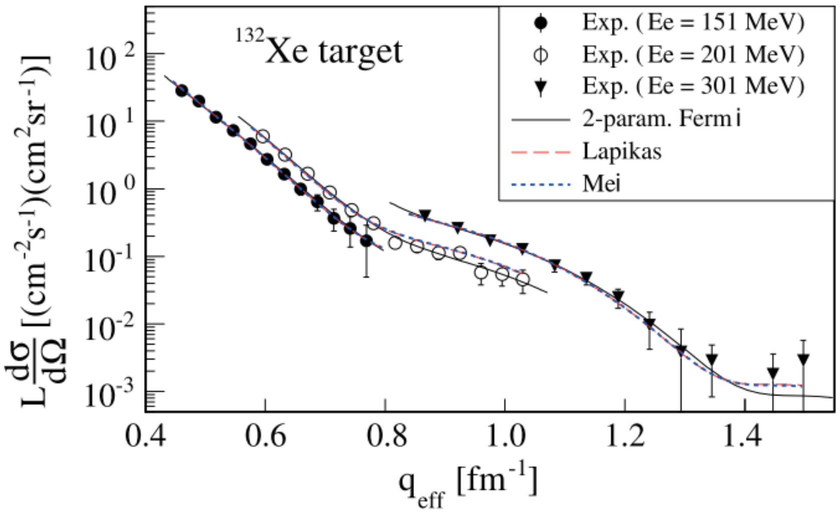


Transverse direction: **Periodic focusing force**

M. Wakasugi *et al.*, Nucl. Inst. Meth. A 532, 216 ('04)
M. Wakasugi *et al.*, Phys. Rev. Lett. 100, 164801 ('08)
T. Ohnishi *et al.*, Phys. Scr. T166, 014071 ('15)
T. Ohnishi *et al.*, PoS (INPC2016) 088.

SCRIT (Self Confining RI Ion Target)

First electron scattering of ^{132}Xe

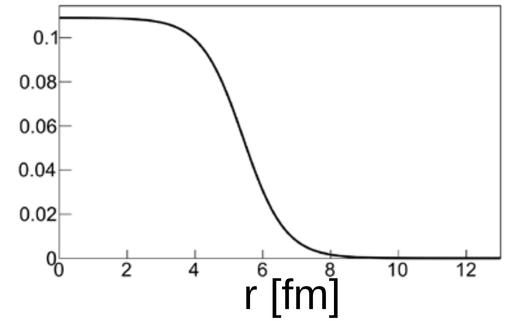


$$\rho_C = \rho/(1 + e^{4.4(r-C)/t})$$

$$C = 5.42^{+0.11}_{-0.08}$$

$$t = 2.71^{+0.29}_{-0.38}$$

$$\langle r \rangle^{1/2} = 4.79^{+0.12}_{-0.10}$$



Achieved luminosity: 1.8×10^{27} cm^{-2}s^{-1} at 250 mA

with 2×10^8 ions /(1pulse injection)

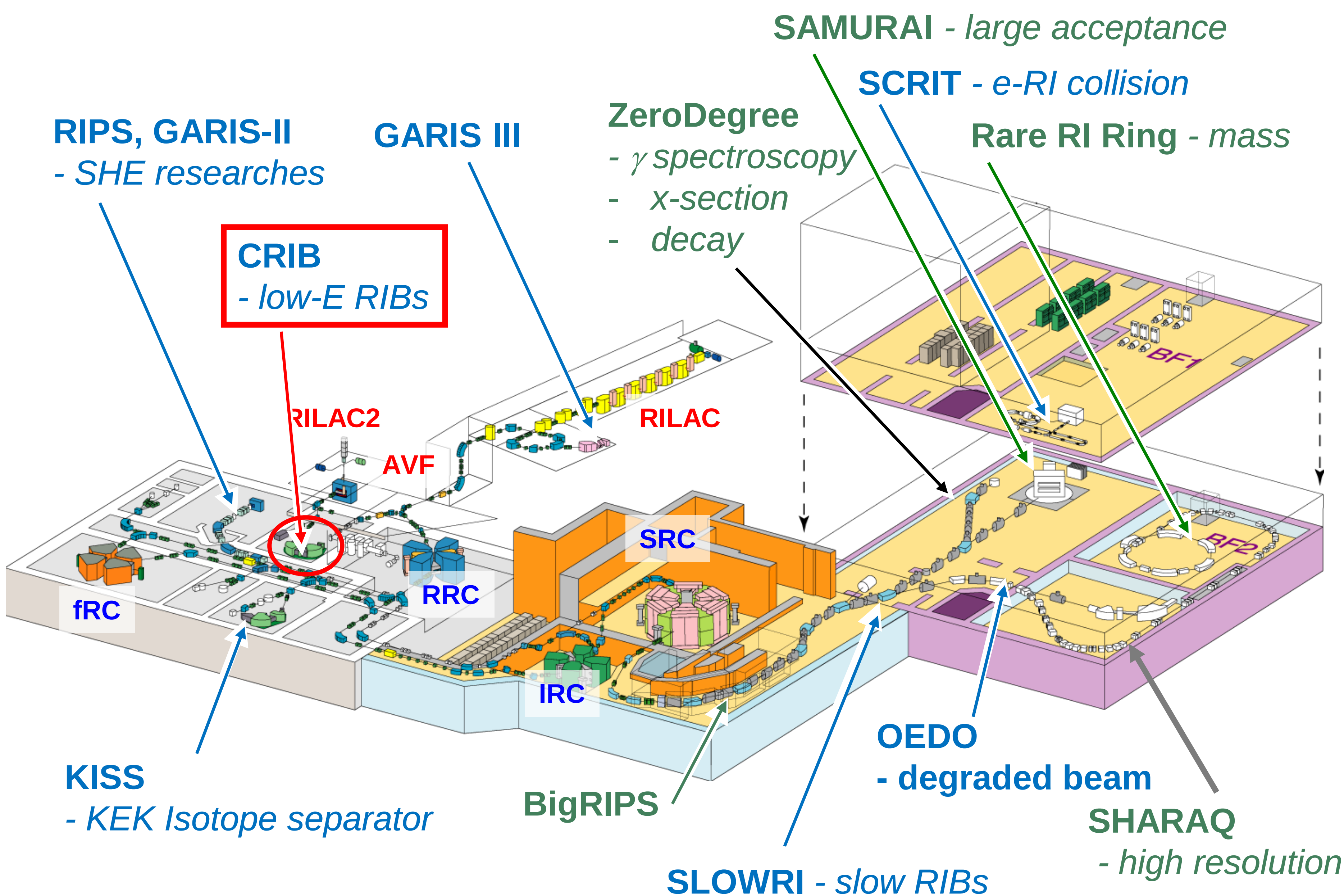
K. Tsukada et al., Phys.Rev.Lett. **118** (2017) 262502.

Ready for unstable nuclei !

e-beam power upgrade : ~ 50W (Now going)

1kW (Future plan)

CRIB

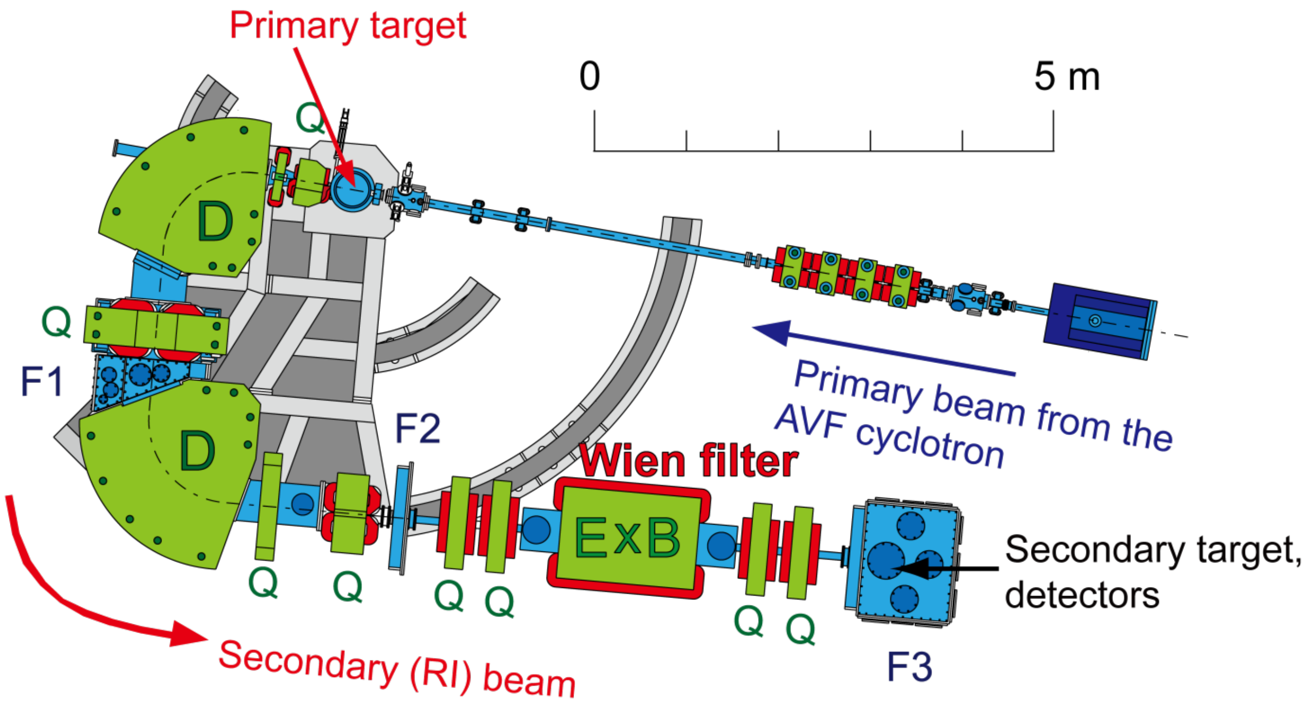


SAMURAI - large acceptance
SCRIT - e-RI collision
ZeroDegree
- γ spectroscopy
- x-section
- decay
Rare RI Ring - mass
RIPS, GARIS-II
- SHE researches
GARIS III
CRIB
- low-E RIBs
RILAC2
AVF
RILAC
BF1
BF2
SRC
RRC
fRC
IRC
KISS
- KEK Isotope separator
BigRIPS
OEDO
- degraded beam
SHARAQ
- high resolution
SLOWRI - slow RIBs

CRIB (CNS Radio-Isotope Beam Separator)

Low-energy RI beams (<10 MeV/u) for astrophysical reactions

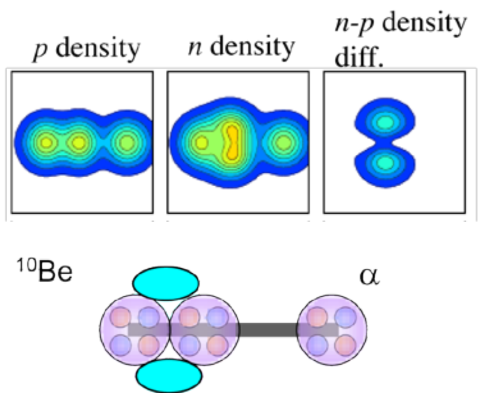
- **Low-energy(<10MeV/u) RI beam** production with in-flight method.
- Two stages of electromagnetic beam purification.
- Typical intensity 10^4-10^6 pps (10^8 pps for 7Be).
- Suitable for **nuclear astrophysics** and **nuclear structure** study.

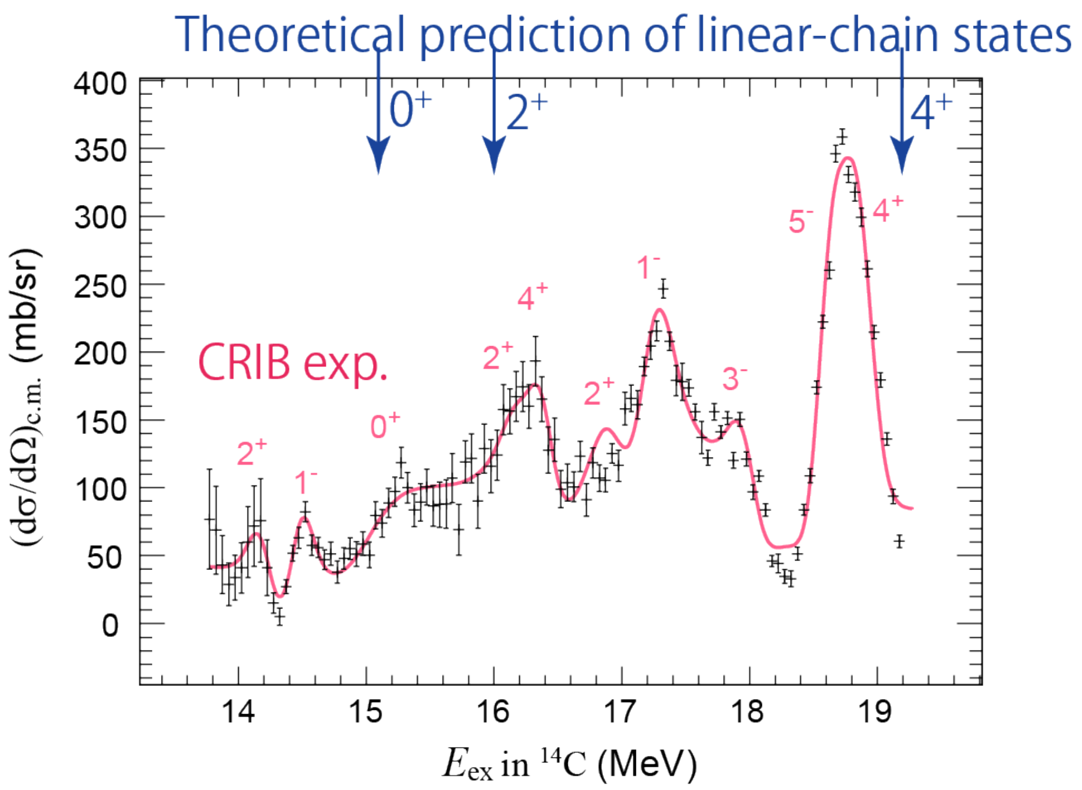


CRIB (CNS Radio-Isotope Beam Separator)

Strong indication of linear-chain structured nucleus found in ^{14}C
- H. Yamaguchi et al., Phys. Lett. B (2017)

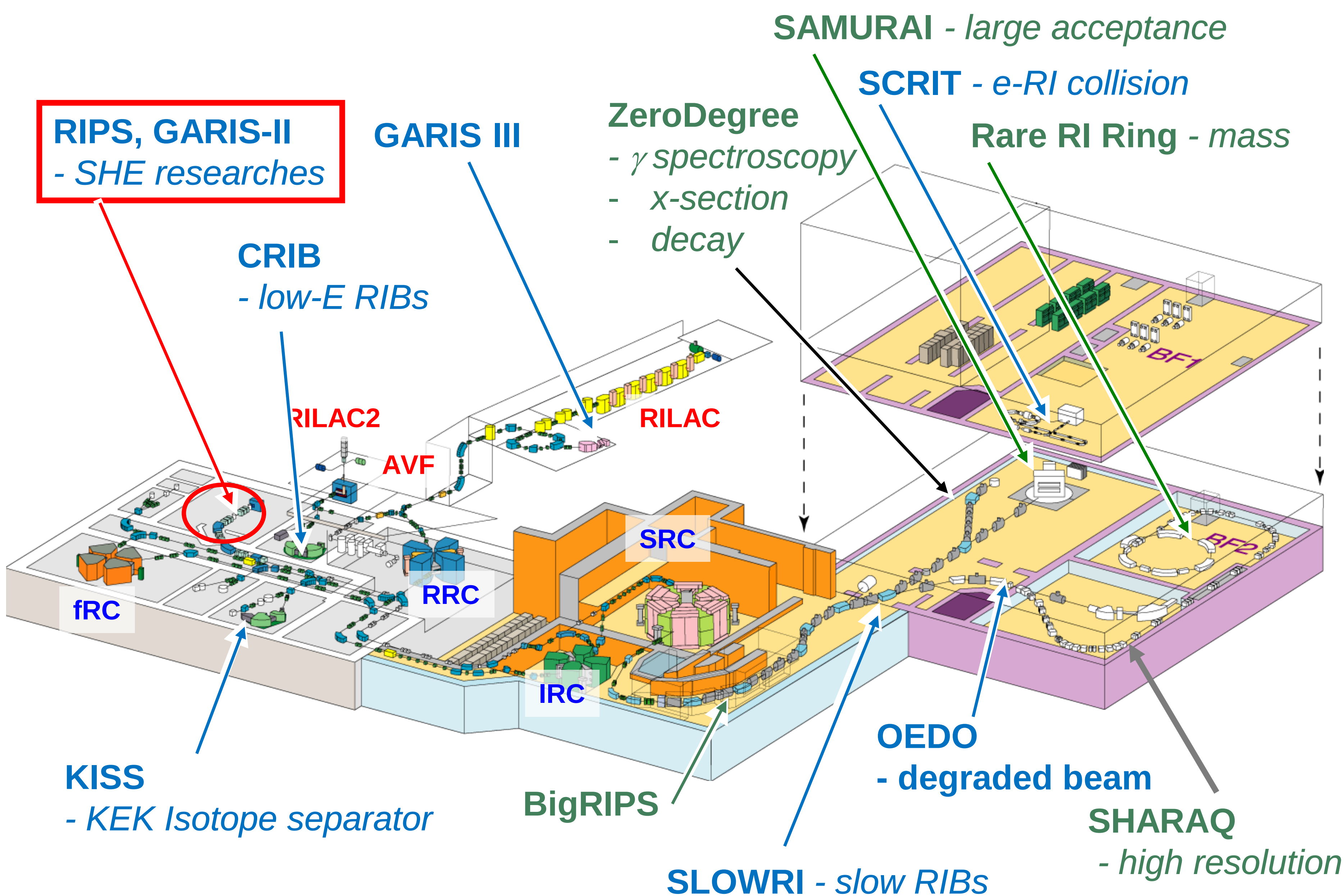
Suhara & En'yo, PRC 2010 and 2011:





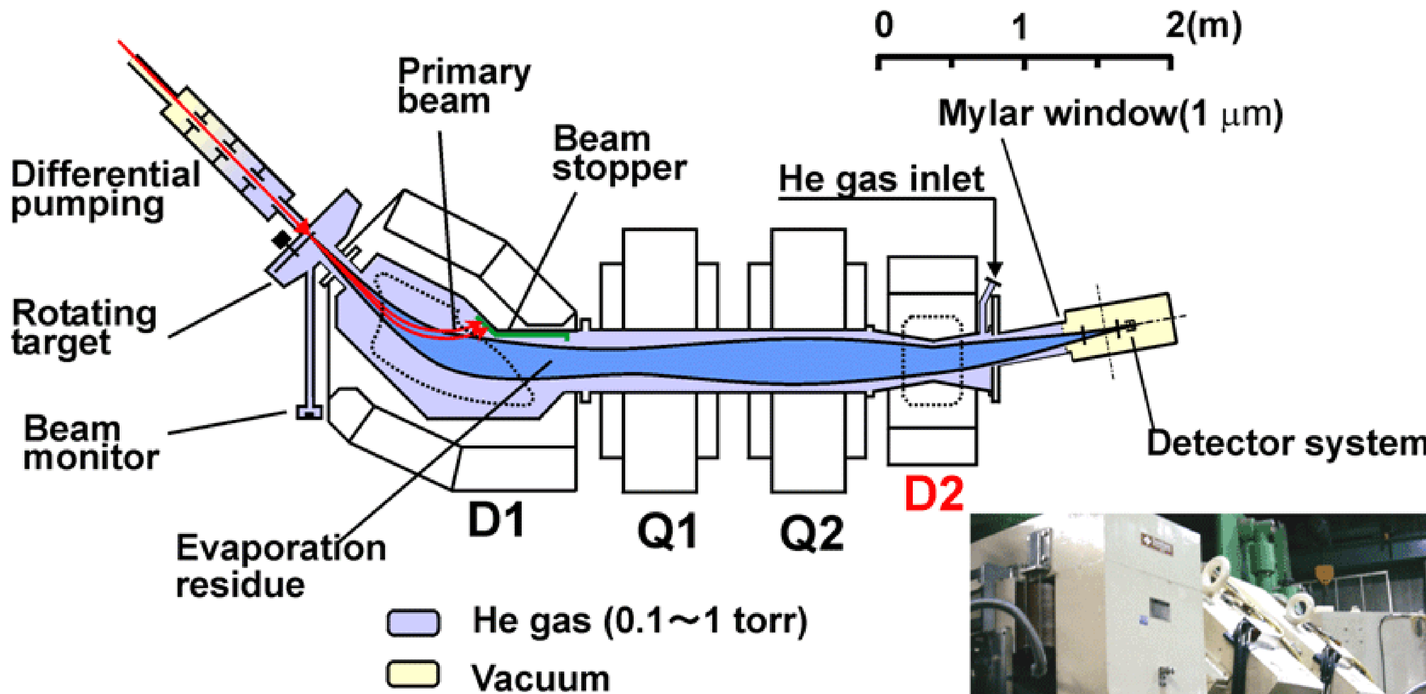
Excellent agreement between experiment and theoretical prediction of the linear-chain (0^+, 2^+, 4^+) states.

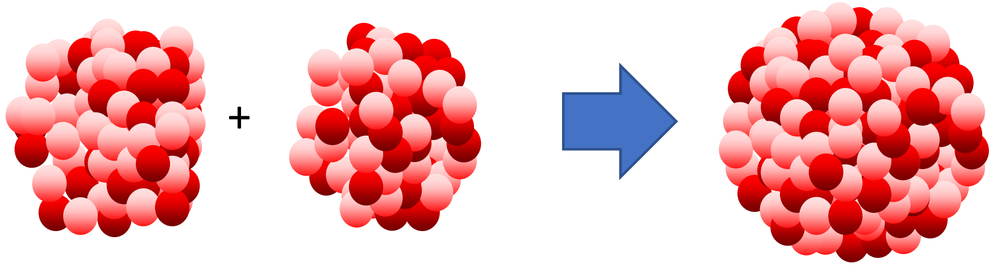
GARIS (Gas-filled Recoil Ion Separator)



GARIS (Gas-filled Recoil Ion Separator)

Search for super heavy elements: coalescence of two nuclei





GARIS (Gas-filled Recoil Ion Separator)

The name of nihonium (Nh) is approved for element 113

$$^{209}\mathrm{Bi} + {}^{70}\mathrm{Zn} \rightarrow {}^{278}\mathrm{Nh} + n$$

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

Advancing Chemistry Worldwide

For Immediate Release 30 November 2016

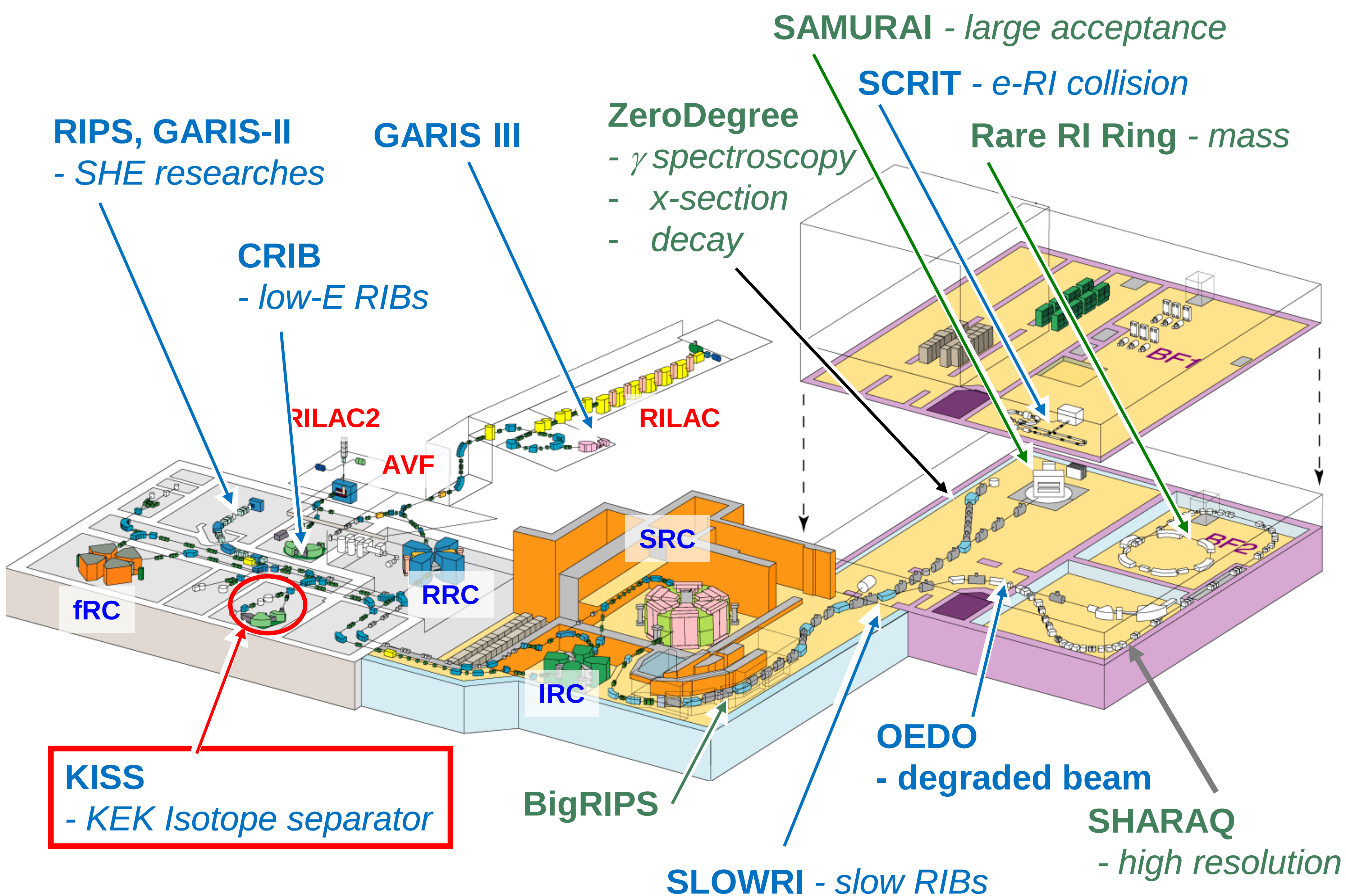
IUPAC Announces the Names of the Elements 113, 115, 117, and 118

Elements 113, 115, 117, and 118 are now formally named nihonium (Nh), moscovium (Mc), tennessine (Ts), and oganesson (Og)

Research Triangle Park, NC (USA): On 28 November 2016, the International Union of Pure and Applied Chemistry (IUPAC) approved the names and symbols for four elements: nihonium (Nh), moscovium (Mc), tennessine (Ts), and oganesson (Og), respectively for element 113, 115, 117, and 118.

Atomic number	Element name	Atomic symbol
113	nihonium	Nh
115	moscovium	Mc
117	tennessine	Ts
118	oganesson	Og

KISS (KEK Isotope Separator)



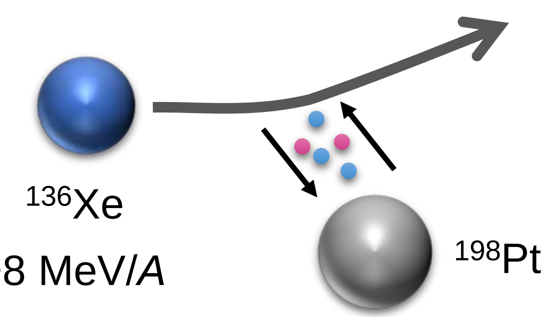
KISS (KEK Isotope Separator)

KISS has been constructed at RIKEN to measure lifetimes and masses of radioactive nuclei relevant to the r-process nucleosynthesis.

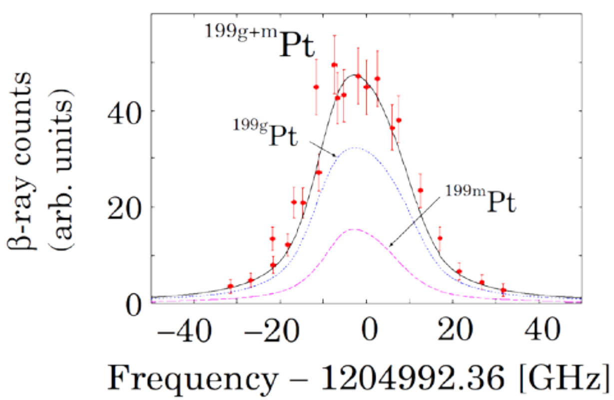
Nuclear properties of neutron-rich nuclei around the closed shell $N = 126$

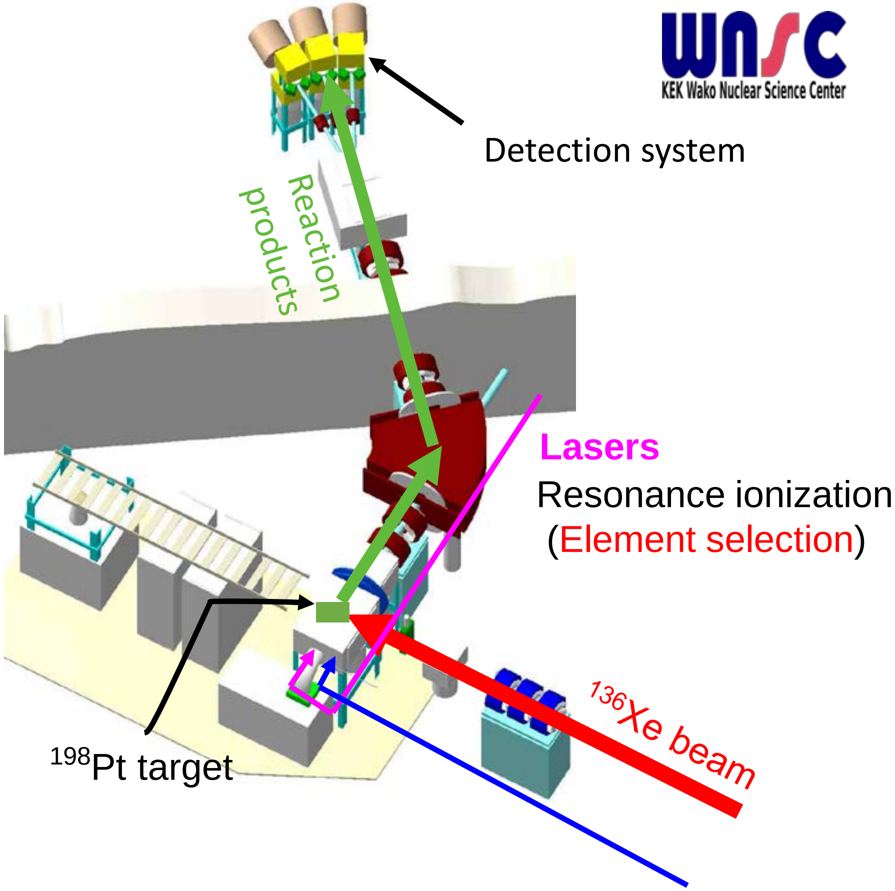
→ Astrophysical environments of r-process

Multiple nucleons transfer reaction



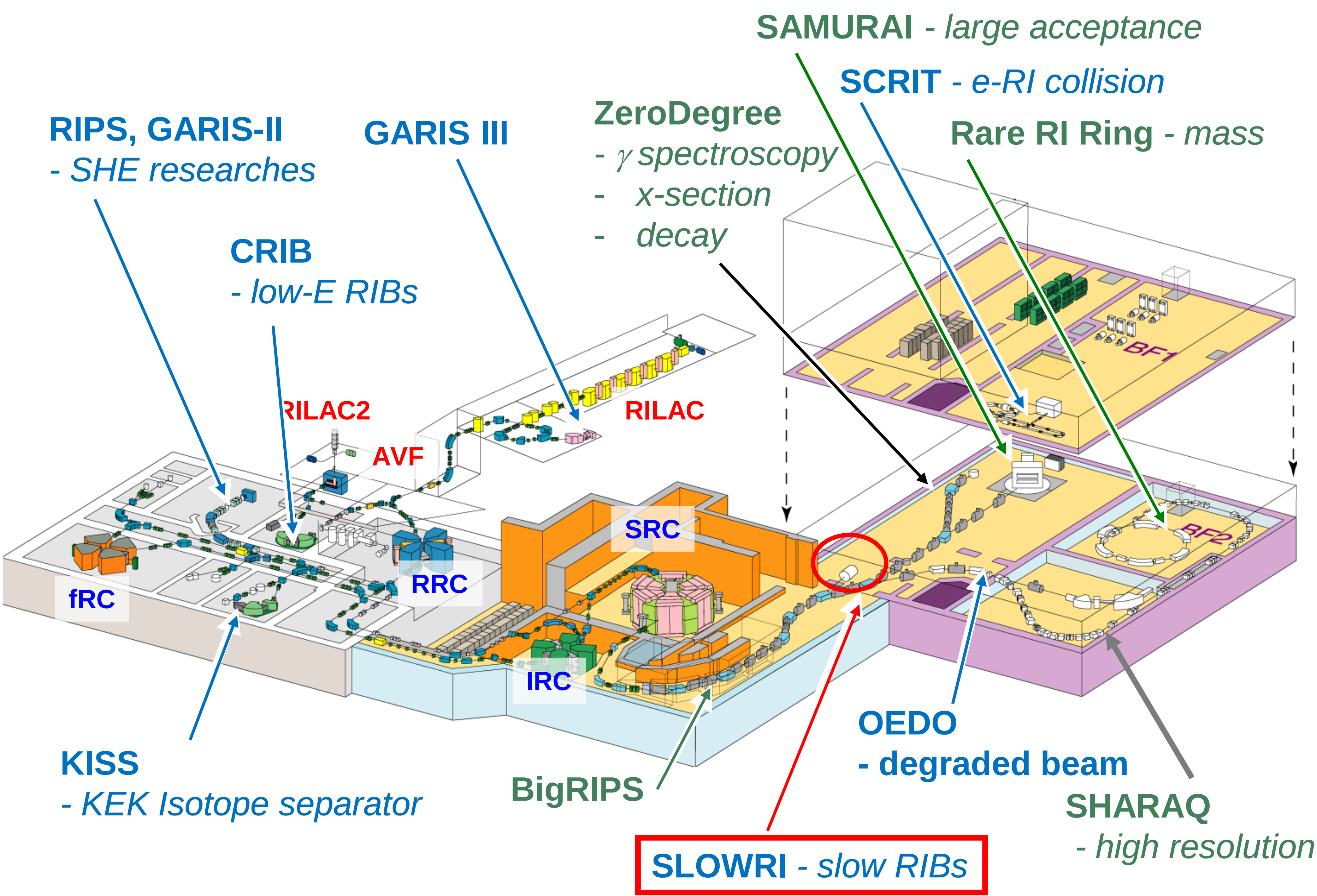
Laser resonance spectrum





Y. Hirayama et al.,
Nucl. Instrum. and Meth. B 353, 4 – 15 (2015).

SLOWRI


SAMURAI - large acceptance
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RIPS, GARIS-II
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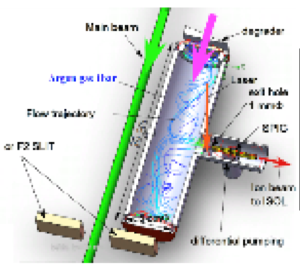
- low-E RIBs
RILAC2
RILAC
AVF
SRC
RRC
fRC
IRC
BF1
BF2
KISS
- KEK Isotope separator
BigRIPS
OEDO
- degraded beam
SHARAQ
- high resolution
SLOWRI - slow RIBs

SLOWRI

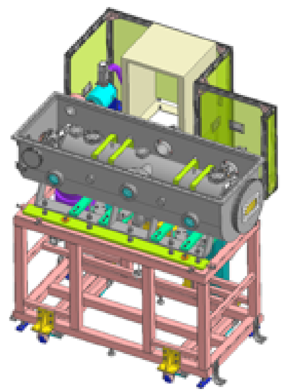
Universal ultra-slow beam production

BigRIPS

Relativistic RI Beam

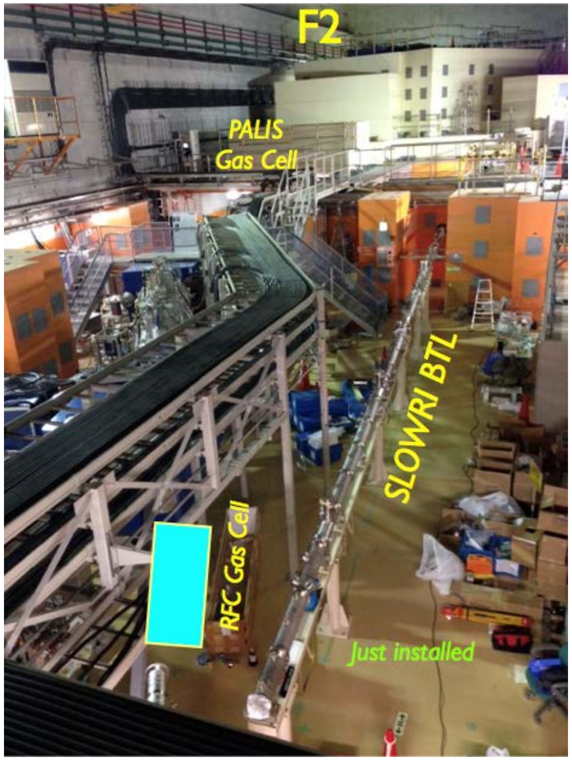


PALIS Gas Cell	***RF Carpet Gas Cell***
Parasitic RI	*Universal RI*



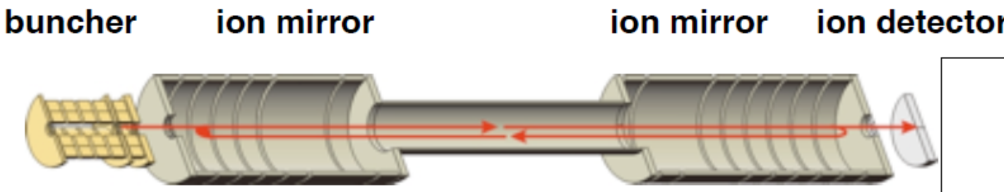
Low-energy or Trapped RI Beam

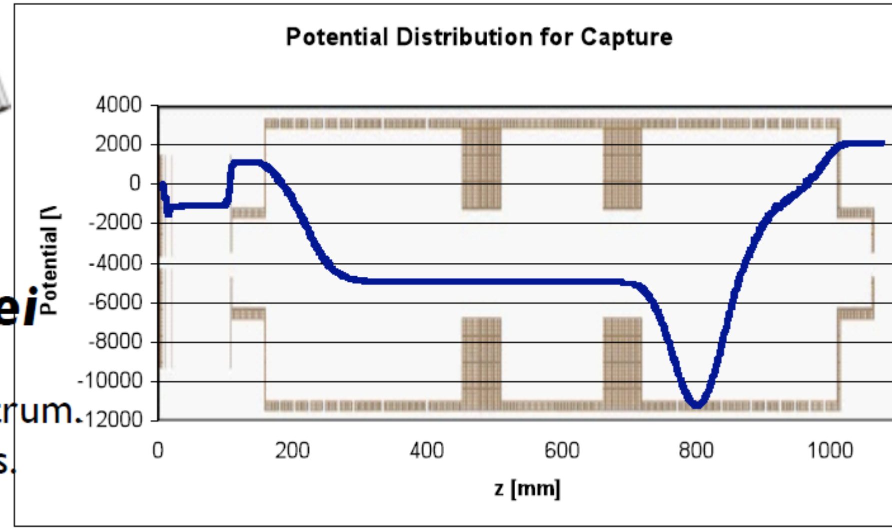
Mass Spectrograph
Laser Spectroscopy
Trap Apparatuses
αβγn spectrometers



1. Wide Range of Nuclides
2. High Purity
   No Isobar No Isotone Contamination
3. Small Emittance
   ～πmm・rad
4. Variable Beam Energy
   1-50 keV Slow Beam, <1eV Trapped RI, 1MeV/u (future)
5. Human Accessibility during On-line Exp.

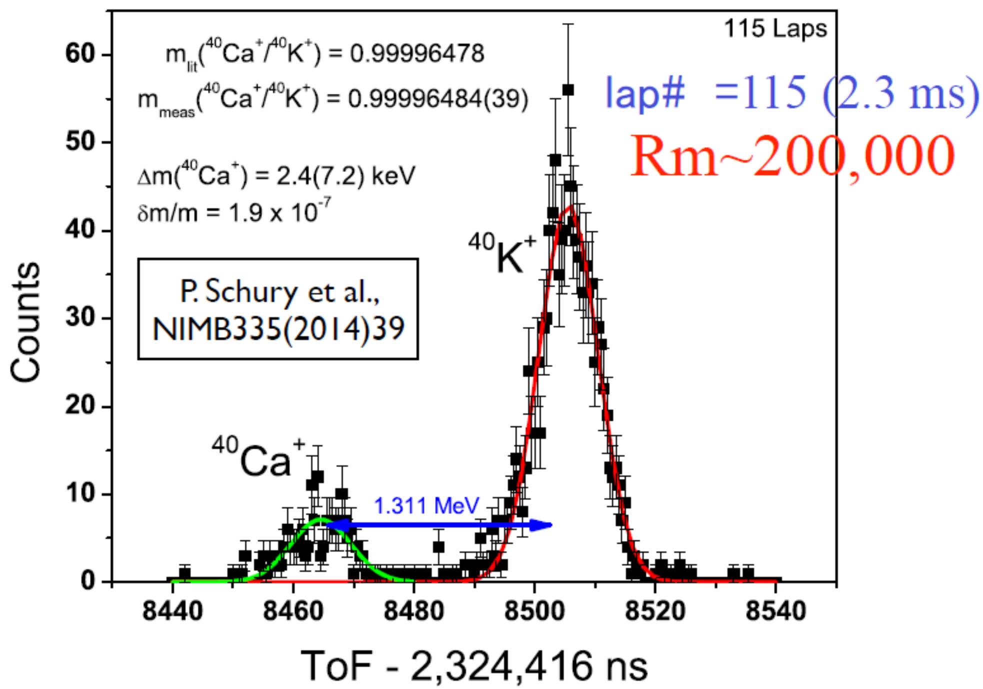
MRTOF Mass Spectrograph

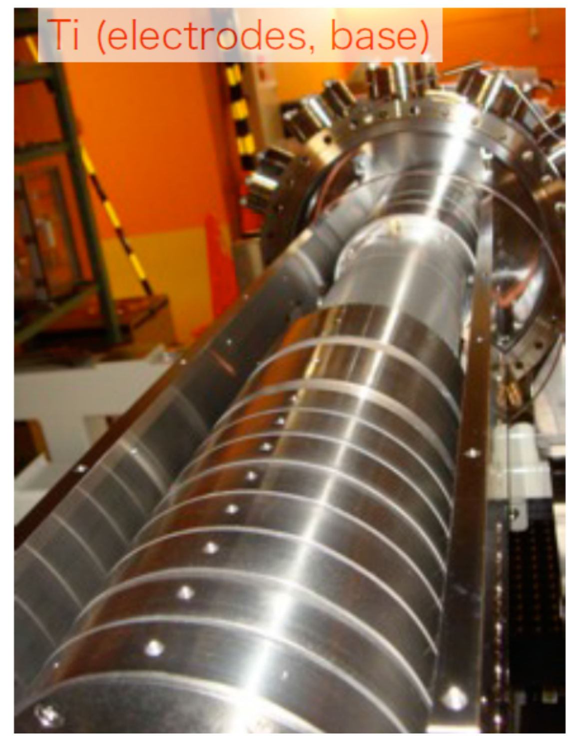




Simple device but advantage to Penning Trap for short-lived nuclei

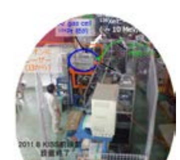
- All isobars are measured (simultaneously) in one spectrum.
- No scan is needed, all particles contribute to statistics.
- $\Delta M \sim 10$ keV/c^2 is feasible in 2 ms cycle.





RIBF provides opportunities

- Mass?
- Half-life?
- Excited states?
- Deformation?
- Charge radii?
- Matter radii?
- Charge distribution?
- Matter distribution?
- EM moments?
- Single particle states?
- Astrophysical reactions?
- Giant resonances?
- Exotic modes?
- Equation of state?



;-) Let’s go to tour!