Nuclear mass measurements for the r-process in Rare-RI Ring

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Rare-RI Ring Collaboration

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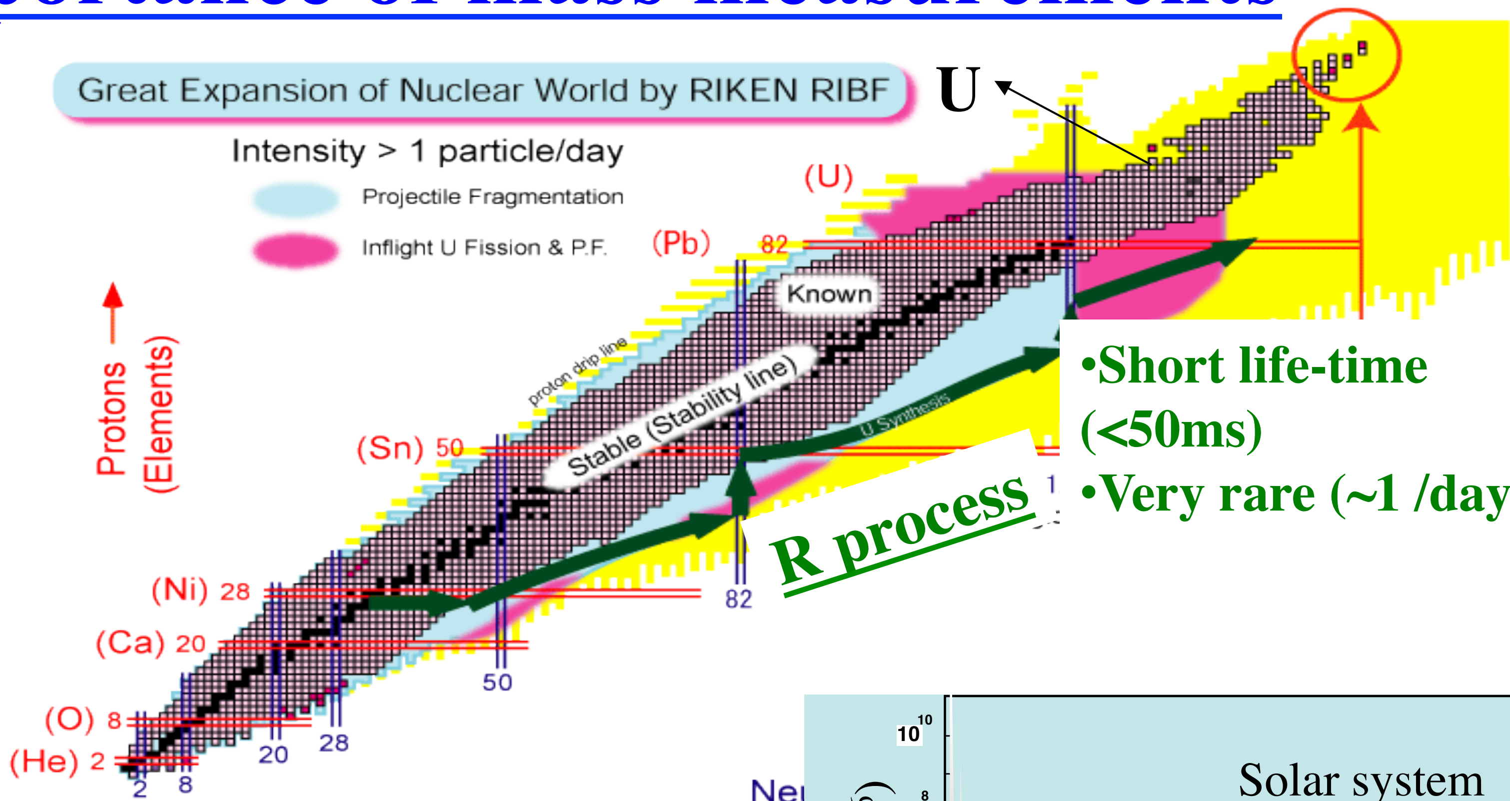
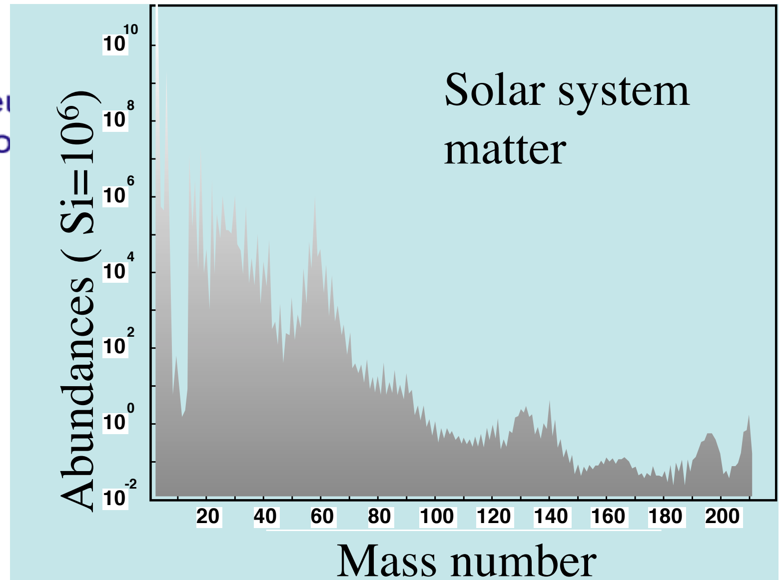
§ Importance of mass measurements



- Short life-time (<50ms)
- Very rare (~1 /day)

How are heavy stable nuclei created in universe ?

Can we reproduce observed abundances ?



Prediction of the r-process

Parameters for astrophysics ：Temperature (T), Neutron density (N_n), Time (t)
Parameters for nuclear physics：Mass (Q_n)、Decay constant (τ_β, etc.)

Approx. 1： (n,γ)-(γ,n), Waiting point approximation

$$\lambda_{\gamma n} \approx \frac{T^{3/2}}{N_n} \exp\left(-\frac{Q_n}{kT}\right)\lambda_{n\gamma}$$

From mass prediction

Astrophysical inputs: N_n、T

Approx. 2： Steady flow approximation

$$\lambda_{Z-1}(t)N_{Z-1}(t) = \lambda_Z(t)N_Z(t)$$

$$N_Z \propto 1/\lambda_Z = \tau_\beta(Z)$$

Predictable by mass

Mass measurements are very important!

Necessary mass accuracy

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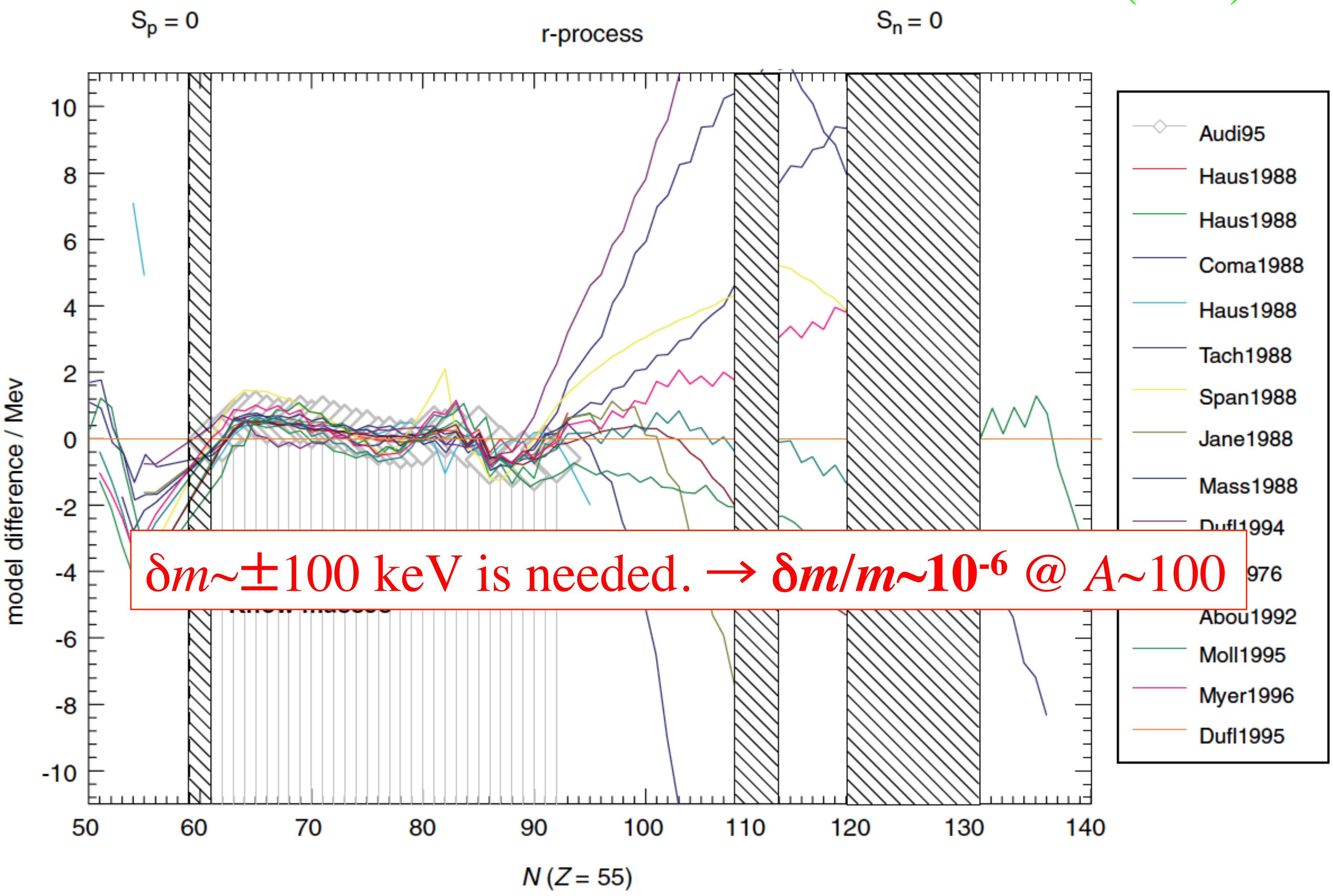

$\delta m \sim \pm 100$ keV is needed. → $\boldsymbol{\delta m/m \sim 10^{-6}}$ @ $A \sim 100$

Mass measurements in Penning Trap

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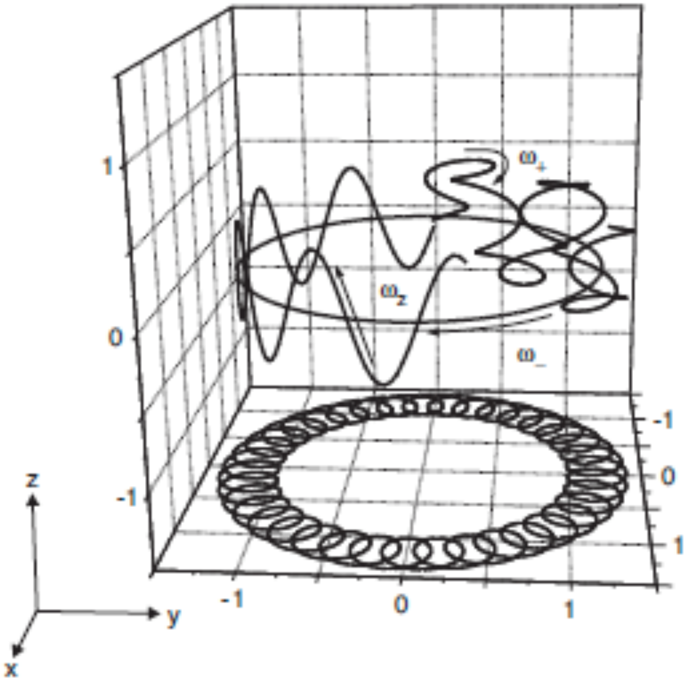
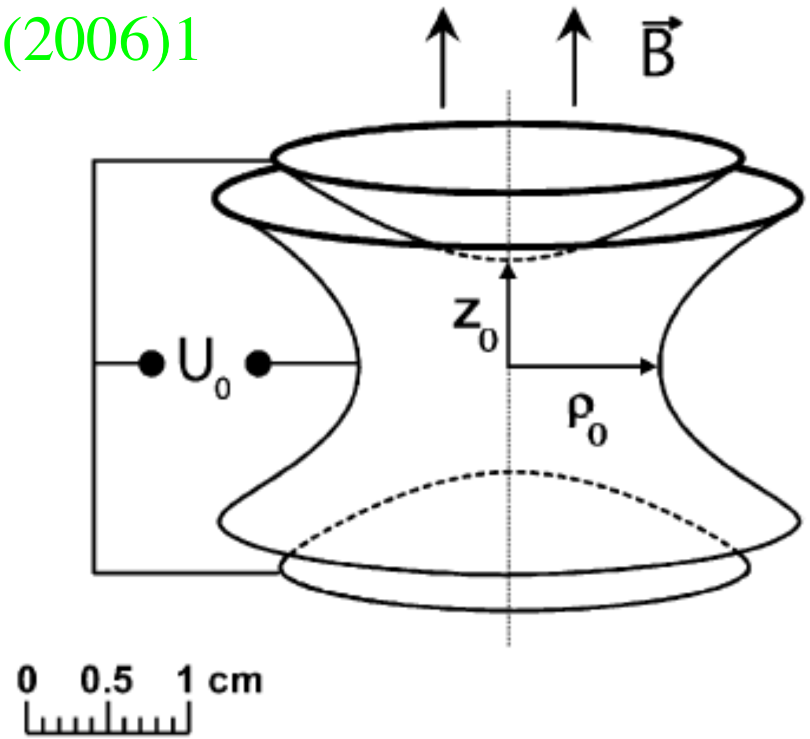
Cyclotron frequency: ω_C

Magnetron frequency





$$\omega_C = \omega_+ - \omega_-$$

$$\omega_C = \frac{qB}{m}$$

Advantage:

High resolution (<10^{-6})

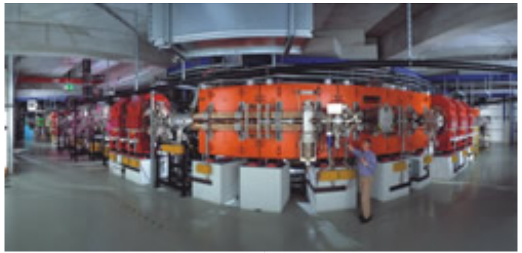
Disadvantage:

Low energy RI beams

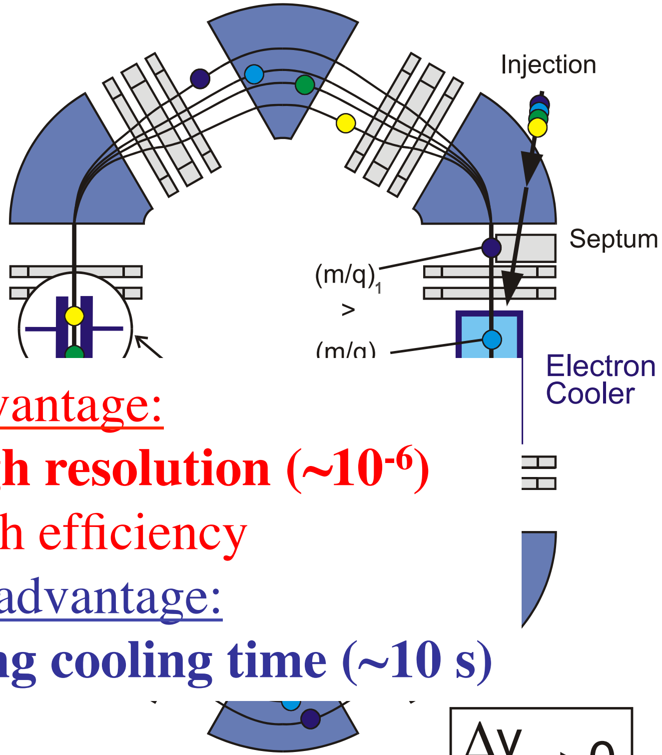
Long measurement time (~1 s)

Specified isotopes

Mass measurements in ESR/GSI



SCHOTTKY MASS SPECTROMETRY



Advantage:

High resolution (~10^{-6})

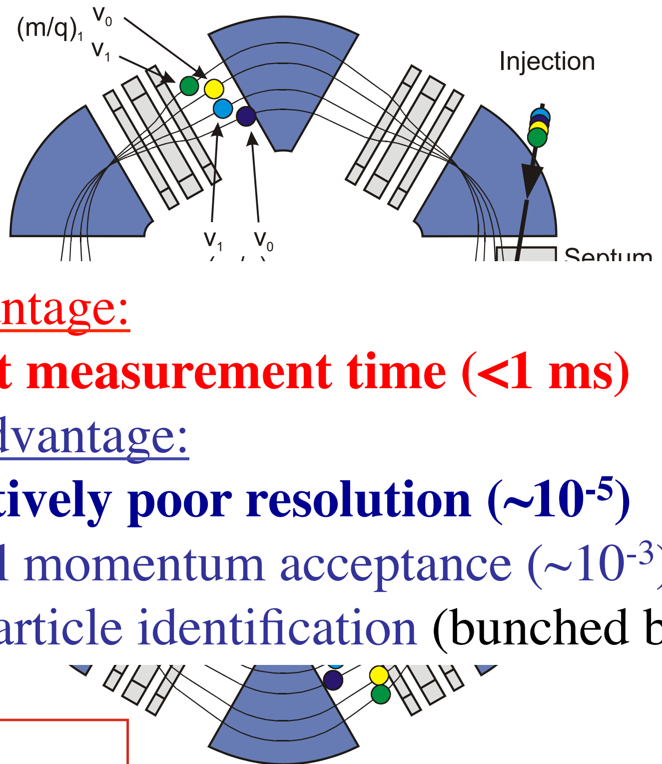
High efficiency

Disadvantage:

Long cooling time (~10 s)

Cooled Fragments

ISOCHRONOUS MASS SPECTROMETRY



Advantage:

Short measurement time (<1 ms)

Disadvantage:

Relatively poor resolution (~10^{-5})

Small momentum acceptance (~10^{-3})

No particle identification (bunched beam)

Hot Fragments

$$\frac{\Delta v}{v} \rightarrow 0$$

$$\gamma_t \rightarrow \gamma$$

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1 - \frac{\gamma^2}{\gamma_t^2}\right)$$

§ Mass measurements in Rare-RI Ring

Principle

Based on $f_c = \frac{1}{2\pi}\frac{qB}{m}$ **: cyclotron frequency**

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

Isochronous optics

For $m_1/q = m_0/q + \Delta(m_0/q)$

Isochronism is no longer fulfilled.

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

Measurement of β or $B\rho$ is indispensable.

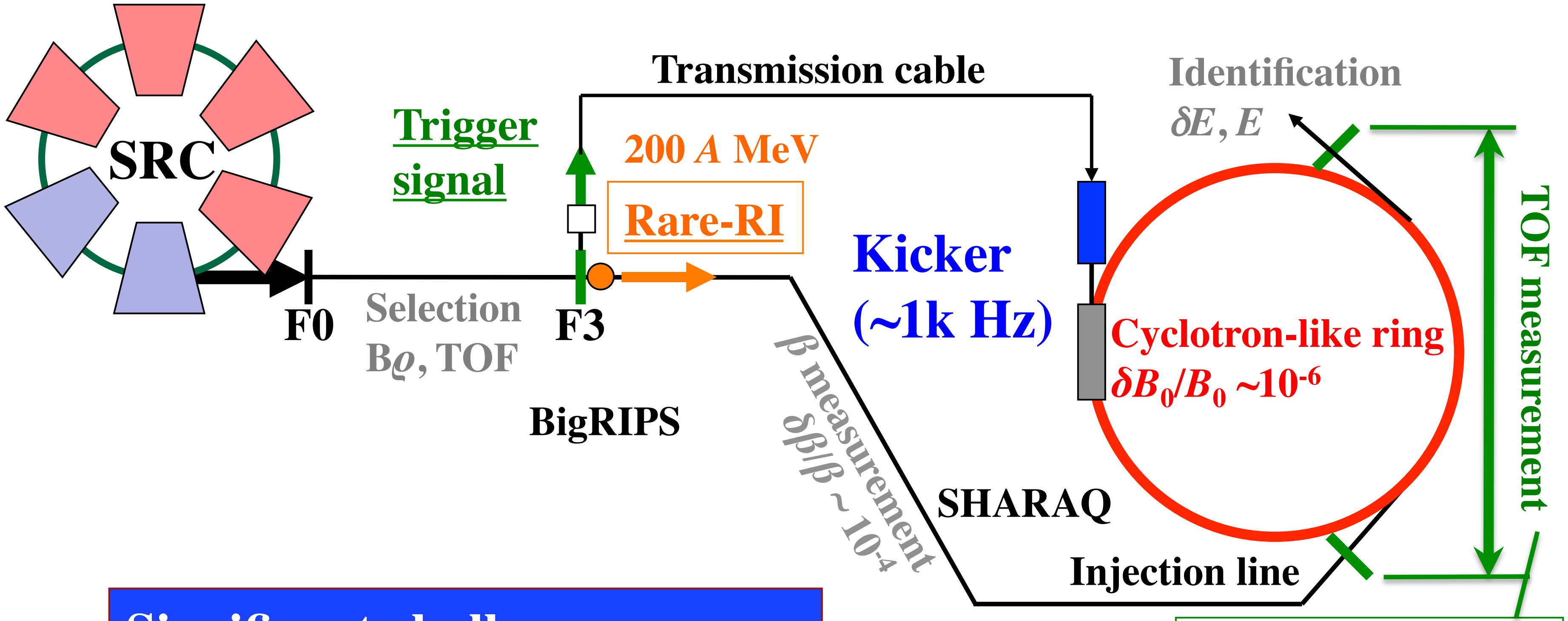
$\delta\beta/\beta \sim 10^{-4}$ → $\delta(m_1/q)/(m_1/q) \sim 10^{-5}$ for 10% m/q difference

Scheme for mass measurements

Only 1 particle is stored.

Isochronous mass spectrometry → **Short measurement time (<1 ms)**

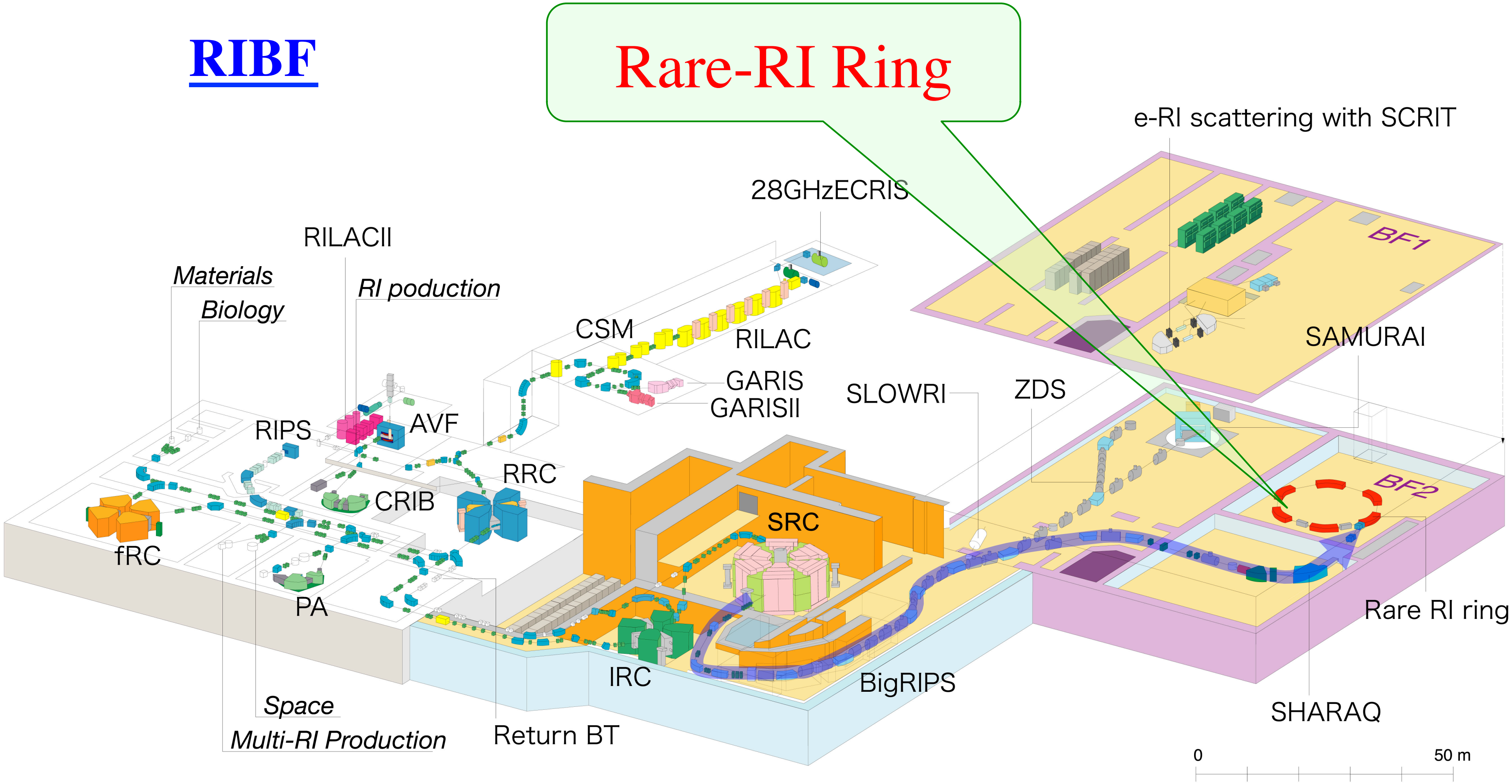
- **Isochronous field ~10^{-6}** → **Good resolution (~10^{-6})**
- Beam-triggered individual injection → High efficiency (~100%)



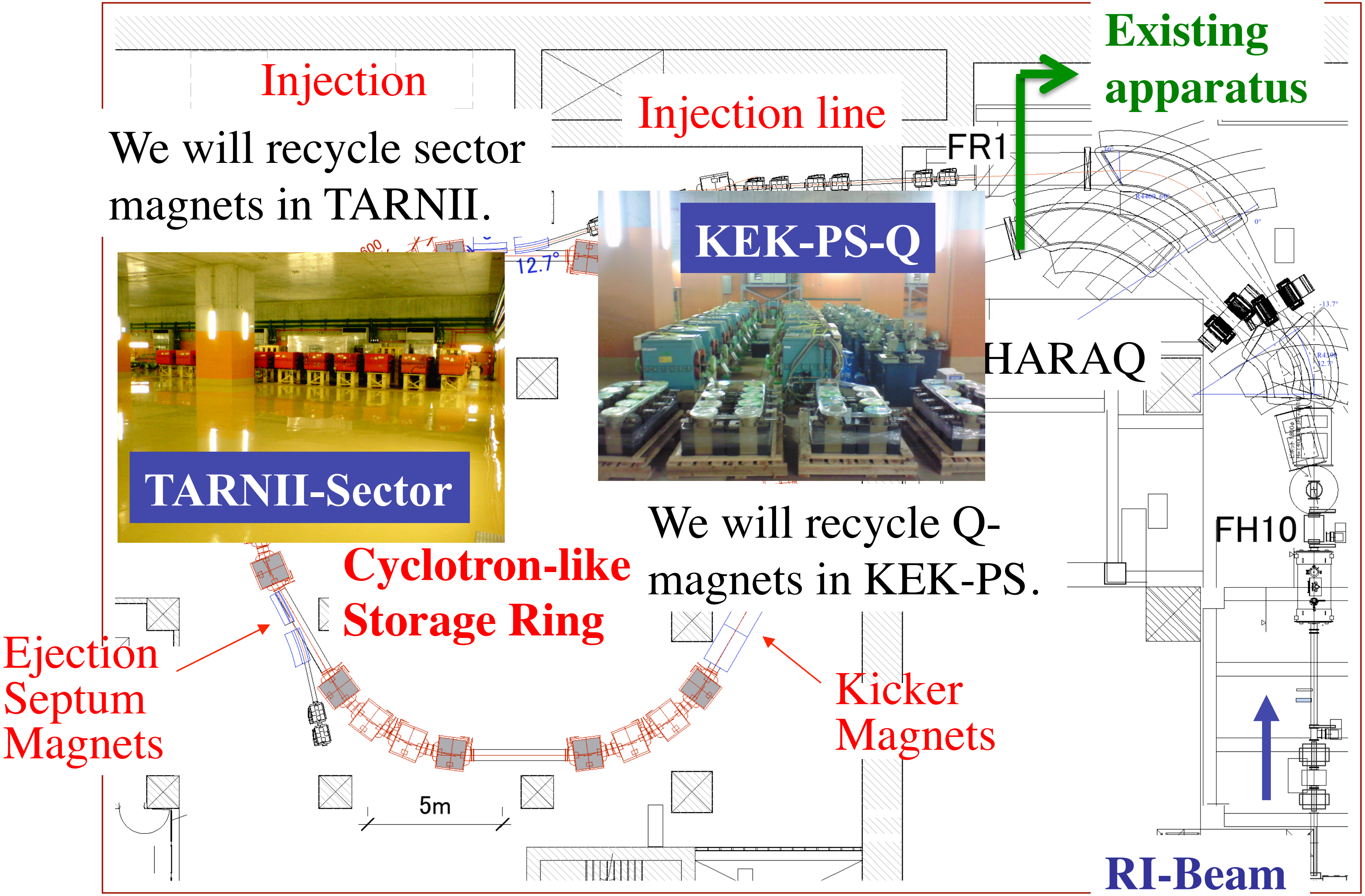
Significant challenges

- **Design for 10^{-6} isochronous field**
- **Fast response kicker-system**

Rare-RI Ring in RIBF



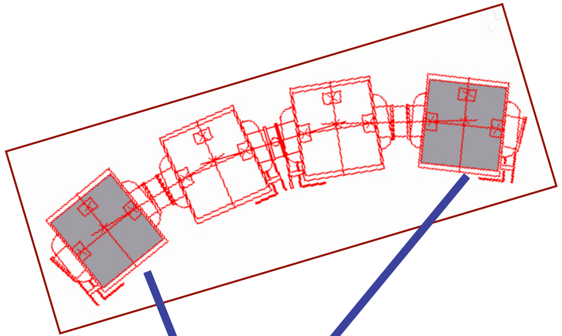
Floor arrangement @ RIBF B2F



Basic characteristics of cyclotron-like storage ring

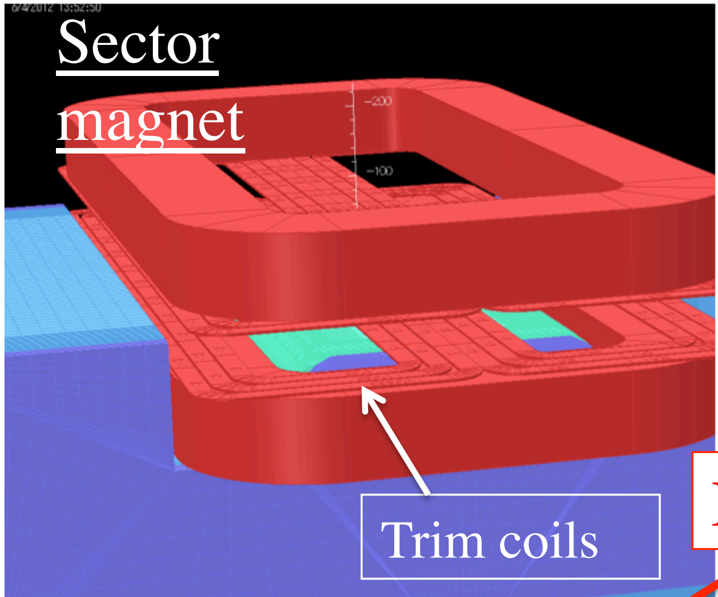
- Beam energy :	200 *A* MeV
- Lorentz factor γ :	1.2147
- Circumference :	60.3507 m
-Momentum acceptance :	±0.5 %
- Revolution frequency :	2.82 MHz
- Revolution time :	355 ns
- Betatron tune :	$Q_x = 1.25$, $Q_y = 0.82$
- Dispersion of straight part :	62.55 mm/%

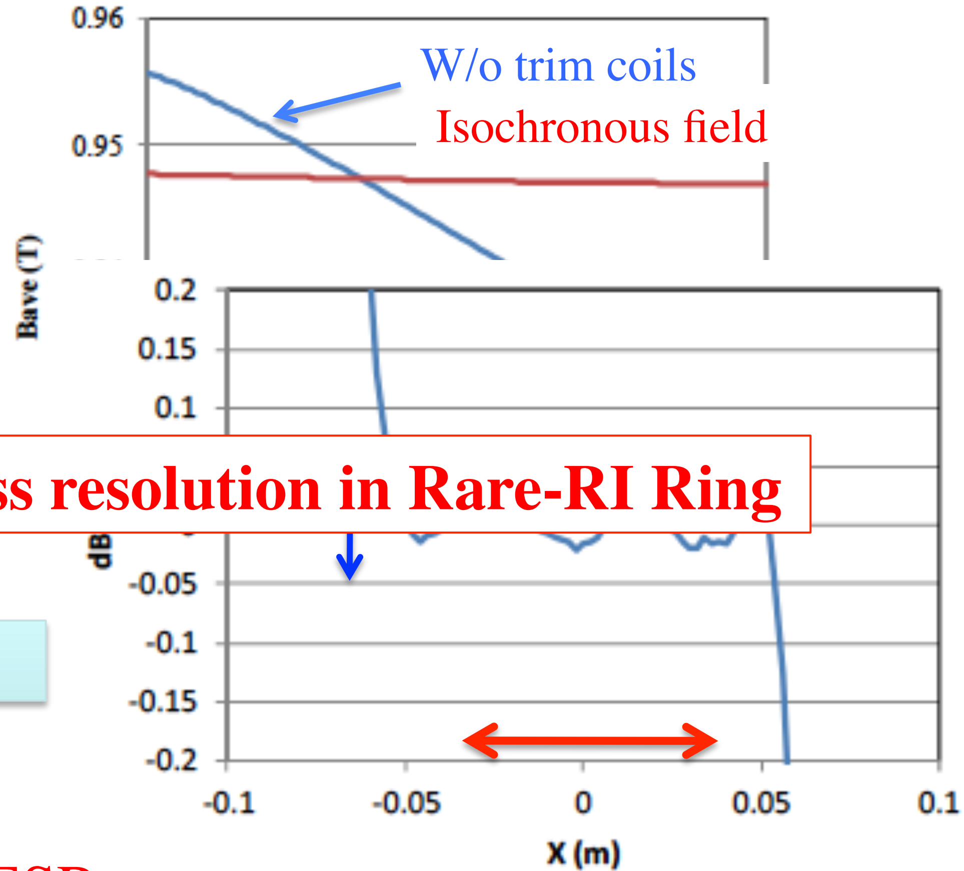
- Outer 2 sector magnets are modified to achieve a precise isochronous field.



Design of cyclotron-like storage ring

We locate trim coils.



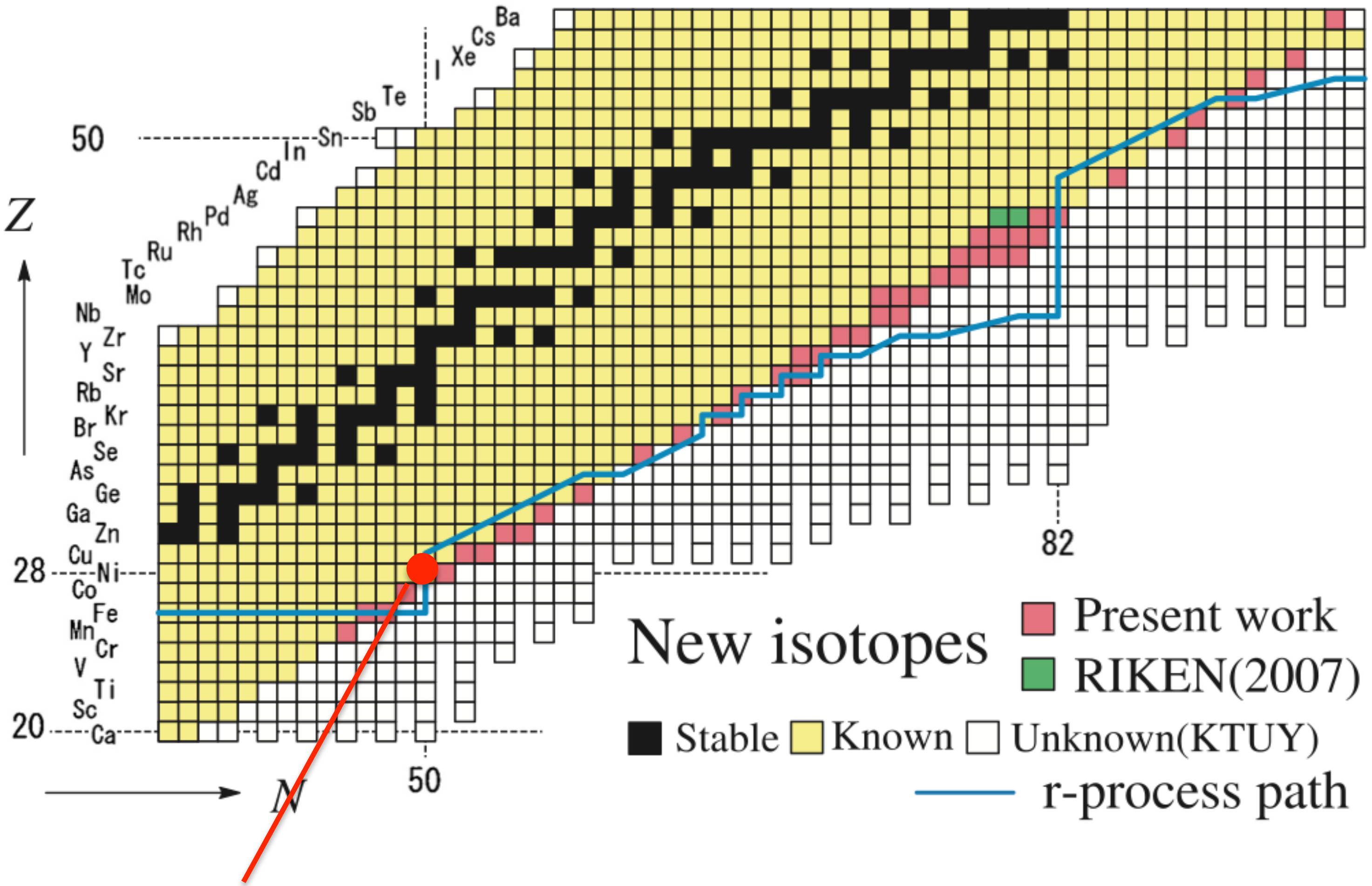


Mass resolution in Rare-RI Ring

Since central field is 1.5T, isochronicity is **2×10^{-6}**.

This is much better than ESR.

Example of mass measurements: case for ^{78}Ni



^{78}Ni (~0.005cps/pnA in BigRIPS)

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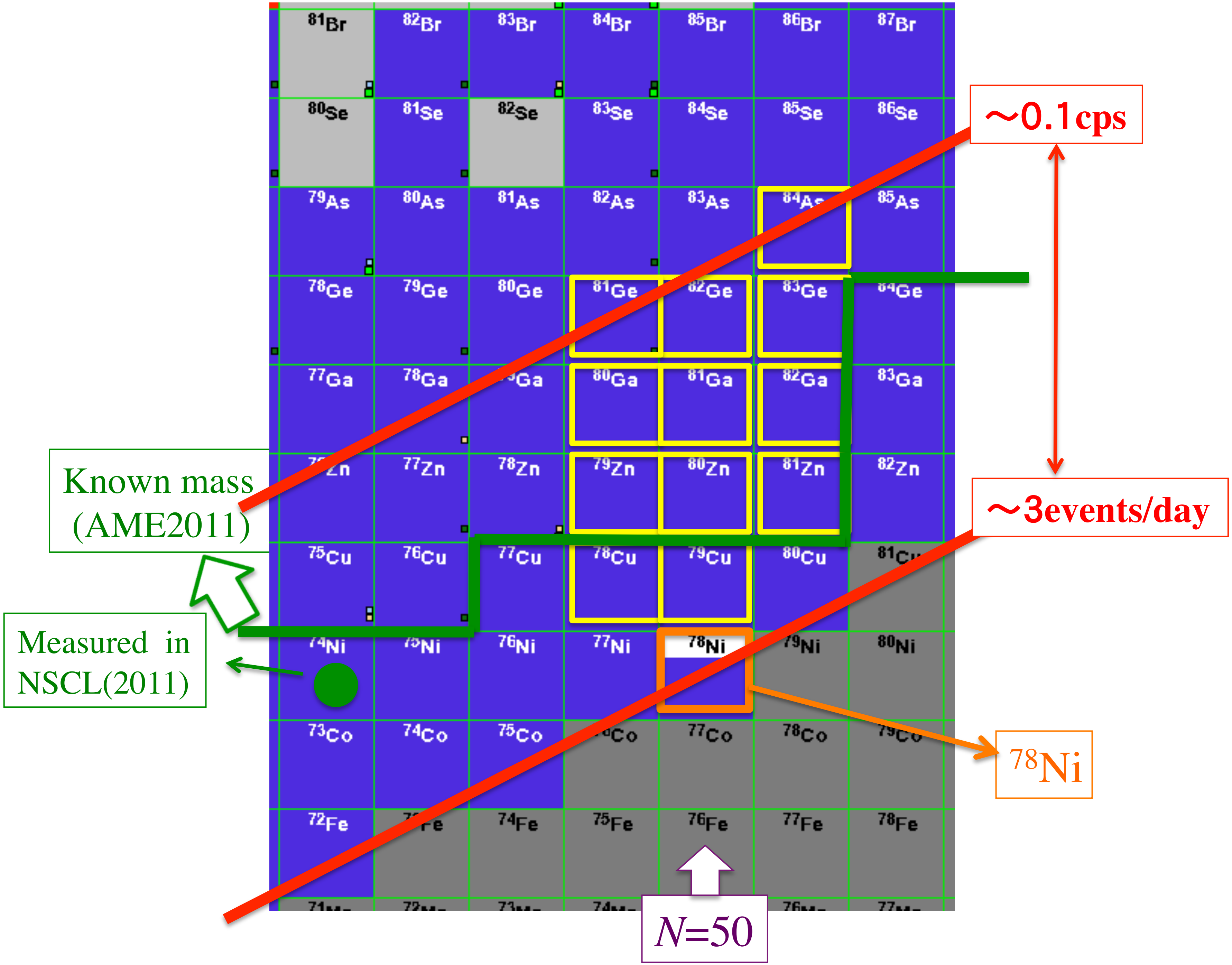
Yield estimation of ^{78}Ni in Rare-RI ring:

~5×10^{-3} cps/pnA in BigRIPS (Full acceptance)

	Reduction factor from BigRIPS
Energy: ~290 *A* MeV→200 *A* MeV	~0.9
Momentum acceptance 6% → 1%	1/6
Angular acceptance 80πmm mrad→~20πmm mrad	~1/16
Transmission eff. at injection	~0.8
Total	~0.0075

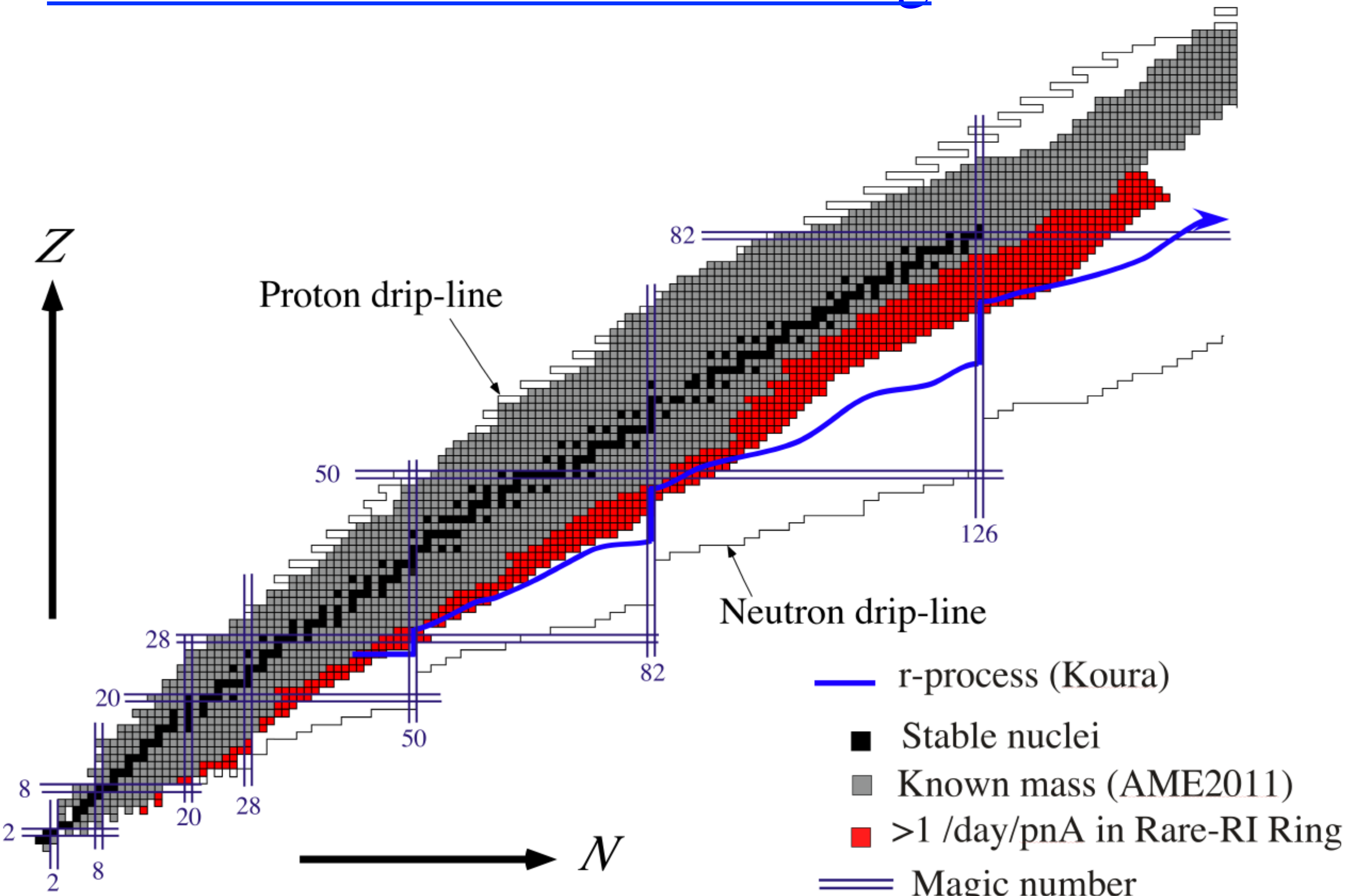
4×10^{-5} cps/pnA → ~3 events/day/pnA in Rare-RI ring

Still feasible!

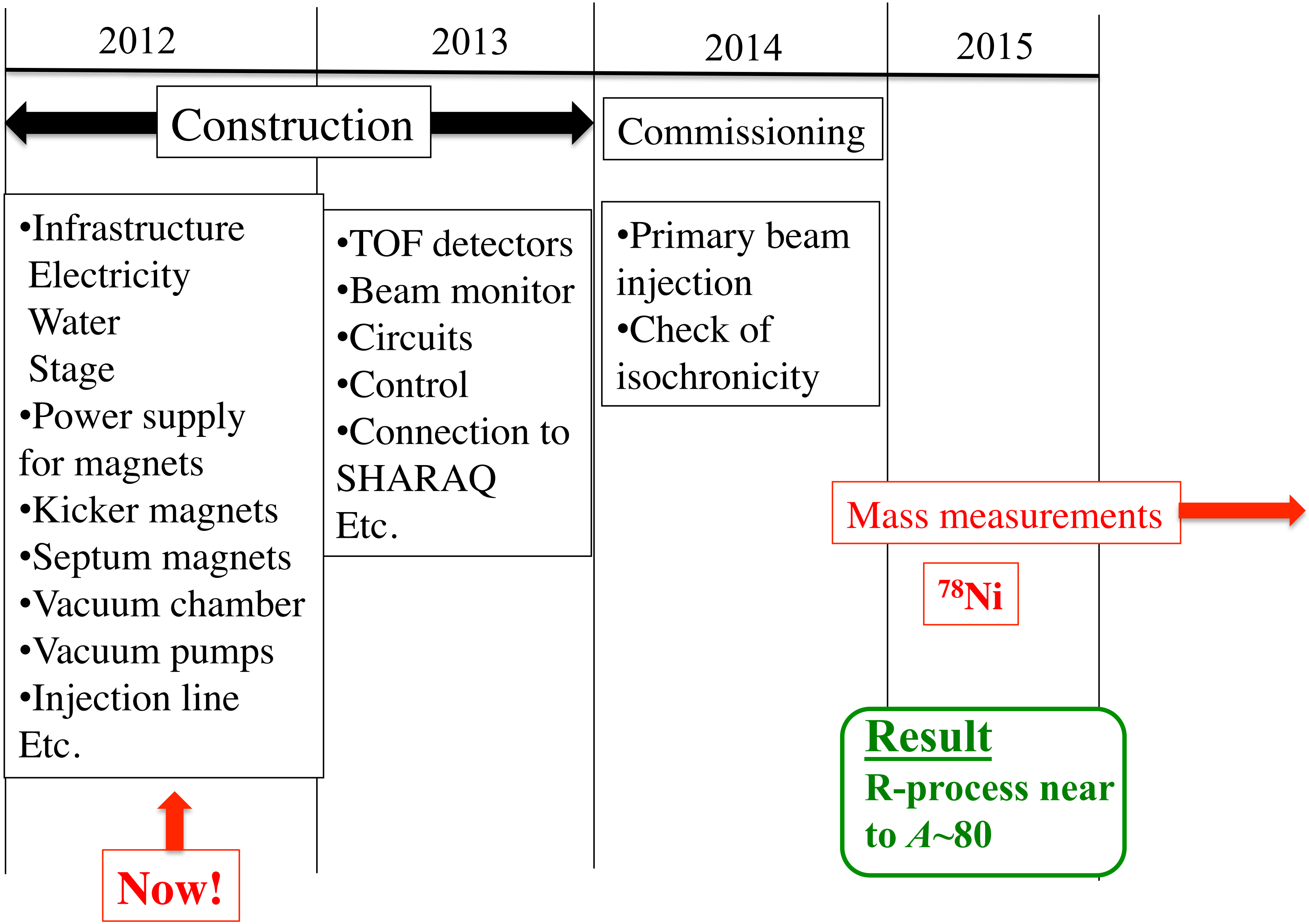


~0.1cps
~3events/day
Known mass
(AME2011)
Measured in
NSCL(2011)
^{78}Ni
N=50
81Br
82Br
83Br
84Br
85Br
86Br
87Br
80Se
81Se
82Se
83Se
84Se
85Se
86Se
79As
80As
81As
82As
83As
85As
78Ge
79Ge
80Ge
81Ge
83Ge
77Ga
78Ga
80Ga
81Ga
82Ga
83Ga
77Zn
78Zn
79Zn
80Zn
81Zn
82Zn
75Cu
76Cu
77Cu
78Cu
79Cu
80Cu
76Ni
77Ni
78Ni
79Ni
80Ni
73Co
74Co
75Co
77Co
78Co
72Fe
74Fe
75Fe
76Fe
77Fe
78Fe

Accessible area in Rare-RI Ring



Schedule for mass measurements



§ Summary

- Construction of Rare-RI Ring started from this April.
- Rare-RI Ring will complete until the end of 2013.
- Only 1 particle is stored in Rare-RI Ring by individual injection.
- Its mass resolution is ~10^{-6} because of cyclotron-type storage ring (isochronous storage ring).
- Mass measurement for ^{78}Ni is quite feasible.
- Mass measurement in Rare-RI Ring will start from 2014.
- In Rare-RI Ring, we can newly measure the mass for ~600 nuclei.