TCHoU 26 Nov. 2021

蓄積リングを用いたRIの質量測定に関する研究
Research of nuclear mass measurements for radioactive isotopes with storage ring

鈴木　伸司 (Shinji Suzuki)

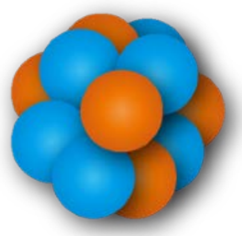
University of Tsukuba

Contents

- Nuclear masses
- Methods of nuclear mass measurement
- Detector developments
- Mass resolution

Nuclear masses

mass → binding energy → interaction

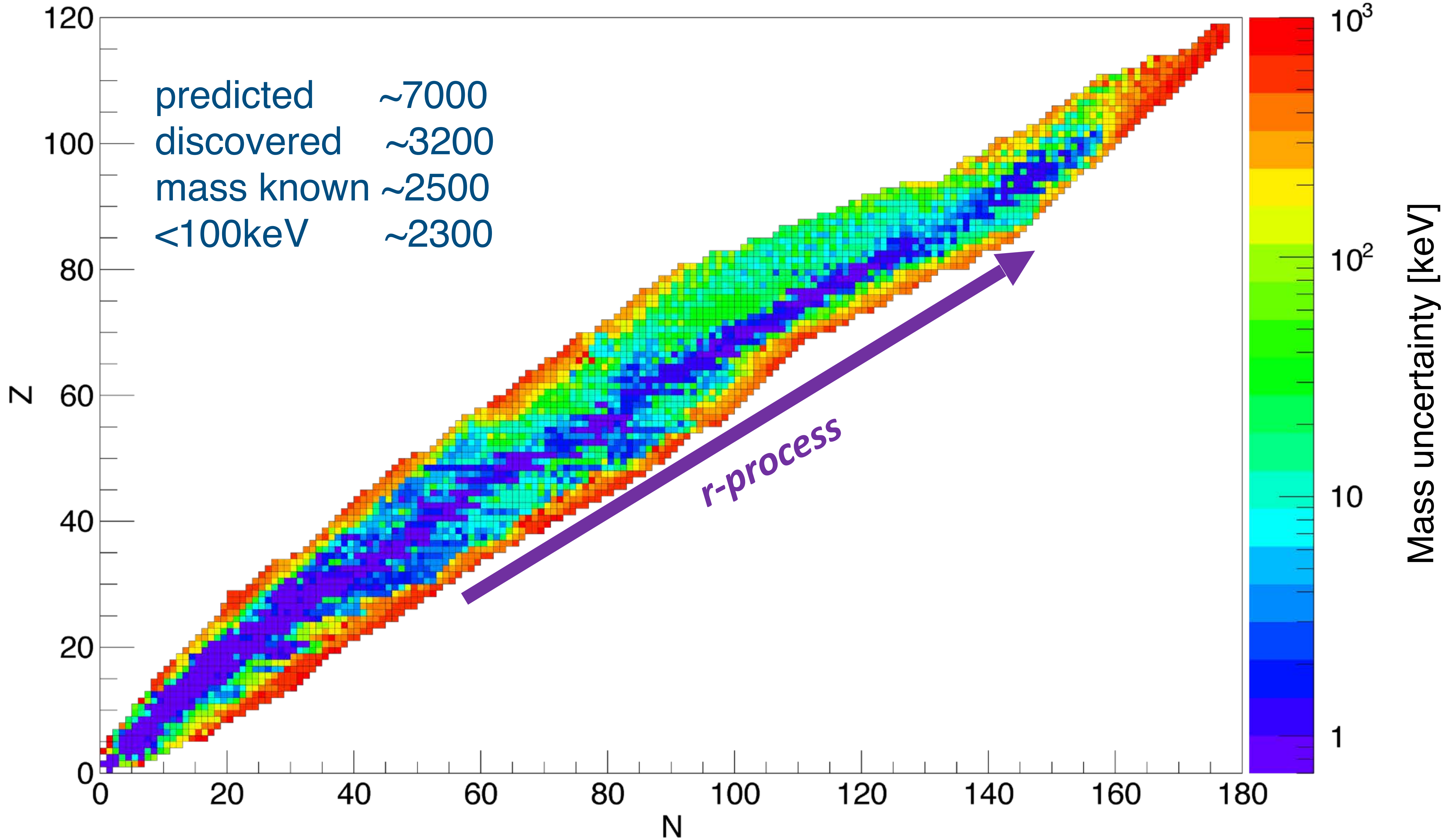


Nuclear mass = N ×  + Z ×  - Binding energy

Field of application	Required uncertainty
Chemistry: identification of molecules	10^{-5}–10^{-6}
Nuclear physics: shells, sub-shells, pairing	10^{-6}
Nuclear fine structure: deformation, halos	10^{-7}–10^{-8}
✔ **Astrophysics**: r-process, rp-process	10^{-7}
Nuclear models and formulas: IMME	10^{-7}–10^{-8}
Weak interaction studies: CVC hypothesis, CKM unitarity	10^{-8}
Atomic physics: binding energies, QED	10^{-9}–10^{-11}

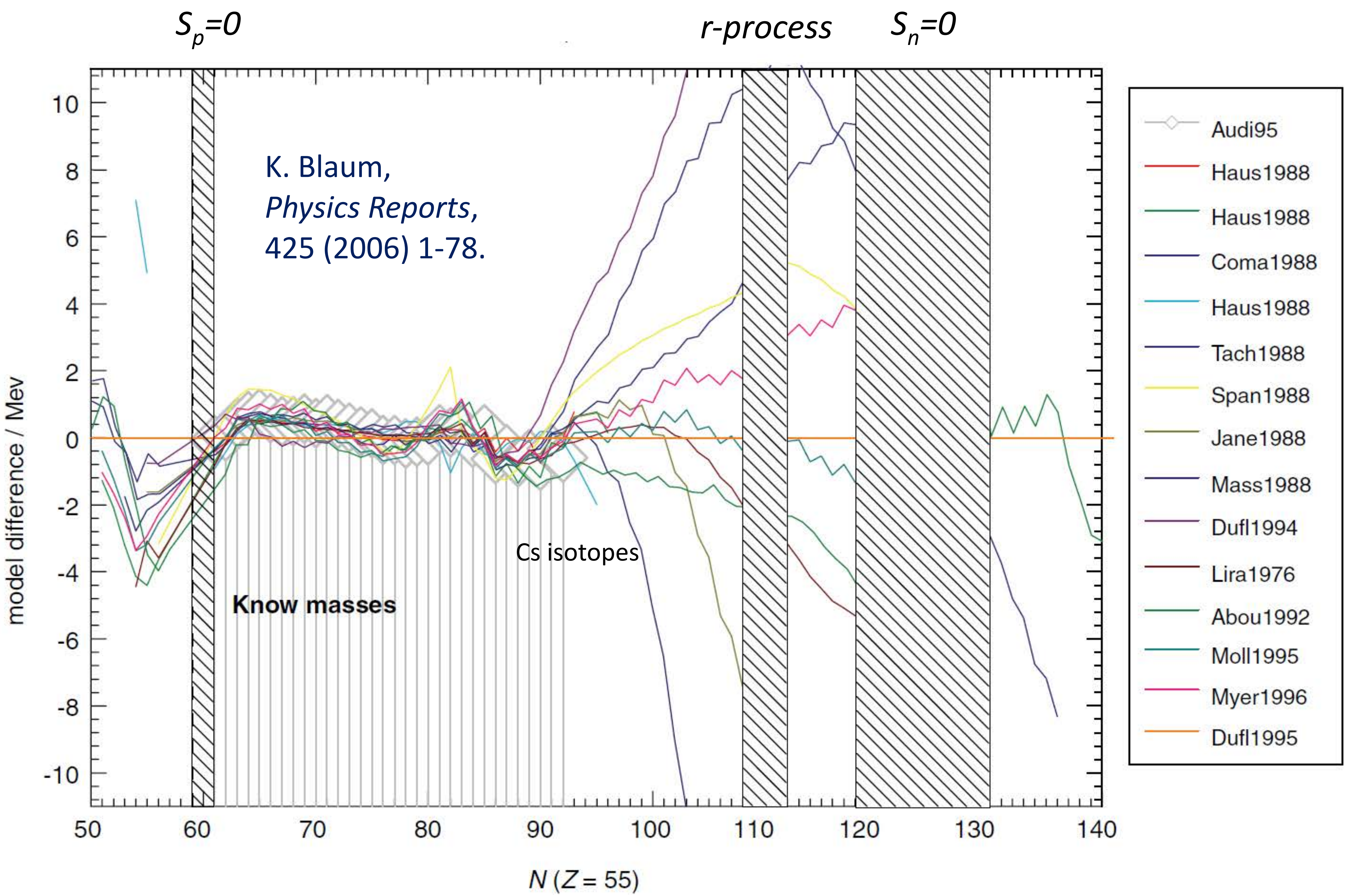
K. Blaum, Physics Reports 425, 1 (2006)

Mass uncertainty



AME2016
Chinese Physics C, 41, 030001 (2017)

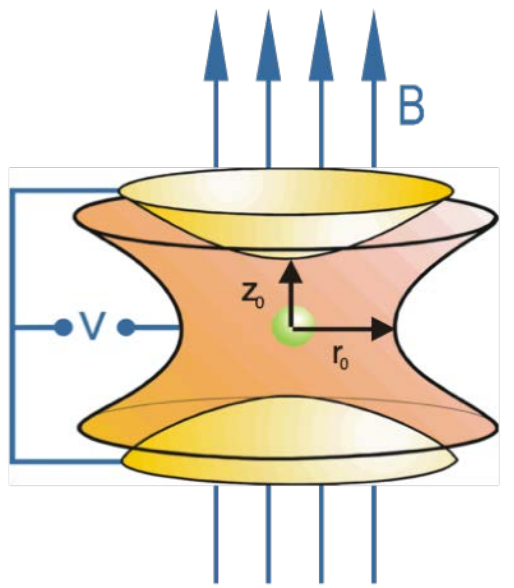
Mass prediction



Masses of radionuclides should be measured

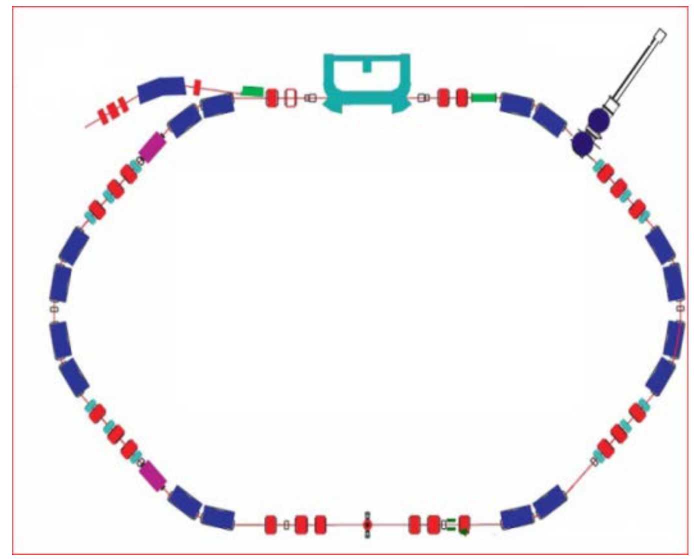
Methods of nuclear mass measurement

Penning trap



$$f_c = \frac{B}{2\pi}\frac{q}{m}$$

Storage ring



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

Isochronous mass spectrometry (IMS)

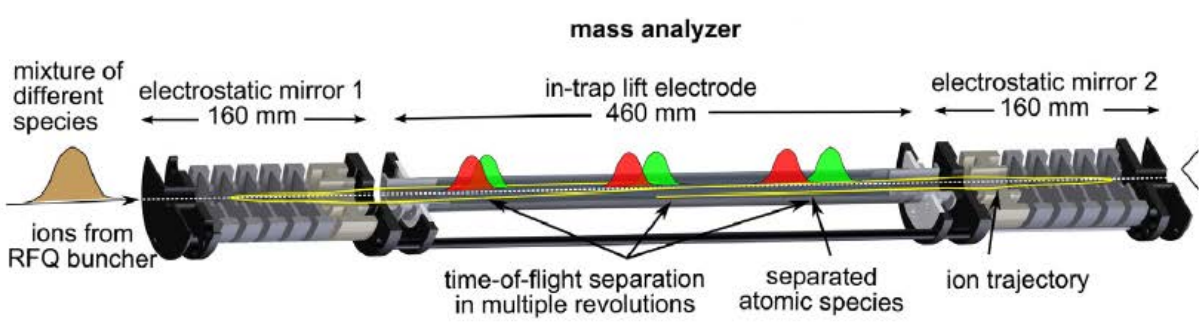
$$\left(1 - \frac{\gamma^2}{\gamma_t^2}\right) \rightarrow 0$$

Schottky mass spectrometry (SMS)

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

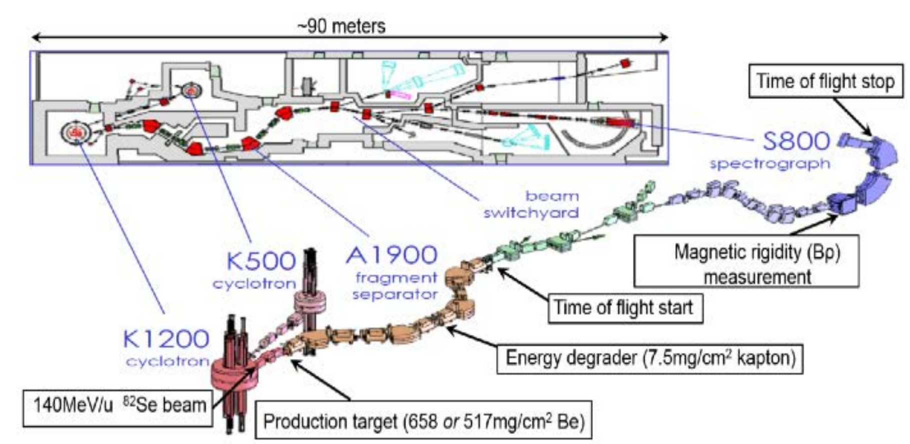
Multi-reflection TOF (MR-TOF)

$$T(n) = T(0) + n \cdot b\sqrt{m}$$



Bρ TOF

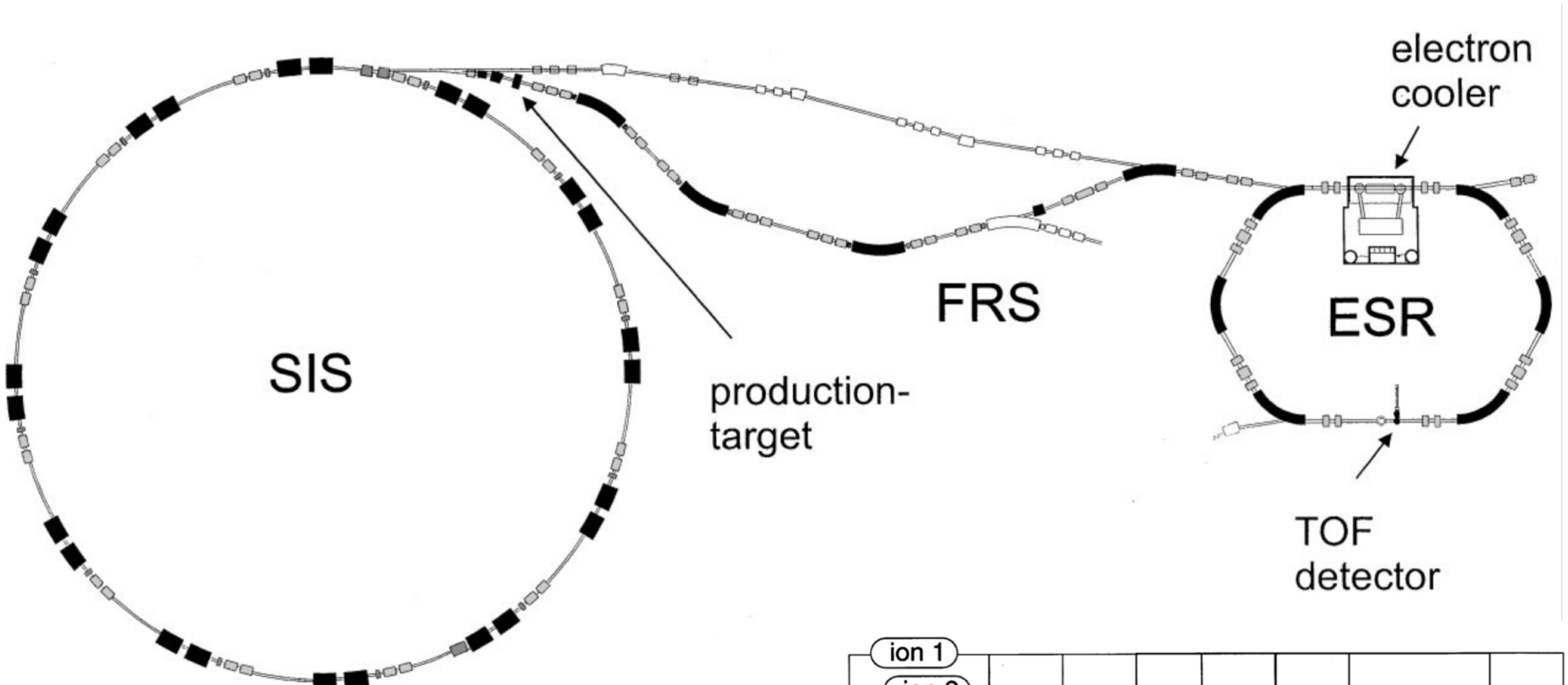
$$B\rho = \frac{m}{q}\beta\gamma c$$

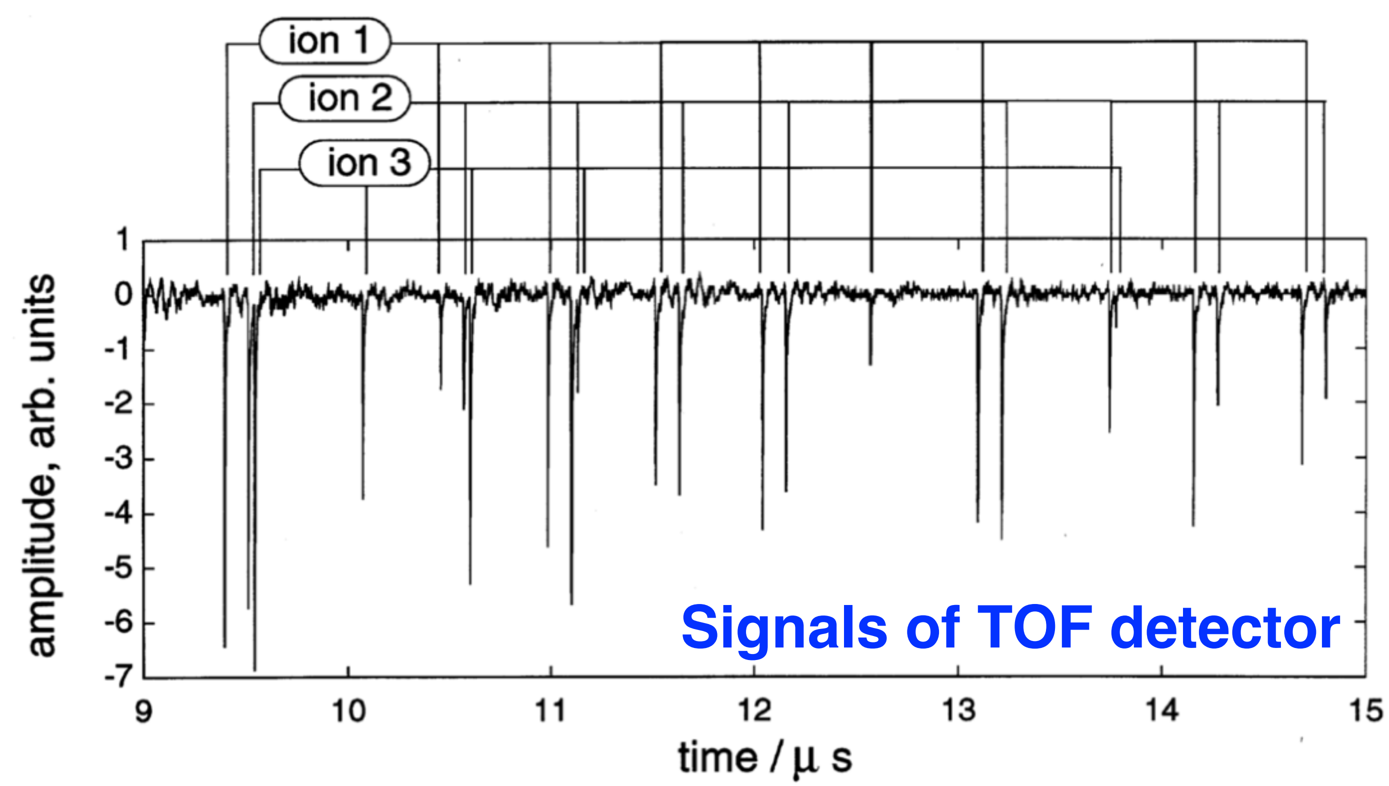


- **Time**： Bρ-TOF, **IMS** < MR-TOF < PTMS < SMS
- **Precision**： PTMS > SMS, **IMS**, MR-TOF > Bρ-TOF

IMS is suitable for short-lived radionuclides

Isochronous mass spectrometry (IMS)



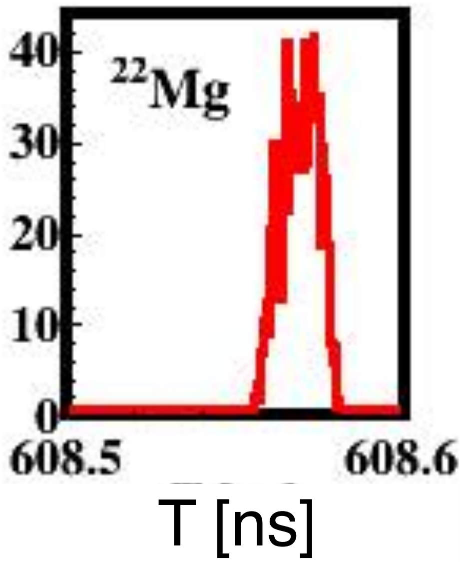


First IMS experiment in GSI

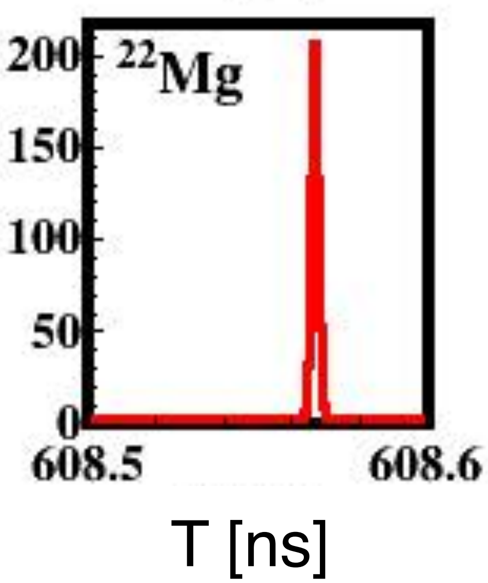
Nucl. Inst. Meth A 446 (2000) 569-580

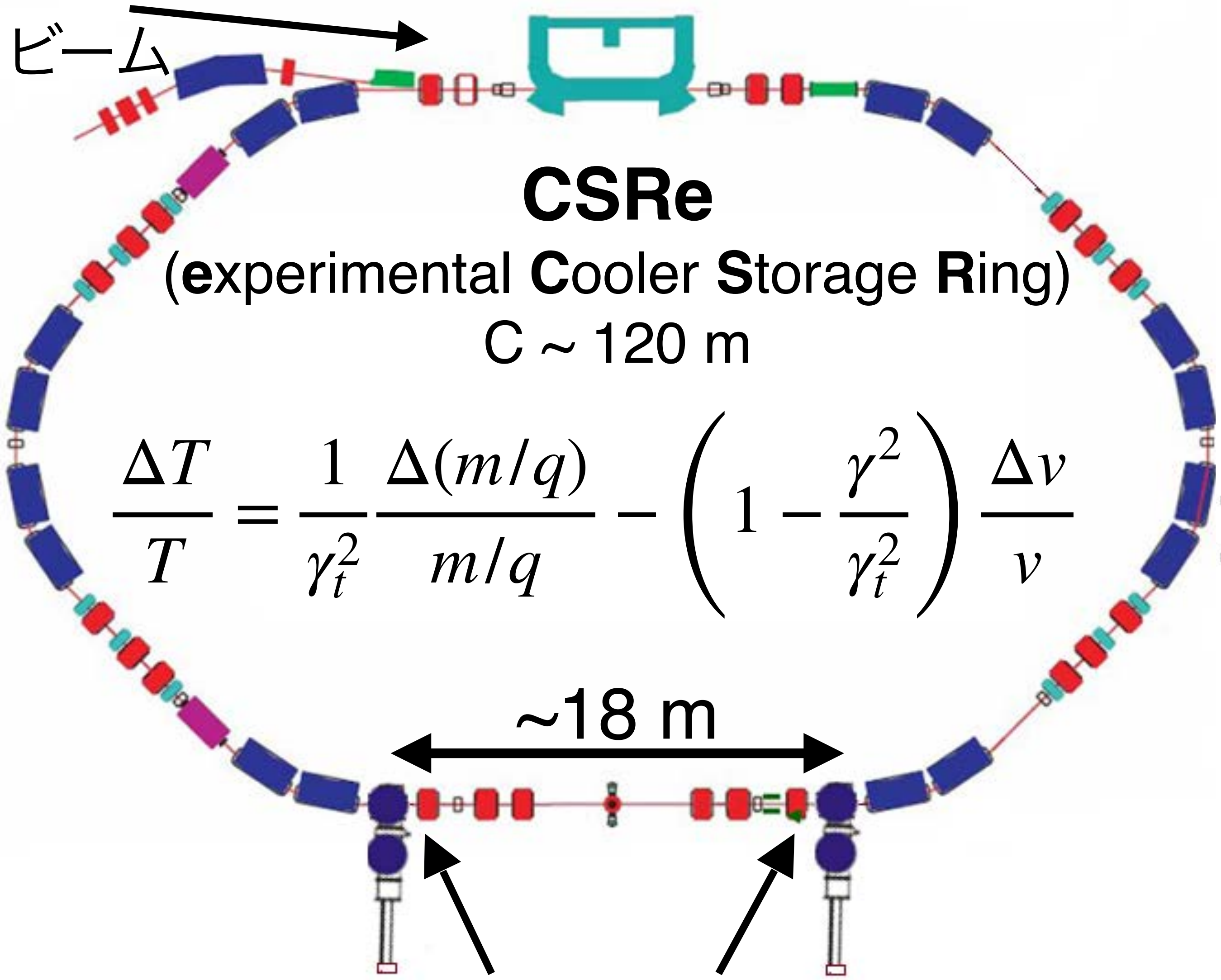
Double TOF IMS

Singal TOF



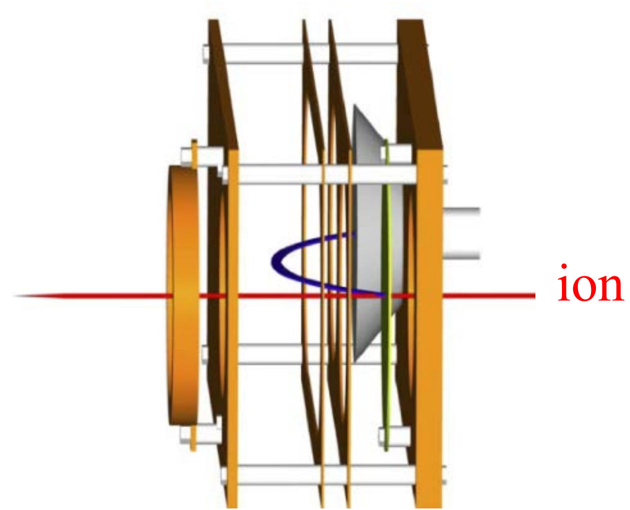
Doubel TOF



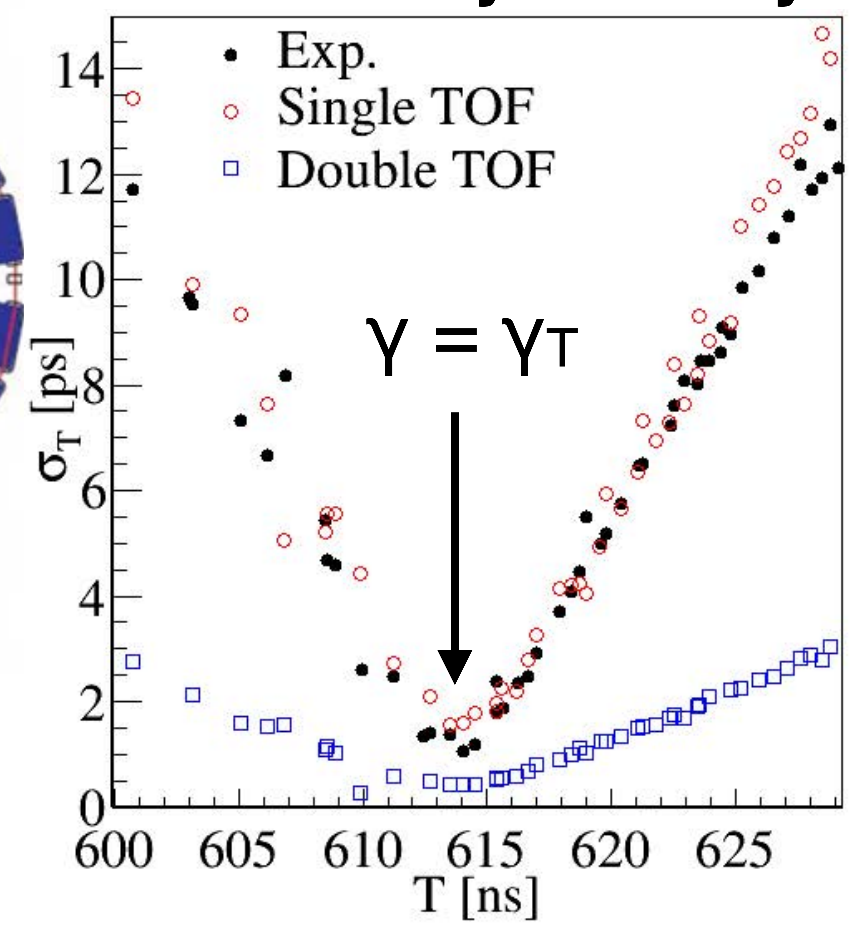


$$\frac{\Delta T}{T} = \frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} - \left(1 - \frac{\gamma^2}{\gamma_t^2}\right)\frac{\Delta v}{v}$$

Two TOF detectors (*T, v*)



Revolution time can be corrected by velocity

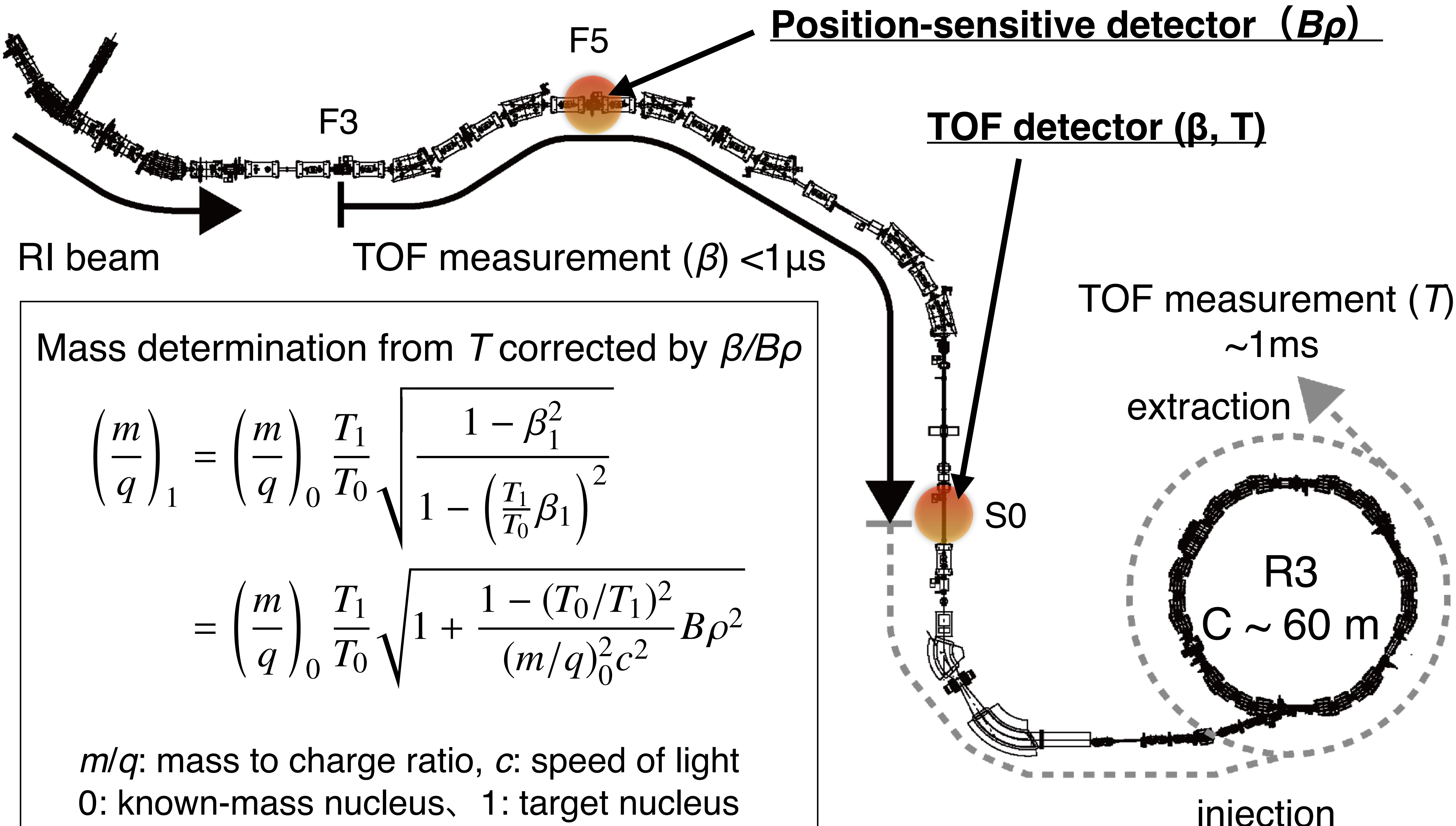


Devised in GSI

J. Pays. G 31 (2005) S1779-S1783

Performed in IMP

IMS with R3 (Rare RI Ring) in RIKEN



Mass determination from T corrected by $\beta/B\rho$

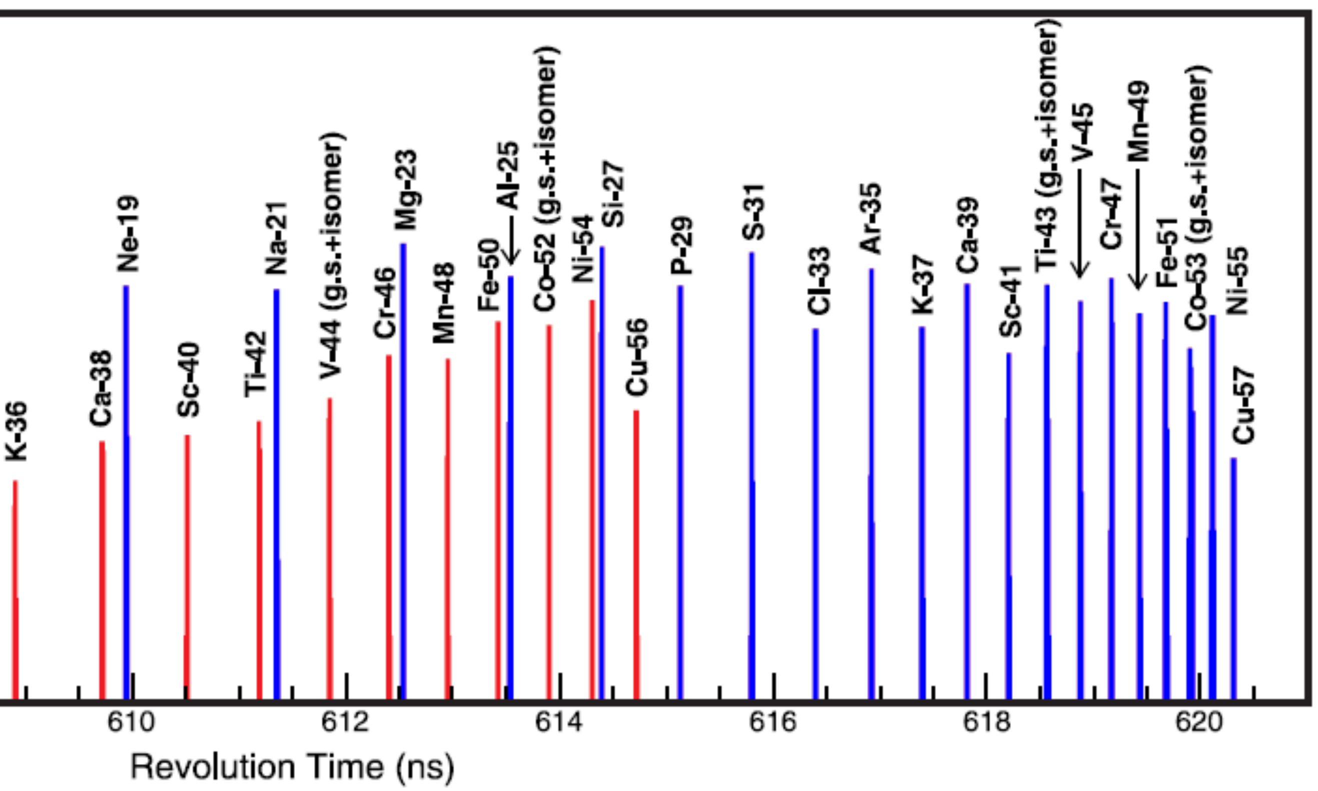
$$\left(\frac{m}{q}\right)_1 = \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-\left(\frac{T_1}{T_0}\beta_1\right)^2}}$$

$$= \left(\frac{m}{q}\right)_0 \frac{T_1}{T_0}\sqrt{1+\frac{1-(T_0/T_1)^2}{(m/q)_0^2 c^2}B\rho^2}$$

m/*q*: mass to charge ratio, *c*: speed of light
0: known-mass nucleus、1: target nucleus

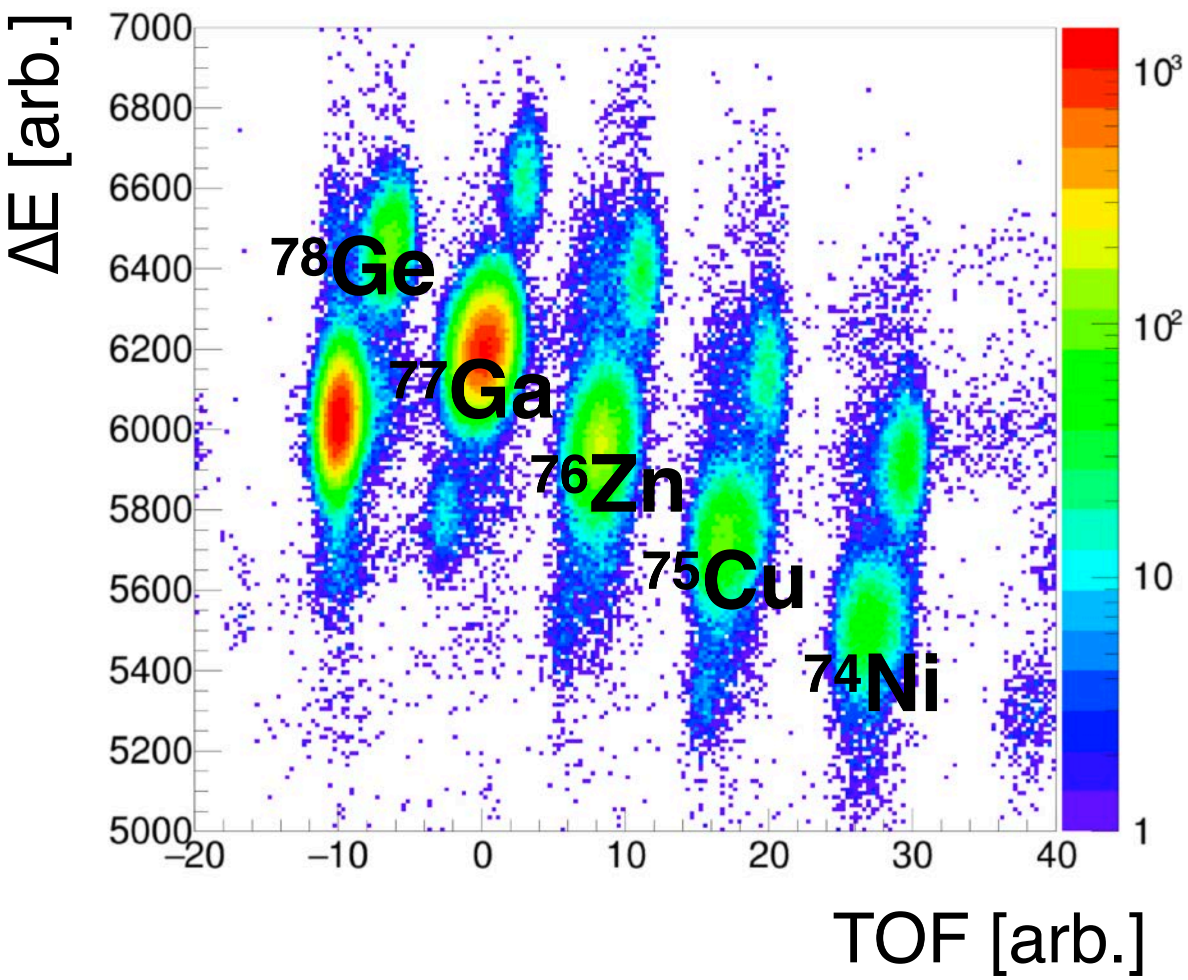
Particle identification

IMS with in-ring detector



Particle identification is based on the revolution time analysis
→ ions having the same A/Z cannot be identified (e.g. A/Z = 2: ^{40}Ca, ^{100}Sn)

IMS in RIKEN

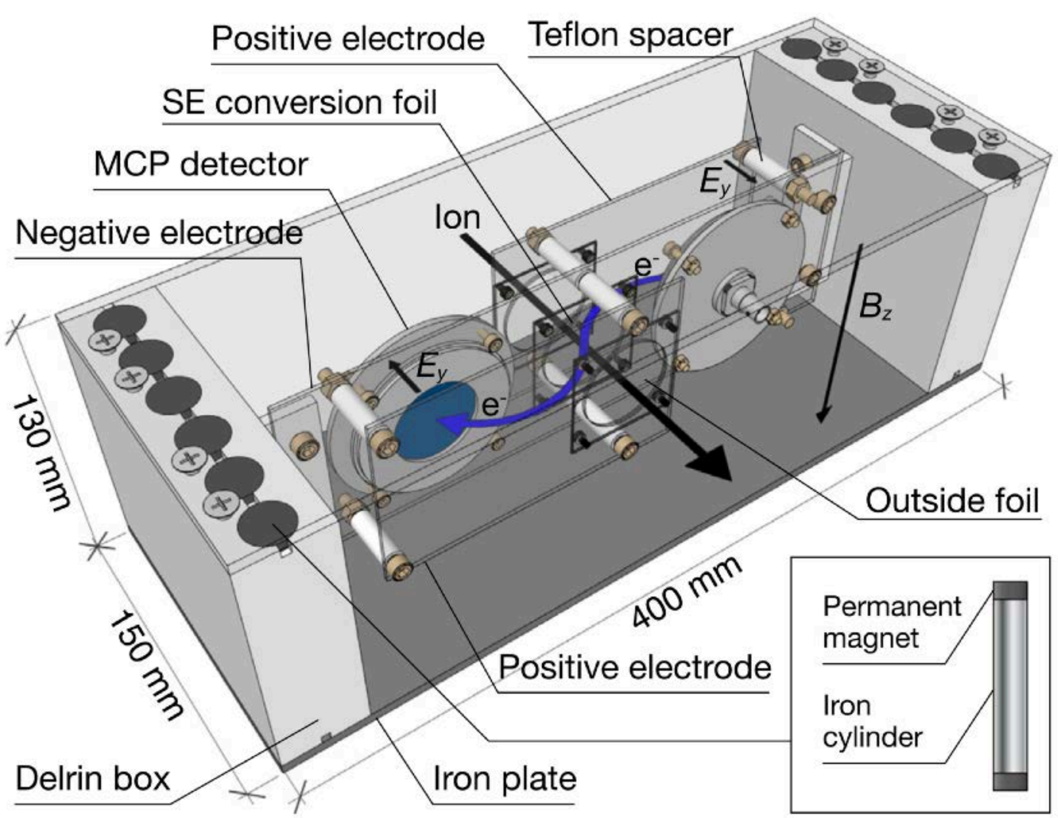


Particle identification can be performed by using detectors installed in the beam line

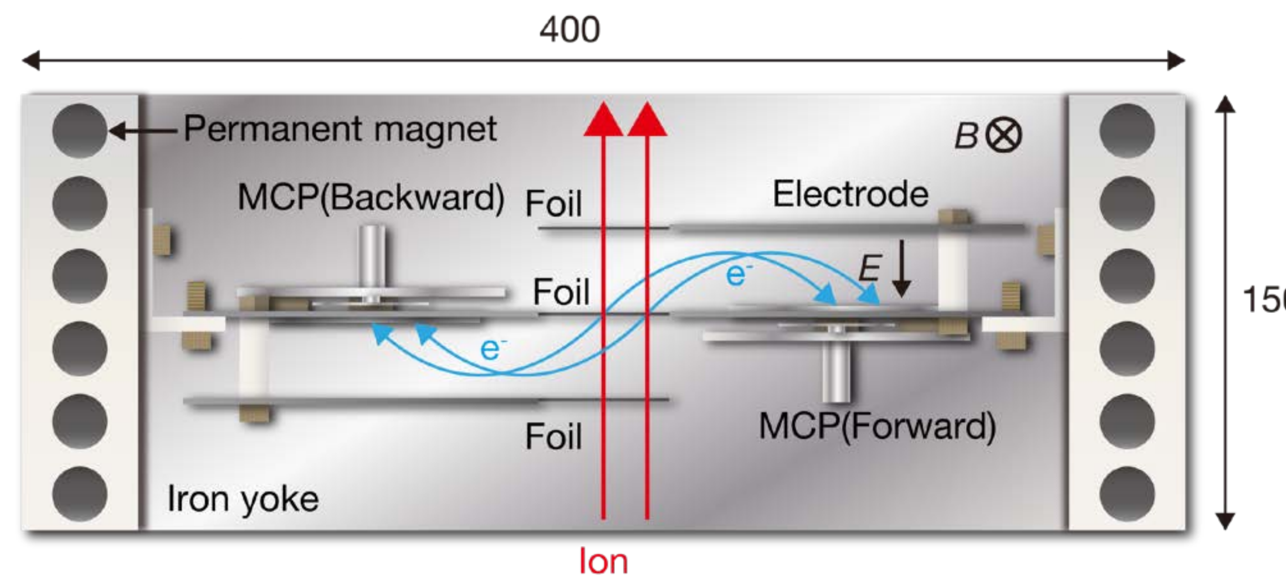
TOF detector using secondary electrons

Requirements

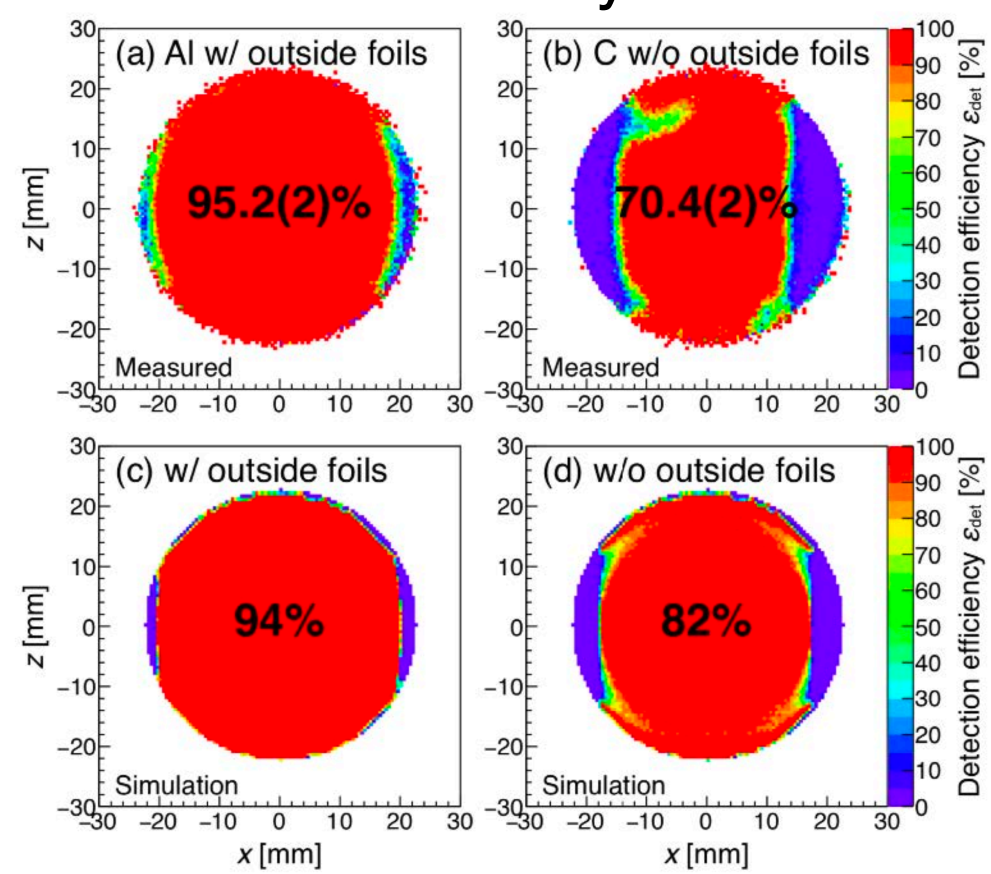
- Time resolution < 100 ps ($\Delta\beta/\beta < 1\times10^{-4}$)
- Good detection efficiency close to 100%
- Must be as thin as possible ($\Delta\beta/\beta < 1\times10^{-4}$)



- Aluminized Mylar foil (φ45 mm)
- B ~ 150 gauss
- E ~ 500 V/mm



- Detection efficiency

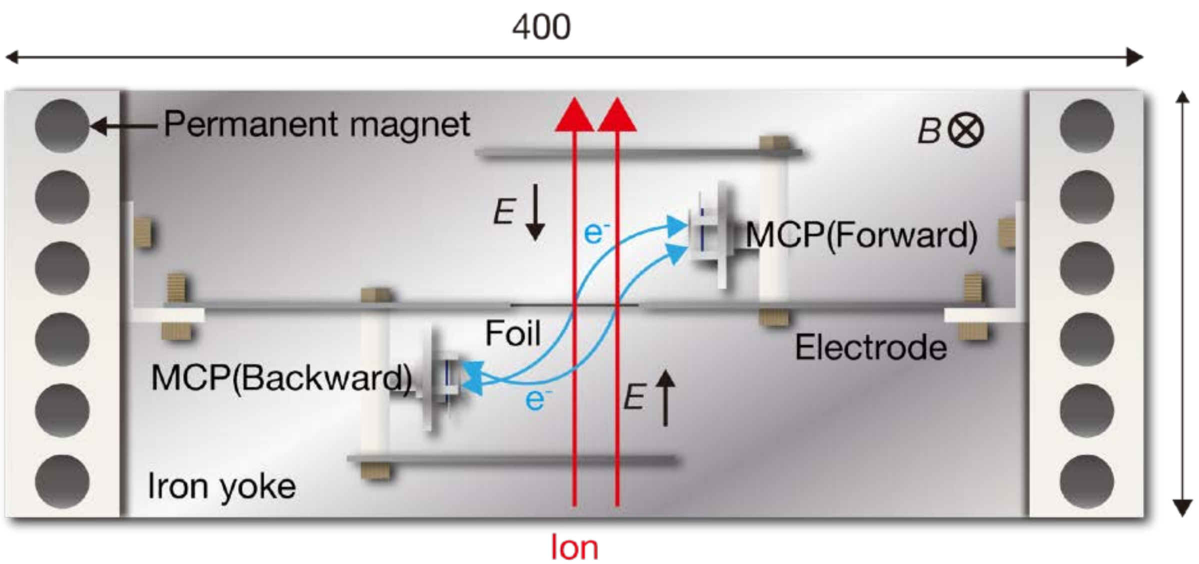


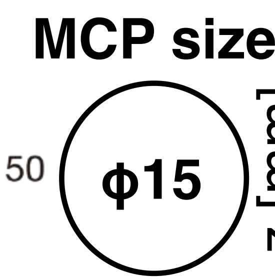
- Time resolution: 38.6(2) ps

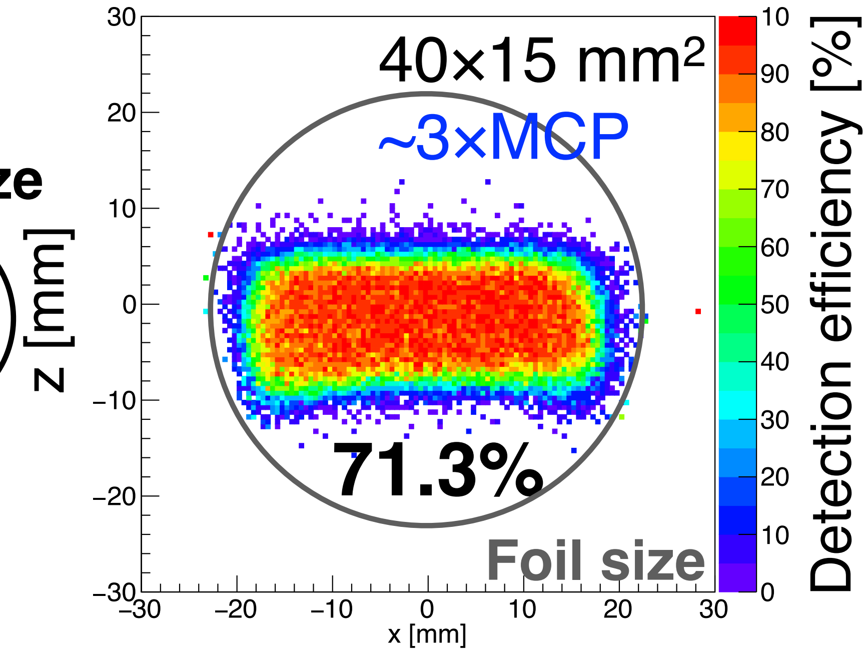
S.Suzuki et al., Nuclear Inst. and Methods A 965, 163807 (2020)

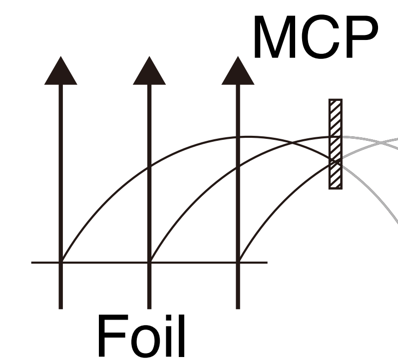
Novel position-sensitive detector

change in ion velocity in a position-sensitive detector (PPAC) cannot be ignored ($\Delta\beta/\beta \sim 1\times10^{-3}$)

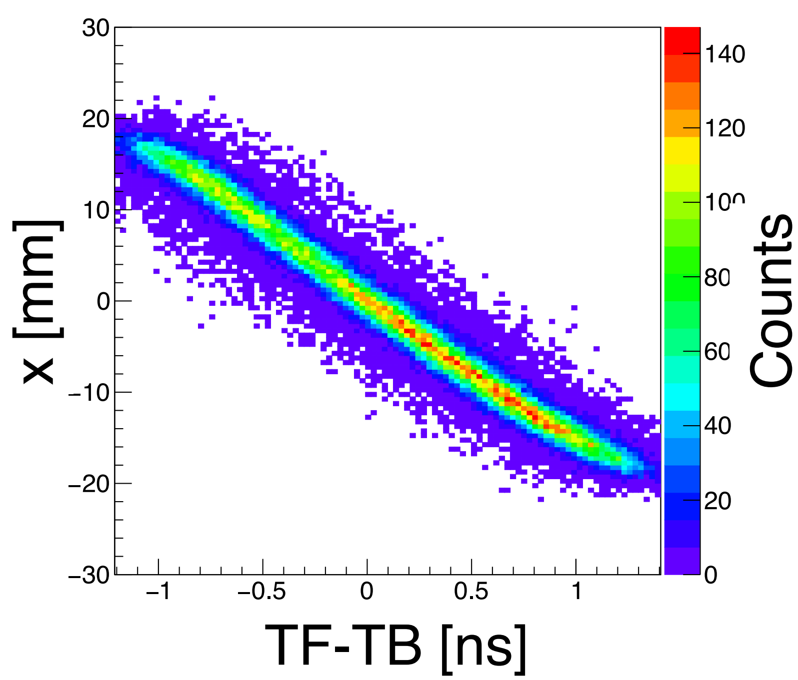




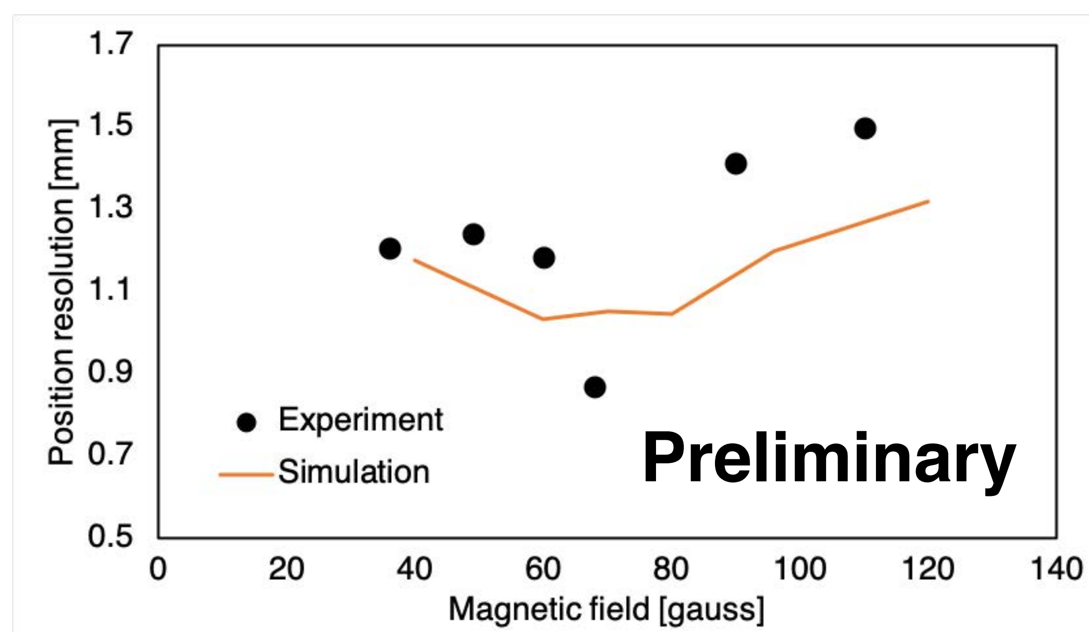




B = 36 ~ 110 gauss/E = 10 ~ 380 V/mm



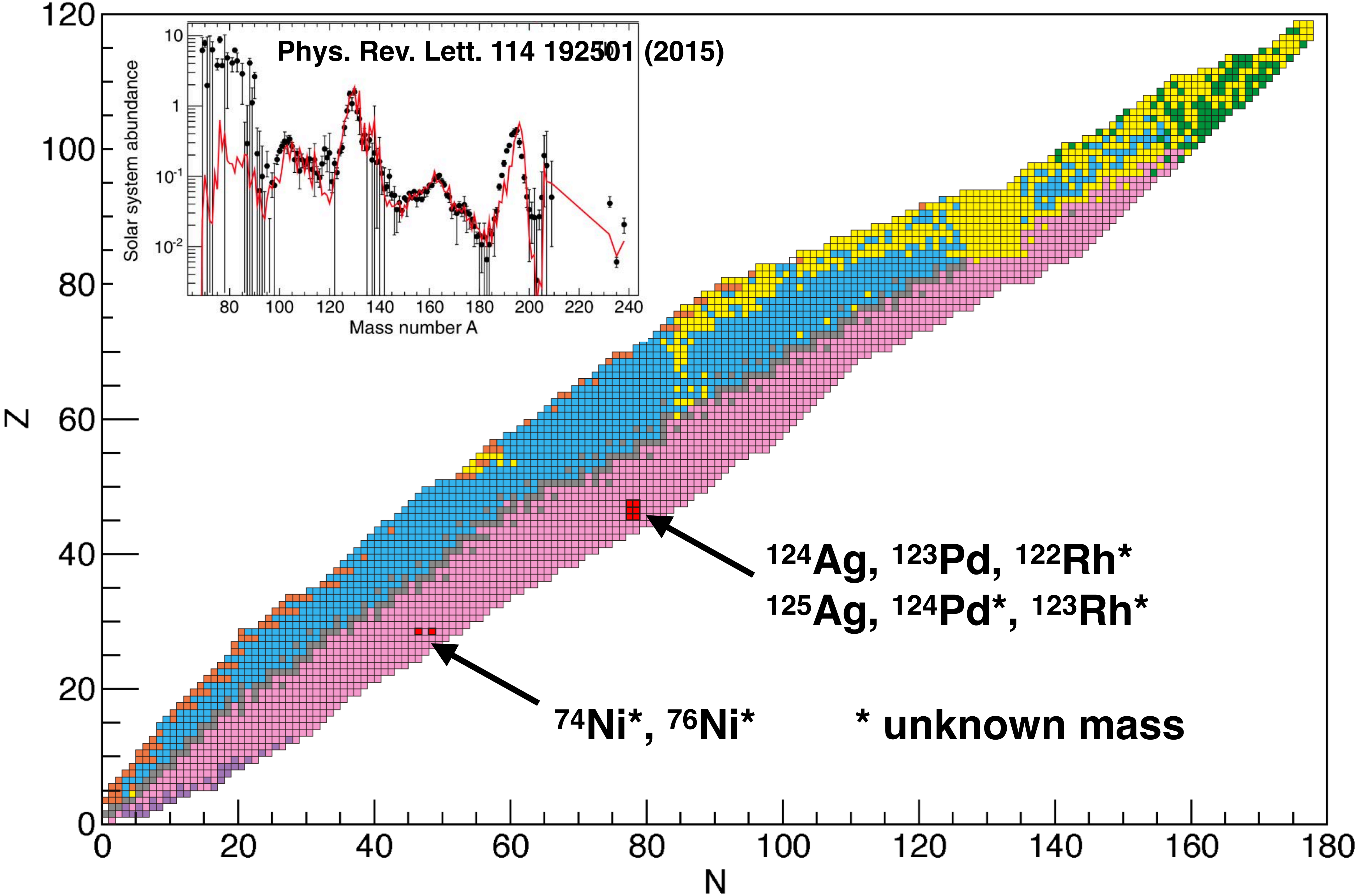
S.Suzuki et al., JPS Conf. Proc. 35, 011017 (2021)



The best position resolution of ~ 0.9 mm was obtained in about 70 gauss

Basic research for the detector finished

Measured masses using R3



Analysis is under going

Collaborators

University of Tsukuba

A. Ozawa, T. Moriguchi,
N. Kaname, A. Yano

Saitama University

T. Yamaguchi

Kyushu University

D. Nagae

JAEA

F. Suzaki

RIKEN

Y. Yamaguchi, S. Naimi,
Y. Abe, T. Uesaka,
M. Wakasugi

GSI (Germany)

Y. A. Litvinov

IMP (China)

M. Wang, H. F. Li,
Y. H. Zhang