Storage-ring mass spectrometry

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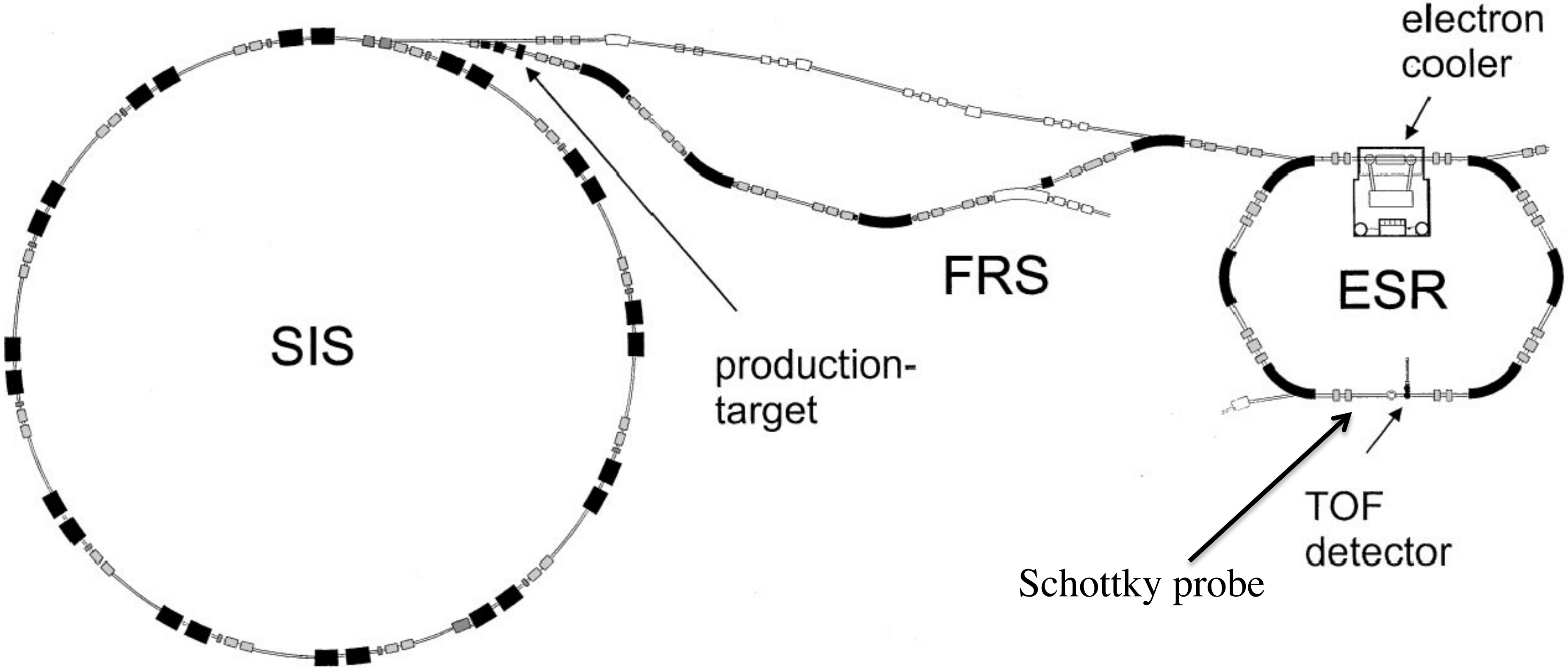
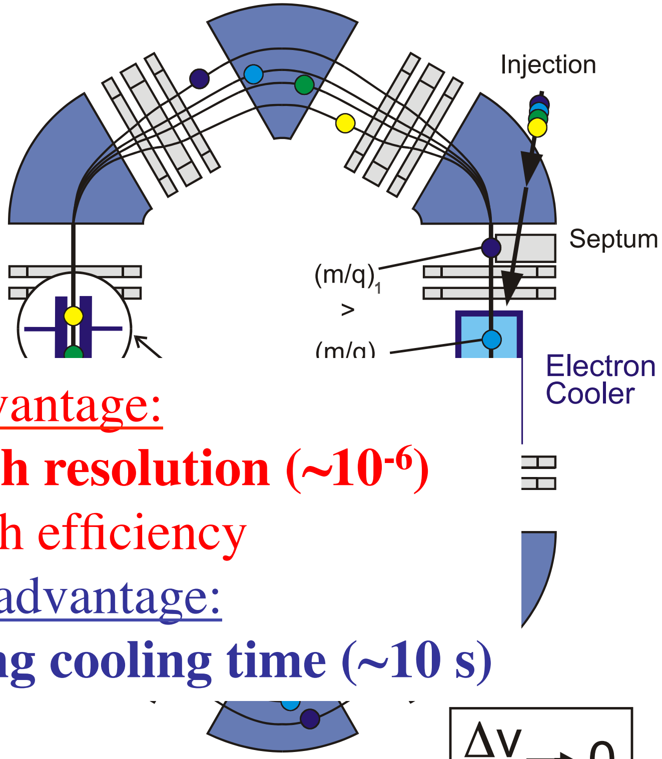
Construction started from FY2012!

§ Mass measurements in ESR/GSI

Experimental setup in ESR/GSI



SCHOTTKY MASS SPECTROMETRY



Advantage:

High resolution (~10^{-6})

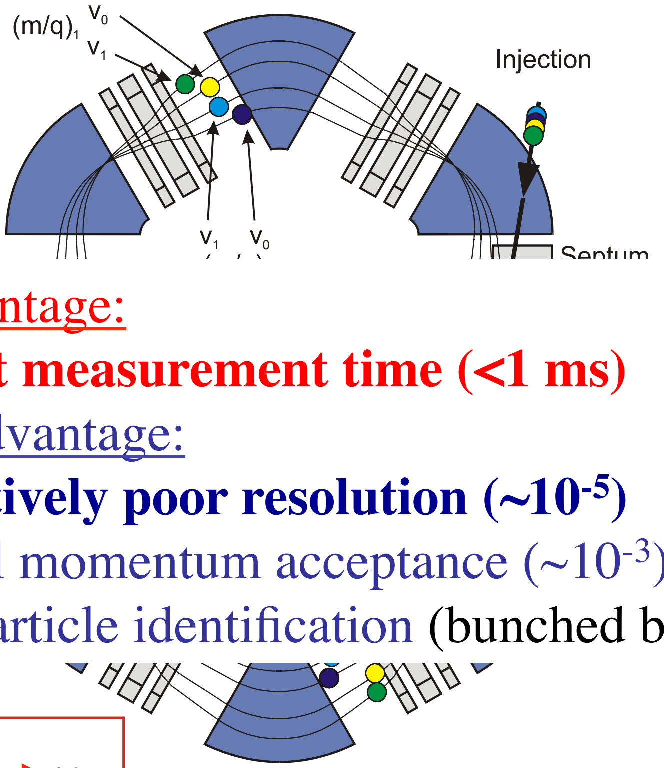
High efficiency

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

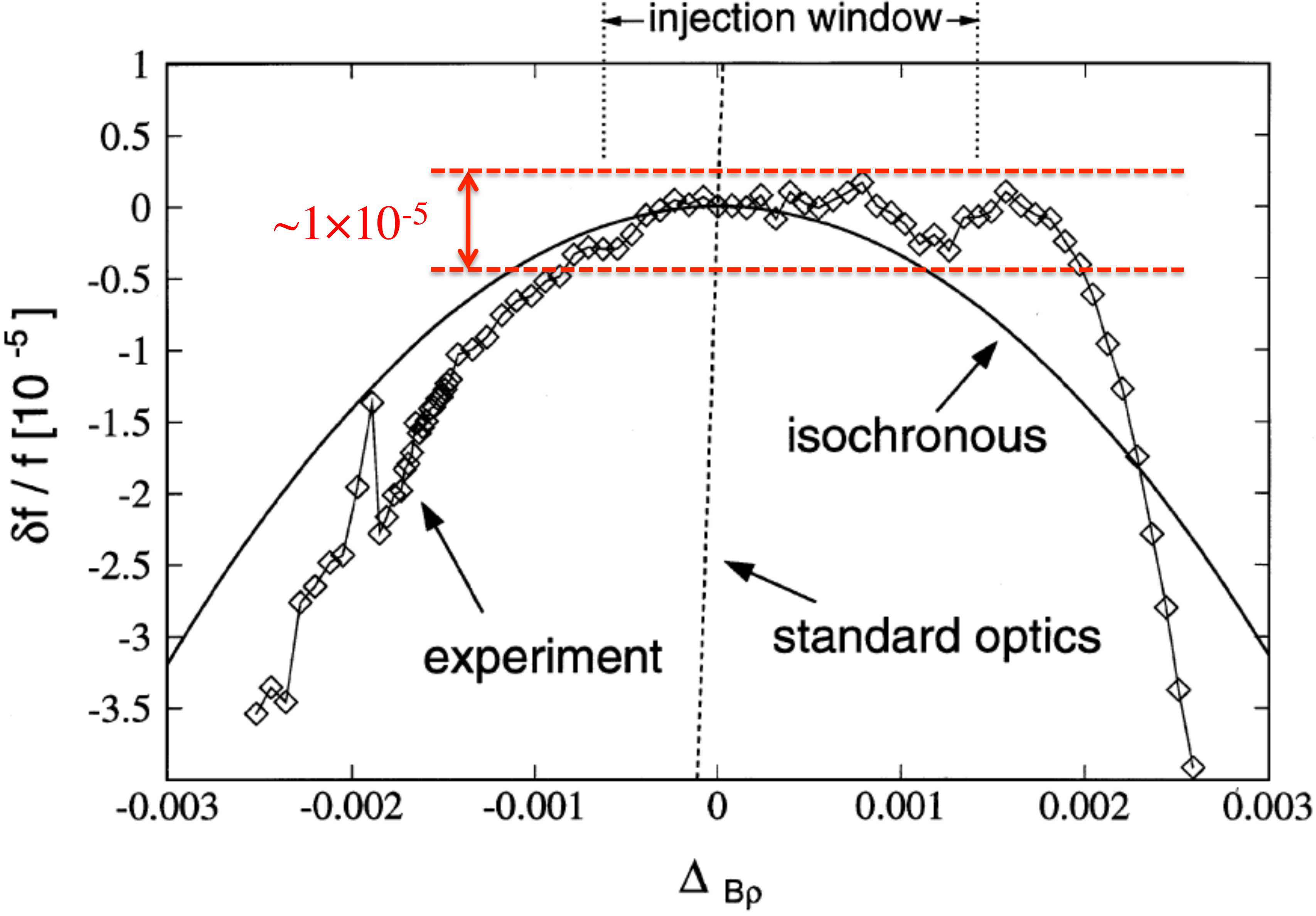
$$\boxed{\frac{\Delta v}{v} \rightarrow 0} \qquad \boxed{\gamma_t \rightarrow \gamma}$$

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

γ_t=1.37 in ESR

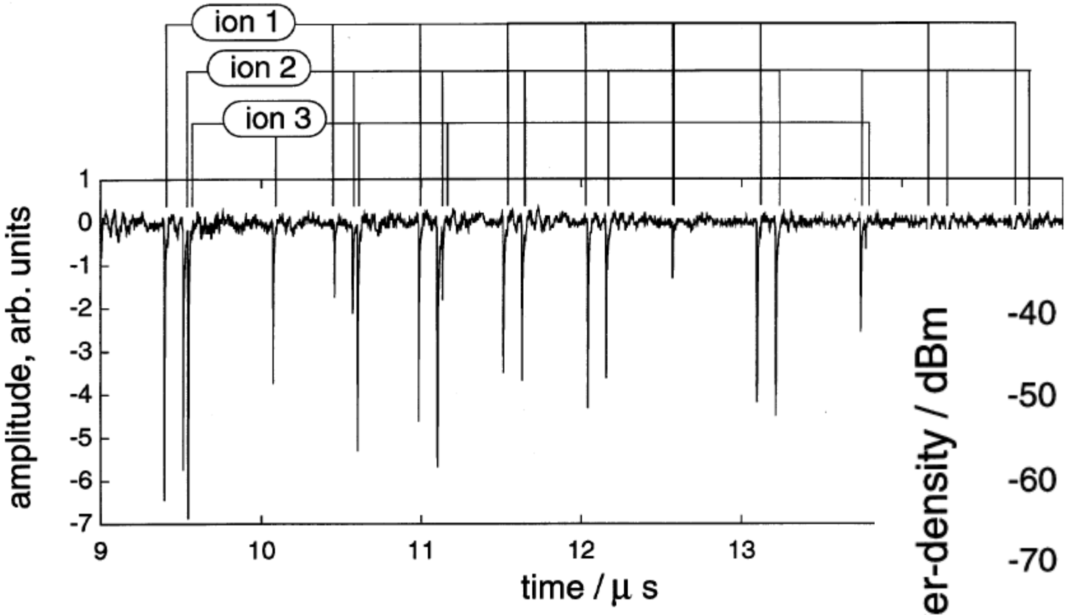
Isochronous field in ESR

NIMA446,569(2000)



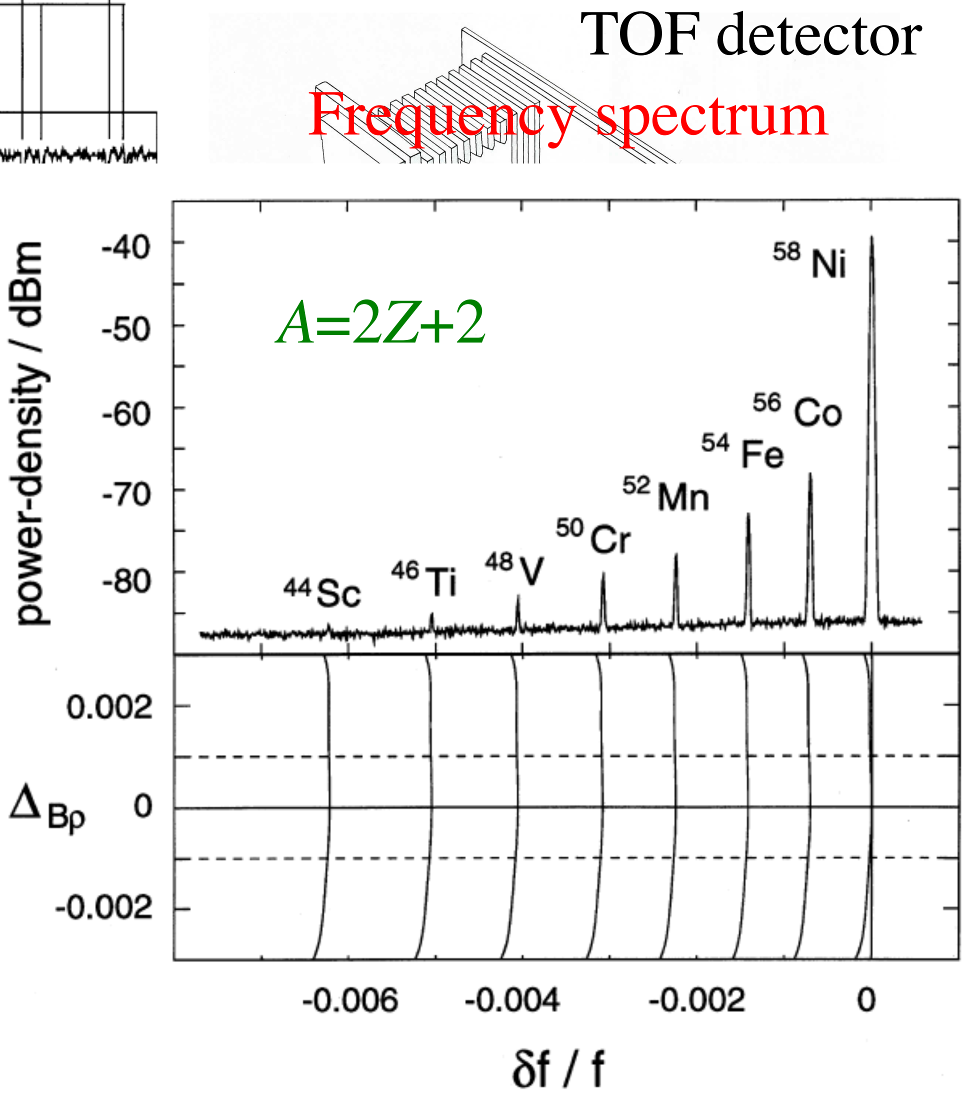
How to deduce mass in IMS

Signal from TOF counter



$\delta t/t$~4×10^{-5} with 50 turns

NIMA446,569(2000)


TOF detector

Frequency spectrum

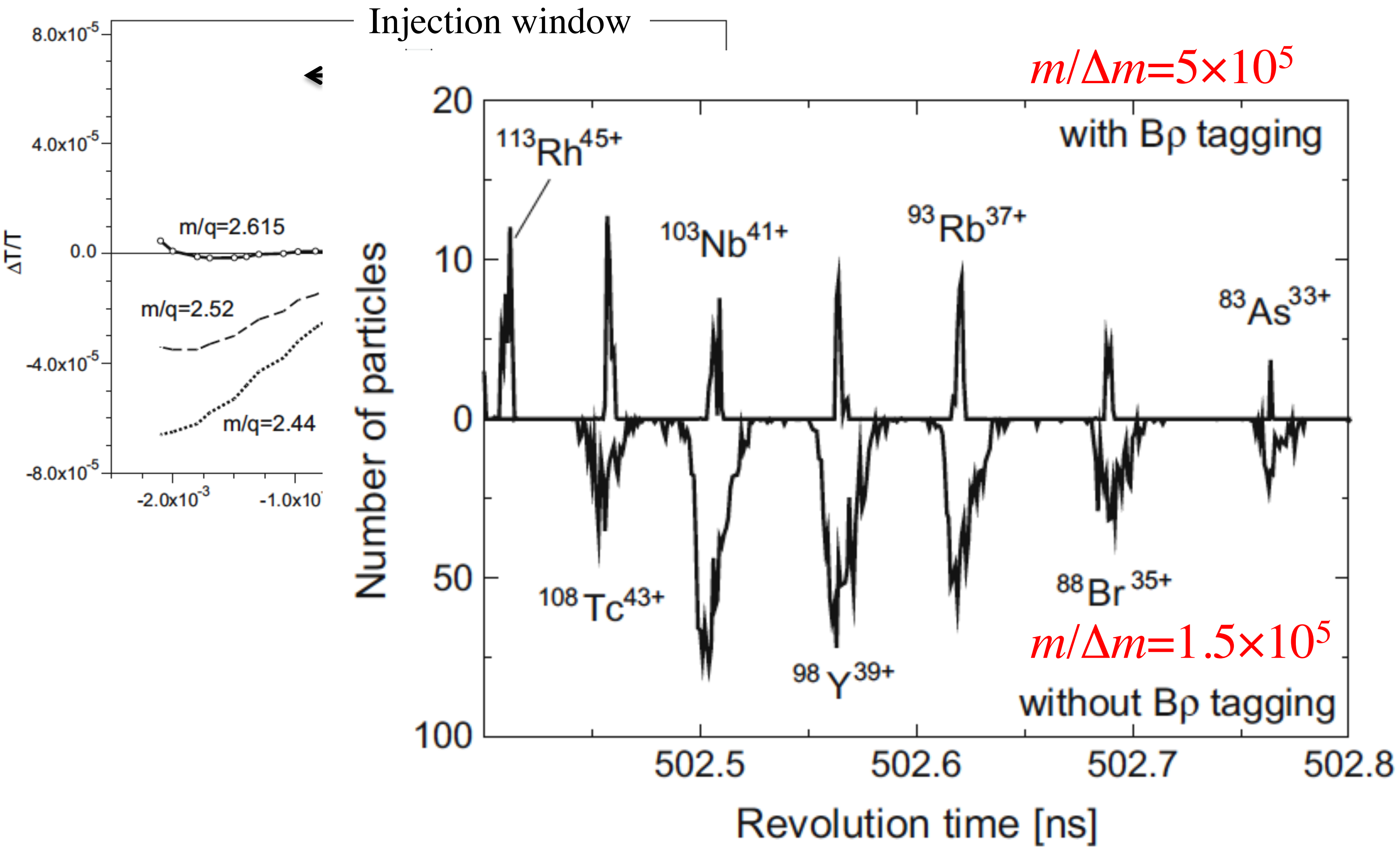
$A=2Z+2$

$$\frac{m}{q} = a_0 + a_1 f$$

Recent improvement of IMS in ESR

Bρ tagging technique

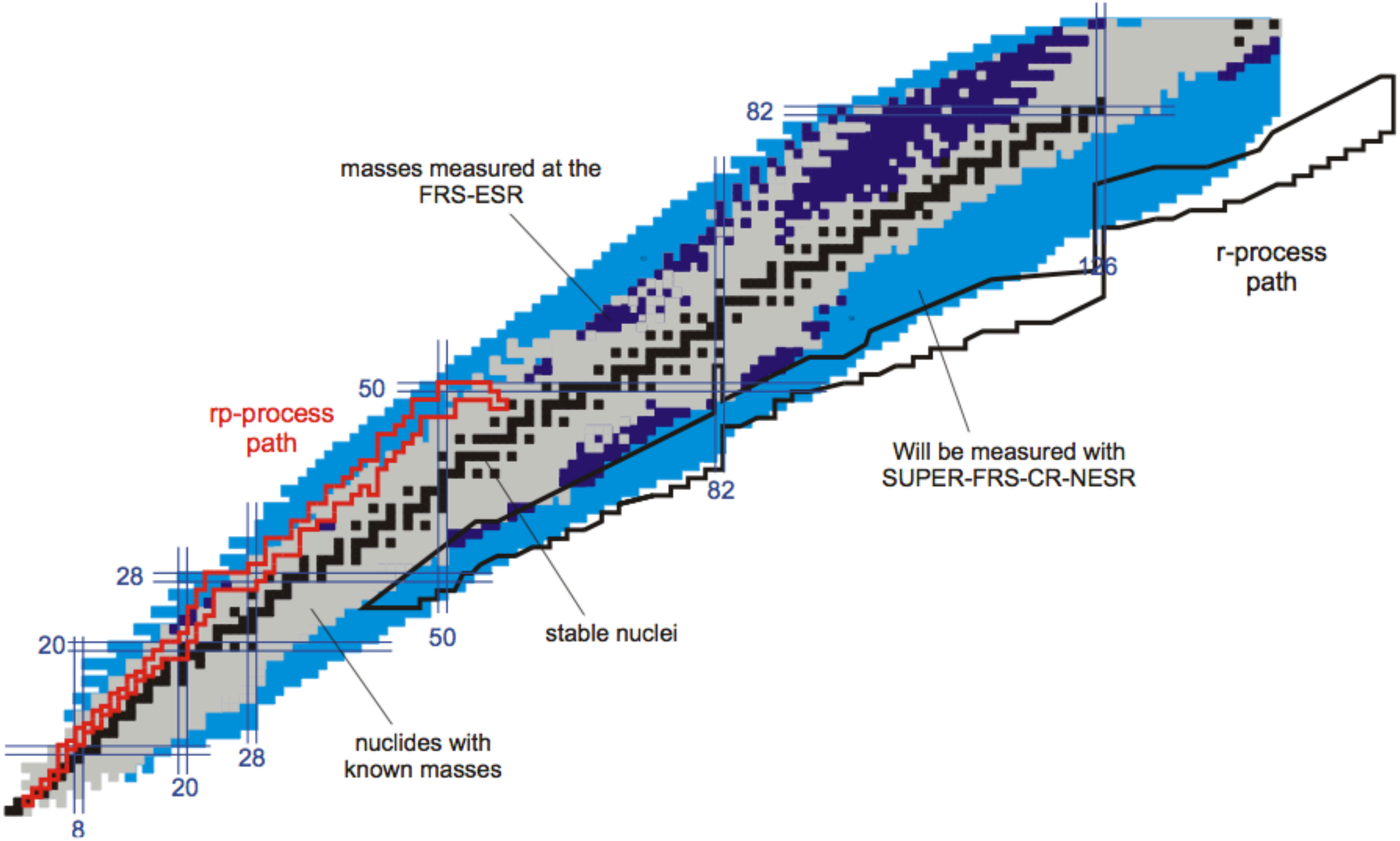
Hyperfine Int. 173 49 (2006).



$m/\Delta m = 5\times10^5$

$m/\Delta m = 1.5\times10^5$

Results of mass measurements in GSI



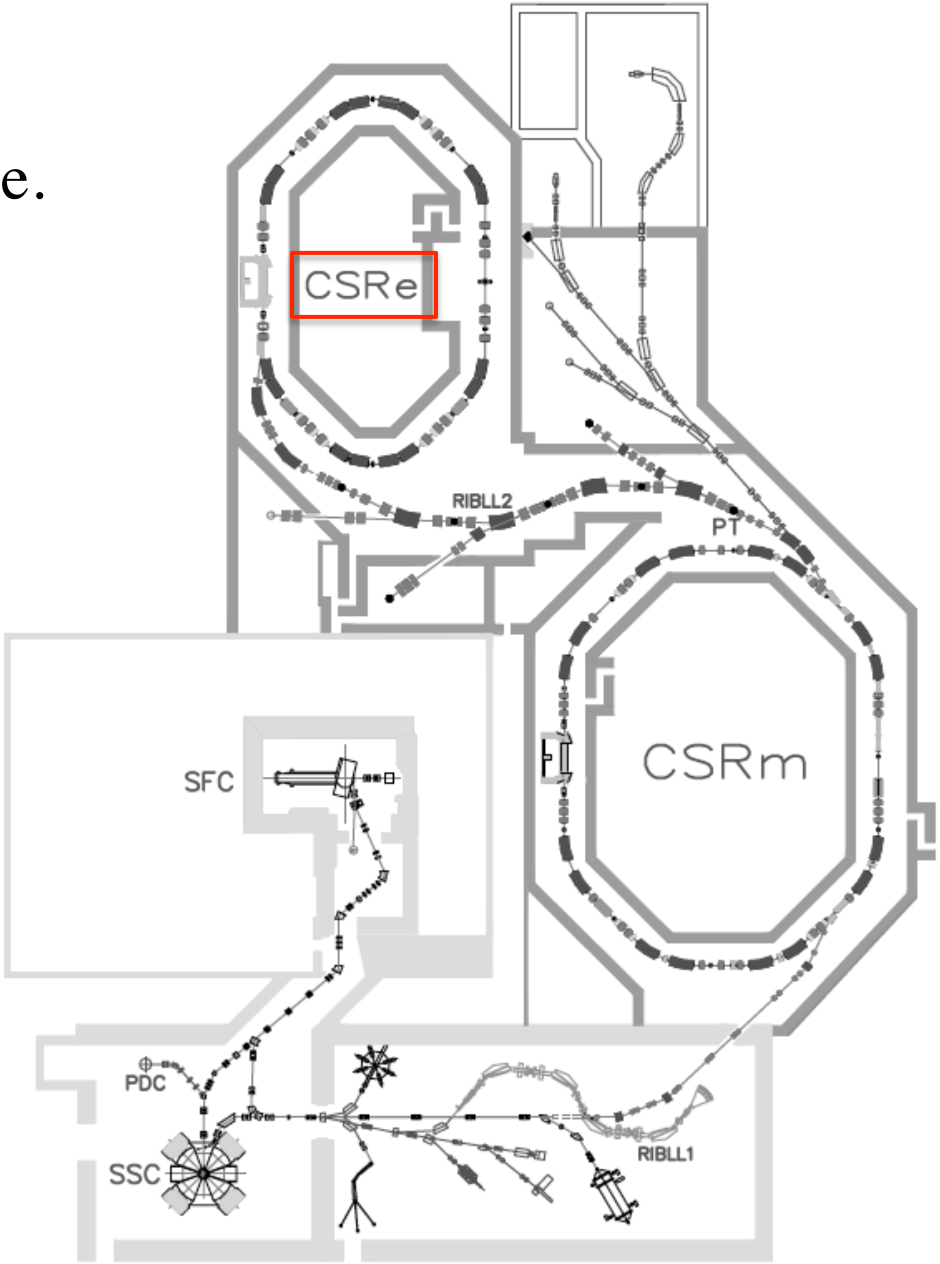
§ Mass measurements in CSRe/IMP

- Only IMS is performed in CSRe.

  $B\rho$ acceptance : ±0.2 %

  $m/\Delta m = 1.8\times10^5$

  PRL 109, 102501(2012).

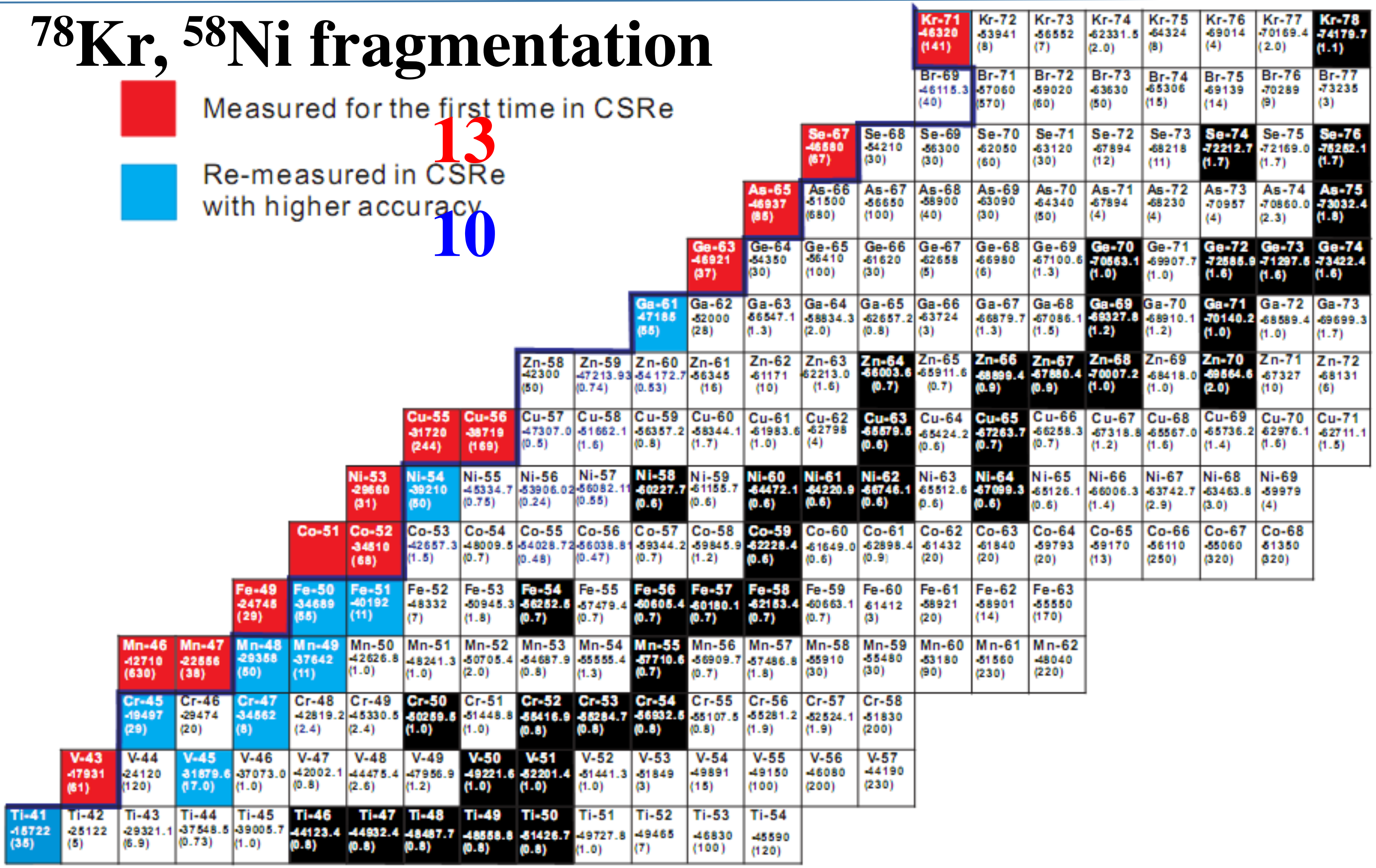


Results of mass measurements in CSRe

^{78}Kr, ^{58}Ni fragmentation

🟥 Measured for the first time in CSRe **13**

🟦 Re-measured in CSRe with higher accuracy **10**



																🟥 Kr-71 -46320 (141)	Kr-72 -53941 (8)	Kr-73 -56552 (7)	Kr-74 -62331.5 (2.0)	Kr-75 -64324 (8)	Kr-76 -69014 (4)	Kr-77 -70169.4 (2.0)	Kr-78 -74179.7 (1.1)
																Br-69 -46115.3 (40)	Br-71 -57060 (570)	Br-72 -59020 (60)	Br-73 -63630 (50)	Br-74 -65306 (15)	Br-75 -69139 (14)	Br-76 -70289 (9)	Br-77 -73235 (3)
														🟥 Se-67 -46580 (67)	Se-68 -54210 (30)	Se-69 -56300 (30)	Se-70 -62050 (60)	Se-71 -63120 (30)	Se-72 -67894 (12)	Se-73 -68218 (11)	Se-74 -72212.7 (1.7)	Se-75 -72169.0 (1.7)	Se-76 -75252.1 (1.7)
													🟥 As-65 -46937 (85)	As-66 -51500 (680)	As-67 -56650 (100)	As-68 -58900 (40)	As-69 -63090 (30)	As-70 -64340 (50)	As-71 -67894 (4)	As-72 -68230 (4)	As-73 -70957 (4)	As-74 -70860.0 (2.3)	As-75 -73032.4 (1.8)
												🟥 Ge-63 -46921 (37)	Ge-64 -54350 (30)	Ge-65 -56410 (100)	Ge-66 -61620 (30)	Ge-67 -62658 (5)	Ge-68 -66980 (6)	Ge-69 -67100.6 (1.3)	Ge-70 -70563.1 (1.0)	Ge-71 -69907.7 (1.0)	Ge-72 -72585.9 (1.6)	Ge-73 -71297.5 (1.6)	Ge-74 -73422.4 (1.6)
											🟦 Ga-61 -47185 (55)	Ga-62 -52000 (28)	Ga-63 -56547.1 (1.3)	Ga-64 -58834.3 (2.0)	Ga-65 -62657.2 (0.8)	Ga-66 -63724 (3)	Ga-67 -66879.7 (1.3)	Ga-68 -67086.1 (1.5)	Ga-69 -69327.8 (1.2)	Ga-70 -68910.1 (1.2)	Ga-71 -70140.2 (1.0)	Ga-72 -68589.4 (1.0)	Ga-73 -69699.3 (1.7)
									Zn-58 -42300 (50)	Zn-59 -47213.93 (0.74)	Zn-60 -54172.7 (0.53)	Zn-61 -56345 (16)	Zn-62 -61171 (10)	Zn-63 -62213.0 (1.6)	Zn-64 -66003.6 (0.7)	Zn-65 -65911.6 (0.7)	Zn-66 -68899.4 (0.9)	Zn-67 -67880.4 (0.9)	Zn-68 -70007.2 (1.0)	Zn-69 -68418.0 (1.0)	Zn-70 -69564.6 (2.0)	Zn-71 -67327 (10)	Zn-72 -68131 (6)
							🟥 Cu-55 -31720 (244)	🟥 Cu-56 -38719 (169)	Cu-57 -47307.0 (0.5)	Cu-58 -51662.1 (1.6)	Cu-59 -56357.2 (0.8)	Cu-60 -58344.1 (1.7)	Cu-61 -61983.6 (1.0)	Cu-62 -62798 (4)	Cu-63 -65579.8 (0.6)	Cu-64 -65424.2 (0.6)	Cu-65 -67263.7 (0.7)	Cu-66 -66258.3 (0.7)	Cu-67 -67318.8 (1.2)	Cu-68 -65567.0 (1.6)	Cu-69 -65736.2 (1.4)	Cu-70 -62976.1 (1.6)	Cu-71 -62711.1 (1.5)
						🟥 Ni-53 -29660 (31)	🟦 Ni-54 -39210 (50)	Ni-55 -45334.7 (0.75)	Ni-56 -53906.02 (0.24)	Ni-57 -56082.11 (0.55)	Ni-58 -60227.7 (0.6)	Ni-59 -61155.7 (0.6)	Ni-60 -64472.1 (0.6)	Ni-61 -64220.9 (0.6)	Ni-62 -66746.1 (0.6)	Ni-63 -65512.6 (0.6)	Ni-64 -67099.3 (0.6)	Ni-65 -65126.1 (0.6)	Ni-66 -66006.3 (1.4)	Ni-67 -63742.7 (2.9)	Ni-68 -63463.8 (3.0)	Ni-69 -59979 (4)	
					🟥 Co-51	🟥 Co-52 -34510 (68)	Co-53 -42657.3 (1.5)	Co-54 -48009.5 (0.7)	Co-55 -54028.72 (0.48)	Co-56 -56038.81 (0.47)	Co-57 -59344.2 (0.7)	Co-58 -59845.9 (1.2)	Co-59 -62228.4 (0.6)	Co-60 -61649.0 (0.6)	Co-61 -62898.4 (0.9)	Co-62 -61432 (20)	Co-63 -61840 (20)	Co-64 -59793 (20)	Co-65 -59170 (13)	Co-66 -56110 (250)	Co-67 -55060 (320)	Co-68 -51350 (320)	
				🟥 Fe-49 -24745 (29)	🟦 Fe-50 -34689 (55)	🟦 Fe-51 -40192 (11)	Fe-52 -48332 (7)	Fe-53 -50945.3 (1.8)	Fe-54 -56252.5 (0.7)	Fe-55 -57479.4 (0.7)	Fe-56 -60605.4 (0.7)	Fe-57 -60180.1 (0.7)	Fe-58 -62153.4 (0.7)	Fe-59 -60663.1 (0.7)	Fe-60 -61412 (3)	Fe-61 -58921 (20)	Fe-62 -58901 (14)	Fe-63 -55550 (170)					
		🟥 Mn-46 -12710 (630)	🟥 Mn-47 -22556 (38)	🟦 Mn-48 -29358 (50)	🟦 Mn-49 -37642 (11)	Mn-50 -42626.8 (1.0)	Mn-51 -48241.3 (1.0)	Mn-52 -50705.4 (2.0)	Mn-53 -54687.9 (0.8)	Mn-54 -55555.4 (1.3)	Mn-55 -57710.6 (0.7)	Mn-56 -56909.7 (0.7)	Mn-57 -57486.8 (1.8)	Mn-58 -55910 (30)	Mn-59 -55480 (30)	Mn-60 -53180 (90)	Mn-61 -51560 (230)	Mn-62 -48040 (220)					
		🟦 Cr-45 -19497 (29)	Cr-46 -29474 (20)	🟦 Cr-47 -34562 (8)	Cr-48 -42819.2 (2.4)	Cr-49 -45330.5 (2.4)	Cr-50 -50259.5 (1.0)	Cr-51 -51448.8 (1.0)	Cr-52 -55416.9 (0.8)	Cr-53 -55284.7 (0.8)	Cr-54 -56932.5 (0.8)	Cr-55 -55107.5 (0.8)	Cr-56 -55281.2 (1.9)	Cr-57 -52524.1 (1.9)	Cr-58 -51830 (200)								
	🟥 V-43 -17931 (61)	V-44 -24120 (120)	🟦 V-45 -31879.6 (17.0)	V-46 -37073.0 (1.0)	V-47 -42002.1 (0.8)	V-48 -44475.4 (2.6)	V-49 -47956.9 (1.2)	V-50 -49221.6 (1.0)	V-51 -52201.4 (1.0)	V-52 -51441.3 (1.0)	V-53 -51849 (3)	V-54 -49891 (15)	V-55 -49150 (100)	V-56 -46080 (200)	V-57 -44190 (230)								
🟦 Ti-41 -15722 (35)	Ti-42 -25122 (5)	Ti-43 -29321.1 (6.9)	Ti-44 -37548.5 (0.73)	Ti-45 -39005.7 (1.0)	Ti-46 -44123.4 (0.8)	Ti-47 -44932.4 (0.8)	Ti-48 -48487.7 (0.8)	Ti-49 -48558.8 (0.8)	Ti-50 -51426.7 (0.8)	Ti-51 -49727.8 (1.0)	Ti-52 -49465 (7)	Ti-53 -46830 (100)	Ti-54 -45590 (120)										

§ Mass measurements in Rare-RI Ring

$$T_0 = \frac{1}{f_c} = 2\pi\frac{m}{qB} = 2\pi\frac{m_0}{q_0 B_0}$$

PTEP2012, 03C009(2012)

Cyclotron frequency f_c

Mass is determined relatively

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

$$\frac{m_1}{q_1} = \left(\frac{m_0}{q_0}\right)\frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \left(\frac{m_0}{q_0}\right)\frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-\left(\frac{T_1}{T_0}\beta_1\right)^2}}$$

$$\frac{\delta(m_1/q_1)}{m_1/q_1} = \underbrace{\frac{\delta(m_0/q_0)}{m_0/q_0}}_{\text{reference} < 10^{-6}} + \underbrace{\frac{\delta(T_1/T_0)}{T_1/T_0}}_{\text{measurement} < 10^{-6}} + k\underbrace{\frac{\delta\beta_1}{\beta_1}}_{\text{measurement} \sim 10^{-4}} \Longrightarrow 10^{-6}$$

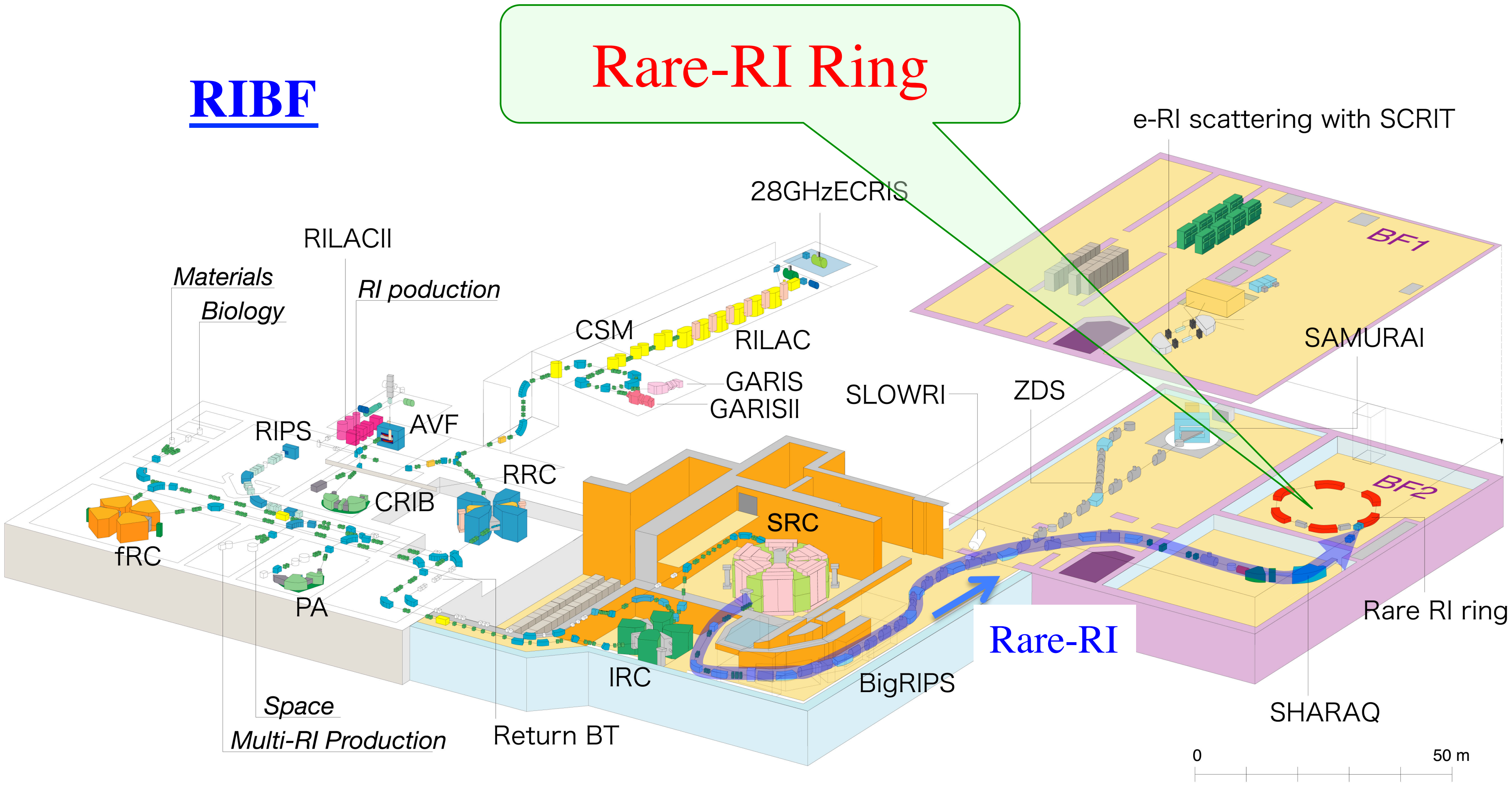
$$k = -\frac{\beta_1^2}{1-\beta_1^2} + \left(\frac{T_1}{T_0}\right)^2\frac{\beta_1^2}{1-(T_1/T_0)^2\beta_1^2}$$

$k \sim 10^{-2}$

difference of T ~ 1%

(difference of *m/q* ~ 1%)

Rare-RI Ring in RIBF

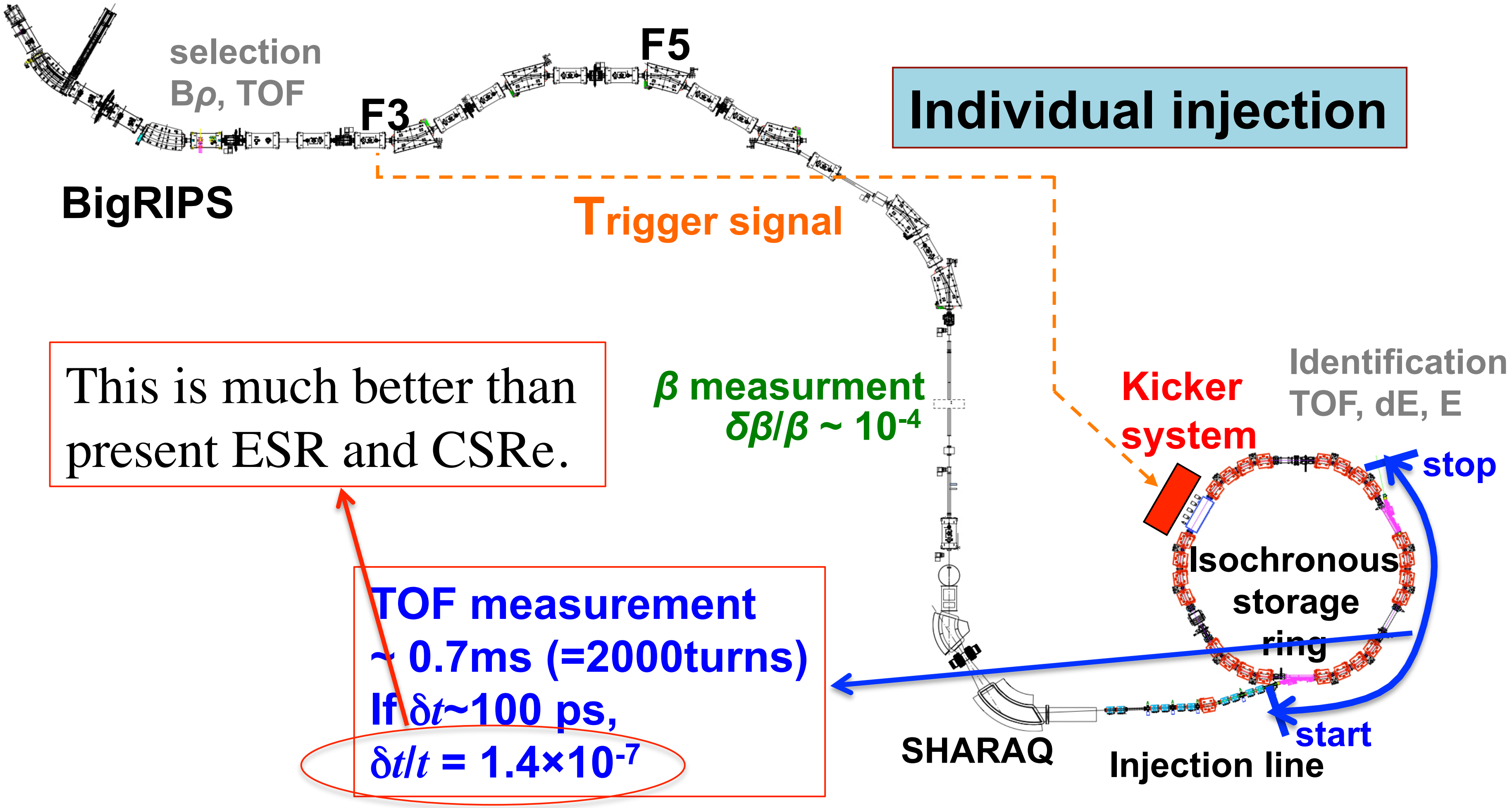


Scheme for mass measurements

Only 1 particle (200 *A* MeV) is stored.

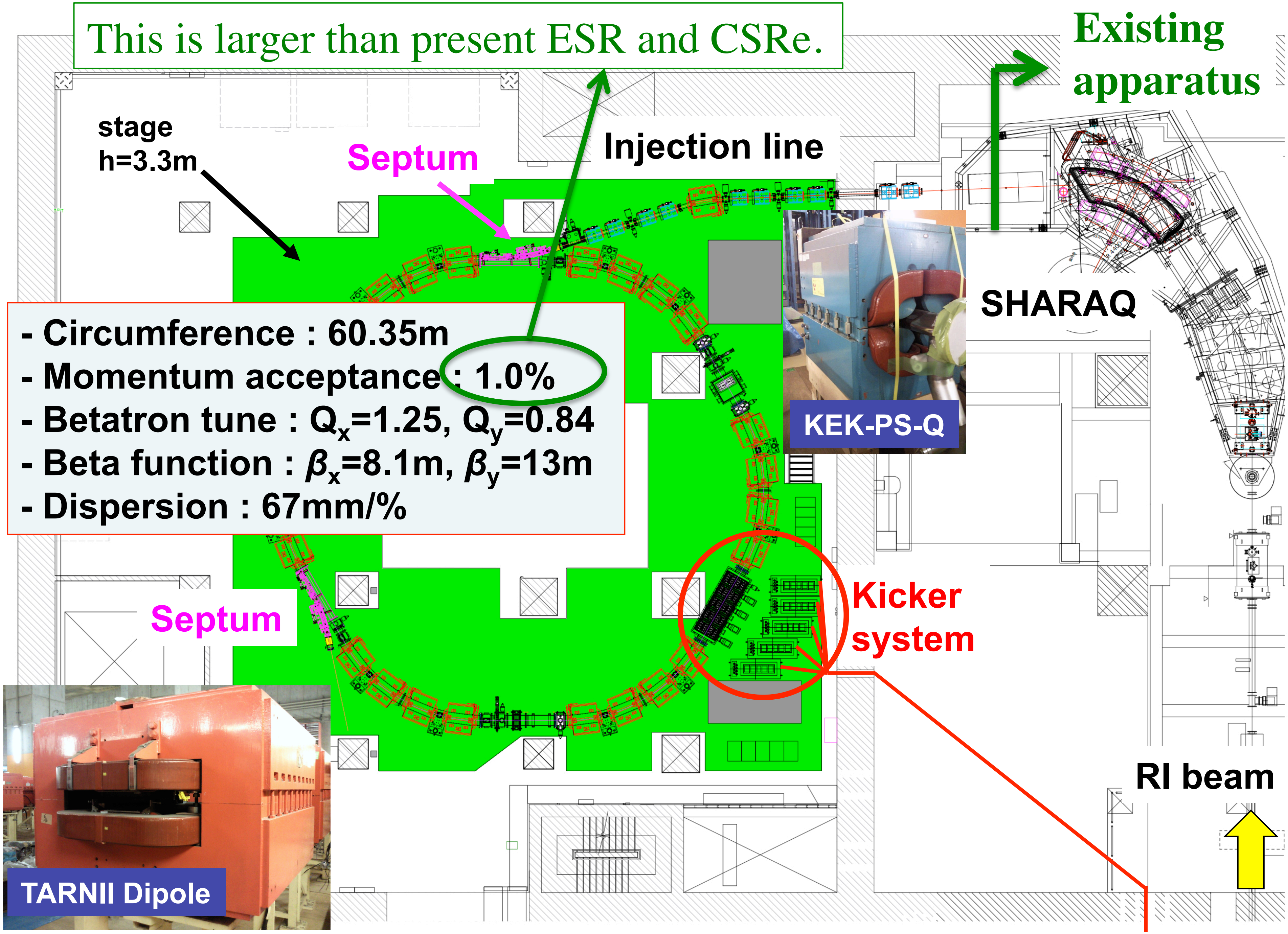
Isochronous mass spectrometry ⇨ **Short measurement time (<1 ms)**

- **Cyclotron-like storage ring** ⇨ **Good isochronous field (~10^{-6})**
- Individual injection ⇨ High efficiency (~100%)



This is much better than present ESR and CSRe.

TOF measurement
~ 0.7ms (=2000turns)
If δ*t*~100 ps,
δ*t*/*t* = 1.4×10^{-7}



This is larger than present ESR and CSRe.

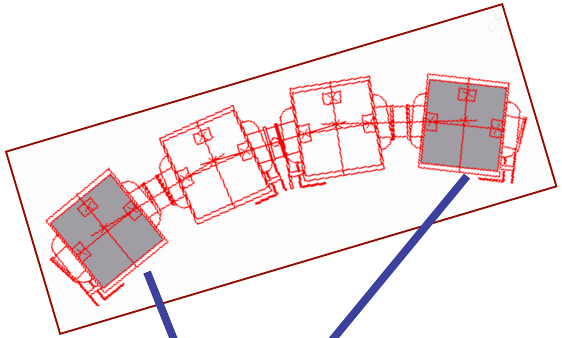
Existing apparatus

stage
h=3.3m

Septum

Injection line

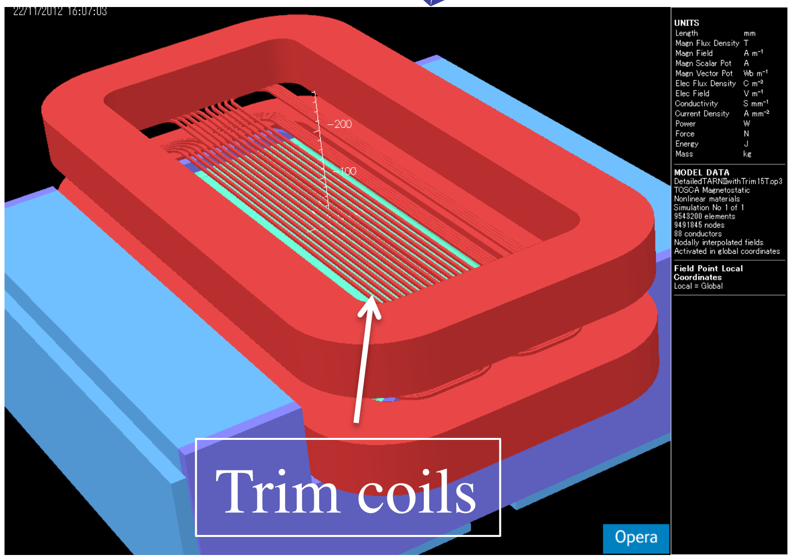
- Circumference : 60.35m
- Momentum acceptance : 1.0%
- Betatron tune : Q_x=1.25, Q_y=0.84
- Beta function : β_x=8.1m, β_y=13m
- Dispersion : 67mm/%



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

Design of cyclotron-like storage ring

We locate trim coils.

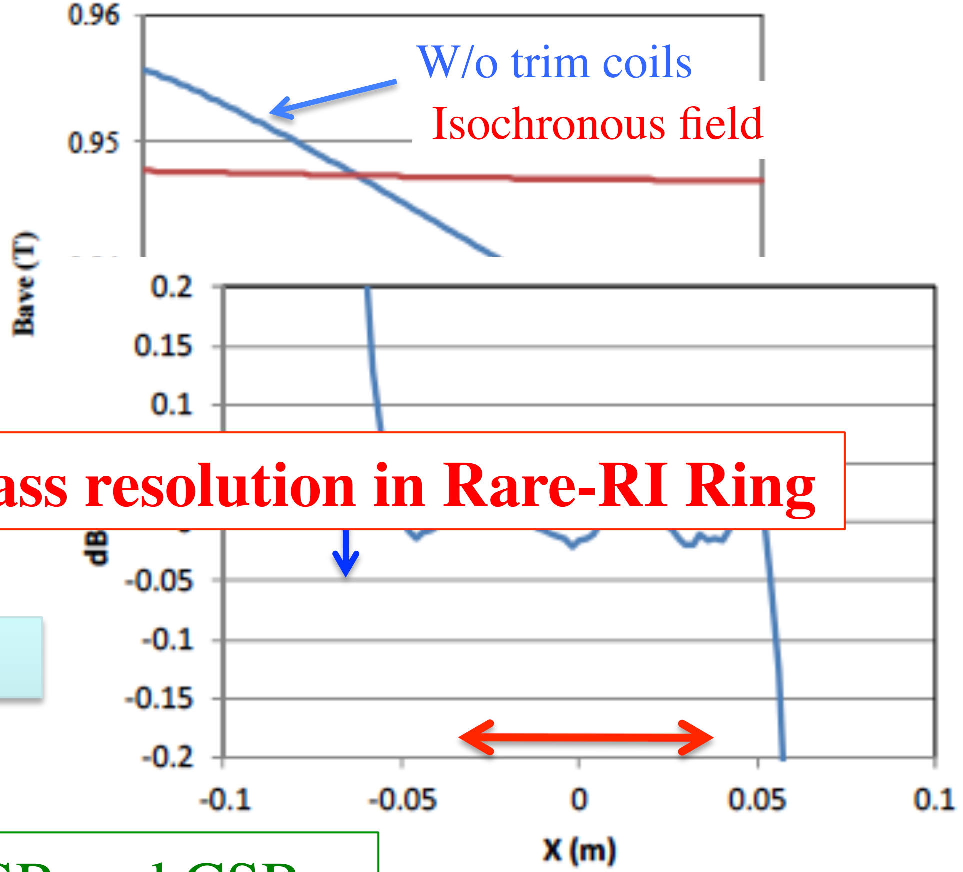


UNITS

Length	mm
Magn Flux Density	T
Magn Field	A m^{-1}
Magn Scalar Pot	A
Magn Vector Pot	Wb m^{-1}
Elec Flux Density	C m^{-2}
Elec Field	V m^{-1}
Conductivity	S mm^{-1}
Current Density	A mm^{-2}
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA
DetailedTARNIIwithTrim15T.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
9543200 elements
9491845 nodes
88 conductors
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates
Local = Global

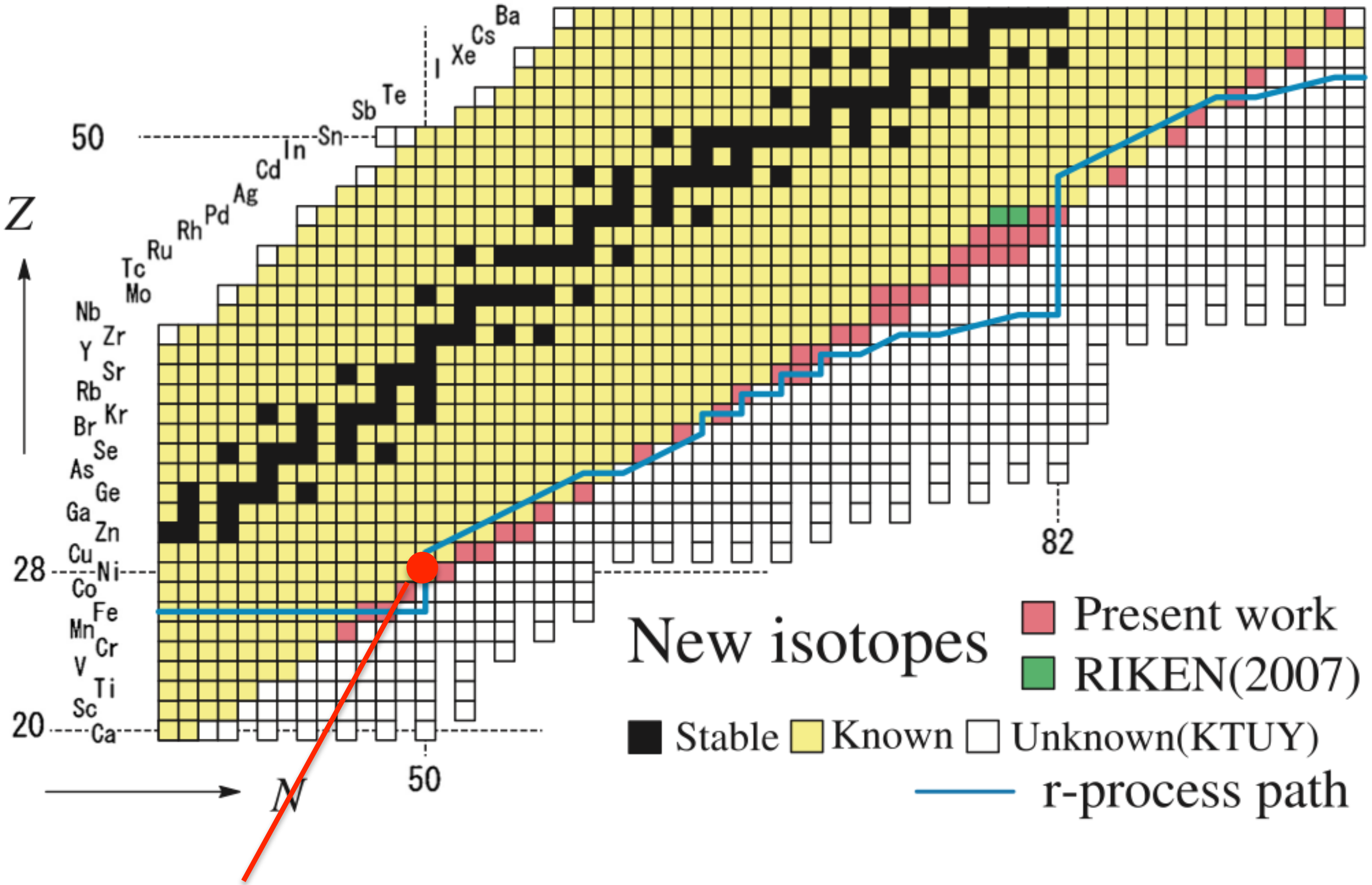


Mass resolution in Rare-RI Ring

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

This is better than present ESR and CSRe.

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



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

JPSJ 79, 073201

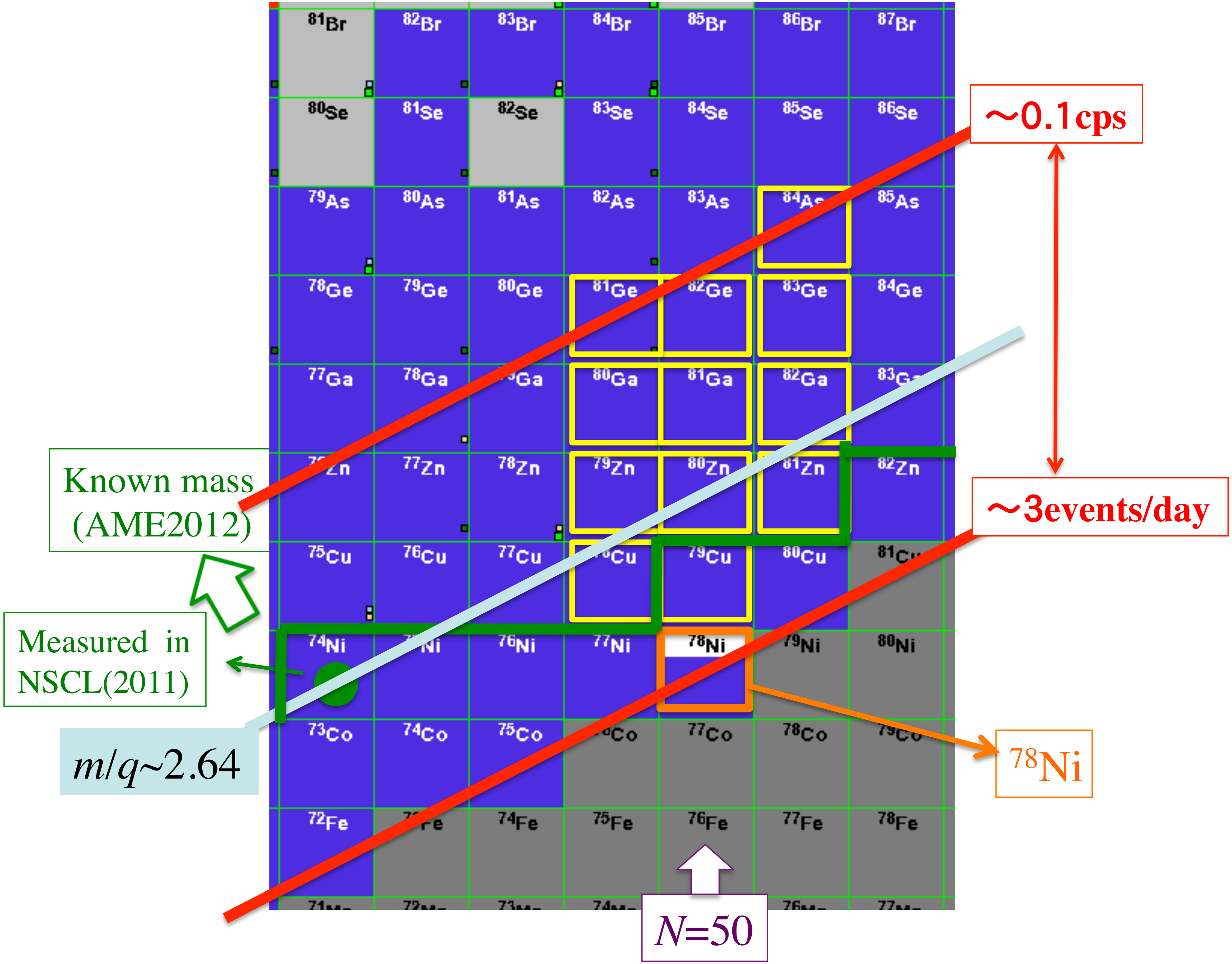
Yield estimation of ^{78}Ni in Rare-RI ring

~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 (AME2012)

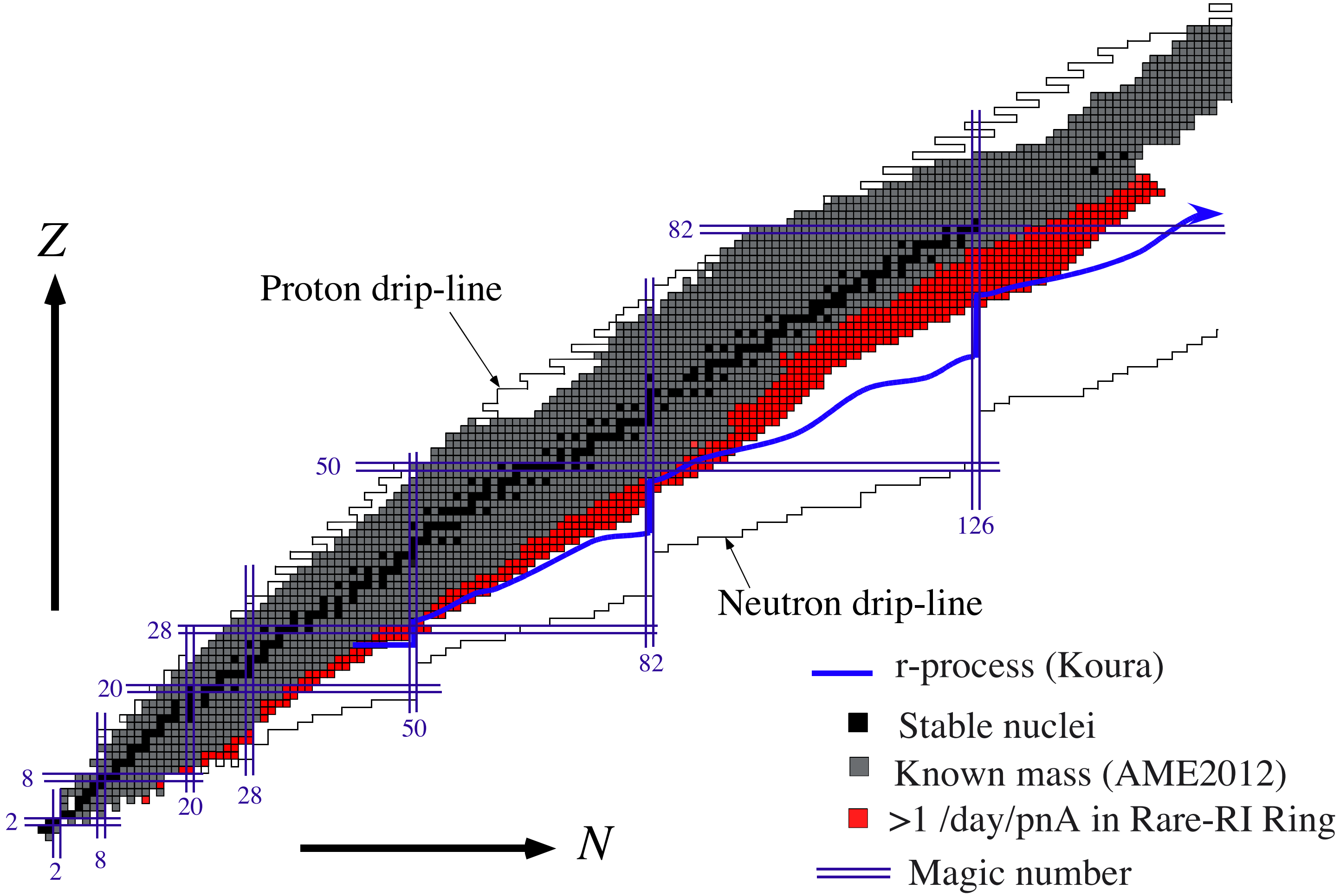
Measured in NSCL(2011)

m/q~2.64

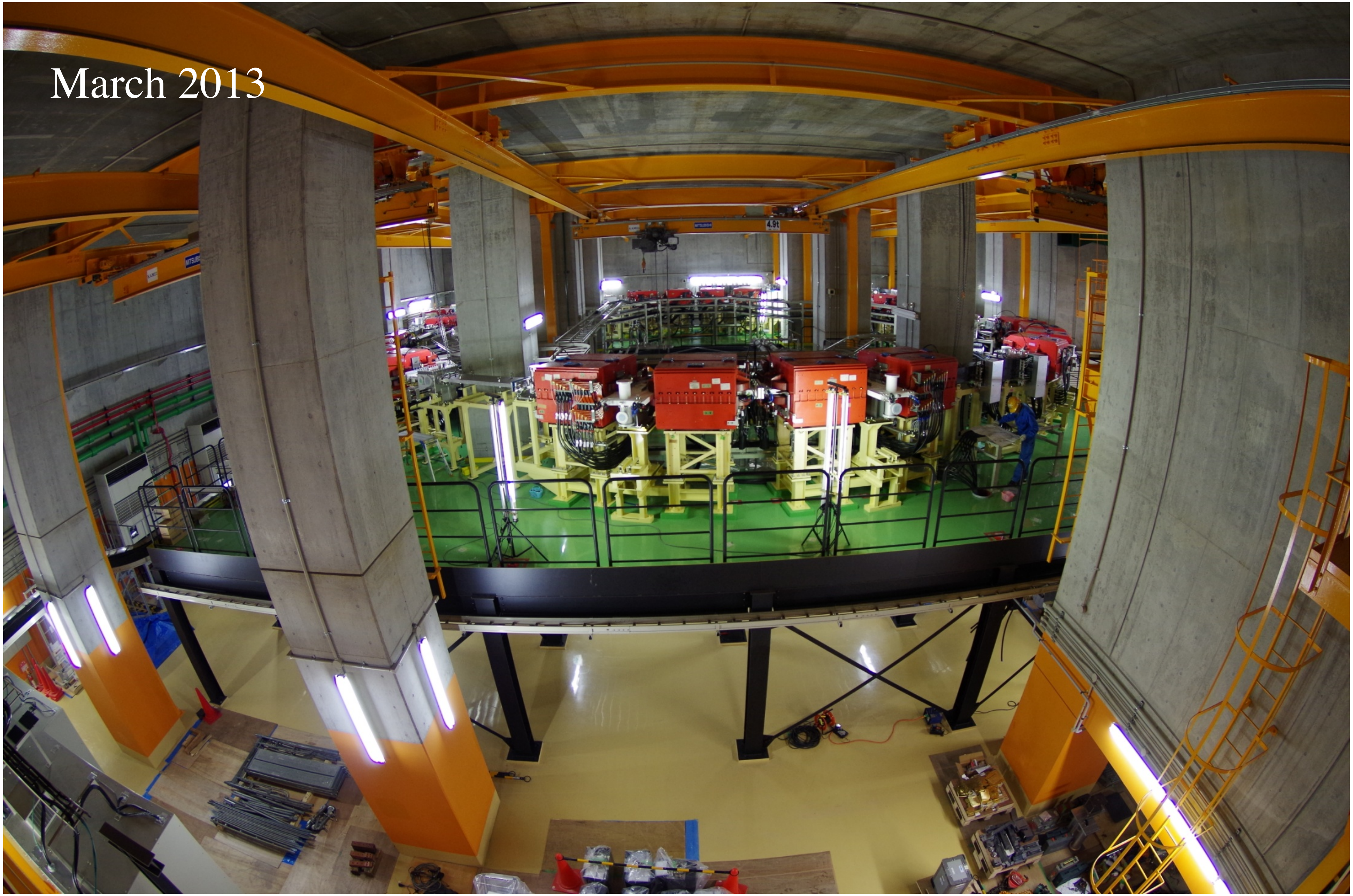
^{78}Ni

N=50

Accessible area in Rare-RI Ring



Present status of construction



March 2013

Schedule of mass measurements in Rare-RI Ring

FY2013	FY2014	FY2015	FY2016 FY2017
Preparation	**Commissioning**	**Mass measurement**	**Mass measurement**
- Trigger system - Control system - Beam monitor -NMR monitor - Excitation - Chamber baking - Connection to SHARAQ R&D - Kicker system - Schottky system - TOF detector ...	Primary beam Performance check - Individual injection - Extraction - Accumulation - Isochronous tuning	Day 1 experiment ^{78}Ni	Around the waiting point of r-process path N=50, 82, 126 ...

↑

Now!

§ Summary

- Construction of Rare-RI Ring started from 2012 April.
- Rare-RI Ring will be completed until the end of FY2013.
- Only 1 particle is stored in Rare-RI Ring by individual injection.
- $m/\Delta m \sim 10^{-6}$ with $\delta p/p \sim \pm 0.5\%$ because of cyclotron-type storage ring (isochronous storage ring).
- Mass measurement in Rare-RI Ring will start from the end of 2014.
- Mass measurement for ^{78}Ni is quite feasible.
- In Rare-RI Ring, we can newly measure the mass for ~600 nuclei.

Rare-RI Ring Collaboration

Spokespersons: A.Ozawa (Univ. of Tsukuba) and T.Uesaka (RIKEN)
Project manager: M.Wakasugi (RIKEN)

Research group:

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Y. Abe, T.Komatsubara, D.Nagae (Univ. of Tsukuba)
J.Zenihiro (RIKEN), Y.J.Yuan, H.S.Xu (IMP),
T.Ohtsubo (Niigata Univ.)

Detector development group:

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Construction group:

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K.Yoshida, K.Yamada, Y.Yanagisawa, Y.Yano (RIKEN)
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