Nuclear Experiments with Radioactive Isotope Beams I

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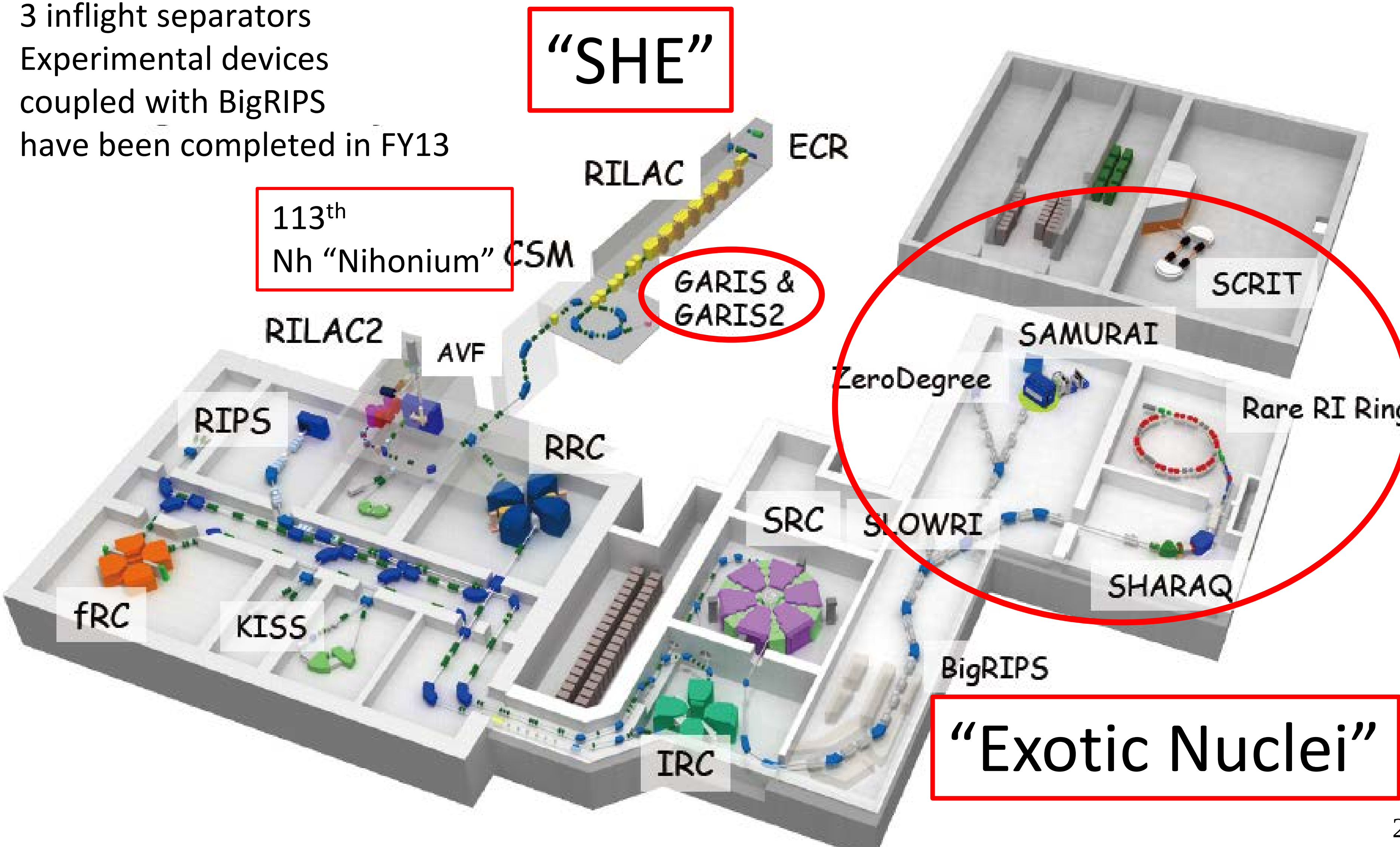
RI Beam Factory

5 cyclotrons + 2 linacs
3 inflight separators
Experimental devices coupled with BigRIPS have been completed in FY13



Radioactive isotope productions
and particle identification

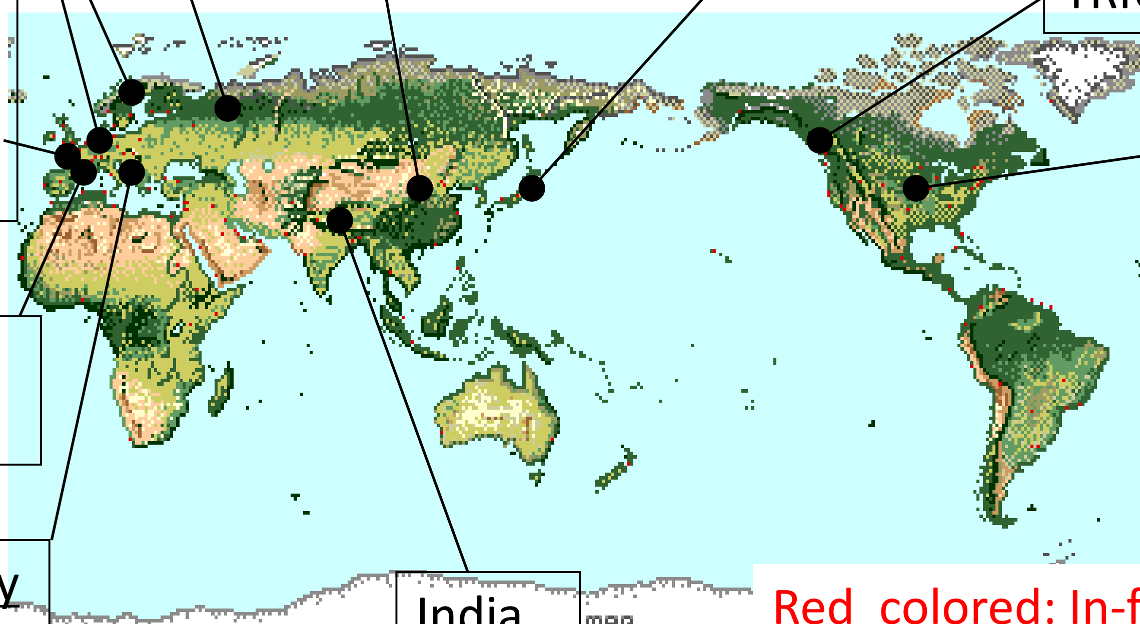
In-beam gamma spectroscopy
Decay spectroscopy

Mass spectroscopy

Invariant mass spectroscopy
Missing mass spectroscopy
Others

Major RI Beam Facilities in the world

Our “Frenemy” (friend+enemy)



Finland
JYFL

Germany
GSI

Russia
JINR

China
IMP
CIAE

Japan
RIKEN-RIBF

Canada
TRIUMF

France
GANIL
SPIRAL-I, II
LISE

USA
MSU/NSCL
ANL
Texas A&M

Switzerland
CERN/ISOLDE

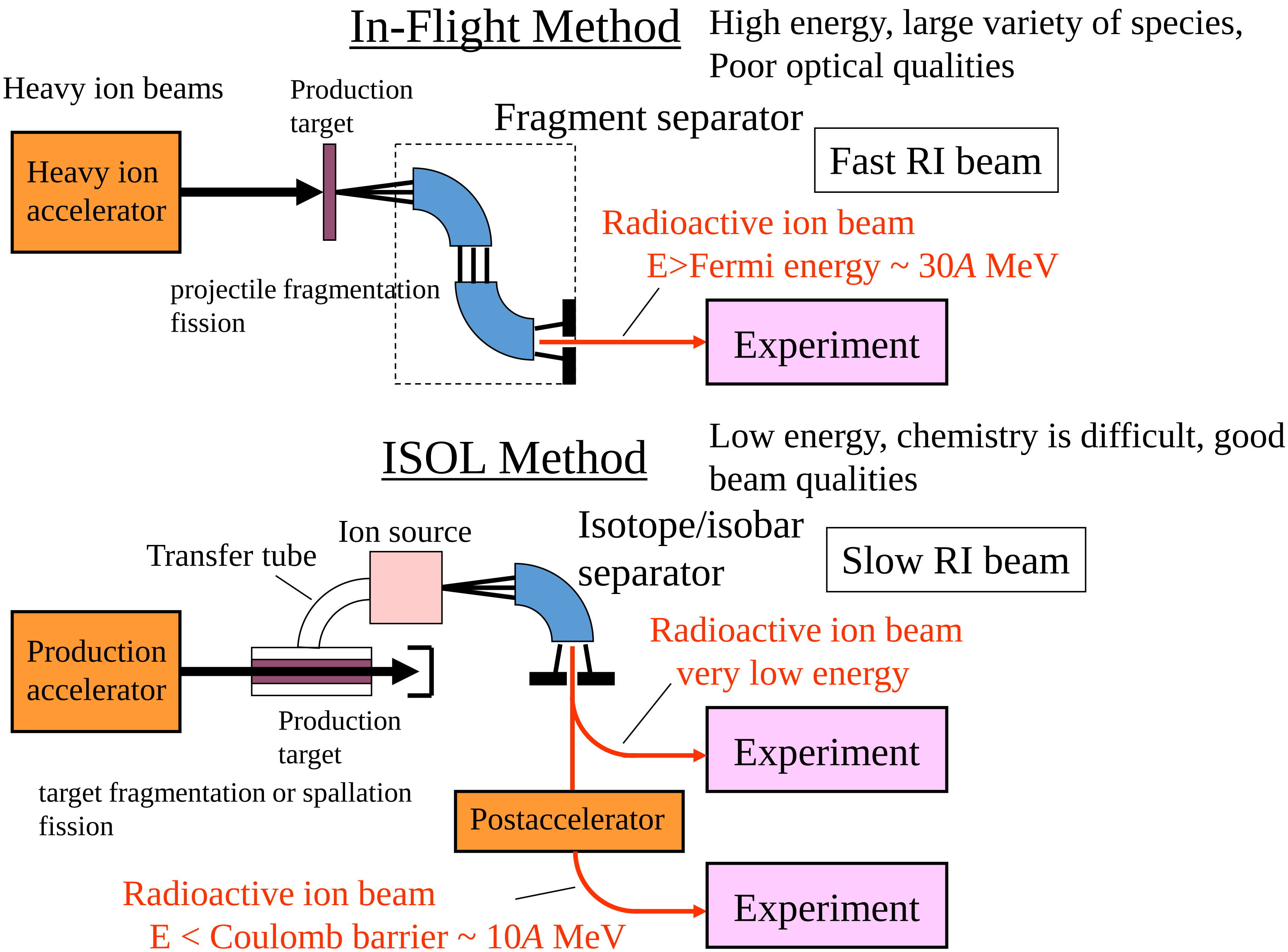
Italy
LNS

India
VECC
IUAC

Red colored: In-flight method

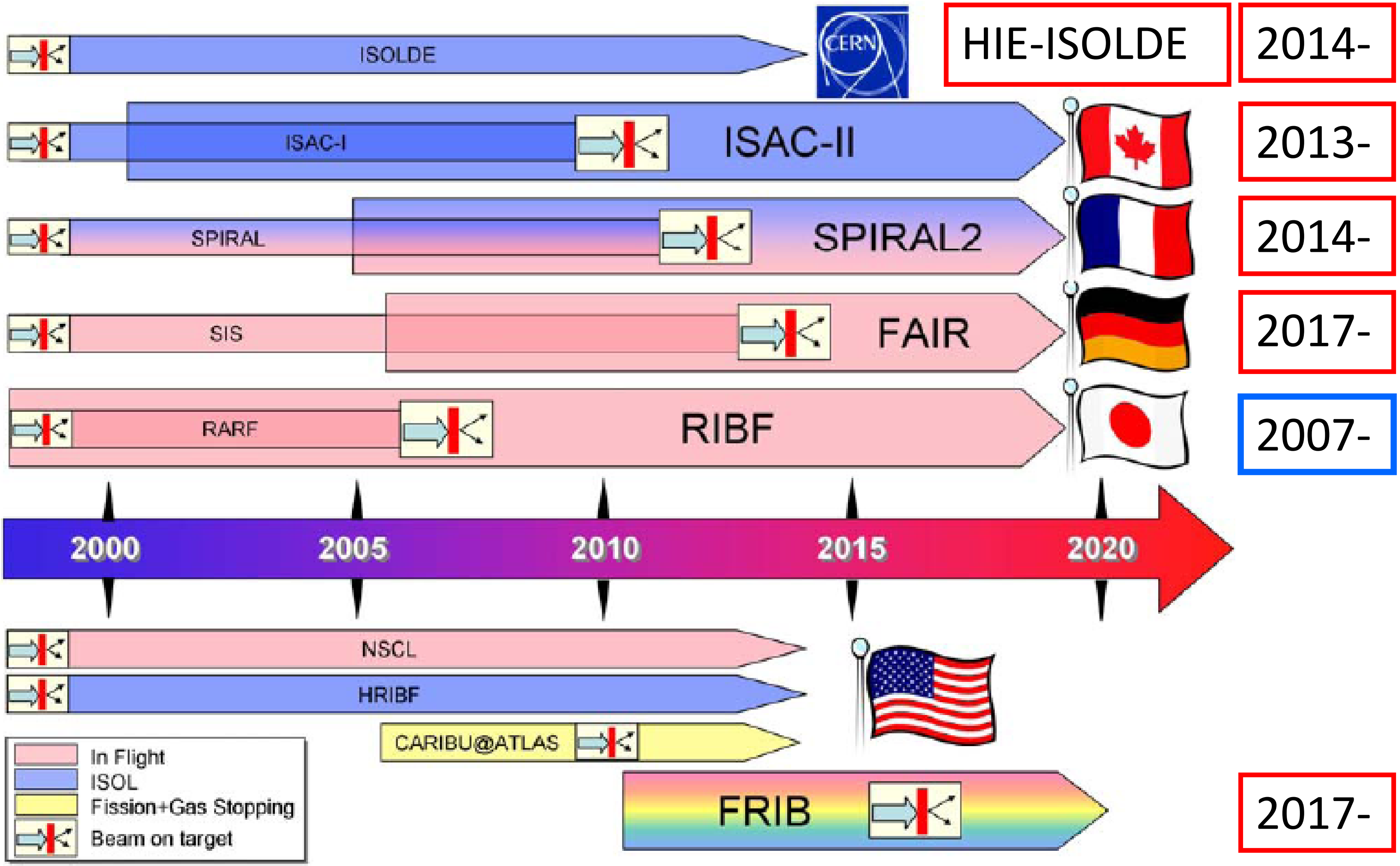
Next generation facility
FAIR at GSI 2021-
FRIB at MSU 2020-

In-flight and ISOL methods to produce radioactive ions



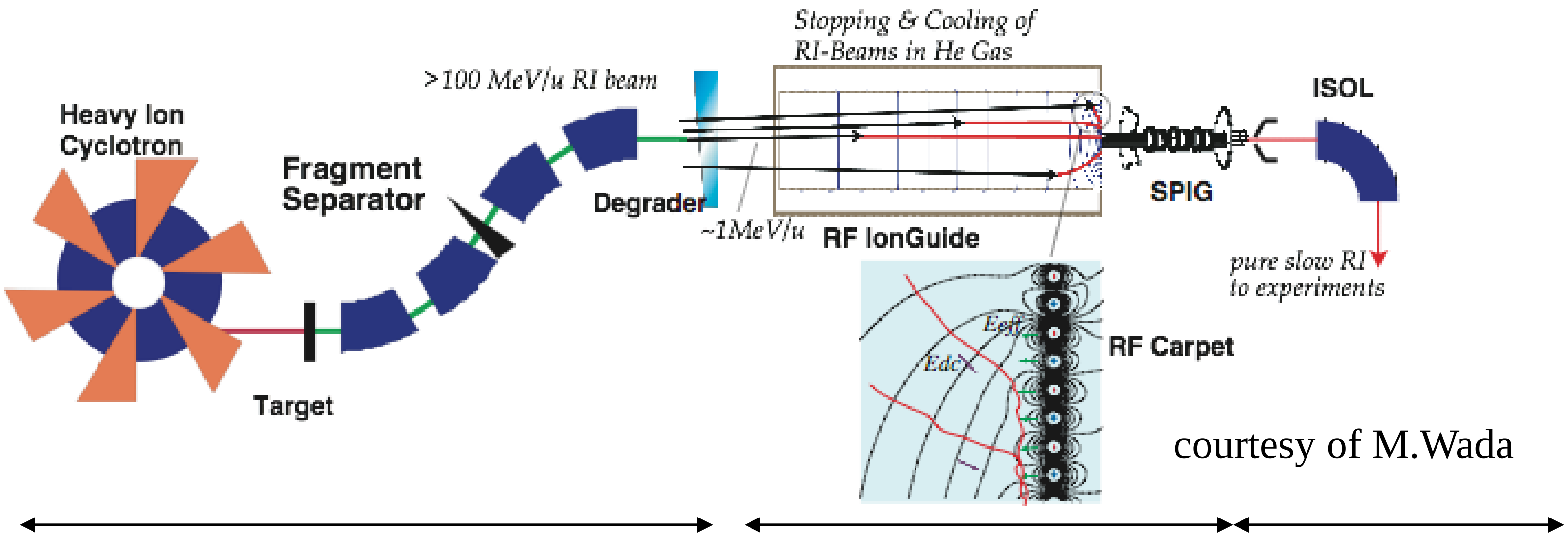
Large-scaled Facilities in the world

H.S. at PKU Summer School 2011



New experimental techniques to have very slow RI beams

RIKEN, NSCL/MSU, ANL



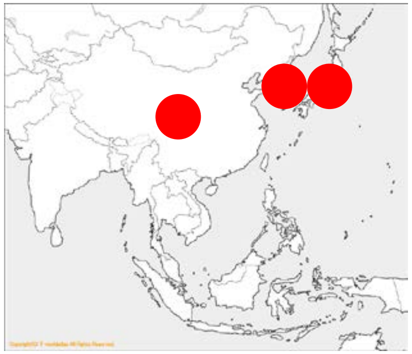
courtesy of M.Wada

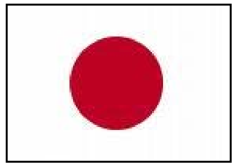
In-flight Method	Gas-catcher system	ISOL

High energy, large variety of species,
Poor optical qualities → large variety of species, good optical qualities, nice purity

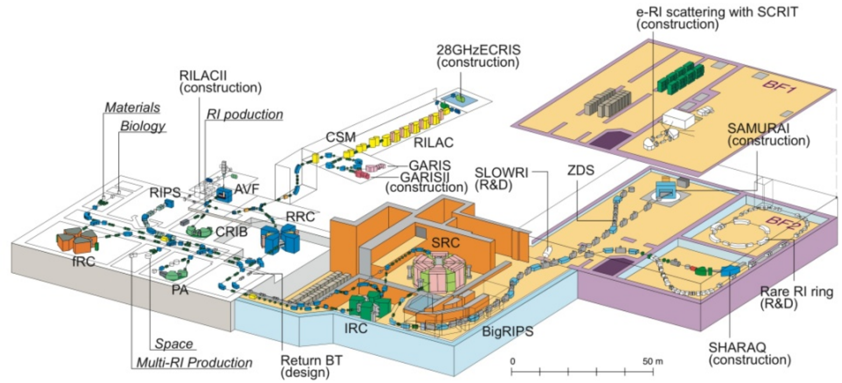
FRIB : post-acceleration for radioactive isotopes after ISOL

Large-scaled facilities in operation and proposed in East Asia

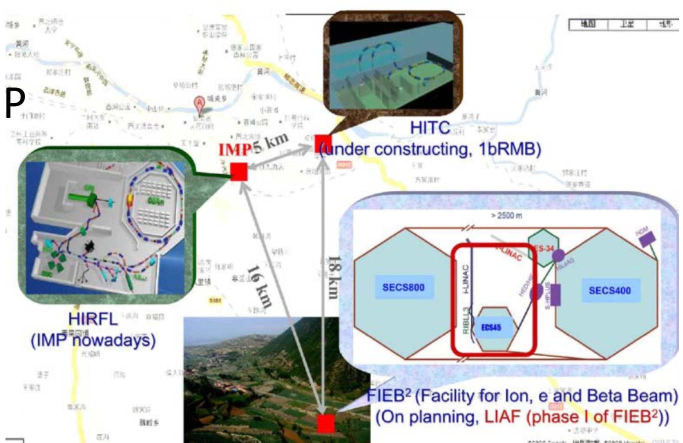




RIBF (RIKEN)
In-flight



IMP



HIRFL (IMP)
In-flight + Ring

BRIF project (CIAE) ISOL
HIAF project(IMP) In-flight funded in 2015
ADS project (CAS) funded in 2015

RISP (RAON) Project
ISOL+In-Flight+ISOL

History of In-flight Method

0th Generation (70's) LBL
"Discovery" of Projectile Fragmentation

1st Generation (80's) GANIL/LISE   LISE was originally designed for atomic-physics
Establishment of Separation Technique $B\rho$-ΔE-$B\rho$ Method

2nd Generation (90's) GSI/FRS, NSCL/A1200-1900, GANIL/SISSI, RIKEN/RIPS
High-Collection Technique

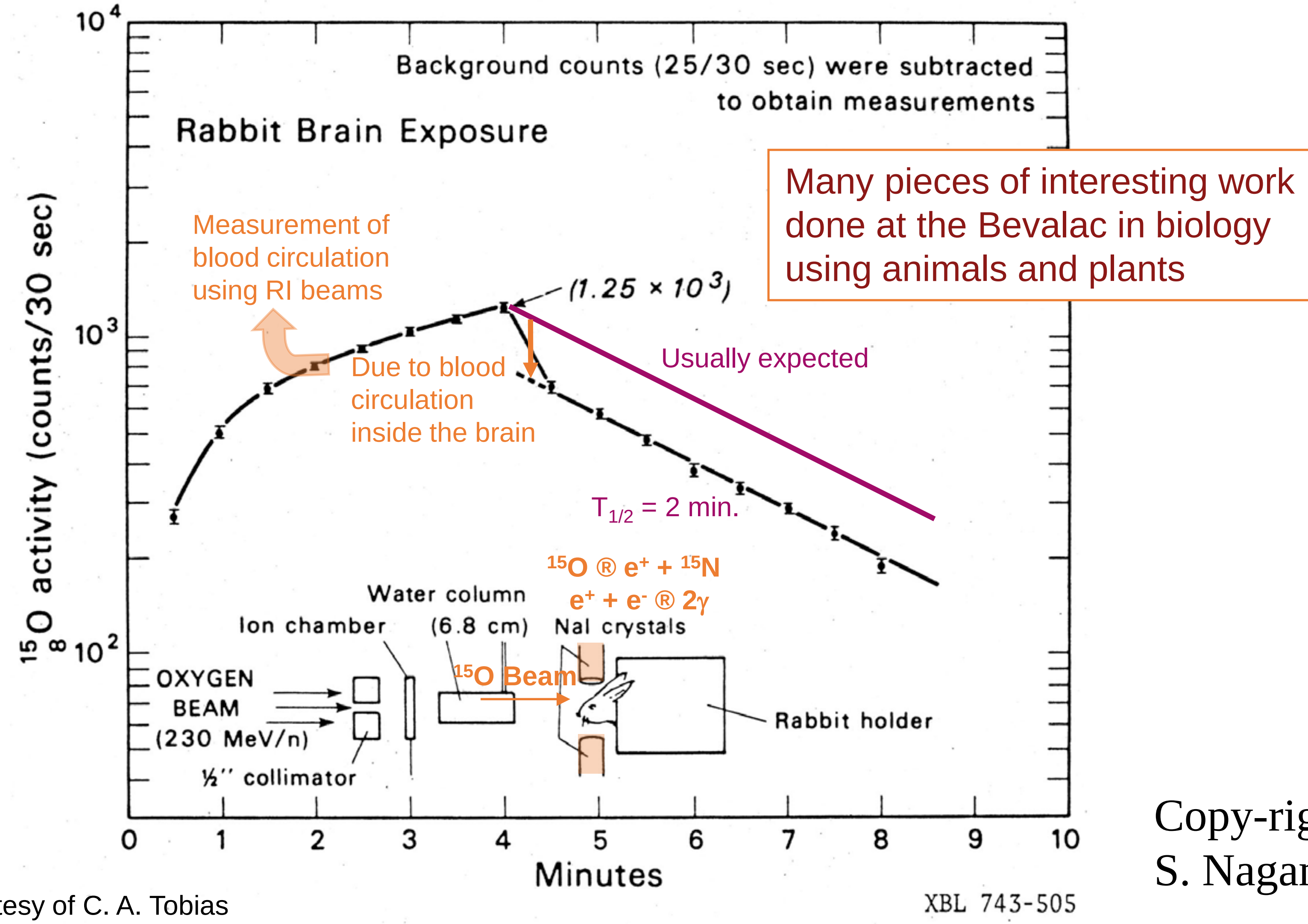
Max. $B\rho$ and Large Acceptances	RIKEN/RIPS
Emittance-transformation	GANIL/SISSI

Further Purification Methods

ExB filter	GANIL/LISE
rf-deflector	RIKEN/RIPS
In-flight Fission for neutron-rich nuclei	GSI/FRS
Combination of Separator + Spectrometer	GANIL, NSCL, GSI

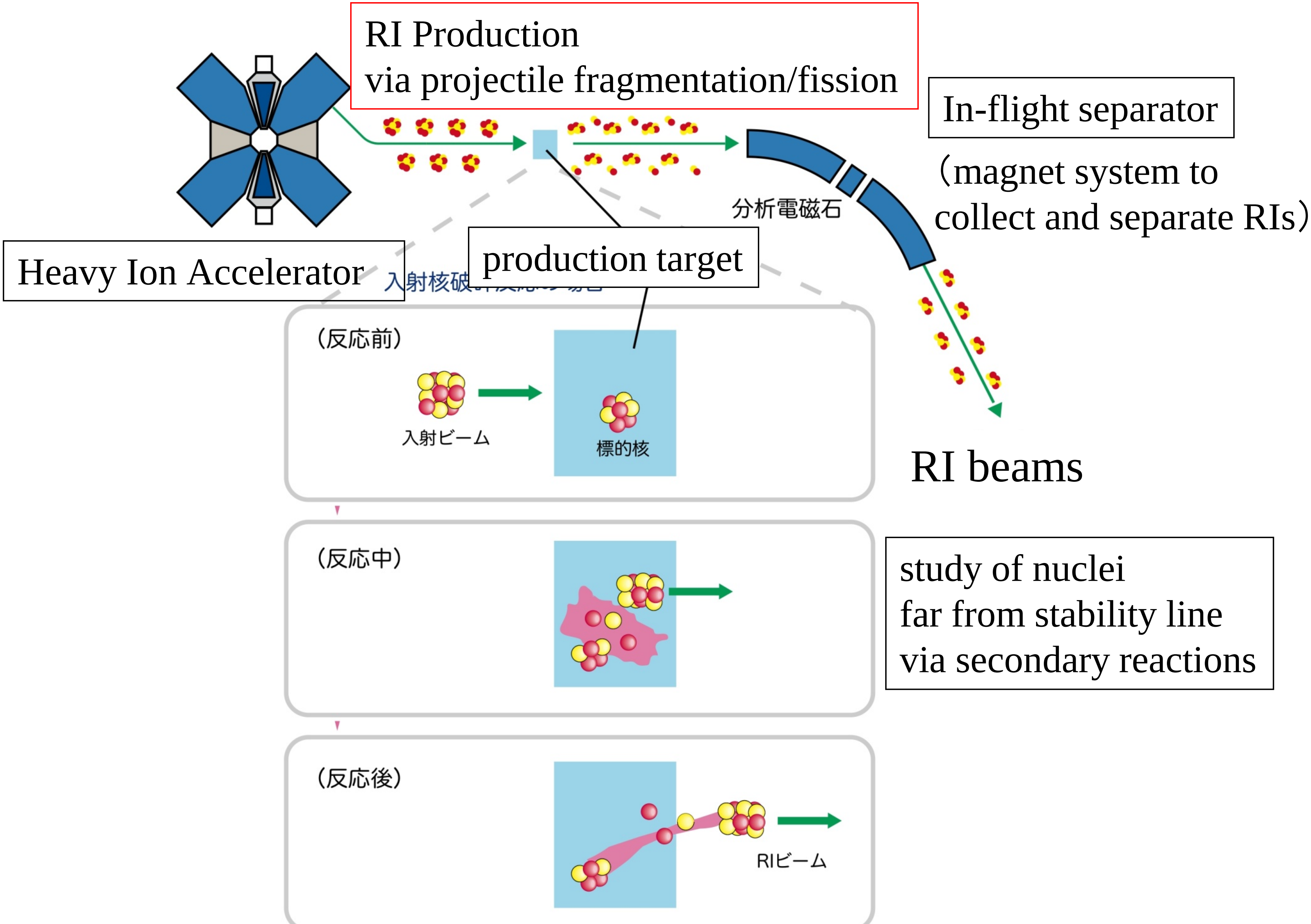
3rd Generation (00's -) RIKEN/RIBF, GSI/FAIR, MSU/FRIB
High-Power Heavy-Ion Beams up to U

The First RI Beam Experiment (1974)



Courtesy of C. A. Tobias

In-flight Production Method of RI beam



RI Beam Factory

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3 inflight separators
Experimental devices
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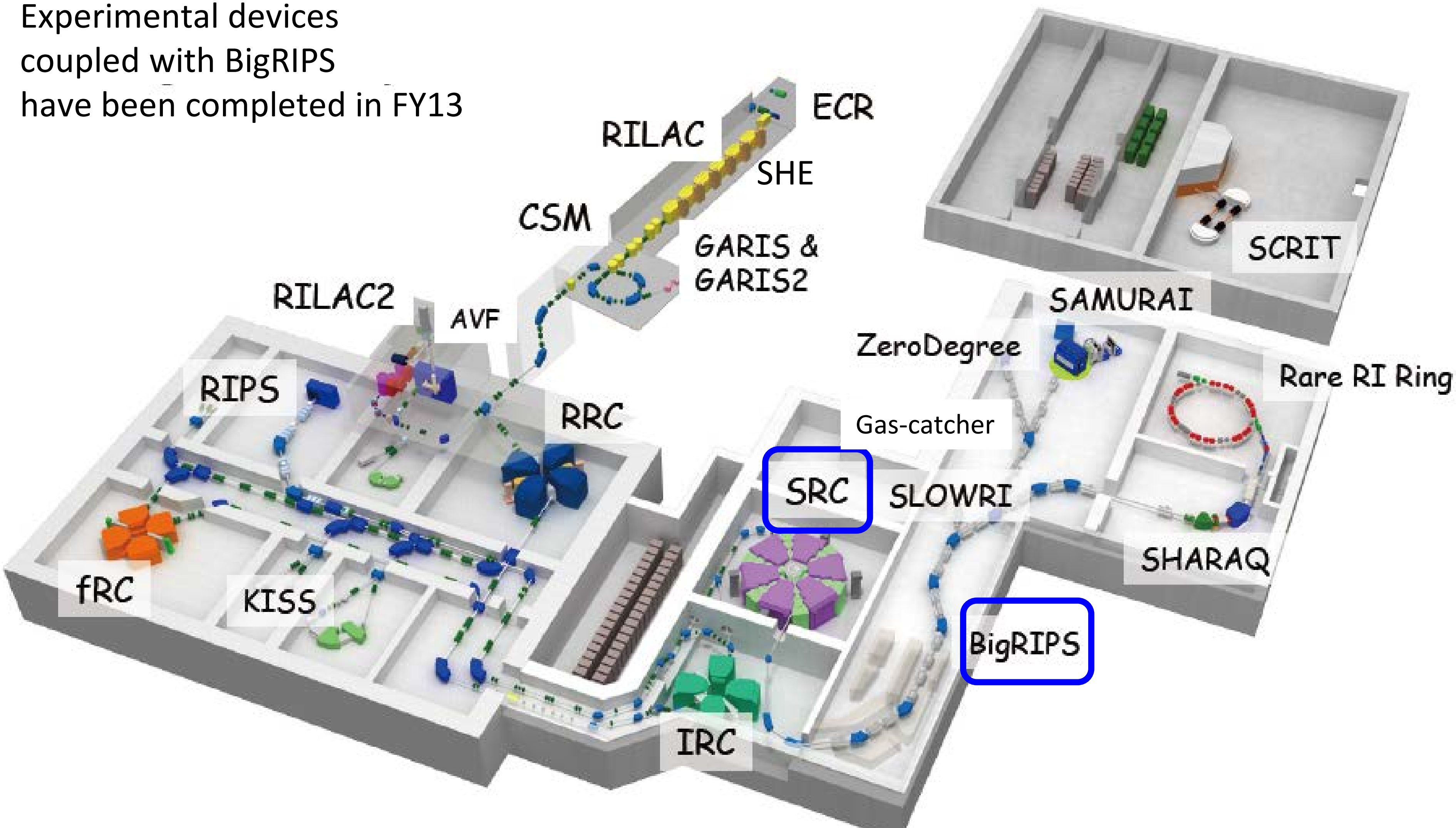
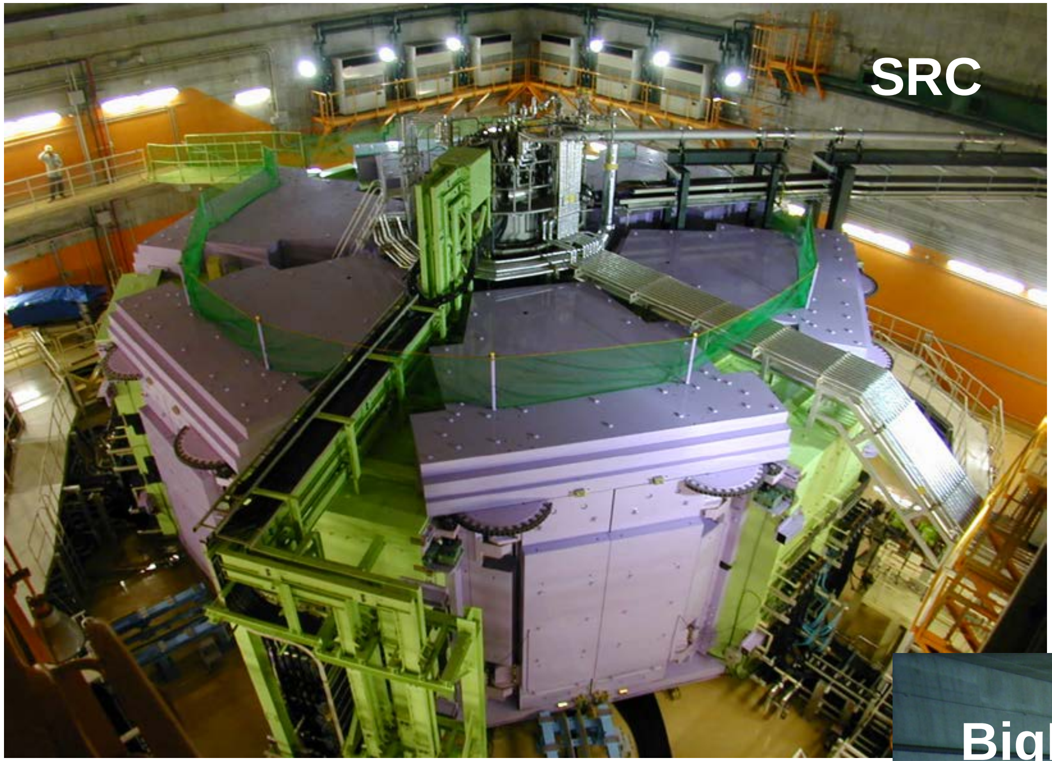




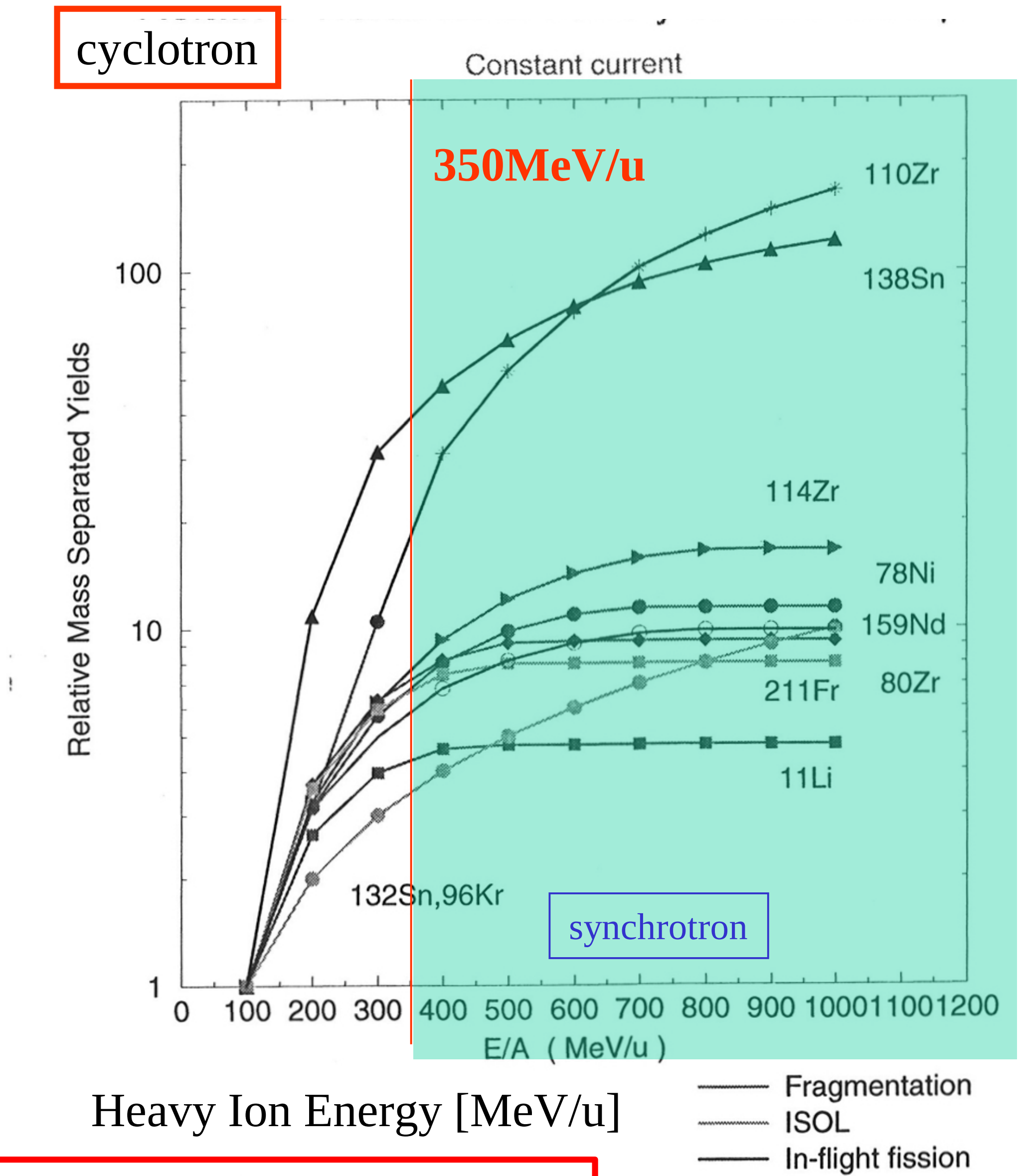
World's First and Strongest
K2600MeV
Superconducting Ring Cyclotron

400 MeV/u Light-ion beam
345 MeV/u Uranium beam

World's Largest Acceptance
9 Tm
Superconducting RI beam Separator

~250-300 MeV/nucleon RIB

Energy Dependence of RI Yields



Heavy Ion Energy [MeV/u]

Cyclotron provides more intense beams than synchrotron.

FRIB HI-Linac (SRF) upto 200 MeV/u

PID to determine Z and A

Standard Technique

Z=Q case

TOF $1/\beta$

ΔE Z^2/β^2 (non-relativistic approx.)

$B\rho$ $A/Z*\beta$

If $\Delta Br/Br < 1/A$, Br may not be measured.

But, you may lose intensity of RIB.

$Z \neq Q$ case

$B\rho$ $A/Q*\beta$

+E $A\beta^2$

We have to stop beams? No reaction studies??

BigRIPS was designed

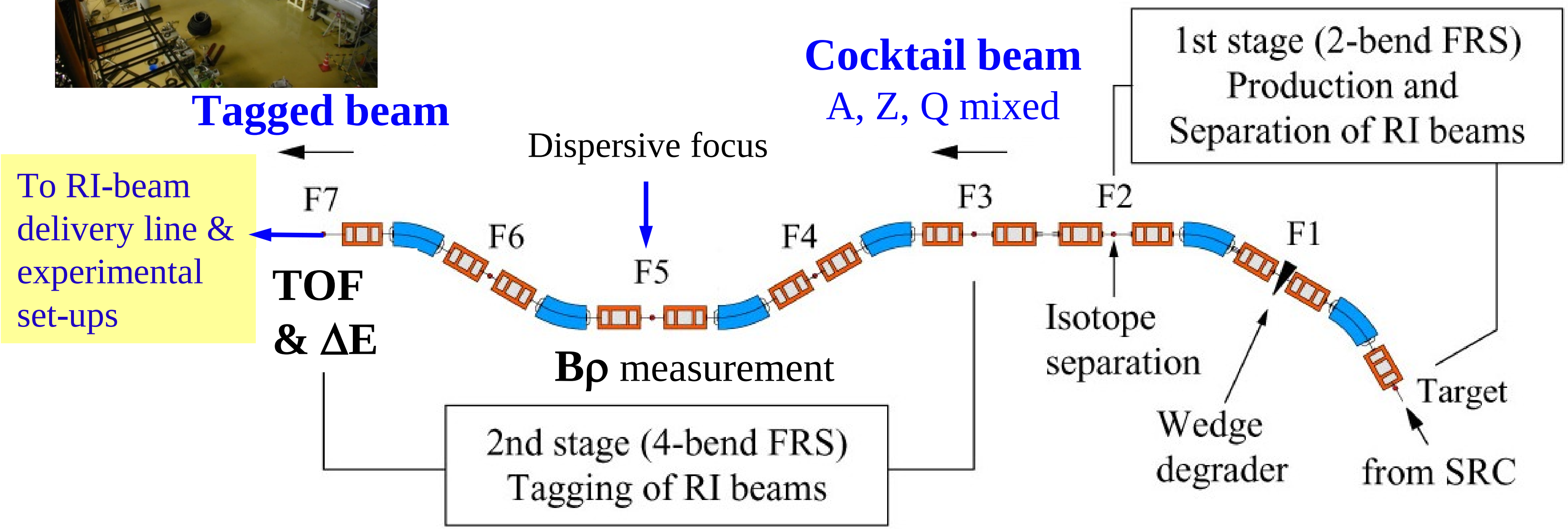
to have nice resolving power to determine A/Q

without E measurement.

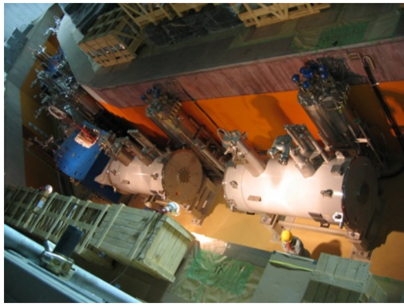
Delivery of tagged RI-beam

Based on two-stage separator scheme

T. Kubo et al.



Identify RI-beam species Z, A/Q by measuring ΔE, Bρ, TOF in an event-by-event mode using beam-line detectors on the 2nd stage. Aim at tagging rate up to 1 x 10^6 pps.



Standard		New Scheme
Bρ-TOF-dE-**E**	→	Bρ-TOF-dE
Z, A, Q		Z, A/Q

Basic parameters of BigRIPS

T. Kubo et al.

Configuration	**Two-stage separator**
First stage	**Two bends**
Second stage	**Four bends**
Energy degrader	**Achromatic wedge**
Quadrupoles	**Superconducting**
Angular acceptance	
Horizontal	**80 mr**
Vertical	**100 mr**
Momentum acceptance	**6 %**
Max. magnetic rigidity	**9 Tm**
Total length	**77 m**
Momentum dispersion*	
First stage	**-2.31 m**
Second stage	**3.3 m**
Momentum resolution(1st order)**	
First stage	**1290**
Second stage***	**3300**

In-flight fission of ^{238}U at 350 MeV/u
~ 100 mr
~ 10 %

* At the mid-focus of the stage.
** Those in the case when a 1 mm beam spot is assumed.

RI-beam tagging based on two-stage separator scheme

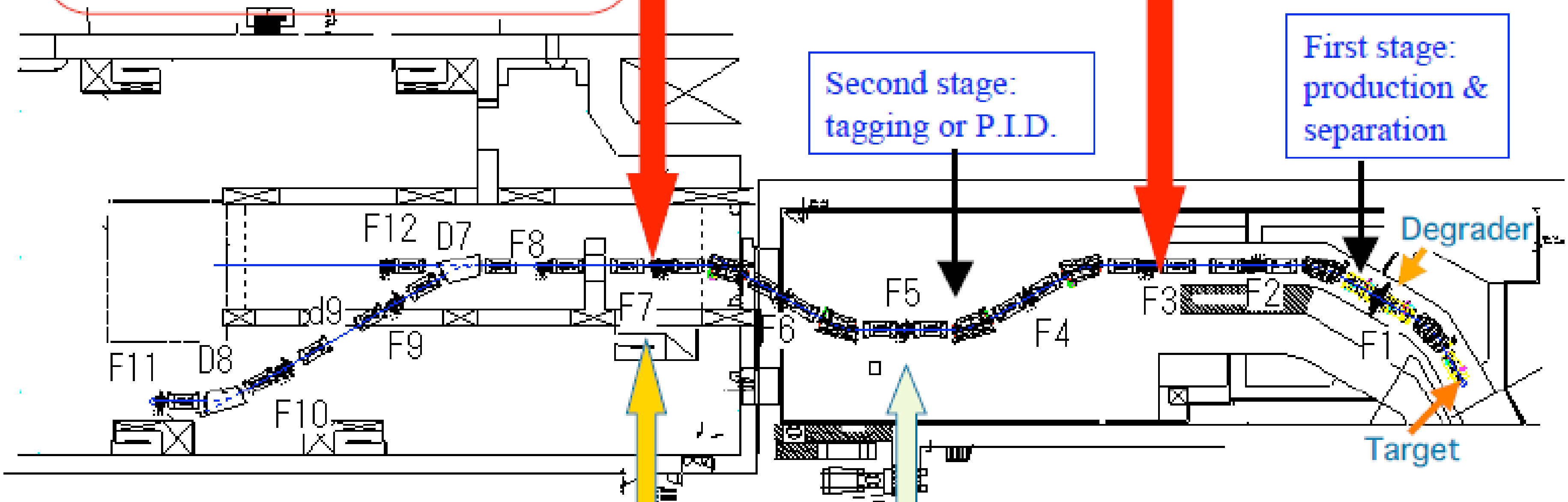
PID: Bρ-ΔE-TOF method

Bρ	PPAC
ΔE	Ion chamber, Si
TOF	Plastic

up to 1×10^6 Hz

TOF

Plastic



PID of Z and A/Q

ΔE

IC, Si

Bρ

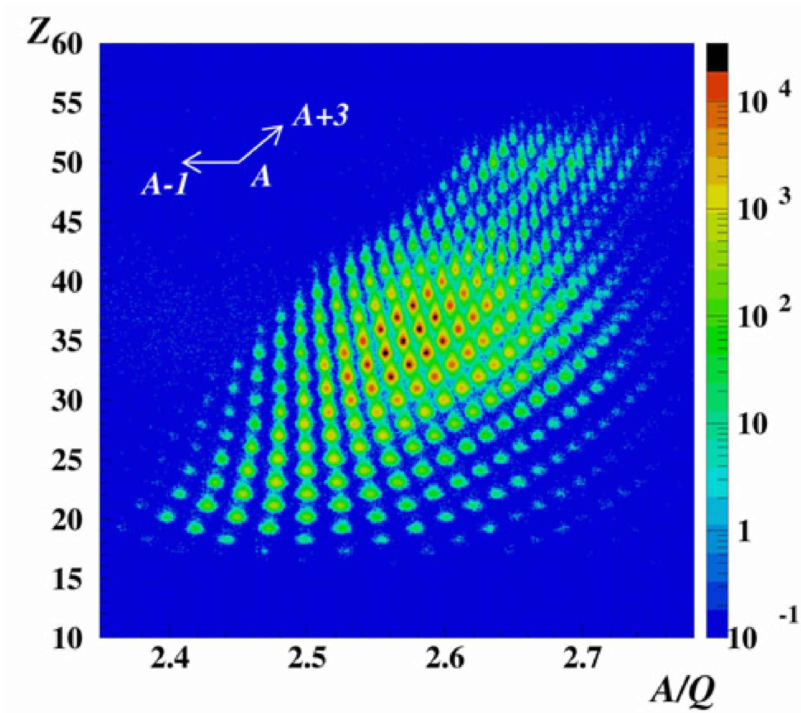
PPACx2

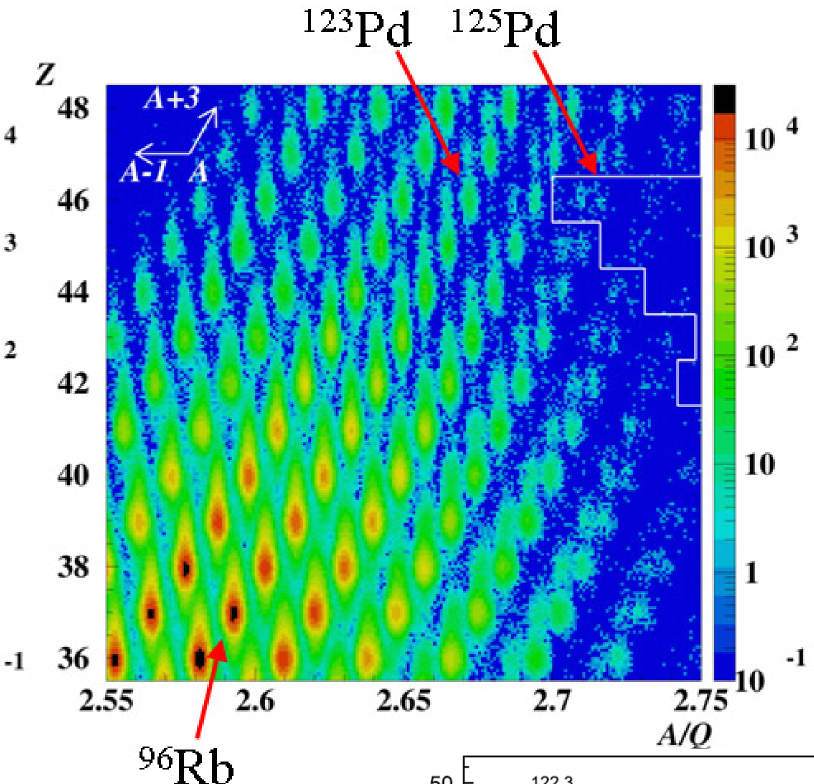
Put another degrader at F5 to make the two-stage separation

F5: Momentum dispersive focal plane

New isotopes of $^{125,126}Pd$

T. Onishi et al, JPSJ 77 (08)083201.





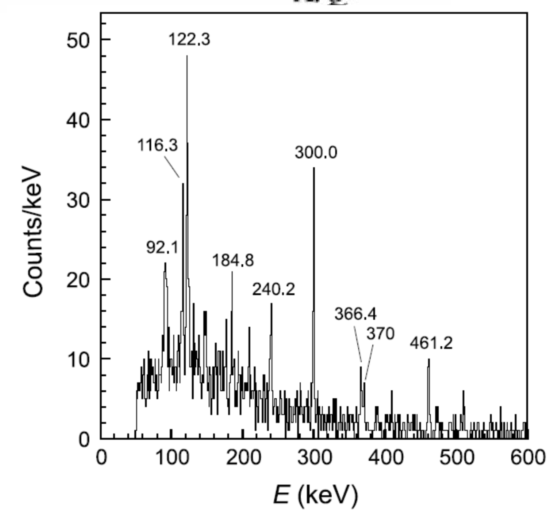
Bρ: 7.438 Tm, ΔP/P=2%

^{238}U + Be(7mm) at 345 MeV/u

2007 MAY-JUNE

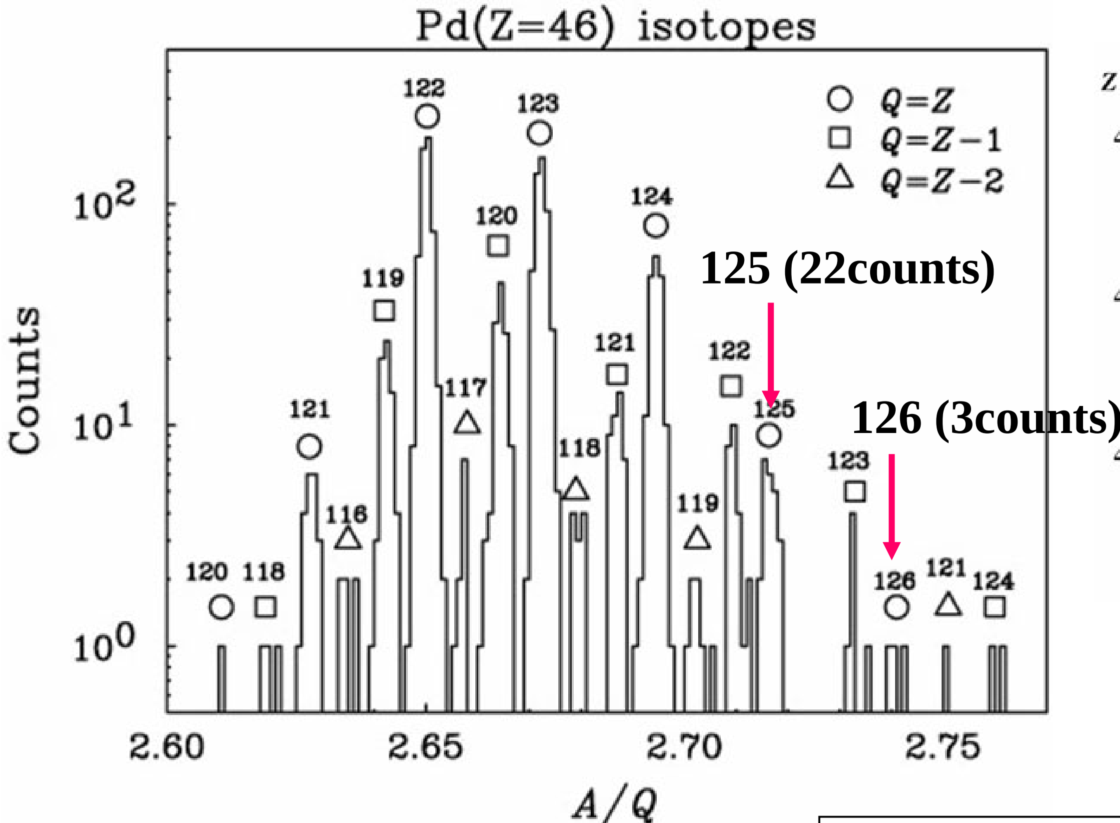
Total dose: 3.6×10^{12}

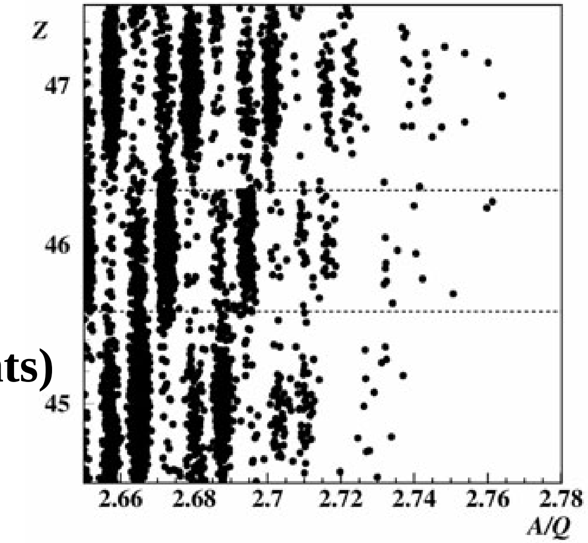
Isomer ^{96}Rb



Identification of new isotopes ^{125,126}Pd

T. Onishi et al, JPSJ 77 (08)083201.



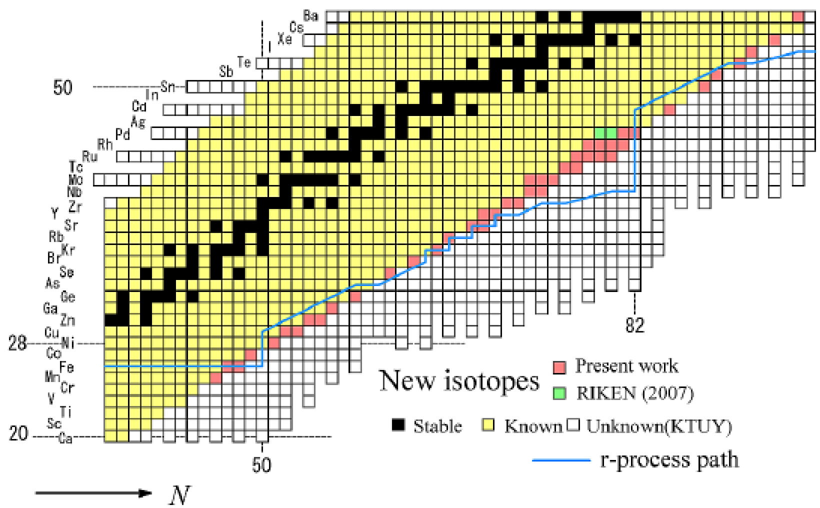


Total dose 3.6x10^{12} for 25 hrs
I ~0.01 pnA on average

A/Q resolution(r.m.s): 0.041% at Z=46
Bρ resolution (r.m.s): 0.02%
ΔT resolution (r.m.s.): 40 psec

Cf. ^{124}Pd 19 counts, ^{125}Pd(cand.) 1count at GSI, 1997
PLB 415, 111 (97); total dose ~1x10^{12}

Identification of 45 New Neutron-Rich Isotopes Produced by In-Flight Fission of a ^{238}U Beam at 345 MeV/nucleon



T. Ohnishi, et al., JPSJ 79, 073201 (2010).

Nov., 2008

Averaged beam intensity ~0.2 pnA

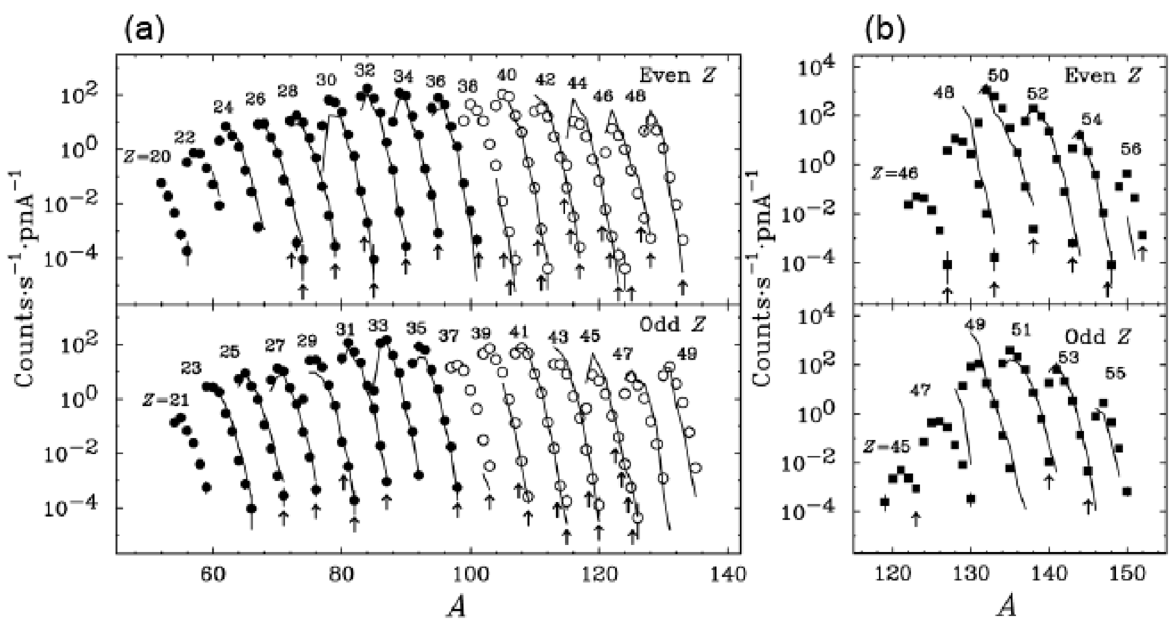
Maximum intensity 0.4 pnA

Mn (Z=25) to Ba (Z=56)

Covered by three Brho settings

Be and Pb targets

Total dose 1-2x10^{14} for each Brho setting



Yield rates reasonably reproduced by LISE++

RI Beam Production at BigRIPS Since 2007