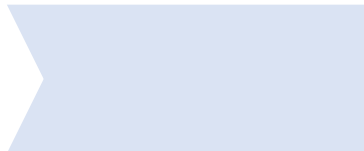


Simulation study of RI-beam circulation in FFAG-ERIT toward synthesis of long-lived superheavy nuclei

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(Kyushu University)



Collaborators

Kyushu University

- S. Sakaguchi (previous speaker)
- Y. Yonemura
- T. Niwase

Kyoto University

- Y. Ishi
- Y. Mori

JAEA

- K. Nishio

Outline

1. Introduction

- i. Frontier of superheavy elements
- ii. Island of stability
- iii. Fusion reaction using RI beams
- iv. FFAG-ERIT

2. Simulation study

- i. RI-beam circulation

3. Summary and perspective

Expansion of the periodic table

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
	119	120		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

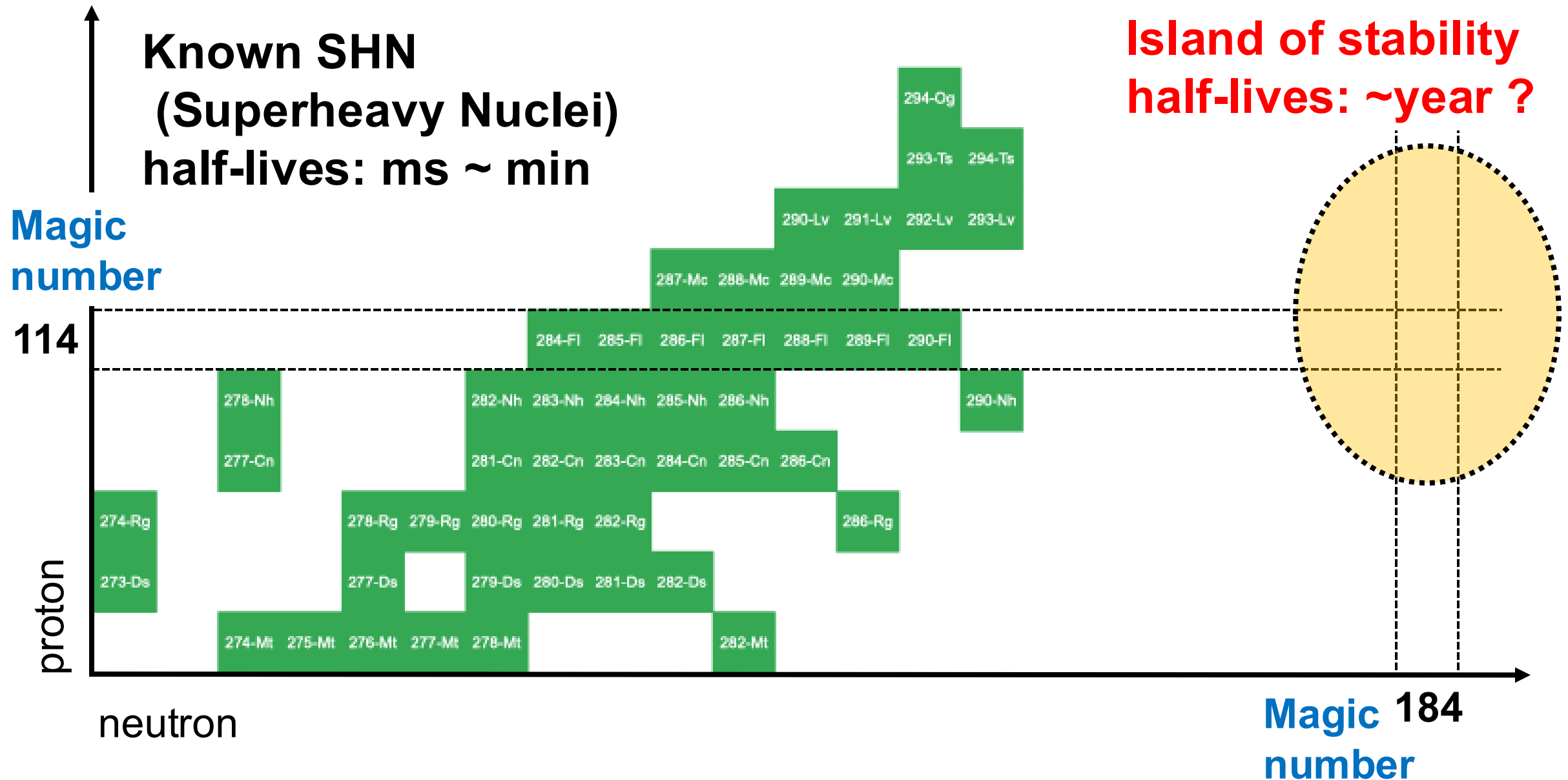
Nh (Nihonium):
($Z = 113$)
Synthesized in Japan
for the first time.

Superheavy Element (SHE)
($Z \geq 104$)

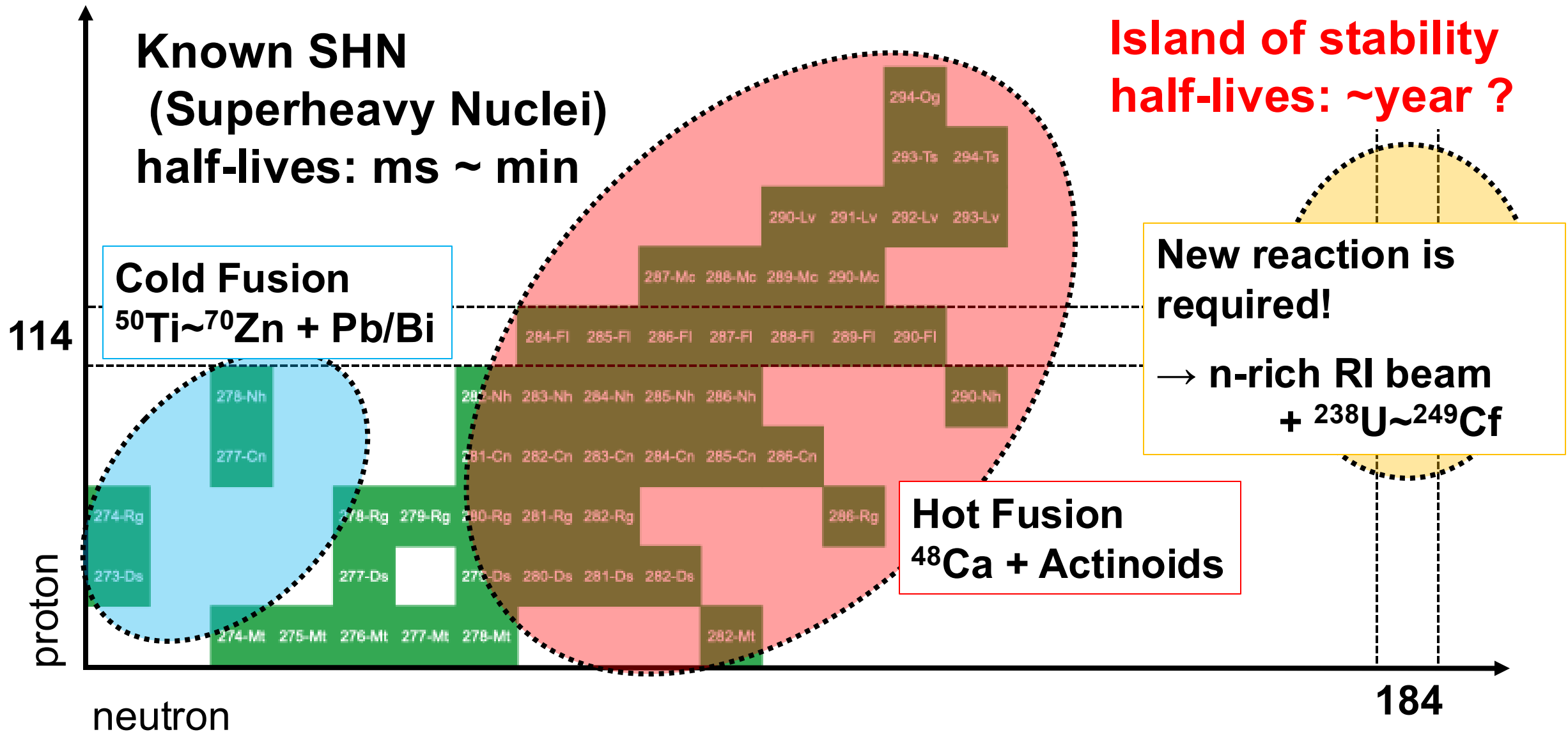
Short-lived

Search for
New Elements
@RIKEN and ...

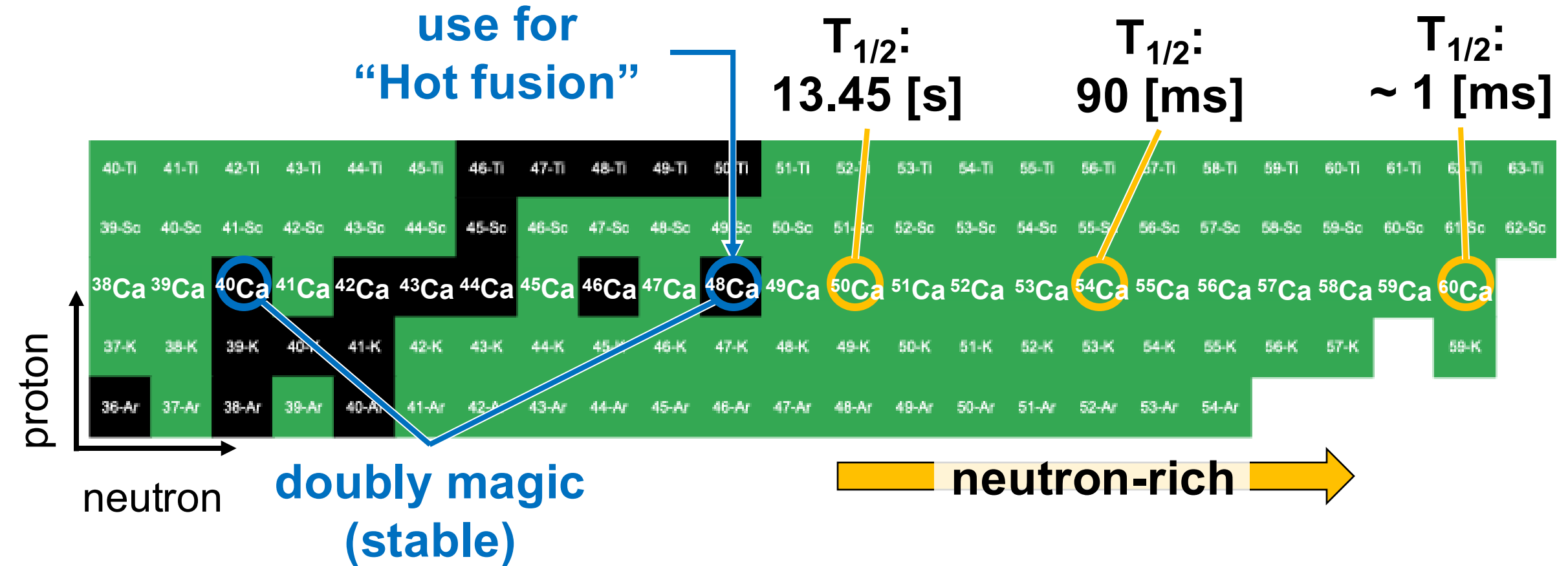
Expansion of the nuclear chart



Expansion of the nuclear chart



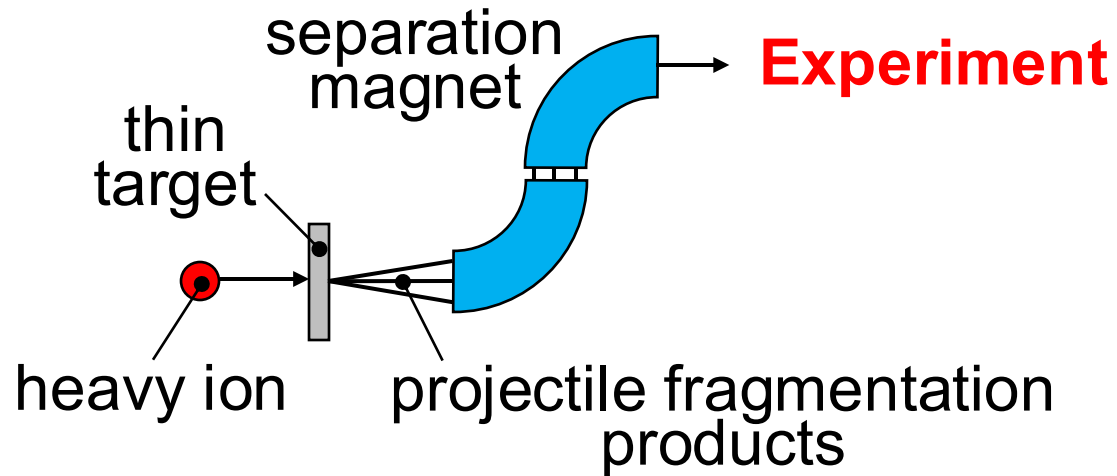
Neutron-rich RI beam



How to produce such neutron-rich RI beams? (next slide)

Neutron-rich RI beam

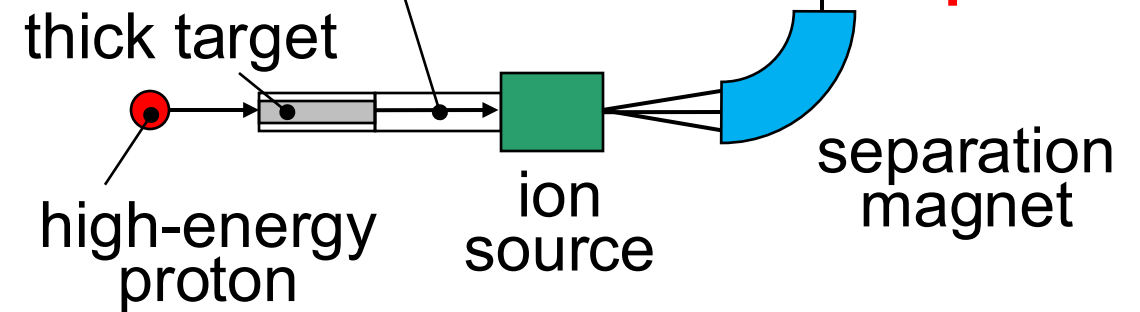
In-Flight Method



ISOL Method

(Isotope Separation Online)

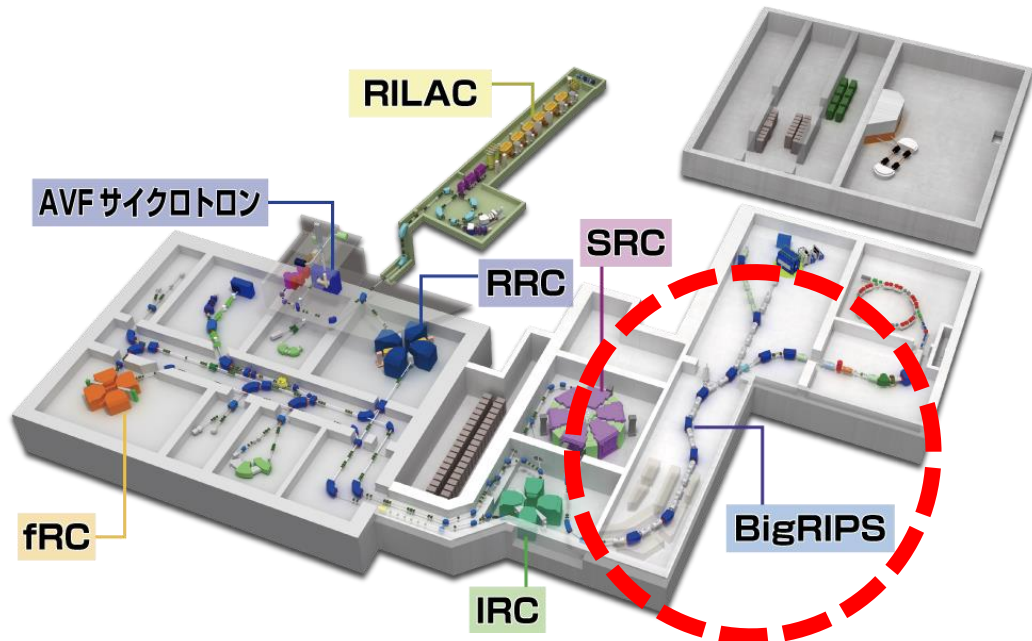
target fragmentation
or spallation products



	Low	Intensity	High	
for fast RI beam	High	Energy	Low	for slow RI beam
for short-lived nuclei	~100 ns	Separation Time	100 ms ~ 1 s	
	Large	Emittance	small (same as primary beam)	

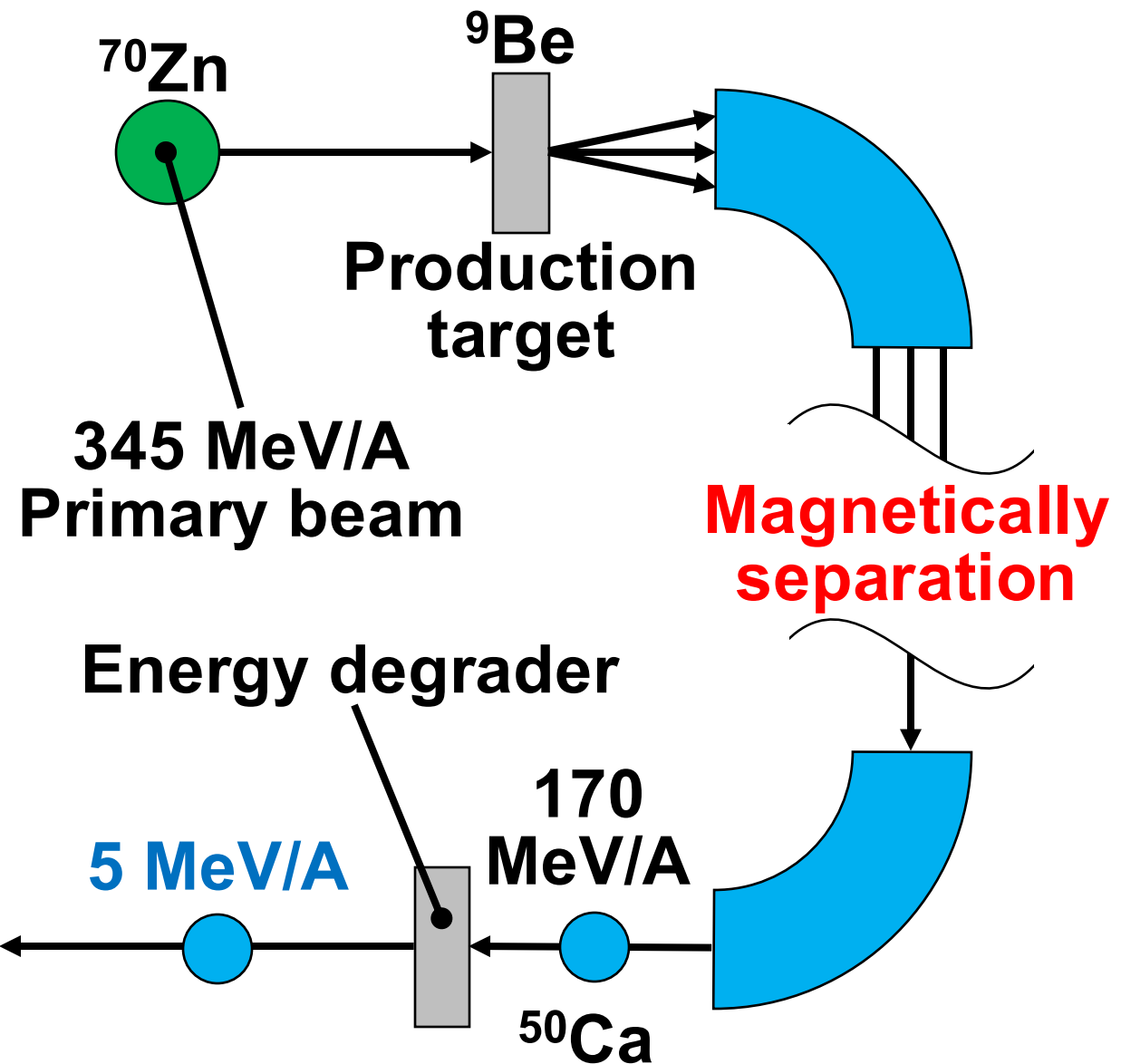
RI-beam production by in-flight method

RIBF, RIKEN



<https://www.nishina.riken.jp/facility/RIBFfacility.html>

**Fusion
reaction**



Difficulties in SHN production with RI-beams

Difficulties in superheavy element synthesis

- **Extremely small cross sections**

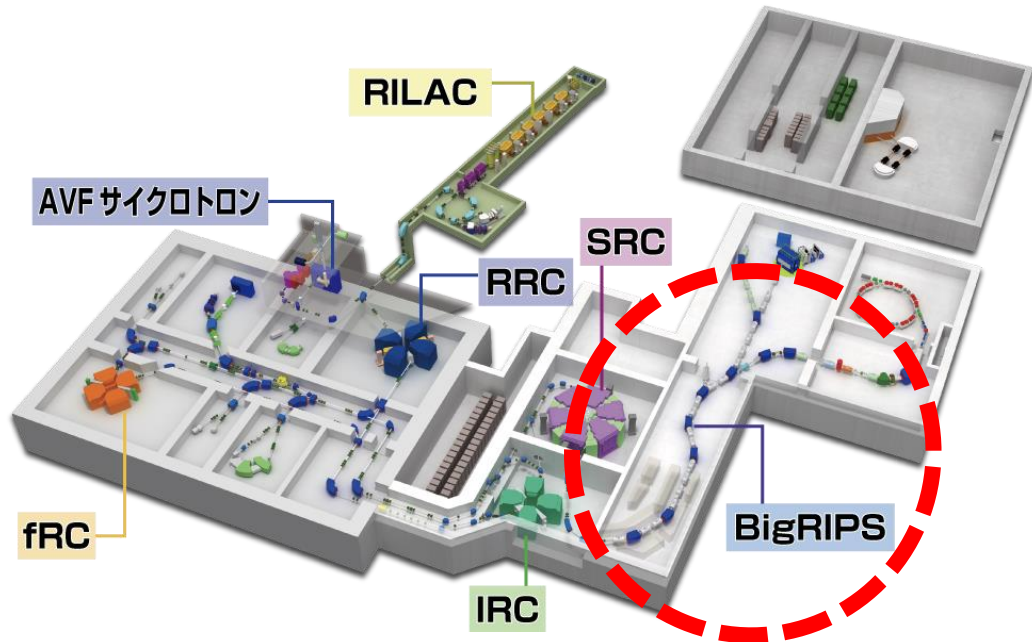
Difficulties in Fusion Reactions with RI Beams

- **Low intensity**
 - Many orders of magnitude lower than stable nuclear beams
 - Need for **beam recycling scheme** to achieve higher luminosity
 - **short-lived**
 - **large emittance**
- Can the RI beam be efficiently recycled?

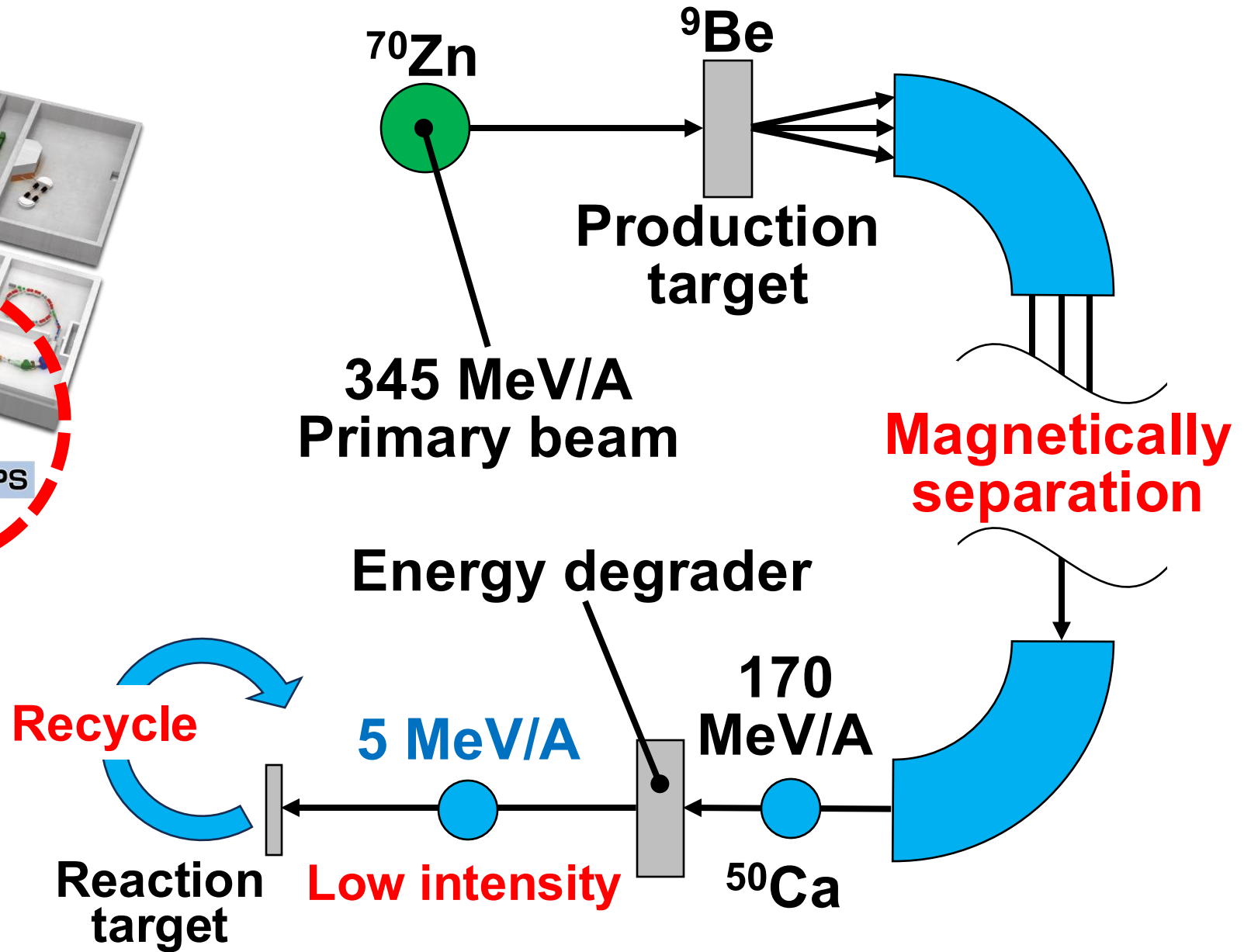
**Small cross section × Low beam intensity
makes experiments very difficult**

RI-beam production by in-flight method

RIBF, RIKEN

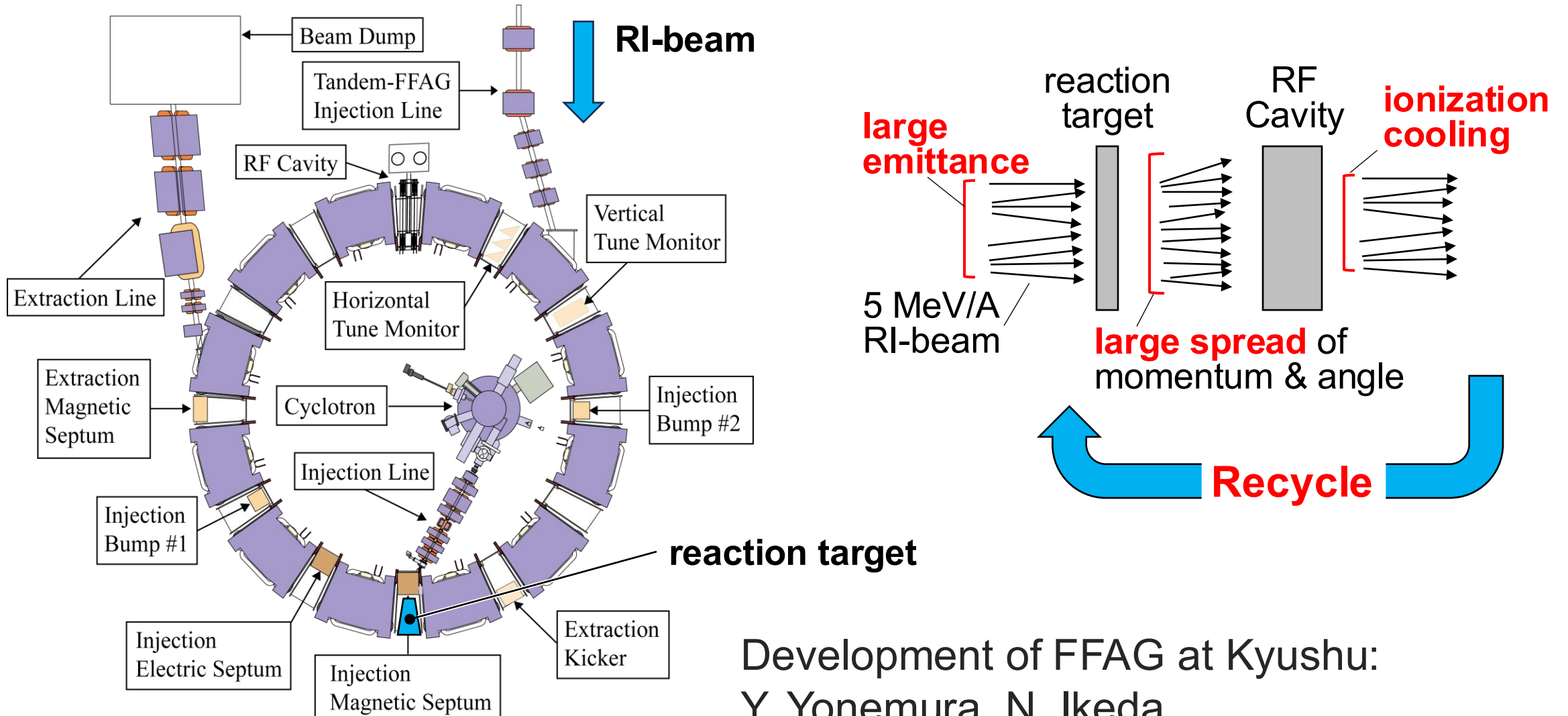


<https://www.nishina.riken.jp/facility/RIBFfacility.html>



Beam recycling scheme

FFAG-ERIT (FFAG-Energy Recovery with Internal Target)



Development of FFAG at Kyushu:
Y. Yonemura, N. Ikeda

Motivation of this study

Motivation

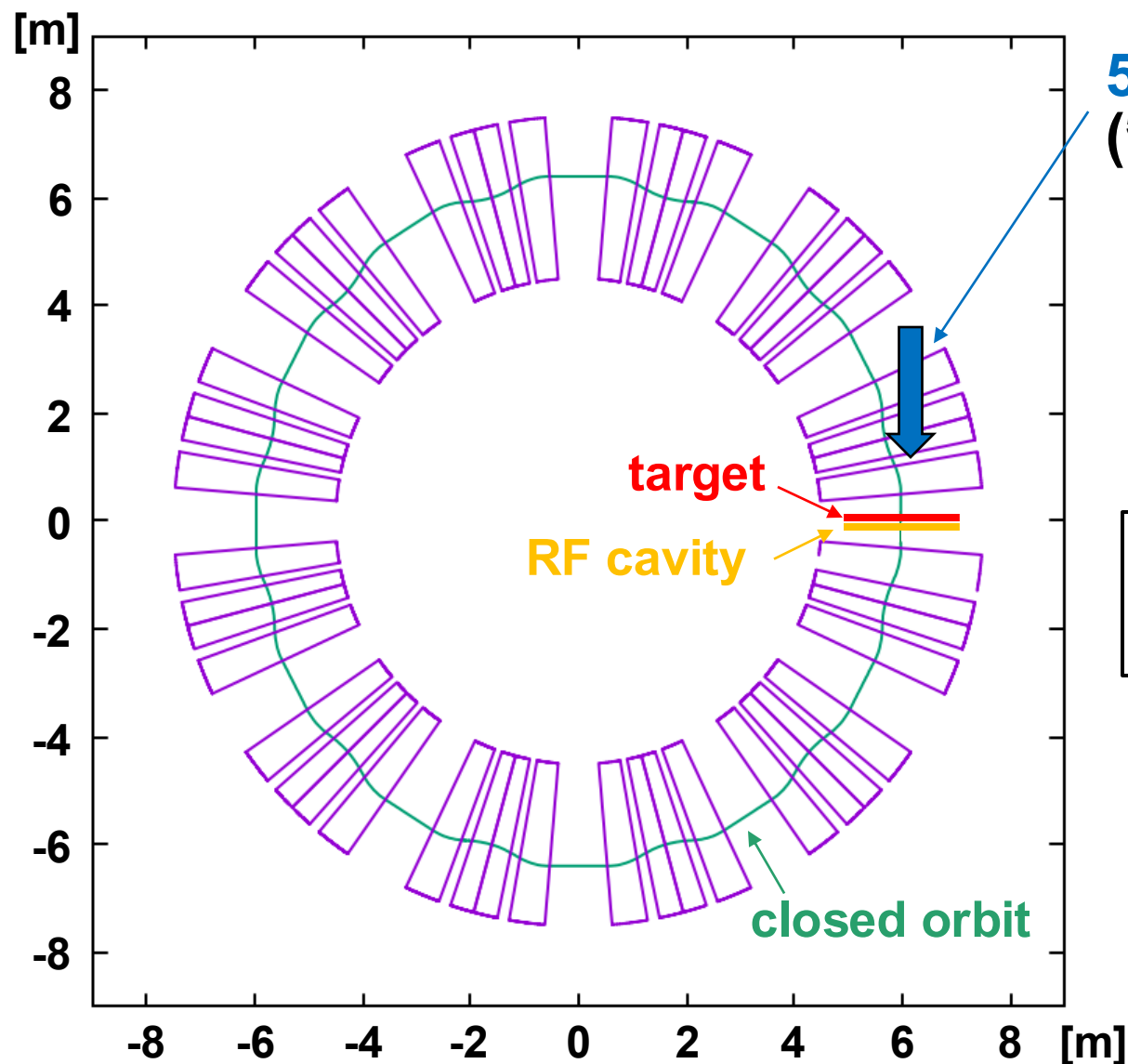
Is it possible to efficiently recycle the RI-beams with **low energy** and **large emittance**?

Things to consider

- Beam energy is as low as 5 MeV/A, leading to **significant energy loss** and **emittance growth**
- Original RI-beam has **large emittance** (in-flight method)
- Beam loss due to **radioactive decay**
- Beam loss due to **nuclear reactions** (not evaluated in this study)

⇒ **Simulation study to calculate the average number of circulations of RI beams with the FFAG-ERIT schem.**

Simulation study of RI-beam circulation



5 MeV/A RI-beam
(^{50}Ca , ^{54}Ca , ^{60}Ca)

initial emittance

x: 818 [mm•mrad]

y: 1496 [mm•mrad]

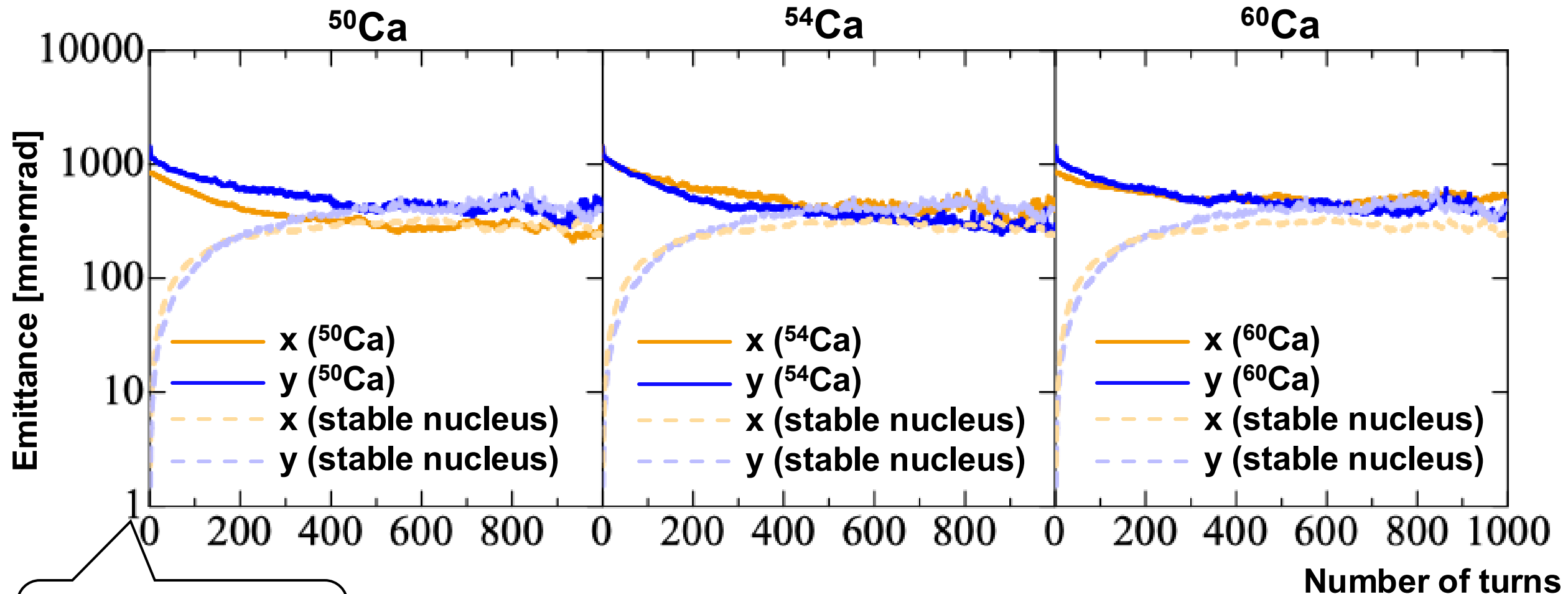
In the case of a 5 MeV/A
RI beam produced at RIKEN

**Can the RI beam
be efficiently recycled?**

- Emittance evolution
and beam loss turn by turn
→ Average number of circulations
- Beam loss due to the radioactive decay

Simulation code by Ishi-san

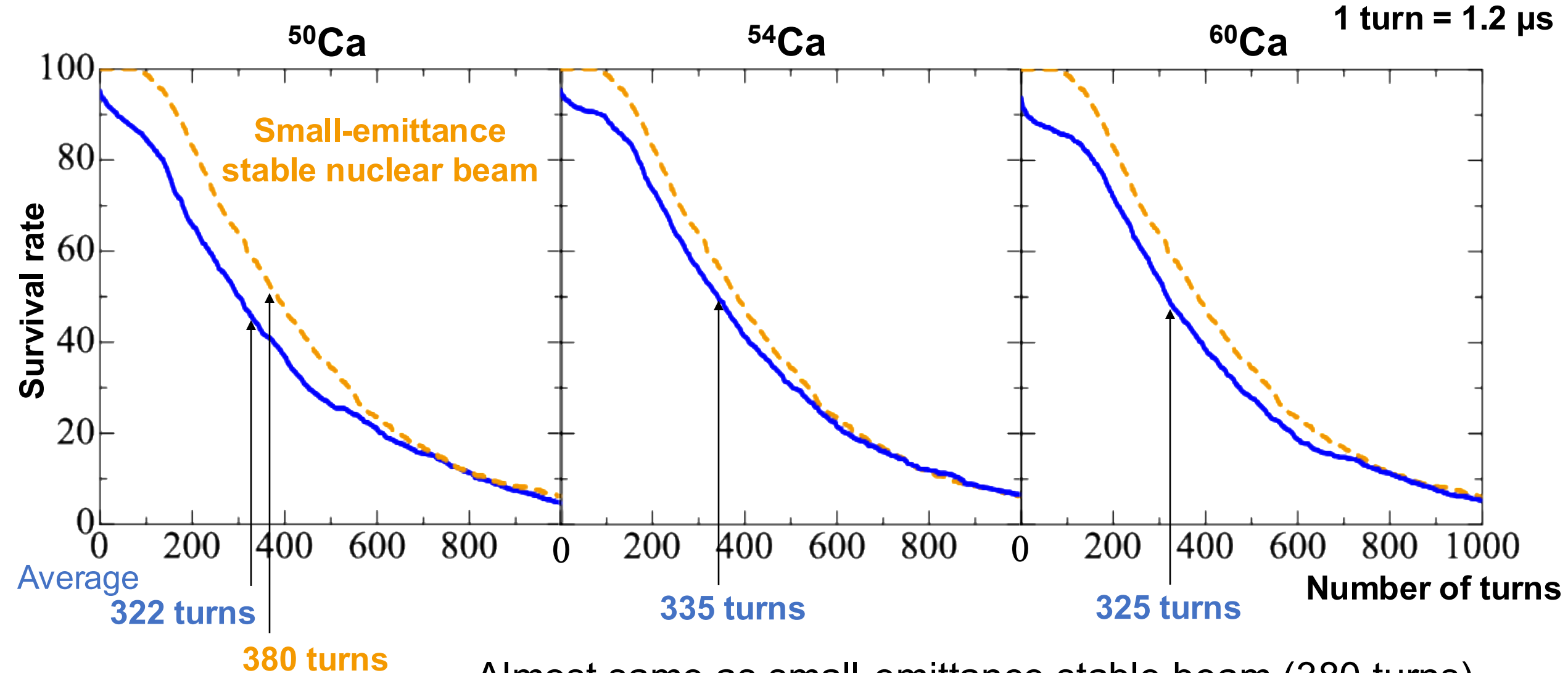
Emittance evolution



initial emittance
of stable nucleus is
1 $\text{mm}\cdot\text{mrad}$

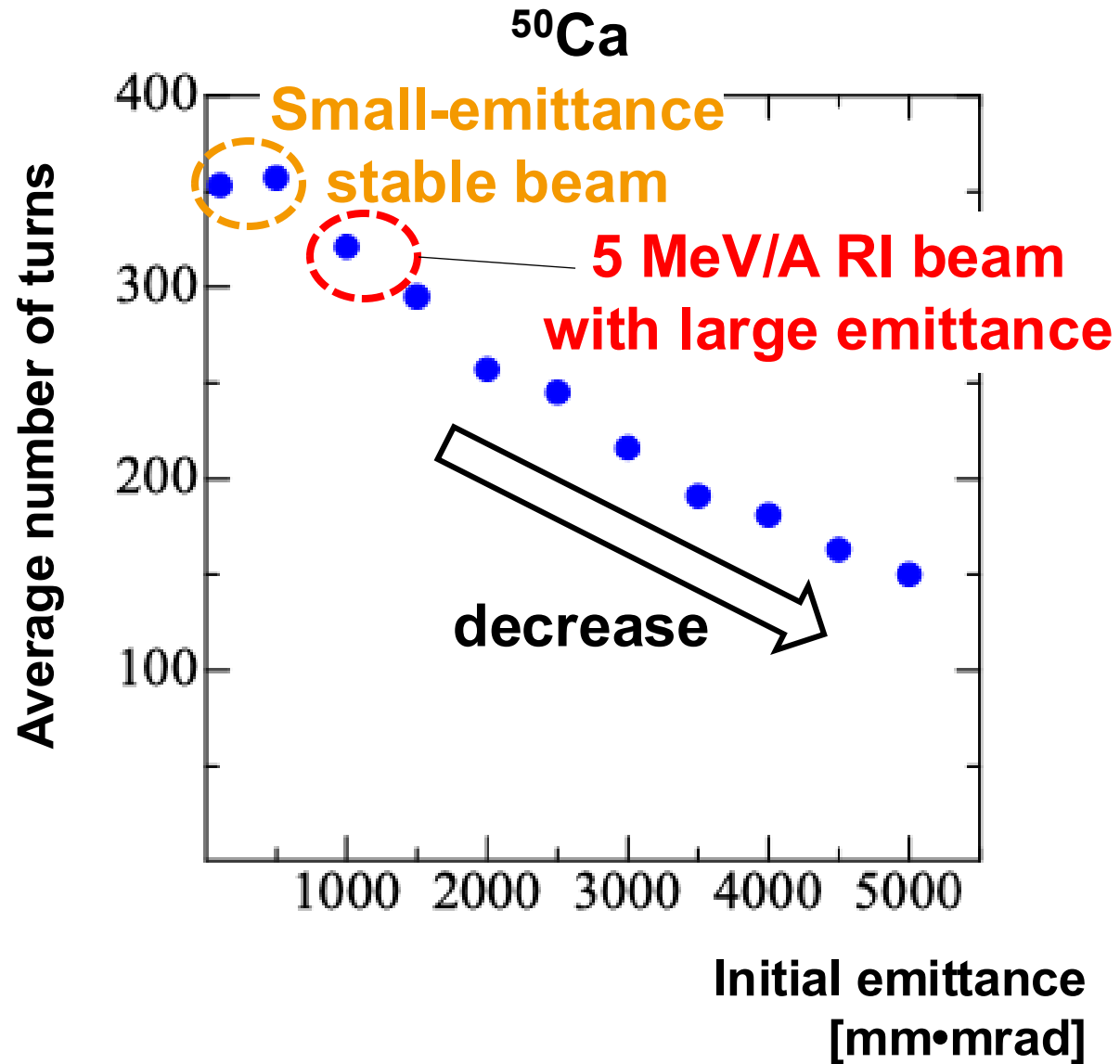
emittance approaches a certain value
(the effect of **ionization cooling** in the RF cavity)

Average number of turns (effect of large emittance)



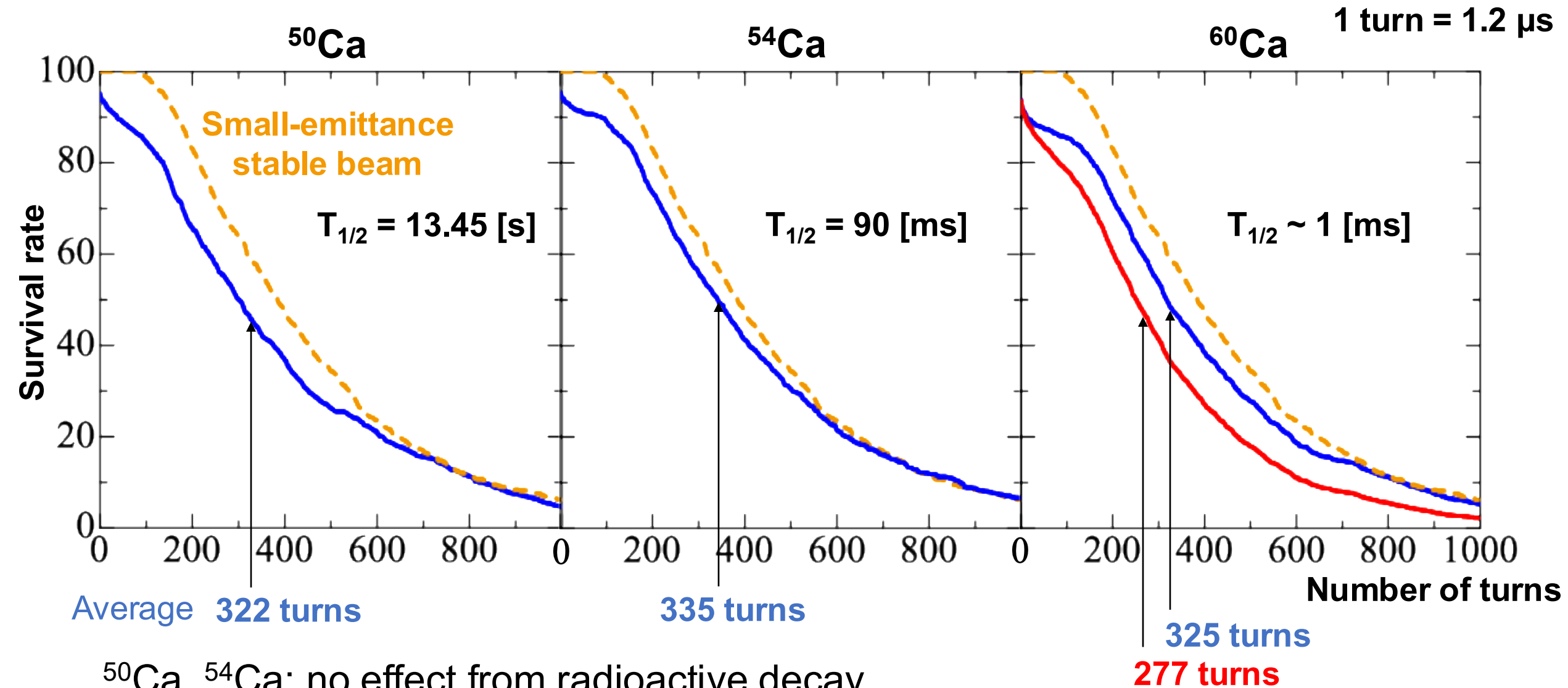
Almost same as small-emittance stable beam (380 turns), thanks to **large acceptance** of the FFA ring

Initial emittance v.s. Average number of turns



x and y directions
is the same for simplicity

Beam loss due to radioactive decay



^{50}Ca , ^{54}Ca : no effect from radioactive decay

^{60}Ca : reduced number of circulations due to decay (-15%)

Summary and perspective

Key question:

Can the RI beam be **efficiently recycled** using FFAG-ERIT?

→ **Yes!**

- Almost same as small-emittance stable beam, thanks to **large acceptance** of the FFA ring
- Effect of radioactive decay
 - ^{50}Ca , ^{54}Ca : no effect
 - ^{60}Ca : reduced number of circulations (-15%)

Next stage:

- Analysis of the evolution of energy distribution
- Yield estimation
- Super-large-acceptance ERIT ring for 5 MeV/A beam?