Study of the heaviest elements at RIKEN, status and perspective

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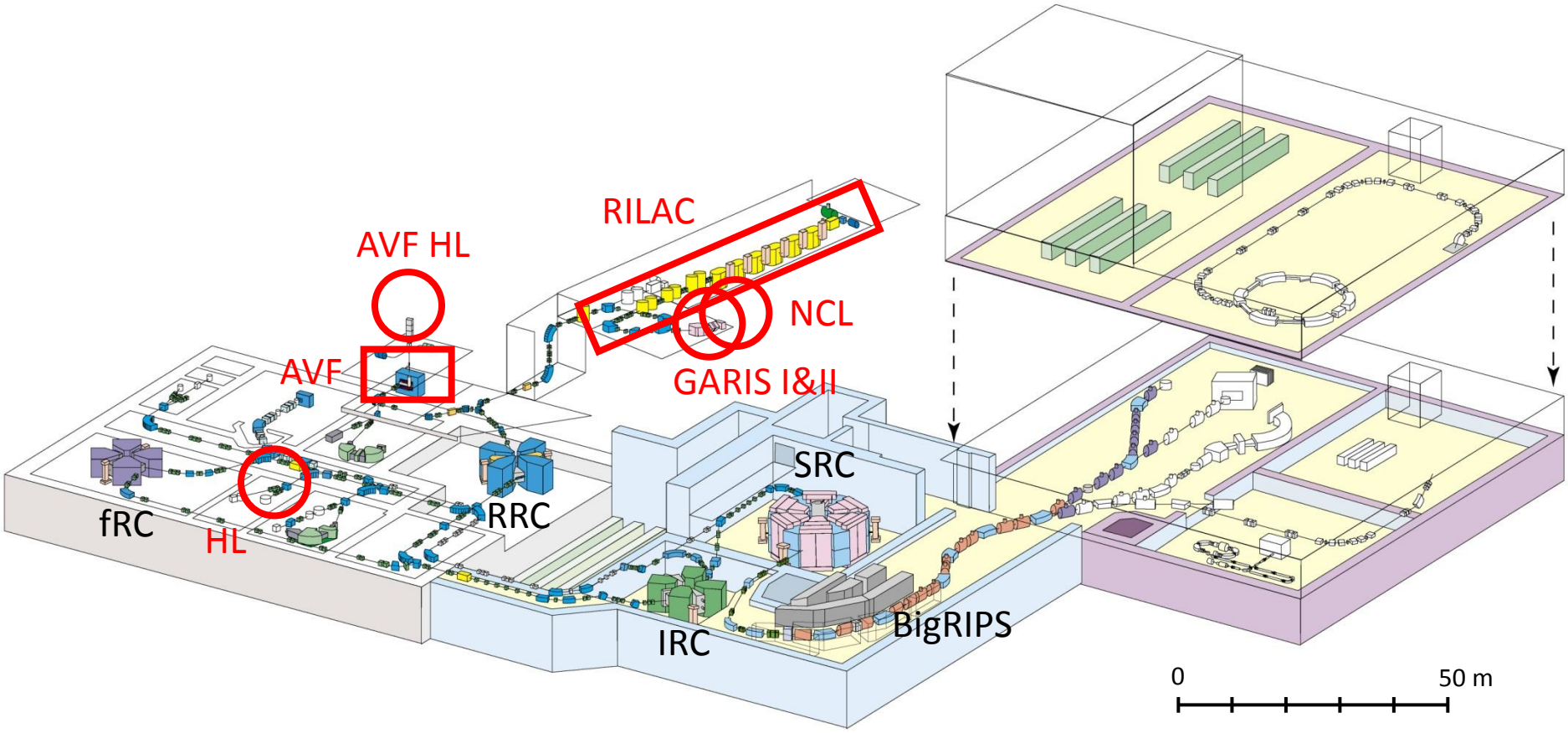
4th International Conference on the Chemistry and Physics of the Transactinide Elements
TAN'11 Sochi, Russia, 6 – 11 September 2011

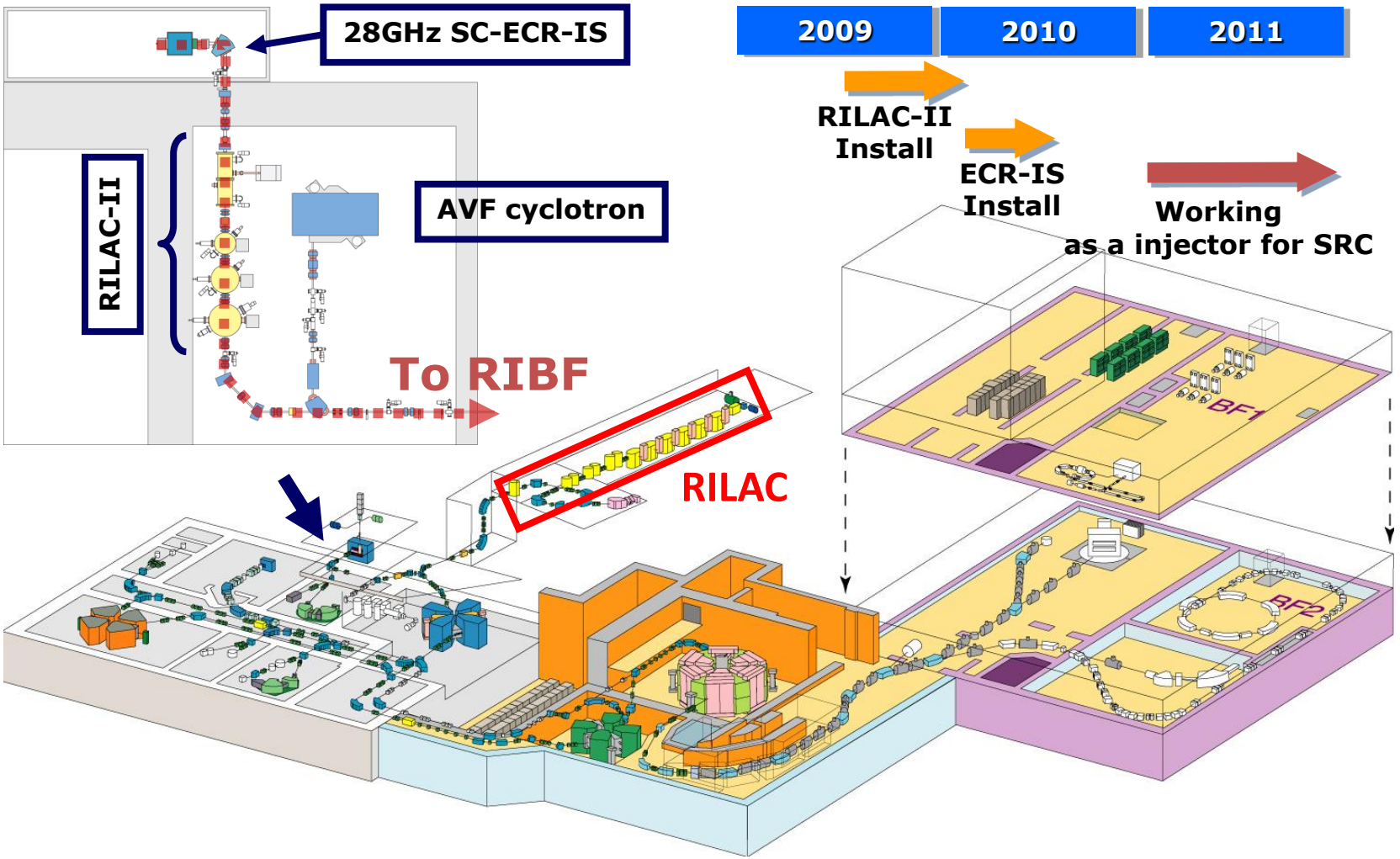
RIKEN facilities for SHE research program

RILAC, GARIS, GARIS-II, and Nuclear Chemistry Laboratory (NCL)

AVF Cyclotron, Hot Laboratory (HL), and AVF Hot Laboratory (AVF HL)

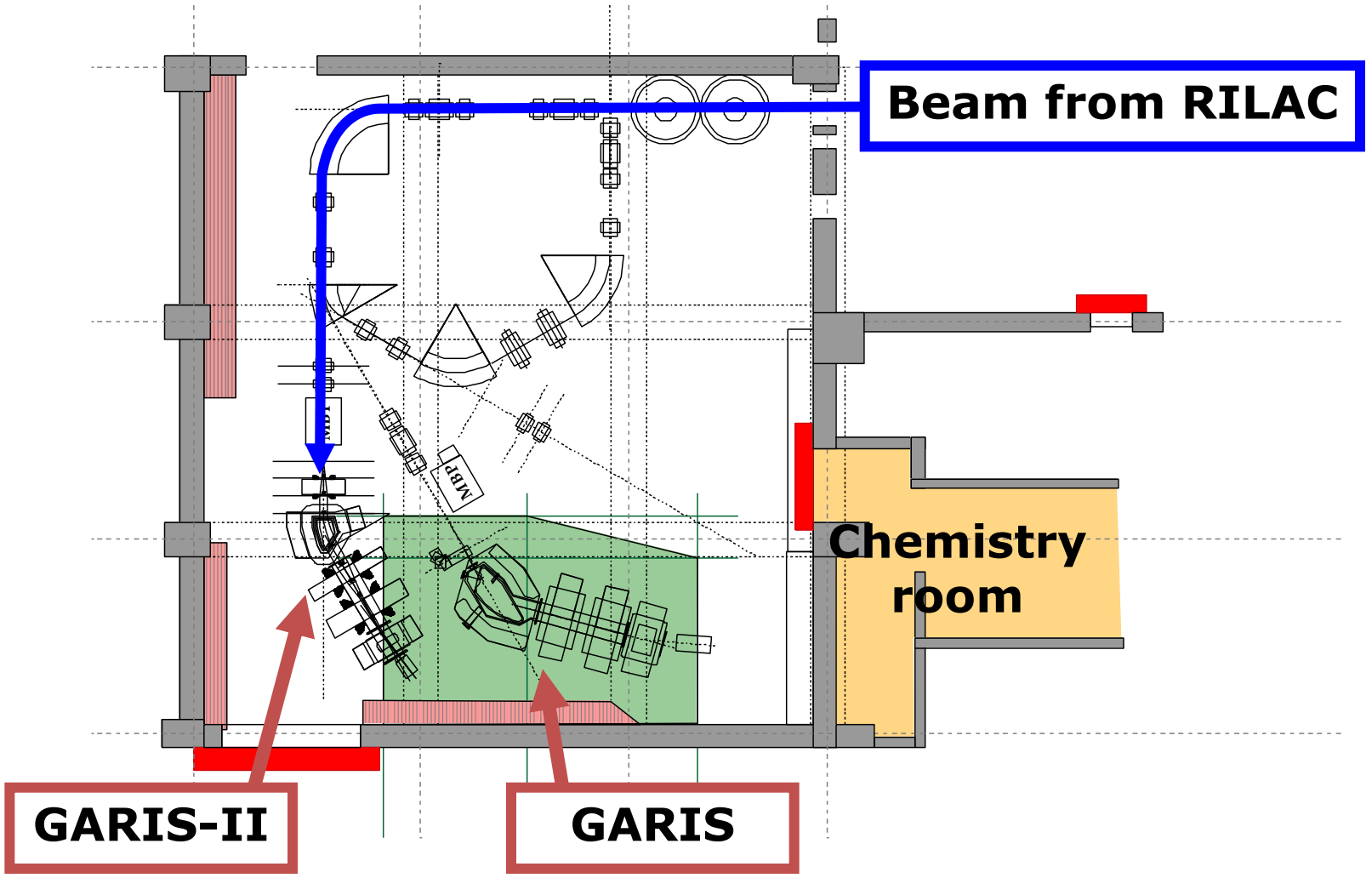


New injector RILAC-II for SRC, installation completed



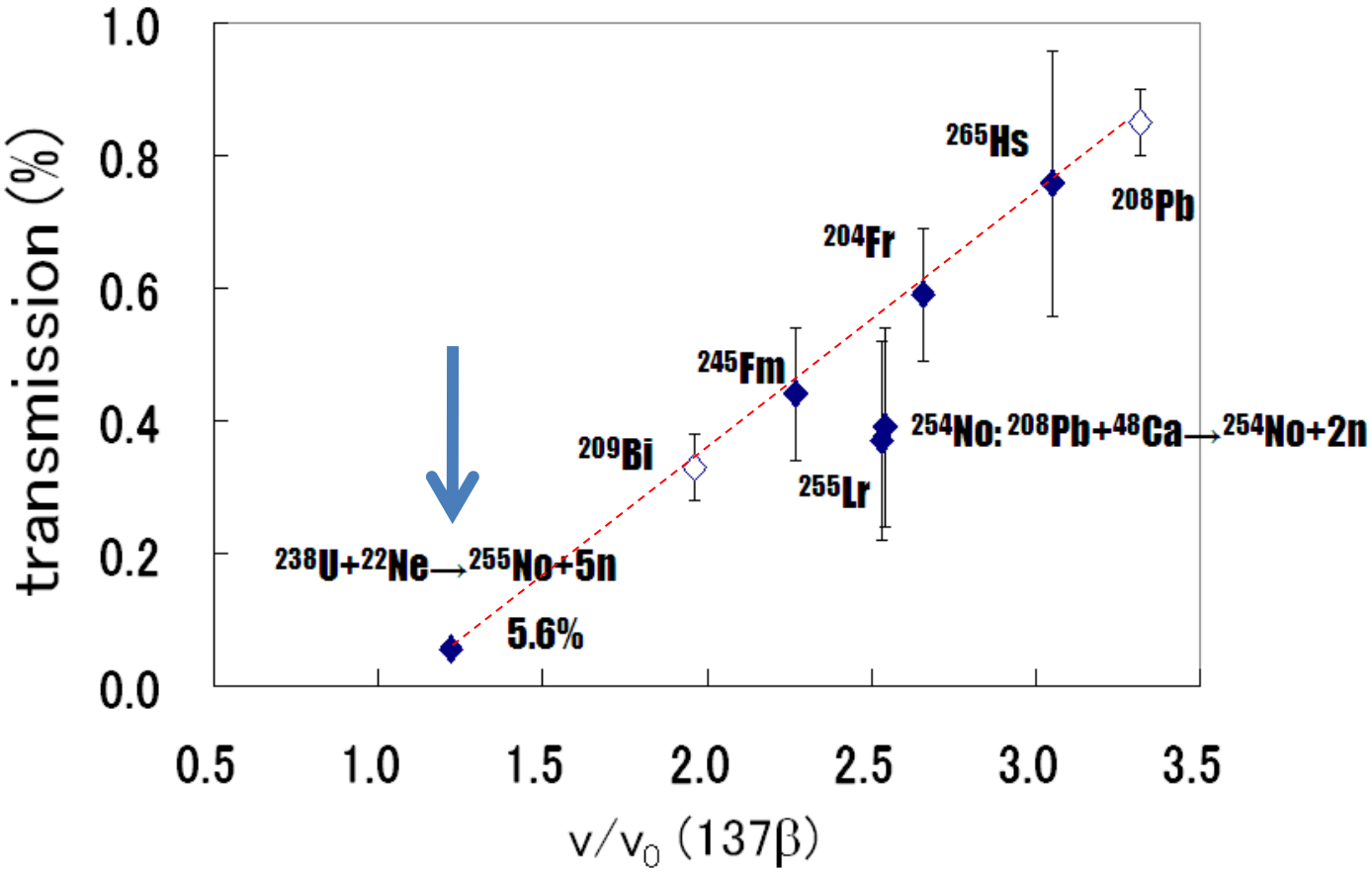
RILAC became a dedicated machine for SHE program!!

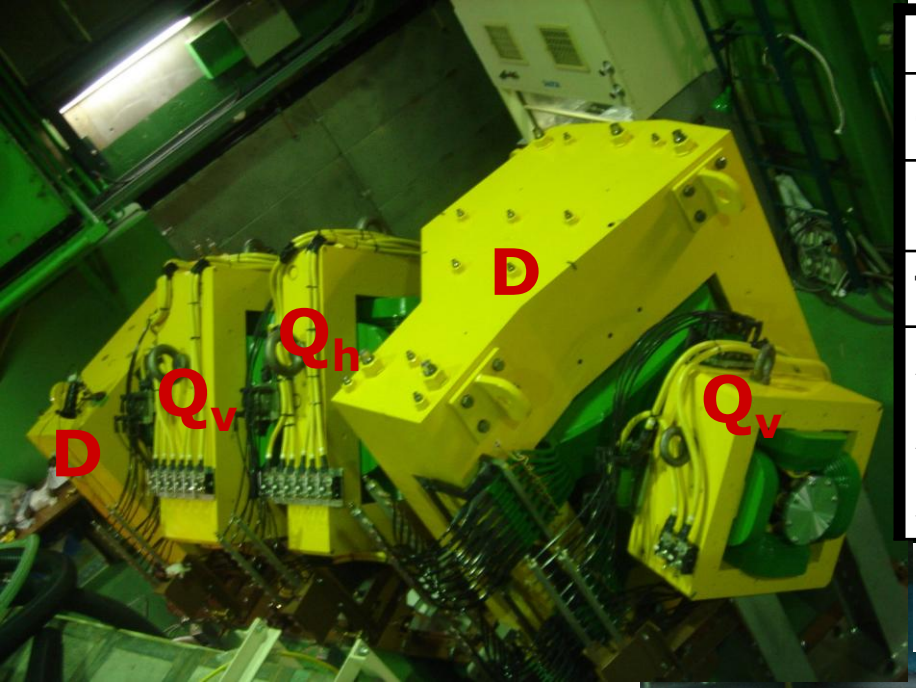
GARIS-II installation completed



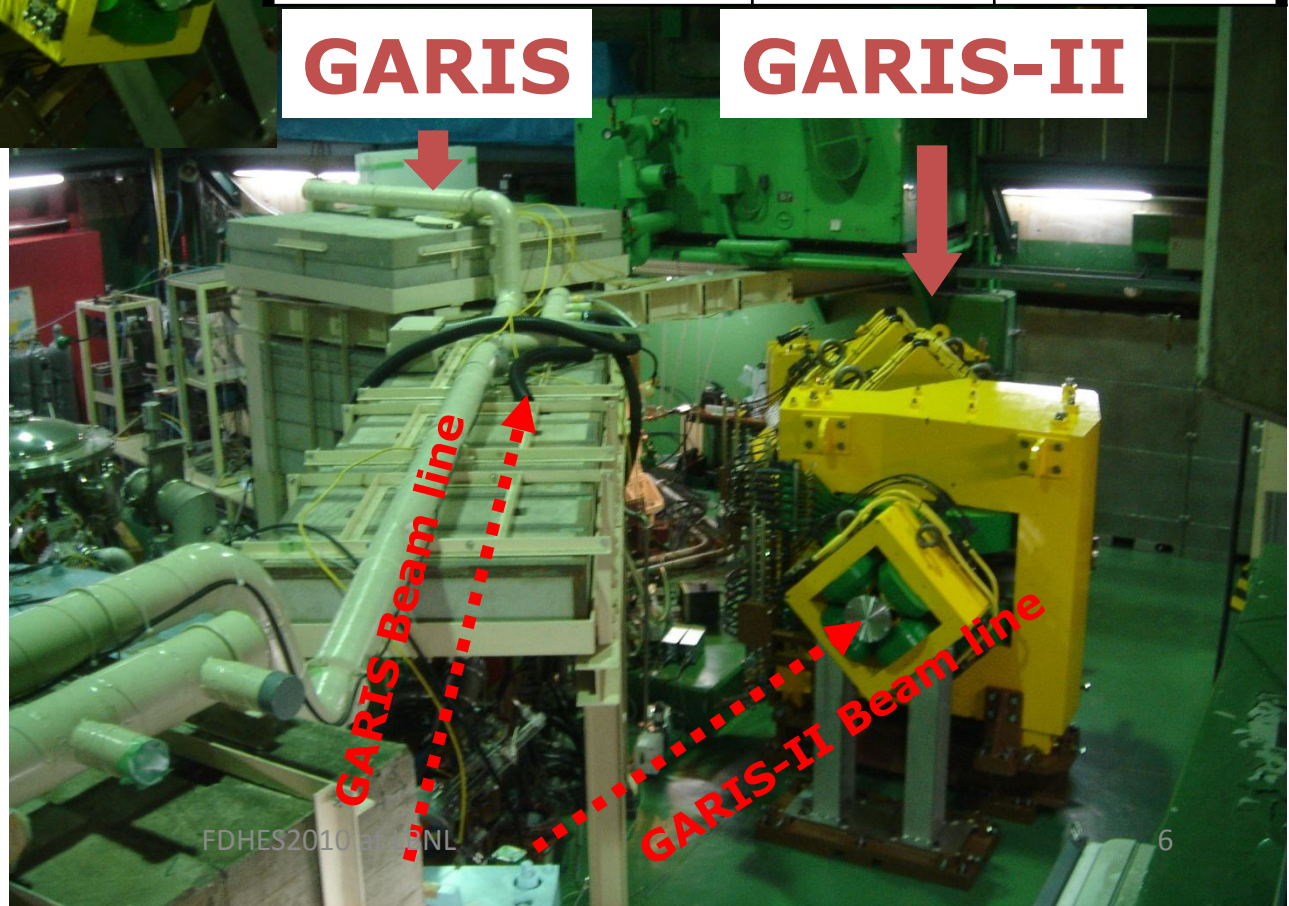
Motivation of development of GARIS-II

Transmission of GARIS-I

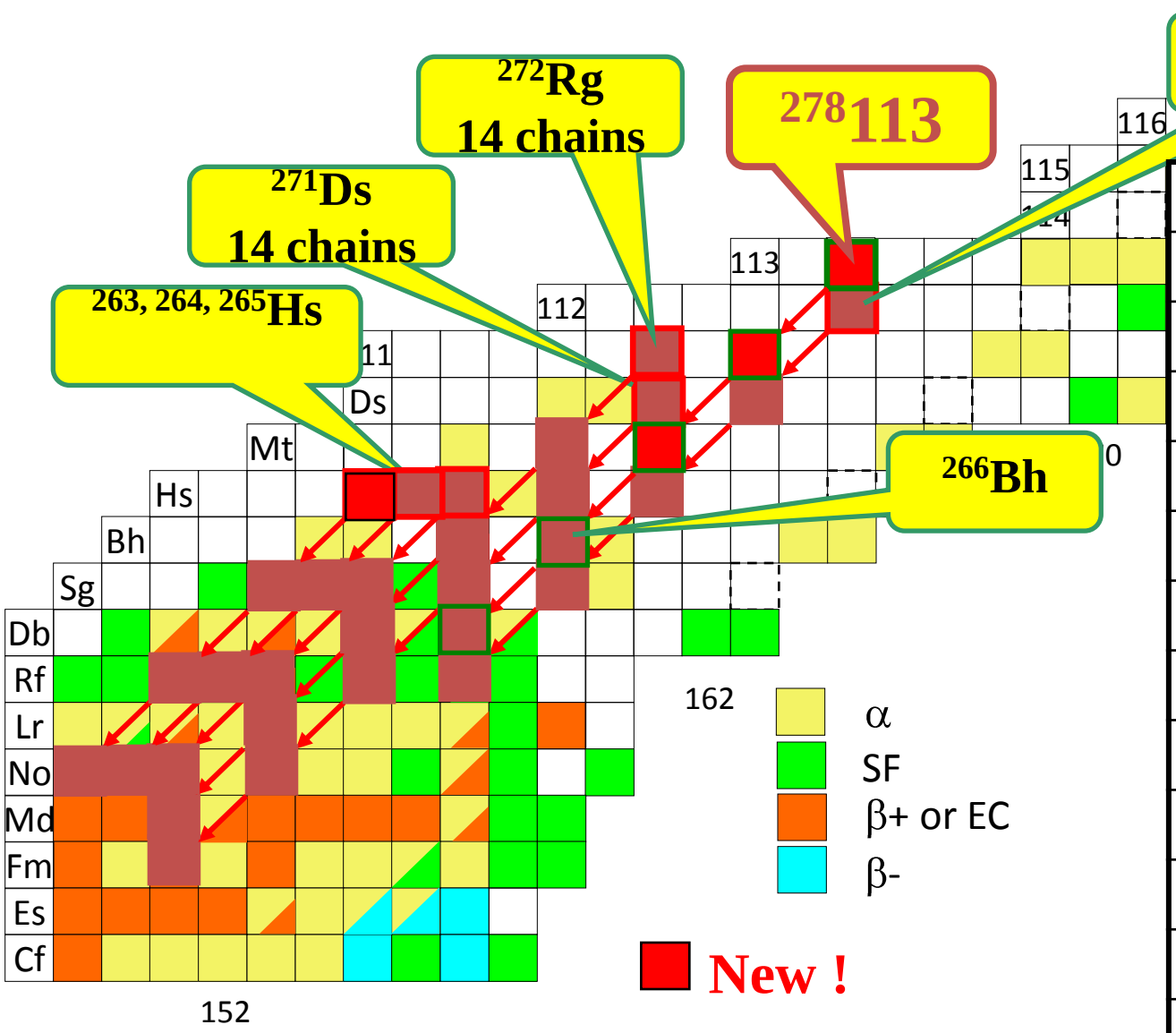




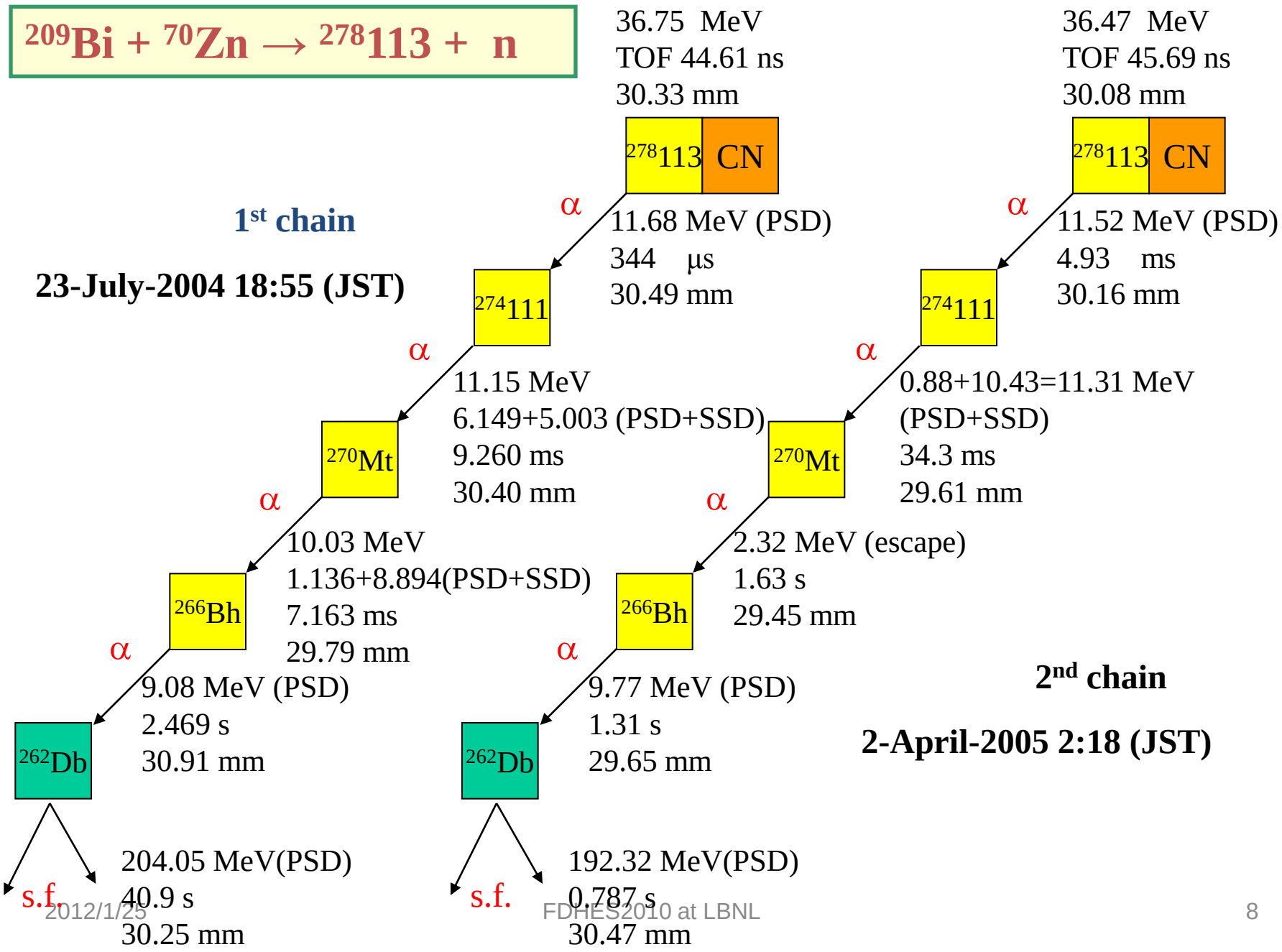
	GARIS	GARIS-II
Configuration	DQ_vQ_hD	$Q_vDQ_hQ_vD$
Bending angle [deg]	45 + 10	30 + 7
Total path length [m]	5.76	5.06
Acceptance (X) [mrad]	±61	±47
Acceptance (Y) [mrad]	±57	±120
Solid angle [msr]	12.2	20.1



Reactions studied at RIKEN-GARIS



^{208}Pb(^{58}Fe, n)^{265}Hs
^{208}Pb(^{64}Ni, n)^{271}Ds
^{209}Bi(^{64}Ni, n)^{272}Rg
^{208}Pb(^{70}Zn, n)^{277}112
^{209}Bi(^{70}Zn, n)^{278}113
^{207}Pb(^{58}Fe, n)^{264}Hs
^{206}Pb(^{58}Fe, n)^{263}Hs
^{208}Pb(^{56}Fe, n)^{263}Hs
^{208}Pb(^{58}Fe, 2n)^{264}Hs
^{248}Cm(^{18}O,5n)^{261}Rf
^{248}Cm(^{19}F,5n)^{262}Db
^{248}Cm(^{22}Ne,5n)^{265}Sg
^{248}Cm(^{23}Na,5n)^{266}Bh

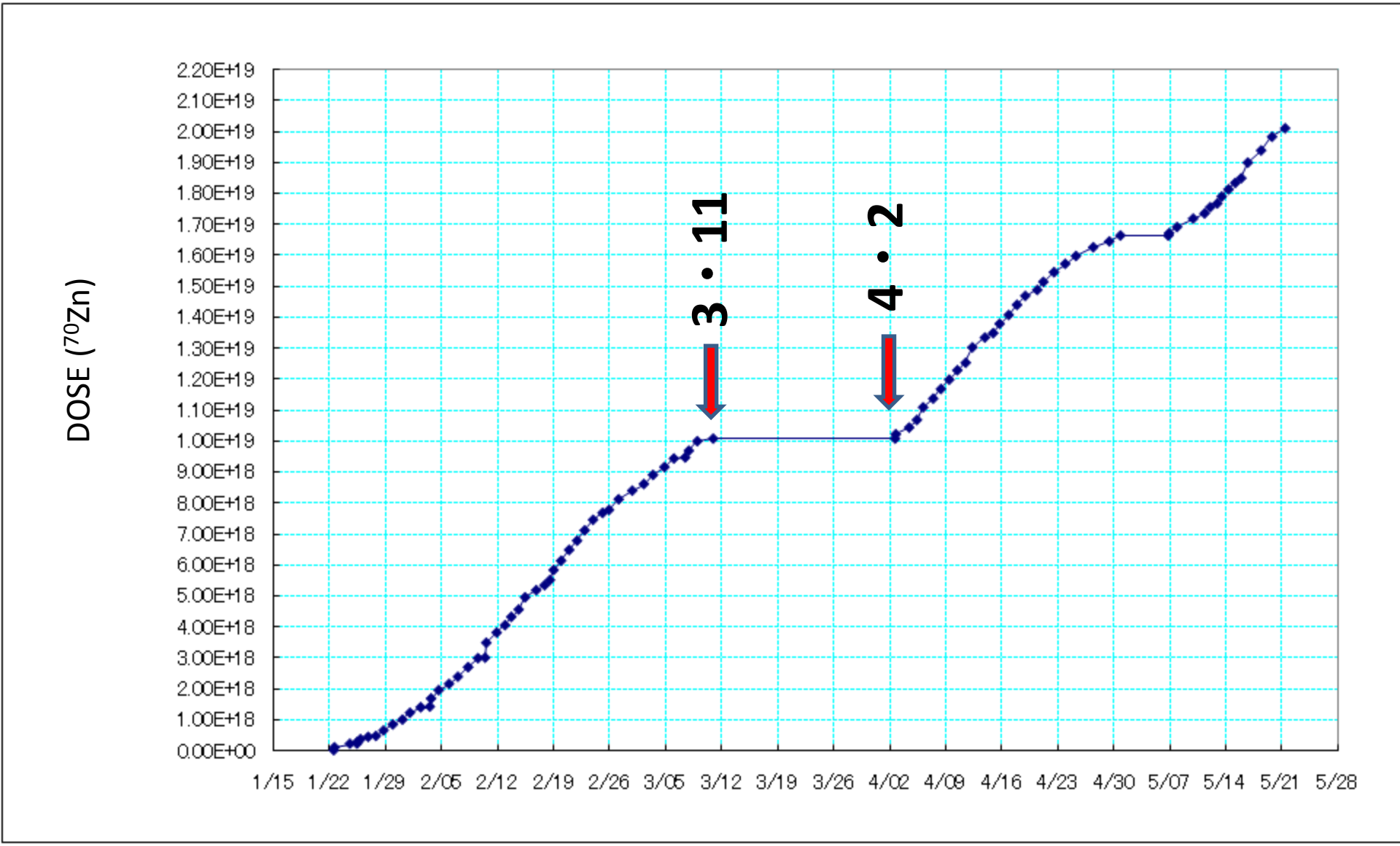

209Bi + 70Zn → 278113 + n
1st chain
23-July-2004 18:55 (JST)
36.75 MeV
TOF 44.61 ns
30.33 mm
278113 CN
α
11.68 MeV (PSD)
344 μs
30.49 mm
274111
α
11.15 MeV
6.149+5.003 (PSD+SSD)
9.260 ms
30.40 mm
270Mt
α
10.03 MeV
1.136+8.894(PSD+SSD)
7.163 ms
29.79 mm
266Bh
α
9.08 MeV (PSD)
2.469 s
30.91 mm
262Db
s.f.
204.05 MeV(PSD)
40.9 s
30.25 mm
36.47 MeV
TOF 45.69 ns
30.08 mm
278113 CN
α
11.52 MeV (PSD)
4.93 ms
30.16 mm
274111
α
0.88+10.43=11.31 MeV
(PSD+SSD)
34.3 ms
29.61 mm
270Mt
α
2.32 MeV (escape)
1.63 s
29.45 mm
266Bh
α
9.77 MeV (PSD)
1.31 s
29.65 mm
262Db
s.f.
192.32 MeV(PSD)
0.787 s
30.47 mm
2nd chain
2-April-2005 2:18 (JST)

Summary of ^{209}Bi + ^{70}Zn experiment

period	2003/9/5 ～ 2011/5/22
Beam Energy	5.03 AMeV
	348 MeV at target half depth
Total Dose	1.00×10^{20}
Target Thickness	1.3×10^{18} /cm^2 (0.45 mg/cm^2)
ε_GARIS	0.8
σ(2-ev.)	2.3×10^{-38} cm^2
	$23\ ^{+30}_{-15}$ fb
Irradiation time	10375 Hours (432 Days)
Beam Intensity	3.0×10^{12} /s (0.5 p-μA)

J. Phys. Soc. Jpn., Vol. 73, No. 10, p.2593(2004)

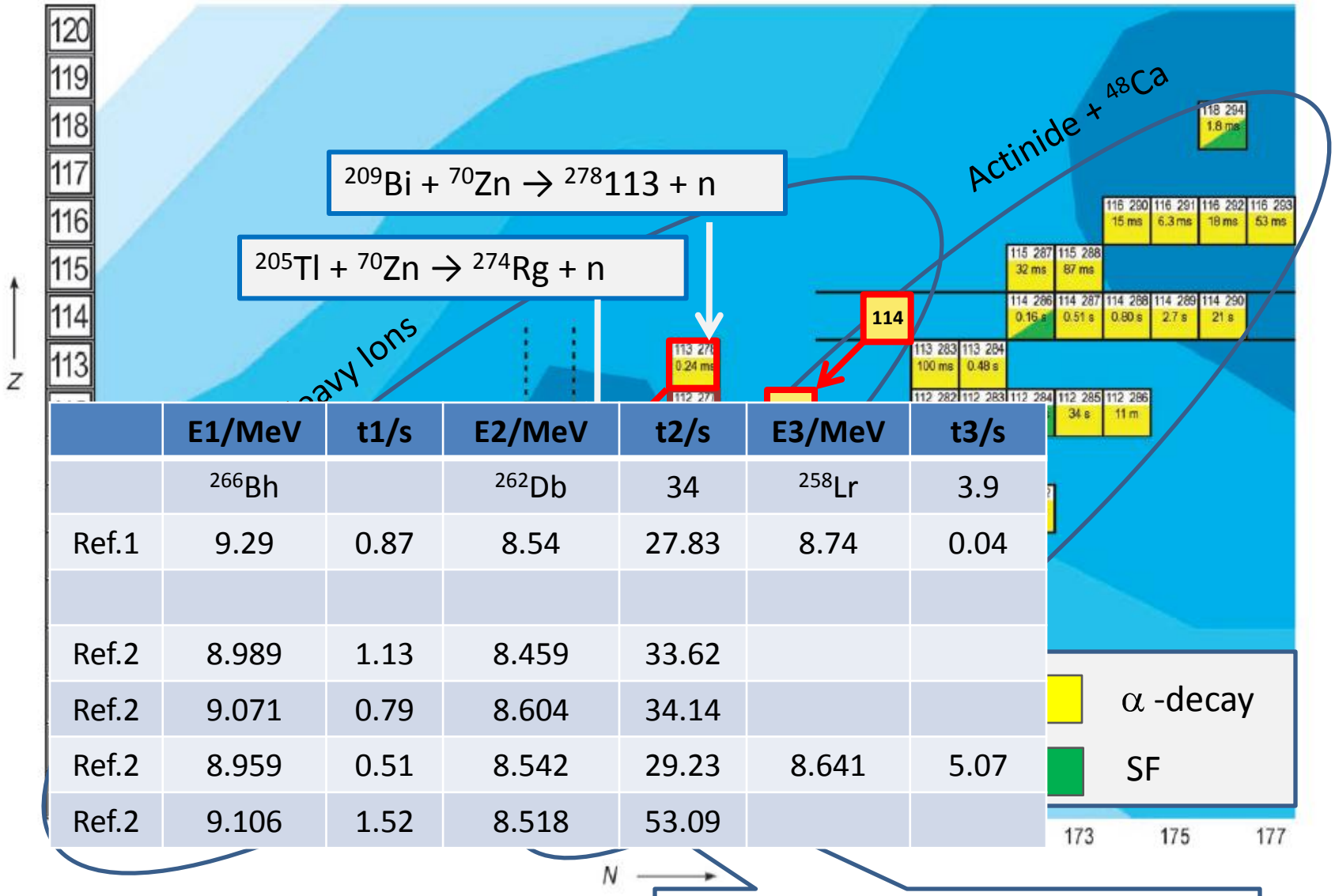
J. Phys. Soc. Jpn., Vol. 76, No. 4, p.045001(2007)


DOSE (^{70}Zn)
2.20E+19
2.10E+19
2.00E+19
1.90E+19
1.80E+19
1.70E+19
1.60E+19
1.50E+19
1.40E+19
1.30E+19
1.20E+19
1.10E+19
1.00E+19
9.00E+18
8.00E+18
7.00E+18
6.00E+18
5.00E+18
4.00E+18
3.00E+18
2.00E+18
1.00E+18
0.00E+00
3・11
4・2
1/15 1/22 1/29 2/05 2/12 2/19 2/26 3/05 3/12 3/19 3/26 4/02 4/09 4/16 4/23 4/30 5/07 5/14 5/21 5/28
DATE 2011

Z=113

year	start	stop	hours /days	dose/sum [x 10^{19}]	σ [fb]	error+	error-
2003	9/5	12/29	1389/57.9	1.24/1.24	75.3(upper limit)		
2004	7/8	8/2	526/21.9	0.51/1.75	55	130	45
2005	1/20	1/23	72/3.0	0.07/1.82	52	120	43
	3/23	4/22	650/27.1	0.71/2.53	75	100	49
	5/19	5/21	48/2.0	0.05/2.58	74	98	48
	8/7	8/25	386/16.1	0.45/3.03	63	83	40
	9/7	10/20	937/39.0	1.17/4.20	45	59	29
	11/25	12/15	469/19.5	0.63/4.83	39	51	25
2006	3/14	5/15	1300/54.2	1.37/6.20	31	40	20
2008	1/9	3/31	1701/70.9	2.28/8.48	23	30	15
2010	9/7	10/18	742/30.9	0.52/9.00	21	28	14
2011	1/22	5/22	2156/	2.01/10.0	17	22	11

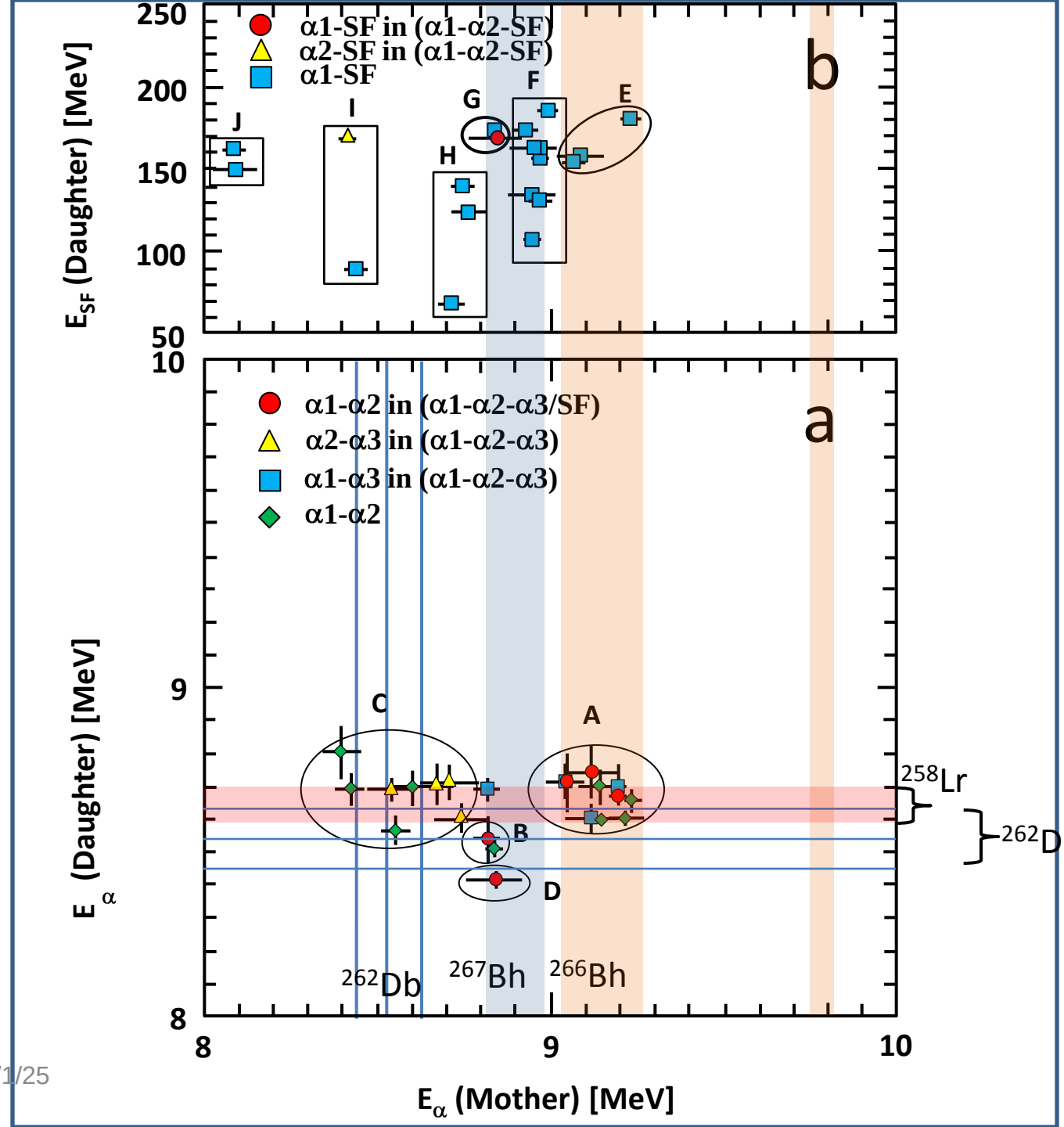
Total 10375/432 2 events



	E1/MeV	t1/s	E2/MeV	t2/s	E3/MeV	t3/s
	^{266}Bh		^{262}Db	34	^{258}Lr	3.9
Ref.1	9.29	0.87	8.54	27.83	8.74	0.04
Ref.2	8.989	1.13	8.459	33.62		
Ref.2	9.071	0.79	8.604	34.14		
Ref.2	8.959	0.51	8.542	29.23	8.641	5.07
Ref.2	9.106	1.52	8.518	53.09		

P. A. Wilk et al., PRL85, 2697 (2000)
$^{249}Bk(^{22}Ne,5n)^{266}Bh$

Z. Qin et al., Nucl. Phys. Rev. 23, 400 (2006)
$^{243}Bk(^{26}Mg,3n)^{266}Bh$


b
α1-SF in (α1-α2-SF)
α2-SF in (α1-α2-SF)
α1-SF
E_SF (Daughter) [MeV]
250
200
150
100
50
J
I
H
G
F
E
a
α1-α2 in (α1-α2-α3/SF)
α2-α3 in (α1-α2-α3)
α1-α3 in (α1-α2-α3)
α1-α2
E_α (Daughter) [MeV]
10
9
8
C
A
B
D
258Lr
262Db
262Db
267Bh
266Bh
8
9
10
E_α (Mother) [MeV]

Experimental condition $^{208}Pb(^{70}Zn, n)^{277}112$

period	2004/4/2 ～ 2004/5/24	
Beam Energy	346 MeV at target half depth	
Total Dose	4.4×10^{18}	
Target Thickness	450 μg/cm^2	
number of events	2	
σ	$0.44^{+0.59}_{-0.29}$ pb	
Irradiation time	693 Hours	(28.9 Days)
Beam Intensity	1.76×10^{12} /s	(0.3 p-μA)
Counting rate	～1 cps	

J. Phys. Soc. Jpn., Vol. 76, No. 4, p.043201(2007)

Observed events at RIKEN in $^{208}Pb + ^{70}Zn$ reaction

16-April-2004
E (^{70}Zn) = 349.5 MeV

Strip #8

34.42 MeV
23.33 mm

$^{277}112$ CN

11.09 ± 0.07 MeV
1.10 ms
23.57 mm

^{273}Ds

11.14 ± 0.04 MeV
0.52 ms
23.45 mm

^{269}Hs

9.17 ± 0.04 MeV
14.19 s
23.34 mm

^{265}Sg

8.71 ± 0.04 MeV
23.02 s
23.45 mm

^{261}Rf

197.3 MeV
2.97 s
23.41 mm

Strip #11

35.13 MeV
18.45 mm

$^{277}112$ CN

11.32 ± 0.04 MeV
1.22 ms
18.31 mm

^{273}Ds

11.15±0.07MeV (2^{nd} trig. PSD+SSD)
39.9 μs
20.18 mm

^{269}Hs

9.25 ± 0.07 MeV(PSD+SSD)
0.270 s
19.03 mm

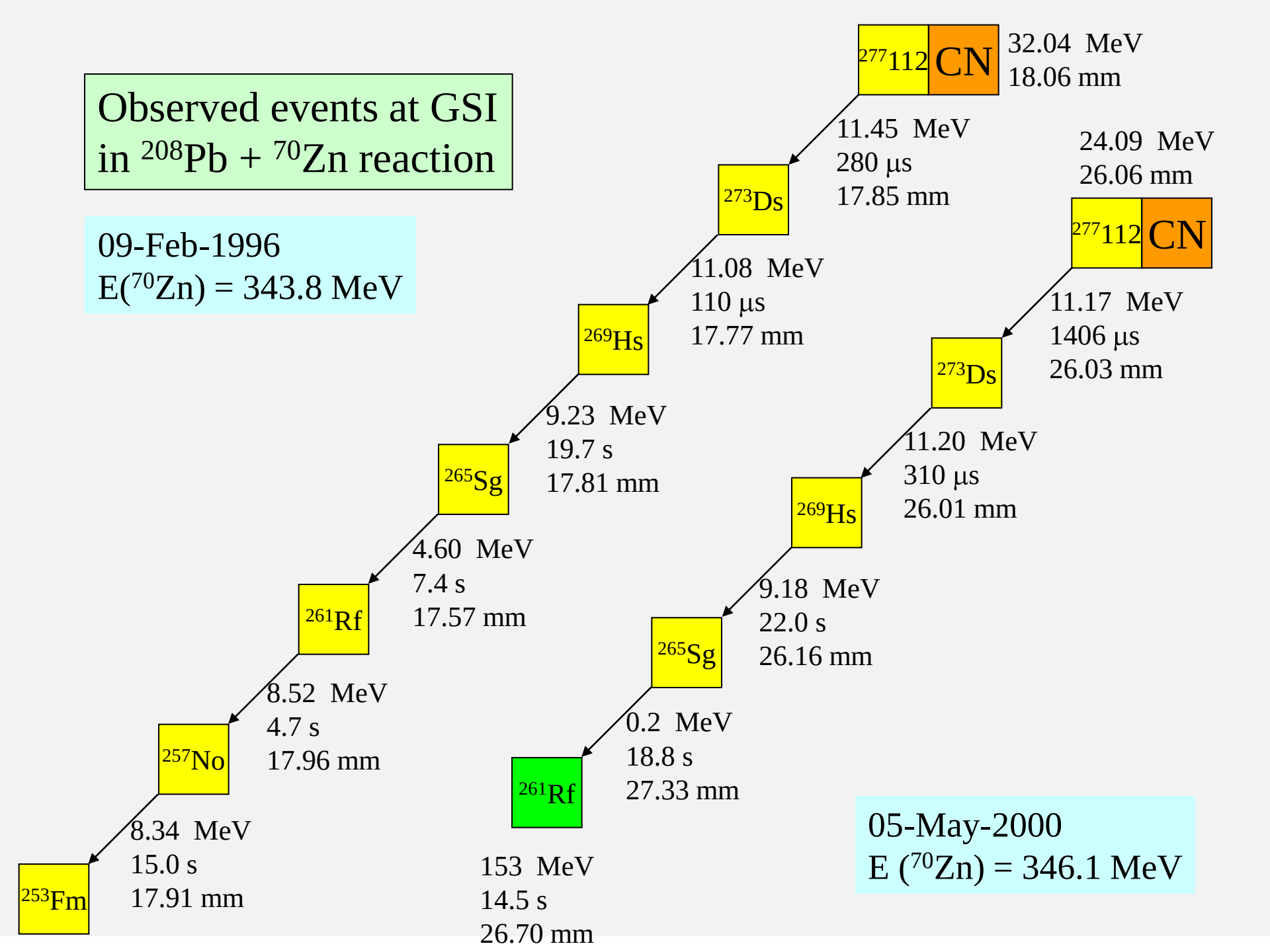
^{265}Sg

8.70 ± 0.04 MeV
79.9 s
18.05 mm

^{261}Rf

156.3 MeV
8.3 s
18.50 mm

22-May-2004
E (^{70}Zn) = 349.5 MeV


Observed events at GSI
in 208Pb + 70Zn reaction
09-Feb-1996
E(70Zn) = 343.8 MeV
277112 CN
32.04 MeV
18.06 mm
11.45 MeV
280 μs
17.85 mm
273Ds
11.08 MeV
110 μs
17.77 mm
269Hs
9.23 MeV
19.7 s
17.81 mm
265Sg
4.60 MeV
7.4 s
17.57 mm
261Rf
8.52 MeV
4.7 s
17.96 mm
257No
8.34 MeV
15.0 s
17.91 mm
253Fm
24.09 MeV
26.06 mm
277112 CN
11.17 MeV
1406 μs
26.03 mm
273Ds
11.20 MeV
310 μs
26.01 mm
269Hs
9.18 MeV
22.0 s
26.16 mm
265Sg
0.2 MeV
18.8 s
27.33 mm
261Rf
153 MeV
14.5 s
26.70 mm
05-May-2000
E (70Zn) = 346.1 MeV

Observed events at RIKEN
in ^{208}Pb + ^{70}Zn reaction

18-June-2011 15:08 run034
E (^{70}Zn) = 351.5 MeV
^{208}Pb/C=490/60 ug/cm^2

Strip #14

35.41 MeV
35.02 mm
TOF 46.458 ns

^{277}Cn CN

11.07 MeV(PSD+SSD)
2.713+8.354
0.370 ms
33.08 mm

^{273}Ds

11.03 MeV(PSD+SSD)
3.314+7.710
0.373 ms
36.05 mm

^{269}Hs

9.14 MeV
36.01 s
34.84 mm

^{265}Sg

8.66 MeV(PSD+SSD)
2.971+5.689
13.84 s
34.47 mm

^{261}Rf

175.8 MeV
3.73 s
34.98 mm

Preliminary

σ $0.08^{+0.17}_{-0.06}$ pb cf. $0.44^{+0.59}_{-0.29}$ pb

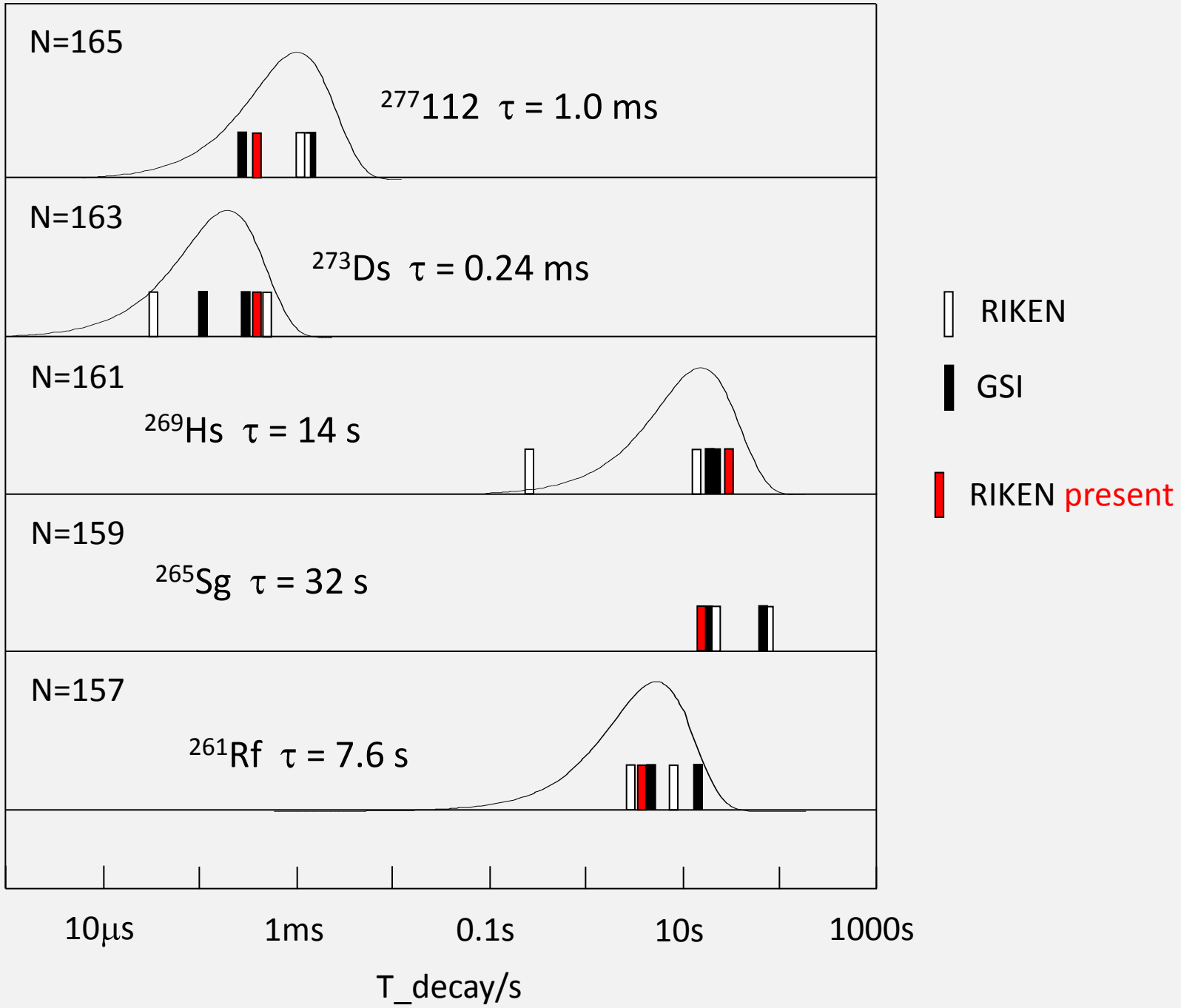
dose 9.0×10^{18} 4.4×10^{18}

	GSI		RIKEN			FLNR	
ref.	1	2	3	4	present	5	6
^{277}112	11.45	11.17	11.09±.07	11.32±.04	11.07		
	0.28 ms	1.41 ms	1.10 ms	1.22 ms	0.37 ms		
^{273}Ds	11.08	11.20	11.14±.04	11.15±.07	11.03	11.35	
	0.11 ms	0.31 ms	0.52 ms	0.04 ms	0.373 ms	0.39 ms	
^{269}Hs	9.23	9.18	9.17±.04	9.25±.07	9.14		
	19.7 s	22.0 s	14.2 s	0.27 s	36.01 s		
^{265}Sg	4.60	0.20	8.71±.04	8.70±.04	8.66	8.63	
	74.0 s	18.8 s	23.0 s	79.9 s	13.84 s	158 s	
^{261}Rf	8.52	153	197	156	176		8.30±0.06
	4.70 s	14.5 s	2.97 s	8.30 s	3.73 s		54^{+8}_{-4} s
^{257}No	8.34					8.22	8.24, 8.34
	15.0 s					384 s	17 s

ref.

1 Hofmann S. et al., Z. Phys. A354, 229 (1996)
2 Hofmann S. and Münzenberg G., Rev. Mod. Phys. 72, 733 (2000)
3,4 J. Phys. Soc. Jpn., Vol. 76, No. 4, p.043201(2007)
present
5 Lazarev Yu. A. et al., Phys. Rev. C54, 620 (1996)
6 Lazarev Yu. A. et al., Phys. Rev. C62, 064307(2000)

^{208}Pb + ^{70}Zn → ^{277}112 + n
^{208}Pb + ^{70}Zn → ^{277}112 + n
^{208}Pb + ^{70}Zn → ^{277}112 + n
^{208}Pb + ^{70}Zn → ^{277}112 + n
^{244}Pu + ^{34}S → ^{273}Ds + 5n
^{244}Pu + ^{22}Ne → ^{261}Rf + 5n

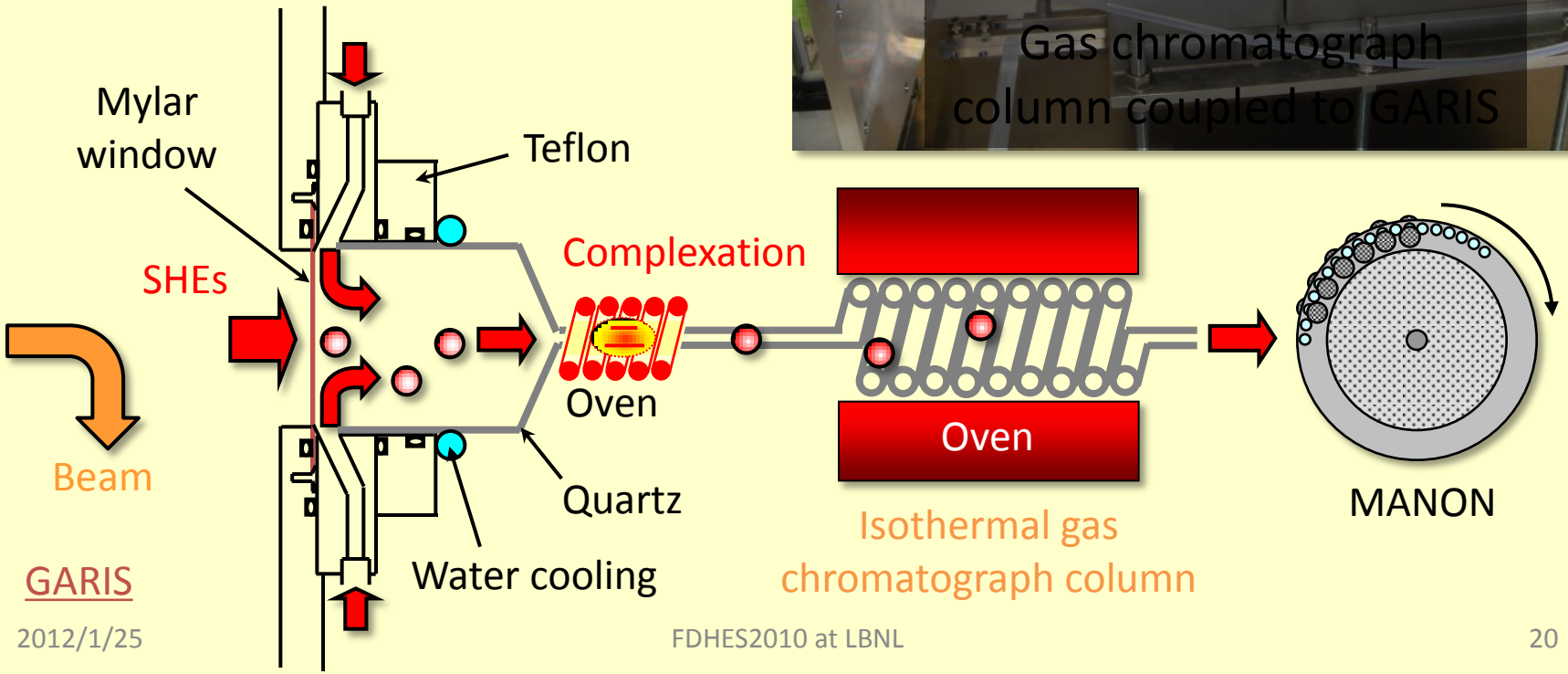

N=165
^{277}112 τ = 1.0 ms
N=163
^{273}Ds τ = 0.24 ms
N=161
^{269}Hs τ = 14 s
N=159
^{265}Sg τ = 32 s
N=157
^{261}Rf τ = 7.6 s
RIKEN
GSI
RIKEN present
10μs
1ms
0.1s
10s
1000s
T_decay/s

4.2. Gas chemistry

Adsorption enthalpy

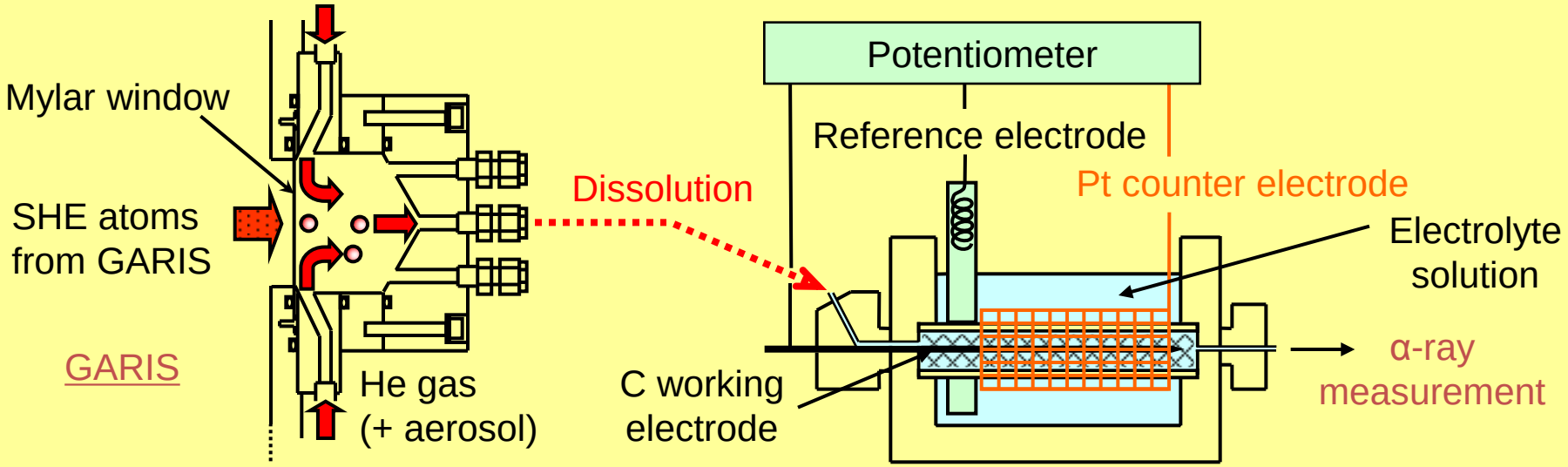
- Isothermal gas chromatograph column (Niigata Univ. and JAEA)
- Gas chromatograph column directly coupled to GARIS (RIKEN)

Chemical reagents without aerosols



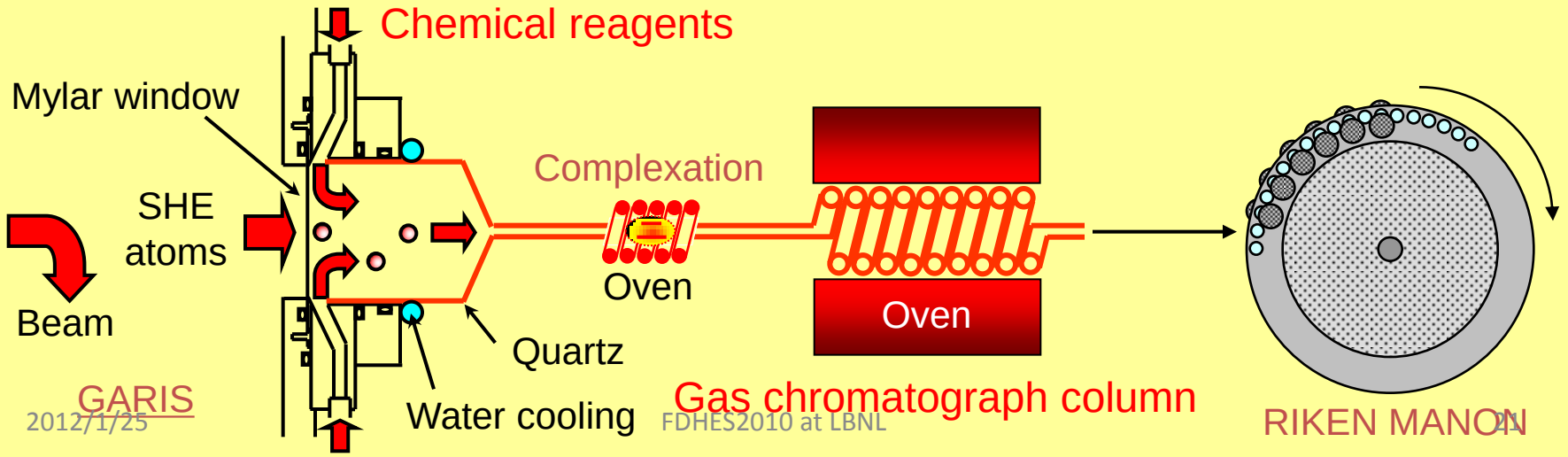
(b) Flow-electrolytic column

Redox potential ⇒ Direct information on electronic structure of SHEs



(c) Gas chromatograph column coupled to GARIS

Direct injection of chemical reagents without aerosol material



Beam time available 7months/year

beam intensities at RILAC (E < 5.8 AMeV)

$^{12,13}C$, $^{16,18}O$, ^{19}F, $^{20,22}Ne$, ^{23}Na,^{40}Ar	3-5 pμA
^{48}Ca	1-2 pμA
^{58}Fe, ^{64}Ni, ^{70}Zn, ^{86}Kr	-1 pμA
^{50}Ti, ^{54}Cr, ^{76}Ge	not known

Future

Production	$^{248}Cm_{152} + {}^{54}Cr_{30} \rightarrow {}^{302}[120]_{182}{}^{*}$
Chemistry	Sg, Bh, Hs, Mt,
Spectroscopy	GARIS+FPD, GARIS+GAS jet GARIS+RF_ion_Guide GARIS+RF_ion_Guide+mTOF New isotope search $E\alpha$, $T_{1/2}$ α - γ

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Thank you for your kind attention!!

Search for superheavy elements in RIKEN

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RIKEN Nishina Center, RIKEN

XXXII Mazurian Lakes Conference on Physics
The legacy of Maria Skłodowska-Curie. 100 years after the discovery of the atomic nucleus
Piaski, Poland, 11 – 18 September 2011

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Present status and prospects of SHE researches at RIKEN

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The 2nd collaboration meeting on superheavy element research
Nagano, 23 September 2011

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