Wear diagnostics using low-energy RIBs and their γ-ray imaging

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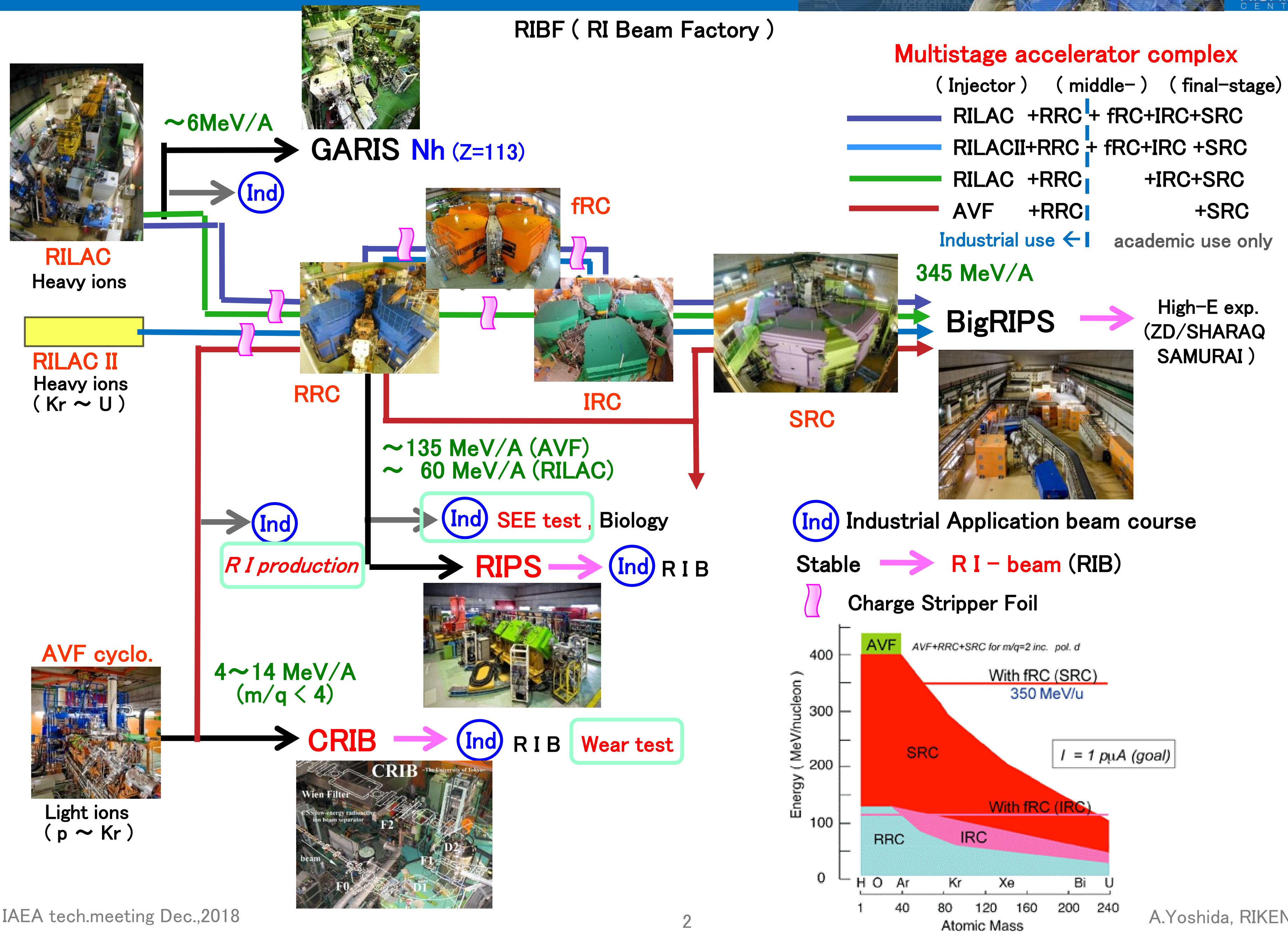
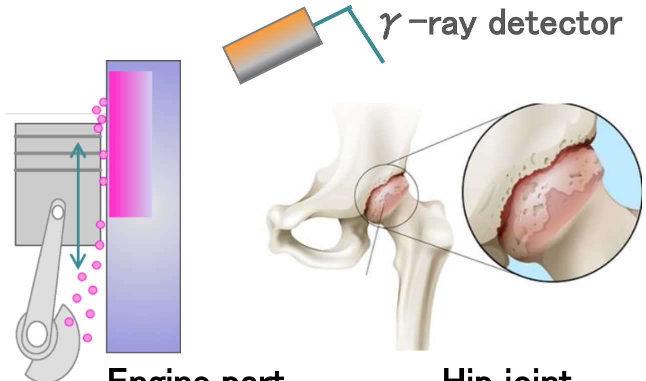
- Activation method for wear test using low-energy in-flight RI-beam separator
- γ-ray Inspection for Rotating Object (GIRO) system
- Irradiation test of space-use semiconductors using "stable" HI-beams in atomsphere

RIKEN RIBF : acceleration diagram



Wear test using RI tracer (History)

On-line & Real-time wear test using RI tracers



Engine part Hip joint

- **long-life RI**
  $T_{1/2}$: month～year ＝ test period
  RIs near the stable line
- **concentrated at near surface**
  with high density

⇩

Activation method
investigated

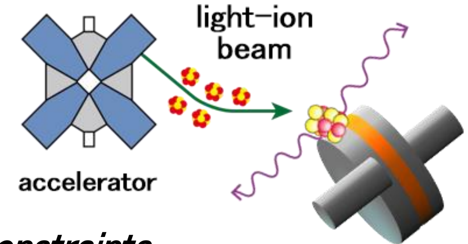
Activation method (History)

➢ **Direct-beam activation** — activation layer / density

Neutron (reactor) — "Thick" "Low"

1970's～ Light-Ion beams

Thin-Layer Activation (TLA)
at Karlsruhe — "Thin" "High"



constraints

✗ produced RI depends on the material
✗ strong Heat & Radiation damage
✗ depth-profile determined by the reaction energy and cross section

1990's～

➢ **RI-beam implantation**
Indirect activation

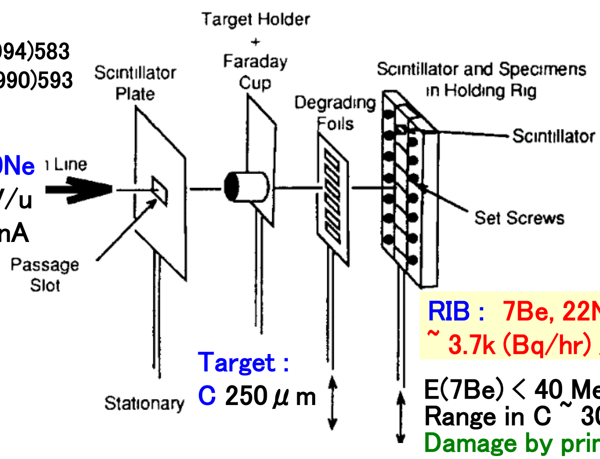
Wear : R I B implantation (History)

1990's~ **Beam Fragmentation**

MSU

N.Phys A353(1994)583
A299(1990)593

Beam :
14N, 20Ne
40MeV/u
~100 p.nA



Target :
C 250 μ m

RIB : 7Be, 22Na
~ 3.7k (Bq/hr) / 0.1p μ A

E(7Be) < 40 MeV/u
Range in C ~ 3000 μ m
Damage by primary beam

1995's~ **Recoil Angular Distribution**

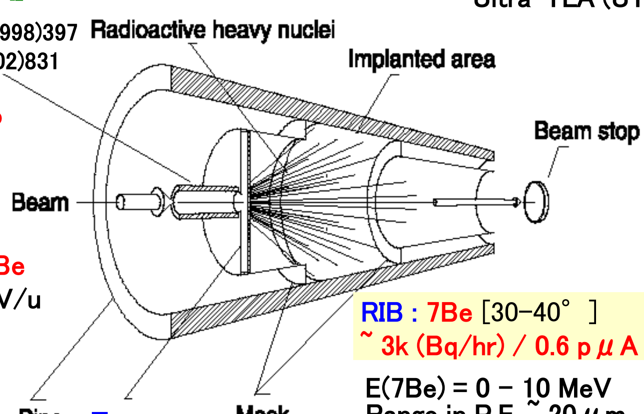
CNRS-CERI

Ultra-TLA (UTLA)

7Be: N.Phys B143(1998)397
56Co: NIM B190(2002)831

56Fe(p,n) 56Co
Ep 23MeV

12C(3He,2 α) 7Be
E(3He) 8.3 MeV/u
~ 3.5 p. μ A



Target :
C 130 μ m

RIB : 7Be [30-40°]
~ 3k (Bq/hr) / 0.6 p μ A

E(7Be) = 0 – 10 MeV
Range in P.E. ~ 20 μ m
Scattered 3He contaminant

1995's~ **RI accelerator**

HRIBF-ORNL ?
TRIUMF, ISOLDE ?

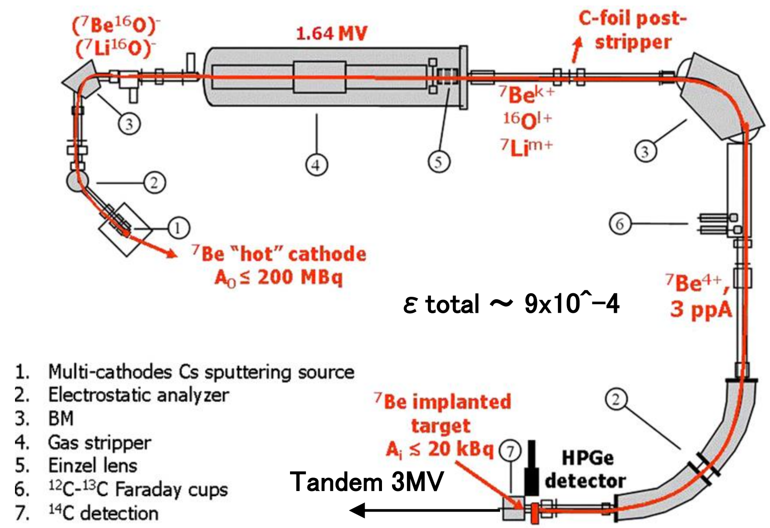
INFN-Napoli

NIM B266(2008)2117, B197(2002)150
Z.Phys A356(1996)107, N.Phys A701(2002)235c

@ Debrecen ATOMKI, Hungary
7Li (p,n) 7Be 20G Bq Ep=11MeV, 20 μ A, 2week

@ Bochum Isotope-Lab, Germany
Radio-chemical separation → make cathode by press.

@ Napoli Tandem 2.4 MV
7Be 200M Bq cathode mounted in sputter ion source

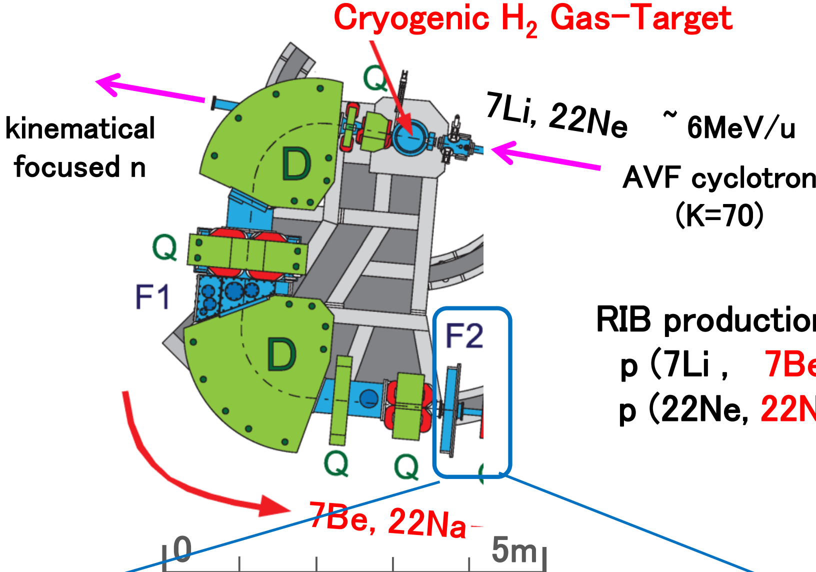


RIB : 7Be
~ 2 p pA = 1.2 x 10^7 cps = 6.5k (Bq/hr) NIM B266
~ 17 p pA = 1.1 x 10^8 = 60k Z.Phys A356

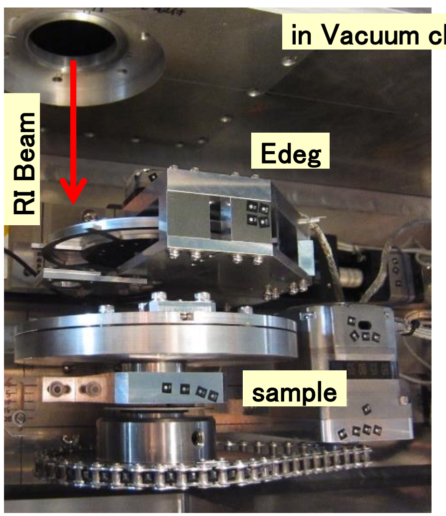
E(7Be) = 1 – 8 MeV pure beam, mono-energy
Range in steel ~ 10 μ m
Beam line activation

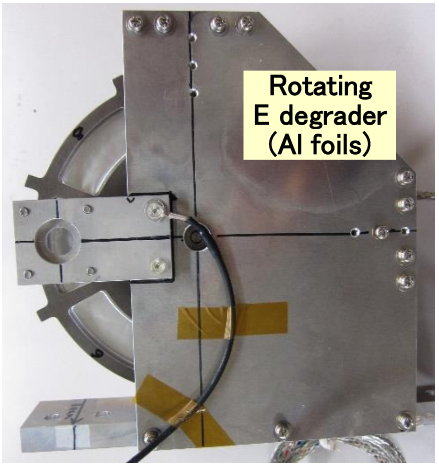
Wear : R I B implantation (in-flight R I B separator)

CRIB (Univ.Tokyo)
CNS RI Beam separator

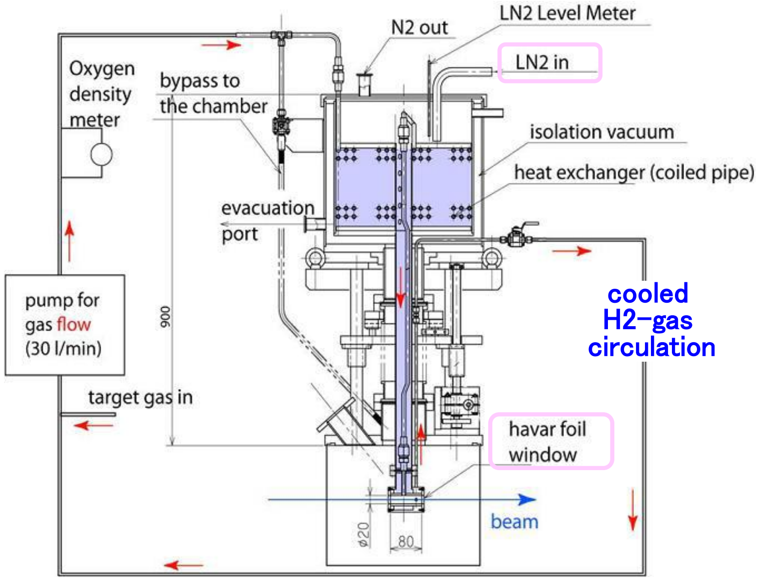


RIB production
p (7Li , 7Be) n
p (22Ne, 22Na) n





H.Yamaguchi et.al. NIM A589(2008)150-156



Cryogenic Gas-Target system
H2 gas (90K L=8cm max.1atm)
Vac. foil Havor 2.5 μm φ 2cm

7Be Beam spot (ZnS)
～φ 5mm

R I B parameters (CRIB)

R I beam	7Be4+	22Na11+	
reaction	p(7Li,7Be)n	p(22Ne,22Na)n	unit
E γ (branch)	477(10%)	1275(100%)	keV
		511(200%)	
Energy	4.16	3.67	MeV/u
E fwhm	0.39	0.41	MeV/u
Purity	80%	78%	
contaminants	7Li3+	22Ne10+,19F9+	
*1 Beam spot x/y	4.8 / 8.1	4.7 / 4.3	mm fwhm
Intensity	(2.3~3.7)x10^8	3.1x10^7	particl/sec
Activation rate	(126~200)	0.9	kBq/1hr
max.Range in Al	~60	~35	μm
Primary beam	7Li2+	22Ne7+	
Energy	5.7	6.1	MeV/u
Intensity (avr.)	(1.7~2.0)	~0.3	pμA
Production target	H2 @ 90K, L=8cm		
Pressure	760	400	Torr
circulation	~30	~20	slm
⊿E gas	5.9	5.4	Watt
*2 ⊿E vac.foil	1.4	2.5	Watt

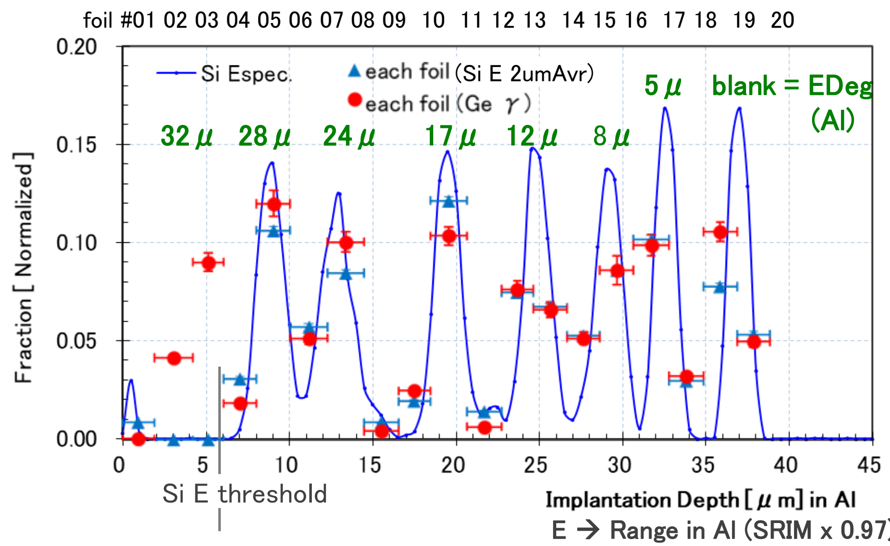
*1) when F1 mom. slit was dP/P=±3.1% (full acceptance)
*2) at exit vacuum foil : Havar 2.5 μm thick φ 2cm

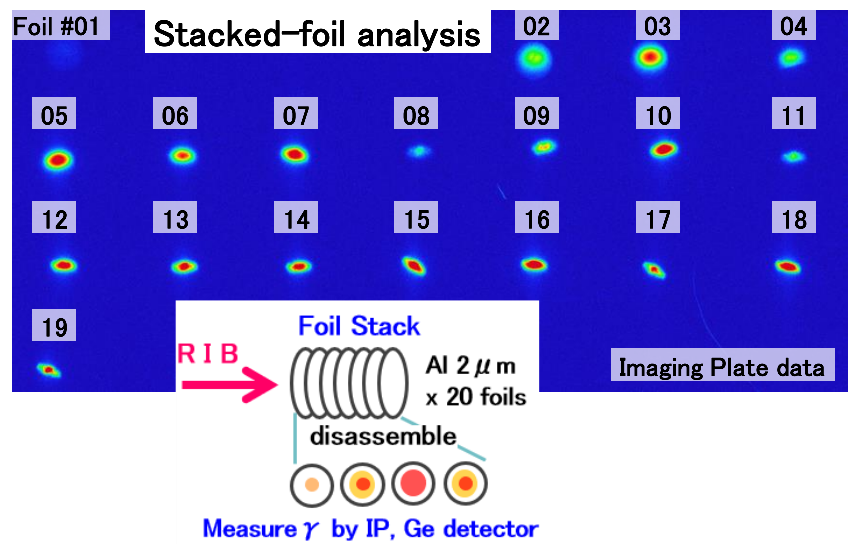
NIM B317(2013)785-788, RIKEN Acc.PR 48(2015)240, 47(2014)171
CNS Ann.Rep (2013)76-77, (2012)65-66

- 7Be intensity is similar to <u>RI-accelerator method</u>
  <u>60 kBq/hr, 1.1x 10^8 pps (particle/sec)</u>
- Constraint : heat loss at Gas-target
  Vacuum foil broken
  Effective gas density reduction

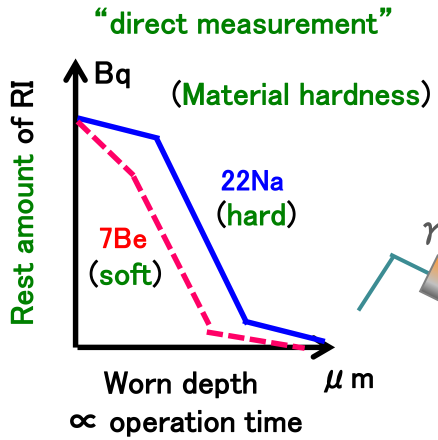
Pulse-shaped Depth-profile (22Na)

F1slit (dP/P = ±1%)

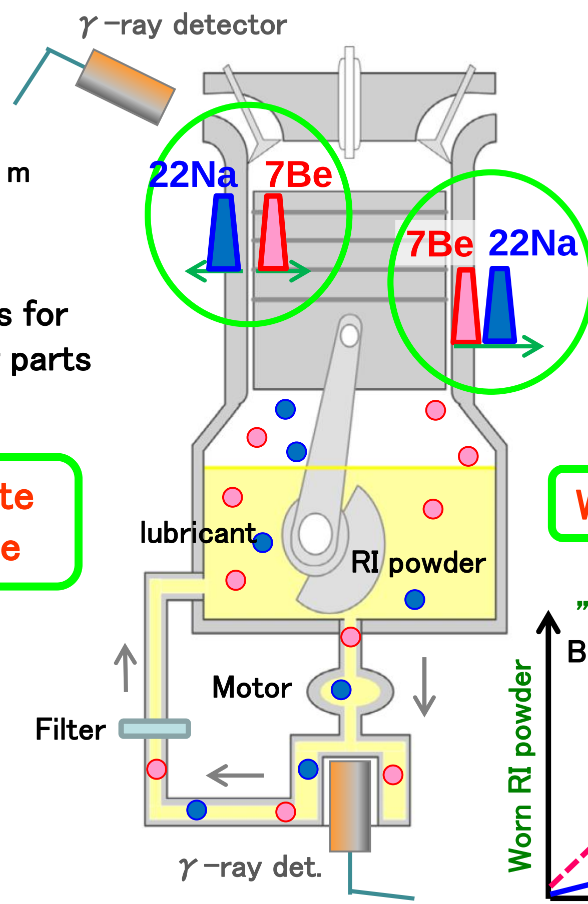




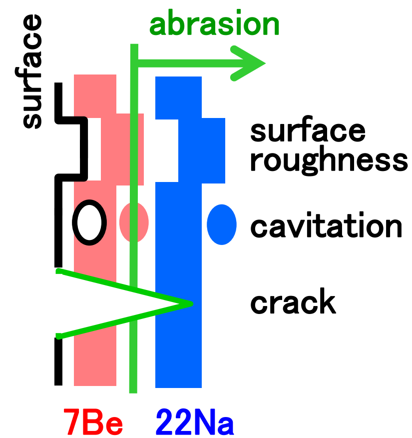
Wear : Possibility of Advanced wear analysis



R I beam		22Na	7Be
	T 1/2	2.6 year	53 day
Possible	material	Hard	Soft
Application	test period	Long run	Short run



Pulse-shaped depth profile



Different RIs for each rubbing parts

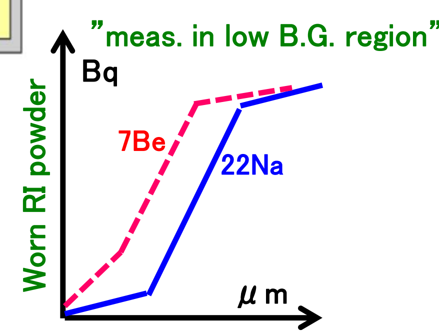
⇩

Wear-Rate difference

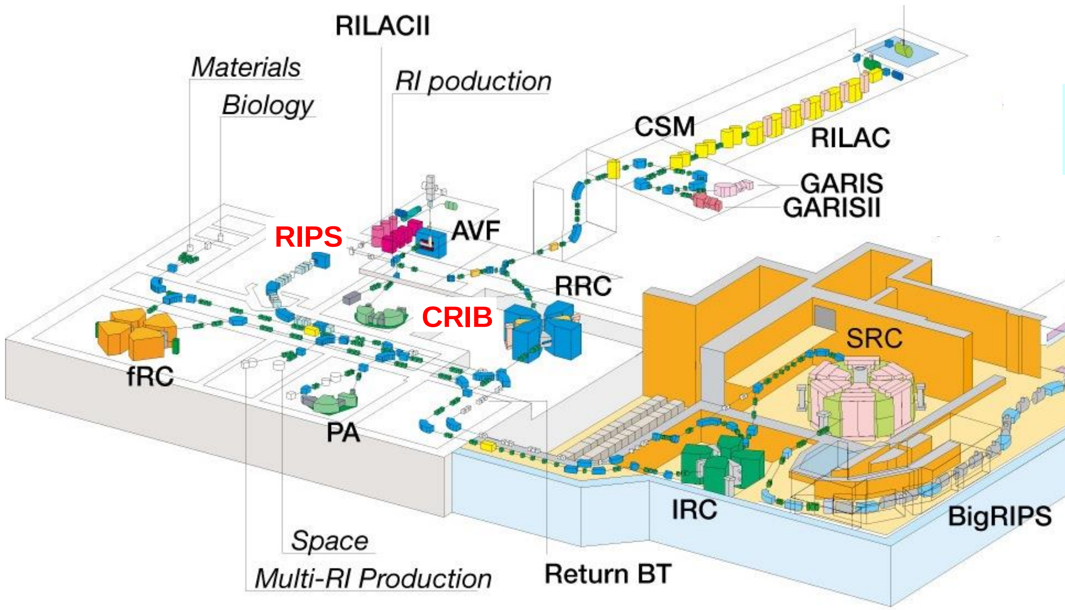
Different RIs for same part with different depth

⇩

Wear-depth Gauge



Wear : RIB separator (middle- vs low-energy)



- Using middle-energy R I B separator (R I P S)

✔ 22Na purity & intensity were better

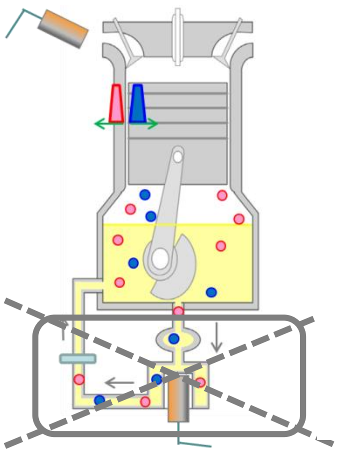
✗ RIB energy was too high for implantation at near surface
→ depth profile became low-density

→ low-energy in-flight R I B-separator is suitable for wear test

RIB Separator	RIPS (middle energy)		CRIB (low energy)		
R I beam	7Be	22Na	7Be	22Na	
reaction	Fragmentation	Fragmentation	p(7Li,7Be)n	p(22Ne,22Na)n	unit
Energy	73.0	26.6	4.16	3.67	MeV/u
⊿P/P	±3%	±3%	±3%	±3%	
Purity	~ 78%	100%	80%	78%	
contaminants	6Li3+, 8B5+,3H	–	7Li3+	22Ne10+,19F9+	
Beam spot size	~φ30	~φ30	~φ6.5	~φ4.5	mm fwhm
Intensity	~ 1x10^8	1.5x10^8	(2.3~3.7)x10^8	3.1x10^7	particl/sec
max.Range in Al	~9500	~660	~60	~35	μm
Primary beam	13C6+	23Na11+	7Li2+	22Ne7+	
Energy	100	63.4	5.7	6.1	MeV/u
Intensity (avr.)	0.3~2.0	~1.0	(1.7~2.0)	~0.3	pμA
Production Target	Be 6.0mm	Be 1.5mm	H2 @ 90K, L=8cm		
Irradiation	in atmosphere		in vaccum		

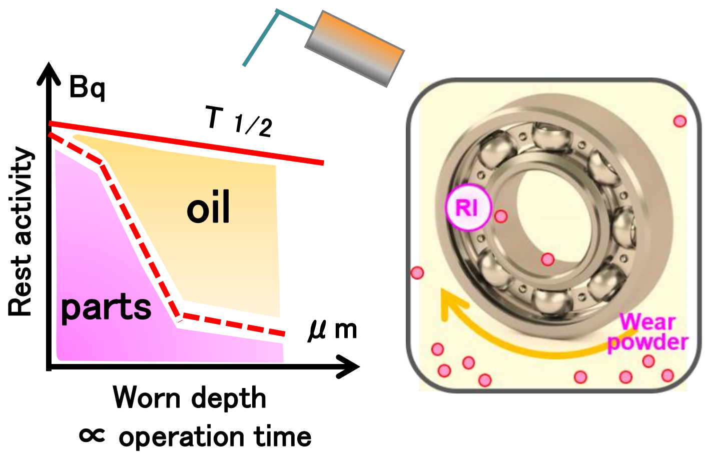
*) 7Be is not well studied yet

γ − ray imaging for wear diagnostics



Difficulty, if the object is ..

- oil−closed system
- high−viscosity oil

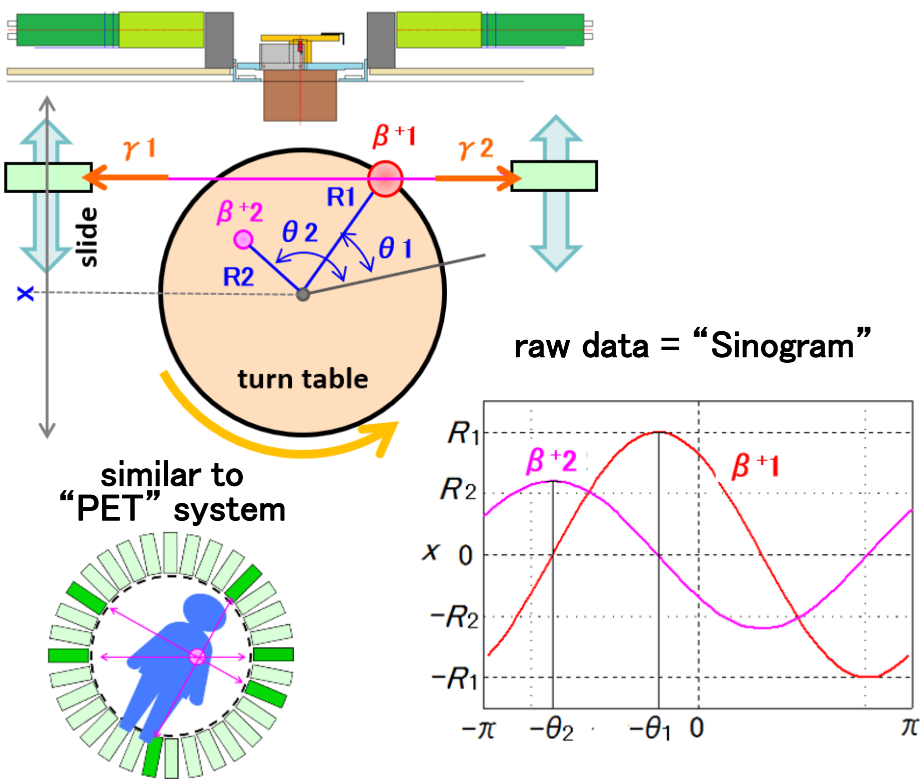


Can not distinguish "oil" vs. "parts"

→ need help of "γ−ray imaging"

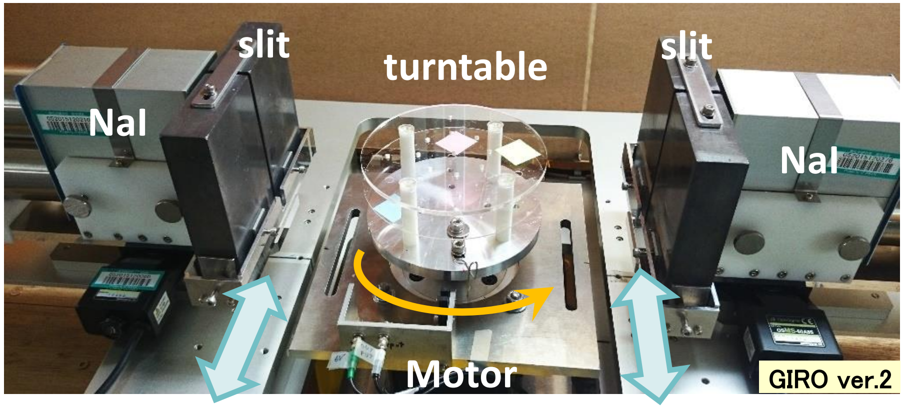
Gamma−ray Inspection for Rotating Object (GIRO)

T.Kambara et al, NIM A 797 (2015) 1−7
Nucl. Pyhs. News 26:4, (2016)26−29
Japanese patent app. No.6278330/2018



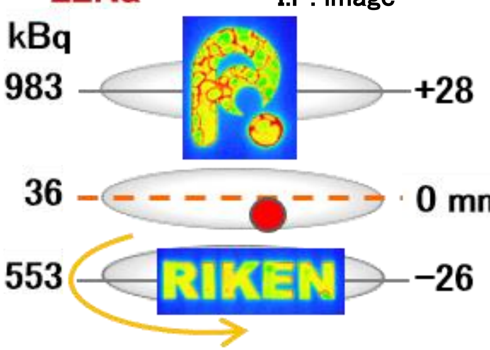
γ-ray imaging : G I R O (3D demo)

← 25 cm →
(system size is scalable)

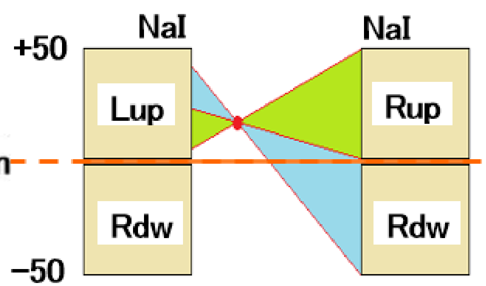


NaI(Tl) □50 x 50 x t100mm
Pb-slit □80 x 120 x t30mm
Slit width 4mm

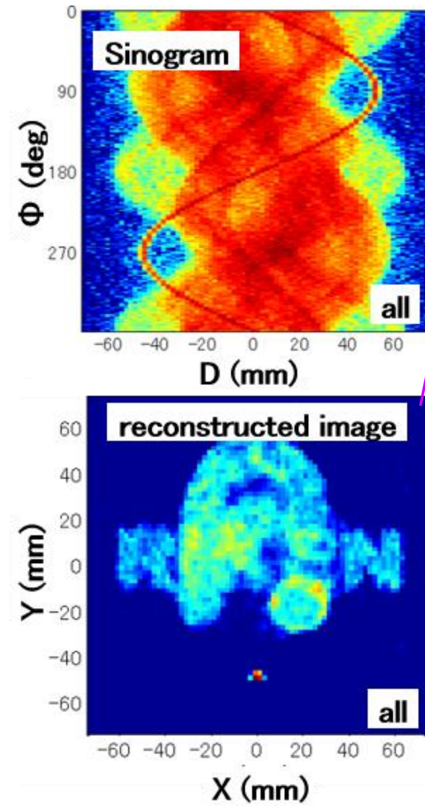
3-layer sources

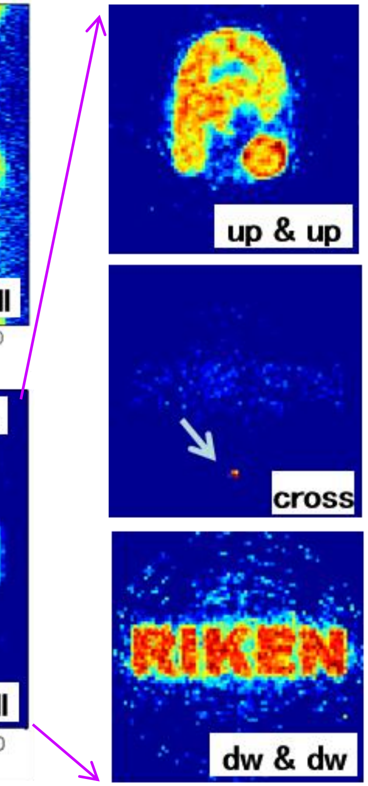


150 rpm, 24 hr measurement



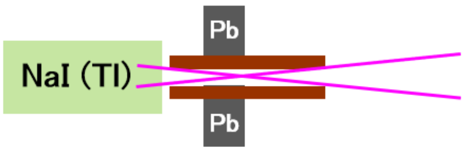
Coin. condition



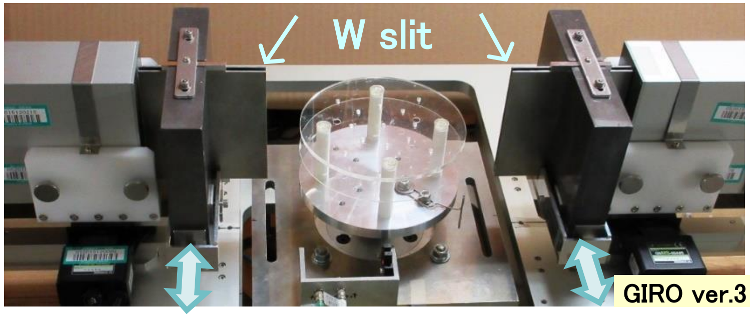


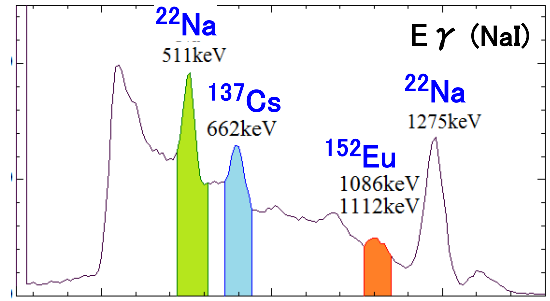
γ-ray imaging : G I R O (PET & SPECT demo)

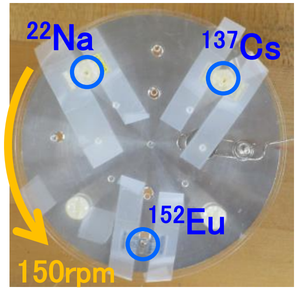
add W slit



W-slit w4mm t2mm

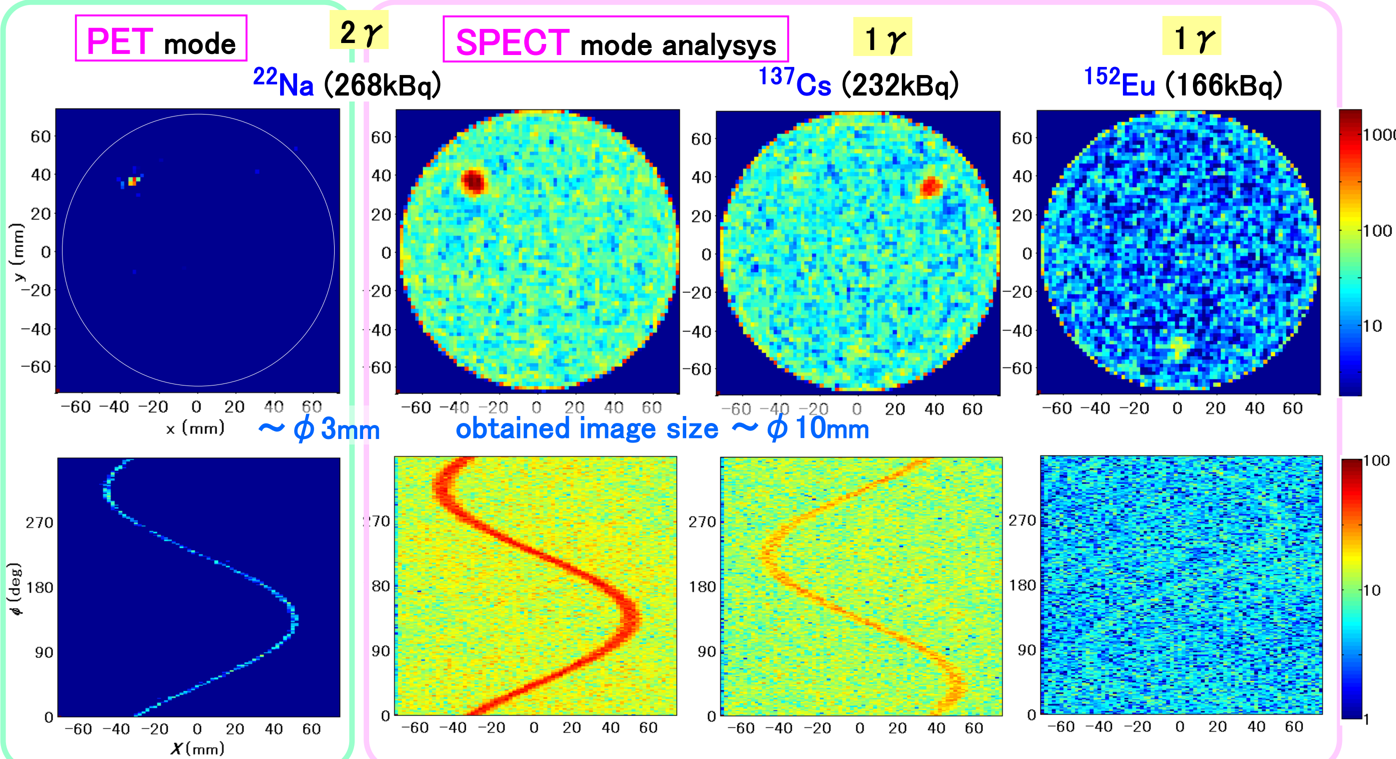






γ source size φ 2mm

150 rpm,
26 min measurement

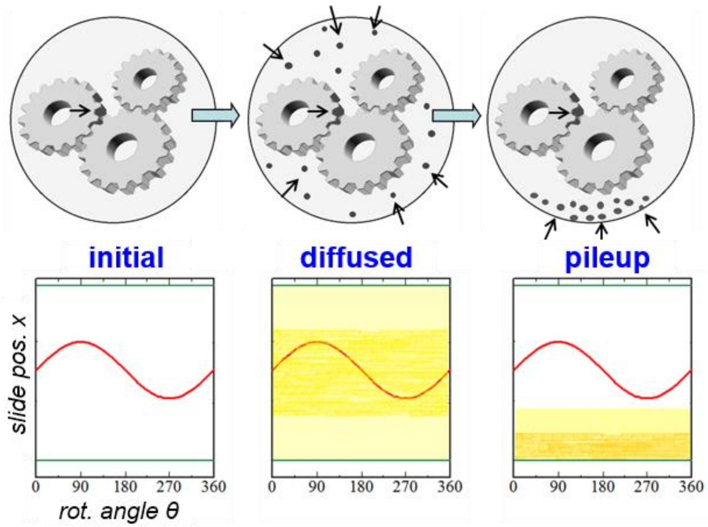


γ-ray imaging : Prospects of G I R O

	GIRO	PET
Inspect. Object	Rotating / Periodic motion	stationary
Num. of detectors	✔ at least Two	many, depends on object size
System size	✔ scalable & portable	
Price	✔ less expensive ～ 10 k $	expensive ～ 1 M $
	✔ applicable low～high rotation	
Measurement time	a few 10 min～10 hr / picture	✔ a few min / picture
Position resolution	determined by slit width	

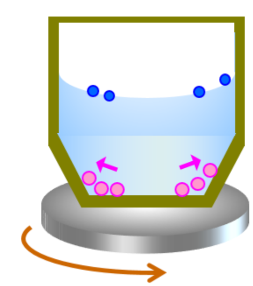
- GIRO is not suitable for living bodies,
  but is applicable for slow processes on continuously rotating object.

- eg.1) wear powders deposition on "Sinogram coordinates"



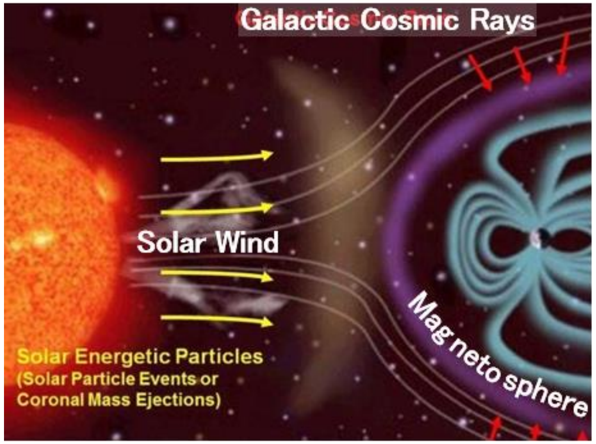
- eg.2) other possible rotating objects

metabolism of plant



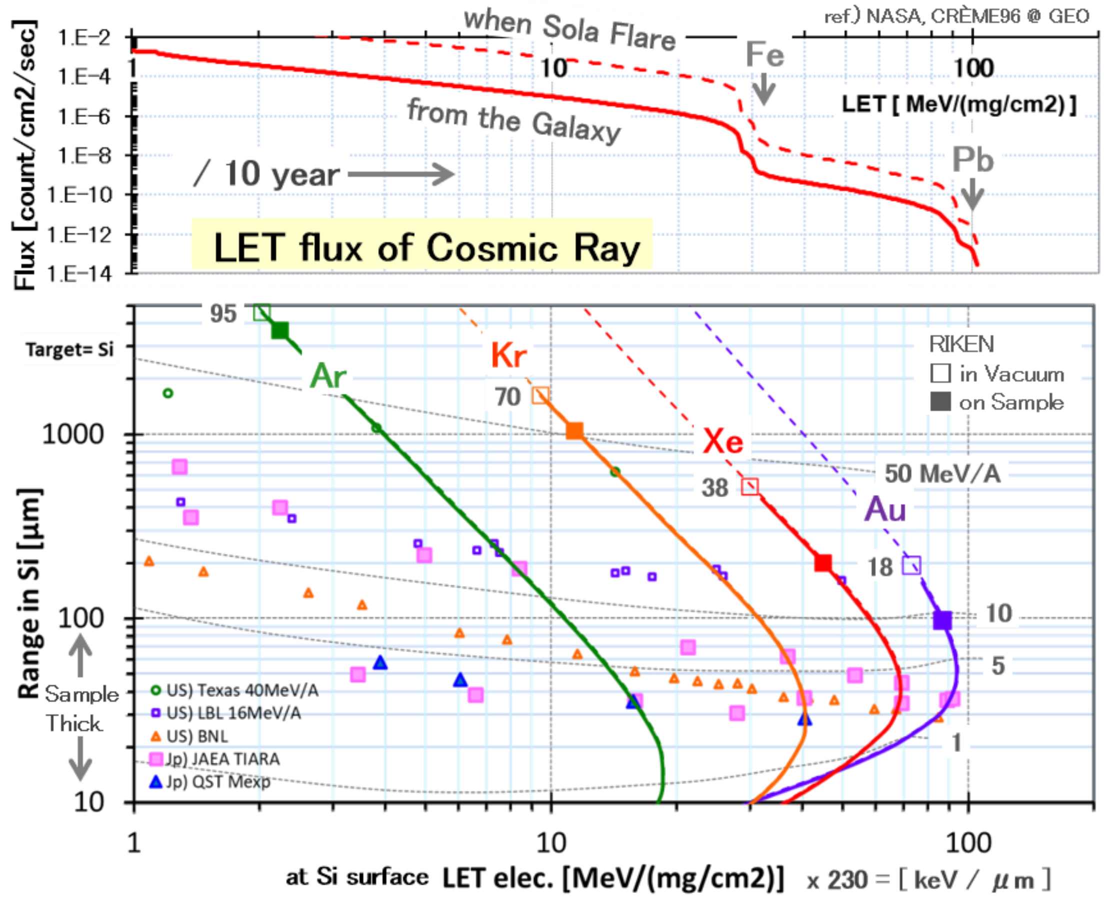
centrifugal force inside liquid vessel

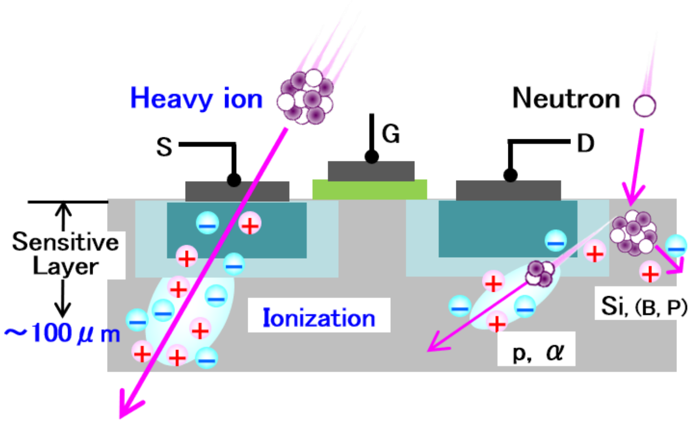
Radiation resistance test of space use semiconductors



ref.) Wikipedia

- **Single Event Effects (SEEs)**
  caused by High LET Cosmic Ray
- **Power devices**
  steep Elec. Field gradient



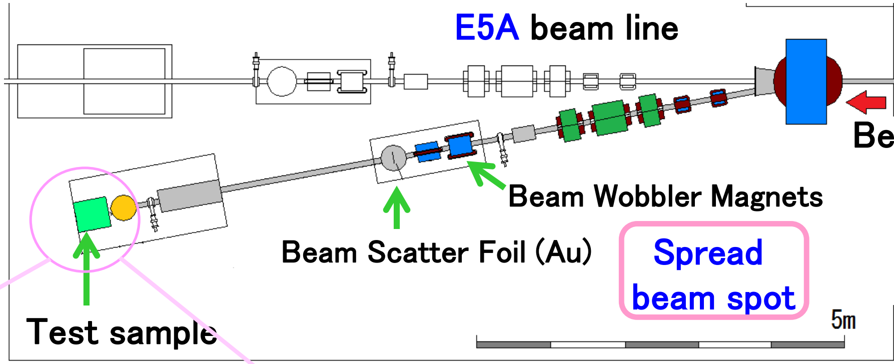


- SEEs resistance > ~ 10 year
- Examine threshold-LET of
  SEEs (Upset, Latch-up, Rupture)
- Beam Range 20~100 μm ← 3D-LSI, FPGA

SEEs test : Irradiation beam line

Beam passed through

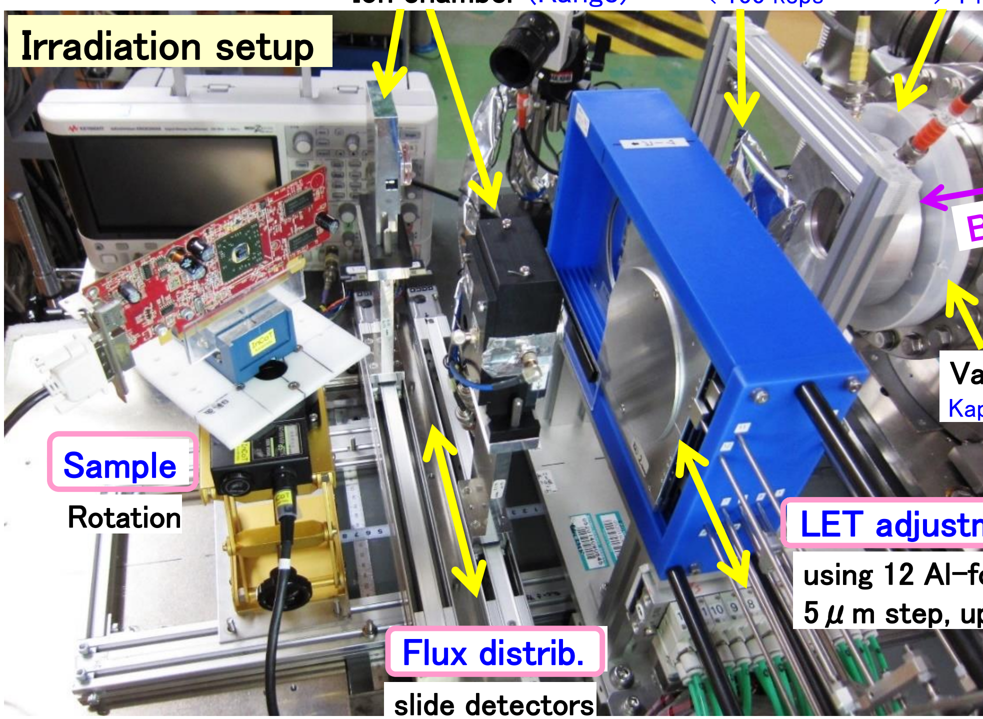
Materials	[μ m]
Au scat. foil	50
Kapton Vac. foil	75
Ion chamber Mylar	24
PL scintillator	100
light cover Mylar	48
Air	305 mm



Beam MeV/A
Ar 95
Kr 70
(Xe 39)
(Au 18)

beam E meas.
Si detector (E)
Ion chamber (Range)

beam Flux meas.
Plastic Scinti. < 100 kcps
Ion chamber > 1 kcps



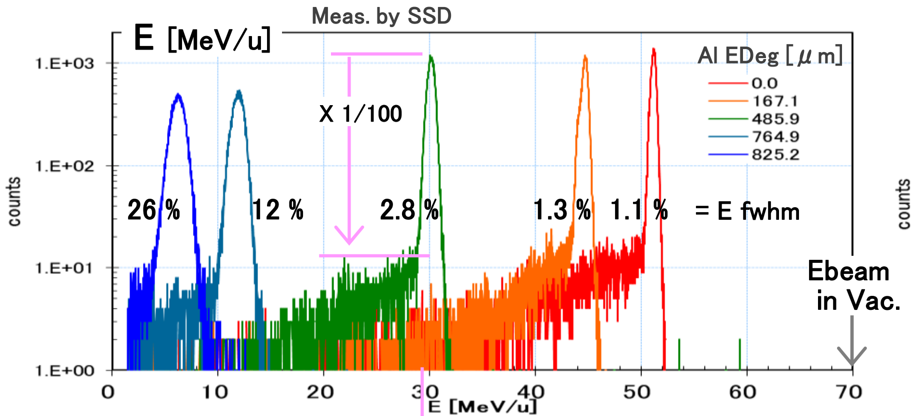
- Spread beam spot ϕ 5cm with flat distribution
- Irradiate in atmosphere
- Beam Flux 10 ^ (1～5) cps / cm^2
- LET adjustable
- Bragg-peak measurement determines beam energy

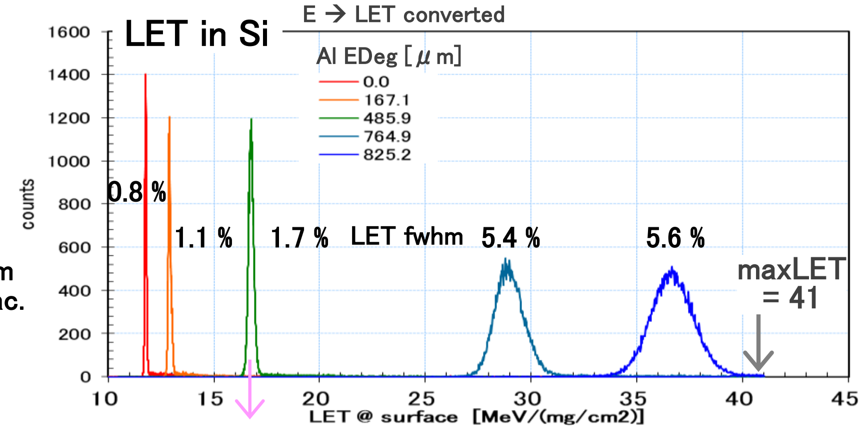
Beam time record

2014	Kr (43hr)	
2015	Kr (32hr)	Ar (20hr)
2016	Kr (120hr)	Ar (30hr)
2017	Kr (80hr)	
2018	Kr (48hr)	Ar (20hr)

SEEs test : Beam impurity by nuclear reactions

84Kr 70MeV/u (in Vac.)

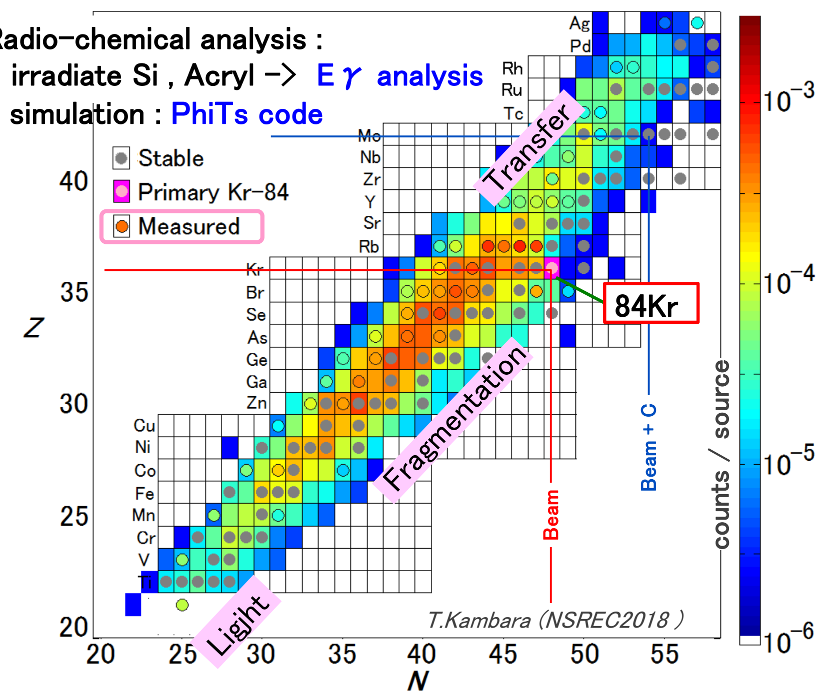


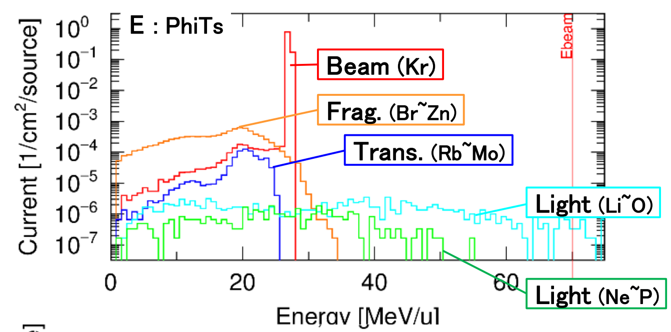


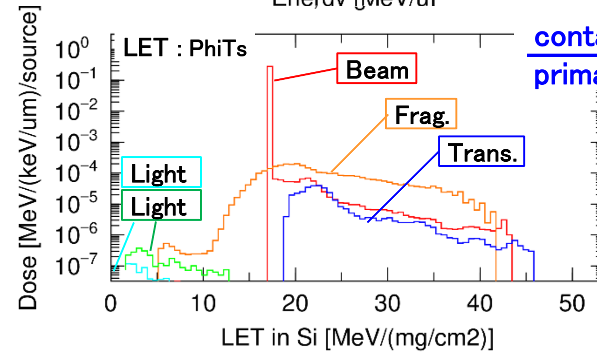
Nuclear Reactions: measured vs. simulation

Radio-chemical analysis :
irradiate Si , Acryl -> Eγ analysis
simulation : PhiTs code

EDeg = 586 μm (Al)







contaminants / primary beam ≲ 1 %

Summary

- Activation method for wear test using low-energy in-flight RIB separator
  - Intense RIB of 7Be, 22Na （~3x10^8, ~3x10^7 pps) are available.
  - Pulse-shaped depth-profile implantation is possible.
  - ➢ 2 trial use, a collaboration research with 2 companies. No new offer now …

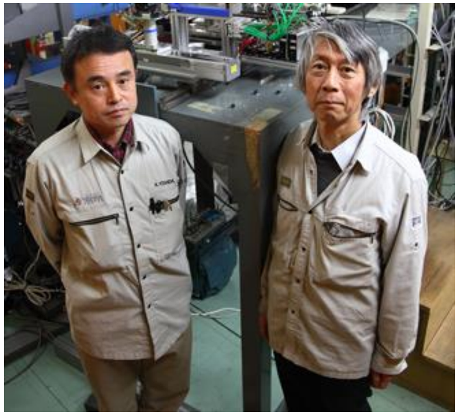
- γ-ray Inspection for Rotating Object (GIRO) system
  - Simple setup, less expensive, size scalability
  - Fundamental properties were investigated ; 3D-, SPECT-mode

➢ next) portable-size system using waveform digitizer.
try more practical demonstrations to develop value-added wear analysis.

- SEEs test of space-use semiconductors using stable HI-beams
  - Irradiation in atmosphere, contaminant nuclei $\lesssim$ 1%
  - Continuous users : 3 ~ 4 companies in Japan.

➢ Request) higher-LET test using Xe, Au

Thank you for your attention.



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http://ribf.riken.jp/sisetu-kyoyo/