SPES @ Ferrara, Italy, 30/01/2019

Compact Accelerator-driven Neutron Sources (CANSs) and their applications in Japan

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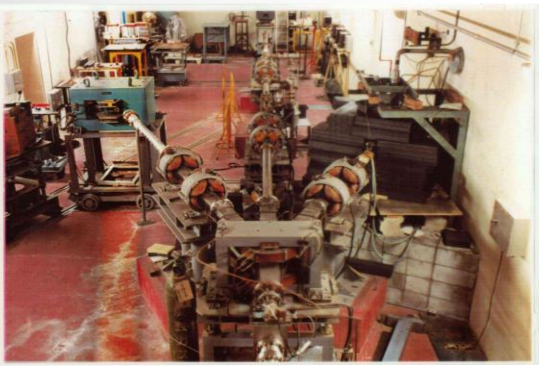
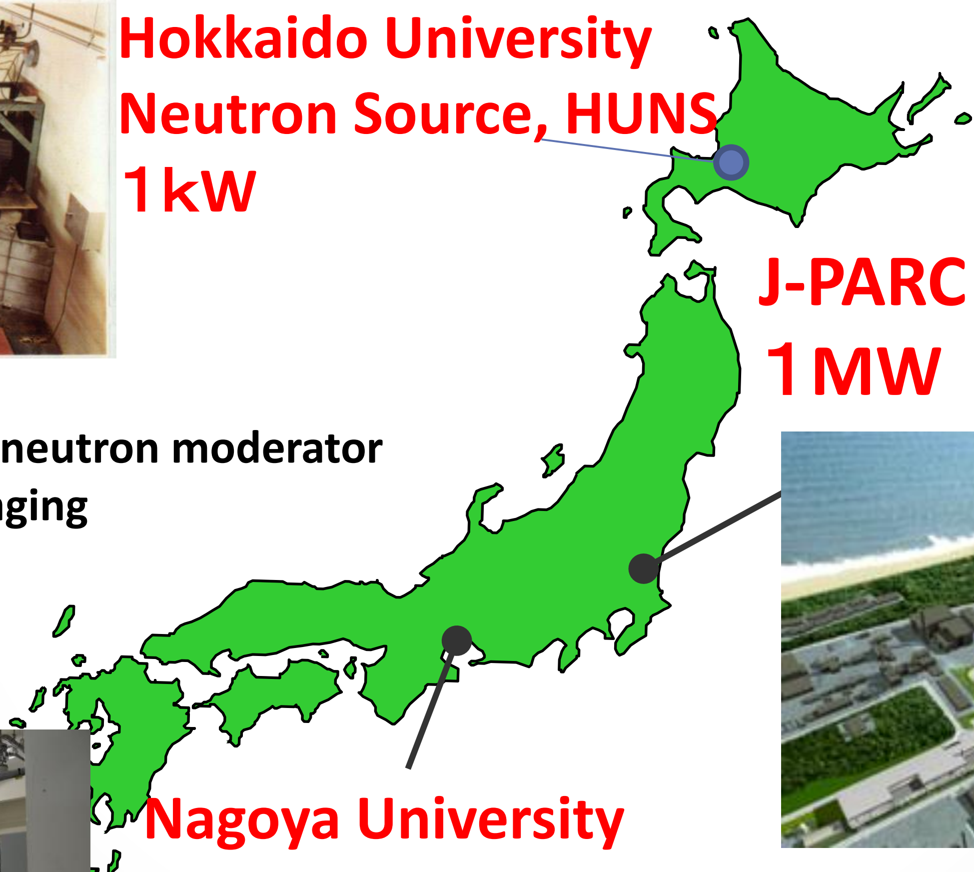
Designated Professor of Nagoya University, Japan
President of Japanese Society for Neutron Science

Honorary Professor of Hokkaido University
Honorary Professor of Xian Jiaotong University

Self-Introduction





Hokkaido University Neutron Source, HUNS
1kW

Most efficient cold neutron moderator
Pulsed neutron imaging
Soft error test

J-PARC（Tokai village）
1MW

J-PARC cold neutron moderator
Nuclear data beam line, ANNRI
Imaging beam line, RADEN

Nagoya University Neutron Source, NUANS
42kW

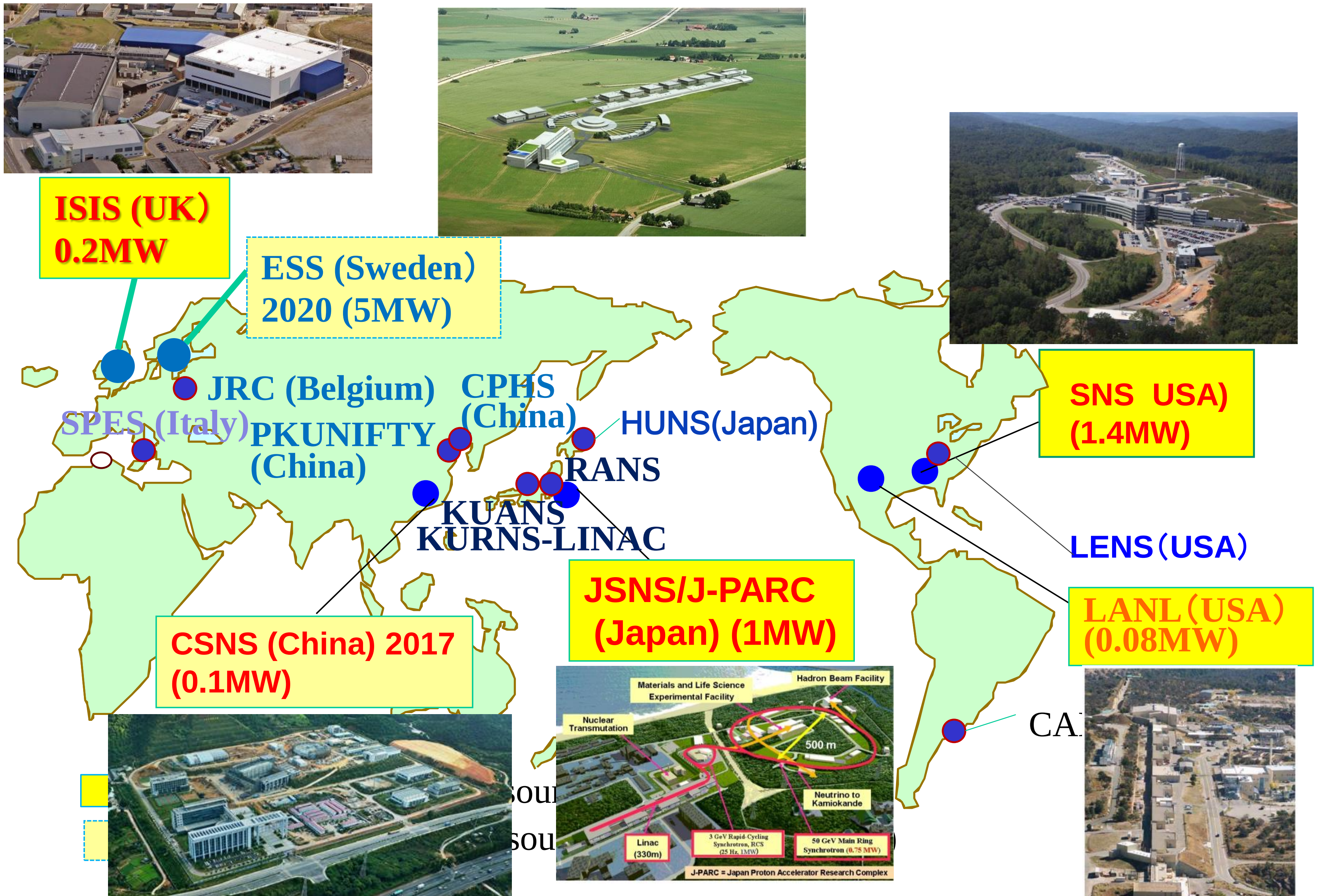
Engineering study of BNCT

Outline

Introduction of neutron applications at compact accelerator-driven neutron sources.

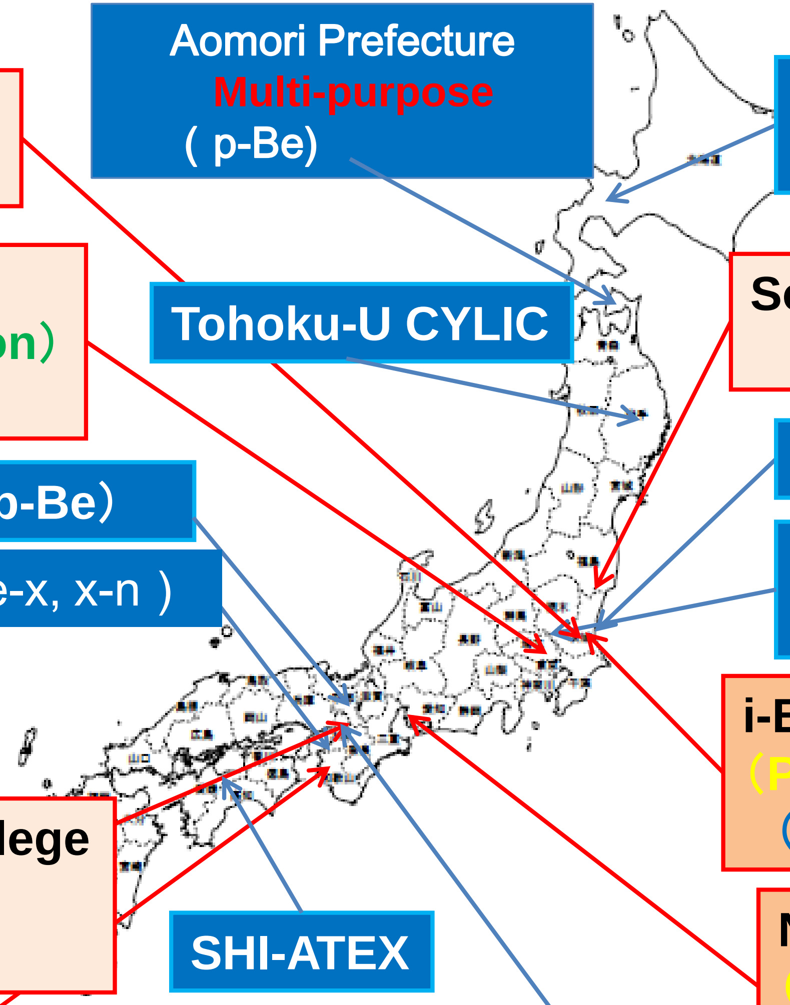
1. Accelerator-driven neutron sources in the world and Japan
2. Neutron scattering and imaging
3. Soft error acceleration test
4. Boron Neutron Capture Therapy
5. Summary

1. Accelerator driven neutron sources in the world



There are many small accelerator driven neutron sources for nuclear data measurement and imaging.

Accelerator-driven Neutron Sources in Japan



National Cancer Center
(Solid Li target)

Aomori Prefecture
Multi-purpose
(p-Be)

Hokkaido-U HUNS
(e-x, x-n)

Edogawa Hospital
(Under construction)
(Solid Li target)

Tohoku-U CYLIC

South Tohoku Hospital
(Be target)

Kyoto-U KUANS (p-Be)

KURNS-LINAC (e-x, x-n)

MLF/J-PARC

RIKEN RANS
(p-Be)

i-BNCT Multi-purpose
(Physical measurement)
(Be target)

Osaka Medical College
(commissioning)
(Be target)

SHI-ATEX

Nagoya-U Multi-purpose
(commissioning)
(Li target)

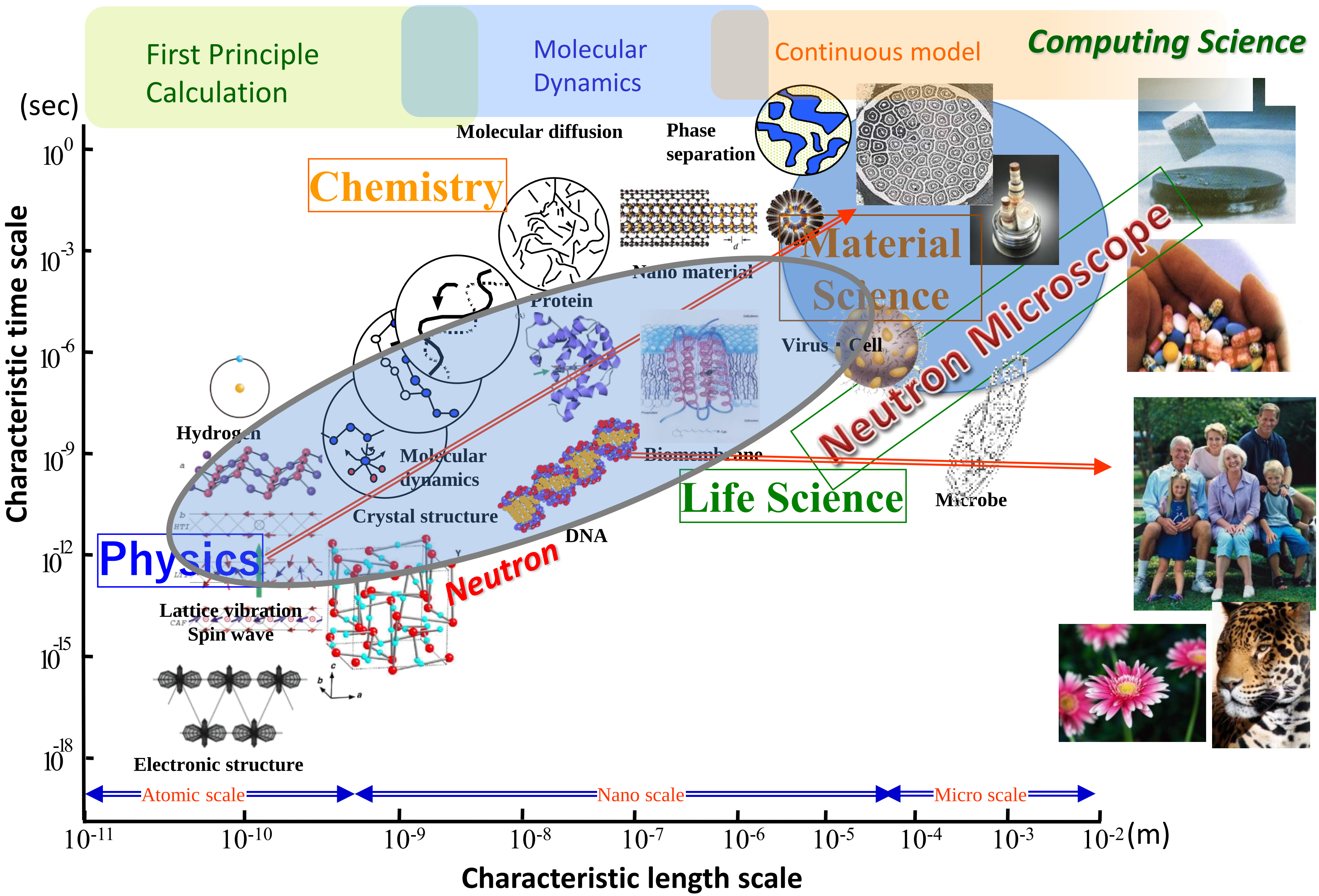
Kyoto-U
(Be target)

Osaka-U RCNP

BNCT: 7

Neutron Imaging, Scattering, etc.: 10

2. Neutron scattering and imaging



Layered Structure of Neutron Sources

Large — High resolution, High intensity, General research target, Long term, etc.

Medium — Medium resolution, Preliminary, Fundamental , Challengeable, Repetitive experiments, etc.

Compact — Low resolution, Easy access, Various samples, Challengeable, Trial or idea experiment, Flexible, Various experiments, Sustained education

A compact source (CANS) is nearer to users than a large facility geographically and also emotionally, which is useful to expand the number of users, and it can educate and train students and users.

It may open new area of applications.

The CANS can perform ‘Scattering experiments’, ‘Imaging’, ‘soft error’, ‘BNCT’ etc.

Neutron sources for beam experiments

HUNS(35MeV, 30μA)
10^3~10^4n/sec/cm^2 @7m
Cold-fast neutrons

Aomori Prefecture Quantum Science Center(20MeV, 50μA)
6.1X10^5n/sec/cm^2 Thermal

J-PARC (3GV, 333mA)
RADEN:
~10^8n/sec/cm^2

RANS(7MeV, 100μA)
~fewX10^4n/sec/cm^2 @5m
Thermal neutron

KUANS (3.5MeV, 100μA)
~5x10^2n/sec/cm^2
@5m@0.35kW
Thermal neutron

Nagoya

NUANS(2.8MeV,15mA)
~10^5n/sec/cm^2 Thermal

SHI-ATEX (18MeV, 20μA)
~2x10^5n/sec/cm^2
Thermal

KUR (Reactor): Thermal
E2: ~4x10^5n/sec/cm^2@5MW
B4: ~$10^{6\sim7}$n/sec/cm^2@5MW

KURNS-LINAC
(40MeV, 100mA)
~10^3n/sec/cm^2

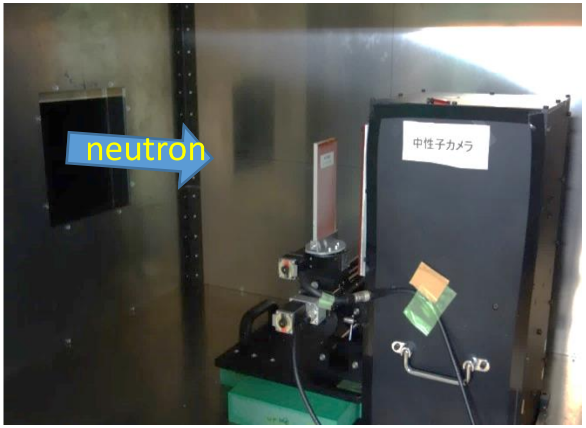
JRR-3 (Reactor) 2020
TNRF: ~10^8n/sec/cm^2
Thermal neutron
CNRF: ~10^7n/sec/cm^2
Cold neutron

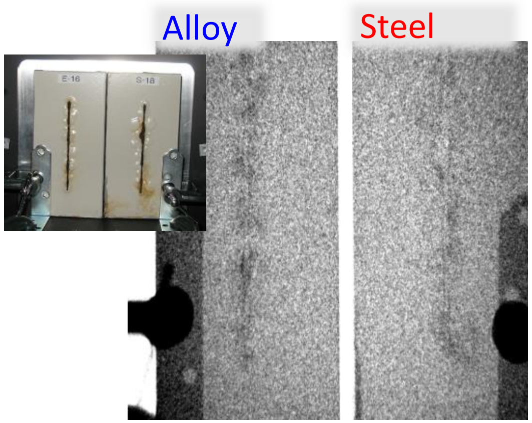
Fluxes at imaging lines

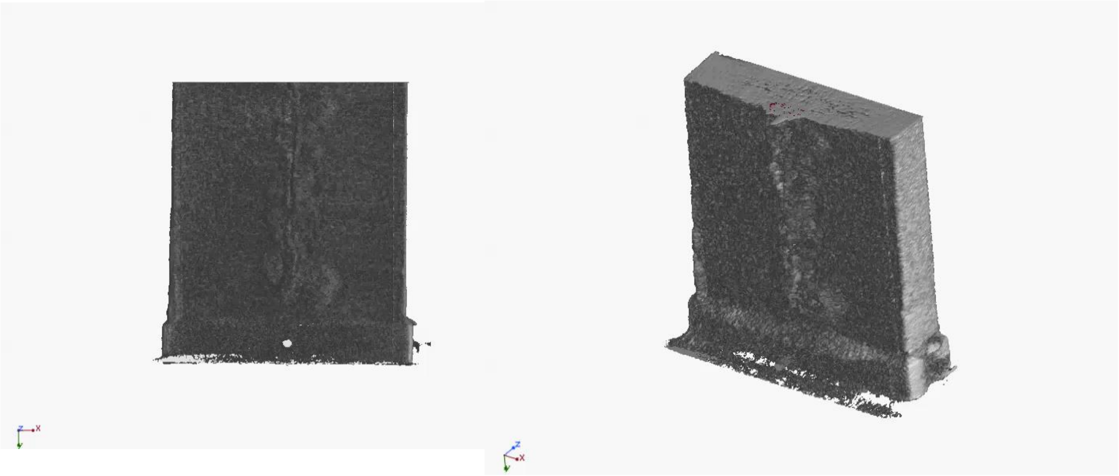
1) RANS (RIKEN Accelerator-driven compact neutron source)

compact neutron source for practical use

A) Imaging : Corrosion and water movement







CANS makes it possible to analyze quantitatively water content under paint of a steel and a special alloy, and it accelerates the research on antirust steels.

Courtesy of Dr. Yoshie Otake

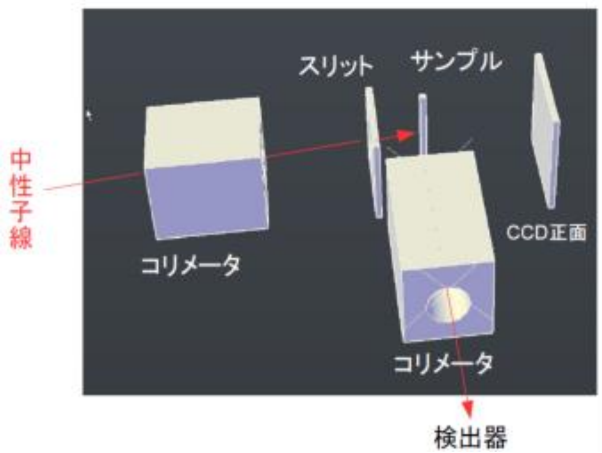
"Atsushi Taketani, et al：ISIJ International Vol. 57, No. 1 (2017)

B) Texture measurement by diffraction

Texture → Crystal plasticity theory → Mechanical characteristics of steel

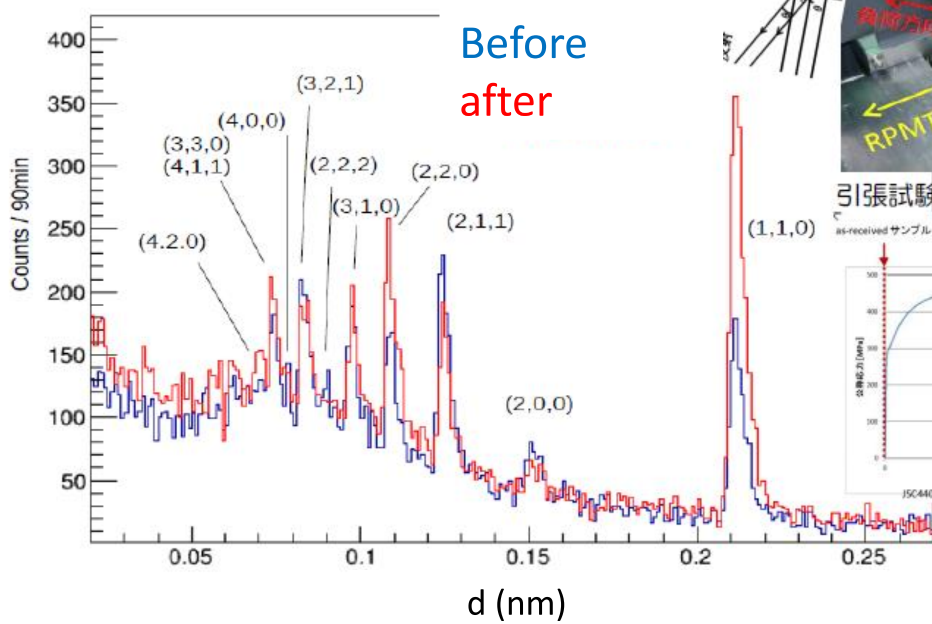
Dr.H.Suzuki(JAEA),
Dr.M.Kumagai (T.C.U)

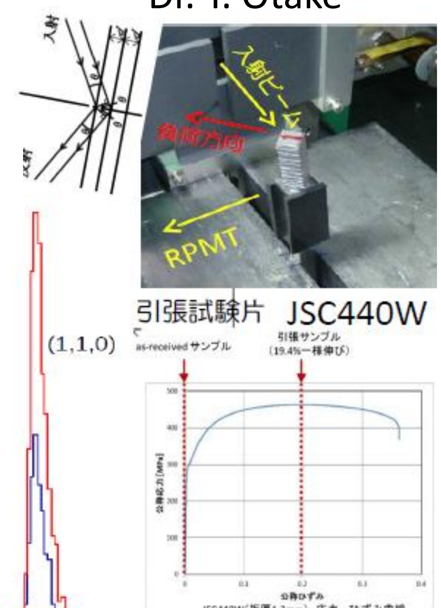
Dr.Y.Ikeda,
Dr.M.Takamura
Dr. Y. Otake



Experimental setup

Tensile test





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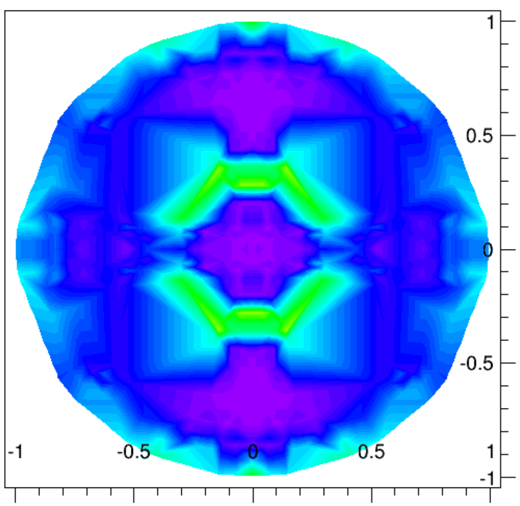


(110) Pole figure (IF steel)

Polar figure

Texture change was successfully observed.

2) HUNS (Hokkaido University Neutron Source)

A) Lab (SAXS) and Lab(SANS) complementary use

Scattering intensity = $(\Delta\rho)^2$ x Number dens. x (Volume x Grain form factor)^2

Composition

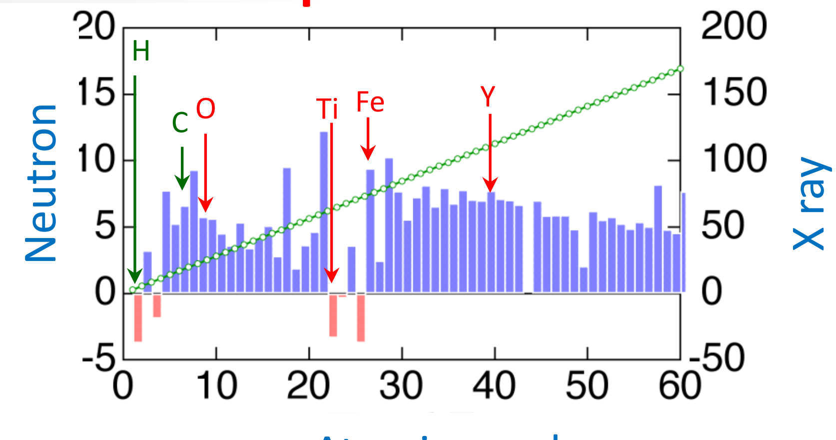
Intensity factor
Number density and composition will be separated

Common in X and N

N/X cancel out material structure parameter

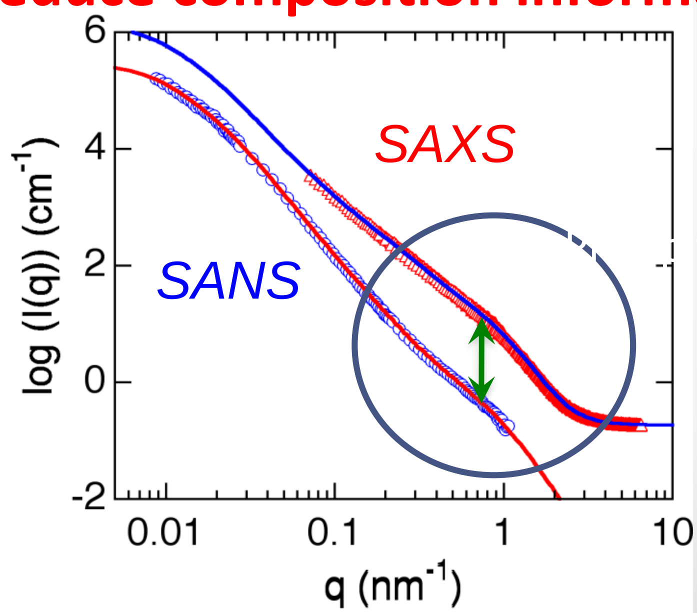
$$\Delta\rho = \rho - \rho_{\text{matrix}} \qquad r = \sum_i n^a c_i^a b_i$$

Different between X and N in the same composition case



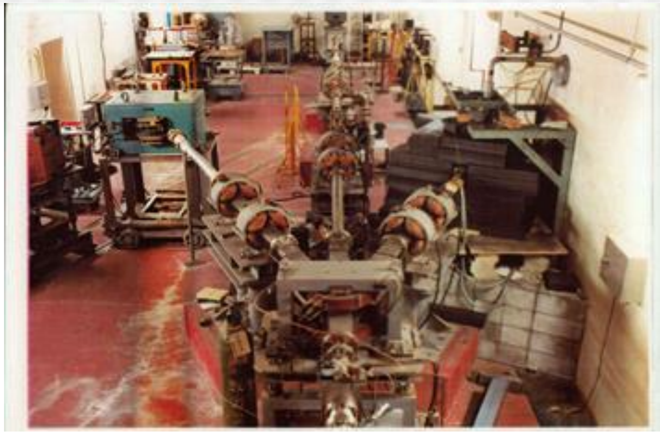
Scattering length (fm)

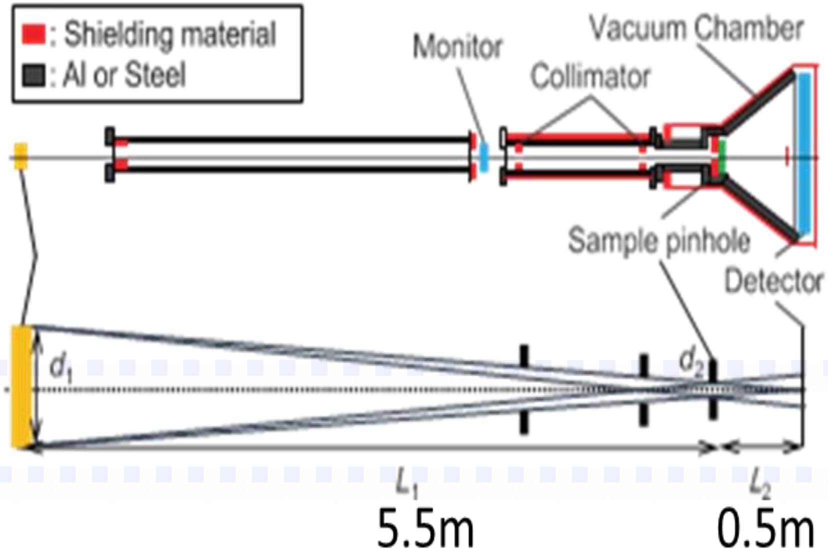
Deduce composition information



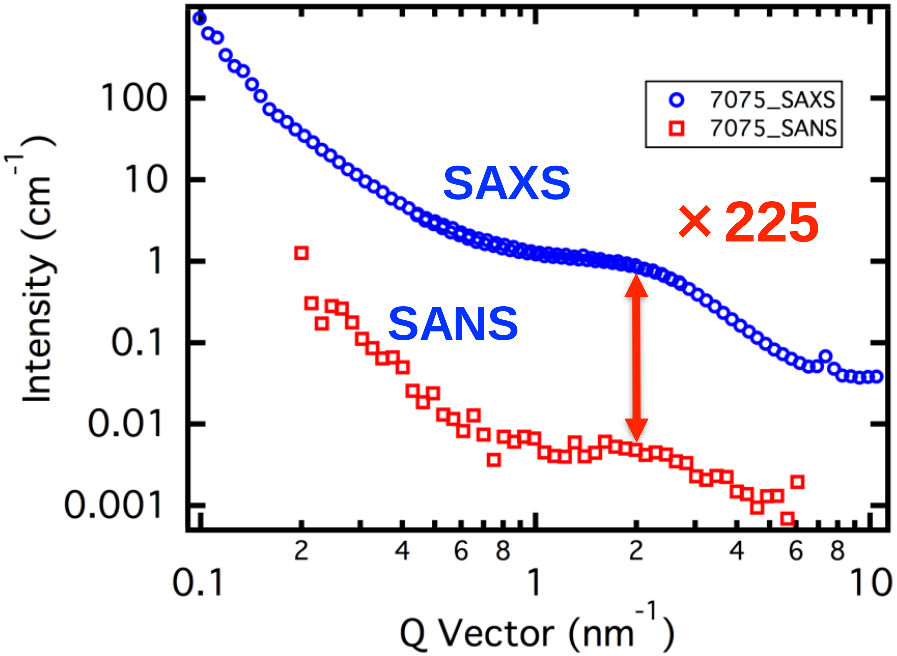
Relatively high q region is useful.

iANS, intermediate-angle neutron scattering instrument





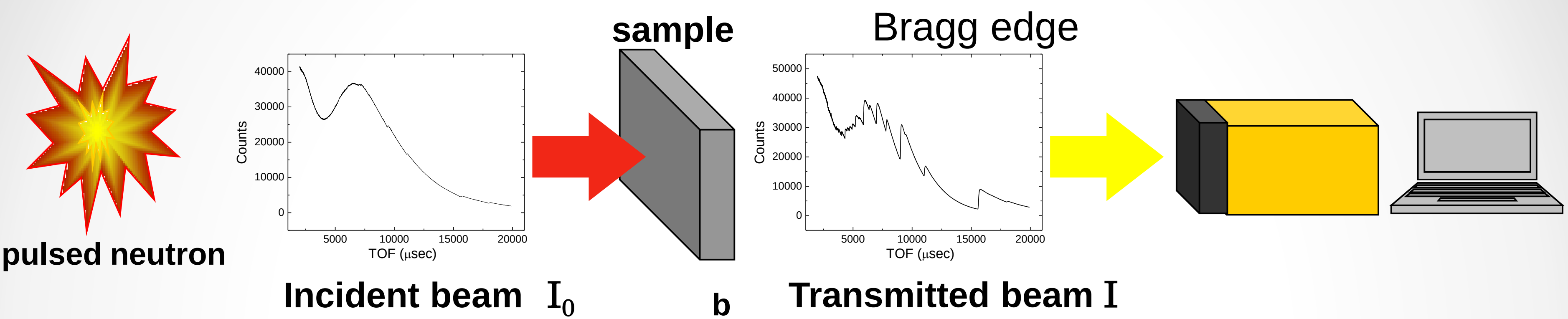
Al alloys：7000 series



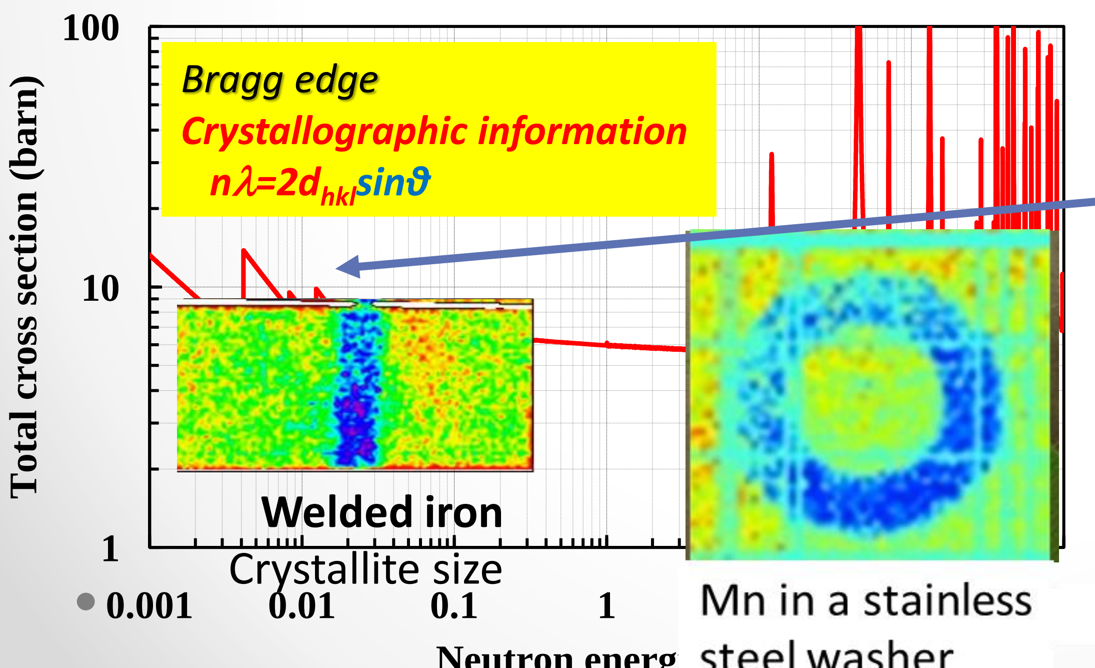
Precipitates are TiCMgZn$_2$: 230

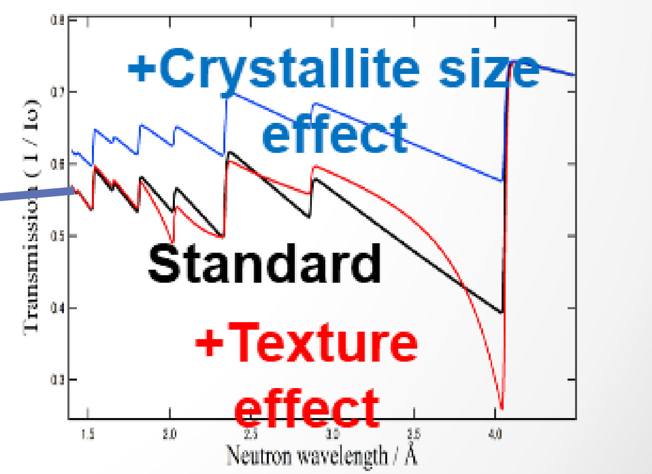
T. ISHIDA, M. OHNUMA, B. SEONG and M. FURUSAKA,ISIJ International, Vol. 57 (2017), No. 10, pp. 1831–1837

B) Pulsed neutron imaging



Bragg edge and resonance imaging

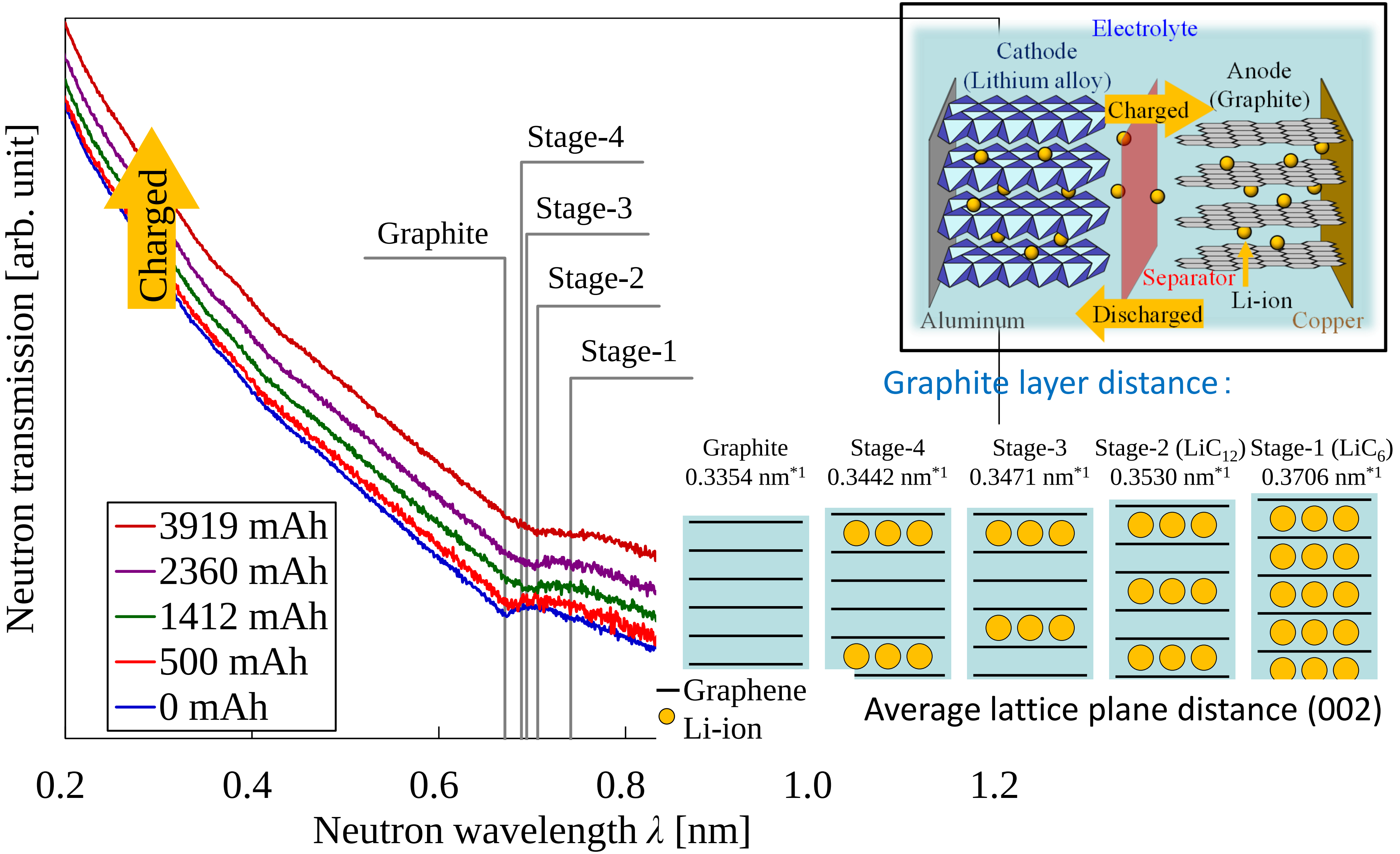




Transmission spectra

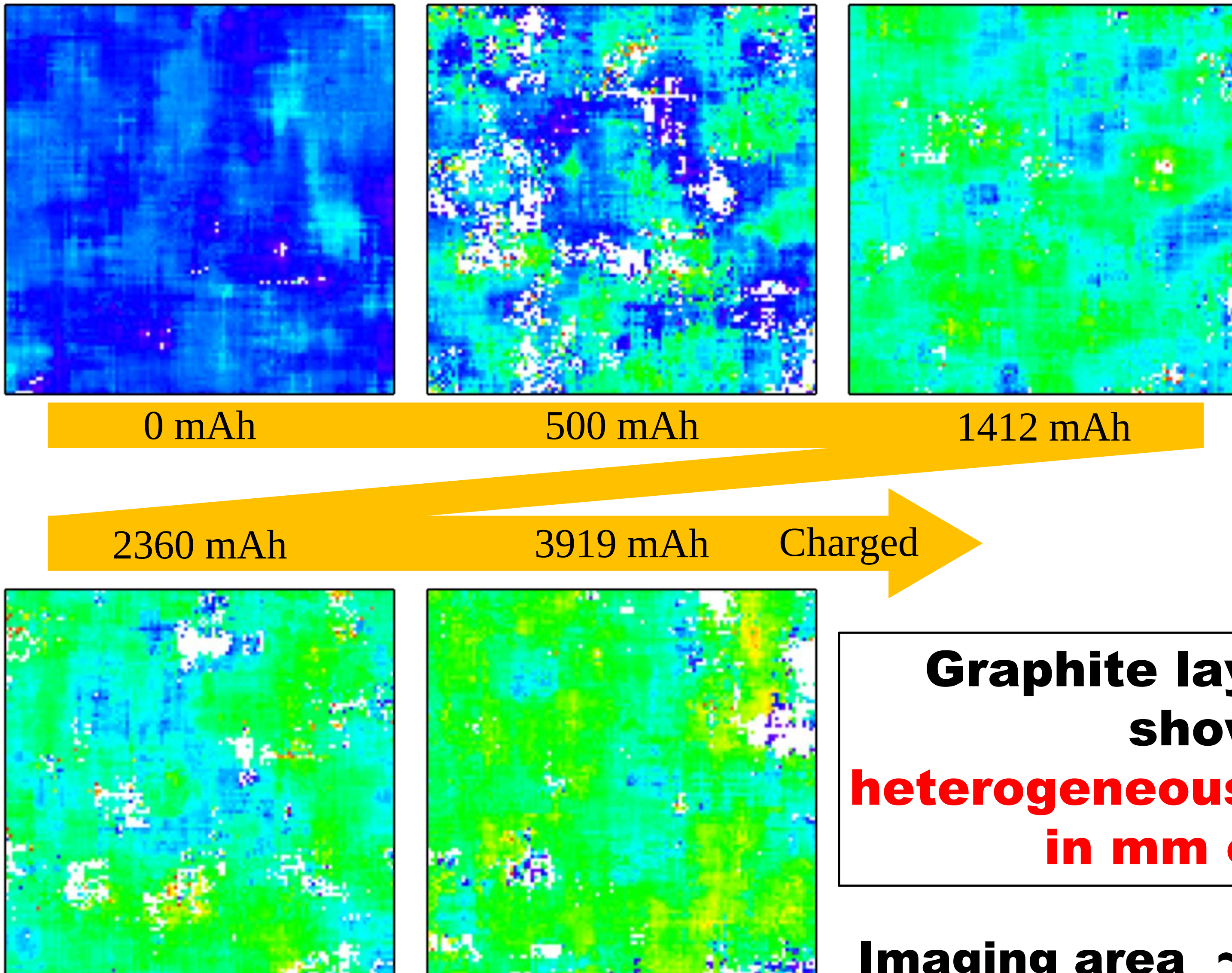
b) Spatial distribution of layer space in Li-ion battery

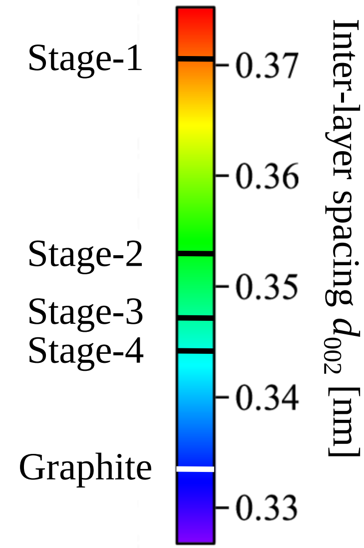
Bragg-edge spectra depending on charge level



T Kamiyama, Y Narita, H Sato, M Ohnuma, Y Kiyanagi, Physics Procedia 88 (2017) 27 – 33.

Inter-layer spacing distriution





Graphite layer space shows heterogeneous distribution in mm order.

Imaging area ~ 9 cm × 9 cm

d) Magnetic field distribution @J-PARC RADEN (Big Facility)

Electricity consumption of magnetic devices like motor is very large, about 50% of total consumption. 1% loss reduction saves a 1-million-kW power plant.

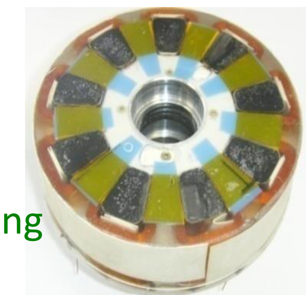
Motor manufacturing process

Raw material

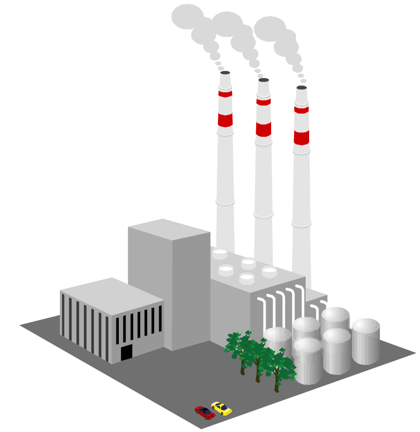
Processing

Motor core

Assembling



Motor stator



Loss is a max of ten times higher than an expectation value of design

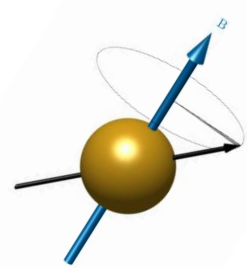
In order to reflect the real performance to the design,

it is necessary to use a method that can observe the magnetic field directly.

Neutron has spin magnetic moment

Neutron spin precesses in a magnetic field.

＝ Spin state change



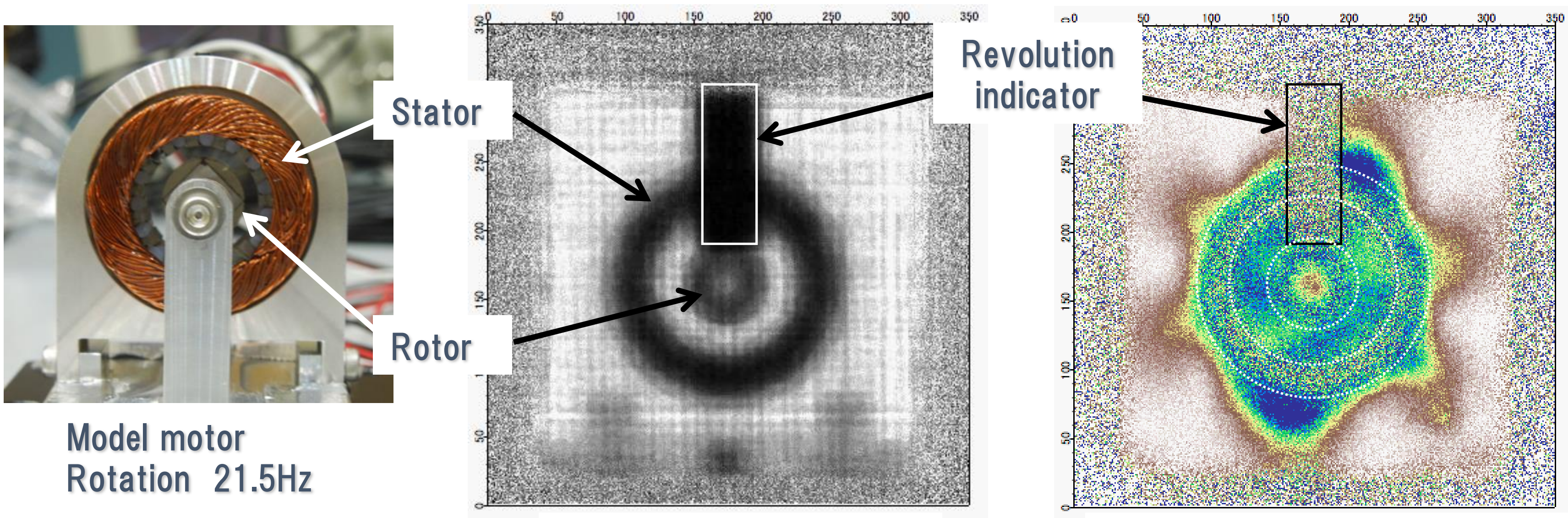
Magnetic field imaging using neutron high penetration power and magnetic interaction

⬇

Polarized neutron imaging for magnetic field obsevation

Magnetic field of a model motor

Direct comparison of a real field with a design field



Model motor
Rotation 21.5Hz

Neutron transmission image

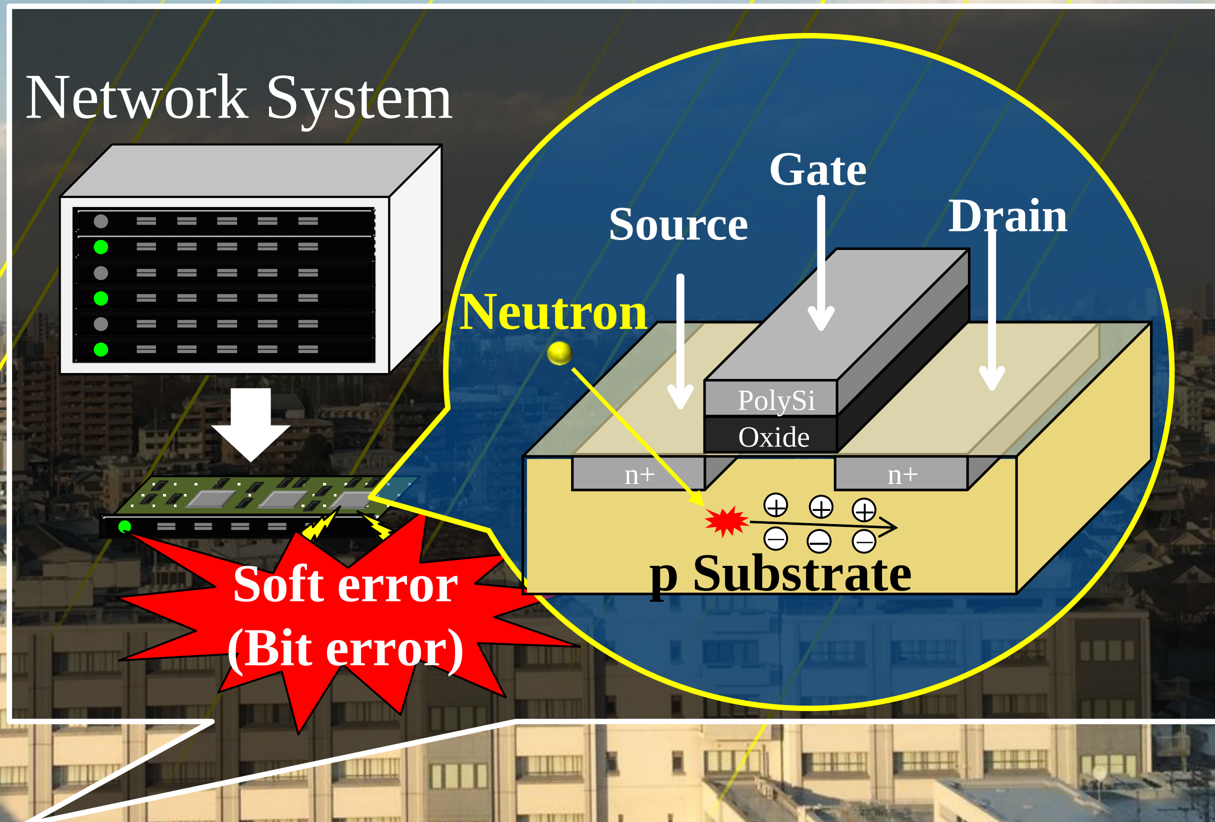
Neutron polarity image

3. Soft error acceleration test

NTT Network Service Systems Laboratories
*NTT (Nippon Telegraph and Telephone Corporation)
Hokkaido university
Nagoya University

Higher integration causes higher frequency of the soft error.

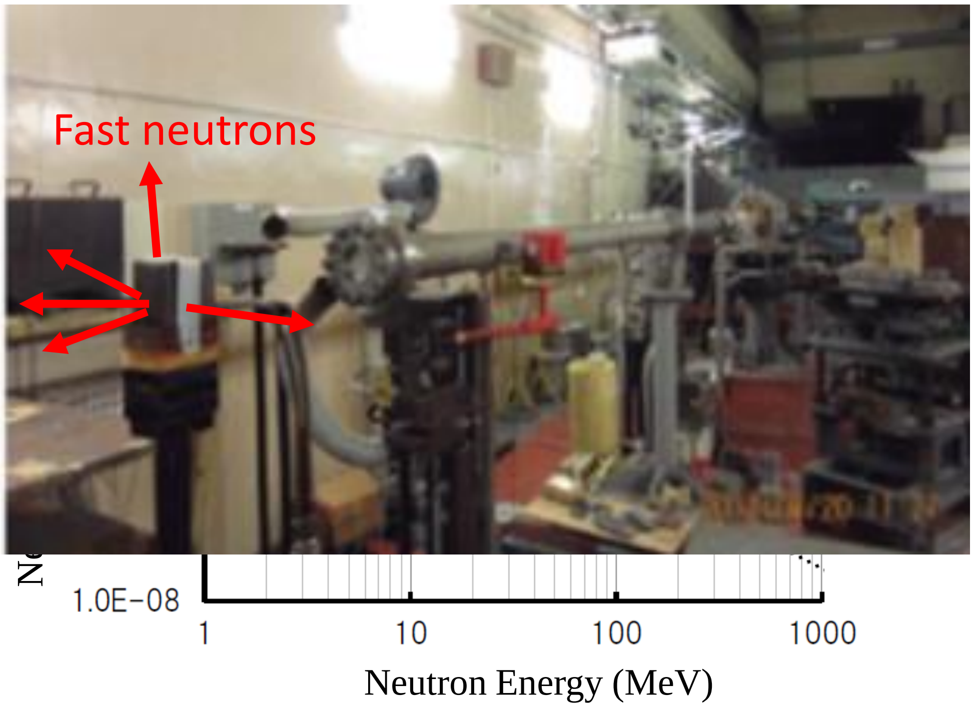
Neutrons



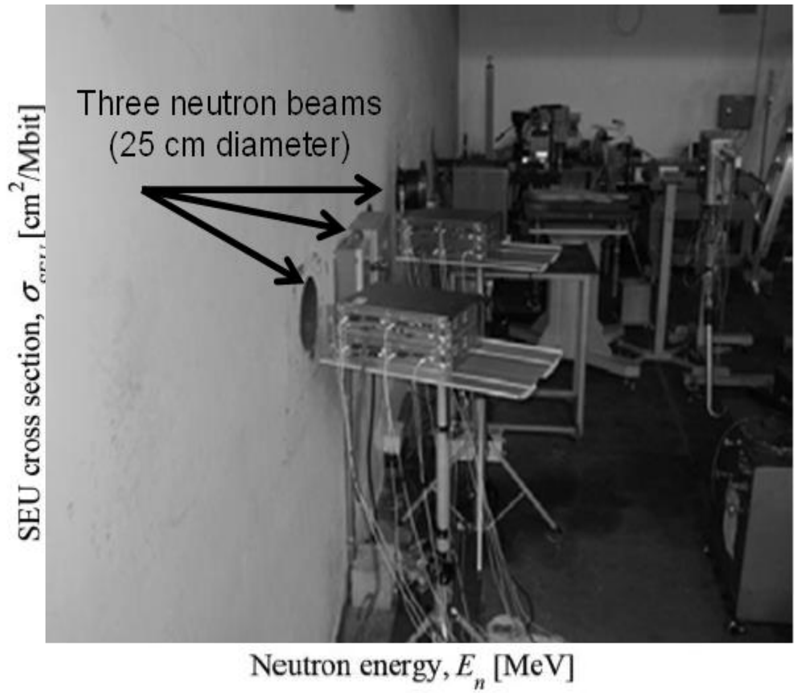
H. Iwashita, H. Sato, H. Arai, T. Kotanigawa, K. Kino, T. Kamiyama, F. Hiraga, K. Koda, M. Furusaka and Y. Kiyanagi, IEEE Transactions on Nuclear Science, Vol 64, pp.689-696, 2017.

Soft error test using HUNS

We designed the neutron source for the soft error test and made it.



Neutron Energy spectrum



SEU* cross section by neutron energy*

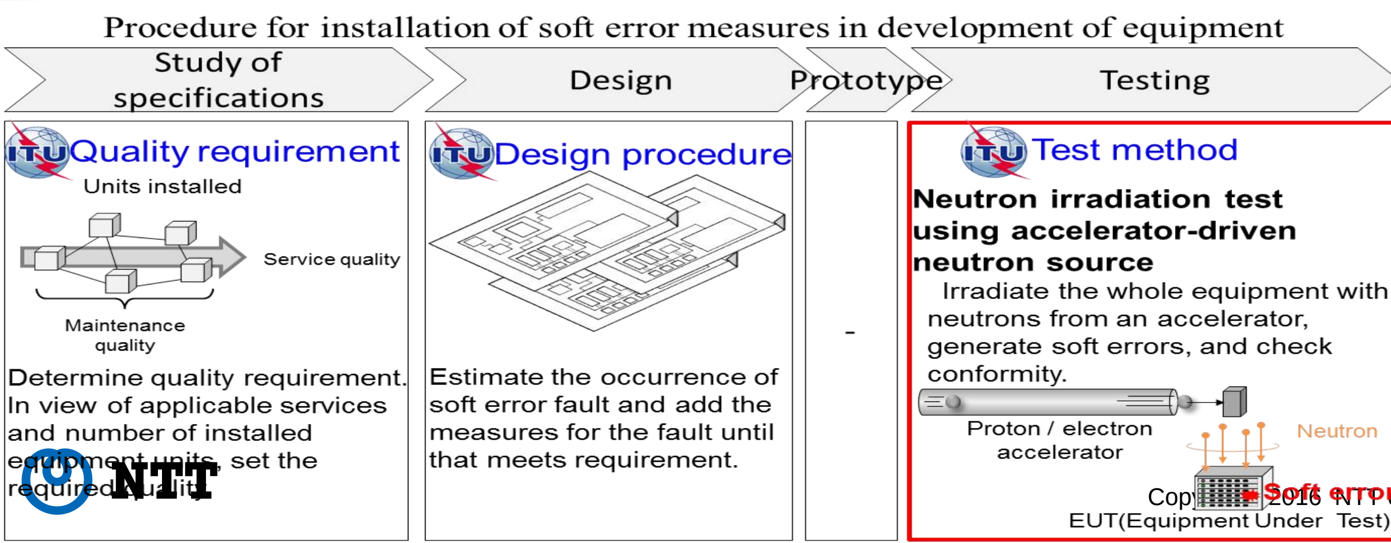
Soft errors occur in a few or ten minutes, and HUNS was proved to be effective.

*SEU (Single Event Upset)

NTT ※ : S.abe and Y.Watanabe, IEEE Transaction on Nuclear Science, 61, 3519-3526(2014)

Standardization for soft error test was completed at ITU according to proposals by NTT

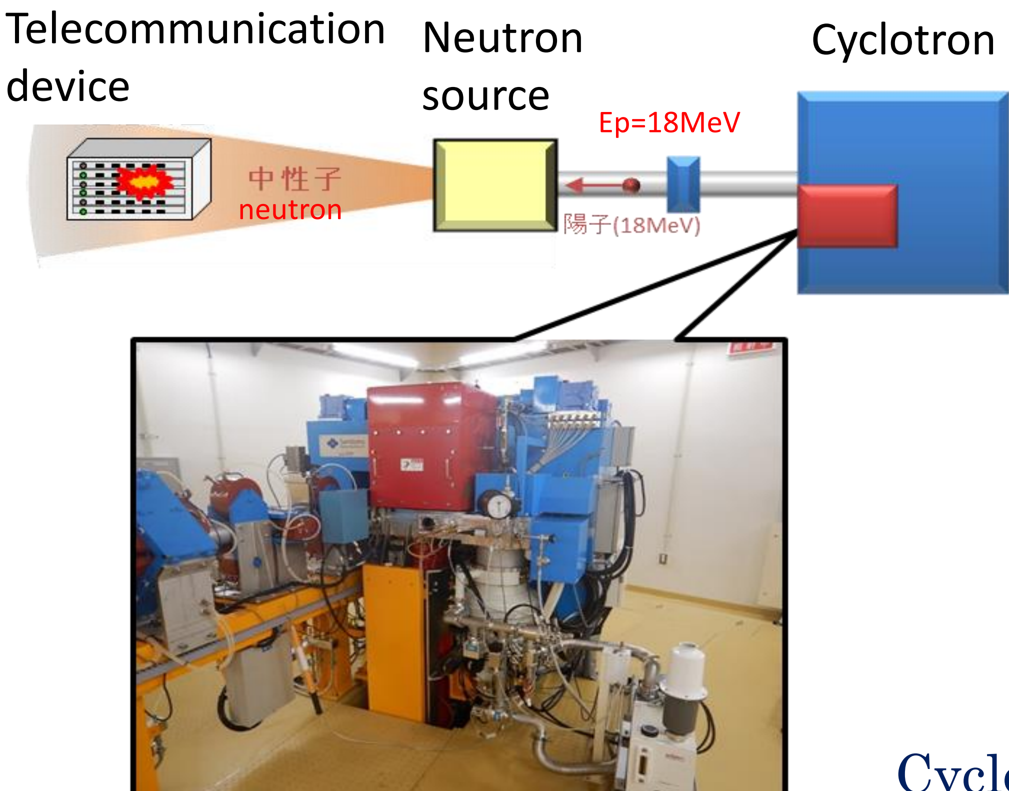
Recommendation	Title	Status
K.124	Overview of particle radiation effects on telecommunications systems	Approved in 2016
K.soft_des	Design methodologies for telecommunication systems applying soft error measures	Approved in 2017
K.soft_test	Soft error test method for telecommunication equipment	Approved in 2017
K.soft_mes	Quality estimation methods and application guidelines for mitigation measures based on particle radiation tests	Approved in 2018



ITU: United Nations specialized agency for information and communication technologies – ICTs.

Commercial service of acceleration test of the soft error

New step for industrial application



Proton energy : 18MeV
Max current: 20μA

From 19 Dec. 2016

NTT
Nagoya University
Hokkaido University
SHI-ATEX
*NTT Advance Technology
(Responsible for the tests)

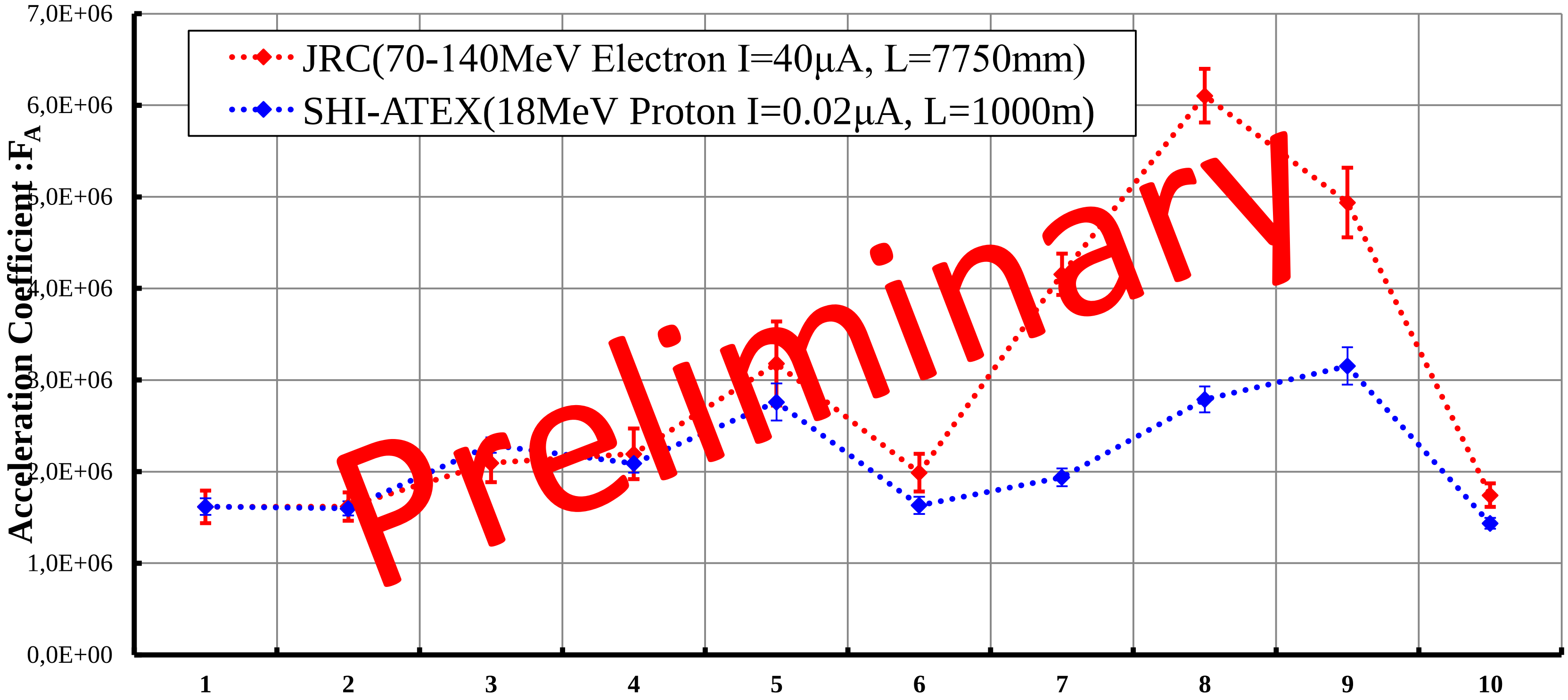
Cyclotron-driven neutron source at SHI-ATEX

Cf. Acceleration coefficient of compact neutron sources

We evaluated acceleration coefficients for various devices at different facilities.

Acceleration coefficient= (Soft error rate at CANS) / (Soft error rate in natural condition)

Natural condition: Soft error rate at LANSCE



Various device types

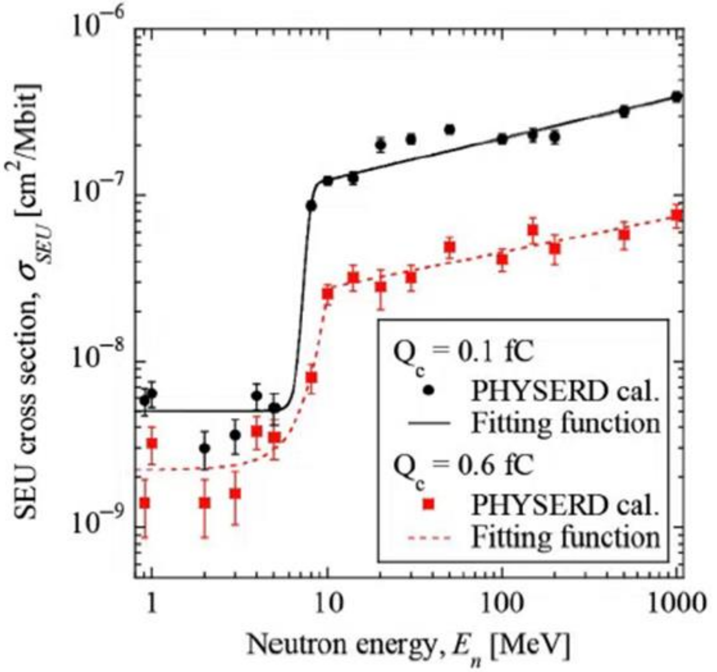
JRC measurements are proceeded by collaboration with JRC group and Dr. Mastinu et al. at LNL.

We need acceleration coefficients for future new devices.

SEU cross section is **necessary** to evaluate the coefficient more effectively.

Main reactions contributed to SEU.

Reaction with Si	$E_{threshold}$
$^{28}Si + n \longrightarrow\ ^{28}Al + p$	3.999[MeV]
$^{28}Si + n \longrightarrow\ ^{25}Mg + \alpha$	2.749[MeV]
$^{29}Si + n \longrightarrow\ ^{29}Al + p$	3.009[MeV]
$^{29}Si + n \longrightarrow\ ^{26}Mg + \alpha$	0.035[MeV]
$^{30}Si + n \longrightarrow\ ^{30}Al + p$	8.040[MeV]
$^{30}Si + n \longrightarrow\ ^{27}Mg + \alpha$	4.341[MeV]

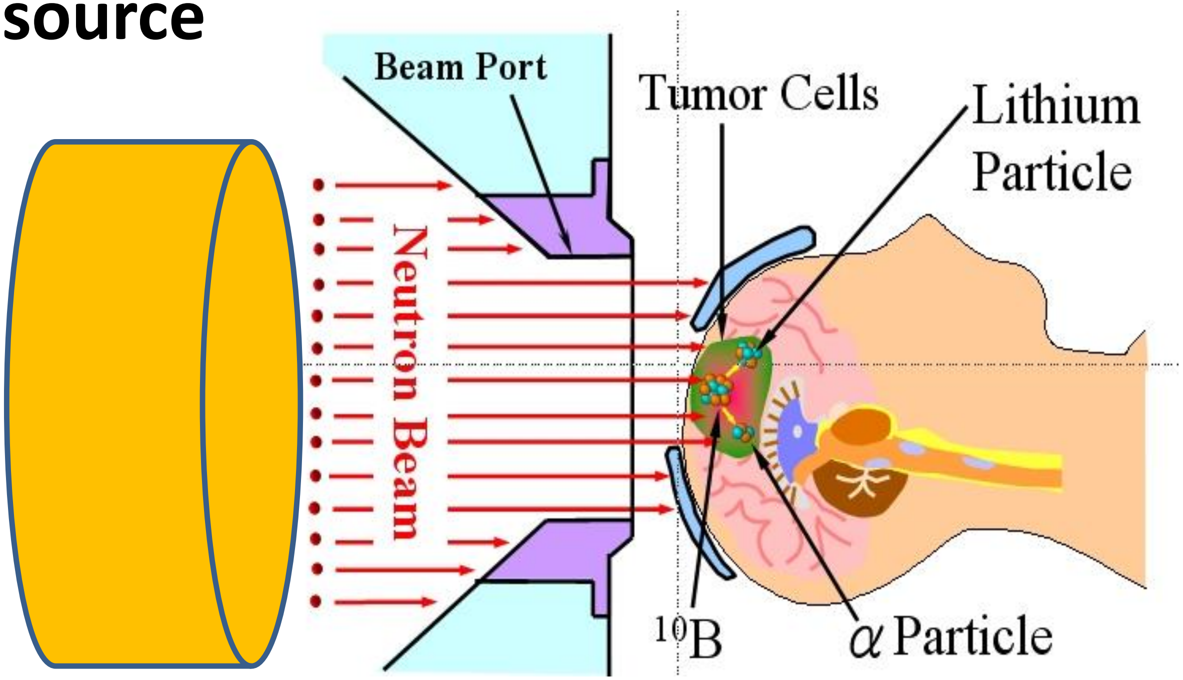


4. Boron Neutron Capture Therapy（BNCT)

Neutron source

Nuclear reactor

Accelerator based source

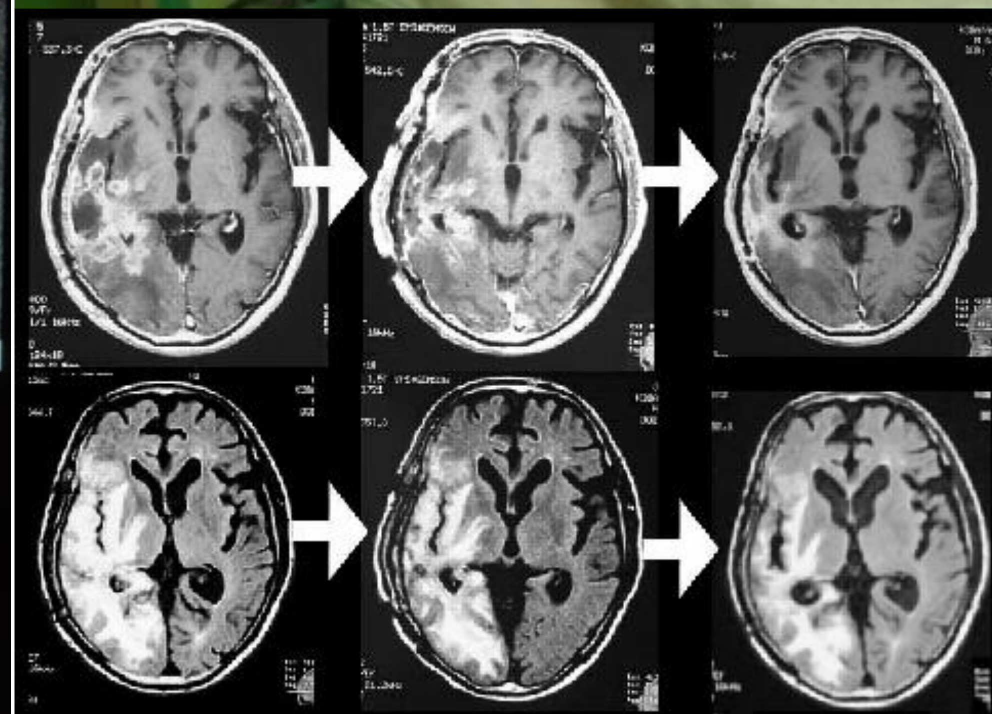


Boron drug is delivered mainly to cancer cells. Thermal neutron (~0.025eV) is absorbed by a boron nuclei and induces a nuclear reaction, $^{10}B(n, \alpha)^{7}Li$. α and Li kill the cancer cell. Cell selective treatment!

Treatment effect of BNCT

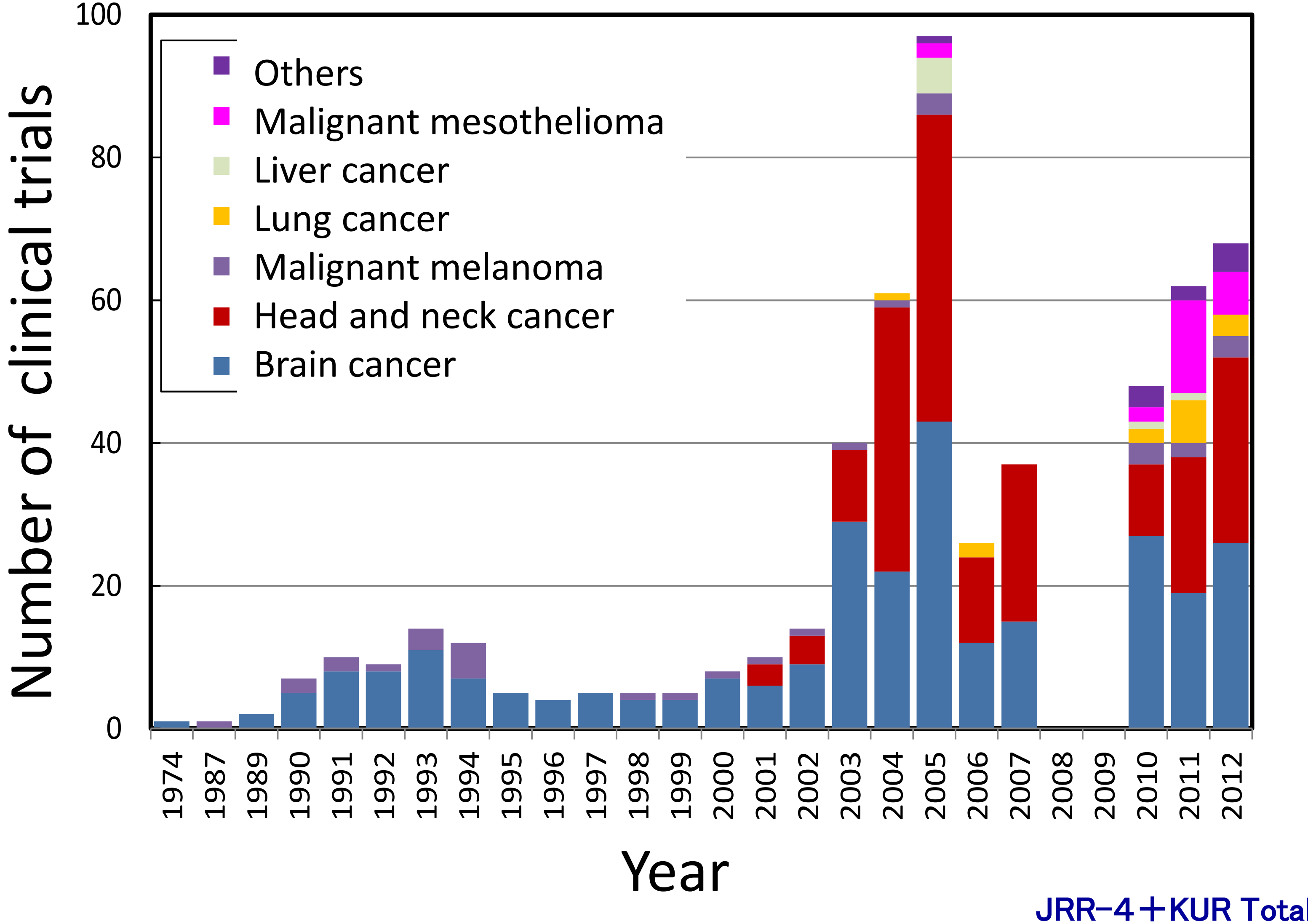
Malignant Melanoma

Glioblastoma (Brain cancer)

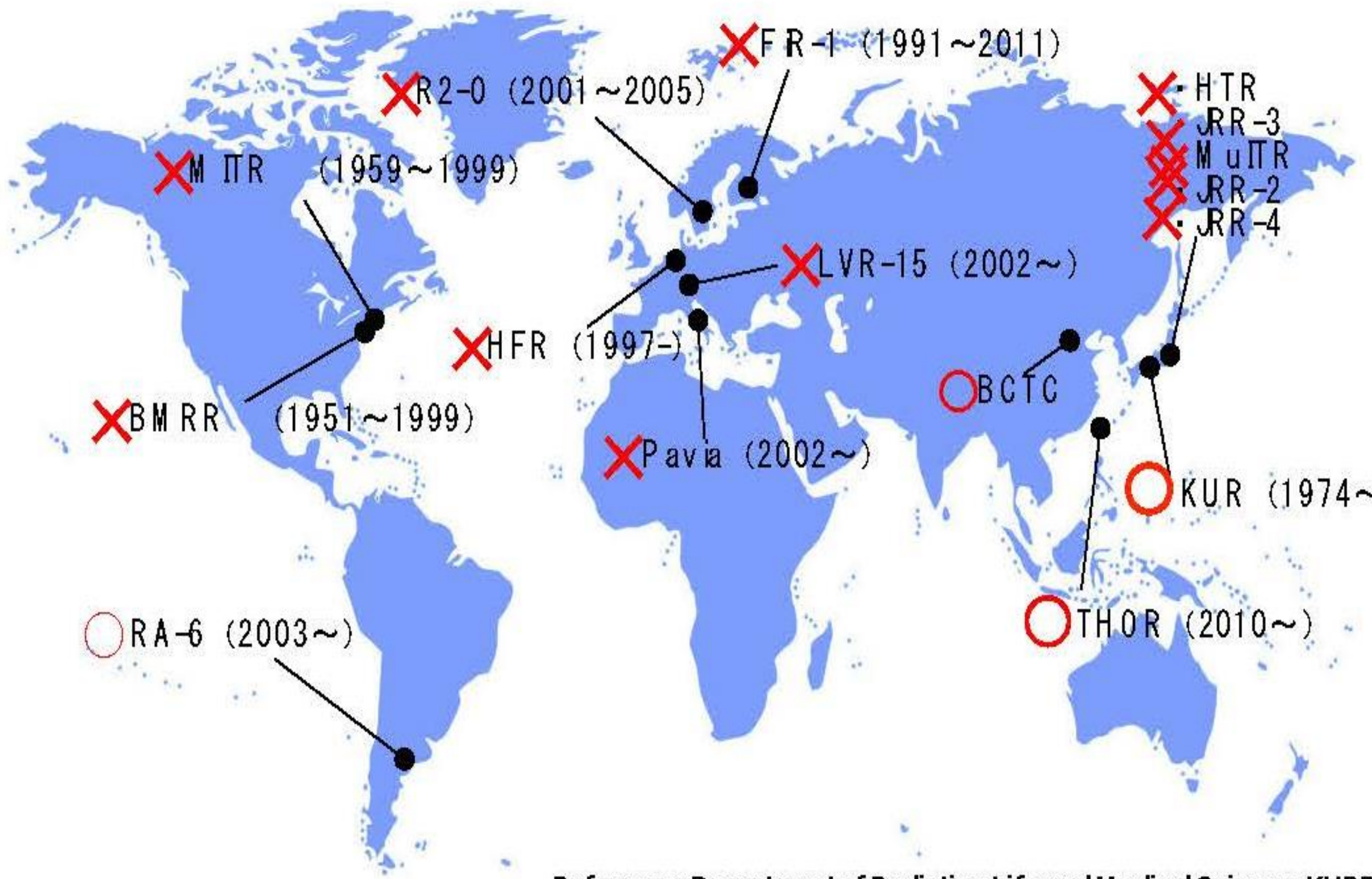


http://www.rri.kyoto-u.ac.jp/nct.html

Number of clinical trial and applicable diseases



Reactor BNCT facilities in the world



Reference: Department of Radiation Life and Medical Science, KURRI

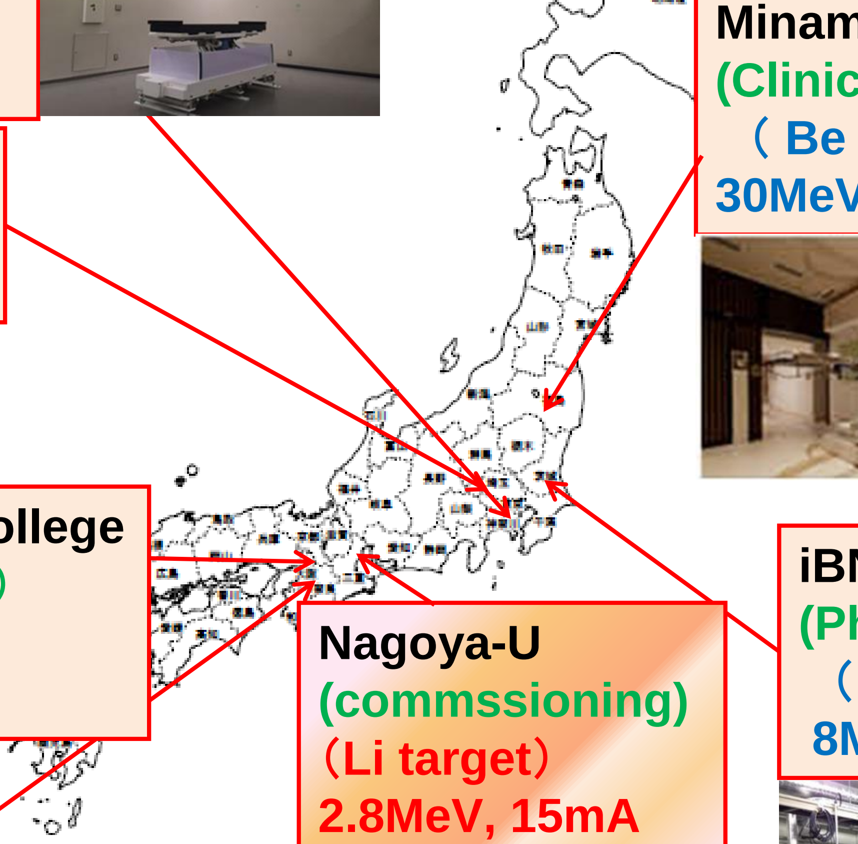
Based on the Report of BNCT screening working group in Japan

There have been many reactor facilities for BNCT, but many of them were already shutdown, and accelerator-driven neutron sources have been desired.

Accelerator based BNCT facilities in Japan

National Cancer Center
(Physical meas.)
（Solid Li target)
2.5MeV, 20mA

Edogawa hospital
（construction)
（ Solid Li target ）



Minami Tohoku Hospital
(Clinical trial)
（ Be target ）
30MeV, 1mA

Osaka Medical college
（commissioning)
（ Be target ）
30MeV, 1mA

Nagoya-U
(commssioning)
（Li target)
2.8MeV, 15mA

iBNCT
(Physical meas.)
（ Be target ）
8MeV, 5mA

Kyoto Univ.
（Clinical trial)
（Be target)
30MeV, 1mA

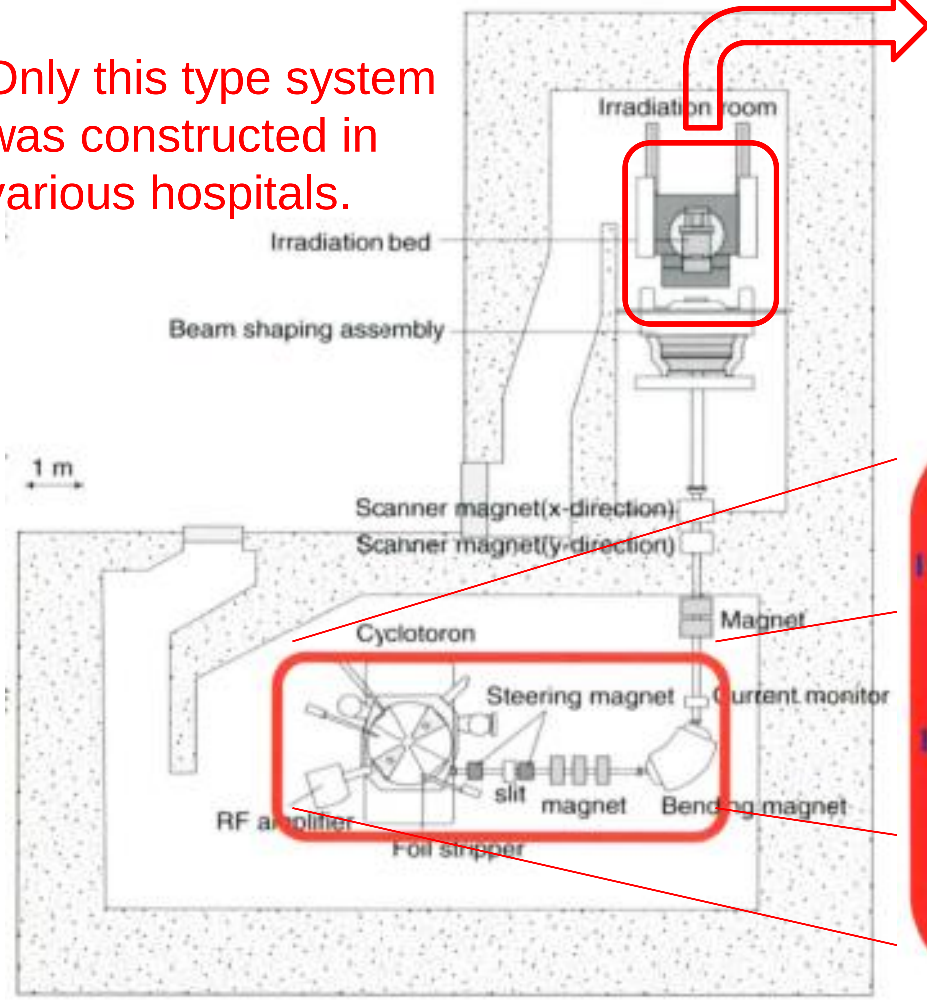
Kyoto Univ. (Cyclotron / Be BNCT)：CBENS

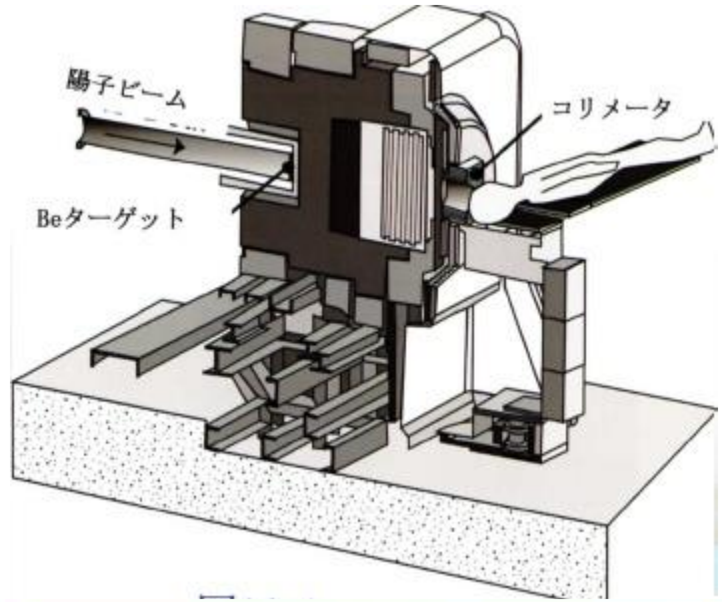
30MeV　1mA

・Heat removal is easy and blistering is avoided due to high energy

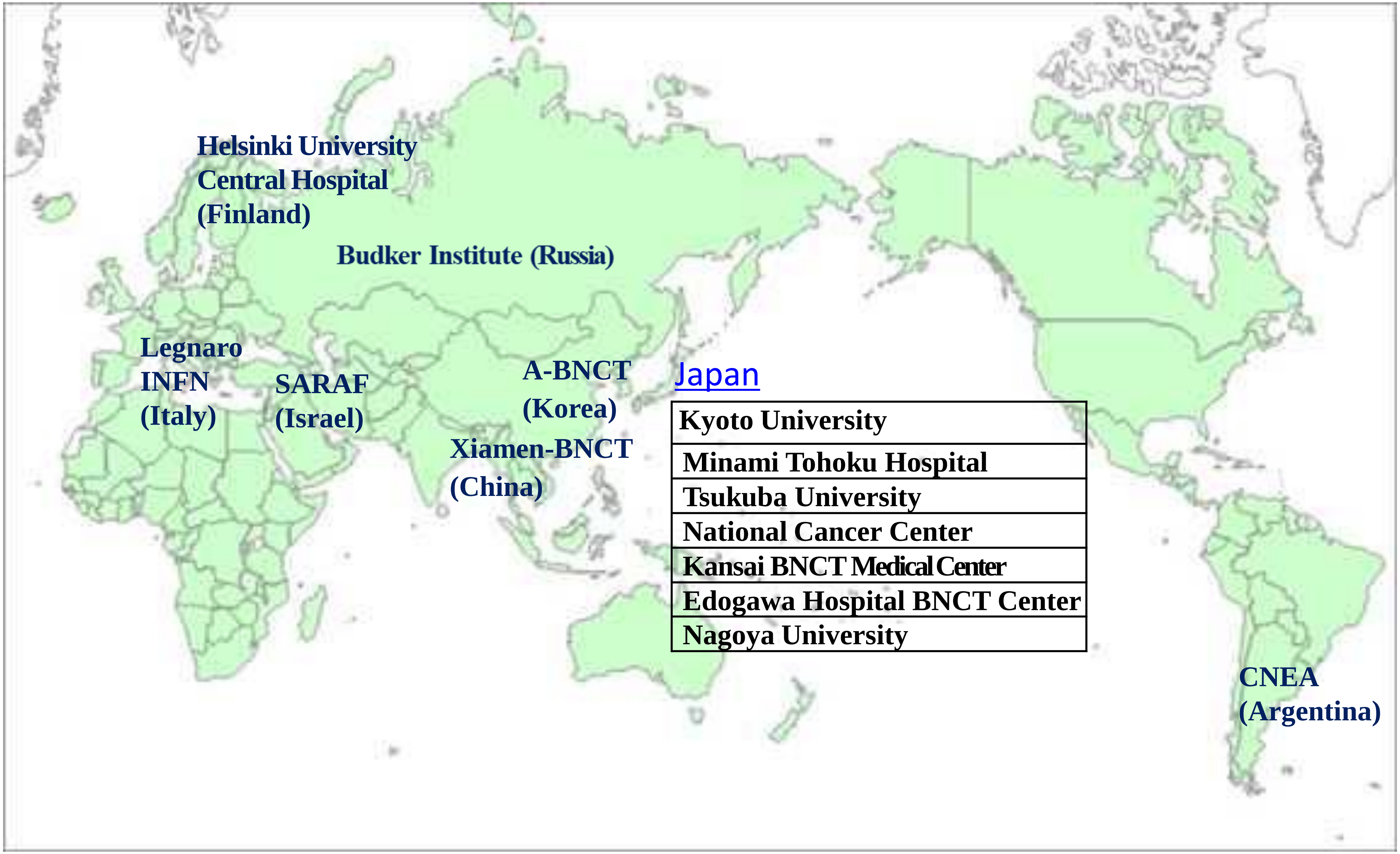
・Residual radioactivity is high.

Only this type system was constructed in various hospitals.





Accelerator based BNCT neutron sources in the world



List of accelerator based BNCT facilities in the world

Facility name	Accelerator	Target	Incident particle, Produced neutron energy (MeV)	Designed current (mA)	Present current status (mA)	Present status
Kyoto University	Cyclotron	Be	P: **30**, N: < 28	1	1	Clinical trial
Minami Tohoku Hospital	Cyclotron	Be	P: **30**, N: < 28	1	1	Clinical trial
Tsukuba University	Linac	Be	P: **8**, N: <6	5	<2	Physical meas.
National Cancer Center	Linac	Solid Li	P: **2.5**, N: < 1	20	12	Physical meas.
Kansai BNCT Medical Center	Cyclotron	Be	P: **30**, N: < 28	1	—	Commissioning
Edogawa Hospital BNCT Center	Linac	Solid Li	P: **2.5**, N: < 1	20	—	Commissioning
Nagoya University	Electrostatic	Solid Li	P: **2.8**, N: < 1	15	—	Commissioning
Budker Institute (Russia)	Electrostatic	Solid Li	P:**2.0**, N: < 1	10	3	Developing
Helsinki University Central Hospital (Finland)	Electrostatic	Solid Li	P:**2.6**, N: < 1	30	20	Constructing
SARAF (Israel)	Linac	Liq-Li	P<4, N: < 1	20 (?)	1-2	Developing
CNEA (Argentina)	Electrostatic	Be, ^{13}C	P, **d**: **1.4,** N: < 6	30	<1	Constructing
Legnaro INFN (Italy)	Linac	Be	P<4, N: < 2	30	—	Developing
A-BNCT(Korea)	Linac	Be	P:**10**, N:<8	8	—	Construction
Xiamen BNCT Center	Electrostatic	Solid Li	p:**2.5**, N:<1	10	—	Developing

Based on the Report of the BNCT screening working group in Japan

New BNCT projects have been proposed in the world and will be proposed furthermore.

5. Summary

CANS is useful.

(Experiments performed at CANS)

Neutron yield（n/sec）

KUR

JRR-3

10^{11}	10^{12}	10^{13}	10^{14}	10^{15}	10^{16}	10^{17}

KUANS

HUNS
RANS
KURNS-L

AIST

BNCT

Imaging
Device
Cross section
Scattering？

Imaging
Device
Pulse imaging
Diffraction
Medium& Small angle
Reflectometer
Prompt γ–ray analysis

Soft error

(CANS)

J-PARC

Imaging
Device
Pulse imaging
Diffraction
Medium& Small angle
Reflectometer
QES
Inelastic scattering
Prompt γ–ray analysis
Soft error

Thank you for your attention!