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Beijing, China

Review of Projects of Compact Neutron Sources in Japan

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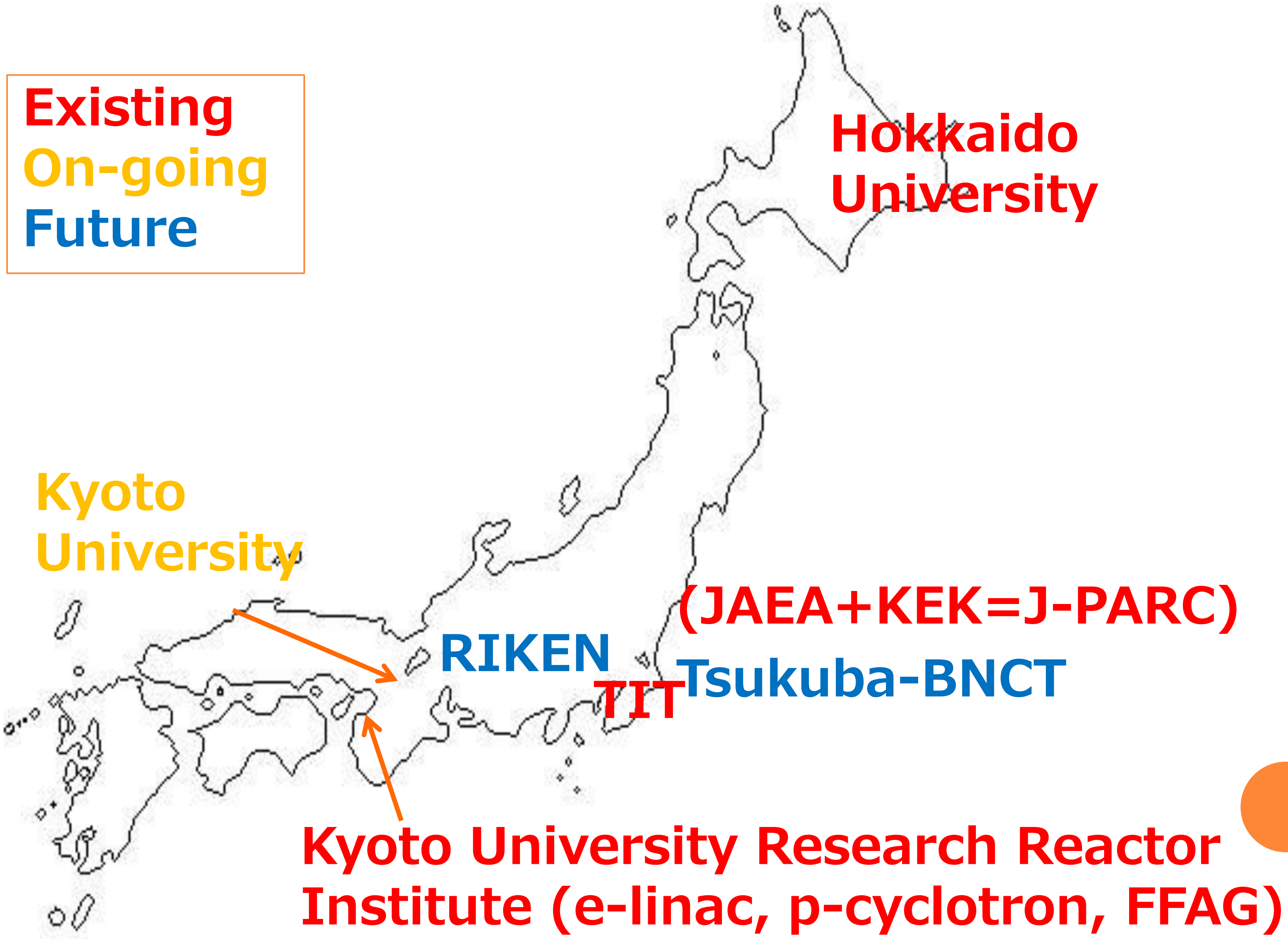
Usefulness of the compact neutron sources are being recognized gradually in Japan, since they are very useful for on-site-use and at-hand-use, which promote the exploratory research, the industrial use, education at the universities, and so on.

Here, *I briefly introduce the existing compact neutron sources, and on-going and future plans in Japan*, since the details will be presented by corresponding persons in this meeting

List of compact neutron sources in Japan

- Existing facilities
  Tokyo Institute of Technology:
  Pelletron for nuclear data
  Kyoto University Research Reactor Institute: By Dr. Mori
  e-Linac for nuclear data and so on
  Cyclotron for BNCT
  (FFAGs for nuclear reactor physics and BNCT)
  Hokkaido University
  e-Linac for neutron science and so on
- On going and future plans
  Kyoto University: By Dr. Iwashita
  p-Linac for neutron science
  KEK & Tsukuba U & Hokkaido U & JAEA: By myself
  p-Linac for BNCT
  RIKEN: By Dr. Yamagata & Dr. Hirota
  Accelerator-driven neutron sources for imaging

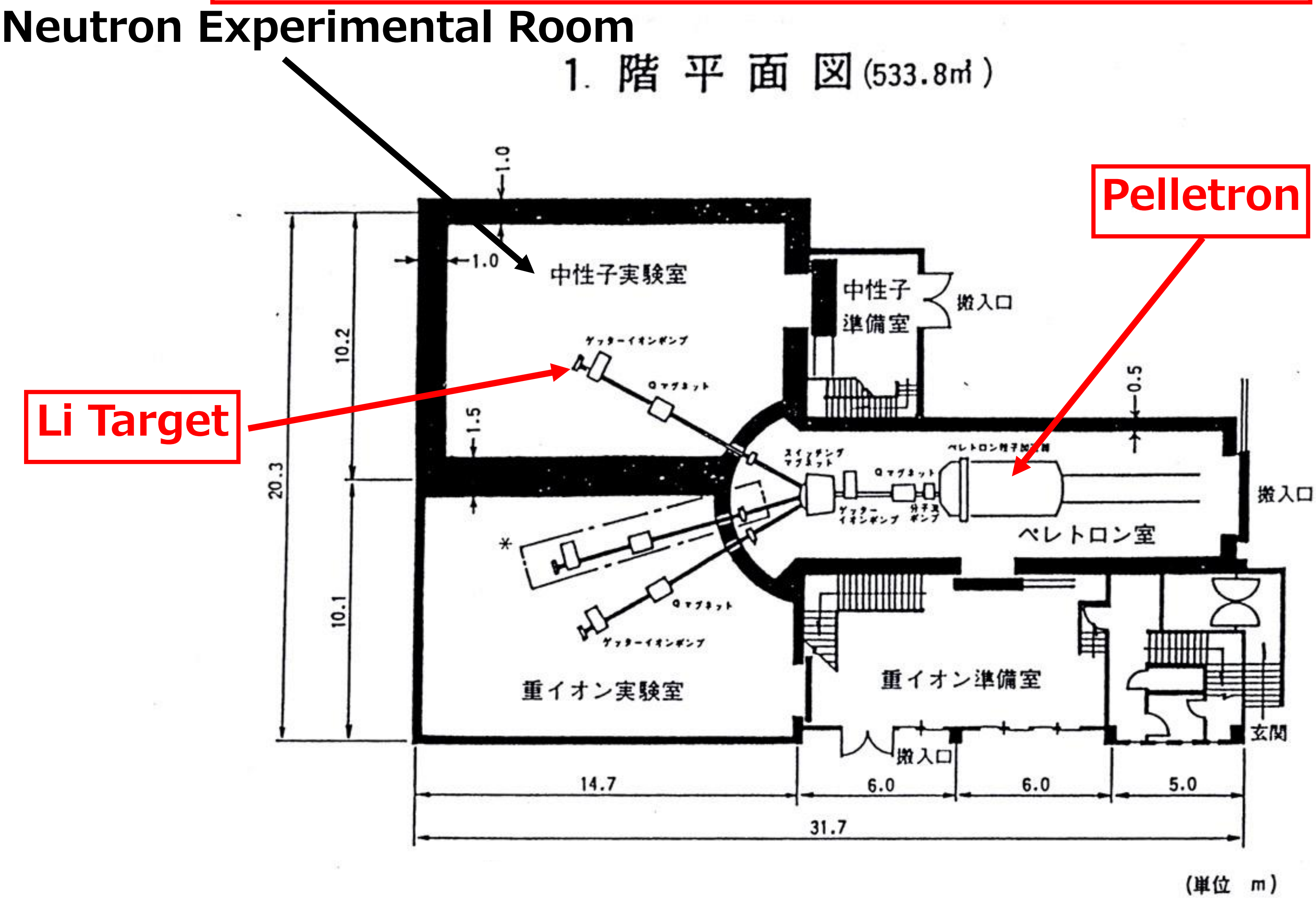
Sites of the compact neutron sources



$^{7}Li(p,n)^{7}Be$ Neutron Source at Tokyo Institute of Technology

By M. Igashira

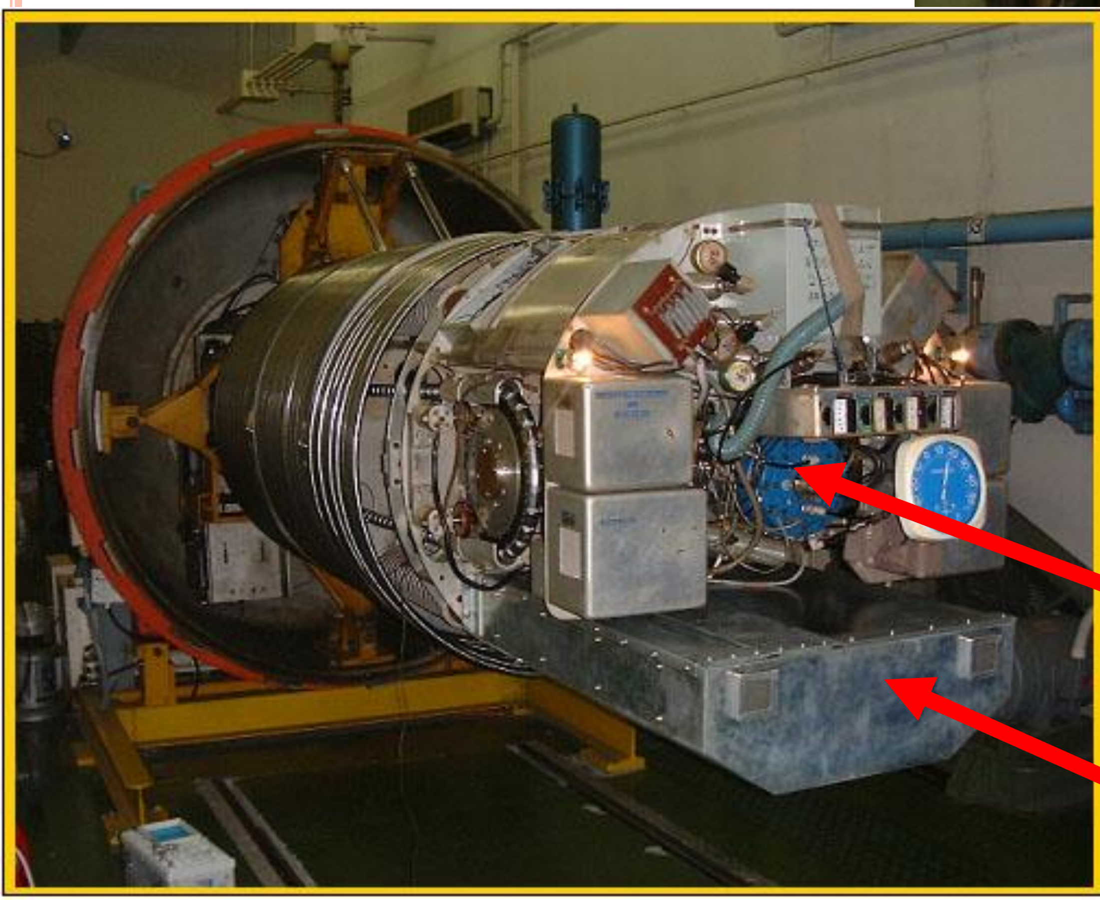
Pelletron Facility at Tokyo Institute of Technology



3U-HC Pelletron at Tokyo Tech

Beam Pulsing System at Terminal

Pulse Width: 1.5 ns (FWHM)
Peak Current: 2 mA
Repetition: 4, 2, 1, 0.5 MHz

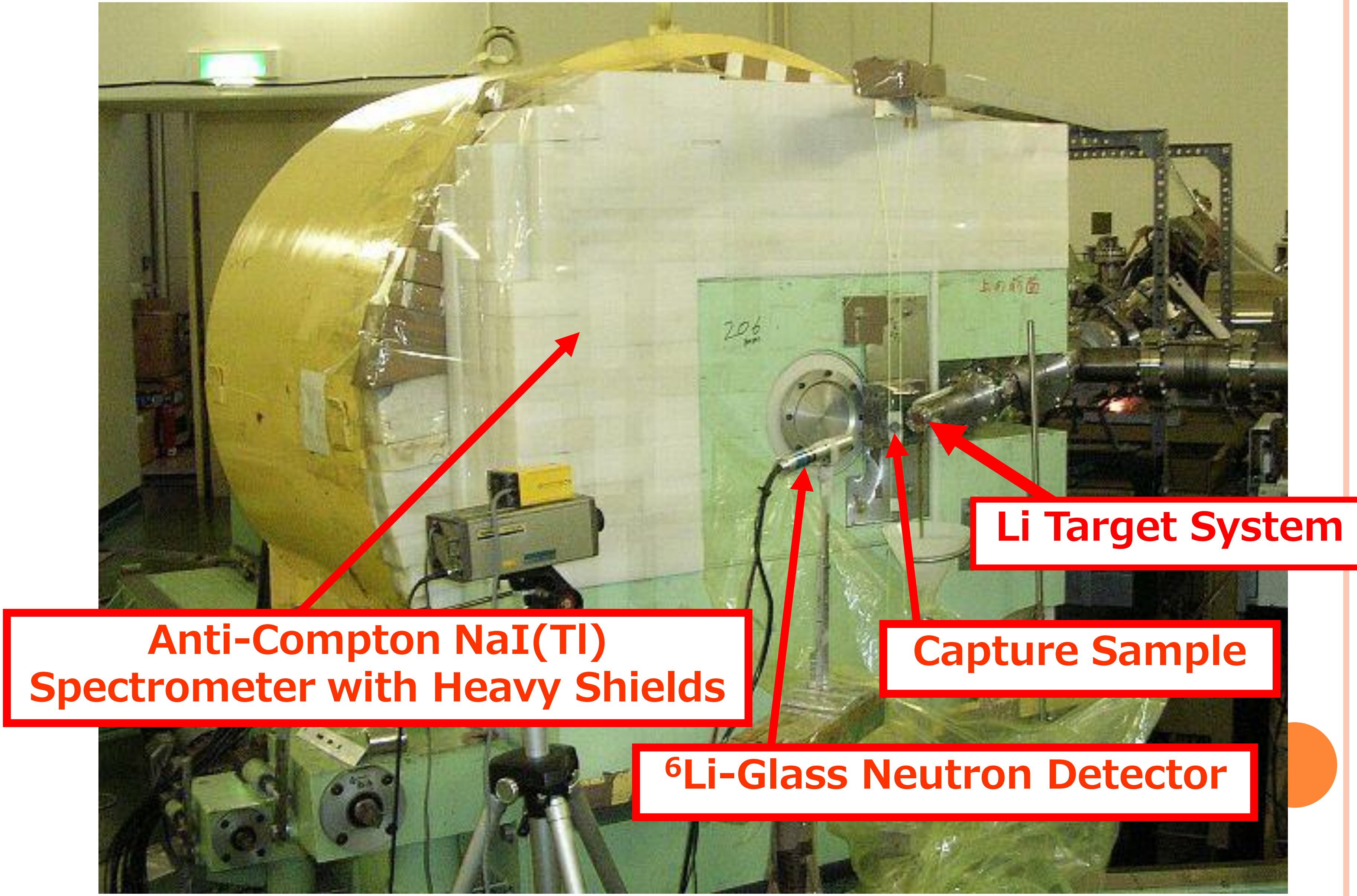


^{7}Li(p,n)^{7}Be Pulse Neutron Source

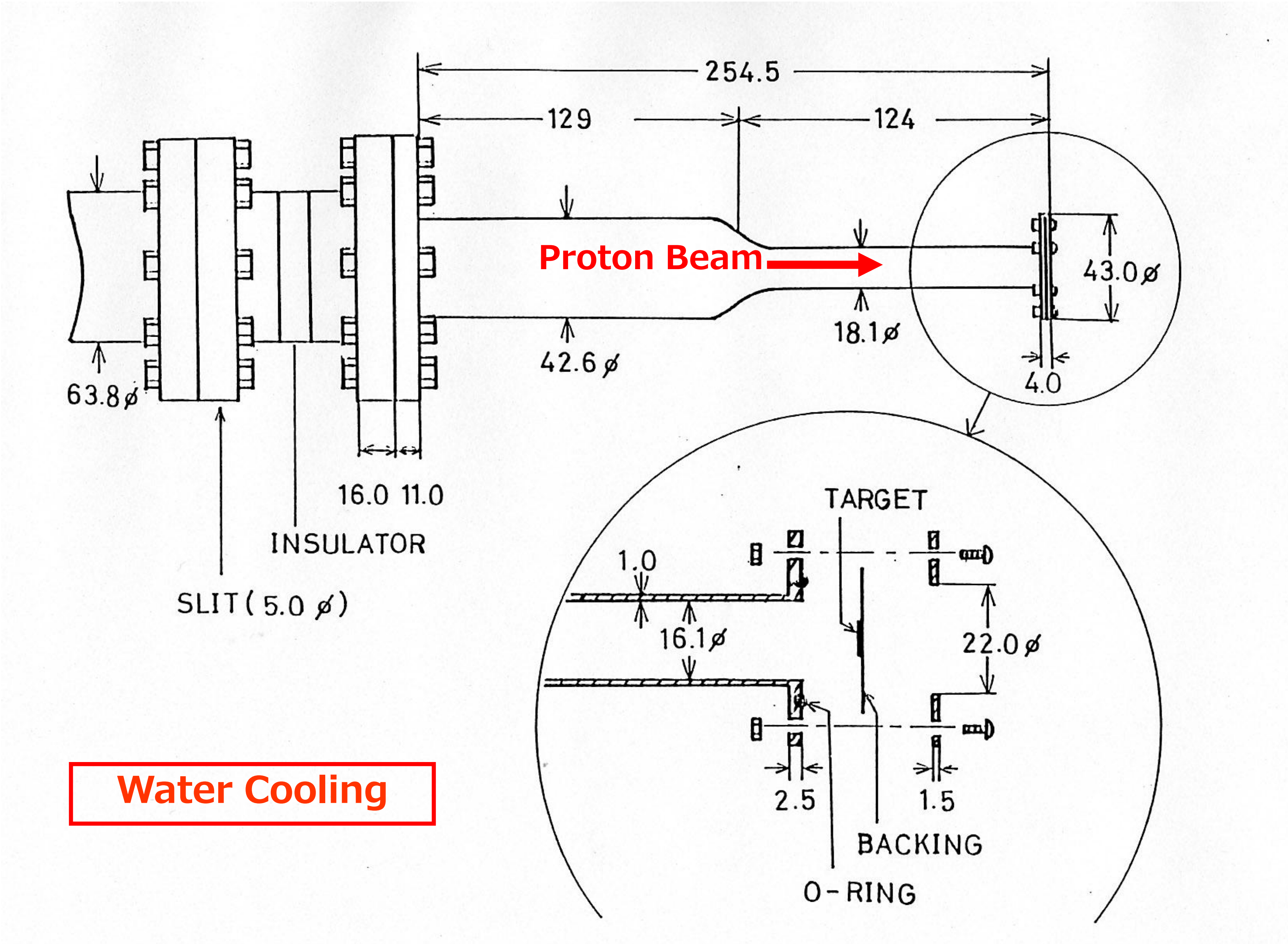
Ion Source: Duo-Plasmatron

Electronics for Pulsing System

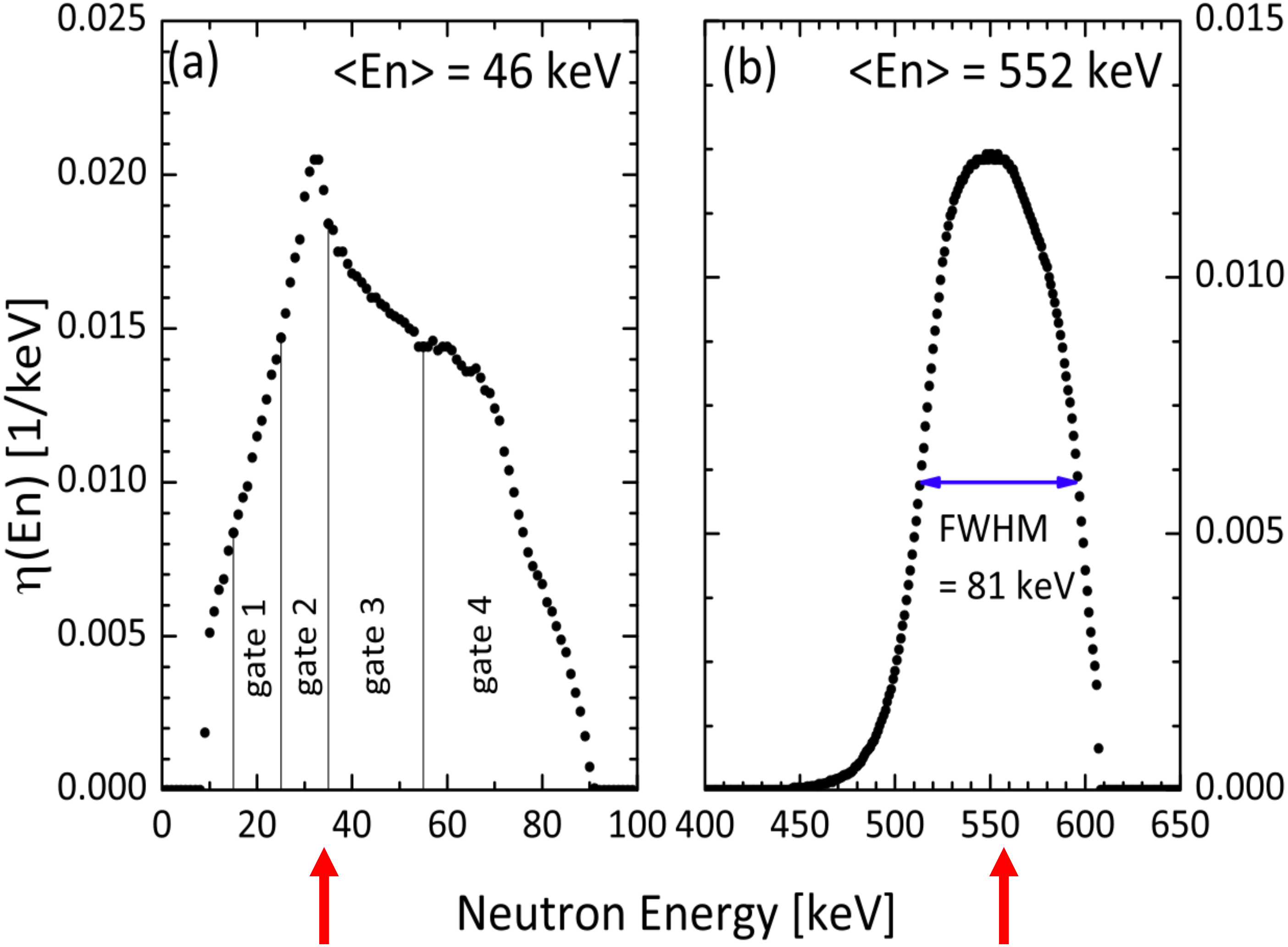
Typical Experimental Setup for keV-Neutron Capture Gamma-Ray measurement at Tokyo Tech.



Li Target System at Tokyo Tech.



Typical Neutron Spectra and Intensities



5×10^5 n/cm^2/s @ 12 cm **1×10^6 n/cm^2/s @ 20 cm**

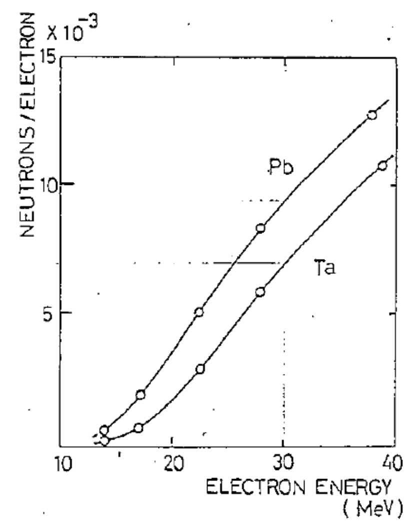
A capture sample is located 12 or 20 cm from the neutron source.

KURRI-Linac

Research Reactor Institute,
Kyoto University
By J. Hori

Specs of the KURRI-Linac

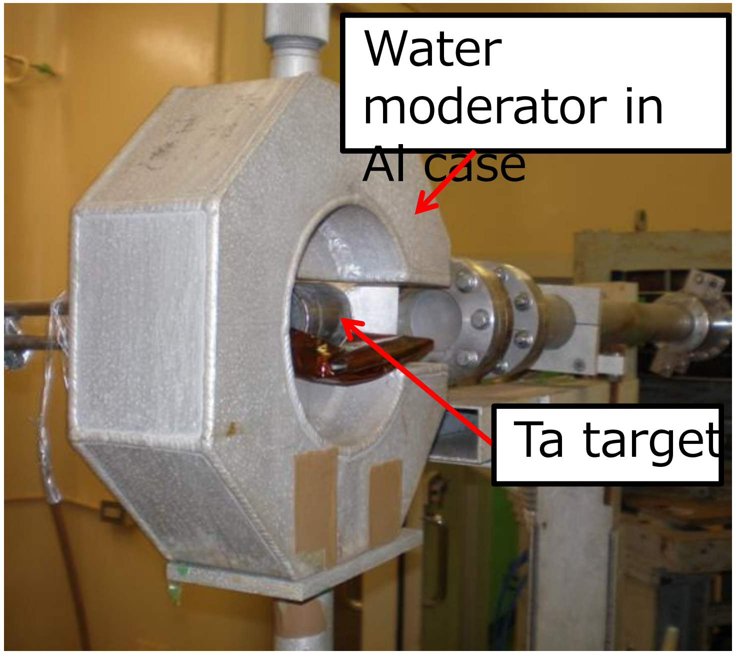
- Specification of injector
  - electric gun : YU-156(EIMAC)
  - incident voltage : 100kV DC, incident current : Max 10A
- Specification of RF driver
  - output : 3kW, frequency : 1300.8 MHz
- Energy of electron for neutron generation ： ～30 MeV
- Peak current : ～5A (short pulse) 2～100ns width
  - ～0.5A(long pulse) 0.1～4 μs width
- Frequency： 1～300 Hz (short pulse)
  - 1～100Hz (long pulse)
- Neutron target : Ta with H_2O moderator
- Power on target : Maximum 6 kW (200μA, 3
- Electron beam diameter on target : ～1 cm
- Neutron production : ～8×10^{12} n/s @6kW



7×10^{-3} n/e @30MeV

Injector and accelerator tubes

Target room



Ta target and water moderator

Lead spectrometer (1.5×1.5×1.5m^3)

Cyclotron for BNCT at KURRI

By Y. Sakurai

LAYOUT OF A CYCLOTRON AND A TMRA

30MeV, 1mA (Maximum 2mA)
Target: Be, Moderator: Pb-Fe-Al-AlF(Pb),
Reflector: Pb

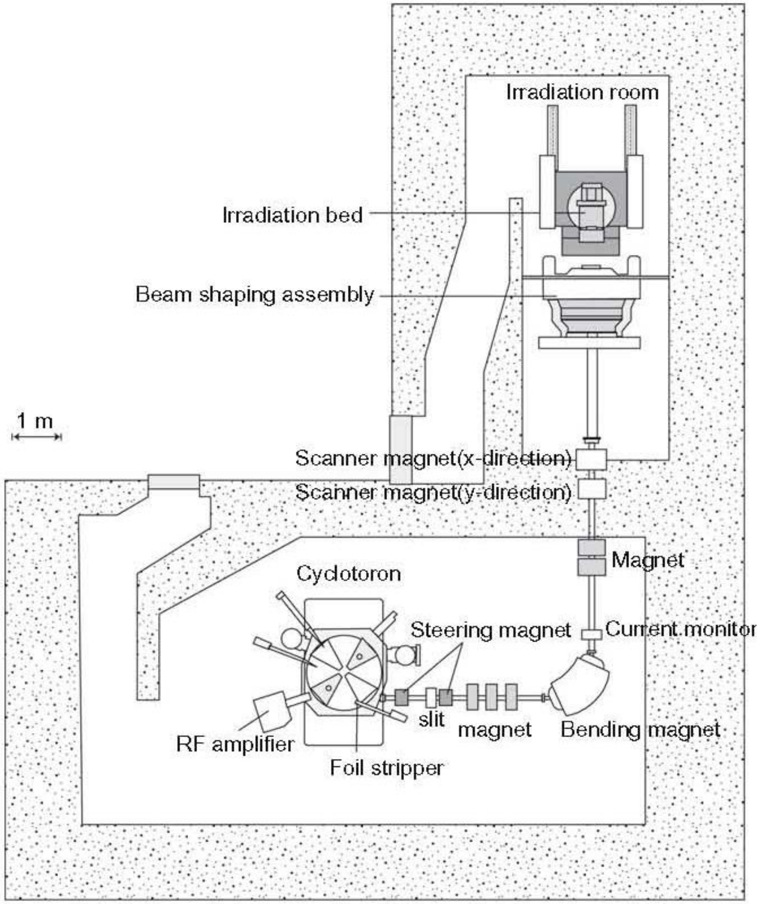


Fig. 1. Schematic layout of cyclotron-based neutron source.

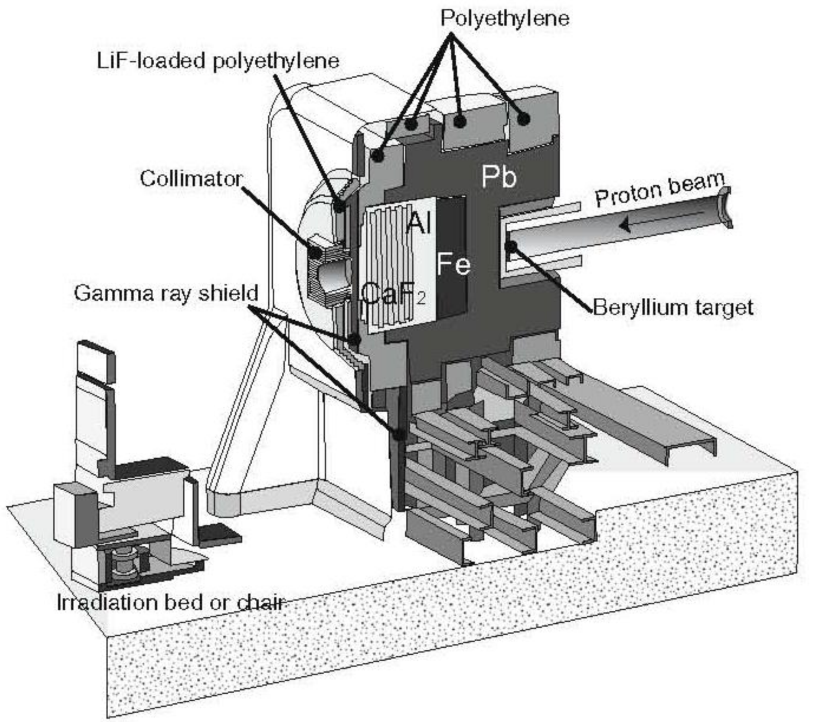


Fig. 3. Schematic layout of a beam-shaping assembly for epithermal neutron generator using 30-MeV proton cyclotron and Be target.

Energy Spectra

Epithermal neutron intensity at the exit of collimator: 1.88E+09 ($cm^{-2}s^{-1}$)
Mixing of High energy neutrons /epithermal neutrons:5.84E-13 (Gy/cm^{-2})
Mixing of γ rays /epithermal neutrons:7.75E-14 (Gy/cm^{-2})、

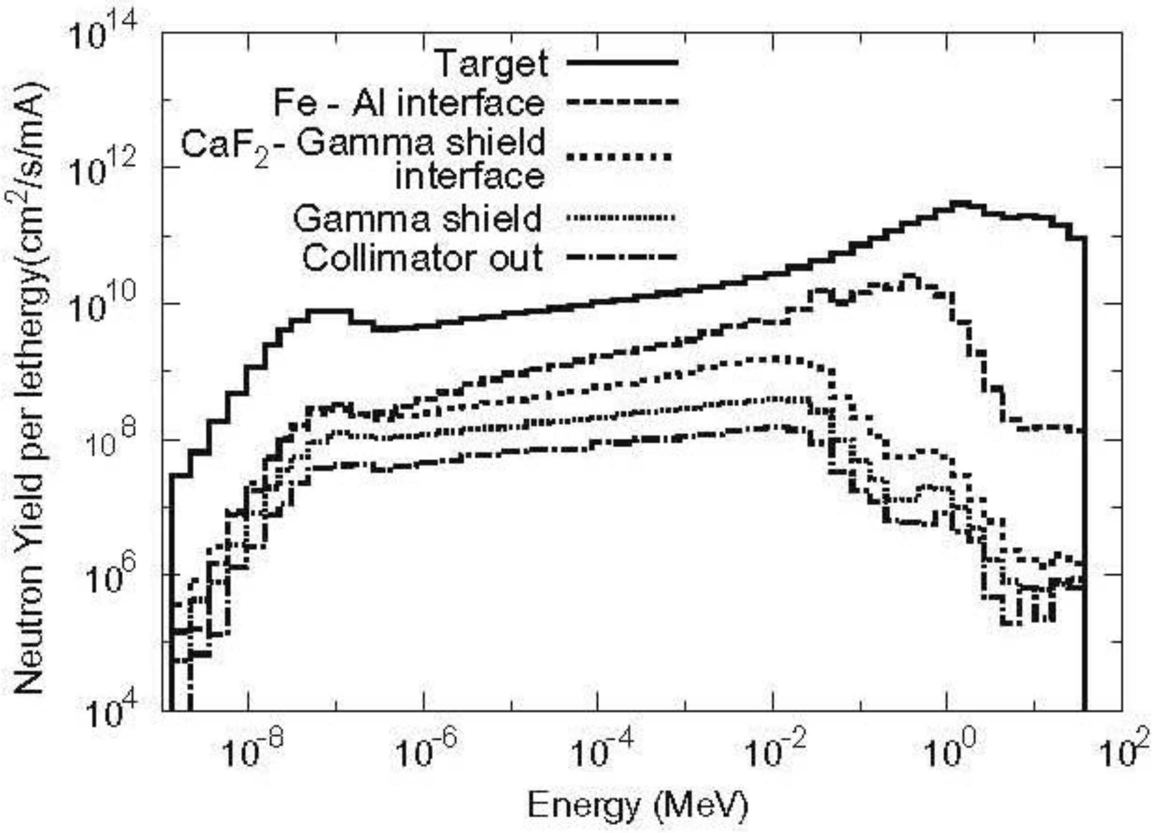
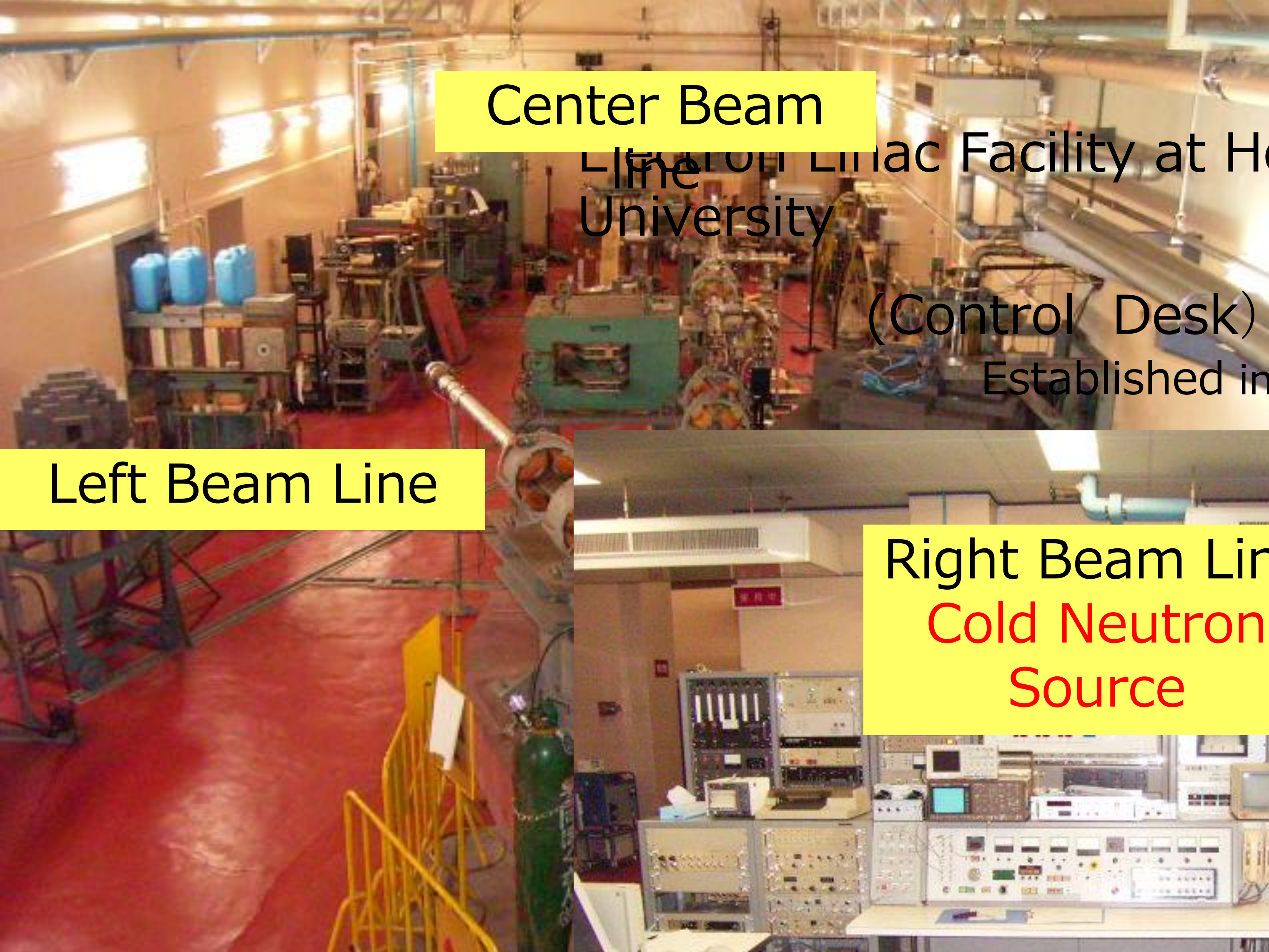
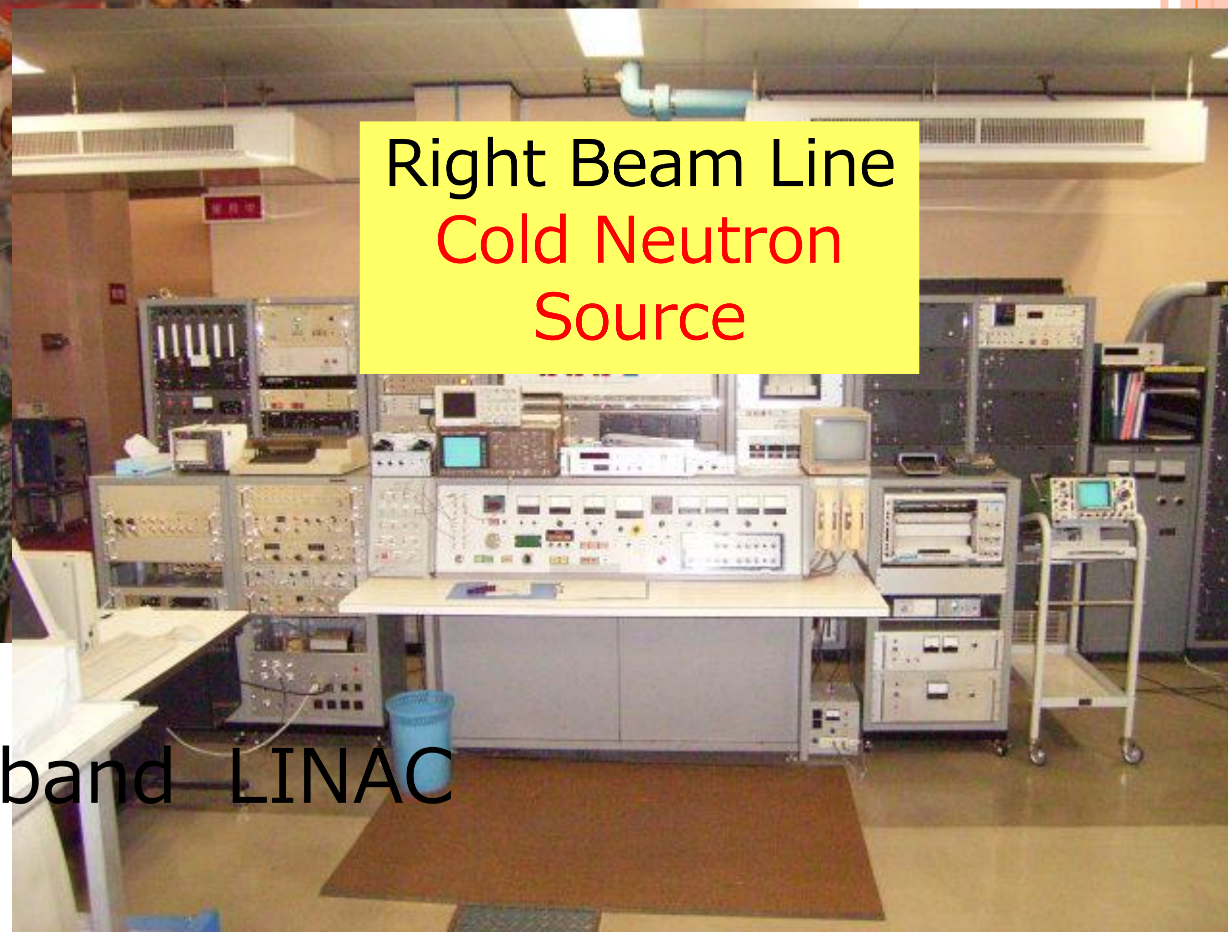


Fig. 4. Neutron energy spectrum at each evaluation point of a beam-shaping assembly.

electron-Linac neutron source at Hokkaido University

Electron Linac Facility at Hokkaido University





(Control Desk)

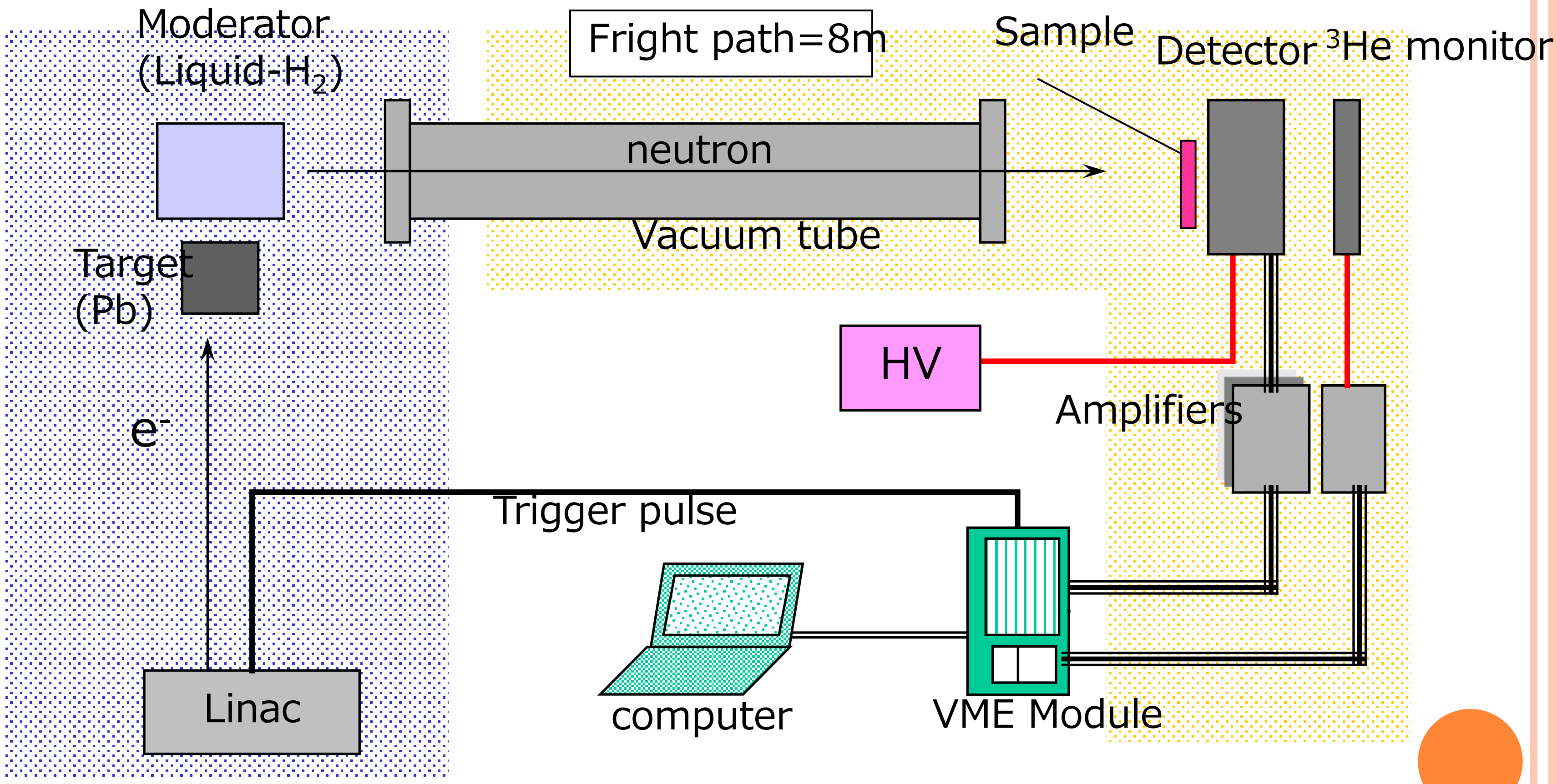
Established in March 1974

45 MeV S-band LINAC

Perfromance of 45MeV electron Linac

Items	Performance
Electron Energy	At peak current 1mA
	46 MeV
	At peak current 100 mA
	31. 5 MeV
Electron Current	At exit of center beam line
	230 mA
	Maximum average current
	140 μA
Electron Pulse	0. 01 ～3 μs
	10～200 PPS
	Single pulse
Beam diameter	At exit of center beam line
	12 mmφ
Neutron intensity	6.1×10^3 n/cm^2/sec /kW at 5 m (<5meV)

Pulsed neutron imaging

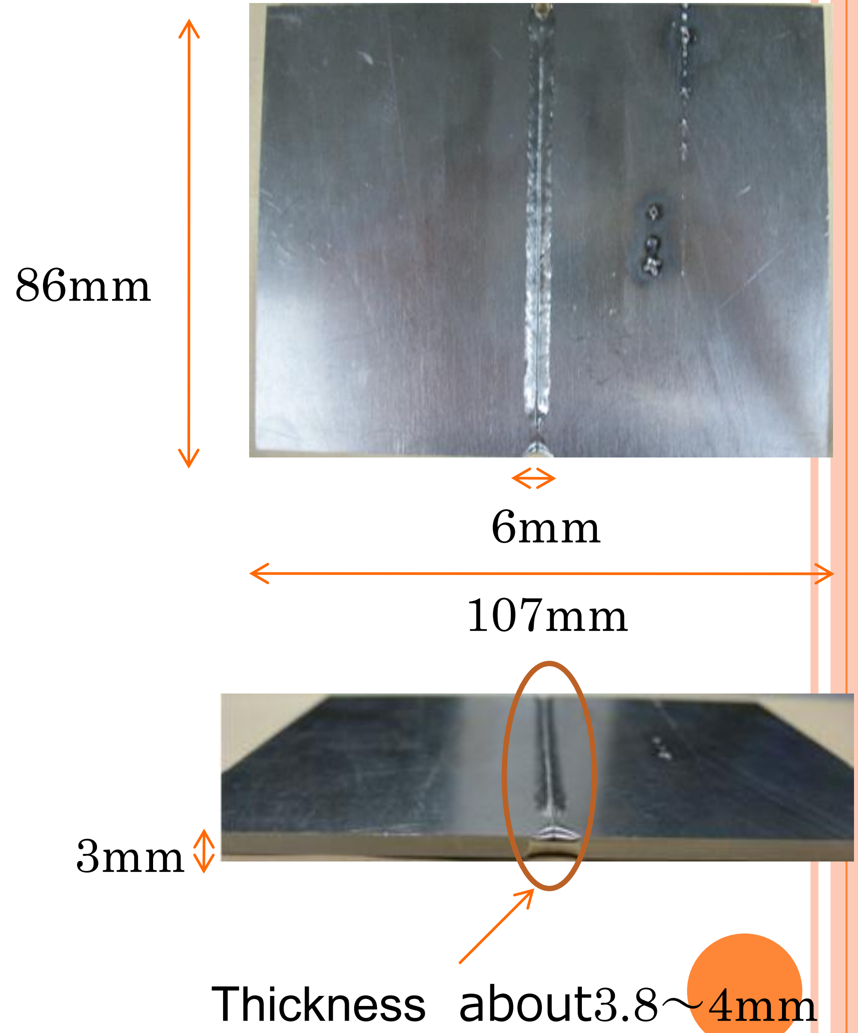


Experimental setup

Super conductive cavity

(Nb welded sample: by KEK)

Crystallite size < ~ 100μm
Electron Beam Welding
It is considered the welding make the crystallite size bigger.

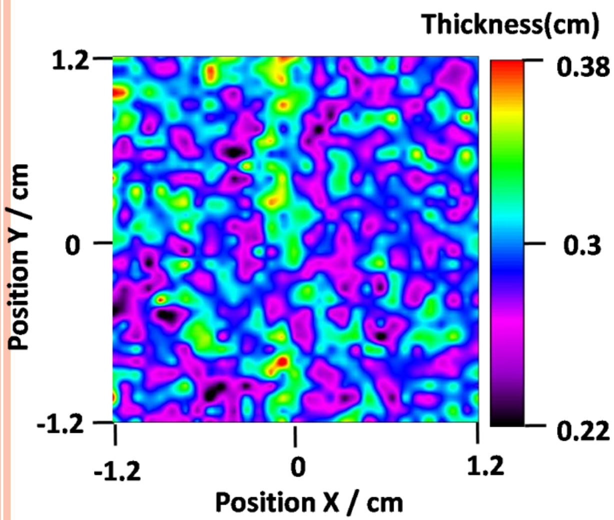


Pulsed neutron imaging using GEM

(1) Effective thickness (Atomic number density)
(2) Crystallite size
(3) Preferred orientation

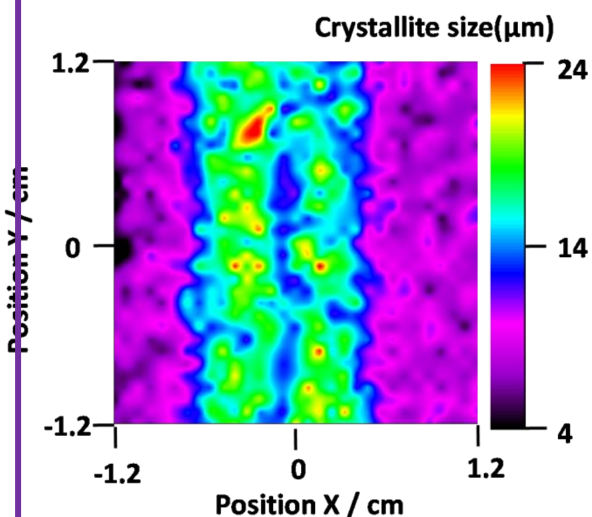
TEXTURE IMAGING OF NB WELDED SAMPLE

Effective thickness



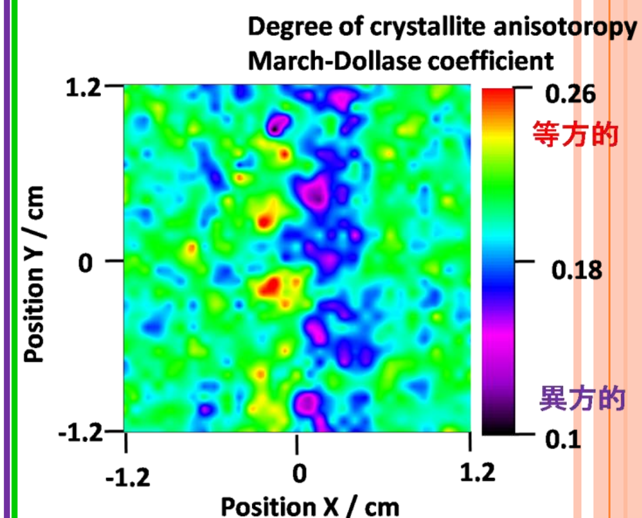
Left side of the welding is little bit thicker

Crystallite size



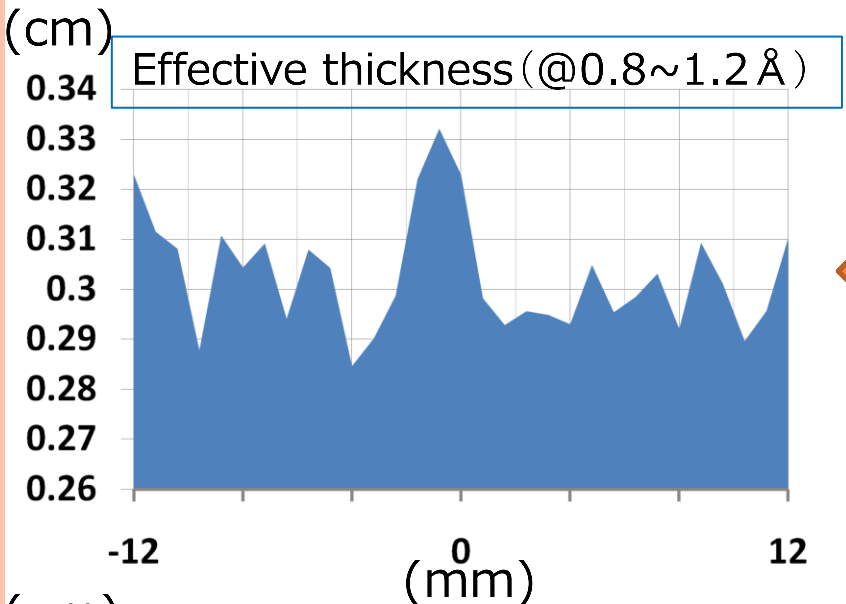
Crystallites around the weld has much larger size.

Preferred orientation

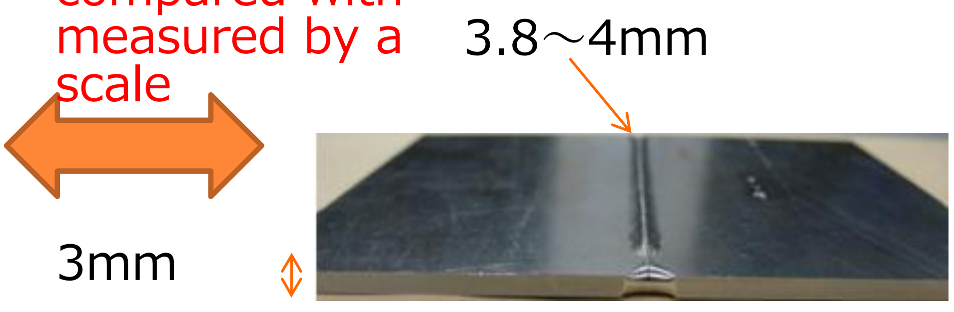


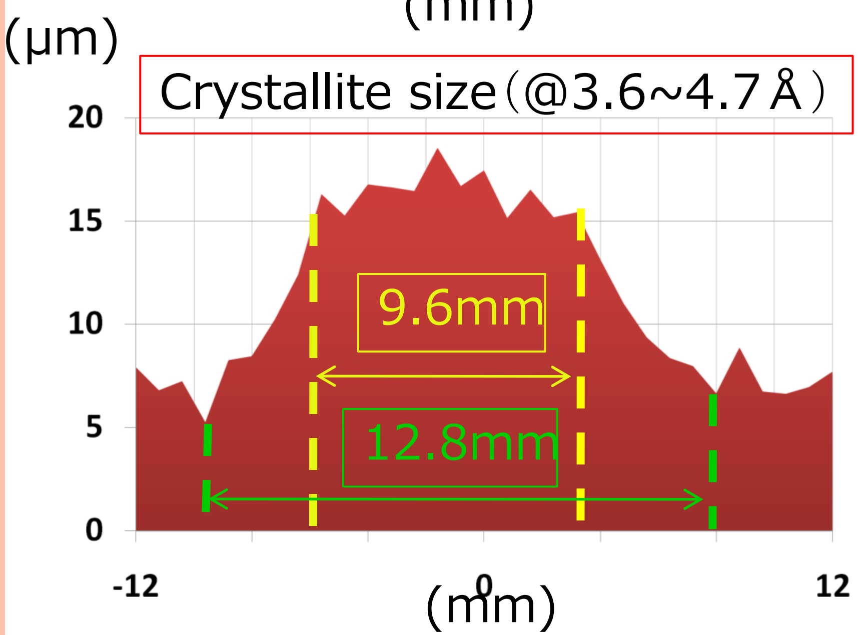
Right side is more anisotropic than the left.

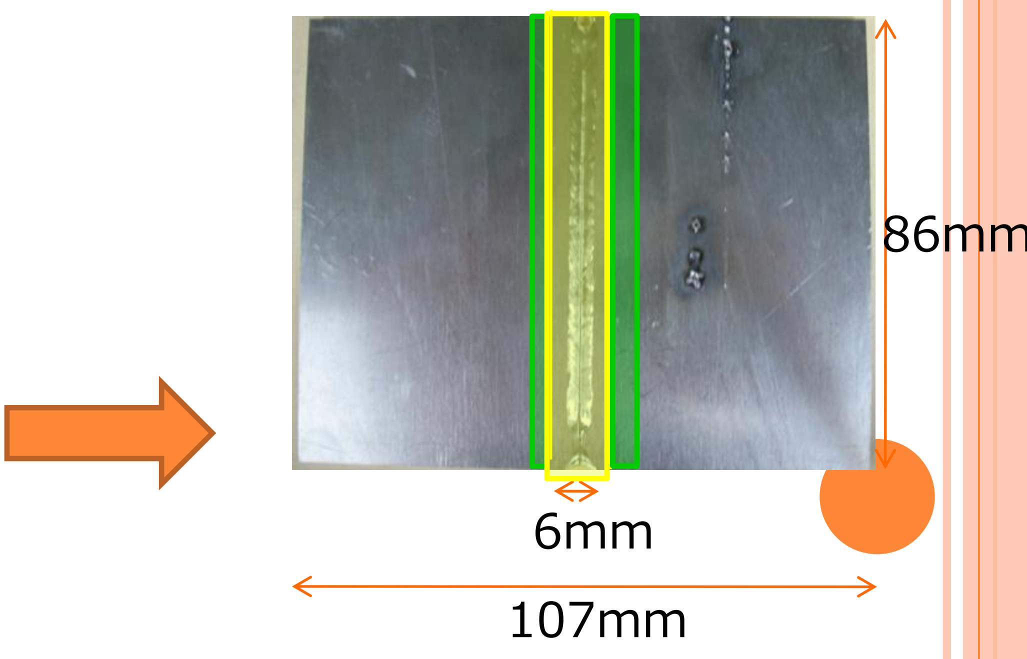
EFFECTIVE THICKNESS AND CRYSTALLITE SIZE AVERAGED OVER THE LONGITUDINAL DIRECTION



Welded area seems to be thinner compared with measured by a scale

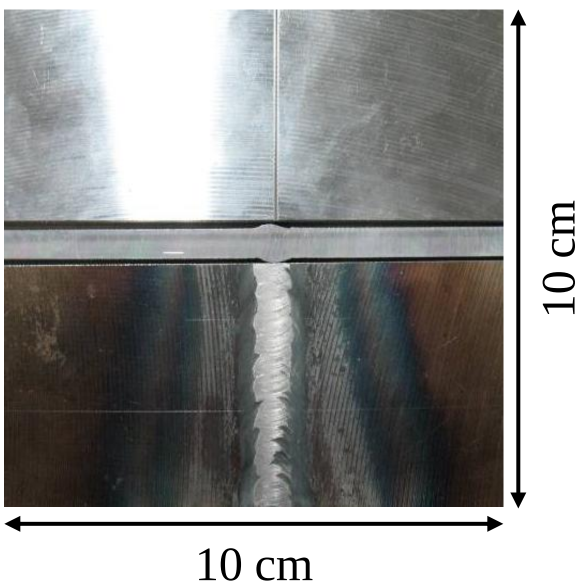


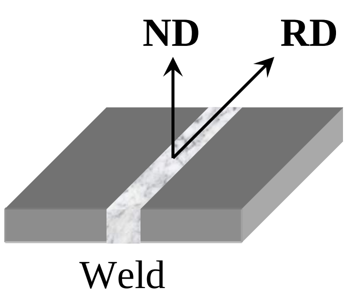




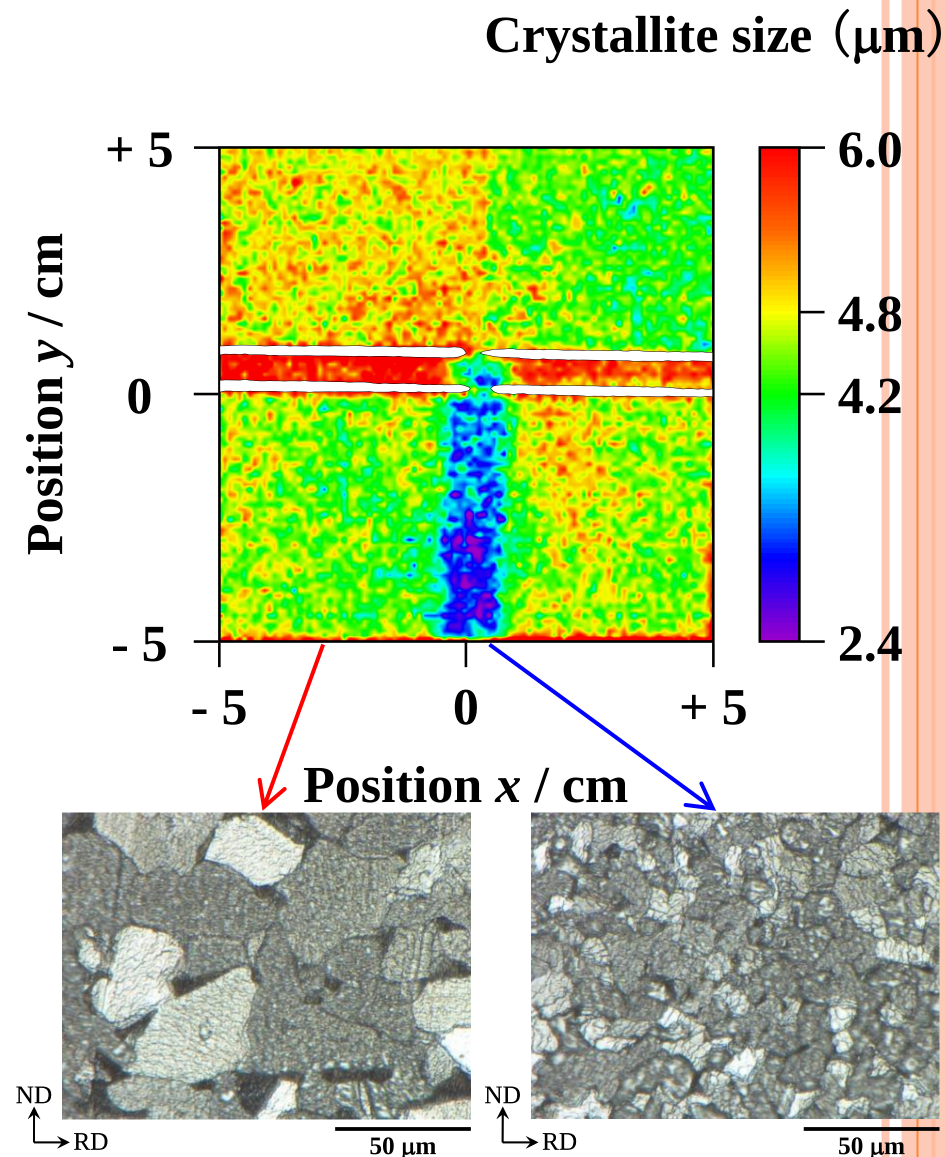
Crystallite size imaging of a rolled iron sample

H. Sato, T. Kamiyama and Y. Kiyanagi (Journal in preparation).





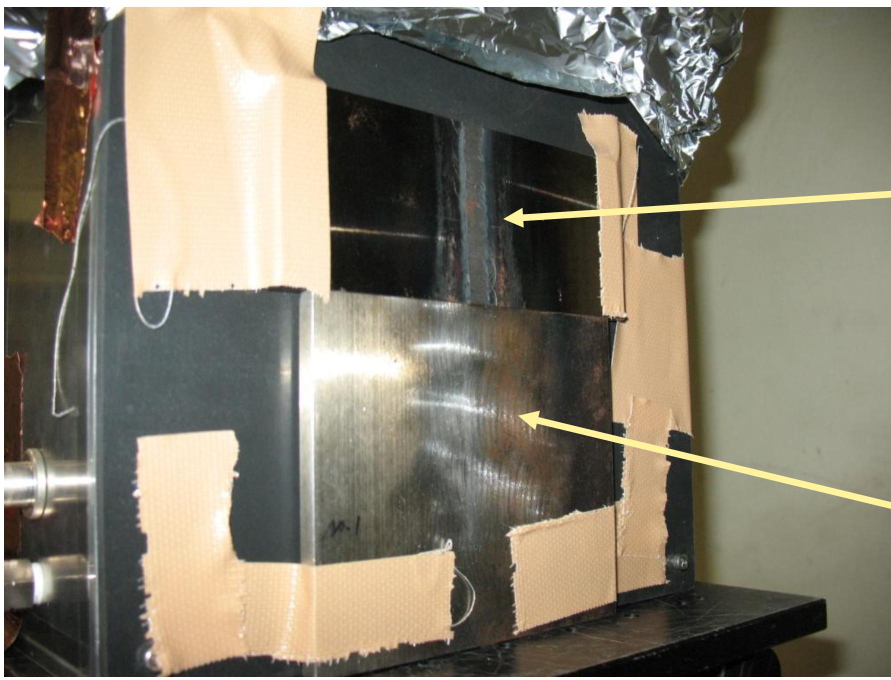
0.6 cm thickness

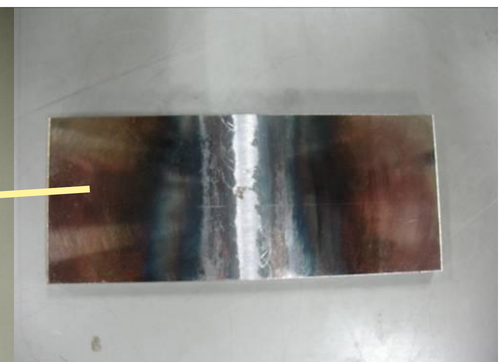


grain size by a microscope

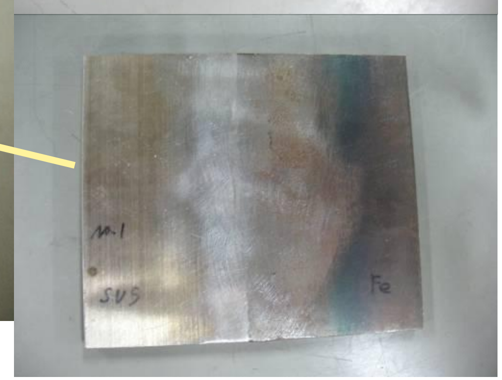
GEM DETECTOR EXPERIMENTS

GEM detector





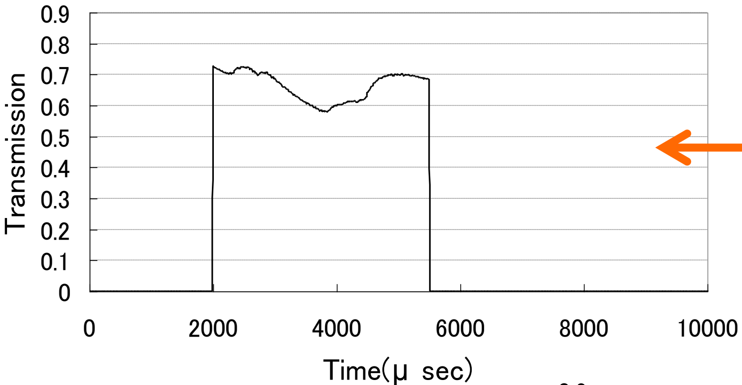
Fe-Fe welded sample

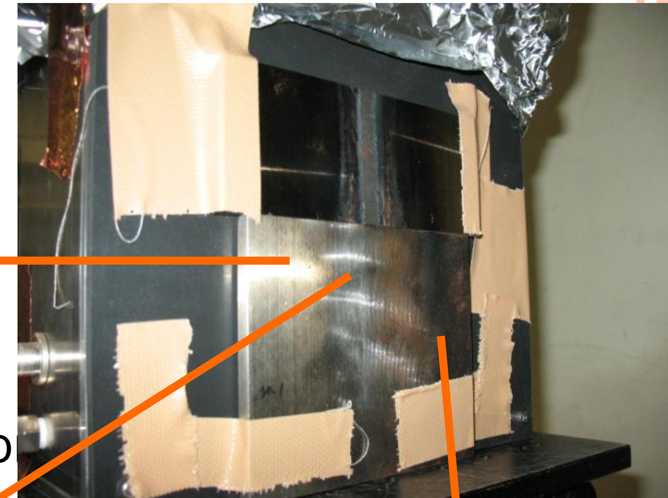


Fe-SS welded sample

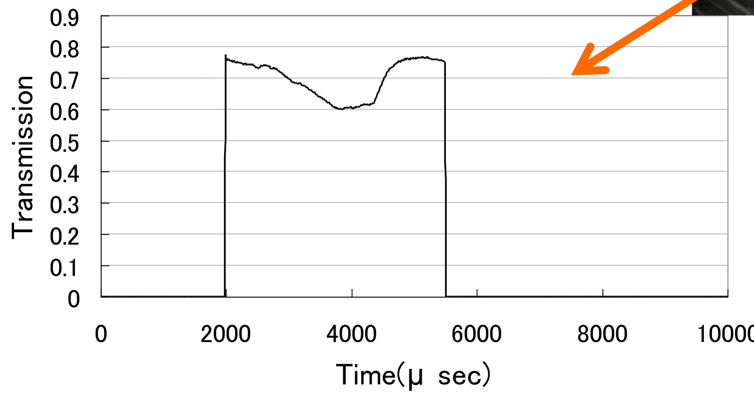
Transmissions at different positions

SS in Fe-

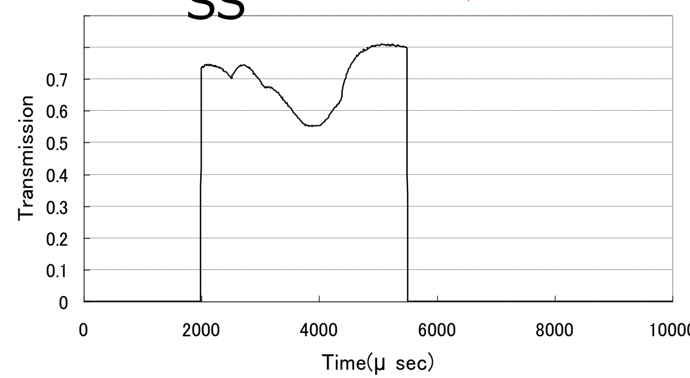




Welding positio



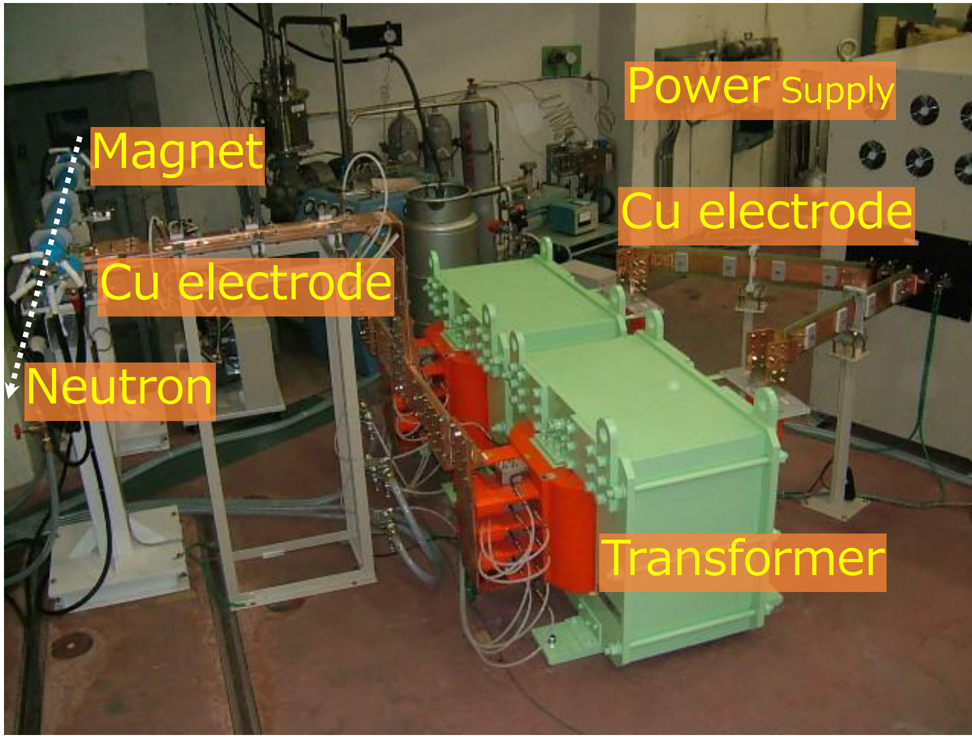
Fe in Fe-SS

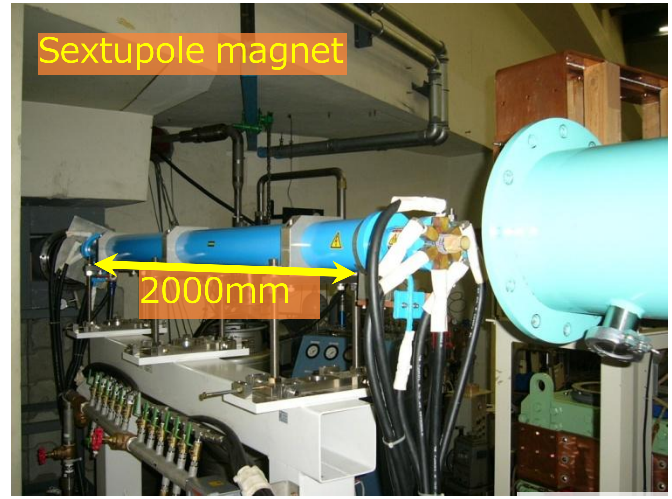


Neutron focusing by using a pulsed magnetic lens

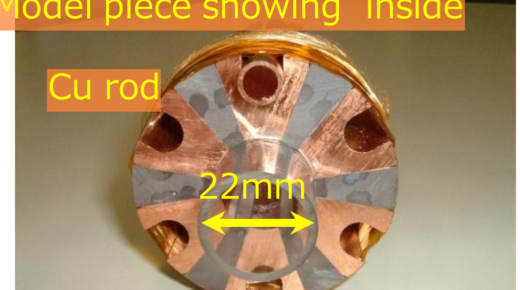
(Collaboration with JAEA)

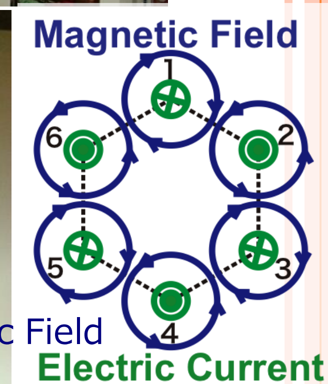
Pulsed sextupole magnet for focusing over wide wavelength region





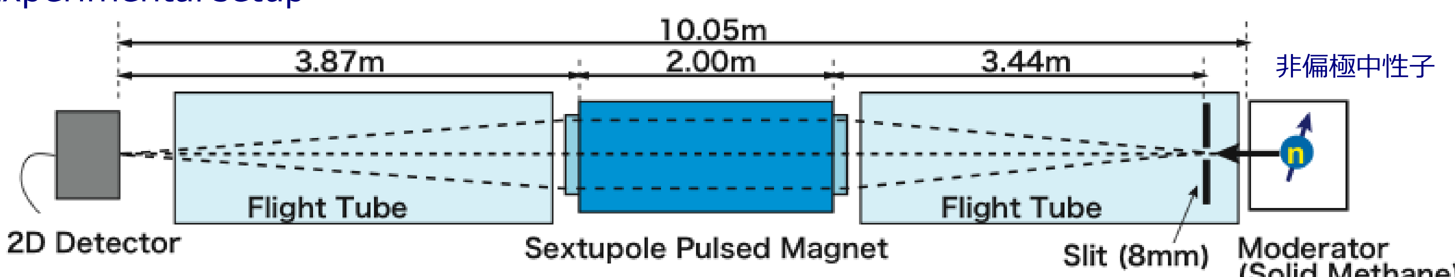
Model piece showing inside





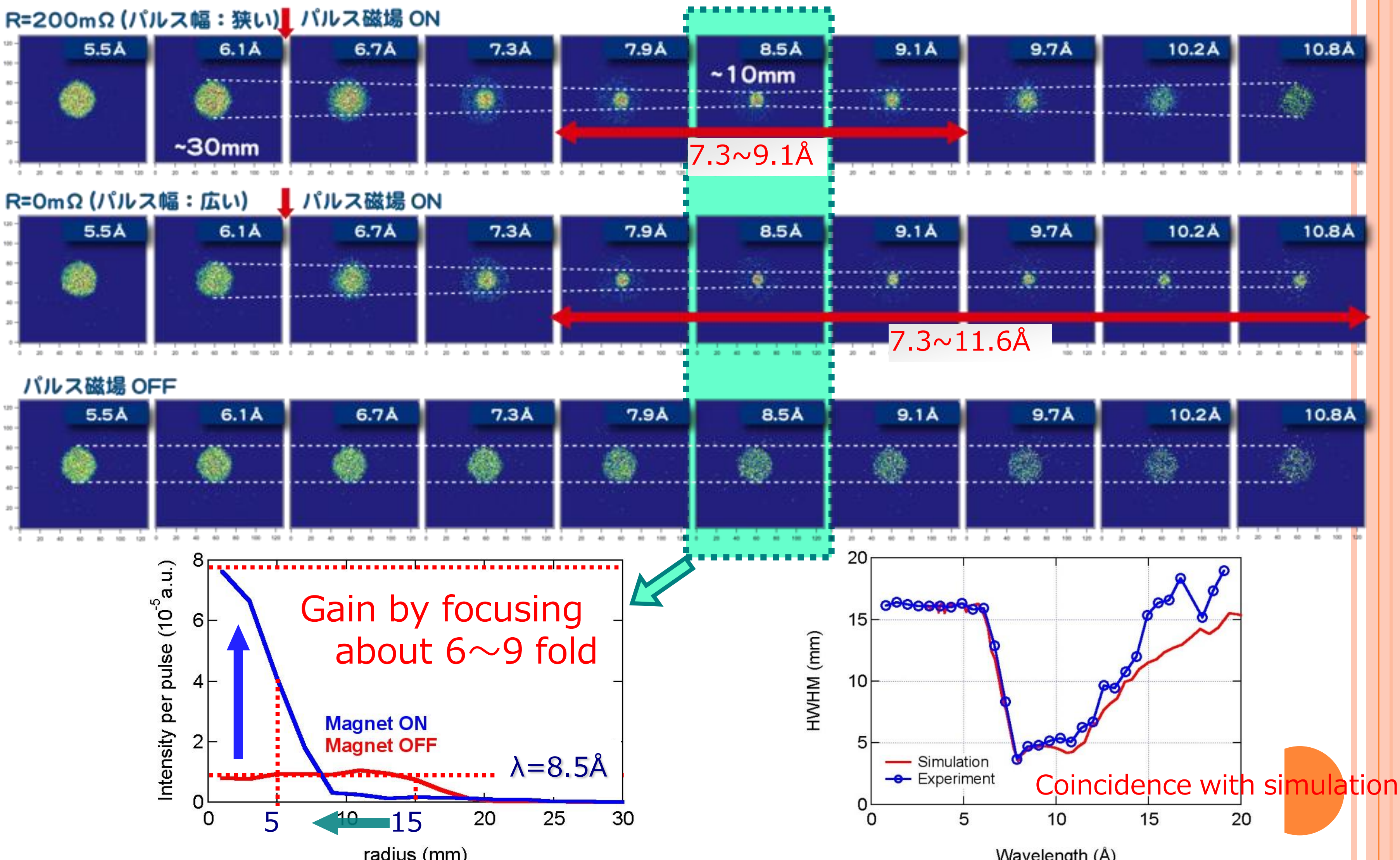
Maximum Gradient of Magnetic Field
12,000 T/m^2@I=60 kA

■ Experimental setup



Focusing performance of the pulsed sextupole magnetic field

- Two dimensional intensity distribution

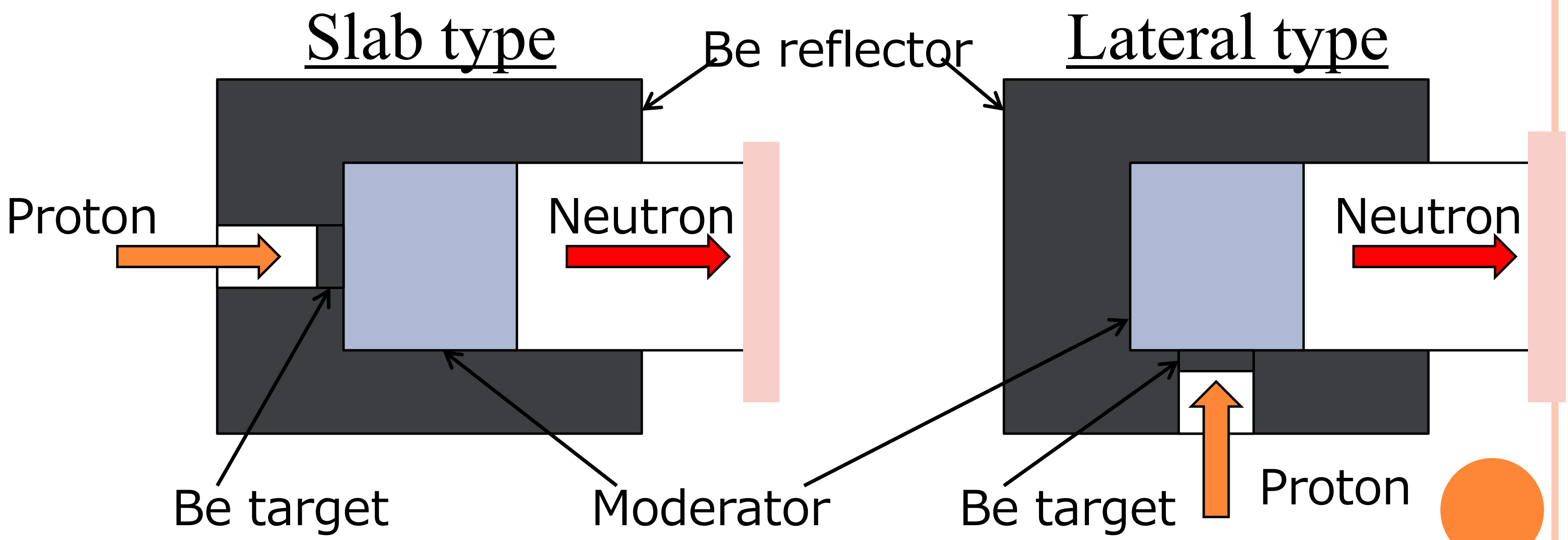


On going and future projects

- Kyoto University project for education and neutron science
- RIKEN project for imaging
- Ibaraki prefecture BNCT project

Design Philosophy for compact sources

So far the performance of the accelerator constructed placed a restriction on the neutron sources, but we should design the neutron sources totally optimizing from the accelerator to the output results we want.
Therefore, we should know the characteristics of each neutron production method.
We have studied efficiency for neutron production at two geometries.



The fast neutron yield from a target, the average neutron energy from a target, the neutron fluxes and the conversion ratio to the cold neutrons from the realistic moderator systems in the case of various neutron production reactions.

Type of source		Fast neutron yield from a target [n_f/s/kW]	Fast neutron yield from a target [n_f/s/mA]	Average neutron energy from a target [MeV]	Neutron flux at 5m from a moderator (E<5meV) [1/cm²/kW]	Neutron flux at 5m from a moderator (E<10meV) [1/cm²/kW]	Neutron flux at 5m from a moderator (E<5meV) [1/cm²/mA]	Neutron flux at 5m from a moderator (E<10meV) [1/cm²/mA]	Conversion ratio to cold neutrons (E<5meV) [1/cm²/n_f]
^{7}Li(p, n), E_p=2MeV	S-type	5.50×10^{10}	1.10×10^{11}	0.075	$1.925\text{x}10^3$	$3.212\text{x}10^3$	$3.850\text{x}10^3$	$6.424\text{x}10^3$	3.50×10^{-8}
	L-type				$1.661\text{x}10^3$	$2.794\text{x}10^3$	$3.322\text{x}10^3$	$5.588\text{x}10^3$	3.02×10^{-8}
^{7}Li(p, n), E_p=2.5MeV	S-type	3.52×10^{11}	8.80×10^{11}	0.326	$1.028\text{x}10^4$	$1.7283\text{x}10^4$	$2.5696\text{x}10^4$	$4.3208\text{x}10^4$	2.92×10^{-8}
	L-type				$9.363\text{x}10^3$	$1.5770\text{x}10^4$	$2.3408\text{x}10^4$	$3.9424\text{x}10^4$	2.66×10^{-8}
^{9}Be(p, n), E_p=11MeV	S-type	1.95×10^{12}	2.15×10^{13}	2.04	$4.202\text{x}10^4$	$7.1341\text{x}10^4$	$4.6225\text{x}10^5$	$7.8475\text{x}10^5$	2.15×10^{-8}
	L-type				$4.046\text{x}10^4$	$6.9582\text{x}10^4$	$4.4505\text{x}10^5$	$7.6540\text{x}10^5$	2.07×10^{-8}
Bremsstrahlung (γ, n), E_e=35MeV	S-type	1.60×10^{12}	5.60×10^{13}	2.52	$3.248\text{x}10^4$	$5.5360\text{x}10^4$	$1.137\text{x}10^6$	$1.9376\text{x}10^6$	2.03×10^{-8}
	L-type				$3.072\text{x}10^4$	$5.2960\text{x}10^4$	$1.075\text{x}10^6$	$1.8536\text{x}10^6$	1.92×10^{-8}

The electron machine gives relatively higher neutron intensity per kW, and easy to construct because the target system, the accelerators are established.

The P-Be reaction gives higher intensity than the electron source, and may need less shield volume compared with the electron one. However, a long life target is issue.

The p-Li reaction gives lowest intensity per kW among them, but the efficiency is highest and the shield may be very small. Therefore, this will be a candidate for a transportable source. However, the target is still very difficult.

Kyoto University Project
(On going)

SPECIFICATIONS

- 3.5MeV, <15mApk, <100μAave.
  <100Hz, <0.1ms, duty <1%,
  Beam Power < 0.35kW
- Compact (< 4m)

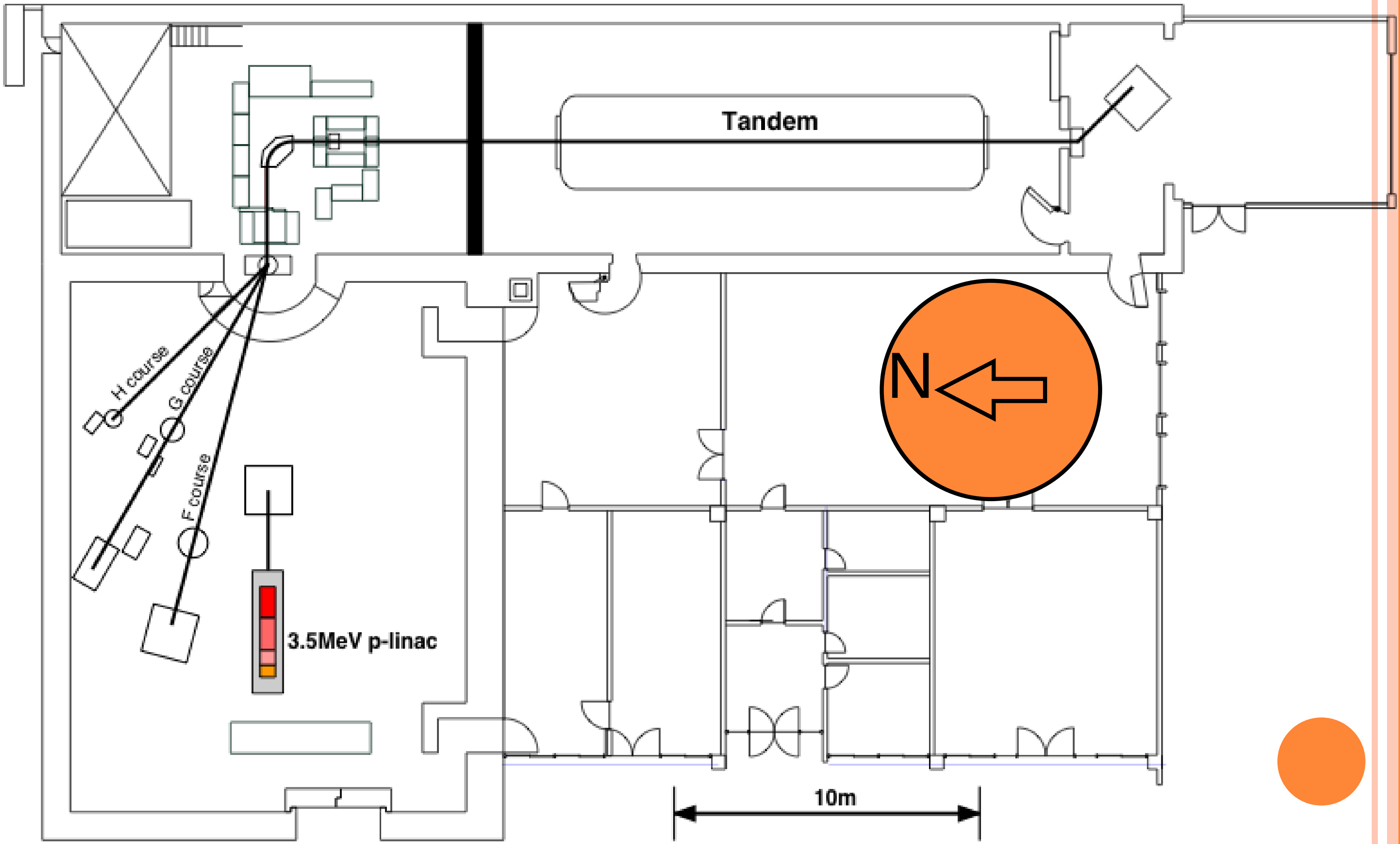
✓ low energy

✓ less shield and moderator

○ gain neutron flux

This has been designed to built a very compact source ~ (0.7-2.3)×10^{11} n/s.

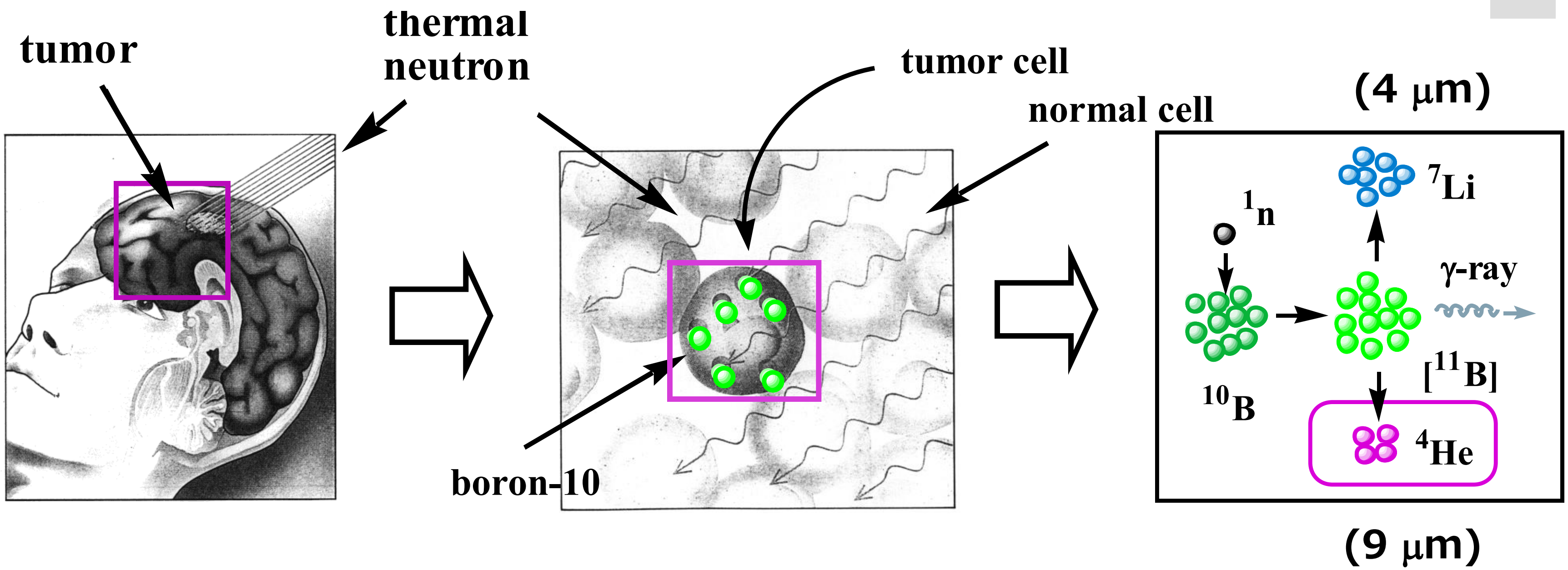
LAYOUT PRESENTED NOW



Ibaraki prefecture BNCT project

By A. Matsumura, T. Kumada, K. Yoshioka

(Boron Neutron Capture Therapy: BNCT)



$$^{10}B + {}^{1}n \rightarrow [^{11}B] \rightarrow {}^{7}Li + {}^{4}He + 2.79\ MeV$$

BNCT is a tumor cell selective charged particle therapy

Overall Plan of the Development Project

1. Accelerator for BNCT

Compact proton Linac which can install in a hospital (<100m^2)
Proton Beam Spec. : around 10MeV x a few mA beam on average

2. Neutron Source System

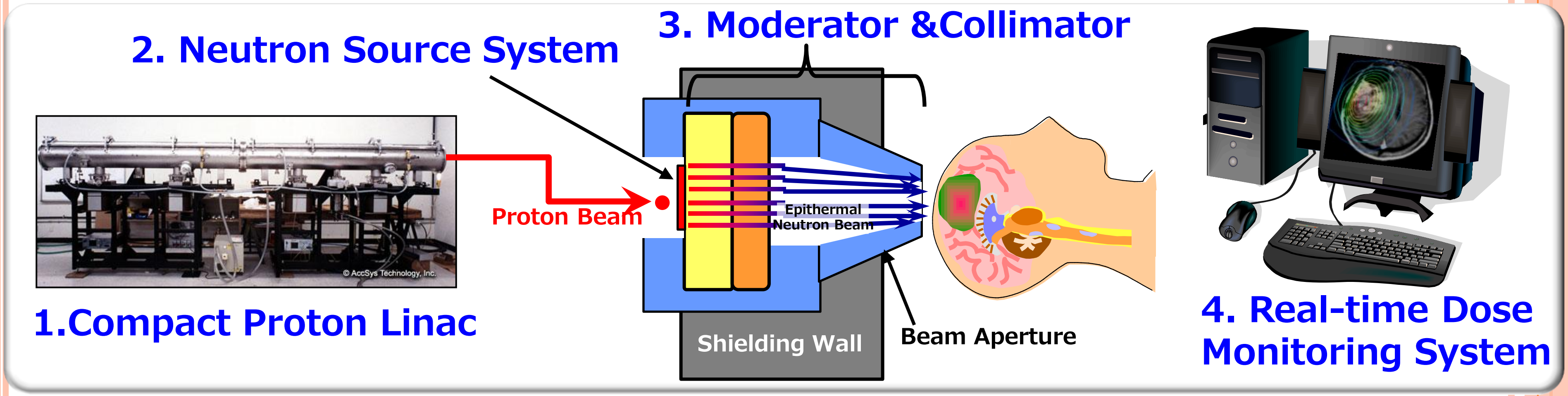
High Current Neutron Generator & Cooling System
Neutron Target Material : Be, C, etc.

3. Moderator and Collimator

Optimum Design of Neutron Moderator and Collimator
Goal : Epithermal neutron: >1x10^9 (n/cm^2/s) at beam aperture

4. Real-time Dose Monitoring System

Online Neutron Monitor , Real-time Boron Measurement System,
Multi-Modal Monte-Carlo Treatment Planning System, etc.



RIKEN PROJECT

Compact neutron sources for imaging

Imaging for

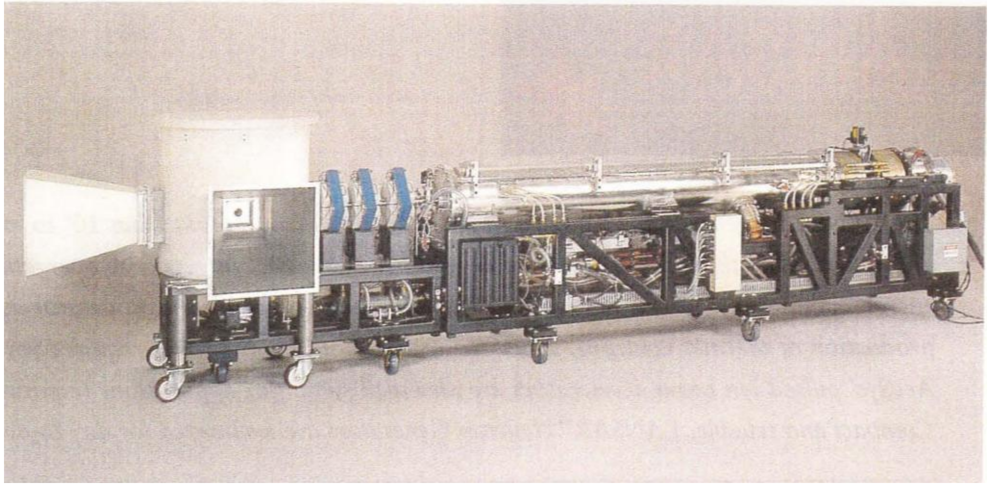
- Remaining stress
- Magnetic field, temperature, element
- Cracking
- Combined material
- Internal configuration of products
- Large structural material (Iron in concrete in Bridge, etc)

Several kinds of neutron sources are required.

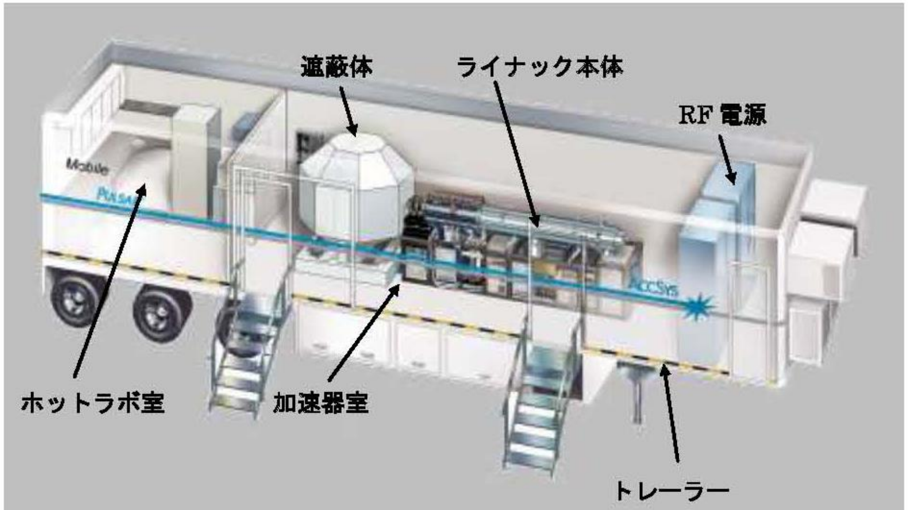
- Stationary type around $\sim 10^{11\sim 12}$ n/sec
- Transportable type around $\sim 10^{10\sim 11}$ n/sec
- {High intensity sources like J-PARC (for remaining stress)}

Proton, electron, deuteron etc. are candidate particles.

Example of proton accelerator–driven neutron source LANSAR



Neutron source on a trailer, By Yamagata



Summary

Several project to construct neutron sources based on the accelerators are now on going or under planning.

They will be optimized totally. However, they have issues to be solved other than the electron linac system. Especially the target system is the most important issue.

To design the compact neutron source we need careful optimization concerning to not only the TMRA but also the shield system, and should consider low activity system.