

Neutron sources and instrumentation

Shibayama,  CROSS

2nd day (Aug. 11)
14:00 - 15:30

Mitsuhiro Shibayama

**Comprehensive Research Organization for
Science and Society (CROSS), Japan**

2nd day (Aug. 11)
09:30 - 10:00 Fundamental properties of neutrons
(Prof Bruce Gaulin)
10:00 - 11:30 Elementary neutron scattering theory
(Prof Bruce Gaulin)

**<https://neutron.cross.or.jp/mitsu/>
<https://neutrons.cross.or.jp/en/>**

Contents



Part 0. Self introduction

Part 1. Overview:

1. Neutron, X-ray, and light
2. History, generation, facility world map, etc.

Part 2. Neutron Sources (YouTube)

1. World leading facilities (reactor): ILL, NIST, JRR-3, OPAL, ...
2. World leading facilities (spallation): ISIS, SNS, J-PARC MLF, ...

Part 3. Instrumentation

1. Structure/dynamics: order - concentration - energy overview
2. Methodology: TOF, angle dispersion, imaging
3. Classification: crystal structure, nano structure, spectroscopy, Imaging

Part 4. Summary and references

Self introduction

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Mitsuhiro Shibayama. (柴山 充弘)

Dr. Engineering
(**Kyoto University** 京都大学, 1983)



Prof. T. Hashimoto, Kyoto U.



Prof. R. S. Stein, U. Mass



Prof. T. Tanaka, MIT

1983 - 1984 Research Associate, **Univ. Massachusetts at Amherst**

1984 - 2000 **Kyoto Institute of Technology** 京都工芸繊維大学

(Ass. Prof. / Assoc. Prof. / Prof.)
(1991 Visiting Scientist, **Massachusetts Institute of Technology**)

2000 - 2020 Institute for Solid State Physics (ISSP), **The University of Tokyo**
(Prof.) 東京大学物性研究所

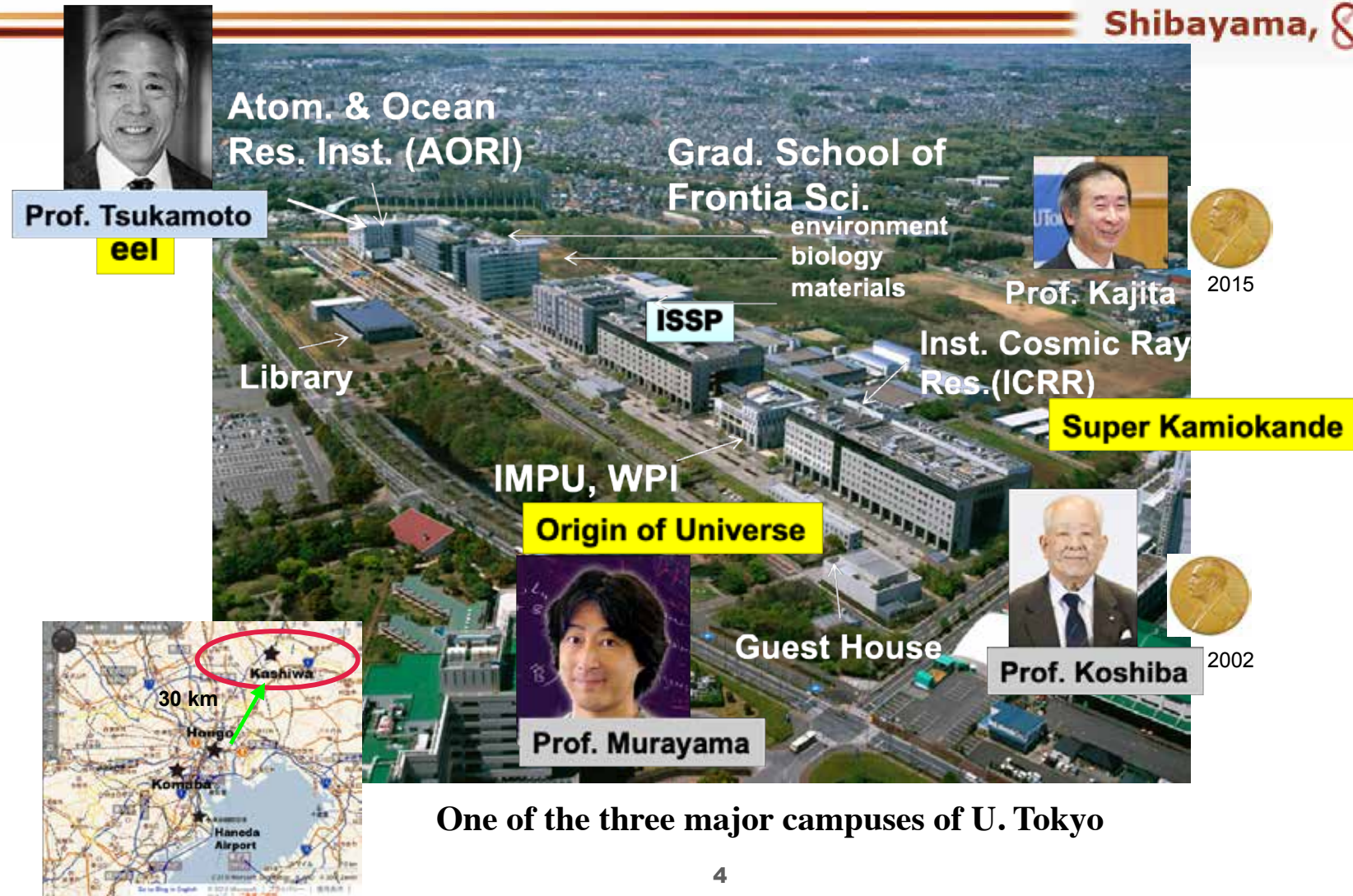
(2009 - 2020 Director, Neutron Science Lab.)

2020 - Director, Neutron Science and Technology Center,
Comprehensive Research Organization for Science and Society
(CROSS) 総合科学研究機構

Kashiwa Campus, U. Tokyo

2000 ~ 2020

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Atom. & Ocean Res. Inst. (AORI)

Grad. School of Frontia Sci.
environment
biology
materials

ISSP

Library

IMPU, WPI

Origin of Universe

Guest House

Inst. Cosmic Ray Res. (ICRR)

Super Kamiokande

Prof. Tsukamoto
eel

Prof. Kajita
2015

Prof. Koshiba
2002

Prof. Murayama

30 km

Kashiwa

Haneda Airport

Komaba

One of the three major campuses of U. Tokyo

Where are CROSS and J-PARC?

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Imagery ©2022 TerraMetrics, Map data ©2022 Google, TMap Mobility 200 km



Comprehensive Research Organization for Science and Society (CROSS)

CUHK Lecture, M. Shibayama
2025.8.10 - 16

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2020 ~

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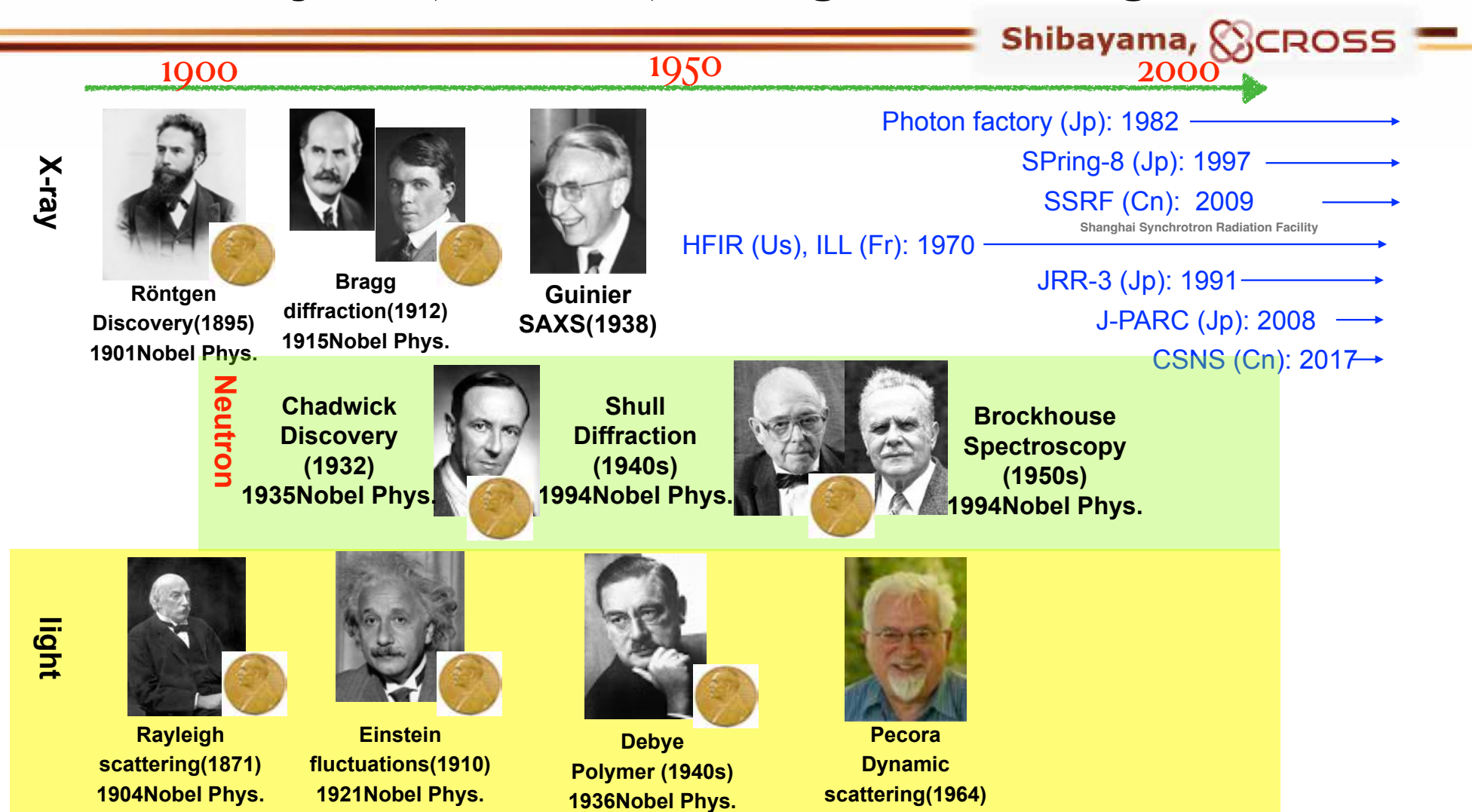
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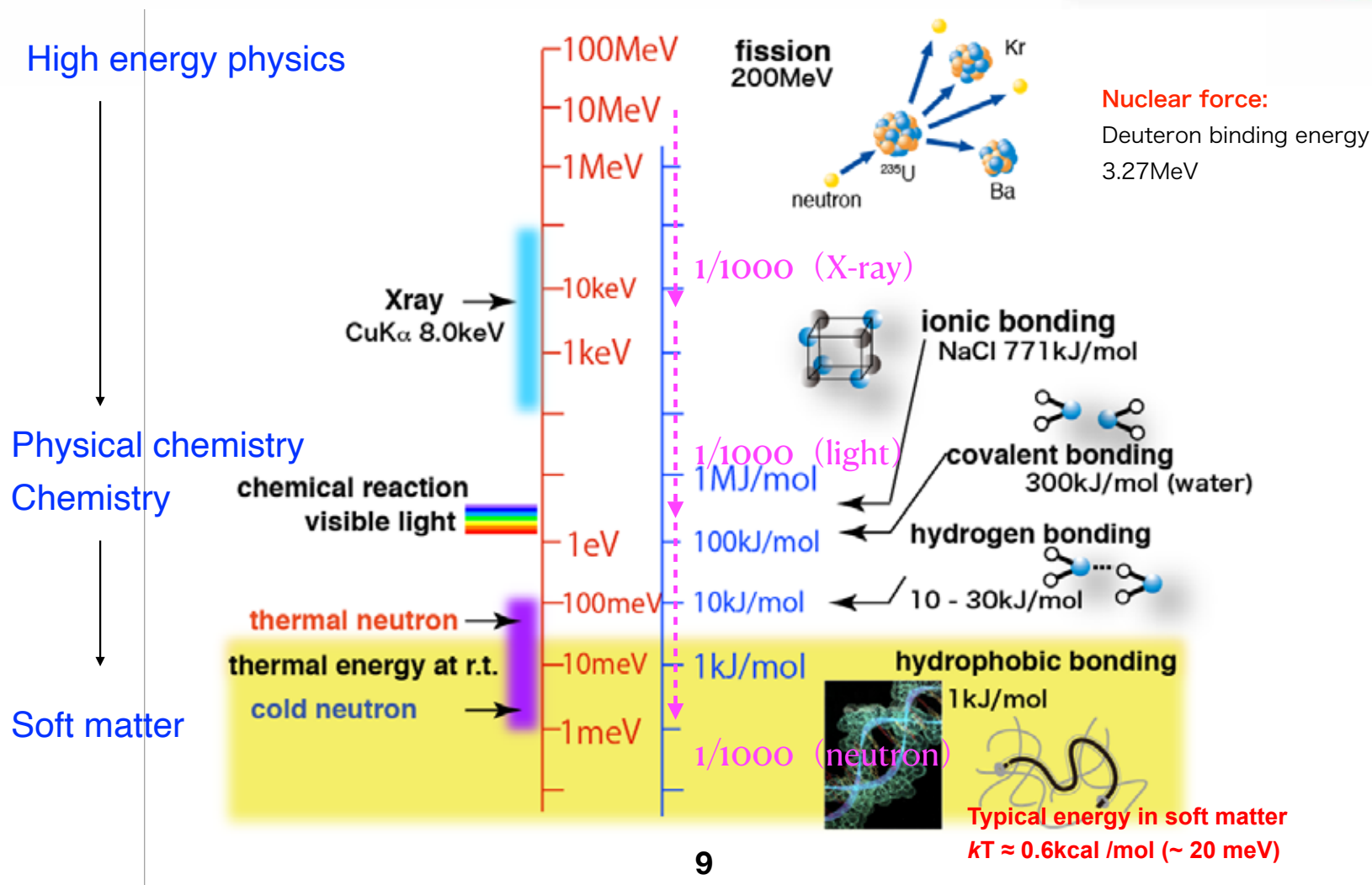
Part 4. Summary and references

History of X, neutron, and light scattering



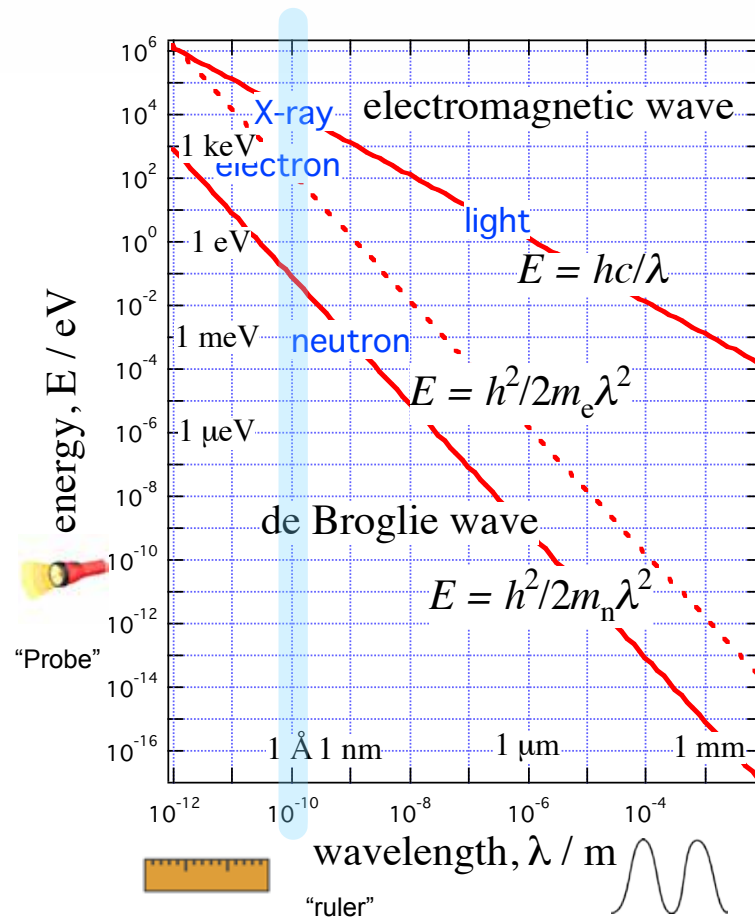
Choosing suitable energy

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energy dispersion

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photon (electromagnetic wave)

$$E = \hbar\omega = \frac{hc}{\lambda} \quad h = 6.626 \times 10^{-34} \text{ [Js]}$$

$1[\text{\AA}] \rightarrow E \approx 10[\text{keV}]$

Electron

$$E = \frac{\hbar^2 k^2}{2m_e} = \frac{h^2}{2m_e \lambda^2} \quad m_e = 9.109 \times 10^{-31} \text{ [kg]}$$

$1[\text{\AA}] \rightarrow E \approx 100[\text{eV}]$

Neutron

$$E = \frac{\hbar^2 k^2}{2m_n} = \frac{h^2}{2m_n \lambda^2} \quad m_n = 1.675 \times 10^{-27} \text{ [kg]}$$

$(m_n \approx 2000 \times m_e)$

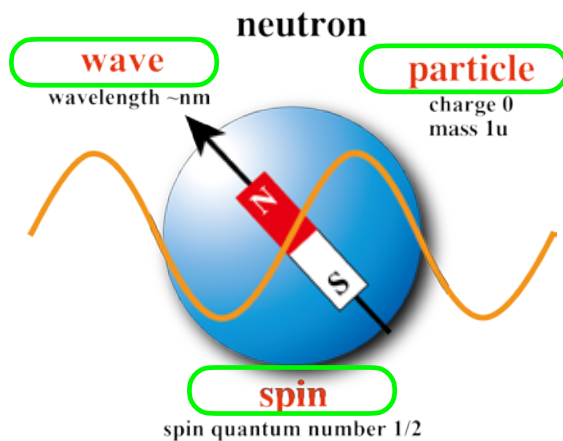
$1[\text{\AA}] \rightarrow E \approx 80[\text{meV}]$

Neutron: an excellent probe for material research

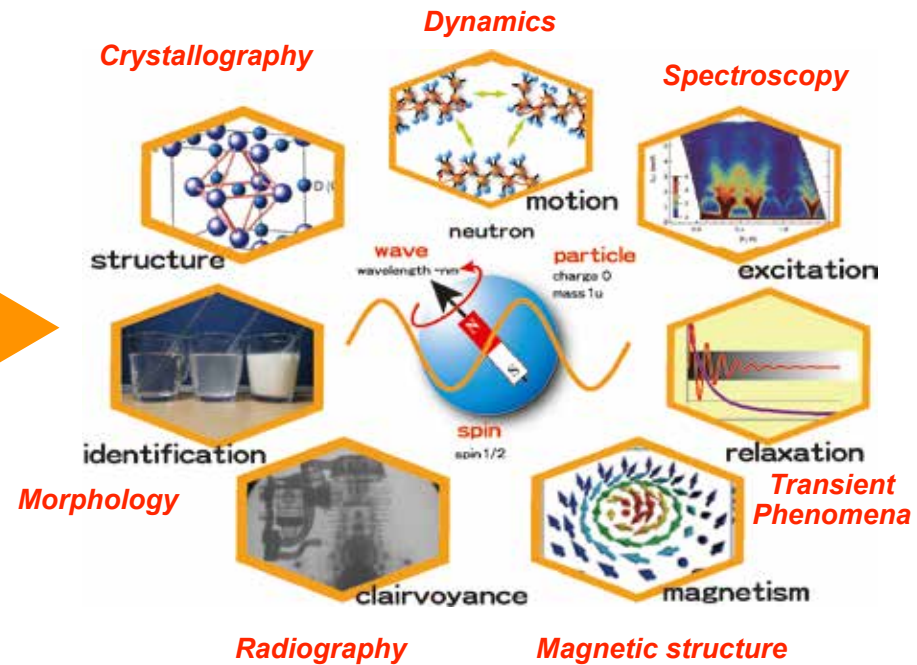
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3 basic properties



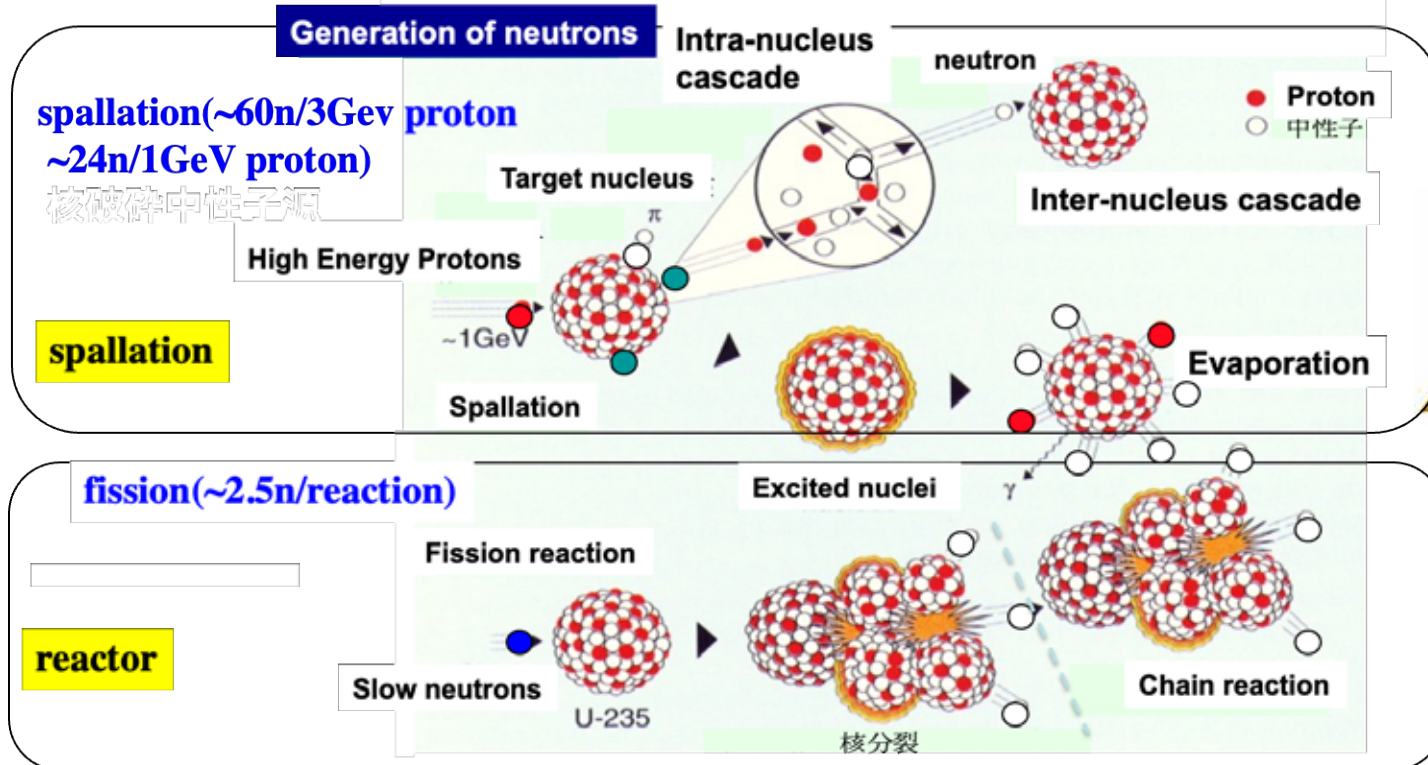
7 major applications



Neutron generation

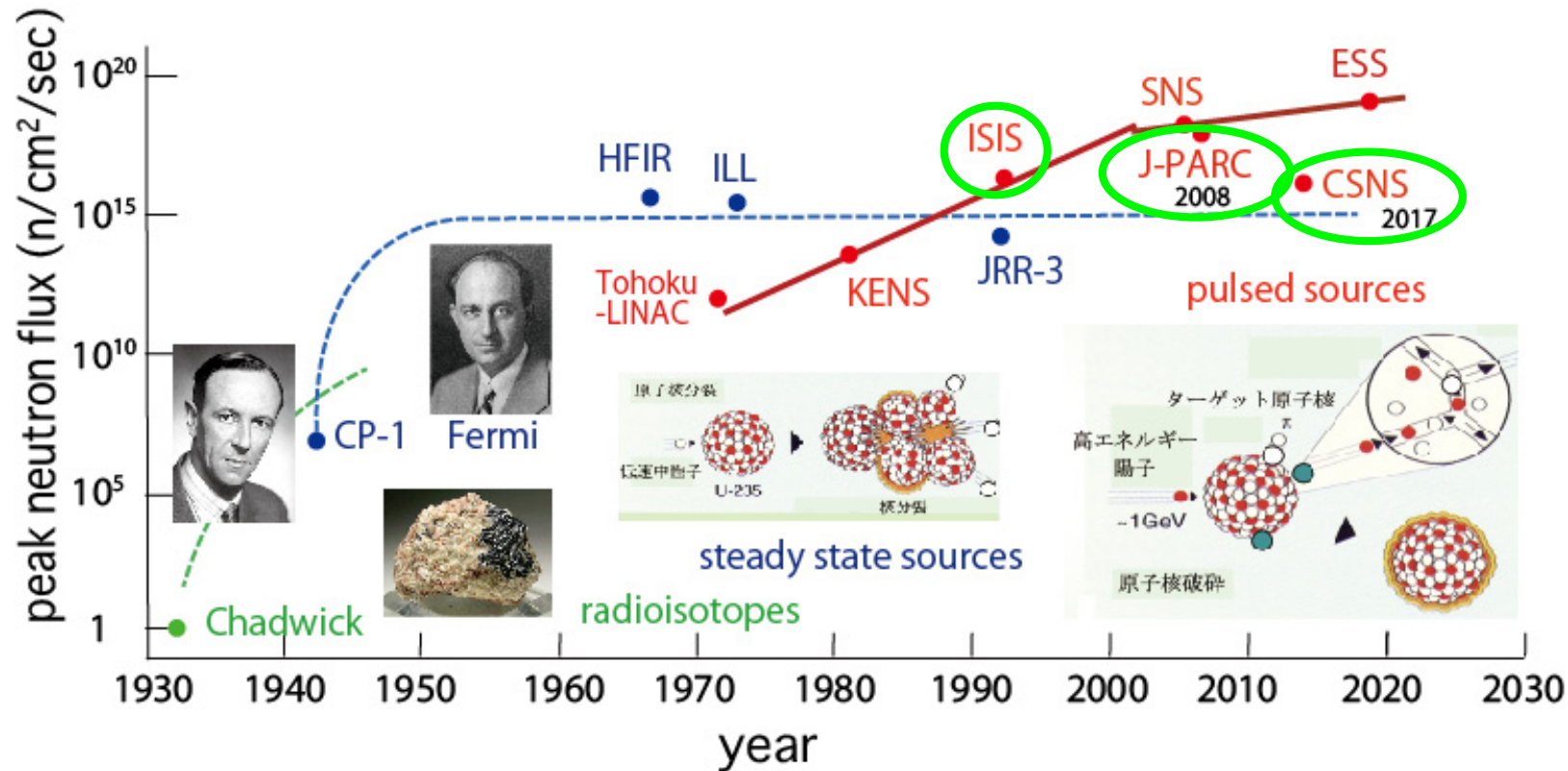
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very effective (no. neutrons $\propto$ proton power)
(spallation 1MW $\sim$ reactor 15MW)
low heat generation ($\sim$ proton power)



Development of neutron beam sources

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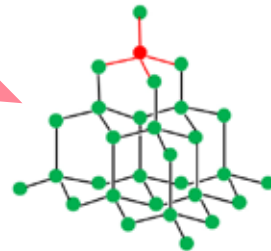


Atom, nucleus, and neutron

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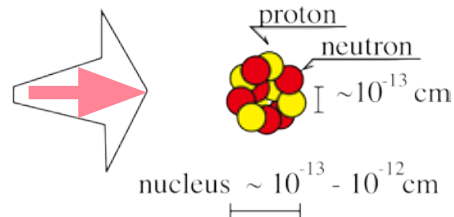
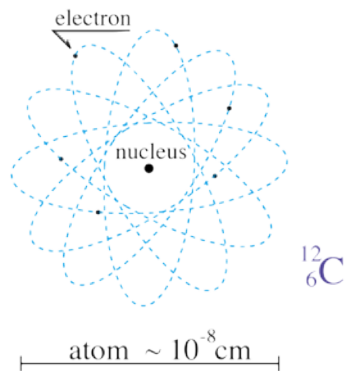


Diamond



Chem. Str.

atom and nucleus



**The nucleus in an atom is compatible to Japanese pinball (~1 cm) in Tokyo Dome (100m).
A neutron is about 1/10 of a nucleus.
Hence, it is just about a 1mm ball in Tokyo Dome.**



Nucleus



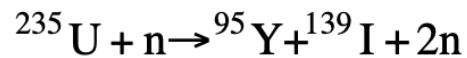
Neutron

Good Material permeability

Neutron generation (1)

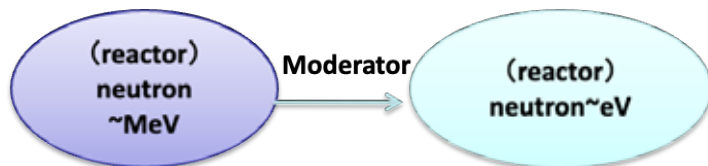
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1. Reactor: fission of uranium-235



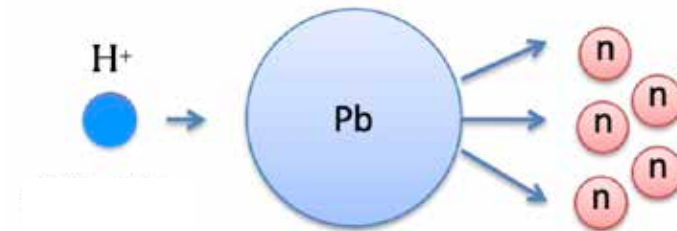
$$\begin{array}{ccccccc} 235 & + & 1 & > & 95 & + & 139 & + & 2 & \text{mass defect} & \Delta E = mc^2 \\ (236) & & & & (244) & & & & & & \end{array}$$

- * Generation of 2~3 neutron by 1 fission
- * Energy of ca. 200MeV $\approx 3.2 \times 10^{-11}$ J
(8.2×10^{10} J/1g U)



Maxwell distribution characterized by the temperature of the moderator

2. accelerator: spallation



When a proton with an energy of 1 GeV hits a target nucleus, 20 to 25 neutrons are produced.

$$(*) \quad E = (3.2 \times 10^{-11}[\text{J}]) \times (6.02 \times 10^{23})/235 \approx 8.2 \times 10^{10}[\text{J}]$$

Neutron velocity/energy distribution

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The velocity distribution of neutrons in a nuclear reactor has the same shape as that of a monatomic gas.

<Review> Velocity distribution of monatomic gases

Maxwell–Boltzmann distribution

$$f(v) = 4\pi v^2 \left(\frac{m_n}{2\pi k_B T} \right)^{3/2} \exp\left(-\frac{m_n v^2}{2k_B T}\right)$$

Most probable velocity

$$v_{mp} = \sqrt{\frac{2k_B T}{m_n}} \quad m_n : \text{neutron mass}$$

Average velocity

$$\bar{v} \equiv \langle v \rangle = \int_0^\infty v f(v) dv = \sqrt{\frac{8k_B T}{\pi m_n}}$$

Distribution fn.
velocity

Root mean square velocity

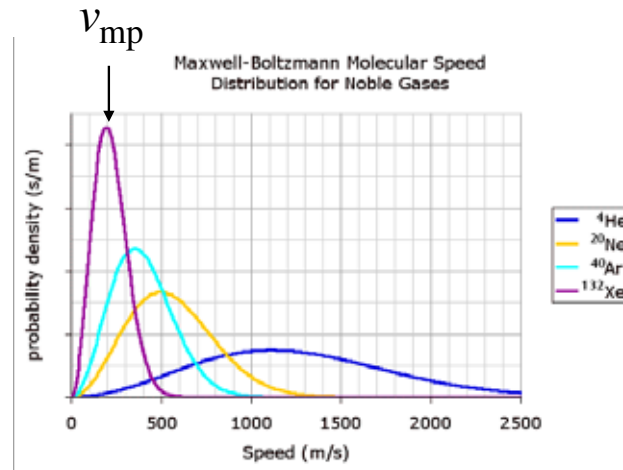
$$v_{rms} \equiv \sqrt{\langle v^2 \rangle} = \sqrt{\frac{3k_B T}{m_n}} \quad \langle v^2 \rangle = \int_0^\infty v^2 f(v) dv$$

$$v_{mp} : \bar{v} : v_{rms} = \sqrt{2} : \sqrt{8/\pi} : \sqrt{3}$$

Relationship between Energy and Speed

$$E = \frac{1}{2} m_n v_{mp}^2 = k_B T \quad (\text{neutron})$$

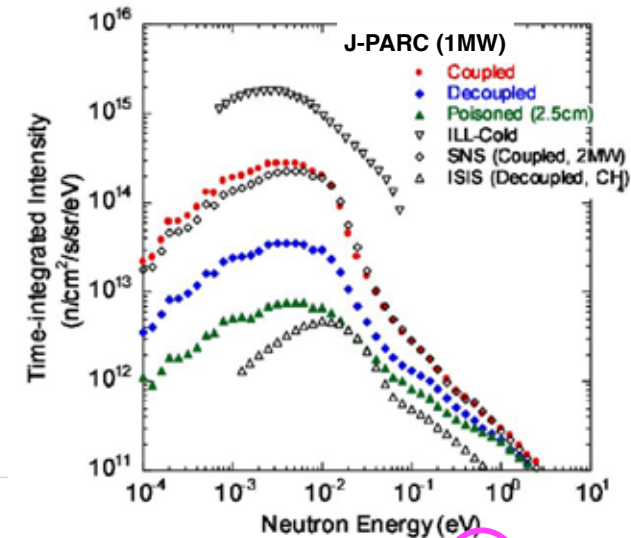
(monatomic gases)



$$E = \frac{1}{2} m_i v_{rms}^2 = \frac{3}{2} k_B T$$

m_i : mass of monoatomic gas

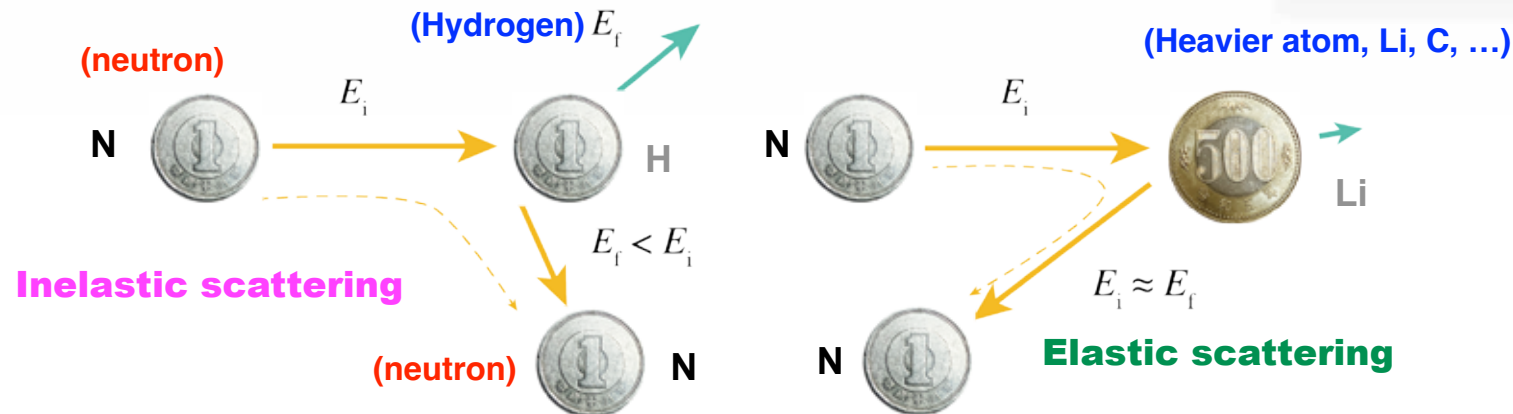
(neutron)



$$E = \frac{1}{2} m_n v_{mp}^2 = k_B T$$

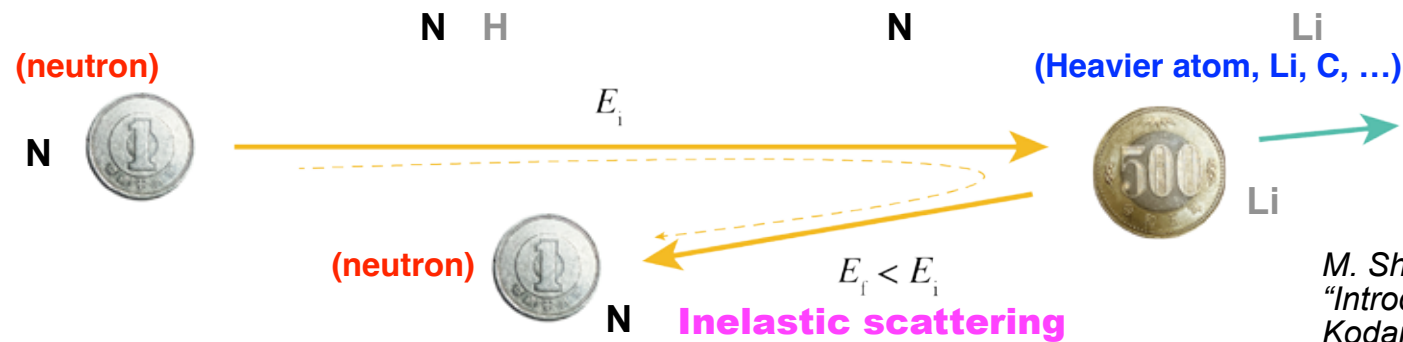
Neutron velocity (energy) and elastic/inelastic scattering

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(a) collision of 1 yen (1g) coins

(b) collision of 1 yen coin (1g) to 500 yen (7g) coin



(c) collision of 1 yen coin (1g) to 500 yen (7g) coin with a high speed

M. Shibayama,
"Introduction to Neutron Scattering",
Kodansha, 2025. (Jpn)



Elastic/Inelastic scattering depends mass and temperature (velocity) difference between neutron stars and atom.

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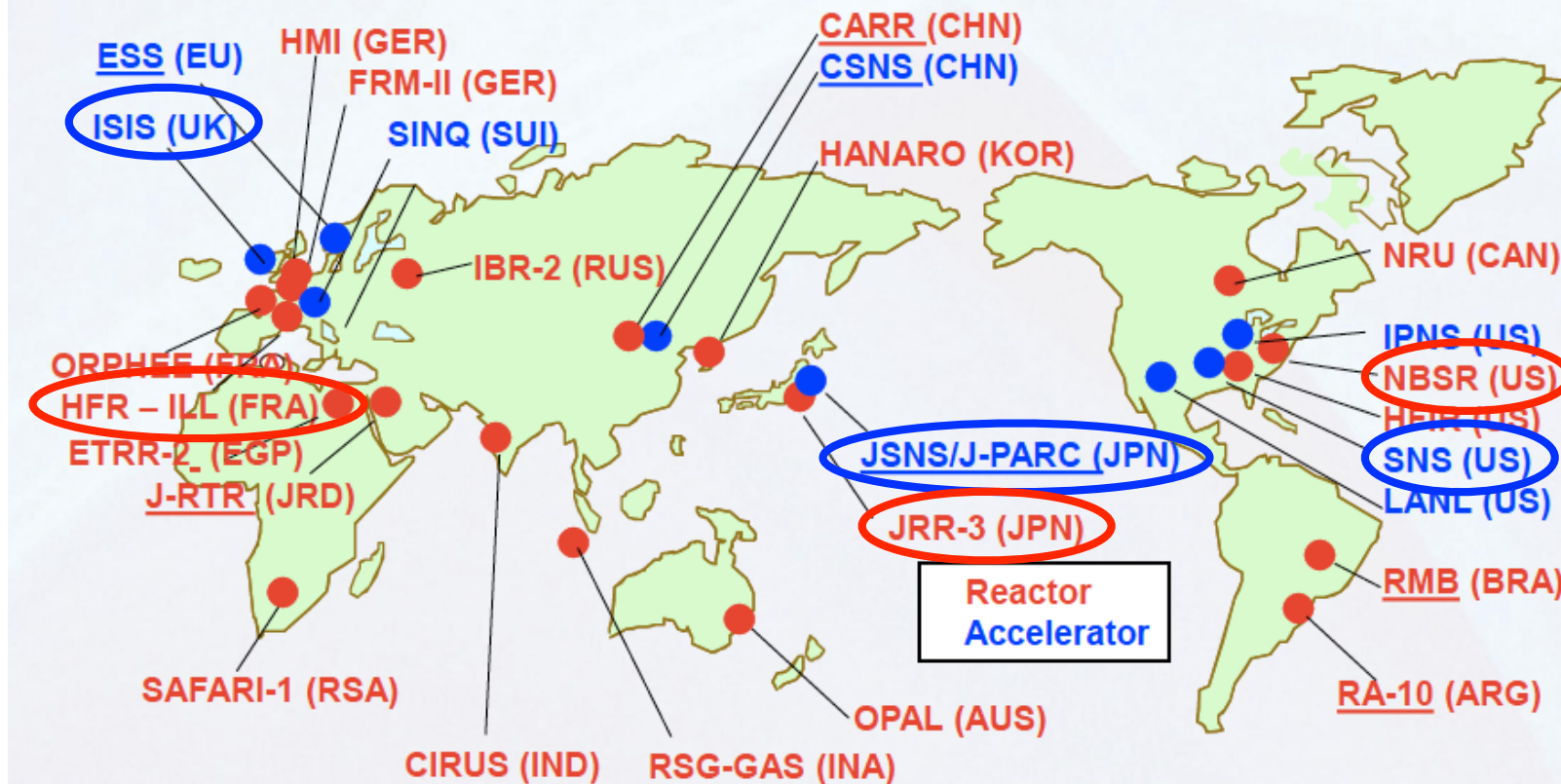
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Major neutron facilities in the world

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Major Neutron Beam Facilities Worldwide

Underlined names show facilities in planning or construction phase



ILL (Institut Laue Langevin) (France)

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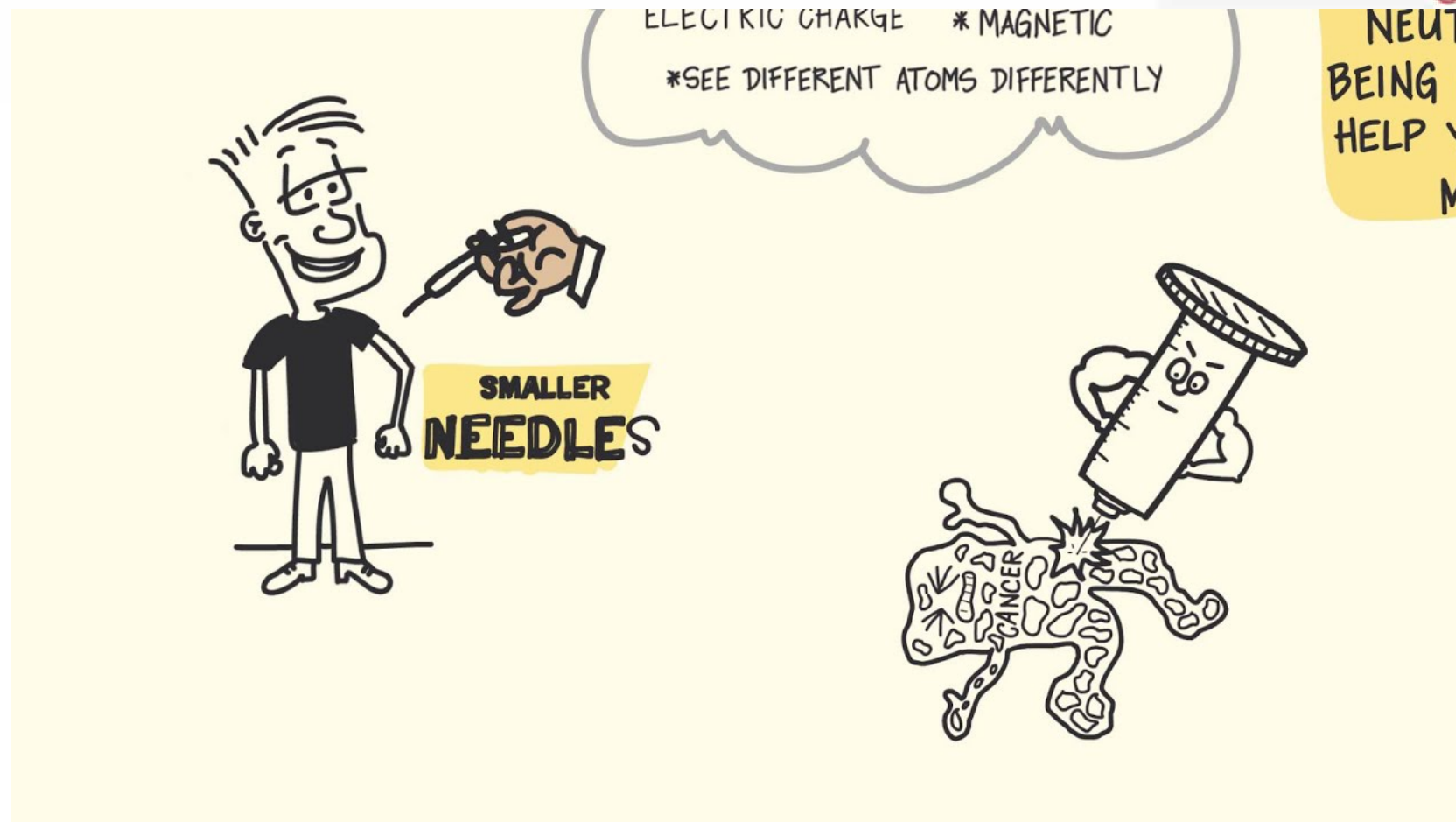
2' 52"

<https://www.ill.eu/about-the-ill/ill-at-a-glance>

https://youtu.be/xrQgURmcAlc?si=TekXI_COy0csnYlk

NIST neutron center (USA)

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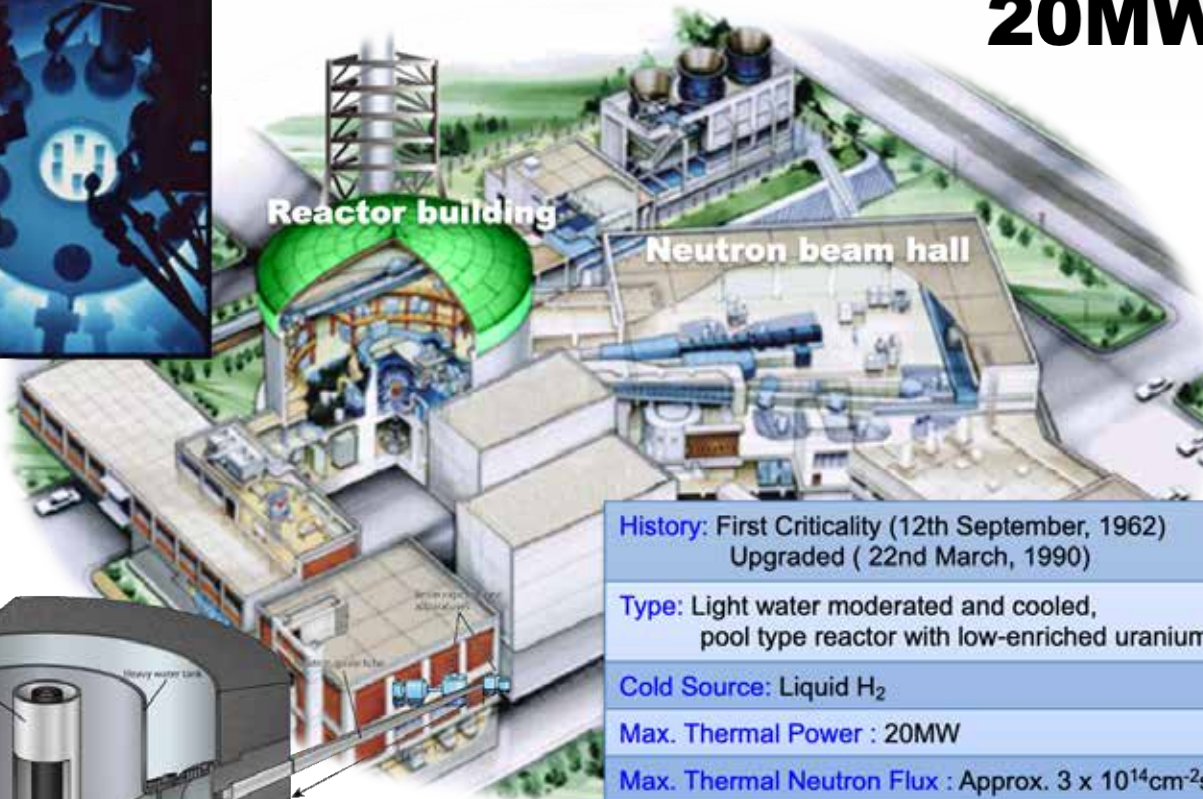
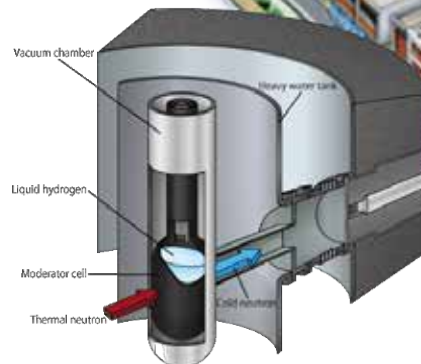
<https://www.youtube.com/watch?v=ZHSm6ZcGpkA>

2' 32"

Japan Research Reactor 3 (JRR-3)

20MW

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History: First Criticality (12th September, 1962)
Upgraded (22nd March, 1990)

Type: Light water moderated and cooled,
pool type reactor with low-enriched uranium

Cold Source: Liquid H₂

Max. Thermal Power : 20MW

Max. Thermal Neutron Flux : Approx. $3 \times 10^{14} \text{cm}^{-2}\text{s}^{-1}$

Operation Mode : Cycle Operation, 26 days/cycle
6-7cycle Operation/year

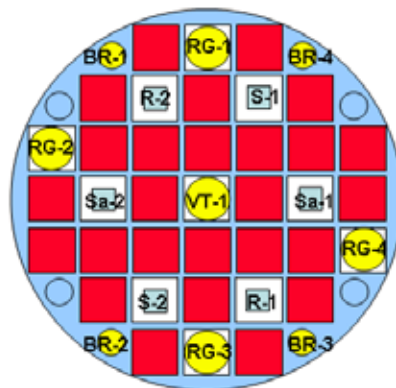
Award : American Nuclear Society Nuclear Historic
Landmark Award August 2007

3

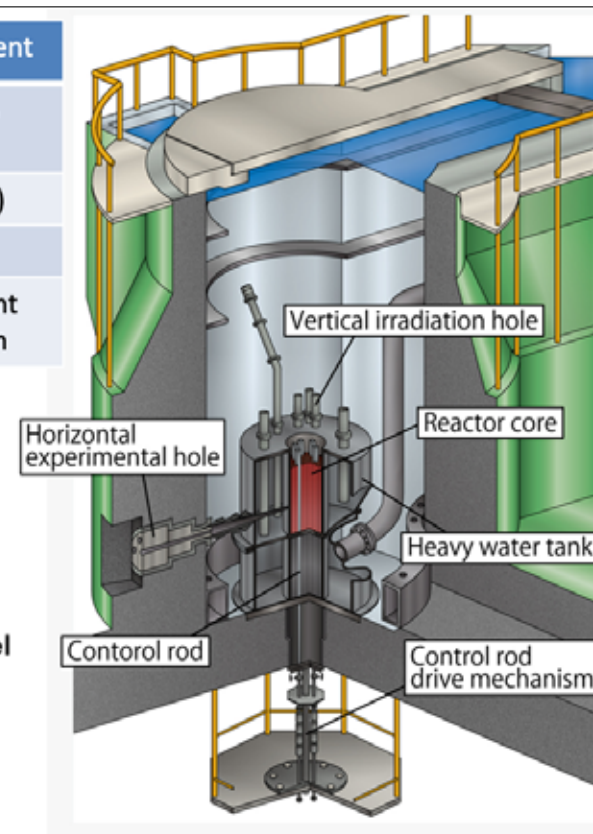
Specification of Fuel

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	Standard fuel element	Follower fuel element
Enrichment of U-235	Approx. 20wt%	Approx. 20wt%
Mass of U-235	Approx. 472g	Approx. 302g
Fuel core material	Uranium-Silicon dispersion alloy (U_3Si_2 -Al)	
Cladding material	Aluminum alloy	
Number of fuel plates	21plates/element	17 plates/element
Fuel plate thickness	Approx.1.27mm	Approx. 1.27mm



- Standard Fuel Element
- Control rod with Follower Fuel
- Vertical Irradiation Hole
- Beryllium Reflector



Courtesy of Dr. M. Take
@2019 Asia-Oceania Faculty Director Meeting, CSNS

SNS@ORNL (USA)

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<https://neutrons.ornl.gov/sns>

<https://youtu.be/BKVBkenVWVU?si=IXp8g0IP-IQXybyY>

3' 21"

J-PARC: Japan Proton Accelerator Research Complex

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What is J-PARC?

Brief Overview of J-PARC



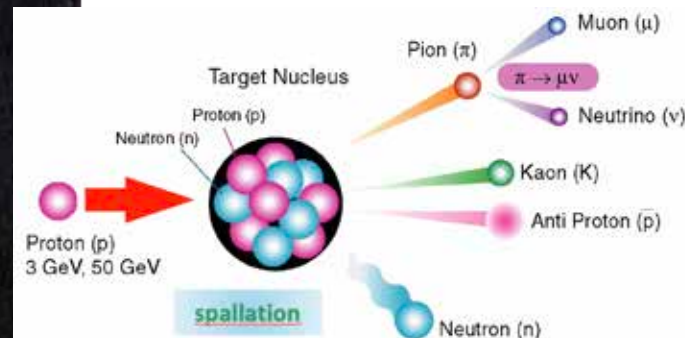
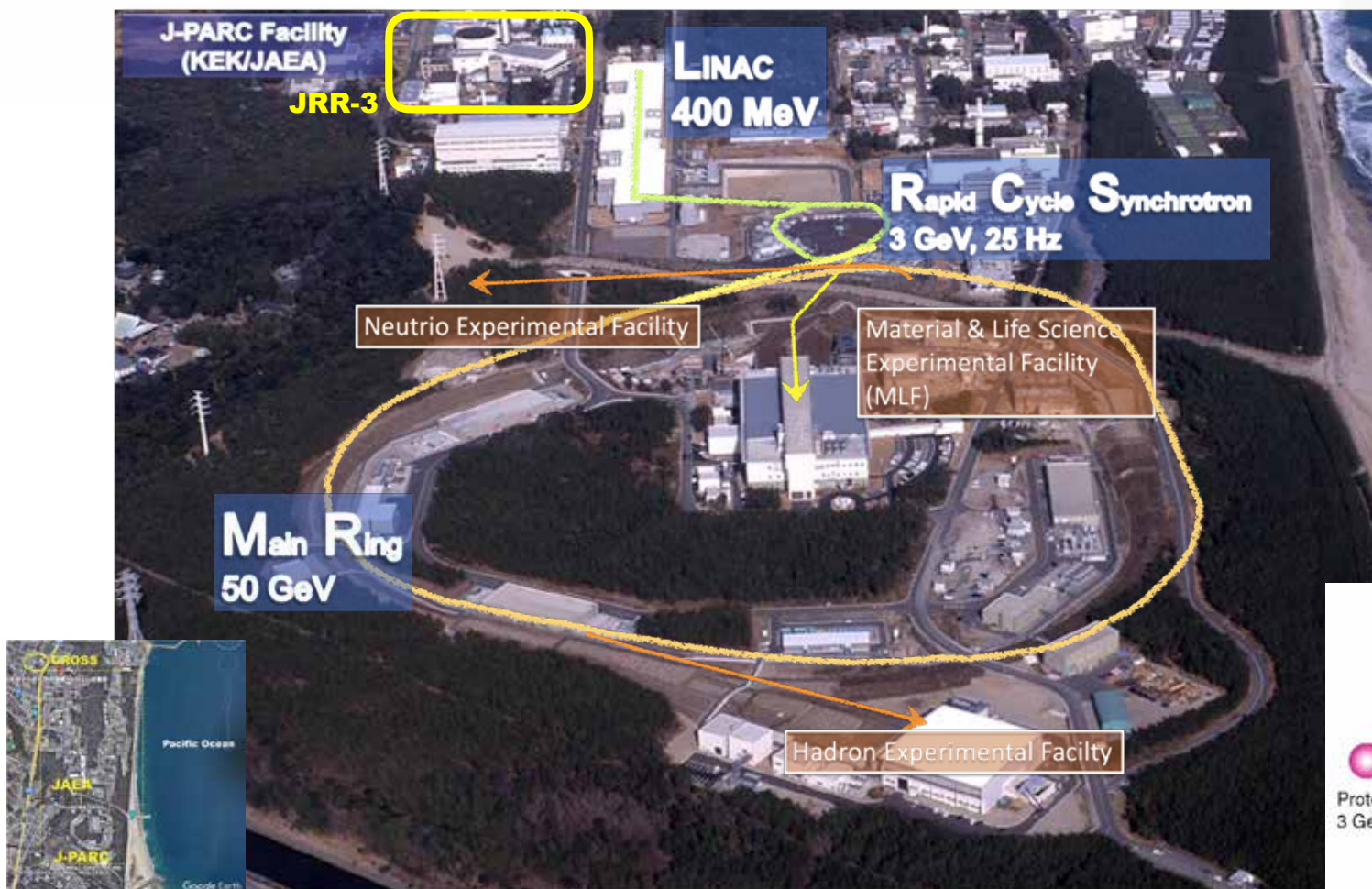
<https://www.youtube.com/watch?v=Ra1l5BwPczg>

3' 08"

J-PARC: Japan Proton Accelerator Research Complex and JRR-3

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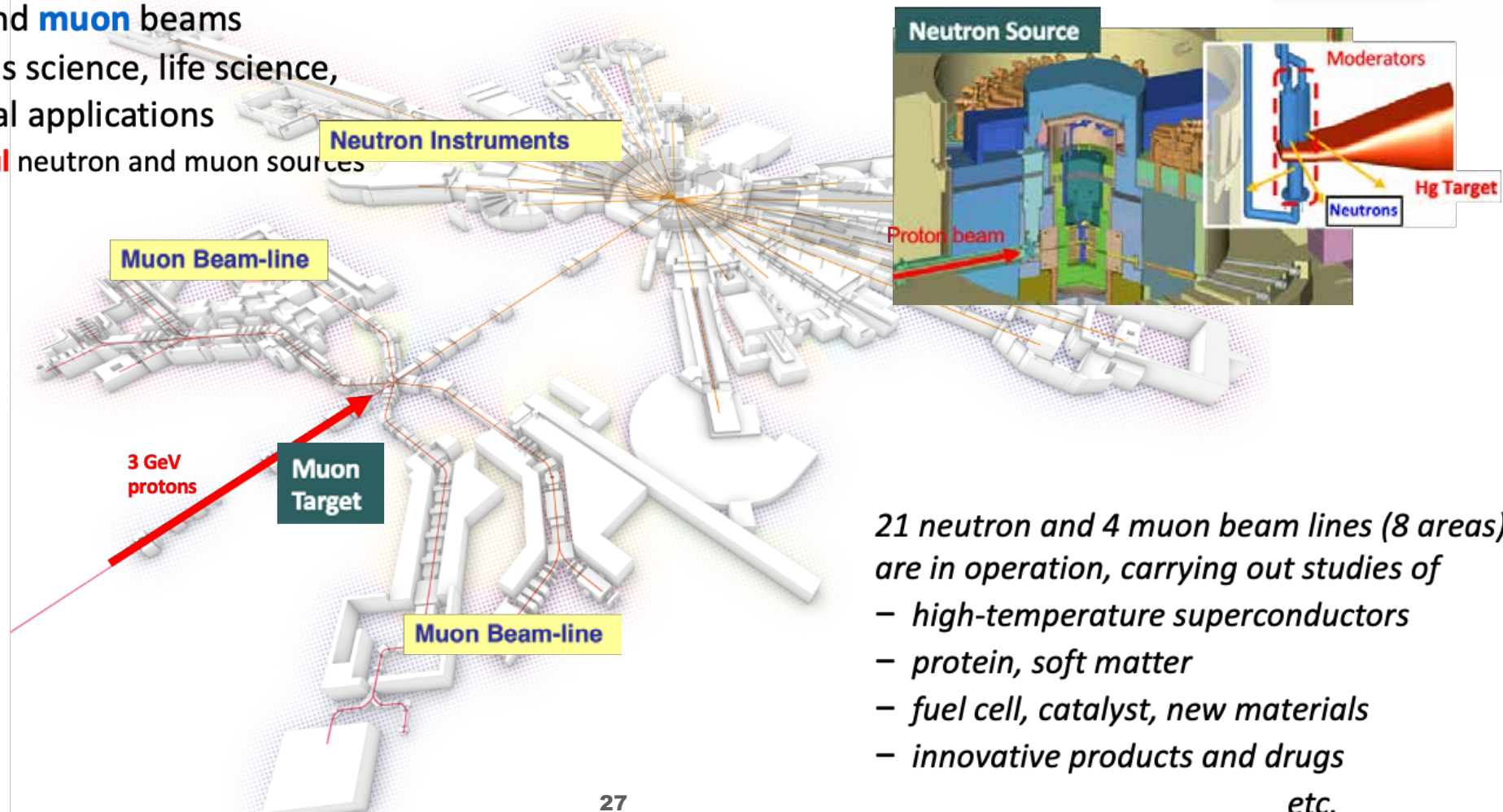
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Materials and Life Science Experimental Facility (MLF)

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- **Neutron** and **muon** beams
 - materials science, life science, industrial applications
- **most powerful** neutron and muon sources



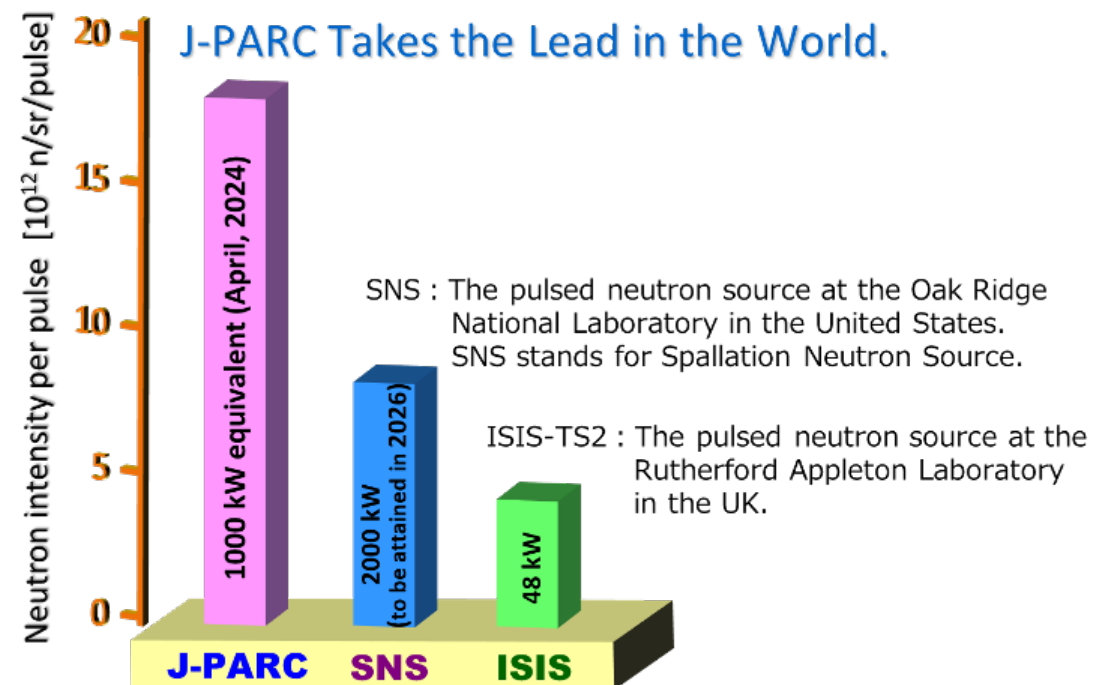
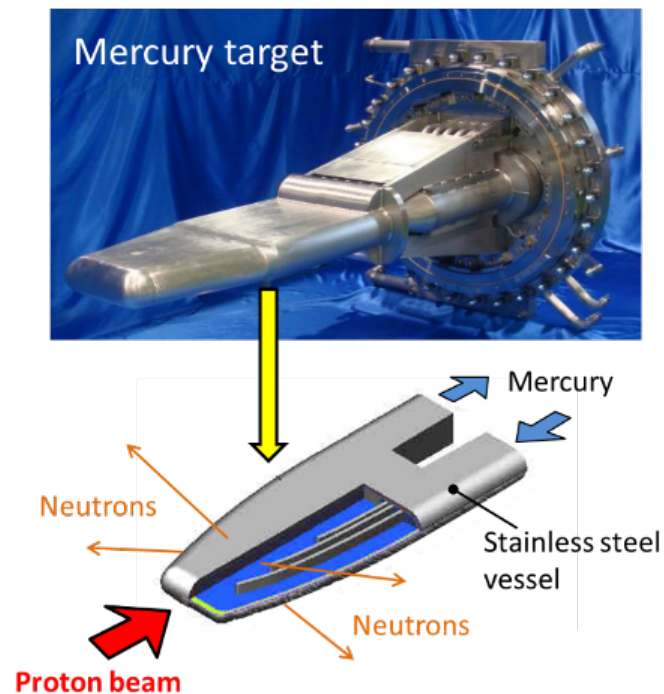
J-PARC MLF: Performance

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◆ The World's Most Powerful Pulsed Neutron Source at J-PARC MLF Achieved Target Performance (press released on May 31)

- "continuous operation with a proton beam power equivalent to 1000 kW" starting from April 8, 2024



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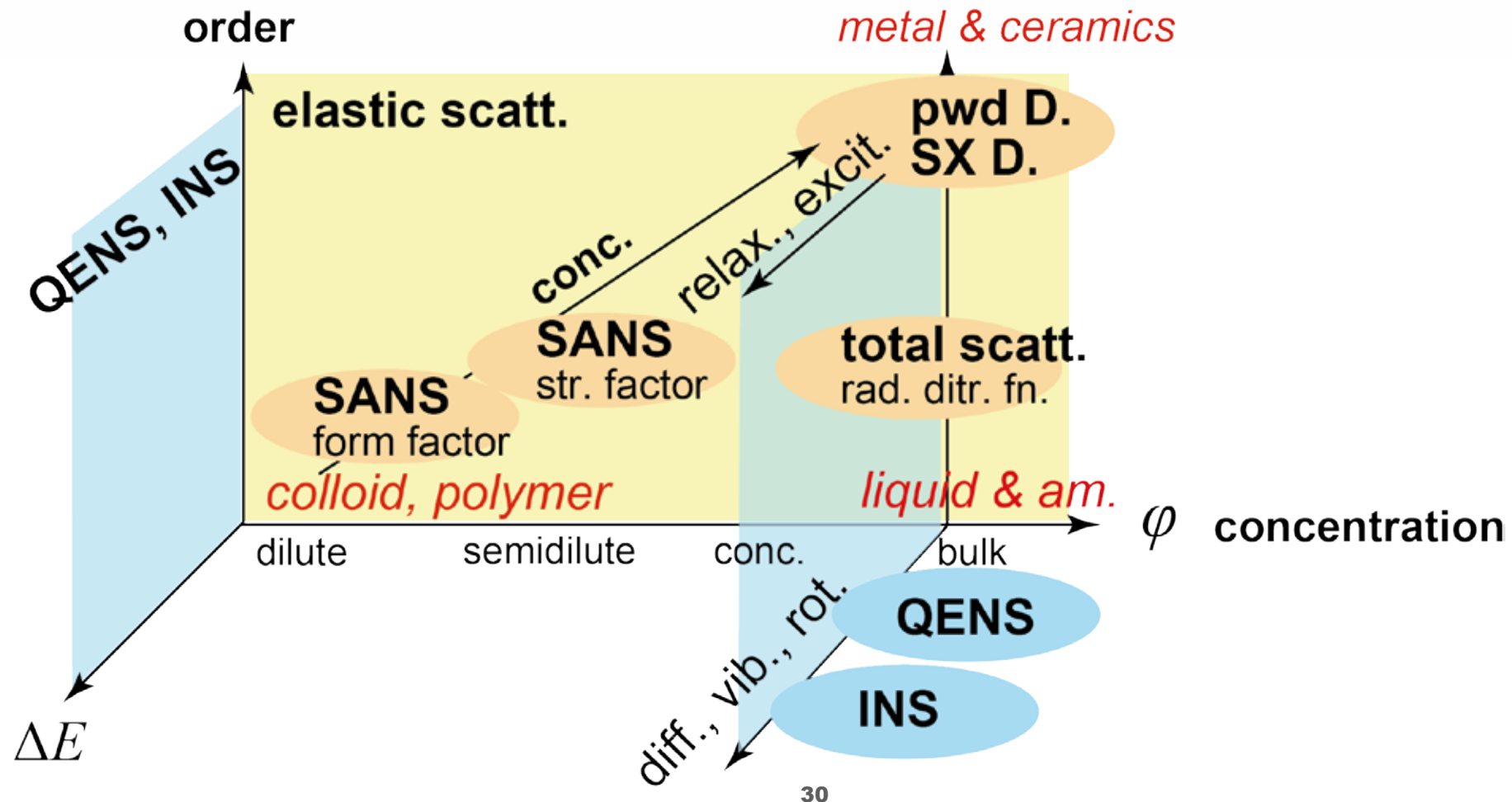
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Various methods of neutron scattering vs materials

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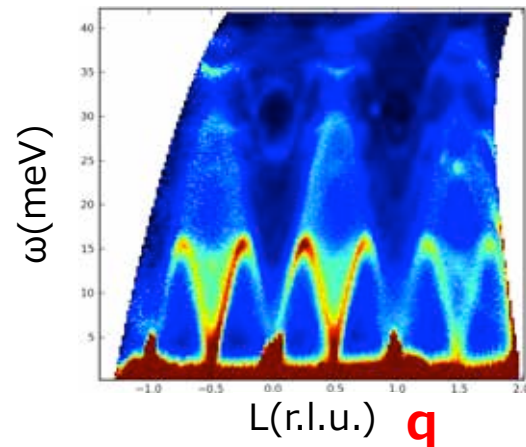


Various neutron scattering methods

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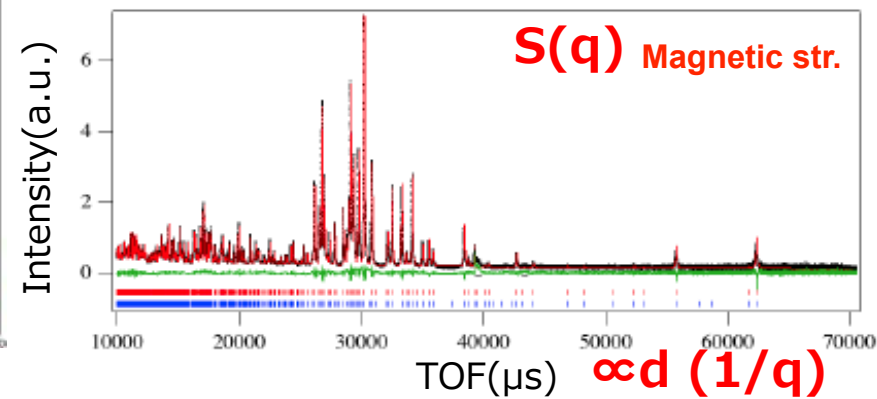
Inelastic scattering

$S(\mathbf{q}, \omega)$ Excitation

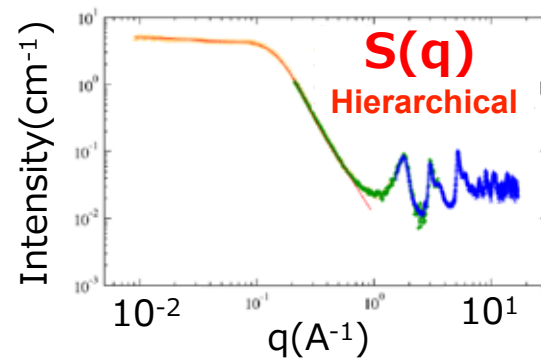


Diffraction

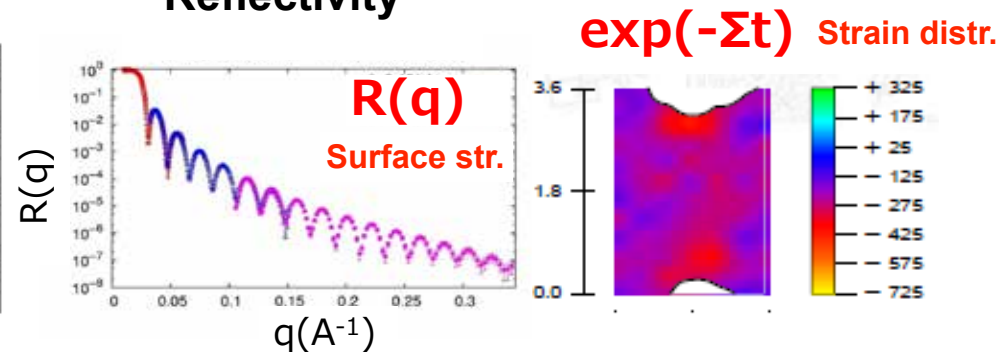
$\times \mathbf{q}, \hbar\omega$: Changes in momentum transfer/energy



Small angle scattering



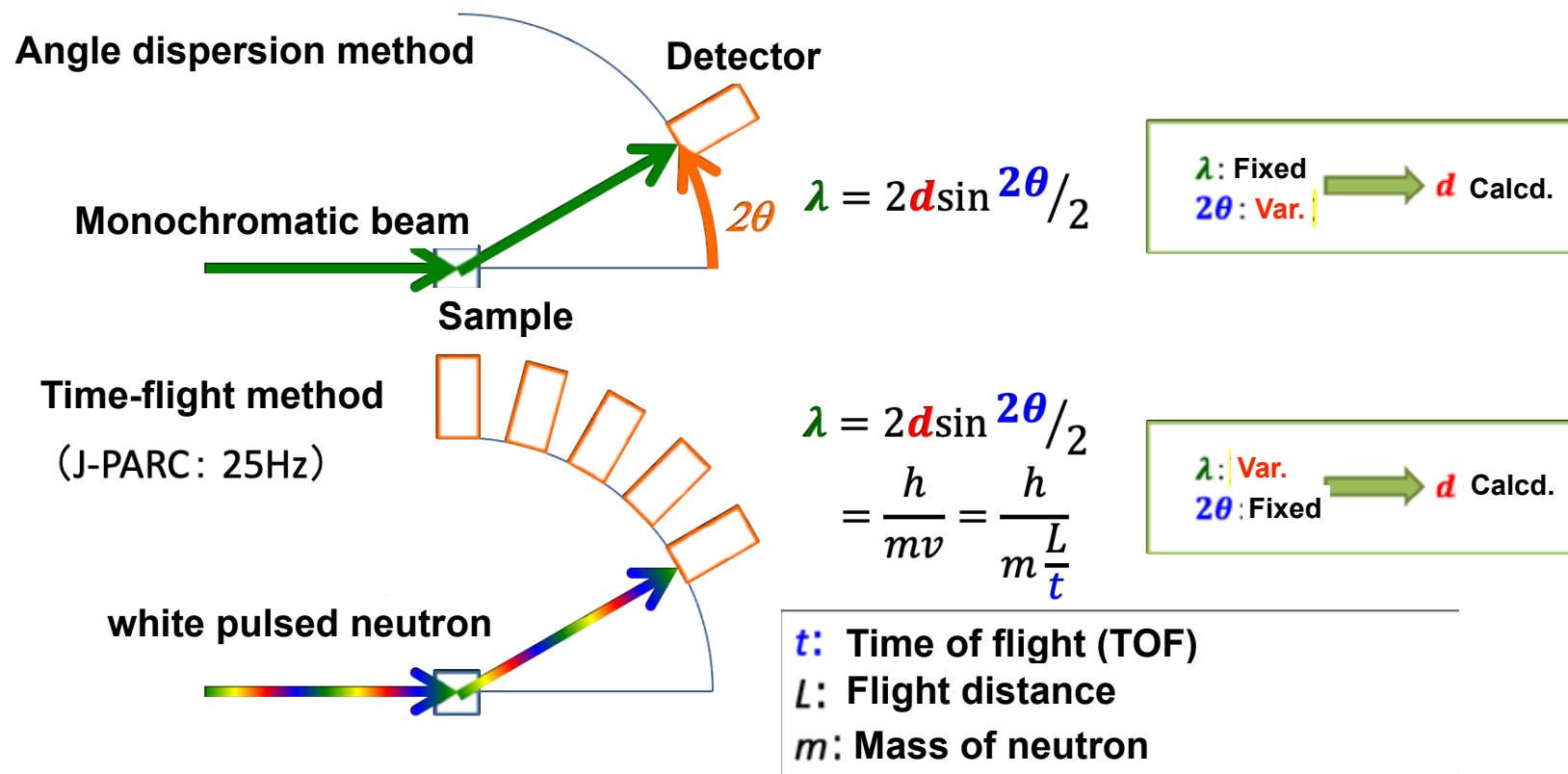
Reflectivity



Two methods of neutron data collection: Angle dispersion vs time-of-flight methods

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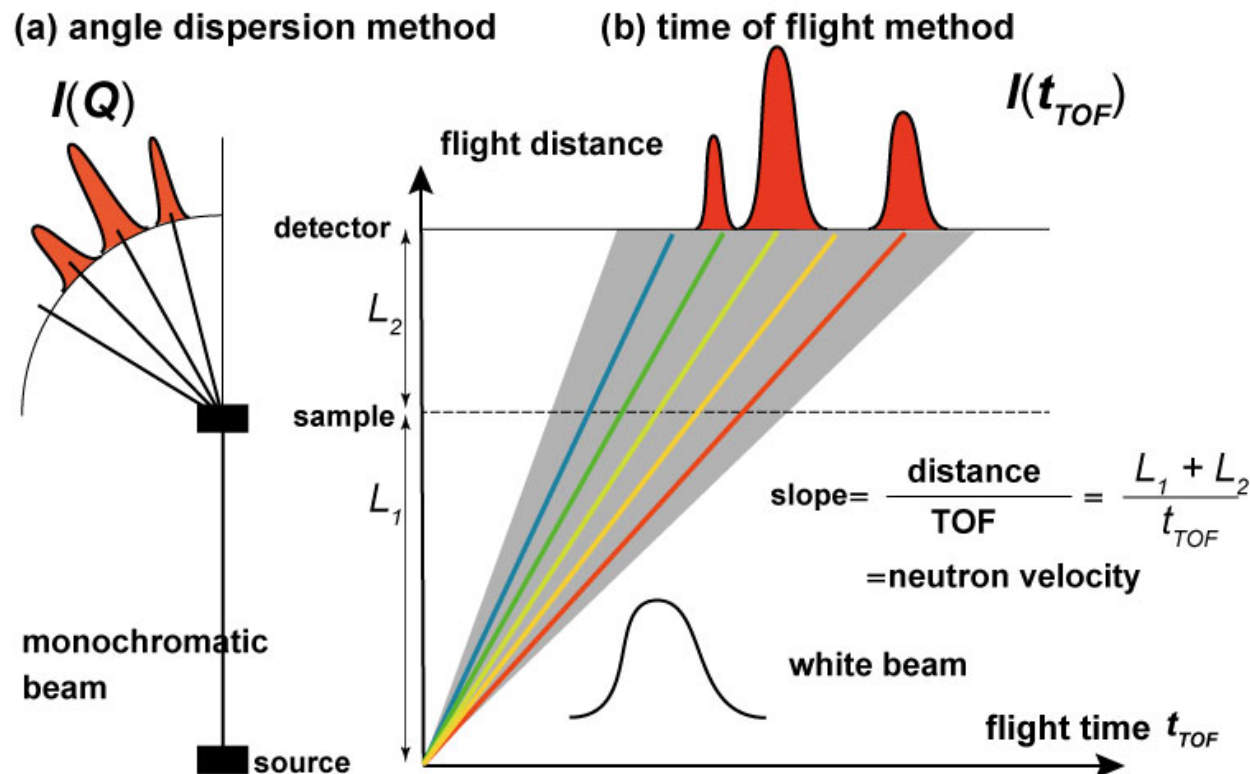


$$t[\mu s] = \lambda[\text{\AA}] \cdot L[\text{cm}] / 0.3956$$

Angle dispersion vs time-of-flight methods (1)

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Elastic scattering (diffraction, scattering, reflection)



$$\text{Velocity: } v = \frac{L}{t}$$

$$\text{Wavelength: } \lambda = \frac{h}{mv} = \frac{ht}{mL}$$

$$\text{Energy: } E = \frac{1}{2}mv^2 = \frac{1}{2}m\left(\frac{L}{t}\right)^2$$

$$\text{Bragg's law: } 2d \sin \theta = \lambda = \frac{ht}{mL}$$

L : Flight path length

t : Time of flight

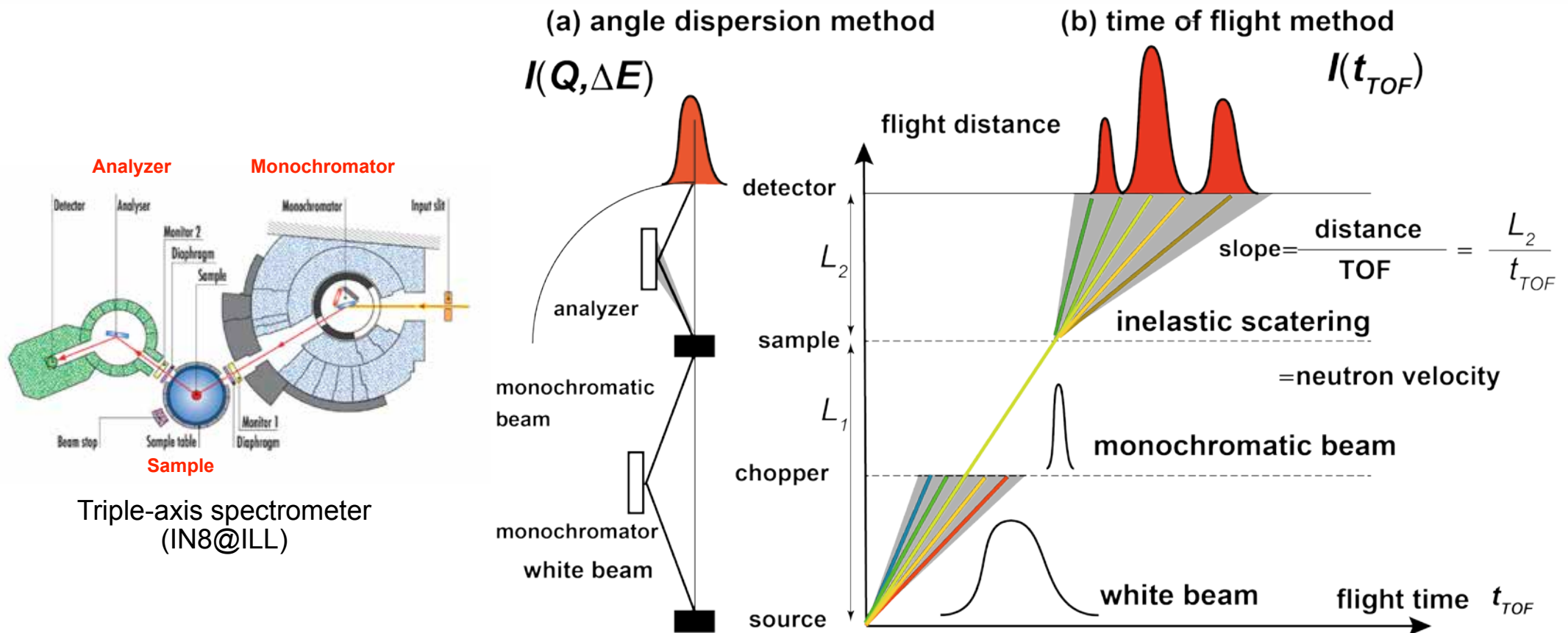
$$t[\mu\text{s}] = \lambda[\text{\AA}] \cdot L[\text{cm}] / 0.3956$$

Q: Calculate the wavelength And the velocity of neutron with TOF = 4000 [μsec] for $L = 4$ [m].

Angle dispersion vs time-of-flight methods (3)

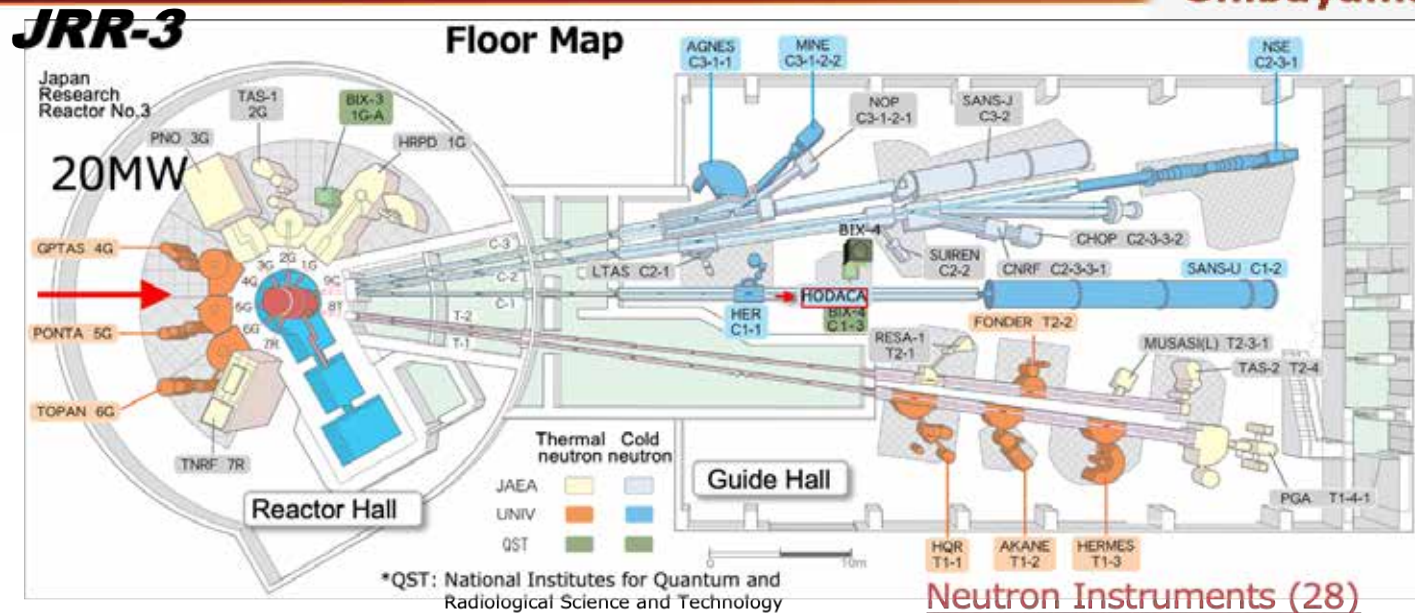
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Inelastic scattering (inelastic, quasi elastic scattering), spin-echo



JRR-3: Japan Research Reactor 3

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Neutron Instruments (28)

- Diffractometer : 7 (JAEA: 3, Univ.: 2, QST: 2)
- Spectrometer : 11 (JAEA: 3, Univ.: 8)
- SANS : 3 (JAEA: 2, Univ.:1)
- Reflectometer : 2 (JAEA: 1, Univ.:1)
- Imaging Fac. : 2 (JAEA)
- Prompt γ -ray analysis : 1 (JAEA)
- Dev. of optical device / Test port : 3 (JAEA: 2, Univ.: 1)

Reactor Hall



Guide Hall

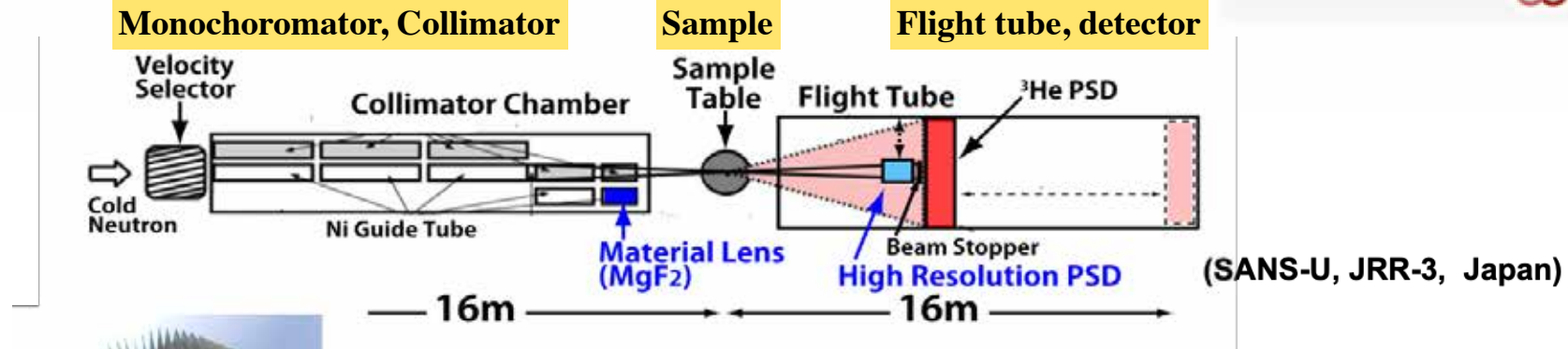


Typical angle disp. Instrument, SANS (SANS-U, JRR-3)

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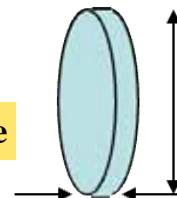
Okabe, et al., Nuclear Inst. and Methods in Physics Research, A, 2007, 572, 853.

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Typical sample size

Sample

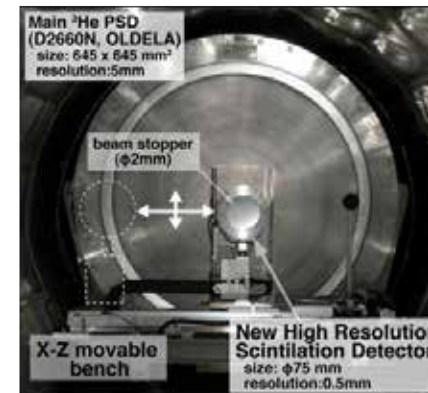


1.0 ~ 2.5 cm
(beam diameter)

0.1 ~ 10 mm



Sample holder



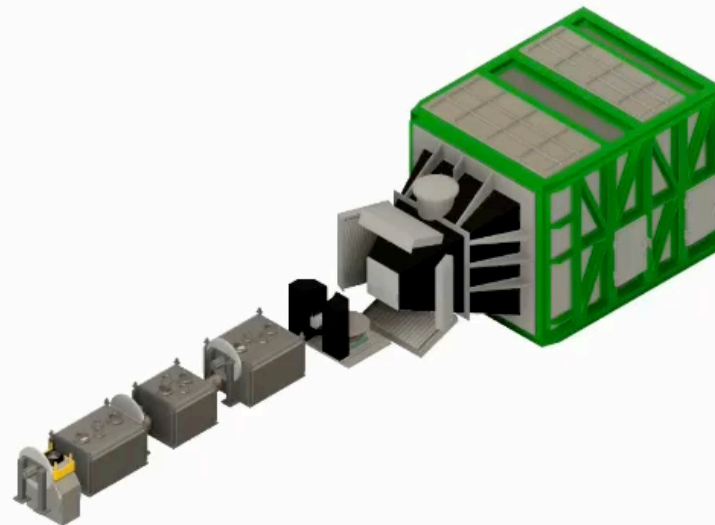
J. Appl. Crystallogr., 2011, 44, 558.

- SANS is used for structural investigation for solid, liquid, polymers, etc., of the order of **1 nm – 100 nm**.

Typical TOF Instrument, SANS (BL15 TAIKAN@J-PARC)

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Neutron Instruments at J-PARC MLF

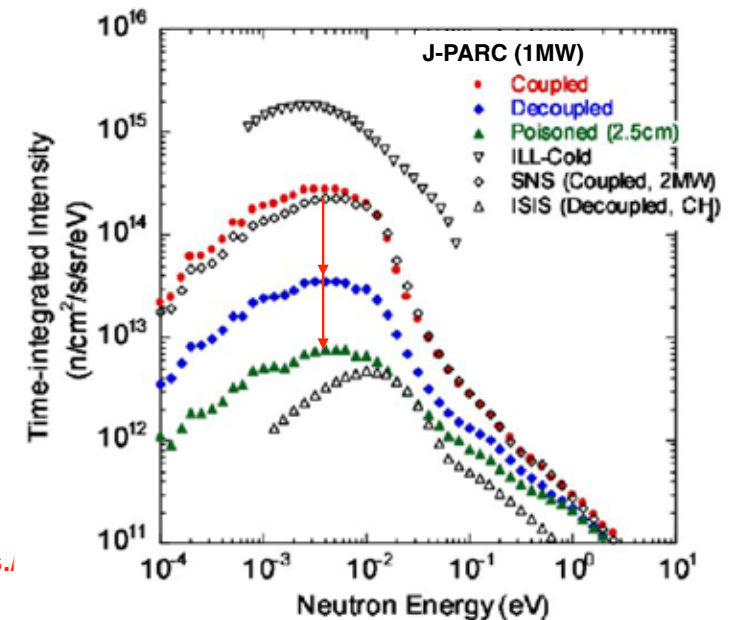
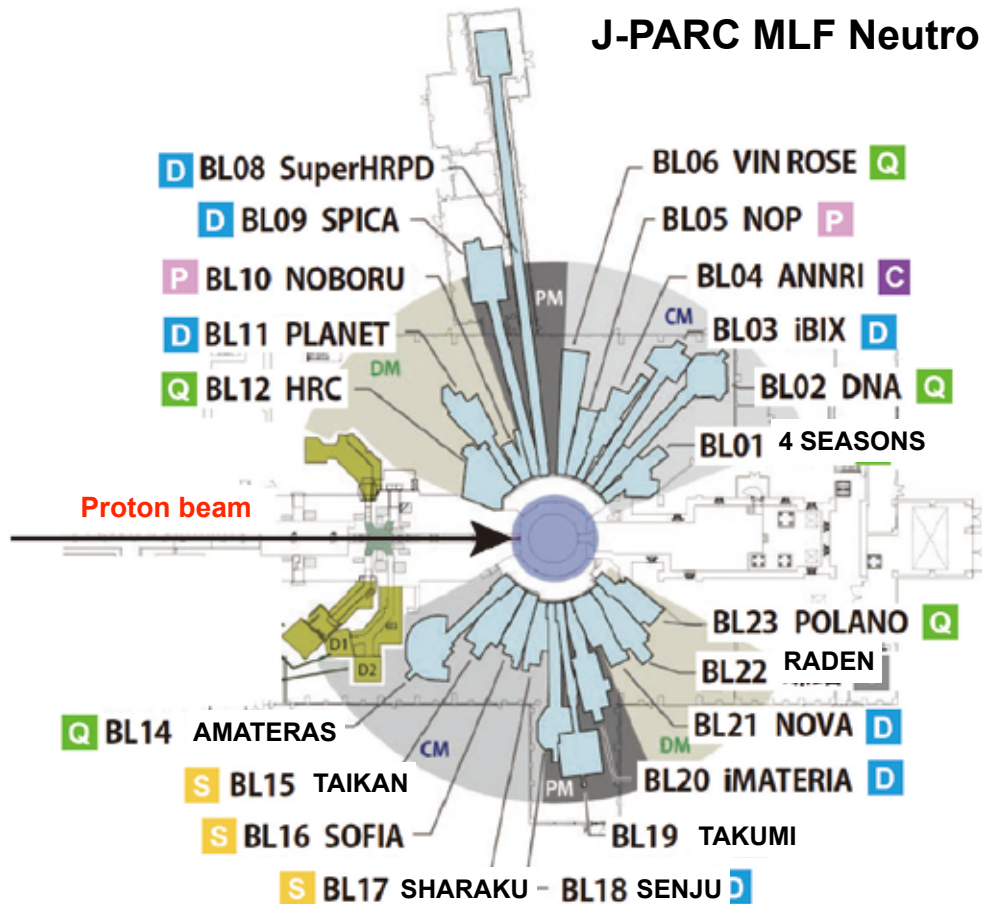
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MLF : Materials and Life Science Experimental Facility

J-PARC MLF Neutron Instruments layout

CM; coupled (high intensity)
DM; decoupled (high resolution)
PM; Poison (very high resolution)

D Diffraction
S Diffraction/Reflection
Q Quasielastic/Inelastic
I Imaging
C Cross section/Prompt gamma
P Fundamental Phys./Device Develop.



Neutron Instruments at MLF

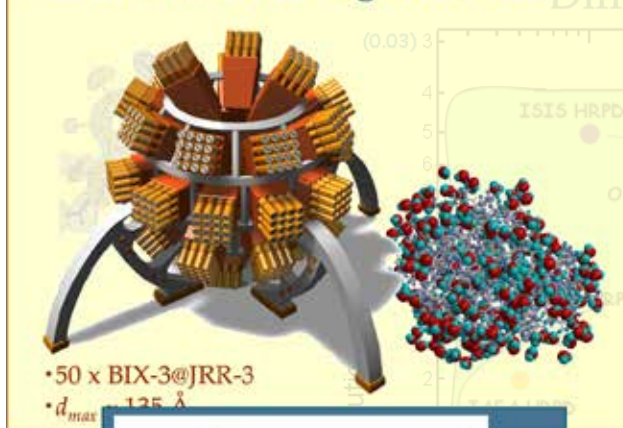
Shibayama,  CROSS



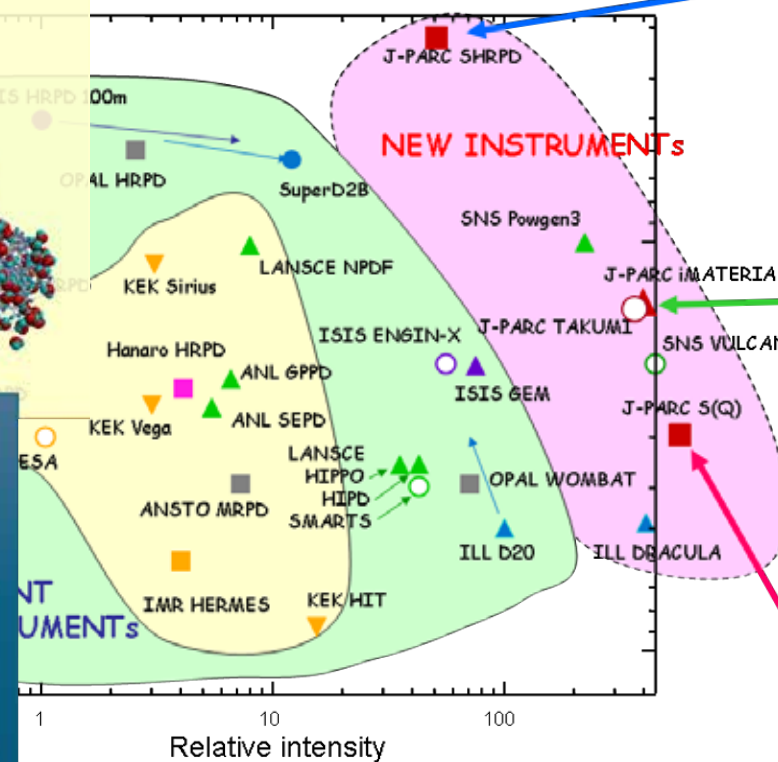
Crystal Structure

Shibayama,  CROSS

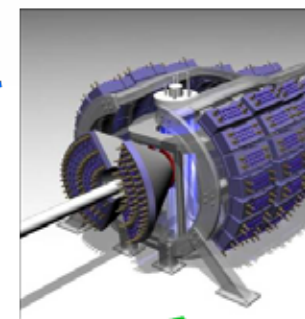
Ibaraki Biomaterial Single-Xtal Diff.



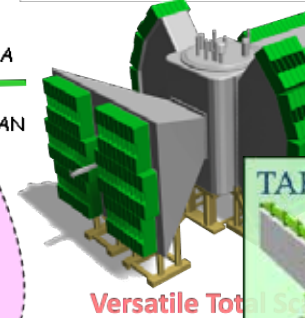
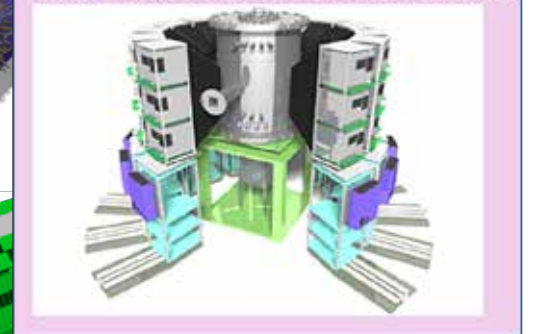
Diffractometer in the World



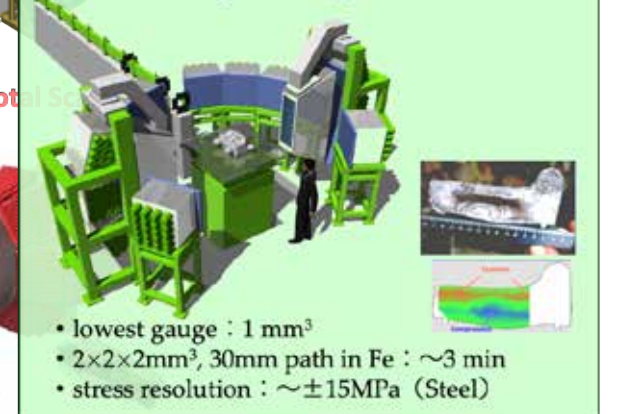
SHRPD



BL18, SENJU
Single Crystal Neutron Diffractometer

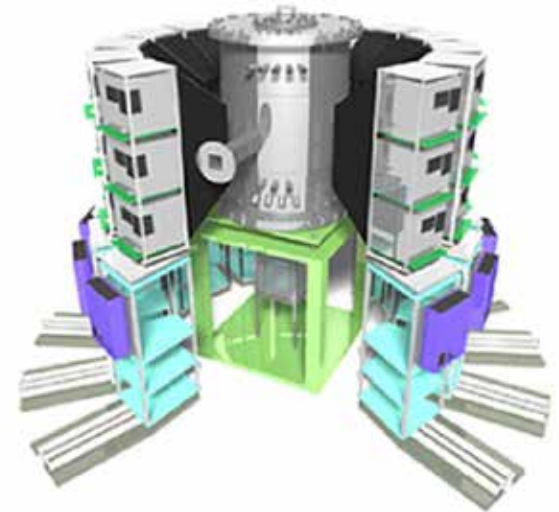
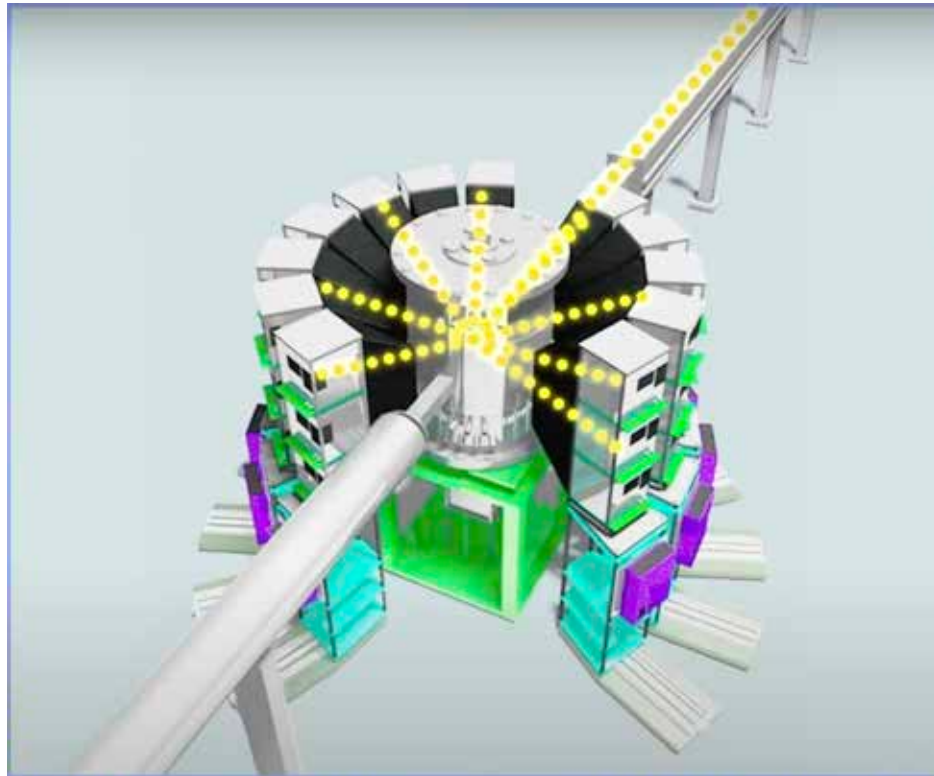


TAKUMI: Engineering Materials Diff.



SENJU 千手 (BL18): Single crystal

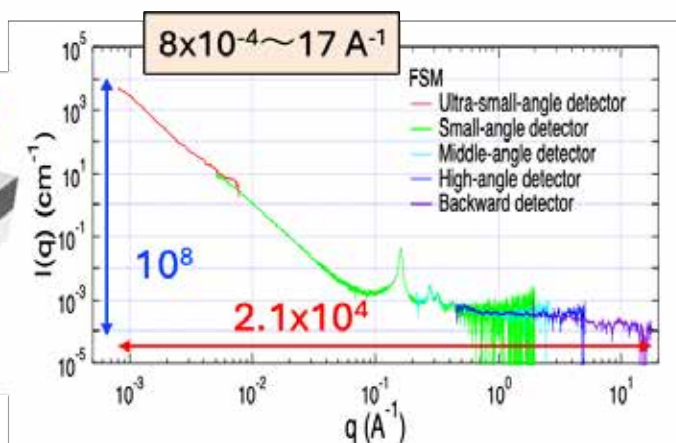
Shibayama,  CROSS



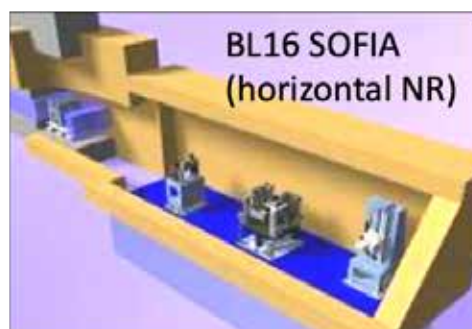
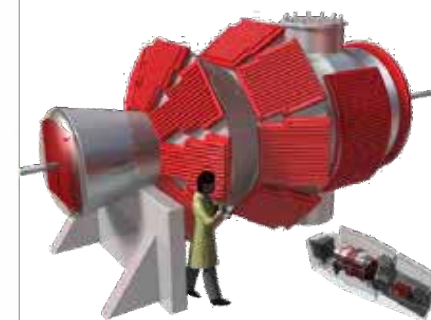
Nano Structure

Shibayama, CROSS

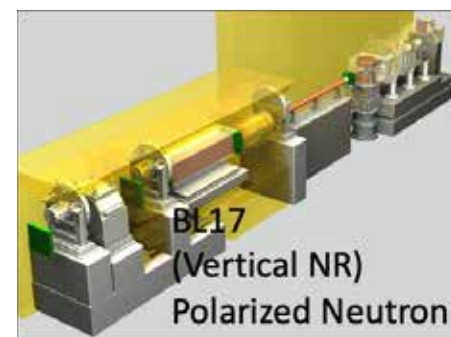
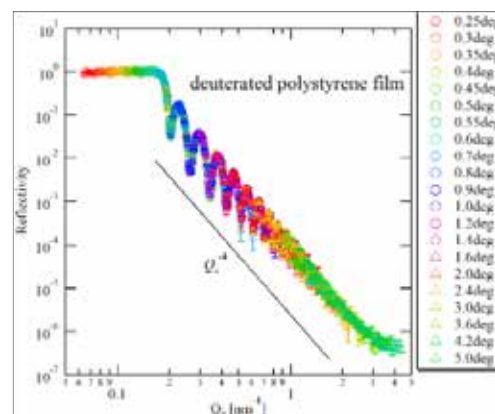
BL15 TAIKAN
(SANS)



BL21 Versatile Total
Scattering Diff. (NOVA)



BL16 SOFIA
(horizontal NR)



BL17
(Vertical NR)
Polarized Neutron

SANS/WANS

NR

BL15 TAIKAN

CUHK Lecture, M. Shibayama
2025.8.10 - 16

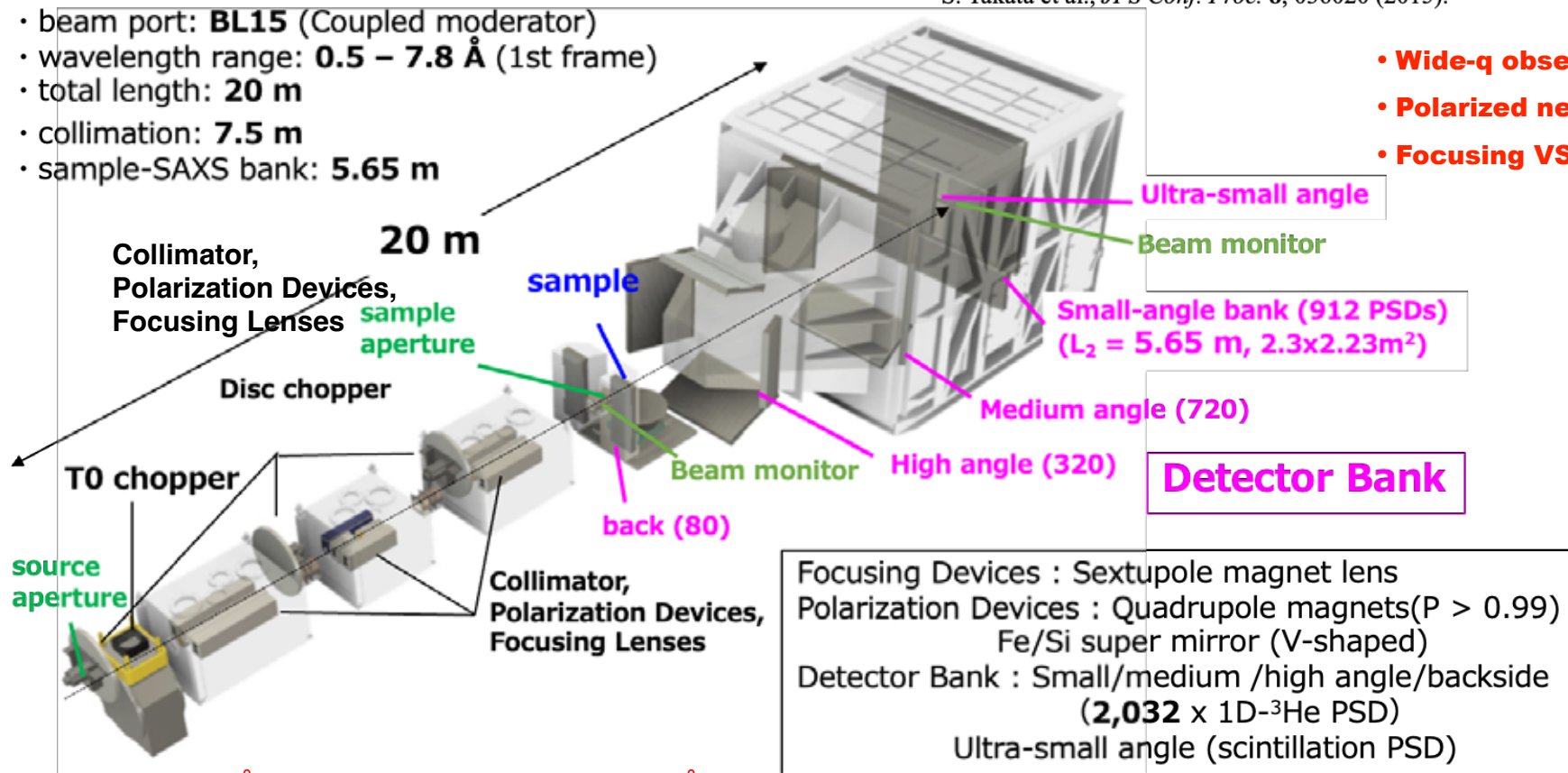
Small and Wide Angle Neutron Scattering Instrument

Shibayama, CROSS

Time-of-Flight Small and Wide angle Neutron Scattering Instrument

S. Takata et al., *JPS Conf. Proc.* 8, 036020 (2015).

- beam port: **BL15** (Coupled moderator)
- wavelength range: **0.5 – 7.8 Å** (1st frame)
- total length: **20 m**
- collimation: **7.5 m**
- sample-SAXS bank: **5.65 m**



Q-range: $5 \times 10^{-3} - 17 \text{ Å}^{-1}$ (optionally, $Q_{\min} = 8 \times 10^{-4} \text{ Å}^{-1}$)

BL15 TAIKAN: sample environment

CUHK Lecture, M. Shibayama
2025.8.10 - 16

Presented at SAS2024 2024.11. 3 - 11.8 TICC, Taipei

Shibayama,  CROSS

For soft matter

Sample changer

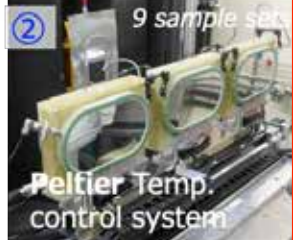
① 10 sample sets



Water circulation chiller + heater control system

$T = 5^{\circ}\text{C} - 180^{\circ}\text{C}$
(For high temp.)

② 9 sample sets

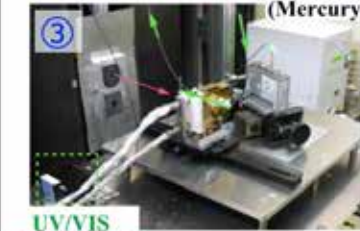


Peltier Temp. control system

$T = -20^{\circ}\text{C} - 80^{\circ}\text{C}$
(For low temp.)

Ultraviolet (UV) / visible (VIS) light control system

③



UV/VIS spectrometer

⑦



humidity cell

80% humidity @ 80°C .

Pressure cell

④



$P_{\text{max}} : 50\text{MPa}$
 $T_{\text{max}} : 500^{\circ}\text{C}$

⑤



Rheometer (Anton Paar :MCR302)

Humidity gas generator

⑥ Automatic control of gas ratios (H_2O and D_2O)

Gas adsorption measuring system (H_2O , CO_2 , H_2 ..)

⑩



Sample changer with humidity chamber

⑧ 7 sample sets 80% humidity @ 80°C .

Stretching machine with load cell

⑨



For hard matter

Magnets

①



10T magnet with Laser heating furnace

②



4T magnet with Dilution refrigerator

$0.3\text{K} < T < 300\text{K}$

③



1T magnet

④



4K cryostat

⑤



Laser heating furnace

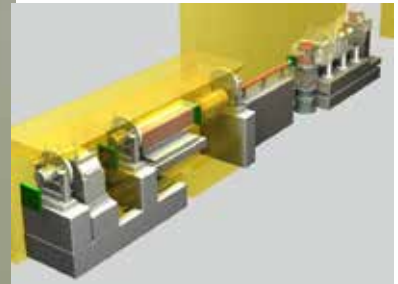
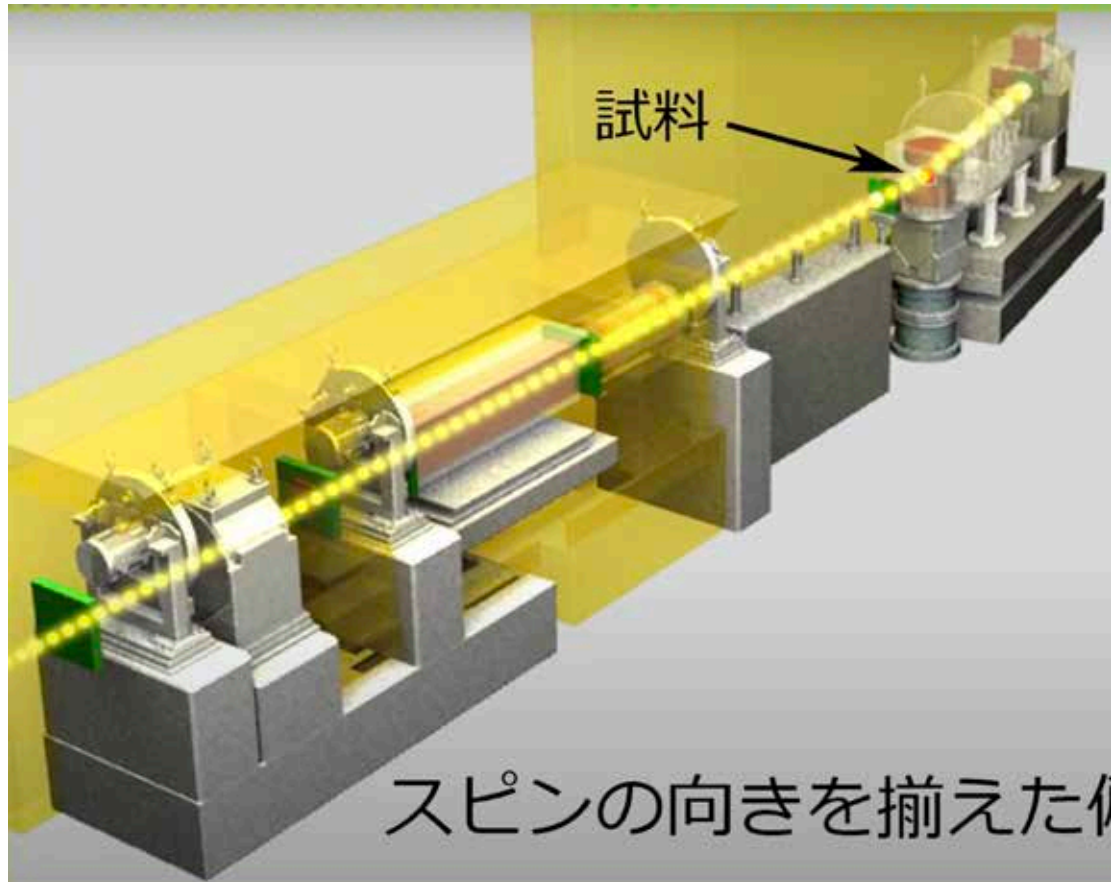
$T = \sim 1300\text{K}$

44

Courtesy of Dr. Shinichi Takata, BL15

SHARAKU 写楽 (BL17): Reflectivity

Shibayama,  CROSS



Spectroscopy

Shibayama,  CROSS

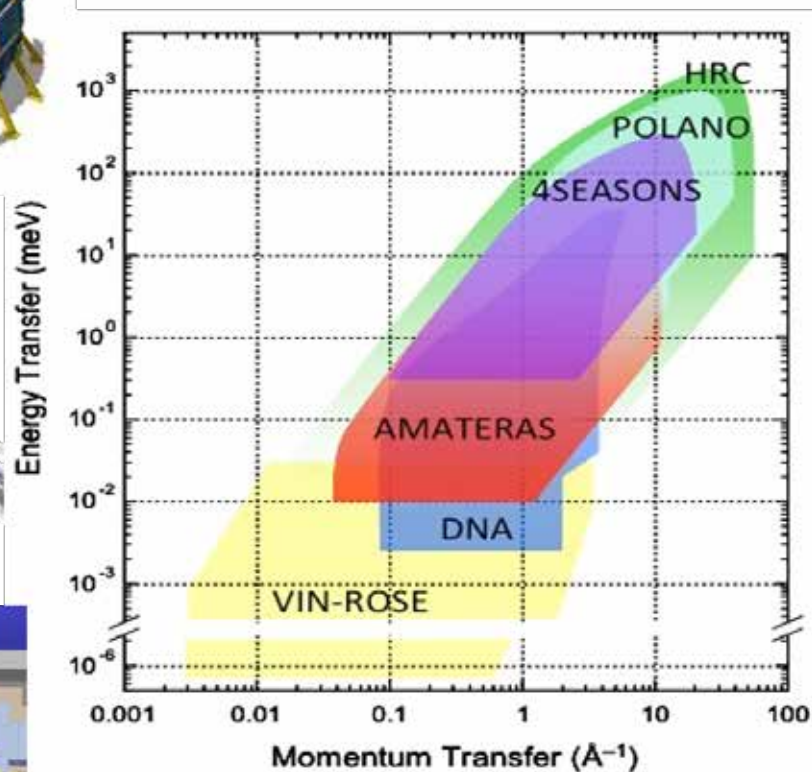
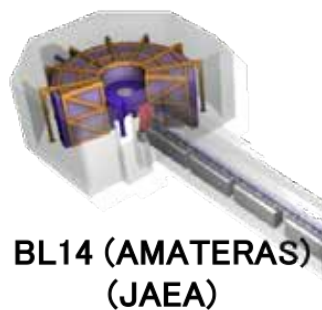
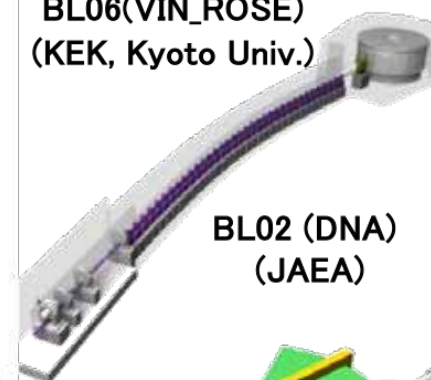
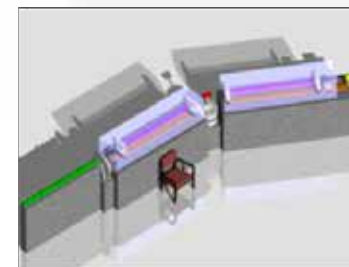
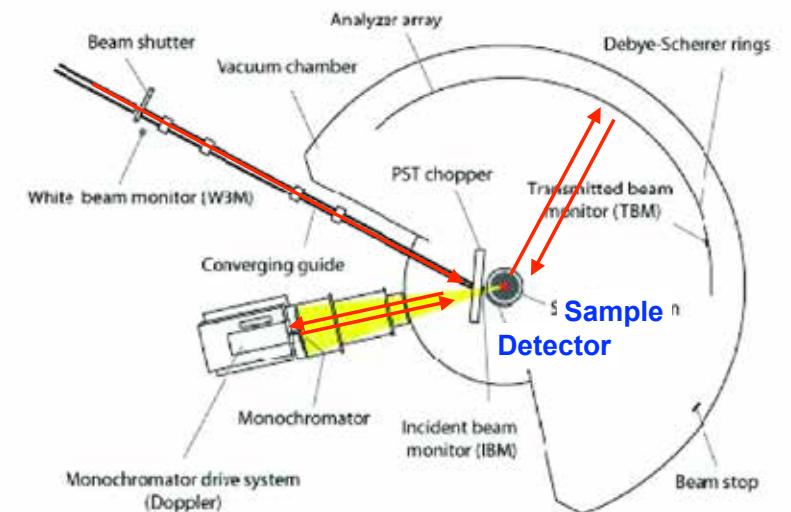
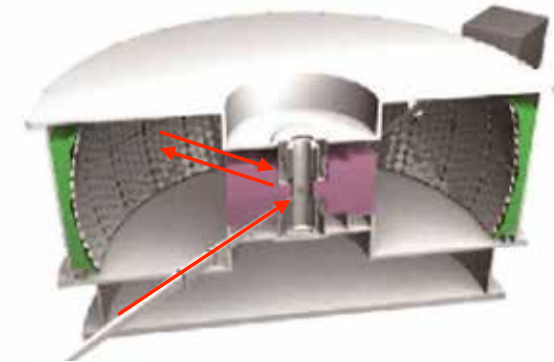
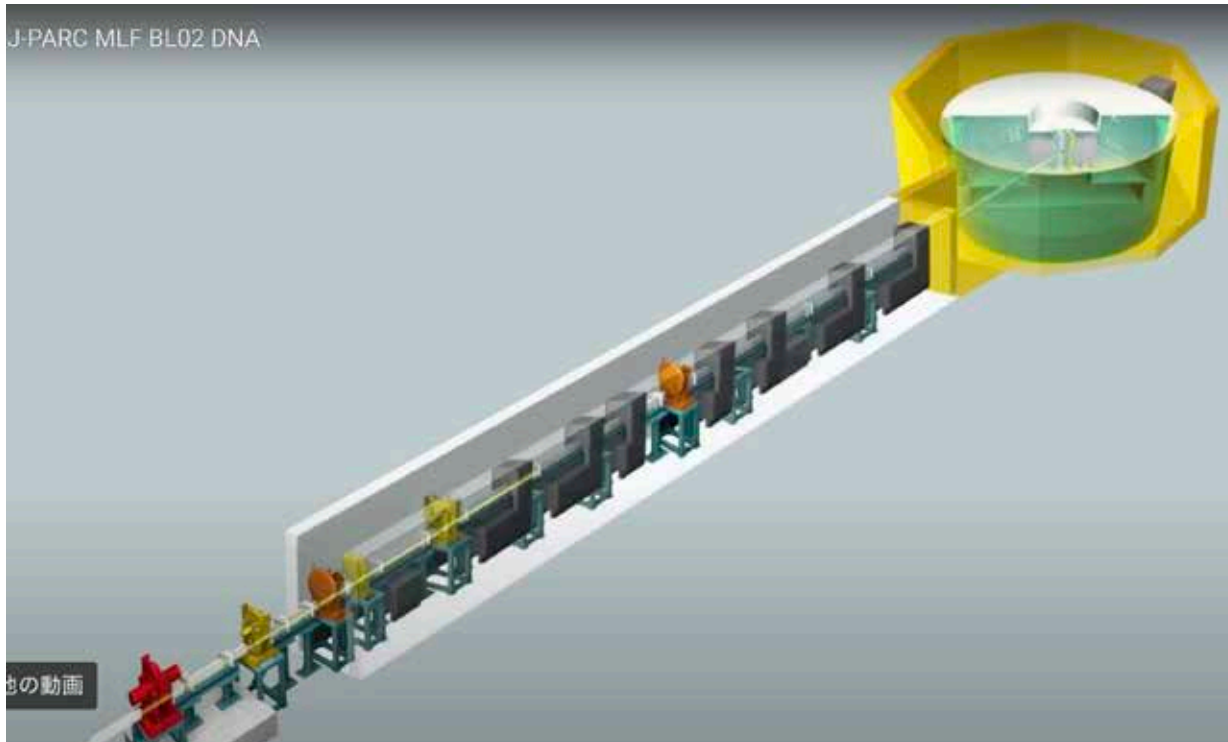


Figure 2 Covered E-Q space of inelastic neutron scattering instruments in MLF.



DNA (BL02): Inelastic (Back scattering)

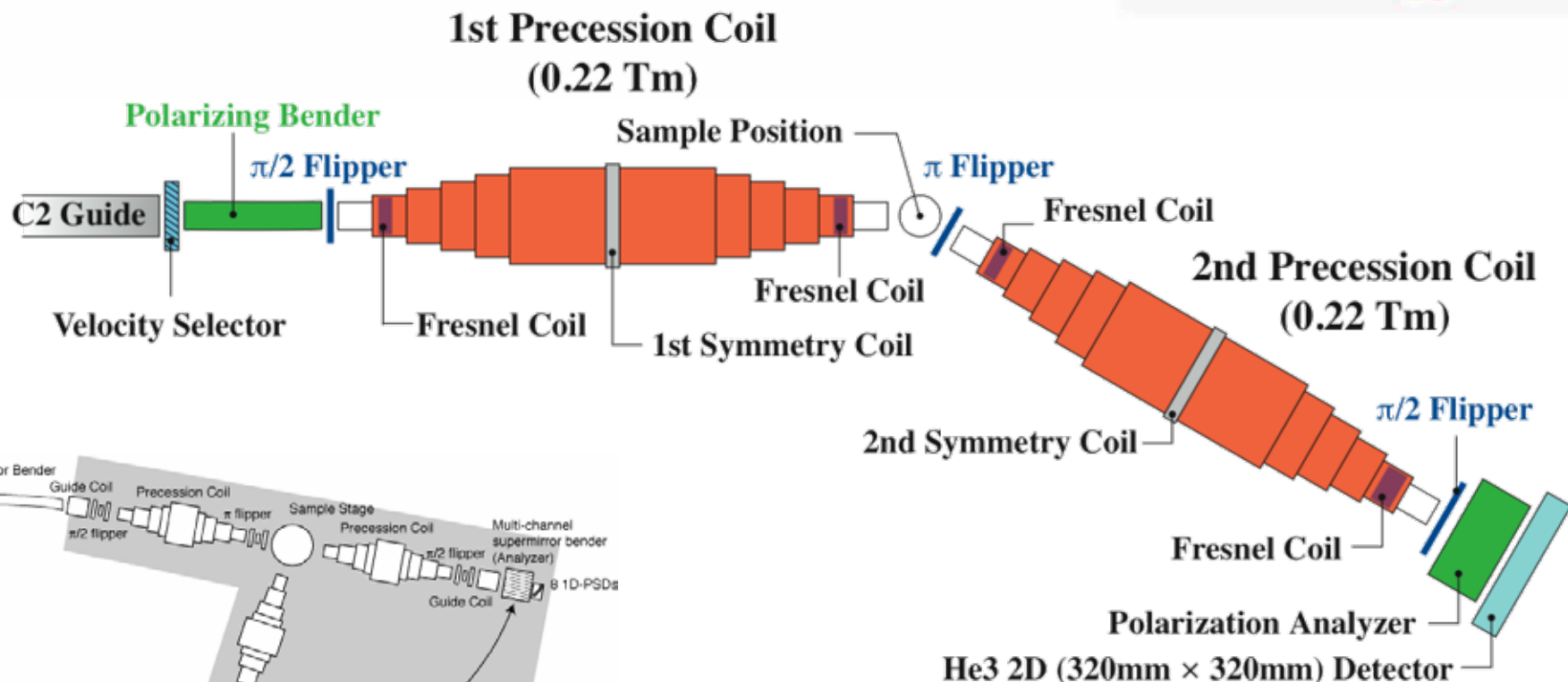
Shibayama,  CROSS



Back scattering instr. (@NIST)

iNSE (C2-3-1): spin-echo spectrometer @JRR-3

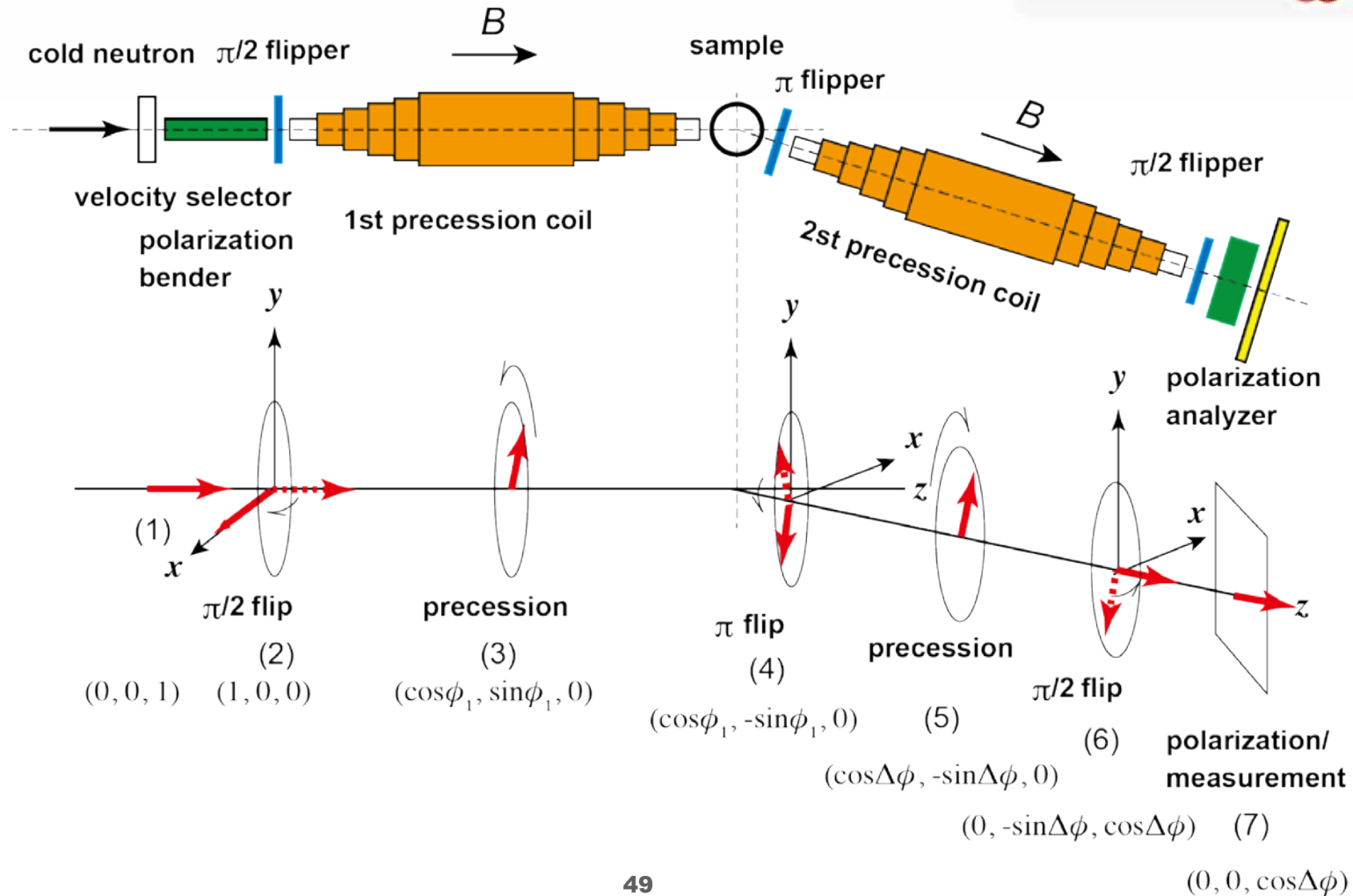
Shibayama, CROSS



<https://www.issp.u-tokyo.ac.jp/labs/neutron/inst/NSE/en/index.html>

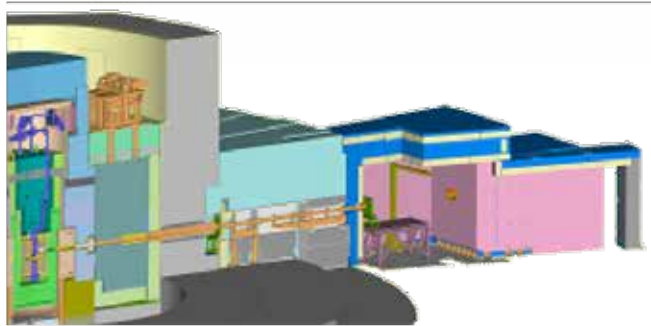
iNSE (C2-3-1): spin-echo spectrometer @JRR-3

Shibayama, CROSS

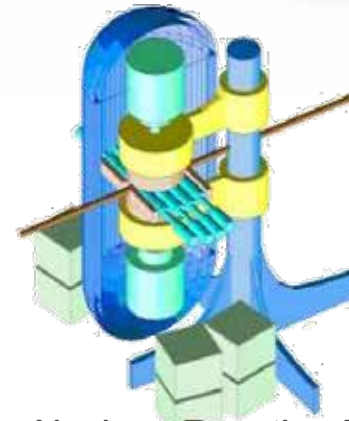


Pulsed Neutron Application

Shibayama,  CROSS



Neutron Source Diagnostic & Test Port
BL10: NOBORU



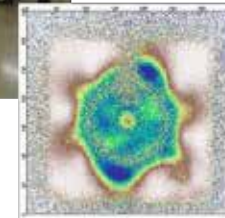
Neutron-Nucleus Reaction Meas. Inst.
BL04: ANNRI



Fundamental Physics
BL05: NOP



Neutron Imaging
BL22: RADEN



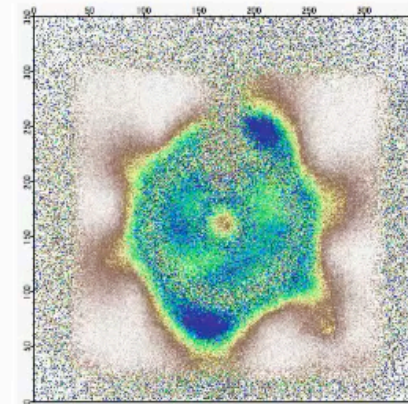
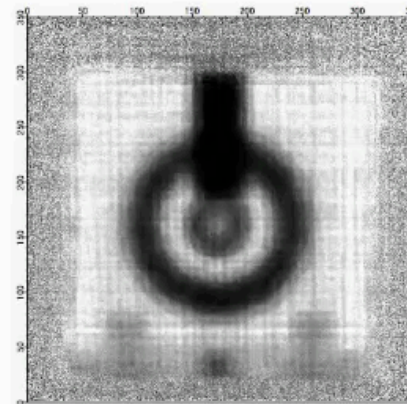
RADEN 螺鈿 (BL22): Neutron Imaging

Shibayama,  CROSS





Magnetic Imaging @ RADEN



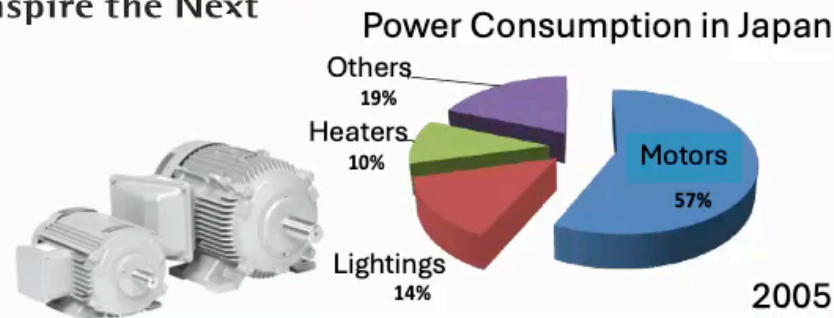
The world's 1st demonstration of visualizing magnetic field of a working motor.

Collaboration with Hitachi Ltd.

HITACHI
Inspire the Next

RADEN results are used to improve simulation technology to design higher performance motors.

Supported by Photon and Quantum Basic Research
Coordinated Development Program by MEXT (2013-2018)



Motors consume more than 50% of total electric power in Japan

MLF instrument handbook

Shibayama, CROSS

MLF_spec_2020j.pdf



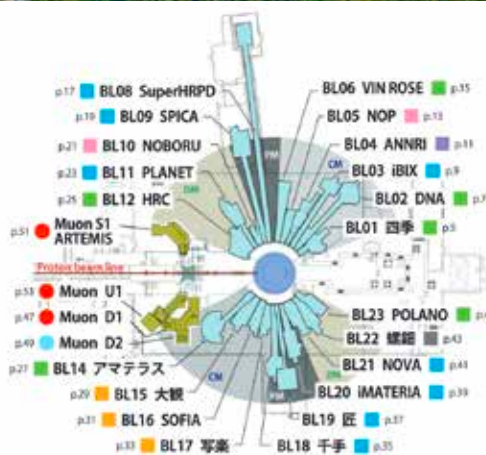
MLF実験HP

<https://mlfinfo.jp/ja/aboutmlf/neutron.html>

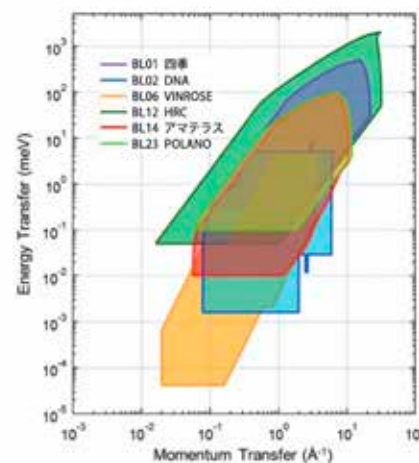
MLF Handbook



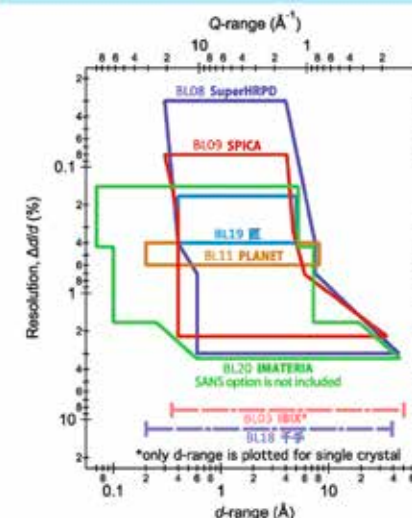
https://mlfinfo.jp/src/resource/PEPngy9XwF/MLF_spec_2020j.pdf



中性子準弾性・非弾性散乱装置



中性子回折装置



Quantum Beam Sci. 2017, 1(3), 9; <https://doi.org/10.3390/qbs103009>
(© 2017 by the authors. Licensee MDPI, Basel, Switzerland.)

Contents

Part 0. Self introduction

Part 1. Overview:

1. Neutron, X-ray, and light
2. History, generation, facility world map, etc.

Part 2. Neutron Sources. (YouTube)

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2. World leading facilities (spallation): ISIS, SNS, J-PARC MLF, ...

Part 3. Instrumentation

1. Structure/dynamics: order - concentration - energy overview
2. Methodology: TOF, angle dispersion, imaging
3. Classification: crystal structure, nano structure, spectroscopy, Imaging

Part 4. Summary and references

Summary

1. There are a number of Neutron sources:
Reactor- or spallation-neutron sources
2. Various neutron scattering instruments;
SANS, NR, triple-axis spectrometers, QENS, INS, spin-echo,...
Imaging, ...
3. Two types of measuring methods;
Angle dispersion and time-of-flight
4. It is very important to choosing the best equipment,
Considering the Q-range, E-range, sample environments, etc.
5. It is strongly encouraged you to consult with an instrument scientist
before submitting your proposal.

Reference Books

Shibayama,  CROSS

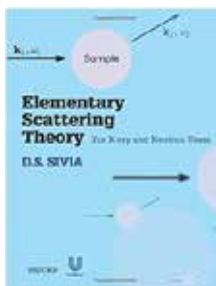
(1) Higgins,
1994



(2) Brückel, 2005



(3) Sivia, 2011



(4) Fernandez-Alonso and Price,
2017



(5) Hashimoto
2022



(6) Shibayama
2025



References:

- (1) J. S. Higgins, H. C. Benoit, Polymers and Neutron Scattering, Oxford Press, 1994.
- (2) T. Brückel, et al., Neutron Scattering, Jülich, 2005
- (3) D.S. Sivia, Elementary Scattering Theory for X-ray and Neutron Users, Oxford, 2011.
- (4) Fernandez-Alonso, F. and Price, D. L. Eds., "Neutron Scattering – Applications in Chemistry, Materials Science and Biology", 2017
- (5) T. Hashimoto, Principles and Applications of X-ray, Light and Neutron Scattering, Springer, 2022.
- (6) M. Shibayama, Introduction to Neutron Scattering, Kodansha, 2025. (Jpn)

(0) B. Hammouda, The SANS Toolbox, (NIST)

https://www.eng.uc.edu/~beaucag/Courses/Properties/the_SANS_toolbox.pdf