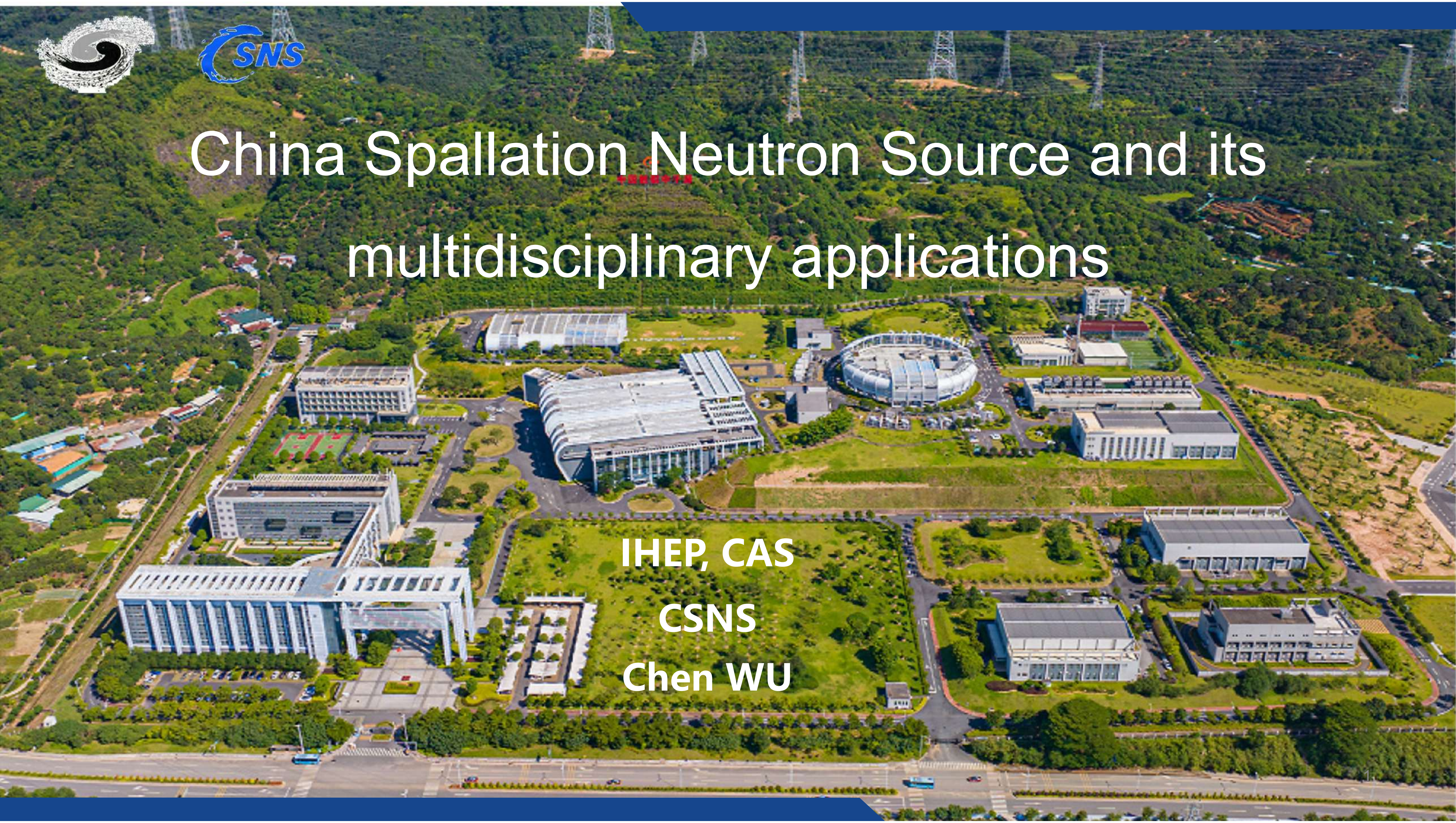
China Spallation Neutron Source and its multidisciplinary applications



IHEP, CAS

CSNS

Chen WU

CONTENTS

PART
01

Neutrons as probe

The way we see things

The progress of science depends not only on new theories, but also on new ways of seeing.

Optical microscope

Robert Hooke, “Micrographia”, 1665

X-ray radiography

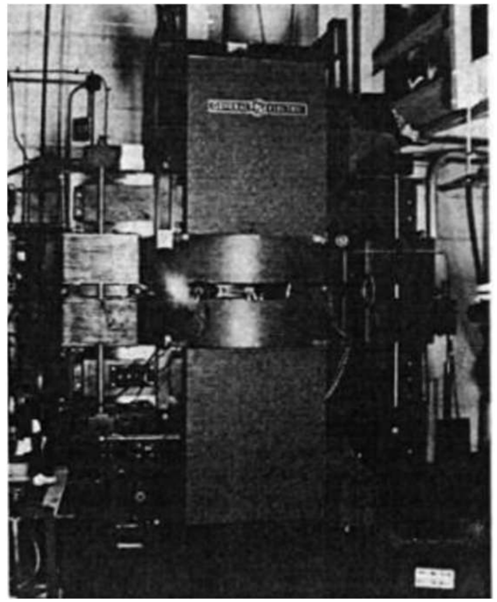
Wilhelm Röntgen, 1896

Electron microscopy

Knoll and Ruska,1930s

Synchrotron light

GE Lab, 70-MeV synchrotron, 1947

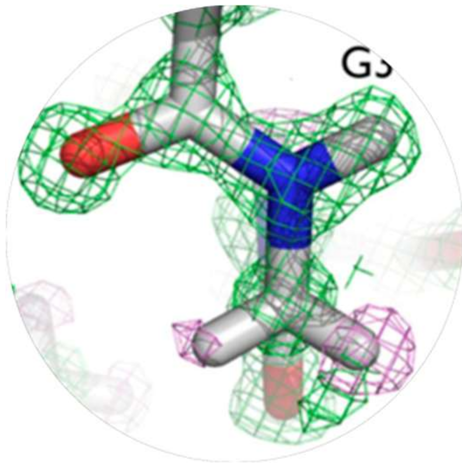


What remains difficult to see with conventional probes

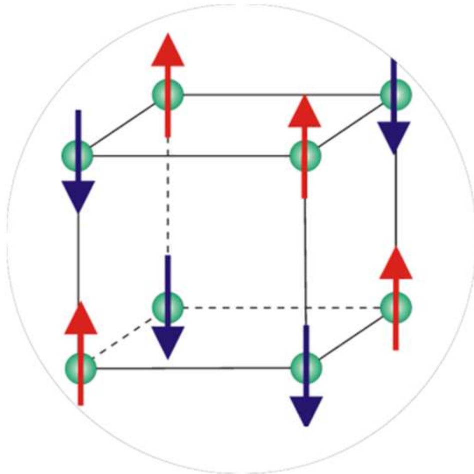
Residual Stresses and Fatigue in Aircraft Engines

Lithium in operating batteries

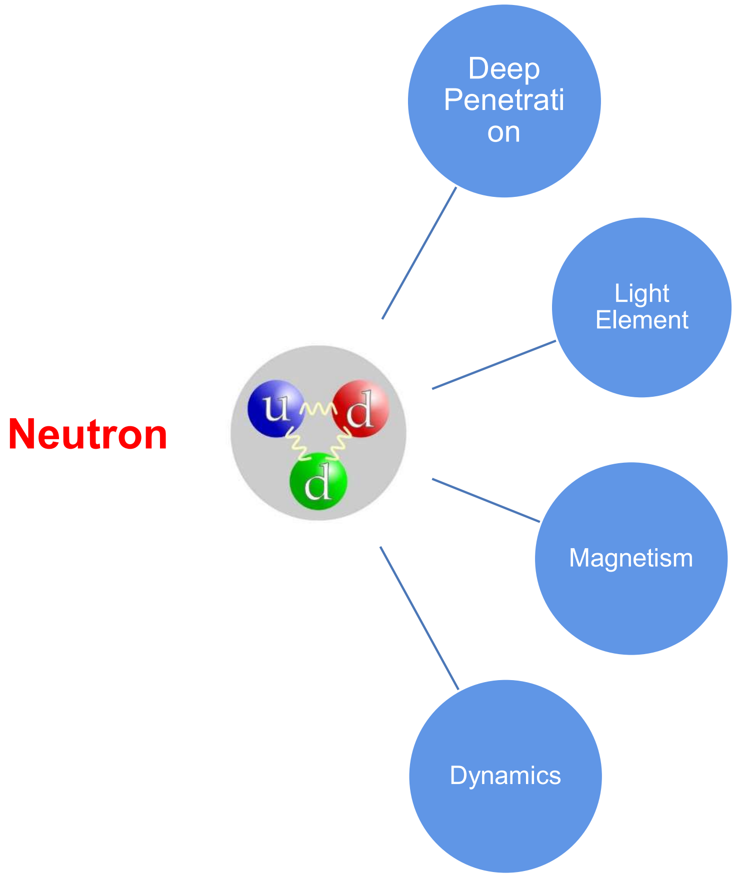
Hydrogen-Bond Structures in Drug Molecules



Magnetic Structures of Magnetic Materials



A complementary probe: Neutrons



- **High penetrating power for most elements**

Critical applications in aerospace, high-speed rail, shipping, deep-sea exploration, etc.

- **Highly sensitive to light elements**

Economic and public welfare sectors such as energy, catalysis, medicine, and biology

- **Detect magnetic materials**

Cutting-edge scientific and technological fields such as magnetism, superconductivity, and quantum science

- **Dynamics**

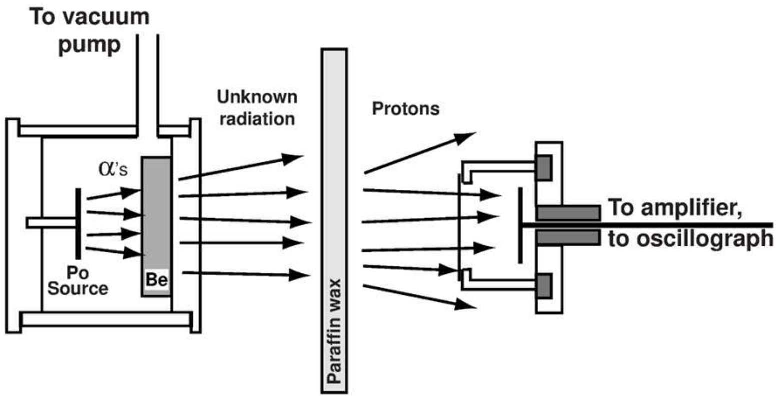
Atomic and spin motions

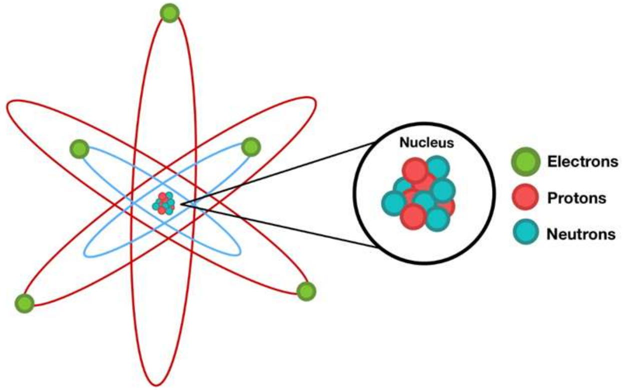
A constituent of the nucleus

1932: The neutron completed the modern picture of the nucleus.

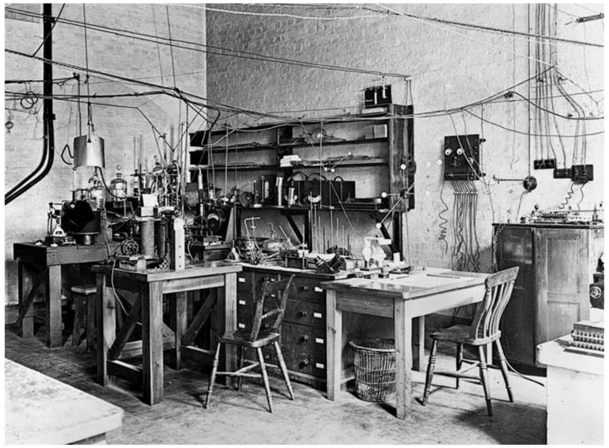
A=Z+N

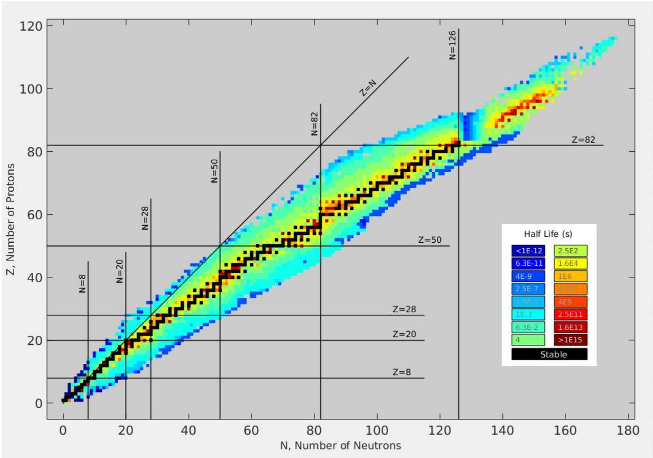
Received the Nobel Prize in Physics in 1935 for his discovery of the neutron





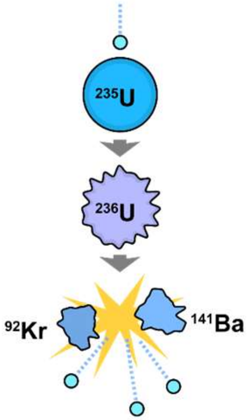
James Chadwick

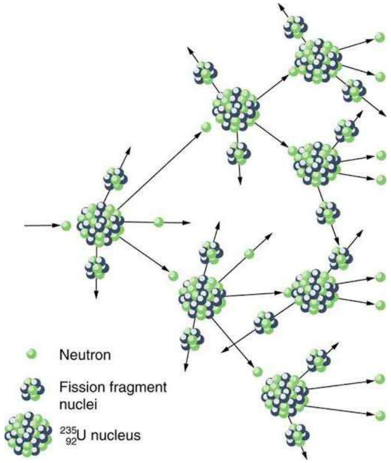




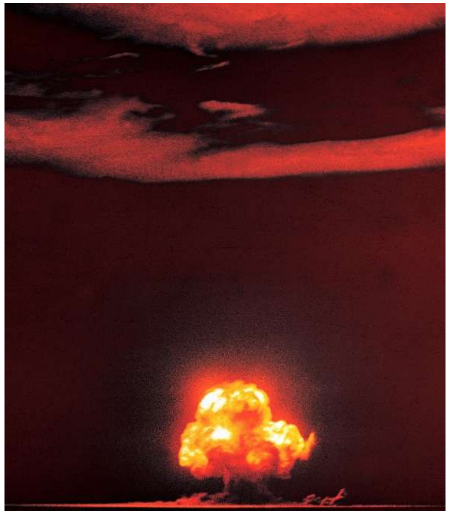
Neutrons as agents of nuclear reactions

Received the Nobel Prize in Physics in 1938 for his demonstrations of new radioactive elements produced by neutron irradiation and his discovery of nuclear reactions brought about by slow neutrons



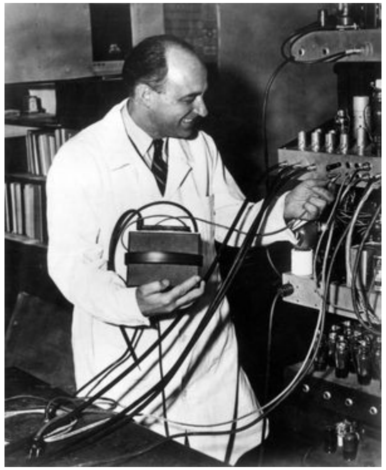


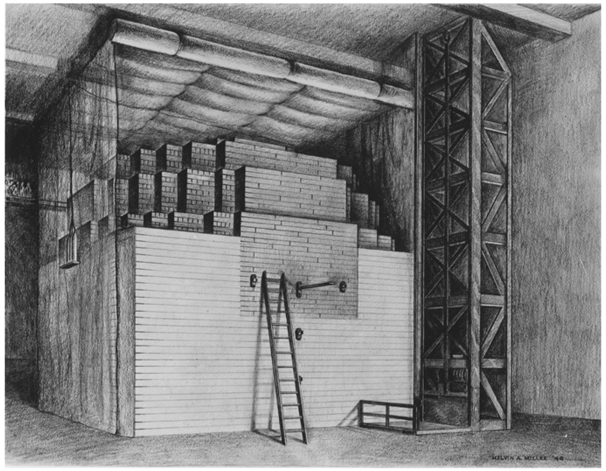
First nuclear bomb in 1945



Enrico Fermi

Chicago pile-1, first reactor in 1942



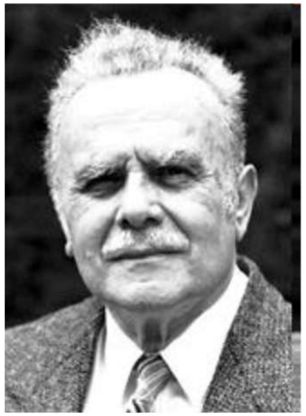


EBR-I, first produced usable electric power in 1951

The new role — a probe of matter

Clifford G. Shull
(Neutron Diffraction)

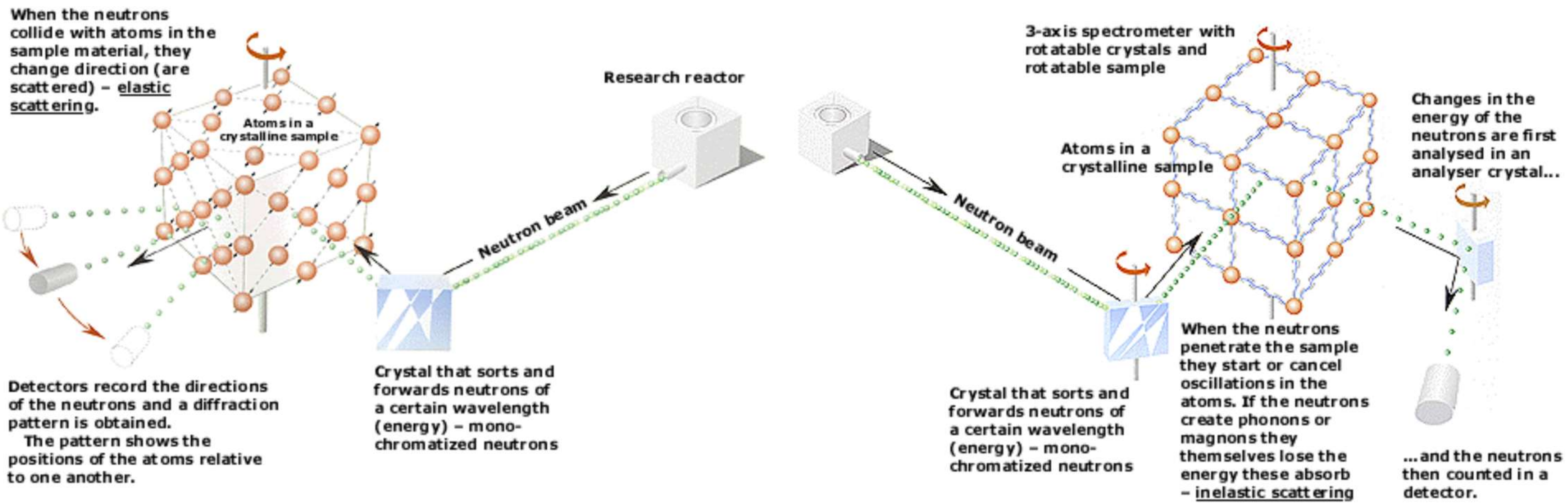
Diffraction tells us where atoms are



Bertram N. Brockhouse
(Neutron Spectroscopy)

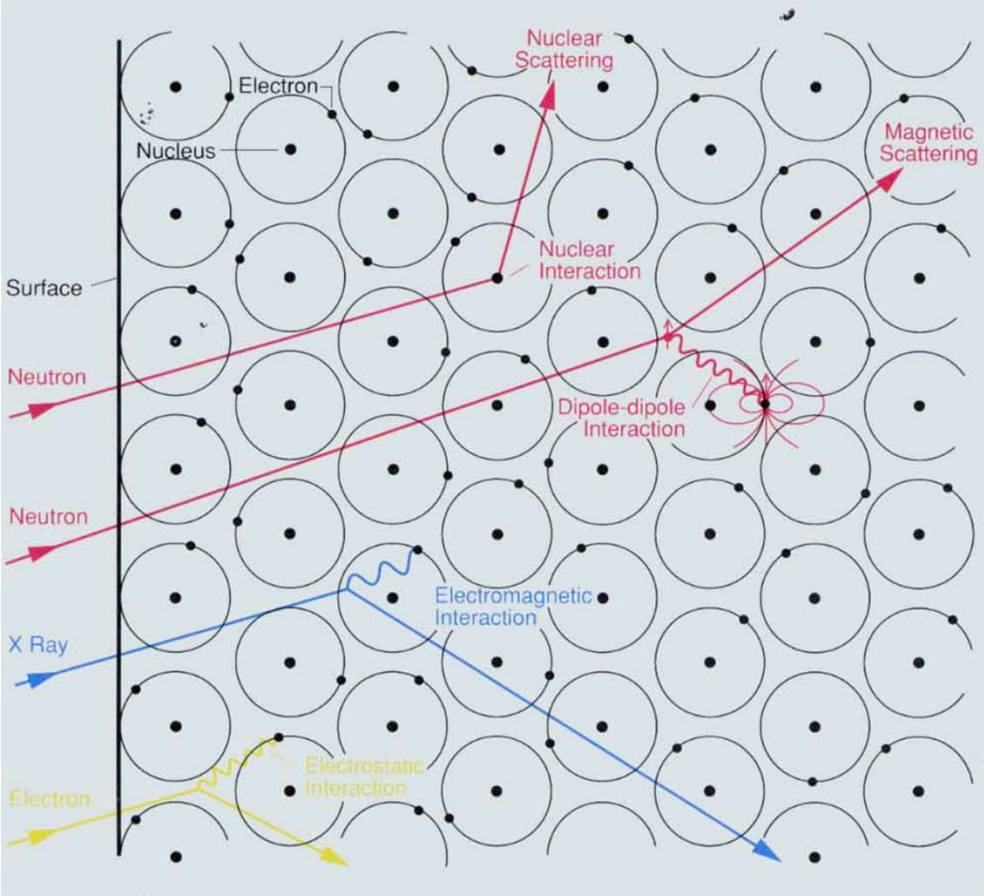
spectroscopy tells us how they move

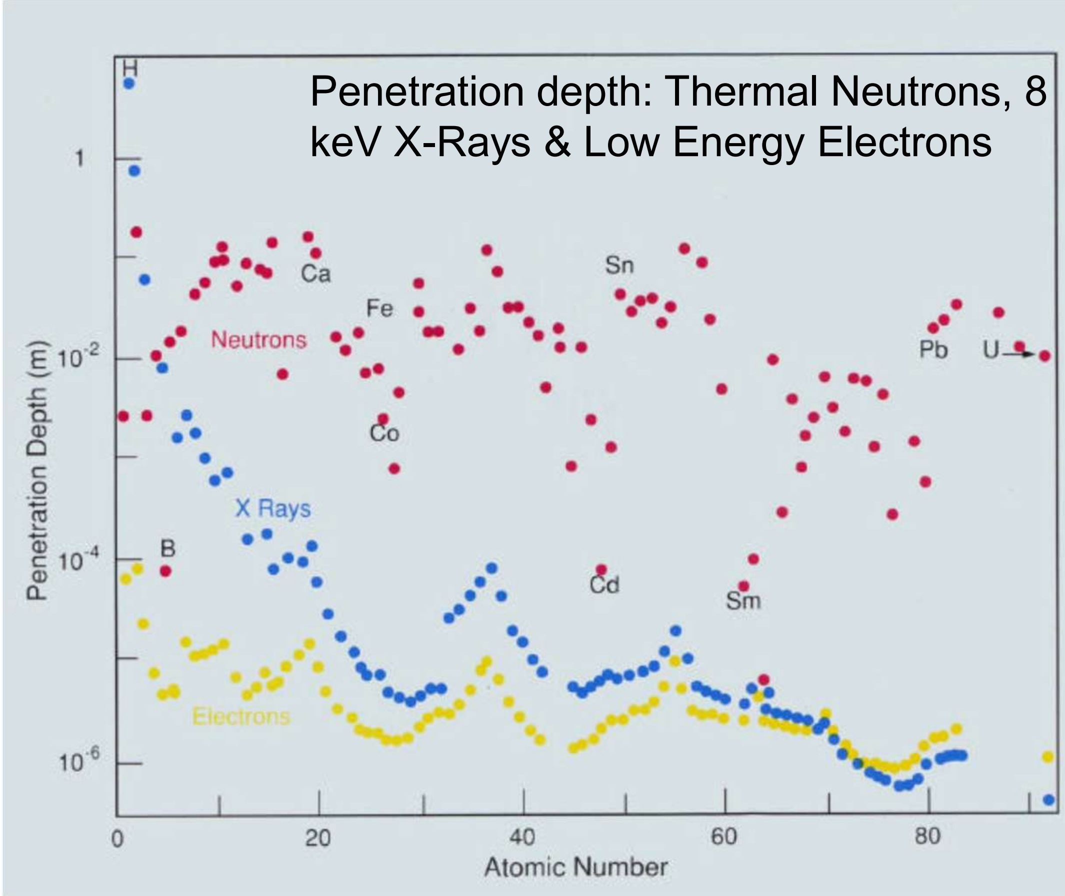
Received the Nobel Prize in Physics in 1994, for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter



Neutron Interaction Mechanisms

Adapted from: Roger Pynn, Neutron Lecture





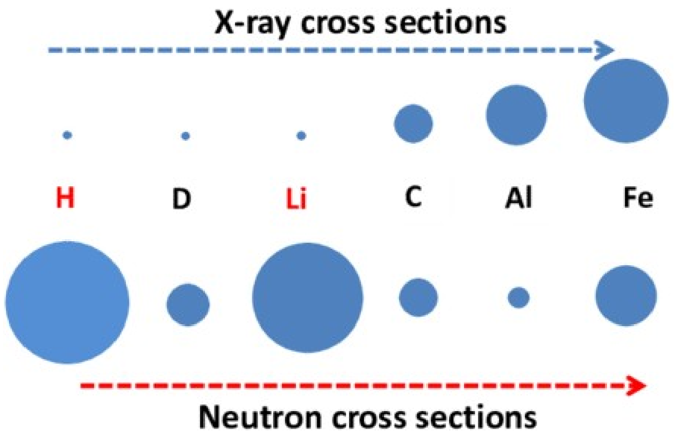
- Neutrons interact with atomic nuclei via very short range (~fm) forces.
- Neutrons also interact with unpaired electrons via a magnetic dipole interaction.

- Neutron interaction strengths vary irregularly among elements and isotopes, rather than increasing monotonically with atomic number

Neutron Imaging

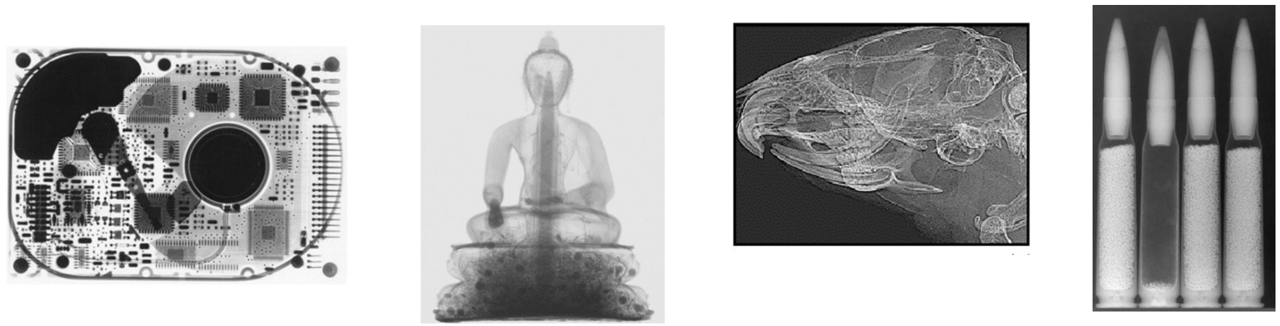
Courtesy of Fan Ruirui

X-rays highlight heavy elements.
Neutrons can highlight light elements and hydrogen-rich materials.



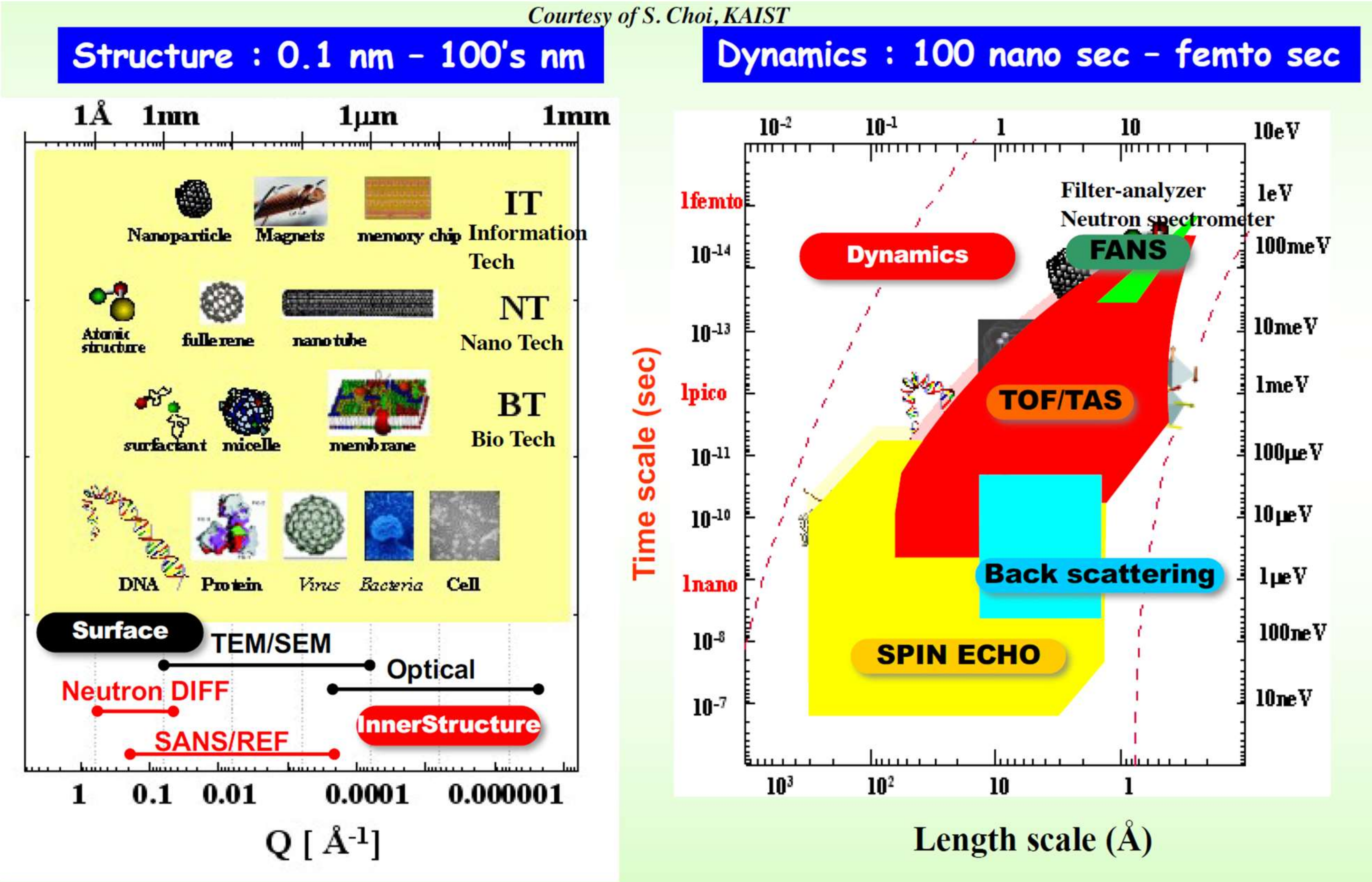
X-ray

Neutron



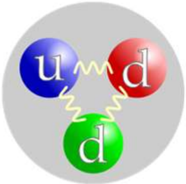
A powerful probe

Source: M. Shibayama, Neutron and Muon School

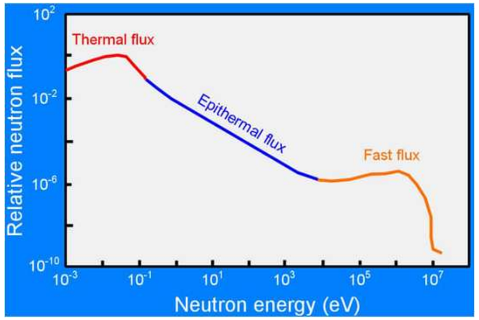


Why neutrons?

Up quark: 2/3 e
Down quark: -1/3 e
Sum: 0 e

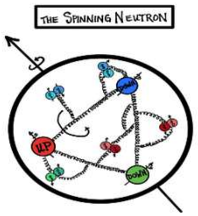


No electric charge → Deep penetration into many materials

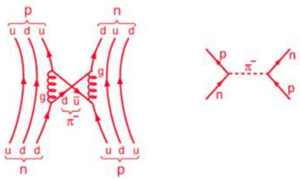


Small wavelength
Å ~ nm → Atomic length scale & Nano length scale

Energy ~ meV → Same magnitude as basic excitations in solids



Spin and magnetic moment → Magnetic structure & dynamics



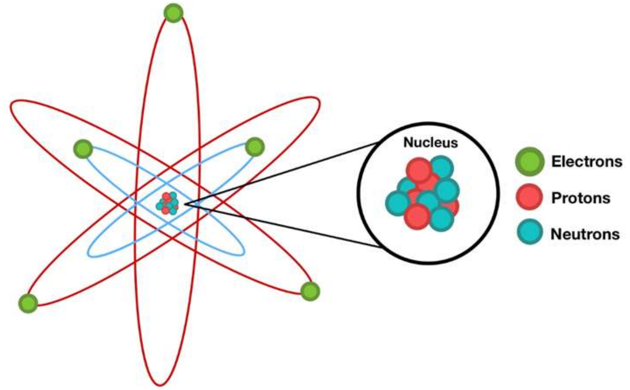
Interact with nuclei → Light-element sensitivity and contrast variation

PART
02

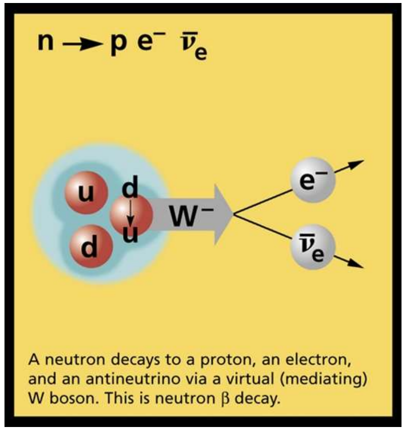
From reactors to spallation sources

Why are free neutrons difficult to obtain?

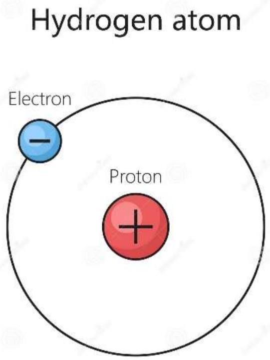
Neutrons are everywhere—but useful neutron beams are rare



Free neutron is unstable:
lifetime 889.1 ± 2.1 sec



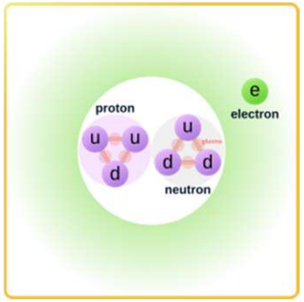
To get the electron/proton: break the atom



Atomic
binding energy
13.6 eV

To get the neutron: break the nuclear!

Deuterium nuclear



Nuclear
binding energy
2.22 MeV!

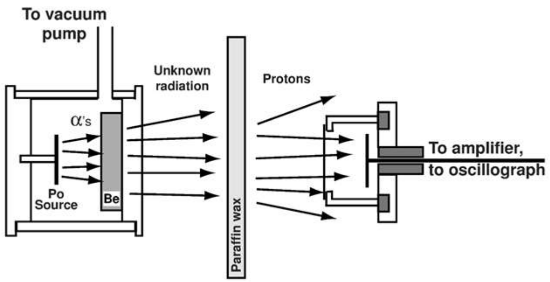
Early and compact neutron sources

Radioisotope sources

Po–Be source used in the discovery of the neutron, 1932

$$^{210}_{84}\text{Po} \xrightarrow[138.376\ \text{d}]{} {}^{206}_{82}\text{Pb} + {}^{4}_{2}\text{He}$$

$\alpha + {}^{9}\text{Be} \rightarrow {}^{12}\text{C} + n$



Spontaneous fission

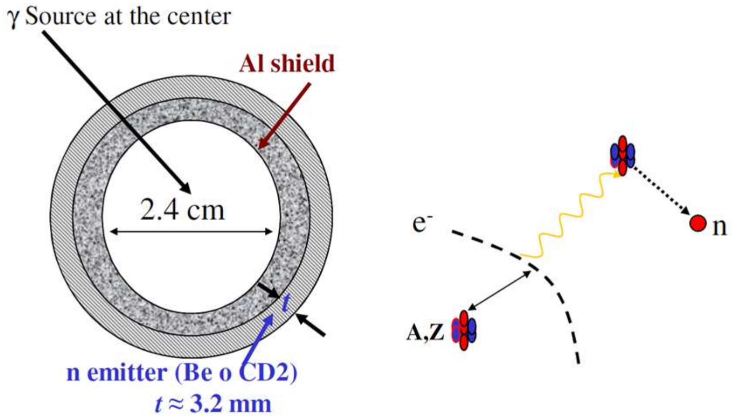
$$^{252}\text{Cf} \rightarrow {}^{140}\text{Xe} + {}^{108}\text{Ru} + 4n + Q$$
$$^{252}\text{Cf} \rightarrow {}^{140}\text{Cs} + {}^{109}\text{Tc} + 3n + Q$$

Simple and compact, but weak, isotropic and continuously emitting

Photoneutron sources

$^{9}\text{Be}_4 + \gamma \rightarrow {}^{8}\text{Be}_4 + n$ (-1.666 MeV)

$^{2}\text{H}_1 + \gamma \rightarrow {}^{1}\text{H}_1 + n$ (-2.226 MeV)



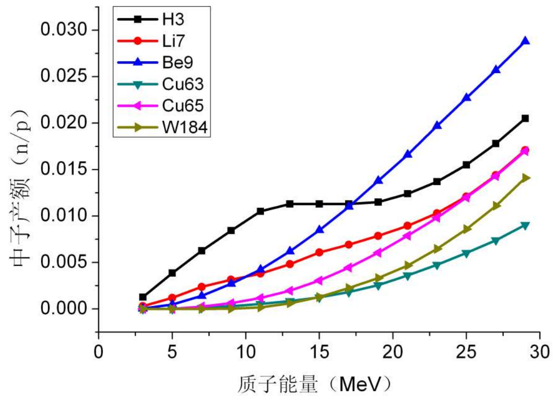
Source: A. Pietropaolo, Neutron Sources

inefficient photon-to-neutron conversion accompanied by strong gamma radiation

Compact proton/ion-beam sources

D+T→4He+n.

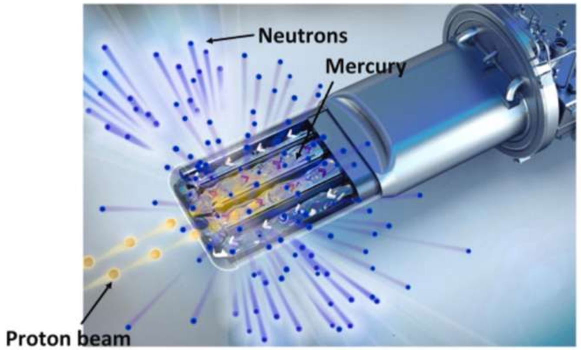
p/d→Li or Be target→n

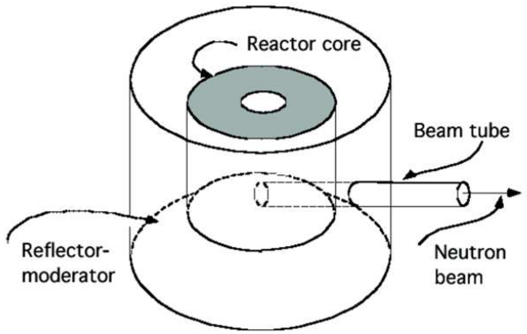


Still actively driven by cancer therapy (BNCT)

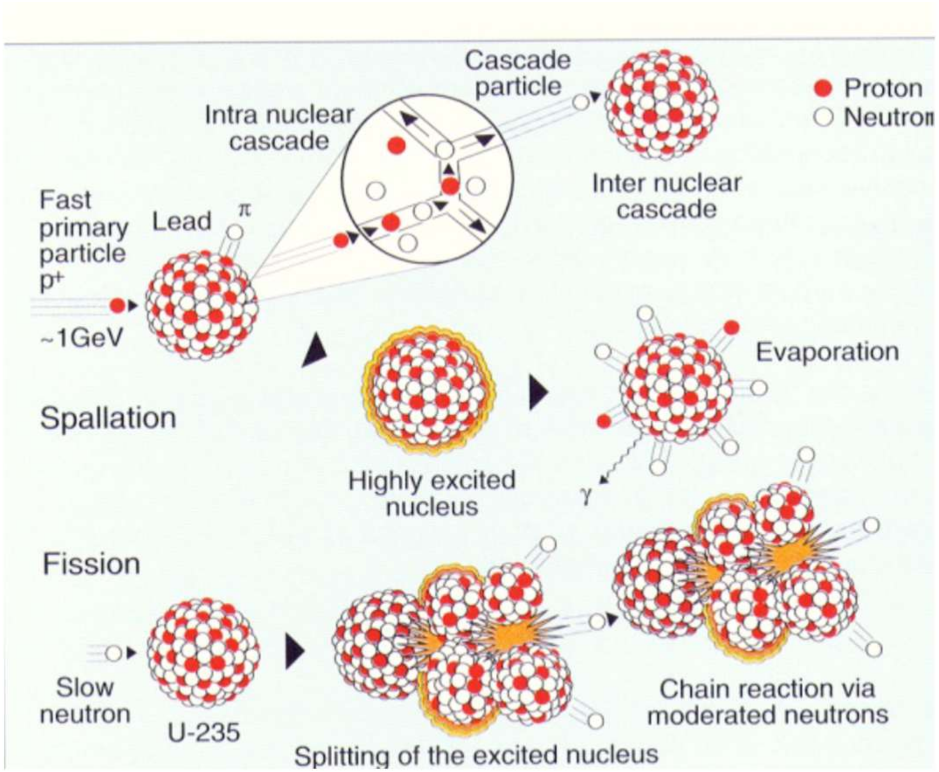
Limited by neutron yield & high power density on the target

Reactors VS Spallation Neutron Sources





Source: A. Pietropaolo, Neutron Sources



Source: M. Shibayama, Neutron and Muon School

Heat load in target/core center

Courtesy of Fan Ruirui

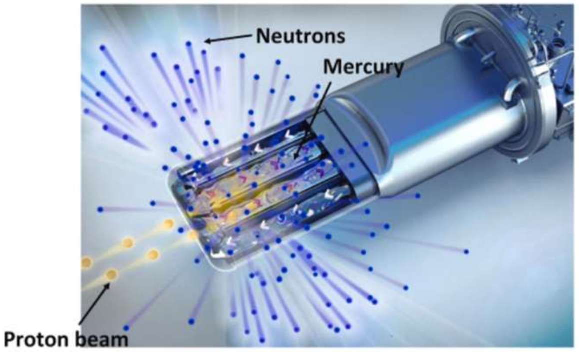
1 GeV proton in:
Only part of the energy is deposited
30 neutrons produced
⇒ 25 MeV/neutron

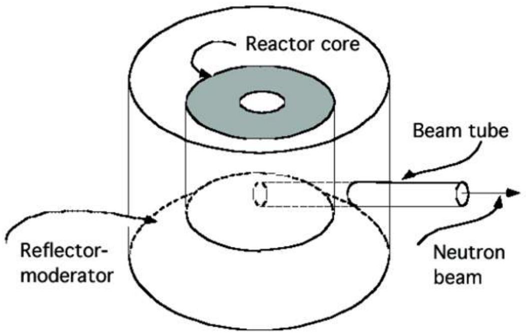
200 MeV/fission
2.35-1=1.35 excess neutrons produced
⇒ 150 MeV/neutron

Spallation source: higher neutron yield under a source-region thermal-load constraint

Reactors VS Spallation Neutron Sources

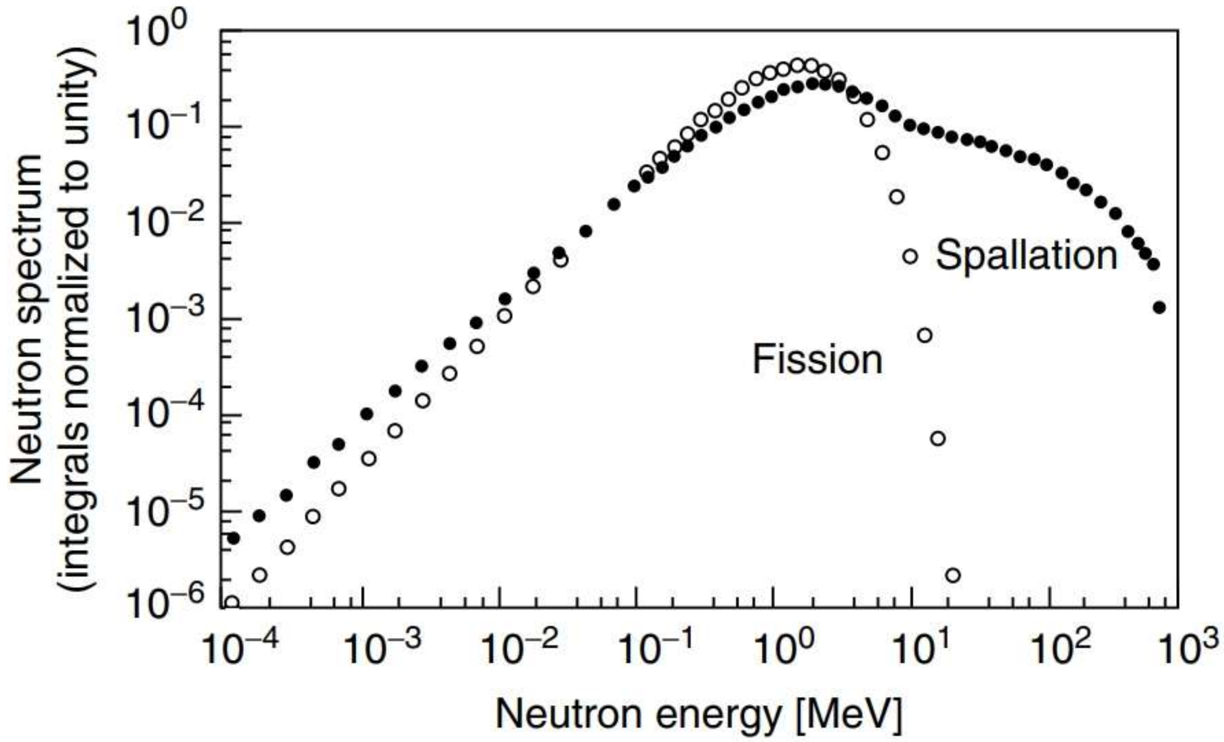
Courtesy of Fan Ruirui





Source: A. Pietropaolo, Neutron Sources

Unmoderated source neutron spectra

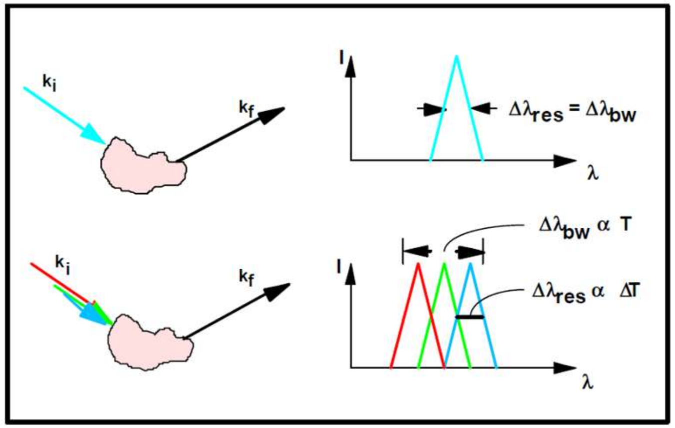


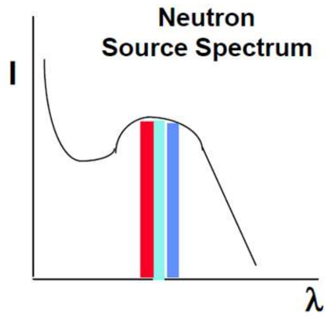
After moderation and beam conditioning, both can provide thermal and cold neutron beams for multi-instrument user facilities.

Time of flight: why pulses matter

The pulse provides both intensity and information.

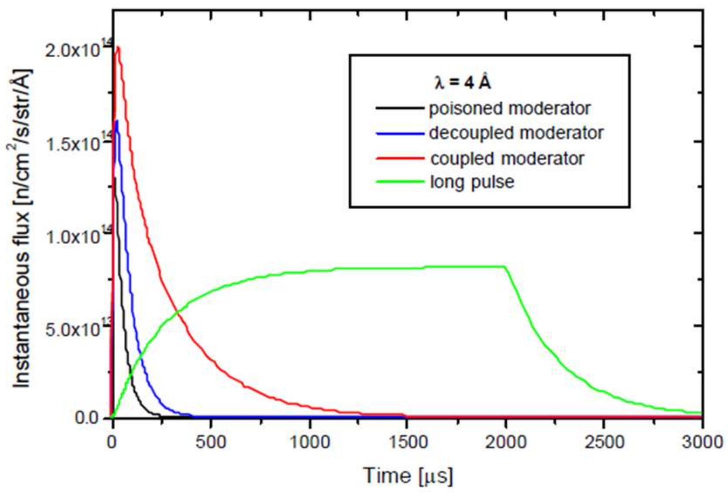
Simultaneously Using Neutrons With Many Different Wavelengths Enhances the Efficiency of Neutron Scattering Experiments





Potential Performance Gain relative to use of a Single Wavelength is the Number of Different Wavelength Slices used

Low background between pulses => good signal to noise

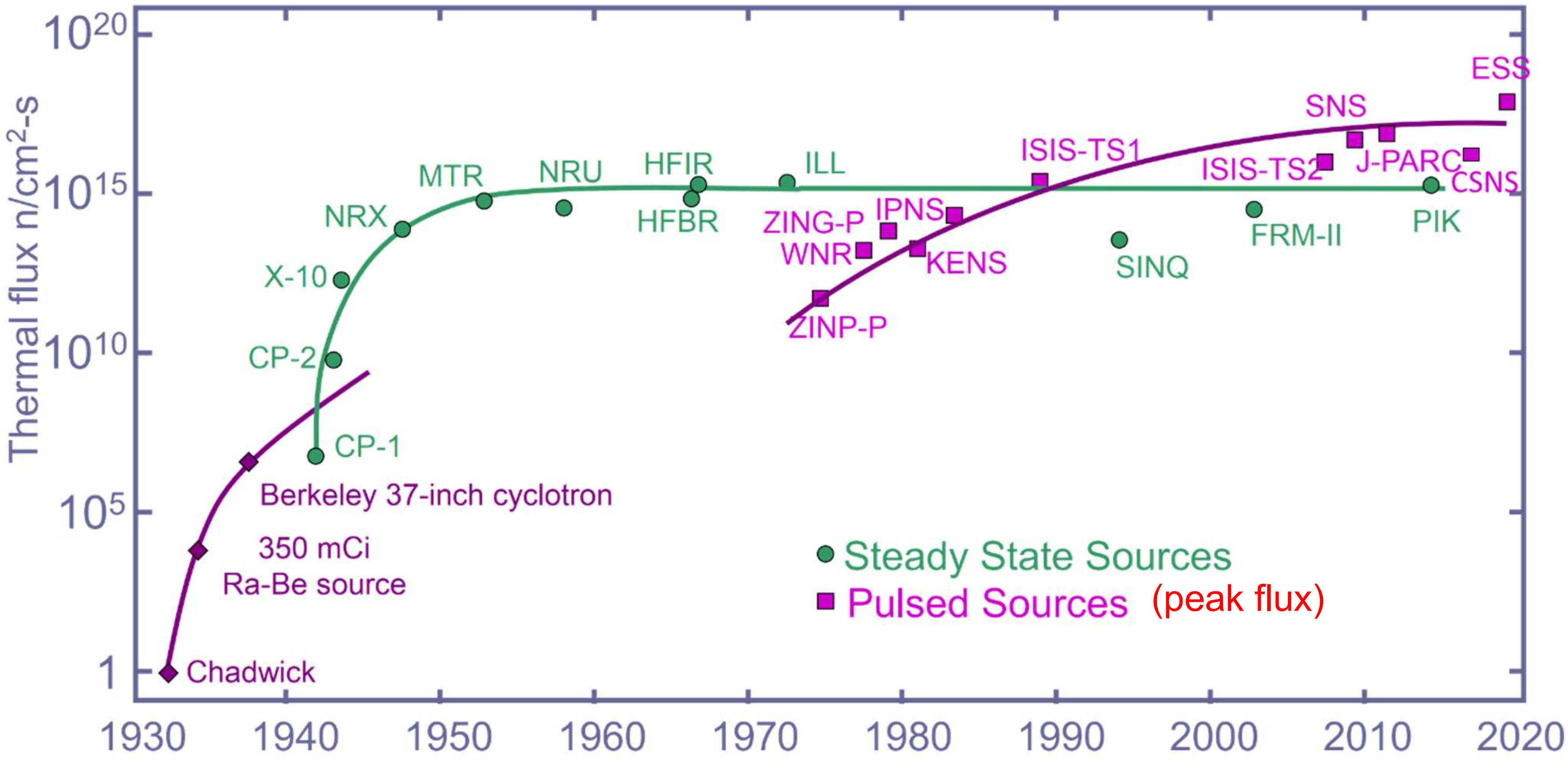


O(10) msec until next pulse

Source: Roger Pynn, Neutron Lecture

The rise of pulsed spallation sources

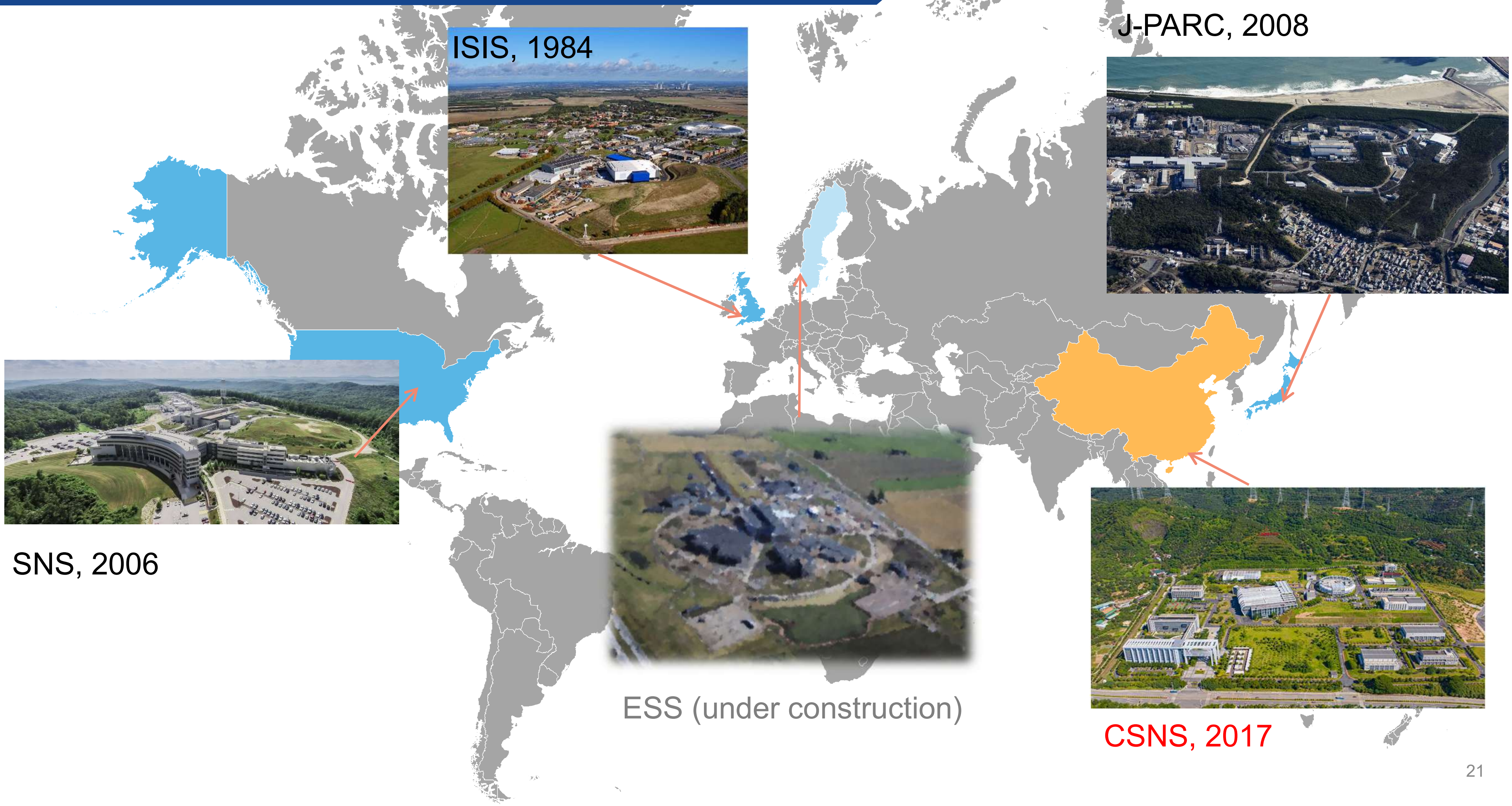
Courtesy of Fan Ruirui



Updated from Neutron Scattering, K. Skold and D. L. Price, eds., Academic Press, 1986

Major spallation neutron sources

Courtesy of Fan Ruirui



PART 03

Building CSNS

China Spallation Neutron Source

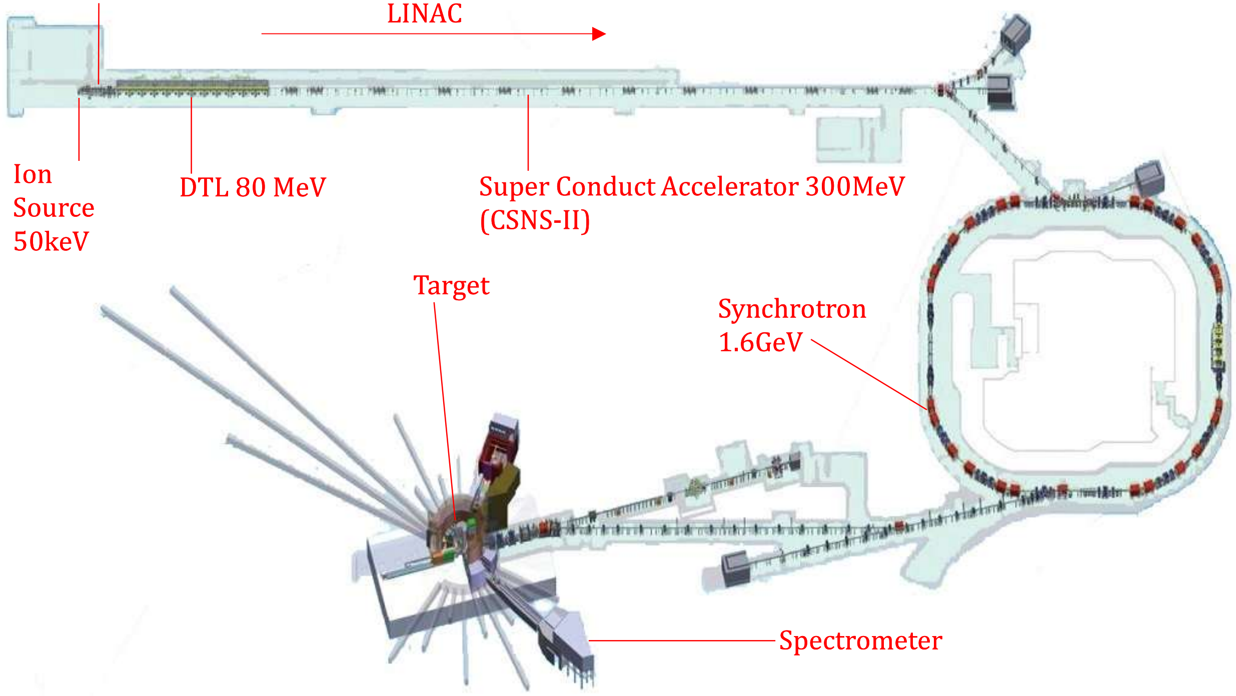
Location of CSNS

Located in the Greater Bay Area

To Guangzhou, Shenzhen, Hongkong:
90KM、50km、120km

Structure of CSNS accelerator

Courtesy of Fan Ruirui



Beam-power = Current × Energy × Pulse-width × Repetition × Chopping factor

Beam-power	Current	Energy	Pulse-width	Repetition	Chopping factor
500 kW	40~55 mA	1.6 GeV	500-600 us	25 Hz	50-60%

Parameters	CSNS-I	CSNS-II
I.S. Current (mA)	>12	40~55
Repetition Rate (Hz)	25	25
Pulse-width (us)	415	500-600
Chopping Factor	42%	35-50%
LINAC Components	R.T.	R.T.+SC
LINAC-energy (MeV)	80	300
RCS-energy (GeV)	1.6	1.6
Beam Power (kW)	100	500

LINAC and RCS

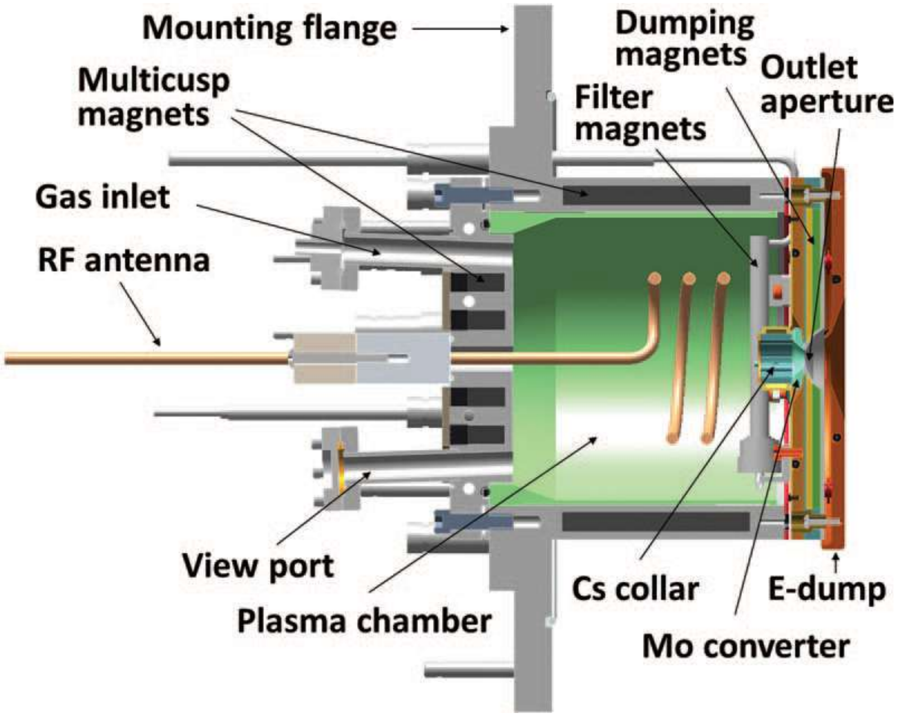
Courtesy of Fan Ruirui

- The Radio Frequency Quadrupole（RFQ）
- Linear Accelerator（DTL）
- Synchrotron （RCS）



Ion source and negative hydrogen ion

Courtesy of Fan Ruirui



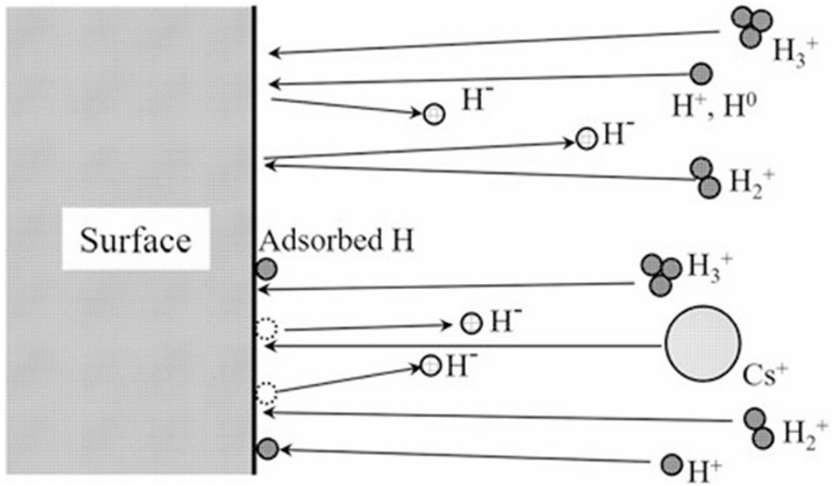


Fig. 2.1 A schematic illustration of H^- surface production. Hydrogen ions and neutrals bombard the H^- ion production surface, and part of these fluxes are converted to H^- ions. In a H^- ion source, atomic and molecular hydrogen ions as well as Cs^+ bombard the surface to produce H^- ions by backscattering and ion-stimulated desorption processes

Schematic view of the RCS injection section

Courtesy of Fan Ruirui

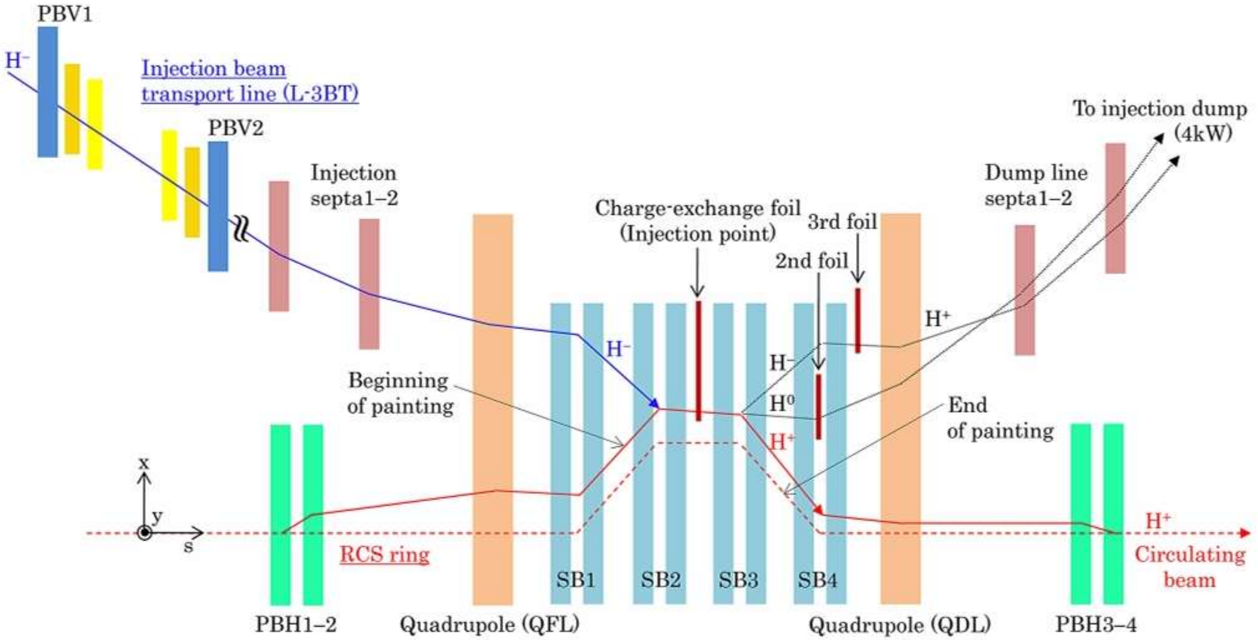
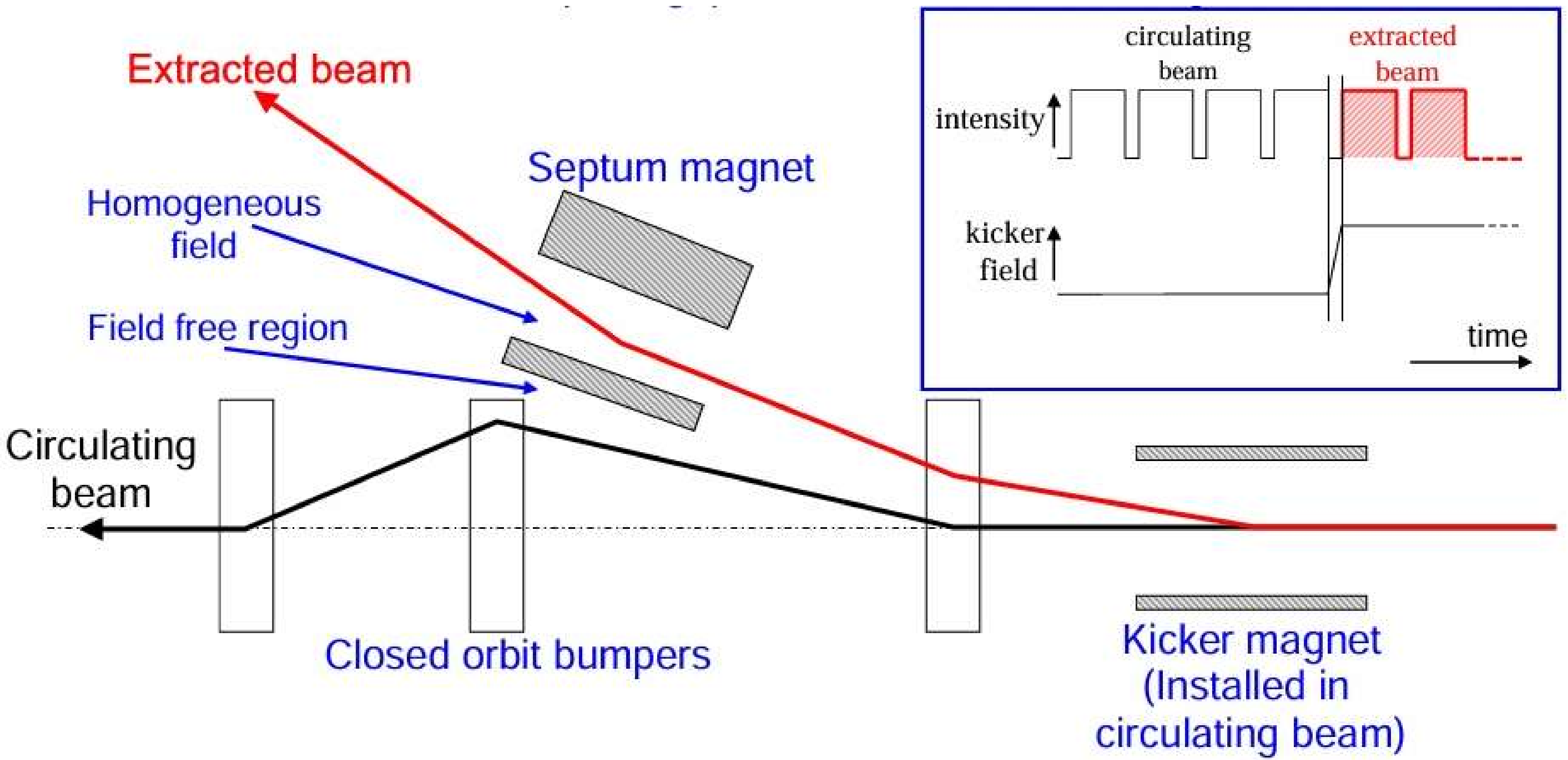


FIG. 2. Schematic view of the RCS injection section.

stripping foil

Beam fast extraction

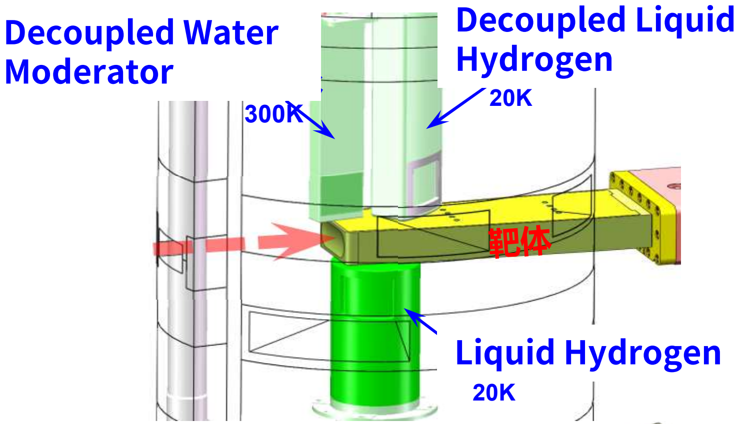
Courtesy of Fan Ruirui

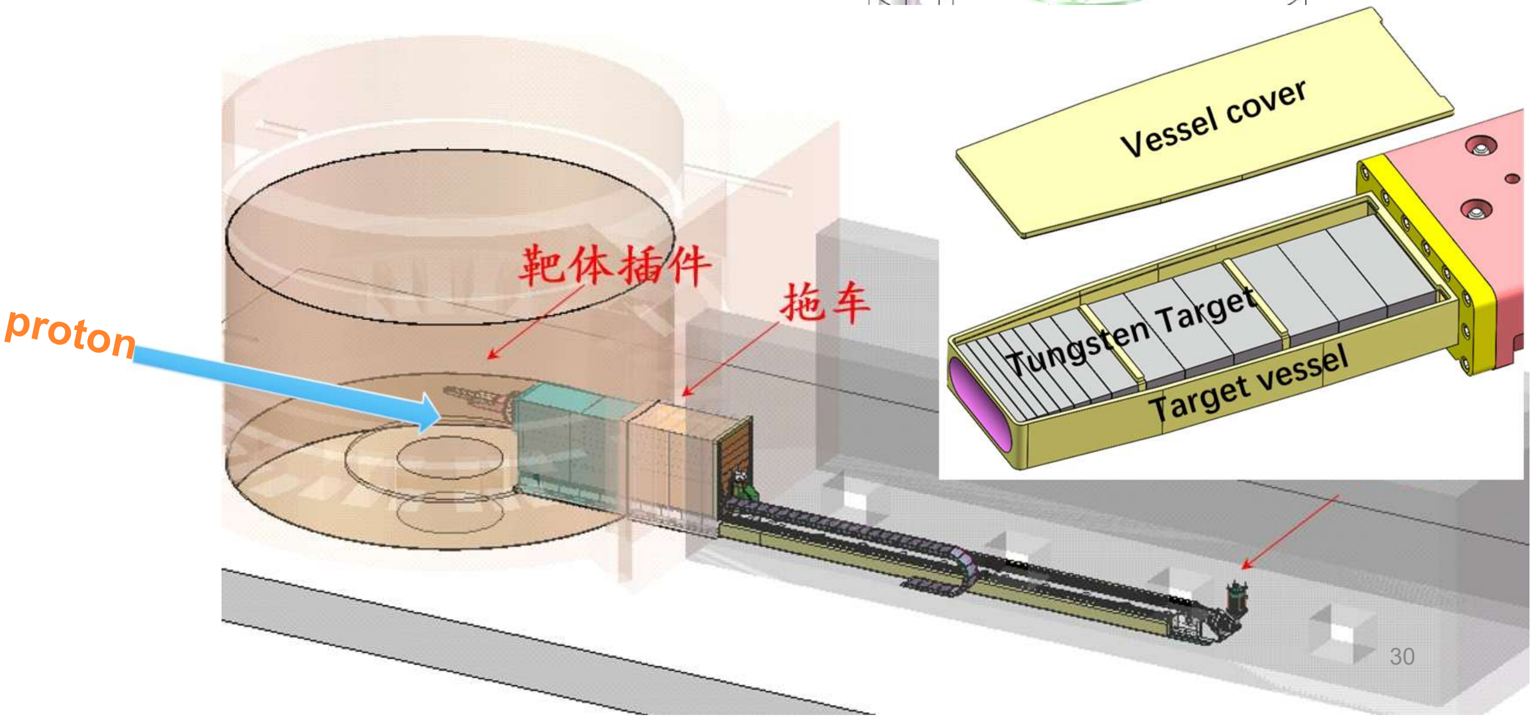


Target station

	parameters	Phase I	Phase II
1	Beam power	100kW	500kW
2	Target material	W	W
3	Target thickness	650mm	650mm
4	Coating material	Ta	Ta/Zr
5	Coating thickness	0.3/0.5mm	0.5mm
6	Vessel Material	SS316L	SS316L
7	Beam area	40mm×120 mm	60mm×160 mm
8	Heating consumptio n	56.5kW	286kW
9	cooling	Light water	Heavy water
10	lifetime	3～5 years	1-2year

Courtesy of Fan Ruirui

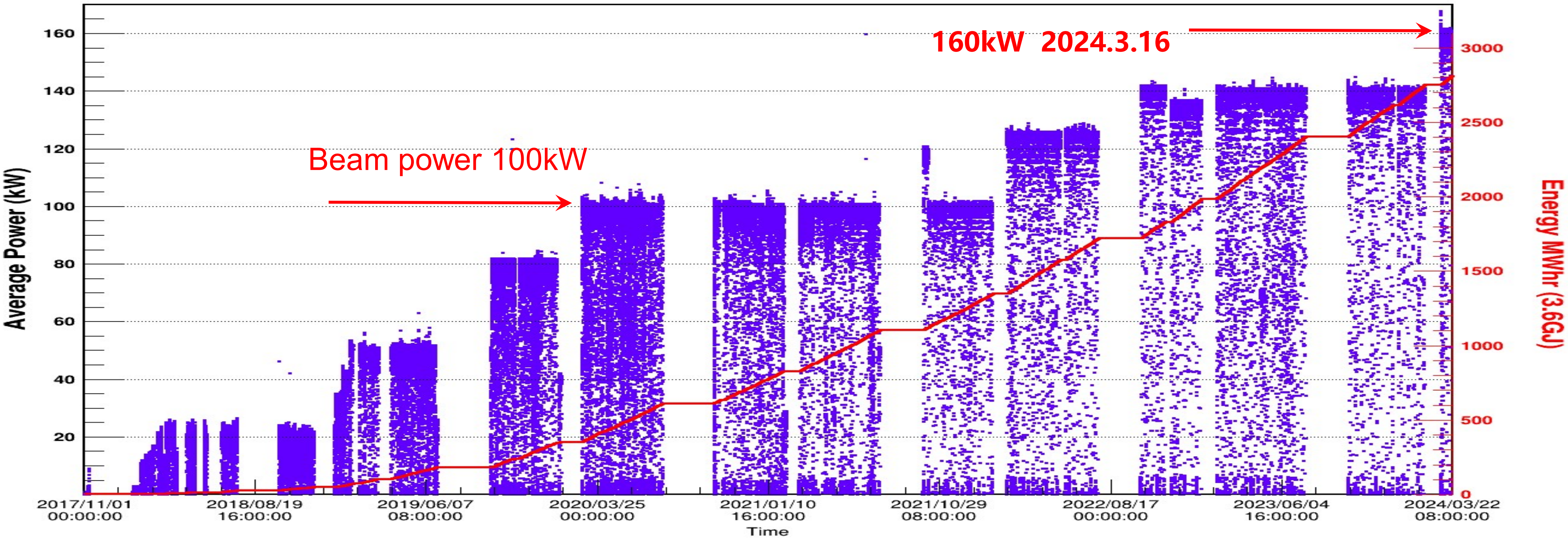




CSNS Beam History

Courtesy of Fan Ruirui

The neutron beamtime 5262 hours and the availability 97%, reach the best operation level in world

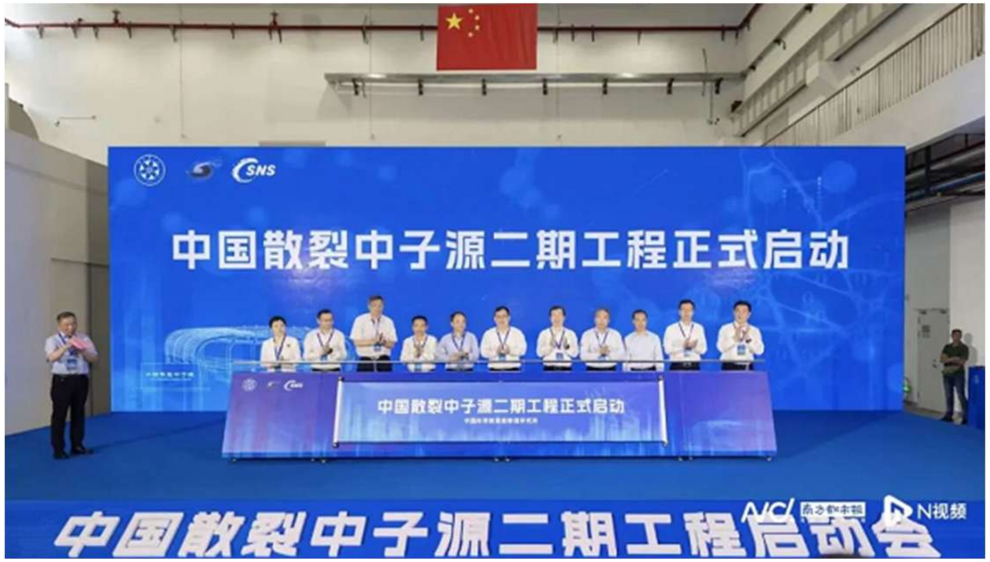


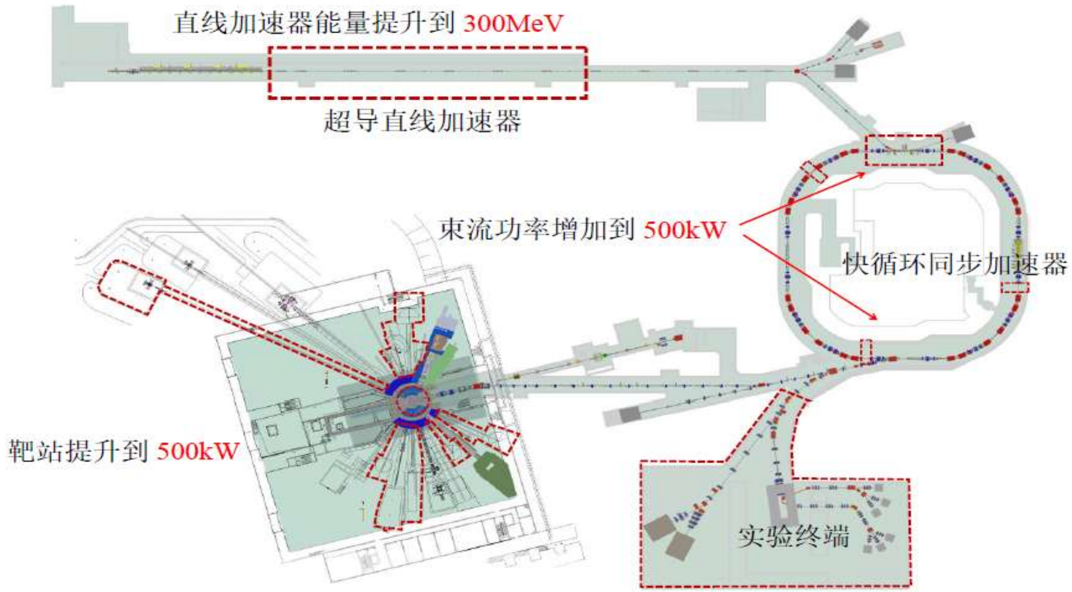
Two round per year

4054h 4687h 4884h 5262h 4995h

From CSNS-I to CSNS-II

- ✓ **CSNS-II construction schedule: 2024~2029.**
- ✓ **CSNS-II includes: power from 120 kW to 500 kW; +9 new spectrometers, +1 proton experiment terminal, +1 muon source.**





CSNS-II layout

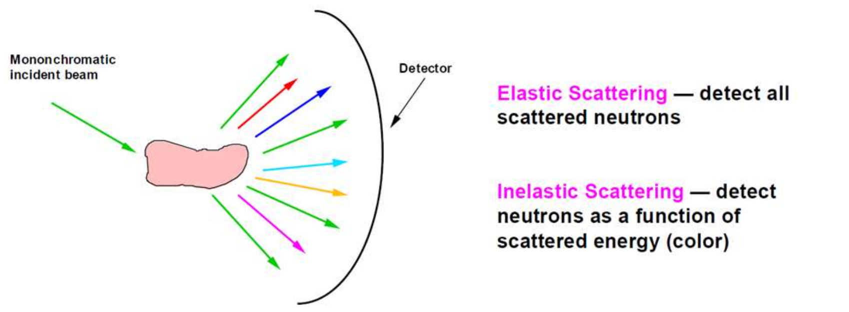
PART
04

Multidisciplinary applications at CSNS

One target, many beam ports

Source: Roger Pynn, Neutron Lecture

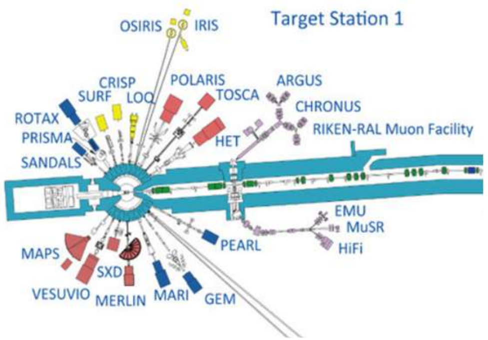
Why Isn't There a Universal Neutron Scattering Spectrometer?

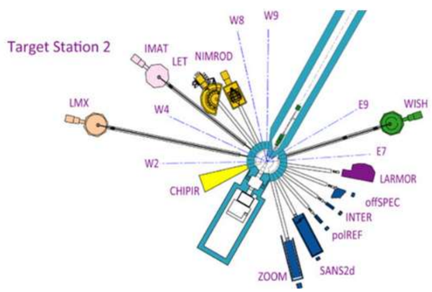


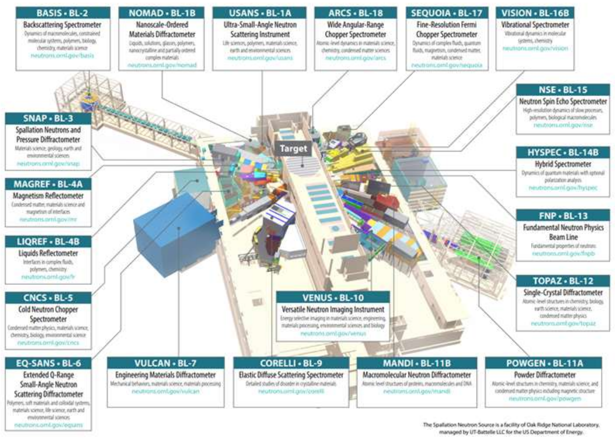
- Conservation of momentum => $\underline{Q} = \underline{k}_f - \underline{k}_i$
- Conservation of energy => $E = (h^2 m / 8 \pi^2) (k_f^2 - k_i^2)$
- Scattering properties of sample depend only on Q and E, not on neutron λ

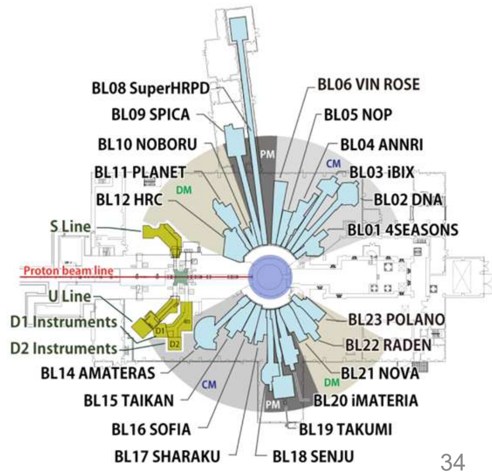
Many types of neutron scattering spectrometer are required because the accessible Q and E depend on neutron energy and because resolution and detector coverage have to be tailored to the science for such a signal-limited technique.

- Multiple beam ports harvest neutrons emitted in different directions.
- Different moderator views provide different wavelength spectra and pulse shapes.
- Multiple instruments to address different scientific questions

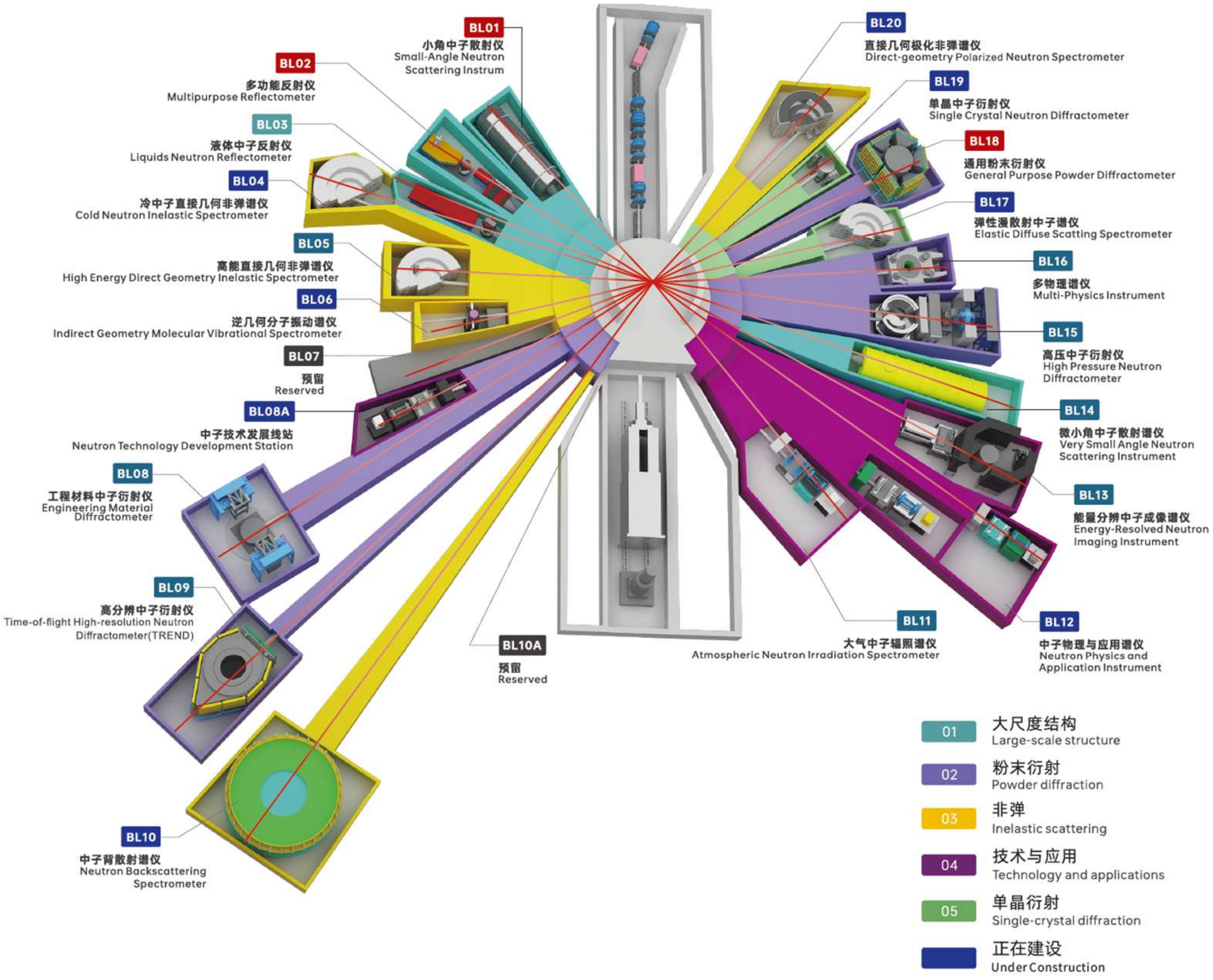








CSNS Instruments and Beamlines



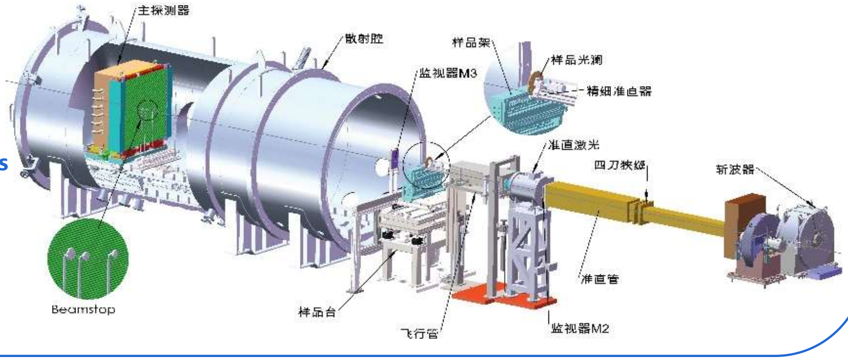
CSNS Instruments and Beamlines

BL01 Small-Angle Neutron Scattering Instrument (SANS)

Probes particle size, morphology, and interactions on the **1–100 nm scale**, with versatile in-situ sample environments.

Applications:

- soft matter
- Nanomaterials
- Magnetism
- biology

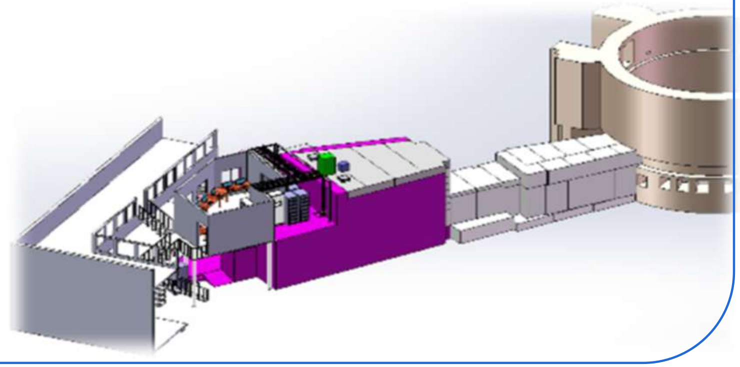


BL02 Multipurpose Reflectometer (MR)

Studies the **structure and magnetism of thin films, multilayers, and interfaces**, with polarized neutrons and external fields.

Applications:

- metallic multilayers
- oxides/nitrides
- Superconducting
- polymer films

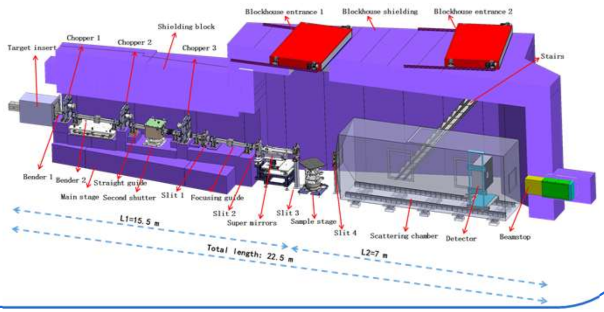


BL03 Liquid Neutron Reflectometer (LNR)

Characterizes the structure, composition, and evolution of horizontal liquid and soft-matter interfaces.

Applications :

- metallic multilayers
- oxides/nitrides
- Superconducting
- polymer films

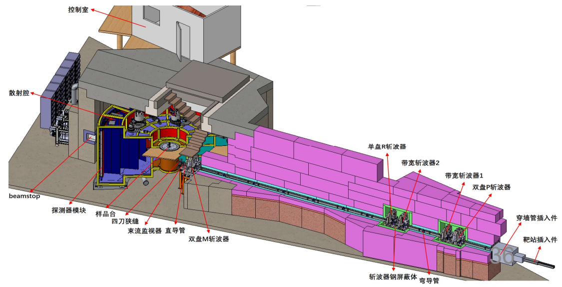


BL04 Cold-Neutron Direct-Geometry Spectrometer (CNIS)

Measures low-energy phonons, spin excitations, and molecular dynamics with high energy resolution.

Applications :

- Superconductors
- Magnetic materials
- Thermo electrics
- soft matter



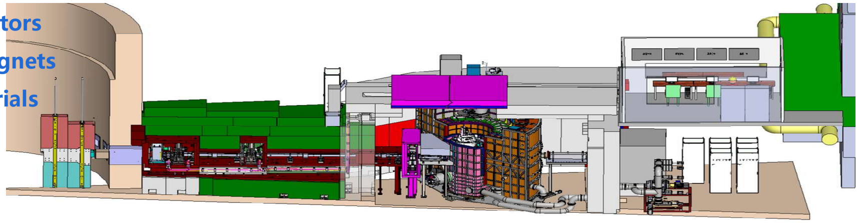
Diffraction and neutron technology

BL05 High-Energy Direct-Geometry Spectrometer (HD)

Measures high-energy lattice, magnetic, and molecular excitations using time-of-flight spectroscopy.

Applications:

- Superconductors
- quantum magnets
- energy materials
- catalysts

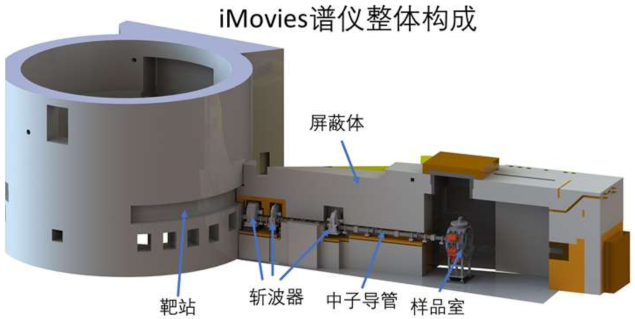


BL06 Molecular Vibration Spectrometer (iMovies)

Uses neutron vibrational spectroscopy to investigate molecular dynamics and reaction mechanisms.

Applications:

- Catalysis
- Adsorption
- biomolecules
- hydrogen bonding
- hydrogen storage

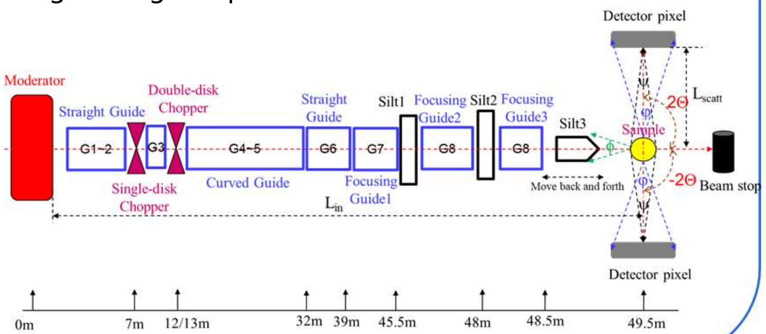


BL08 Engineering Materials Diffractometer (EMD)

Maps residual stress, strain, texture, phases, and service-induced evolution inside large engineering components.

Applications:

- engineering alloys
- Welding
- manufacturing
- operando testing

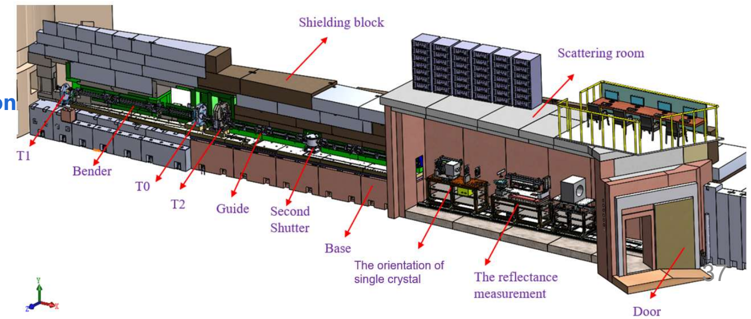


BL08A Neutron Technology Development Station (NTDS)

Provides a flexible pulsed-neutron beam for detector, component, material, and metrology development.

Applications:

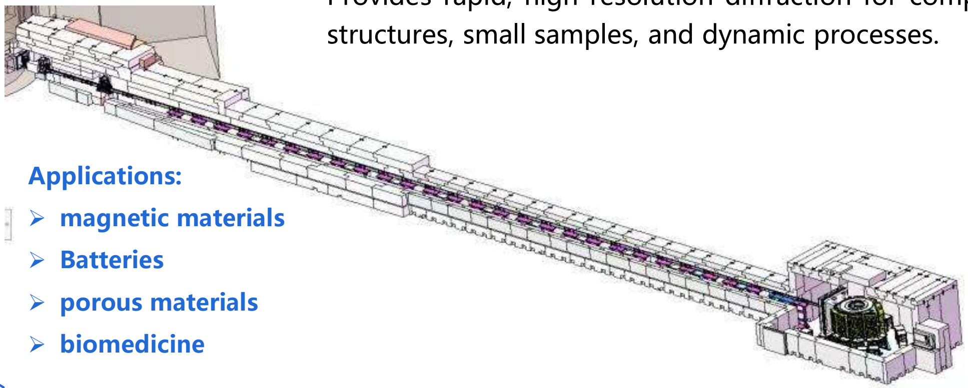
- Instrumentation
- testing
- Calibration
- methodology



Diffraction, Dynamics, and Neutron Physics

BL09 High-Resolution Neutron Diffractometer (TREND)

Provides rapid, high-resolution diffraction for complex structures, small samples, and dynamic processes.

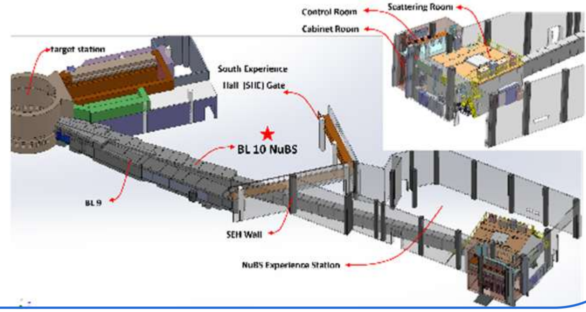


Applications:
- magnetic materials
- Batteries
- porous materials
- biomedicine

BL10 Neutron Backscattering Spectrometer (NuBS)

Probes picosecond-to-nanosecond dynamics with very high energy resolution.

Applications:
- soft matter
- Diffusion
- Biomaterials
- Polymers
- slow dynamics



BL11 Atmospheric Neutron Irradiation Spectrometer (ANIS)

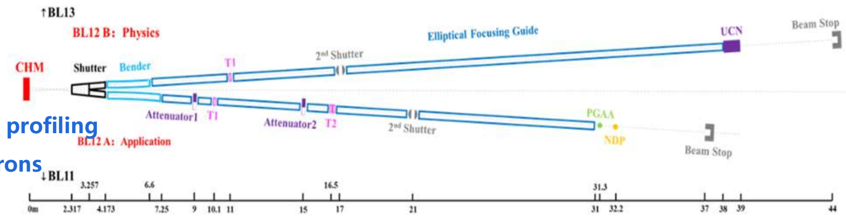
Reproduces the atmospheric neutron environment for single-event-effect and radiation-reliability testing.

Applications:
- aerospace electronics
- neutron effects
- Imaging
- radiobiology

BL12 Neutron Physics and Applications Instrument (NPAI)

Combines elemental analysis, depth profiling, and fundamental neutron-physics studies.

Applications:
- PGNAA
- neutron depth profiling
- ultracold neutrons



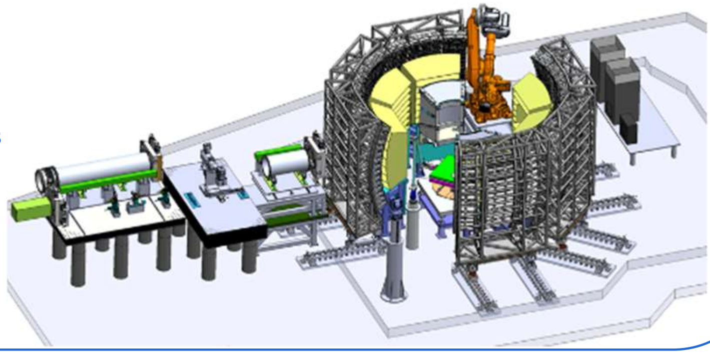
Imaging and Specialized Instruments

BL13 Energy-Resolved Neutron Imaging Instrument (ERNI)

Combines radiography, tomography, Bragg-edge imaging, and diffraction imaging for multiscale internal-structure analysis.

Applications:

- Batteries
- engineering materials
- Magnetism
- cultural heritage

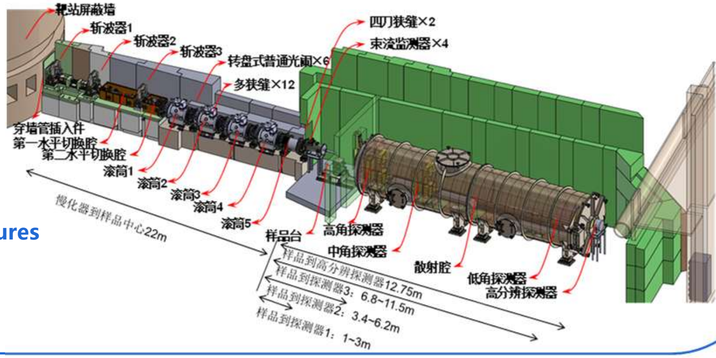


BL14 Very-Small-Angle Neutron Scattering Instrument (VSANS)

Probes structures from approximately 3 nm to 1 μm using several small-angle scattering modes.

Applications:

- Polymers
- Biomacromolecules
- energy materials
- magnetic nanostructures

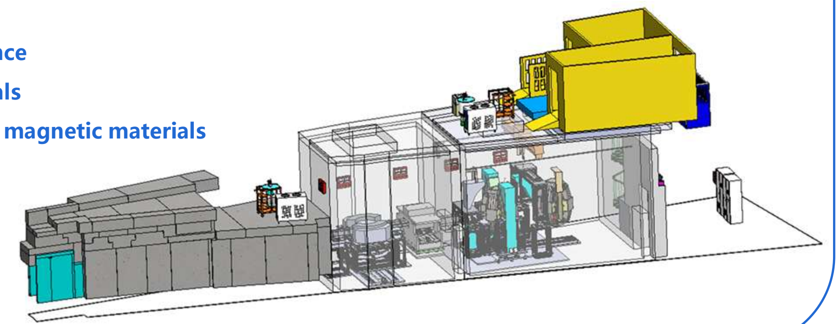


BL15 High-Pressure Neutron Diffractometer (HPND))

Studies materials under coupled high pressure, temperature, and magnetic fields, with diffraction and imaging capabilities.

Applications:

- planetary science
- energy materials
- functional and magnetic materials

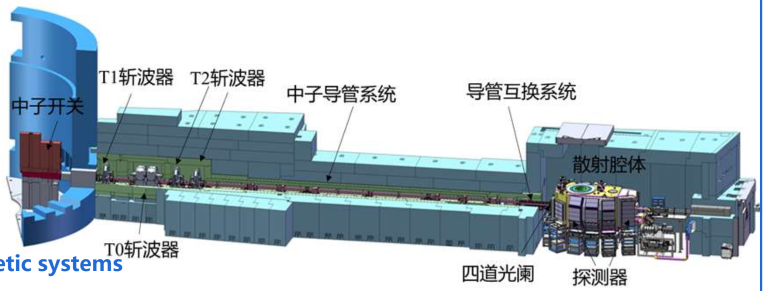


BL16 Multipurpose Instrument (MPI)

Investigates the structure and dynamics of liquids, glasses, crystals, and nanomaterials under in-situ conditions.

Applications:

- Batteries
- Alloys
- amorphous materials
- rare-earth and magnetic systems



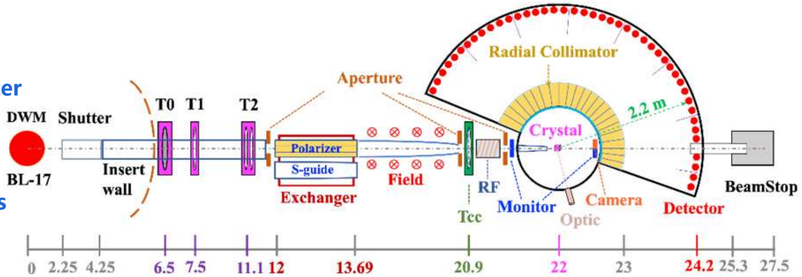
Elastic and Inelastic Scattering

BL17 Elastic Diffuse Scattering Spectrometer (EDS)

Measures short-range atomic and magnetic correlations in single crystals, including polarized-neutron modes.

Applications:

- condensed matter
- Chemistry
- Geology
- energy materials

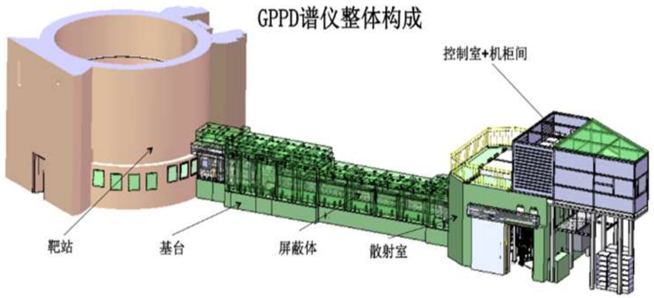


BL18 Applications: condensed matter • chemistry • geology • energy materials

Determines crystal and magnetic structures using three detector banks optimized for resolution, large-scale structures, and stress measurements.

Applications:

- Batteries
- Alloys
- Magnetism
- superconductors

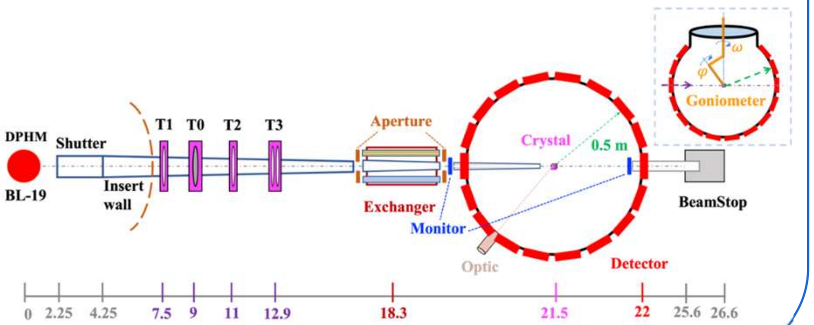


BL19 Single-Crystal Neutron Diffractometer (SCND)

Determines crystal structures and magnetic symmetries of inorganic, organic, and biomolecular single crystals.

Applications:

- Crystallography
- functional materials
- Magnetism
- biomedicine

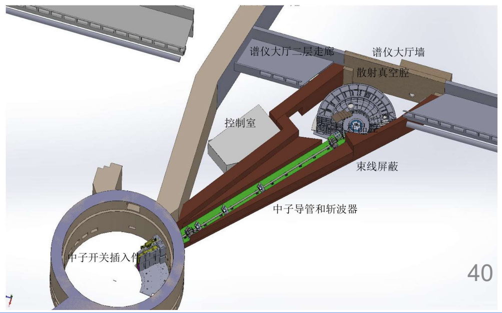


BL20 Polarized Direct-Geometry Inelastic Spectrometer

Separates lattice, spin, coherent, and incoherent excitations using polarized time-of-flight spectroscopy

Applications:

- quantum materials
- Magnetism
- superconductors
- soft matter

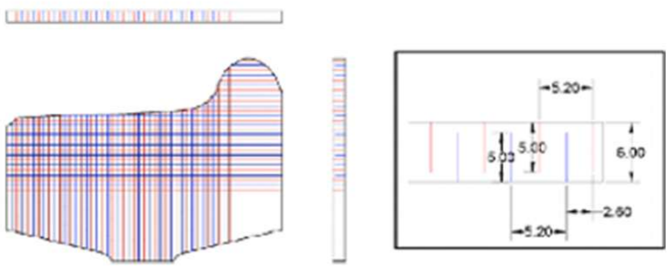


Residual-Stress Research

High-speed railway wheels

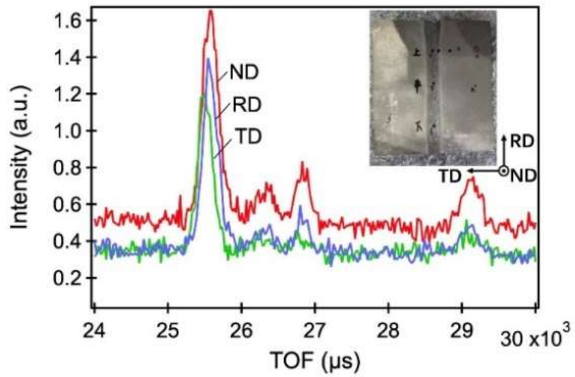
First time in China, internal residual-stress data were obtained from deep inside railway wheels, supporting operating speed from 350 km/h toward 400 km/h.

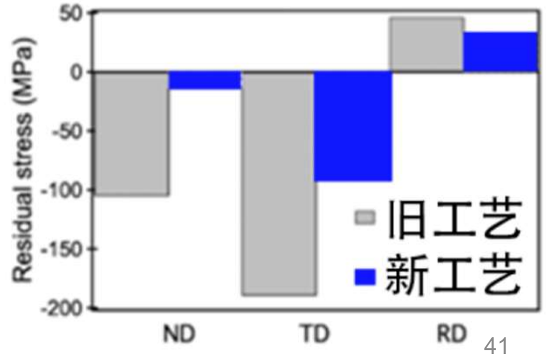
服役前车轮　　服役后车轮



deep-sea titanium alloys

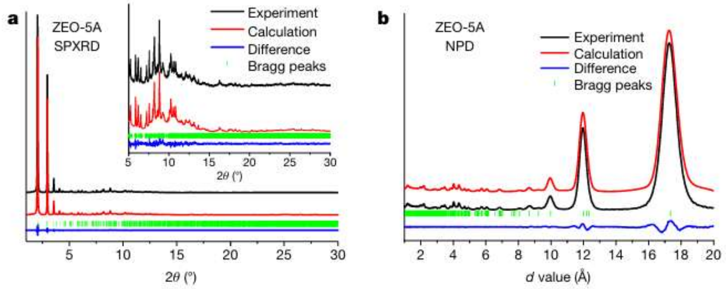
Internal residual-stress measurements support for process optimization, ensure safe operation, help predict service lifetime



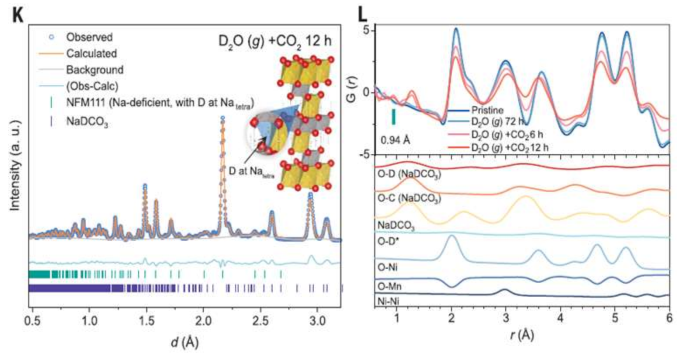


Recent CNS Papers

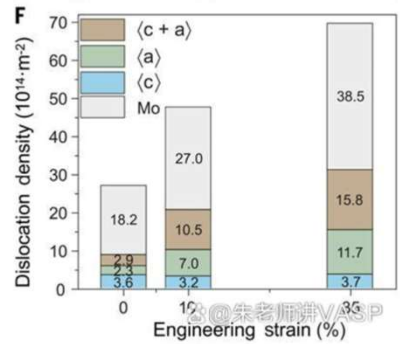
- **Chemical engineering, supermolecular sieves:** Precise 3D structure by neutron diffraction. Stable triple four-membered-ring motif. Beyond conventional zeolite crystallization. **Nature, 2024, 628, 99–103**



- **Sodium-Ion Batteries:** Layered-oxide cathodes. Degradation by atmospheric H_2O and CO_2. Mechanism revealed by neutron scattering. **Science 385, 744–752 (2024)**



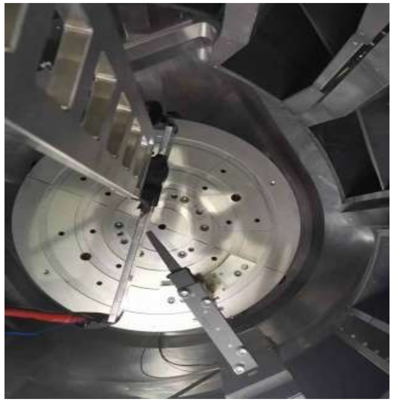
- **Ductile Ceramics:** Large tensile ductility at room temperature. Dislocation density quantified by neutron diffraction. “Borrowing dislocations” from metals. **Science 385, (2024) 422–427**

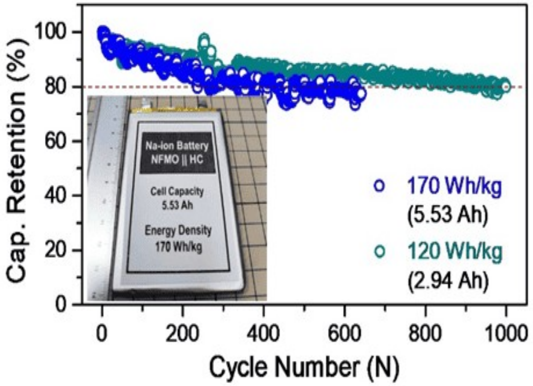


Supporting Industrial R&D

Batteries

- **BYD traction batteries**
- **Operando neutron diffraction**
- **Charge-distribution anisotropy**
- **Next-generation cathode materials**
- **Na-ion batteries after 1,000 cycles**
- **Long-life energy storage**



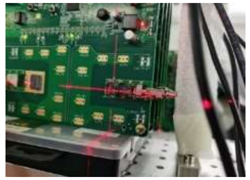


Electronic Components

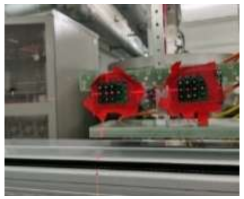
- 1,000+ devices tested
- Chips and integrated circuits
- FPGA · CMOS · SiPM · IGBT
- Optical modules · server memory
- Radiation reliability and single-event effects

FPGA

CMOS



Optical Module



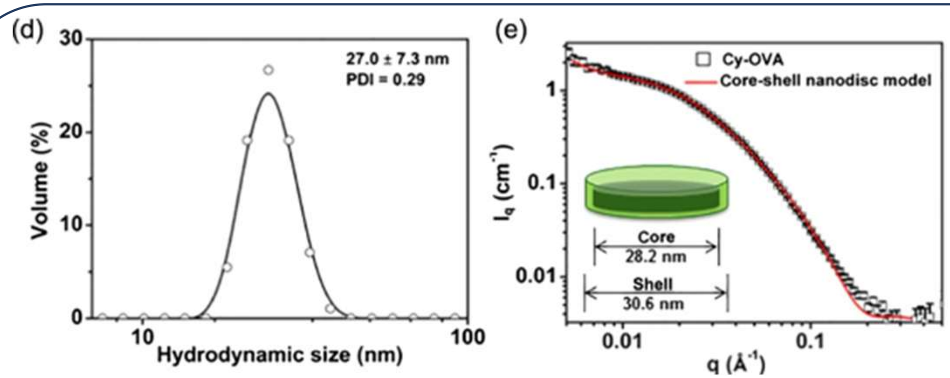
Rad-hard SiPM

IGBT

Memory Module

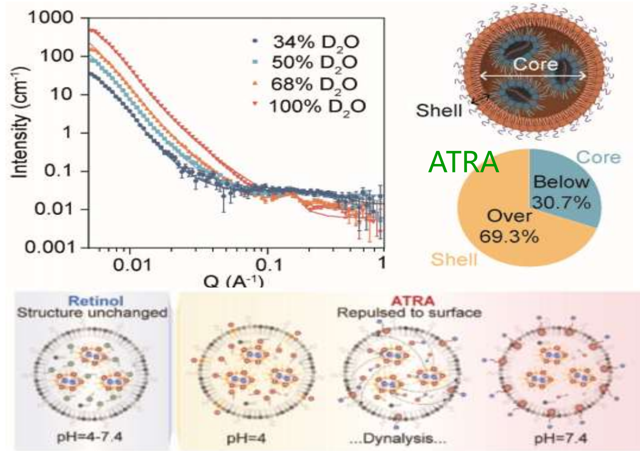
Public Health and Drug Development

SANS for nanomedicine, drug delivery, and biomolecular structures



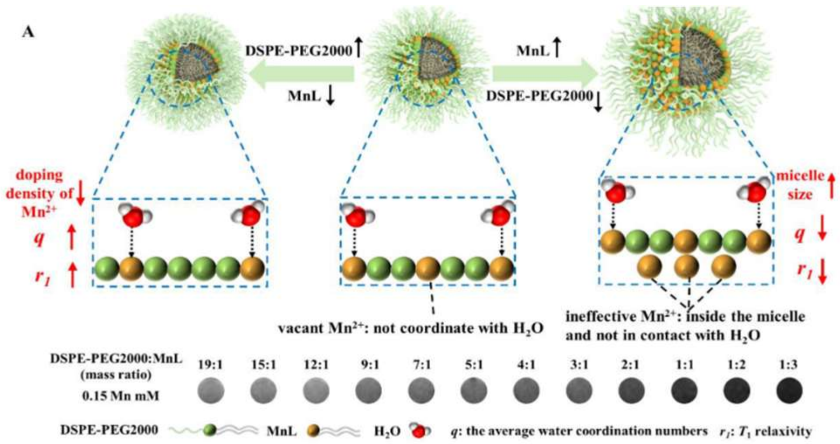
▲ **Cancer Nanomedicine Cy-OVA@CpG**

(CCS Chemistry 2021: 1-21)



▲ **Liver-fibrosis treatment LNP-mRNA**

(Nature Comm. 2024，15：7263)



◀ **MRI Nanocontrast Agents, Hydration and molecular coordination**

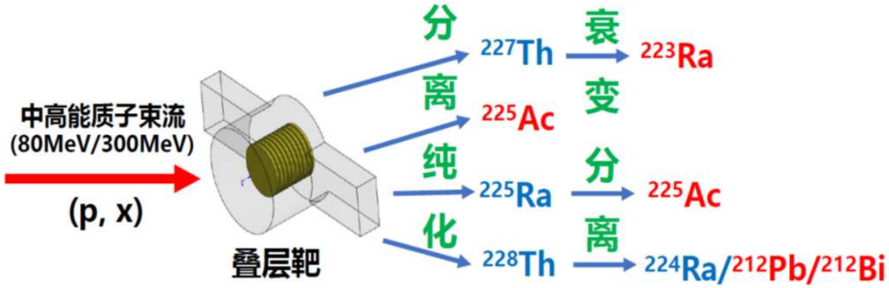
（Nano Letters, 2023, 23, 18, 8505–8514）

CSNS in-house

Production of medical α-emitting isotopes using CSNS LINAC

- Innovative use of a large-scale facility
- High energy, high intensity, high power;
- High yield, high purity, cost-effective production

Targeted cancer therapy

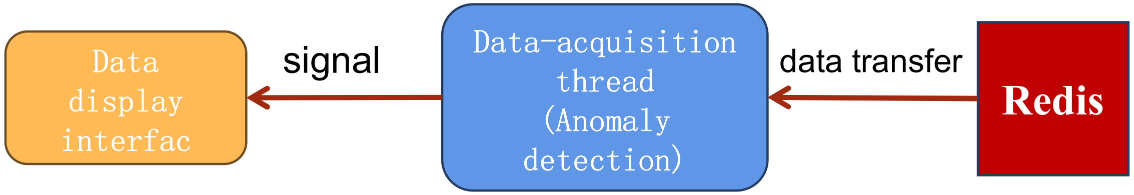


Artificial Intelligence

AI-assisted neutron-source data management and database

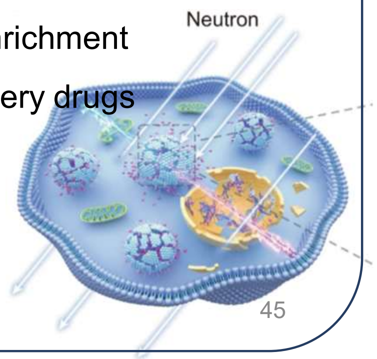
RZERA

RZera online architecture



Novel Boron Drug Development

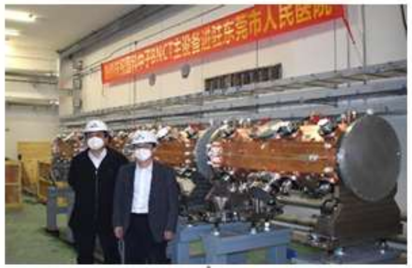
(1) Design and synthesis of boron compounds
(2) Intracellular targeting and enrichment
(3) In-vivo tracing of boron-delivery drugs



BNCT Boron Neutron Capture Therapy

CSNS in-house

BNCT therapy



2022年1月
项目正式启动

2022年7月
BNCT大楼封顶

2022年12月
主设备RFQ加速器进场安装

2023年3月
加速器主体完成安装调试

2023年12月
实现打靶出中子束

2024年4月
整机调试测试初步完成
由上海医疗器械检验研究院负责型式检验

2024年8月
细胞动物实验完成
系统治疗效果初步验证

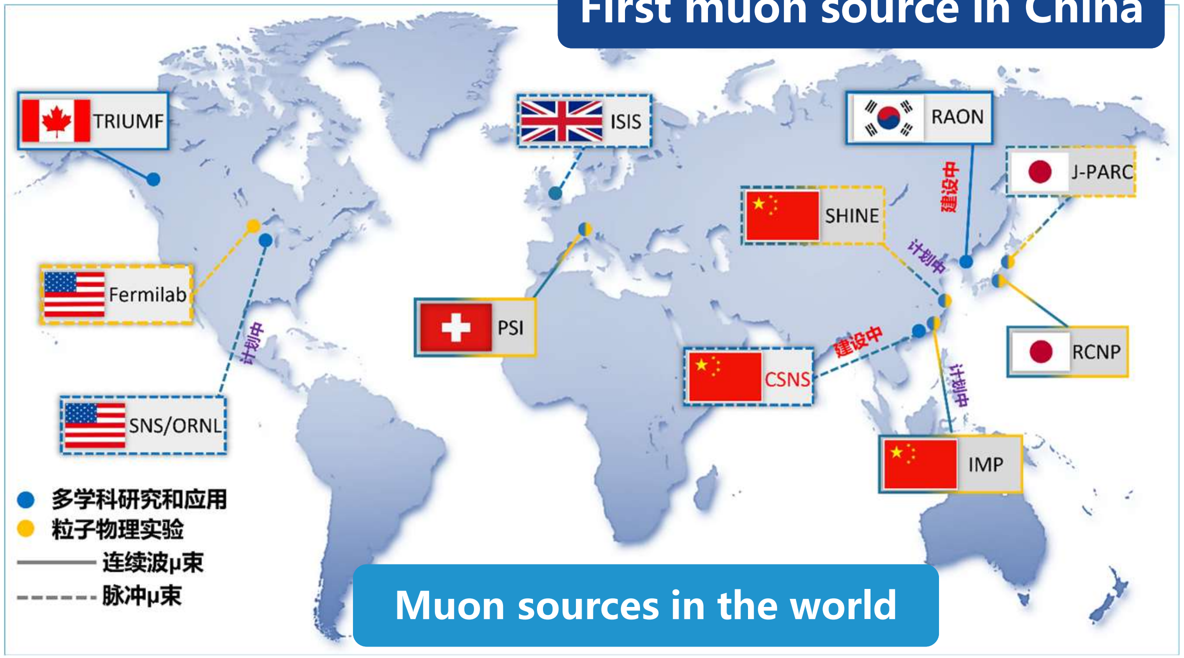
CSNS Experimental Stations

MELODY Muon Source

Muon station for sci**E**nce techno**LO**gy and in**D**ustr**Y**

MELODY will provide a highly spin-polarized **4 MeV surface muon beam** for μSR studies of magnetic materials.

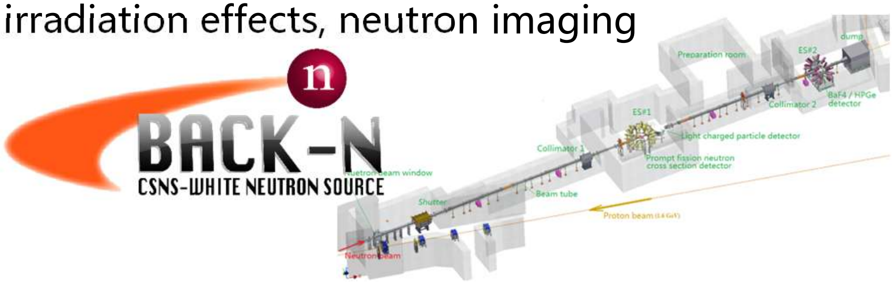
First muon source in China



Muon sources in the world

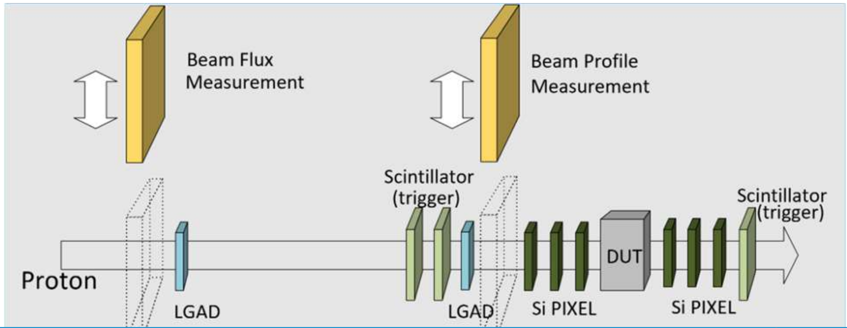
Back-n White Neutron Facility

Back-n supports: Neutron nuclear-data measurements, detector calibration, neutron irradiation effects, neutron imaging



High-Energy Proton Experimental Station

HPES provides 0.8–1.6 GeV proton beams for advanced detector testing and calibration, irradiation-effect studies

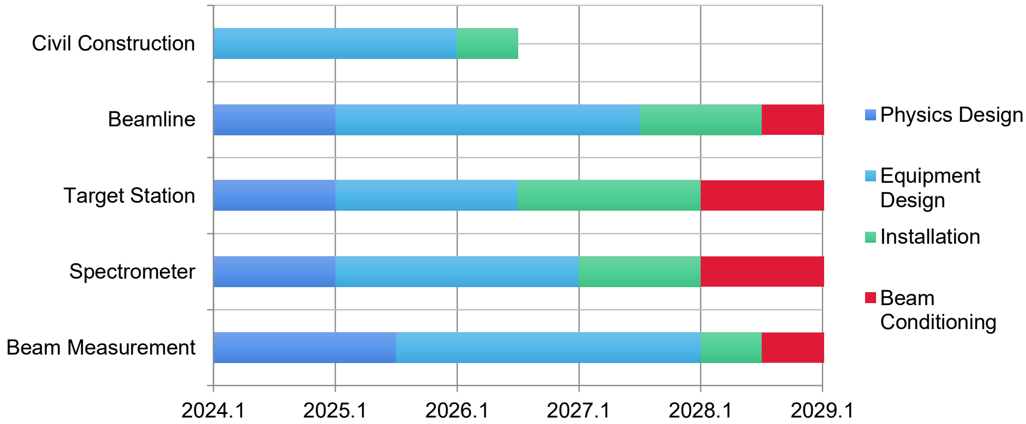


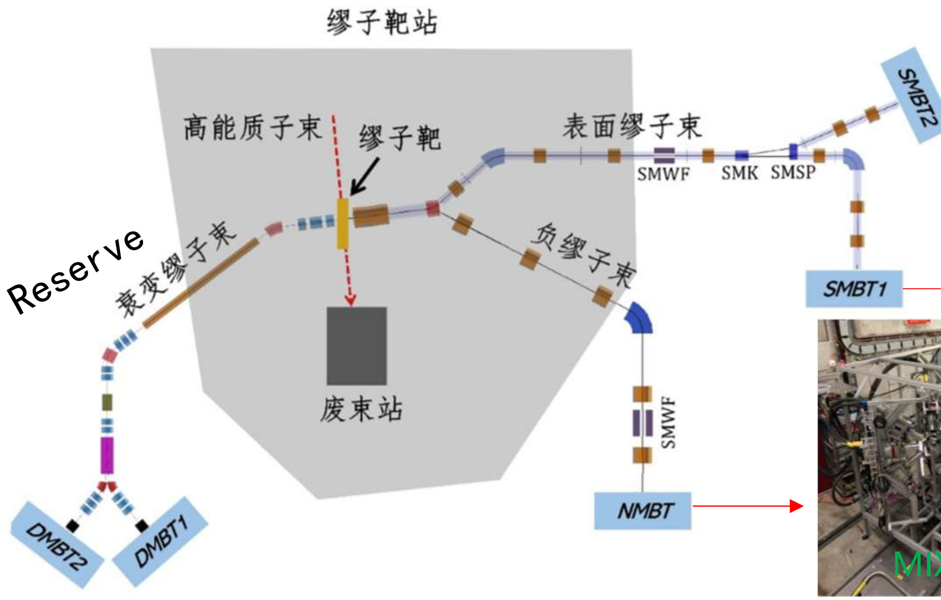
First high-energy proton test beam in China

MELODY

Constructing surface muon beamline (4 MeV μ^+, ~100% polarization), negative muon beamline, 3 terminals, 1 μSR, 1 MIXE

- SMBT1 for μSR experiments
- SMBT2 for R&D, e.g. muon cooling
- NMBT for MIXE elemental analysis

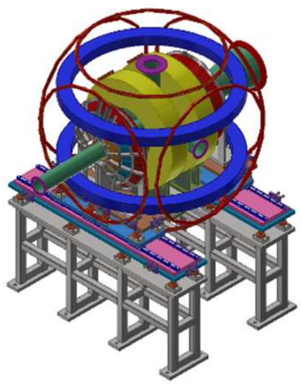


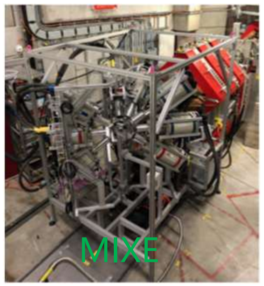


Testing terminal

e.g. muon cooling

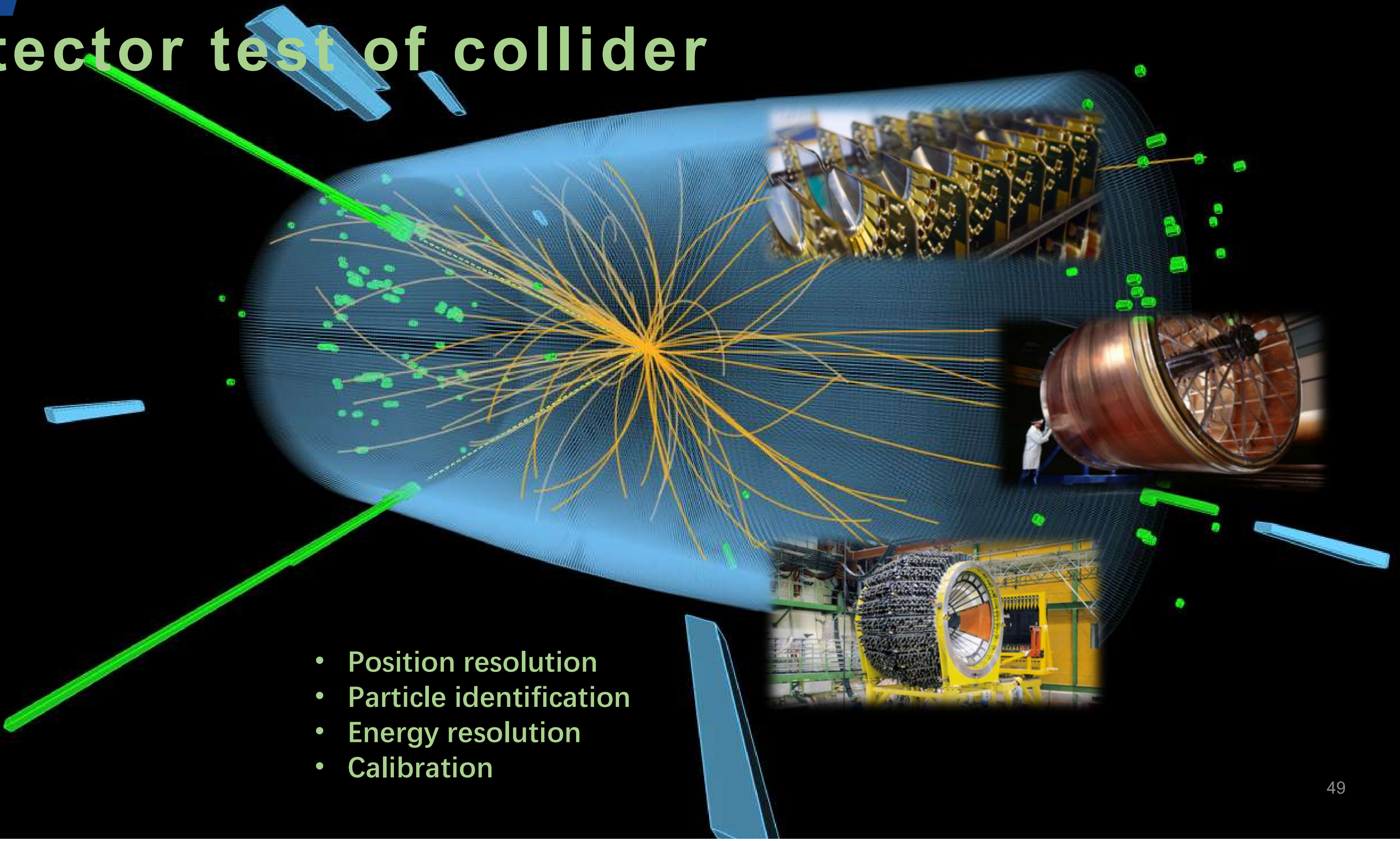
μSR





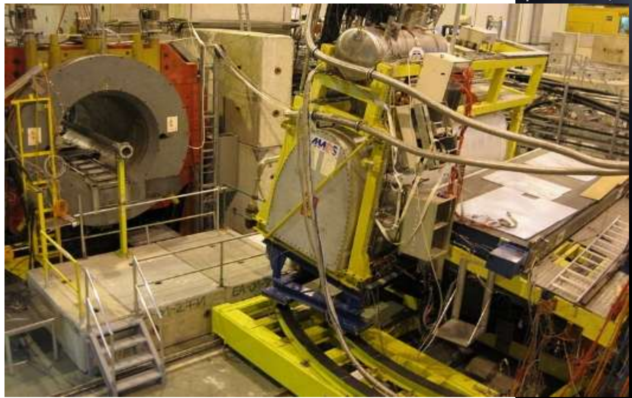
Detector test of collider

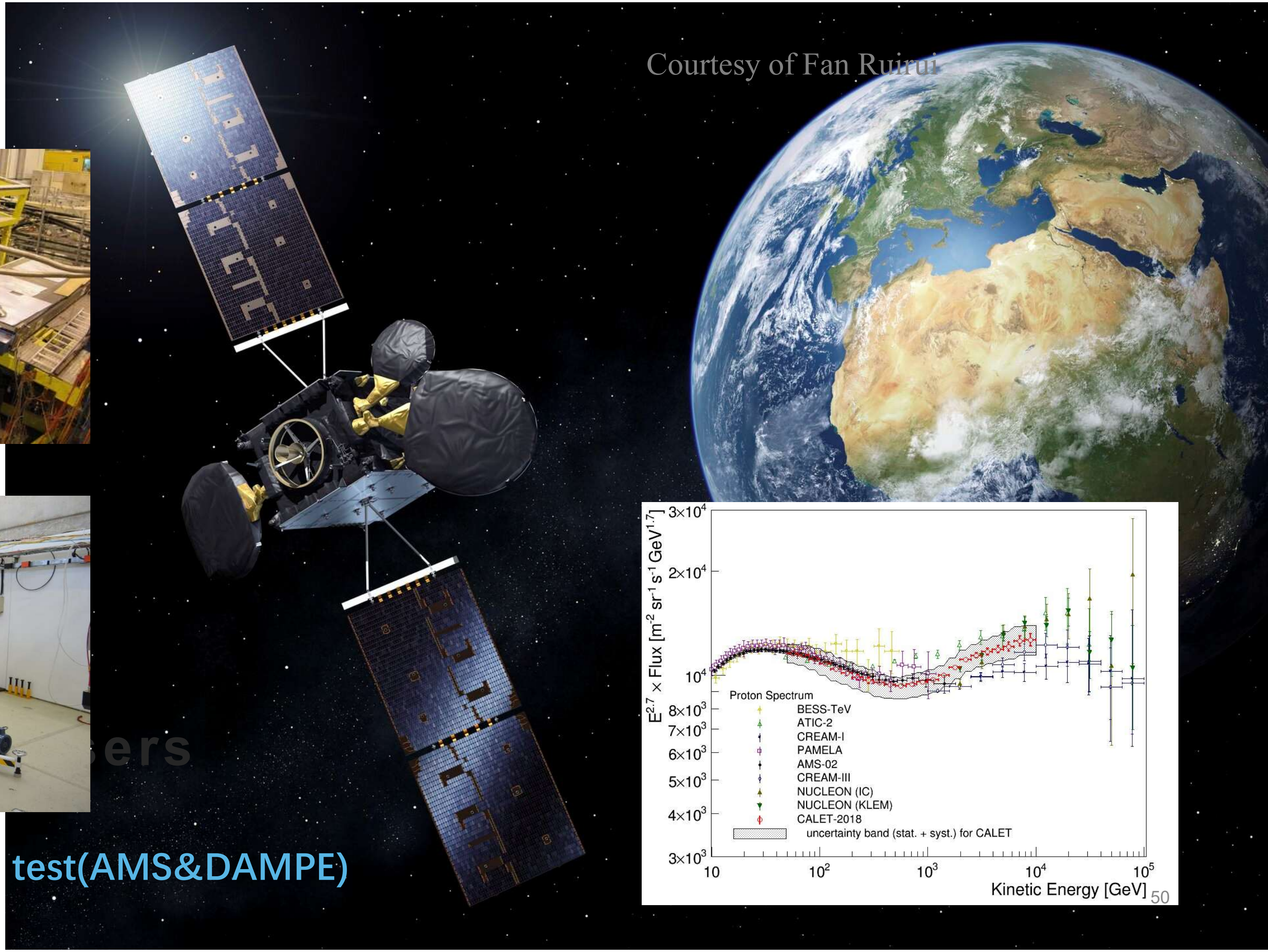
Courtesy of Fan Ruirui



- Position resolution
- Particle identification
- Energy resolution
- Calibration

HPES



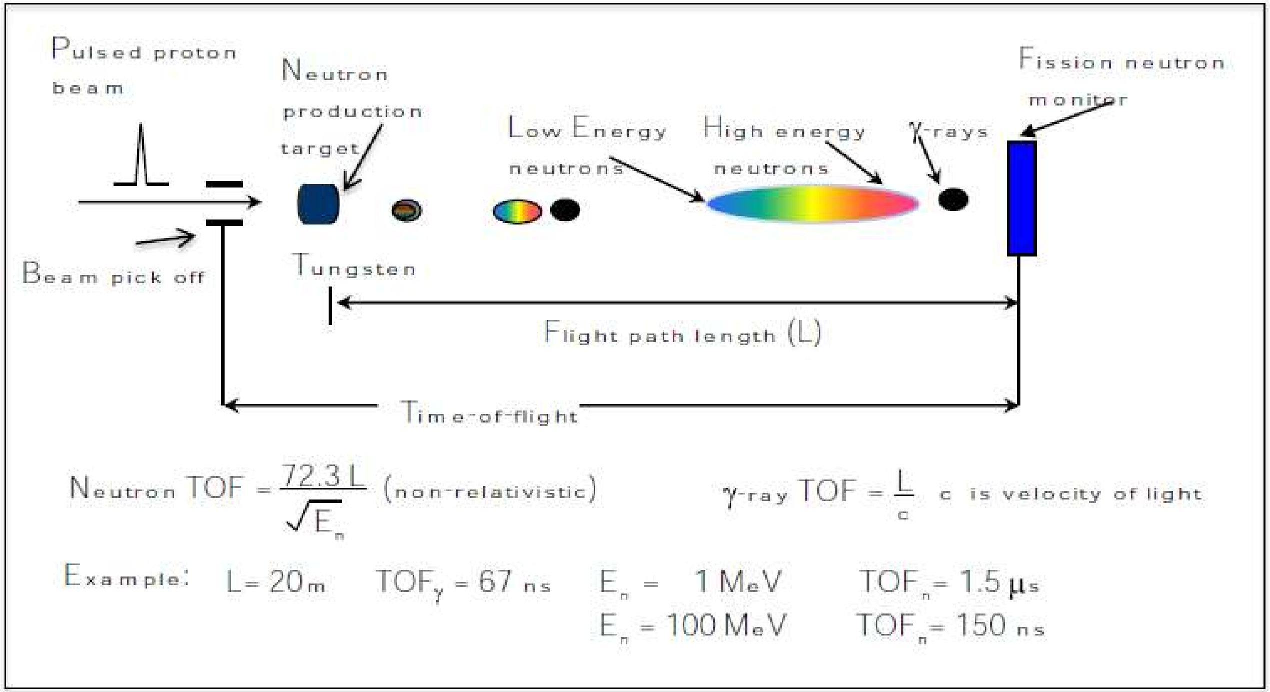


- Space Payload beam test(AMS&DAMPE)

Courtesy of Fan Ruirui

What Are White Neutrons?

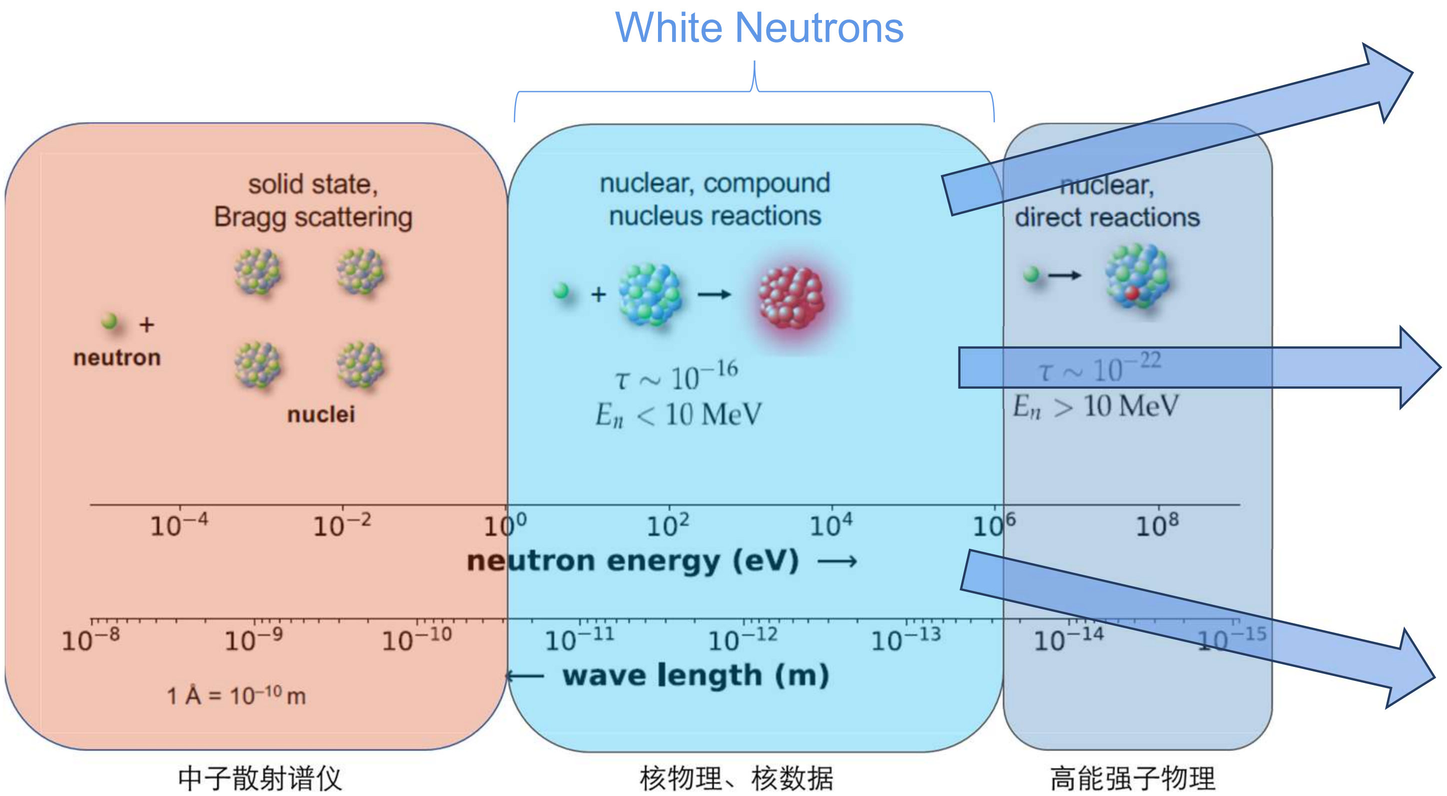
- A white neutron beam is a broad-spectrum neutron beam.
- Produced by pulsed accelerators:
  - electron accelerators: photonuclear reactions
  - proton accelerators: spallation reactions
  - laser-driven sources: D–D / D–T reactions
- Energy range: from thermal neutrons ~0.025 eV to hundreds of MeV
- Neutron energy determined by time of flight
- Long flight paths: typically tens to hundreds of meters



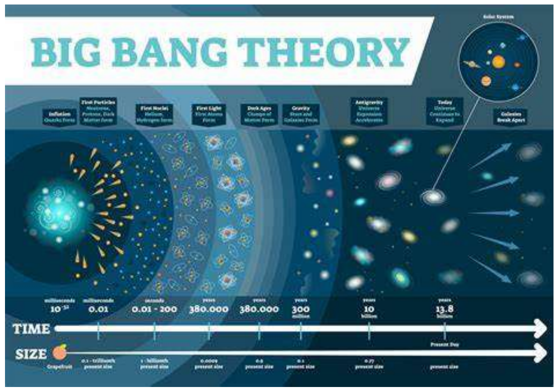
Typical layout of a white-neutron time-of-flight beamline

Back-n

Applications of White Neutrons



Courtesy of Fan Ruirui



White neutrons in the eV–MeV range are ideal for nuclear physics and nuclear-data measurements.

Thank you！