International Collaboration on Advanced Neutron Sources (ICANS XXIV)

(Compact Accelerator-driven Neutron Source)

CANS Projects in China

Xuewu WANG
Professor, Tsinghua University, Beijing, China
wangxuewu@tsinghua.edu.cn
Nov. 3rd, 2023 @ Dongguan, China

清華大學工程物理系
Department of Engineering Physics, Tsinghua University

Outline

CANS Projects in China

CONTENTS

Large Neutron Sources in China

Chinese Neutron Scattering Society

2004/05/06/08, Workshop on Applications of Spallation Neutron Source

2010/11/12, Workshop on Applications of National Neutron Facilities

2012.12-, **CNSS: Chinese Neutron Scattering Society**

2013/14/15/16/17/18/19/20/23, **National conference on neutron scattering & Workshop on Applications of National Neutron Facilities**

UCANS

The Official Web Page of
Union for Compact Accelerator-driven Neutron Sources
(UCANS)

http://www.ucans.org/

Meetings

UCANS-0, March 13, 2010; Hotel Allegra, Kloten, Switzerland

UCANS-I, August 15-18, 2010; Tsinghua University, Beijing, China

UCANS-II, July 5-8, 2011; Indiana University, Bloomington, Indiana, USA

UCANS-III, July 31-August 3, 2012; Bilbao, Spain

UCANS-IV, September 23-27, 2013; Hokkaido University, Sapporo, Japan
(40th Anniversary of Hokudai LINAC)

UCANS-V, May 12-15, 2015; Laboratori Nazionali di Legnaro, Padova, Italy
(Proceedings: Il Nuovo Cimento C - Open Access, Vol.**38**, N.6, 2015)

UCANS-VI, October 25-28, 2016; Xi'an Jiaotong University, Xian, China

UCANS-VII, March 11-15, 2018; Bariloche, Argentina

UCANS-VIII, July 8-11, 2019; Paris, France
(Proceedings: EPJ Web of Conferences - Open Access, Vol.**231**, 2020)

UCANS-WEB, Nov.30 - Dec.3, 2020; RIKEN, Japan (ONLINE, only invited talk)

UCANS-IX, March 29-31, 2022; RIKEN (Online, including poster session)
(Proceedings:Journal of Neutron Research Vol.**24**, issue 3-4, 2022)

UCANS-X, Oct. 16-19, 2023; Budapest

Outline

Although the field of neutron scattering has been flourishing for many decades now, advances in science and technology in this field have been dominated by a fruitful combination of major international facilities (based on reactors as at the ILL, HBIR, NCNR, JRR or large accelerators such as at IPNS, ISIS, SNS and JSNS) supported by networks of smaller research reactor facilities (e.g. those at Berlin, Vienna, Budapest, Missouri and many others). Recent advances in accelerator technology and neutronic design have made possible the construction of small-scale accelerator-driven neutron facilities that will be able to play a significant role in future advancements in neutron technology and science. This opens up new opportunities for organizations to enter the field of neutron physics with modest investments and without the proliferation and safety concerns associated with building a new research reactor. Such facilities can be used in fields as diverse as materials science, nuclear physics, medical physics, engineering, and cultural heritage. A satellite meeting to the ICANS-XIX Meeting (March 2010, Grindelwald, Switzerland) offered an opportune occasion to consolidate an alliance among institutions interested in constructing and operating such facilities. At this meeting participants unanimously acceded to the establishment of the Union for Compact Accelerator-driven Neutron Sources (UCANS). The eight initial members—those in attendance at this initial meeting—were: from the USA, Argonne National Lab (ANL) and Indiana University, from Japan, the High Energy Accelerator Research Organization (KEK), Hokkaido University, Kyoto University and RIKEN, from China, Peking University and Tsinghua University, with additional potential members from elsewhere. Jack Carpenter of ANL serves as the initial spokesperson of UCANS. In view of the actively ongoing works on accelerators, target-moderators, instruments and optics, all members felt a genuine need for frequent meetings (every ~6 months rather than 2 years like ICANS). The participants of this new collaboration are united in their firm believe that UCANS is complementary to ICANS membership in both collaborations is encouraged.

C-CANS: Chinese Collaboration on CANSs

- Communication, Collaboration, Education, Development
- 3 topical group with topical seminars:
  ☆Accelerator Yuanrong LU， Qingzi XING, Chunlei WU
  ☆TMR Tianjiao LIANG, Sheng WANG, Kun ZHU
  ☆Application Yuntao LIU, Yuanhao LIU, Yigang YANG
- Seminar: might be together with CNSS conference
- Contact office: Tsinghua University;
- Contact person: Xuewu WANG wangxuewu@tsinghua.edu.cn

C-CANS Seminar - 1
@ Jan 20, 2019
@ Tsinghua Univ.

C-CANS Seminar - 2
@ Jan 04-05 2020
@ CIAE

C-CANS Seminar - 3
to be held @ CSNS

CCANS

Outline

CANS Projects in China

CONTENTS

Cyclotron-based BNCT @ CIAE

CCANS

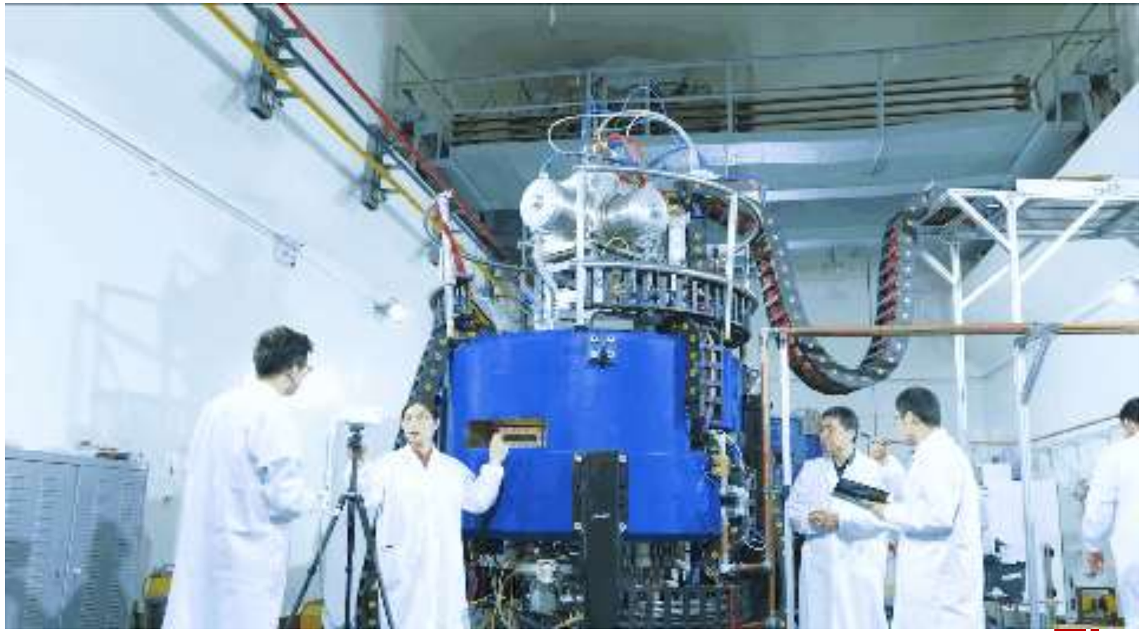
中国原子能科学研究院
CHINA INSTITUTE OF ATOMIC ENERGY
中核集团 CNNC

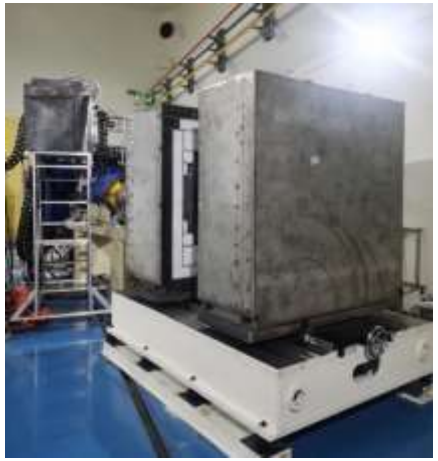
The full power shooting test of 14kW Beryllium target was completed, and the Neutron flux was larger than 1×10^9 n/cm²/s

Courtesy Yuntao LIU @ CIAE

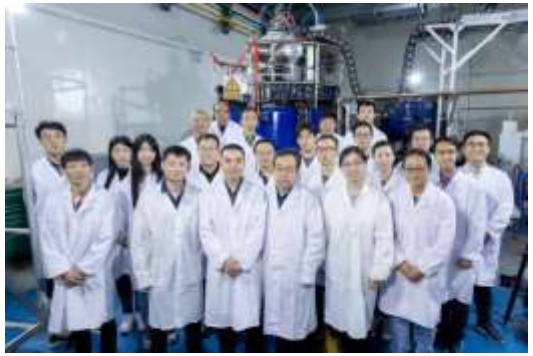
Installation started in September 2020

Device Commissioning in March 2021



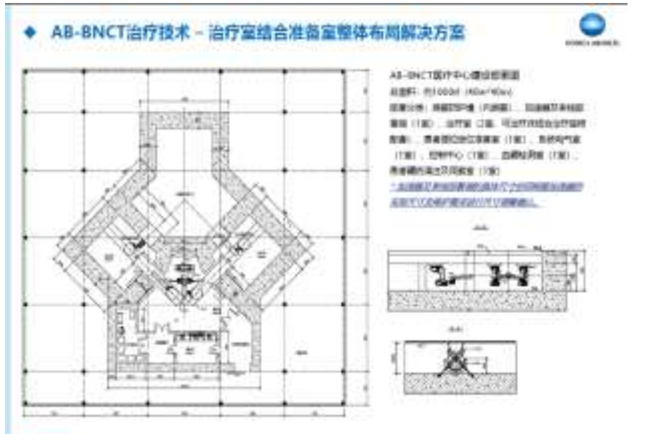


The neutron target was installed in June 2021



The current exceeded 1mA in Jan 2022

➢ BNCT equipment clinical center cooperation with Tai'An hospital



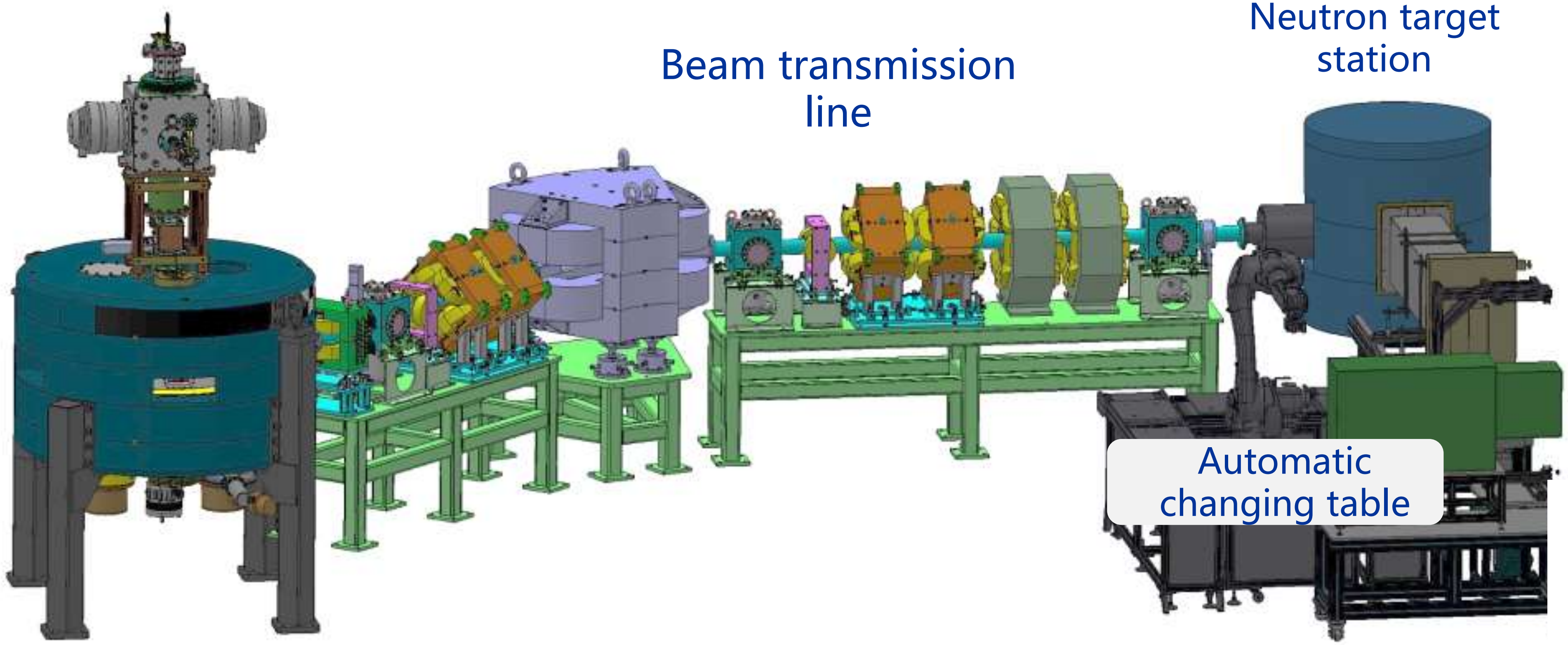
CCANS

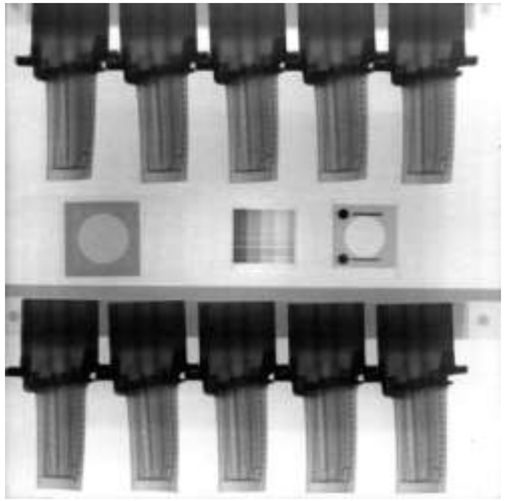
Cyclotron-based Neutron Imaging

中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY 中核集团 CNNC

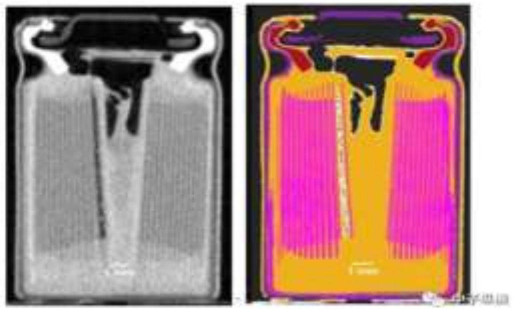
A neutron imaging system is developed based on an 18MeV cyclotron.

Energy: 18MeV / Current : 1mA / Flux at sample position :>1×10^{6} n/cm^{2}/s





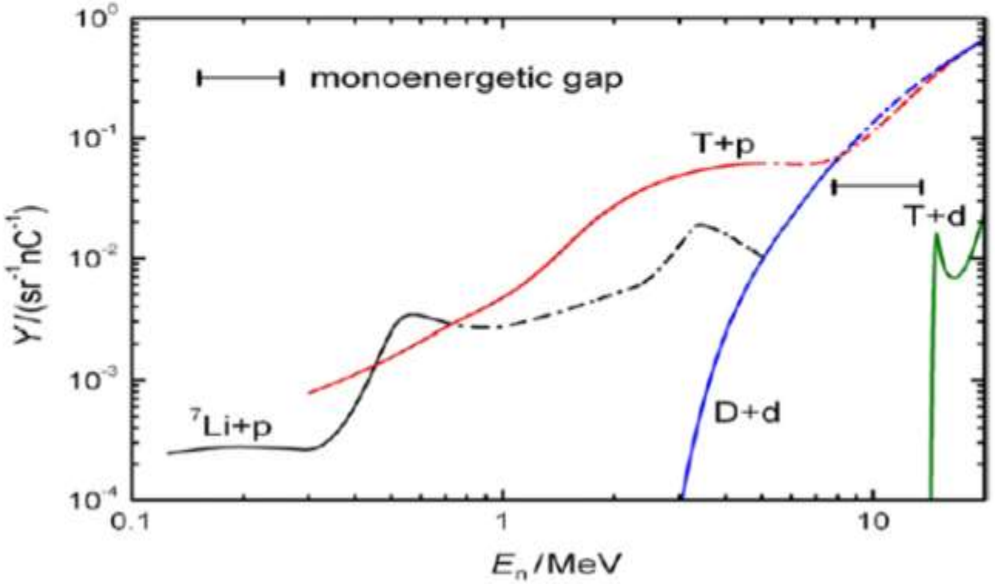
Imaging system



Neutron Reference field——fast

- Fast neutrons（1keV~20MeV)
  - Based on 2×1.7 MV tandem accelerator
  - Parameters of the accelerator：
    - ✓ Terminal voltage：2×1.7MV
    - ✓ Ion sources：p、d、C、O、Cu ...
    - ✓ Beam mode：steady/pulsed
    - ✓ Beam current：on ion source（>100uA), on target（1uA~20uA)
    - ✓ pulse width：2ns
  - Nuclear reactions：^{45}Sc(p,n), ^{7}Li(p,n), T(p,n), D(d,n), T(d,n)

5 SDH-2 tandem accelerator

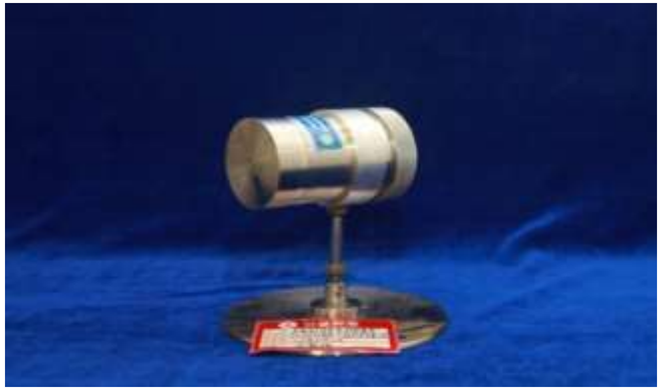


Neutron Reference field——fast

中国原子能科学研究院
CHINA INSTITUTE OF ATOMIC ENERGY
中核集团 CNNC

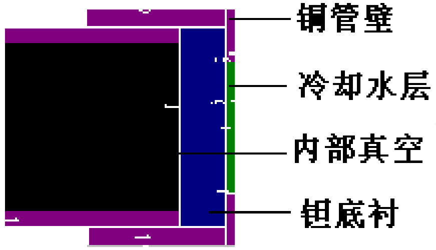
Neutron Energy(MeV)	Nuclear reaction	Measurement standard
0.144	$^{7}Li(p,n)^{7}Be$	Hydrogen-filled proportional counter(H_2)
0.25	$^{7}Li(p,n)^{7}Be$	Hydrogen-filled proportional counter(H_2)
0.565	$^{7}Li(p,n)^{7}Be$	Hydrogen-filled proportional counter(CH_4)
1.2	$T(p,n)^{3}He$	Hydrogen-filled proportional counter(C_3H_8)
2.5	$T(p,n)^{3}He$	Recoil-proton telescope
5.0	$D(d,n)^{3}He$	Recoil-proton telescope
14.8	$T(d,n)^{4}He$	associated alpha particle detector
19	$T(d,n)^{4}He$	Recoil-proton telescope (scintillation)
8keV、27.4KeV	$^{45}Sc(p,n)^{45}Ti$	LiF-SSD、Recoil-proton telescope

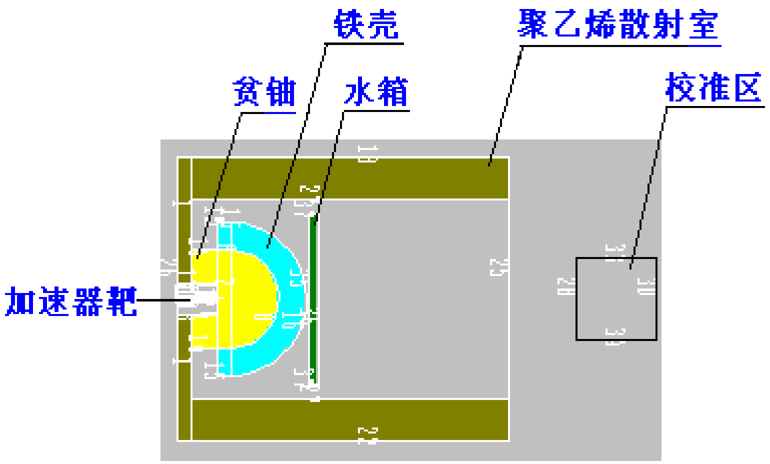

Recoil proton proportional counter

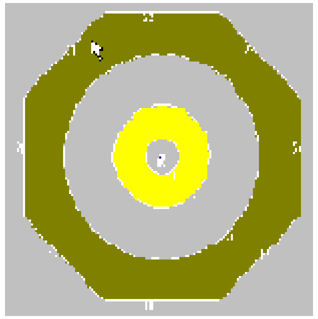

Semiconductor telescope

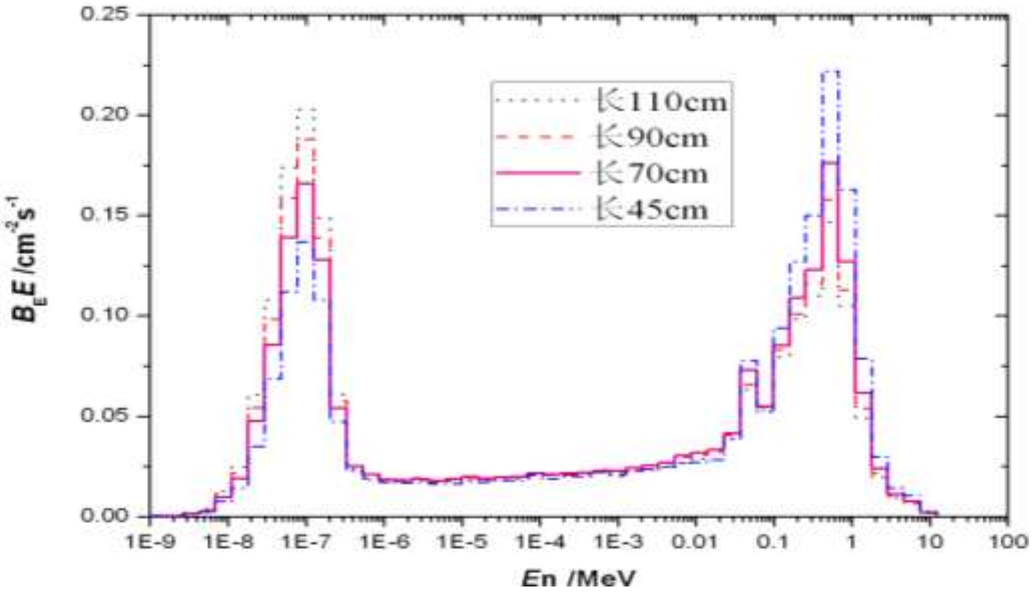

Recoil proton telescope

Neutron dose equivalent standard for simulation of PWR working place



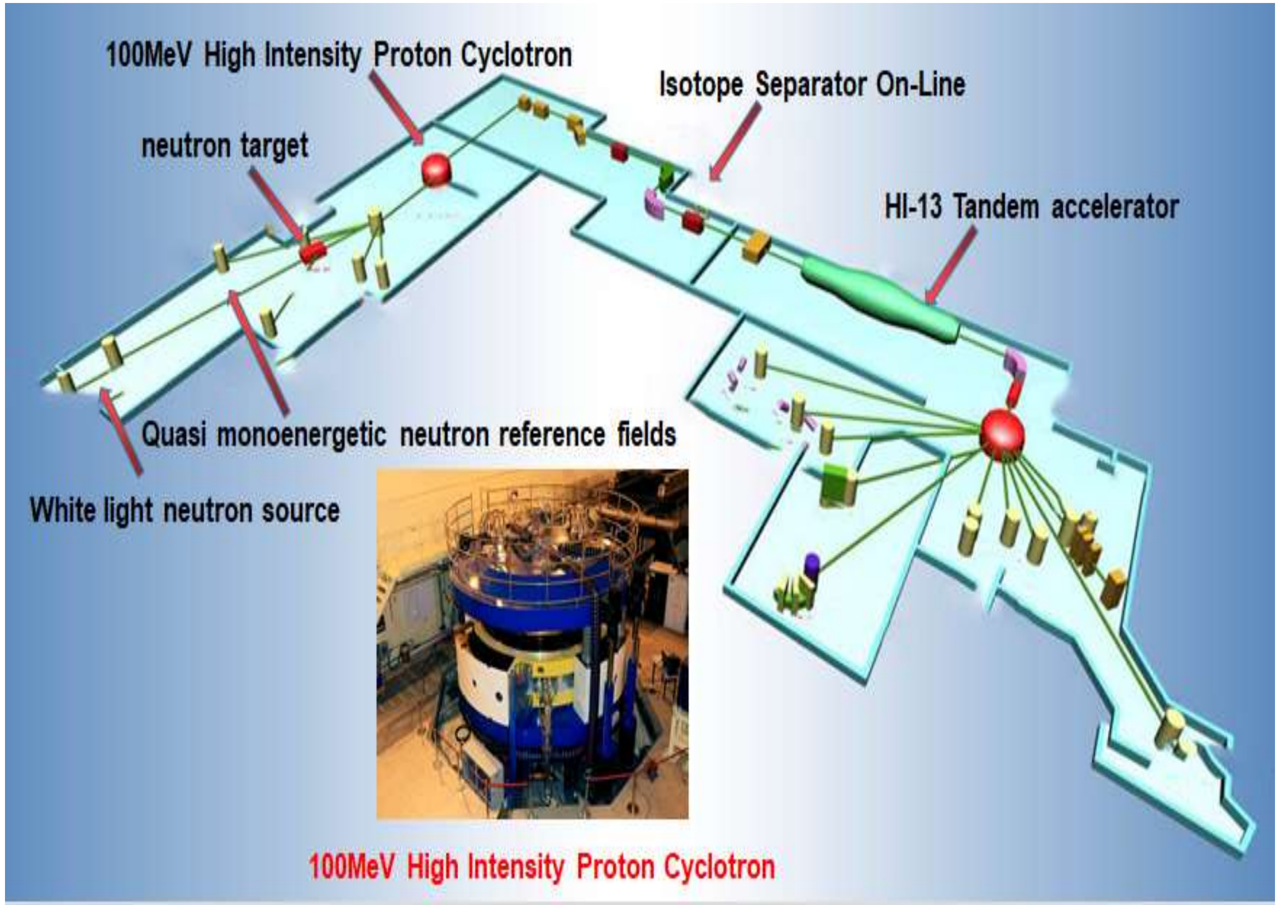


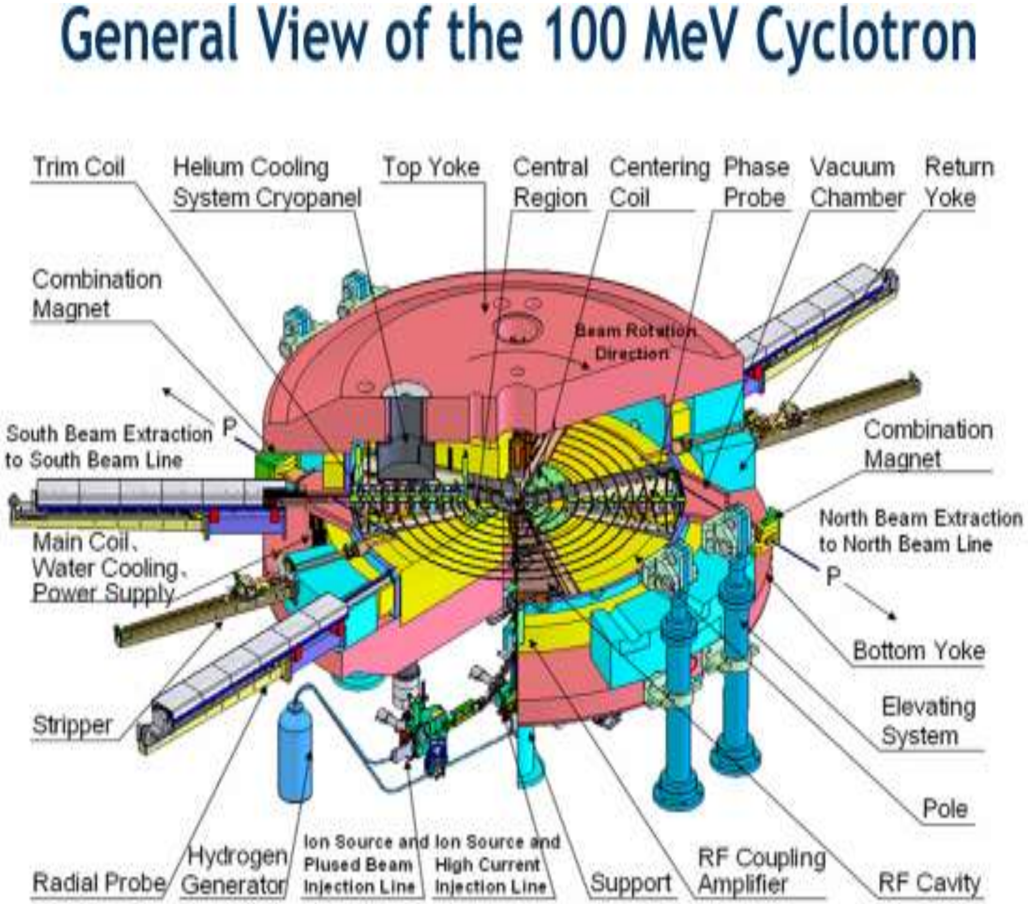




CCANS Neutron Reference field (>20MeV)

中核集团 CNNC 中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY



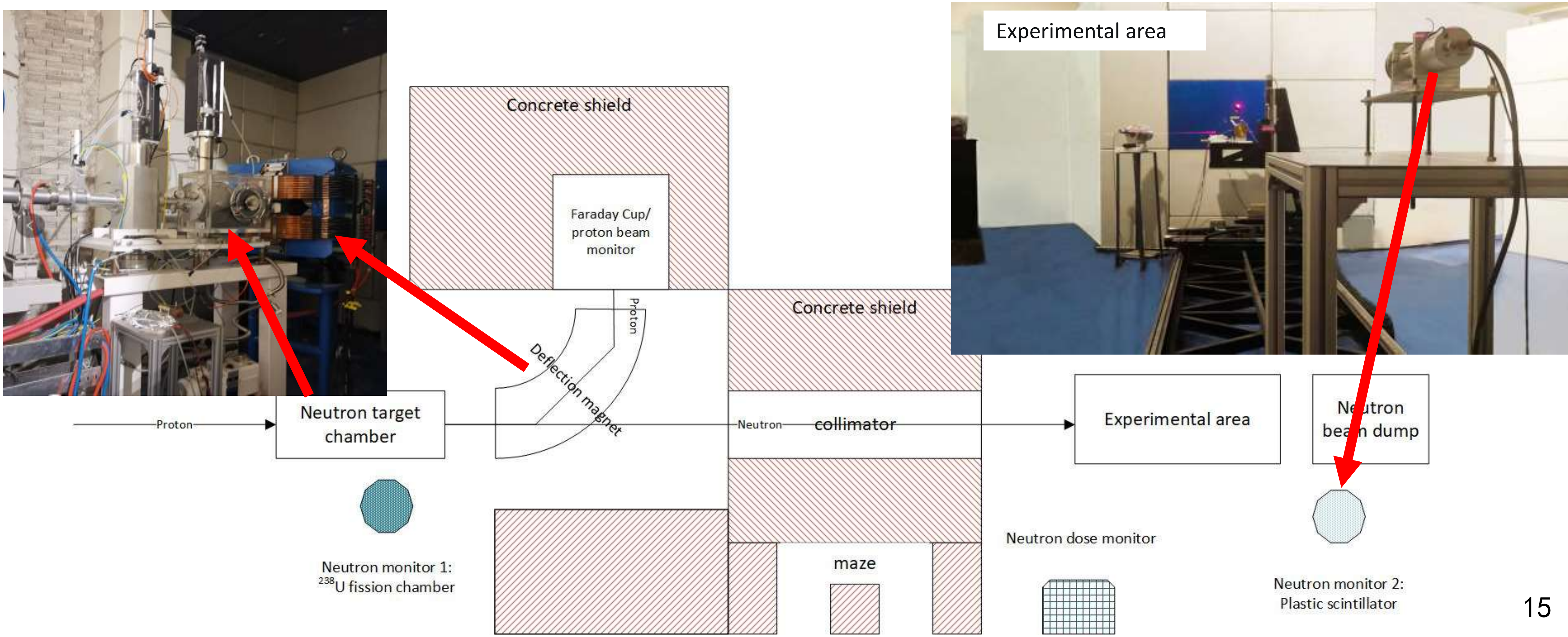


- **The current at ion source : more than 10 mA**
- **Proton energy: 70~100 MeV (neutron energy: 68MeV- 98 MeV)**
- **Pulse width: 10 ns / Pulse interval time: 100-1000 μs (on developing)**

Neutron Reference field (>20MeV)

➢ High energy range

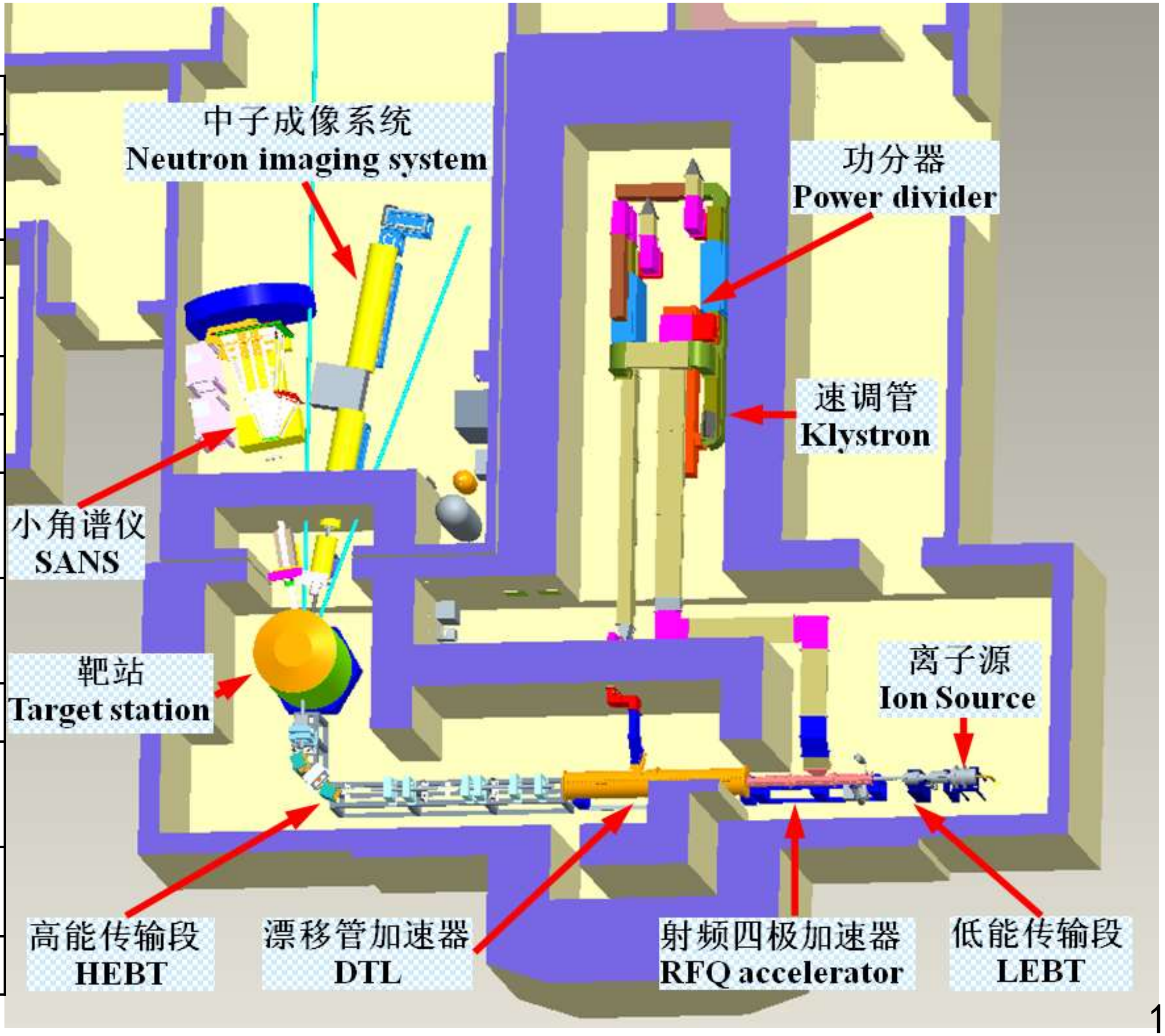
- 70MeV~100MeV quasi-monoenergetic neutron reference fields



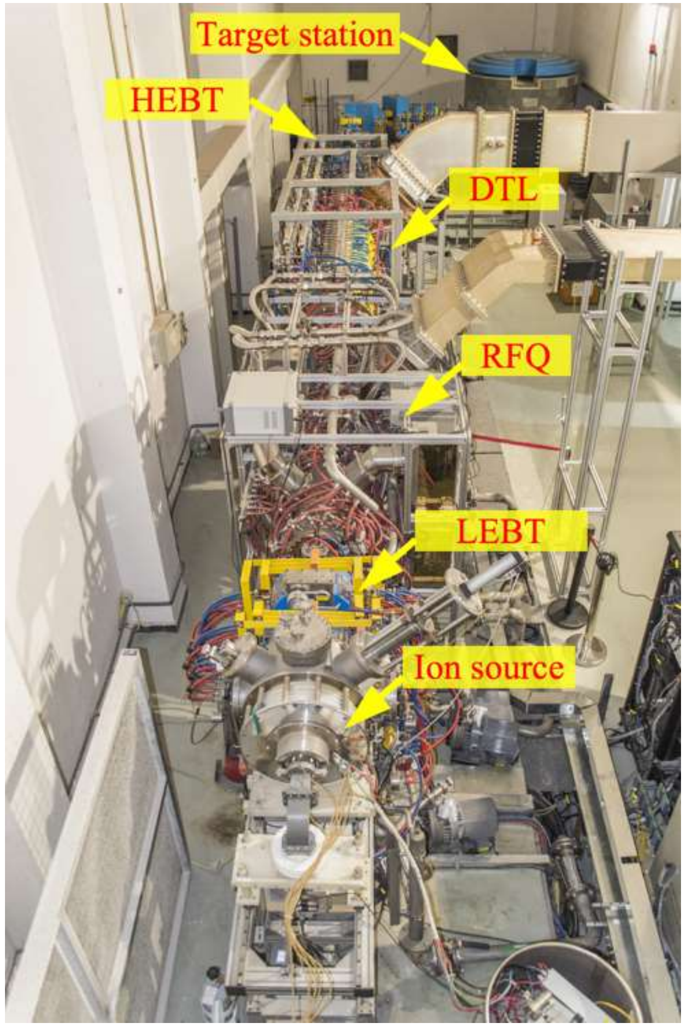
CCANS Compact Pulsed Hadron Source @ THU

Key design parameters of CPHS

Protons		Neutrons	
Beam power on target	**16 kW**	Target for ~6 cm x 6cm proton beam	
Output energy		**Material**	**Be ~1.2 mm thick**
DTL	**13 MeV**	Coolant	Chilled water
RFQ	3 MeV	**Moderator**	
Ion source	50 KeV	**Material**	**Solid CH_4 ~20 K**
Average beam current	1.25 mA	*n*-emitting surface	10 cm x 10 cm
Pulse repetition rate	50 Hz	Reflector	Water
Pulse length	**0.5 ms**	Pulse length	~1 ms
Peak beam current	50 mA	**Neutron yield (est.)**	**~5 x 10^{13} /s**
Protons per pulse	1.56 x 10^{14}		
RF frequency	325 MHz		



CPHS @ Tsinghua Univ.



Compact Pulsed Hadron Source

Project cost: ~10M USD, supported by Tsinghua University

System designed and built: by Dep. of Engineering Physics

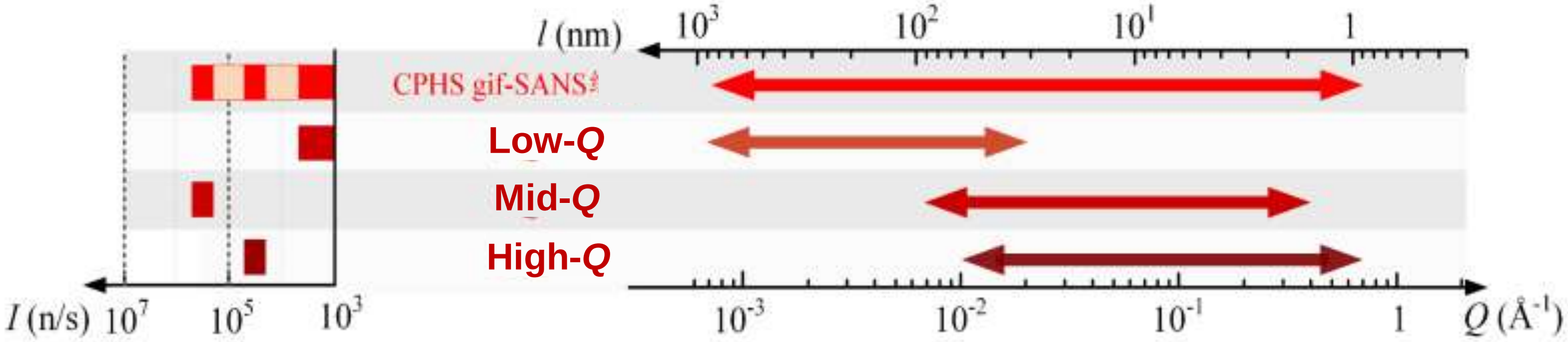
Project Schedule

- Project approved by the univ. in 2009
- 3 MeV proton beam from RFQ and neutron beam with Be target and room temperature PE moderator achieved in **2013**
- ~2000 hrs beam time for neutron imaging, test of the neutron detectors including Boron-coated straw-tube array and Gadolinium-doped MCP
- 13 MeV/ 42mA/~250W proton beam with RFQ and DTL, and cold neutron beam with ~12K solid methane achieved in **2019**

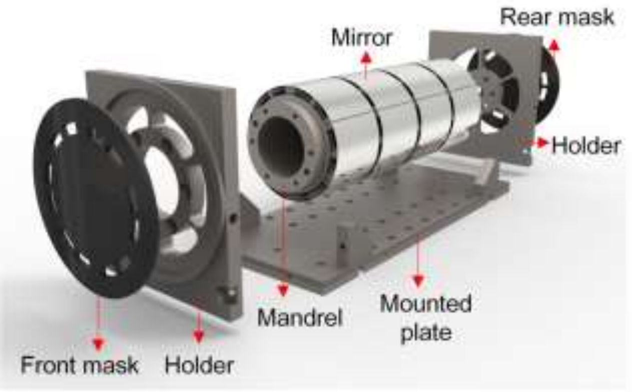
Project Current Status

- **Accelerator operation: 13 MeV/ 34.5 mA/6 kW**; neutron production: **1.6 kW proton on Be target**
- Application: proton implantation/ **gif-SANS(grazing-incidence focusing Small-Angle Neutron Scattering)**
- Operation time: **~700 hrs in 2022**

grazing-incidence focusing SANS

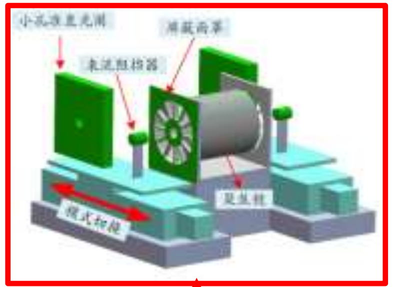


National Natural Science Foundation of China (NSFC)

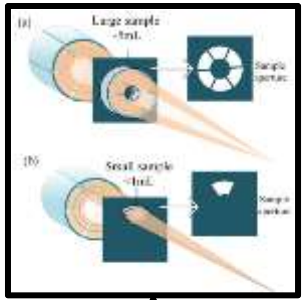


Source aperture

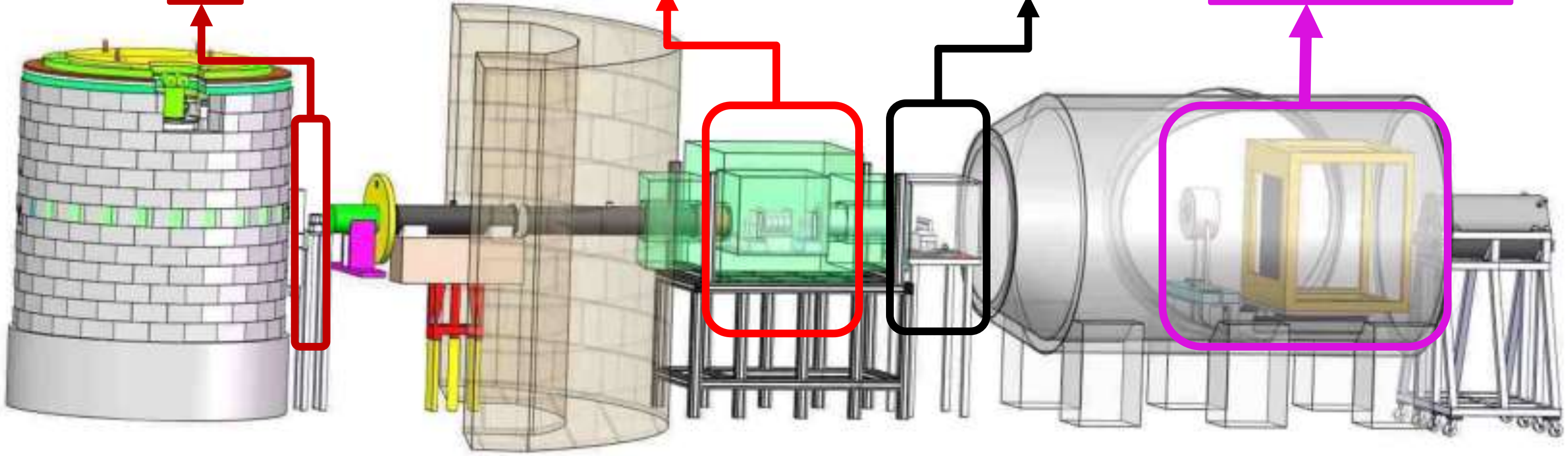
Focusing mirrors/ Pinhole collimators



Sample vol.



Double detectors ^3He/^nMCP



RFQ-based BNCT @ THU

Key design parameters of the accelerator and neutron station for AB-BNCT

Parameter	Value
Epithermal neutron flux	$> 1 \times 10^9$ n/s/cm^2
Fast neutron component (per epithermal neutron)	$< 2 \times 10^{-13}$ Gy · cm^2
Gamma ray component (per epithermal neutron)	$< 2 \times 10^{-13}$ Gy · cm^2
Ratio of thermal flux to epithermal flux	<0.05
Ratio between the total neutron current and the total neutron flux	>0.7
Proton beam energy	2.7 MeV
Proton beam current	30 mA
Beam duty factor	100%
Neutron target	Solid Li (rotatable)

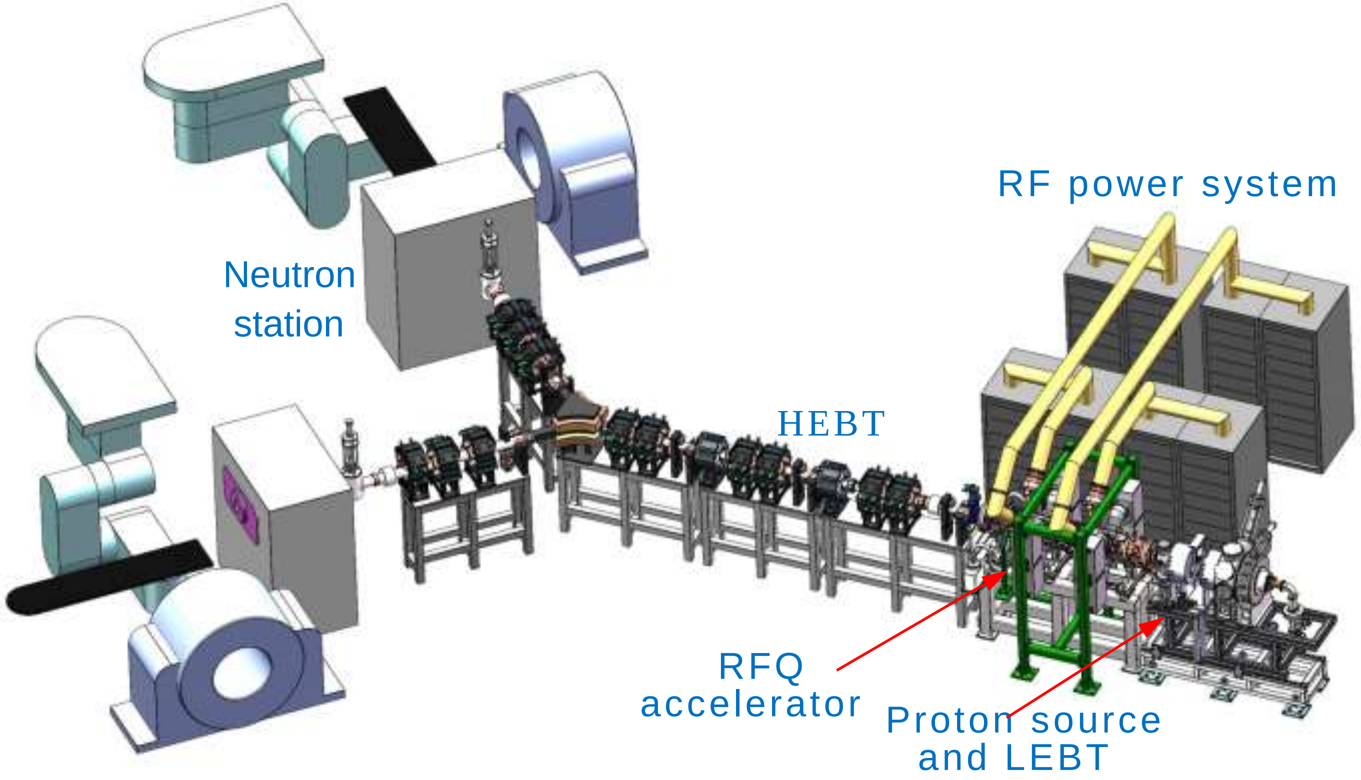
Project information:

Accelerator and neutron station designed by Tsinghua University

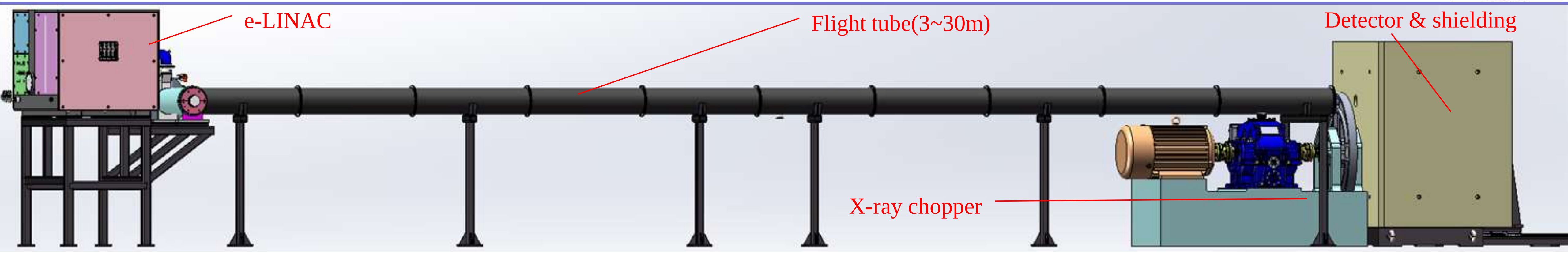
Project will be supported by China Baoyuan Investment Co., Ltd.

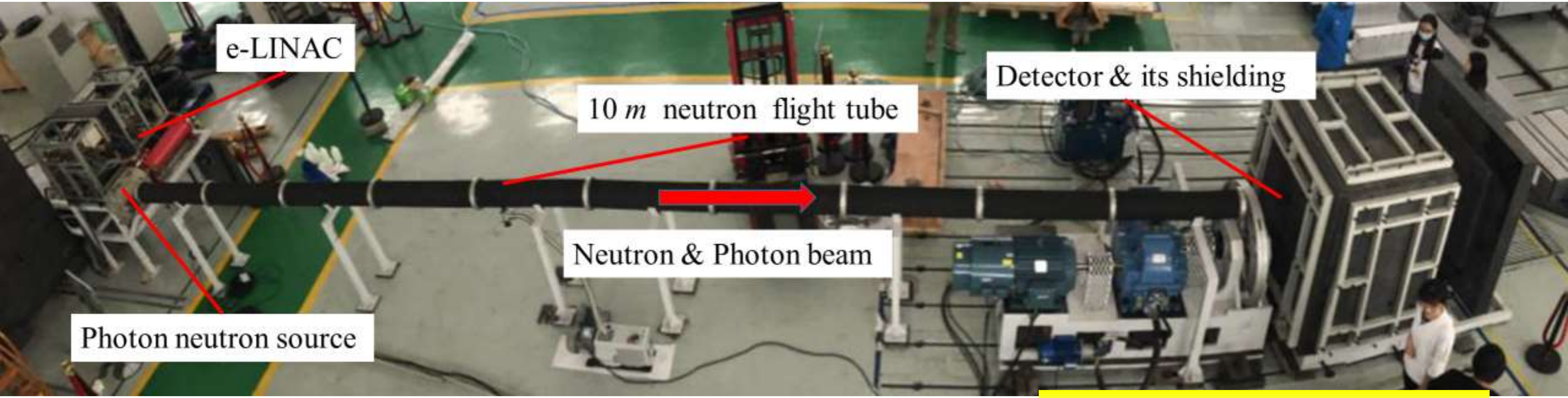
Project Schedule

- Design in 2023
- Manufacture in 2024
- Assembly and beam commissioning in 2025



Bimodal imaging with a single e-LINAC@THU





Courtesy Yigang YANG @ THU

e-LINAC driven bimodal source @ THU

- Supported by the National Natural Science Foundation of China (1735008, 3.5M¥);

National Natural Science Foundation of China

- A **9MeV/900W electron linac** is used to deliver bremsstrahlung photons, and a **heavy water convertor** is used to generate photoneutrons with a **yield of 2×10^{11} n/s**;
- The brilliance of imaging neutrons (thermal neutrons) is **$2500 n/cm^2/s$@L/D=100**;
- The imaging photons share the same imaging geometry with that of imaging neutrons, and have the brilliance of 100~1000 folds higher, in order to compensate the lower intrinsic detection efficiency for 100 keV photons.
- The detector used is a ^{n}MCP readout by a CMOS camera to acquire the photons' image and neutrons' image successively.
- **A cross delay-line ^{n}MCP** is also successfully involved to register neutrons to form neutron image with a ultra-low dark count background, say , 3.55×10^{-5} count/pix/sec
- This prototype system has been used for the inspection of residual core of turbine blades and analysis of lithium ore grades.

Bimodal imaging with a single e-LINAC

$$\frac{Flux_{photon}}{Flux_{neutron}} \approx 10^{2\sim3}$$

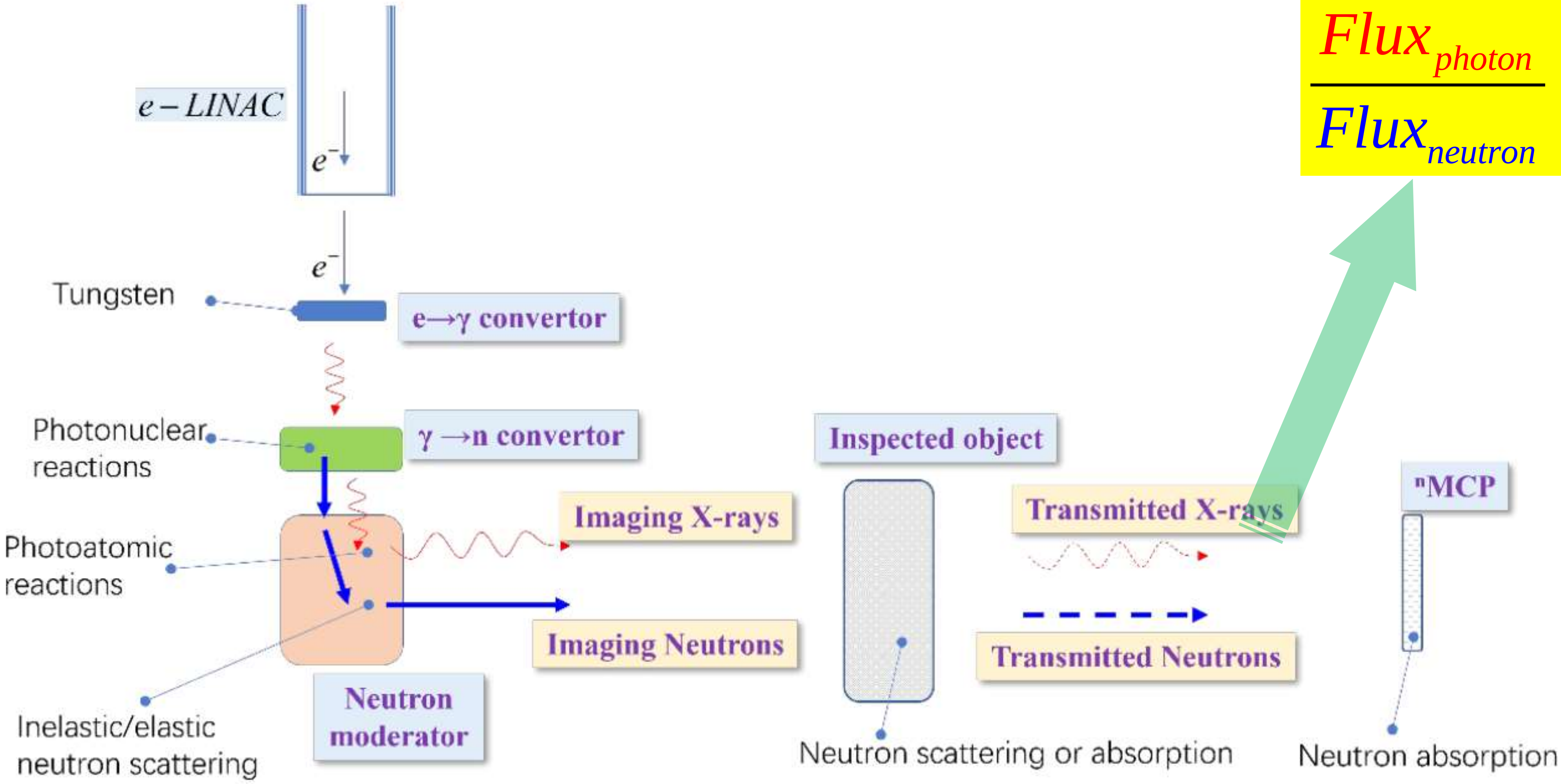
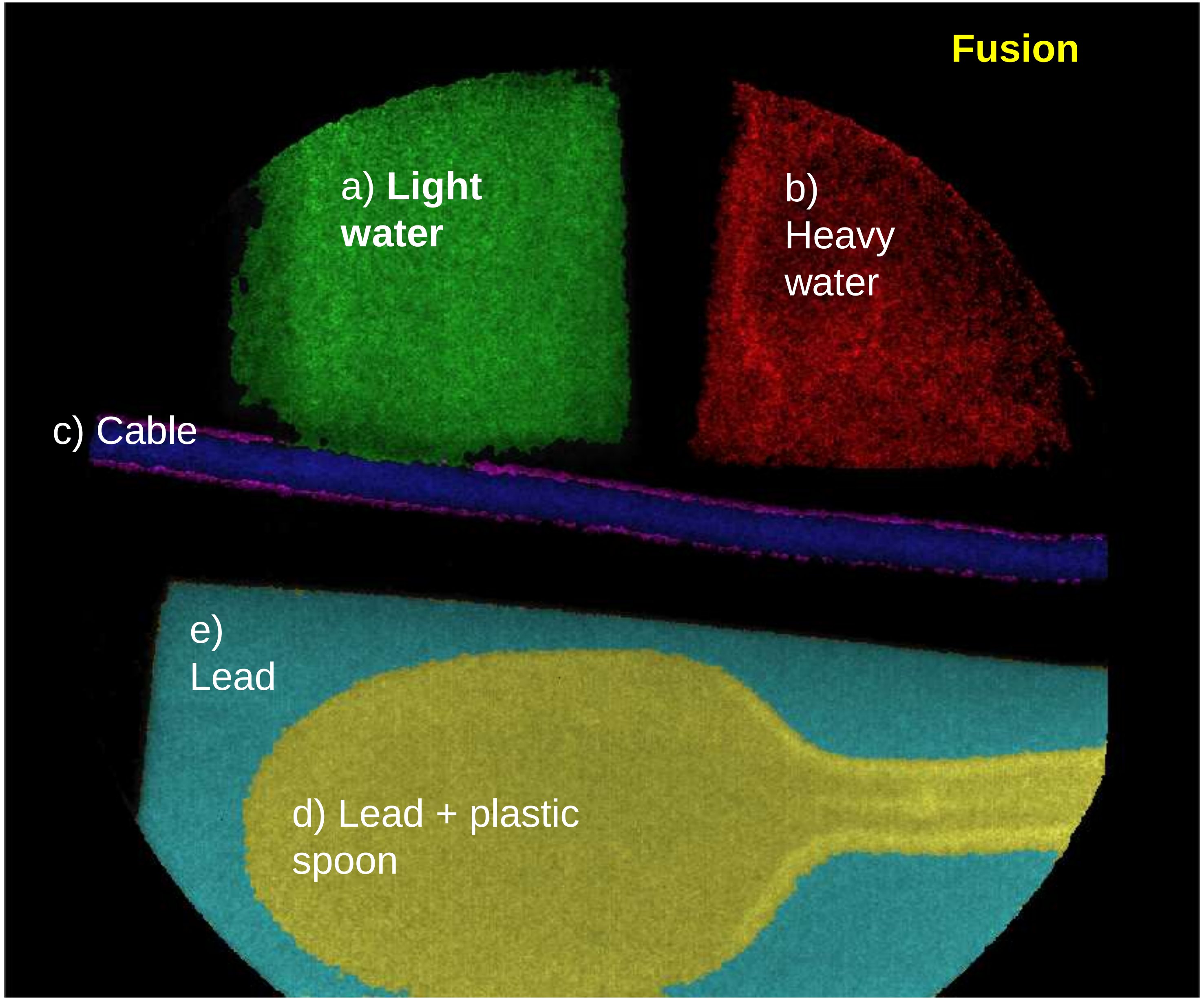


Fig. 2 Principles of e-LINAC-driven bimodal imaging.

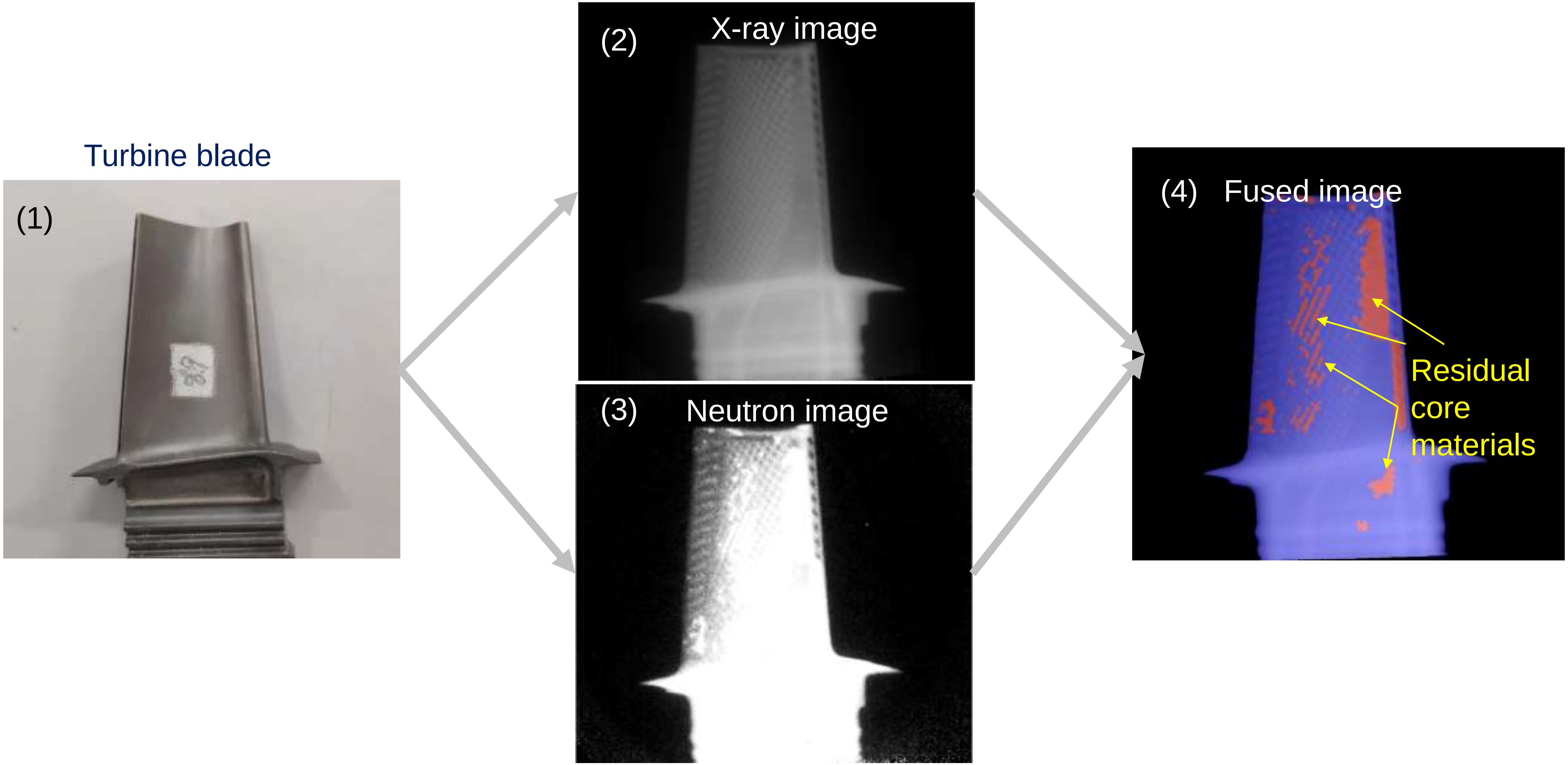
Bimodal imaging with a single e-LINAC@THU



Bimodal imaging:

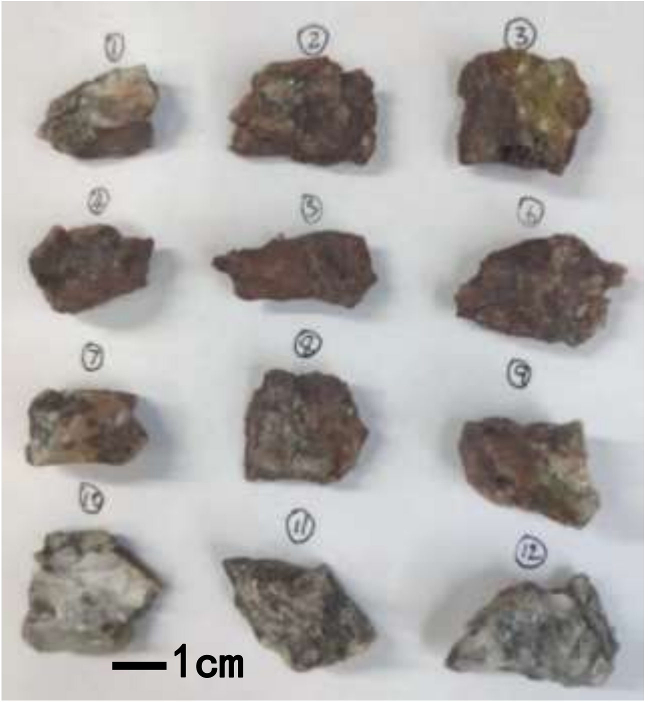
- ✓ **Pixel-wise fusion**
- ✓ **Material identification**
- ✓ **Isotope sensitive**
- ✓ **Light element sensitive**
- ✓ **Heavy metal penetrating**

Bimodal imaging with a single e-LINAC@THU

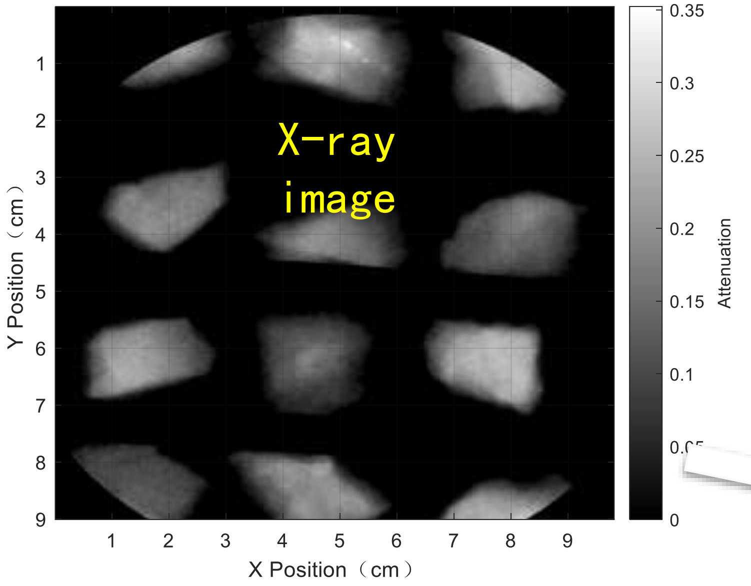


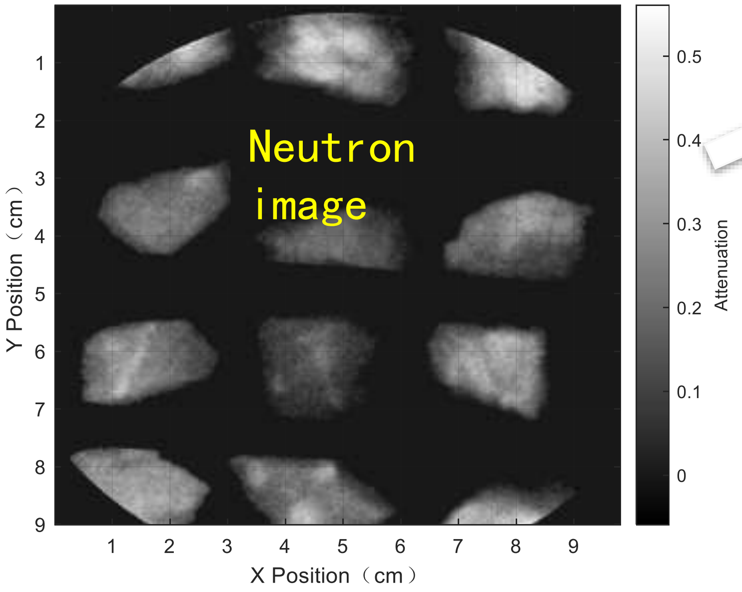
Application: grade analysis of lithium ore

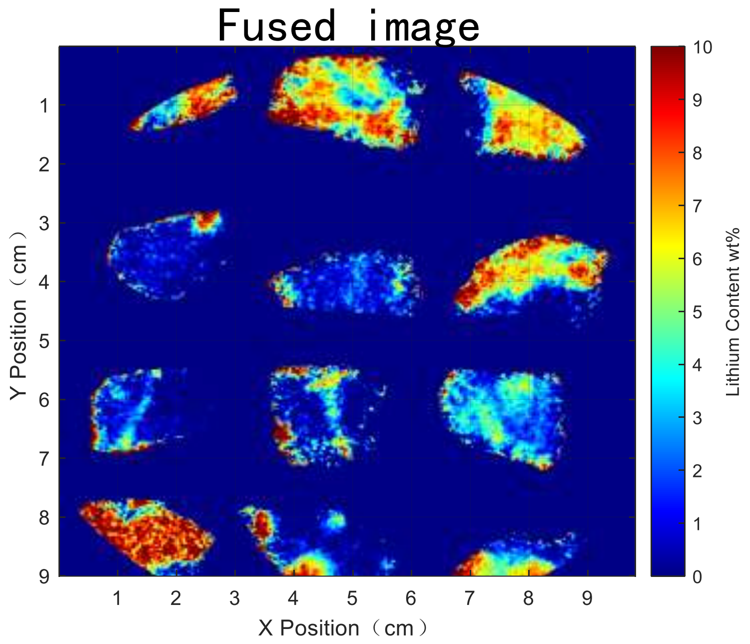
Neutron	H 3.44	Li 3.30	O 0.17	Si 0.11
X-ray	H 0.02	Li 0.06	O 0.16	Si 0.33

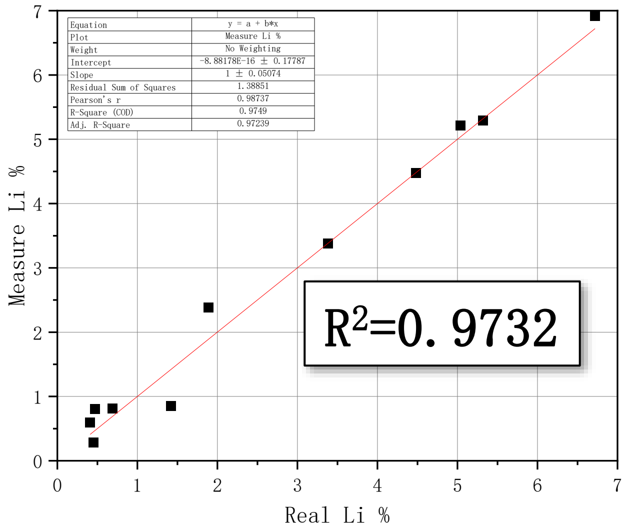


Photo

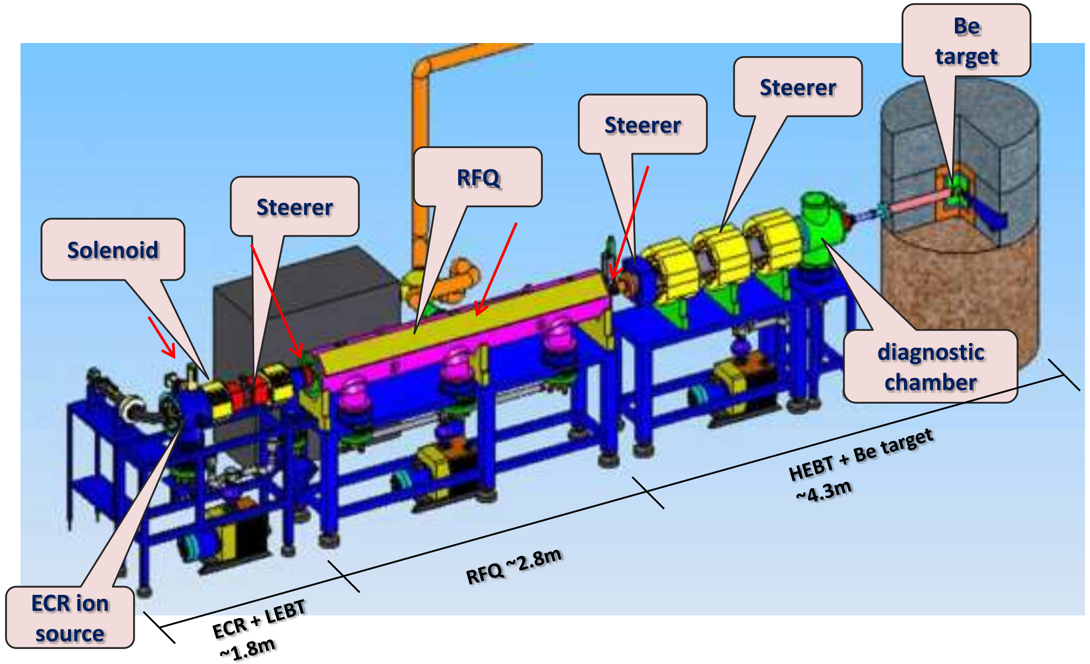








PKUNITY: D$^+$ RFQ & Be target & Thermal n



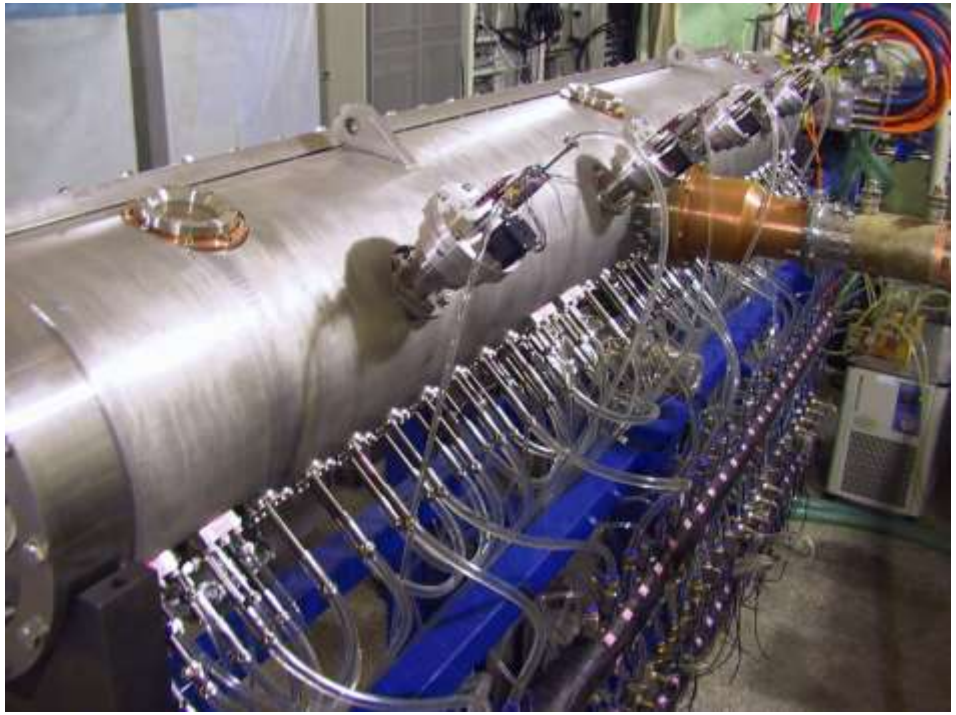
Courtesy Yuanrong LU @ PKU

CCANS PKUNITY: Four-Pole High-intensity D^+ RFQ

201.5MHz，2.0MeV D^+

10 mA, 4%, 400ms, 100Hz

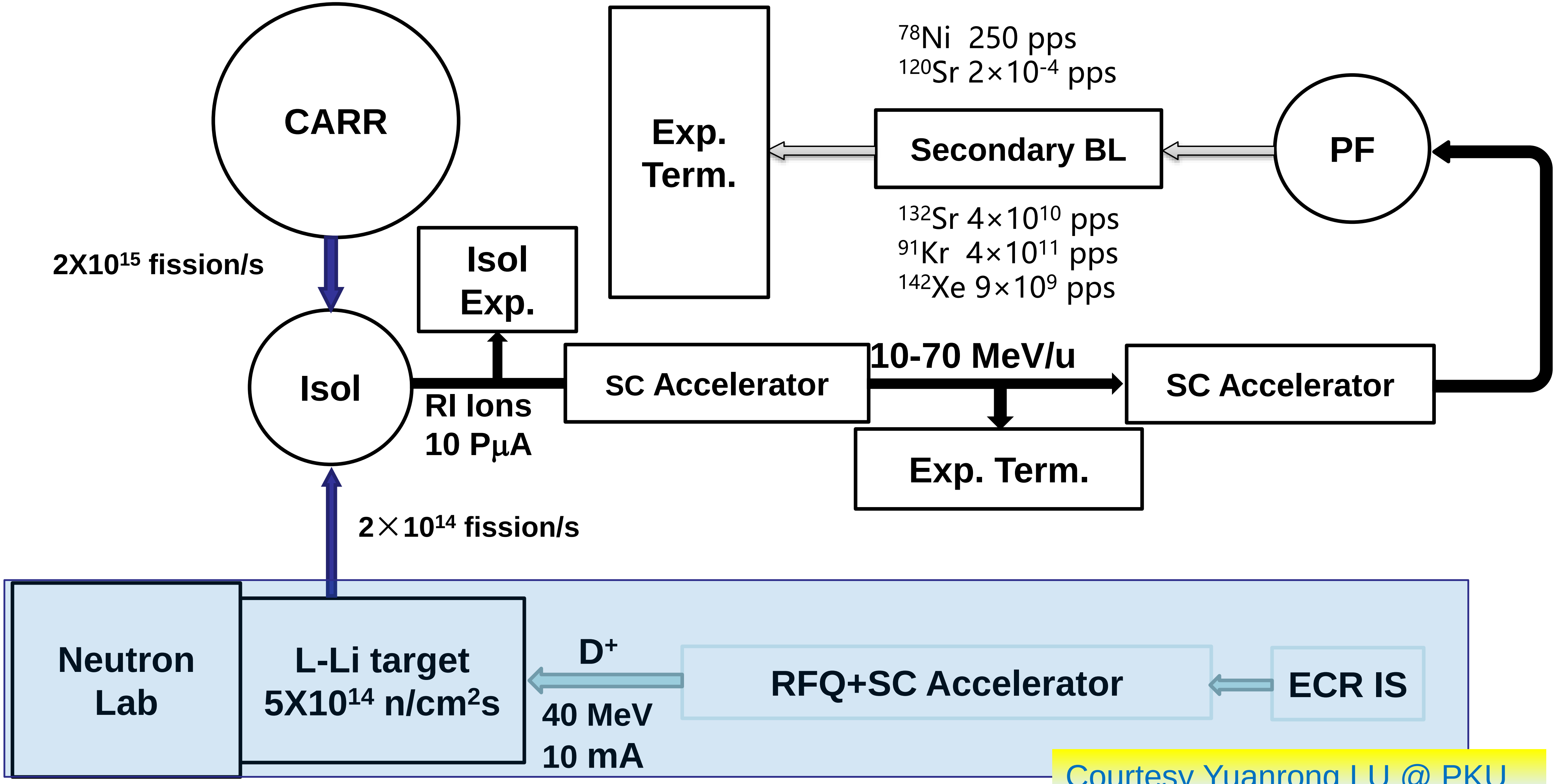
Water cooled



PKUNITY: neutron parameters

Technical data	designed	measured
Fast Neutron yield	>10^{11} n/s	2.4 × 10^{11} n/s
Neutron flux at imaging plane	>10^4 n/cm²/s	2.35 × 10^4 n/cm²/s (L/D=50)
Image dimension	20 cm × 20 cm	21 cm × 21 cm
Camera resolution	Better than 0.4 mm	Horiz: 0.33 mm Vert: 0.28 mm
Imaging resolution	Better than 0.2 mm	Horiz: 0.13 mm Vert: 0.11 mm
Dynamic range	>80:1	195:1
Contrast sensitivity	5%	5%
Dose	<2.5 μSv/h	<0.5 μSv/h

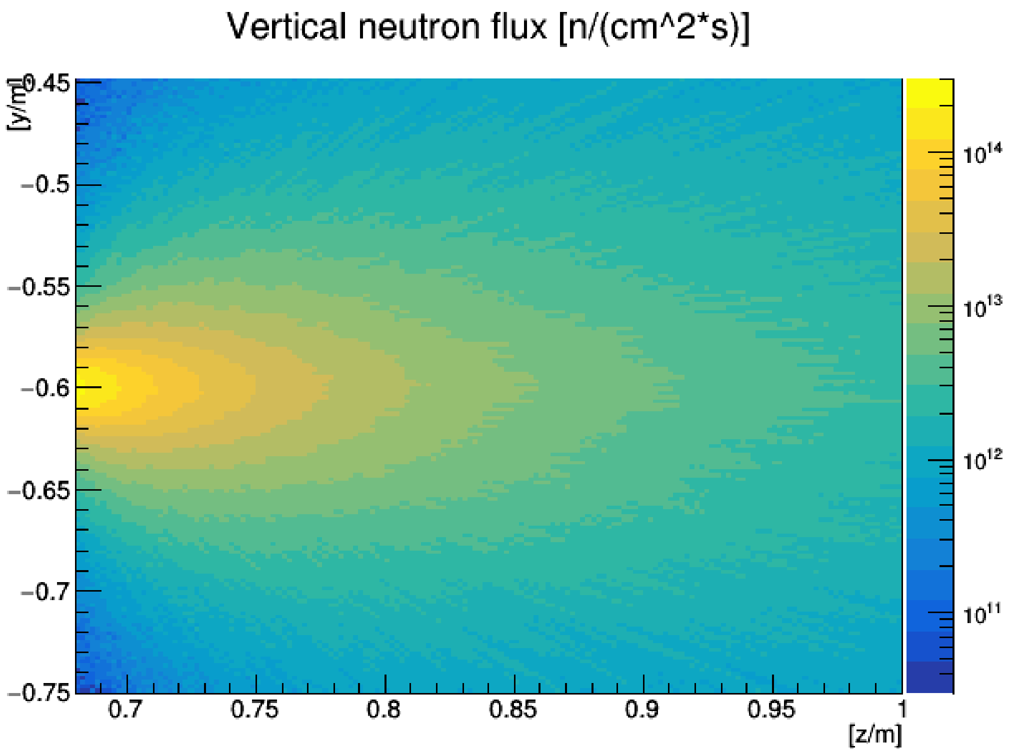
BISOL-D+ Driver LINAC @ PKU

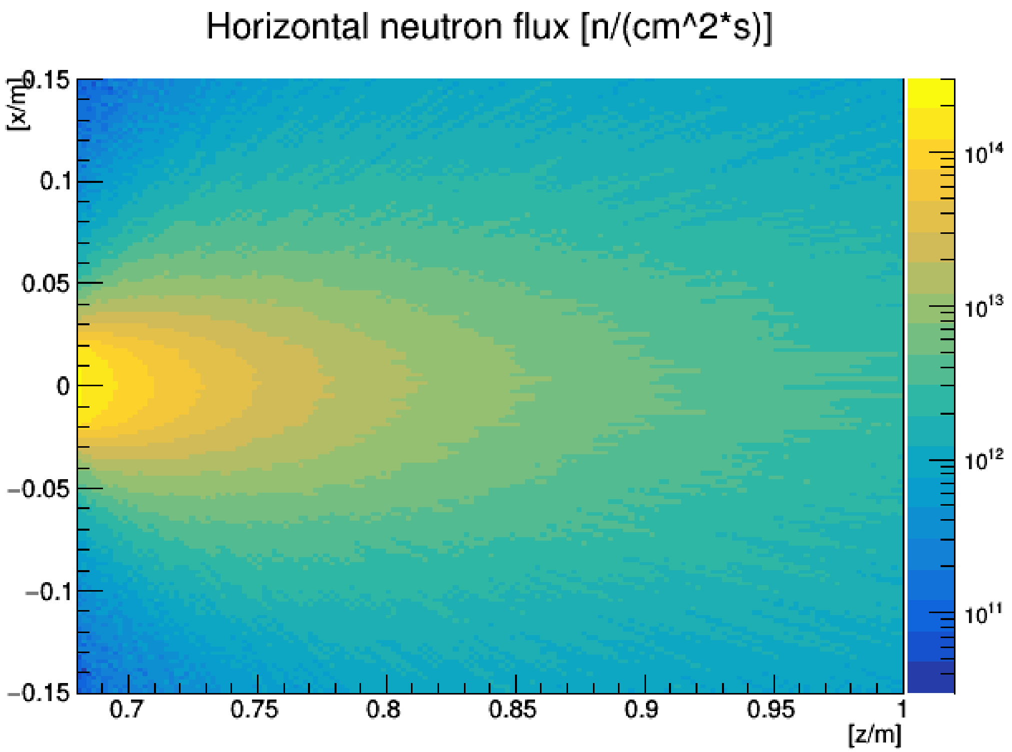


Courtesy Yuanrong LU @ PKU

BISOL-D+ Driver LINAC @ PKU

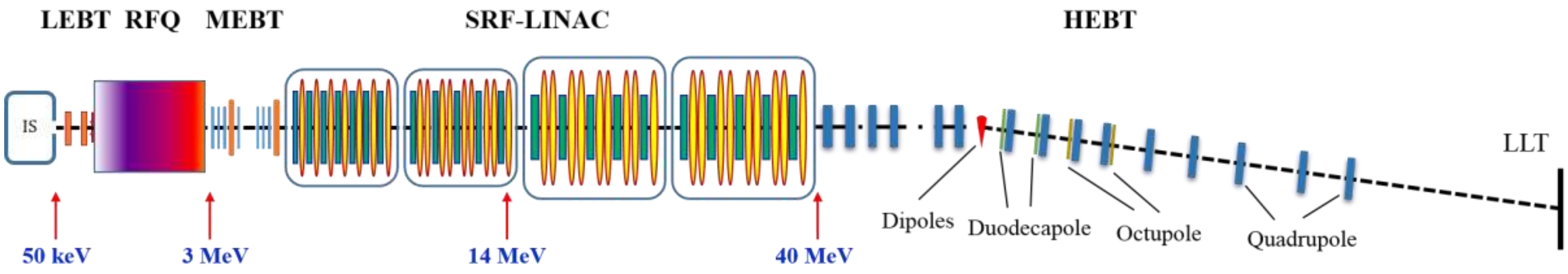
10 mA D+, lithium target, neutron energy ~20 MeV





n flux, n/cm^2/s	>10^{14}	>5×10^{14}	>10^{13}
dpa in steel, dpa/fpy	> 8	> 4.4	> 1.3
Volume, cm^3	~12	~60	~100

BISOL-D+ Driver LINAC @ PKU



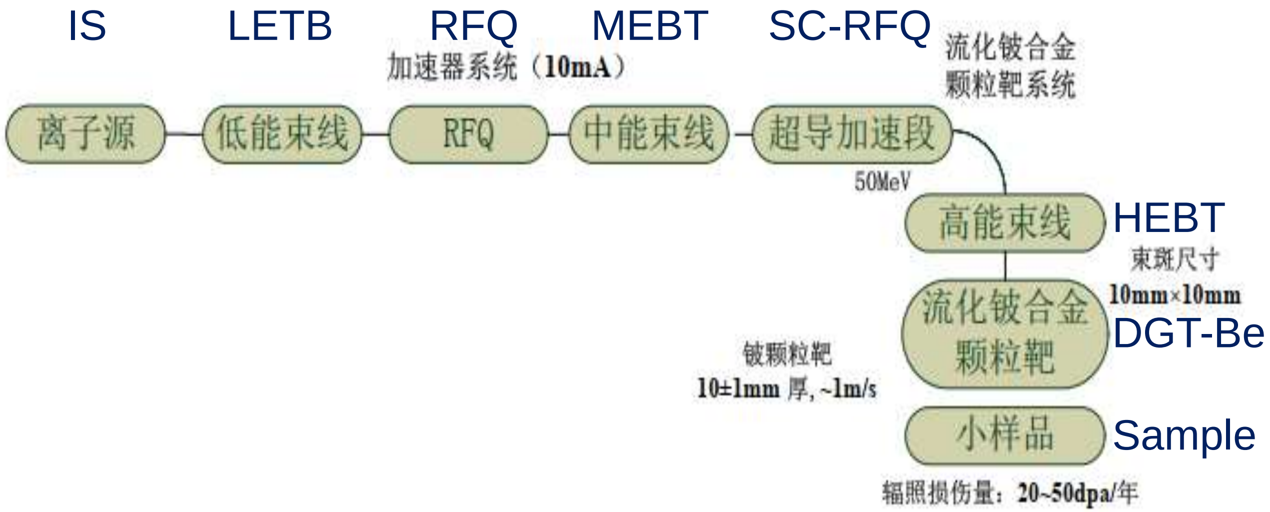
- D+ variable energy (3~40MeV)
- D+ 25mA, also for proton and Alpha particles
- Proton, 33MeV; He^{2+} , 81MeV)
- Components：LEBT+RFQ+MEBT+SRF+HEBT，162.5MHz
- CW mode
- Beam power loss ≤1 W/m

Compact high-energy high-flux deuterium-beryllium neutron source @ CAS-IMP

The compact high energy and high flux deuterium-beryllium neutron source uses the deuterium beam to bombade the beryllium target to generate forward neutrons.

The flux in the forward region is comparable to that of IFMIF, and then uses the neutrons produced to irradiate the small sample material.

The neutron source mainly consists of superconducting linac, fluidized beryllium alloy particle flow target system, differential system, etc.



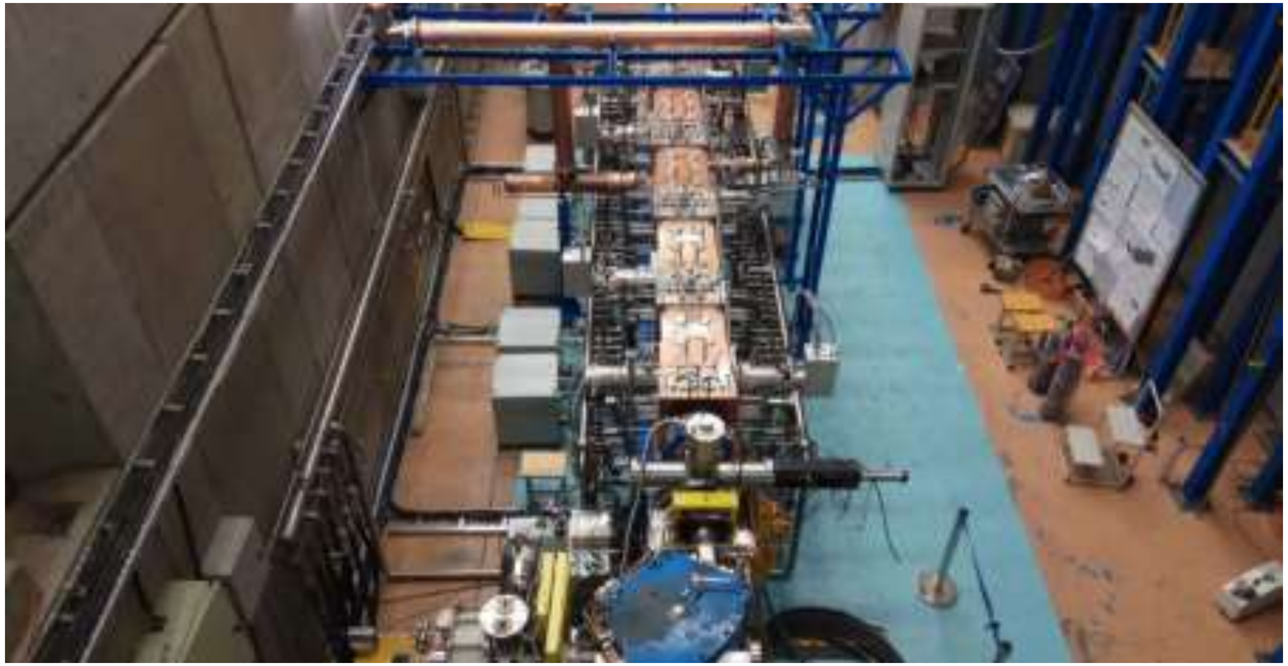
Schematic diagram of a compact high-energy high-flux deuterium-beryllium neutron source

Parameters	Value
Reaction	D+Be
Design index	50MeV@5-10mA
Neutron energy	~14MeV
Sample size	~cm
Irradiation intensity	20-50dpa/y
Construction time	~6.5y

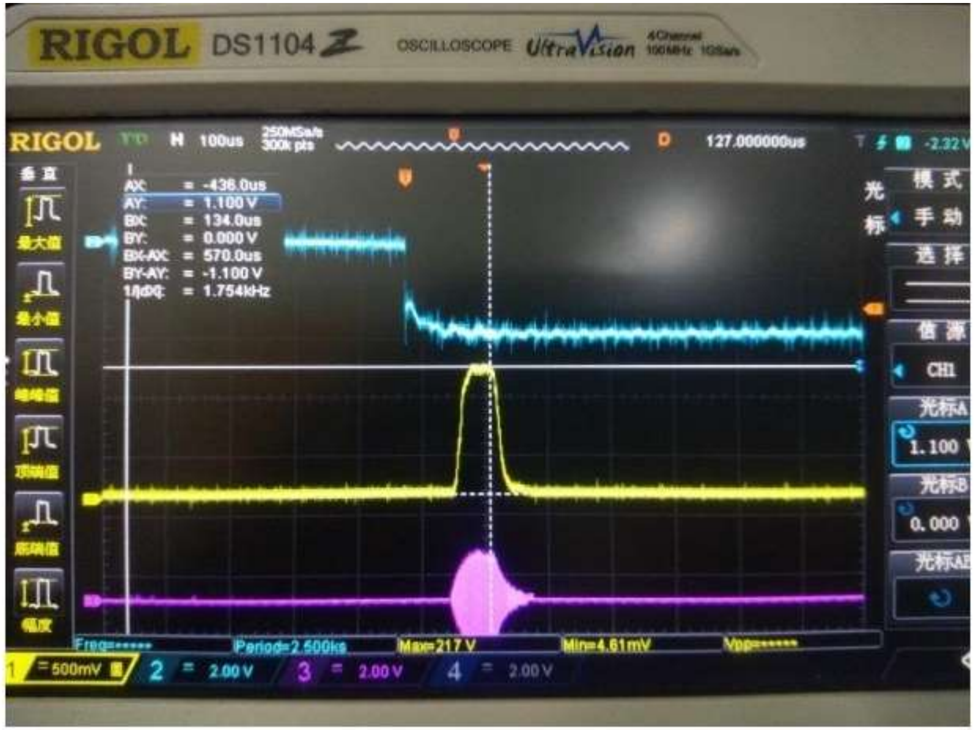
Courtesy Lei YANG @ CAS-IMP

Compact high-energy high-flux deuterium-beryllium neutron source @ CAS-IMP

Superconducting linac (RFQ)



Picture of RFQ



Results of the outlet beam current

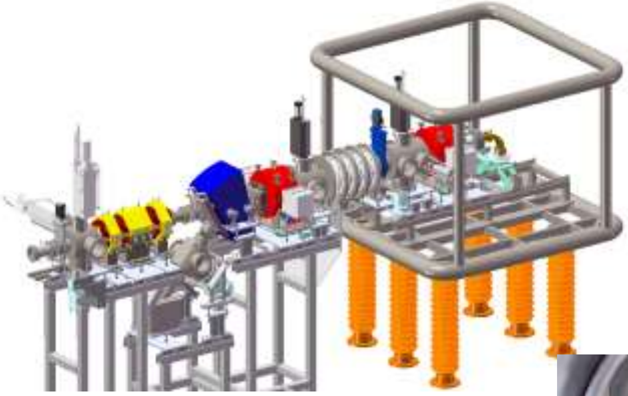
The RFQ has an incident power of 122kW and successfully elicits H_2^+ with beam energy~1.55MeV/u@~7.0mA

Compact high-energy high-flux deuterium-beryllium neutron source @ CAS-IMP

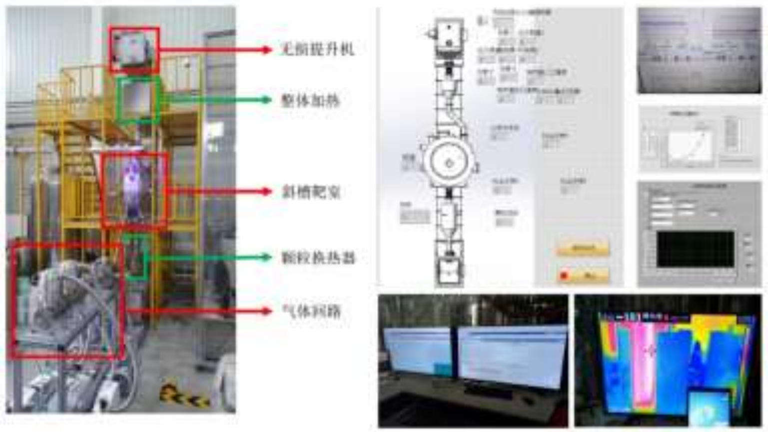
210keV@11.2mA coupling thermal test of proton beam and Dense Granular flow Target

Long time flow test demonstration of granular flow target

Real-time image of granular flow and ion beam coupling thermal test



low energy high current ion beam thermal measurement platform



Granular flow target electric heating 400℃ high temperature long time flow test display

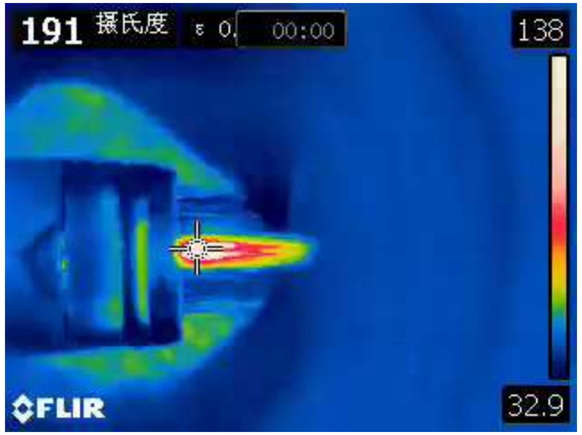


Image of granular flow and ion beam coupling thermal test

Low energy high current ion beam coupled with granular flow target thermal measurement platform

D-BNCT01&02 by CAS-IHEP

History of IHEP BNCT technological development

2006

The first high-current RFQ accelerator in China successfully developed

2012

Key technology invention started

2014

BNCT device design scheme technical review meeting was held

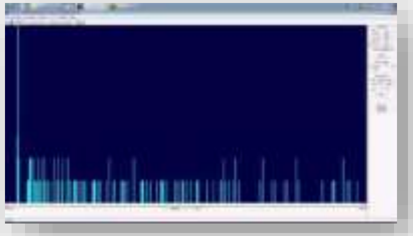
2017

BNCT project launched

2018

Core equipment machining and construction initiating

2019



BNCT produces neutron beams for the first time

2020

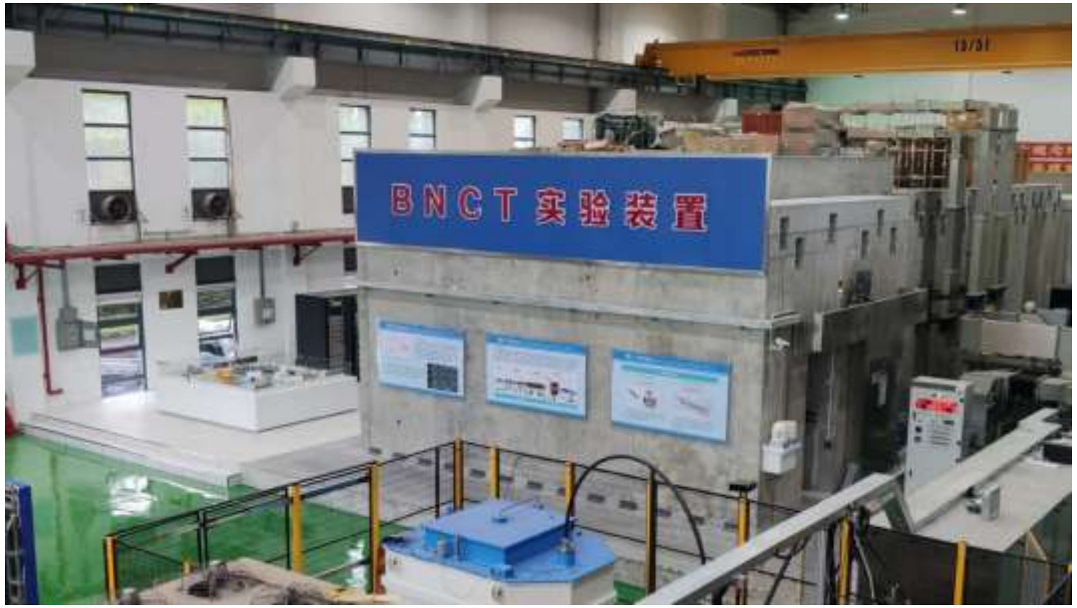
China's first accelerator-based BNCT experimental device (D-BNCT01) successfully developed

2021

Cooperation with Dongguan People's Hospital started (D-BNCT02)

Courtesy Tianjiao LIANG @ CAS-IHEP

D-BNCT01 by CAS-IHEP

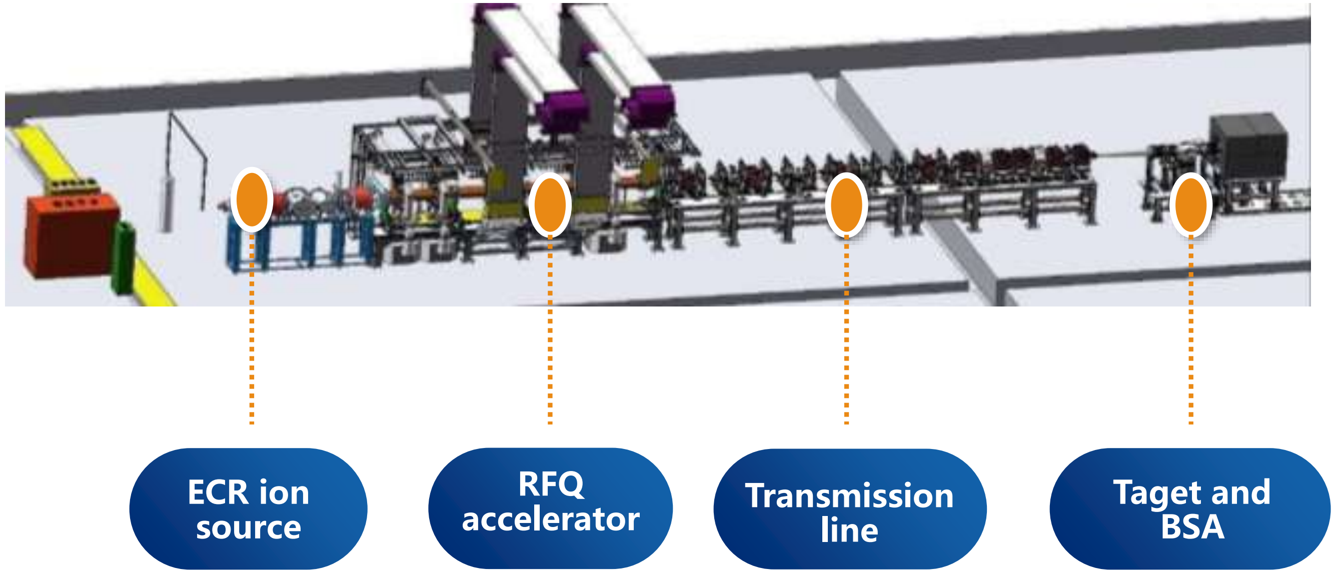


- **Purpose**: Engineering verification, Boron drug test platform
- **Organization**: IHEP (Institute of high energy physics, www.ihep.ac.cn), CASBNCT (www.casbnct.com)
- **Budget**: about$5,000,000 (reuse some old accelerator equipment)
- **Progress**: 2017 started， 2020 completed, under operation

D-BNCT01 by CAS-IHEP

Institute of High Energy Physics
Chinese Academy of Sciences

BNCT01- experimental device



Accelerator Type	RFQ
Proton Energy	3.5MeV
Mean Current	5mA
Radiation Room	1
Target Type	Solid lithium Target
Target maintenance	Robotic arm
Spot on target	10x10 cm^2
Designed proton beam Power	17.5kW
Current beam power	~8kW
Fast neutron component	Variable
γ component	< $2x10^{-13}$ Gy cm^2/epi-n
Thermal neutron flux ratio	< 0.05

Key solution: RFQ+ Solid lithium target

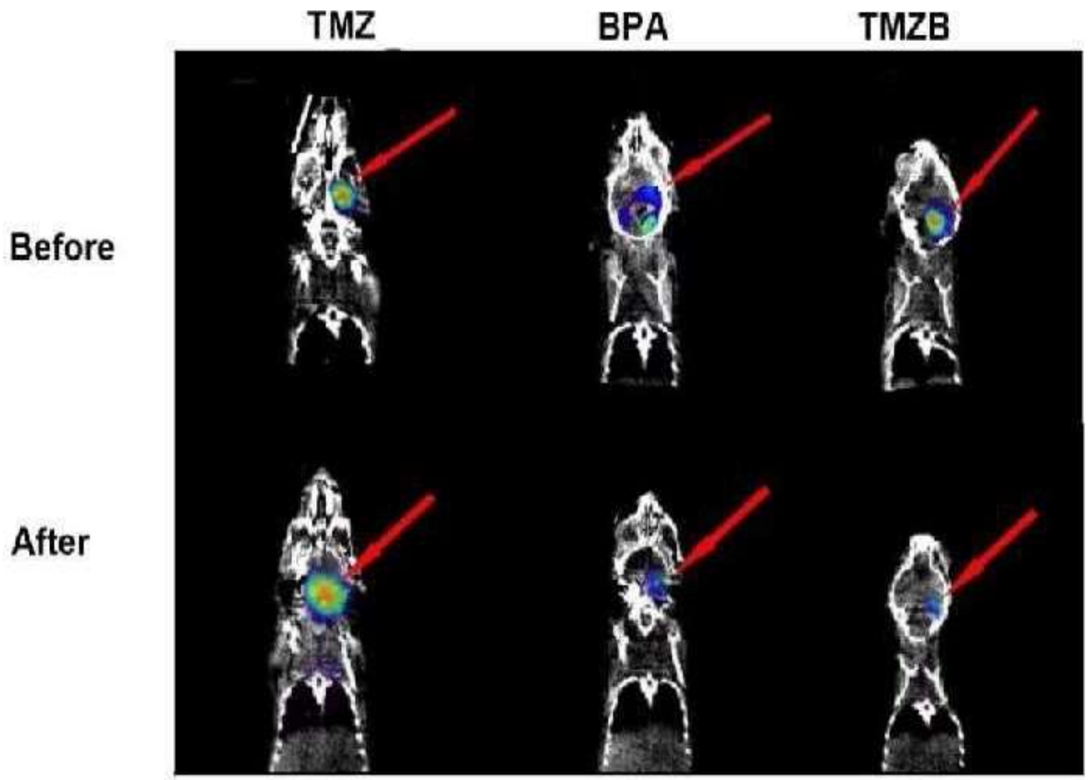
Breakthrough in key technologies: lithium target, BSA, remote maintenance of target

J.Y. Chen, J. Y., J. F. Tong, Z. L. Hu, X. F. Han, B. Tang, Q. Yu, R. Q. Zhang, C. G. Zhao, J. Xu, S. N. Fu, B. Zhou and T. J. Liang* (2022). "Evaluation of neutron beam characteristics for D-BNCT01 facility." Nuclear Science and Techniques **33**(1)12.

D-BNCT01 by CAS-IHEP

BNCT01- experimental device

- The BNCT experimental device has been running steadily since August 2020
- 100+ times for cell and rat BNCT experiments



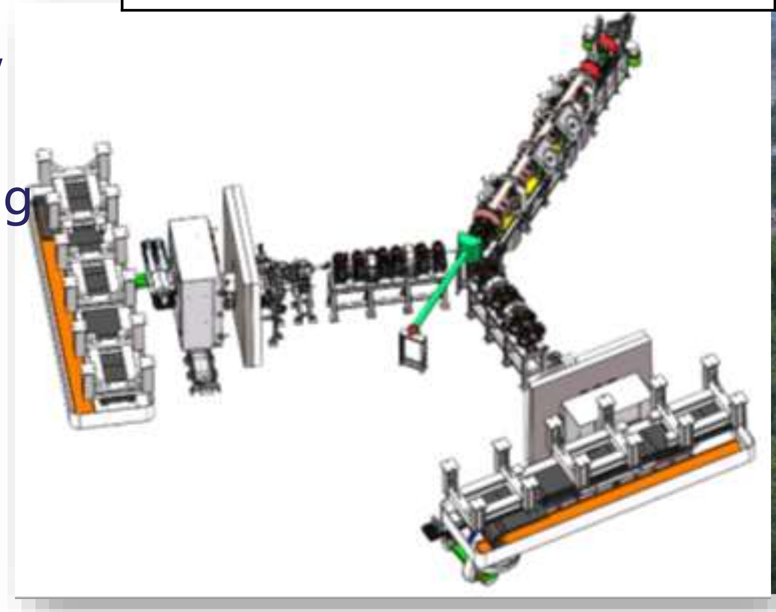
- K. Chen, S. Liu, L. W. Lv, J. F. Tong, J.Y. Chen, H.J. Liang, Y.J. Wang, F. Hu, Q.Y. Liu, H. Li, Z.T. Chen, J.C. Li, Z.J. Wang, Y.N. Chang, J. Li, H. Yuan, S.N. Fu, T.J. Liang and G.M. Xing (2023) , Well-established immunotherapy with R837-loaded boron neutron capture-shocked tumor cells, Nano Today **52** 101995
- J. Xiang, L. Ma, J. F. Tong, N. Zuo, W. T. Hu, Y. P. Luo, J. Q. Liu, T. J. Liang, Q. S. Ren and Q. Liu (2023). "Boron-peptide conjugates with angiopep-2 for boron neutron capture therapy." Frontiers in Medicine **10**.3389

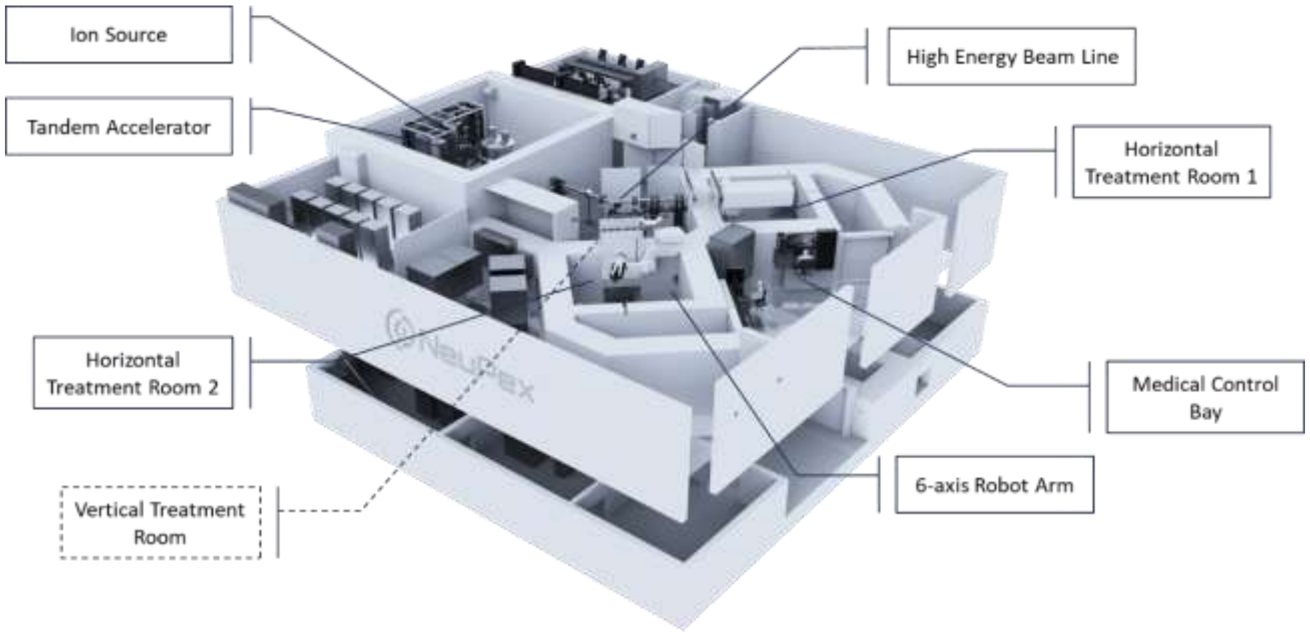
D-BNCT02 by CASBNCT

The Dongguan People's Hospital project:

- The total construction area of the Boron Neutron Treatment Center building is 18,421 ㎡, which can accommodate two BNCT devices.
- This project is lead by **CASBNCT**, with support of **IHEP&CSNS.**
- It consists of a RFQ accelerator, target, BSA, patient positioning and support system, dose monitoring system, treatment planning system (TPS) and treatment control system(TCS).
- **Key technological breakthroughs:** RFQ & rotating lithium target, TCS,TPS.

Accelerator Type	RFQ
Proton Energy	2.8MeV
Mean Current	20mA
Treatment Room	2
Tartget Type	Rotating Lithium Target
epithermal neutron flux	$> 1\text{x}10^{9}$ n/s/cm²
Fast neutron compoent	$< 2\text{x}10^{-13}$Gy cm²/n
γ compoent	$< 2\text{x}10^{-13}$ Gy cm²/n
thermal neutron flux ratio	< 0.05





Compact Accelerator-driven Neutron Source

System Name: Neuboron NeuPex, Model Block-I

System designed and built by Neuboron Medical Group

Project 3rd Party: TAE Life Sciences

NeuPex Specification

- Epithermal Neutron Beam: > 1.0×10^9 n cm^{-2} s^{-1}
- Conversion Efficiency: >5×10^7 epi-n cm^{-2} s^{-1} kW^{-1}
- Tandem Accelerator: proton beam @ 2.35 MeV, 10 mA
- Target Material: stational lithium target
- Beam Lines: 2 horizontal, 1 vertical

Project Current Status

- Fully commissioned and stably running at 2.35 MeV/10 mA
- One horizontal beam built and commissioned
- IIT: 15 patients treated with 19 irradiations
- Planned Clinical Trial: 2024 Q1

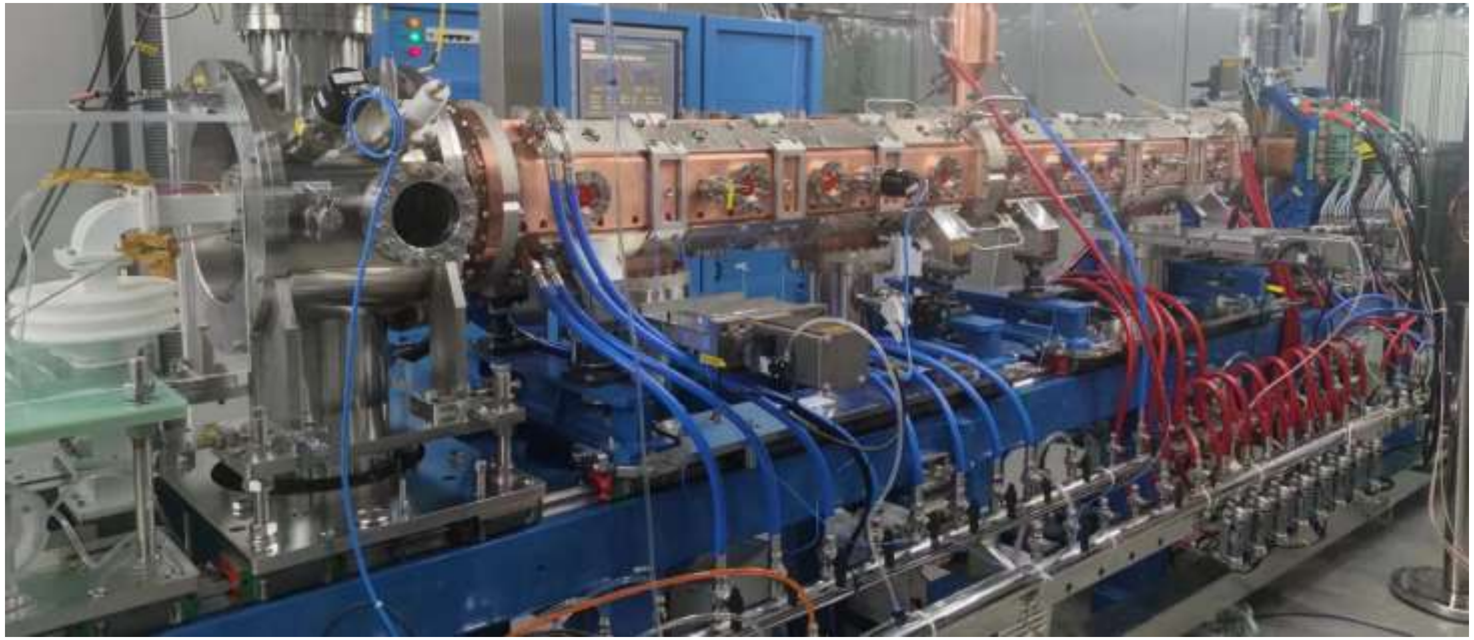
Courtesy Yuanhao LIU @ Neuboron

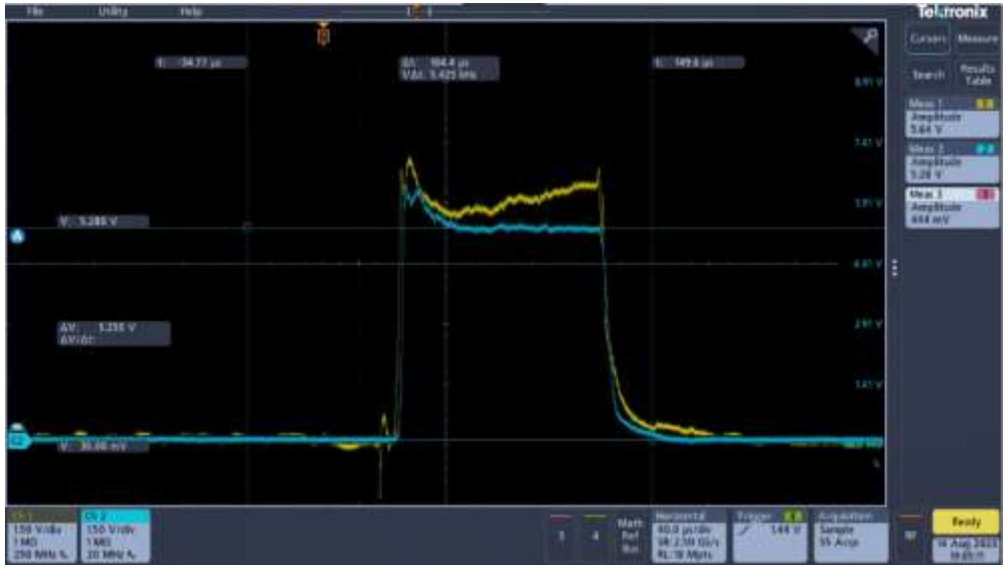
1. Zhang, Z.; Chong, Y.; Liu et al. A Review of Planned, Ongoing Clinical Studies and Recent Development of BNCT in Mainland of China. Cancers 2023, 15, 4060. https://doi.org/10.3390/cancers15164060
2. International Atomic Energy Agency. Advances in Boron Neutron Capture Therapy; International Atomic Energy Agency: Vienna, Austria, 2023.

X-TANS by XJTU

- ECR IS+ELEBT+RFQ+HEBT
- Proton beam: 2.5MeV, 10mA
- Beam commission:
  RFQ input 11.28mA, output 10.56mA
  Transmission efficiency: 93.6%

Parameter	value
Frequency [MHz]	325
Peak Beam current [mA]	12
duty factor	3%
Input energy [keV]	30
Output energy [MeV]	2.5
Accelerator length [m]	2.60
Trans. [%]	98.1
Acc (PARMTEQM) [%]	93.2
Cavity power consumption [kW]	125

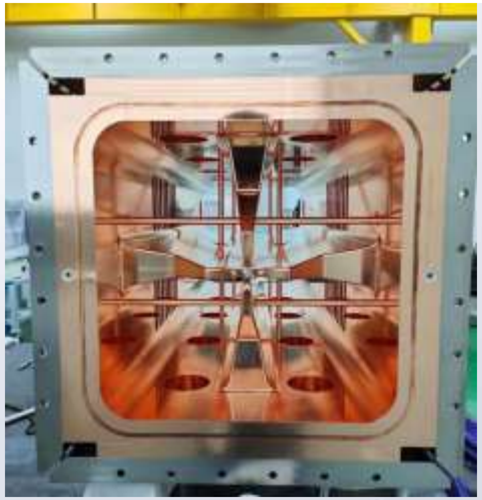


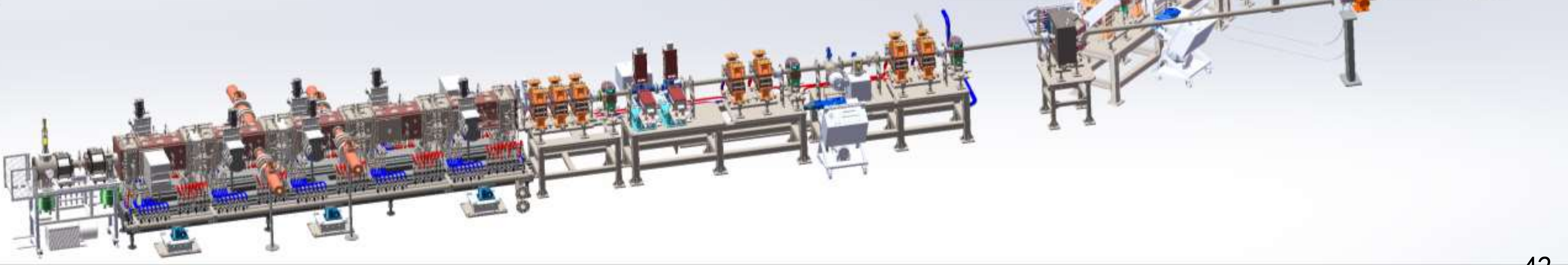


Courtesy Sheng WANG @ XJTU

RFQ-BNCT by XJTU

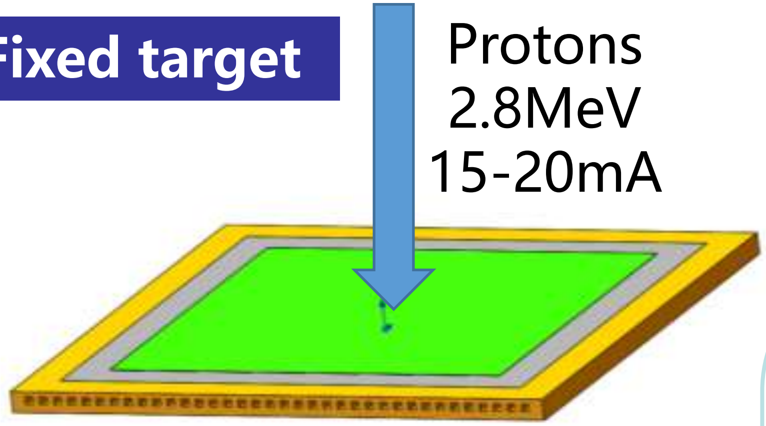
- **Accelerator: RFQ**
- **Component: ECR IS+LEBT+RFQ+HEBT+Target**
- **Main parameter**
  - Frequency: 165MHz
  - Beam current: 25mA
  - Duty factor: 100%
  - Input-output energy: 40keV - 2.8MeV
  - Transmission efficiency: >99.0%



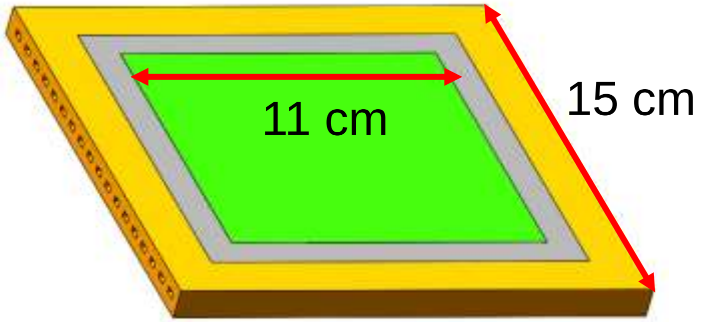


RFQ-BNCT by XJTU

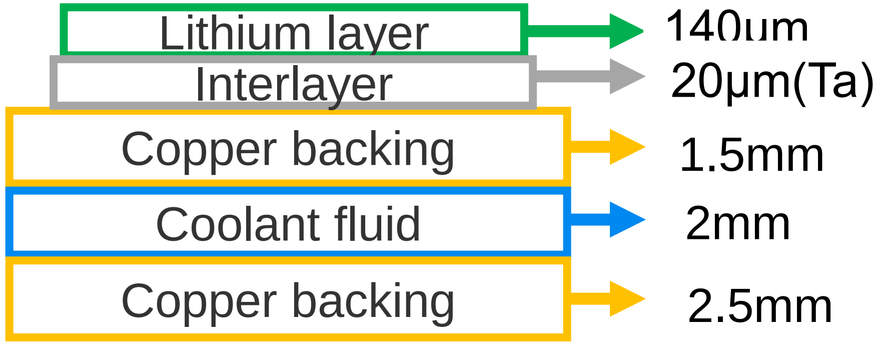
Fixed target



Fixed lithium target



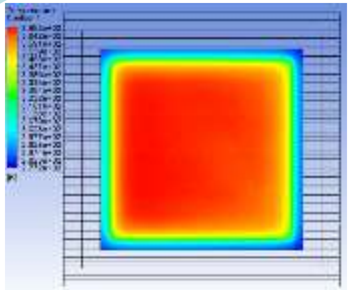
Square beam spot(10cm×10cm)



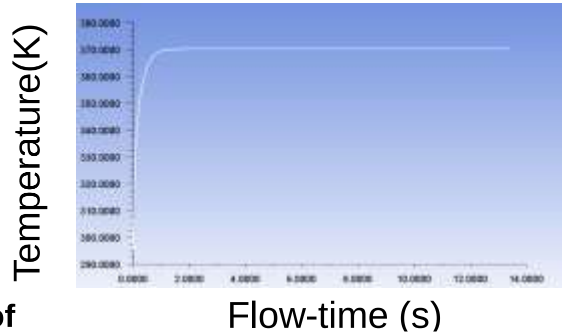
Fixed lithium target cross section and thickness

Channel size:
2mm(width)*2mm(height)

Coolant fluid: Water
Inlet:10m/s 10℃

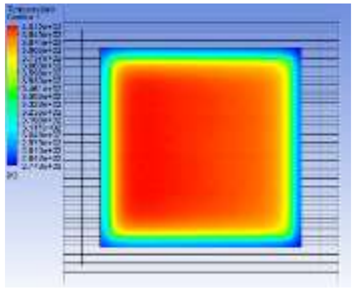


The maximum temperature of the target（15mA, 42kW）

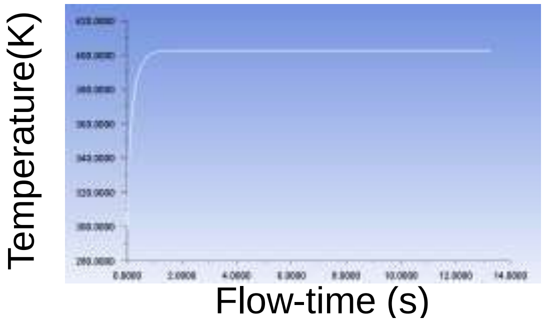


The maximum temperature changes with time

- **The maximum temperature of 42kw is 97 ℃**



The maximum temperature of the target（20mA, 56kW）



The maximum temperature changes with time

- **The maximum temperature of 56 kw is 130 ℃**
- **With fixed target, the proton beam intensity can not be higher than 20mA**

□ Development of high intensity steady neutron sources HINEG :

- **HINEG-I:** D-T neutron generator coupled with zero power reactor CLEAR-0, 6.4×10^{12} n/s, completed
- **HINEG-II:** high intensity D-T source HINEG-IIa, cyclotron base regulatable spectrum steady neutron source HINEG-IIb, **$10^{13\sim14}$n/s, under construction, operations expected around the end of 2023**
- **HINEG-III/GDT:** High flux steady neutron source HINEG-III, GDT-based V-FNS HINEG-GDT, **under design**

□ **A series of compact neutron generators, $5\times10^{9}\sim10^{10}$ n/s DD neutrons,** have been developed and applied in radiography, etc.

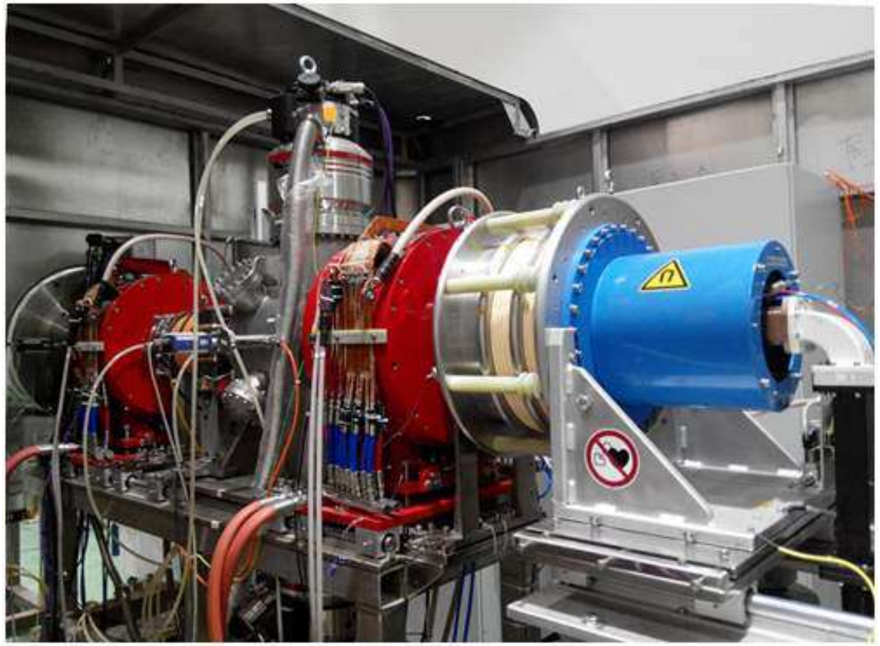
□ **Different mini neutron generators, with yield of $10^{7\sim8}$n/s,** have been developed and applied for logging, elements analysis, etc.

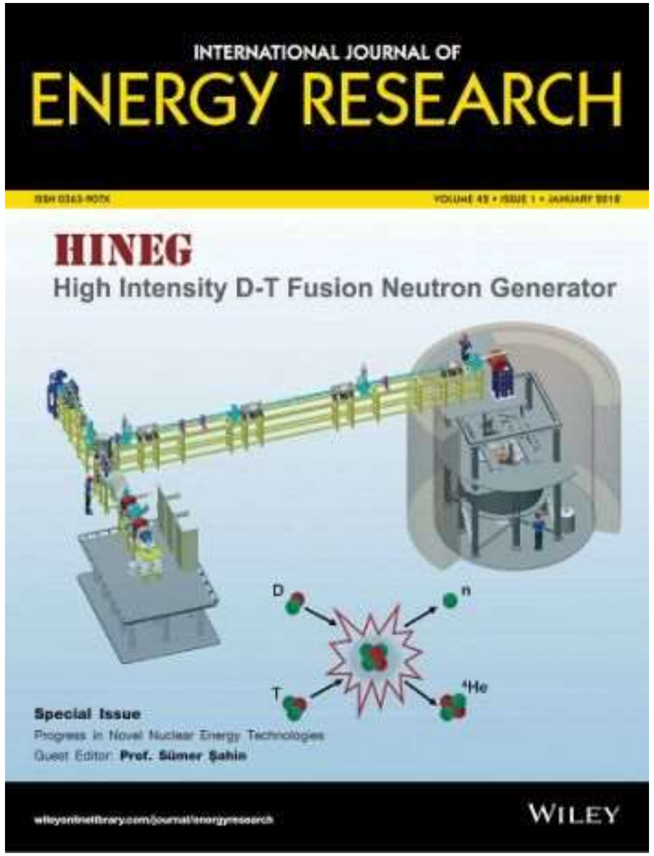
Courtesy Qi YANG @ FDS

For more information, visit www.fds.org.cn

HINEG-I @ FDS

Jan, 2018
6.4×10^{12} n/s
Fast n imaging
Thermal n imaging



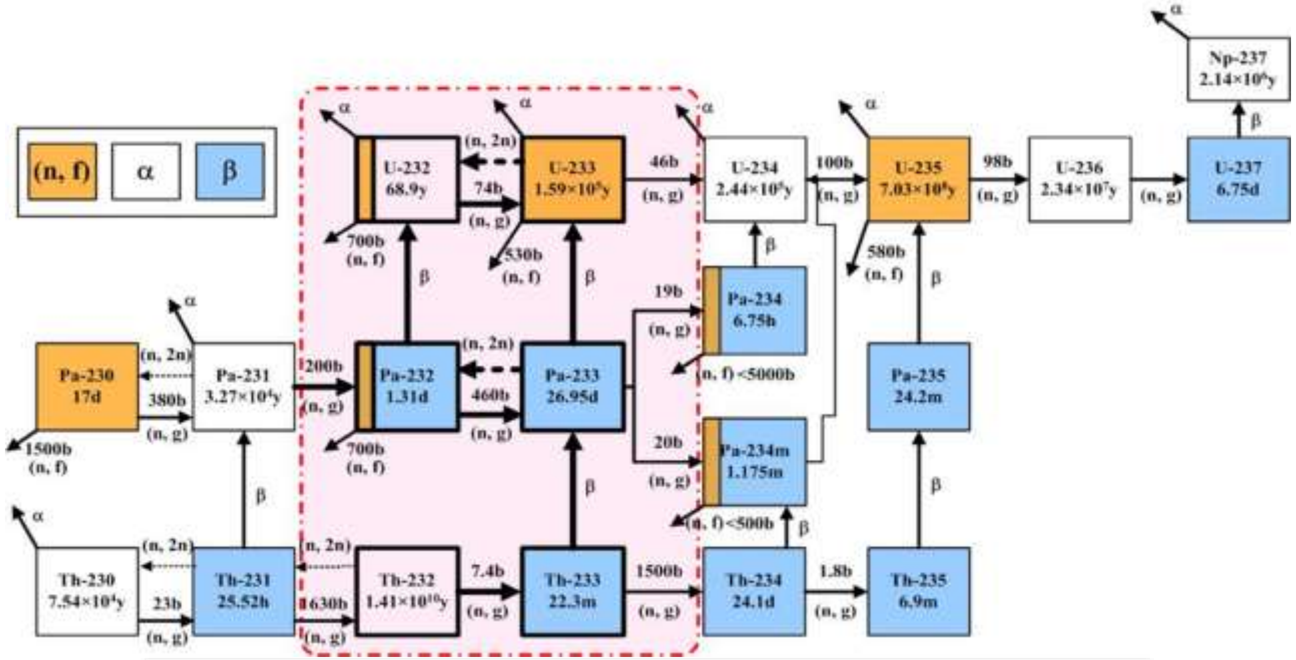


Int. J. Energy Res.
2018, 42(1): 68-72

TMSR-PNS @ CAS-SINAP

Based on the requirements of **Thorium Molten Salt Reactor Nuclear Energy System (TMSR)** for **thorium-uranium fuel cycle** and **molten salt key nuclear data**, an e-linac-driven white neutron source (**TMSR-PNS**) was established, and experimental studies on the **full cross section, capture cross section and thermal neutron scattering cross section** of ^{232}Th, F, Li, Be, graphite and other nuclides were carried out to provide basic data for TMSR research.

Reaction cross section	energy
^{233}U(n,f)	10-200eV
	>500eV
^{233}U-(n,γ)	5-50eV
	>500eV
^{232}Th(n,γ)	10eV-5KeV
^{232}Th(n,f)	<60KeV
	1-500KeV
^{233}Pa(n,γ)	Thermal
	>0.1 MeV
^{19}F (n,inl)	0.23~2.8MeV
^{6}Li (n,T)	0.1~10MeV
^{9}Be(n, γ)	>100eV



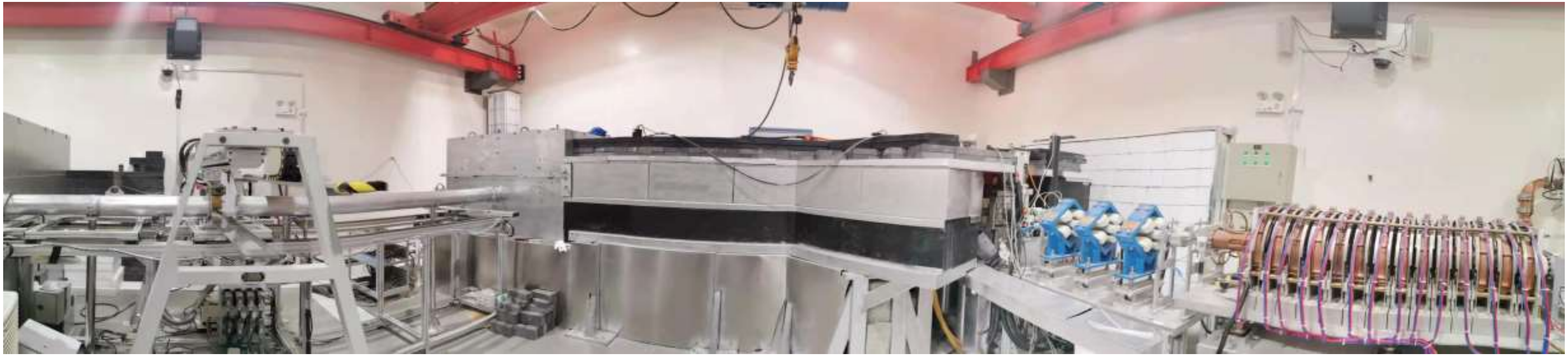
Thorium-uranium fuel cycle key nuclear data

Courtesy Jingeng CHEN @ CAS-SINAP

TMSR-PNS @ CAS-SINAP

- Electron energy: 15 MeV
- Pulse duration : 3-10 ns/15-30 ns/0.5-3 μs
- Repetition frequency : 1-260 Hz
- Beam intensity : 0.1 mA
- Neutron yield : ~10^{11} n/s

- Nuclear data measurement
- Boron equivalent measurement
- Material shielding performance test
- Verification of thorium uranium conversion



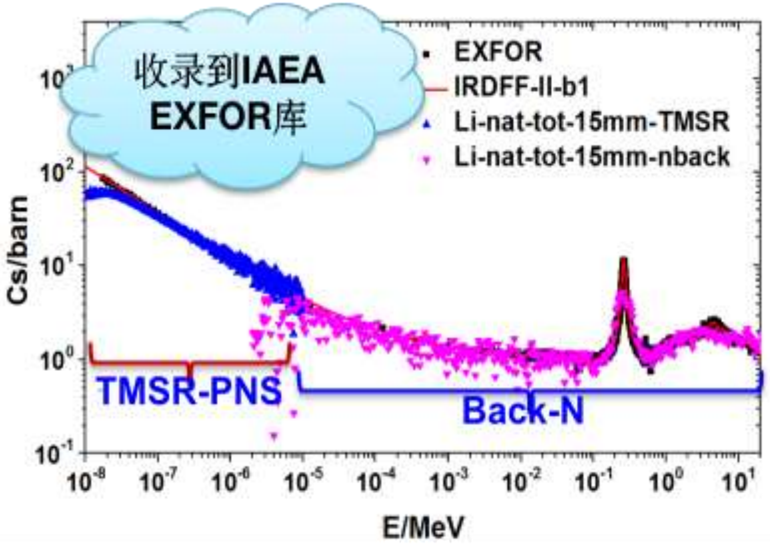
TMSR-PNS @ CAS-SINAP

Key nuclear data measurements

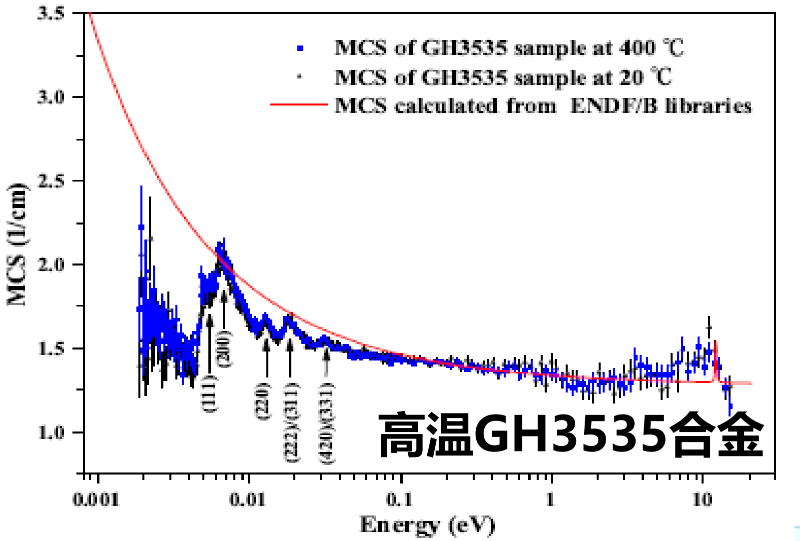
- Total cross section of ^{232}Th, $^{6,7}Li$, ^{nat}Be in thermal energy range
- Scattering cross section of GH3535, graphite, fused salt with thermal neutron

Applied neutron research

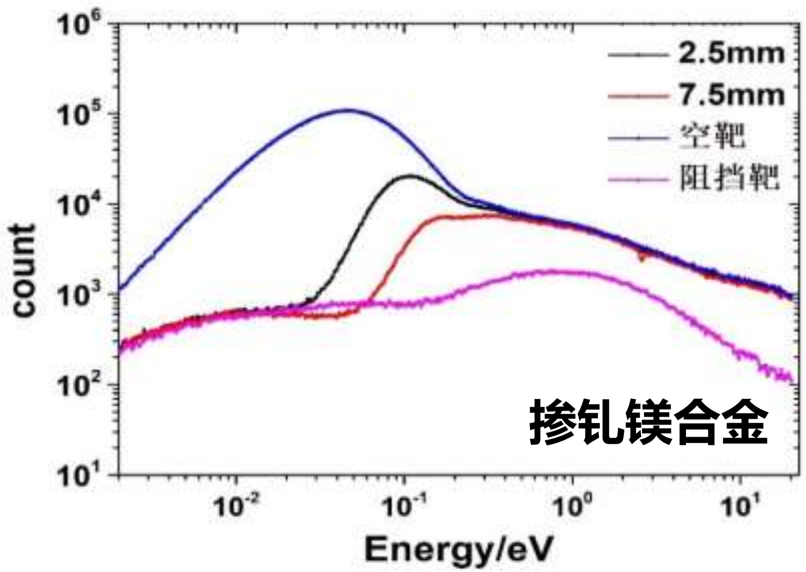
- Graphite, fused salt boron equivalent measurement
- Structure function integrated rare earth alloy shielding material performance test
- Neutron/gamma mixed field irradiation for semiconductor and alloy measurements



TMSR-PNS is complementary to the Back-n white neutron experimental facility of CSNS



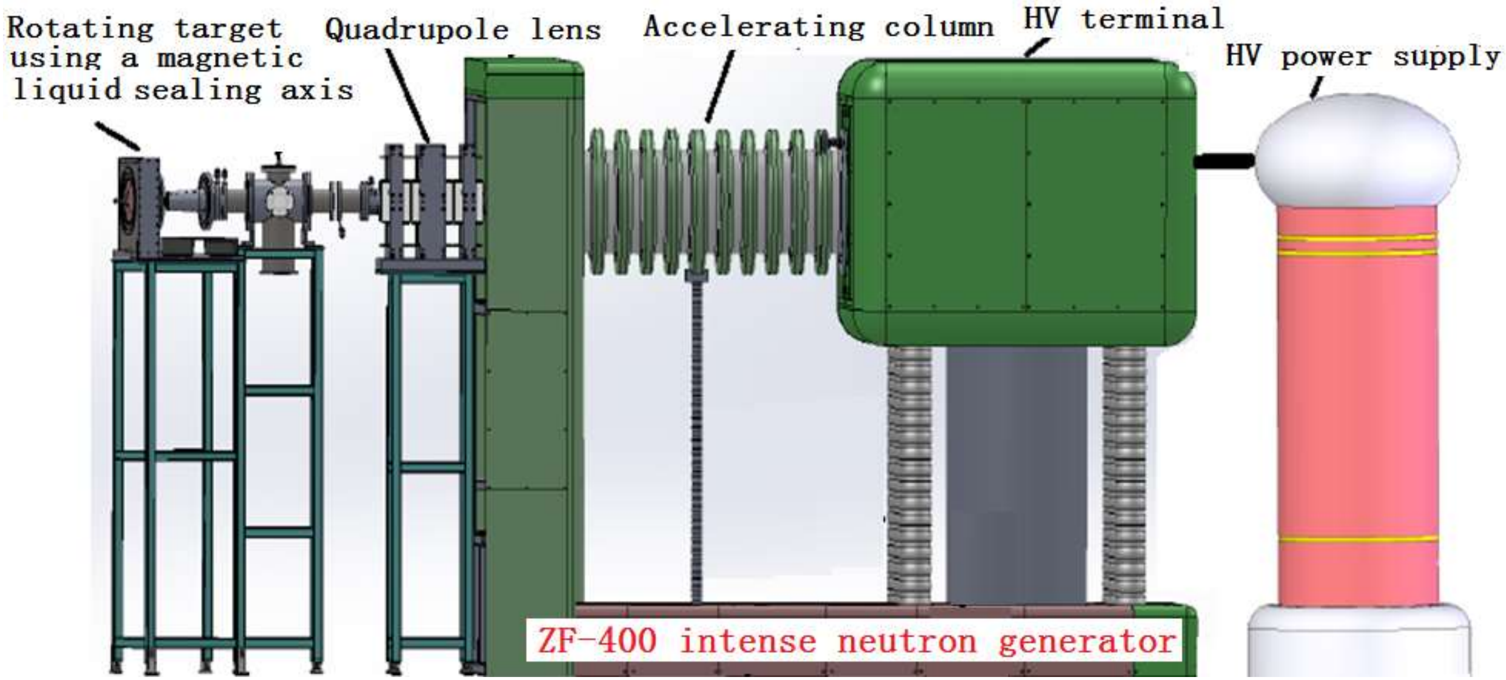
The measurement of thermal neutron scattering data of high temperature molten salts and alloys has extended the research direction of nuclear data measurement



Material irradiation and shielding performance measurements extend the application of the facility

Intense D-T neutron generator @ LZU

➢ **An intense D-T neutron generator is being developed at Lanzhou Univ.**



——Design parameters

★ D^+ Beam energy: 400 keV
★ D^+ Beam current : 40mA
★ D-T neutron yields: >5x10^{12} n/s

——Progress and Plan

★ The installation was completed in 2022 and the high-voltage power supply was loaded to 400kV

★ TiT targets with a diameter of 202 mm were prepared in May 2023

★ Plan to generate neutrons (D-T) in the end of 2023

Courtesy Ze'en YAO @ LZU

Compact neutron generator @ LZU

➢ **A compact D-D neutron generator with a neutron yield of 10^8 n/s had been developed in 2019**

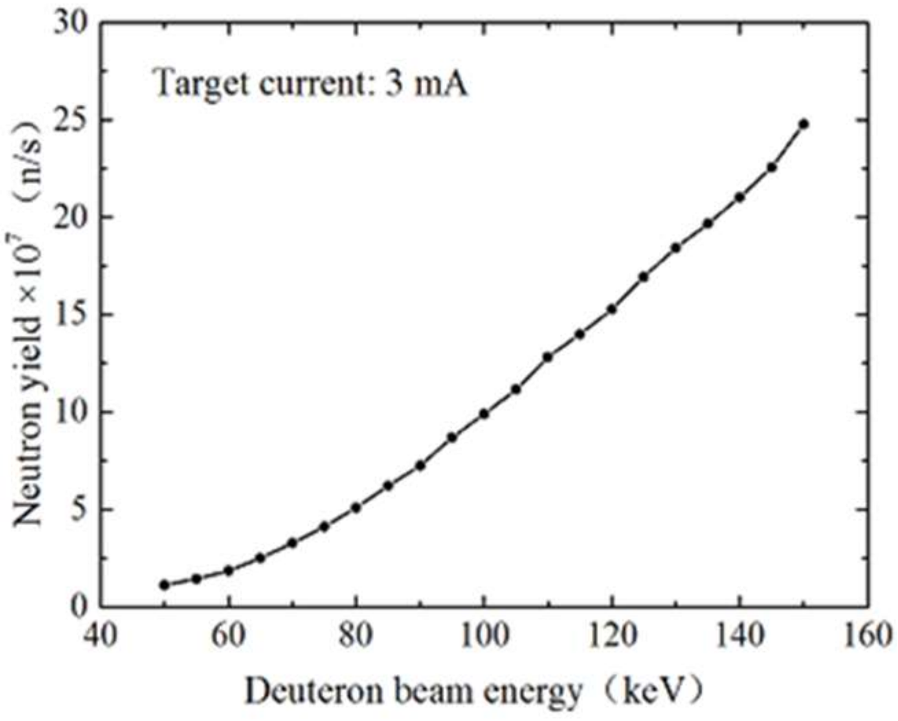
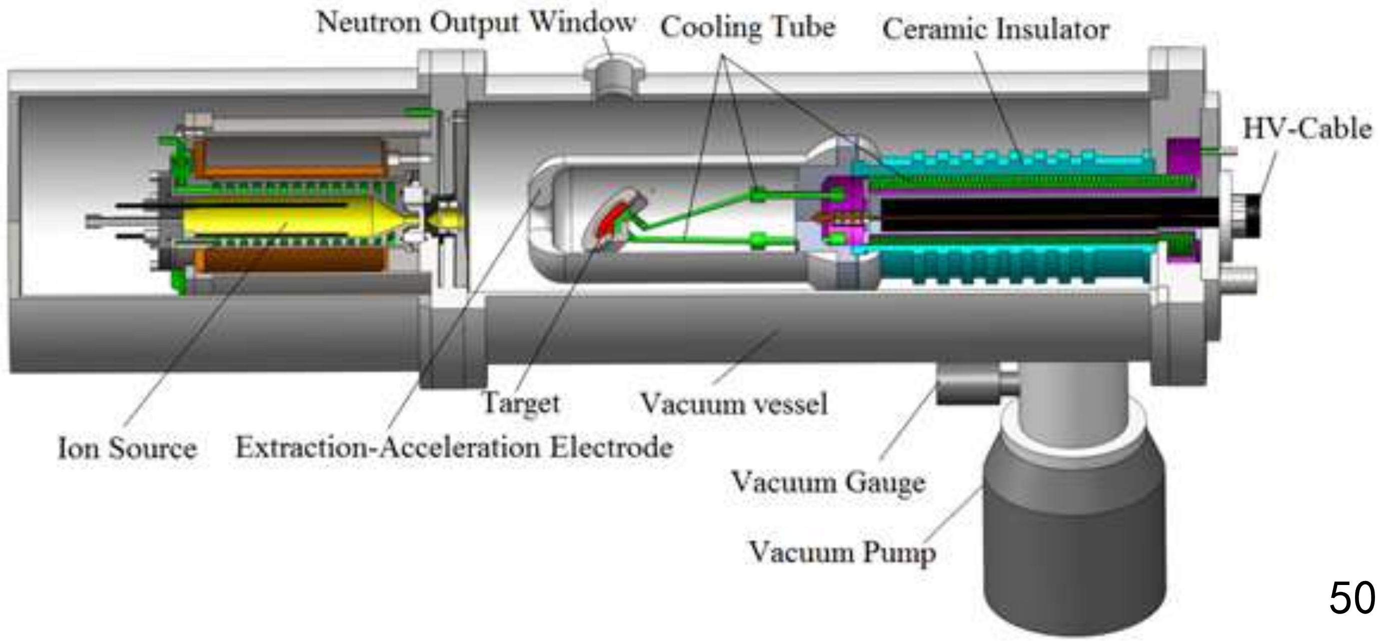


Fig.1 Neutron yield vs. the deuteron bean energy

Two neutron generators have been provided to users

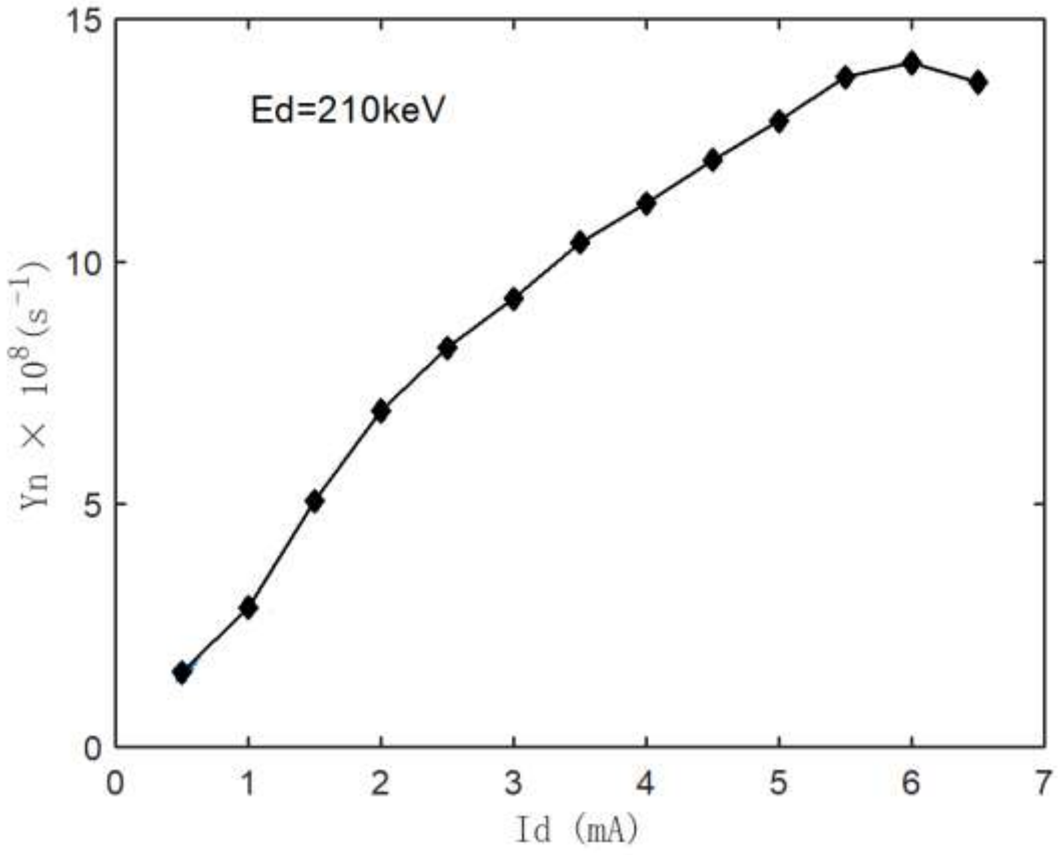
Parameters

★ D Beam energy: 120 keV-150keV
★ D Beam current : >3mA
★ Target: Mo
★ D-D neutron yields: >$1x10^8$ n/s
★ Size: 234 mm(diameter)x 984 mm(length)



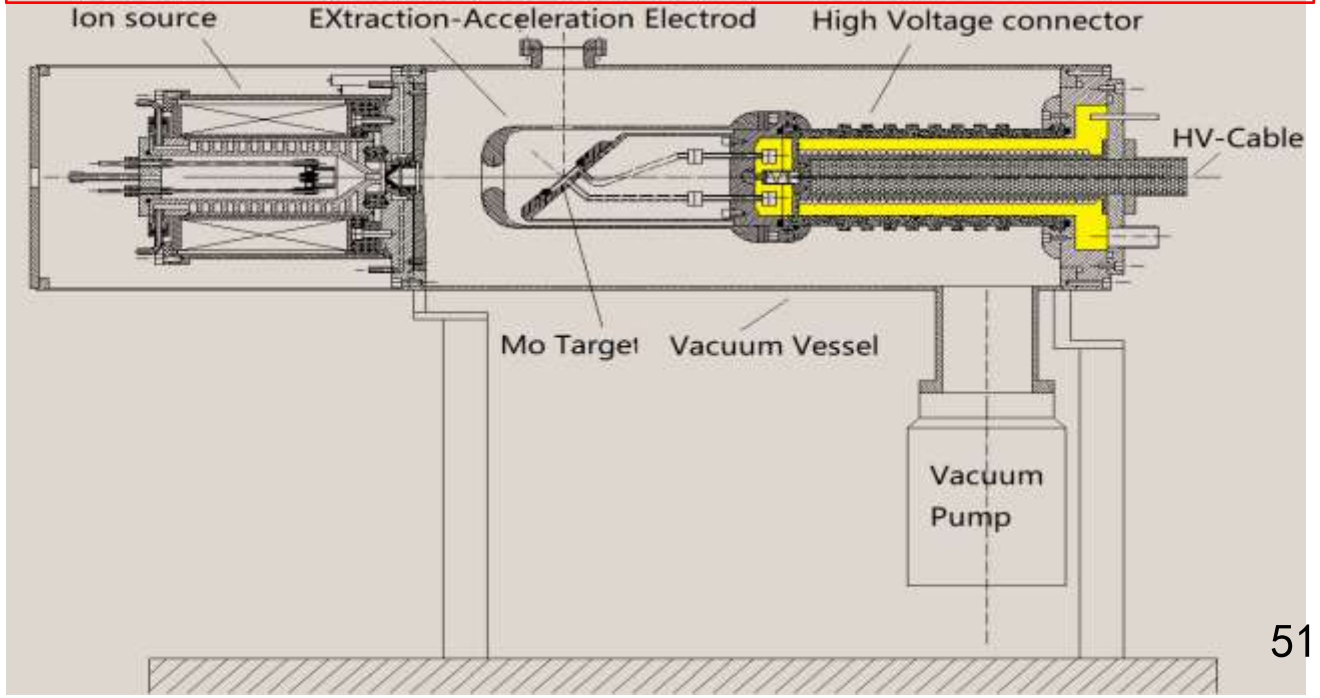
Compact neutron generator @ LZU

- A compact D-D neutron generator with a neutron yield of 10^9 n/s have also be developed in 2023



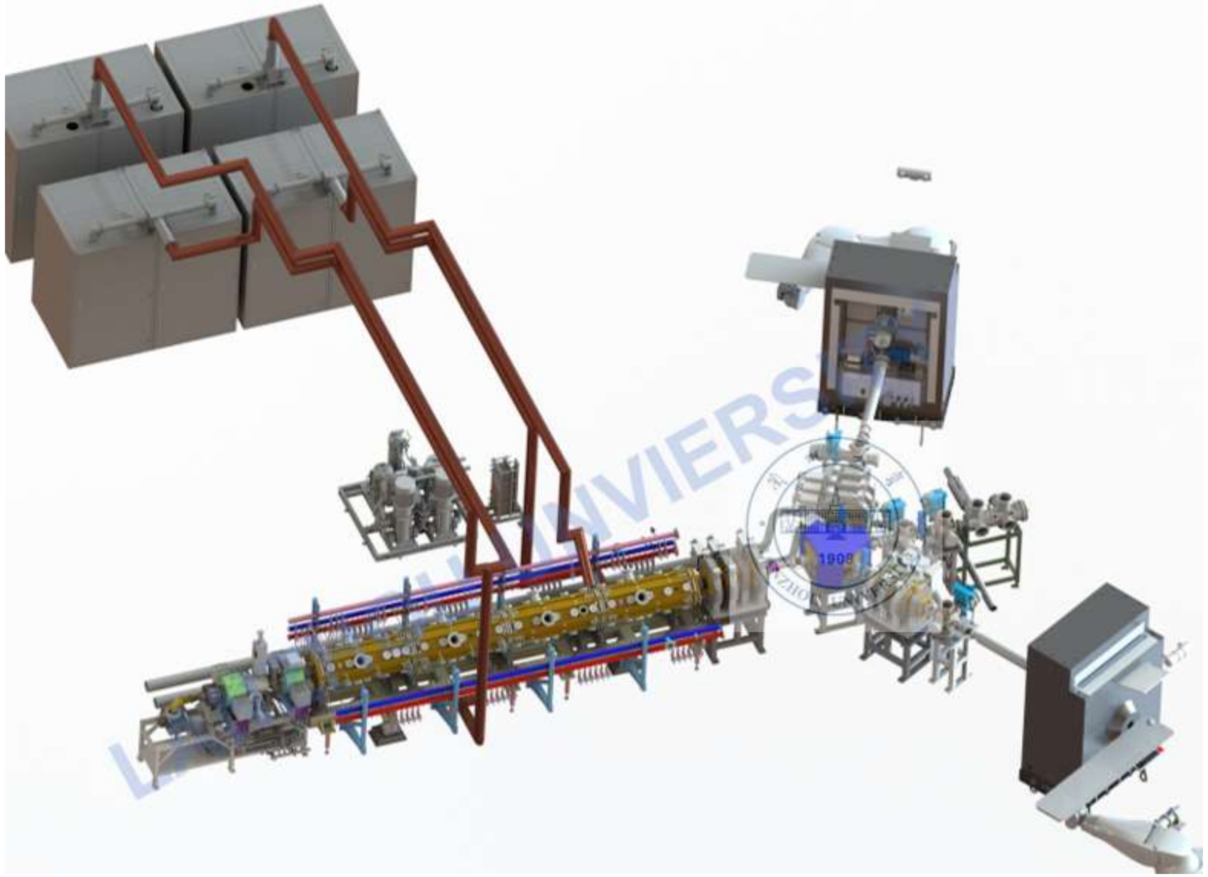
Parameters

★ D^+ Beam energy: 200 keV-220 keV
★ D^+ Beam current : >5mA
★ Target: Mo
★ D-D neutron yields: >1x10^9 n/s
★ Size: 280 mm(diameter)x 1000mm(length)



RFQ-BNCT in Mazu Hospital by LZU

Fujian Medical University Union Mazu Hospital



RFQ Driven BNCT Device (In commission)

Courtesy Long GU @ LZU

RFQ-BNCT in Mazu Hospital by LZU

Parameter	Value
Primary Particle	Proton
Proton Energy	2.6 MeV
Current during Commission	6-15 mA
Target	Lithium
Epithermal Neutron Flux	5.0×10^{8}~1.23×10^{9} $n\cdot cm^{-2}\cdot s^{-1}$
Fast neutron Contamination	1.9×10^{-13} $Gy\cdot cm^{2}$
Photon Contamination	1.6×10^{-13} $Gy\cdot cm^{2}$
Current to Flux	0.72
Thermal Neutron Fraction	0.03

RFQ-BNCT in Mazu Hospital by LZU

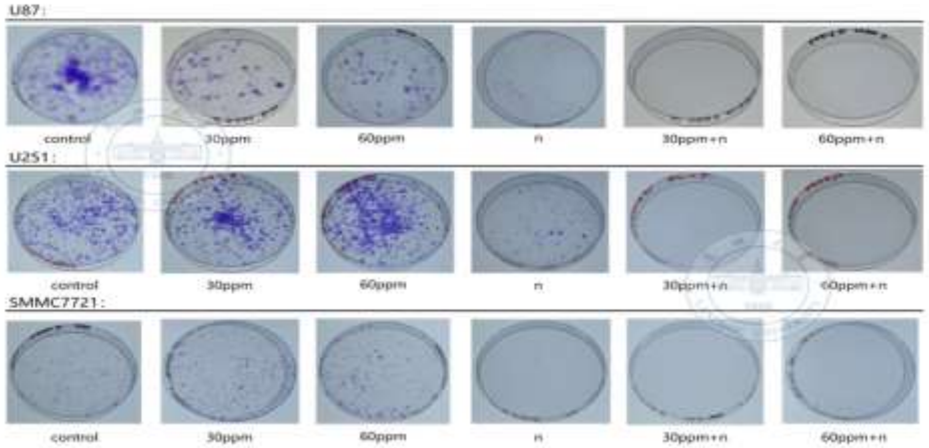
- **2022.08， Equipment installation begins**
- **2023.01， System commision begins**
- **2023.07， Beam Current reach 6 mA**
  - ✓ Neutron Flux， Spectrum， Spatial Distribution were measured
  - ✓ Cell and animal experiments were carried
- **2023.08， Beam Current reach 8 mA**

$$\varphi_{epi}=6.8\times10^{8}\ n\cdot cm^{-2}\cdot s^{-1}$$

Working towards higher flux Ongoing

2023.11， To complete registration inspection

2024.03， Proposed IIT experiments



AB-BNCT in Bo’ao, Hainan

HAINAN FREE TRADE PORT BO’AO HOPE CITY

On June 23, 2022, **China Biotech Services** signed a purchase agreement with **Sumitomo Heavy Machinery Co., LTD** and pharmaceutical company **Stella Pharma** for **BNCT therapeutic equipment and related drugs**. Officially introduced the world's only approved international most advanced cancer treatment technology BNCT equipment, drugs and services.

CANS @ CAEP-INPC

No.	Name	Reaction	Voltage（MV)	Current（mA)	Yield（n/s)	Application	Status
1	PD-300（2007)	D-T	0.3	20	1×10^{12}	Nuclear Data, Neutron Imaging, Radiation	Operational
2	NG-11（2014，2017)	D-T	0.25	1	1×10^{11}	Neutron Imaging	Operational
3	CANS-INPC	D-D	13	0.5	6.4×10^{11}	Neutron Imaging	designed
4	NG-308（2017, 2020, 2022)	D-D	100	5	3×10^{8}	Material analysis, Research	Operational
5	NG-10	D-D	240	30	1×10^{10}	Neutron Imaging	designing

【1】Tritium target lifetime: >90h@8×10^{11}n/s

【2】Tritium target lifetime: >40h@1×10^{11}n/s

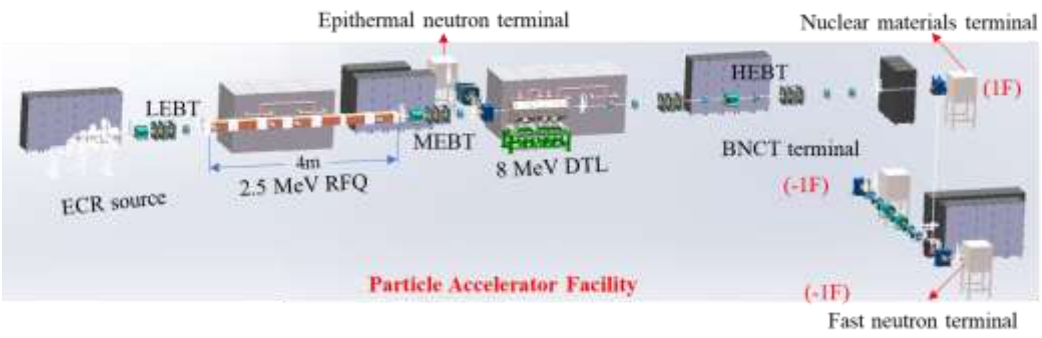
【3】A compact accelerator-driven deuterium–deuterium neutron source using heavy water jet target, Nuclear Inst. and Methods in Physics Research, A 997 (2021) 165165

【4/5】Development and applications of compact deuterium-deuterium neutron generator at INPC, CAEP, UCANS-10

E-mail addresses: wuchunlei@caep.cn (Wu Chunlei) , kejianlin@caep.cn (Ke Jianlin).

Courtesy Chunlei WU @ CAEP-INPC

CCANS Proton Accelerator Facility (PAFA) @ SYSU



PAFA (Proton Accelerator FAcility): a multi-terminal experiment platform based on accelerator-based neutron sources

Beam-line system: ECR IS+ 2.5 MeV RFQ+MEBT+8 MeV DTL+HEBT

Terminal system: Four terminals for nuclear experiment (epithermal and fast neutron), materials irradiation and BNCT, respectively.

The parameters of PAFA-RFQ

Parameters	Value
Particles	H^+
Frequency [MHz]	200
Beam current [mA]	20
Output energy [MeV]	2.5
Length of vane [mm]	3945.3
Kilpatrick factor	1.46
Transmission efficiency	99.5%
Q factor	12848
Power loss [kW]	98.38

The parameters of PAFA-DTL

Parameters	Value
Particles	H^+
Frequency [MHz]	200
Beam current [mA]	10
Output energy [MeV]	8.0
Cavity length [mm]	2409.43
Transmission efficiency	100%
Beam dynamics type	APF
Kilpatrick factor	1.42
Q factor	13987
Power loss [kW]	90.78

Terminals

- **Epithermal neutron terminal (1F): ^{7}Li (p, n)^{7}Be +moderator to produce hundreds keV neutrons**
- **Nuclear materials terminal (1F): study on material irradiation damage of protons**
- **Fast neutron terminal (-1F): ^{9}Be(p, n)^{9}B+moderator to produce neutrons with a average energy of 1 MeV;**
- **BNCT terminal (-1F): 1.3×10^9 n/cm^2/s of neutron flux to meet the requirement of IAEA for BNCT applications**

Courtesy Liang LU @ SYSU

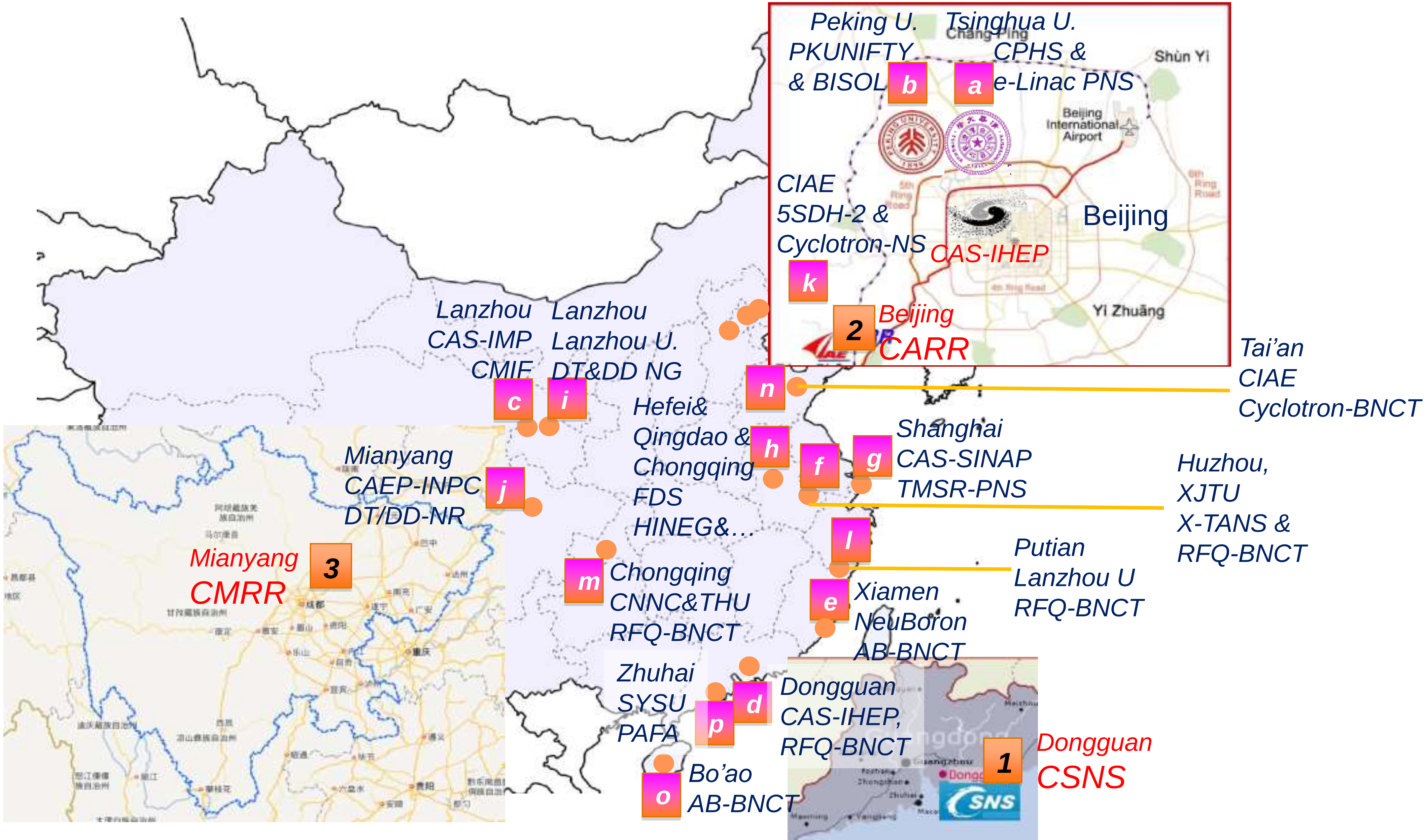
Outline

CANS Projects in China

CONTENTS

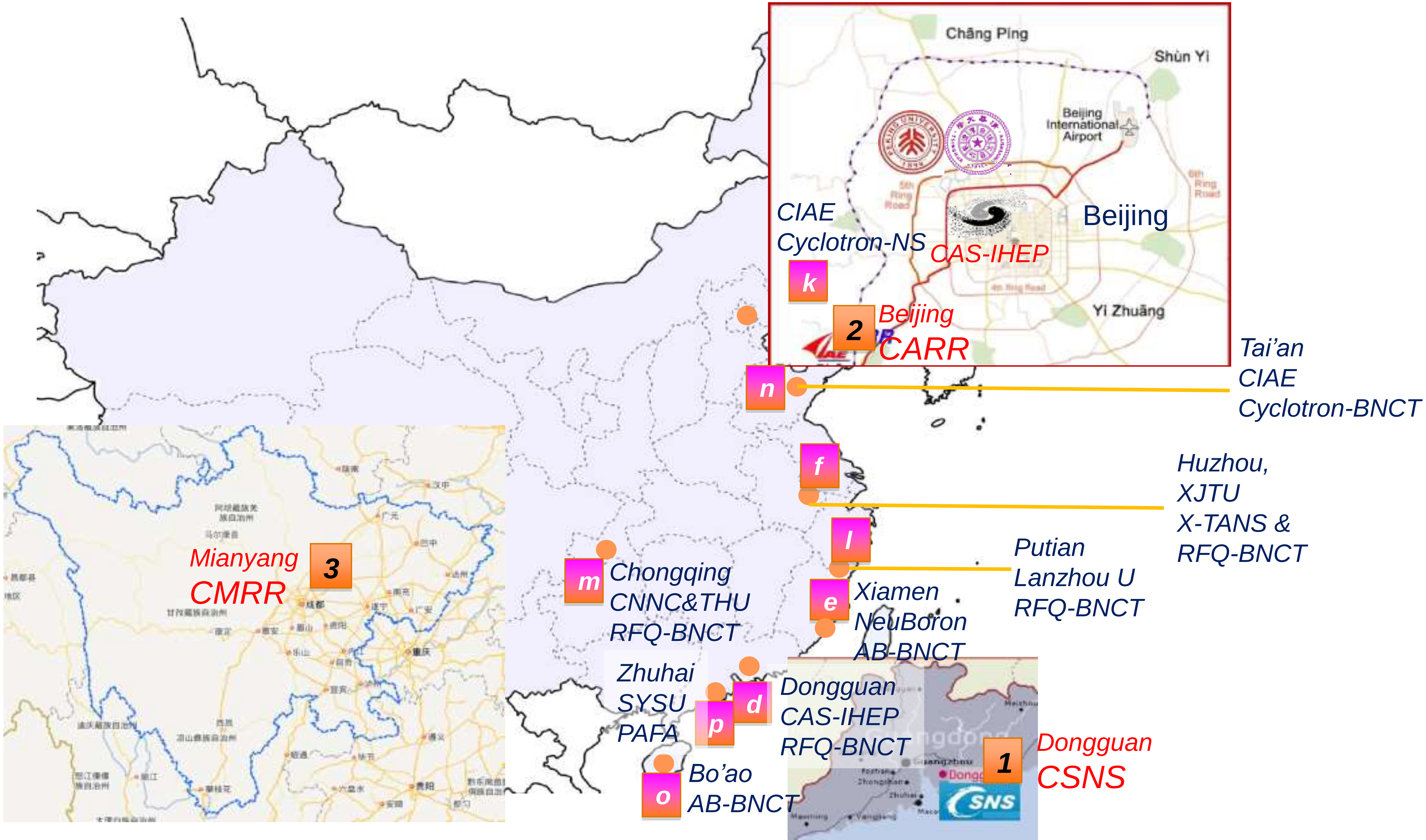
CCANS

Large NSs and CANSs in China



CCANS

AB-BNCT projects in China



AB-BNCT projects in China

Facility	Affiliation	Reaction	Accelerator	Flux n/cm²/s	Energy	Purpose	Status
AB-BNCT	NeuBoron @Xiamen	p-Li	2.35MeV-10mA / ES	$>1\times10^9$	Epi-th	BNCT	Clinical trial
D-BNCT01	CAS-IHEP @Dongguan	p-Li	3.5MeV-5mA / RFQ	-	Epi-th	BNCT exp	Experimental
D-BNCT02	CASBNCT @Dongguan	p-Li	2.8MeV-20mA / RFQ	$>1\times10^9$	Epi-th	BNCT	Constructional
RFQ-BNCT	by LZU @Mazu	p-Li	2.6MeV-15mA / RFQ	$>1\times10^9$	Epi-th	BNCT	Commissioning
X-TANS RFQ-BNCT	by XJTU @Huzhou	p-Li	2.5MeV-10mA / RFQ 2.8MeV-25mA / RFQ	- -	Epi-th	Multi-P BNCT	Commissioning Planning
Cyc-BNCT Cyc-BNCT	CIAE @Tai'an	p-Be	14MeV-1mA/Cy-tron	$>1\times10^9$	Epi-th	BNCT exp BNCT	Commissioning Planning
RFQ-BNCT	CNNC&THU @Chongqing	p-Li	2.7MeV-30mA / RFQ	$>1\times10^9$	Epi-th	BNCT	Planning
Cyc-BNCT	CBS & SHI @Bo'ao	p-Be	30MeV-1mA/Cy-tron	$>1\times10^9$	Epi-th	BNCT	Constructional
PAFA	SYSU @Zhuhai	p-Li	8MeV-10mA/p-linac	$>1\times10^9$	Epi-th	BNCT	Planning

- Clinical requirements and investment climate
- University, institution, or enterprise based organization?
- CANS technology: Reaction, accelerator type, and beyond

The other CANS projects in China

Facility	Affiliation	Reaction	Accelerator	Yield(n/s)	Energy	Purpose	Status
5SDH-2	CIAE	Multi	1.7MeV$\times$2-10μA Pelletron tandem	10^6~10^8	Fast	Metrology	Operational
Cyc-NS	CIAE	p-Be	18MeV-1mA/Cyc-tron 100MeV /Cyclotron	＞10^6@sam		NR Fast	Commission
CPHS e-PNS	Tsinghua U	p-Be e-γ-n	13MeV-1.25mA/linac 9MeV/0.9kW/e-linac	5×10^{13} 2×10^{11}	Cold/Th Th	Multi-P NR(BiMo)	Operational Operational
PKUNIFTY BISOL	Peking U	D-Be D-Li	2MeV-0.4/3.5mA/RFQ 3~40MeV-25mA /linac	2.4×10^{11} 2.5×10^{12}	Th Fast	NR, Edu Sci-Res	Interval oper Design
CMIF(DGT)	CAS-IMP	D-Be	50MeV, 10mA RFQ+HWR (SC)	~10^{14}	Fast	Material Irradiation	Commission
TMSR-PNS	CAS-SINAP	e-γ-n	15MeV-1.5kW/e-linac	~1×10^{11}	white	Nuc data	Operational
HINEG-I HINEG-II HINET-III/GDT NGs	INEST, CAS	D-T / DD	350keV-60mA / ES Cyclotron GDT ES	6.4×10^{12} 10^{13}~10^{14} ~10^{18} 10^7~$10^{8\sim10}$	Fast/Th	Material Irradiation NR NAA	Operational Construction Design Developed
ZF-400 Compact	Lanzhou U	DD/DT DD/DT	400keV-40mA 120keV-3mA	5×10^{12} $1\times10^{8/10}$	Fast/Th	NAA	Developed
NR-FTY	CAEP-INPC	DT/DD DD	100~300keV-1~30mA 13MeV-0.5mA	3×10^8-10^{12} 6.4×10^{11}	Fast/Th	NR, NAA	Developed
PAFA	SYSU	p-Li p-Be	2.5MeV-20mA/RFQ 8MeV-10mA/RFQ+DTL	-	Epi-th Fast	Nucl Phys Irradiation	Planning

Summary & Discussion

- CANS projects have been rapidly increased recent years in China
- Requirements on BNCT, scientific research (BISOL, NS), energy(ADS, TMSR), NR, NAA, have been driving the development
- Series of technical progress have been made, provide the solid foundation of CANS projects
- Not only governmental fund, but also industrial investment have been interested in CANS projects
- CANSs can collaborate with big facilities
- Not only construction, but also operation and application should be concerned

清华大学
Tsinghua University

北京大学
Peking University

兰州大学
Lanzhou University

西安交通大学
Xi'an Jiaotong University

南京航空航天大学
Nanjing University of Aeronautics and Astronautics

南京中硼联康医疗科技有限公司
Nanjing Zhongboron Liankang Medical Technology Limited Company

中国科学院高能物理研究所
The Institute of High Energy Physics of the Chinese Academy of Sciences

凤麟核团队
FDS Consortium

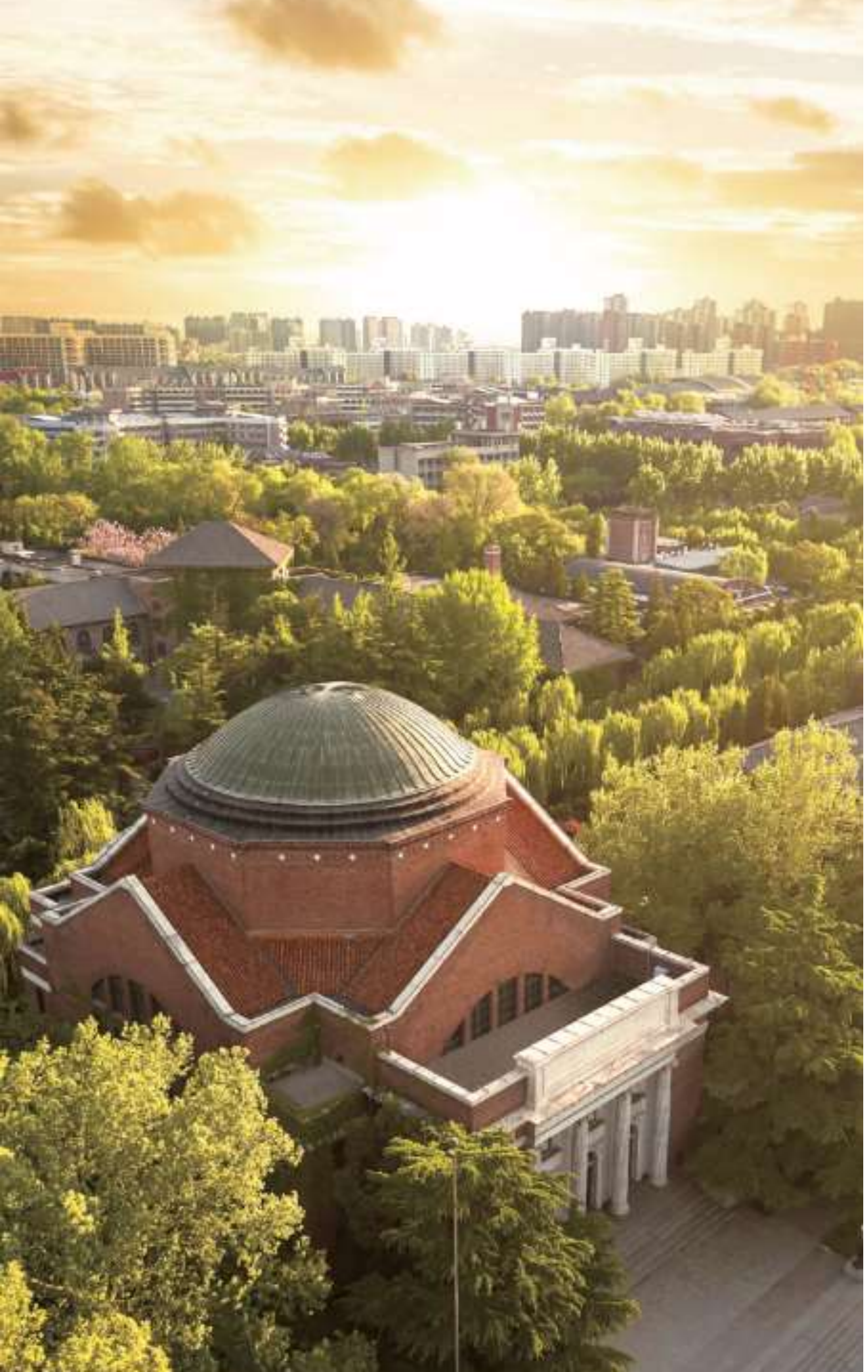
中国原子能科学研究院
China institute of atomic energy

中国工程物理研究院核物理与化学研究所
Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics

中山大学
Sun Yat-sen University

中国科学院上海应用物理研究所
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

中国科学院近代物理研究所
Institute of Modern Physics,Chinese Academy of Sciences



Thanks for Your Attention!

CCANS

清華大學
Tsinghua University