Studies on Fusion Nuclear Technology, Materials and Safety at FDS

Yican WU

Contributed by FDS Team/INEST
International Academy of Neutron Science (IANS)

FDS: The Consortium for Nuclear Technology Innovation

Qingdao ~200 researchers

Aims at Neutron Science and Advanced Nuclear Energy

International Academy of Neutron Science (IANS)

(Headquarters located in Qingdao, supported by the government)

SuperRay Technology Co., Ltd., Neutron health Medical Technology Co., Ltd. …

Hefei ~150 researchers

Aims at Neutron Science and Nuclear Safety

Institute of Nuclear Energy Safety Technology (INEST)

(Legal entity invested jointly by CAS, government and IANS)

SuperNuclear Science & Technology Co., Ltd., SuperSafety Science & Technology Co., Ltd. …

Chongqing ~150 researchers

Aims at Neutron Science and Nuclear Medicine

Institute of Neutron Science (Chongqing) (INSC)

(supported by the government)

Neutron High Tech Industrial Development Co., Ltd. …

Nanjing ~100 researchers

Aims at High-end Radiotherapy Equipment Manufacturing

SuperAccuracy Science & Technology Co., Ltd. …

Other bases under construction (Beijing, Shanxi, Guangdong, Zhejiang, etc.)






Orientation of Fusion Studies at FDS

Innovative Concepts

FDS-MFX
FDS-I/-SFB, C-DEMO
FDS-II, FDS-III, FDS-ST
…

D-T Tokamak

+

GDT mirror
…

Alternative concepts

Common Technologies

Fusion Nuclear Technology, Materials and Safety

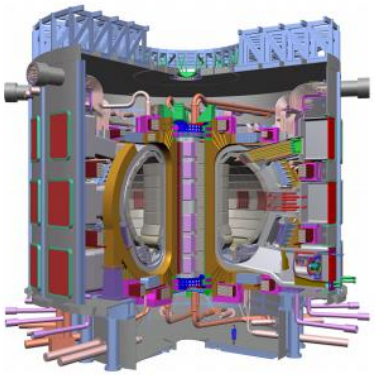
1. Neutronics & Nuclear Technology
2. Materials & Blanket Technology
3. Fuel Cycle & Tritium Technology
4. Safety, Environment & Socio-economics

Develop technologies shared among various fusion concepts

Fusion/Hybrid Reactor Projects at FDS

I. 1986-2000, “863”/“973” Programs from MOST

- Fusion hybrid fuel breeder design activities



II. 2001-2006, supported by NSFC, CAS, etc.

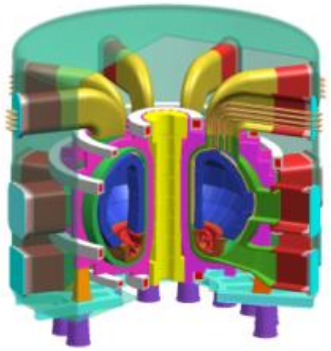
- Fusion hybrid waste transmuter concept development
- Fusion power reactor/DEMO concept design

III. 2002-present, CRP Programs from IAEA

- FDS-I: Fusion Driven Subcritical System for Nuclear Waste Transmutation
- FDS-GDT: Compact Fusion Volumetric Neutron Sources/Hybrid reactor

IV. 2007-present, supported by MOST

- Fusion/Hybrid engineering test reactor concept design
- Blanket engineering technology and Materials R&D
- Fusion nuclear safety and radiation protection
- Contribution to ITER construction and TBM program



Continuously Supported by National Programs & International Collaboration Programs

Developed Fusion Reactor/Blanket Concepts

1. Fusion TEST Reactor

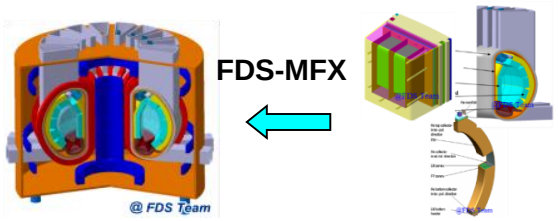
- **FDS-MFX:** Multi-Functional eXperimental Reactor abbreviated as MFX
- **CFETR:** Chinese Fusion Engineering Testing Reactor (Liquid LiPb Blanket)

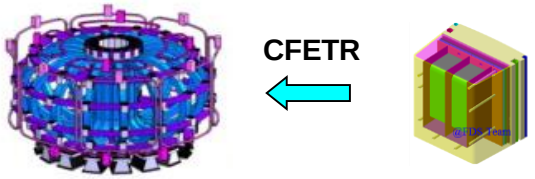
2. Fusion DEMO Reactor

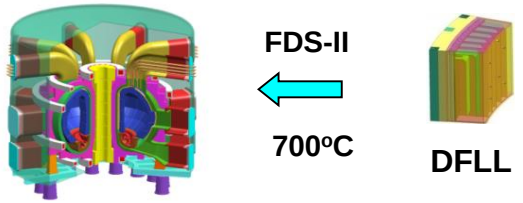
- **C-DEMO:** Chinese DEMO Reactor (energy production, fuel breeding, multiplication)
- **FDS-I/-SFB:** Fusion Reactor for Spent Fuel Burner (early application)

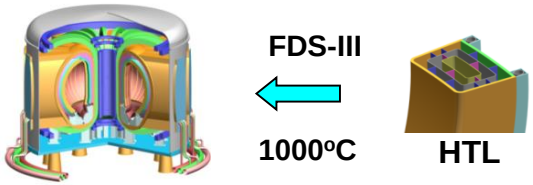
3. Fusion POWER Plant

- **FDS-II: Fusion Power Reactor**
  for high-efficiency electricity generation
- **FDS-III: High Temperature Fusion Reactor**
  for advanced applications, e.g. hydrogen production
- **FDS-ST: Spherical Tokamak-based Reactor**
  for exploiting and assessing innovative concepts









A series of distinctive fusion and fusion-fission hybrid reactor concepts were developed

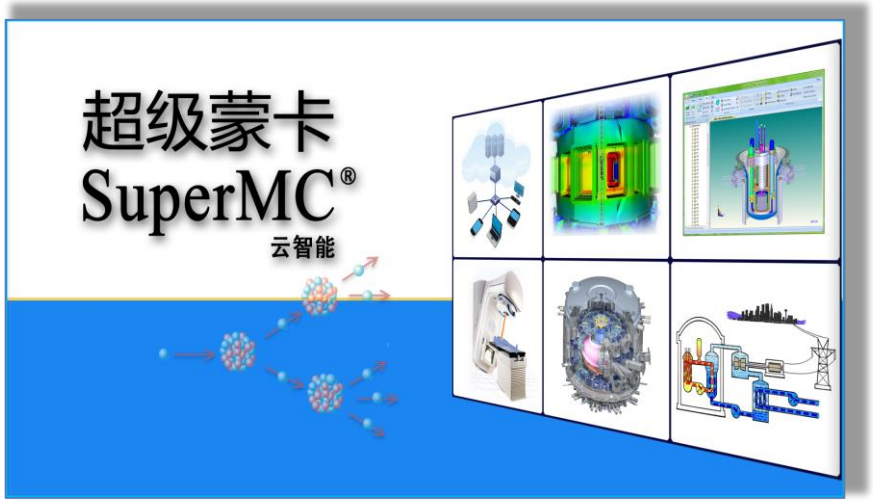
Y. Wu. Fusion Eng. Design, 81 (2006) 2731-2736.

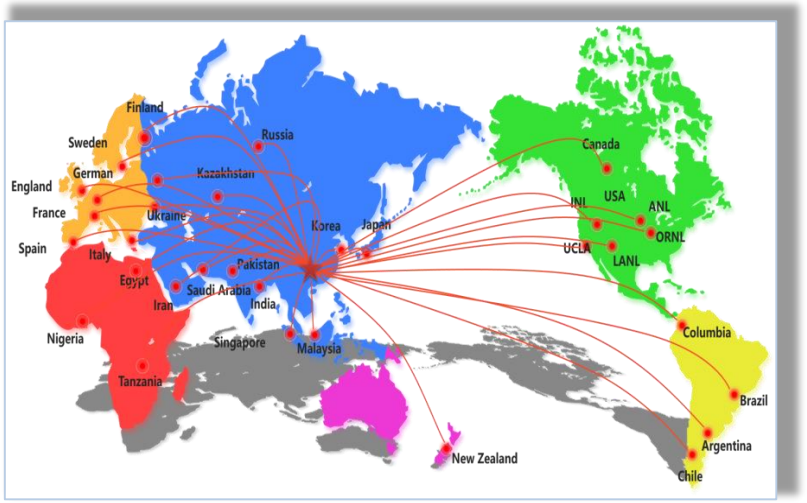
Development of SuperMC

Super Multi-functional Calculation Program for Nuclear Design and Safety Evaluation

- **Full-function & high-efficiency** neutronics calculation
- CAD/Image-based **accurate** modeling for complex **irregular** geometry
- Data analysis based on **multi-D/multi-style visualization**
- **Intelligent** nuclear and multi-physics design based on **Cloud computing**

- Widely used in **70+ countries** and 40+ mega-projects
- Selected as the reference code by ITER, and supported to build **ITER 3D basic neutronics models**
- Available from OECD/NEA, ONR&EA in the UK and RIST/NCC in Japan





Snapshot of High Intensity Neutron Sources by FDS

Mini → **HINEG-I** → **HINEG-II** → **HINEG-III** (High Intensity)

Completed

Mini Neutron Generator
MINEG
(ø25/43mm,10^8 n/s)

Completed

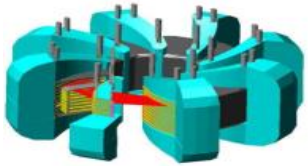
D-T Neutron Generator
HINEG-Ia in Hefei
(6.4×10^{12} n/s)

Under Construction

Ultra-high D-T Neutron Source
HINEG-IIa in Chongqing
(≥ 10^{13} n/s)

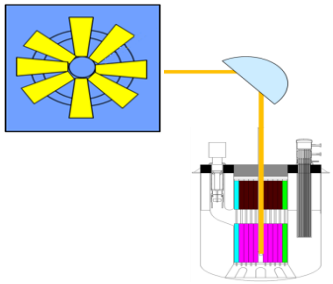
+

Under Design



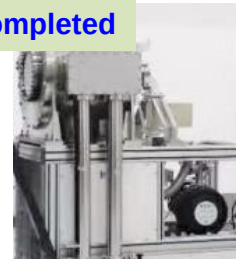
High Intensity Cyclotron-based
Neutron Source HINEG-IIb
(≥ 10^{15} n/s)

Planning



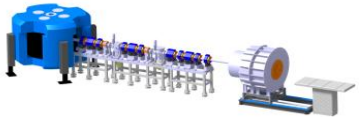
High Flux Steady State Neutron
Source HINEG-III
(6×10^{15} n/(cm²•s))

Completed



Compact Neutron
Generator CONEG
($10^{9\sim11}$ n/s)

Under Construction



Cyclotron-based
Steady Neutron Source
HINEG-Ib in Qingdao
(≥ 10^{14} n/s)

Advanced Nuclear Energy systems
(Fusion, LFR/ADS...)

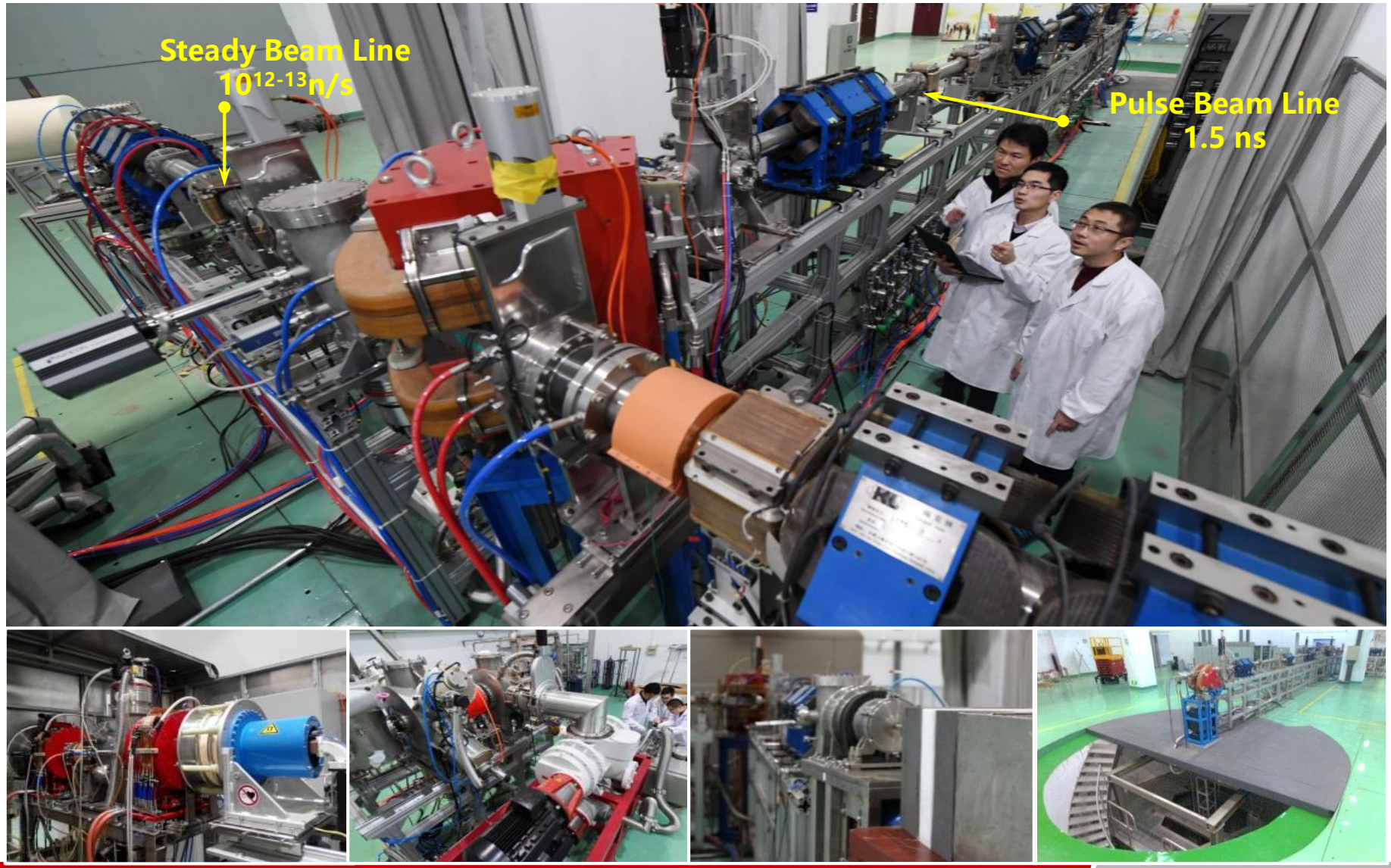
Neutronics & Shielding Design Validation → Core Physics & Advanced Reactor Technology Validation → Material & Component Engineering Validation

Extended Nuclear Technology Applications

Neutron logging, Security Inspection, Radiography, Radiotherapy, Isotope Production, ...

HINEG-Ia: High Intensity D-T Fusion Neutron Generator

Neutrons yield: 6.4×10^{12} n/s, coupling with Lead-based zero power reactor CLEAR-0



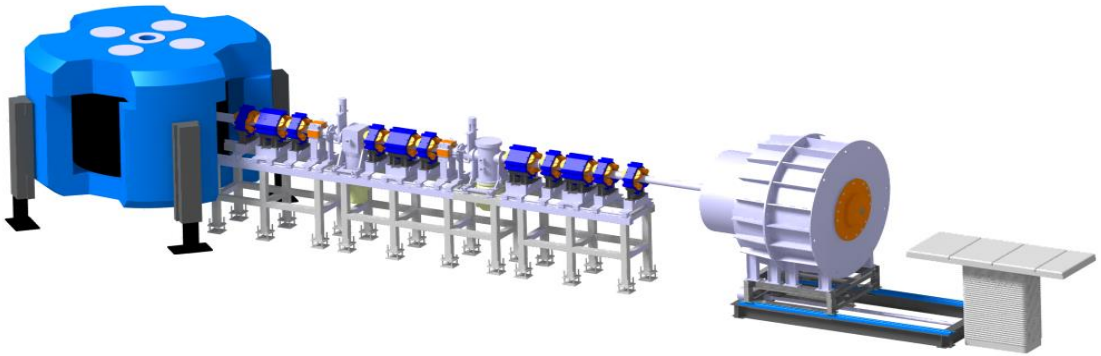
HINEG-Ib: Cyclotron-based Steady Neutron Source

Application Goals

- Validation of accelerator-based neutron therapy technology and isotope production technology
- Validation of neutronics & shielding design for advanced reactors

Main parameters

- Neutron yield: ≥10^{14} n/s
- Accelerator：proton, 30 MeV/1 mA
- Target material: Be



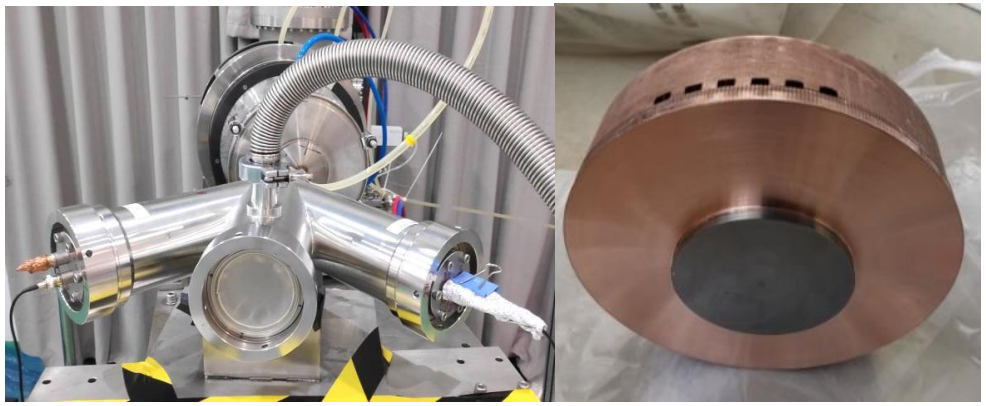
Engineering construction of HINEG-Ib is on going

Progress of HINEG-Ib

Accelerator

Beam Transport System

Support Structure & Power Supply



Neutron Target

BSM Module

Main components have been manufactured and are under assembly

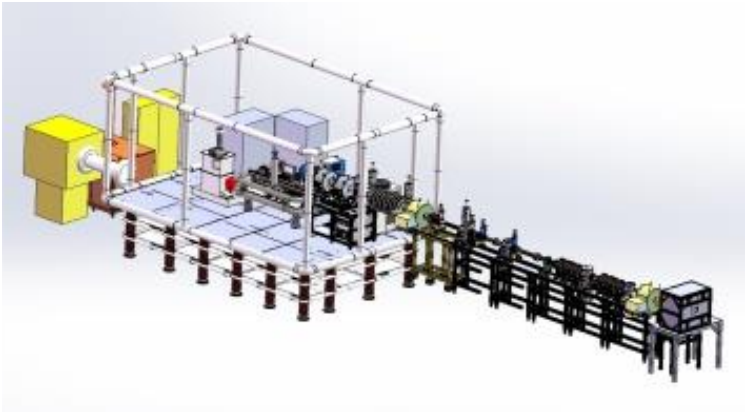
HINEG-IIa：Ultra-high Intensity D-T Neutron Source

Application Goals

- Radiation damage mechanism of materials under fusion neutron irradiation environment
- Validation and calibration of materials irradiation data obtained with other ion/neutron source (e.g. reactor, spallation)
- Extended nuclear technology applications including radiography, neutron therapy, isotope production, etc.

Main parameters

- Neutron yield：≥10^{13} n/s
- Beam Energy: 300-500 keV
- Beam Current: 80~180mA
- D-D and D-T dual operation mode

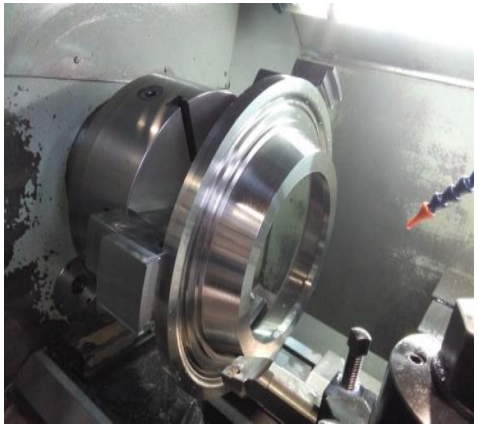


Construction of HINEG-IIa is on going

Progress of HINEG-IIa

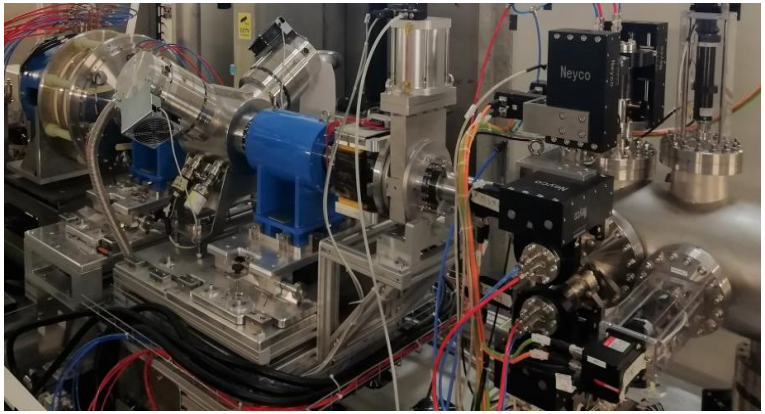
Ion source

Extraction system



Vacuum Vessel

Insulating Transformer



Beam Diagnostic System

HV Power Supply

Chiller and C&C Cabinet

Engineering design has been finished, components manufacture and assembly are under going

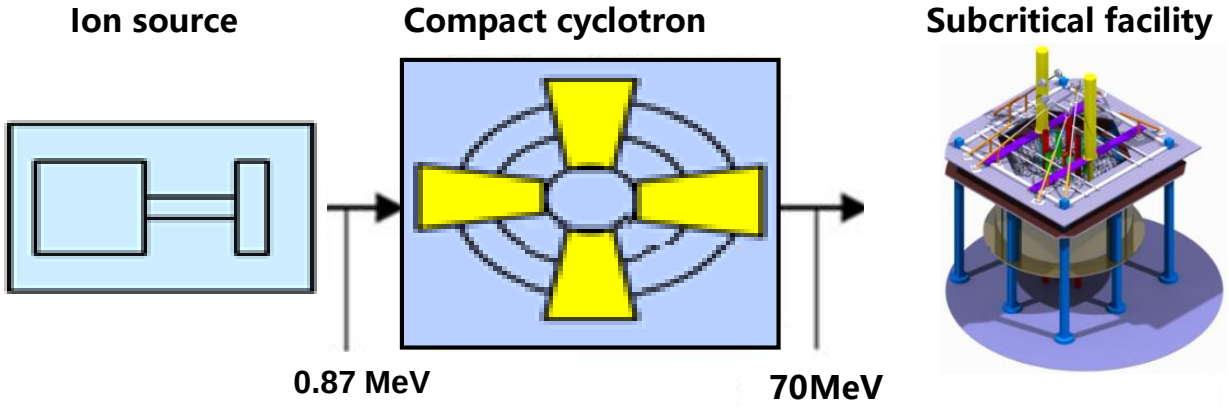
HINEG-IIb: High Intensity Cyclotron-based Neutron Source

Application Goals

- Validation of core physics and advanced reactor technology
- Technical validation for HINEG-III
- Other applications

Main Parameters

- **Neutron yield: ≥10^{15} n/s**
- **Accelerator:** 70MeV/3 mA CW proton beam



design of HINEG-IIb is on going

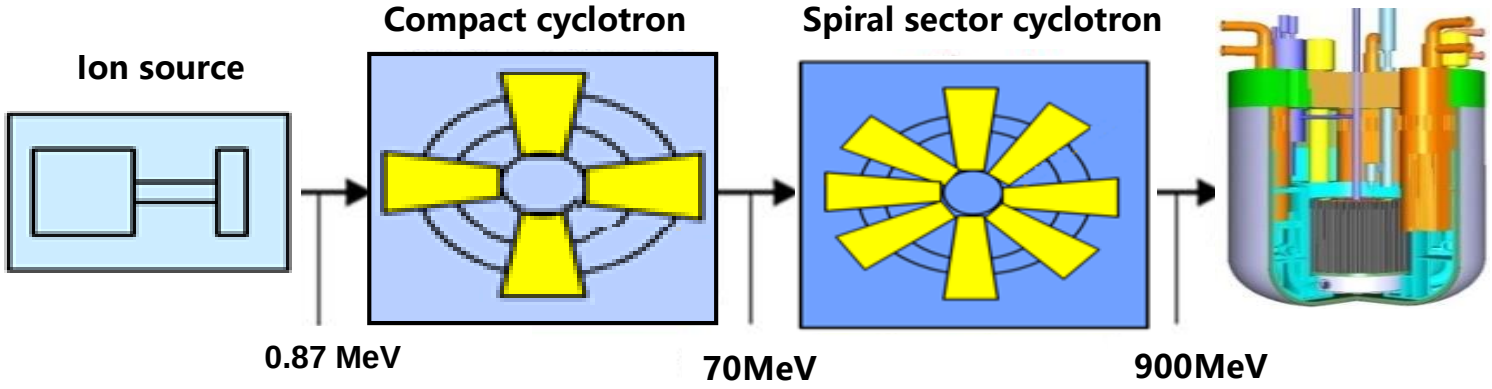
HINEG-III: High Flux Steady-state Neutron Source

Application Goals: Multi-purpose neutron irradiation platform

- Irradiation test for fuel, material and components of advanced reactor
- Technology development for isotope production, neutron therapy, activation analysis, etc.

Main Parameters

- **Neutron yield** of accelerator-based neutron source: **3×10^{17} n/s**
- **Neutron flux** of subcritical reactor: **6×10^{15} n/cm^2/s**



Conceptual design of HINEG-III is on going

Structural Materials and Test Blanket Modular

I. CLAM: China Low Activation Martensitic steel

- 3×6-ton Ingots & Components
- Breakthrough in 3D printing of blanket first wall

National RAFM steel standard is published (GB/T 38820-2020)

II. ODS-CLAM: Oxide Dispersion-Strengthened CLAM

- Nanoparticles: <10 nm, >10^{24} m-3
- Yield strength at 700 ºC: >500 MPa
- Creep life at 120 MPa/650ºC: >10,000 hr
- Swelling after 200 dpa ion irradiation: <0.1%

Supported by National Key Technology R&D Project of China

III. China TBM Program

- Fabrication of 1/3 scaled DFLL-TBM by welding technologies

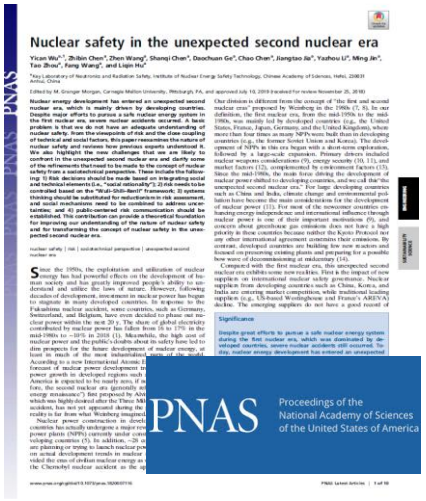
Supported by National Key Technology R&D Project of China

Study of Safety, Environment and Socio-economics

1. **Identification of Safety Gaps analysis for Fusion DEMO Reactors and published in Journal of Nature Energy.**

2. **Organized and hosted two international workshops on ESEFP to promote research on fusion safety assessment and regulatory, such as safety approach, safety design, licensing, et al.**

3. **Safety philosophy was proposed for advanced reactor design and published in PNAS.**

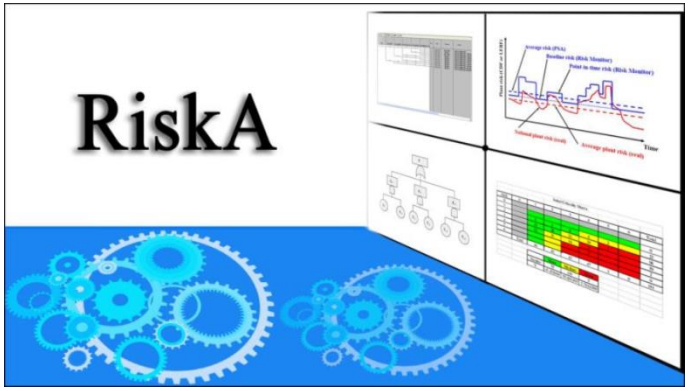


Reliability and Safety Assessment of Fusion Reactor

Reliability and safety is a key challenge for fusion reactor in steady operation. Supported by MOST and other projects, RAMI and reliability analyses of fusion reactors have been done using RiskA.

ITER safety and license work group

- **Fully self-developed Reliability and Safety Assessment Suite RiskA**
  - Fault Tree Analysis
  - Event Tree Analysis
  - Failure and Model Effect Analysis
  - Failure Rate Database
  - Uncertainty Analysis



Highlights of International Activities

1. Organizing activities of the IEA NTFR TCP

- **Organize the 2022 ExCo meeting of NTFR on 22nd September, and Prof. Yican Wu was reelected as the ExCo chair**
- **Invite UK to join the NTFR TCP as a new contracting party**

2. Under the current situation of Chinese policy regarding the Quarantine for Covid-19, although intensive efforts, ISFNT-15 host was changed to CIEMAT on September 10-15, 2023 in Canaria Island, Spain.

3. International Academy of Neutron Science (IANS) was set up in Qingdao. As an open platform, prestigious experts from all over the world are welcome, promoting international cooperation on R&D related to neutron science and technology, including for fusion.

Thanks for Your Attention!

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