Studies on Fusion Nuclear Technology and Safety at FDS

Yican Wu, Qi Yang

International Academy of Neutron Science，FDS Consortium

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FDS: The Consortium for Nuclear Technology Innovation

Chongqing Base

Aims at Neutron Science and Nuclear Medicine

International Academy of Neutron Science (Chongqing)

+Guozhong Medical Technology(Chongqing) Co., Ltd. ...

Qingdao Base

Aims at Neutron Science and Advanced Nuclear Energy

International Academy of Neutron Science (Qingdao)

+Institute of Nuclear Science and technology, Shandong University

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

Nanjing Base

Aims at High-end Radiotherapy Equipment Manufacturing

+ SuperAccuracy Science & Technology Co., Ltd. ...

Hefei Base

Aims at Neutron Science and Industrial Safety

International Academy of Neutron Science (Hefei)

+Institute of Nuclear Energy Safety Technology Co., Ltd. (INEST)

+Thinking Neutron Technology Co., Ltd., SuperSafety Science & Technology Co., Ltd. ...

Other bases under construction (Anqing, Jinan, Jiuquan, etc.)

- FDS Consortium focuses on R&D of advanced nuclear systems and applications of nuclear technology.
- FDS Consortium has registered more than 20 subsidiary independent legal entities and established four R&D bases located in Chongqing, Qingdao, Nanjing, and Hefei with additional bases under construction in other major cities of China.
- FDS Consortium has over 600 excellent employees.

International Academy of Neutron Science (IANS)

- IANS as an example representative of research institutes
- Three branches in Qingdao, Chongqing and Hefei.

Qingdao Branch
International Academy of Neutron Science (Qingdao)

- Institute of Nuclear Materials and Equipment
- Institute of Neutron Radiography
- Institute of Advanced Nuclear Energy Technology
- Neutron Medical Center, Qilu Hospital of Shandong University
- Institute of Nuclear Science and Technology, Shandong University
- Shandong Key Laboratory of Neutron Science and Technology
- Qingdao Key Laboratory of Neutron Detection

Chongqing Branch
International Academy of Neutron Science (Chongqing)

- Institute of Neutron Physics
- Institute of Nuclear Pharmaceutical
- Institute of Nuclear Battery
- Institute of Neutron Medicine
- Institute of Advanced Nuclear Energy Engineering

Hefei Branch
International Academy of Neutron Science (Hefei)

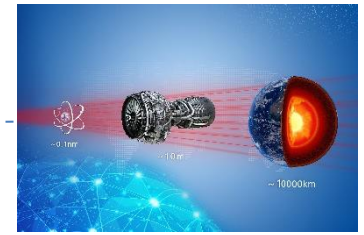
- Institute of Nuclear Energy Safety Technology
- Institute of Neutron Logging
- Institute of Radiation Medical Physics

Main Research Fields

Fundamental & Applied Research

Key Technologies & Products

Neutron Science and Technology

- **Nuclear Informatics and Software Applications**
  - 
  - **Advanced Nuclear Software**
- **Neutron Detection and Applications**
  - 
  - **Neutron Detection Equipment**
- **Advanced Nuclear Energy and Safety**
  - 
  - **China Lead-based Reactors (CLEAR)**
- **Radiation Medicine and Applications**
  - 
  - **Accurate Radiotherapy Systems (KylinRay)**

Outline

1. Background
2. Challenges in Fusion Nuclear Technology and Safety
3. R&D Progress at FDS
4. Summary

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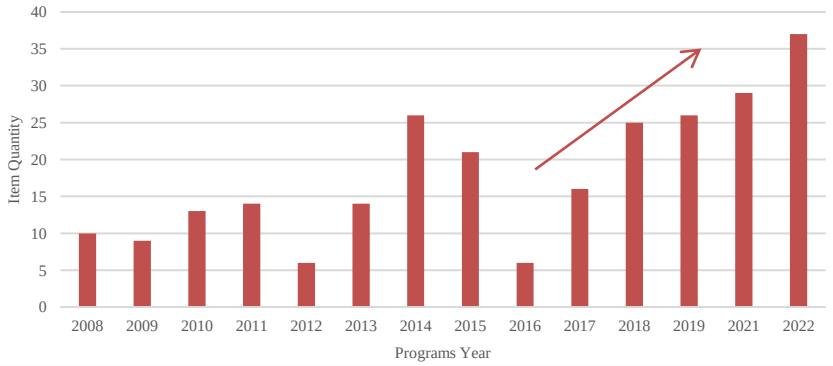
1 Background

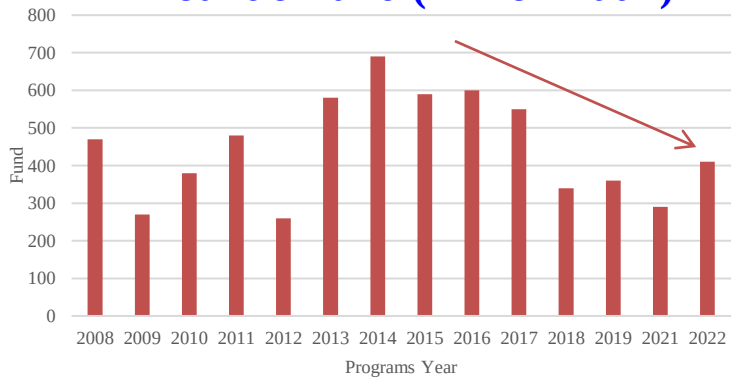
National R&D Projects for MCF in China

- Since the launch of MCF domestic projects in 2008，252 projects were executed with fund of about 6.3 billion CNY.
- Although the number of projects was increasing, but annual funding was decreasing. New fusion approaches are being supported by government.

Number of Project



Amount of fund (million Yuan)



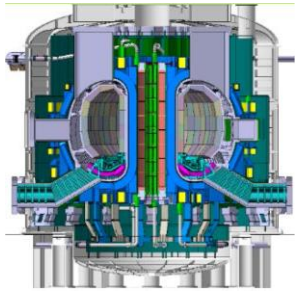
1. Delong Luo, IEA FPCC Annual Meeting, 2021.3
2. Ministry of Science and Technology, 2022

Zhigang WANG, Minister of Science and Technology of China:

It still need to be re-evaluated that which approach should be adopted for nuclear fusion in China among those various fusion approaches such as magnetic confinement, hybrid reactor, and hydrogen boron fusion. The development roadmap should be retrodicted, based on the goal of commercialization of fusion energy.

(《Science and Technology Daily》, June 16，2023)

More and More Fusion Energy Approaches in China

Regular Tokamak	Experimental facilities and design	Institutions or Companies
	**EAST, HL-2A, HL-3, BEST, CFETR, FDS Series FPP……**	**ASIPP, SWIP……**

Alternative concepts

- Gas dynamic trap
- Spherical tokamak
- Field reversed configuration
- Z-pinch
- Stellarator
- Dipole field magnetic confinement device
- ……

- FDS-GDT
- ELX-50, SUNIST-I/II, NCST
- HFRC, KMAX-FRC
- Z-FFR
- CFQS、CN-H1
- CAT-1
- ……

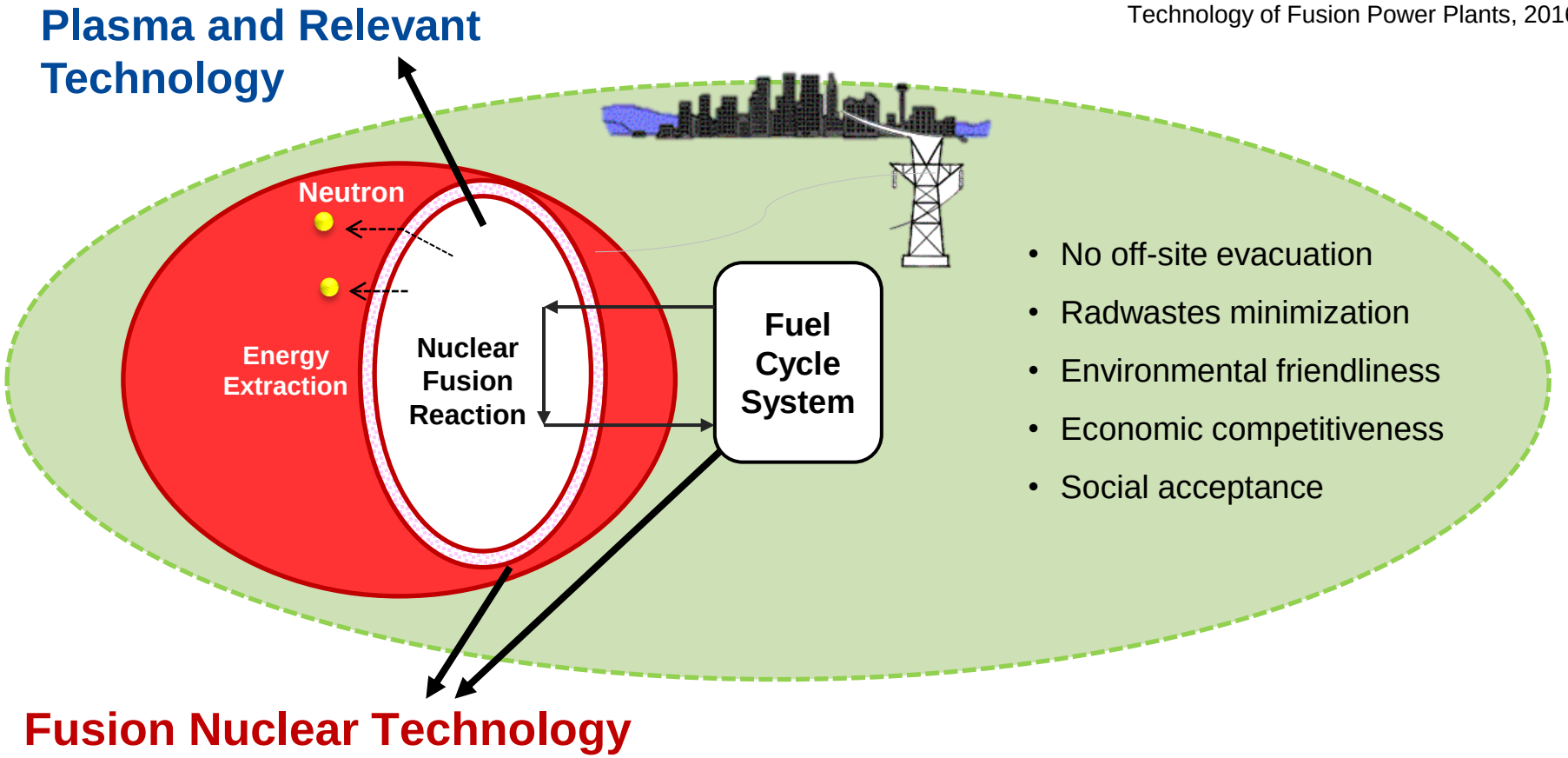
- FDS Consortium, HHMAX-ENERGY
- ENN, THU, NCU
- HUST, USTC
- CAEP, Andong Fusion
- SJU,USC
- ECUT
- ……

More and more investment are focused on lower cost compact fusion energy systems

2 Challenges in Fusion Nuclear Technology and Safety

The Gap Between Plasma and Fusion Energy

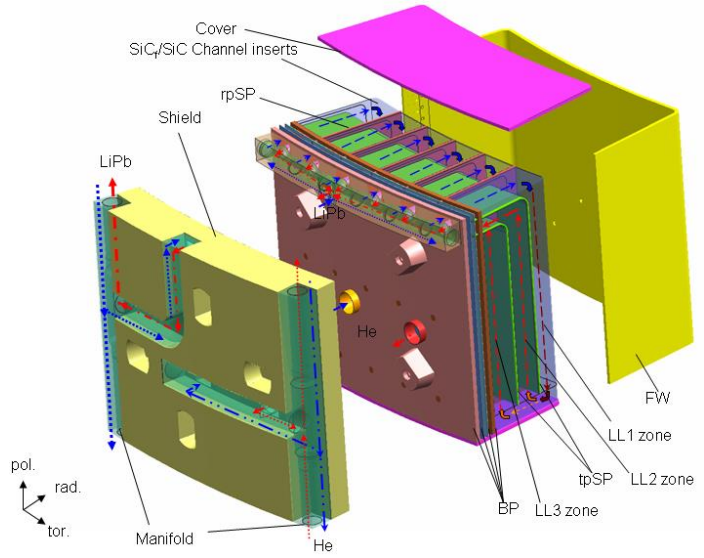
[1] Mohamed Abdou, Role and Challenges of Fusion Nuclear Science and Technology (FNST) toward DEMO.PBNC 2016.
[2] Susana Reyes, et al. 1st IAEA TM on the Safety, Design, and Technology of Fusion Power Plants, 2016.



Commercialization of fusion energy will be determined largely by "Fusion Nuclear Technology"

Breeding Blanket: Integrated Testing is Urgent

- **Breeding blanket is the key nuclear component for power extraction and energy convert, tritium fuel sustainability, radiation shielding…**
- **Great Challenges for breeding blanket:**
  - **Complex structure, difficult to manufacture**: intermixed structure of breeder, coolant, shielding, RAFM…
  - **Multiple-field environment, difficult for material selection**: high neutron irradiation damage, heat/particle fluxes, magnetic field, etc.
  - **Sharp gradients of multiple- field, difficult for safety assessment:** sharp gradients of nuclear heat, radiation, temperature….
  - **Complex configuration inside vacuum vessel, low fault tolerance and long repair/replacement time**



- **No breeding blanket has ever been built or tested under integrated conditions, Large uncertainties and concerns for the manufacture, performance, feasibility, availability….**

Recognized as one of the principal remaining challenges and the most urgent gaps for fusion energy

[1] Mohamed Abdou, et al. Fusion Eng. Design, 100 (2015) 2-43.
[2] G. Federici, IEEE Symposium on Fusion Engineering, Oxford (UK), 9-13 July, 2023

Main Gaps in Ensuring the Safety of Fusion Reactors

Safety Characteristics of Fusion Reactor

- Large mobilizable and widely distributed radioactive inventories
- Strong-permeability of tritium
- High energetic neutron flux
- Large complex systems
- Multiple field environment with high magnitude and steep gradients
- Large volume of activation materials
- High dose rate and decay heat of in-vessel components
- ……

Main gaps in ensuring the safety of fusion reactors

1 **Limit Radiation Exposure to the Workers**

(ORE As lower as possible)

2 **Prevent Releases of Radioactive Materials**

(no off-site evacuation)

3 **Radioactive Waste Management**

(minimize the radwaste)

4 **Safety Regulation**

(socially acceptable)

Fusion Nuclear Technologies

- **Study of fusion power plants Design** (neutronics, safety assessment, Environment & Socio-economics, etc.)
- **Testing of nuclear components**
- R&D for **fusion materials**
- R&D for **nuclear heat convert and electricity generation**
- R&D for **Fuel Cycle & Tritium Technology**
- R&D for **radioactive material confinement and waste management**

Fusion Nuclear Technology Addresses the Challenges Related to Fusion Safety

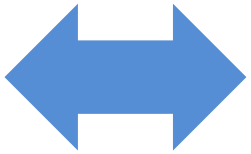
[1] Y. Wu, Identification of safety gaps fro fusion demonstration reactors, Nature Energy, 16154(2016)
[2] U.S. DOE Office of Science, https://www.energy.gov/science/doe-explainsfusion-nuclear-science-and-technology, 20 August, 2023

3 R&D Progress at FDS

Orientation of Fusion Studies at FDS

Innovative Concepts and Approaches

- FDS-MFX
- FDS-I/-SFB
- C-DEMO
- FDS-II
- FDS-III
- FDS-ST
- FDS-GDT
- ...



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
Search for optimized approaches for fusion energy realization

Fusion and Hybrid Conceptual Design

1. Fusion TEST Reactor

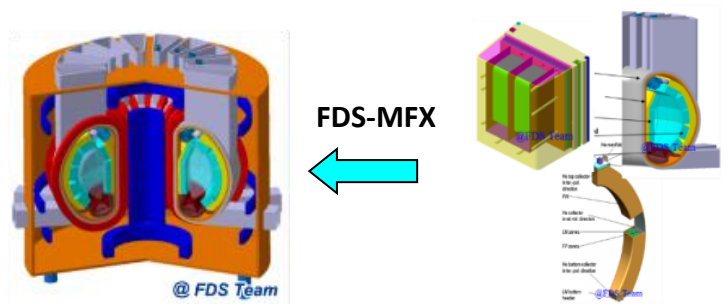
- **FDS-MFX:** Multi-Functional eXperimental Reactor abbreviated as MFX

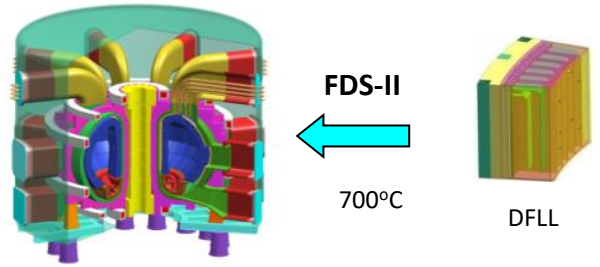
2. Fusion DEMO Reactor

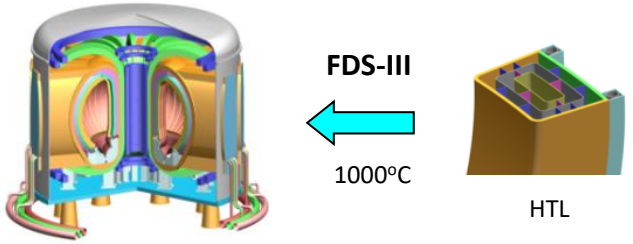
- **C-DEMO:** Chinese DEMO Reactor (energy production, fuel breeding, multiplication)
- **FDS-I/-SFB:** Fusion Reactor for Spent Fuel Burner (early application)
- **FDS-GDT: Gas-dynamic Trap Driven Subcritical Traveling Wave Reactor**

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. Neutronics of Advanced Nuclear Systems, Springer, 2019.

High Intensity Steady Neutron Sources HINEG

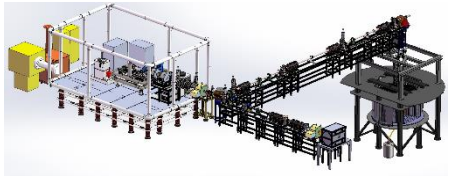
HINEG-I

Completed

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

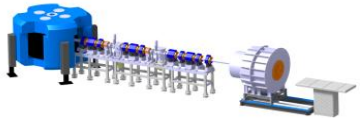
HINEG-II (2021-2024)

Under Construction



High Intensity D-T Neutron Generator
HINEG-IIa in Chongqing
($\geq 10^{13}$ n/s)

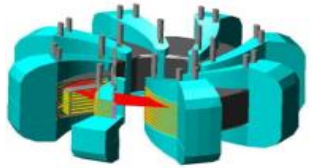
Under Construction



Cyclotron-based Regulatable Spectrum Steady Neutron Source
HINEG-IIb in Qingdao
($\geq 10^{14}$ n/s)

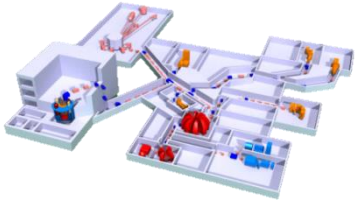
HINEG-III/GDT (2025-2035)

In Design



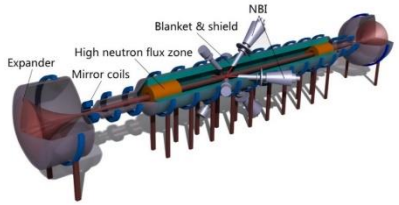
High Intensity Cyclotron-based Regulatable Spectrum Steady Neutron Source **HINEG-IIIa**
($\geq 10^{15}$ n/s)

In Design



High Flux Regulatable Wide Spectrum Steady Neutron Source **HINEG-IIIb**
($\geq 10^{15}$ n/(cm^2·s))

In Design



GDT-based Volumetric Fusion Neutron Source **HINEG-GDT**
($\geq 10^{18}$ n/s)

Extended Nuclear Technology Applications
(Radiography, Radiotherapy, Isotope Production...)

Fundamental Research of Technology → **Key Technology Validation and Demonstration** → **Frontier Technology Development and Extended Applications**

Advanced Nuclear Energy Systems
(Fusion, Fission, Hybrid...)

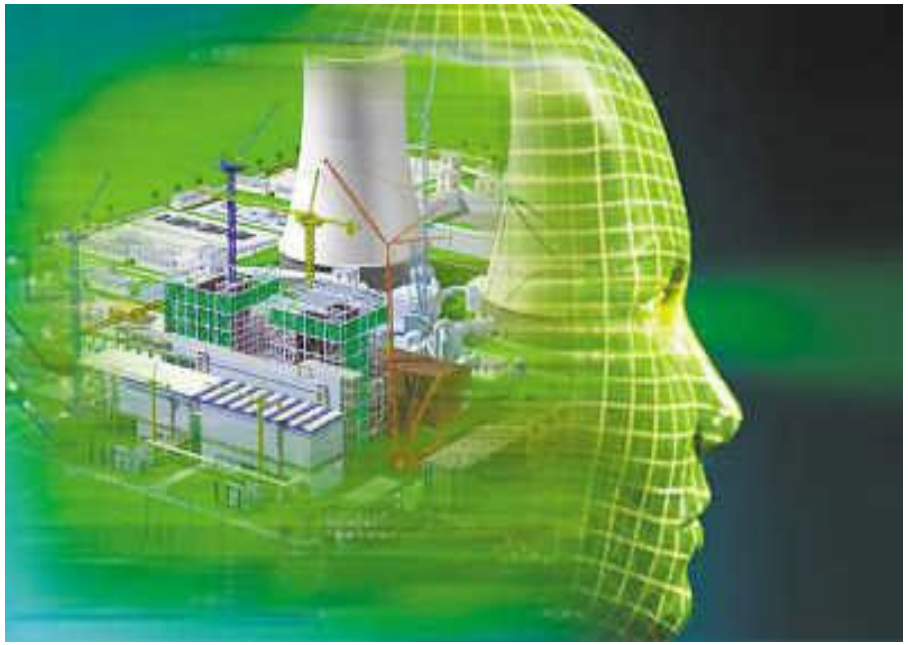
Neutronics & Shielding Design Validation → **Core Physics & Advanced Reactor Technology Validation** → **Material & Component Engineering Validation**

Advanced Nuclear Software

Advanced Nuclear Software, which includes the codes for the intelligent nuclear design, automation and safety assessment with self-dependent intellectual property rights, has been invested with more than 1000 year•man.

I. Physics & Engineering Calculation

- TopMC/SuperMC — Multi-functional Calculation Program for Nuclear Design and Safety Evaluation
- NTC — Neutronics-Thermohydraulics Coupled Simulation Program
- MTC — Magnetic-Thermohydraulics Coupled Simulation Program
- TAS — Tritium Analysis Program for Fusion System
- HENDL — Hybrid Evaluated Nuclear Data Library
- FusionDB — Fusion Database Management System



II. Interactive Design and Optimization

- RiskA
- RiskAngel/TQRM — Reliability and Probabilistic Safety Assessment Program
- RiskBase — Risk Monitor for Nuclear Power Plant
- SYSCODE — Database Management System for Reliability Analysis
- KylinRay — Fusion System Design and Economical Assessment Program

III. Multi-process Integrated Comprehensive Simulation

- Virtual4DS — Virtual Nuclear Power Plant in Digital Society Environment
- VisualBUS — Digital Nuclear Reactor
- CLEAR-V — Virtual Lead-based Nuclear Reactor
- Fusion-V — Virtual Fusion Reactor
- CROSS — Informatization Collaboration Platform for Scientific Research
- NCloud — Nuclear Cloud Platform
- NBigData — Nuclear Big Data Platform

Development of TopMC/SuperMC

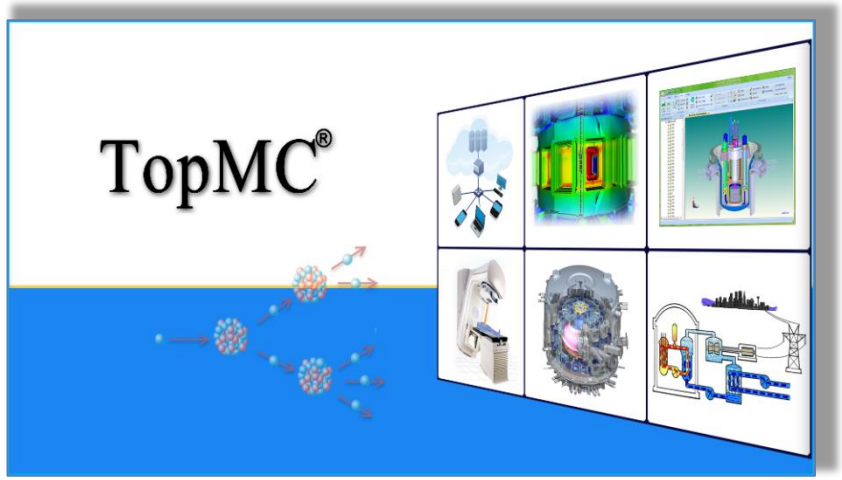
Multi-functional Calculation Program for Nuclear Design and Safety Evaluation
(TopMC: Updated and extended version of SuperMC)

- **More Powerful Functions:**

  Charged particle transport: **electron**, proton, ion, etc. (not only neutron/photon)

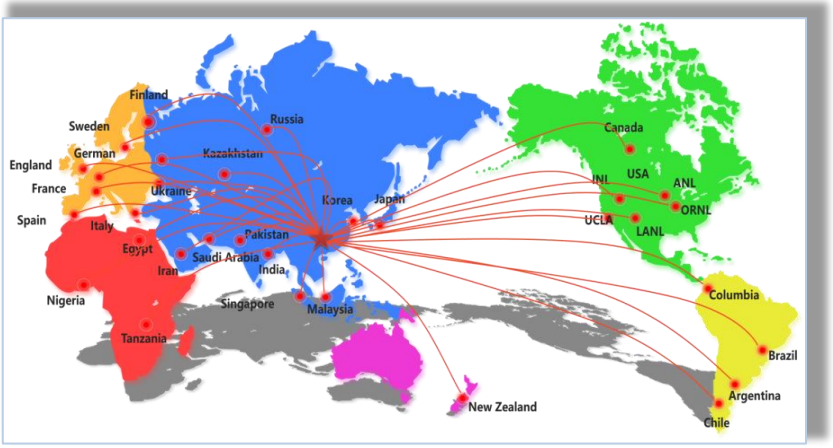
  High efficient analysis: **pulse height tally coupled with variance reduction technology**, intelligent nuclear design, etc.

- **More Application Fields: Extended to nuclear technology application** design/application of nuclear detection and accelerator...
- **More Professional Services: Standardized and professional services** presales technical support, systematic training, aftermarket service



- **Widely applied hundreds of renowned institutions in 90+ countries**
- **Selected as the reference code by ITER**
- **Passed the Generic Design Assessment with UK HPR1000**
- **Available from OECD/NEA and RIST/NCC**

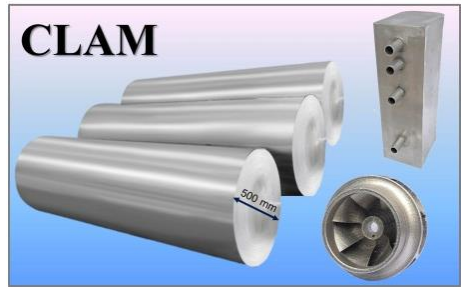
http://www.oecd-nea.org/tools/abstract/detail/iaea1437
http://www.tokai.rist.or.jp/nucis/codetable.html



Materials & Blanket Technologies

I. CLAM: China Low Activation Martensitic steel

- 3×6-ton Ingots & Components
- Breakthrough in 3D printing of blanket first wall
- Fabrication of 1/3 scaled DFLL-TBM by welding technologies
- 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%

III. Lead-lithium/Lithium Experimental Loops

- China multi-functional liquid PbLi Experimental Loop (DRAGON-V) was built in Hefei in 2020 to support the engineering design validation of liquid metal blanket.
- New large scale integrated experimental facility for liquid lithium metal was built in Qingdao in 2021, the temperature of liquid lithium metal is up to 1250 ºC

Lead-lithium Loop: 550ºC, 2 T, 40 kg/s

Supported by National Key Technology R&D Project and local government in China

Large Scale Lithium Experimental Loop in Qingdao

- **Lithium Loop: ≥1250°C, ≥5m/s, ≥100kWth**
- **≥ 500 hours operation for service performance tests of materials and key components in Lithium loop**

- Evaluation of liquid lithium interaction with V-alloy etc.
- Thermal hydraulic research and accidents test
- Key technologies of coolant investigation
- Components and blanket module integrated validation
- Research on liquid lithium-based walls for fusion system
- Feasibility verification of key components
- Power generation demonstration
- Corrosion resistance evaluation of material

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.

4. Fusion System Analysis and Economical Assessment Program(SYSCODE) was developed. SYSCODE was selected as the highlight of 2015 by IEA.

Y. Wu, et al. Nature Energy, 2016, 1:16154.

Y. Wu, et al. PNAS, 116(36)(2019)

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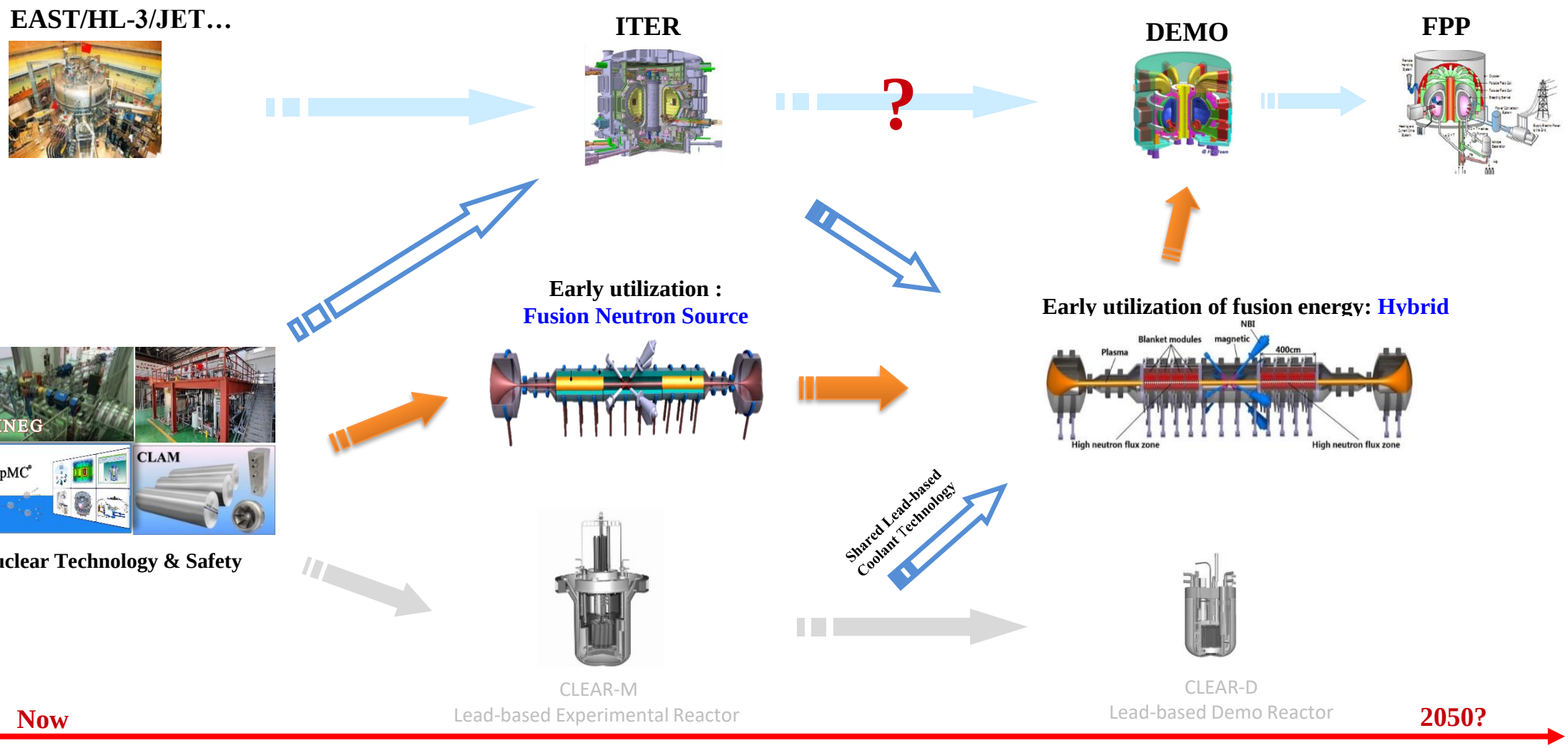
4 Summary

Proposed Roadmap for Fusion & Fission & Hybrid

- **Big gaps between ITER and Fusion DEMO, making it great challenge to realize fusion energy before the year 2050**
- **A roadmap with R&D in nuclear technology and safety is proposed to fill the gap and realize the early utilization of fusion energy**



Summary

- There are still important gaps and challenges in fusion nuclear technology and safety from plasma technology to fusion energy commercialization. The traditional mode of national research projects should be optimized to introduce the commercialization mode.
- The government and commercial companies in China have paid more and more attention to diverse fusion approaches, especially great funds from commercial companies have been invested to new approaches. The joining of commercial companies should bring great benefits and greatly accelerate the early utilization of fusion energy.
- FDS is continuously working on the innovative concepts and approaches, and various shared common technologies including neutronics & nuclear technology, materials & blanket technology, safety, environment & socio-economics.

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Better Technology, Better Life!

Thanks for Your Attention!

Website: www.fds.org.cn
E-mail: contact@fds.org.cn