FDS 凤麟核

Overview and Prospects for Fusion Fission Hybrid System Development in China

Minghuang WANG, Yunqing BAI, Qi YANG, et al.

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

Technical Meeting on Synergies in Technology Development between Nuclear Fission and Fusion for Energy Production
Virtual Meeting, 2022.6.10

International Academy of Neutron Science (IANS)

Headquarter located in Qingdao

President: Academician Prof. Yican WU

Executive Director: Prof. Fang WANG

Personnel in Qingdao: ~300 researchers

10 Institutes of IANS:

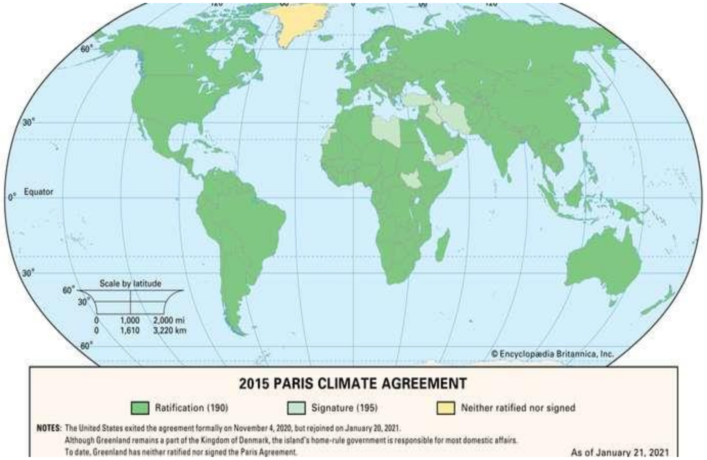
- Institute of Neutron Source
- Institute of Neutron Transportation and Reactor Physics
- Institute of Radiation Shielding and Protection
- Institute of Nuclear Materials
- Institute of Nuclear Measurement and Control
- Institute of Reactor Thermal-Hydraulics
- Institute of Nuclear Design and Simulation
- Institute of Nuclear Energy Safety Technology (INEST)
- Institute of SuperAccuracy Advanced Technology (ISAT)
- Institute of Nuclear Informatics

Contents

1 Why to Develop Hybrid Reactor?

Climate Warming is a Common Challenge Facing Mankind

The Paris Agreement: Aims to substantially reduce global greenhouse gas emissions and **to limit the global temperature increase in this century to 2℃** while pursuing means to limit the increase even further to 1.5 ℃.



China strives to achieve carbon peak by 2030 and achieve carbon neutrality by 2060.

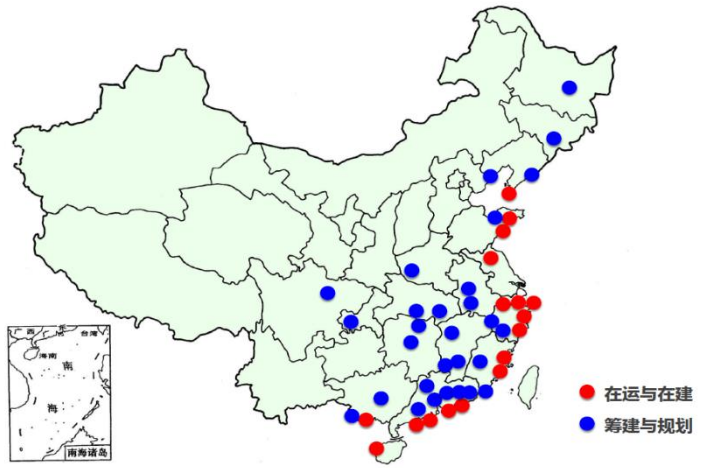
---President Xi Jinping, Sept.22, 2020, United Nations Assembly

The CPC Central Committee and the State Council, Oct.24, 2021:
"Build a green, low-carbon and circular economic development system,……, to ensure that carbon peak and carbon neutralization can be achieved on schedule"

Current Status of Nuclear Power in China

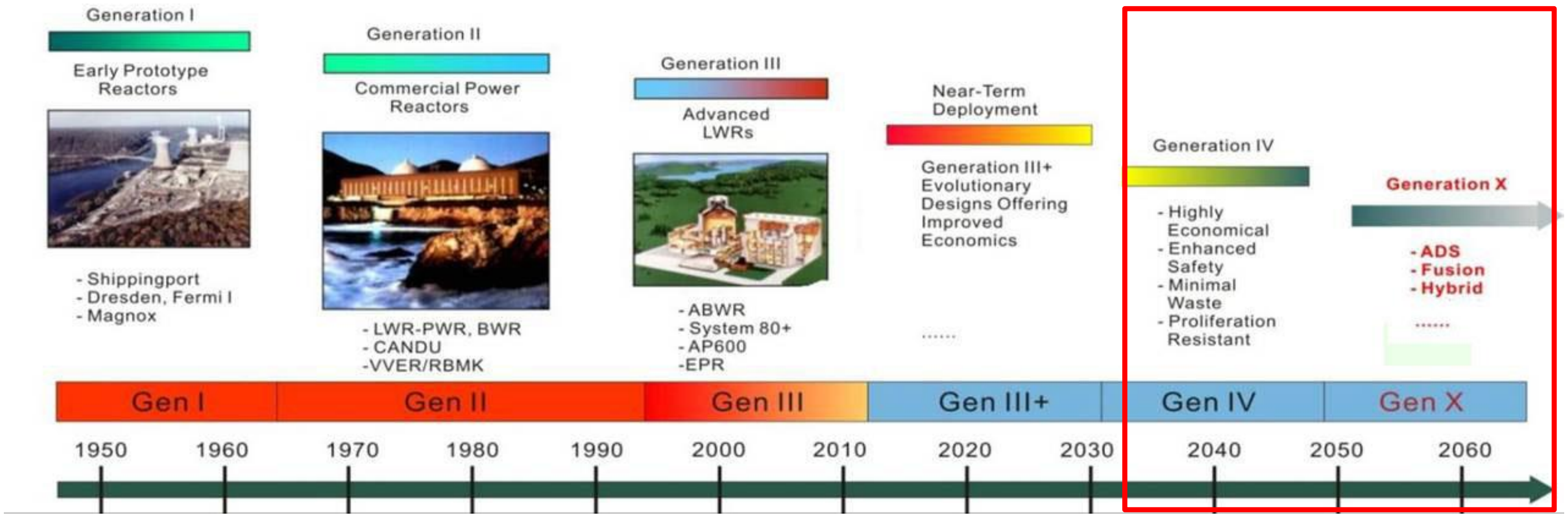
Nuclear Power in Mainland China as of Oct. 2021:

- **51 units in operation**
- **18 units under construction**
- **37 units planned**
- **168 units proposed**
- **including Generation III+ reactors AP1000, EPR, etc**
- **Nucl.power accounts for ~4.9% of tot.electricity production**



The CPC Central Committee and the State Council, Oct.24, 2021:
"Actively, safely and orderly develop nuclear power"

Key Issues of Nuclear Energy Development



Advanced and innovative nuclear energy system should be a viable way to solve problems below.

Nuclear Safety: TMI, Chernobyl, Fukushima

Disposal of Nuclear Waste: long term radioactive toxicity

Limitation of Fuel Resources: decades of available uranium

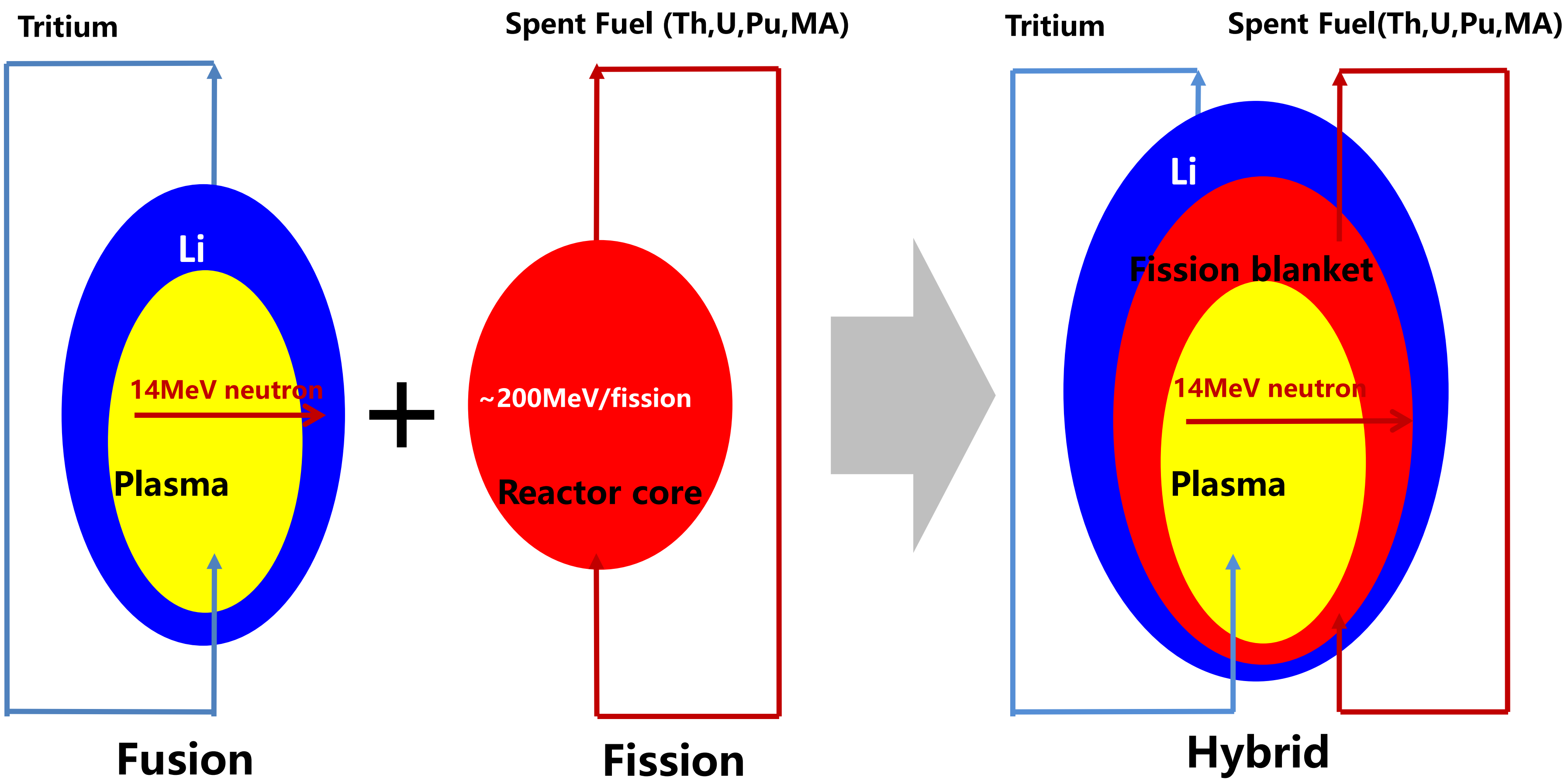
Economic Competitiveness: renewable energy development

→ 1. Safe?

→ 2. Sustainable?

→ 3. Economical?

Principles and Features of Hybrid Reactor

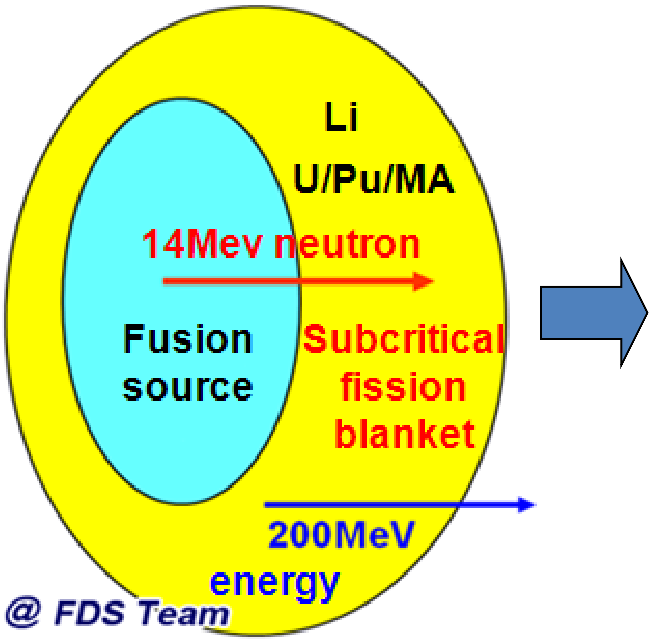


Rich neutrons but poor energy

Rich energy But poor neutrons

Combination of Fusion and Fission

Functions of Hybrid Reactor



Produce energy

n + U/Pu/MA ➔ Energy

Breed nuclear fuel

n + U^{238}/Th^{232} ➔ Fissile material

Transmute nuclear waste

n + MA/FP ➔ Less-harmful nucleus

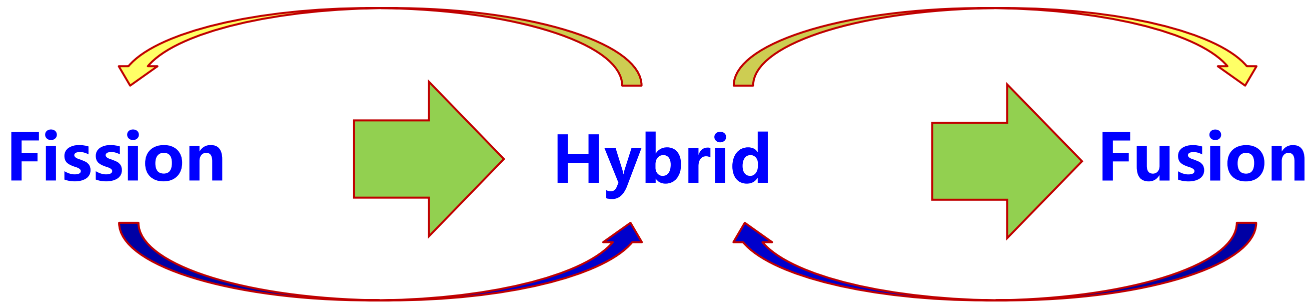
Breed tritium

n + Li^{6}/Li^{7} ➔ Tritium

Hybrid can as a Bridge between Fission and Fusion

To improve safety and sustainability for fission energy

To facilitate the early realization of fusion energy



Based on viable technologies from fission & fusion

- Fuels
- Materials
- Coolants
- ……

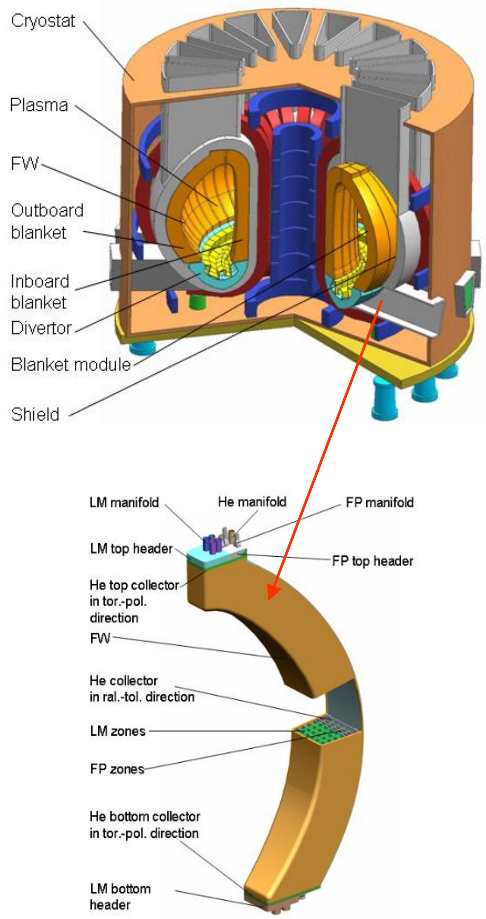
- Easy achieved plasma parameters
- Lower requirements of materials
- Improved tritium breeding ratio
- ……

2 Design and R&D Activities

- Typical Concepts
- R&D Activities

FDS-SFB Configuration

— D-T Fusion Power (P_f)	150 MW
— D-T energy	14.06 MeV
— Neutron Wall Loading	0.5 MW/m^2
— Neutron Source Intensity	5.334×10^{19} n/sec
— Major Radius (R)	4 m
— Minor Radius (a)	1 m
— Elongation (κ)	1.7



Main Functions

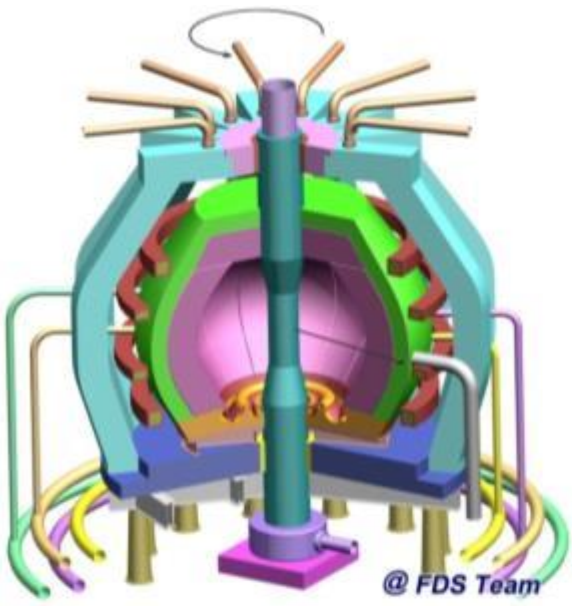
— Transmute long-lived nuclear wastes from fission power plants
— Breed fissile fuel for fission power plants
— Generate energy
— Self-sustain tritium for fusion core

Burn the spent fuel directly without reprocessing to producing power, make the waste to wealth

Y. Wu, Fusion Eng. Design 81(2006)1305-1311.

FDS-ST: Spherical Tokamak-Based System

– **Goal :**
  - Exploit and assess innovative approach of fusion energy
– **Plasma Core:**
  - Fusion power: 100~200 MW
  - Power Gain ~5
  - Neutron wall loading 0.5~1 MW/m2
– **Blanket:**
  - Sub-critical outboard, high energy multiplication to compensate the large fraction of re-circulating power
– **CCP :**
  - Innovative liquid metal CCP concepts to prolong lifetime, to increase tritium breeding



Blanket: optional (DWT);
CCP: innovative concepts of Center Conductor Posts

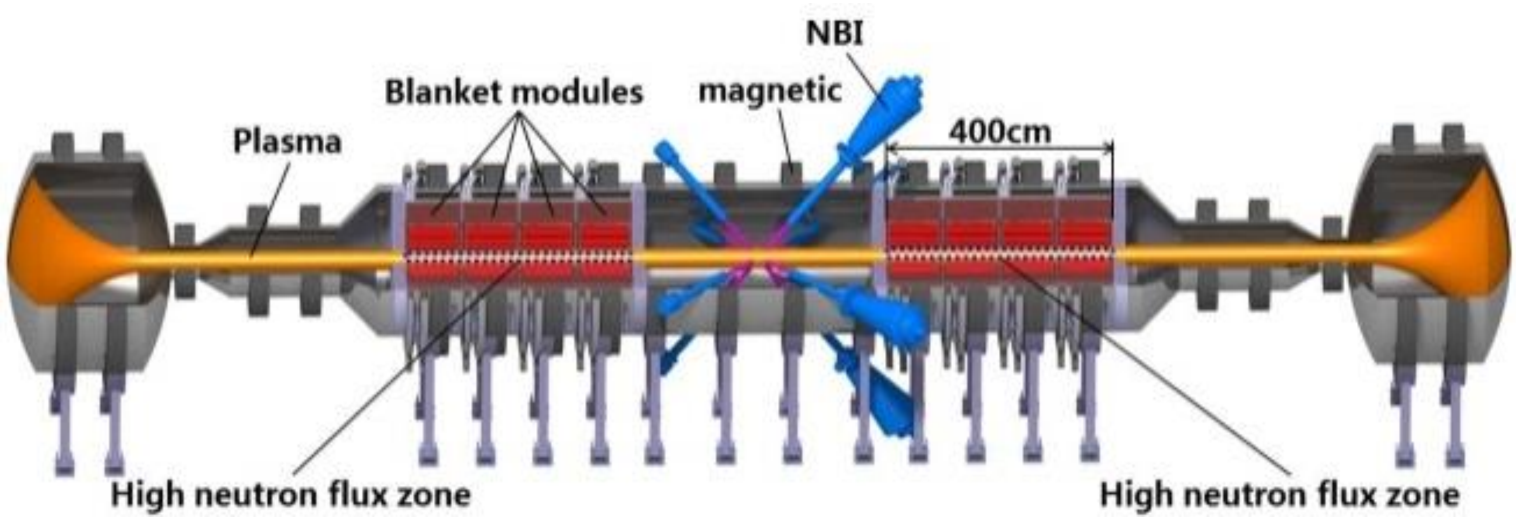
Y. Wu, el al., Fusion Eng. Design 51(2000)395-399.

FDS-GDT: Gas Dynamic Trap Driven Hybrid System

Goals of FDS-GDT:

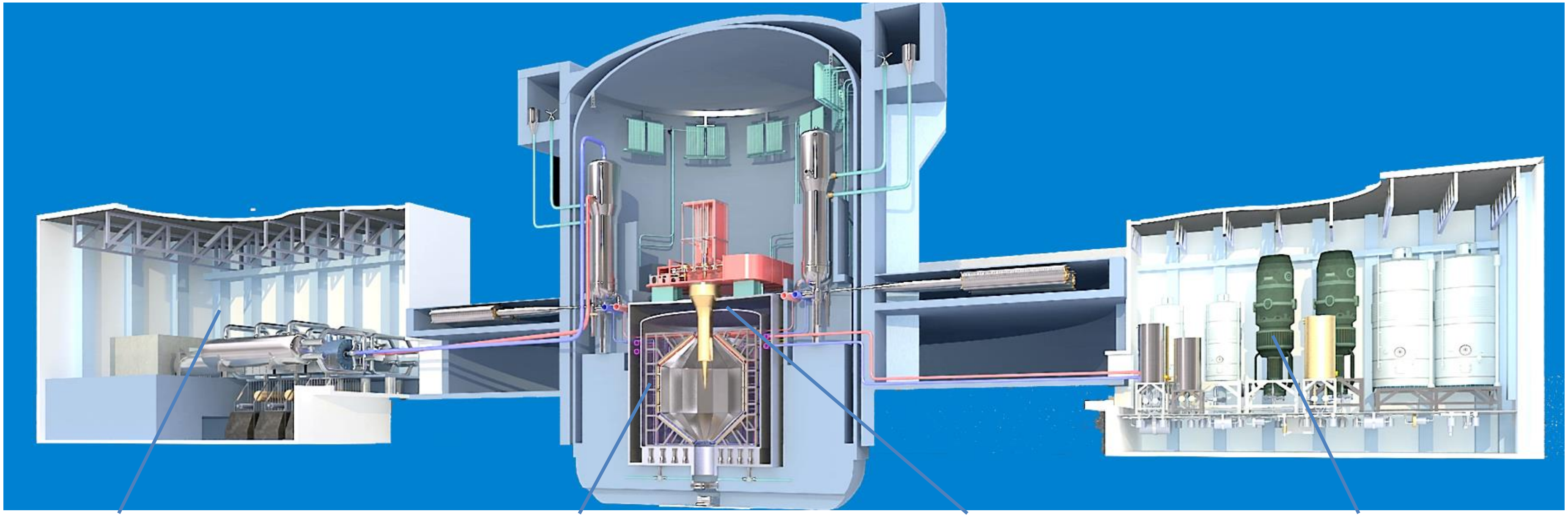
- **Adopt simple structure, compact and economical driven system;**
- **Use gas dynamic trap to drive a subcritical traveling wave blanket, which can realize the minimum generation of nuclear waste and the maximum fuel utilization efficiency, etc.**

Parameters	Values
Fusion power	~15MW
System Power	~500 MWt
K_{eff}	0.95~0.97
Fuel	UZr
Coolant	PbLi



Q. Zeng, el al., Nuclear Fusion, 56(2017).

Z-FFR: Z-pinch Driven Hybrid System



Fusion power： ~150MW, 0.1Hz, ~10mg DT ice fuels per capsule, burn-up rate of more than 40%

Sub-critical blanket: Energy magnification of ~11, U-10Zr natural uranium fuels of ~830t, refueling with 5t depleted uranium every 5 years, 15.5MPa H_2O coolant and moderator as in LWRs

Fuel cycle: deep-burn , Non-chemical-reprocessing, removing fission gases at 1700K/2600K

Tritium self-sufficiency: TBR~1.17 at the very start, 10% increasing after 3 years without refueling or any reprocessing, capability of available TBR high up to ~1.5 (Structure and coverage effect considered)

X. Peng, el al., High Power Laser and Particle Beams, 26(2014)1-6.

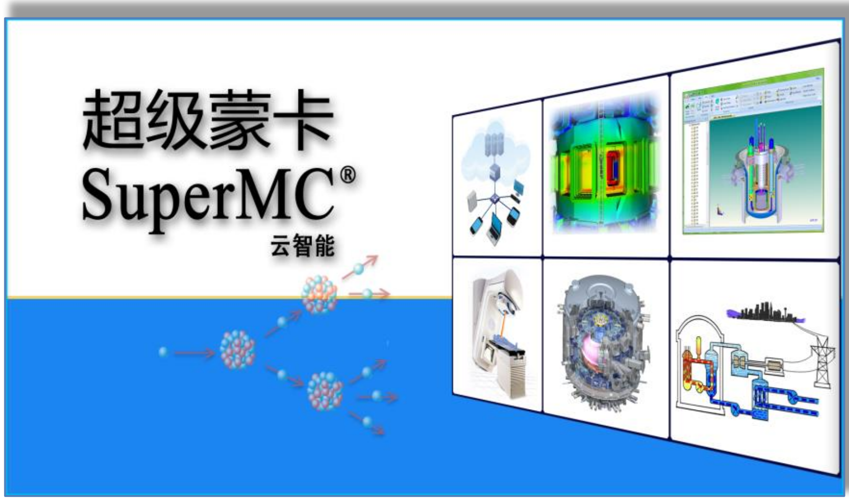
- Typical Concepts
- **R&D Activities**

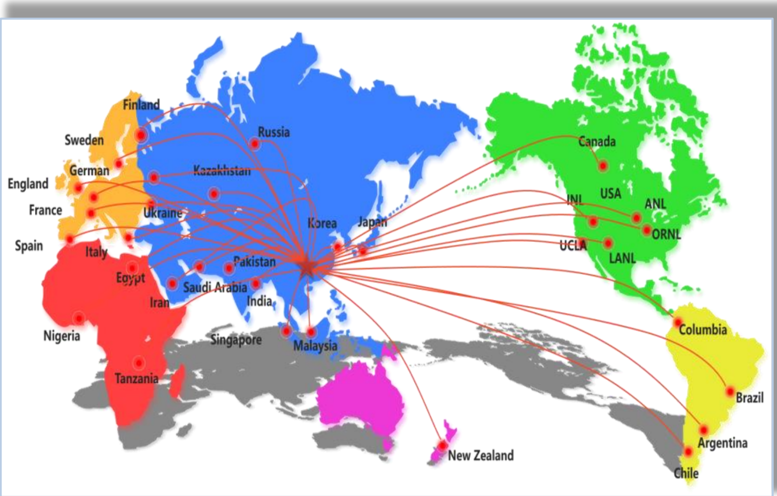
Development of SuperMC

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**





Roadmap of High Intensity Neutron Sources by FDS

Mini ← → High Intensity

HINEG-M	HINEG-I	HINEG-II	HINEG-III
10^{8-11} n/s	10^{12-13} n/s	10^{13-15} n/s	10^{17-18} n/s

HINEG-M

(a) Mini neutron generator (ø25/43mm, 10^{8} n/s)

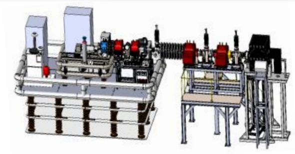
(b) Compact neutron generator ($10^{9\sim11}$ n/s)

HINEG-I

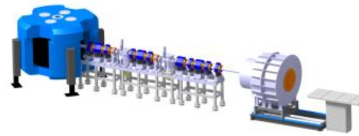
(a) D-T neutron Generator

(b) China Lead-based Zero-Power Reactor CLEAR-0

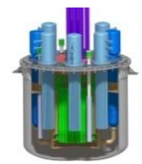
HINEG-II



(a) Ultra-high D-T neutron source

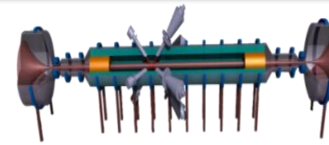


(b) Cyclotron neutron source (30MeV, ~1mA)

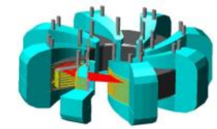


(c) China Lead-based Experimental Reactor CLEAR-A10 (~10MWt)

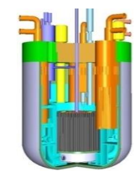
HINEG-III



(a) GDT-based V-FNS



(b) High Flux SNS (900MeV, 1~10mA)



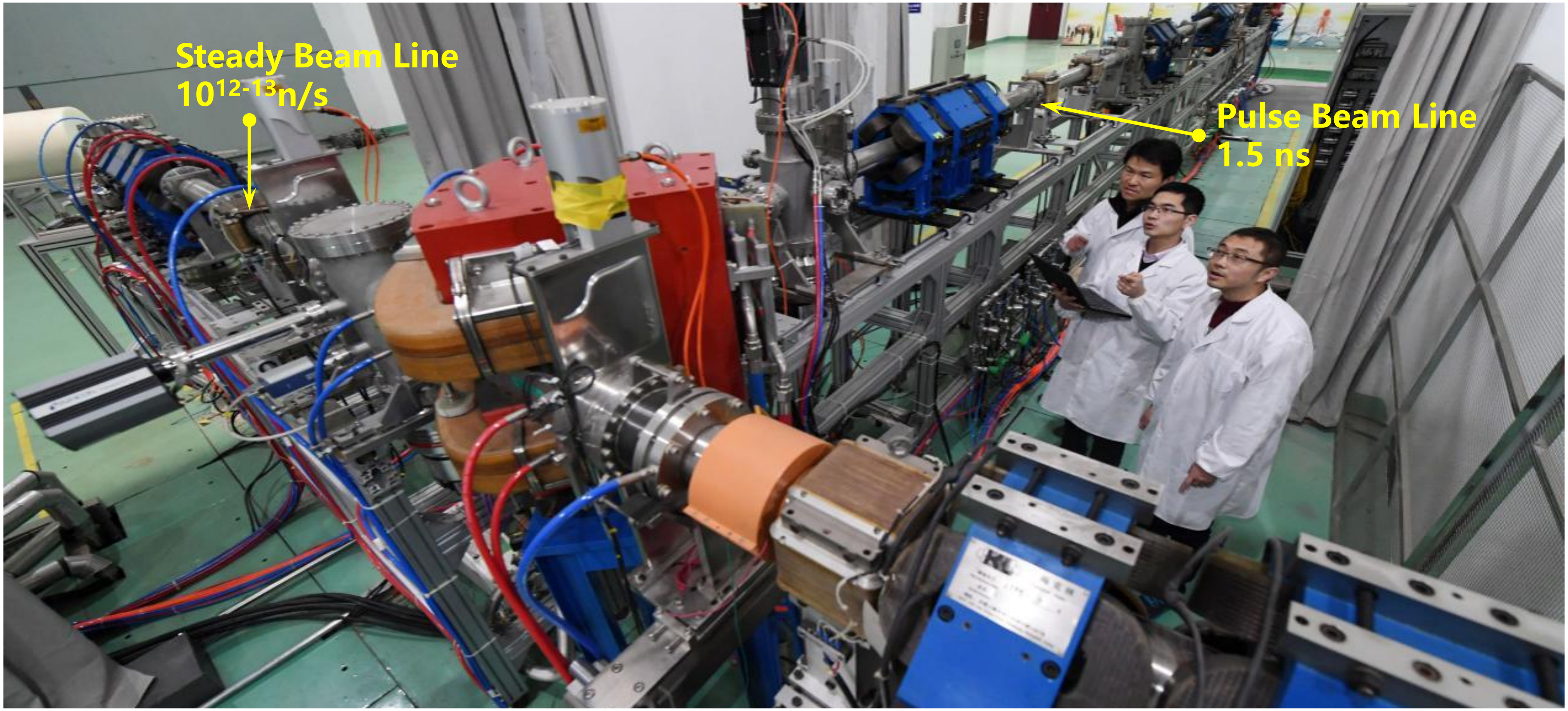
(c) China Lead-based Demo Reactor CLEAR-A100 (~100MWt)

	HINEG-I	HINEG-II	HINEG-III
Fusion	**Neutronics Design Validation**	**Material Irradiation Test**	**Components Performances Test**
Fission (LFR / Subcritical System...)	**Core Physics& Shielding Design Validation**	**Lead-based Mini-Reactor(~10 MWt)**	**Nuclear Fuel Breeding and Transmutation**

Extended Nuclear Technology Applications: **Neutron logging, Security Inspection, Radiography, Radiotherapy, Isotope Production, ...**

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

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



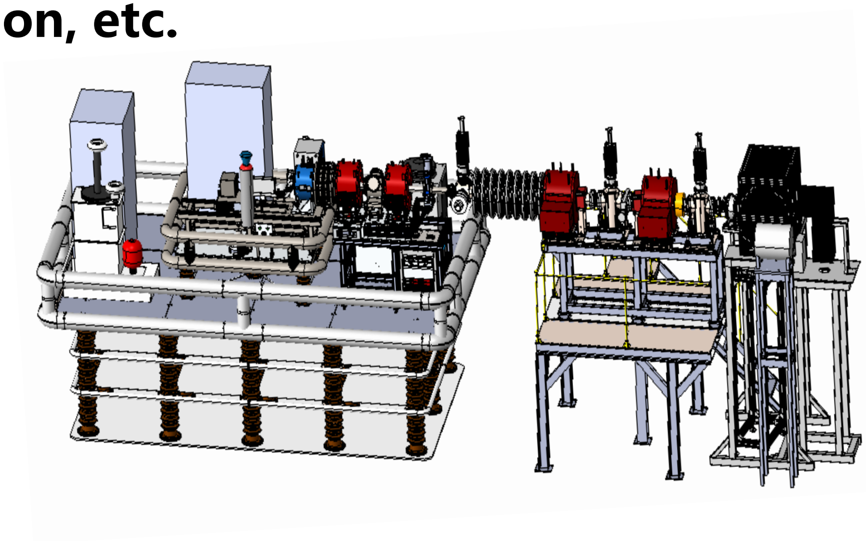
HINEG-IIa：Ultra-high Intensity D-T Neutron Source

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.**

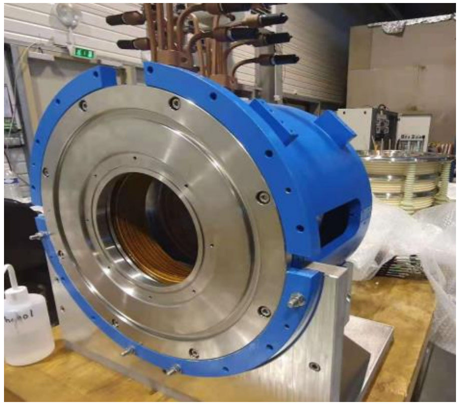
Main parameters

- **Neutron yield：10^{13}-10^{14} n/s**
- Beam Energy: 300-500 keV
- Beam Current: 50~180mA
- D-D and D-T dual operation mode



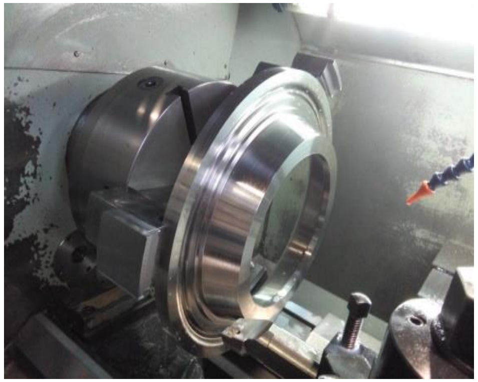
Design optimization and construction of HINEG-IIa are on going

Progress of HINEG-IIa



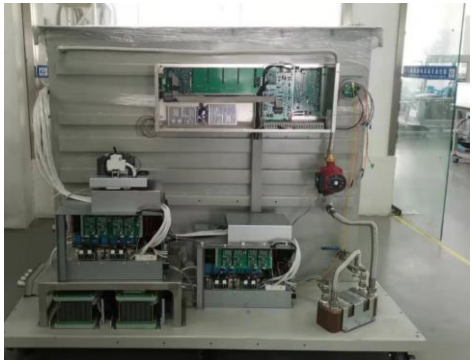
Ion Source

Extraction system



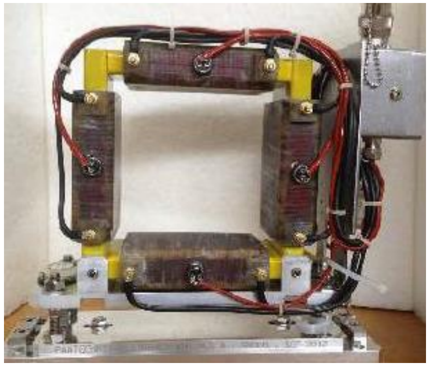
Vacuum Vessel

Insulating Transformer



HV Power Supply

Chiller



Steerer

C&C Cabinet

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

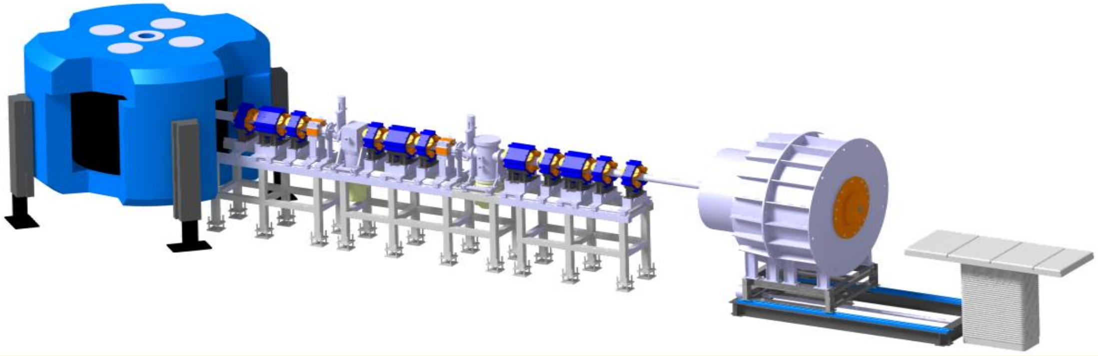
HINEG-IIb: High Intensity Steady Cyclotron-based Neutron Source

□ Application Goals

- Validation of accelerator based neutron therapy technology and isotope production technology
- Validation of accelerator and target technologies for subcritical system
- Research platform for fundamental science development and neutron irradiation application

□ Main parameters

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



Engineering construction of HINEG-IIb are on going

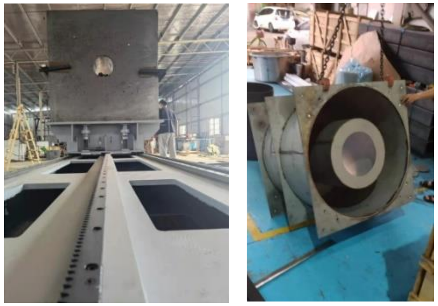
Progress of HINEG-IIb

Accelerator

RF Cavity

Support Structure
& Power Supply

Ion Source



BSM Module

Main components have been manufactured and are under assembly

Buildings for HINEG-II Facilities

The construction of shielding room and supporting laboratories have been finished

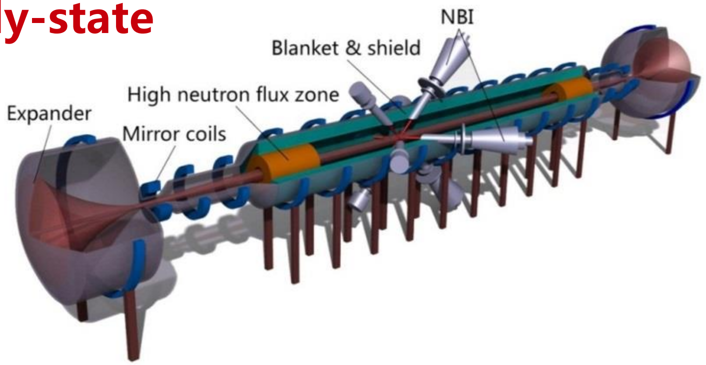
HINEG-IIIa: High Flux GDT based VFNS

◻ Application Goals

- Full lifetime irradiation test of fusion materials (≥20 dpa/FPY)
- Component test of blanket and divertor
- Reliability data of nuclear components
- Validation of radioactive waste transmutation

◻ Main Parameters

- **Neutron yield: ≥10^{18} n/s, volumetric, steady-state**
- Tritium consumption rate: <200 g/FPY
- Neutron flux and test volume:
  - ≥ 2 MW/m^2 (~35 L)
  - ≥ 1 MW/m^2 (~100 L)
  - ≥ 0.5 MW/m^2 (~1 m^3)



- **Linear, simple and compact structures**
- **Relative low demand of technologies**

Based on HINEG-IIIa, an international mega-science project proposal titled
"Axisymmetric LInear Advanced Neutron sourCE (ALIANCE) "
was jointly initiated by FDS & BINP in 2018, with more invitations on-going

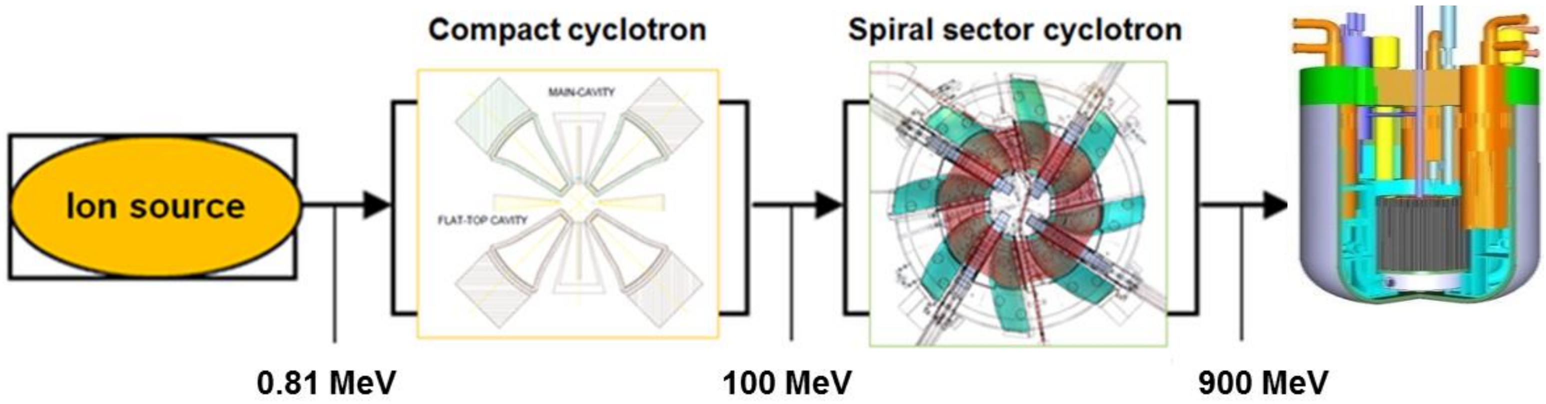
HINEG-IIIb: High Flux Spallation Neutron Source

Application Goals

- Driver of a multi-purpose subcritical nuclear system (China Lead-based Demo Reactor CLEAR-A100).
- Multi-purpose and flexible fast neutron irradiation platform

Main Parameters

- **Neutron yield: $10^{17\text{-}18}$ n/s**
- Accelerator: 900MeV/1-10mA proton beam
- Spallation Target: Pb



Conceptual design of HINEG-IIIb are 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%

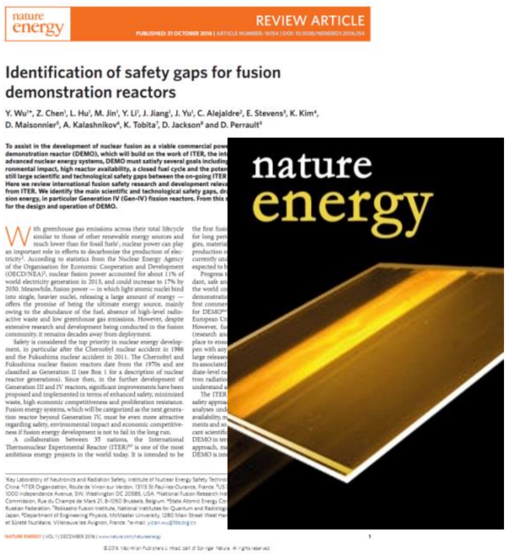
Supported by National Key Research and Development Project of China

III. China TBM Program

- Fabrication of 1/3 scaled DFLL-TBM by welding technologies
- PD phase of CN HCCB TBM Program officially started at 2016

Study of Safety, Environment and Socio-economics

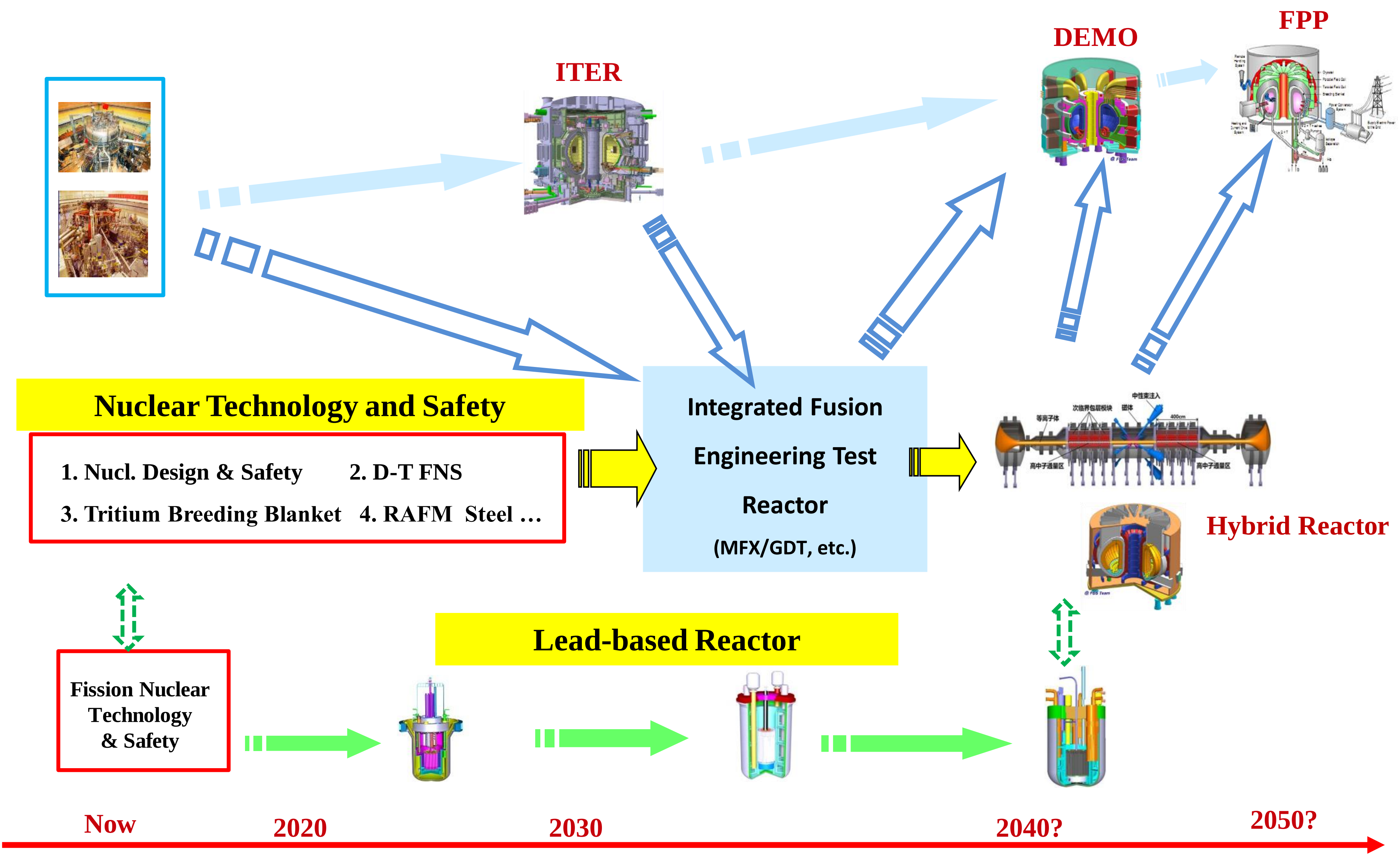
1. Identification of Safety Gaps analysis for Fusion DEMO Reactors and published in Journal of Nature Energy.
2. Organized and hosted two international workshops on ESEFP to promote research on fusion safety assessment and regulatory, such as safety approach, safety design, licensing, etc.
3. Fusion System Analysis and Economical Assessment Program(SYSCODE) was developed. SYSCODE was selected as the highlight of 2015 by IEA.



FDS 凤麟核

3 Proposed Roadmap and Summary

Proposed Roadmap for Fusion & Fission & Hybrid



Summary

- Hybrid reactor is proposed to serve as a candidate to solve the key problems of current fission energy development and to facilitate the early realization of fusion energy.
- Series of innovative fusion fission hybrid concepts have been developed in China to evaluate the feasibility and attractiveness of fusion fission hybrid system.
- Common fusion fission hybrid technologies of design software, neutron sources, materials, and safety have been developed continuously, especially the several new neutron source facilities under construction recently.

Thank you for your attention

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