Latest Fusion R&D Activities at INEST

Presented by Yican Wu
(Zhibin Chen on behalf)

Contributed by FDS Team

Institute of Nuclear Energy Safety Technology (INEST)
Chinese Academy of Sciences
www.fds.org.cn

Institute of Nuclear Energy Safety Technology
Chinese Academy of Sciences • FDS Team

Main Research Areas

Fundamental research:

- Neutron Physics

Applied research:

1. Advanced Fission Energy → LFR etc.
2. Fusion Energy → FNT & Materials etc.
3. Extended Nuclear Technology Applications

Headquarter in Hefei, Anhui, China

Three Integrated Test Reactors

❖ **Key Programs:**

- Strategic Priority Research Program of CAS
- ITER Related International and Domestic Program
- Nuclear Energy & Safety Technology Innovation Program

❖ **400 Staff + 100 Students**

A professional institute is devoted to design and R&D of advanced nuclear energy and safety technology

Outline

I. Highlights of Fusion R&D Activities

- Fusion Neutron Sources
- Neutronics Methodology and Simulation
- Fusion Safety
- Materials and TBM Technologies

II. International Communication and Collaboration

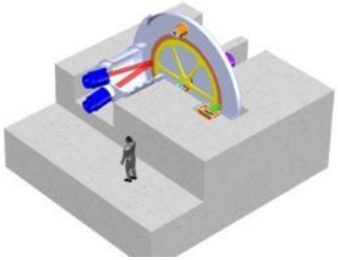
1. Fusion Neutron Sources

Development of Fusion Neutron Sources at INEST

10^{12}-10^{13} n/s

HINEG-I
(in Operation)

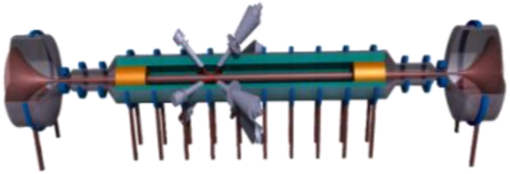
- Nuclear Data
- Methods and Software
- Radiation Protection



10^{15}-10^{16} n/s

HINEG-IIa
Mixed-beam Fusion Neutron Source

- Materials Irradiation
- Nuclear Design and Performance Test of Component
  - ✓ shielding, tritium production



≥ 10^{18} n/ s

HINEG-IIIa
Fusion Volumetric Neutron Source (e.g. GDT-FVNS)

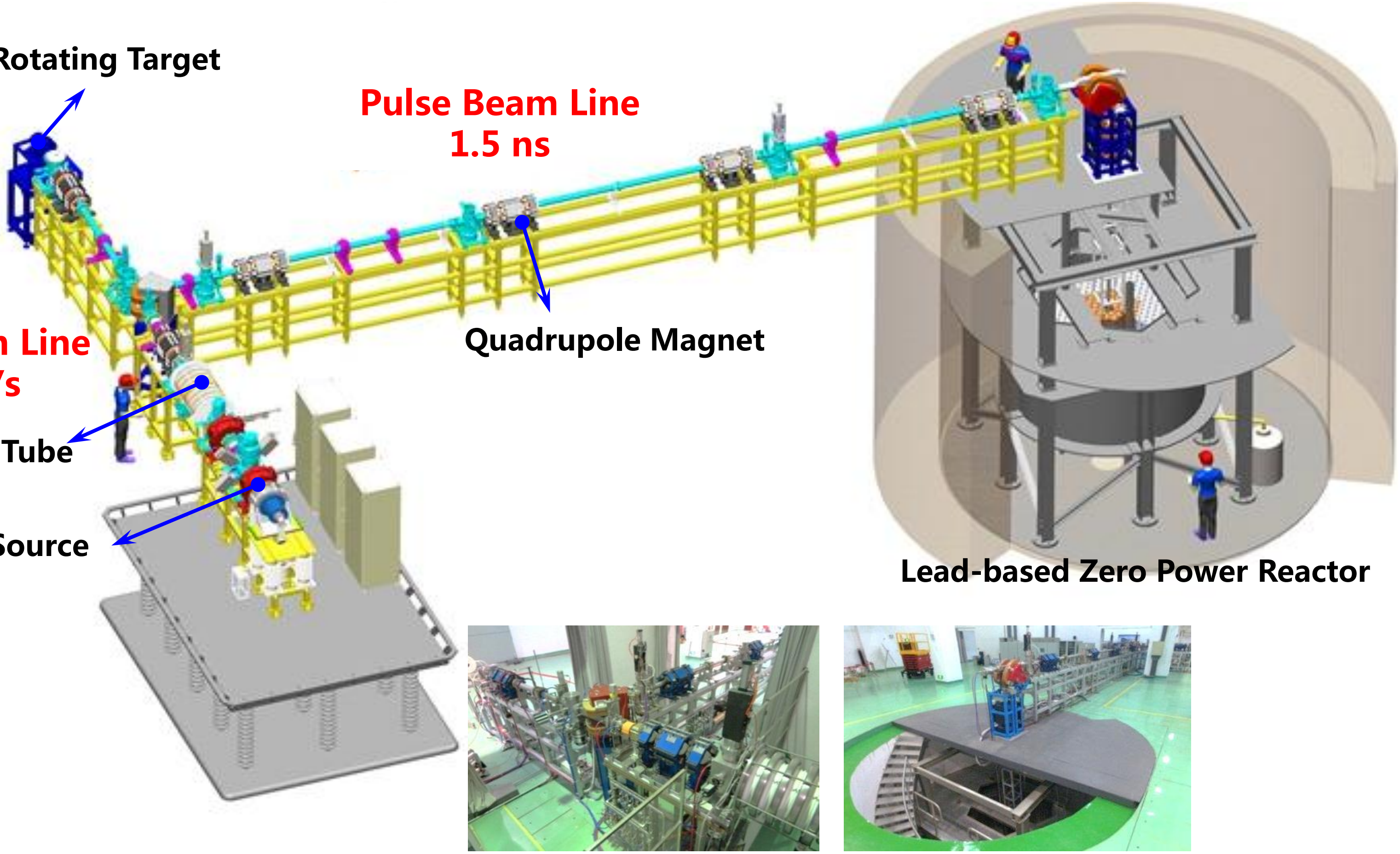
- Fusion materials (≥20dpa/FPY)
- Multi-Physics Coupling Test
- System Engineering Integration Test
- Driving Hybrid system

Fundamental Research on Neutronics & Nuclear Technology

Materials & Components Performances test

Fusion / Hybrid Testing

HINEG-I: D-T Fusion Neutron Generator
Coupling with Lead-based Zero Power Fission Reactor



Fusion neutrons with yield up to 6.4×10^{12}n/s

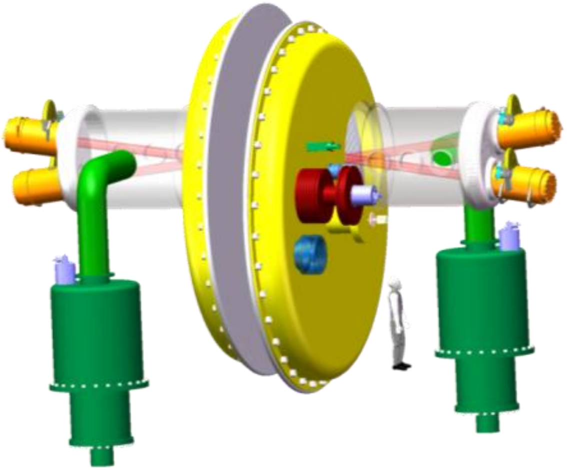
HINEG-IIa：Mixed-beam Fusion Neutron Source

Goals

- With yield of 10^{15}-10^{16} n/s for materials irradiation as well as breeding blanket validation in actual D-T spectrum.
- Validation and calibration tool to link experimental data collected in fusion spectrum to those collected in other type neutron source.

Main Parameters

- DPA: 4 dpa/FPY
- Beam current: 40 A per target
- Beam energy: 200 keV
- Rotating target: 4m in diameter

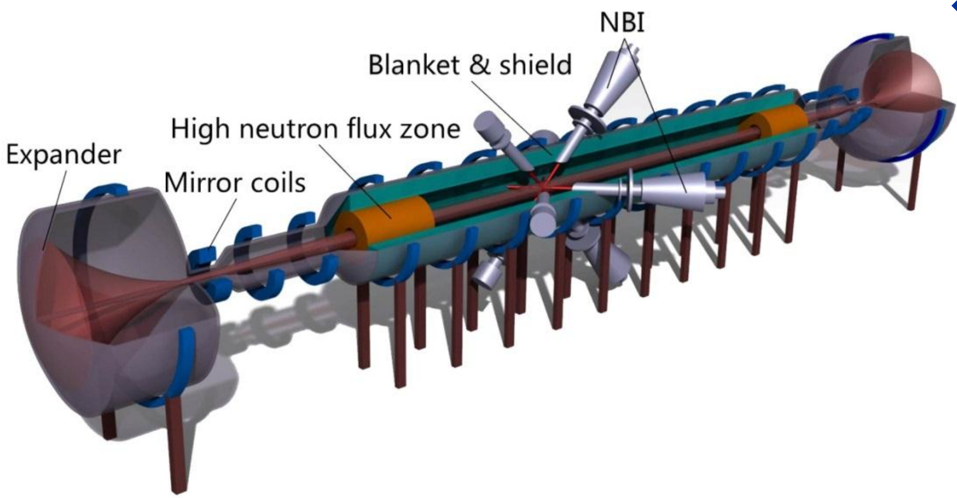


Conceptual Design

Design and R&D for key technologies of HINEG-IIa is on-going

Initiate an International Mega-science Project

International Fusion Volumetric Neutron Source (FVNS)



- **Design target for FVNS**
  - **Neutron spectrum：fusion neutron**
  - **Availability: > 70%**
  - **Operation：quasi-continuous**
  - **Tritium consumption rate for D-T operation: <200g/year**
  - Neutron flux and test volume：

  $\geq$2MW/m^2 (~10L); $\geq$ 1MW/m^2 (~100L); $\geq$ 0.5MW/m^2 (~1 m^3);

International Cooperation:

- Design and Licenses in ~5 years
- Construction in ~5 years
- Operation in ~20 years
- Construction Cost is ~1Billion $

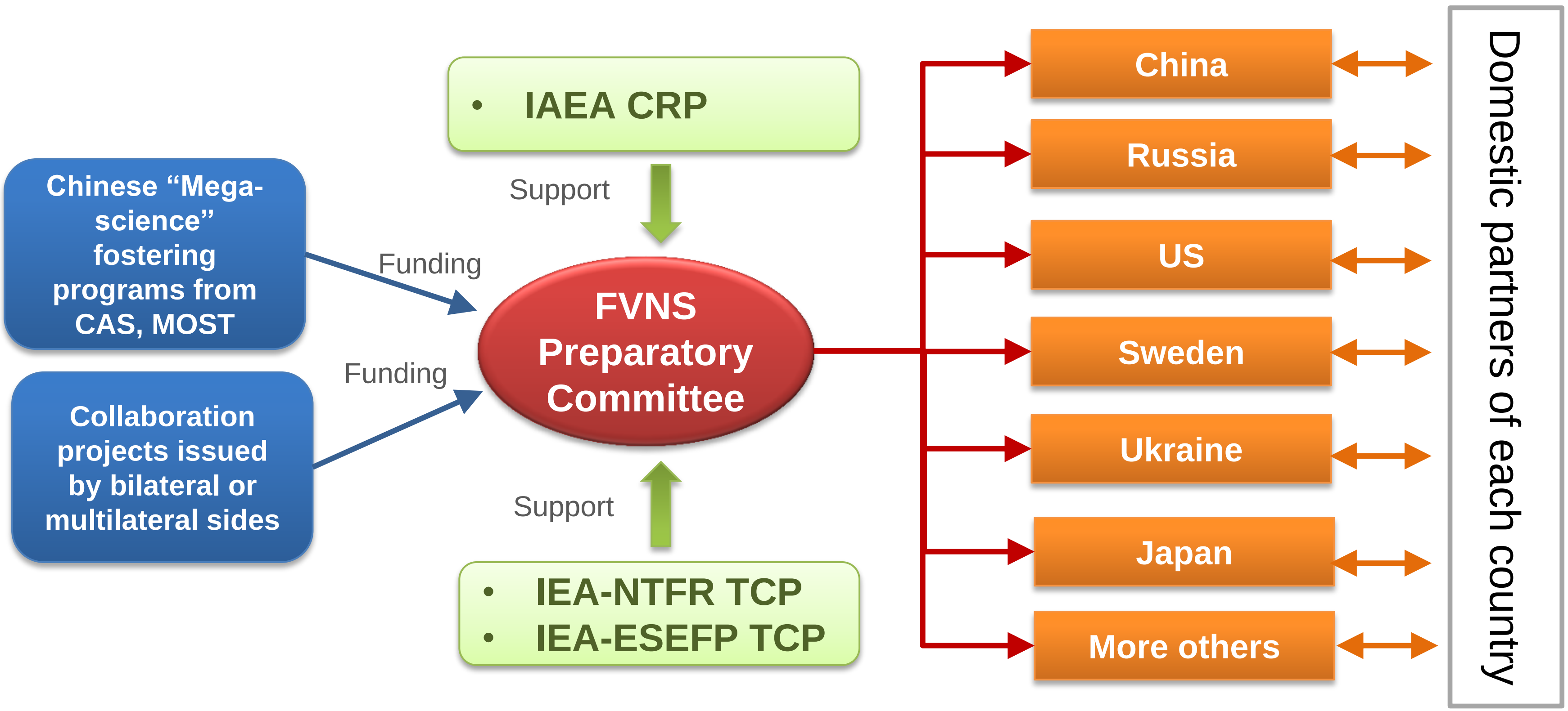
Multi Applications of FVNS

- **Fusion nuclear technology**
  - Materials test, blanket tritium breeding validation, in-vessel components(blanket, etc.) reliability test
- **Subcritical reactor**
  - Performance test of MA transmutation, spent fuel burning and energy production of fission blankets
- **Neutron radiography**
  - Higher resolution will be reached by high flux of fast neutron radiography
- **Medical isotope production (99Mo)**
  - 2015 Global 99Mo requirement is 9000 6-day Ci/week and worth about 200 million $ (6-day Ci is worth about $470) [1]
- **Neutron therapy**
  - Provide multi collimators at 25m from plasma column to provide $10^{8\text{-}9}$n/(cm·s) of neutron flux for neutron therapy [2]
- **Neutron scattering and diffraction**
  - Determination of the atomic and/or magnetic structure of a material
- **Others**

[1] Molybdenum-99 for Medical Imaging. Washington, DC: *The National Academies Press*. 2016, doi: 10.17226/23563.
[2] P.A. Bagryansky, et al. Fusion Engineering and Design 70 (2004) 13–33

Design Stage（2019-2025）

❖ Build an International Cooperation Framework



In China: could be supported by "Mega-science facility" fostering program from CAS and MOST. The funding will be millions RMB.

2. Neutronics Methodology and Simulation

Accurate Modeling Theories and Calculation Methods

with multi-processes direct coupling for neutron transport in complex systems

Enabling the changes from isolated solutions to whole-process and multi-scale simulation for neutron transport

Innovative idea

Integrated Accurate Irregular Modeling
(geometry, material, source…)

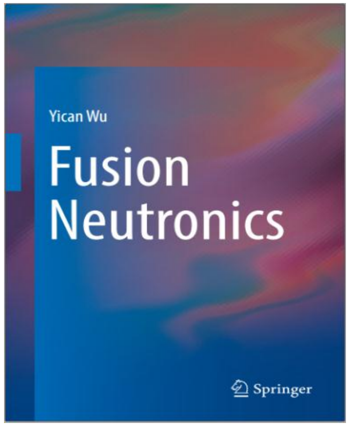
Physical model

Directly Coupling Multiple Processes
(Stochastic + Deterministic)

Advanced approach

Feature Pre-judgment for Efficient Transport Calculation

Discrete ordinates nodal transport method



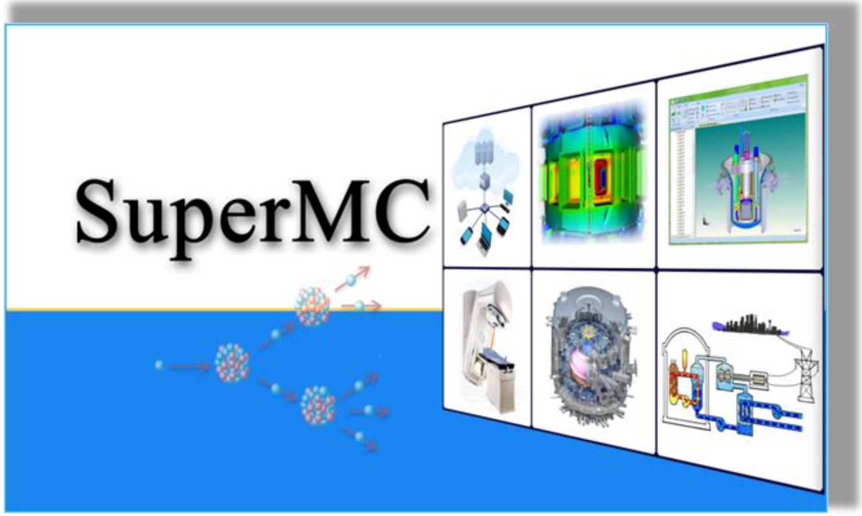
The first monograph "Fusion Neutonics" published by Springer

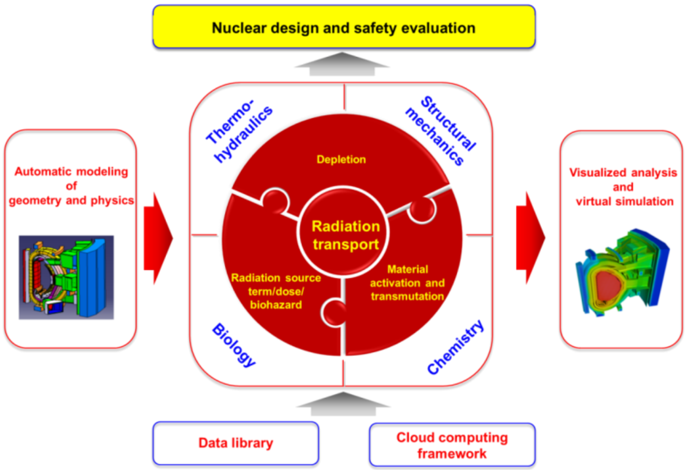
SuperMC: Super Multi-functional Calculation Program for Nuclear Design & Safety Evaluation

20+ years continuous development
300+ person years investment, >1.2 million code lines

- **Whole-process neutronics simulation**: inner-coupling calculations of neutron transport, depletion, activation, dose.
- **Multi-physics coupling simulation** based on unified modeling

SuperMC 3.3 has been released in ANS Winter Meeting (Nov, 2018)





3. Fusion Safety

（Magnetic D-T Tokamak）

Combination of International Efforts

❖ *IEA Framework*

- **Technology Collaboration Program on Environmental, Safety and Economic Aspects of Fusion Power (ESEFP)**

❖ *ExCo Members*

- **China: Y. Wu, INEST**
- **Europe: D. Maisonnier, EC**
- **Japan: Y. Sakamoto, QST**
- **Korea: K. Kim, NFRI**
- **Russia: A. Kalashnikov, ROSATOM**
- **USA: D. Clark, DOE**

❖ *Subtasks*

- **Task 1 In-vessel Tritium Source Terms**
- **Task 2 Transient Thermo-fluid Modeling and Validation Tests**
- **Task 3 Activation Production Source Terms**
- **Task 4 Safety System Study Methodology**
- **Task 5 Failure Rate Database**
- **Task 6 Radioactive Waste Study**
- **Task 7 Socio-Economic Aspects of Fusion Power**
- **Task 8 Magnet Safety**
- **Task 9 Fusion Power Plant Studies**

Joint Paper Published in Nuclear Fusion (2018)

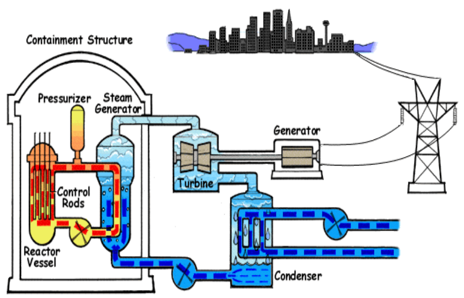
- **Summarized 2nd International Workshop on ESEFP (23rd Sept. 2017, Kyoto, Japan)**
- **Discussion:**
  - **Quantitative Safety Assessment of Fusion Power Plants**
  - **Fusion Safety Issues and Impact on Design and R&D Needs**
- **Organize the 3rd workshop in 2019**

Y. Wu, Z. Chen, Z. Meng, L. Hu, S.M. Gonzalez Vicente, B. Merrill, D. Panayotov, M. Zucchetti, B. Kolbasov, D. van Houtte, C. Bustreo, Y. Kim, Y. Sakamoto, K. Kim, D. Maisonnier, D. Clark, A. Kalashnikov and M. Subbotin, Nuclear Fusion, 2018

Quantitative Safety Assessment of Fusion Power Plants (2017~)

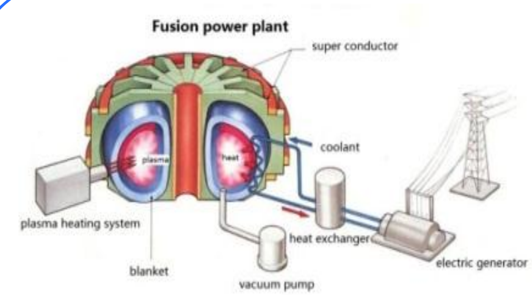
Aims to investigate:

1. what can we learn from the existing PWR safety demonstration?
2. what can we do to make fusion energy the ideal nuclear energy source?



PWR Model (AP1000)

- Core power/ Unit size (GWe) 3.40 / 1.1
- Active fuel length 4.3 m
- Average linear power 5.71kW/ft
- Fuel / Clad UO_2/ZIRLO™



FPP Model (PPCS Basis)

- Fusion power / Unit size (GWe) 3.41 / 1.45
- Major / Minor radius (m) 7.5 / 2.5
- Structure / PFM Eurofer / tungsten
- Blanket Coolant PbLi/ He/ Water
- Divertor Coolant He/ Water

The preliminary findings have been reported in ISFNT-13 and ANS TOFE 2018, supported by IEA ESEFP TCP. More detailed R&D is still on-going.

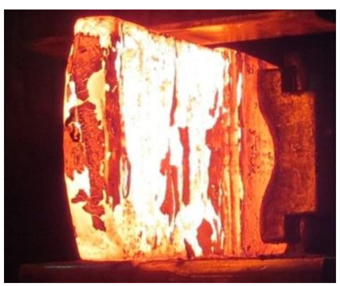
4. Materials and TBM Technologies

Development of CLAM (China Low Activation Martensitic steel)

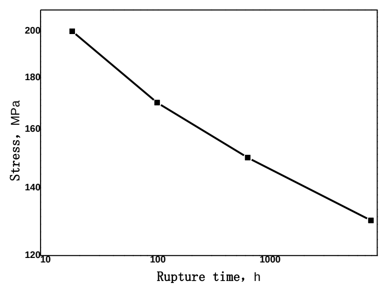
selected as candidate structural material for CN ITER TBM

- **Nominal composition: 9Cr-1.5W-0.2V-0.15Ta-0.45Mn-0.1C**
- **18-ton (3 ingots) smelting: good control of composition**
- **High-dose neutron irradiation experiments**

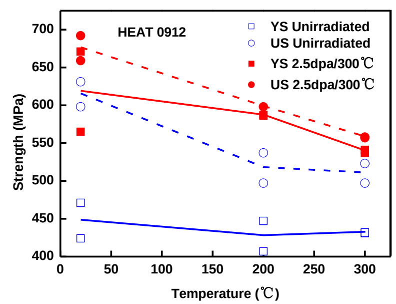
(Spallation source ~ 21dpa) (High Flux Engineering Test Reactor ~3 dpa)



Forging ingot



Creep test ~10,000 hrs



Neturon Irradiation

Nuclear Reactor Material Database (NRMD)

In 2018, China's industry standard of RAFM steel prepared by INEST was issued

Q. Huang, FDS Team. Development Status of CLAM Steel for Fusion Application. Journal of Nuclear Materials, 2014, 455:649-654.

New Project1: Development of ODS alloys for CFETR (Budget: ~ 6M $ from MOST, 2018-2022)

☐ Oxide dispersion strengthened RAFM and Cu alloys

- **Mass production: castable ODS alloys**
- Maximum application temperature: improvement by 100 K
- Ion Irradiation resistance:
  - ✓ ODS-RAFM: lower than 0.1% at 200 dpa (without He)
  - ✓ ODS-Cu: lower than 0.1% at 50 dpa (without He)

☐ Joint research among China's top materials research institutions

INEST (Leading)

Central South University, University of Science and Technology Beijing, Northeastern University, Shanghai Univeristy, Huazhong University of Science and Technology, Tianjin University, Dalian University of Technology, Soochow University

New Project2: Development of Tritium Permeation Barrier (TPB) (Budget: ~ 0.5M \$ from MOST, 2018-2022)

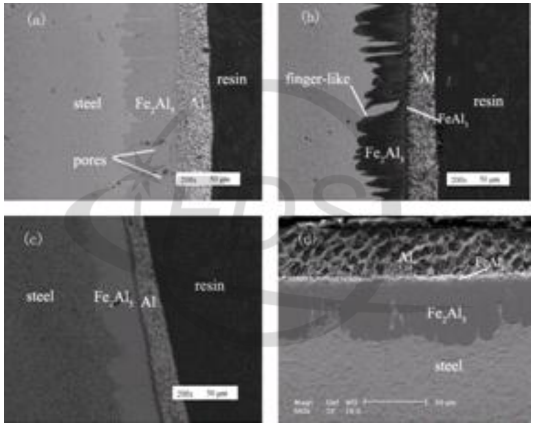
□ Tritium compatibility of $FeAl/Al_2O_3$ TPB :

- ➢ Synthesis of $FeAl/Al_2O_3$ TPB inside pipes and containers

  PRF>1500, Porosity <3%

- ➢ Development of TPB properties during 1~2 years

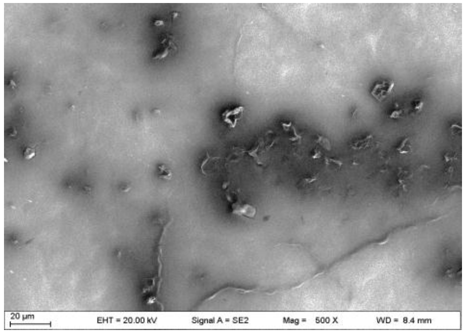
  Tritium partial pressure > 50kPa



$FeAl/Al_2O_3$ TPB [1]

□ Novel Composite (Graphene Oxide) GO/Al_2O_3 TPB :

- ➢ GO：Strong barrier properties to hydrogen isotope atoms
- ➢ Synthesis completed, and the PRF is more than twice as the original Al_2O_3, as well as the toughness



GO/Al_2O_3 TPB [2]

[1] X. Chen, et al., Journal of Nuclear Materials 442(2013): S597-S602; Z. Guo, et al., Fusion Eng. and Des. 85(2010):1469-1473

[2] Unpubilised work

New Project3: Tungsten-diamond composite with high thermal conductivity

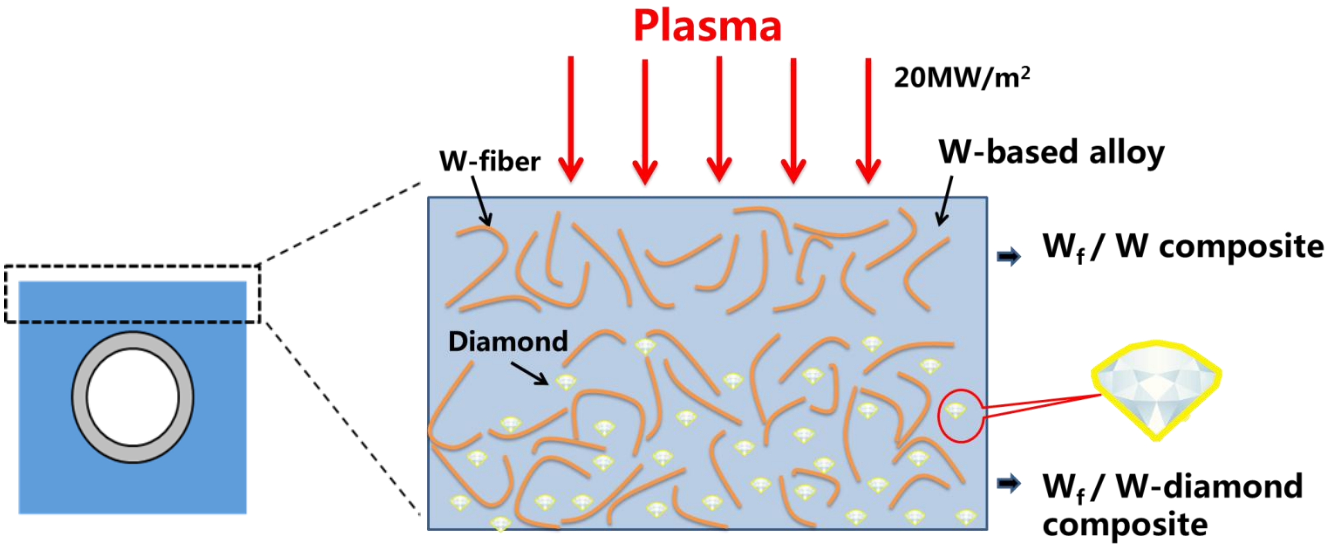
(Budget: ~ 0.5M $ from MOST, 2018-2022)

❖ Contents

- Design and preparation of W_f/W -diamond composite
- Thermal test of tungsten divertor monoblock at 20MW/m^2

❖ Objectives

- W_f/W-diamond composite: thermal conductivity≥ 300W/mK, DBTT≤100 ℃
- No cracks after 1000 cycles at 20MW/m^2



China multi-functional liquid PbLi Experimental Loop (DRAGON)

1st stage: Magnetic field corrosion under DEMO blanket velocity, 3D flow field measurement up to 550 °C.

2nd stage: 1/3 scaled ITER-TBM integrated validation, 1:1 He/PbLi thermal hydraulic and Safety of rupture accident, etc.

☐ 1st Stage: in operation (2018)

- Max. temperature: 550 °C
- Magnetic field: 2 T
- Max. flow rate of PbLi: 40 kg/s

☐ 2nd Stage: under construction

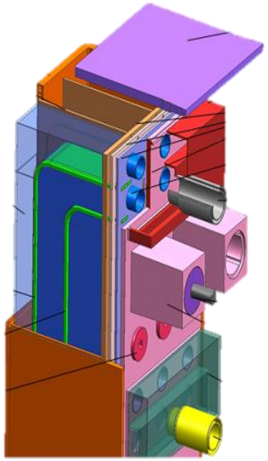
- Max. Test temperature: 1100 °C
- Magnetic field: 5 T
- He gas pressure: 10.5 MPa

To support the engineering design validation of DEMO blanket with the parameters covering the requirements of ITER-TBM and China DEMO

The Role of INEST in CN ITER TBM Program

- **Leading the R&D of CN DFLL TBM (Liquid Breeder)**
- **In Charge of CN HCCB TBM (Solid Breeder) on**

  Structure Materials, Safety Technology, etc.



PD phase of CN HCCB TBM Program officially started at 2016

Outline

I. Highlights of Fusion R&D Activities

II. International Communication and Collaboration

1st Symposium on Neutronics and Innovative Nuclear Systems (SNINS)

(27-30 April 2018, INEST)

3rd International Conference on Fusion Neutron Sources and Subcritical Fission Systems (FUNFI)

(17-19 Nov. 2018, INEST)

Prof. Abdou Receives 2018 Chinese Government Friendship Award

(China's highest award for foreign experts who have made outstanding contributions to the country)

Premier Li Keqiang at the grand award ceremony with the winners of the 2018 Friendship Award

Prof. Yican Wu Receives

American Nuclear Society Fusion Energy Division

2018 Outstanding Achievement Award

"in recognition of his pioneering contributions to the field of Fusion Nuclear Science and Technology, including neutronics, blankets, materials, and safety, and his exemplary leadership in establishing a world-class program"

Summary

1. In the field of fusion research, INEST concentrates on the Nuclear Technology and Safety.
2. In 2018, INEST has made good progress on neutron source, neutronics software, fusion safety, material development, etc.
3. INEST is always open to domestic & international cooperation.

Better Nuclear Energy Technology， Better Life !

Thanks for Your Attention!

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