Institute of Nuclear Energy Safety Technology, CAS
Key Laboratory of Neutronics and Radiation Safety, CAS


Better Nuclear Energy Technology, Better Life!

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Development of Fusion Neutronics Methodology, Software and Testing Facility in FDS Team

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Contributed by FDS Team

Key Laboratory of Neutronics and Radiation Safety

Institute of Nuclear Energy Safety Technology (INEST)

Chinese Academy of Sciences

www.fds.org.cn

ANS Annual Meeting, June 11-15, San Francisco

Contents

1. Challenges of Fusion Neutronics
2. Methodology Innovation
3. Software Development
4. Testing Facility

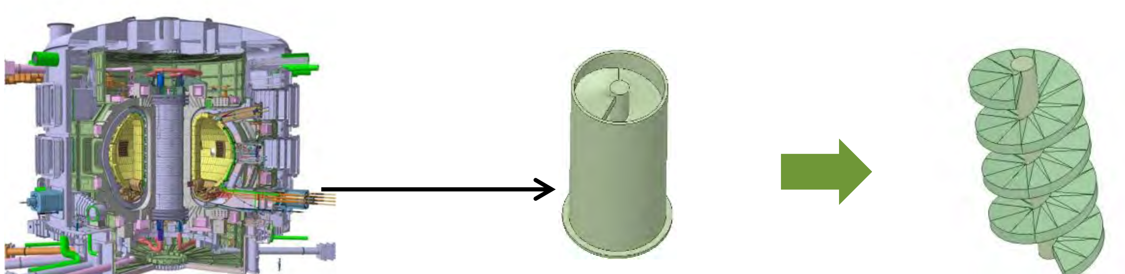
Challenges for Methodology & Software - Modeling

☐ Geometry conversion between CAD and calculation model has been achieved

- **CAD to CSG converting method** – relies on a simplified geometry model compatible with CSG presentation (SuperMC, McCad, Giomet, etc.)
- **Ray tracing method directly on CAD geometry** – relies on a modified geometry without errors (DagMC, etc.)

☐ Time consuming geometry pre-processing is not eliminated

- Simplification of excessive details: screw, chamfer and etc.
- Modification to be compatible with CSG presentation: replace free form surfaces, incompatible quadratic surfaces and etc.
- Modification to remove error: overlaps, gaps, absent faces, and etc.

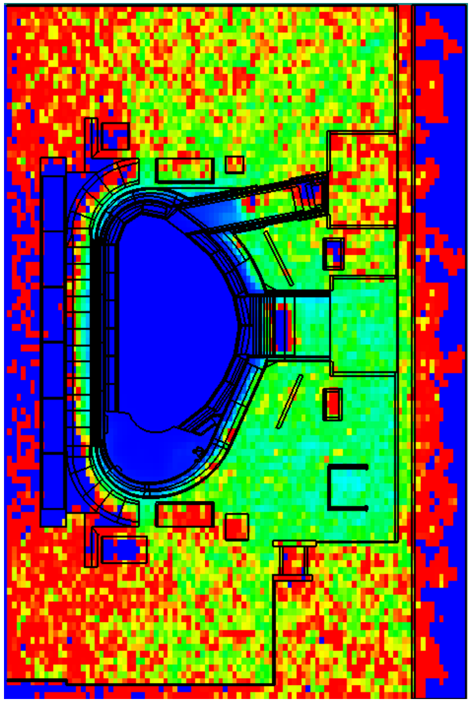


original screw **manual pre-processing**

Challenges for Methodology & Software – Accuracy & Efficiency

Difficult to convergent, time consuming

- **Deep penetration of radiation shielding**
  - ✓ Thick shielding
  - ✓ Streaming through slits and small pipes
  - ✓ Whole space in large scale (height~30m, radius~20m)
- **Approximate continuous calculation** with R/W surface source for large space problem



Difficult to achieve global convergence

Uncertainty quantification

- **Uncertainty caused by**
  - ✓ Simplification of geometry
  - ✓ Homogenized mesh / cell based tally
  - ✓ Nuclear data uncertainty …….
- **Error propagation** between coupled calculation

Challenges for Testing Facility and Experiments

Nuclear Data Library

- Precision: 30%~50% uncertainty for some nuclides
- Lack of cross section:
  - tritium breeder and structural materials
  - (n,p), (n,α), (n,t) cross section of Cu, Fe, W, Ni for material radiation damage

Calculation Code and New Methods

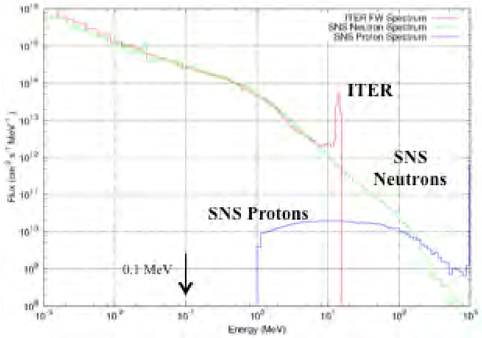
- Correctness of convergence acceleration methods for deep penetration
- No-linear feedback of multiple physics coupling, etc.

Material Irradiation Damage

- Approximation and derivation
- The role of high intensity fusion neutron source

Design Validation

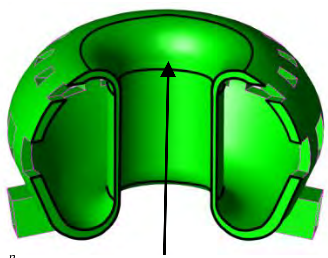
- Just for some blankets, far from enough
- Simplified condition, different from the real environment



Energy spectrum:
Spallation VS Fusion

Fusion Neutronics Work in FDS Team

Methodology

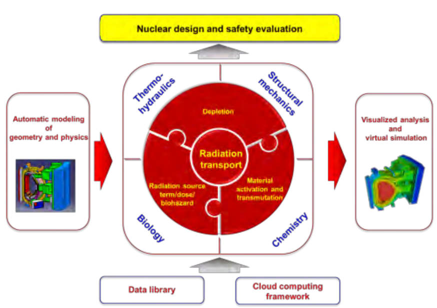


$$S(u,v)=\frac{\sum_{i=0}^{m}\sum_{j=0}^{n}\omega_{i,j}P_{i,j}B_{i,k}(u)B_{j,h}(v)}{\sum_{i=0}^{m}\sum_{j=0}^{n}\omega_{i,j}B_{i,k}(u)B_{j,h}(v)}\quad (u,v)\in[u_{k-1},u_{m+1}][v_{h-1},v_{n+1}]$$

Fundamental basis

V&V

Software



Testing Facility

Contents

Modeling methodology 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 Irregular Modeling based on Hybrid Solids and Surfaces and Decomposition Utilizing Characteristics

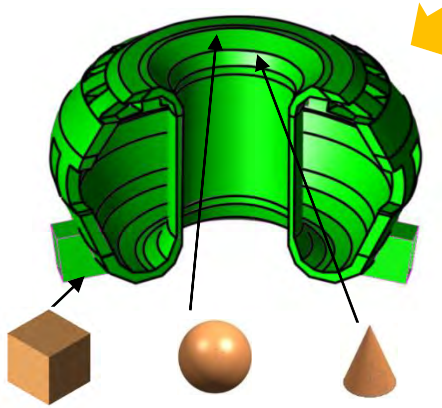
Physical model – Adaptive Transaction Region Model of Hybrid Probabilistic and Deterministic Method

Solution – Location Pre-judgement for Efficient Transport Calculation | Nodal S_N Method on Coarse Mesh in Curvilinear Coordinate System

Integrated Irregular Modeling based on Hybrid Solids and Surfaces and Decomposition Utilizing Characteristics

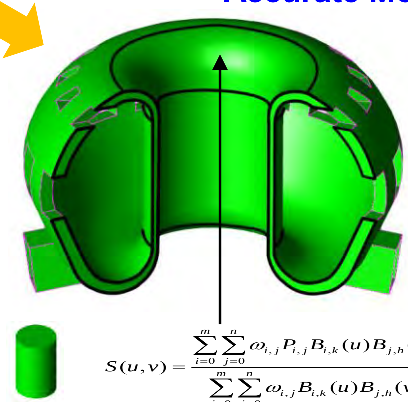
Problem: Conventional isolated and regular modeling approximates irregular geometry boundary and actual physical process in engineering, with a loss of precision

Regular primitives
Approximated Modeling



- Transport calculation model with complete representation and boundary condition
- Calculation model for complete neutronics process
- Multi-physics calculation model
- Dynamic calculation model for whole-life of nuclear system

Irregular modeling with hybrid solids and surfaces
Accurate Modeling



$$S(u,v)=\frac{\sum_{i=0}^{m}\sum_{j=0}^{n}\omega_{i,j}P_{i,j}B_{i,k}(u)B_{j,h}(v)}{\sum_{i=0}^{m}\sum_{j=0}^{n}\omega_{i,j}B_{i,k}(u)B_{j,h}(v)}\quad (u,v)\in[u_{k-1},u_{m+1}][v_{h-1},v_{n+1}]$$

surface

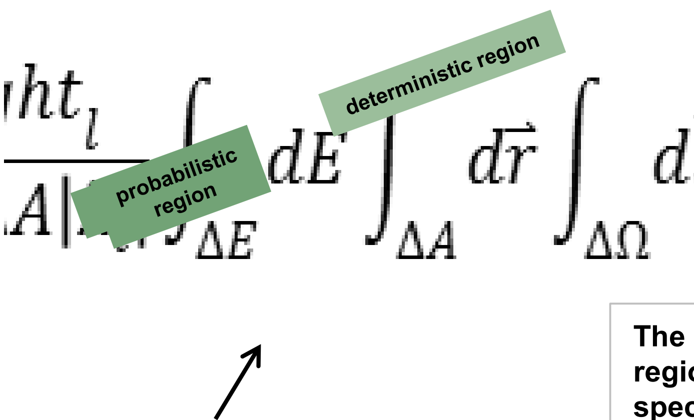
Advancement: Decompose utilizing features of cutting loop, auxiliary surface and similarity, accurately represent irregular boundary with hybrid solids and surfaces.

Adaptive Transaction Region Model of Hybrid Probabilistic and Deterministic Method

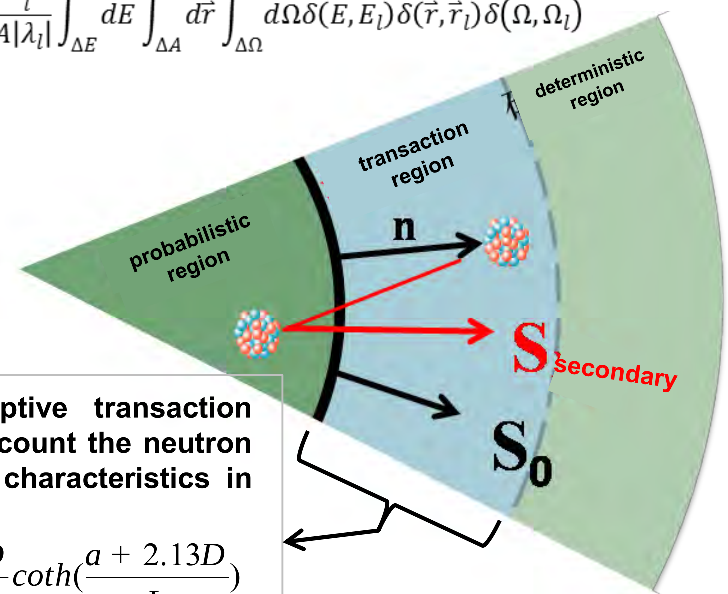
Problem: neglected nonlinear impact of the secondary particles to interface source

Interface source: $S_0 + S_{secondary}$

$$S_{secondary} = \sum_l \frac{weight_l}{w_m N \Delta A |\lambda_l|} \int_{\Delta E} dE \int_{\Delta A} d\vec{r} \int_{\Delta\Omega} d\vec{\Omega}\, \delta(E, E_l)\, \delta(\vec{r}, \vec{r}_l)\, \delta(\vec{\Omega}, \vec{\Omega}_l)$$



Adaptive transaction region



The thickness of adaptive transaction region by taking into account the neutron spectrum and physical characteristics in transaction region

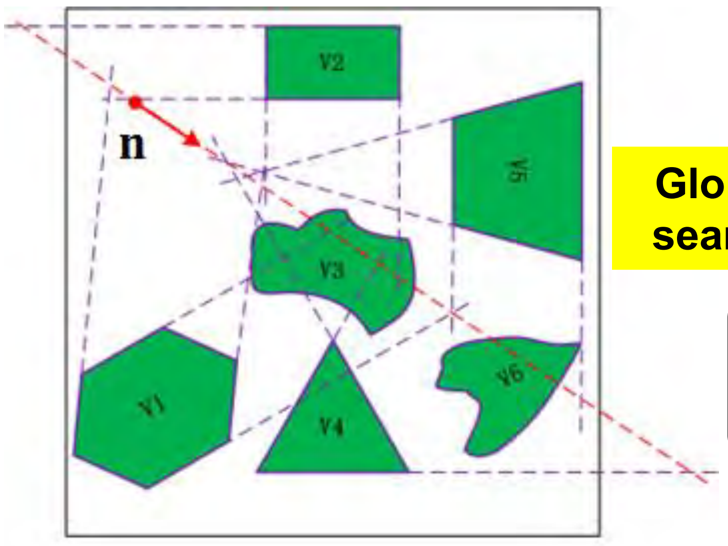
$$\bar{b} = \frac{b}{b_{\infty}} = \frac{1 + \frac{2D}{L}}{1 - \frac{2D}{L}} \cdot \frac{1 - \frac{2D}{L} coth(\frac{a + 2.13D}{L})}{1 + \frac{2D}{L} coth(\frac{a + 2.13D}{L})}$$

Advancement: proposed the complete physical model based on three established regions (adaptive transition region, probabilistic region, deterministic region) with determining the thickness of adaptive transaction region based on diffusion model

Location Pre-judgement for Efficient Transport Calculation

Hierarchical Space Division

Problem: Global search for neutron hitting position (up to tens of thousands) leads to explosive computation amount with the increasing geometry amount

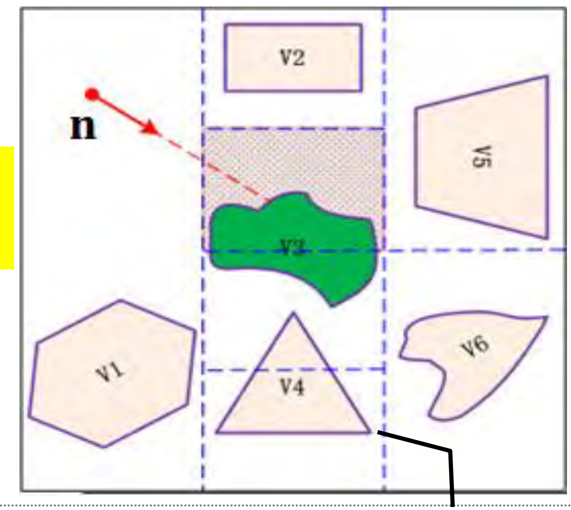


Global search

sub-area pre-judgment

Time complexity

O(N) → O(1)



Optimal evaluation of the space division

$$\min\{F(C)=\frac{\sum_{J=1\sim N_C} M_{J,C}}{\sum_{J=1\sim N_C} N_{J,C}}\},\quad N_{J,C}=\begin{cases}1. & if\,(M_{J,C}>0)\\ 0. & if\,(M_{J,C}=0)\end{cases}$$

Advancement: Fast location of neutron hitting position based on flying characteristics and hierarchical space division

Physical Characteristic Pre-judgement for Efficient Transport Calculation

Based on the uniformity of Particles Density and Historical Mesh Importance

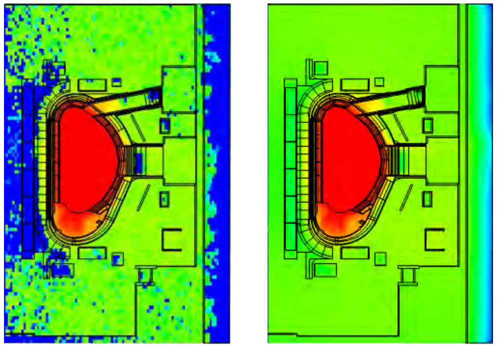
Problem：Getting efficient mesh importance distribution (guide the neutrons bias in whole space) is time consuming (~80% total time)

Importance definition: based on the uniformity of particles density, more accurately represents mesh importance than flux and adjoint flux

$$Importance = \frac{total\ contribution\ to\ particle\ density\ uniformity, C_i}{total\ weight\ entering\ the\ cell, W_i}$$

Iterative optimization of importance: accelerate the convergence rate of mesh/cell importance by accumulating contribution of historical simulation

$$Imp_{N+1} = \frac{\sum_1^N q^{N-k} Imp_{ik}}{\sum_1^N q^{N-k} W_{ik}}$$



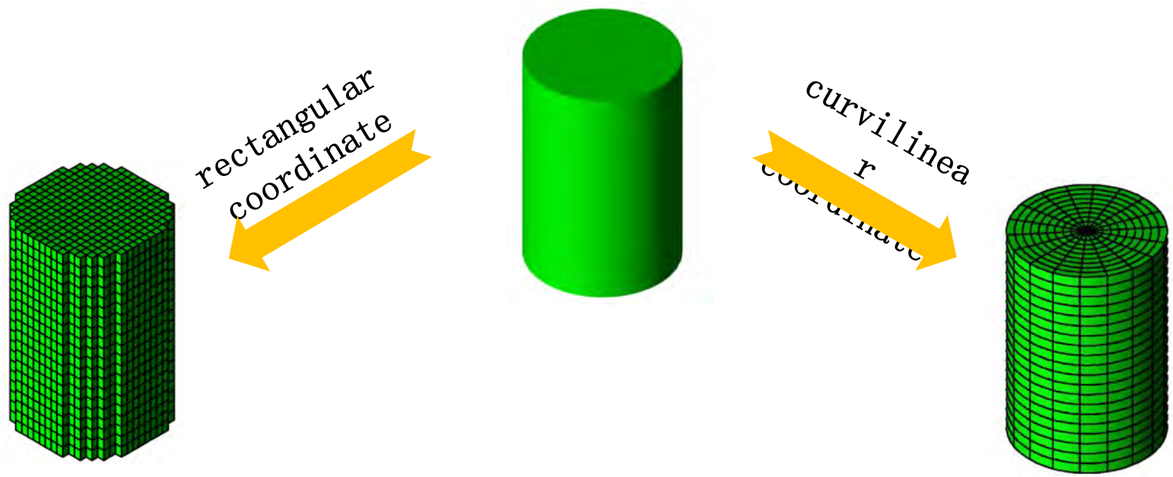
Achieved acceleration by 634 times for ITER reference model while 74 times with other state of the art methods

Criticality mode: the uniformity of particles density and fission source（GWWG+UFS）→HM thermal energy 30.6↑， fast energy 24.83↑

Advancement: define the uniformity function of particles density to represent the mesh importance distribution, accumulate historical contribution and optimize by iteration

Nodal S_N Method on Coarse Mesh in Curvilinear Coordinate System

Problem : Structures in nuclear engineering are usually described by curvilinear geometry, while conventional S_N methods are only available in rectangular coordinates

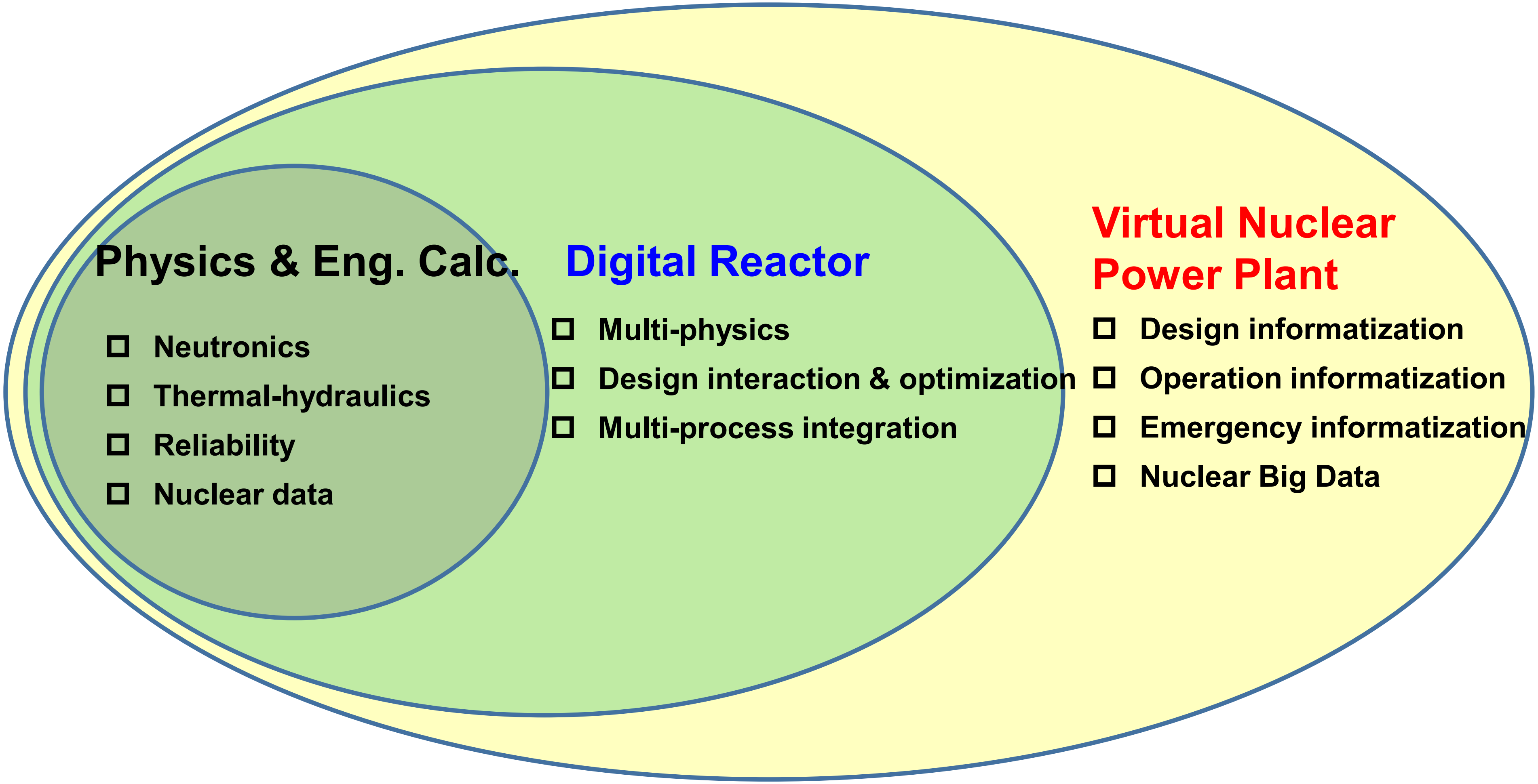


$$\mu_m \frac{\partial}{\partial r}F(r,\mathbf{\Omega}_m) + \Sigma_i F(r,\mathbf{\Omega}_m) - \left(a_{m+\frac{1}{2}}\phi\left(r,\mathbf{\Omega}_{m+\frac{1}{2}}\right) - a_{m-\frac{1}{2}}\phi\left(r,\mathbf{\Omega}_{m+\frac{1}{2}}\right)\right) = aS(r,\mathbf{\Omega}_m)$$

Advancement : Covert the "angular redistribution term" to the special "source", and establish the fast mathematical theory model based on the coarse meshes S_N method for neutron transport calculation in curvilinear coordinate system.

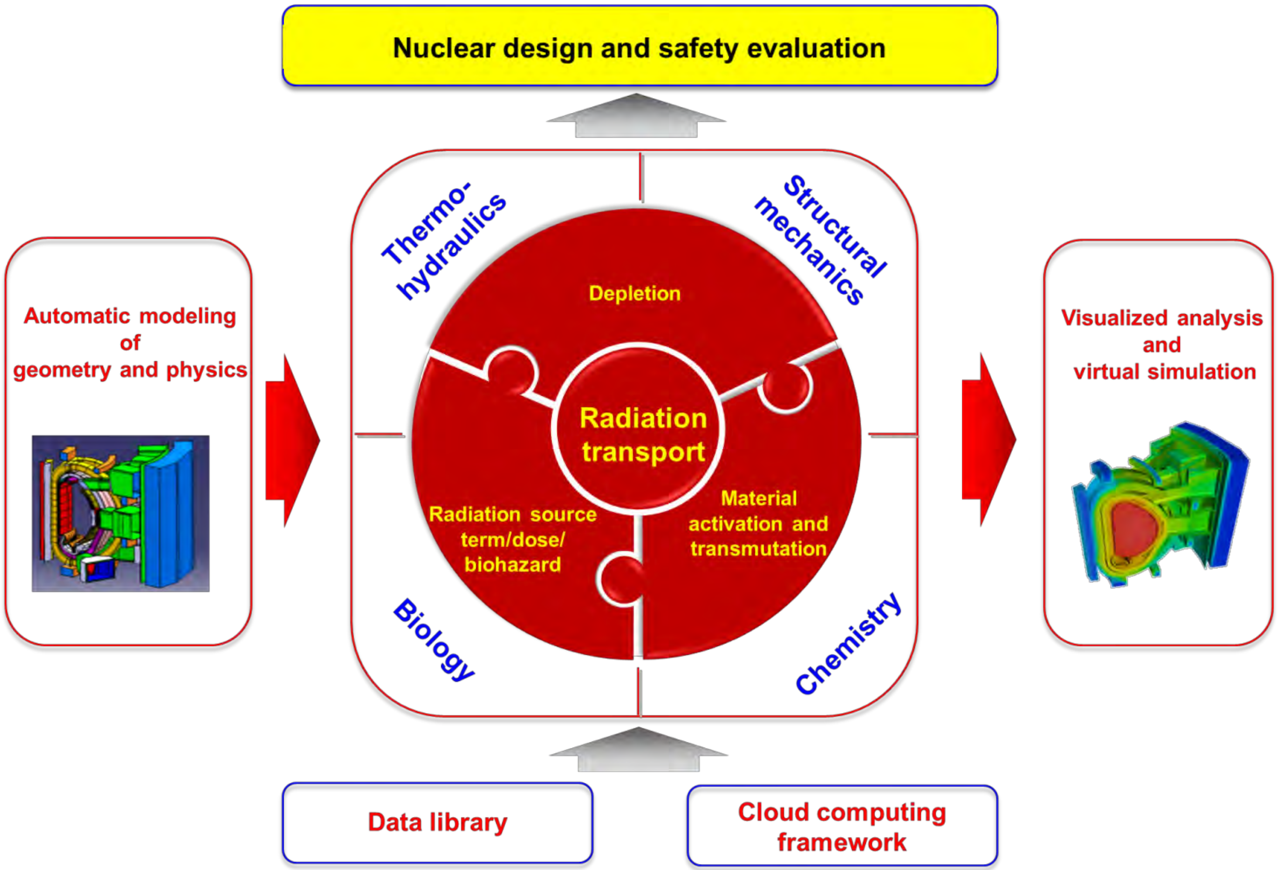
Contents

Strategy of Advanced Nuclear Software Development in FDS



Overall Orientation of SuperMC

Super Monte Carlo Program for Nuclear and Radiation Simulation



Publicly distributed by OECD/NEA Data Bank (IAEA1437)

V3.1.0 —— Basic Functions

Comprehensive Neutronics Simulation

1. Radiation transport calculation

- **Multi-particle** neutron (1e-11~150MeV), photon (1keV~1GeV)
- **Flexible source description** general source, critical source, surface source, user-defined source
- **Physical parameters** k_{eff}, kinetic parameter, surface/cell/mesh/detector flux, energy deposition, energy spectrum, reaction rate, flux-to-dose conversion, etc.
- **Abundant variance reduction** weight window, adaptive variance reduction based on weight window smoothing, global weight window generator (GWWG), GWWG coupled with uniform fission site method (UFS), etc.
- **Efficient parallel** MPI & OpenMP sharing memory parallel, Data decomposition parallel etc.

2. Isotopes depletion calculation

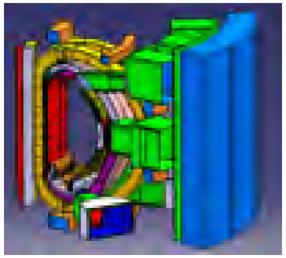
- **Solving method** Chebyshev Rational Approximation Method (CRAM)
- **Inner-coupling** beginning-of-step constant flux approximation (BOS), predictor-corrector (PC)

3. Material activation and transmutation

- **Computational modes** point activation calculation, transport-activation coupling calculation
- **Activation properties** activity, decay heat, biological hazard, dose rate, clearance index, and the corresponding contribution of each nuclide in the activation properties

V3.1.0 —— Advanced Capability (1)

CAD/Imaged-based Modeling



CAD model
autoCAD, CATIA, UG, Solidworks, PRO/E, etc.

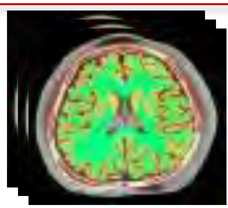
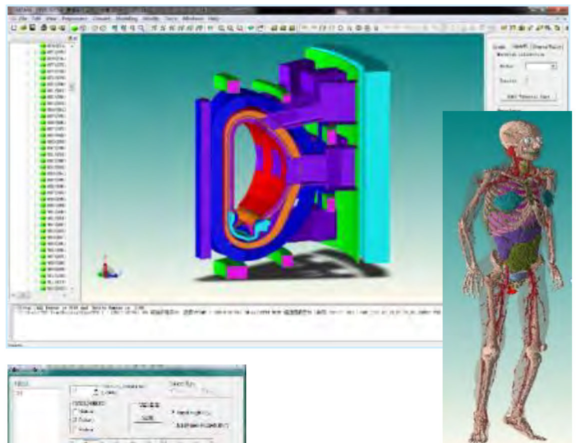


Image
CT / MRI / segmented images



Physics modeling
material, source, tally, variance reduction, cut..

SuperMC
direct calculation

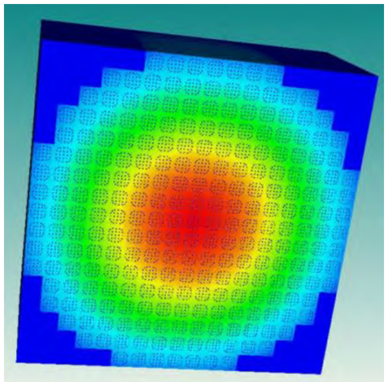
Export
calculation model of
- **MCNP**
- **TRIPOLI**
- **Geant4**
- **FLUKA……**

CAD system

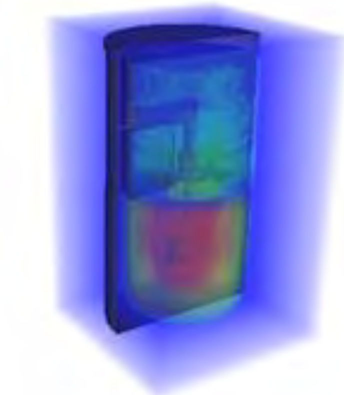
to create a CAD model without the help of other commercial CAD software

V3.1.0 —— Advanced Capability (2)

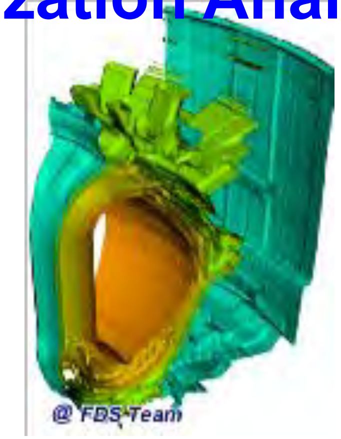
Multi-D Visualization Analysis



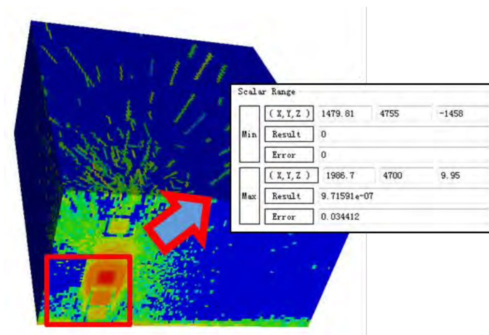
Surface rendring



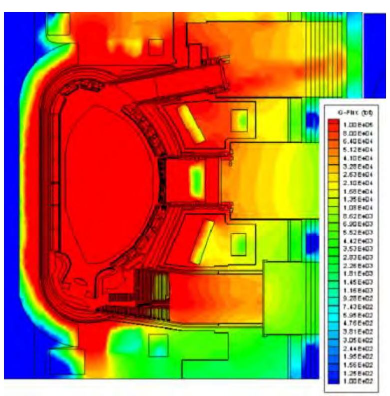
volume rendering

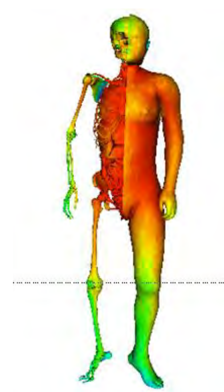


iso-surface

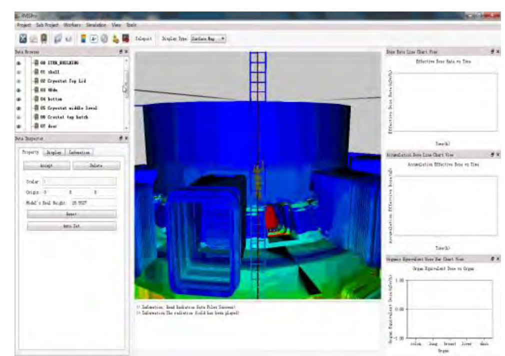


Data extract





Visualization mixed with geometries



Virtul-reality based simulation

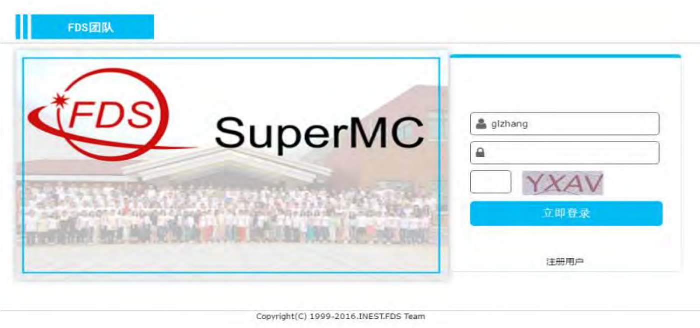
Visualization interface for multiple codes : MCNP, TORT, FISPACT …

V3.1.0 —— Advanced Capability (3)

□ Efficient Radiation Transport Calculation

- ✓ Geometry processing acceleration method based on particle location prejudgment
- ✓ Advanced intelligent adaptive variance reduction techniques
  - Adaptive variance reduction based on weight window smoothing
  - Global weight window generator (GWWG)
  - GWWG coupled Uniform fission site method(UFS)
- ✓ Hybrid MC and deterministic methods with transition region
- ✓ Cell geometry multi-tree based method for massive tallies
- ✓ Other acceleration: source convergence, union energy grid, etc.

□ Cloud Service http://www.SuperMC.cn



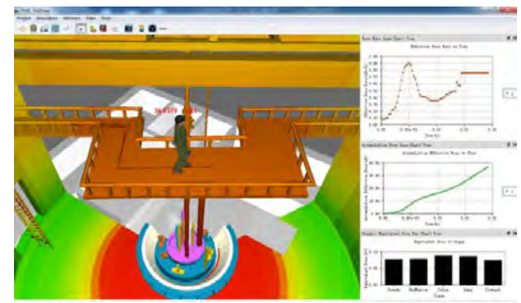
Extended Functions: Coupling Simulation

1. Multi-physics coupling simulation

- Coupling neutronics calculation with thermo-hydraulics, structural mechanics, chemistry and biology

2. Organic dose evaluation based on virtual roaming

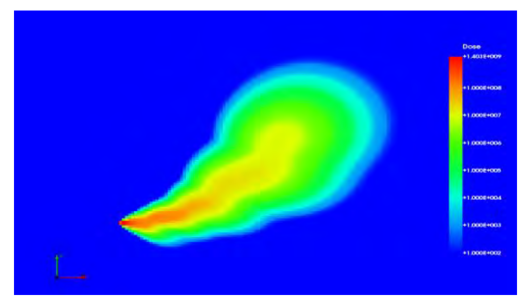
- Virtual roaming of maintenance in radiation environment
- Real-time evaluation of organic dose and collective dose
- Automatic optimization of work path



Organ Dose Evaluation

3. Accident evolution simulation

- Rapid prediction of accident evolution process
- Full-scale and real-time simulation of radionuclides diffusion
- Accurate inversion of accident source term
- Intelligent decision support



Simulation of Radionuclides Diffusion

V3.1.0 ——Features

——Compared with MCNP

1. **Rapid and high fidelity full reactor transport simulation**
   - Acceleration methods using physical characteristics-based (eg.GWWG…), improving the calculation efficiency for ITER analysis.
   - Directly-coupled stochastic and deterministic method based on transition region
2. **Effective and accurate depletion/activation/dose calculation**
   - Lockless concurrency data decomposition parallel, solving the memory issue on high-fidelity full core calculation
   - Activation source term calculation on full reactor, direct one step shutdown dose calculation
   - Hybrid evaluation database (depletion, activation, radiation damage, etc.)
   - Accurate radiation dose calculation based on human phantom Rad-Human
3. **CAD/Image based accurate automatic modeling**
   - Automatic and accurate description for complex irregular models
   - Integrated modeling: transport (MC for multiple codes, deterministic, MC-deterministic coupled, human…), neutronics (depletion, activation, radiation damage…), multi-physics coupling, ...
4. **Intelligent massive data analysis based on multi-D visualization**
5. **Integration of modeling, calculation and visualization on cloud platform based on collaborative network**

List of China-ITER Neutronics Tasks

Task 2003 : Upper Port Shielding Analysis

Task 2004 : Update of Basic MCNP Model for ITER and Extension of Data Library

Task 2005: Testing and Application of a CAD/MCNP Interface Program for ITER Neutronics Design Calculations

Task 2009 : A : Creating Neutronics Model of ITER Building
B : Gamma Dose Map in Building during Cask Movements
C: Activation of the ITER Cooling Water
D : Neutronics of the Bio-shield Plug

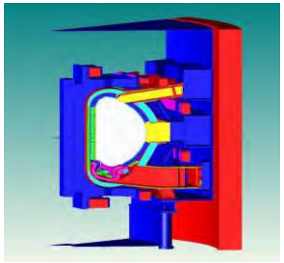
Task 2012: A : Production of CAD Neutronics Models for ITER
B : Radiation Transport in ITER buildings

Task 2013: A: Radiological calculation for port cell doors
B: Virtual-reality simulation for ITER PF4 coils maintenance

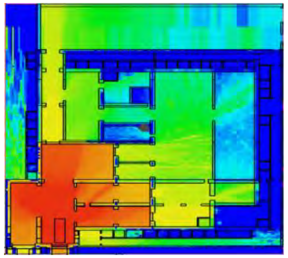
Task 2015: Shielding Analysis of Bio-shield Plugs in B1 of ITER

Task 2016: Production of Activation Data Handbook for ITER Neutronics

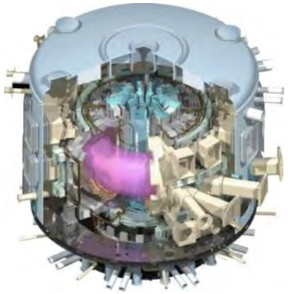
ITER Building Model



ITER Neutronics Model



Radiation Map in Hotcell



ITER Tokamak Machine

Production of Activation Data Handbook for ITER

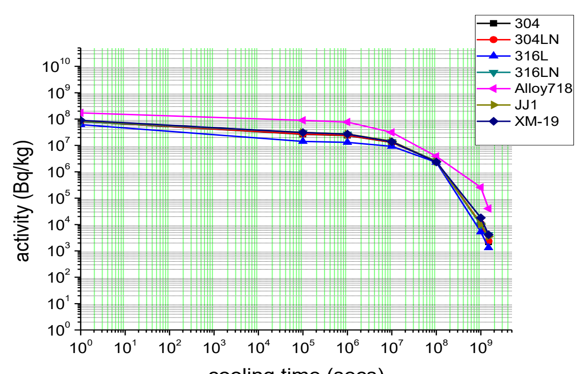
Objective

- Predict the activation of materials for accelerating the procedure of ITER neutronics studies without running codes

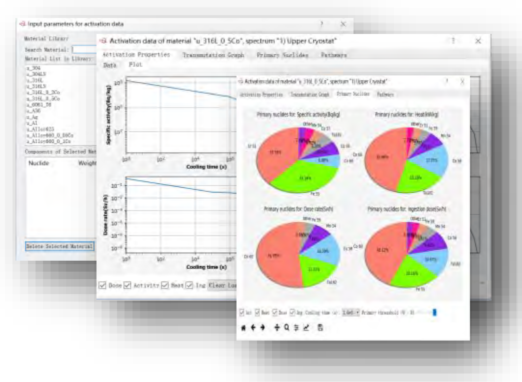
The activation data handbook using SuperMC

- Activation data: 90 natural elements, 17 widely used materials, neutron spectra of 6 different locations
  - Activity, heat, dose, transition, major elements, pathway
- Interface program for easy activation assessment

Activation results of 316L



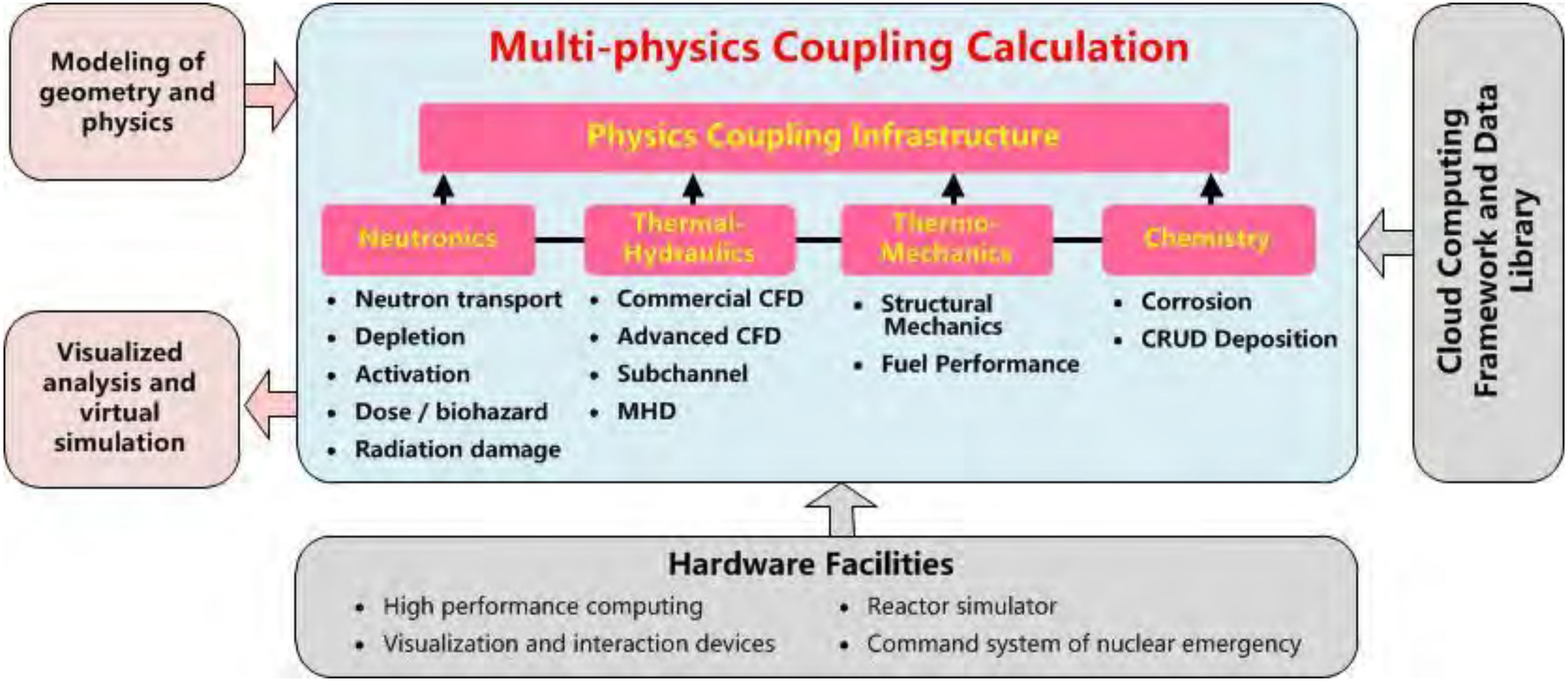
Activity of typical materials in upper cryostat



Interface program

Digital Reactor VisualBUS

High fidelity integrated simulation of multi-physics-process-coupling nuclear system performances



Virtual Fusion Reactor (Fusion-V)

- **Simulation and prediction of new phenomena based on multi-physics-coupling**

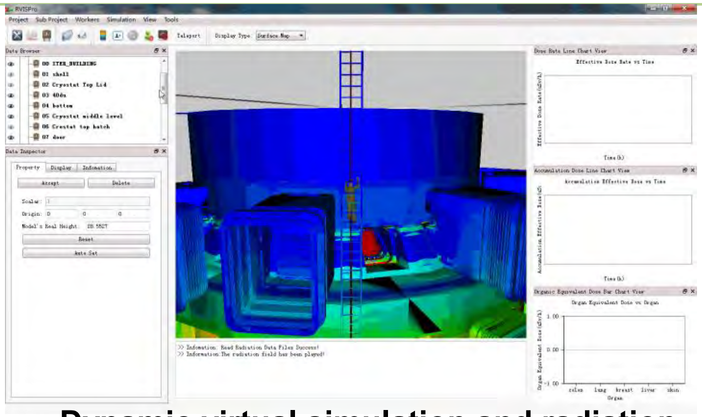
  Neutron transport in media of high-gradient-attenuation radiation, new coolant, tritium breeding and cycle, etc.

- **Safety design and evaluation in the whole space with high fidelity**

  Radiation safety design and evaluation, operation and control safety, repair safety, accident evolution, etc.

- **Collaborative research platform**

  Collaboration-based research tasks management, cloud-based research such as co-design, intelligent analysis based performance evaluation and decision support



Dynamic virtual simulation and radiation dose assessment

Supporting the accomplishment of 10+ ITER tasks, and realizing dynamic simulation of radiation dose

Contents

1. Challenges of Fusion Neutronics
2. Methodology Innovation
3. Software Development
4. Testing Facility

Roadmap of Fusion Neutron Source HINEG in FDS Team

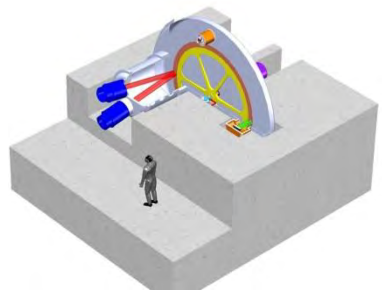
10^{12}-10^{13} n/s

HINEG-I

Steady and Pulse Dual-Mode Neutron Source

- Nuclear Data
- Methods and Software
- Radiation Protection

Basic Research on Neutronics



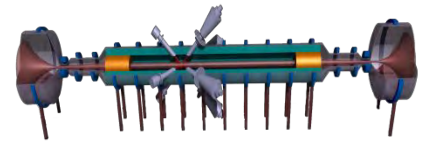
10^{15}-10^{16} n/s

HINEG-II

High Intensity Steady Neutron Source

- Materials Irradiation
- Neutronics Performance Test
  - ✓ Activation, Tritium breed, Radiation shielding…
- Nuclear Technology Application

Research on Nuclear Technology and Safety



>10^{18} n/s

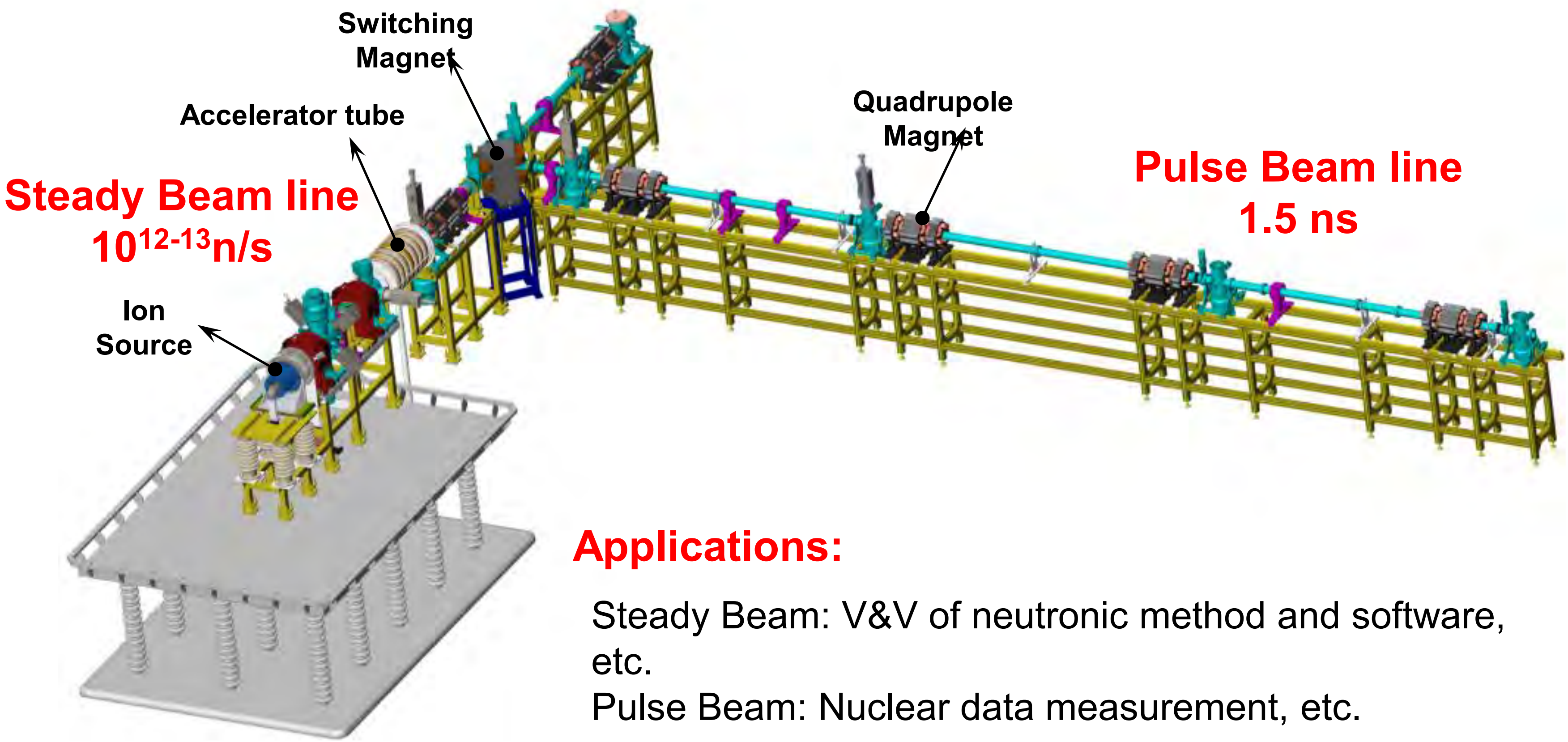
HINEG-III

Volumetric Fusion Neutron Source:(e.g. GDT-VFNS)

- Multi-Physics Coupling Test
  - ✓ Neutrons, Ions, Heat, Magnetic Field…
- High Volume Nuclear Heat Deposition
- Service Performance Integration Test

Integration Test of Components Nuclear Performance

Overview of HINEG-I

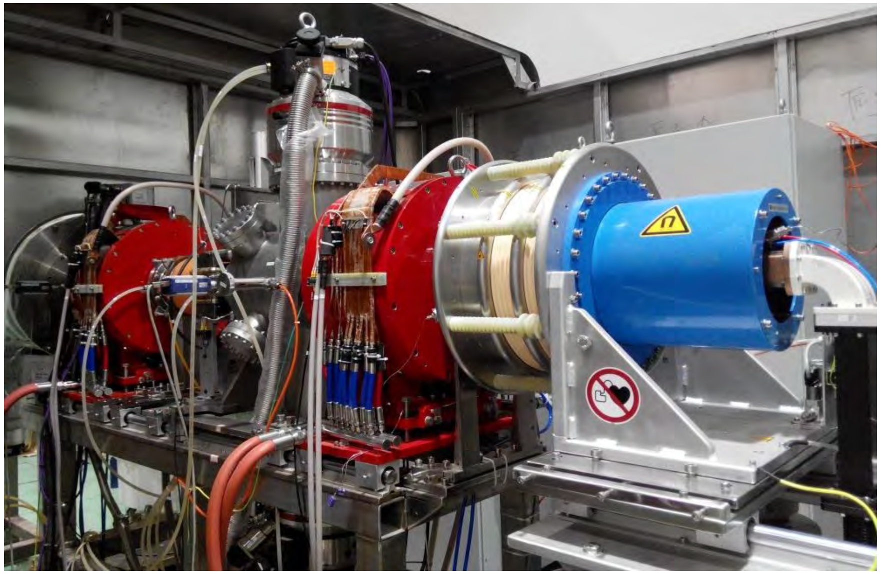


Applications:

Steady Beam: V&V of neutronic method and software, etc.
Pulse Beam: Nuclear data measurement, etc.

Fusion neutrons with yield up to 6.4×10^{12}n/s have been generated, and currently it is in operation.

HINEG-I Main Sub-systems


Ion Source and Low Energy Beam Transportation

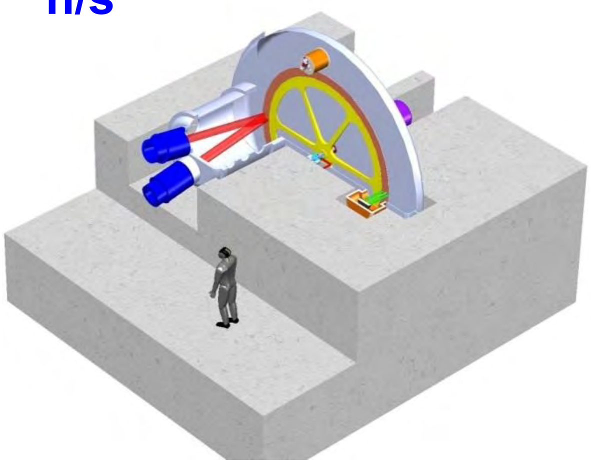

Steady Beam Line


Pulse Beam Line

Control Room

Preliminary Scheme of HINEG-II

- Neutron yield：10^{15}-10^{16} n/s



Conceptual Design Option

- Key Technology of HINEG-II

Ultra-High Power Rotating Target	High Heat Flux (≥8MW) Removal Technology
Ion Accelerator	Ampere Level Ion Source & Accelerator Technology

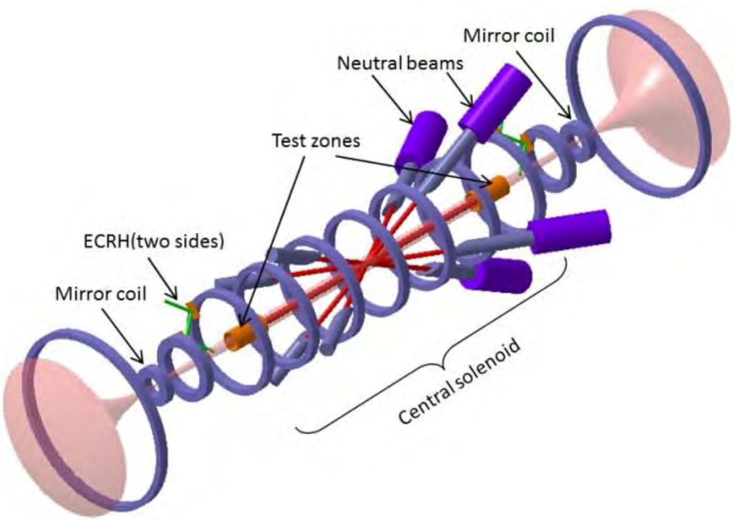
R&D of key components of HINEG-II are on-going

Optional Conceptual Design of HINEG-III

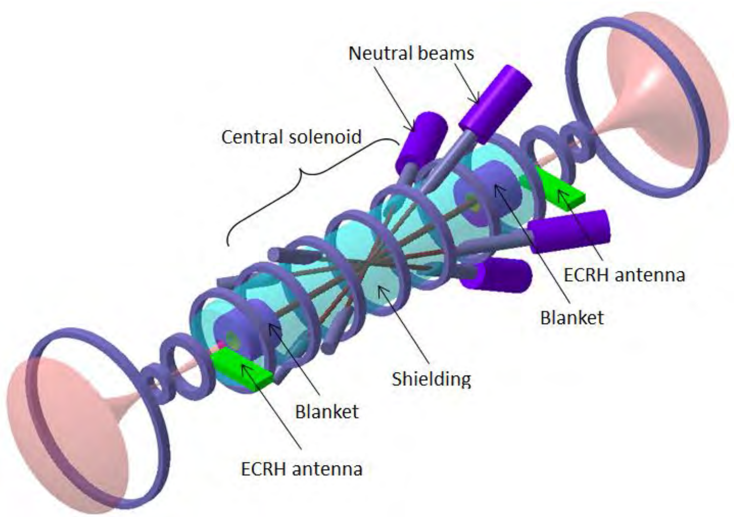
Support Project：**IAEA Coordinated Research Project F1.30.15 (2012-2016)**

International Cooperation：**8 countries (12 institutions) currently involved**

- **GDT-VFNS:** **Fusion Materials and Component Testing facility**
- **GDT-Hybrid:** **Fusion-Fission Hybrid System**



GDT-VFNS

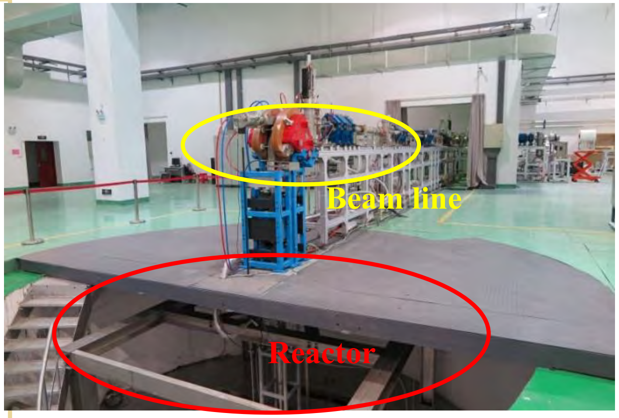


GDT-Hybrid

The conceptual design of HINEG-III has been preliminarily finished

AFDS-0 Accelerator-based Fusion Neutron Source Driven Zero Power Subcritical Reactor

- **The experimental platform for the integrated validation of lead based reactor neutron and safety control**
  - Physical design and analysis method, program and database verification of lead based reactor
  - Integrated test of physical plan and control technology of lead based reactor
- **The test equipment for physical and engineering validation of lead base reactor core**
  - The energy spectra are similar to that of CLEAR-I core（similar coolant, similar fuel and similar structure）
  - The core arrangement is flexible and other small and medium sized metal cooled fast reactor core can be simulated in full-scale
- **Taking into account the development requirements of ADS sub critical lead reactor technique**
  - Can be coupled with the external neutron source to achieve sub critical operation
  - Can provide necessary nuclear physics data support for applying for permits of CIADS construction



AFDS-0

Summary

1. INEST / FDS Team invested great efforts on R&D of fusion neutronics

2. Progress has been made on methodology innovation, software development and testing facility.

3. International collaboration is open especially for the development and application of SuperMC, fusion neutron source HINEG and other aspects.

Thanks for Your Attention !

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