FDS Team

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Highlights of Cross-Cutting R&D Activities for ADS and FDS systems in China

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ADS: Accelerator-Driven Sub-critical System

FDS: Fusion-Driven Sub-critical System

Program Overview with emphasis on Cross-Cutting R&D Activities

Contents

Economy Development and Energy problem

(In the present)

- **Population is ~1.3 billion**
- **Aver. energy consumption per person in China is less than 1/2 of the world level and less than 1/10 of the developed country's level.**
- **Fast development of economy with annual rate of 8-10 % has kept for more than 25 yeas (this year expected ~11%)**
- **China has been the 2nd largest energy producing and consumption country in world**
- **China has been the 2nd largest CO_2 producer**

Economy Development and Energy Problem

(In the future)

- **Conservatively predicted capacity of electricity will be 1200~1500 GWe**
- **Population would be 1.5 billion at 2050**
- **China would be the 1st largest CO_2 producer at 2025.**

Serious shortage of energy resources ???
Serious pollution of environment ???

Renewable energy + Nuclear Energy

Fission Power Development and Problem

(Current policy)

Develop nuclear power as fast as possible

- **2010: ~11GWe (~2% of total capacity)**
- **~2020: 40GWe (4% of total)-100GWe**

  >3 new units to be constructed

  per year from now to 2020
- **~2050: 240GWe (20% of total)?**

Fission Power Development and New Problem

(future prediction)

Scenario	Ratio A	Ratio B	Nucl. Power	Capacity (Approximate Scale)
Low Level	10%	6%	120Gw	Double in France
Mid. Level	20%	12%	240Gw	Sum in US, France and RF
High Level	30%	18%	360Gw	> Sum all over the world

A: fraction of nucl. power in total electricity capacity

B: fraction of nucl. power in total primary energy capacity

Nuclear fuel supply ?
Radioactive waste disposal ?
Safety problem ?

Fusion Status and Its Long Road to Go

- **Current:** **EAST/HL2A, KSTAR, MAST, …(~2020)**
- **Near Future:** **ITER/IFMIF/CTF…(2020~2040)**
- **Far Future:** **fast/ultra-fast track to DEMO**

(???~???)

Fusion has a very good progress, but **still needs hard work to economical utilization:**

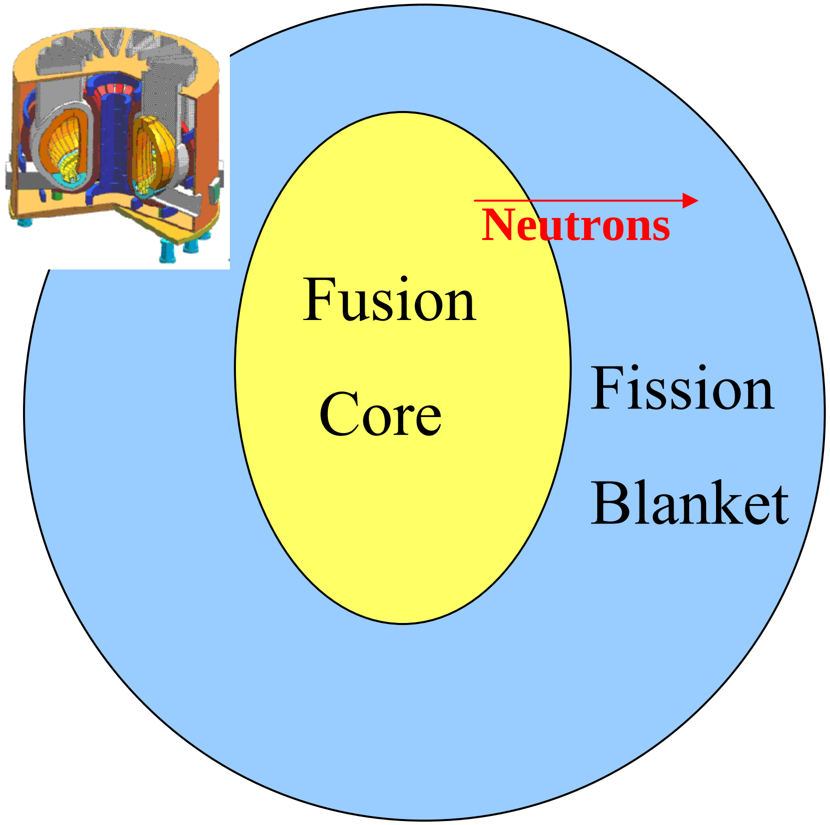
➔ feasible to seek for near-term applications

➔ necessary to find out near-term applications

Fusion-Driven Subcritical System - FDS

Multi-Functional Hybrid Reactor

Fusion driver + Subcritical Fission Blanket

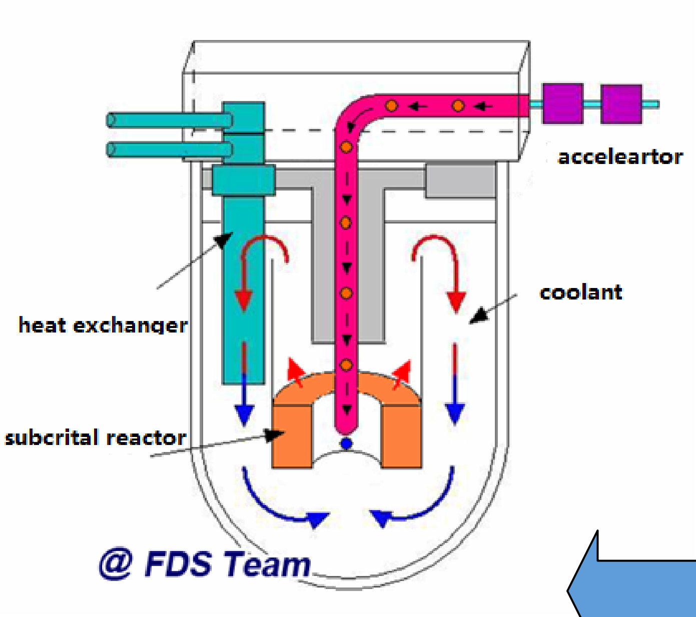


Functions:

- **waste transmutation**
- **fuel breeding**
- **energy production**
- **material test**
- **other applications**

Accelerator-Driven Subcritical System - ADS

Accelerator/target driver + Subcritical Fission Blanket



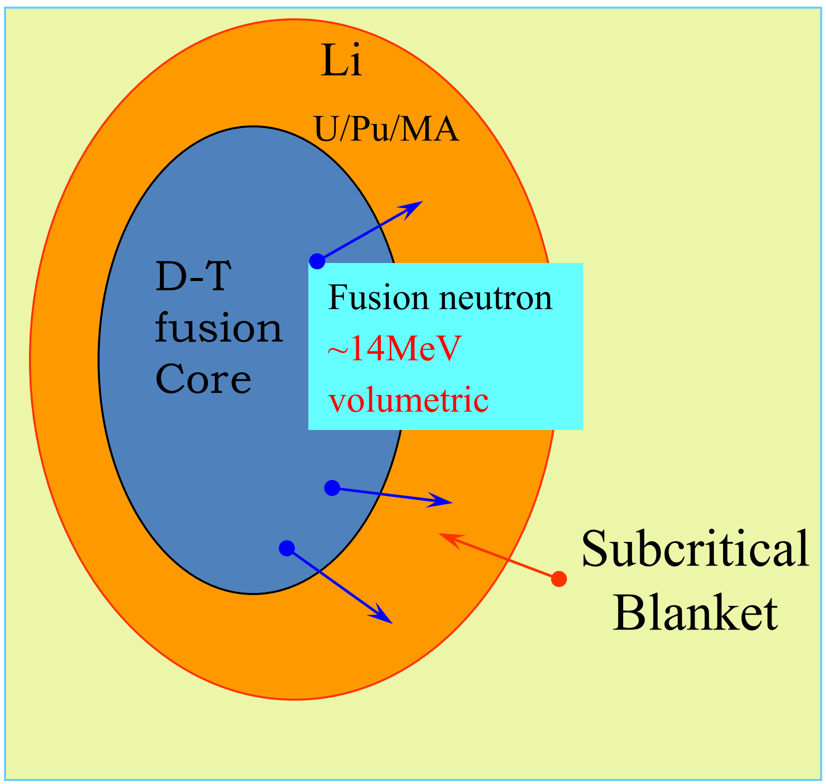
Spallation reaction: Accelerator supplies protons to bombard heavy metal target

Fission reaction: spallation neutrons drive the fission reactions in a subcrital blanket

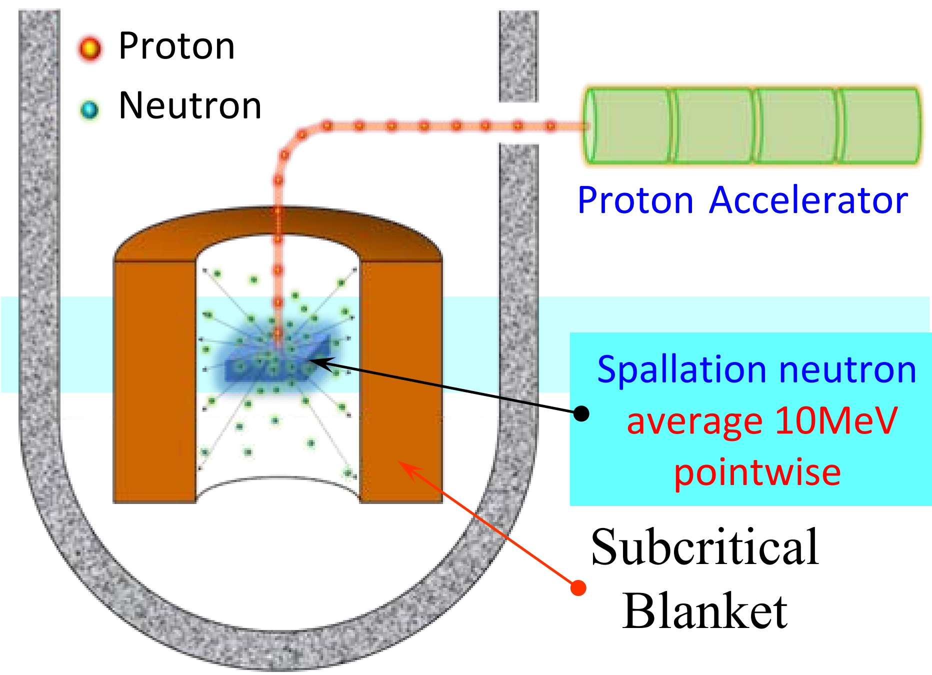
Main functions:

1. Energy production: n + U/Pu/MA ➔ Energy
2. Fuel breeding: n + U^{238}/Th^{232} ➔ Fissile
3. Waste transmutation: n + MA/FP ➔ less-harmful nucleus

Rationale of Two Types of Subcritical Systems
(FDS and ADS)



FDS - torus



ADS - cylinder

Potential Advantages of Hybrids

- **Lower requirement on driver-related parameters**

  (improved energy balance by fission blanket)
- **Rich neutrons to achieve multi-goals**

  (improved neutron balance by fusion neutrons)
- **Good passive and inherent safety performances**

  (subcritical)
- **Avoidance of nuclear proliferation**

  (large design margin from subcritical features)
- **In general, it can benefit both fusion and fission**

  (fill in the gap, solve left problems by fission, promote fusion)

History of R&D Activities on FDS

1986-2000, supported by MOST

"National 863 program"

fusion hybrid fuel breeder design activities

(conceptual design, engineering outline design etc.)

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

fusion hybrid waste transmuter design activities

(concept development, safety analysis etc.)

2007-present, supported by MOST, CAS, NSFC

hybrid applications for Energy Production

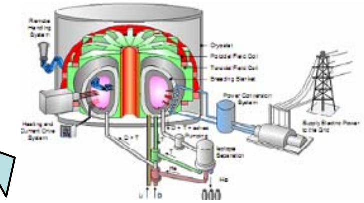
/Fuel Breeding/Waste Transmutation

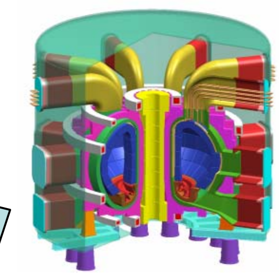
"National 973 program"

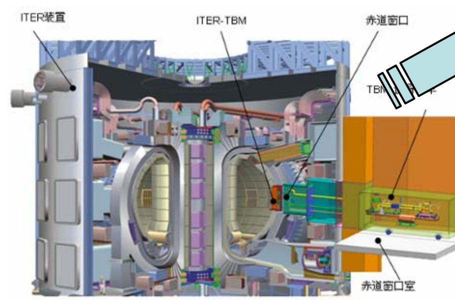
(concept optimization and key technologies R&D,

with emphasis on utilization of viable technologies)

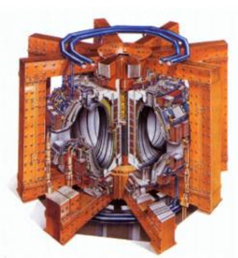
Roadmap of Fusion Application
Through FDS Hybrid


Power Plant


Fusion DEMO



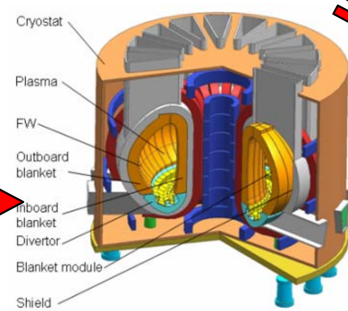
ITER


JET


JT60


EAST & HL2A
TBM & Mater. R&D

FDS-MFX



FDS-SFB (Hybrid DEMO)

- Waste Transmutation
- Fuel Breeding
- Energy Multiplication
- Materials Test

15~20 yr earlier

Now~2015 | 2015~2025 | 2030~2040 | 2050

History of R&D Activities on ADS

1995-1999, supported by MOST

"National 973 program"

Conceptual study:

Blanket concepts, reactor/accelerator physics,

Nuclear data

Nuclear materials

Physical experiment etc.

2000-present, supported by MOST, CAS

"CAS special program"

Key technology R&D program:

Verification facilities (RFQ, Venus etc.)

Accelerator technology

PbBi loop technology

Contents

FDS Concepts

FDS Series Fusion Reactors & Blankets Conceptual Design for DEMO

- **FDS-I: Fusion-Driven Subcritical System**
  for early applications of fusion (multi-function)
  e.g. waste transmutation, fuel breeding etc.
- **FDS-II: Fusion Power Reactor**
  for highly efficient 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 conceptual path

developed

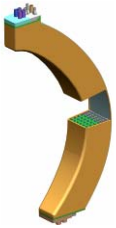
In progress:

based on available or very limitedly extrapolated fusion and fission technologies

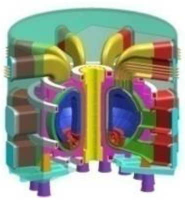
- **FDS-EM: A Fusion-Fission Hybrid reactor**
  for energy production
- **FDS-FB: A Fusion-Fission Hybrid reactor**
  for fuel breeding
- **FDS-WT: A Fusion-Fission Hybrid reactor**
  for waste transmutation
- **FDS-SFB: A Fusion-Fission Hybrid reactor**
  for spent fuel burner

FDS-MF: Multi-Functional Fusion-Fission Hybrid Concept

FDS-I ← 450°C

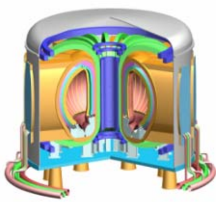


DWT

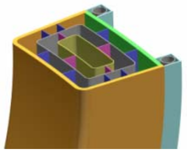


FDS-II ← 700°C

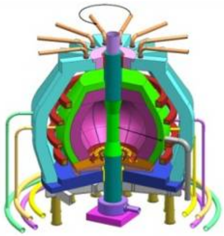
DLL/SLL



FDS-III ← 1000°C



HTL



FDS-ST ← 450°C

CCP

Y. WU et.al, J. of Fusion Engineering and Design, 2006, 81(23-24): 2713-2718

Re-evaluate the Performances of Various Fusion-Fission Hybrid Reactor Concepts

A hybrid reactor for energy production: FDS-EM
A hybrid reactor for fuel breeding: FDS-FB
A hybrid reactor for waste transmutation: FDS-WT

FDS-MF ?

multi-functions based on available or very limited extrapolated fusion and fission technologies

Specific

➔to develop a DEMO concept for application before pure fusion:

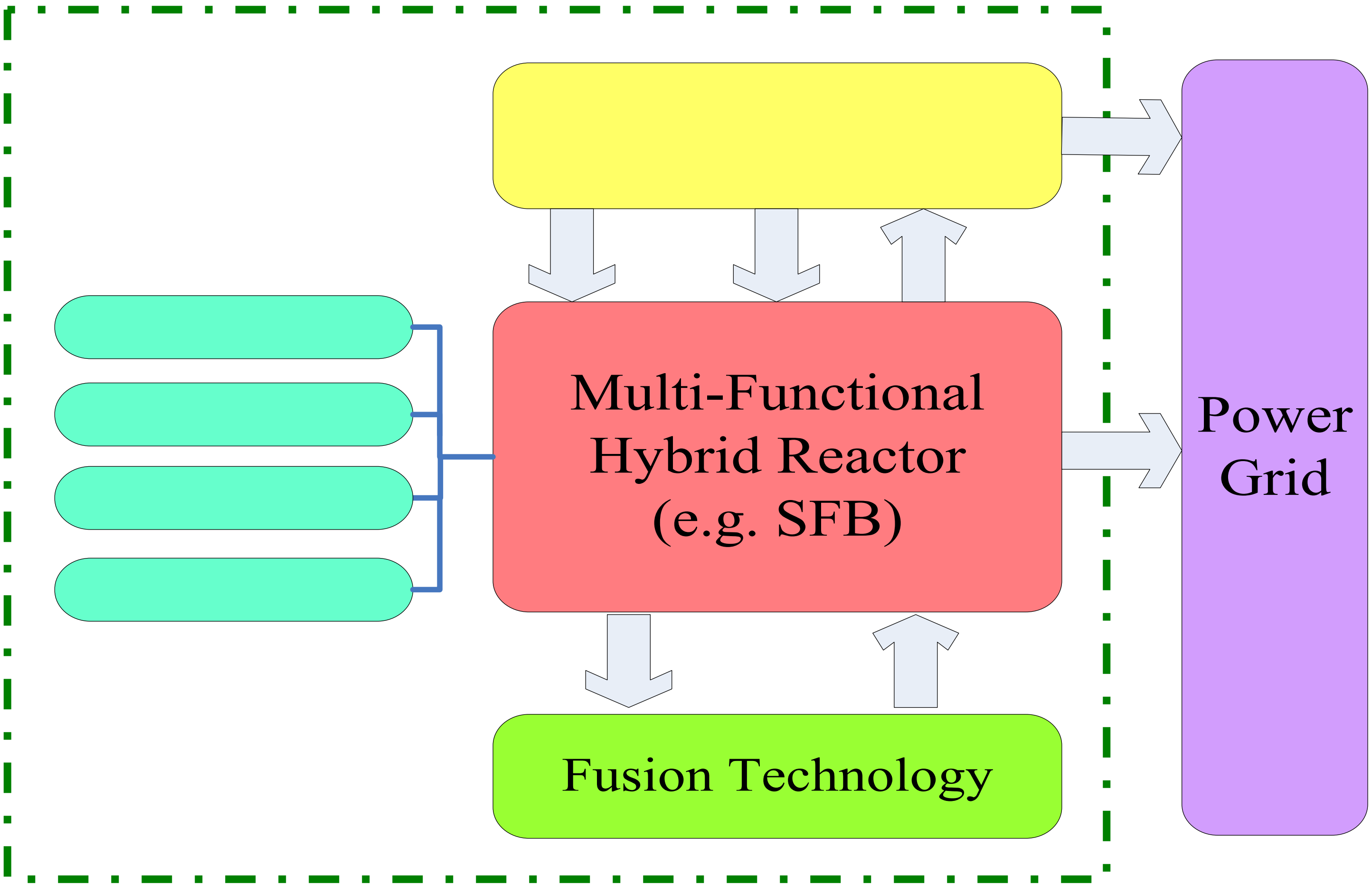
FDS-SFB (Spent Fuel Burner)

➔ to define a Multi-Functional concept as test platform before DEMO:

FDS-MFX (Multi-Functional eXperimental facility)

FDS-SFB

A Fusion-Fission Hybrid Reactor for Spent Fuel Burning

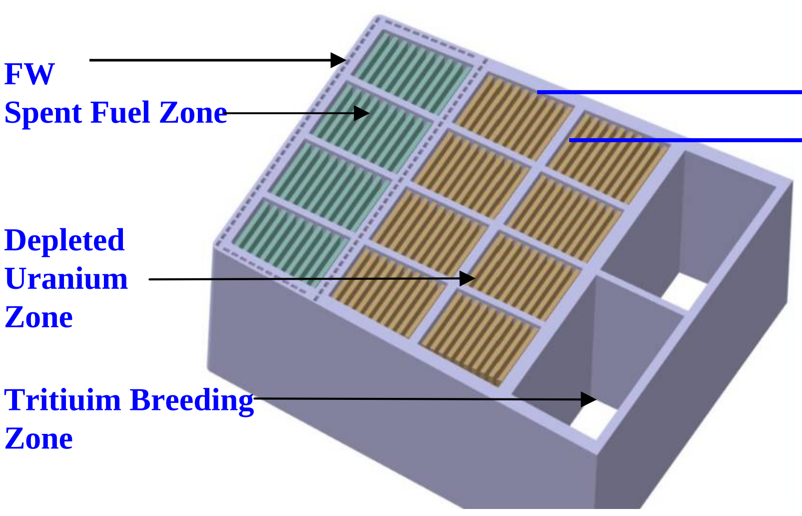


PW

Reference Plasma Core (Driver) Parameters for FDS-SFB/MFX

Parameters	ITER	EAST	FDS-MFX	FDS-SFB
Fusion power (MW)	**500**	**-**	**50**	**150**
Major radius (m)	6.2	1.95	**4**	4
Minor radius (m)	2	0.46	**1**	1
Aspect ratio	3.1	4.2	**4**	4
Plasma elongation	1.85	1.8	**1.7**	1.78
Triangularity	0.33	0.45	**0.45**	0.4
Toroidal magnetic field on axis (T)	5.3	3.4-4.0	**5.1**	6.1
Safety factor / q-95	3	-	**2.83**	3.5
Plasma current (MA)	15	1.5	**6.1**	6.3
Average neutron wall load (MW/m^2)	**0.57**	**-**	**0.17**	**0.49**
Average surface heat load (MW/m^2)	0.27	0.1-0.2	**0.1**	0.1
Fusion gain	>10	3	**~1**	3
Normalized beta， (%)	2.5	-	**3**	3

Blanket Scenario for FDS-SFB



Schematic view of outboard blanket

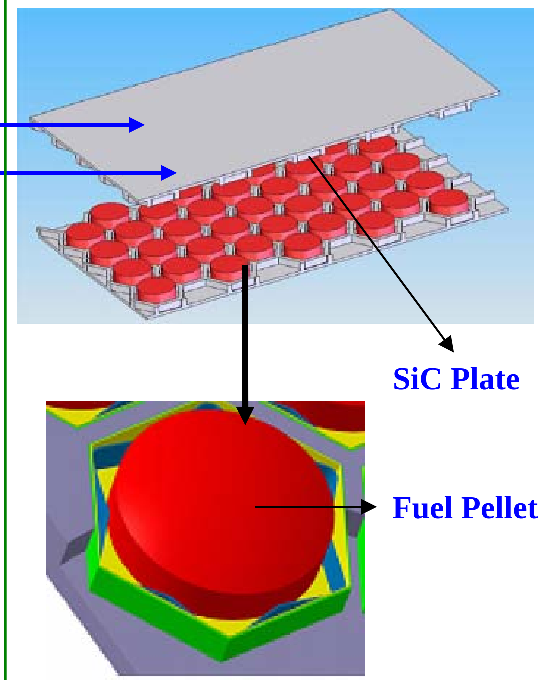
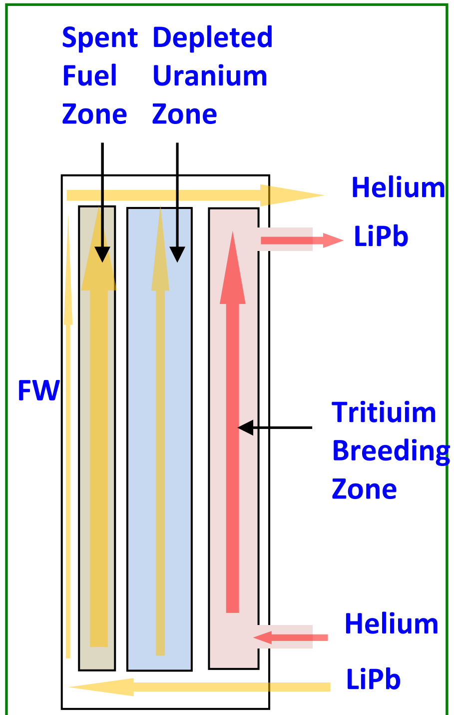


Plate-type Fuel



Coolant flow scheme

Spent Fuel Zone
Coolant： Helium
Flow scheme： Poloidally
Fule style： Plate-type fuel

Depleted Uranium Zone
Coolant： Helium
Flow scheme： Poloidally
Fule style： Plate-type fuel

Tritium Breeding Zone
Coolant： LiPb
Flow scheme： Poloidally

FDS-MFX Concept and Objectives

- Based on easy-achieved plasma parameters extrapolated from the successful operation of the existing tokamaks e.g. EAST and well-developed fission technologies e.g. GEN-IV
- Demonstrate the scientific and technological feasibility of fusion-fission hybrid reactor

- **Main tests:**
  - ✓ Plasma science and engineering
  - ✓ Fusion nuclear technology and engineering (neutronics/thermalhydraulics/material etc.)
  - ✓ Fusion fuel (tritium) technology
  - ✓ Fission fuel technology
  - ✓ Subcritical reactor technology
  - ✓ Reactor operation and remote maintaining technology

FDS-MFX Main Design Characteristics

Fusion Driver			~50 MW
Blanket	**Coolant**		Helium gas
	Fuel	**Exp. Stage 1**	Pin type fuel Natural Uranium (Oxide) Stainless Steel (Cladding)
		Exp. Stage 2	Plate type fuel Enriched Uranium (Carbide) SiC (Cladding)
	Tritium Breeder		LiPb
	Structural Material		RAFM

Fuel Stage 1: For proof-of-principle experiment of hybrid reactor

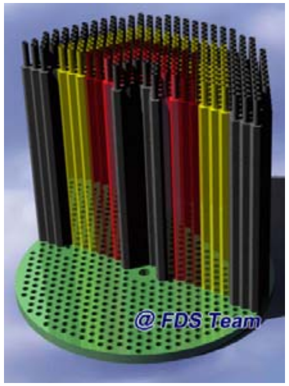
Fuel Stage 2: For technology/eng. demonstration of hybrid reactor

ADS Concepts

CAS-ADS Concept： ADS-WT

（ASIPP-proposed Demonstration Reactor for Waste transmutation ）

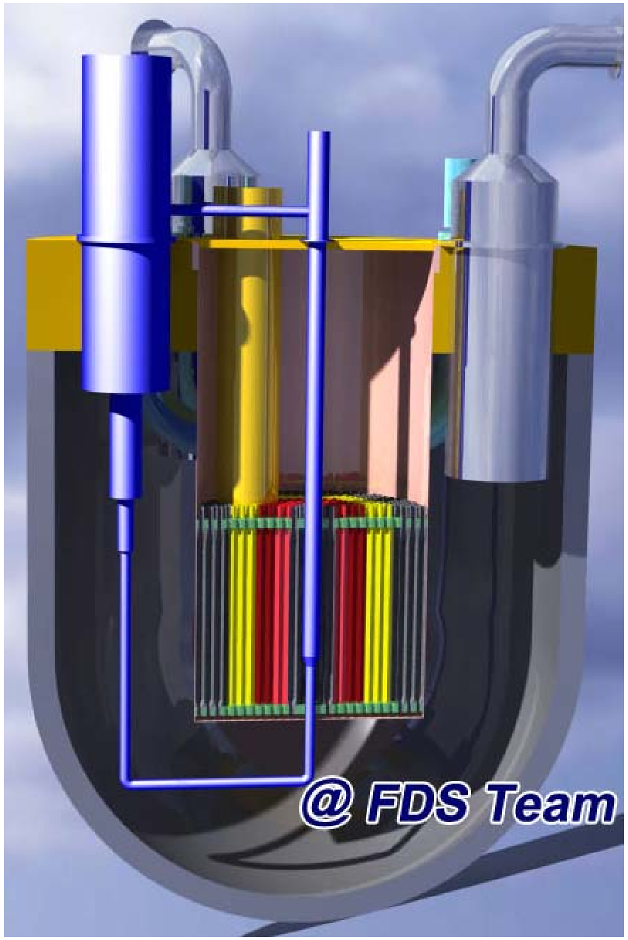
Design objective	Waste transmutation
Accelerator power	1.5GeV/10mA
Keff	0.95-0.98
Thermal power	~1000MW
Spallation target	Windowless PbBi Target
Fuel	Dispersed MA/Pu/Zr alloy
Coolant	Liquid PbBi



Subcritical Blanket

Fuel Assembly

Fuel Pin



ADS -WT

CAS-ADS : Verification & Experimental Facilities

- **Experimental ADS-ER**: Build the ADS transmutation experimental reactor and provide technical support to resolve the ADS demonstration reactor.
- **Initiative ADS-VF**: Build small scale coupling system with accelerator and reactor, to demonstrate the ability of designing, building and operating the ADS system device.

Project	Accelerator power (MW)	K_{eff}	Core Power (MW)	Flux Spectrum ($n/cm^2/s$)	Target	coolant	Fuel
ADS-ER	6-10 (0.6-1GeV/10mA)	0.95-0.98	~100	FR 10^{15}	LBE Windowless	LBE	MOX (MA)
ADS-VF	1 (100MeV/10mA)	~1	~10	FR	LBE (window)	LBE	UO_2

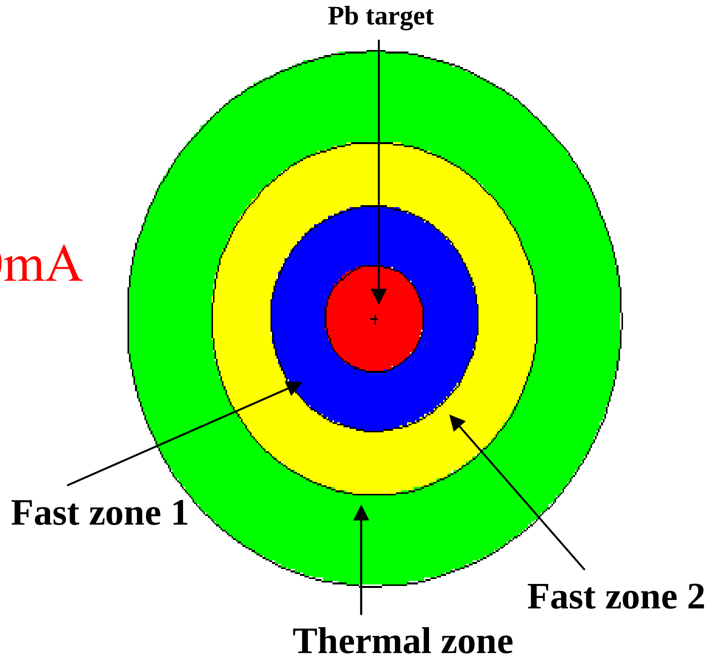
CIAE-ADS Concepts

■ General concept
- Fast-thermal coupled system
- Design goal: Energy production, transmutation

■ Accelerator
- Beam power:10MW
- Proton incident energy: 1GeV, Current: 10mA

■ Target: Pb

■ Preliminary Core design
- Thermal power: ~1000-2300MW
- Fuel design: Natural U, MA and Th



Design & Analysis Tools Development (Software)

1. **Physics and Engineering Calculation PEC**
   - **Multi-functional neutronics calculation & analysis system: VisualBUS**
   - **Multi-physics (neutronics/thermalhydraulics/MHD) coupling simulation codes: NTC/MTC**
   - **System (safety/economy) analysis codes: TAS, RiskA, SYSCODE**
   - **Liquid TBM accident analysis code based on RELAP5**
2. **Computer Modeling and Simulation CMS**
   - **Automatic Modeling Codes: MCAM/SNAM/RCAM/HUMOP**
   - **Visualization/Virtual Roaming/Virtual Assembling Codes: SVIP/RVIS/FVAS**
3. **Database Management System DMS**
   - **Plasma/Nuclear/Material/Component data libraries: FusionDB**
4. **Integrated Design & Simulation Platform 4DS**
   - **Virtual Fusion Reactor (application of 4DS)**

> 50~100 man-years each program

Key Tools for Reactor Design and Analysis

VisualBUS

Multi-Functional Integrated 4D Neutronics Simulation System

Main Functions

4D: Coupled Calculation

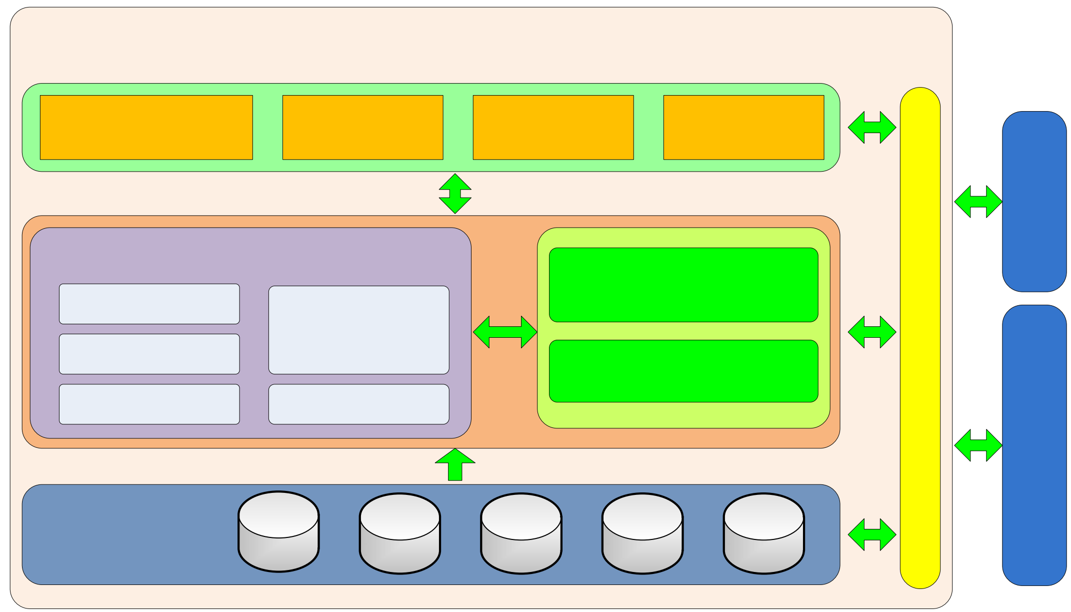
- Particle Transport
- Fuel Isotope Burnup
- Material Activation & Irradiation Damage
- Radiation Dose
- Fuel cycle management

4D: Automatic Modeling

- Monte Carlo (MC) geometries
- Discrete Ordinates (SN) geometries
- MC-SN coupled geometries
- Human dosimetry models reconstructed

4D: Visualized Analysis

- Static / dynamic physical data fields
- Virtual roaming and dosimetry assessment
- Virtual assembling of component models

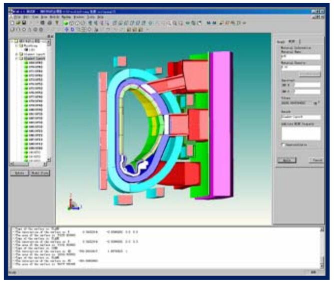


Supporting Components:

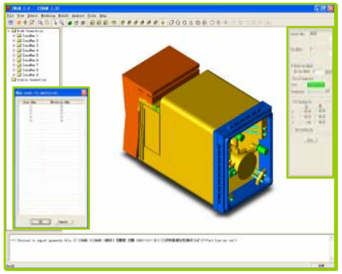
- **Hybrid Evaluated Nuclear Data Library** for fusion/fission/ hybrid
- **Interfaces for other physics process simulations** such as thermal-hydraulics, mechanics, safety, environmental impact and economics etc.

VisualBUS User Interface

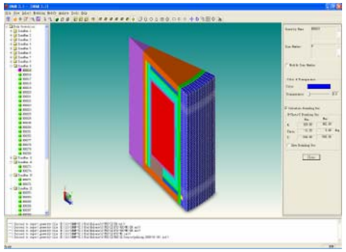
Modeling for MC: MCAM

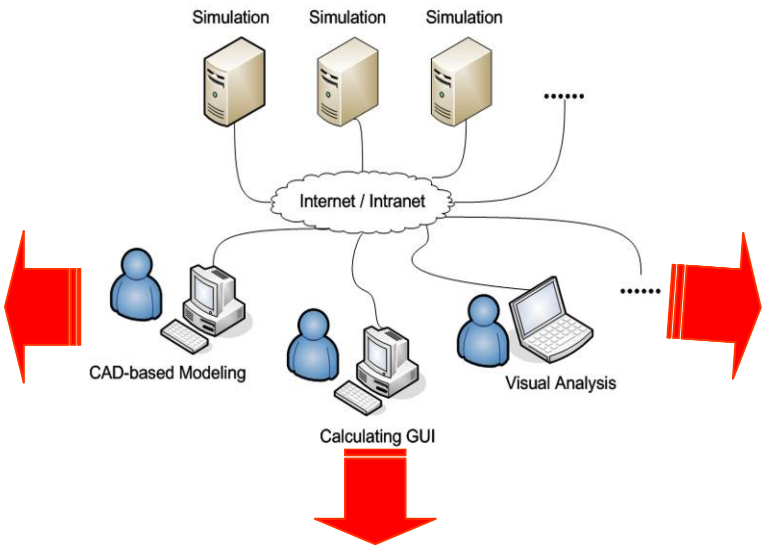


Modeling for Sn: SNAM

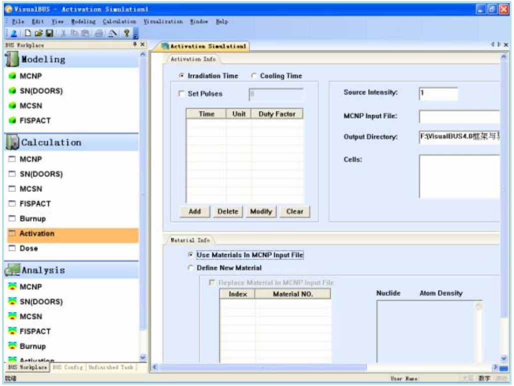


Modeling for MC-Sn: RCAM

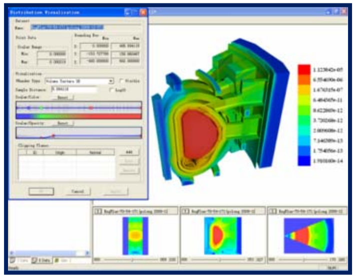




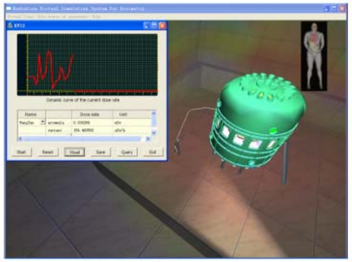
Easy-integrating codes



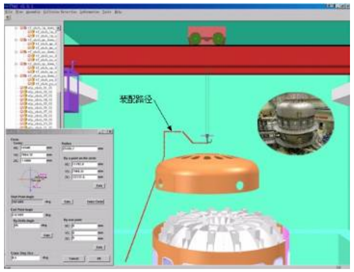
Field Visualization: SVIP



Virtual Roaming: RVIS



Virtual Assembling: FVAS

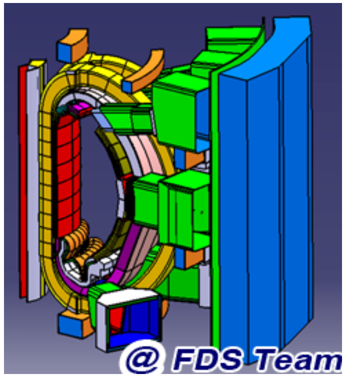


CAD-based Modeling GUI **Coupled Calculation GUI** **Visualized Analysis GUI**

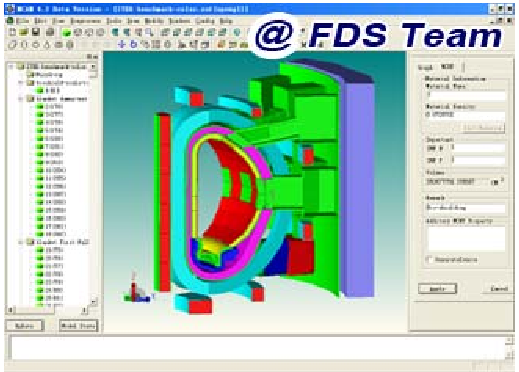
Automatic Modeling Programs

MCAM: Monte Carlo Automatic Modeling Program

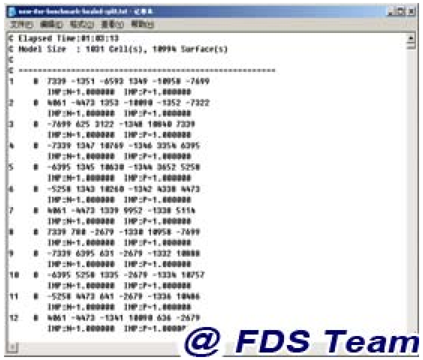
CAD ←→ MC（MCNP / TRIPOLI /…）



CAD model



Model in MCAM



MC model

- **Passed ITER QA verification & validation**
- **Selected as "ITER reference code"**
- **Created the 3D "ITER reference neutronics model"**
- **Applications: > 100 international institution users**

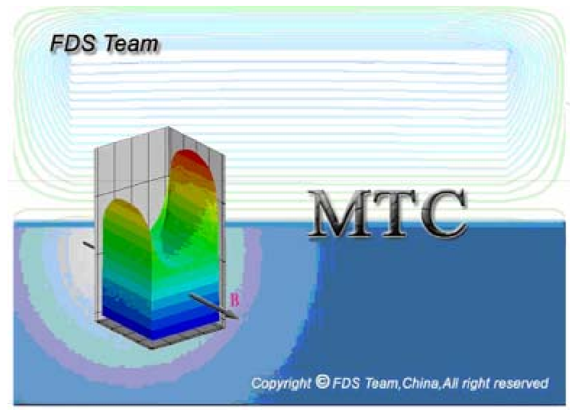
SNAM: SN Automatic Modeling Program （CAD←→SN）

RCAM: MC-SN Coupled Automatic Modeling Program （CAD←→MC-SN）

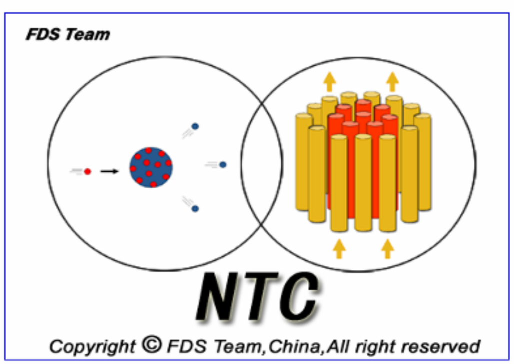
HUMOP: Human Automatic Modeling Program

MTC/NTC: Multi-Physics Coupling Simulation Programs

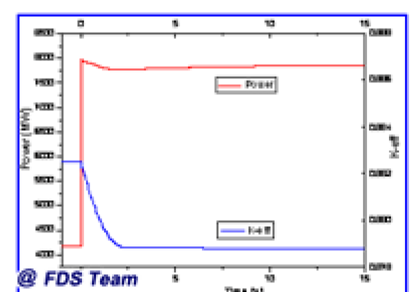
- **MTC（Magnetic - Thermohydraulics Coupled Simulation Program）**
  - **MTC-F 1.0/2.0: Developed base on the B-formulation**
    - MHD effects : FLUENT +User-routine
    - Exact solution on the condition: Ha<500
  - **MTC-H 1.0: Developed base on the ϕ-formulation**
    - Good accuracy for low magnetic Reynolds numbers
    - Consistent and conservative scheme
    - Exact solution for high Ha~10000



- **NTC （Neutronics - Thermohydraulics Coupled Simulation Program）**



- **Safety analysis**
  - —Design basic accidents analysis
  - —Severe accident analysis
- **Advanced reactor design**
  - —Advanced fission reactor design
  - —Advanced fusion reactor design



The influence of neutron source to reactor power and reactivity

Risk and Economy Analysis Programs

RiskA: Probabilistic Safety Assessment Program

- FMEA (Failure Mode and Effects Analysis)
- FTA (Fault Tree Analysis)
- ETA (Event Tree Analysis)

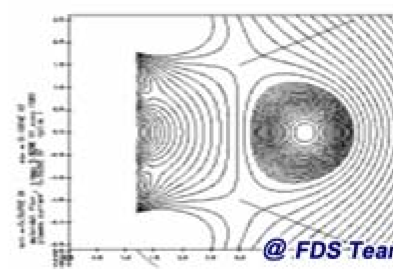
- Importance Analysis
- Uncertainty and Sensitivity analysis
- Optimization of reliability parameters

RiskAngel: Risk Monitor for Nuclear Power Plants (Qinshan nuclear power plant)

- Instantaneous risk calculation
- Component OOS / restore
- Schedules optimization
- Evaluation of AOT/ACT

SYSCODE: System Analysis Program for Parameter Optimization and Economical Assessment of Fusion Reactor

- Physical engineering design
- Economic evaluation
- Design optimization
- Sensitivity & Uncertainty analysis

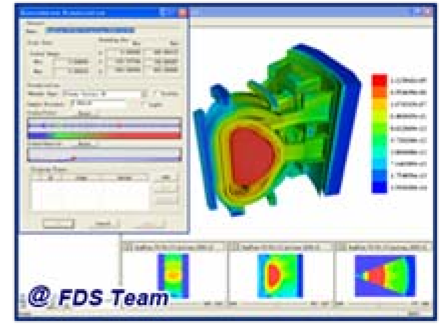


Y. Wu et.al, Chinese J. Nucl. Sci. & Eng. , Vo.27, No.3 (2007)

Visualization & Virtual Simulation Programs

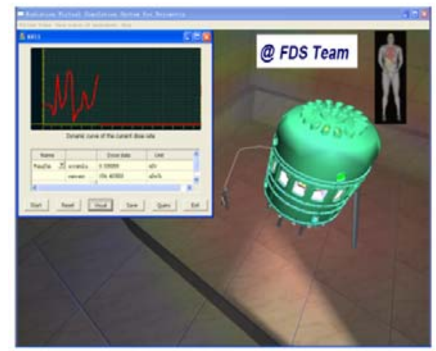
SVIP: Scientific Visualization Program

- 4D visualized data analysis for VisualBUS / MCNP / TORT...
- Various visualization functions (Iso-surface, volume rendering, ...)
- Visualized data analysis coupled with geometries



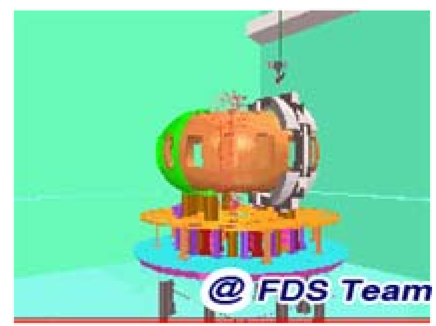
RVIS: Radiation Virtual Simulation System

- **Flexible & realistic virtual roaming**
- **4D visualization of dynamic spatial radiation field**
- **Real-time & accurate evaluation of human & organ dose**
- **Good compatibility & excellent expansibility**



FVAS: Fusion Virtual Assembly System

- **Automatic/semi-automatic/manual virtual manipulation interfaces**
- **Real-time simulation & accurate collision detection**
- **Flexible virtual roaming based on multi-viewpoints**
- **Supporting record & replay of assembly processes**



Virtual assembly of EAST

FusionDB：Database Management System for Fusion

(China Fusion Data Library)

- ◆ **Fusion data management**

  (Plasma, nuclear, material, component…)

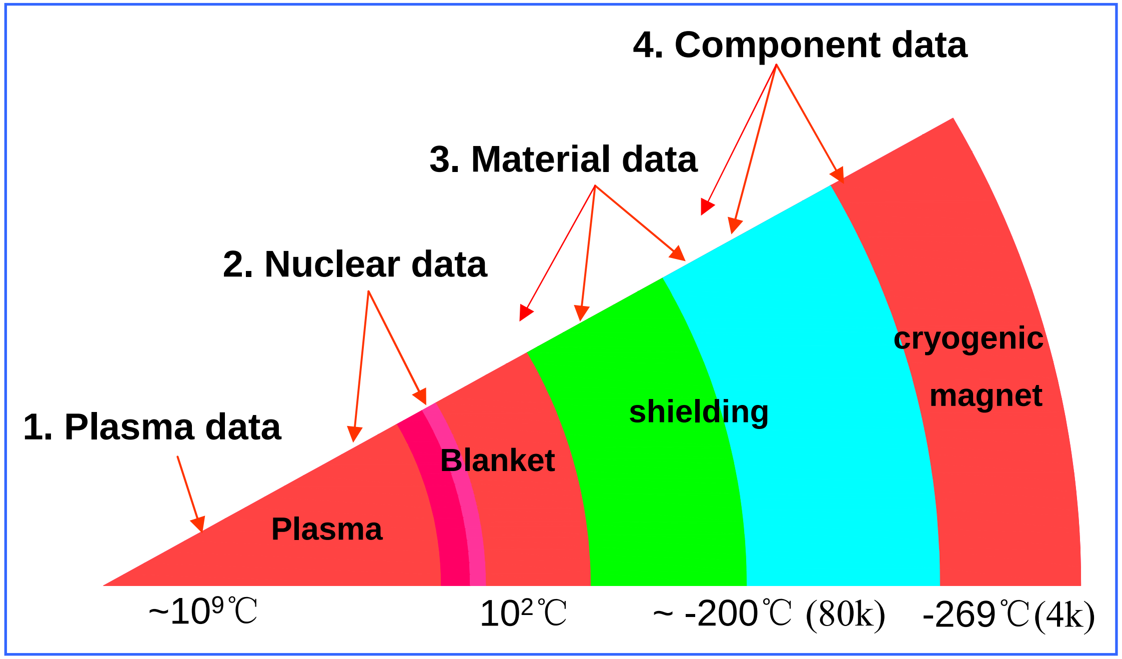
- ◆ **Data processing software**

  (visualization, model auto-conversion…)

Data sources:

EAST data | ITER data | FDS data | …

http://www.fusion.csdb.cn



ADS相关数据库？

更新了

Nuclear Data Library - HENDL

Hybrid Evaluated Nuclear Data Library for Fusion, Fission and Hybrid Applications

- From **various international evaluated neutron nuclear data libraries**, such as **FENDL, ENDF/B, JENDL, JEF** and **BROND**
- Including **Multi-function Working Libraries**, **Transport.lib, Burnup.lib, Activation.lib, Iriradiation.lib, Dose-factors.lib**

Many Kinds of Group Energy Structure

– **HENDL/CG (27n/21g)**

– **HENDL/MG (175n/42g)**

– **HENDL/FG (315n/42g)**

– **HENDL/ADS (372n/42g)**

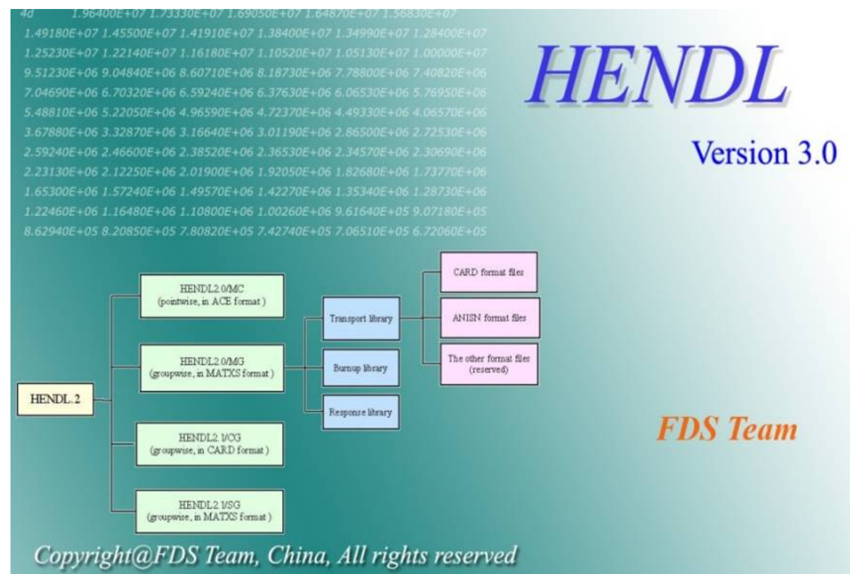
– **HENDL/MC (point-wise)**

Various Kinds of Physics Effects

– **Resonance self-shielding**

– **Temperature Doppler**

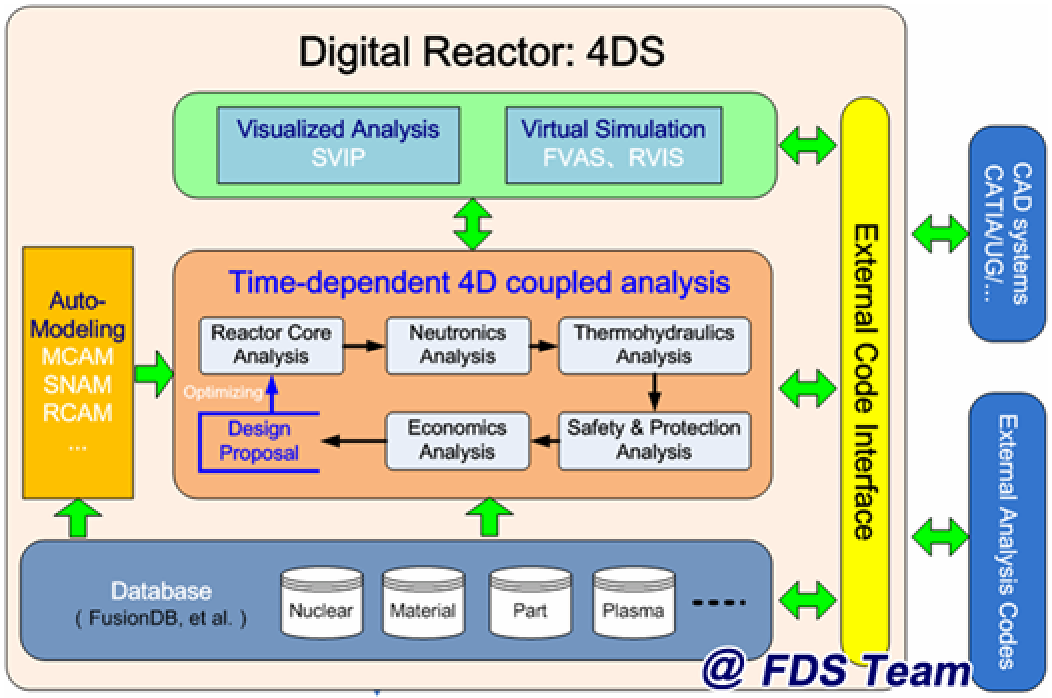
– **Thermal neutron up-scattering**



4DS: the 4-Dimensional System

for Integrated Design and Simulation of Advanced Reactors

- 4D accurate calculation based on multi-physics coupling concept
- Auto-modeling & visualized analysis
- Integration of design & operational simulation
- Auto coupling of multi-processes
- Virtual roaming & assembly



- Easy to integrate new-developed codes, due to hierarchical design
- Serve to Design & Simulation of advanced reactors

Virtual Reactors: Digital FDS and ADS

Parametric Design; Auto-Modeling / Coupled Calculation / Visualized Analysis; Virtual Assembly & Dose Evaluation ➔ Application of 4DS

Neutronics Analysis

Thermo & Safety Analysis

System Analysis/Virtual Simulation

Contents

Structural Materials
&
Irradiation Facilities

Ton Level Melting of CLAM Steel

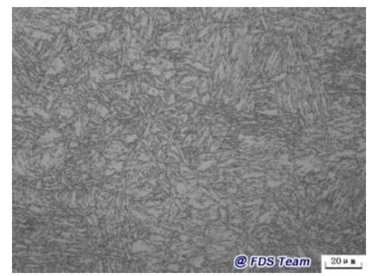
■ Main compositions

CLAM: China Low Activation Martensitic Steel

Elements	Fe	C	Mn	Cr	W	V	Ta
Content (wt%)	Bal.	0.10	0.45	9.0	1.5	0.20	0.15

■ 1.2 ton ingot smelting

■ Microstructures



■ Mechanical properties

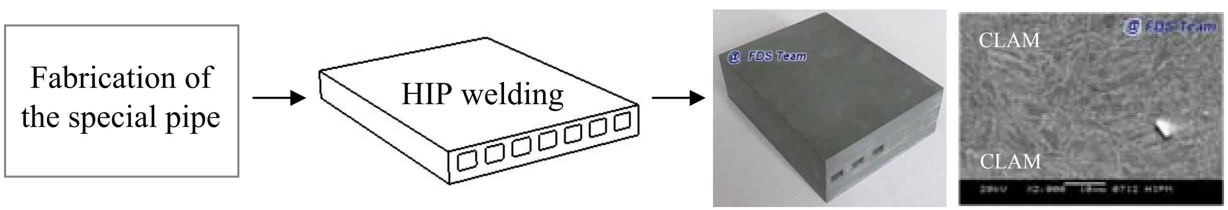
	$R_{P0.2}$	R_m	A/%	Z/%	Akv(J)
Room temperature	533.65	658.11	20.40	70.99	240, 225, 248
	533.96	660.33	24.20	76.38	
	541.51	663.72	21.20	72.97	
High temperature	306.68	349.29	20.00	78.97	
	319.42	362.10	20.80	86.34	
	312.28	350.97	24.00	85.23	

Compositions and mechanical properties agree with the requirements of design.

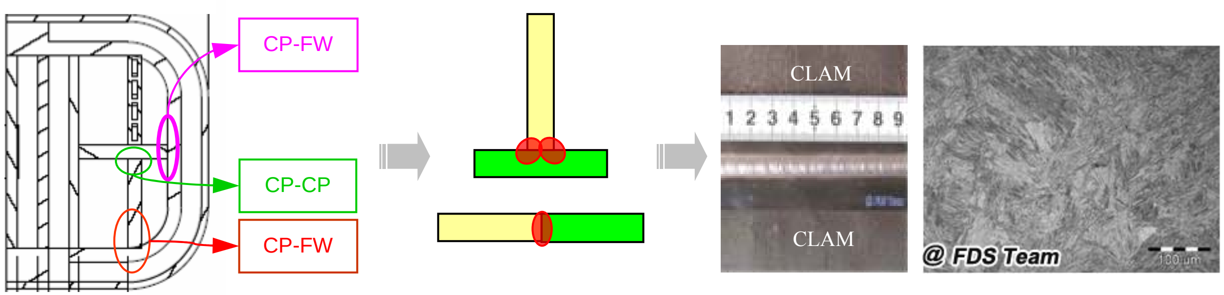
Fabrication and Manufacture of TBM

- **Following the design & test strategy of TBM, exploration for the fabrication and manufacture technique of TBM are being performed.**

⌖ Exploration for fabrication of the FW and CP by HIP welding



⌖ Exploration for assembly of the key components by EB Welding

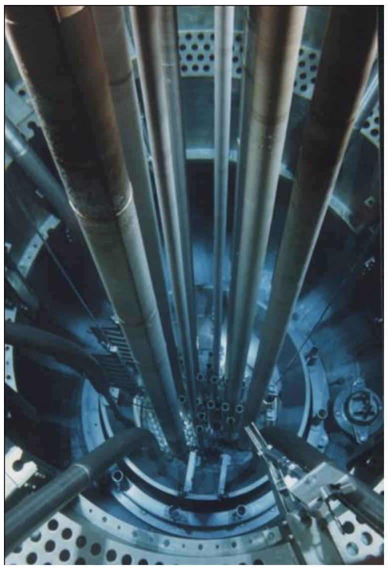


⌖ Small mockups

1/5 TBM of 316SS

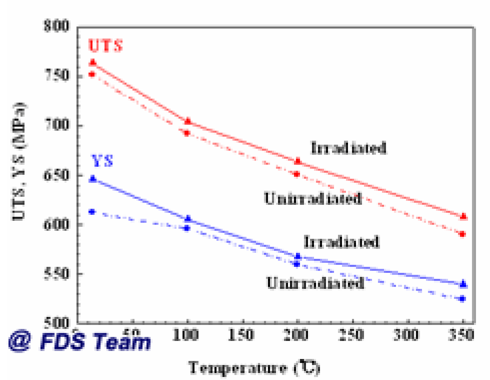

1/3 TBM of P91

Irradiation Test of CLAM Steel

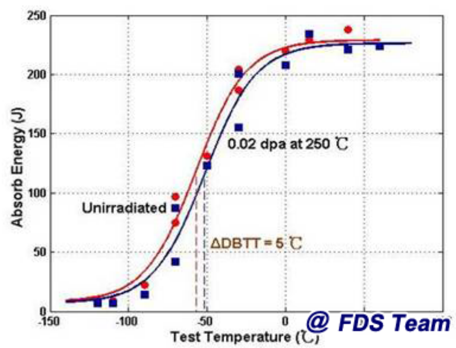


High Flux Engineering Test Reactor (HFETR) in China

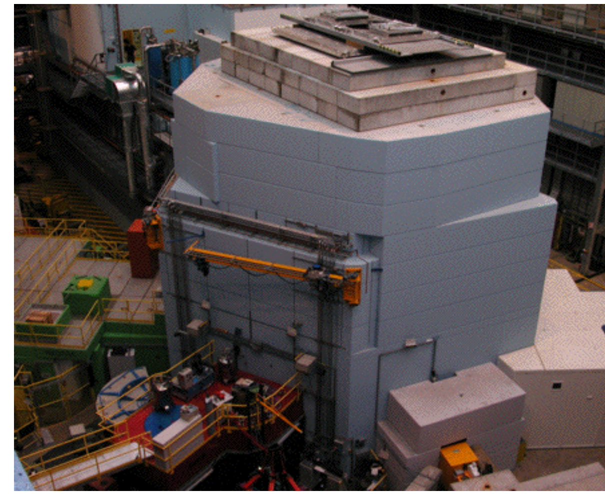
Neutron Irradiation tests (~1dpa, ~300℃) are underway.



Tensile properties



Charpy impact properties



Spallation Neutron Source, SINQ, in PSI, Switzerland

Spallation irradiation tests (>10 dpa, 100~500℃) was finished (STEP-V)

PIE to be done

Ion and electron irradiation tests were also done to investigate irradiation effects.

Related Structural Material R&D Activities

(examples)

W/W-Cu alloys (CAS-ISSP/ASIPP, Fang et al)

plasma-facing material/first wall material

V-4Cr-Ti alloys (SWIP, Chen et al)

advanced low activation structural material

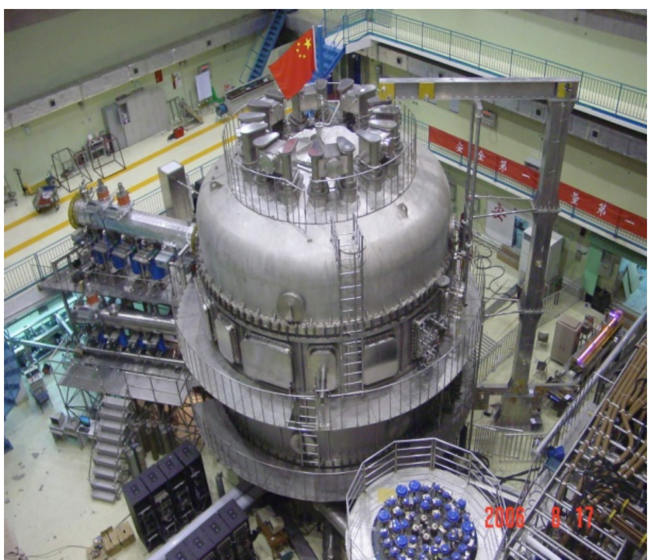
Modified 316SS (CIAE)

fission fuel element cladding material

EAST's Possible Contributions

(The first full superconducting tokamak device in the world)

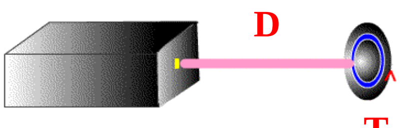
- **EAST is an important platform for fusion driver technologies and physics test at least before ITER D-T plasma operation.**
- **A fusion driver could be designed based on EAST's and other tokamaks' successful operation with long pulsed or staty-state, elongated divertor configuration and high performance plasma.**
- **EAST can make an important contribution to hybrid/DEMO development.**

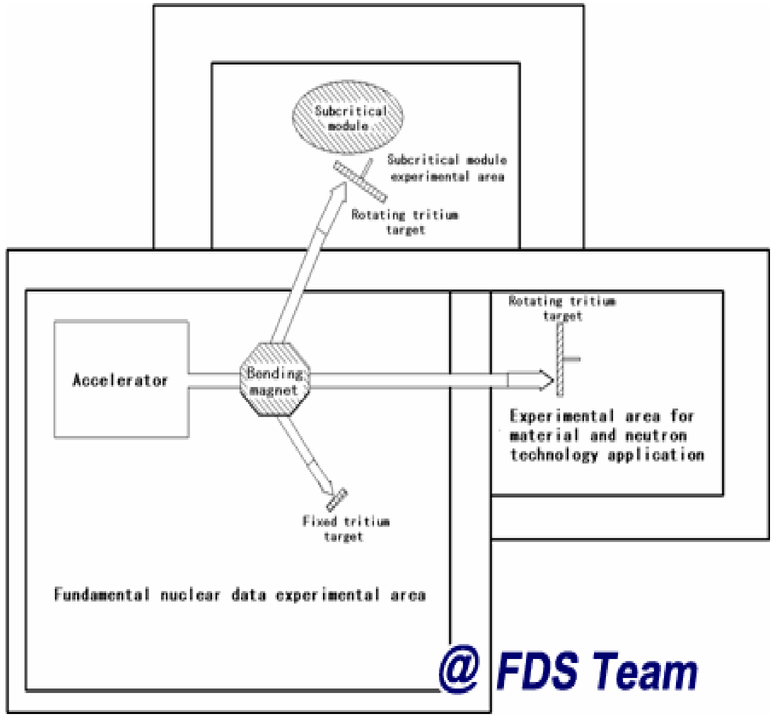


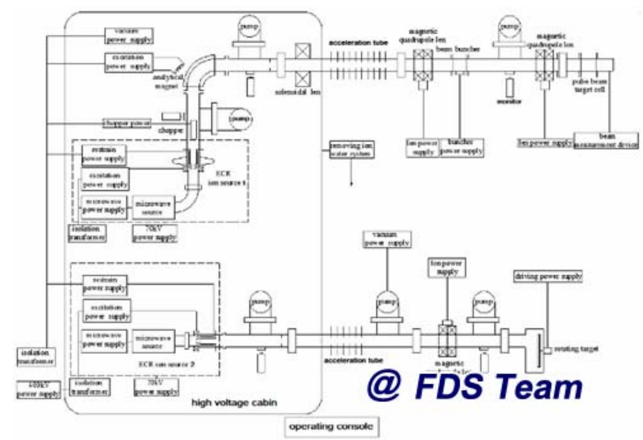
Parameters	ITER	EAST
Total fusion power	500 ~ 700 MW	(~10^{16} D-D Neutrons S^{-1})
Inductive pulse time	≥ 400 s (Q ≥10)	~ 10 s
No-inductive pulse time	1000~3000s (Q ~5)	~ 1000 s
Expected n T τ	~$10^{21\sim22}$ m^{-3} s kev	~$10^{19\sim20}$ m^{-3} s kev
B_T (6.2 m)	5.3 T	3.5 - 4.0 T (1.7m)
R_0	6.2 m	1.7 m (1.85m)
a	2.0 m	0.4 m (0.45m)
κ_{95}	1.70 / 1.85	1.8 / 2.0
δ_{95}	0.33 / 0.49	0.30 / 0.60
Ip	15 (17) MA	1.0 (1.5) MA
Divertor Configuration	Single Null	Single & Double Null
Auxiliary Heating / CD Power	73 – 110 MW	4 – 20 MW

High Intensified D-T Neutron Generator

(HINEG D-T neutron rate: 10^{10}~10^{13} n/sec，under design/concstruction at Hefei)

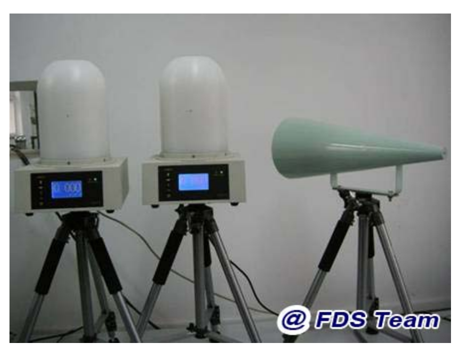






（1）**Fusion neutronics Integrated Testing of Materials and Components**

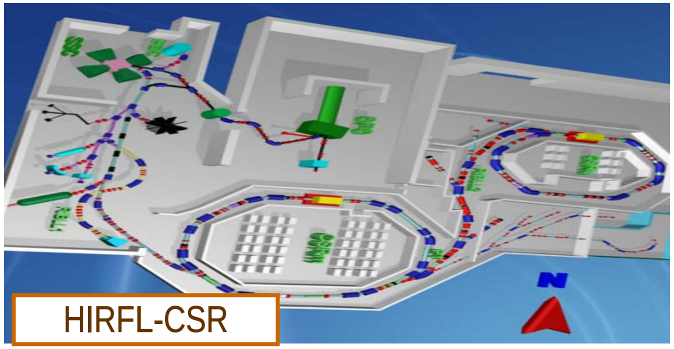
（2）**Validation of Codes and Data libraries**



Accelerator-based Heavy Ion & Synchrotron Radiation Facilities

- **NSRL (National Synchrotron Radiation Lab in Hefei)**
  - ✓ Second-generation of synchrotron light source
  - ✓ Vacuum ultraviolet photon & soft X-ray

- **SSRF (Shanghai Synchrotron Radiation Facility)**
  - ✓ Third-generation of synchrotron light source
  - ✓ ~1600 times higher than the lightness of NSRL



- **HIRFL (Heavy Ion Res. Facilities in Lanzhou)**
  - ✓ ECR + Cyclotrons + CSR
  - ✓ Ions: proton → Pb, U
  - ✓ Energy: KeV→Few GeV

□ **Potentional application for material research**

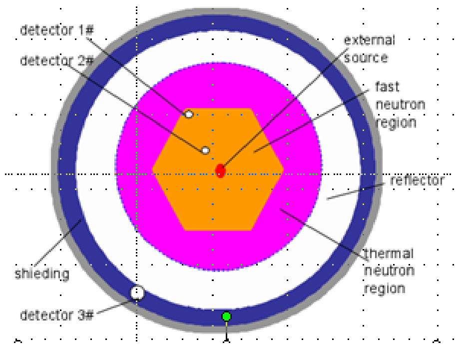
- Material defect
- Atom constitution & electromagnetism structure
- Dynamic image procudure
- Ion irradiation effects

Subcritical System: VENUS （CIAE）

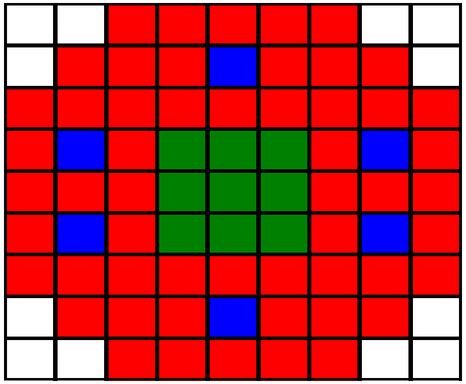
◆Phase 1: Am-Be steady outside neutron source to drive Venus-1 and doing neutronics character tests

◆Phase 2: Outside neutron source generated by high-voltage multiplier to drive Venus-1 and doing neutronics character tests.

	Venus1	**Venus2 (planed)**
Fuel	**natural metal U, enriched UO_2**	**Spent fuel of CARR, U_3Si_2-AL**
Keff	**0.95-0.98**	**0.982**
Spallation target	**-**	**Solid W**
Energy of proton beam	**-**	**100MeV**
Yield of spallation neutron	**-**	**0.3n/p**
Beam Intensity	**-**	**0.3mA**
Beam power	**-**	**30kW**
Thermal power of core	**10W**	**200kW**



Venus 1 subcritical reactor



Venus 2 subcritical reactor

Examples of Fission Test Reactors

HFETR (High Flux Engineering Test Reactor, NPIC)

Light water, 125 MWt, Neutron~1.7×10^{15} n/cm2·s

High Temperature Gas-cooled Reactor （HTR-10, U. QH)

He-cooled, 3MPa, 10MWt, Tout=750℃

Experiment Fast Reactor (CEFR，CIAE)

Na-cooled, 65MWt, N~3.7×10^{15} n/cm2·s,Tou

Advanced Research Reactor（CARR， CIAE

Water, 60MWt, N~1.0×10^{15}n/cm2·s

R&D Activities on SCWR and MSR

SCWR (Super Critical Water Reactor, SJTU)

- The physical concept design, analysis software and database are developed.
- Corrosion behavior, Mechanical Properties and irradiation damage of candidate materials are being performed.
- Thermal hydraulics experiment loop are constructed.

TMSR (Thorium Molten Salt Reactor, CAS-SIAP)

- CAS plans to develop the TMSR technology and construction experimental reactor in the future.

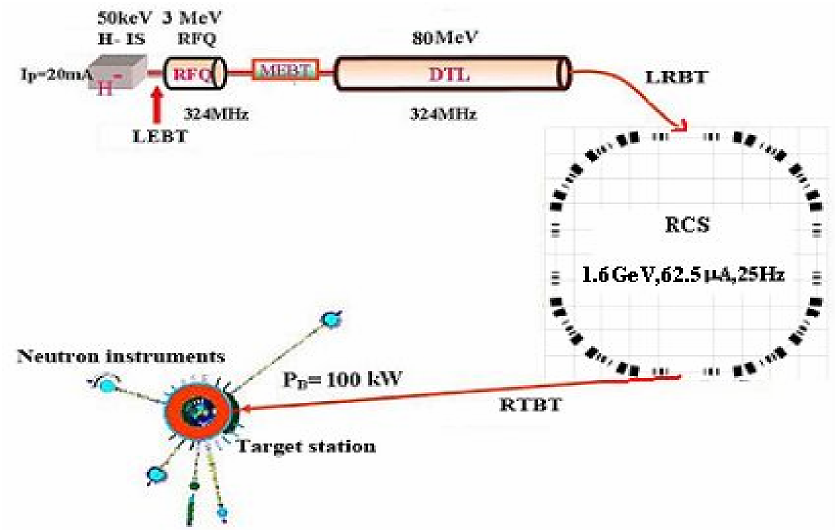
Experimental facility (zero power) (100kW) **10 MW Prototype reactor** **100 MW Prototype reactor**

2015 2017 2020 2030

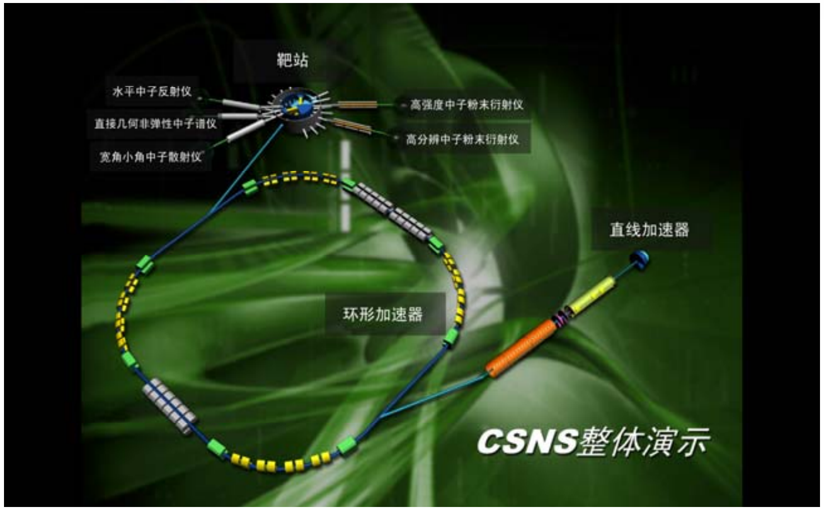
ASIPP · USTC

China Spallation Neutron Source - CSNS

- Advanced researches and applications in physics, chemistry, biology, life science, material science and new energy
- Max impulse neutron flux
  2.5×10^{16} n/(cm^2s)
- Basic design parameters



Basic parameters	CSNS-I	CSNS-II
Beam power(kW)	100	200
Repetition rate(Hz)	25	25
Average current(μA)	62.5	125
Proton energy(GeV)	1.6	1.6
Linac energy(MeV)	80	132

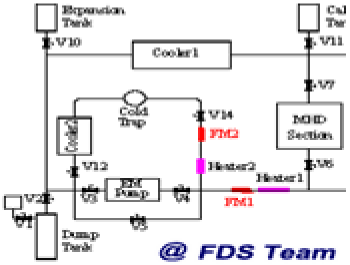


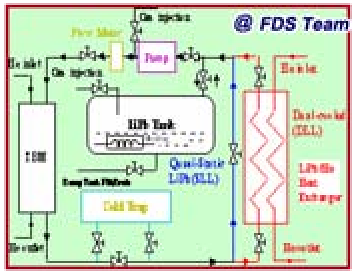
——From http://www.csns.ac.cn

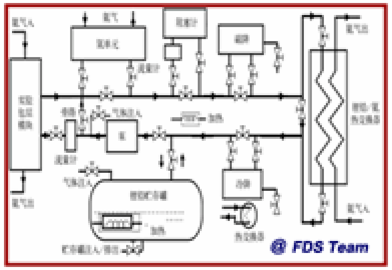
Functional Materials
&
Testing Loops

Development of DRAGON Series LiPb Loops

Loop name	Type	Function	Temperature	Time
DRAGON-I	TC*	Compatibility test under low temperature	420~480^{O}C	2001-2005
DRAGON-II	TC	Compatibility test under high temperature	550~700^{O}C	2004-2006
DRAGON-III	TC	Compatibility test under super-high temperature	800~1000^{O}C	2007-2009
DRAGON-S^{T}	Static	Compatibility test in the static LiPb	250-1000^{O}C	2008-2009
DRAGON-R^{T}	Rotating	Compatibility test in the flowing LiPb	450-600^{O}C	2009
DRAGON-IV	FC$^{\#}$	Compatibility, Thermal-hydraulics, TBM mockup, MHD test, etc.	480-800^{O}C	2007-2010
DRAGON-V	FC	Dual-coolant test for TBM, MHD test for the complex ducts	300-700^{O}C	2010-2011
DRAGON-VI	FC	Auxiliary system for EAST-TBM	300-700^{O}C	2010-2014
DRAGON-VII	FC	Auxiliary system for ITER-TBM	300-700^{O}C	2015-2018
DRAGON-VIII	FC	Auxiliary system for DEMO blanket	-	2019-







DRAGON-IV: Forced Convection LiPb Loop

- **Experiments:**
  - High temperature corrosion (800℃)
  - Stress corrosion (480℃, 4KN)
  - MHD (350℃; 2T; 1m/s)
  - Test Blanket Mockup (1/5-size-reduced)
  - LiPb eutectic purification

DRAGON-IV

- **Components:**

✓ Figure-of-eight type loop with a central heat exchanger, a hot leg and a cold leg;
✓ Hot leg contains Corrosion test section, MHD test section, Mini-blanket, etc;
✓ The cold leg contains the pump, flow meter and cold trap.

Fabrication of SiC_f/SiC Composites

Requirements:

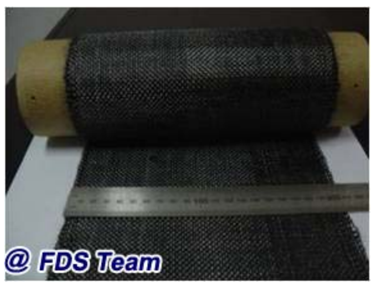
- Low / high thermal conductivity
- Low electrical conductivity
- Good compatibility with LiPb under elevated temp.
- Stable under neutron irradiation

Key issues:

- Fabrication of SiC_f/SiC pipe
- Fabrication of FCI
- Bonding technology of SiC_f/SiC composites

SiC_f/SiC composites

SiC fiber



SiC fiber felt

SiC fiber cloths

Continuous SiC fiber reinforced ceramic matrix composites

Strength of Continues SiC fiber reach 2.8-3.0GPa

Loop Technology

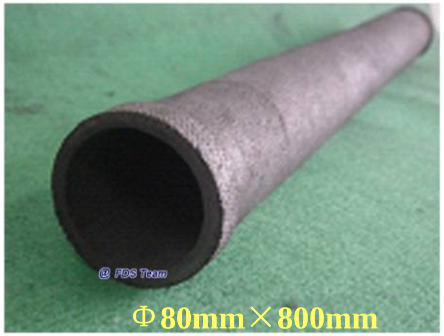
Fiber 3D braid preform

SiC fiber braid tube

Connection of metal and SiC composite

SiC_f/SiC composites were fabricated by **CVI + PIP + CVD**.

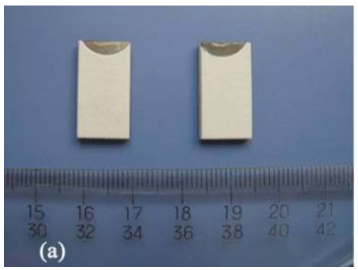
CVI---Chemical Vapor Infiltration
PIP---Polymer Infiltration and Pyrolysis
CVD---Chemical Vapor Infiltration

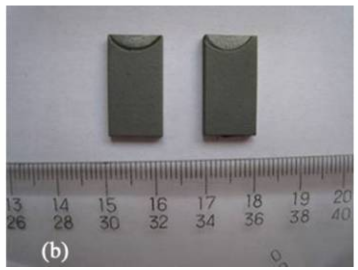


Development of Functional Coatings

Coating fabrication

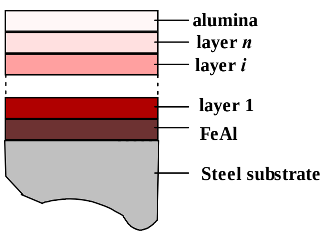
✓ Al_2O_3 / SiC Coatings



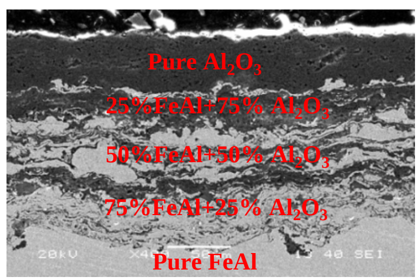


(a) Al_2O_3 (APS) (b) SiC (MS) on Al_2O_3

✓ FeAl/Al_2O_3 Coatings



FGM:Functional Graded Material



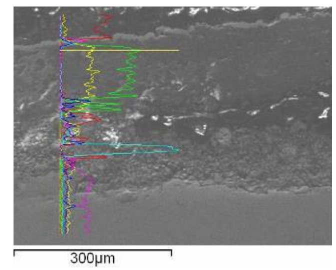
FeAl/Al_2O_3 FGM coatings (VPS)

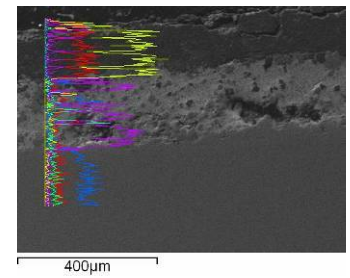
- **Both coatings showed a higher bond strength with CLAM steel, porosity was controlled at a low level;**
- **Al_2O_3/SiC coating showed excellent electrical resistivity ;**
- **FeAl/Al_2O_3 coating showed excellent shock resistance.**

Coating compatibility

✓ **Experiment in the static isothermal capsule**

- **Al_2O_3, Al_2O_3/SiC coatings (550℃, 5000h)**

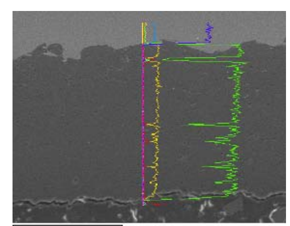


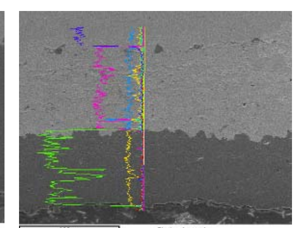


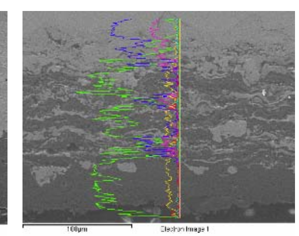
(a) Al_2O_3 (APS) (b) Al_2O_3/SiC (MS)

✓ **Experiment in the revolving isothermal capsule**

- **Al_2O_3, Al_2O_3/SiC, FeAl/Al_2O_3 coatings (550 ℃, 0.16m/s, 300h)**







(a) Al_2O_3 (APS) (b) Al_2O_3/SiC (MS) (c) FeAl/Al_2O_3 (VPS)

- **There's no obvious thinning of external Al_2O_3, SiC layers after 5000hrs exposure in static LiPb.**
- **The coatings showed good compatibility with flowing liquid LiPb after 300hrs exposure.**

Thermal Convection PbBi Loop (KYLIN-I)

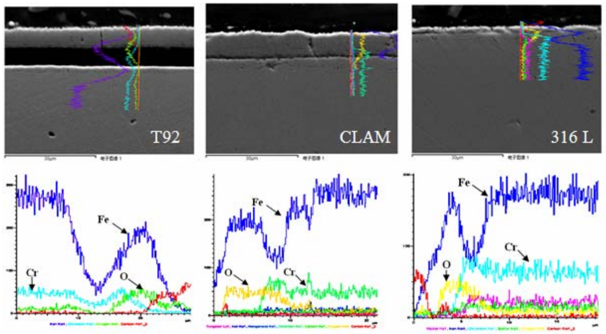
Design Objectives:

- Material compatibility test
- Tasting of PbBi eutectic

Major parameters:

- Loop size : 0.5m×0.5m
- Structural Material : SS316L
- Temperature : 450 ~ 480ºC
- Flowing velocity : 0.14m/s
- Volume of PbBi : ~2L
- Atmosphere : Ar (99.999%)

Operated more than 1000hrs



All Specimens suffered oxidation corrosion at 480ºC

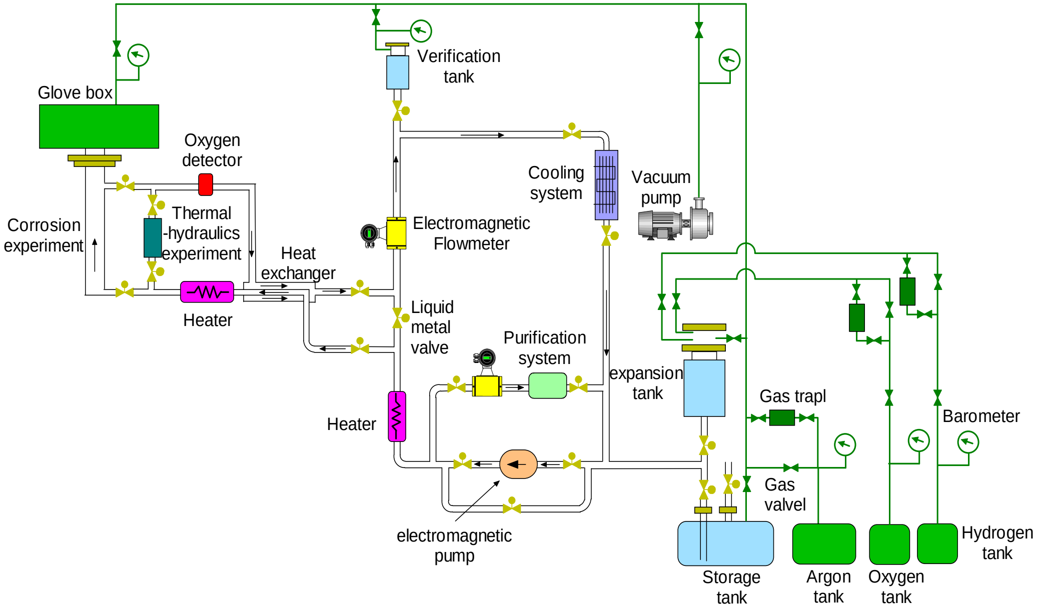
Forced Convection PbBi Loop (KYLIN-II)

◆ Design Objectives:

- **Compatibility experiment**
  - **Search for the approach to reduce corrosion (control of oxygen concentration, coating, etc.)**
- **Thermal-hydraulics experiment under forced convection**
  - **Providing physical model and data for simulation software of reactor design**
- **Thermal-hydraulics experiment under natural convection**
  - **Research of passive safety experiment**

◆ Main Parameters:

Parameter	Value
Temp. of corrosion experiment section	600℃
Velocity of corrosion experiment section	2m/s
Electromagnetic pump pressure head	0.5MPa



To be built at the end of 2011

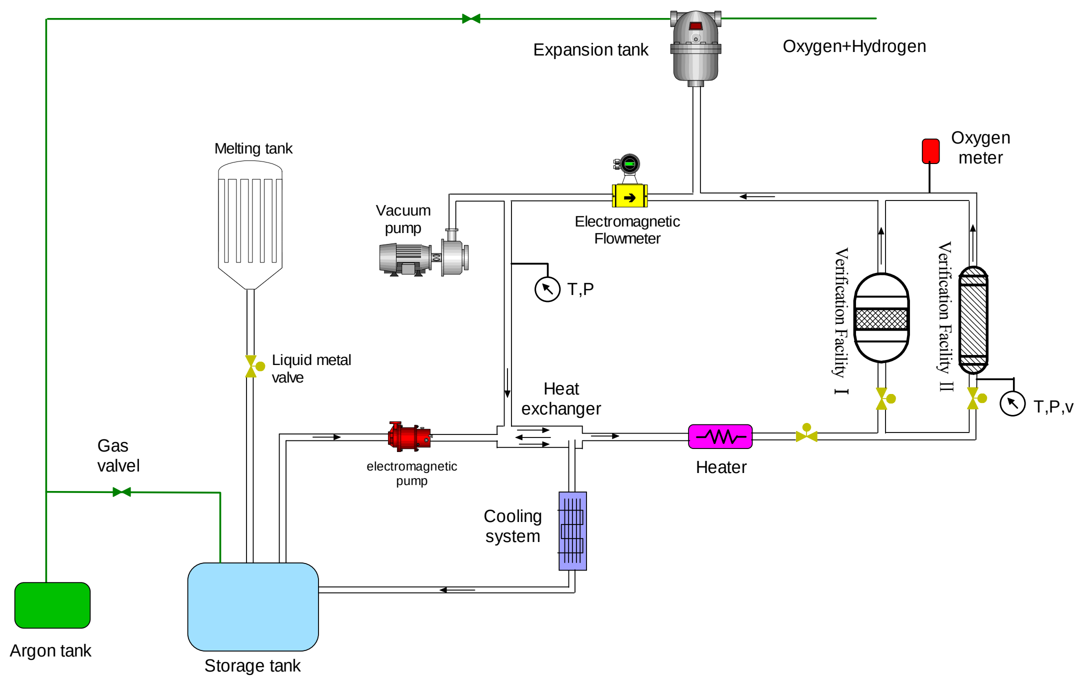
Large-scale PbBi Loop (KYLIN-III)

Design Objectives:

- Thermal-hydraulics Verification Facility for ADS reactor
- Thermo-mechanical Verification Facility for High Power LBE Target

Main Parameters:

Parameter	Value
Outer Diameter, mm	1200
Height, mm	8500
Material	AISI 316L
LBE inventory, kg (max)	~90 000
Electric heat tracing, kW	1000kW
Electric heaters for core power simulation, MW	3.2



Summary

1. FDS and ADS have many similarities in design principle and engineering technology, a number of design tools, testing facilities and expertise may be shared.
2. China has a long history in the development of ADS and FDS concepts and related technologies. Recently FDS research focused on FDS-SFB (Spent Fuel Burnner), and ADS research focused on ADS-WT (high level Waste Transmutation).
3. A series of design & simulation software have been home-developed, especially for the neutronics and safety analysis, some of which have been applied widely in the world.
4. Structural and functional materials (e.g. ton-level CLAM steel) have been developed. Irradiation and compatibility experiments have been performed either in liquid metal loops or test reactors.

FDS Team

Research Team on Advanced Nuclear Energy

FDS History

Fusion/Fission Design Study
(先进聚变和裂变反应堆相关研究)

Fusion Design Study
(聚变设计研究)

Fusion Driven-subcritical System
(聚变次临界系统)

Fusion Digital Simulation
(深度集成数字仿真)

The End

Thanks for your attention !

FDS Website: www.fds.org.cn