Conceptual Design and R&D Activities of DEMO Fusion Plant at SWIP

K.M. Feng，G.S. Zhang, G.Y. Zheng, Z. Zhao, Z. Chen and HCSB-DEMO Team

Reactor & Materials Division

Southwestern Institute of Physics (SWIP), Chengdu

China National Nuclear Corporation (CNNC), Beijing

P.R. China

Presented at 2nd IAEA Technical Meeting on First Generation of Fusion Power Plants: Design & Technology, June 20-22, 2007, Vienna, Austria. Fusion

Outline:

I. Background

II. Fusion Reactor Design Activities

III. Definition of CH DEMO

IV. HCSB-DEMO Concept

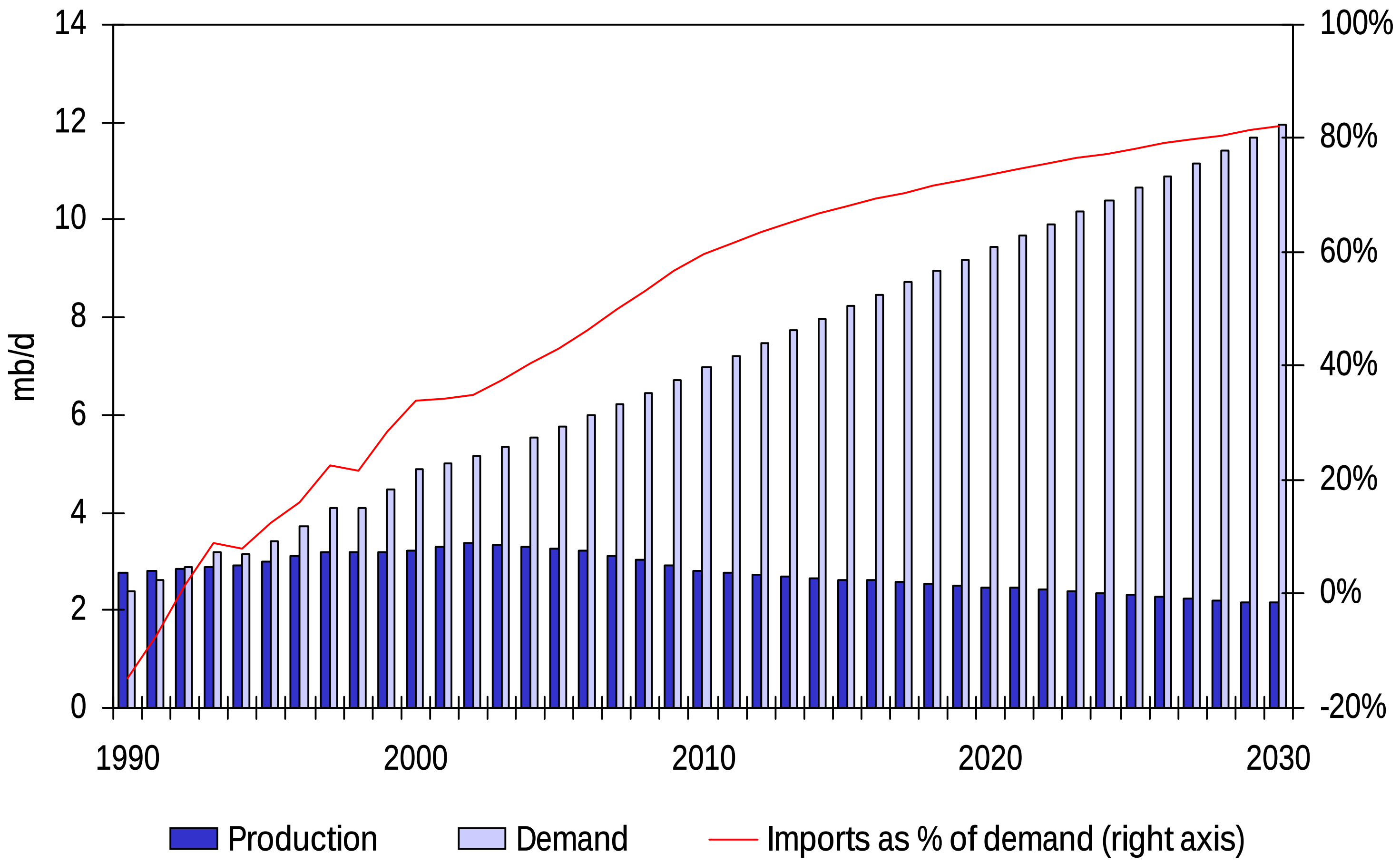
V. Development Strategy and R&D

VI. Summary

I. Background

- Chinese economy has grown up and will continue to grow up fast. The GDP growth rates has been higher than 7% in last decades. Forecast, the 2020's GDP will be near four times of 2000's .
- China has biggest population in the world, more than 1.3 Billions, and will continue to increase to 1.6 to 2.0 Billions, near the middle of this century
- China has limited energy resources. Coal, oil, hydro-power, including Uranium resources are very limited.
- The air-pollution problem in China has been already very serious, mainly by coal burning.

China Oil Supply Outlook



Background

- If large-scale use the nuclear fission energy, several hundreds nuclear power stations should be built in China. Therefore, we need some new technologies for to build more safe, breeder type fusion reactor.

  Fusion-fission Hybrid Reactor

  Fusion Breeder

- So that we should also consider how to dispose so large amount of high-level wastes(HLW) from the nuclear power plants.

  Fusion-transmutation Reactor

- A fusion breeder reactor requires a lower level of fusion technology, so under the fuel demand in China, could probably come into the market much earlier than a pure fusion reactor.

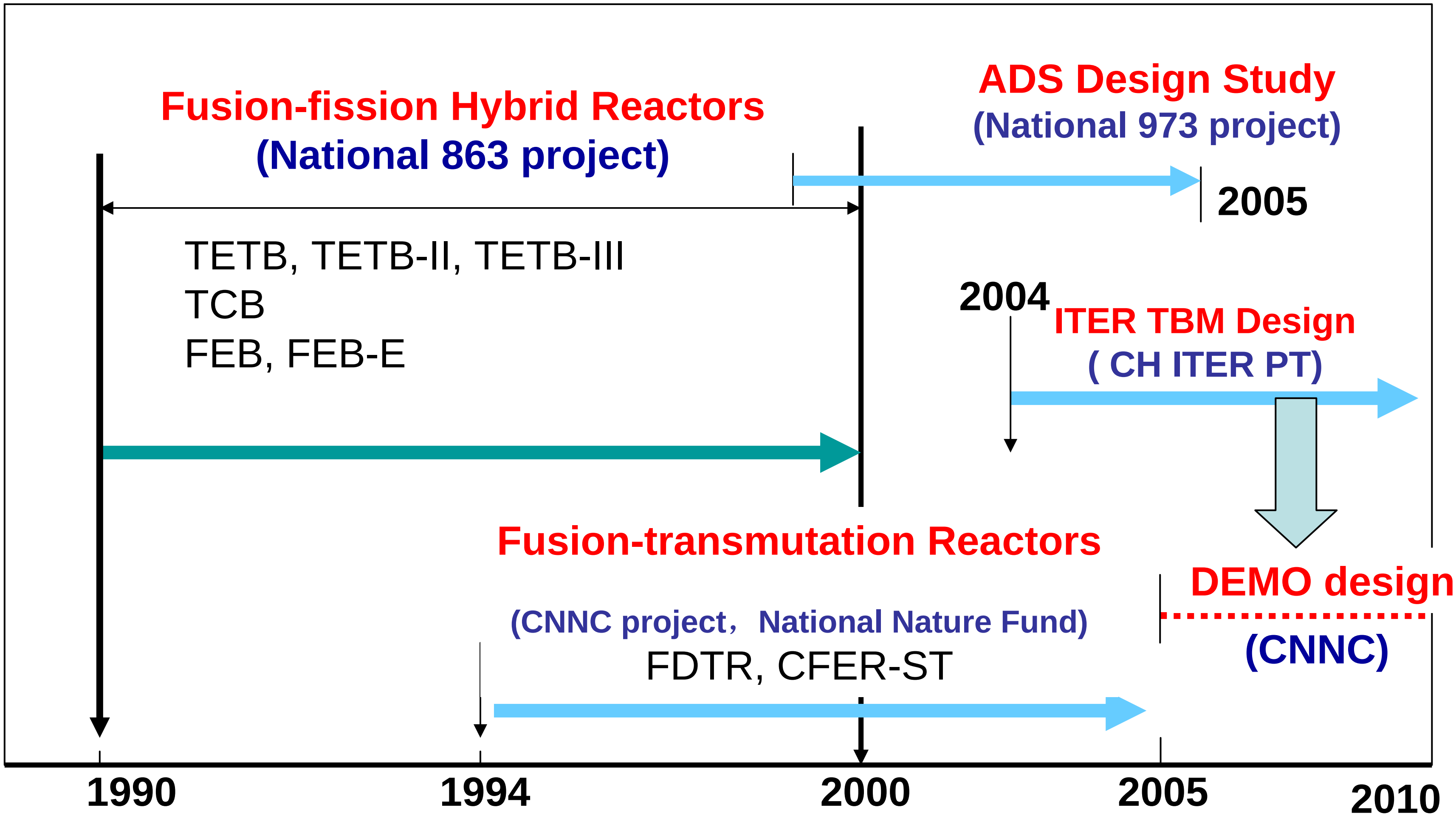
II. Fusion Reactor Design Activities

- The national program for development of the fusion breeder, Its aim is to perform the feasibility of experimental fusion breeder at the early time of the this century in China.

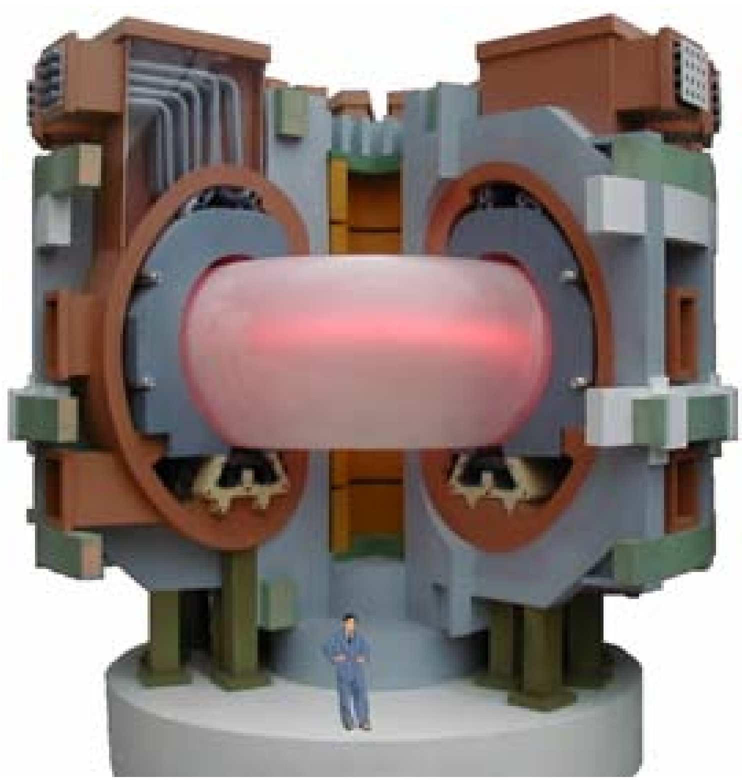
- A series of the conceptual design of experimental fusion breeders have been carried out at SWIP：

  Tokamak Commercial Breeder, TCB
  Fusion Experiment Breeder, FEB
  Fusion-transmutation Reactors, FDTR. CFER-ST
  Accelerator-Driven sub-critical System, ADS, so on .

Design Activities of Fusion Reactor at SWIP



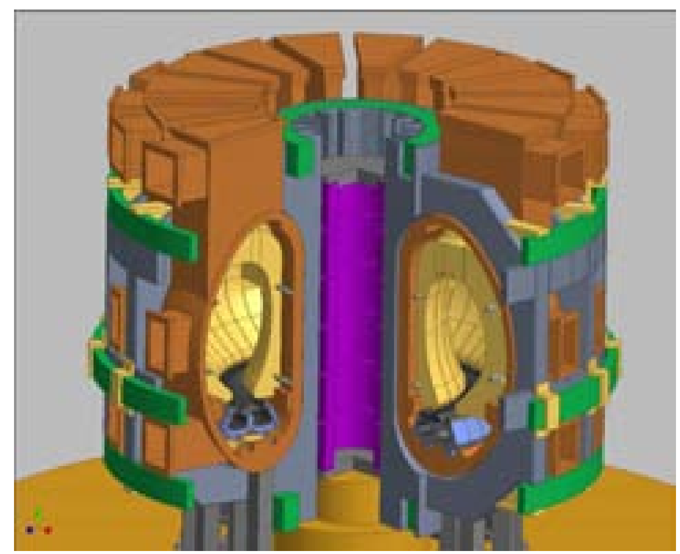
Fusion Experiment Breeder, FEB-E(1995-200)



1:10 Model of FEB-E design

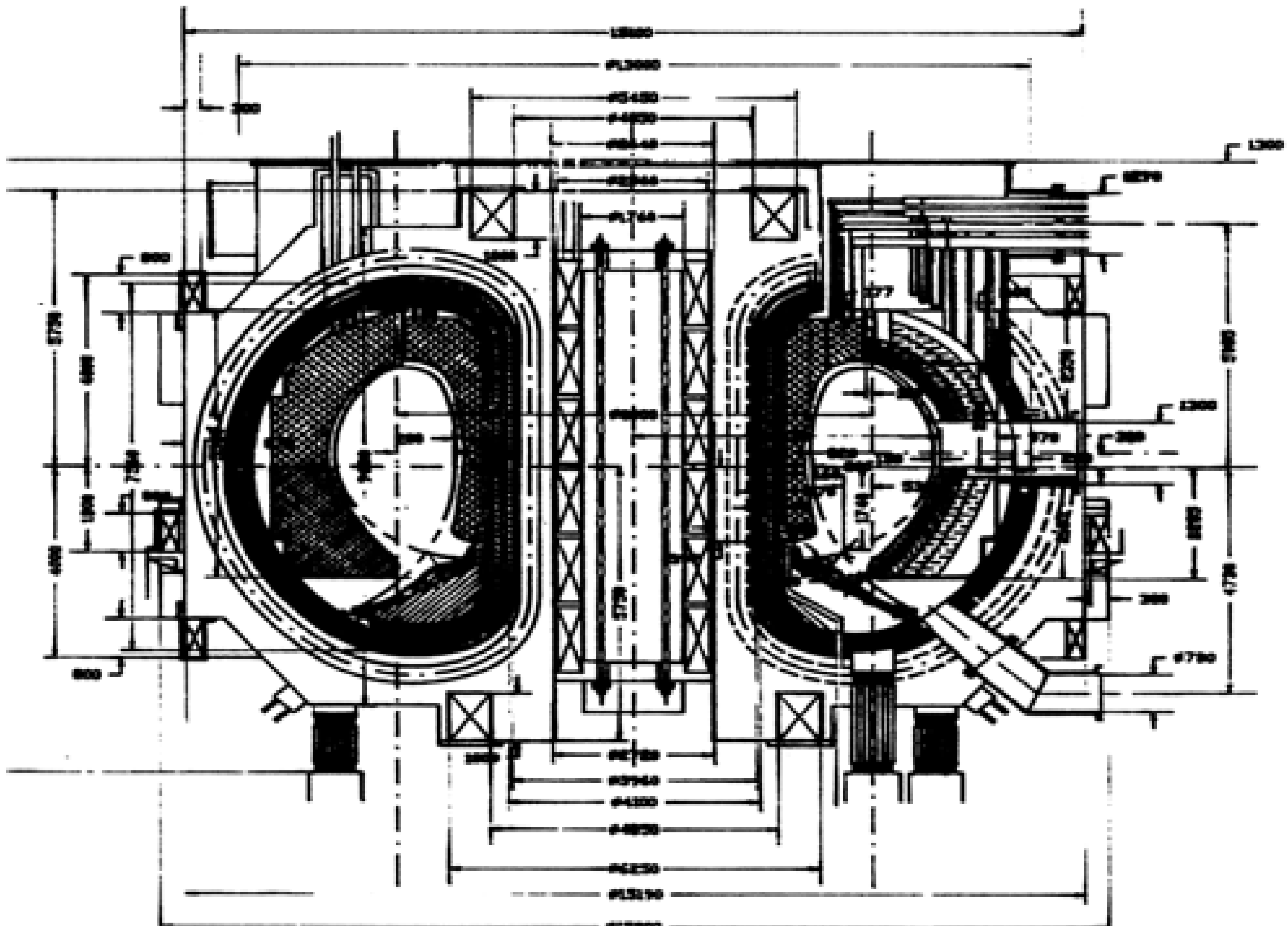
Main parameters

Plasma radius, R/r (m)	3.7/0.9
Fusion power, P(MW)	207
Neutron wall loading, W_L(MW/m²)	0.6
Plasma current, I_p (MA)	6.0
Average temperature, T (KeV)	10
Field at axis, Tesla,	5.9

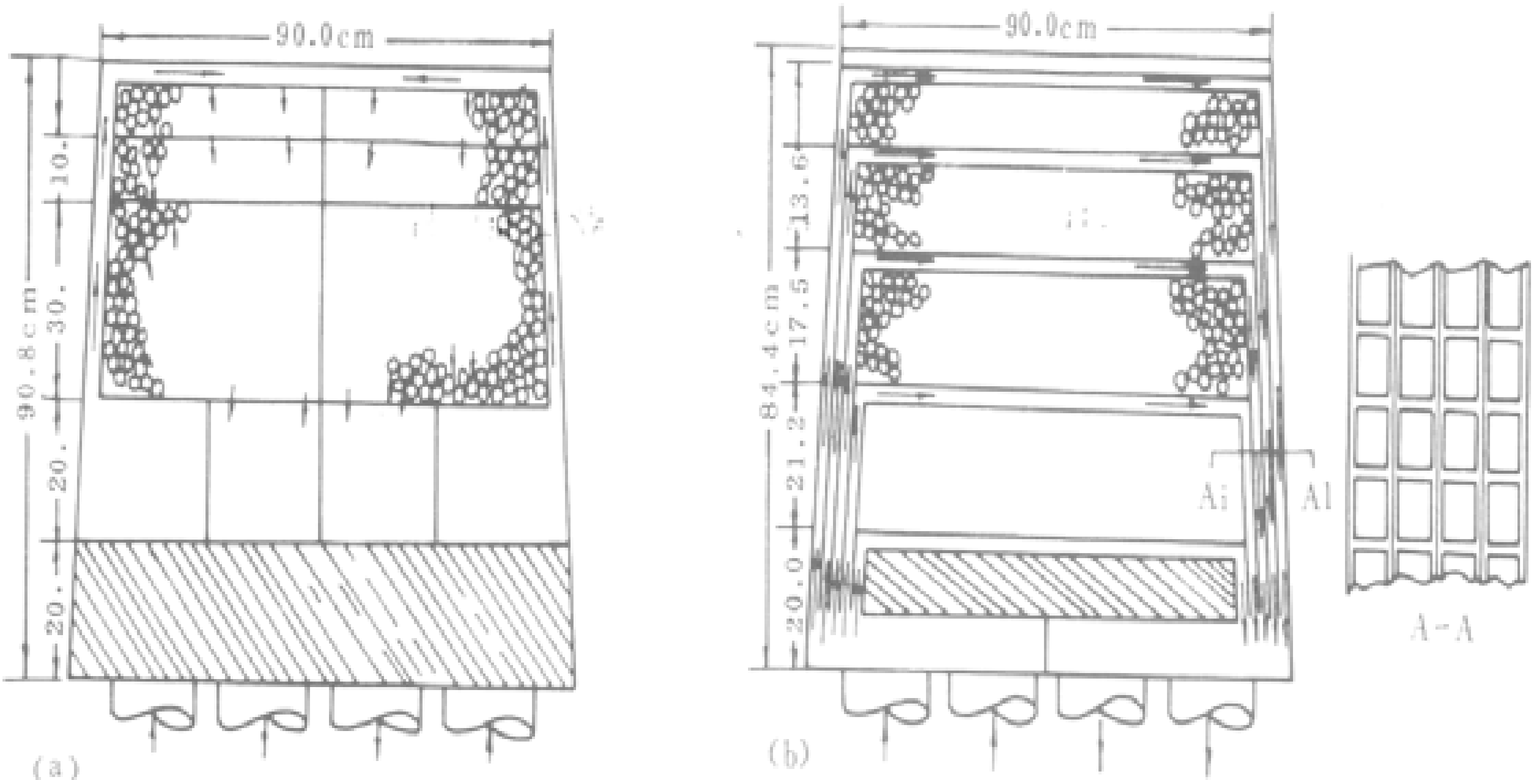


Fusion Experimental Reactor, FEB-E

- Published at J. of *Fusion Science and Technology*, vol.42, July , (2002) 138-145

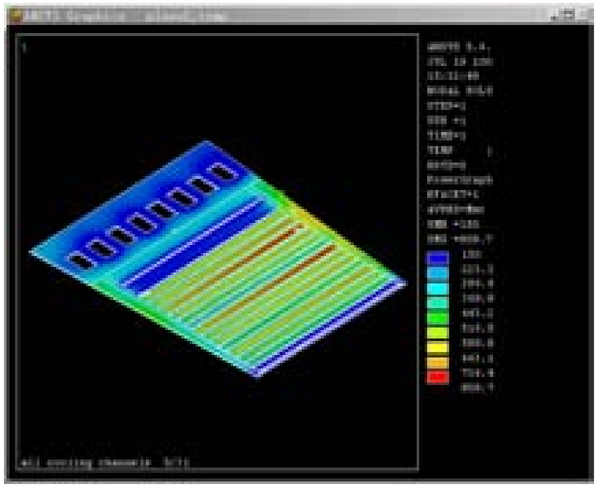


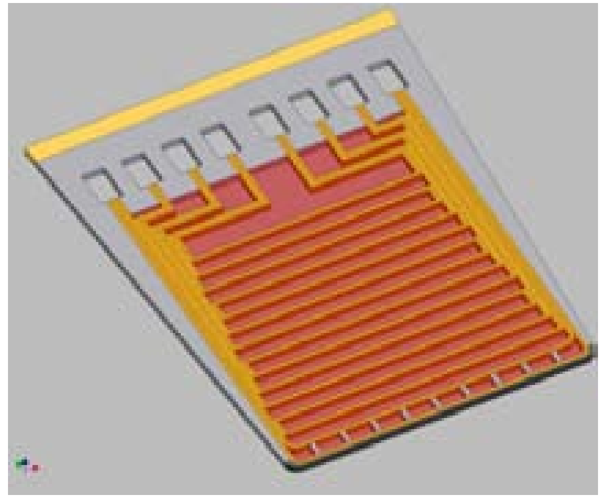
Elevation view of the FEB-E design

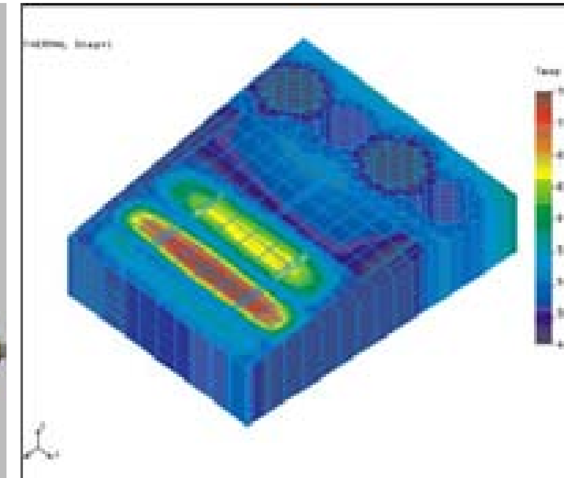


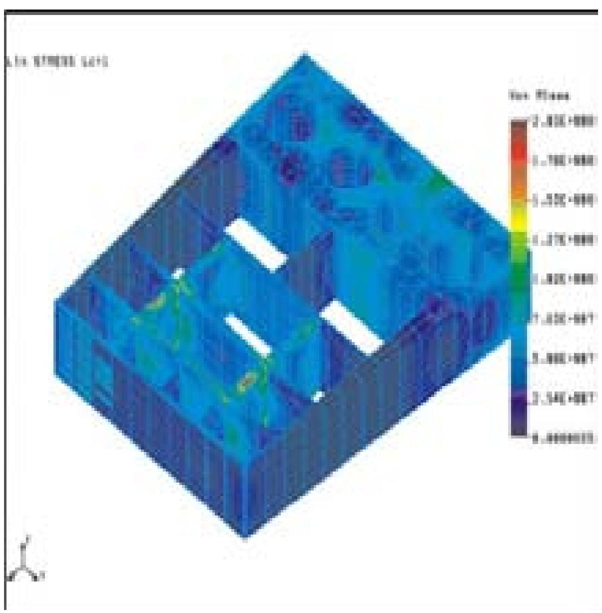
(a) Liquid-Li cooled blanket (B) He cooled blanket

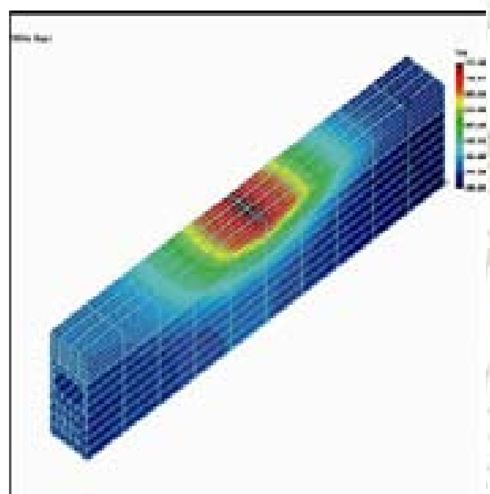
Cooling patterns of FEB-E design

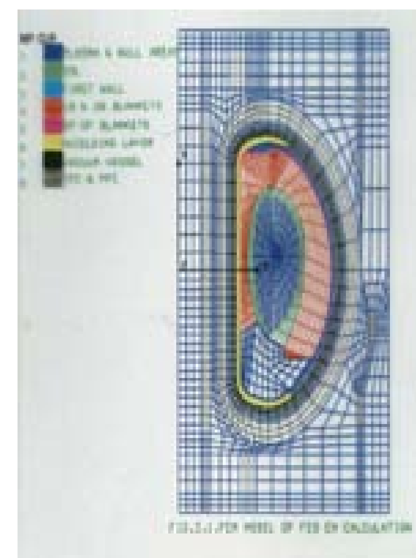




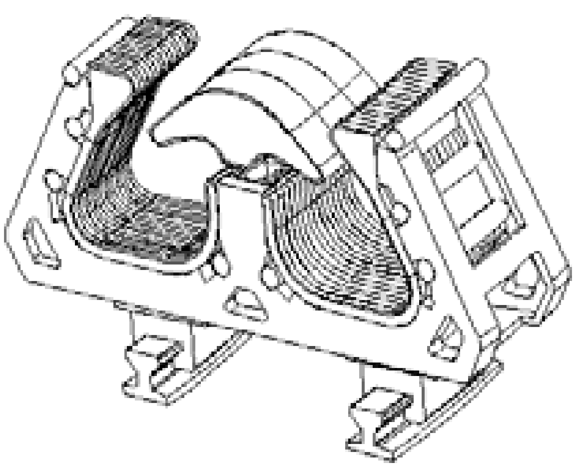




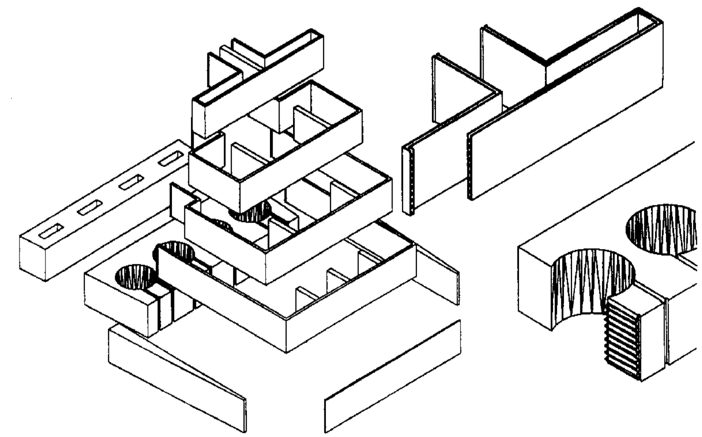




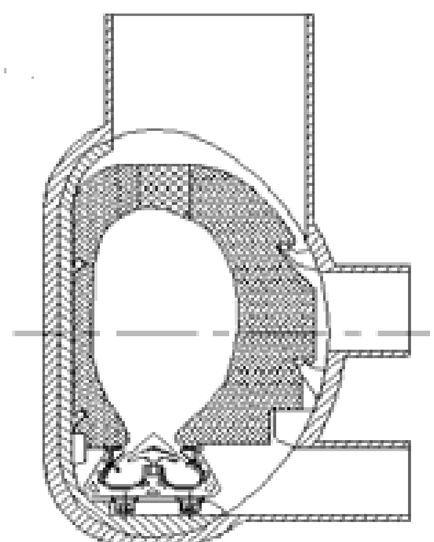
Calculation and analysis for FEB-E design



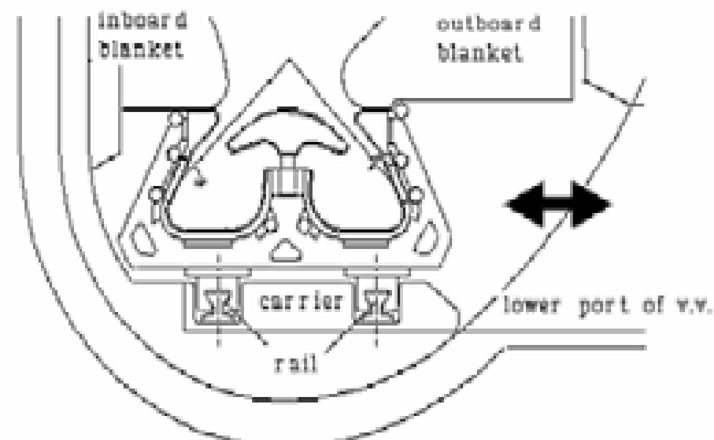
Divertor structure



Exploded view of blanket module.



Attaching lock of blanket in vacuum vessel



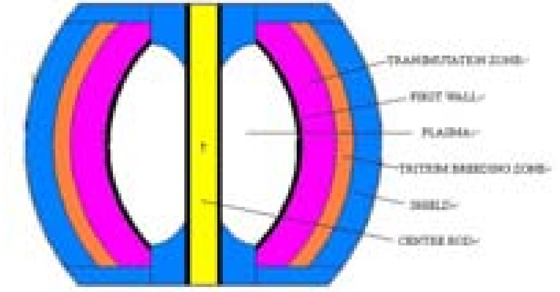
Installation of divertor module

Conceptual Design for Compact Fusion-Transmutation Reactor, CFTR-ST (2001-2005)

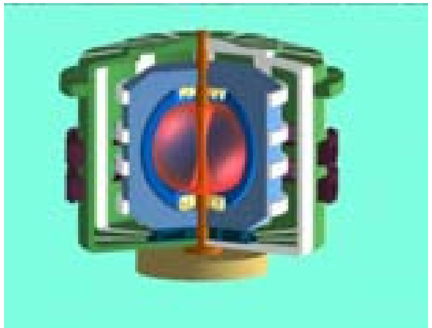
- **Feasibility studies of transmutation the HLW based on ST plasma configuration are performed in SWIP from 2001-2005..**

Main parameters:

Major radius / Minor radius	0.91m/ 0.7 m
Wall loading	0.8 MW/m^2
Fusion power	67 MW
Tritium breeding ratio	>1.2
Support ratio for 1GWe PWR	20-30
Tritium Breeder	Li_2O
Transmutation zone (static)	FLiBe, Pb-Bi
Structure/coolant	SS/He



MCNP 3-D calculation model



3-D Schematic view of FDTR-ST design

Presented at 20th IAEA FEC conference, Feb., Portugal, 2004

III. Definition of DEMO in China

- The DEMO in China is to demonstrate the safety, reliability and environment feasibility of the fusion power plants, meanwhile to demonstrate the prospective economic feasibility of the commercial fusion power plants.

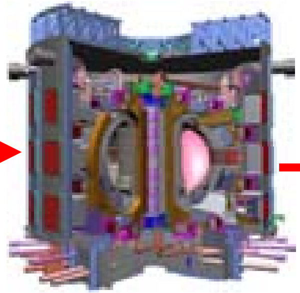
- Judging from the consideration that there is still a long way to go towards an economically competitive commercial power plant, DEMO in China should be an indispensable step prior to the commercial one. Thus, the power level of DEMO might be several hundred MWe.

Definition of DEMO in China（2）

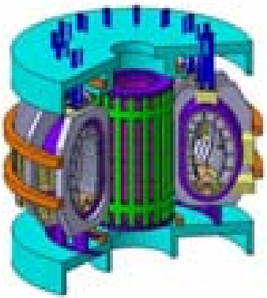
- In addition, China is interested in non-electric applications of fusion energy, such as HLW disposal and hydrogen production; We expect that these applications will benefit the ultimate development of the fusion power plants. So, DEMO in China should also demonstrate the prospect of these applications.

- It was assumed that DEMO is a next step after ITER. Therefore, CH DEMO studies are the important aspects of long-term national program to evaluate the technology, materials, economics, safety, environment and waste processing for the possible magnetic fusion applications.

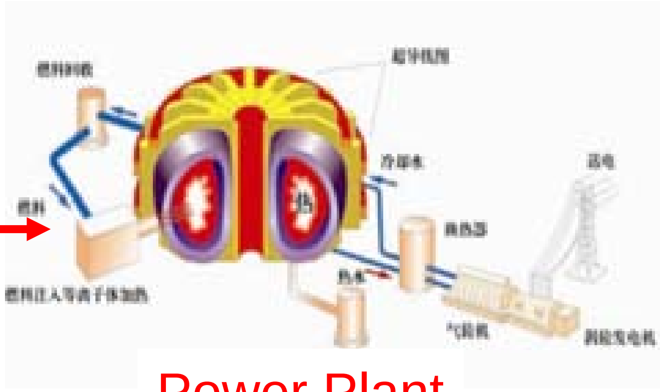
HL-2A



ITER



DEMO

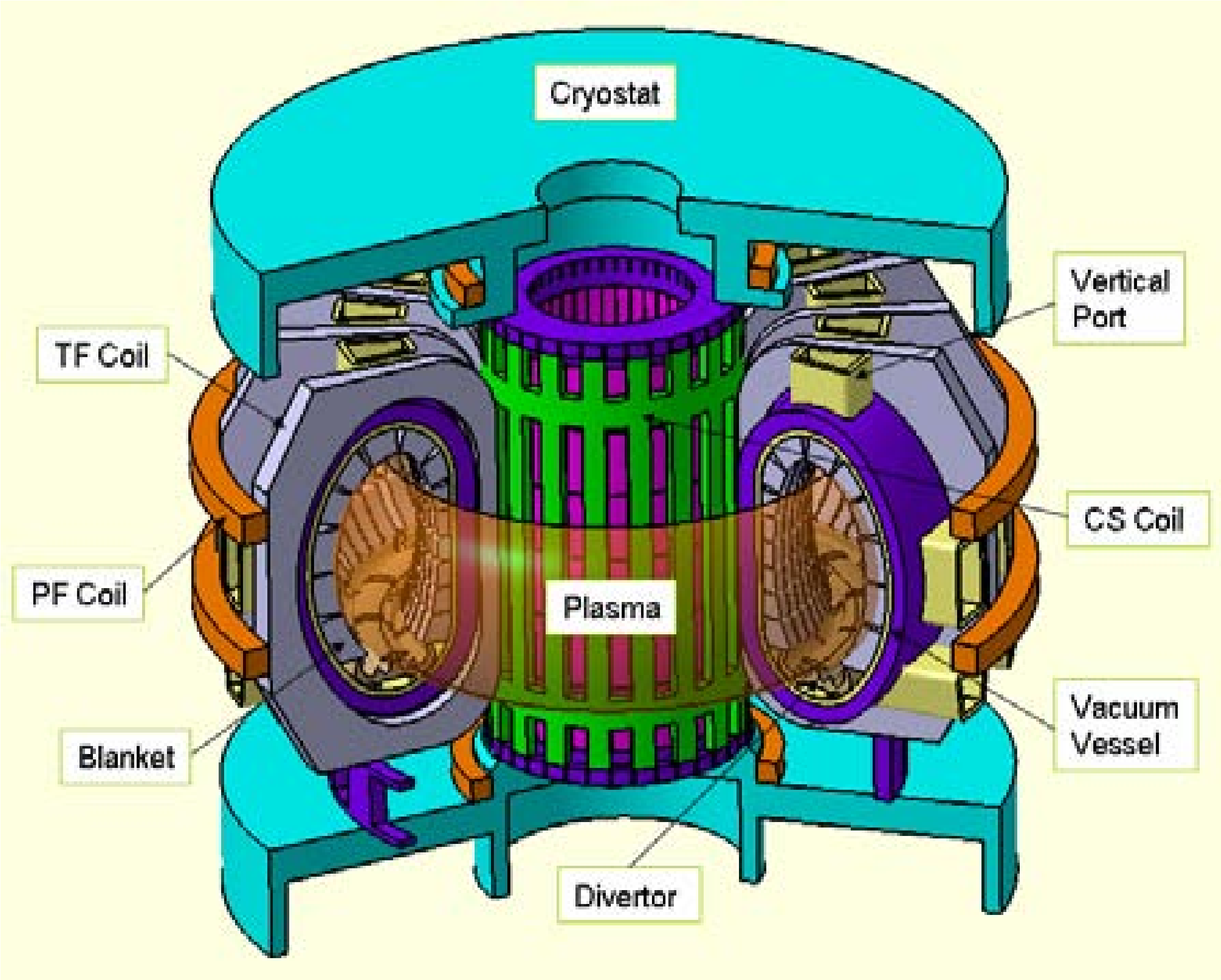


Power Plant

Definition of DEMO in China（3）

- Two options of breeding blanket with ceramic and lead lithium breeders might be chosen as DEMO concepts under the conditions of meeting the requirement of the neutronics, thermalhydraulics and mechanics aspects.
- A conventional type of water/helium cooled divertor targets with reasonable heat load should be considered.
- The safety and low activation performance should meet the requirement of DEMO design.

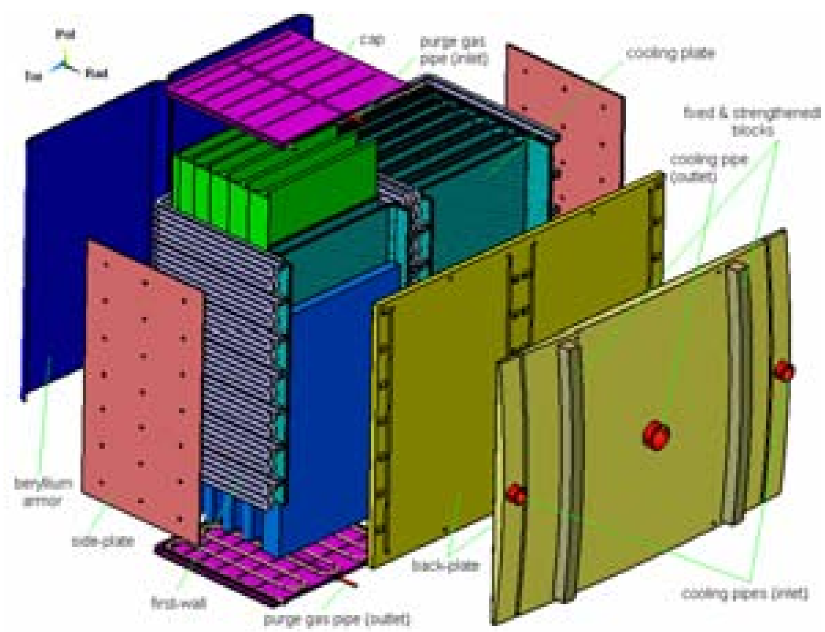
VI. HCSB-DEMO Concept



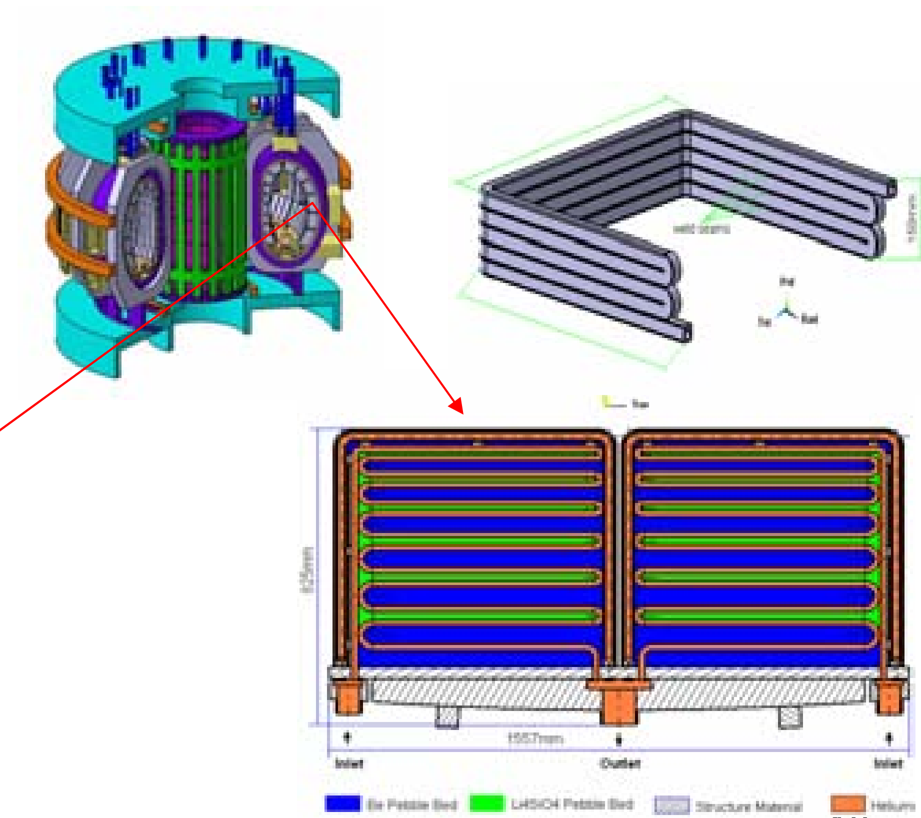
Conceptual View of HCSB-DEMO

HCSB-DEMO Blanket Concept

- As one of options, the breeding blanket with the Helium-cooled Solid Breeders/LRFM (HCSB-DEMO) might be chosen as China's DEMO blanket concepts under the conditions of meeting the requirement of the neutronics, thermo-hydraulics and mechanics aspects.



3-D View of DEMO blanket



HC-SB DEMO Blanket

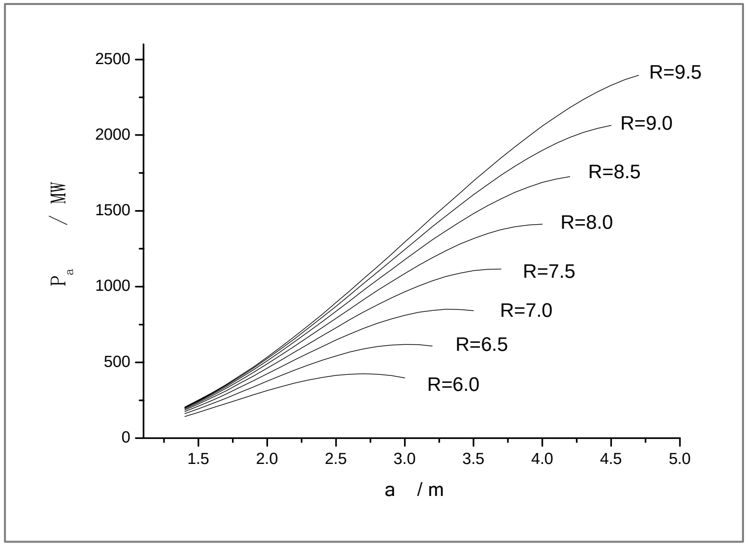
➢**Presented at ITER TBWG-16 meeting, Beijing, 2005**

Basic Feature of HCSB-DEMO

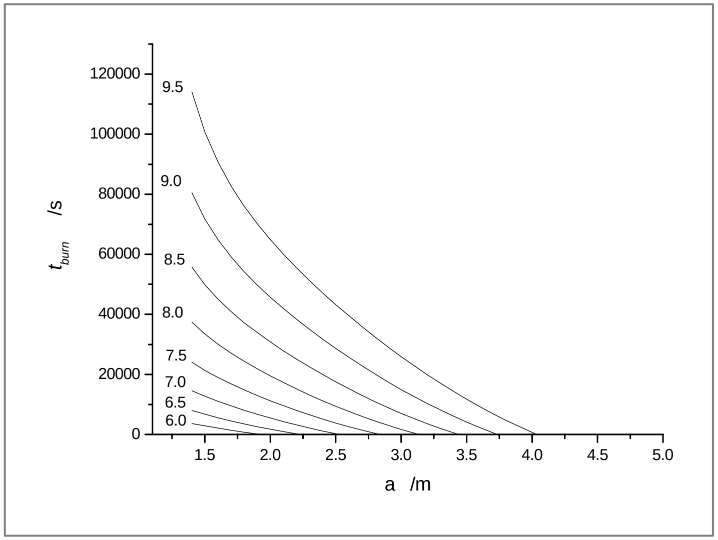
- **Fusion power in a range of 2500~3000 MW with an average neutron wall loading of 2.0~3.0 MW/m^2**
- **Have long burning time with inductive operation**
- **Steady-state operation with reverse shear plasma modes**
- **NBI and RF system for current drive**
- **Detached or semi-detached divertor operation modes; Divertor target loads are decreased by impurity radiation from the main and peripheral plasma**
- **The Nb_3Sn superconductor magnetic system is selected. It includes 18 TF coils, 6 PF coils, central solenoid (CS) and structure elements.**
- **The structure elements combine TF and PF coils and CS into the single structure to withstand the electromagnetic and weight loads.**

Selected DEMO Parameters

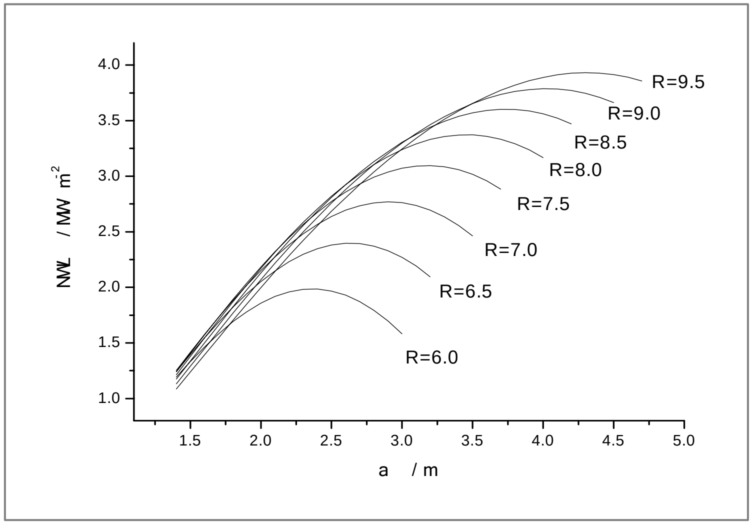
HCSB DEMO	Parameters
Fusion power/electric power, (MW)	2500/ ~ 800 MW_e
Major radius, (m)	7.2
Minor radius, (m)	2.1
Elongation, *k*	1.8
Fusion gain, Q	35
Neutron wall load, ($MW/m^{2)}$	2.3
Surface heating, ($MW/m^{2)}$	0.43
Tritium breeding ratio, (TBR)	>1.1
Availability, (%)	50-70
Divertor peak load, (MWa/m^2)	8.0 (water-cooled)
Plasma operation mode	Steady-state



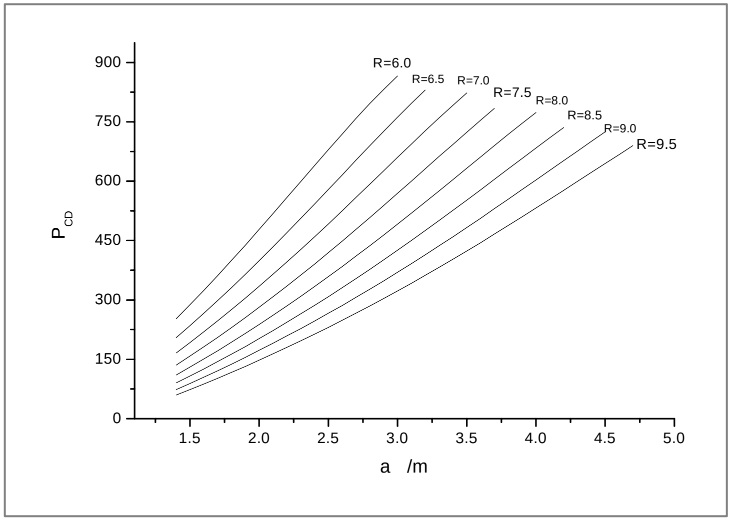
The fusion alpha power of a reactor with different sizes



The burning time of a reactor with different sizes



The neutron wall loading of a reactor with different sizes



The current-drive power of a reactor with different sizes

The final parameters simulated by the 1.5-D transport code for Inductive Operation Scenarios

Parameters		**OP1**	**OP2**	**OP3**
Major radius	R/m	9	8	7.2
Minor radius	a/m	2	2.2	2.1
Aspect ratio	A	4.5	3.6	3.4
Elongation	k	1.7	1.8	1.8
Triangularity	δ	0.33	0.45	0.45
Plasma current	I_p	15.2	15	14.8
TF on axis	B_t	8.23	7.31	6.86
Safety factor	$q(95\%)$	3	4.7	4.6
Average ele density	$<n_e>/10^{20}\cdot m^{-3}$	1.44	1.38	1. 5
Average ele temperature	$<T>$/keV	14.8	15.3	15.4
Average ion temperature	$<T>$/keV	15.3	16.2	15.8
Troyon	β_N	3.2	3.6	4.0
Bootstrap fraction	f	0.528	0.75	0.8
H_H(IPB98y2)	H	1	1.3	1.35
Current drive power	P_{aux}/MW	172	87	74
Fusion power	P_{fus}/MW	2600	2600	2550
Radiation power	P_{rad}MW	275	255	211
Neutron wall load	P_n/MW•m^{-2}	2.1	2	2.3
Z_{eff}	Z_{eff}	1.08	1.93	1.85
Fusion gain	Q	15	30	35

3-D Model of Neutronics / MCNP

Codes:

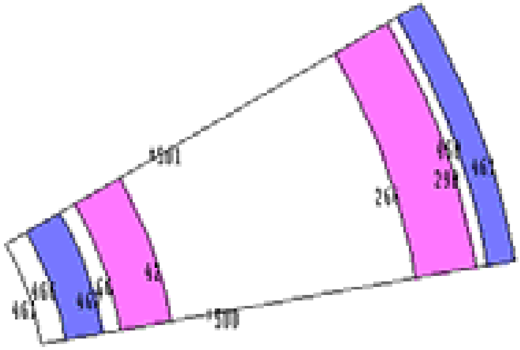
1-D: ONEDEANT

2-D: TWODANT

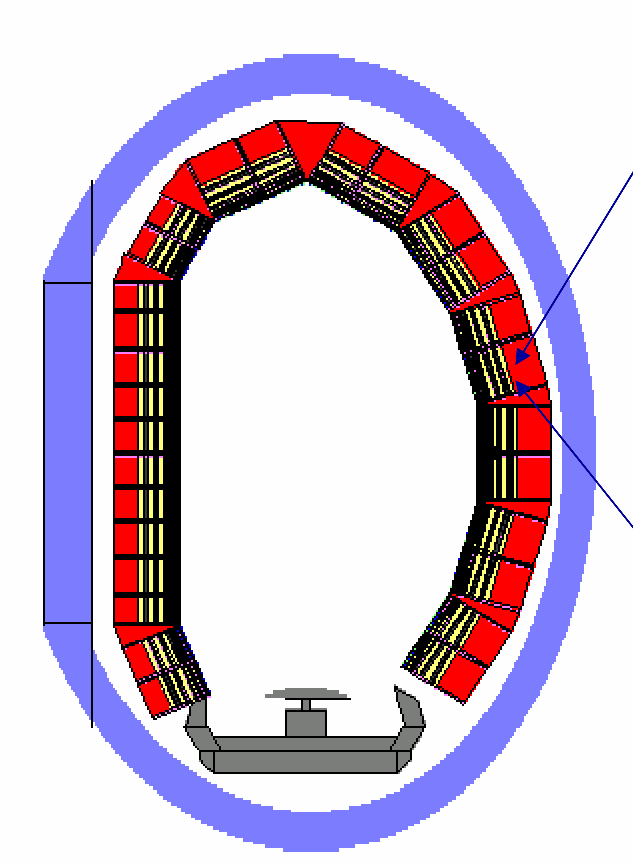
3-D: MCNP

Data libraries:

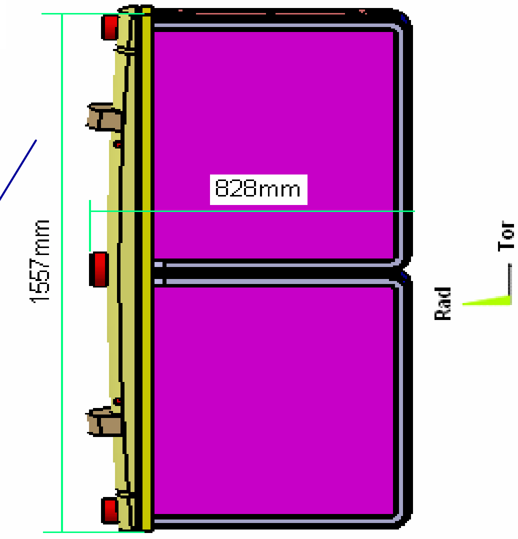
ENDF/B-6, FENDL2.0

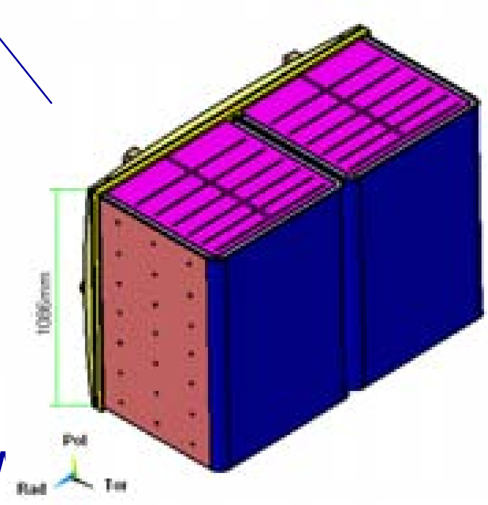


20 degree incision



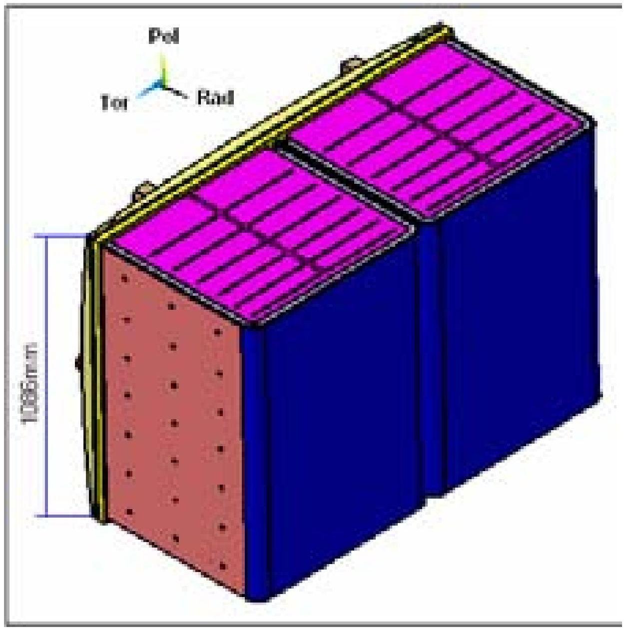
Obverse cross-section view



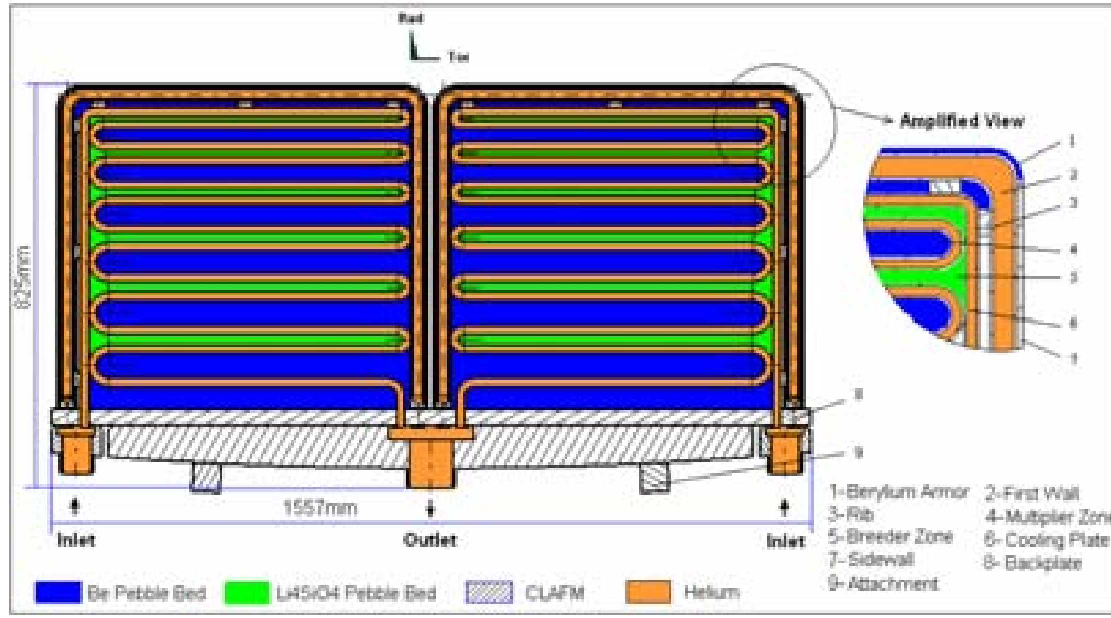


Main Design Parameters

Neutron Wall Loading, NWL [MW/m^2] Max. Surface Heat Load, SHL [MW/m^2] Tritium Breeding Ratio, TBR	2.0-2.3 0.5-0.8 1.05 -1.1
Coolant Inlet/Outlet Temperature, T [^{o}C] Pressure, P [MPa]	He 300/500 8
Tritium Breeder Max. Allowable Temperature, T [^{o}C]	Li_4SiO_4 Pebbles 920
Neutron Multiplier Max. Allowable Temperature, T [^{o}C]	Be pebbles 700
Structure Material Max. Allowable Temperature, T [^{o}C]	CLAFM 550



(a) 3-D View



(b) Cross-section View

Structure Scheme of HCSB-DEMO Blanket

The features of HCSB DEMO blanket:

- The blanket of HCSB-DEMO is designed as modularization structure;
- The 14 modules are connected each other along the poloidal direction, and there are all 72 rows of this connection along the toridal direction. Total number of the modules is about 1008;
- The module mounting/dismounting operations are carried out through the vacuum vessel vertical ports;
- The radial thickness of inboard and outboard modules is 630mm and 800mm, respectively.

V. Development Strategy and R&D

CH DEMO power plant study aims at establishing physics and engineering basis and limitations of the DEMO.

The testing objectives for CH DEMO are:

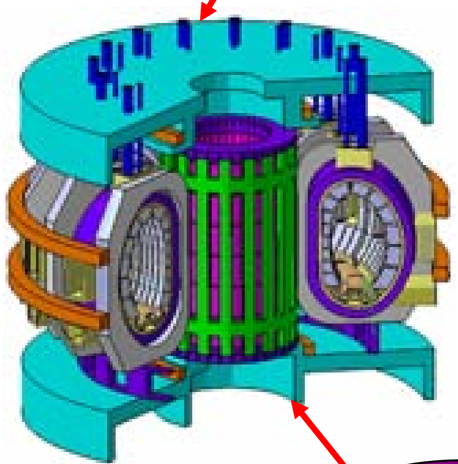
- **To demonstrate the tritium breeding features.**
- **To demonstrate heat remove and electricity production in DEMO blanket.**
- **To demonstrate the economy for total capital cost and Cost of Electricity (COE).**
- **To demonstrate the safety, environment and fuel management.**
- **To demonstrate integration and maintenance.**

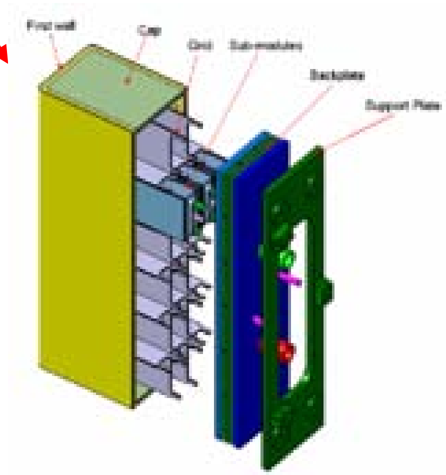
Development Strategy

- To continue the domestic plasma research effort using the experiments such as HL-2A(HL-2M) and EAST;
- To strengthen the domestic fusion reactor research;
- To cooperate with international effort in DEMO design activities;
- The research and development of the fusion experimental reactors in China have already been carried out for more than 15 years under the support of the national Hi-Tech. project. Relevant experiences and technical results will be utilized in the DEMO design activities;
- In order to assort the domestic DEMO strategy, China will consider participation the IFMIF project;
- Found a uniform agency and national fusion laboratory of domestic nuclear fusion research.

R&D on Materials at SWIP

RAFM for ITER-TBM & DEMO





V-base alloy for advanced V-Li blanket

1988-1995: Chinese HT-7, HT-9 and LHT-9.

-- Lithium corrosion;

-- Electron irradiation simulation.

1996—2007: V-base Alloys

-- Hydrogen effects;

-- High-temperature strength;

-- Strengthening;

-- ……

2006—now: RAFM（CLF-1)

-- Small batches for technologies;

-- large one for ITER-TBM (2007-).

CLF: Chinese Low-activation F/M

RAFM — CLF-1

- Small batches: several batches (~10kg) developed.
- (Plan to 2007: 500-1000kg)

Fe-9.0Cr-1.2W-0.25V-0.6Mn-0.10Ta-0.11C-0.025N-0.013O (wt.%)

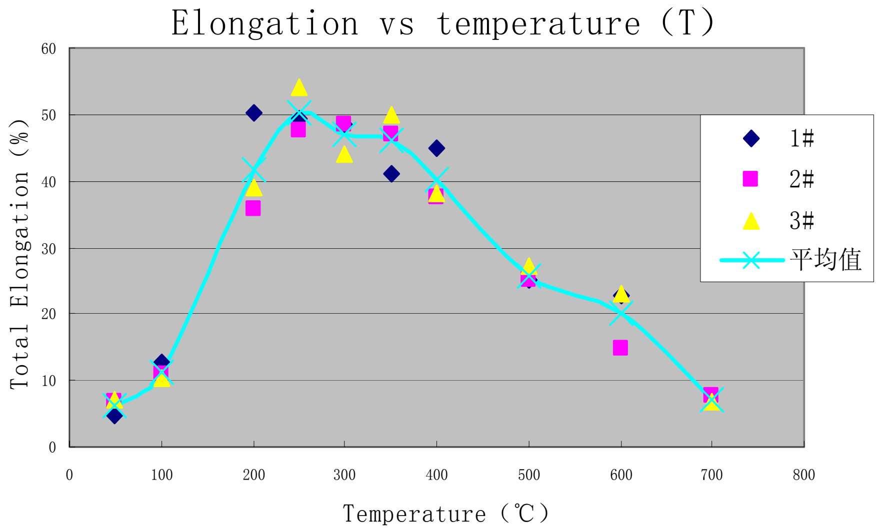
1） Microstructure analysis: ~100% martensite; Grain size ~7µm
2） High temperature tensile test
3） Charpy properties test
4） Heat treatment for better mechanical properties.

Development of Neutron Multiplier(Be)

Main Chemical Composition of Chinese VHP-Be 1#

Chinese VHP-Be	Be	BeO%	Al	C	Fe	Mg	Si	Other metallic elements
1#	≥99%	0.750	0.006	0.060	0.050	0.003	0.009	<0.04

- **China has also large yielding capacity of Be and relevant experiences of neutron multiplier.**
- **A new project, to develop high quality Be in China, is being implemented for ITER project.**



Fabrication Technology on Be Pebble

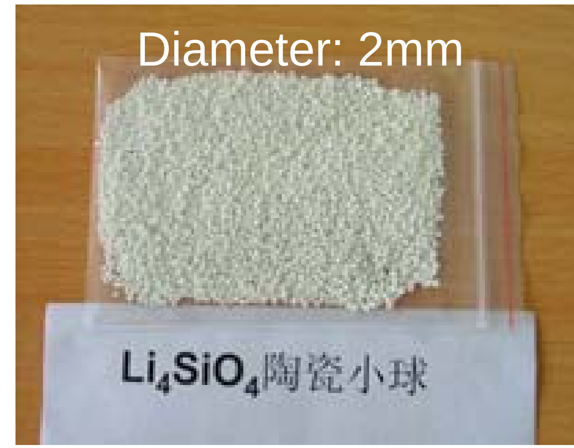
Be alloy pearls with different diameter

Exploration study of Be pebbles fabrication technology has been done. Related performance test is on going. Be alloy pearls are prepared by powder metallurgical (PM) methods

Press failure test device

The load is 5kN above the specific load, the Be alloy pearls we developed do not crack, and its deformation ratio is lower than 40%. The compression strength of Be alloy pearls we developed is as high as 1260 MPa.

Fabrication of Ceramic Breeder Pebbles (Li_4SiO_4) **



***Contribution from CAEP

•**Relative density: 85-90%T.D.**

Foundations on Tritium Technologies

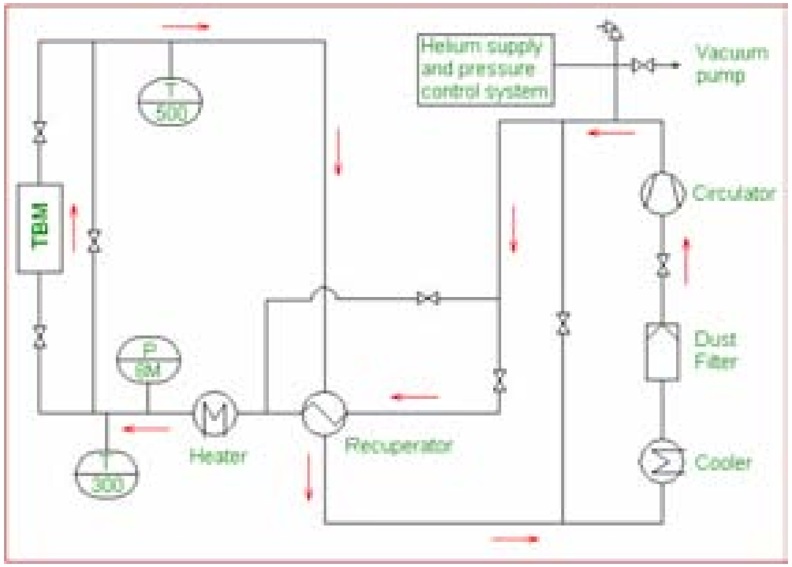
China have accumulated abundant experiences in tritium extraction, storage, waste disposal through a lot of fundamental and engineering investigations on the reliable experimental data.

Experimental system for hydrogen isotope extraction from solid breeders

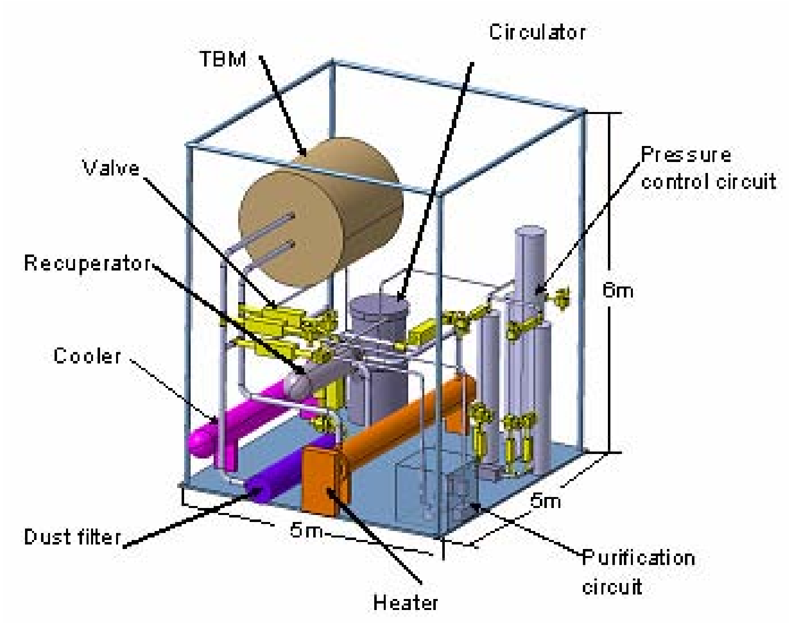
Tritium storage bed

High Temperature He Experiment Loop (HTHEL)

A High Temperature He Experiment Loop (HTHEL) with 500 °C and 8 MPa, which is useful for DEMO design and R&D activities, is proposed to be built in SWIP.



Flow diagram of HTHEL



3-D schematic view of HTHEL

VI. Summary

- The definition, development strategy, preliminary conceptual design and R&D activities for Chinese DEMO power plant are introduced briefly.

- Ceramic Breeder/Helium coolant/ LAFM concept based on ITER-TBM testing on ITER might be one of options in China DEMO development program.

- DEMO is very important one step from ITER to commercial utilization of fusion energy. The DEMO is also one of important ports of Chinese fusion energy development.

- Relevant R&D on the key techniques based on Chinese DEMO development strategy of fusion power plant will be preformed with the cooperation of domestic and international institutions and companies.

Thank you for your attention !