ASIPP FDS

Progress in Conceptual Study of China Fusion-based Hydrogen Production Reactor

Presented by Liu, Songlin

contributed by the members of FDS Team

FDS (Fusion Design Study) Team
Institute of Plasma Physics, Chinese Academy of Sciences
P.O. Box 1126, Hefei, Anhui, 230031, China
http://www.fds.org.cn
Email: slliu@ipp.ac.cn

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NE.O-11

FDS Team – Multidisciplinary Research Team

Fusion Design Study
Fusion Digitalization and Simulation
Fusion Driven (Subcritical) System
Reactor Technology Division, ASIPP, CAS, China

Members at Headquarter

- Staff: ~20
- Ph.D and M. D Students: ~50

In support of ~10 network members

FDS Series Fusion Reactors

—FDS-I: Fusion-driven sub-critical system

for early applications of fusion

e.g. waste transmutation, fuel breeding etc.

based on easy plasma physics and eng. level

—FDS-ST: Spherical tokamak-based reactor

to exploit and assess innovative conceptual path,

based on spherical tokamak neutron source

—FDS-II: Fusion power reactor

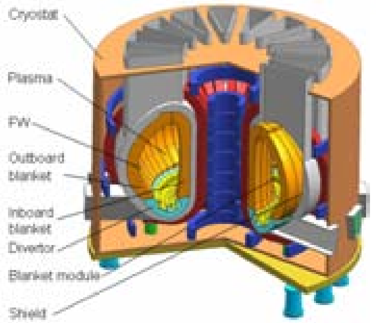
for highly efficient electricity generation,

based on conservatively advanced plasma parameters

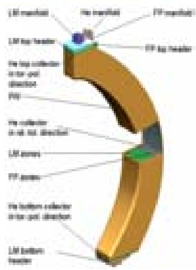
— FDS-III: High temperature fusion reactor

for advanced applications, e.g. hydrogen production,

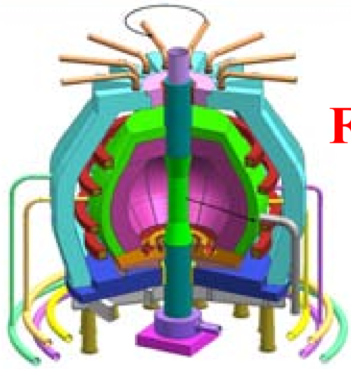
based on advanced plasma physics and engineering extrapolation lever



FDS-I

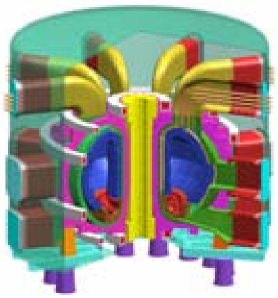


DWT

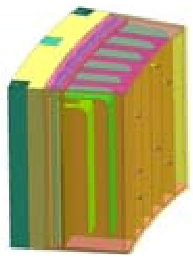


FDS-ST

CCP

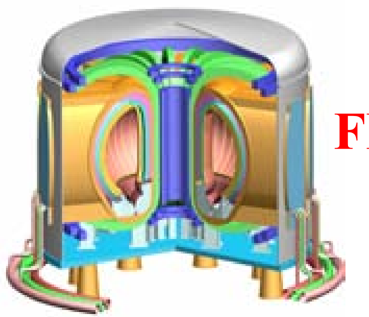


FDS-II

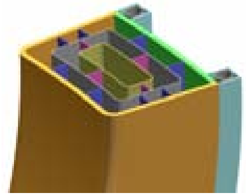


SLL ~450° C

DLL ~700° C



FDS-III



HTL ~1000° C

Contents

Primary Objectives of the FDS-III Research

- Fusion power: 2600MW
- Coolant temperature : ~ 1000 ^{o}C
- Neutron wall load : ~4MW/m^2
- Advanced operation mode of plasma core.
- High maintenance availability
- High thermal conversion efficiency : >50%
- High safety and environmental merits.

Design Principle and Approaches

- 16 sector with big equatorial port for easy access and remove in-vessel components
- The blanket combining large module and banana segment
- He and LiPb dual coolant blanket
- Using a kind of multi-layer SiC/SiC flow channel inserts (MFCI)
- Structural material: ODS steel, RAFM steel.
- Tritium breeder rate : >1.1

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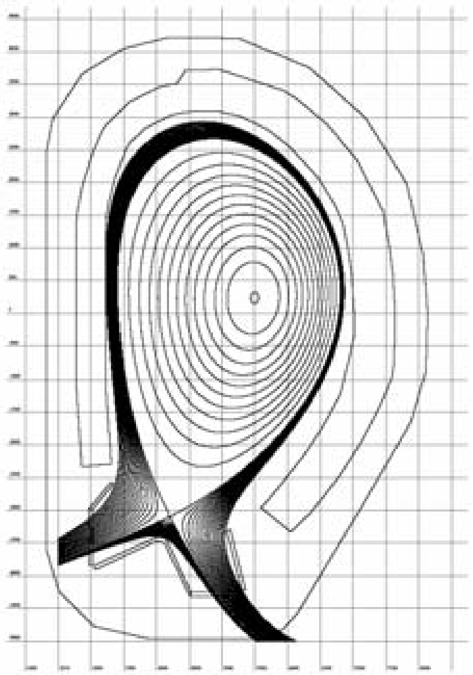
Plasma Core Calculation

- Preliminary core parameter selecting based on SYSCODE developed by FDS team
- Parameters optimized based on the EFIT equilibrium

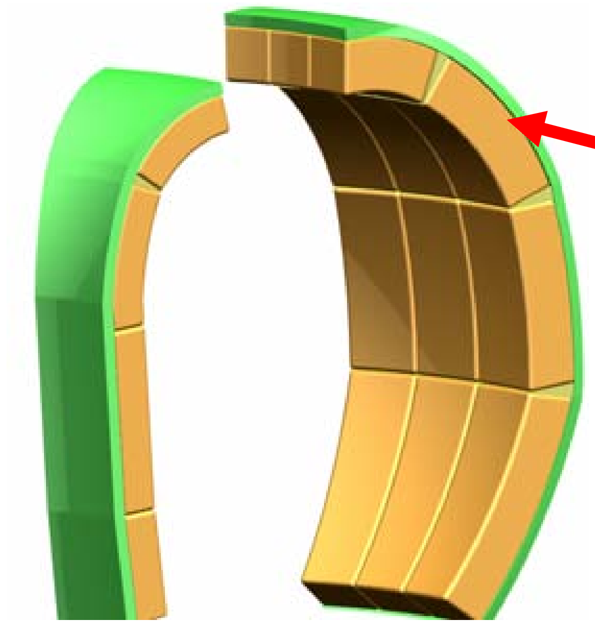


The magnetic configuration and divertor

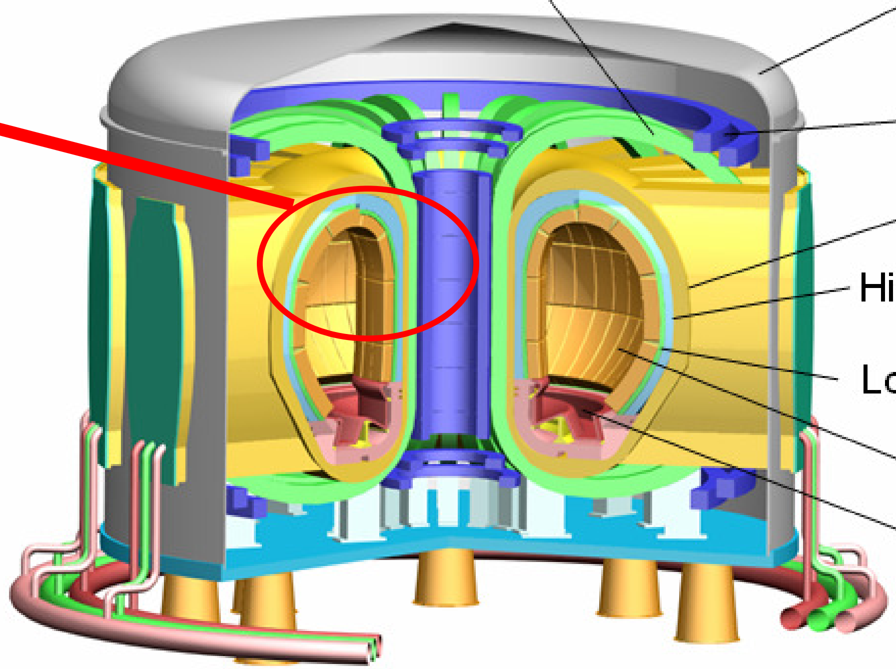
Plasma Core parameters

Major radius	R[m]	5.10
Minor radius	a[m]	1.70
Aspect ratio	A	3.00
Plasma current	I_P[MA]	16.00
Toroidal field	B_0[T]	8.00
Elongation	κ	1.90
Triangularity	δ	0.53
Safe factor	q	8.03
Edge safe factor	q_{95}	3.30
Toroidal β	β_T[%]	5.65
Poloidal β	β_P	1.88
Normalized β	β_N	4.80
Average density	$\langle n_e \rangle [10^{20} m^{-3}]$	1.00
Average temperature	$\langle Te \rangle$[KeV]	10.00
Bootstrap current fraction	f_b	0.65
Fusion power	P_{fu}	2600

Configuration of FDS-III Reactor



Blanket segment

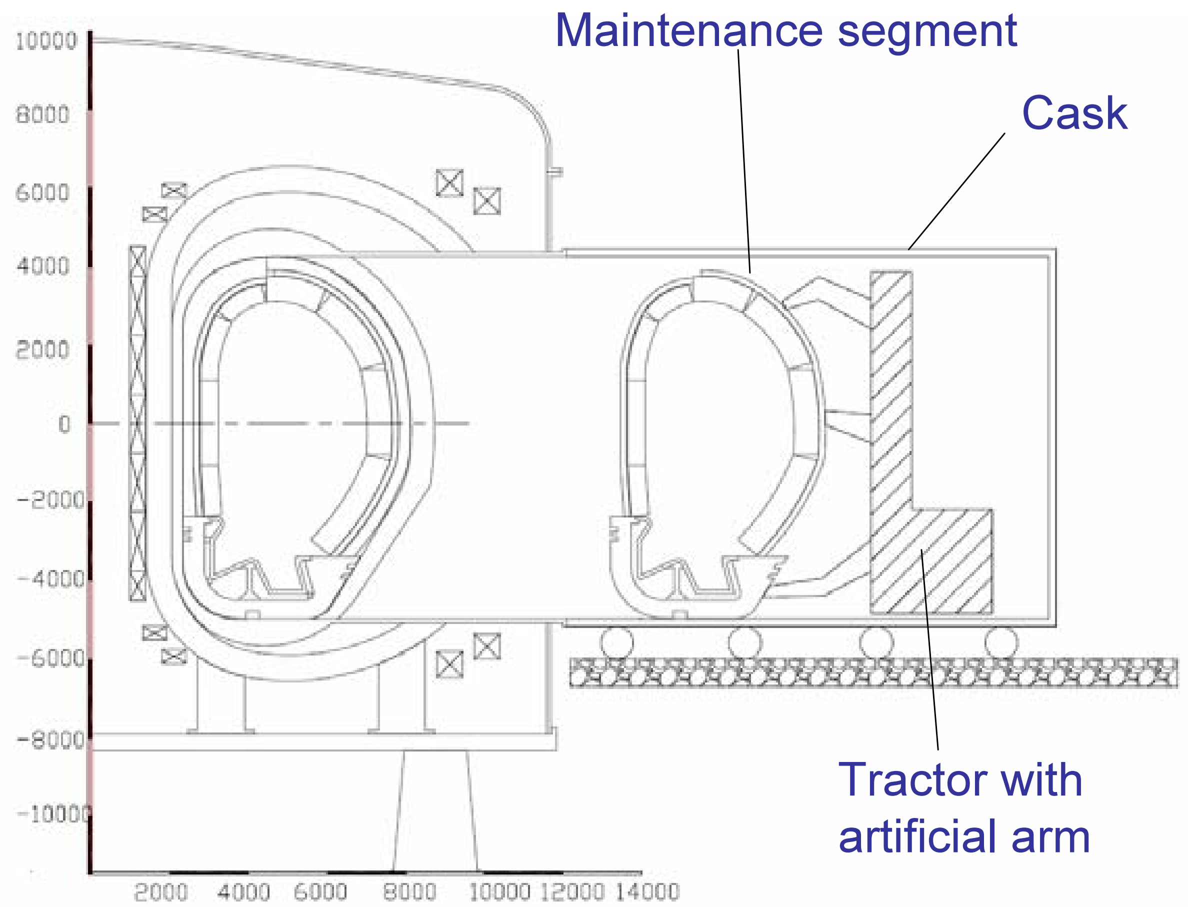


FDS－III reactor 3D view

- Blanket module coupling high temperature as blanket segment
- 12 modules for outboard segment
- 8 module for inboard segment

- Large toroidal coils to gain large horizontal maintenance ports
- Useful lifetime viewpoint of reducing waste
  - Short lifetime: Blanket
  - Intermediate lifetime: high temp. shield
  - Long lifetime: Low temp. shield

Maintenance of FDS-III Reactor



Process of one maintenance unit removed by tractor in cask

The blanket segment and diverter may be integrated one maintenance unit of 22.5º

Process of one unit removed

1) opening the double seal door;

2) cutting and clearing all kind of pipes;

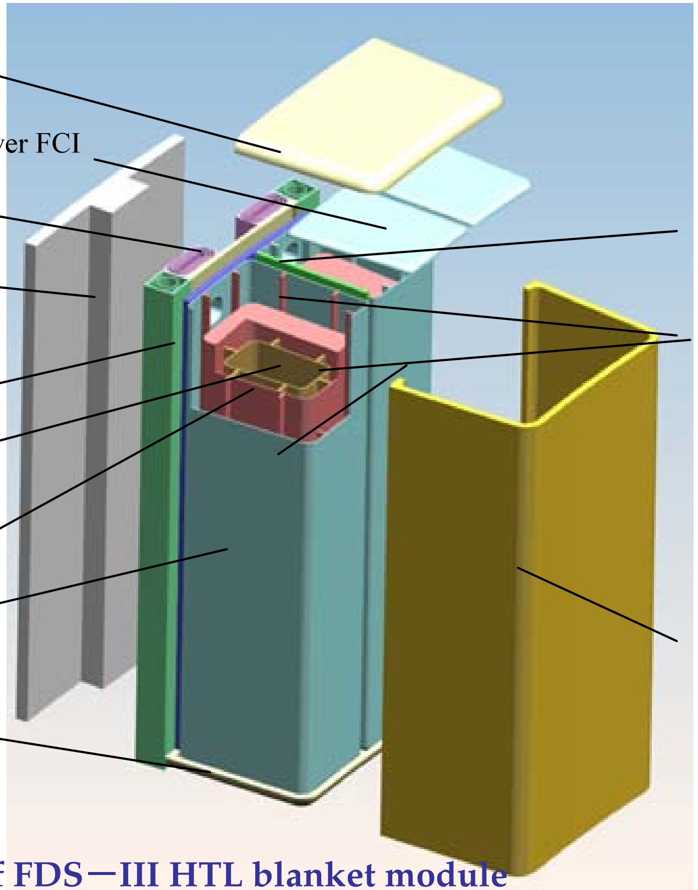
3) removing the out-door of vacuum to temporary parking area outside reactor;

4) removing the out low temperature shield to temporary parking area outside reactor;

5) drawing the maintenance unit out in-vacuum and transfer to Hot Cell.

The installation process is reverse.

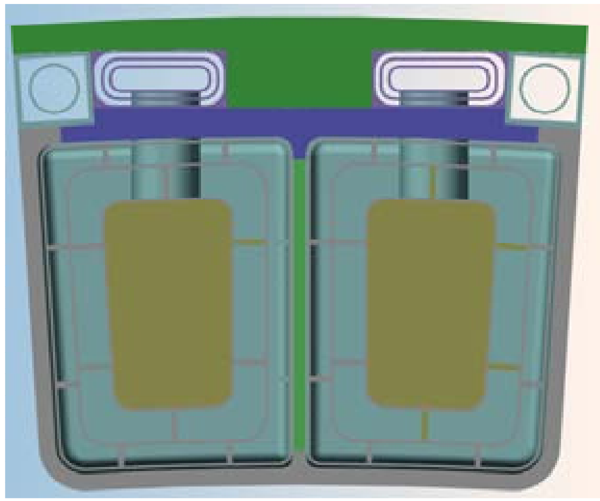
Blanket Module Feature



3D view of FDS—III HTL blanket module at horizontal port

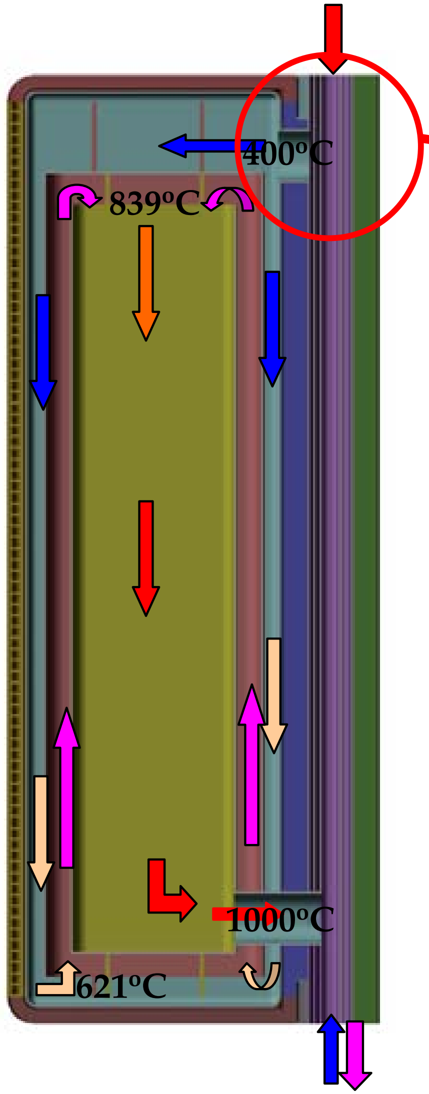
First Wall

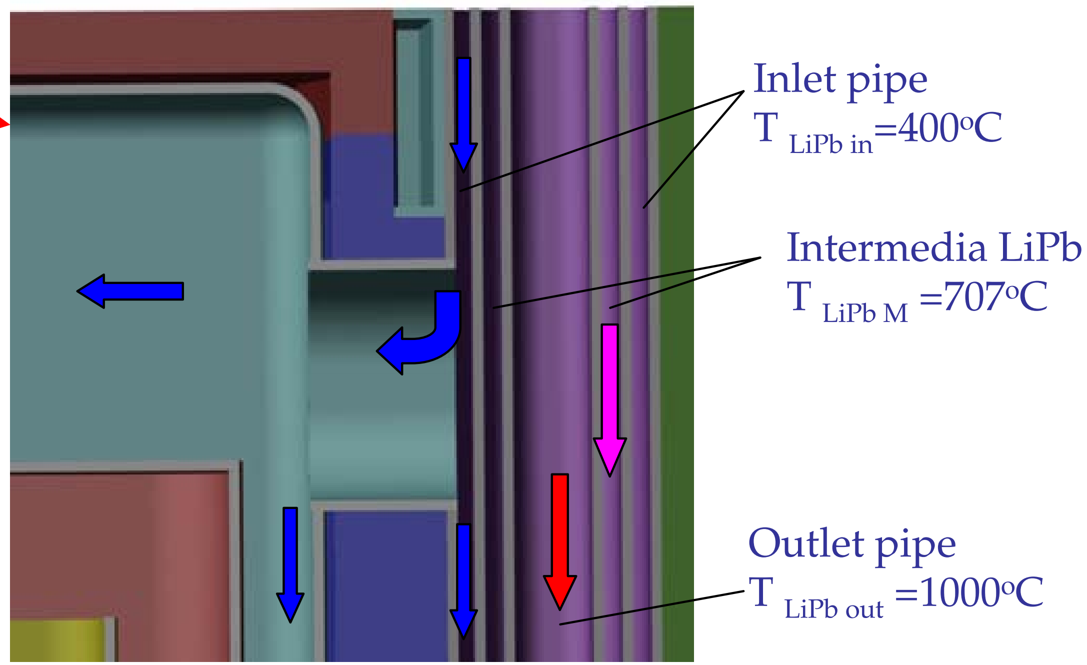
- **Dimension:**
  2120mm(pol.)*910mm(tol.)*640mm(ral.)
- **Materials:**
  ODS steel as the front wall of First Wall
  RAFM steel as main structural material
  SiC_f/SiC composite as FCIs
- **Blanket scheme:**
  Multilayer FCIs (MFCI) in LiPb channel:
  - Increasing LiPb temp. about 1000 ^{o}C
  - Reducing interface temp. RAFM steel /LiPb below 480^{o}C
  - Limited temp. gradient across FCIs



Cross section view of FDS—III HTL blanket module

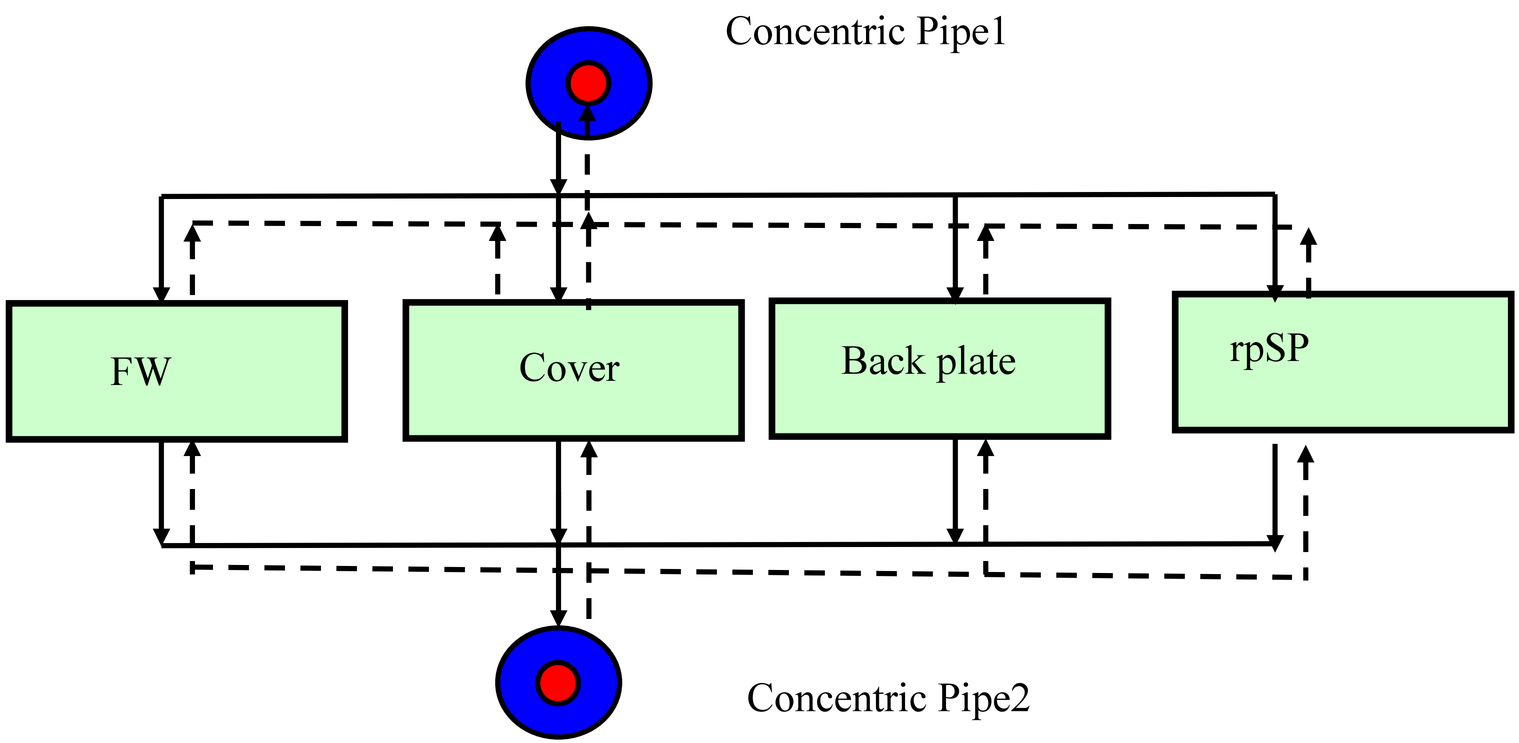
LiPb flow scheme inside Blanket Module





- Flowing from bottom to top in second FCI
- Flowing from top to bottom in first FCI
- Flowing from top to bottom in third FCI
- Flowing LiPb in second pipe of manifold only is circulated and provides intermediates zone to reduce temperature grade between inlet and outlet pipe

He flow scheme inside Blanket Module



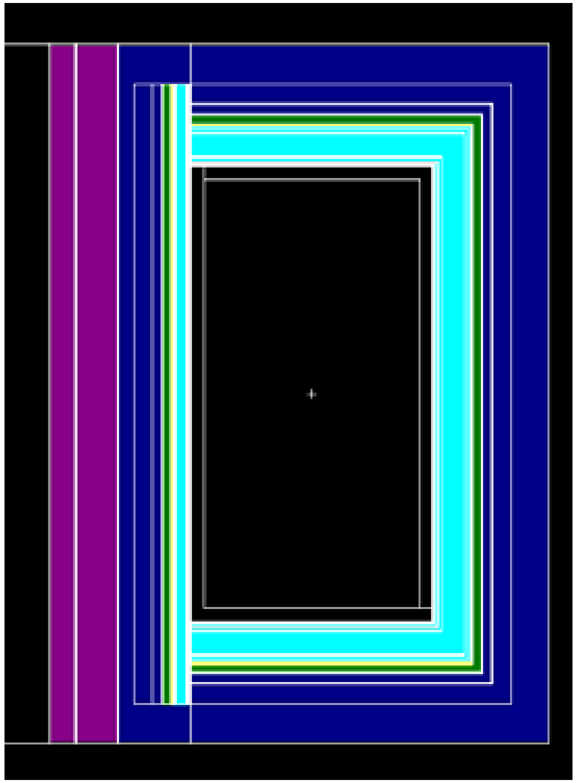
He gas from cold leg of one concentric manifold in rear of module fed in parallel into FW, cover, and back plate, then flow back hot leg of another concentric manifold.

Main Design Parameter

Neutron wall load / MWm^{-2}	4
FW surface heat load / MWm^{-2}	~1.04
FW channel: mm	18X20
T in / T out °C	350 / 366.5
V_{He} m/s	100
Cover channel: mm	12X18
T in / T out °C	350 / 368
V_{He} m/s	88
Radial-poloidal stiffening plate:	
mm	7X14
T in / T out °C	350 / 363.5
V_{He} m/s	81
Helium pressure / MPa	8
$T_{LiPb\ in}$ / $T_{LiPb\ out}$ °C	400/1000
First layer FCI $V_{LiPb\ 1}$ m/s	0.041
Second layer FCI $V_{LiPb\ 2}$ m/s	0.028
Third layer FCI $V_{LiPb\ 3}$ m/s	0.030
LiPb pressure drop MPa	0.01

Preliminary Performance analysis

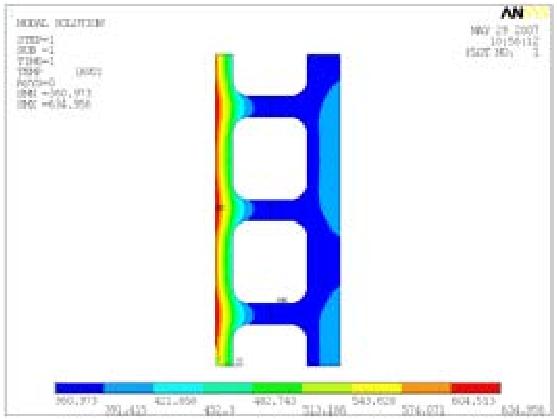
The neutronics analysis



Neutronics model (2D model)

The stress analysis

2D calculation model: radial-poloidal plane.
FW Heat Flux: 1.04MW/m2
Inlet /Outlet helium gas temperature: 350/366.5 °C.
The average velocity of helium gas: 100m/s.



The tritium breeding rate (TBR) by 90 % Li-6 enrichment in LiPb is approximate 1.38

The maximum temperature is 635 °C and the maximum stress is 379 MPa.

One Option of FDS III-based Hydrogen Production Process

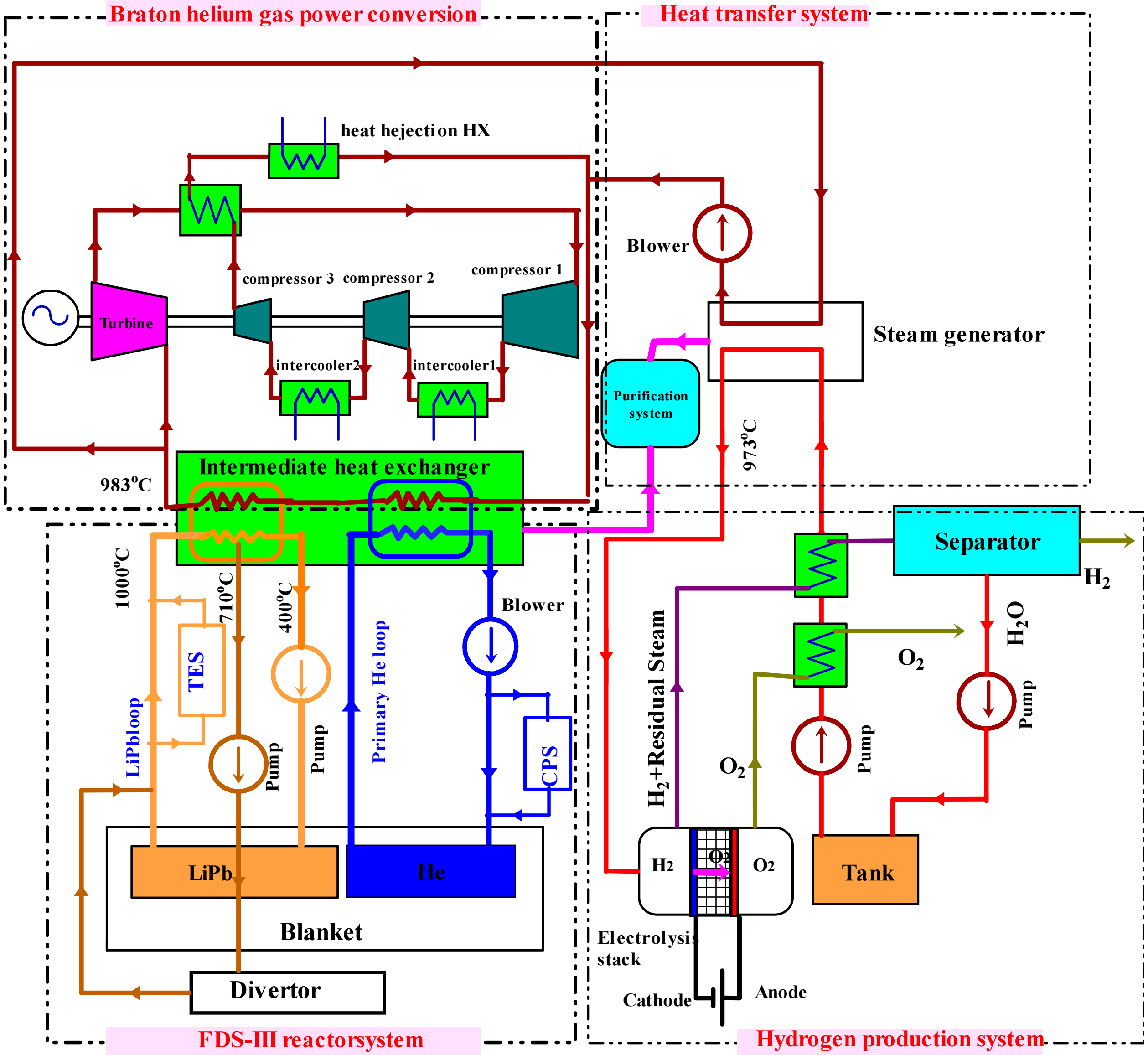


Diagram of HTSE hydrogen production

High **T**emperature **S**team **E**lectrolysis (**HTSE**) hydrogen production process as one of the options

- Indirect Brayton helium gas turbine cycle for power conversion
- Heat transfer loop to electrolysis stack
- Intermediate helium loop isolating loop preventing the tritium and hydrogen from permeation

The Power Conversion efficiency

The efficiency of the components and key parameters of system

Turbine efficiency	90%
Compressor efficiency	89%
Recuperator efficiency	95%
Generator efficiency	98%
Pressure drop ratio	5.0%
Compressor pressure ratio (total of all stages) r	2
Turbine inlet temperature T_O	1000 °C
Lowest helium temperature Ts	35 °C
Overall pressure loss ratio β	1.02
Ratio of helium specific heat γ =Cp/Cv	1.66

The operating pressure of 15 MPa at inlet of helium

$$\eta = \frac{\eta_t \frac{T_{in}}{T_{\min}}\left(1-\beta\left(\frac{1}{r}\right)^{\frac{\gamma-1}{\gamma}}\right)-\left(\frac{3}{\eta_c}\right)\left(r^{\frac{\gamma-1}{3\gamma}}-1\right)}{(1-\eta_x)\left(\frac{T_{in}}{T_{\min}}-1-\frac{1}{\eta_c}\left(r^{\frac{\gamma-1}{3\gamma}}-1\right)\right)+\eta_x\eta_t\frac{T_{in}}{T_{\min}}\left(1-\beta\left(\frac{1}{r}\right)^{\frac{\gamma-1}{\gamma}}\right)}$$

The power conversion efficiency of approximately 54%

--S. Malang,.. Fusion Eng. Des. 41 (1998) 561-567

The Hydrogen Production Efficiency

The electrolysis stack operates at 1 voltage and 973 ^{o}C

- The total energy required for steam electrolysis , Δ H: is 248 kJ/mol,
- The sum of the electrical energy demanded (Gibbs free energy change) for producing a unit amount of hydrogen within the electrolysis process, Δ G:is 194 kJ/mol.
- The energy loss : assumed to be accounted for 2% initially supplying heat.

$$\eta = \frac{\Delta \mathrm{H}}{\mathrm{Q}_{\mathrm{N,El}} + Q_{N,ES} + Q_{loss}} = \frac{\Delta H}{\Delta H + \frac{1-\eta_{\mathrm{El}}}{\eta_{\mathrm{El}}} \bullet \Delta \mathrm{G} + \mathrm{Q}_{\mathrm{loss}}}$$

The thermal-hydrogen production efficiency of approximate 55%

-Zhang ping. Science &technology review. 24(06), 2006 18-22

Summary

- The preliminary study of FDS-III (Fusion-Based Hydrogen Production Reactor) is reported.
- FDS-III features high core parameters, banana segment combining module blanket, and big maintenance port to increase availability.
- One novel high temperature liquid lithium–lead blanket (HTL) module, which install multilayer FCI and use RAFM steel as main structure material, is presented aimed for obtaining coolant outlet temperature of ~1000 ^{o}C
- As one option. the high temperature steam electrolysis for hydrogen production, which coupled FDS-III with Brayton helium gas turbine closed cycle, is selected
- The optimized design of blanket and detailed performance analysis is being carried out, relative R&D is underway, a lot of issues remain to be focused on , such as material evaluation, tritium penetration in high temperature.

FDS Team -- Fusion Design Study

Thanks for your attention !