核工业西南物理研究院 Southwestern Institute of Physics
中核集团 CNNC

Design Optimization and Safety Assessment of CN HCCB TBS

Xiaoyu WANG

Southwestern Institute of Physics (SWIP), China

On behalf of CN TBM team

CNTBM program: *Helium Cooled Ceramic Breeder Test Blanket System (HCCB TBS)*
Leaded by CN DA
Supporting Institutes:
1). Southwestern Institute of Physics (SWIP), China
2). China Academy of Engineering Physics (CAEP), China
3). Institute of Nuclear Energy Safety Technology(INEST), China

Outline

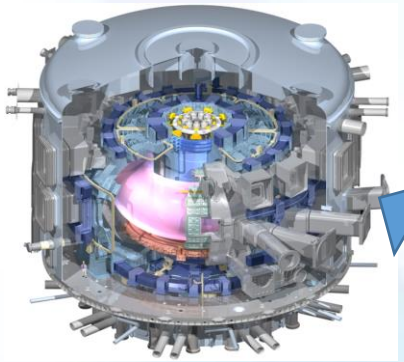
- Introduction
- System Overview
- Design Optimization and R&D Progress
- Safety Assessment
- Summary

Introduction

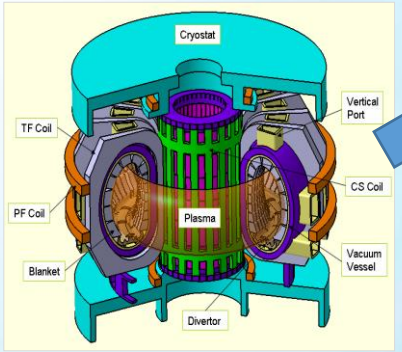
- The ITER facility could offer a unique opportunity to demonstrate the feasibility to test tritium breeding blanket technology in a tokamak reactor and to test Tritium producing components.
- Verification of tritium breeding technology by Test Blanket Module (TBM) program is one of the engineering goals for ITER.
- CN TBM Program was established by CN DA in 2009 and the Helium Cooled Ceramic Breeder (HCCB) TBM concept was selected.
- CN TBM Program is the first step toward the future breeding blanket for CFETR and DEMO.

General Objectives of CN HCCB-TBM Program

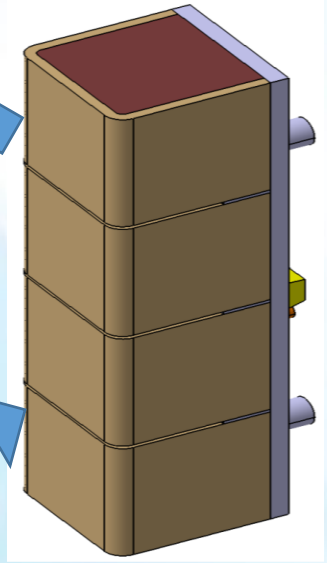
The objectives of CN HCCB TBS is to test the tritium breeding blanket technology in the tokamak operation conditions provided by ITER.



ITER



HCCB DEMO

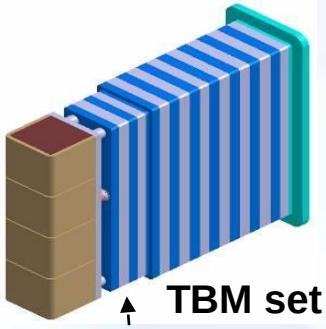


HCCB TBM

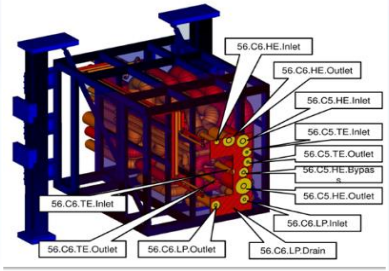
General Objectives

- Tritium technology
- Integral performance
- Power removal
- Diagnostics and control
- Safety
- Maintenance
- PIE

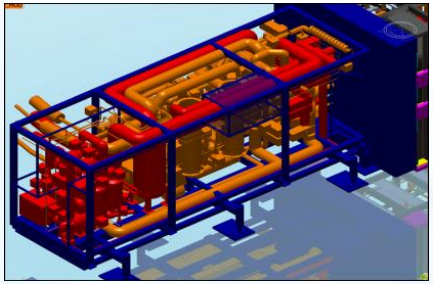
System Overview



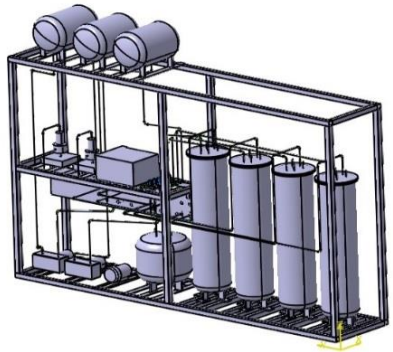
TBM set



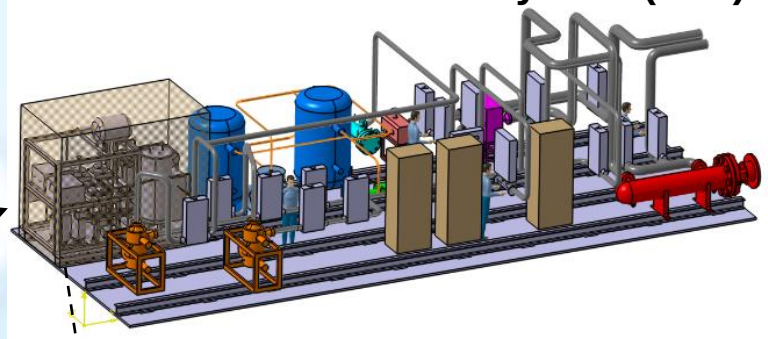
Pipe Forest (PF)



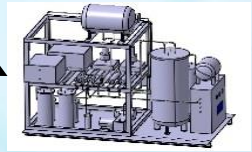
Ancillary Equipment Unit



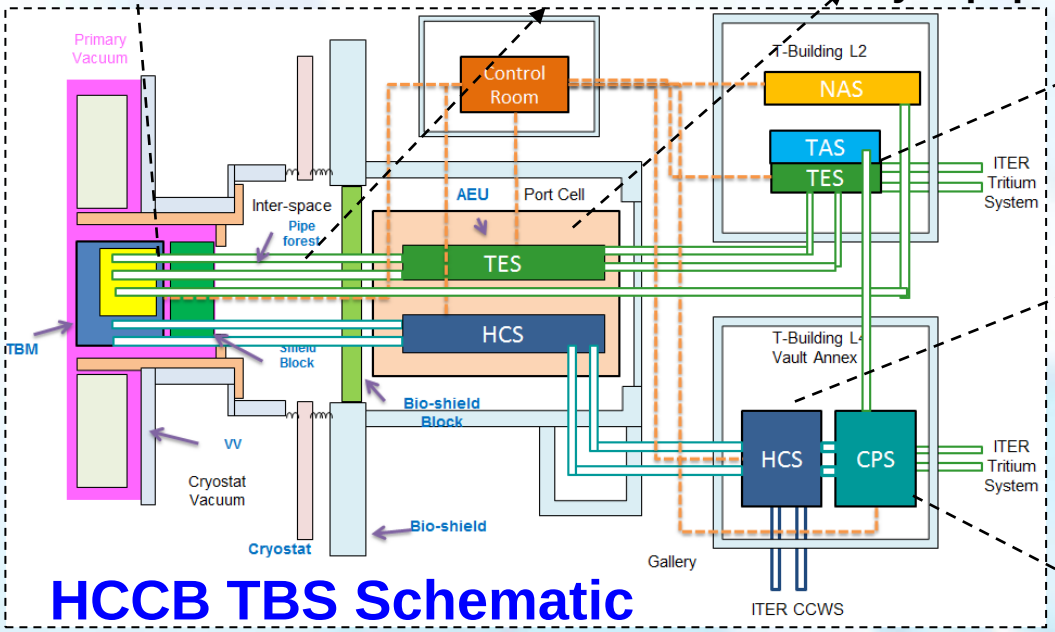
Tritium Extraction System (TES)



Helium Cooling System (HCS)



Coolant Purification System (CPS)



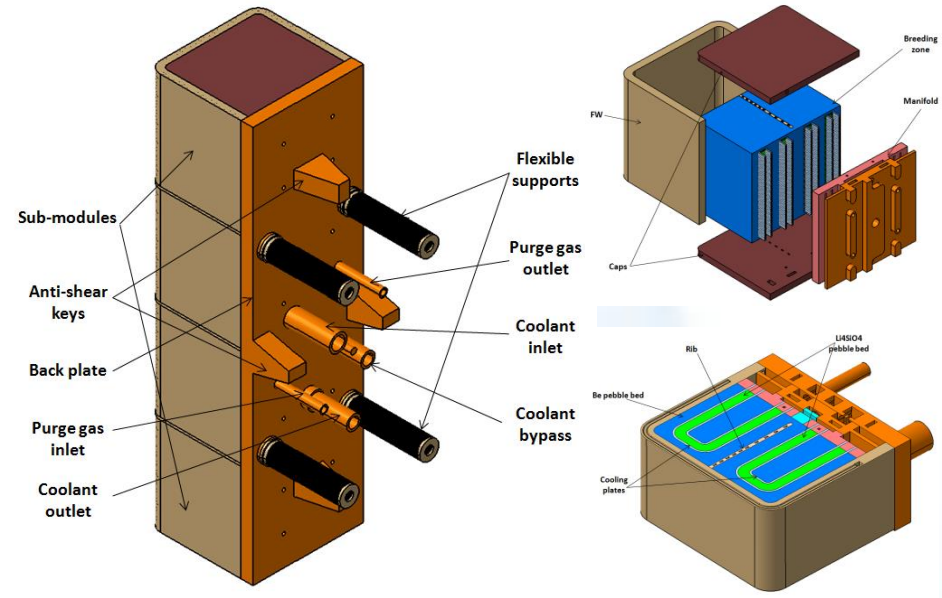
HCCB TBS Schematic

Core component: HCCB TBM

核工业西南物理研究院 Southwestern Institute of Physics
中核集团 CNNC

Main design parameters

Parameters	Values
Neutron wall load	0.78 MW/m^2
Surface heat flux	0.3 MW/m^2
Structural material	CLAM/CLF-1 ~1.3ton (<550ºC)
Tritium Breeder	Li_4SiO_4 pebble bed (<900ºC)
Neutron Multiplier	Beryllium pebble bed (<650ºC)
Coolant	Helium (8MPa) 1.04 kg/s (Normal) FW(300ºC/370ºC) Breeding zone (370ºC/500ºC)
Purge gas	Helium with H_2
TPR	0.061g/FPD



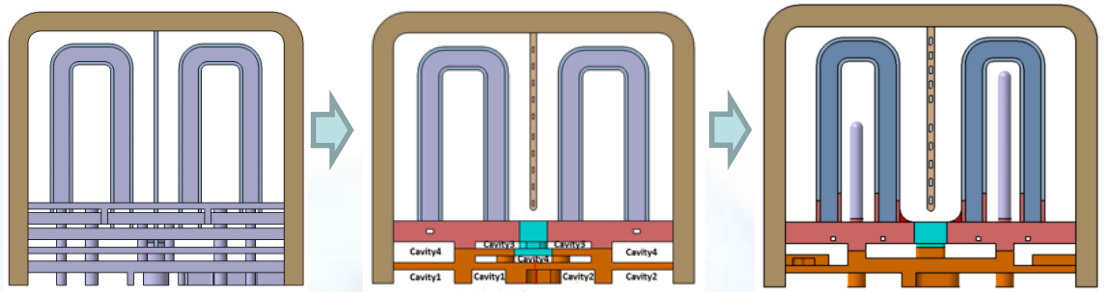
Design of HCCB TBM

- **Design features**
  - Four sub-modules concept
    - Manufacturability
    - PIE/ transportation
  - U shape breeding zone
    - Reduce the structural material

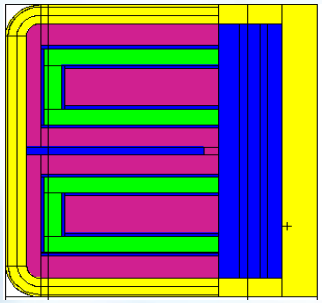
Design Optimization and R&D Progress

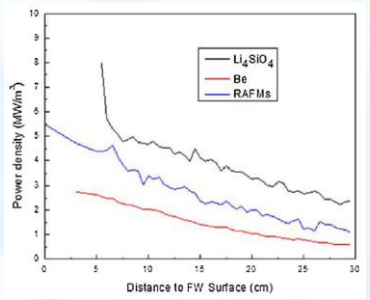
Design Optimization for HCCB TBM-set

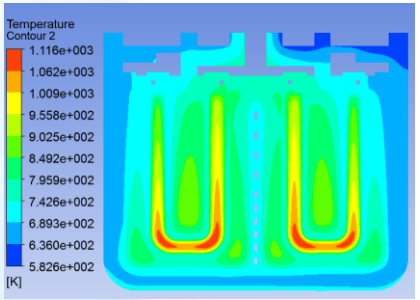
- **Design optimization of TBM**
  - Manufacturing feasibility
  - Engineering performance
- **Preliminary engineering assessment of TBM**
  - Neutronics
  - Hydraulic
  - Thermal
  - EM analysis
  - Structural



Design optimization of HCCB TBM

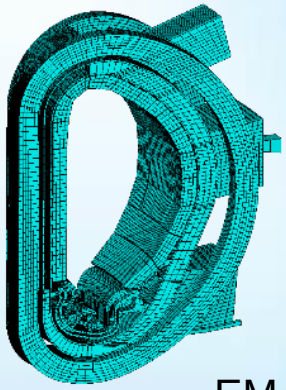


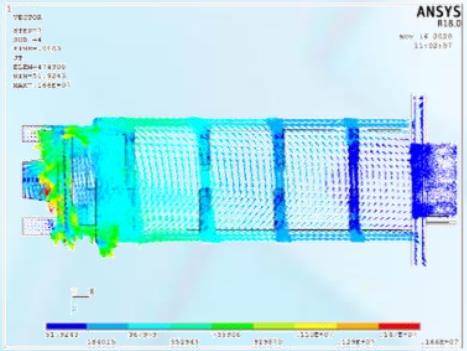




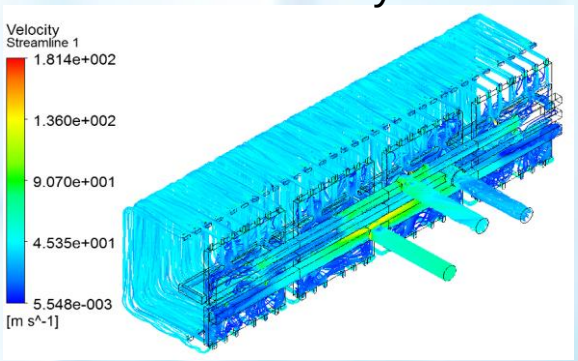
Neutronics analysis

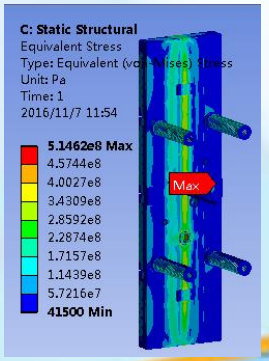
Thermal analysis





EM analysis

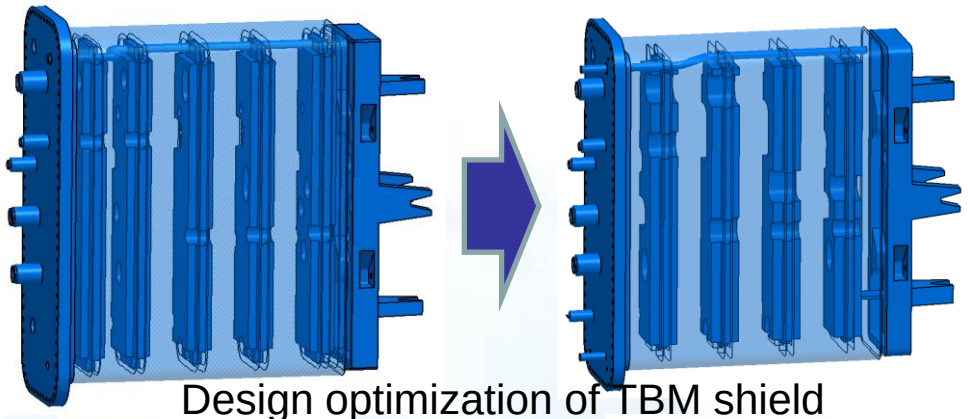




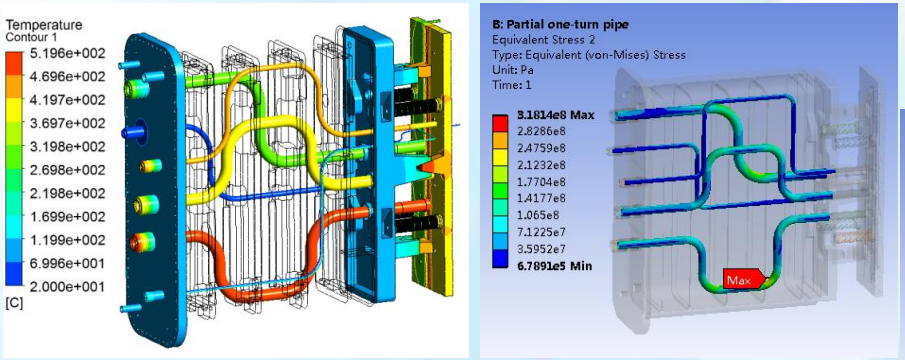
Hydraulic and structural analysis

Design Optimization for HCCB TBM-set

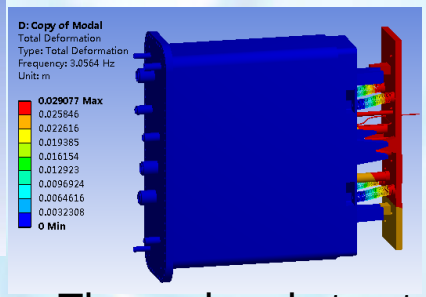
- **Design optimization of TBM shield**
  - Manufacturing feasibility:
  - Engineering performance:
- **Preliminary engineering assessment of TBM shield**
  - Thermal-hydraulic
  - Structural
  - Modal

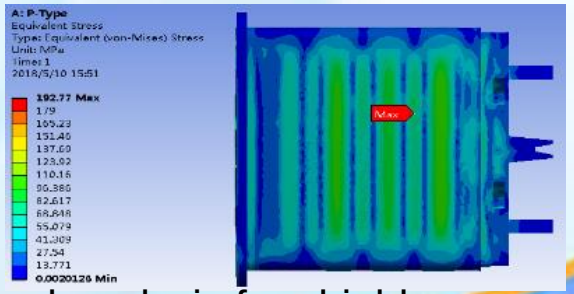


Design optimization of TBM shield



Thermal and structural analysis for pipes



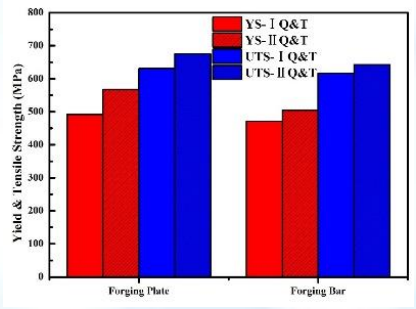


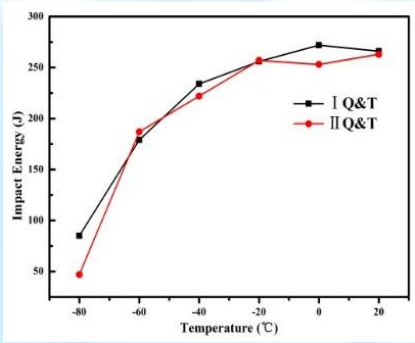
Thermal and structural analysis for shield

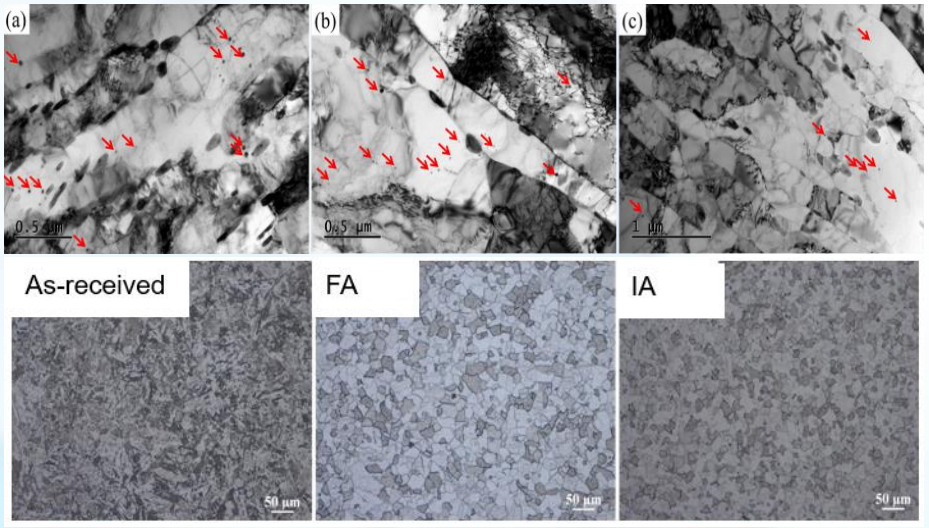
Material Development

- **Industrialized manufacture process of RAFM steel (CLF-1 and CLAM) has been finalized and will be qualified by CN DA.**
- **Up to 5000h, 550℃ thermal aging experiment was performed.**

Several 5-ton ingots of CLF-1 steel and CLAM steel have been fabricated into plates and forgings by industrialized manufacture process.



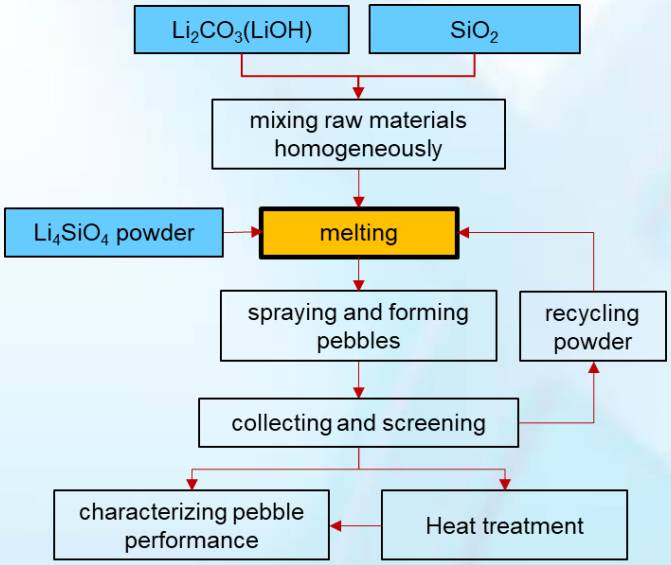




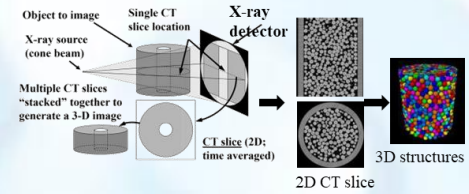
Two types(Full annealing and Isothermal annealing) of annealing process were developed.

Material Development

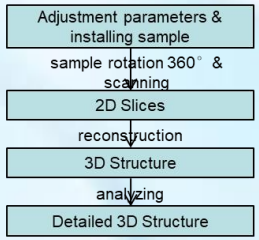
- New facility for Li_4SiO_4 fabrication has been constructed, which will ensure the fabrication capability for the HCCB TBM.
- Facility for thermo-mechanical properties testing of pebble beds under multi-physics field was under construction.
- The X-ray computed tomography (CT) was used to investigate the packing structures of mono-sized and binary-sized pebble beds. The CT experimental results agreed well with DEM simulation results.



Li_4SiO_4 fabrication process



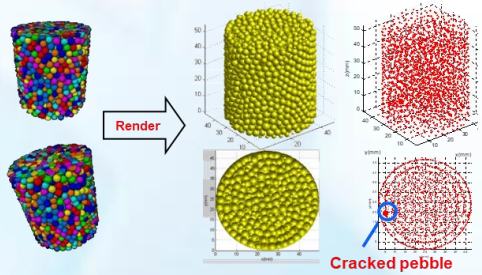
Schematic of the X-ray CT imaging processing



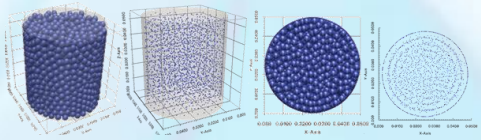
Procedure of X-ray CT experiment

Average Packing factor

Methods	AVG. Packing Factor
X-ray CT	0.6254
DEM	0.6240



Results of the X-ray computed tomography

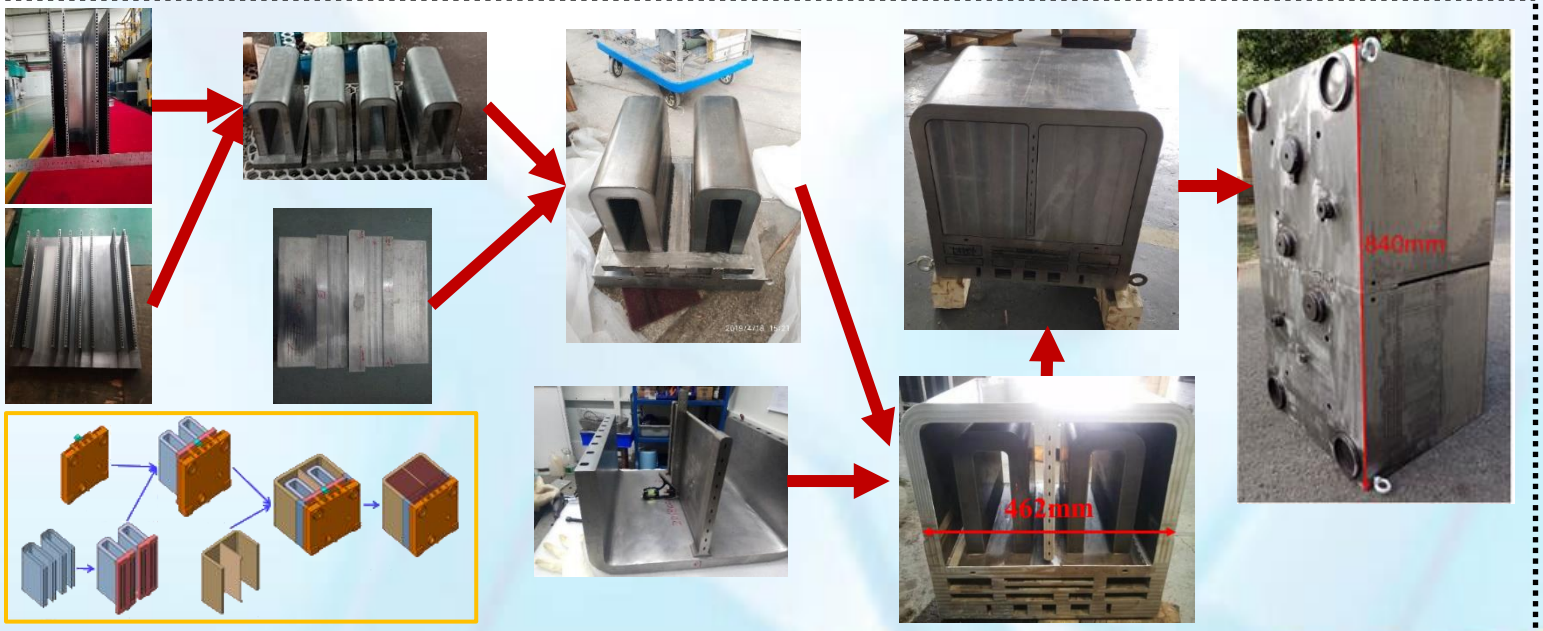


Results of the DEM simulation

Pebble bed packing structure by CT and DEM simulation

TBM Fabrication Technology

- **Semi-prototype mockup of TBM was successfully fabricated and tested by NDT. Pressure test and helium leakage test will be performed.**
- **A small mockup of external frame with inner plate in TBM shield was fabricated and tested by RT. Another mockup of double-layer pipe was under fabrication.**

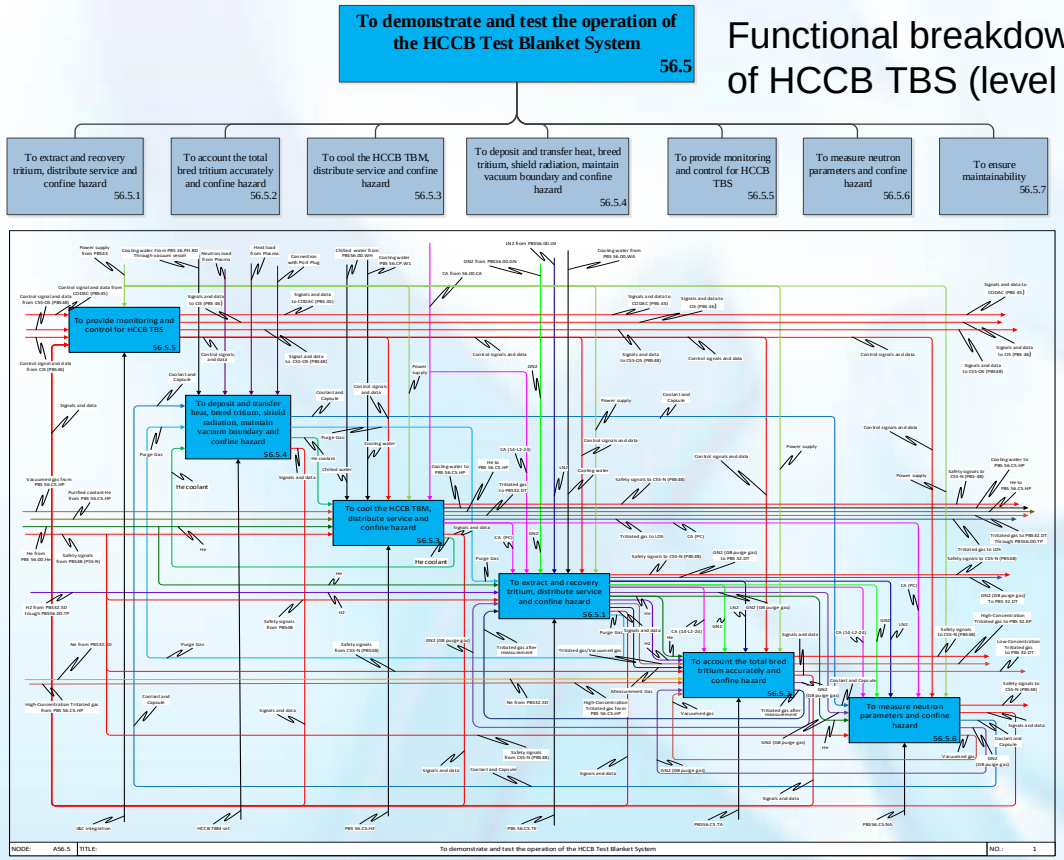


Fabrication processes for semi-prototype of HCCB TBM

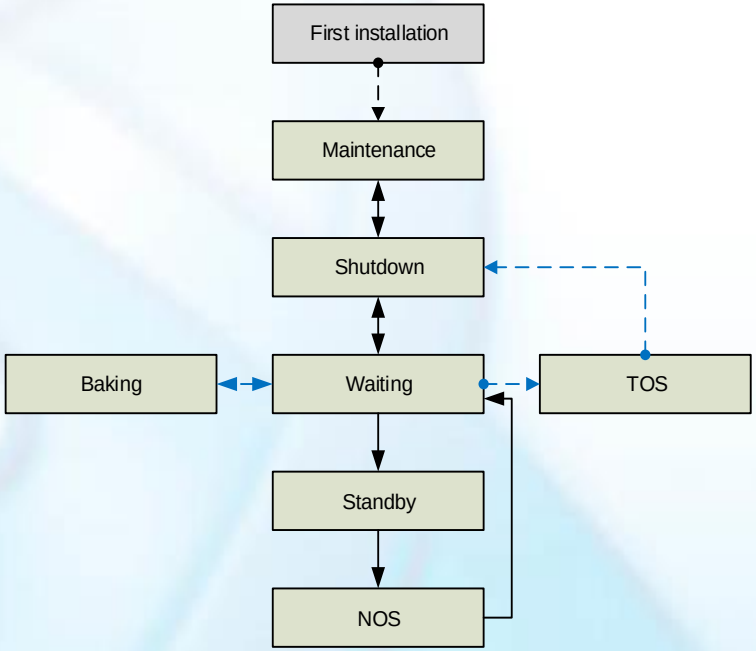
Component sample for TBM shield

Progress on systems integration

- **Updated functional analysis of HCCB TBS for normal operation and maintenance, including functional break down and IDEF0.**
- **Re-defined HCCB TBS operation state and shift scheme.**



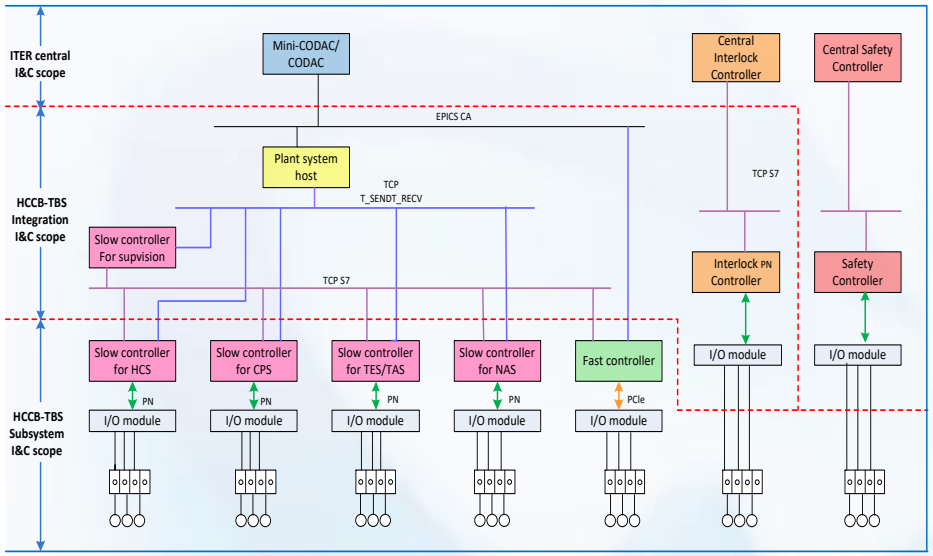
Functional breakdown of HCCB TBS (level 1)



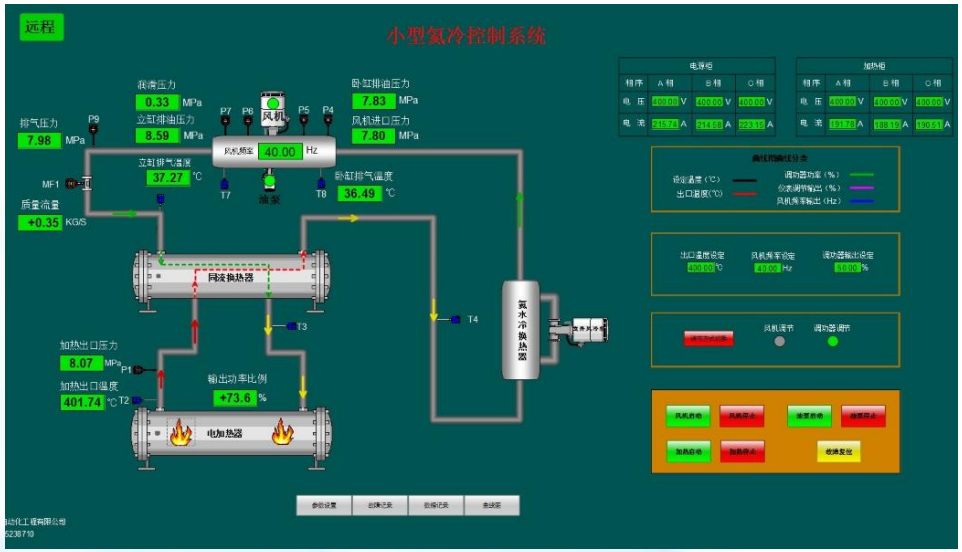
Transitions of the HCCB TBS PSOS

IDEF0 of HCCB TBS (level 1)

Press on I&C design and R&D

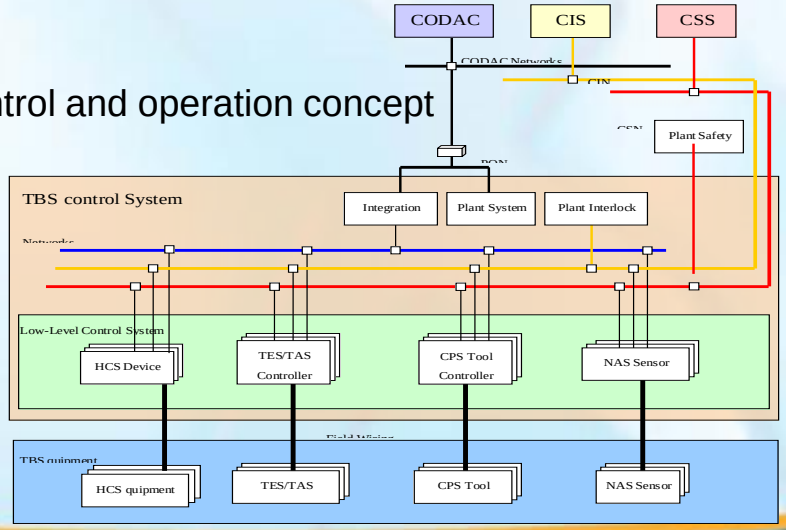


I&C architecture of HCCB TBS



Control of HeCEL-1 helium loop by mini-CODAC

TBS control and operation concept

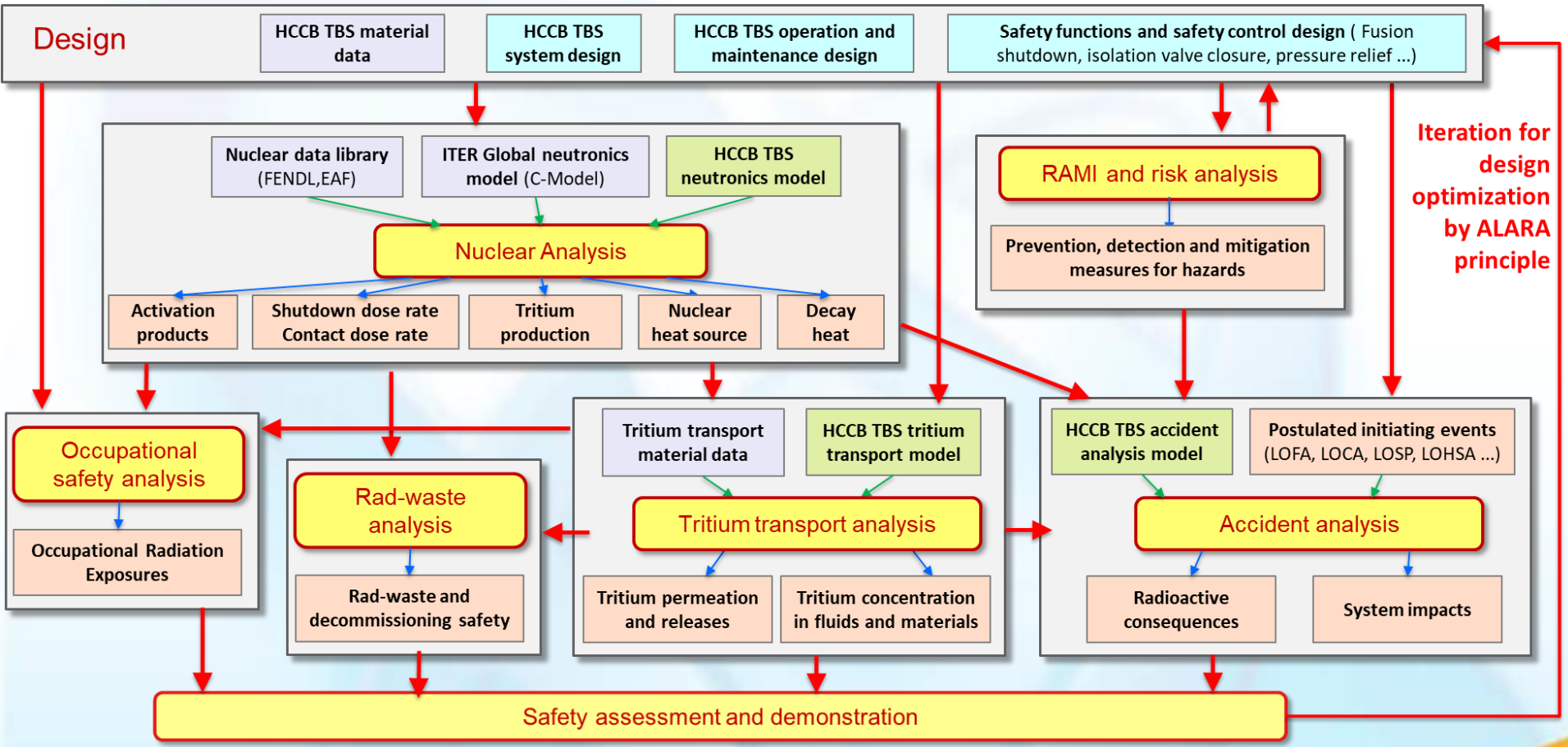


RHA testing

Transmitter-probe separation and long distance signal transmission testing

Safety Assessment

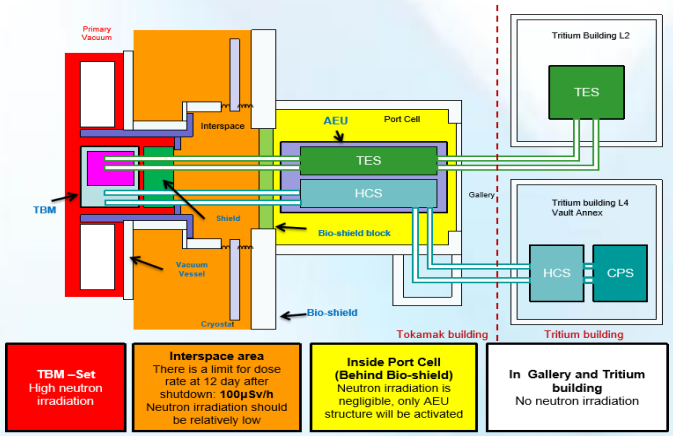
Overview of Safety assessment and demonstration



Nuclear analysis

The Concern

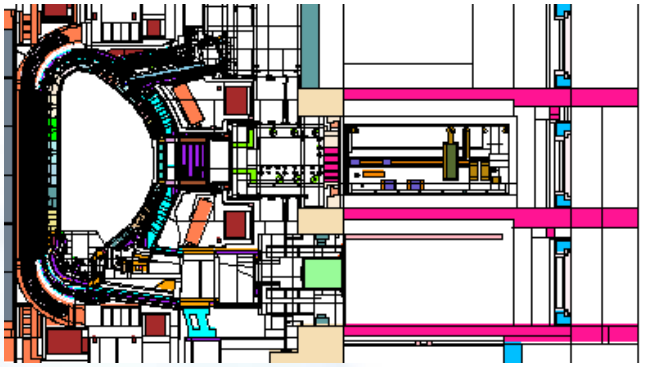
- Shielding functions
- Activation
- Decay heat
- Dose rate
- Rad-waste characteristics.



Irradiation for HCCB TBS

The Methods

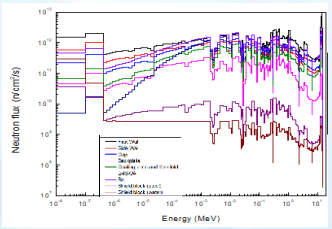
- HCCB TBM+Port Cell+ITER C-Model
- ITER neutron sources
- ITER irradiation scenarios
- MC code, FENDL 2.1
- FISPACT and EAF-2007 library
- Direct One-Step Method.



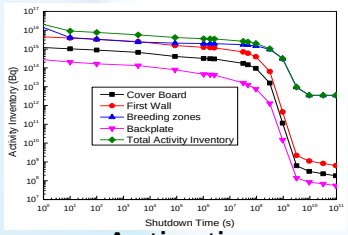
HCCB TBS neutronics model integrated into ITER C-model

The Results

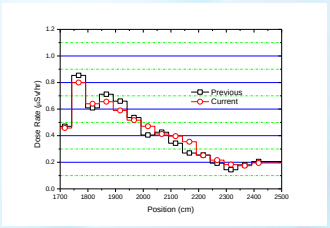
- Neutron fluxes spectrum
- Tritium production rates
- Nuclear heat
- Neutron activation and
- Decay heat
- Contact dose rate
- Shutdown dose rate



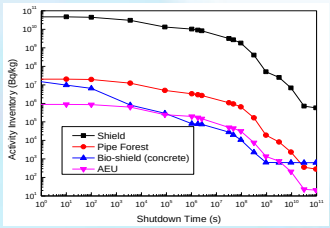
Neutron spectrum



Activation



Shutdown dose rate



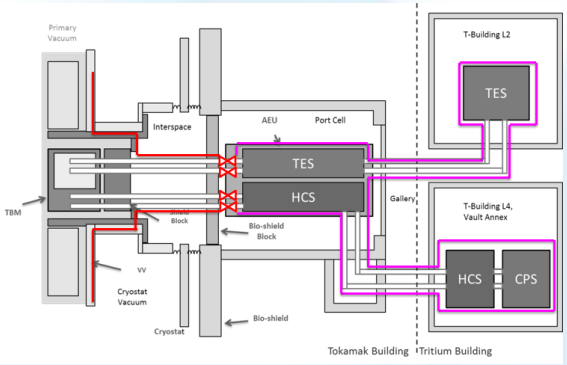
Activation of others

Tritium safety analysis

核工业西南物理研究院 Southwestern Institute of Physics
中核集团 CNNC

The Concern

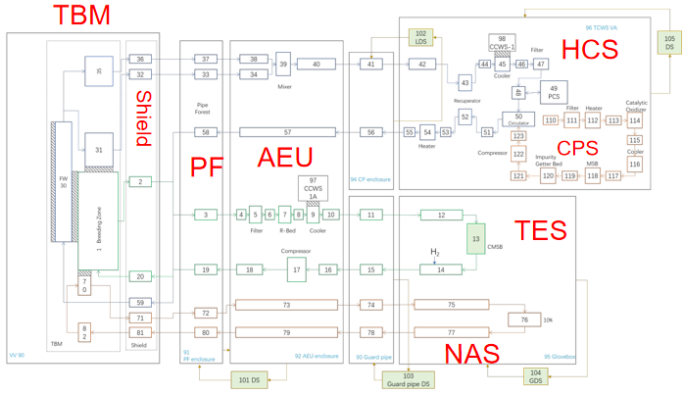
- Tritium → **confinement**
- **Tritium**
  - **concentrations**
  - **inventories**
  - **releases**
- → accident analysis
- → rad-waste analysis.



1st confinement barriers for in-vessel inventory: TBM shield, Frame, VV, pipe forest, isolation valves;
1st confinement barriers for ex-vessel inventory: other pipes and component walls;
2nd confinement barriers: TES Glove boxes, ITER buildings, detritiation systems, ventilation systems …

The Methods

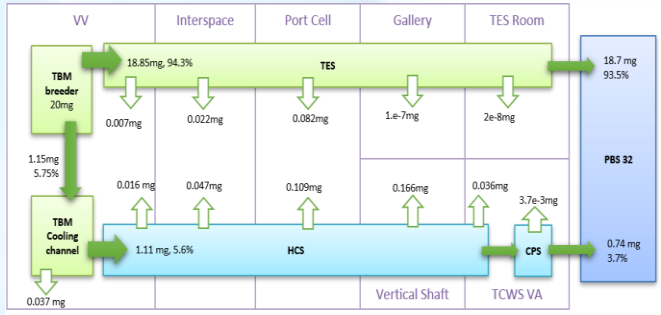
- **Self-developed system transport analysis code**
- Modelling of all sub-systems and interface systems
- **Considered physics:**
  - balance, dissociation
  - recombination
  - Diffusion, trapping
  - isotopic effects
  - Permeation, absorption



Tritium analysis model

The Results

- Tritium **concentration** in different **fluids** in the system
- Tritium **concentration** in **atmosphere** of different confinement compartments
- Tritium **concentration** profile in **solid materials**, tritium **inventories**.
- Tritium **permeation fluxes** through solid walls.
- Tritium **removal rates**

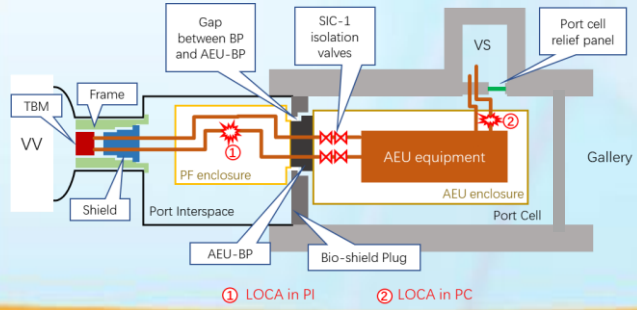


Tritium analysis results

Accident analysis

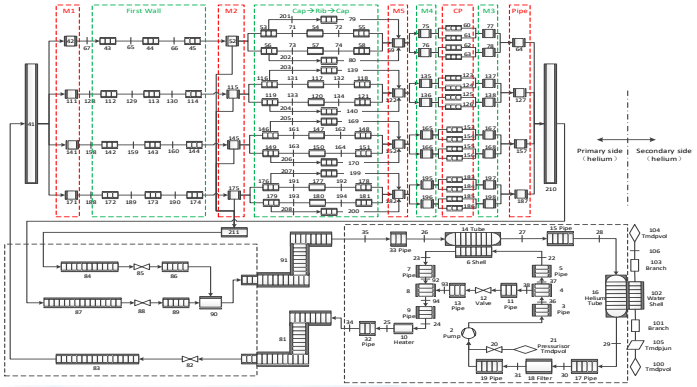
The Concern

- **Postulated initiating events (PIEs)**, : LOFA, In-vessel LOCA, In-TBM Box LOCA, Ex-vessel LOCA, Heat exchange break, tritium process line break etc.,
- **Transient thermal hydraulic behavior** in HCCB TBS and **impacts on surrounding systems**
- Check if the **radioactive releases** are the within the release limits
- Check if the **safety control measures** are appropriate to mitigate the accident consequences.



The Methods

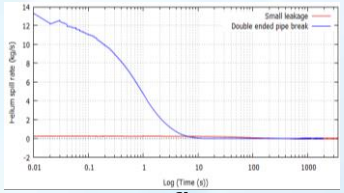
- **Thermal hydraulics codes** like RELAP5
- **Modelling of TBM, HCS, TES and interfacing systems**
- Nuclear heating, plasma heat flux and decay heat sources
- Safety controls
- Considering aggravating failures of neighboring systems



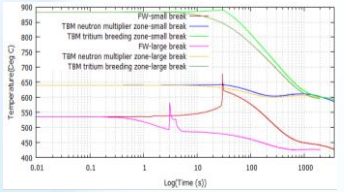
Accident analysis model

The Results

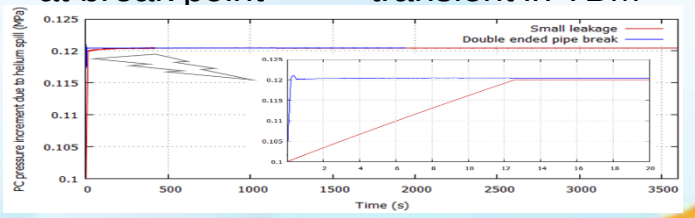
- Transient helium **mass flow rates**
- Transient **pressure**
- Transient **temperature** in TBM and other heat structures
- Helium release and **radioactive release** amounts
- Comparison with acceptance criteria



He mass flow rate at break point



Temperature transient in TBM



Pressurization of Port Cell

Summary

- CN HCCB TBS is **one of the most important part** of China fusion development strategy toward DEMO.
- The design of the HCCB TBS has been **significantly optimized** based on the interface and manufacturability. The **qualification** of materials and **pre-qualification** of fabrication processes are planned to support the design.
- According to the two **main safety functions** in HCCB TBS, **confinement** and **shielding**, the safety of HCCB TBS covering **nuclear analysis**, **tritium analysis** and **accident analysis** has been assessed to ensure and demonstrate the design of main safety functions, as well as supporting safety functions.

Thank you for your attention!