Development of the high temperature PbLi experimental platform for CFETR

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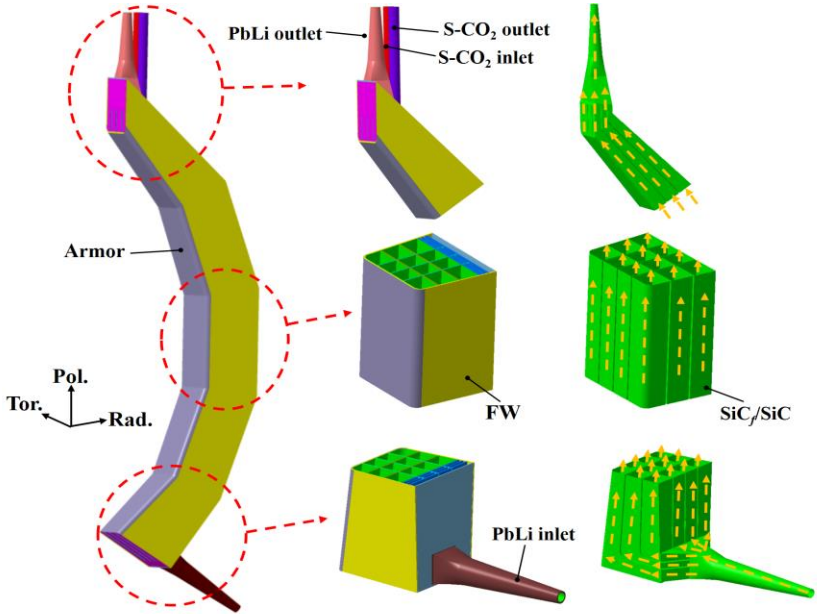
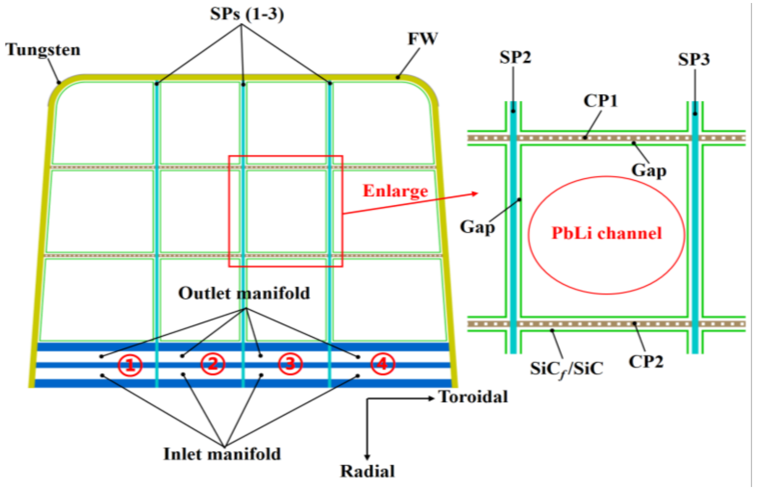
ISFNT-15th September 10 – 15, 2023, Las Palmas de Gran Canaria, Spain

COOL blanket design





COOL blanket structure design

Design features

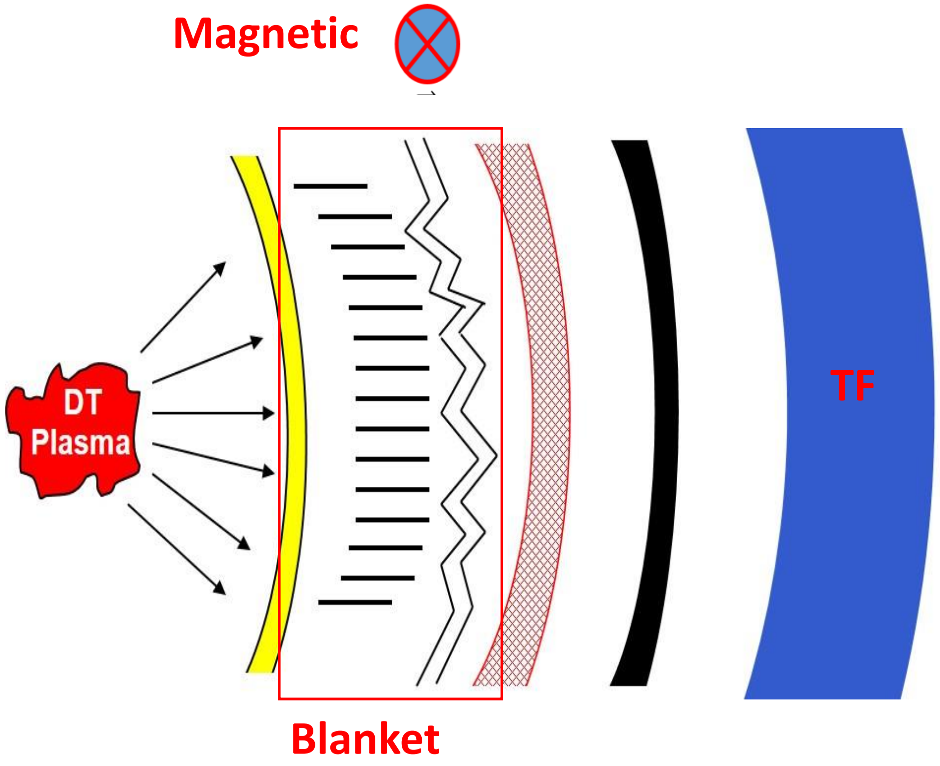
- Single Module Segment,
- RAFM steel as structural material
- S-CO_2: 8 MPa, 350 °C ~ 400 °C
- PbLi: 1~2 MPa, 460 °C ~ 700 °C
- FCIs to mitigate the MHD effect and corrosion
- PbLi “once-through” scheme
- Thermoelectric conversion efficiency: ~42%

Main advantages

- **Economic:** Beryllium-based material is not used as the neutron multiplier
- **Efficiency:** Coolant outlet temperature can reach 700℃, thermoelectric conversion efficiency is high
- **Online refueling and tritium** extraction can be realized

Ref. Chen L., Jiang K., Ma X. and Wu. Q. 2021 Conceptual design of the supercritical CO_2 cooled lithium lead blanket for CFETR Fusion Eng. and Des. 173 112800

COOL blanket design



- ➢ **Complicate turbulent （Re~10^5）**
  - Algorithm and mesh
- ➢ **High magnetic (Ha~10^4)**
  - Thin BL and large velocity gradient
- ➢ **Large temperature difference(Gr~10^{12})**
  - Heat convection instability

Multi-physics coupling

Experiment and computing face great challenges!!

***u*=*f*(*Ha*,*Gr*,*Re*) ???**

Ref. *Mingjiu Ni*, Interdisciplinary Seminar on "Research and Development and Numerical Simulation of Magnetic Confinement Fusion Key Technologies“, November, 18-20, 2020, Hefei, China.

Critical scientific issues to be addressed：1. MHD effects；2. Mixed convection

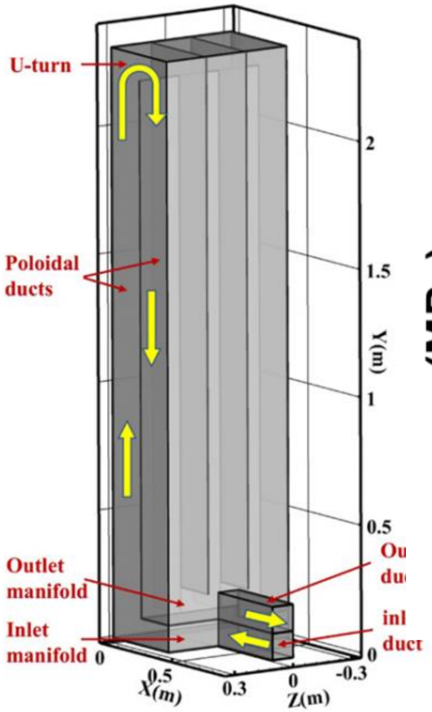
Key scientific issues

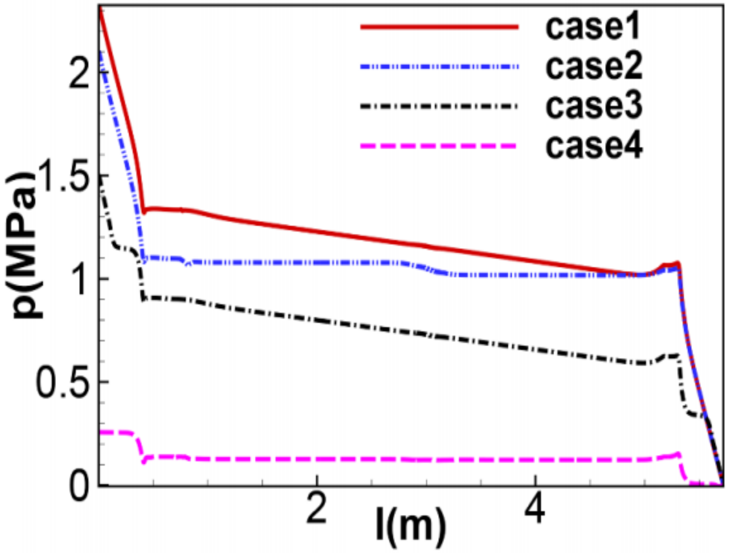
➢ MHD effects

Ha~10^4

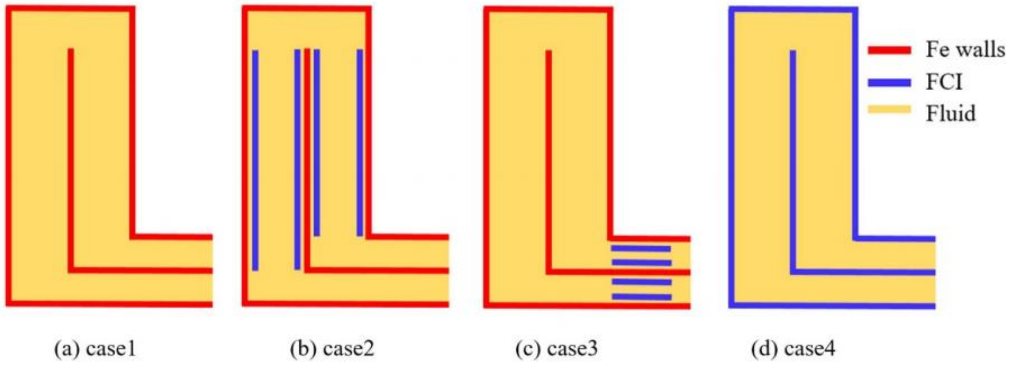
Re~10^5

Gr~10^{10}





L Chen, S. Smolentsev, M.J. Ni Part I, Nuclear Fusion 60 (2020) 076003; Part II, Nuclear Fusion 62 (2022) 026042

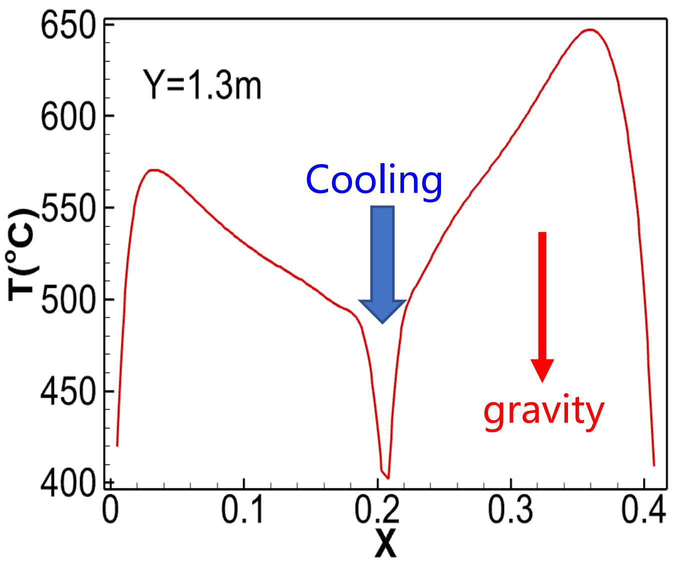


FCIs can largely reduce the pressure drop →10 times comparing case 1 and case 4

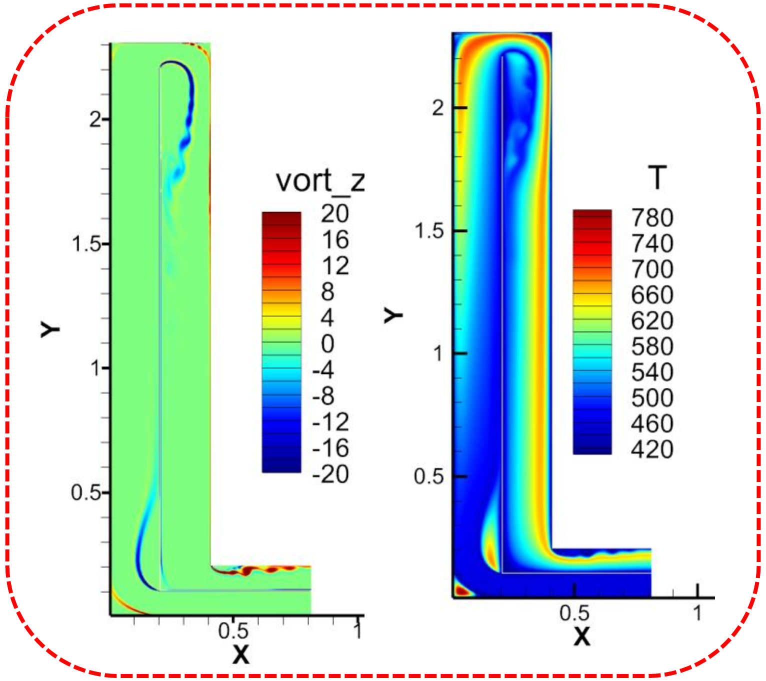
- The FCIs performance under magnetic field needs verification by experiments
- The pressure drop and magnetic have strong nonlinear relationship, the existing experimental parameters are low, thus it is necessary to carry out strong magnetic field related experiments.

Key scientific issues

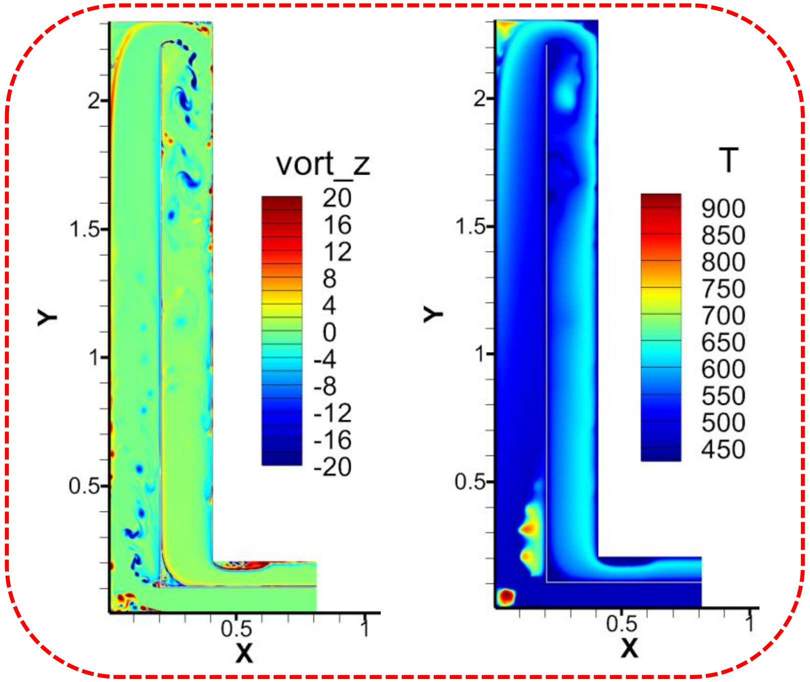
➢ Mixed convection



Radial temperature distribution



Forced convection



Mixed convection (Buoyancy)

Buoyancy has significant effects on flow and heat transfer, even the deterioration of local heat transfer and thermal fatigue occurred, threatening the blanket structure safety

- Experiments on the mixed convection under strong magnetic and buoyancy are scarce, thus the development on the PbLi experimental loop is necessary to study its mechanism

Summary on experiments

- MHD effects
  - Phase diagram and turbulent transition mechanism under different Re/Ha
  - The effects of FCI on the flow and heat transfer
  - MHD flow in complex geometry channel
  - Multi channel under electromagnetic coupling effect

Magnetic

- Mixed convection
  - One-side heat flux conditions
  - Large magnetic/heat source

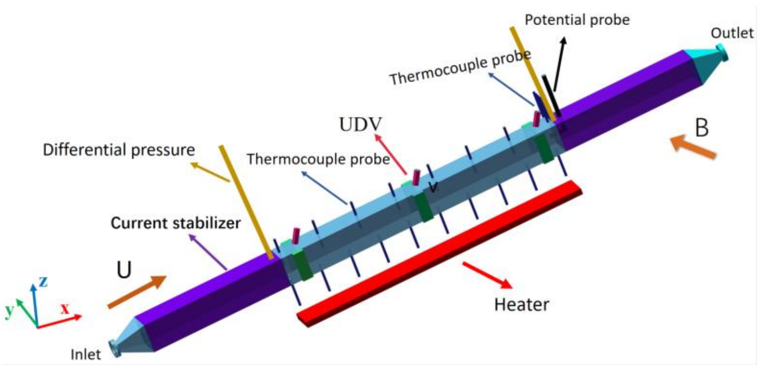
Magnetic + Heat flux

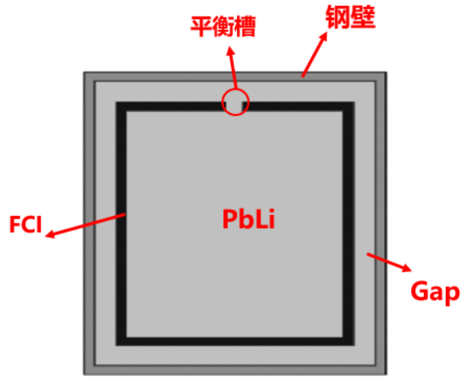
- Out-pipe of Mockup test
  - Mockup prototype component

Experiment design

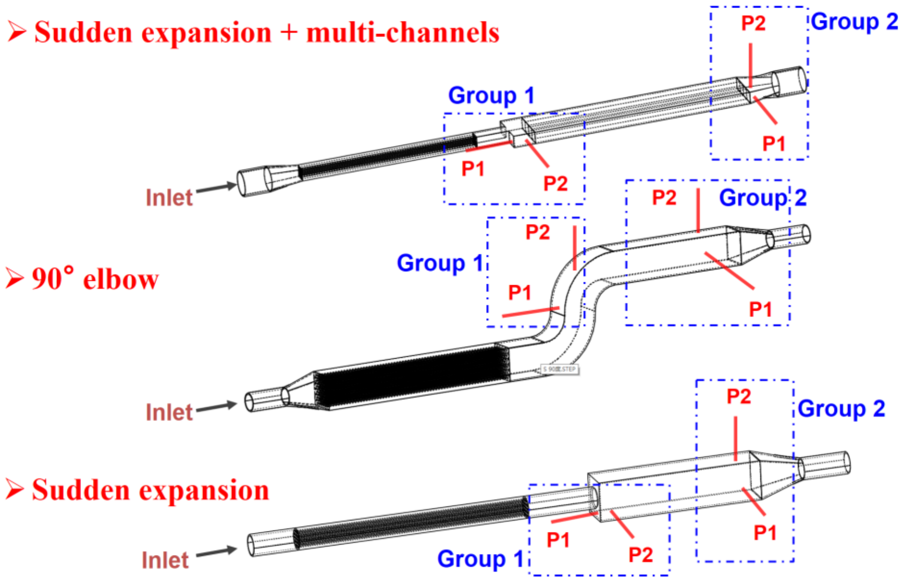
➢ MHD effects and Mixed convection

- **Main purpose**
  - Turbulent phase diagram under different Re/Ha/Gr
  - The effects of FCI on the mixed convection
  - Mixed convection in complex geometry channel
  - Create models: $f,u,Nu=f(Re,Ha,Gr)$





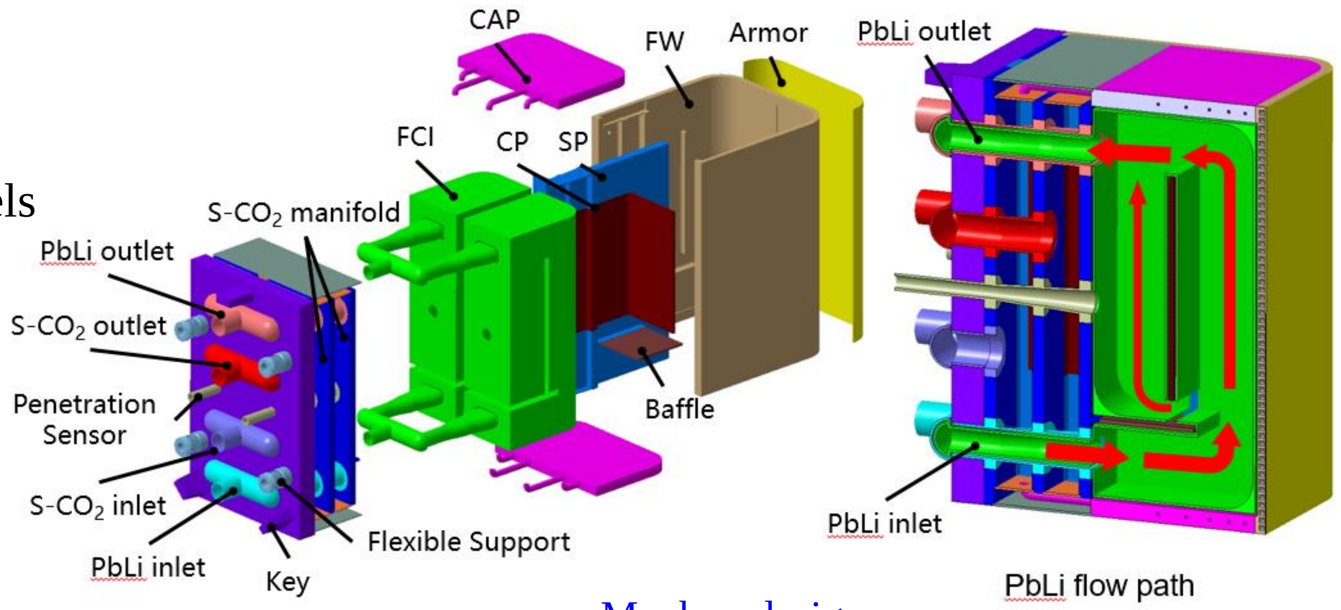
- **Test section**
  - **FCIs** are inserted into the straight channel and complex geometries (the thermal and electrical conductivity are variables)
  - **Operating conditions:** magnetic, heat flux
  - Instruments: thermocouple, potential probe, differential pressure meter, UDV



Experiment design

➢ Out-pipe of Mockup test

- **Main purpose**
  - PbLi flow characteristics
  - Mass flow distribution in parallel multi-channels
  - MHD flow in complex geometry channel
  - Create models: *f,u =f(Re)*
- **Test section**
  - Mockup prototype component
  - Operation conditions： flow, heat insulation
  - Instruments: thermocouple, potential probe, differential pressure meter, UDV



Mockup design

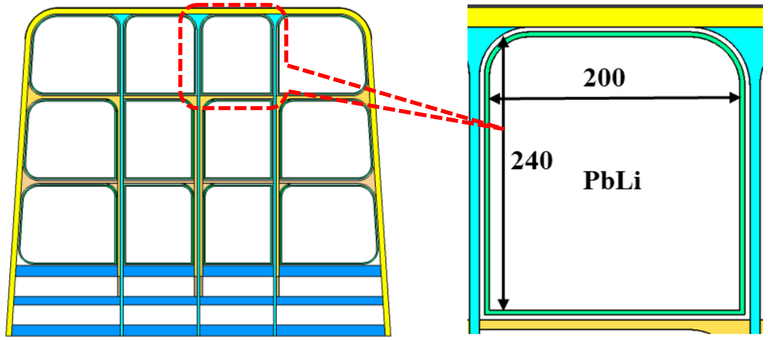
➢ Operation modes

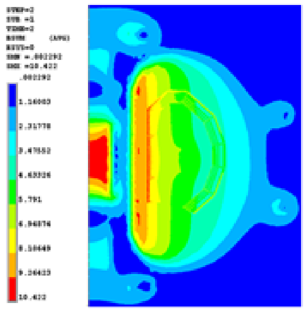
- Low temperature： 400/450 ℃; 1.41kg/s
- High temperature： 460/600 ℃; 0.88kg/s

Experiment design

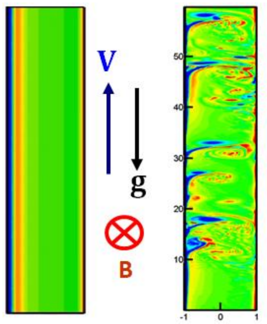
➢ Test parameters deriviation

CFETR COOL





B_{opt}~5T



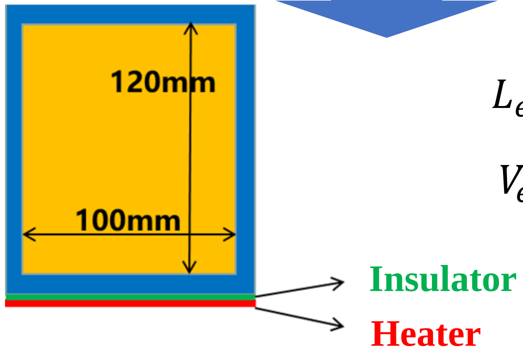
Mixed convection

$$Re = \frac{\rho VL}{\mu} \sim 10^5$$

$$\text{Ha} = BL\sqrt{\frac{\sigma}{\mu}} \sim 10^4$$

$$\text{Gr} = \frac{g\alpha_v \Delta t L^3}{v^2} \sim 10^{10} - 10^{12}$$

Test Section



$$L_{exp} = \frac{1}{2} L_{opt}$$

$$V_{exp} = 2V_{opt}$$

M=32kg/s

$$B_{exp} = 2B_{opt} \sim 10T$$

$$B_{exp} = 3\text{T}$$

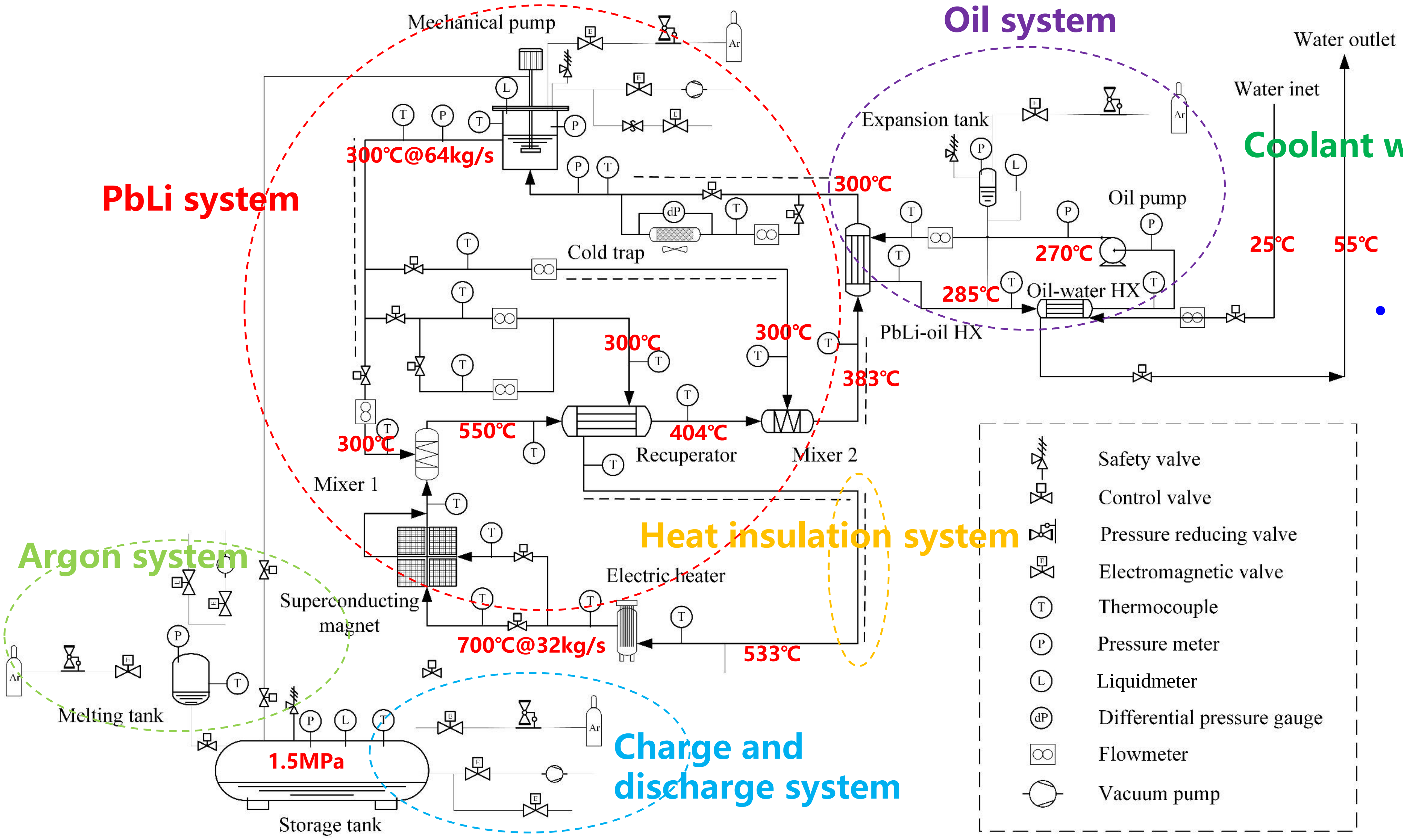
$$\text{Ha}_{exp} \sim 0.3\text{Ha}_{opt}$$

$$\Delta t_{exp} \sim \Delta t_{opt}\ (T_{\text{exp}} = 700°\text{C})$$

$$\text{Gr}_{exp} \sim 0.125\text{Gr}_{opt}$$

Flow area（mm²）	B (T)	Heat flux（kW/m²）	M (kg/s)	High Temp.（℃）	Ha	Re	Gr
100×120	3	250	32	700	7676	10^5	6×10^9

Flow diagram and P&ID design

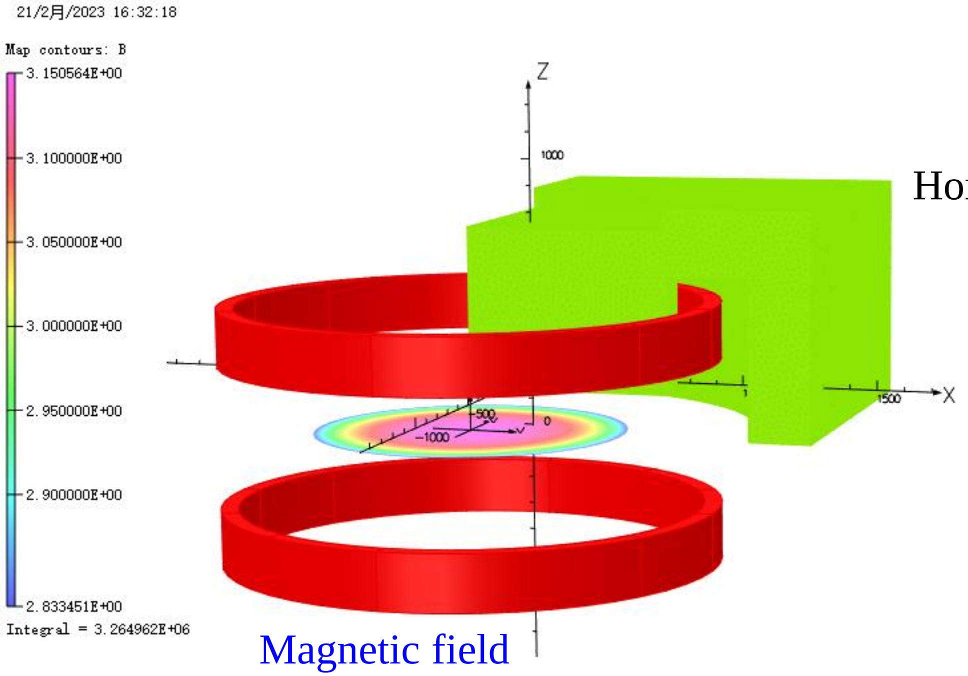


- Main components
  - Recuperator
  - Heater
  - Mechanic pump
  - Supermagnet
  - Storage tank
  - Mixer
  - Cold trap
  - Heat exchanger

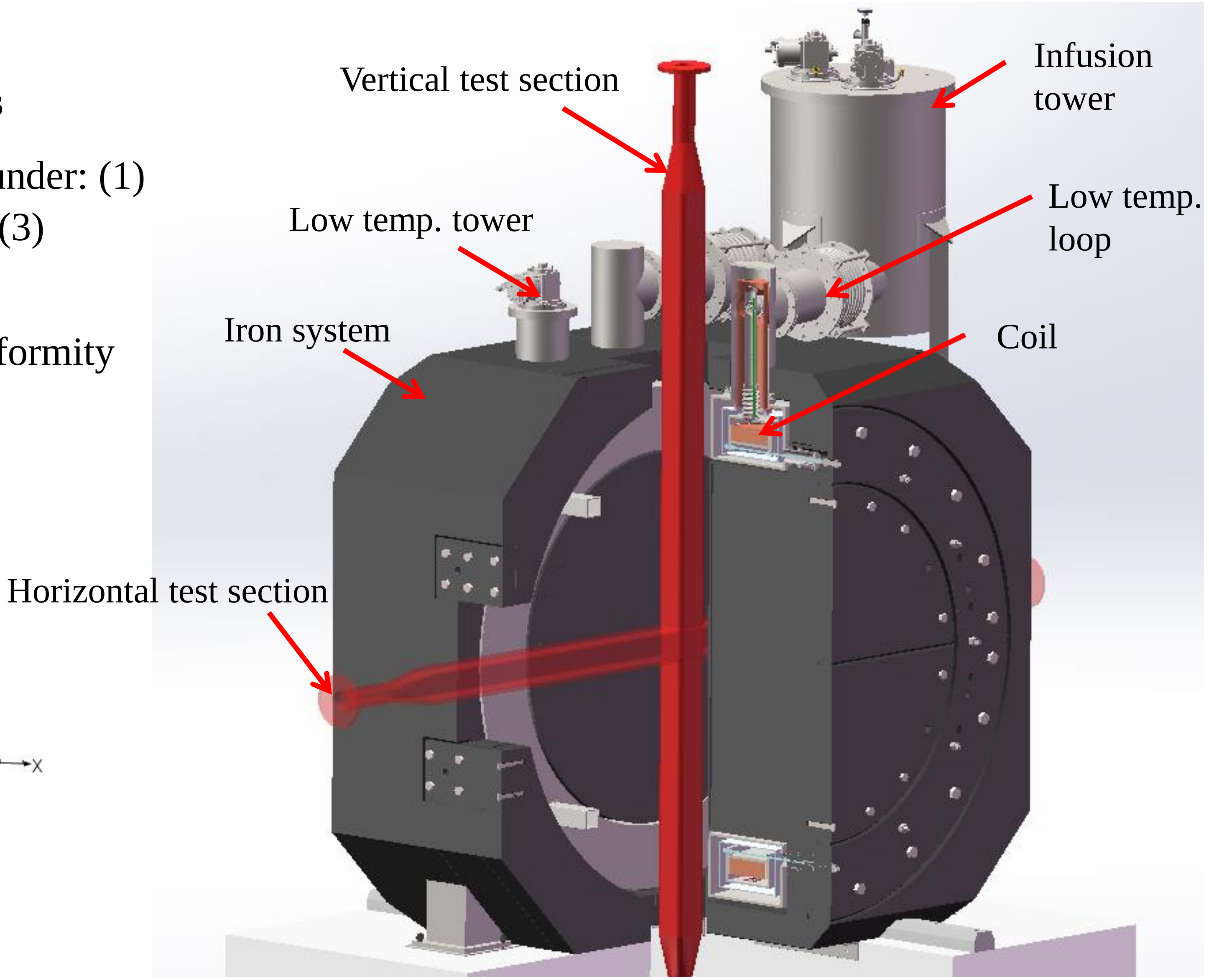
Key components design

➢ Superconduct magnet

- Includes both **vertical and horizontal channels**
- Able to study the **Multi-physics performance** under: (1) Complex geometric; (2) Electromagnetic force; (3) Buoyancy effects
- Wide range uniform magnetic field, the non-uniformity is 8%; Surface magnetic leakage 1 m≤300 Gs

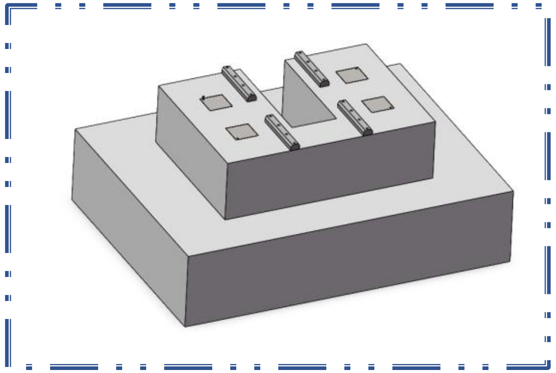


Magnetic field

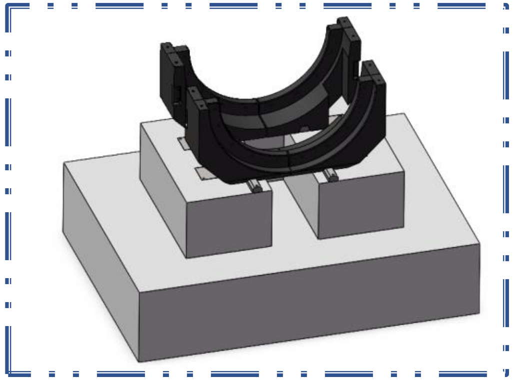


Key components design

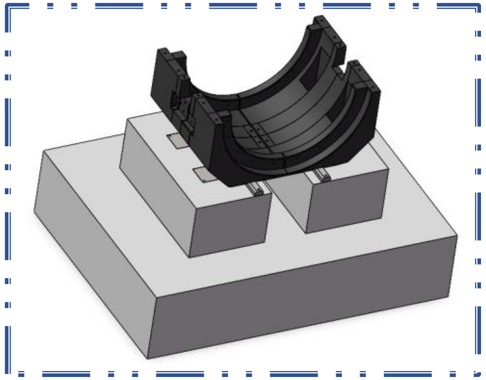
➢ Superconduct magnet



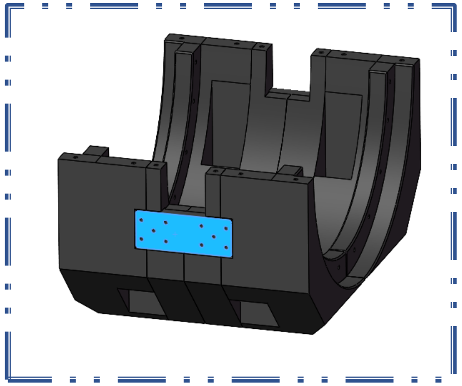
Step 1: Orientation



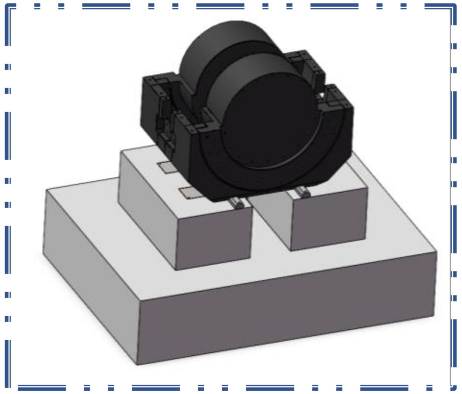
Step 2: Install bottom iron



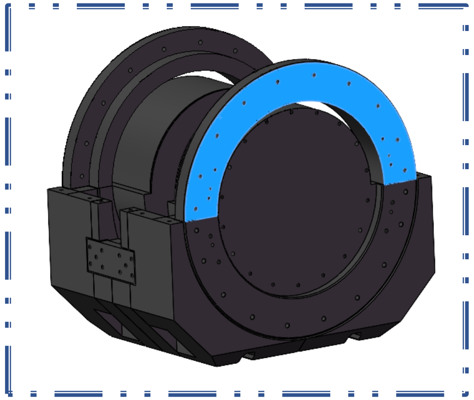
Step 3: Install middle iron



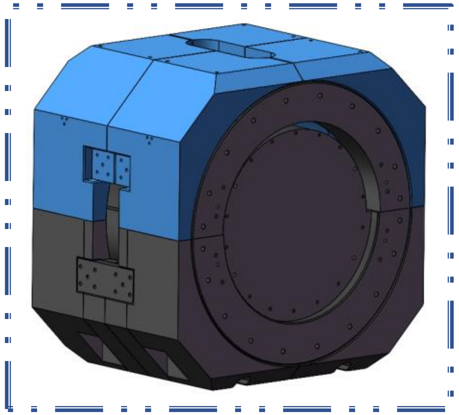
Step 4: Install bottom connect



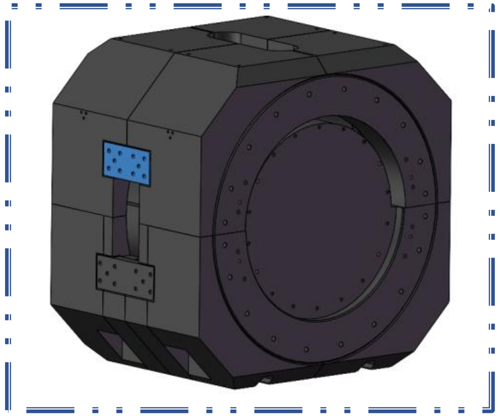
Step 5: Install iron core 1



Step 6: Install iron core 2



Step 7: Install upper iron



Step 8: Install upper connect

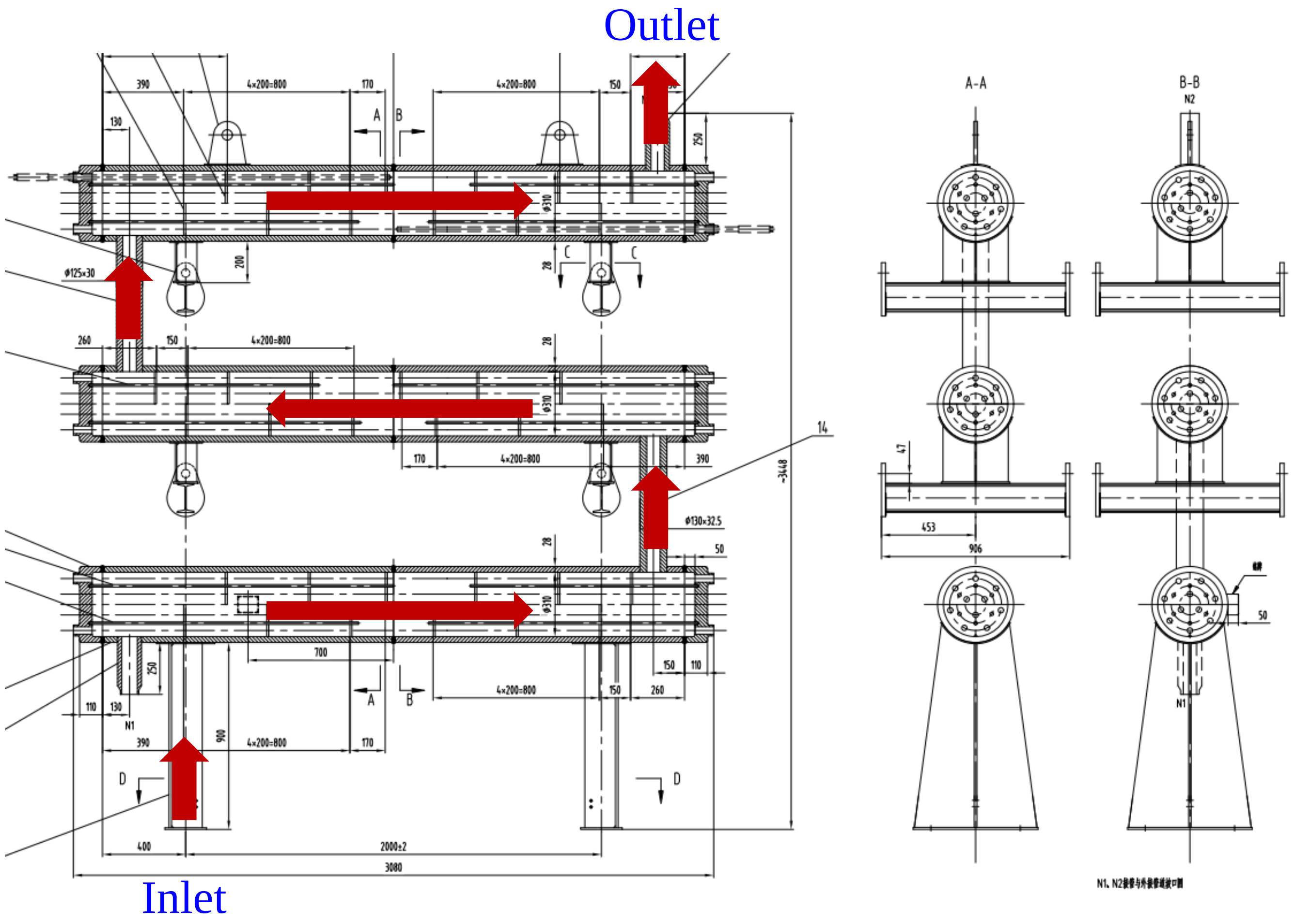
Key components design

➢ Main heater

- Heat the PbLi to the required temperature
- Through DCS control to adjust the running power
- With over temperature protection feedback system

Design parameters

Items	Parameter
Structure	Heat bundles
Power	1.0 MW
Design power	1.2 MW
Operation temp.	700 °C
Design temp.	750 °C
Design pressure	2 MPa
Mass flow rate	0~64 kg/s



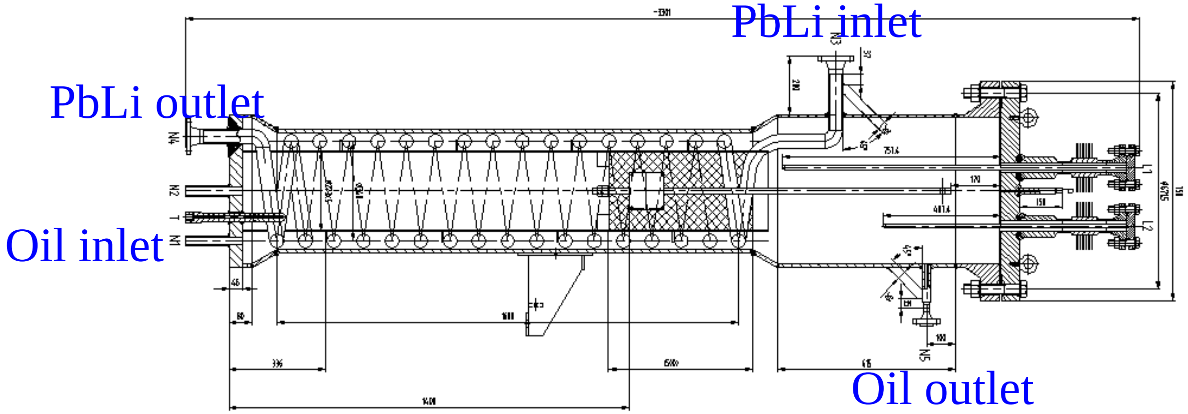
Key components design

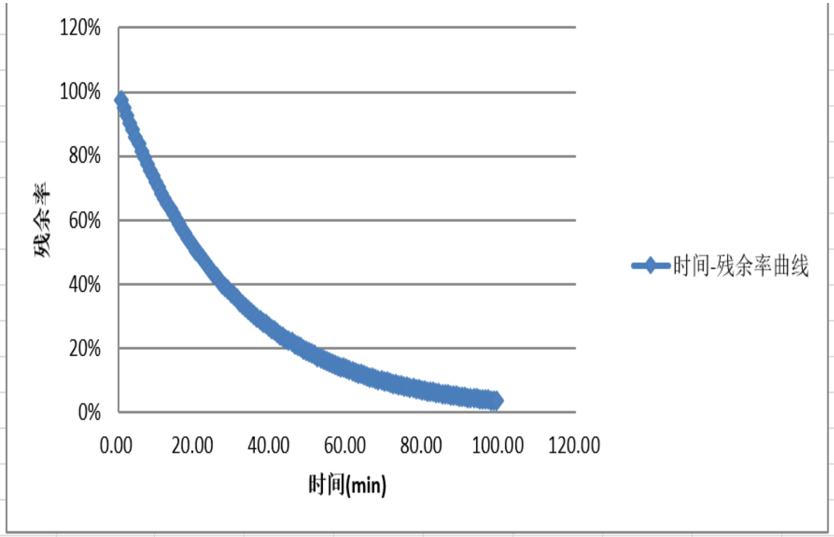
➢ Cold trap

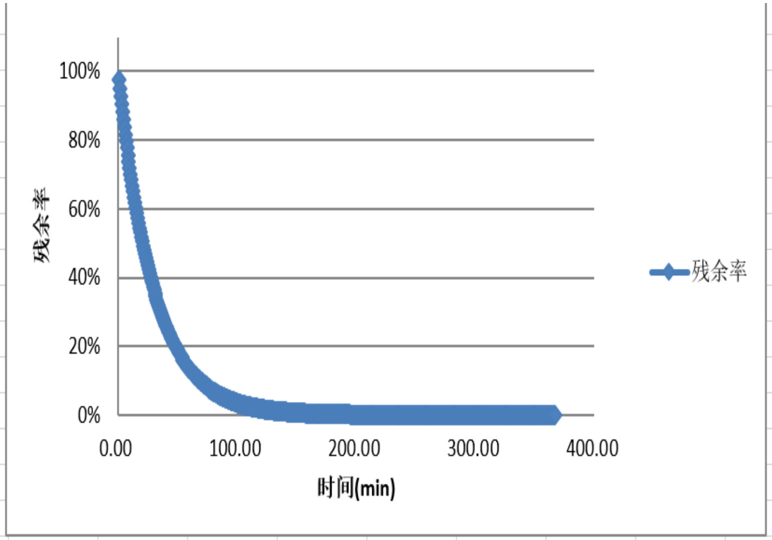
- The 5% PbLi is extracted from the main pipe, the metal and non-metallic impurities are captured
- After running for 100min, the impurity purification rate reached 95%

Design parameters

Item	Parameter
Structure	Oil cooler
Power	50 kW
Design temp.	450 ℃
Design pressure	2.8 MPa
Tube side	PbLi
Shell side	Oil
Inlet temp.	300~350 ℃
Outlet temp.	270 ℃
Motor	Frequency change
PbLi flow range	0~3.2 kg/s
Wires	Metal





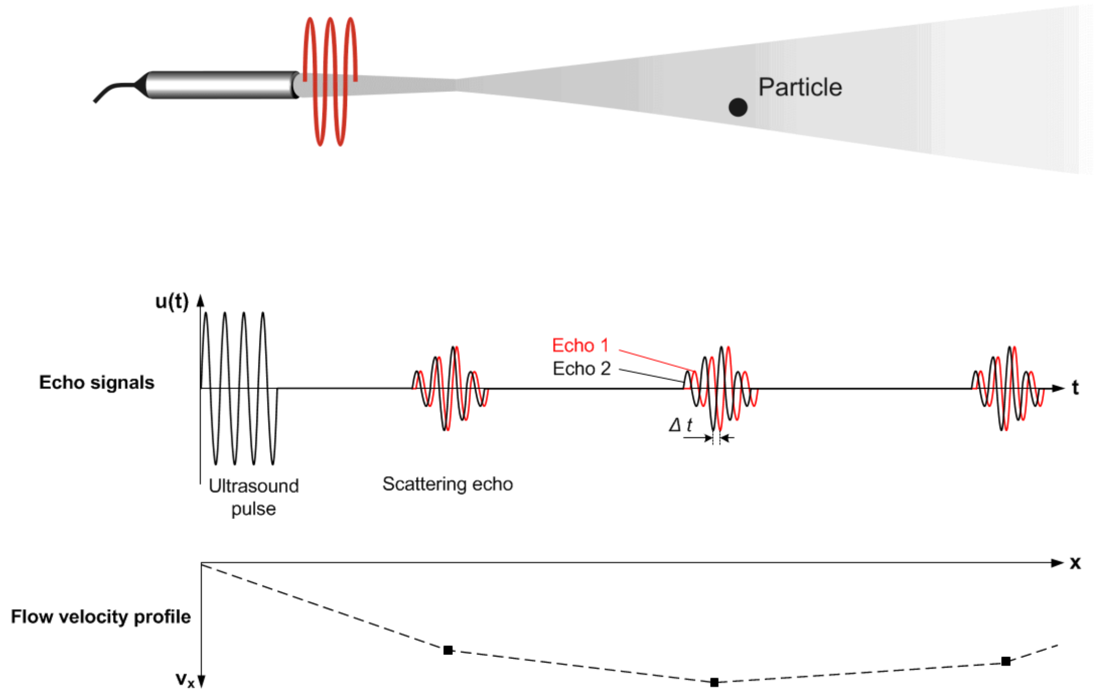


Impurity residual rate varies with time

Key components design

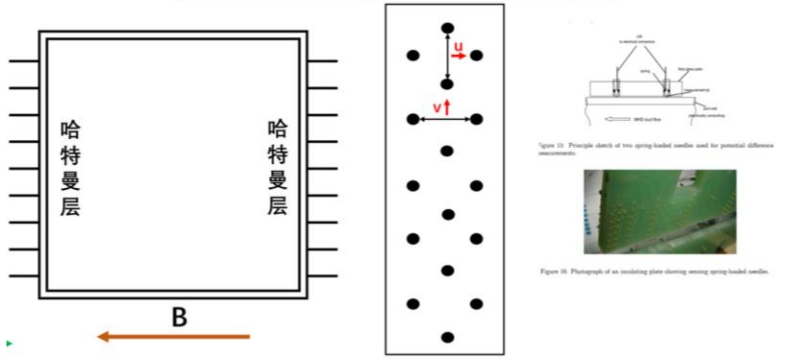
➢ Experimental data measurement and characterization

- The traditional method, i.e. PIV, cannot be used due to the opacity of PbLi
- The velocity field in liquid metal is plan to be measured by ultrasonic Doppler UDV and potential probe tecnologies



Ultrasound Doppler Velocimetry (UDV)

Potential probe array

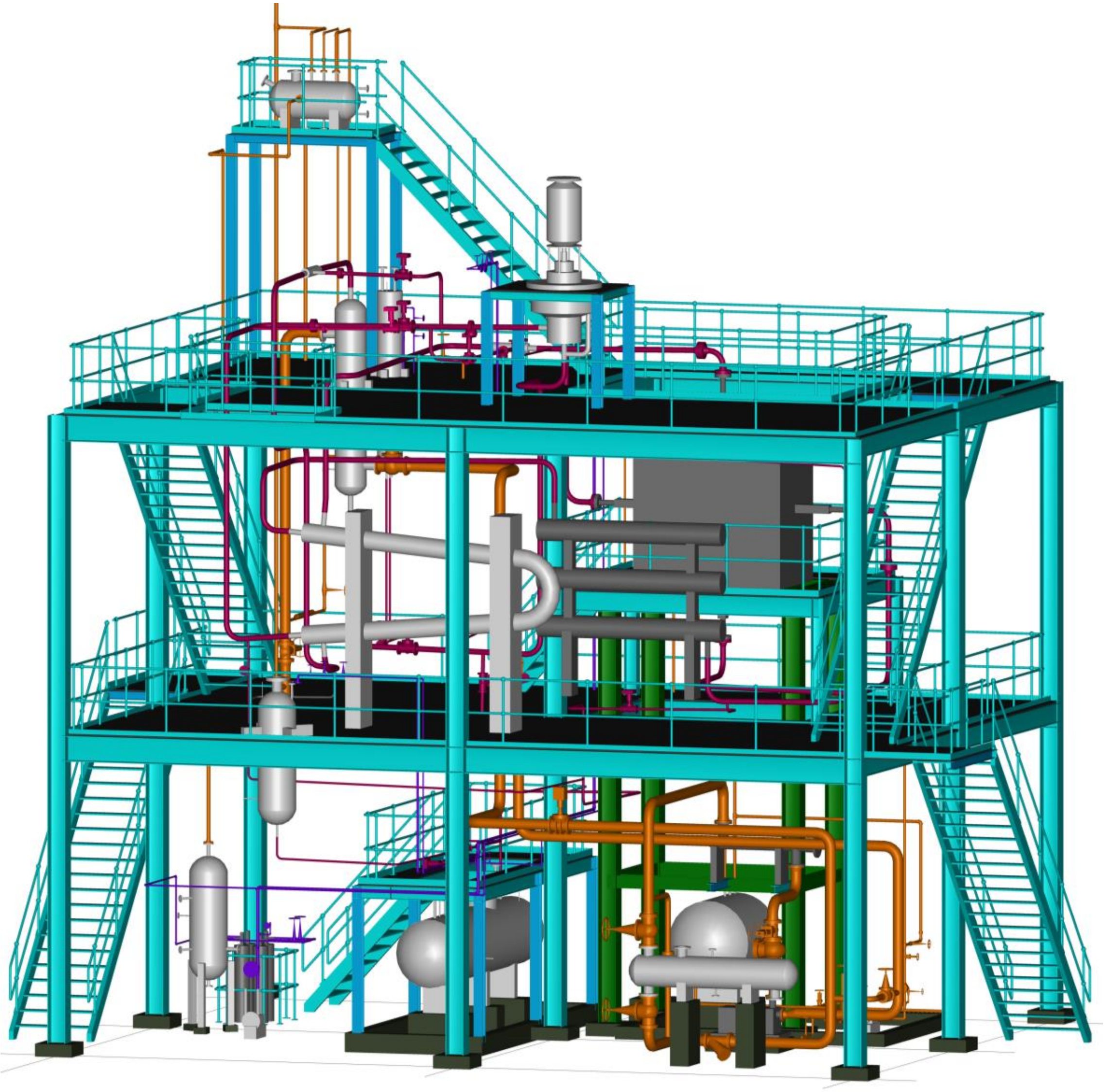


➢ Theory

- Ohm' law $\vec{j}/\sigma = -\nabla\varphi + \vec{u} \times \vec{B}$
- Velocity $u = \frac{1}{B_0}\frac{\partial\varphi}{\partial Z}$ $\quad w = -\frac{1}{B_0}\frac{\partial\varphi}{\partial X}$
- Vorticity $\omega_y = \nabla^2 \varphi / B_0$

Potential probe technology

Components and system layout

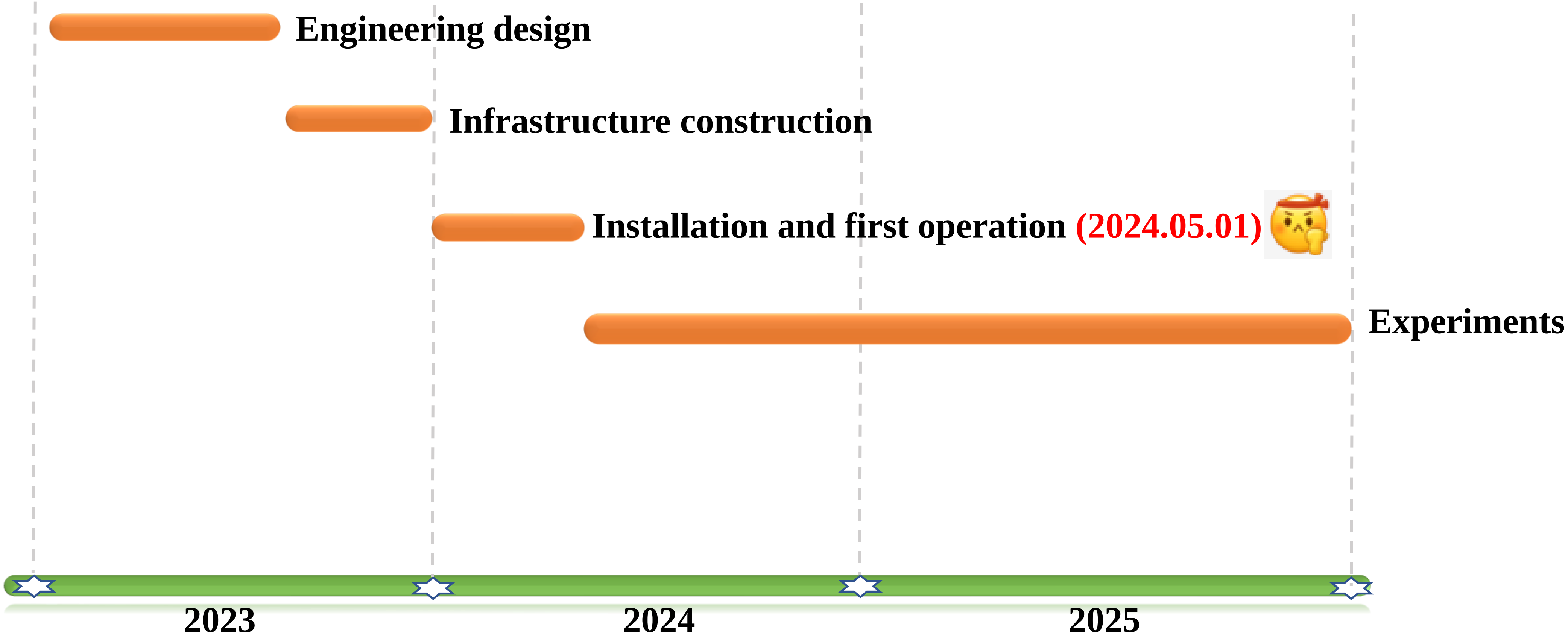


17.5 m (length)×9.5 m (width)×16 m (height)

Summary on the design parameters

Item		Unit	Parameter
Operating pressure		MPa	2
Design pressure		MPa	2.8
Operating temp.		℃	270~700
Materials	Low temp. (316L)	℃	550
	High temp. (800 H)	℃	750
Mass flow rate (PbLi)		m^3/h	30
PbLi consumption		t	25
Design temp. (oil)		℃	350
Mass flow rate (oil)		m^3/h	130
Design temp. (water)		℃	25-35
Design pressure (water)		MPa	0.5
Electricity power		MW	≤1.5
Design life		year	20

Project schedule



Concluding remarks

- **The COOL blanket is being researched at ASIPP for CFETR**
  - The Beryllium-based material is not used as the neutron multiplier → **Economic**
  - Coolant outlet temperature can reach 700℃, thermoelectric conversion efficiency is high → **Efficiency**
  - Online refueling and tritium extraction can be realized
- **The PbLi loop is necessary to address the following scientific issues:**
  - Turbulent heat transfer, MHD effects and mixed convection under large heating source and magnetic fields
  - Based on the experimental requirements, the test section and parameters are clearly designed
  - Moreover, the out-pile of Mockup will be fully tested before it is installed into the fusion reactor
- **The PbLi loop facility with high performance is designed, including:**
  - For the flow diagram and P&ID, it mainly consists of the PbLi, oil and water system et al.
  - The key components, i.e. mechanic pump, main heater, cold trap, are carefully selected to satisfy with the requirements
  - The superconducting magnetic with 3T is adopted, which has the vertical and horizontal channels capable of studying the multi-physics coupling under buoyancy and electromagnetic
  - The 3D layout of system and main components is built and this facility will be under construction soon

Thank you for your attention!