

CONFERENCE PRE-PRINT

PROGRESS OF THE EHL-2 SPHERICAL TORUS ENGINEERING DESIGN

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Abstract

After nearly 40 years of development, the spherical torus has become an important research direction for fusion energy. The UKAEA, PPPL, Japan, and the ENN in China are each beginning to design future spherical torus fusion devices known as STEP^[1], STAR^[2], ST2035^[3], and EHL-3^[4]. In recent years, to extend the plasma parameters of the spherical torus to a magnetic field $B_0 > 1.5\text{T}$, and plasma current $I_p > 2\text{MA}$, a number of devices are being upgraded or newly designed, such as the ST-40^[5], EHL-2^[6], GLOBUS-3^[7]. Among these the ENN EHL-2 is an experimental platform for hydrogen-boron fusion (Fig. 1). The physics design of EHL-2 is focused on addressing three main operating scenarios, i.e., (1) high ion temperature scenario, (2) high-performance steady-state scenario and (3) high triple product scenario.

1. TARGET PARAMETER

The EHL-2's key parameters are set (Table.1): a plasma radius (R_0) of 1.05 m, aspect ratio (A) of 1.85, max central magnetic field (B_0) of 3T, and plasma current (I_p) of 3 MA. The toroidal field holds for 2.3s at 3T, with the central solenoid able to drive plasma current at 5 V·s.

2. ENGINEERING CHALLENGES

For a toroidal field (B_0) of 3 T, the current density needs to be increased to 88 A/mm². This requires experimental validation of the conductor materials and redesign of the magnet joint methods. The low aspect ratio requirement restricts the space on the high-field side. Particularly when $B_0 \geq 3\text{T}$ and the flat-top time exceeds 2s, it is necessary to seek the optimal configuration among the maximum magnetic field, flat-top time, central solenoid volt-second, shot interval, and safety reliability.

The TF magnets require a power supply capability of 200kA and 600 MVA, for which

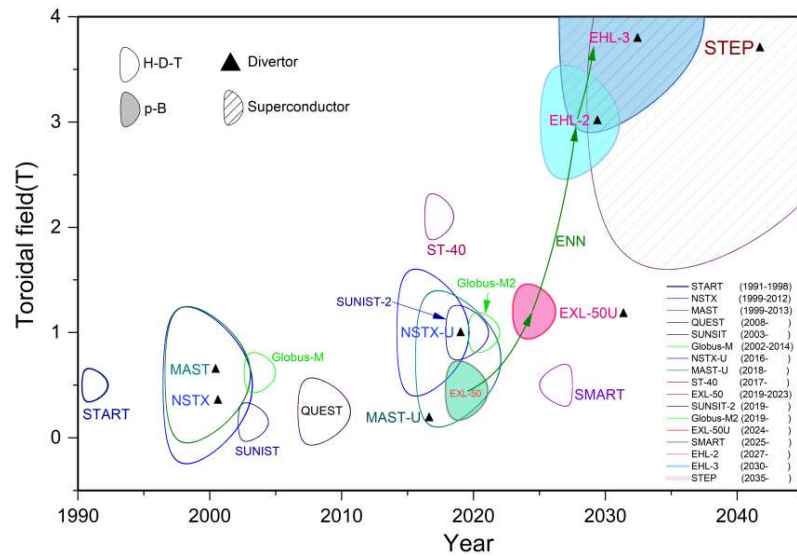


Fig.1 Spherical toruses 1990-2040

Table 1. EHL-2 design Parameters

Parameters	Value
Major radius $R_0(\text{m})$	1.05
Minor radius $R(\text{m})$	0.32
Aspect ratio A	1.85
Elongation ratio k	2.0
Plasma current I_p (MA)	3.0
Toroidal magnetic field B_0 (T)	3@ $R=1.05\text{m}$
Heating Power $P_{\text{heat}}(\text{MW})$	17
Discharge time t_d (s)	2.3/3.0T

a mature design validation has not yet been achieved. To achieve a plasma current of 3 MA, higher current ramp-up rates and multiple plasma drive methods are needed.

The high magnetic field and the high ion temperature required for p-B fusion heating necessitate 100 GHz electron cyclotron resonance heating system and a 200keV negative ion sources neutral beam system. This imposes more specific requirements on the existing wave source suppliers, power supplies, and system integration, and necessitates early design and single-system testing.

3. VERIFICATION OF KEY TECHNOLOGIES

To ensure the reliability of the designed structure under various operating conditions, in addition to conducting design analysis and calculations, experimental verifications have been carried out on components such as the flexible joint, the TF centre bundle, and the CS coils. These include tests like the 200kA current test for the TF flexible joint, development of materials and structures compatible with both room temperature and cryogenic conditions, and testing of the liquid nitrogen cooling circulation systems for TF and CS. Maintenance analysis in case of magnet component damage. Experiment on the plasma current start-up mode with the central solenoid coil and electron cyclotron heating system working in coordination. Coupling tests of the 80keV positive ion source neutral beam, 200keV negative ion source neutral beam, and ion cyclotron heating system.

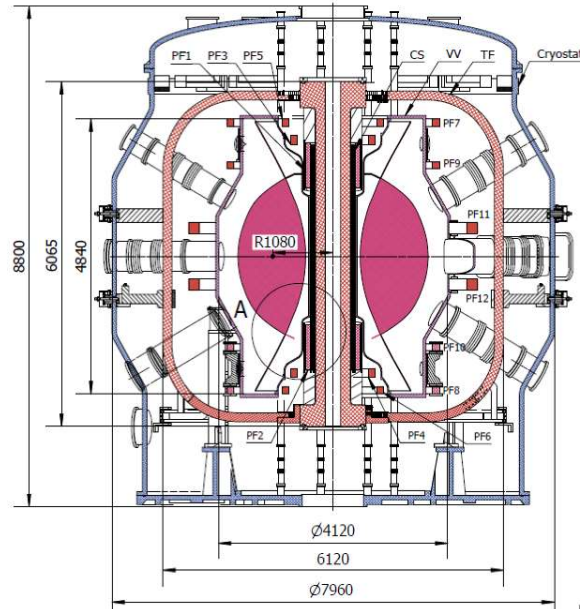


Fig.2 EHL-2 spherical torus layout

4. STRUCTURE AND DESIGN FEATURES

The toroidal field (TF) magnets need to provide a magnetic field over 3T and a flat-top discharge duration exceeding 2.3s, calculations have shown that the temperature rise of the copper conductors operating at room temperature would exceed 160°C. This temperature is beyond the limit of existing insulating materials, making it unfeasible. Therefore, using copper conductors operating at liquid nitrogen temperature range as TF magnets has emerged as a potentially viable option.

According to the design, the main components of the torus include the toroidal field (TF) magnets, poloidal field (PF) magnets, vacuum vessel, magnet supports, and the outer cryostat(Fig.2). Among these, the TF magnets consist of the TF center bundle and the TF C-shaped components, with the center bundle and the C-shaped segments connected by a flexible joint. The central solenoid (CS) is located around the TF center bundle, and operates within the liquid nitrogen temperature range. After being integrally manufactured and assembled with the central tube of the vacuum vessel, it forms a complete component, which is then assembled with the vacuum vessel at the site. The poloidal field coils (PF1-PF12) are arranged outside the vacuum vessel, using water cooling and operating at room temperature.

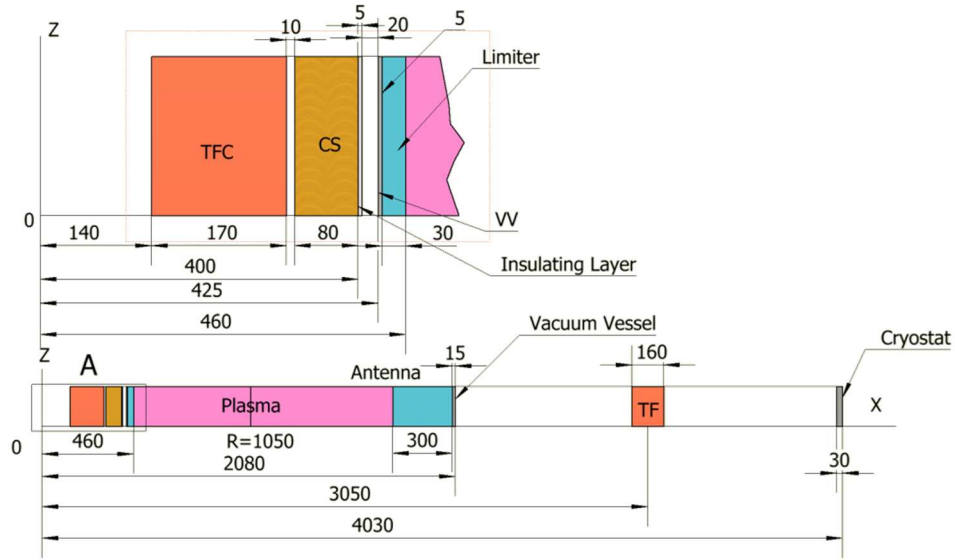


Fig.3 EHL-2 Dimension Chain

5. TORUS SYSTEM

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Table 2. Toroidal magnet field coils

Parameters	EXL-50U	EHL-2
Single turn	150kA	200kA
Turn	2×12	5×16
Operation Temp.	≤100°C	90K-390K
Operation time	≤1.2s	2.3s
Height	4.5m	6.0m
Material	C18150/C10700/AgCu	

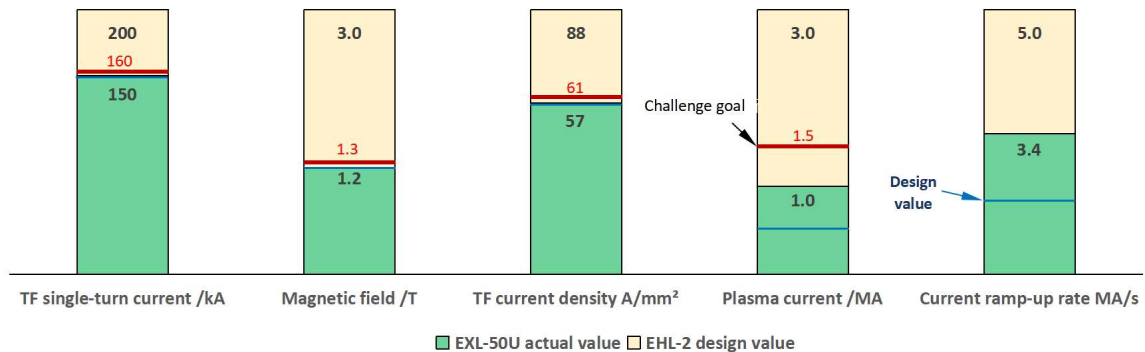


Fig.4 EXL-50U & EHL-2 Parameter Comparison

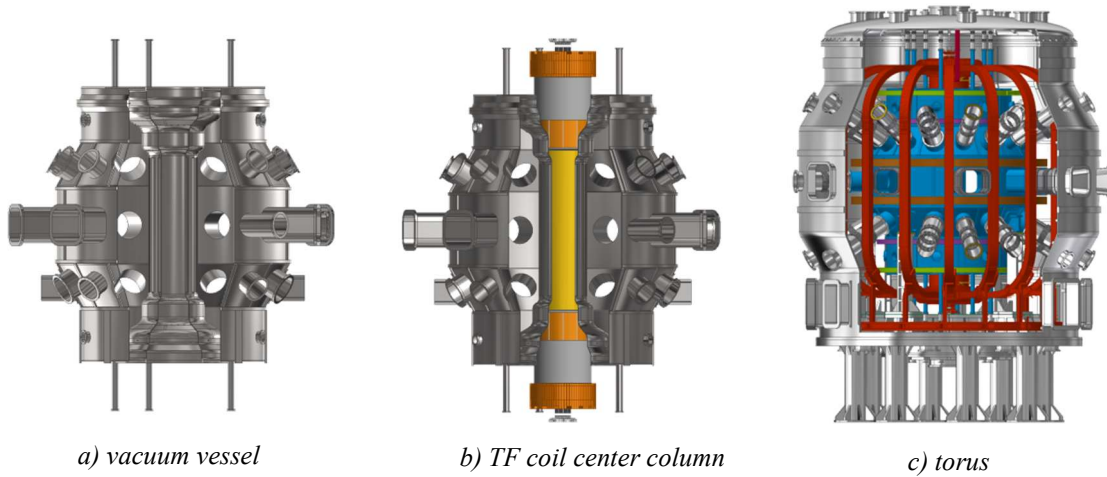


Fig.5 EHL-2 torus systems

PF coil

The PF coil system (Table.3) of the EHL-2 device consists of a total of 17 coils. According to their functions, they can be categorized as follows:

- Central Solenoid Coil (CS);
- Divertor coils (PF1 – PF8);
- Poloidal field coils (PF9 – PF12);
- Passive and active VDE control coils.

The PF coils adopt a conductor cross-section of approximately 20 mm square or rectangular outer profile with a 10 mm diameter circular central hole, through which water or liquid nitrogen is circulated for inter-shot cooling.

Materials are selected according to the mechanical loads at each location: the central solenoid coil uses a silver-bearing copper alloy with a yield strength of 300 MPa, while the remaining coils are fabricated from high-conductivity TU1 copper.

vacuum vessel

The vacuum vessel (Table.4) is an ultra-high-vacuum device consisting of a single-walled cylindrical body formed by a centre-pipe module, a shell module and supporting structures. Fifty-six ports are machined in the shell; four to six vertical ports are provided in both the top and bottom caps. After final welding the vessel becomes a monolithic unit; each port flange (knife-edge or metal-seal type) is connected to its cryostat via a bellows.

Table 3. Poloidal magnet field coils

parameters	unit	value
CS	kA	$V_s \geq 2.3$, 40
PF1-PF6	kA	22turn, 20
PF7-PF10	kA	22turn, 20
PF11-PF12	kA	4turn, 5
PF13-PF14	/	2 turn
Material	/	TU1, C10700, C18150

Table 4. vacuum vessel

parameters	unit	value
Diameter(internal)	mm	4100
Diameter of central tube	mm	920
Height	mm	4900
Volume	m ³	33
Thickness	mm	8-20
Flange size	/	700-600
Relative permeability	/	1.05 (welds 1.1)
Design temperature	°C	200
Baking temp.	°C	160
Ultimate vacuum	Pa	$\sim 10^{-6}$
Material	/	Inconel 625 & 316L
Weight	t	25

Circumferential and longitudinal stiffening ribs are integrated into the shell to guarantee structural strength and stability; these ribs also serve as the support structure for coils PF1 – PF10.

The EHL-2 magnet support structure system has a total height of 7,880 mm, an outer diameter of 7,960 mm, and a weight of 131 tonnes. It consists of torsion support structures, gravity support structures, straight-leg structures, and PF coil support structures. The torsion support structures are made of Inconel718, while the other components are constructed from 316L stainless steel. Post-energization analysis confirms that the support system meets design requirements, with the maximum displacement of 18.13 mm occurring at the flexible connections and the highest stress concentration observed in the torsion disk support structure(Fig.6).

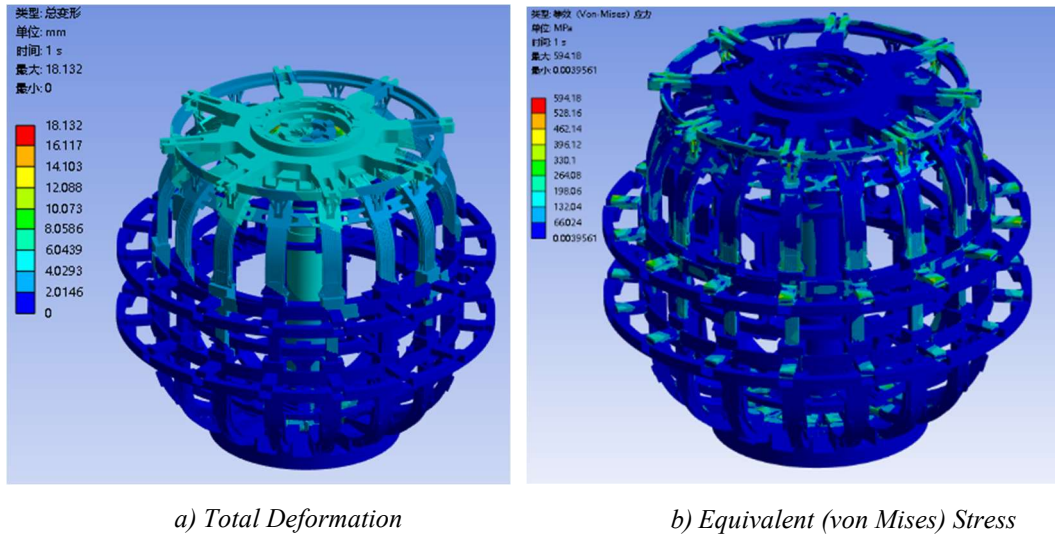


Fig.6 FEA of the Support Structure

Divertor

The divertor assembly comprises an upper and a lower unit(Fig.7). Each unit contains an inner and an outer target plate; the plasma-facing component consists of CFC tiles bonded to a CuCrZr heat sink that is mechanically attached to a stainless-steel support structure. To handle the high heat flux, cooling tubes are embedded in the CuCrZr heat sink for active water cooling of the plasma-facing components.

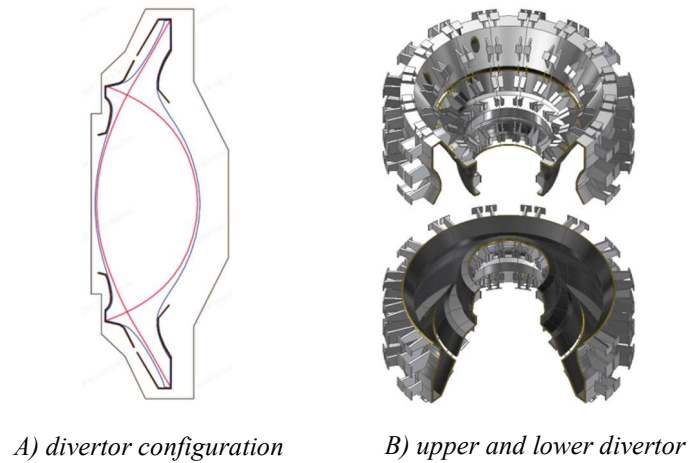


Fig.7 divertor

6. PLASMA HEATING & CURRENT DRIVE SYSTEM

To achieve a 30 keV plasma temperature and provide 3 MA of current-drive capability, the design includes NBI system, an ECRH system, and ICRF, delivering a total injected power of approximately 17 MW, as shown in Table 5. three beams are positive-ion-based neutral beam injectors with a combined injection power of 14 MW; one beam is a negative-ion-based neutral beam injector with an injection power of 3 MW(Fig.8).

Table 5. Plasma Heating & Current Drive system

System	value
NBI	1×4MW @ 60kV/5s
	2×5MW @ 80kV/5s
	1×3MW @ 200kV/5s
ECRH	1x 1MW @ 50 GHz/5s
	6 x1MW @ 105&140 GHz/10s (dual frequency)
ICRF	13.56MHz/80kW/CW;
	25MHz-40MHz/2MW/1s

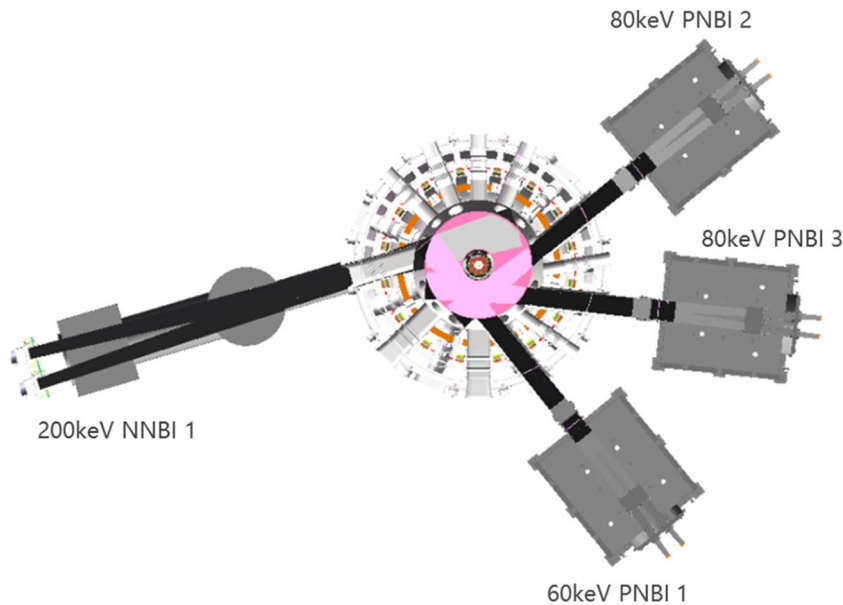


Fig.8 Neutral beam injection system

7. POWER SYSTEM

The EHL-2 will rely on direct grid connection for its baseline electrical loads, rated at roughly 40 MVA. All high-pulse-power loads, however, will be fed by dedicated energy-storage systems. The magnet power-supply system—whose aggregate installed capacity approaches 1 GW will be powered by super-capacitor banks with a total stored energy of about 3.5 GJ. The toroidal field power supply alone is specified for 2kV/200kA(Fig.8).

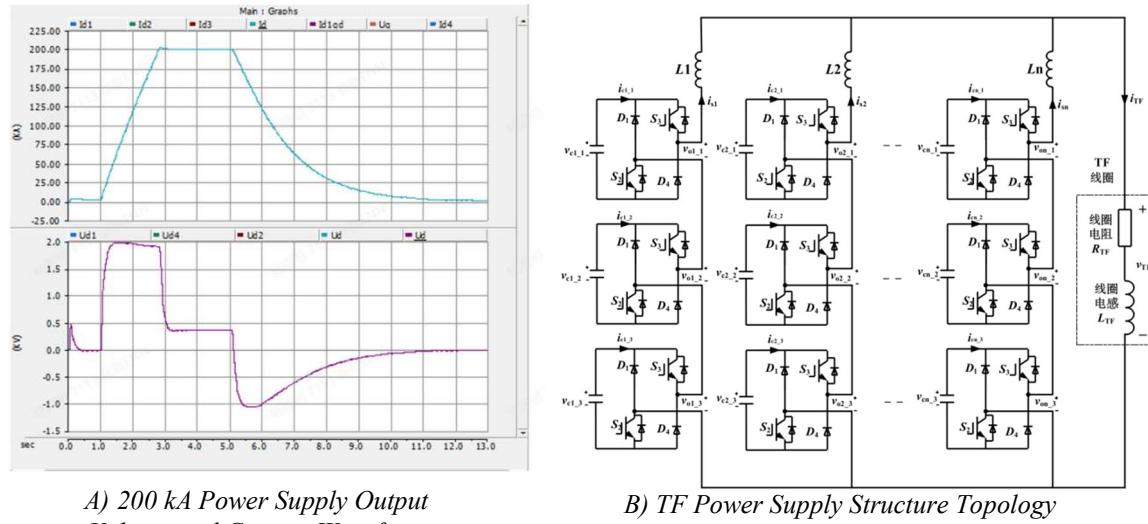


Fig.8 TF Power Supply system design

8. SUMMARY

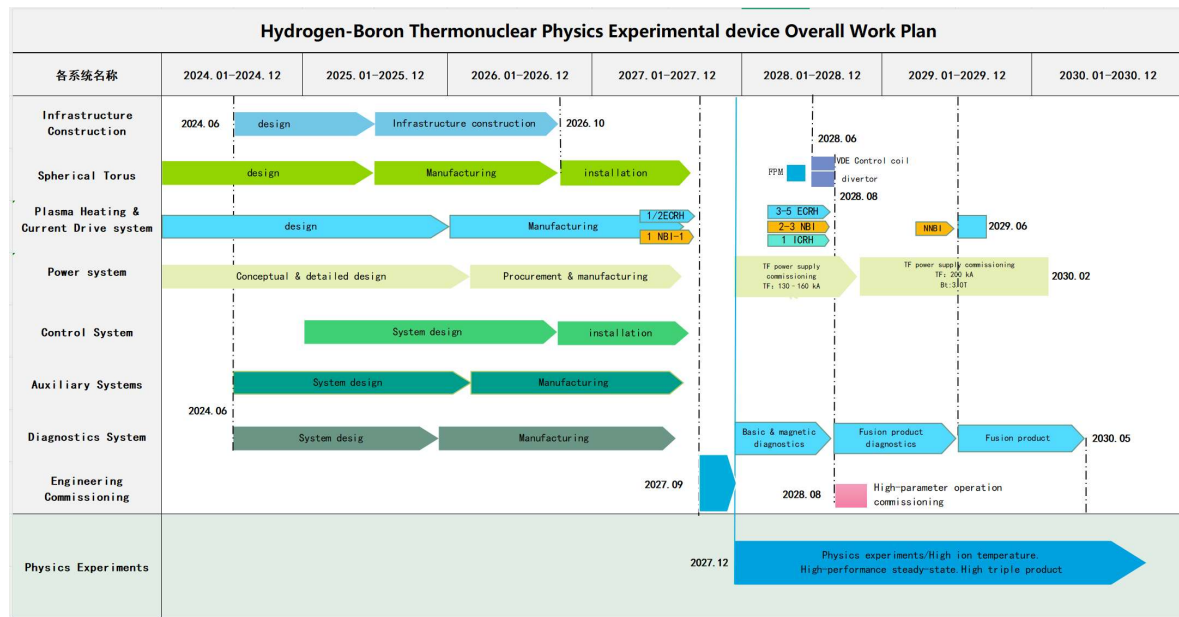


Fig.9 EHL-2 Construction Schedule

Design verification is progressing alongside our construction schedule(fig.9): We completed the engineering concept and preliminary design between June 2023 and June 2025. Detailed engineering and key technology verification will take place from January 2024 through December 2025, followed by the procurement of long-lead items from June 2025 to December 2026.

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