Overview of The Physics Design of The EHL-2 Spherical Torus for Proton-Boron Fusion

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Abstract

- A roadmap for **p-11B fusion** based on spherical torus has been developed [1], with the next generation device named as EHL-2 under physics and engineering design, here EHL is abbreviation for ENN He-Long which means "peaceful Chinese Loong".
- The main target parameters of EHL-2 include **R0~1.05m, A~1.8, B0 ~ 3T, Ti0>30 keV, Ip =3 MA, and Ti /Te >2** [2]. We present the EHL-2 physics design progress here.
- The commissioning of the upgraded fusion device EXL-50U is scheduled for 2024, while the construction of EHL-2 is estimated to be completed by 2026.

Major physics design results

TG10: Charged particle power conversion

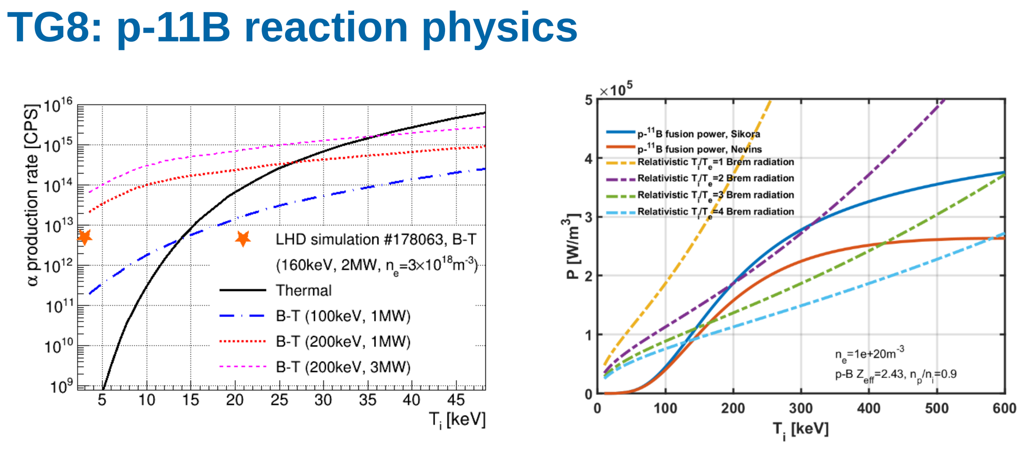
- p-^{11}B: abundant, accessible, economical & environmentally friendly
- Alpha particles can generate electricity power directly

TG9: Disruption prediction and mitigation

Disruption characteristic parameter	Value
Minimum current quench time	4.8 ms
Minimum thermal quench time	0.1 ms
axisymmetric vertical force by halo current	4.05 MN
Eddy current force on single inboard tile	64.8 kN
Eddy current torques on single inboard tile	3.24 kN m
maximum energy deposition	$200\ MJ \cdot s^{-0.5} \cdot m^{-2}$

Disruptions pose a significant threat to the device. MGI、SPI and accurate disruption prediction is important

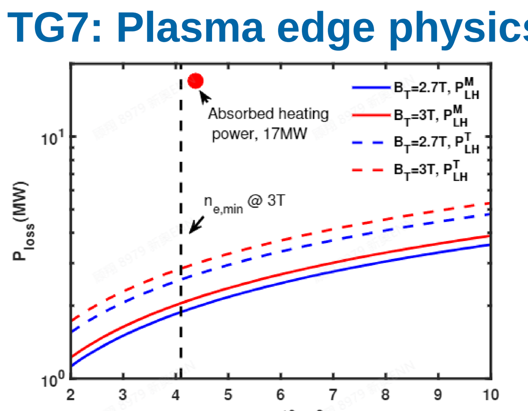
TG8: p-11B reaction physics



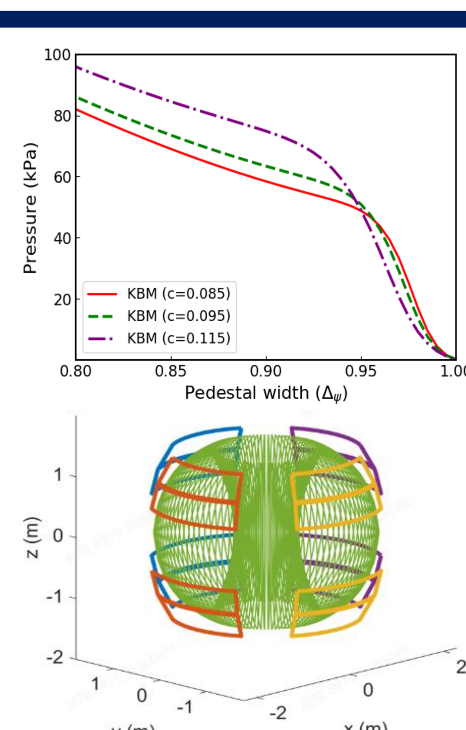
EHL-2 conditions could be sufficient for investigating p-11B thermonuclear reactions, deepening our understanding of burning plasma physics.

	Thermal reaction		Beam-thermal reaction (200 keV, 1 MW, hydrogen)	
	PTC	TGCO	PTC	TGCO
α production rate (/s)	1.4×10^{15}	1.6×10^{15}	5.3×10^{14}	5.4×10^{14}
Fusion power (kW)	~0.7		~0.25	

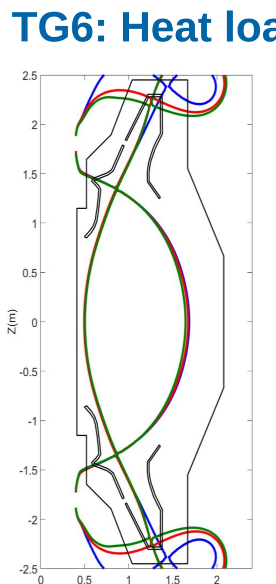
TG7: Plasma edge physics

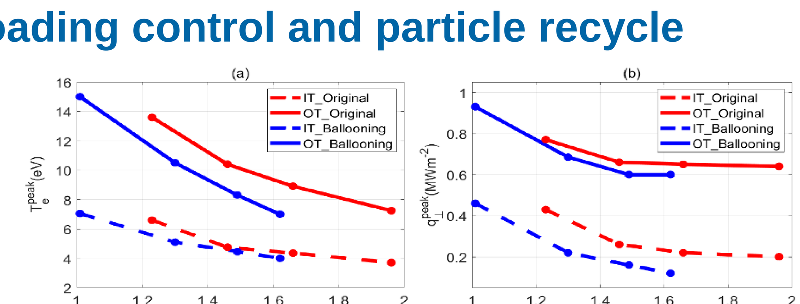


The main operating scenarios of the EHL-2 physics design will in the H-mode regime
ELM suppression may be one of the important research topics in future EHL-2 experiments

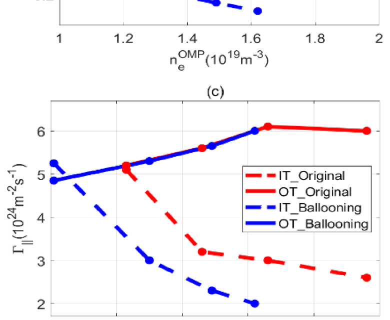


TG6: Heat loading control and particle recycle

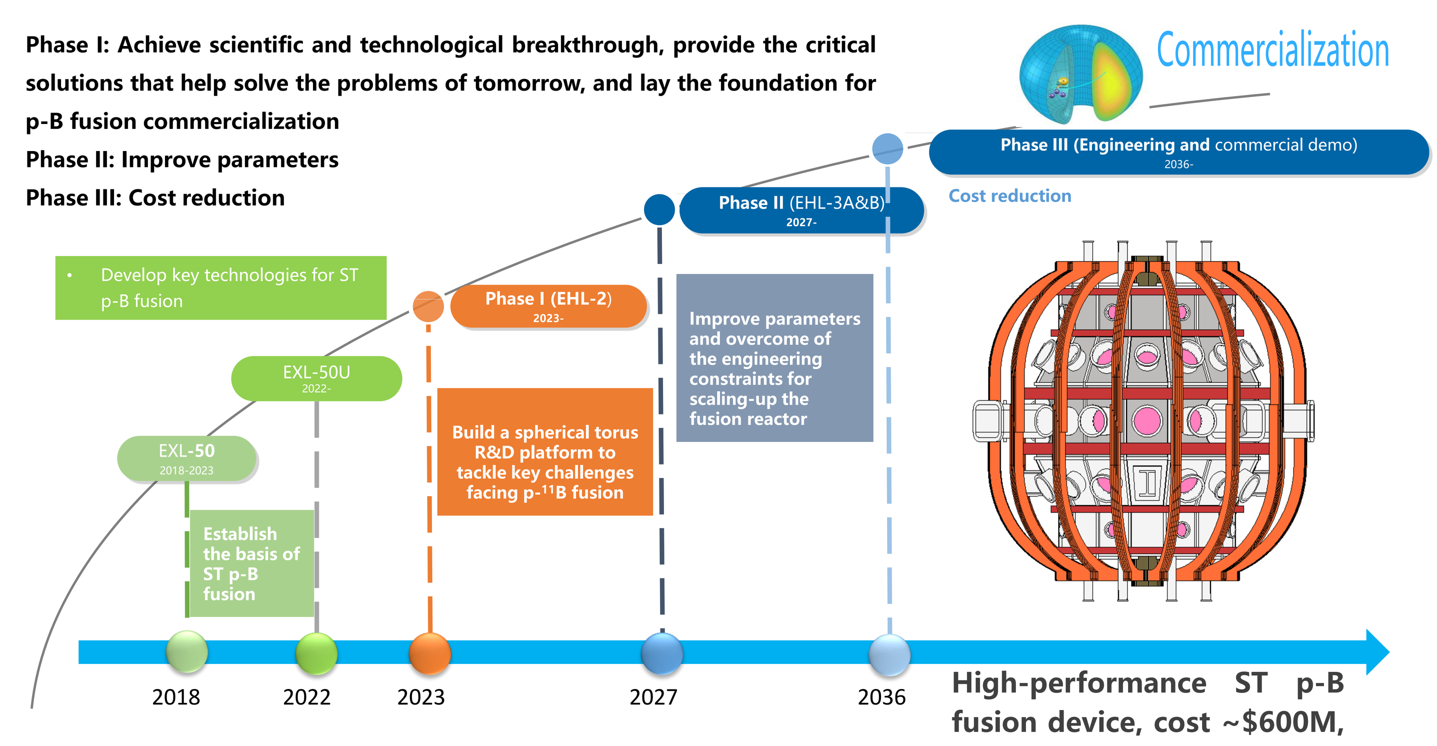




When the outer midplane separatrix density reaches $1.62\times10^{19}m^{-3}$, achieving a fully detached state



ENN's ST p-B fusion roadmap & EHL-2 mission



High-performance ST p-B fusion device, cost ~$600M, first plasma in around 2027.

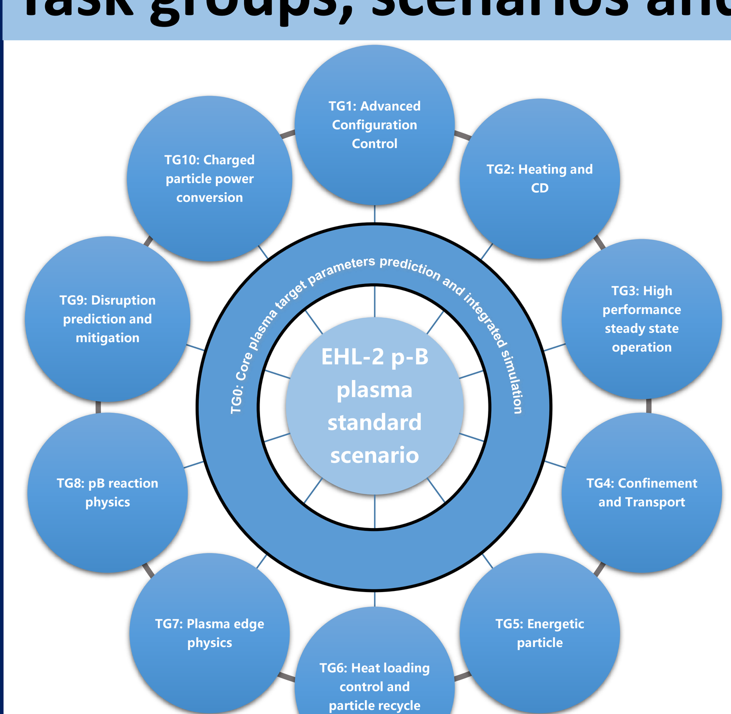
0D system code parameters for EHL-2

Parameters	EHL-2 (Ver1.0)	EHL-2 (Standard)	EHL-2 (Low)	EHL-2 (Medium)	EHL-2 (High)	EHL-2 (Goal)
Plasma current I_p(MA)	3.0	3.0	2.5	2.5	3.8	5.5
B_t(T)	3.0	3.0	2.0	2.0	3.0	3.0
Confinement time τ_E(s)	0.5	0.6	0.3	0.5	2.5	1.2
β	**11%**	**11%**	**10%**	**14%**	**14%**	**21%**
β_N	6.17	6.09	4.7	6.39	6.35	6.47
β_p	3.2	3.1	1.9	2.6	2.6	1.8
Major radius R (m)	1.05	1.05	1.05	1.05	1.05	1.05
Aspect ratio A	1.85	1.85	1.85	1.85	1.85	1.85
Avg./peak T_i(keV)	-/30	-/35	-/25	-/34	-/50	-/50
Avg./peak n_e(m^{-3})	-/1.44e20	-/2.22e20	-/1.33e20	-/1.33e20	-/2.05e20	-/1.66e20
Safety factor q	**3.83 (5.55*)**	**3.83 (5.55*)**	**3.07 (4.45*)**	**3.07 (4.45*)**	**3.03 (4.4*)**	**2.09 (3.03*)**
Density limit n_{avg}/n_{gw}	0.4	0.5	0.36	0.36	0.36	0.25
Heating power P_{heat}(MW)	19	16	13.5	11	6	16
ST H factor H_{ST}	0.657	0.598	0.632	0.94	1.25	0.908
Comments	Sn=0.4, ST=0.8	Overall best	Engineering & Physics low	Engineering low & Physics high	Engineering & Physics high	*ST q, and Sn=0.4, ST=0.8

Even if both the engineering (Bt = 2 T) and physics (Ip = 2.5 MA) parameters are low, the equivalent D-T fusion gain can still larger than 1

- **Mission**: **verify the thermal reaction rate of p-11B fusion**, establish the experimental scaling law at 10's keV ion temperature, and provide a design basis for subsequent experiments aimed at testing and realizing p-11B fusion burning.

Task groups, scenarios and experimental plan



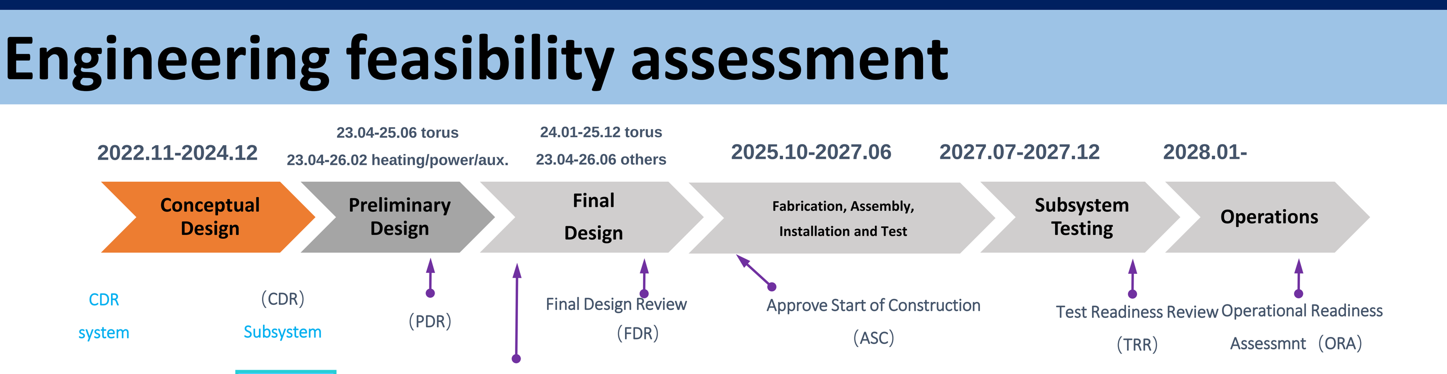
Integrated 11 task groups to do the physics design and engineering iteration

Design three scenarios:

- ***high ion temperature scenario***: Achieve high ion temperature ($T_{i,0} \geq 25keV$) plasma with a high T_i/T_e ratio ($T_i/T_e \gtrsim 2$);
- ***high-performance steady-state scenario***: Demonstrate fully non-inductive current drive ($I_{ni}/I_p = 100\%$) of high-performance plasma with a fraction of bootstrap current component, I_{bs}, larger than 70%;
- ***high triple product scenario***: Confirm the ST high confinement scaling law and validate transport modelling in a wider range of plasma parameters ($H_{ST} \geqslant 0.5$, $\tau_E \geqslant 0.5s$).

EHL-2 Experimental Plan	Phase	Estimated Time	Goal	Divertor	NBI (keV/5s) 60	NBI 80-100	NBI 200	ECRH (GHz/5s) 50	ECRH 105&140	ICRH (MHz/5s) 30-75	LHW (GHz/5s) 2.45-5	Total heating power
Initial Research (1 yr)	I	3 mo.	•Engineering test: toroidal field/control/diagnostics, etc. •Physics test: ECRH startup •1 MA operation	limiter				1 MW	3 MW			4 MW
	(1 mo.) Maintenance/Upgrade											
	II	3 mo.	•2 MA/2 T •Achieve long-leg divertor configuration •Ti > 3 keV, Ti/Te >2 (NBI heating validation)	slab	4 MW			1 MW	4 MW			9 MW
	(1 mo.) Maintenance/Upgrade											
	III	3 mo.	High-ion-temperature scenario validation: Ti > 10 keV, Ti/Te >2		4 MW	5 MW		1 MW	6 MW			16 MW
(2 mo.) Maintenance/Upgrade												
Integrated Research (2 yr)	I	10 mo.	•Ti > 25 keV, Ti/Te >2 •H–B thermonuclear reaction validation •High-performance scenario validation: fully non-inductive current drive	closed	4 MW	10 MW	3 MW	1 MW	6 MW			24 MW
	(2 mo.) Maintenance/Upgrade											
	II	8 mo.	•ICRH–NBI synergy validation		4 MW	10 MW	3 MW	1 MW	6 MW	2 MW		26 MW
(2 mo.) Maintenance/Upgrade												
Extended Research (>1 yr)			•3 MA; 3T •Ti > 35 keV, Ti/Te >2 •High triple-product scenario development, ST scaling law validation •H–B fusion gain validation		4 MW	10 MW	3 MW	1 MW	6 MW	5 MW	2 MW	31 MW

Engineering feasibility assessment



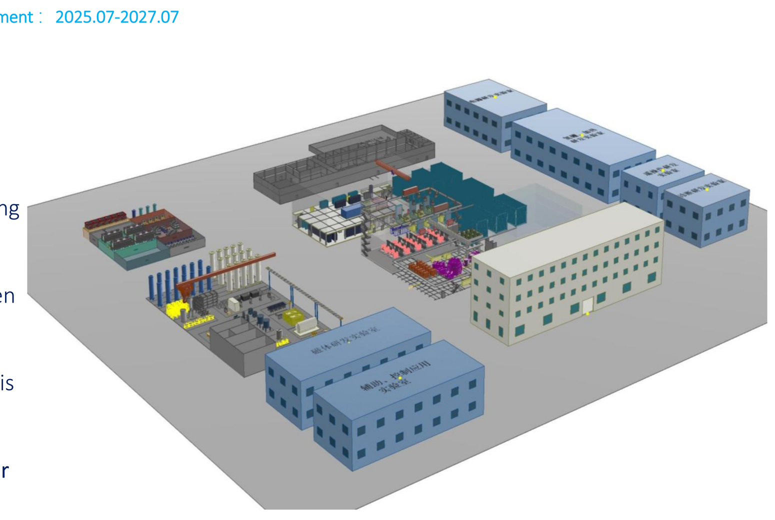
Status of subsystem engineering design:

-- **Magnet coil**: The concept and preliminary analysis design are temporarily feasible, and there are medium to high level risks in existing design. The Preliminary design and proof-of-principle testing of cooling system have been completed.

-- **Vacuum, Cryostat, internal components**: Preliminary design has been completed.

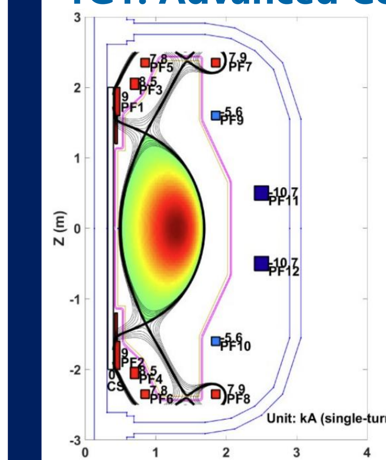
-- **Plasma Heating & Current Drive system**: The 200 keV N-NBI system is currently under design and prototype testing.

-- **Power**: Preliminary optional configuration plan for pulse generator units and power grid capacity expansion plan.



Major physics design results

TG1: Advanced Configuration Control

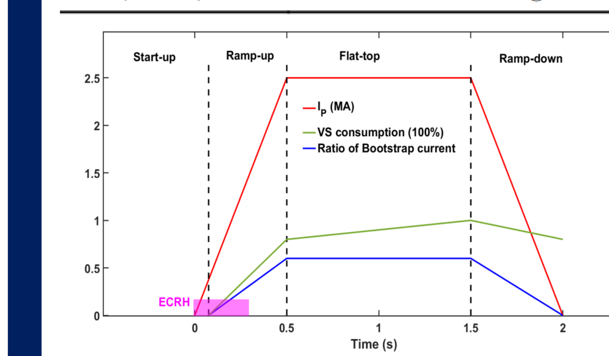


	R/m	Z/m	W/m	H/m	Nr	Nz	Turn	Imax/kA
CS	0.36	0	0.08	4	2	158	305	70
PF1	0.456	1.6	0.072	0.8	3.6	40	144	12
PF2	0.456	-1.6	0.072	0.8	3.6	40	144	12
PF3	0.7	2.05	0.12	0.16	6	8	48	12
PF4	0.7	-2.05	0.12	0.16	6	8	48	12
PF5	0.85	2.35	0.12	0.12	6	6	36	12
PF6	0.85	-2.35	0.12	0.12	6	6	36	12
PF7	1.85	2.35	0.12	0.12	6	6	36	12
PF8	1.85	-2.35	0.12	0.12	6	6	36	12
PF9	1.85	1.6	0.12	0.12	6	6	36	12
PF10	1.85	-1.6	0.12	0.12	6	6	36	12
PF11	2.5	0.5	0.2	0.2	10	10	100	12
PF12	2.5	-0.5	0.2	0.2	10	10	100	12

A set of PF system and relevant XPT configuration has been designed. The PF system also enables Super-X, and conventional double null divertor configurations

TG2: Heating and CD

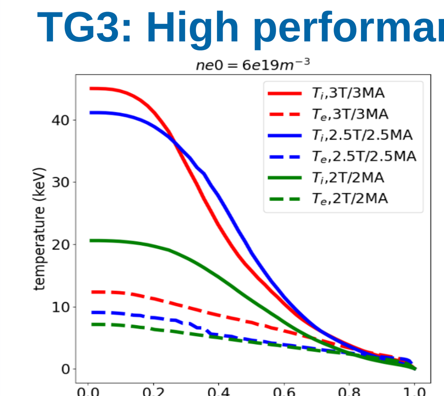
H&CD system	EHL-2 parameters	Input power (MW)
NBI	1×4 MW@60 keV/5 s 2×5 MW@80–100 keV/5 s 1×3 MW@200 keV/5 s	17
EC	1×1 MW@50 GHz/5 s 6×1 MW@105&140 GHz/5 s (dual frequency)	7
IC (Phase II)	5 MW@30–75 MHz/5 s	5
LHW (Phase II)	2 MW@2.45–5 GHz/5 s	2



The system will provide a total injection power of 31MW. NBI for high Ti and Ti/Te, ECRH for Ip

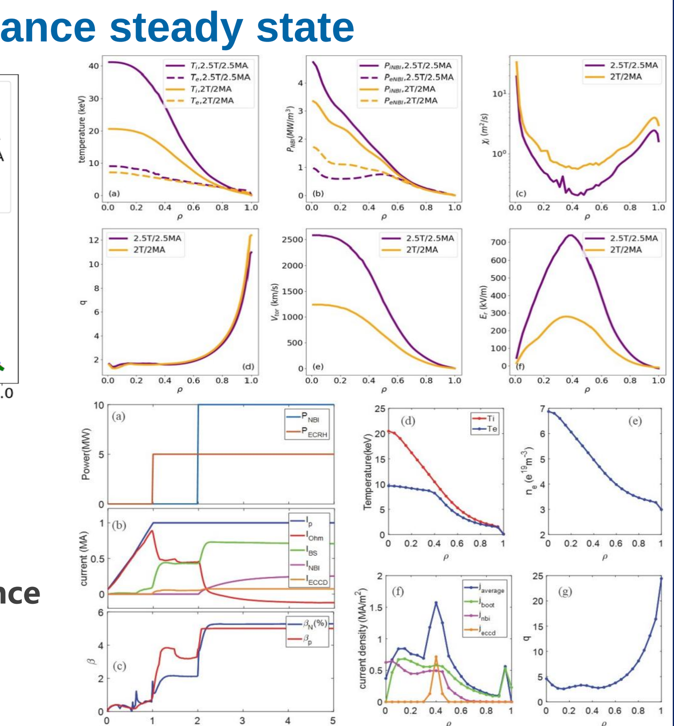
Duration time limited by Copper conductor TF, PF and CS

TG3: High performance steady state

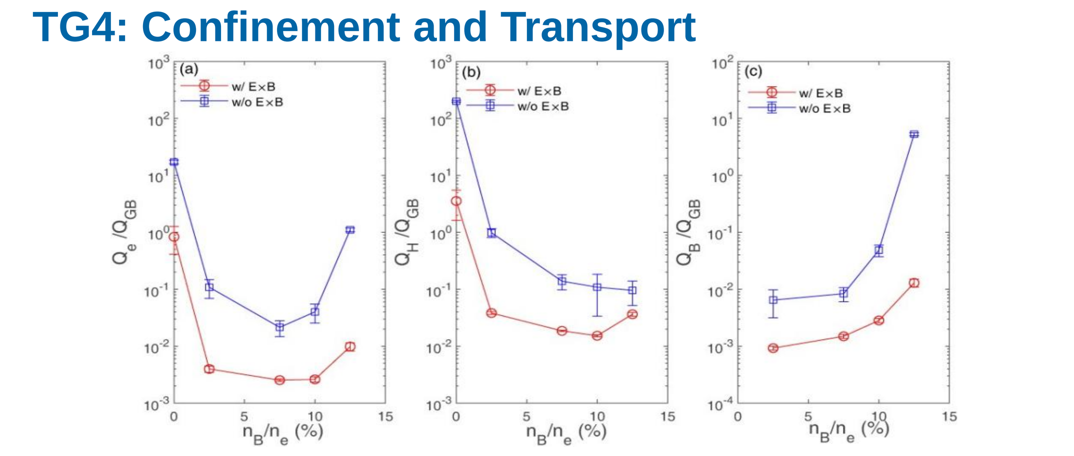


Ti>30keV is feasible (ASTRA simulation)

1 MA high-performance steady-state plasma

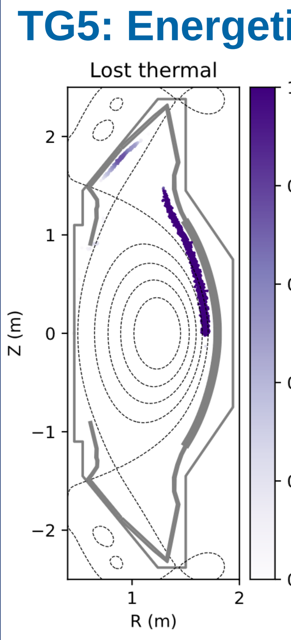


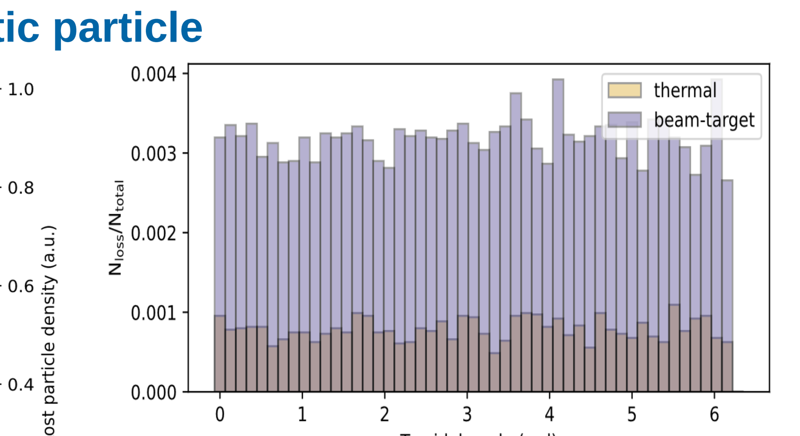
TG4: Confinement and Transport



Gyrokinetic(GENE) simulation shows that the total beta of hydrogen-boron plasma is diluted, which can effectively suppress the ion heat flux.

TG5: Energetic particle

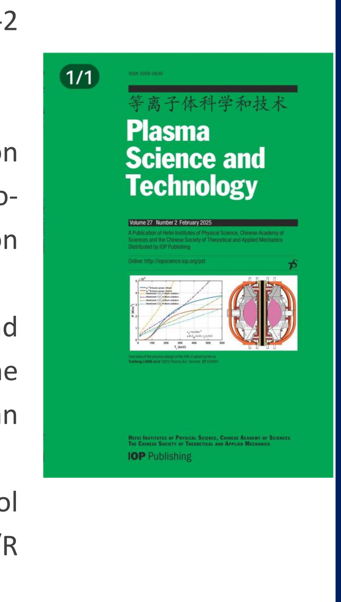




The orbit loss of high-energy particles injected is less than 1%, and the ripple is below 0.2%, while the ripple field loss can be negligible.
In future high-parameter fusion reactors, energetic particle losses may become significant.

Conclusion and outlook

- A new ST EHL-2 for p-B fusion is designed, and details can be found at Special issue "Physics design of the EHL-2 spherical torus", Plasma Sci. & Tech.
- Several unique & significant challenges to address:
  - ➢ establish a plasma with extremely high core ion temperature (Ti,0>30keV), and ensure large ion-to-electron temperature ratio (Ti,0/Te,0 > 2), and boron concentration of 10-15% at the plasma core;
  - ➢ realize the start-up by non-inductive current drive and the rise of MA-level plasma toroidal current. Due to the volt-seconds that the central solenoid of the ST can provide are limited;
  - ➢ achieve divertor heat and particle fluxes control including complete detachment under high P/R (>20MW/m) at relatively low electron densities.



Reference

[1] M. S. Liu, H. S. Xie, Y. M. Wang, et al., ENN's Roadmap for Proton-Boron Fusion Based on Spherical Torus, Phys. Plasmas 31, 062507 (2024)

[2] Y. F. Liang, H. S. Xie, Y. J. Shi et al, Overview of the physics design of the EHL-2 spherical torus, Plasma Sci. Tech., 27, 2, 024001 (2025).