



ENN 新奥

The 21st International Spherical Torus Workshop (ISTW 2022)
Virtual, Tsinghua University, Beijing, China, Oct. 31- Nov. 4 2022

ENN Roadmap for Proton-Boron Fusion Energy Based on Spherical Torus

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- 1. Hebei Key Laboratory of Compact Fusion**
- 2. ENN Science and Technology Development Co., Ltd.**

About ENN

ENN Group

- Private company
- Founded in 1989, Langfang, Hebei Province
- Over 40,000 employees
- Operating revenue and profit of 2021 reached 160.6 billion and 10 billion yuan respectively



ENN Energy Research Institute

- Founded in 2007
- Coal-based low-carbon energy technologies
- Carbon-free technologies, including fusion and deep geothermal technologies, etc.



Fusion Technology R&D Center (FTRC)

- Founded in February, 2018
- 130 researchers with 40% holding PhD degree
- Hebei Key Laboratory of Compact Fusion
- Existing device: EXL-50 (ST), EFRC0 (FRC)
- July 2022, **spherical torus p-11B fusion**



Our goal: commercially-viable fusion



A promising fuel for aneutronic fusion: proton-boron

1. p-B: abundant, accessible, economical and environmentally friendly
2. alpha particles, the product of fusion, can generate electricity directly

Nuclear reaction	Advantages	Disadvantages	Fuel price (RMB/g)	Consumption in 2050	Reserves
1. D-T	Easiest way to fusion	High energy neutron wall material protection, Tritium breeding	Tritium: 18 million	3000 tons	10 kg
2. D-D	Relatively easy, fuel cheap	High energy neutrons , and the peak reaction cross section low *	Deuterium: 30	10000 tons	45 trillion tons
3. D- ³ He	few neutrons and low neutron energy	³ He expensive, D-D side effects	³ He: 1 million	3000 tons	produced by nuclear reactions or mined on the moon**
4. p- ¹¹ B	With very few neutrons, and very cheap raw fuels,, alpha particles generate electricity directly	Extremely high reaction threshold	¹¹ B: 5	10000 tons	170 million tons

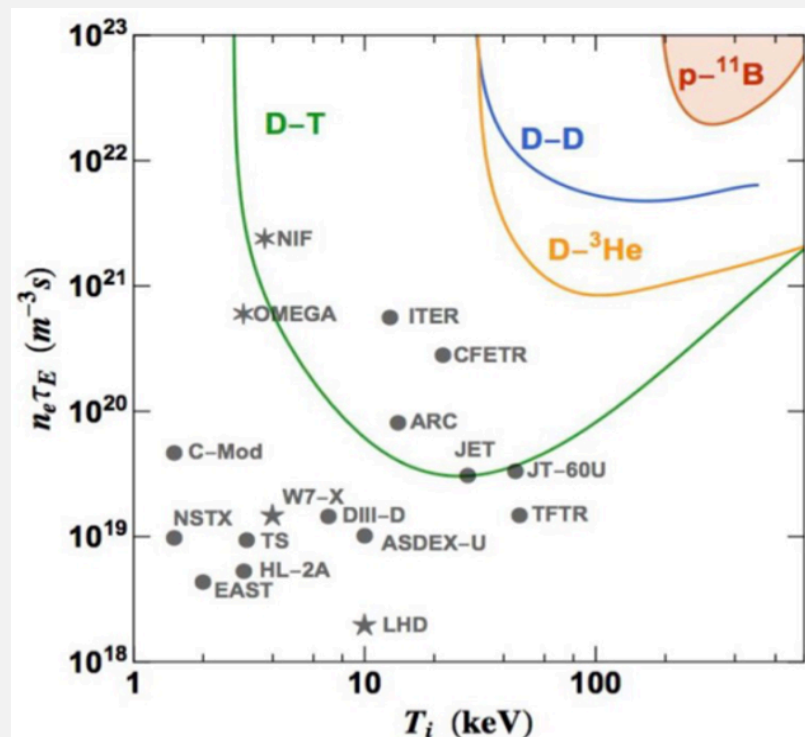
* 1: Catalyzed deuterium-deuterium fusion can reduce reaction conditions, that is, the use of side reactions such as D-D-He3;

**2. Advances in aerospace may make deuterium-helium fusion possible.

- High-energy neutron shielding for D-T fusion, wall material (currently there is no wall material available for commercial fusion reactors) and tritium breeding (TBR is difficult to exceed 1.2 at present, and the recycle requirement of fusion T is extremely high) are the biggest challenges, which are difficult to solve in the short term.
- Export and use of D-T, D-D and D-³He fuels are generally controlled by the government.

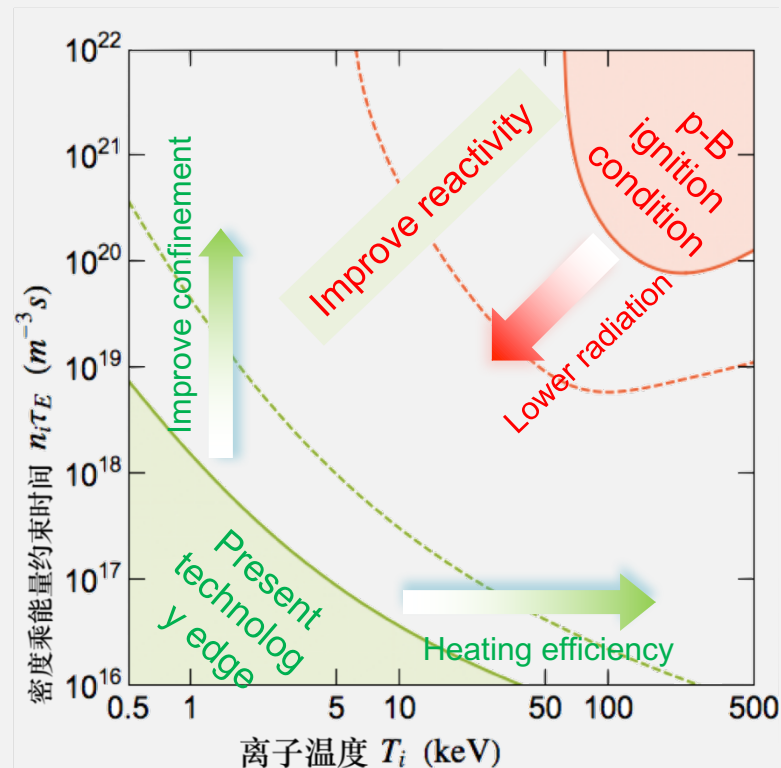
p-B fusion: challenging but theoretically feasible

$p\text{-}^{11}\text{B}$ fusion is theoretically feasible, though challenging to achieve.

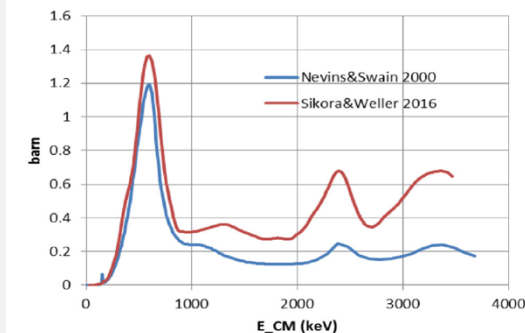
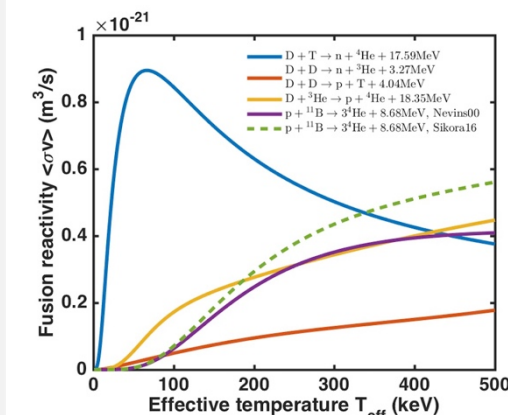


- Lawson criterion for thermal equilibrium. p- ^{11}B fusion is theoretically feasible
- Required quantitative conditions (cyclotron radiation ignored)
 $T_i \sim 200 \text{ keV}$, $n_i \tau_E > 10^{22} \text{ m}^{-3}\text{s}$

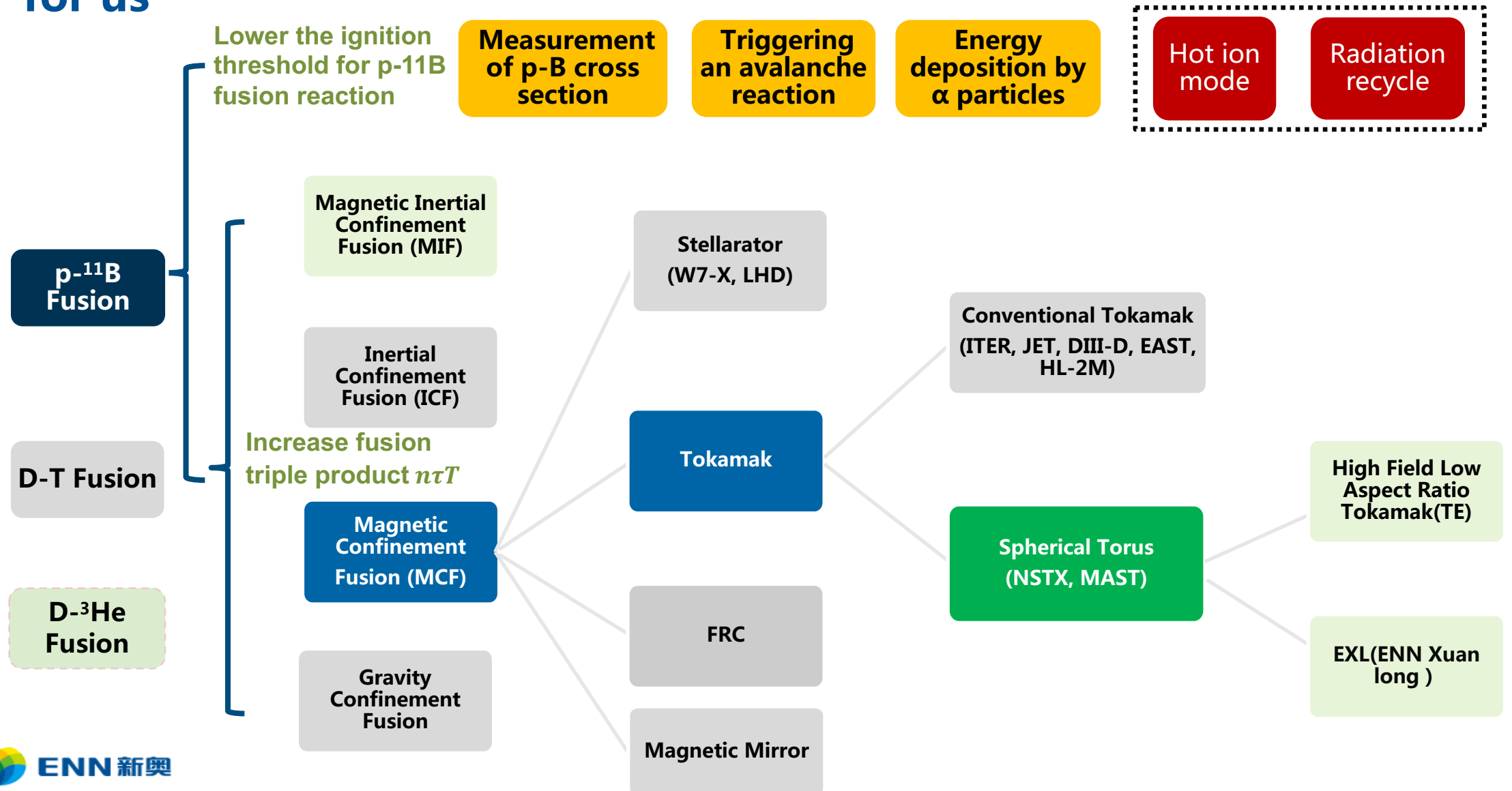
Improve confinement and lower the ignition threshold for p- ^{11}B fusion reaction



- New cross sections or reactivity rate studies, or non-thermal plasma, may lower the ignition threshold for fusion reaction
- Improve the triple product - energy confinement time, temperature, density



Explore p-11B fusion based on Spherical Torus is the optimal choice for us



ST p-B fusion: a new approach towards fusion commercialization

ST with high beta
and potentially
high confinement

Tokamak beta 1-2%

ST beta 20-40%

$$\tau_E^{IPB98y2} = 0.0562 I_p^{0.93} B^{0.15} P^{-0.69} n^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78}$$

$$\tau_E^{ST} = 0.066 I_p^{0.53} B_T^{1.05} P^{-0.58} n^{0.65} R^{2.66} \kappa^{0.78} \quad \text{Kurskiev22}$$

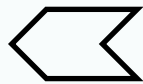
The capacity of p-B fusion can be boosted with ST.

p-B fusion

ST

Challenge

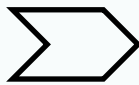
- High fusion triple product
- High radiation loss



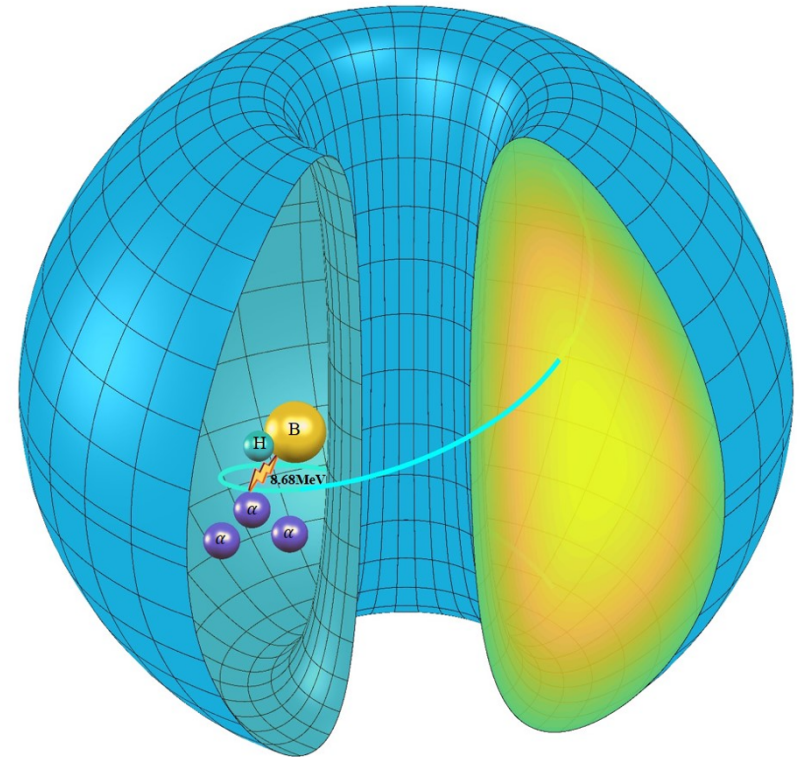
- Easier high confinement
- Lower magnetic field, lower radiation loss

Advantage

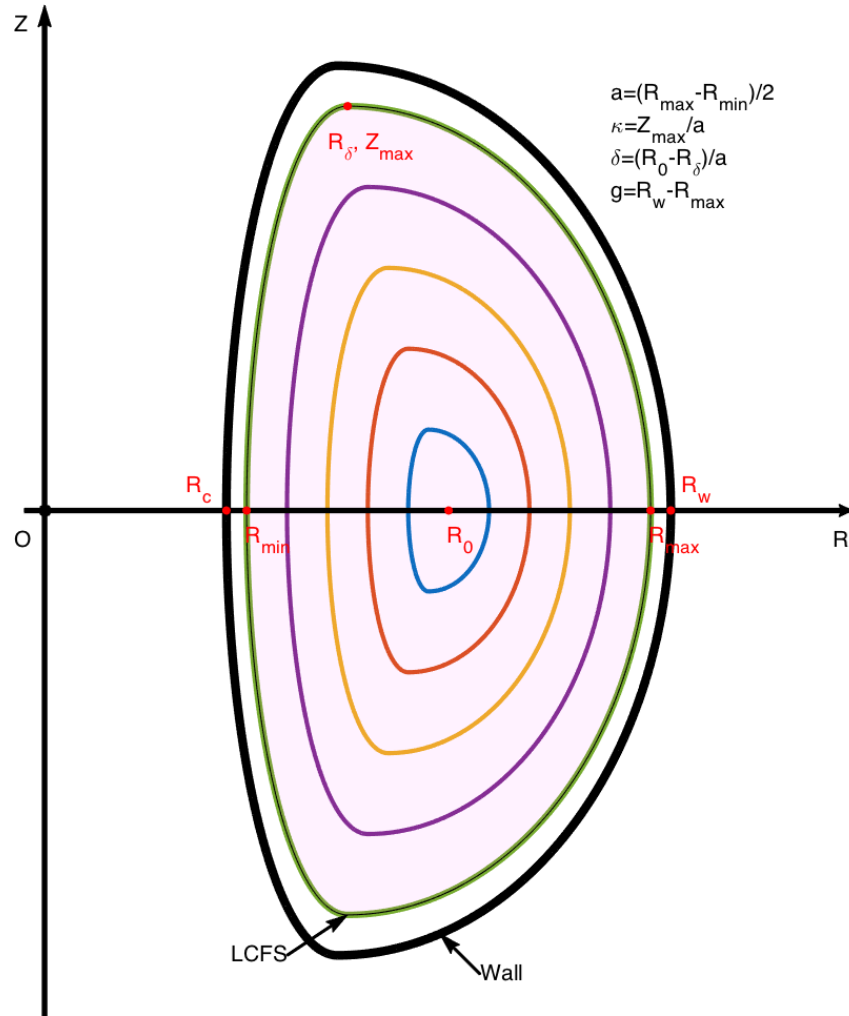
- No need for neutron shielding and fuels breeding



- Limited central post space



Physics design 0D model – system code



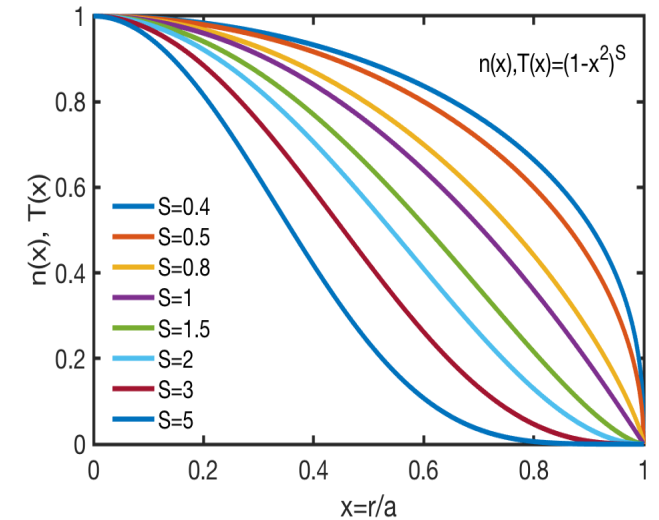
- Geometry configuration parameters: $R_0, A, \delta, \kappa, g$, give a, V_p, S_p

- Profile parameters:

$$n(x) = n_0(1 - x^2)^{S_n},$$

$$T(x) = T_0(1 - x^2)^{S_T},$$

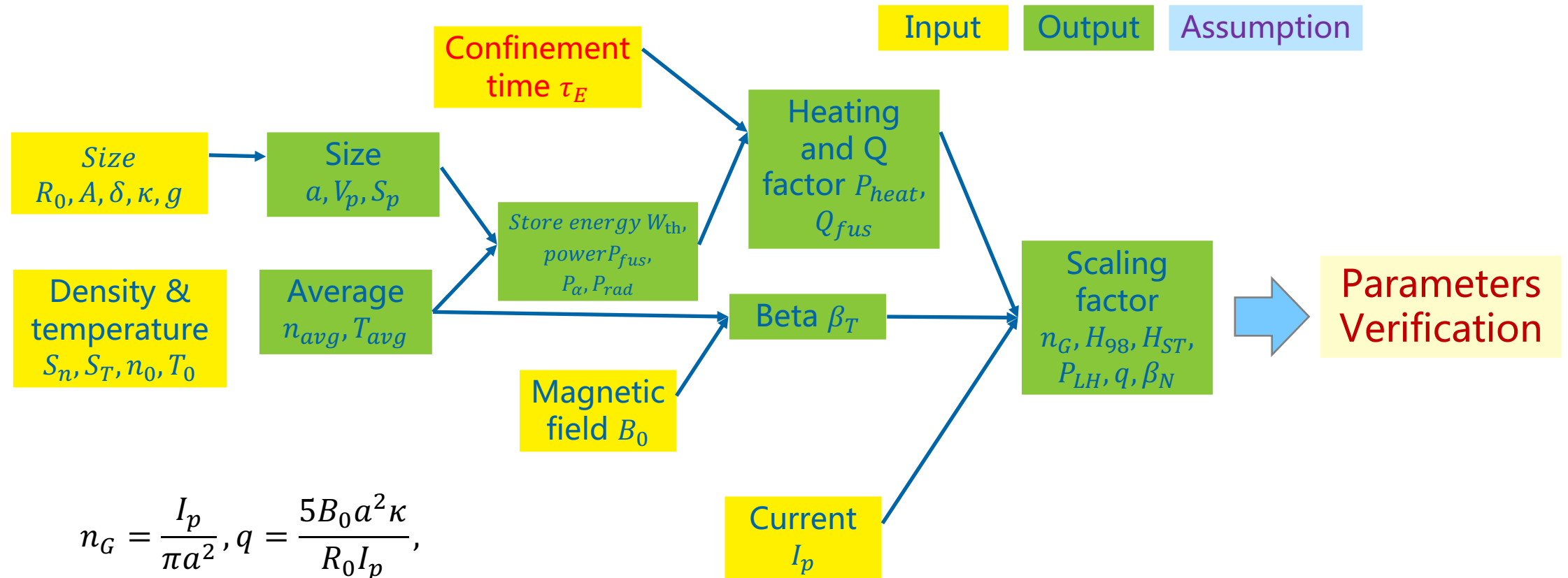
- Given temperature and density, yield store energy W_{th} , fusion power P_{fus}



- Energy confinement time τ_E , yield heating power P_{heat}
- Magnetic field B_0 , yield β
- β_N and plasma current I_p yield each other

Flow chart of 0D physics design model

ENN fusion device design



$$n_G = \frac{I_p}{\pi a^2}, q = \frac{5B_0 a^2 \kappa}{R_0 I_p}$$

$$\beta_N = \frac{\beta_T a B_0}{I_p}, \tau_E = \frac{W_{th}}{P_\alpha + P_{cd} - P_{rad}}$$

$$P_{heat} = P_\alpha + P_{cd}, Q_{fus} = P_{fus}/P_{cd}$$

Verify the ST design model

ITER parameters	Costley15 (Tokamak energy)	ENN model
Central ion temperature T_i (keV)	25	25
Central density n_e (m ⁻³)	0.77e20	0.77e20
Confinement time τ_E (s)	2.0	2.0
Beta β	0.02	0.02
Magnetic field B_0 (T)	5.18	5.18
Major radius R_0 (m)	6.35	6.35
Aspect ratio A	3.43	3.43
Plasma current I_p (MA)	9.2	9.2
Heating power P_{heat} (MW)	70	70.4
Fusion power P_{fus} (MW)	350	356
D-T gain Q	5	5.1

For ITER scenario:

- Using the same input parameters, our model yields close results to Tokamak Energy model (error <2%)

→ **Our model is proved reliable**

Quantitative Analysis: Spherical Torus vs Conventional Tokamak

Parameter	Conventional Tokamak	Basis and judgment	Spherical Torus	Basis and judgment
Average ion temperature T_i (keV)	33	JET and TFTR core ion temperature exceeded 40keV	33	no principle difficulty
Average electron density n_e (10^{20}m^{-3})	1.65	C-Mod average density has reached 8	0.66	no principle difficulty
Confinement time τ_E (s)	5	3.4 times higher than ITER scaling law	19.3	Below ST scaling law
Magnetic pressure β	0.038	achievable	0.32	Much lower than ARIES -ST design
Central magnetic field B_{T0} (T)	12	The same as the SPARC	2.6	Refer to future ST Design
Major radius R_0 (m)	4	2.2m smaller than ITER	3.2	Refer to ARIES-ST design
Gain Q	3.2	optimizability	30	optimizability
Aspect ratio A	3.5	slightly larger than SPARC	1.7	Refer to future ST Design
n_0/n_G	1	below the density limit	0.76	below the density limit
Safety factor q	3.27	Meet the requirements	2.16	Meet the requirements
Elongation κ	2.5	achievable	3.3	Below ARIES-ST design
Normalized β_N	3.45	A little high	7.16	Below ARIES-ST design
Fusion power P_{fus} (MW)	241	Economy need to be evaluated	107	Economy need to be evaluated
Heating power P_{heat} (MW)	74.5	Close to the heating power of ITER	3.56	achievable
Plasma current I_p (MA)	15	need to be evaluated	22	Below the ARIES-ST design
H factor	(98)3.41	3.4 times higher than ITER scaling	(ST)0.98	Below ST scaling law
Hot ion mode (Ti=4Te)	Results of Tokamak been obtained (Key technology)			
p-B Fusion reactivity increase 5 times	Theoretically possible, need further study (Key technology)			

■ Similarities

- The key technologies for p-B fusion are reducing the radiation (hot ion mode) and increasing the reaction rate. It also requires high current drive and energy confinement time

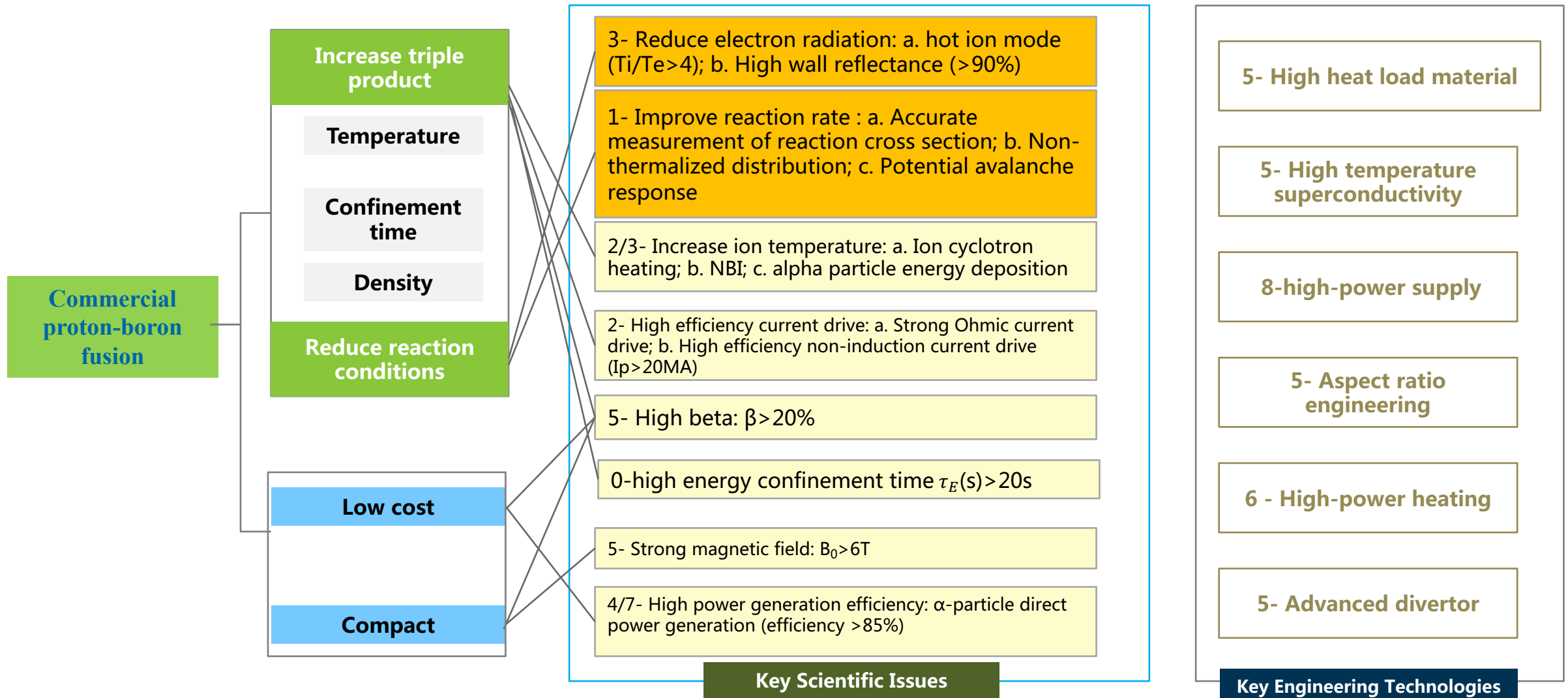
■ Advantages

- Using the ST scaling law of energy confinement time, ST can achieve p-B fusion gain 30 without strong magnetic field, while the tokamak requires strong magnetic fields. The cost of building a ST reactor is much less than tokamak.

■ Disadvantages

- At present, the plasma current, temperature and energy confinement time of ST are much lower than those of the conventional tokamak and need to be verified at high parameters.

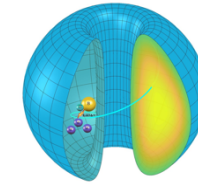
Key issues for spherical torus p-B fusion



➤ **Primary factors can interact with each other. If one technological breakthrough is achieved, other technical requirements may be lowered accordingly.**

Roadmap for spherical torus p-B fusion

Phase I: Achieve scientific and technological breakthrough, provide the critical solutions that help solve the problems of tomorrow, and lay the foundation for p-B fusion commercialization



2050 Commercialization

Phase III (Engineering and commercial demo)
2036-

Cost reduction

Phase II (EHL3)
2027-

Improve parameters and overcome the engineering constraints for scaling-up the fusion reactor

Phase I (EHL2)
2023-

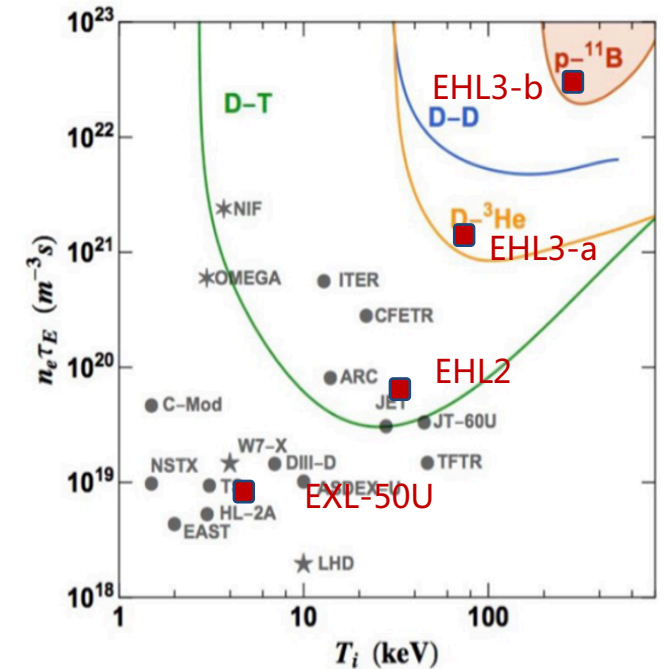
Build a spherical torus R&D platform to tackle key challenges facing p-B fusion

EXL-50U
2022-

EXL-50
2018-

- Develop key technologies for ST p-B fusion

Established the basis of ST p-B fusion



Target parameters for ST devices

Parameters	EXL-50	EXL-50U	EHL2	EHL3-a	EHL3-b (p-B reactor)
Avg./Central ion temperature T_i (keV)	-/1.0	-/6.0	-/30	-/70	46.2/140
Avg./Central density n_e (m ⁻³)	-/2.0e19	-/1.0e20	-/1.3e20	-/1.5e20	0.83/2.5e20
Confinement time τ_E (s)	-	0.07	0.5	5	25
β	-	0.1	0.11	0.18	0.24
Central magnetic field B_0 (T)	0.46	1.2@R=0.6m	3.0	4	4
Major radius R_0 (m)	0.58	0.6-0.8	1.05	2.0	3.2
Aspect ratio A	1.4	1.5-1.85	1.85	1.8	1.7
Heating Power P_{heat} (MW)	3.0	3.0	17	60	6.83+133
Plasma current I_p (MA)	0.5	0.9	3.0	10	25
Hot-ion mode T_i/T_e	-	1.5	3	3	4

*Note: The final design parameters may be different, and the EXL-50U and EHL2 parameters are slightly higher than the physics goals.

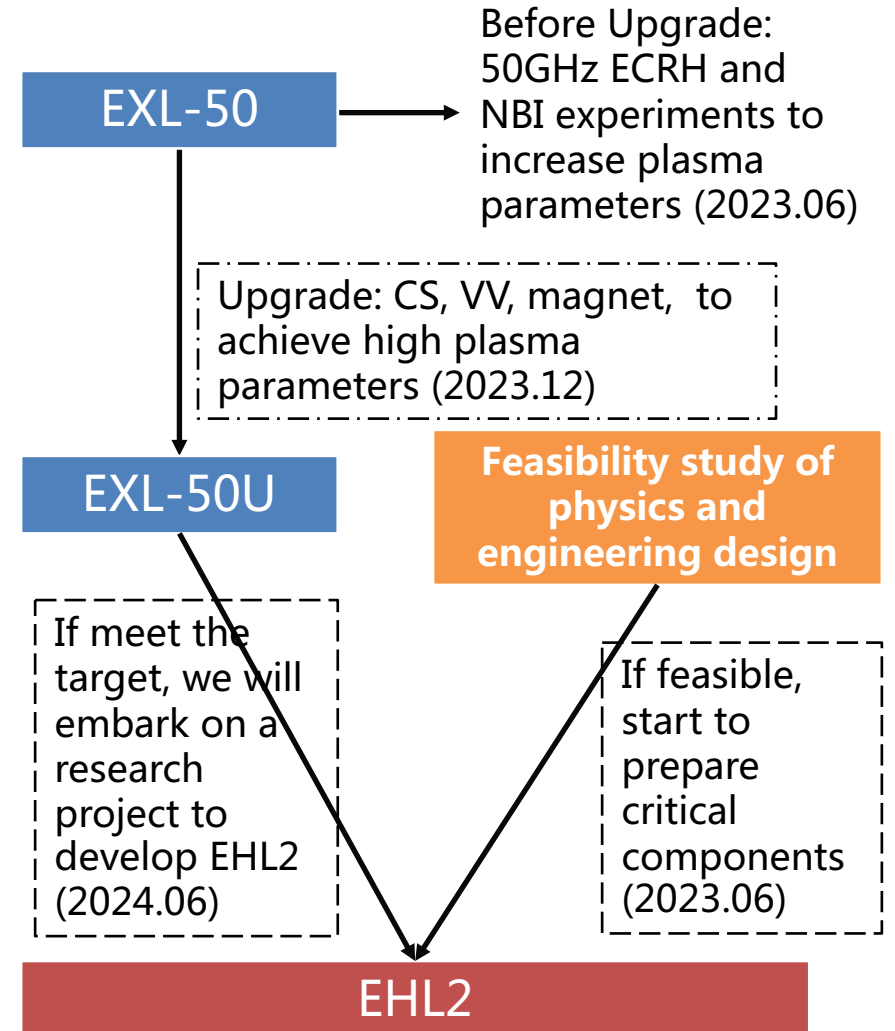
EXL-50U and EHL2 physics goals

EXL-50U
Phase I

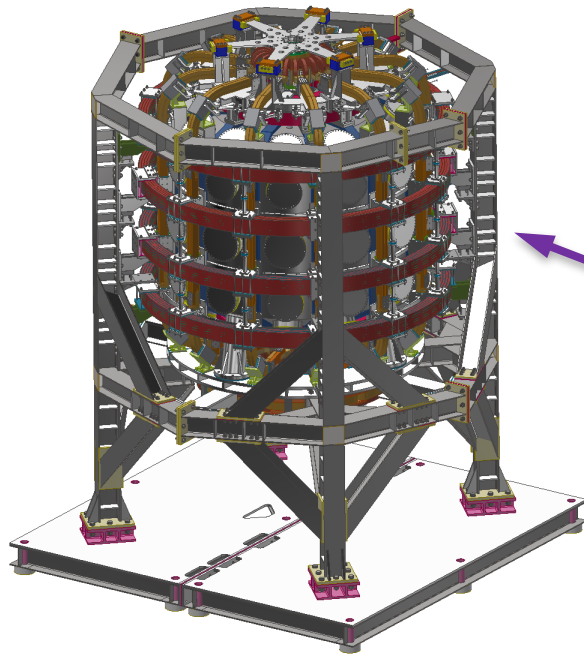
1. Hot ion mode at high T_i ($T_i/T_e \geq 1.5$, $T_i \geq 1.0\text{keV}$)
2. ST confinement scaling ($H_{ST} \sim 1.0$, $\tau_E \geq 0.03\text{s}$)

EHL2

1. High T_i/T_e ($T_i/T_e \geq 2$)
2. Confirm high ST confinement scaling ($H_{ST} \geq 0.5$, $\tau_E \geq 0.5\text{s}$)
3. High current drive efficiency ($I_p \geq 3\text{MA}$)
4. High ion temperature ($T_{i0} \geq 20\text{keV}$)
5. High beta ($\beta_T \geq 0.1$)



From EXL-50 to EXL-50U



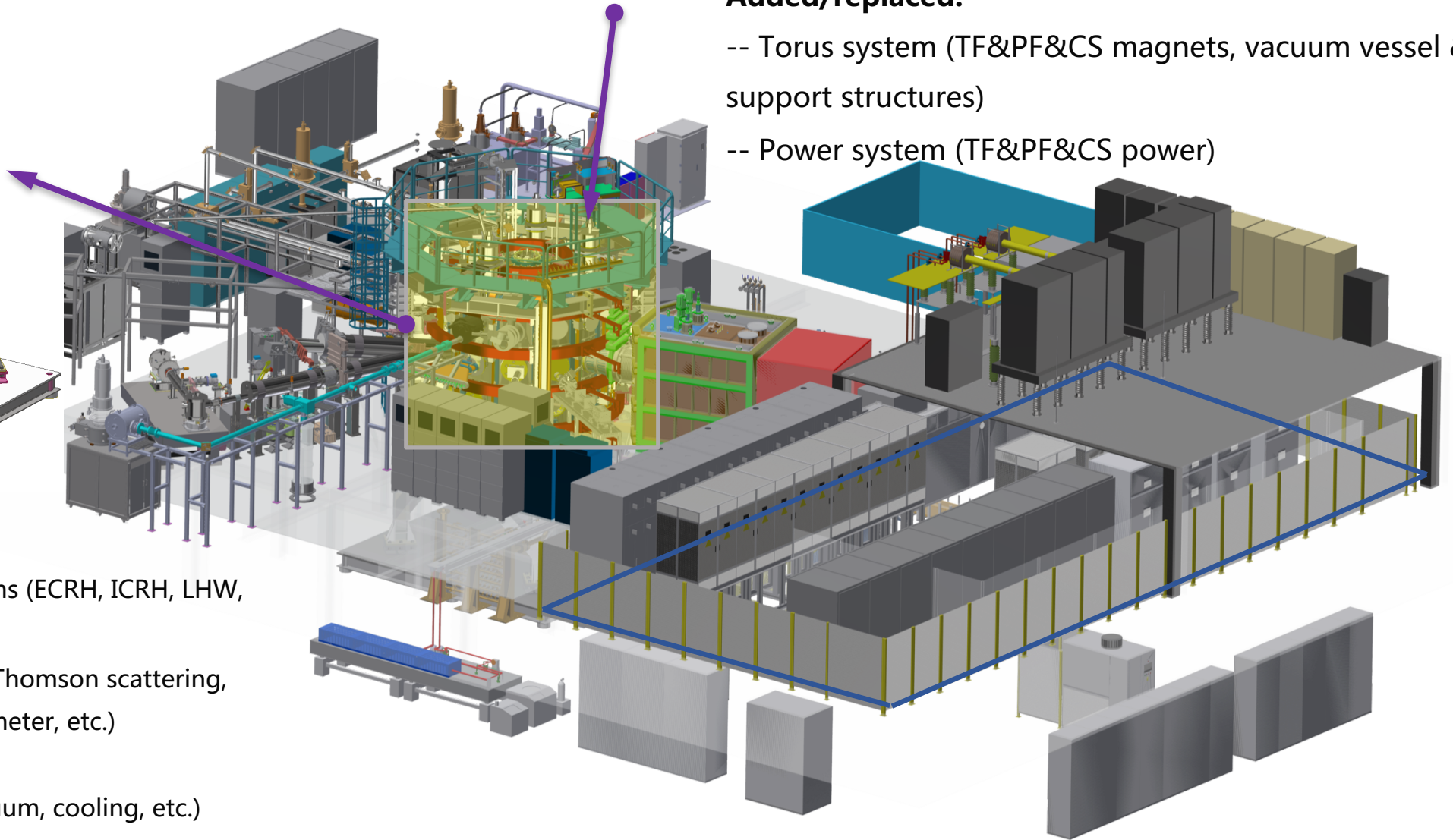
EXL-50U structure

Minor changes:

- Plasma heating systems (ECRH, ICRH, LHW, NBI)
- Diagnostics systems (Thomson scattering, Spectrometer, Interferometer, etc.)
- Control system
- Auxiliary system (Vacuum, cooling, etc.)

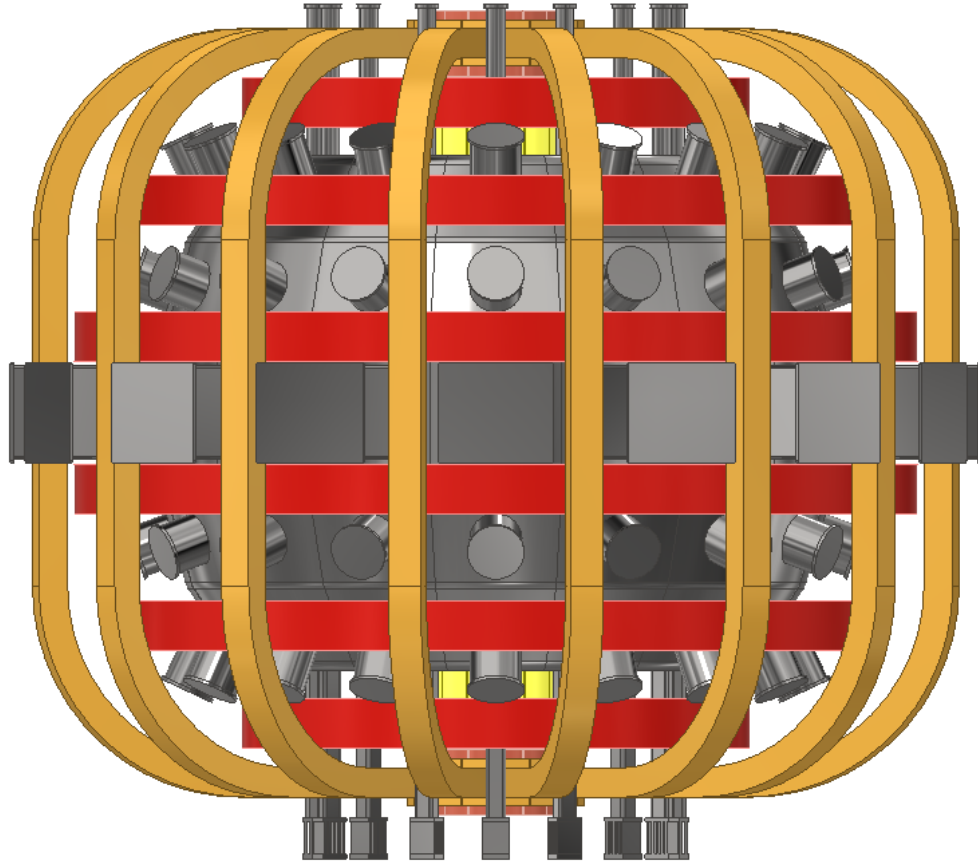
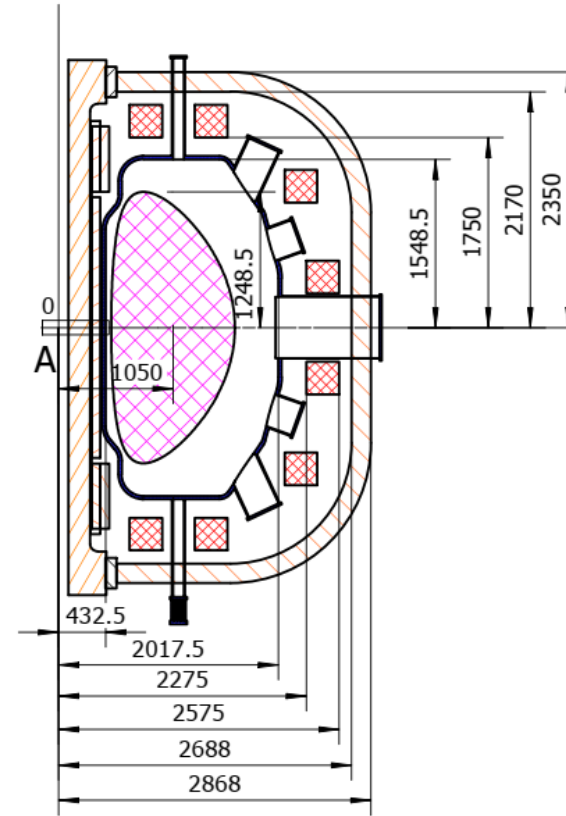
Added/replaced:

- Torus system (TF&PF&CS magnets, vacuum vessel & support structures)
- Power system (TF&PF&CS power)



Next generation ST for p-B fusion (EHL2 , ENN Helong 2)

High-standard ST p-B fusion device, cost ~\$600M



ENN Fusion Team





Thank you for your attention!

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