Обзор статьи “Small Tokamaks for Fusion Technology Testing” Y-K. M. Peng et all

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Предмет исследования

- Параметры и особенности малых стационарных токамаков (TST) как устройств для тестирования новых технологий
- Параметры и особенности малых стационарных нейтронных токамаков (TSNT) для тестирования технологий токамака-реактора

Параметры установок

Parameters of Representative TST and TSNT

Parameters	TST	TSNT
Major radius, R_0 (m)	0.6–0.75	0.8
Minor radius, a (m)	0.33–0.30	0.4
Toroidal field, B_{t0} (T)	1.4–2.2	4.1
Plasma current, I_p (MA)	~0.5	4.6
Edge elongation, κ_{95}	1.8–1.7	2.0
Edge safety factor, q_{95}	7	3.6
Troyon factor, g (mT/MA)	0.03	0.04
Average beta, β (%)	≤4.4–2.3	≤12
Density, $\langle n_e \rangle$ (10^{14} cm^{-3})	≤0.5	≤1.5
Temperature, $\langle T \rangle_n$ (keV)	≤2.0	~8.4
Total drive power, P_{tot} (MW)	≤4.5	~15
Edge heat flux, $Q_\perp$ (MW/m^2)	≤0.25	~0.4
SOL connection, L_{SOL} (m)	~30	~20
Fusion amplification, Q	–	~1.0
Neutron wall load, W_L (MW/m^2)	–	~1.0

L-H переход и время удержания плазмы

$$P_{tot} \geq P_{th} = 0,5 R_0 a k_{95} B_{t0}$$

$P_{th} = 0,5 MBm$ для TST

$P_{th} = 3 MBm$ для TSNT

$$\tau_{PL} = H_f \cdot 0,048 I_p^{0,85} R_0^{1,2} a^{0,3} k_{95}^{0,5} \overline{n}_e^{0,1} B_{t0}^{0,2} A_i^{0,5} P_{tot}^{-0,5}$$

$$\tau_{OL} = H_f \cdot [0,04 I_p^{0,5} R_0^{0,3} a^{0,8} k_{95}^{0,6} A_i^{0,5} + 0,064 I_p^{0,8} a^{0,6} k_{95}^{0,2} \overline{n}_e^{0,6} B_{t0}^{0,35} A_i^{0,2} P_{tot}^{-1}]$$

$$\tau_{NA} = 0,07 R_0^2 a \overline{n}_e A_i^{0,5} P_{tot}^{-0,5} q_*$$

$$q_* = \frac{5a^2 B_{t0}}{R_0 I_p}[1 + \frac{k_{95}^2 (1 + 2\delta_{95}^2 - 1,2\delta_{95}^3)}{2}]$$

Предел стабильности по β

$$\beta \le \beta_c = \frac{gI_p}{aB} = gI_N$$

$$I_N = \frac{I_p}{aB}$$

$$k_x = k_0(1+0,44\varepsilon^2)$$

$$k_{95} = 0,9k_x$$

$$\delta_x = \delta_0(1+0,77\varepsilon^3)$$

$$\delta_{95} = 0,5\delta_x$$

$$\frac{I_p}{aB} = \frac{1,9k_{95}^2\varepsilon^{0,5}}{q_{95}(1-\varepsilon)^{0,9}}$$

$$\varepsilon\beta_p \equiv \varepsilon\beta\frac{B^2}{B_p^2} \le 7,6gq_{95}\varepsilon^{0,5}(1-\varepsilon)^{0,9}$$

$\varepsilon\beta_p \le 0,6$ для TST

$\varepsilon\beta_p \le 0,4$ для TSNT

Поддержание тока плазмы

Current Drive Parameters for TST and TSNT

Parameters	TST	TSNT
Total drive power, P_{tot} (MW)	≤4.5	~15
LHCD power, P_{LH} (MW)	~1.0	~2.0†
Frequency (GHz)	2.45	~4.6
ICH power, P_{ICH} (MW)	~2.0	–
Frequency (MHz)	20–80	–
NBICD power, P_{NB} (MW)	~1.5	~15
Energy E_b (keV)	~50	~160A_i
Isotope	H,D	D,T

†For current ramp-up and maintenance at moderate densities only.

$$\varepsilon\beta_p \leq 0,6$$

$$f_{bs} \equiv \frac{I_{bs}}{I_p} \Box\, C_{bs}(\varepsilon^{0,5}\beta_p)^{1,3}$$

$$C_{bs} = 1,3 - 0,24\frac{q_{95}}{q_0} + 0,019\left(\frac{q_{95}}{q_0}\right)^2$$

$$f_{bs,TST} = 0,3 \div 0,4$$

$$f_{bs,TSNT} = 0,2$$

Инжекция нейтральных пучков

$$\gamma_{NB} = \frac{n_e R_0 I_{NB}}{P_{NB}} = 0,2 T_e J_{xy} F_{Zs}$$

	TST	TSNT
Топливо	H	D
γ_{NB}, А·Вт$^{-1}$·м$^{-2}$	$0,03\cdot 10^{20}$	$0,22\cdot 10^{20}$
f_{bs}, отн. ед.	0,3–0,4	0,2
n_e, см$^{-3}$	$0,5\cdot 10^{14}$	$1,5\cdot 10^{14}$
P_{NB}, МВт	5	15

$$Q = 100 \langle \sigma v \rangle_{bp} \frac{T_e^{\frac{3}{2}}}{E_b} \frac{\ln(1 + \frac{E_b}{20 T_e^{\frac{3}{2}}})}{\ln(\Lambda)}$$

Нижнегибридный нагрев

$$\gamma_{LH} = 0,1 \div 0,4 \cdot 10^{20}\, A \cdot Вт^{-1} \cdot м^{-2}$$

$$N_{\square} \geq N_c = y + [1 + y^2 - 0,12(1 + y^{-2})^{0,5}]^{0,5}$$

$$y^2 \equiv \frac{10 n_c}{B_{t0}^2}$$

$$\left.\begin{array}{l} B_{t0} = 2,2 \to 1,4 Тл \\ A = 2,5 \to 1,8 \end{array}\right\} \Rightarrow n_c = (7 \to 3) \cdot 10^{13} см^{-3}$$

$$P_{LH} = 2 МВт \to T_e = 1 \div 2 кэВ$$

$$T_e \leq \frac{20}{N_{\square}^2}$$

Комбинация методов нагрева

NBI + LHCD

$$I_{NB} = 0,1MA \qquad P_{NB} = 1,5MBm$$

$$I_{LH} = 0,2MA \qquad P_{LH} = 1MBm$$

$$I_{bs} = 0,2MA \qquad P_{heat} = 2MBm$$

$<T_e> \geq 1$ кэВ внутри области r < 0,55a

NBI + ICRH

$$\gamma_{NB+IC} = \gamma_{NB}(1 + 0,5\frac{P_{IC}}{P_{NB}})$$

$$\gamma_{NB+IC} = 0,06 \cdot 10^{20} A \cdot Bm^{-1} \cdot м^{-2}$$

$$I_{NB+IC} = 2MA$$

Генерация тока быстрыми волнами

$$\gamma_{FW} = 0,6 \frac{T_e}{2 + Z_{eff}}$$

$$\gamma_{FW} = 0,015 \cdot 10^{20} \, A \cdot Bm^{-1} \cdot м^{-2}$$

$$\gamma_{LH+FW} = 0,1 \cdot 10^{20} \, A \cdot Bm^{-1} \cdot м^{-2}$$

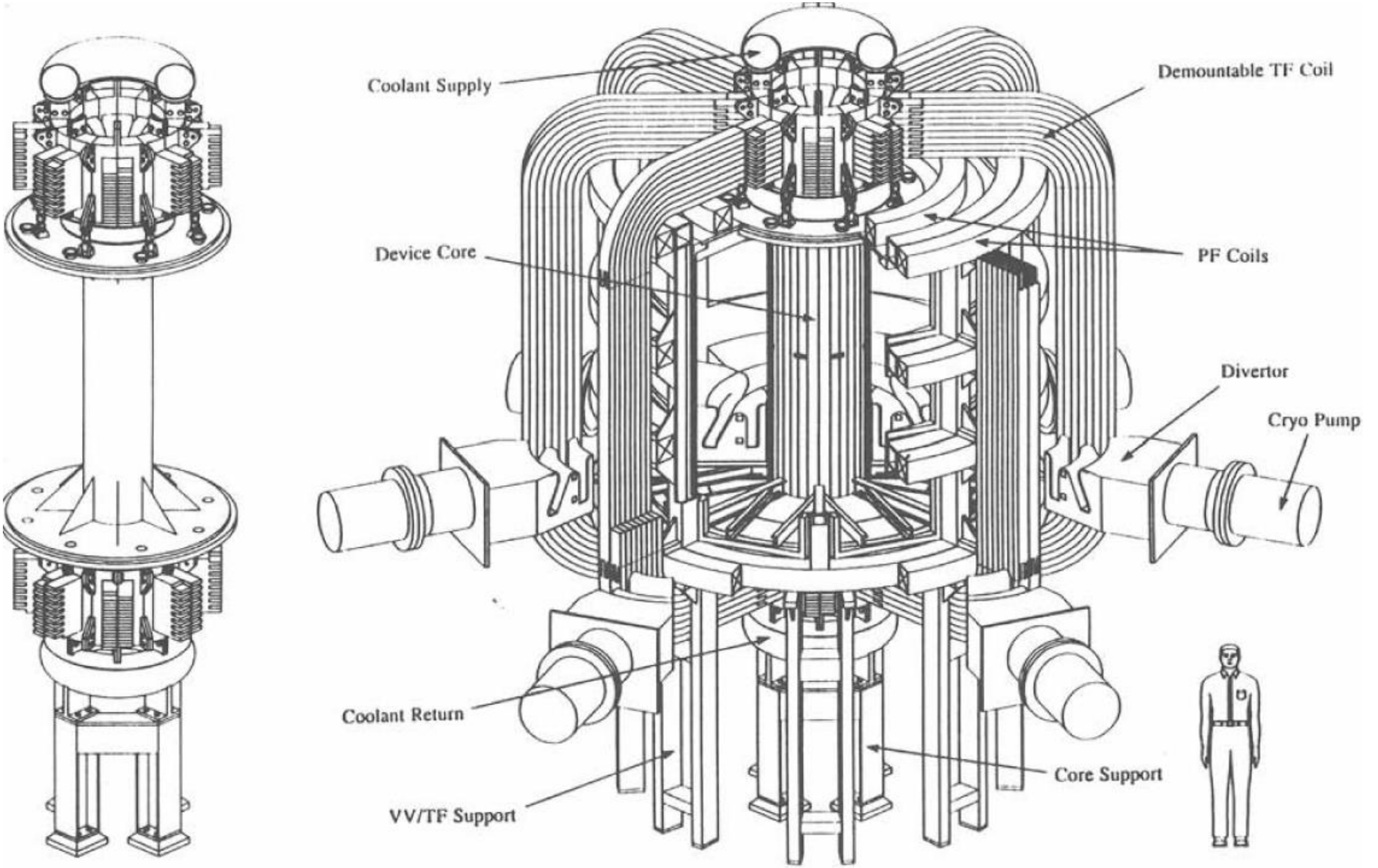
Условия на диверторе и в SOL

Conditions Needed for Testing Divertors

Condition	Considerations
Poloidal divertors	Correct configuration
$Q_{\perp} \geq 0.2$ MW/m^2	High avg. heat flux at edge
$T_{\times} \sim 0.1$–0.2 keV	H-mode edge, plate erosion
$n_{\times} \sim 1.5$–3×10^{13} cm^{-3}	High-recycle divertor
$n_{\times} \leq n_{\times dis} \sim 3.2\times10^{13}$ cm^{-3}	Disruption-free operation
$L_{SOL} \sim \lambda_{ex} \sim 30$ m	Connection length for ⊥-diffusion and e-i equil.
$Q_{div} \sim 5$ MW/m^2	High avg. heat flux on plate
$T_{ed} \sim 5$–50 eV	High-recycle to high-erosion
$\tau_{dura} \sim 10^5$ s	Particle equilibration; plate erosion, migration, and redeposition

$$F_D = \frac{Dpa}{D \cdot T}$$

Устройство TST



Технологические особенности TST и TSNT

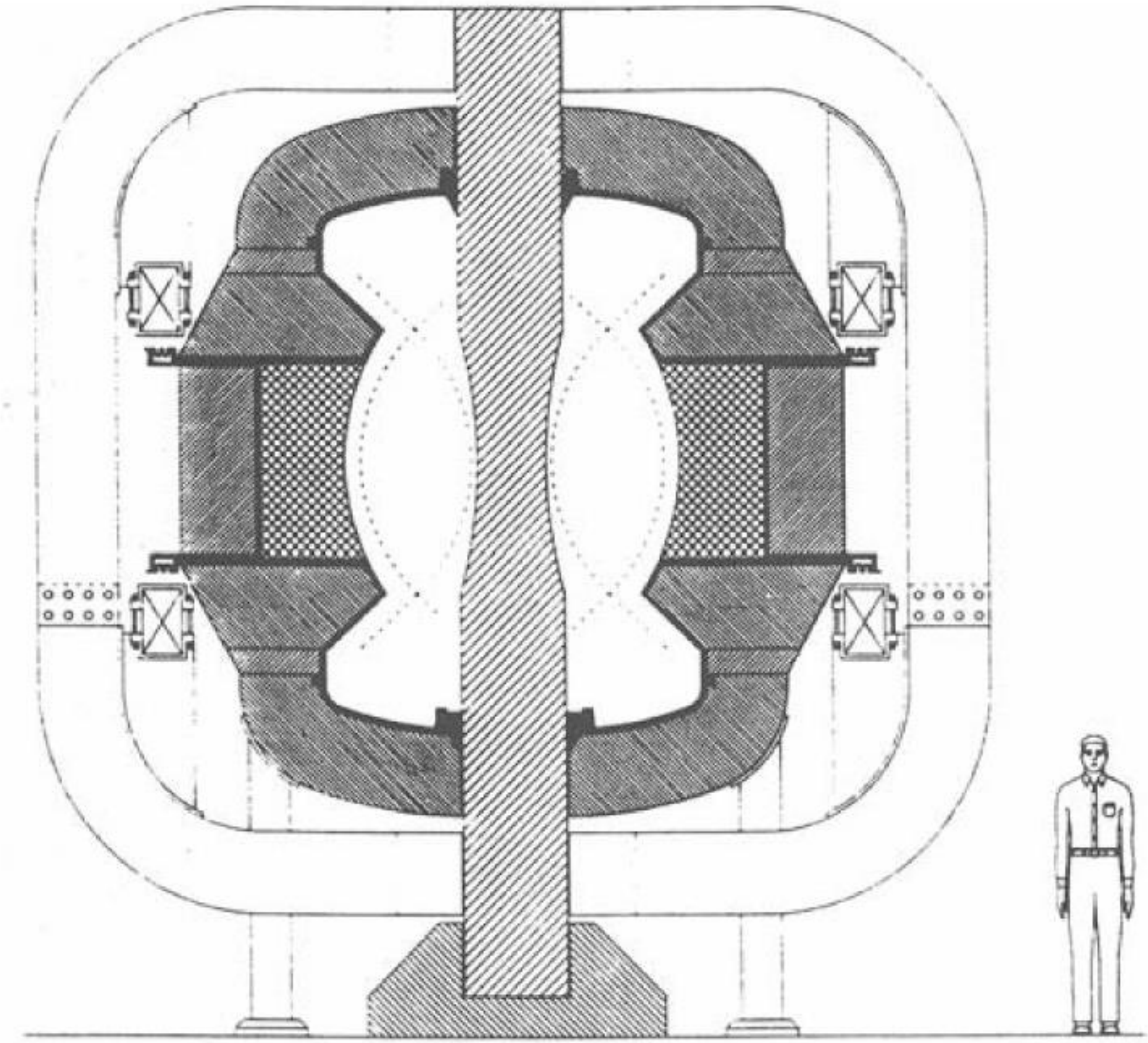
TST

Approach	Considerations
LHCD at 2.45 GHz	Steady-state operation for $\langle n_e \rangle \leq 0.3\times10^{14}$ cm^{-3}; peripheral CD at higher $\langle n_e \rangle$
ICH at 20–80 MHz	For high heat flux
NBICD at 50 keV	Core CD for $\langle n_e \rangle \leq 0.5\times10^{14}$ cm^{-3}
Plasma duration $\leq 10^5$ s	For 10–20% testing duty factor
Modular cassette divertor	Minimum turnaround time
Eight TFC return legs	Access for divertor cassettes
Demountable TFC	Flexibility and repairability
Conductor $J_c \leq 3$ kA/cm^2	Conventional steady-state coils
Demountable center core	Permit $R_0/a = 1.8–2.5$

TSNT

Approach	Considerations
LHCD at 4.6 GHz	Noninductive ramp-up and steady-state operation for $\langle n_e \rangle \leq 0.5\times10^{14}$ cm^{-3}
NBICD at $160A_i$ keV	Heating, beam-plasma fusion, and CD for $\langle n_e \rangle \leq 1.5\times10^{14}$ cm^{-3}
Plasma duration $\leq 10^7$ s	For a duty factor of 10–20%
Modular test blankets	Minimum turnaround time
Eight TFC return legs	Access for blanket modules
Single-conductor center leg	No inboard shielding, minimum size
Demountable TFC	Flexibility and repairability
Demountable center core	Permit regular replacement

Концепт TSNT



Спасибо за внимание!