On working parameters option of compact tokamak-reactors with transmutation and "pure" blanket.

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The first proposals for spherical tokamak based power units have been proposed by M. Peng and J. Hicks, D. Robinson, R. Stenbaugh, and JUST team (TRINITI, Kurchatov, Ioffe).

After impressible results of START experiments and NSTX and MAST construction the significant works concerning analysis of physical and technical possibilities of tight configuration have been carried out.

The experimental confirmation of basic physical properties, made recently, allows to start more detailed development of low-aspect ratio tokamak-reactor (power unit) with worm magnetic system.

There are also a lot of complicated technical problems must be solved.

Among them:

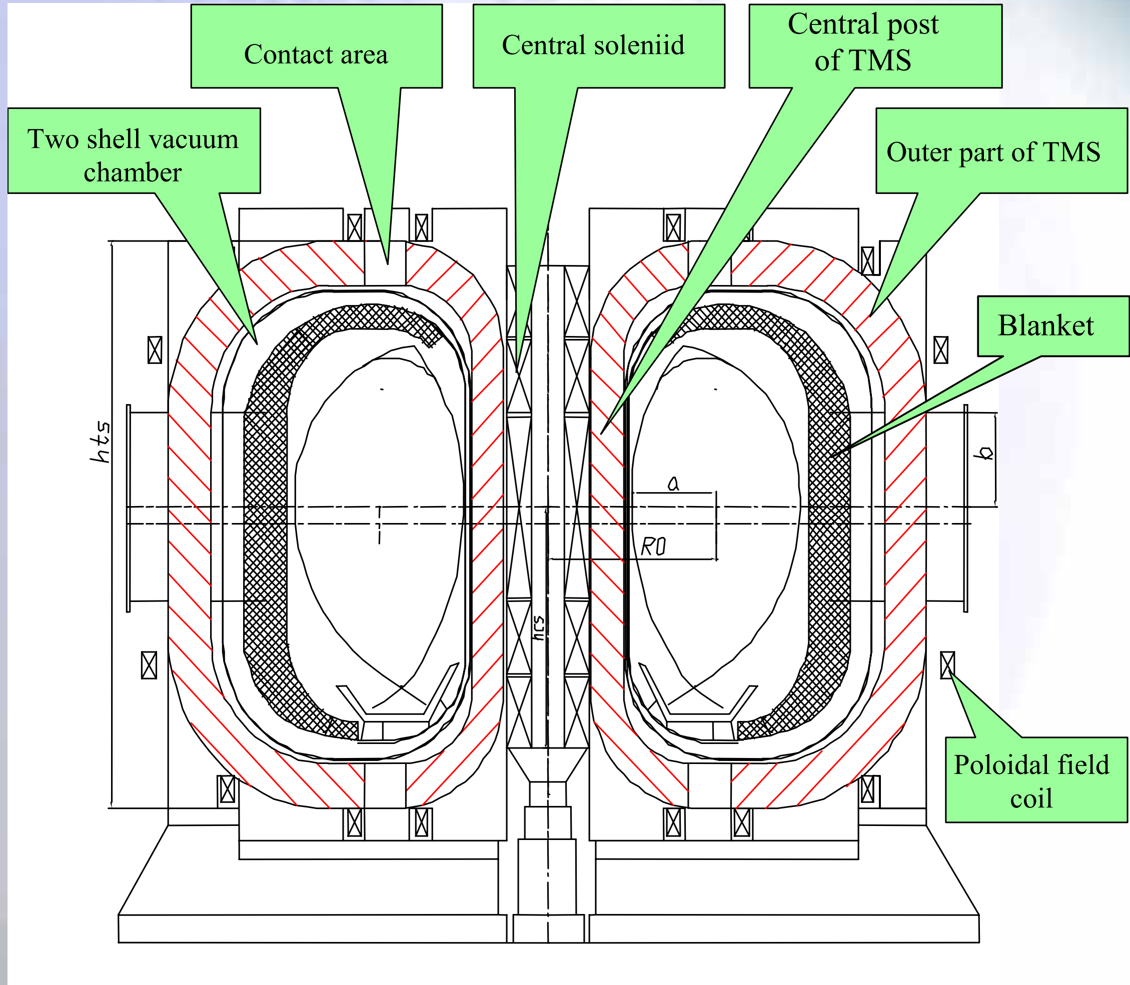
- Ensuring of stationary operation of warm electromagnetic system;
- Materials radiation stability of electromagnetic system (including insulation), vacuum chamber, divertor, etc);
- Effectiveness of blanket;
- Stationary injectors of neutral beams with energy up to the 500 keV and power up to 100 MW;
- Control of current and density profiles and plasma shape.

We considered the possibility to develop compact stationary fusion power unit basing on rather conservative physical assumptions:

1. Plasma density is within Greenwald limit
2. β_N value corresponds to the scaling law $\beta_N \leq (5\text{-}6)\cdot l_i$
3. The energetic time $\tau_E = H\ \tau_{EIPB(y,2)}$
4. Stationary plasma current is maintained by bootstrap-current and current-drive due to the tangential injection of neutrals
5. Aspect ratio A = 2.
6. Plasma elongation k =1.7 with single X-point divertor configuration.

The simplified scheme of compact fusion power unit

Version	R_0, м	a, м	h_{ts}, м	t_{cs}, м	b, м
I	2	1	6,32	2,7	1,2
II	3	1,5	9,48	4,05	1,8
III	4	2	12,64	5,4	2,4



The main task of our modeling is to calculate stationary regimes of compact power units with Q > 1 in case of transmutation blanket and with Q > 10 in case of pure blanket. It was taken for calculations that start and ramp up of plasma current up to 2.5 MA is produced by central solenoid discharge. Stationary current is produced by combination of inductive current, bootstrap-current and current-drive.

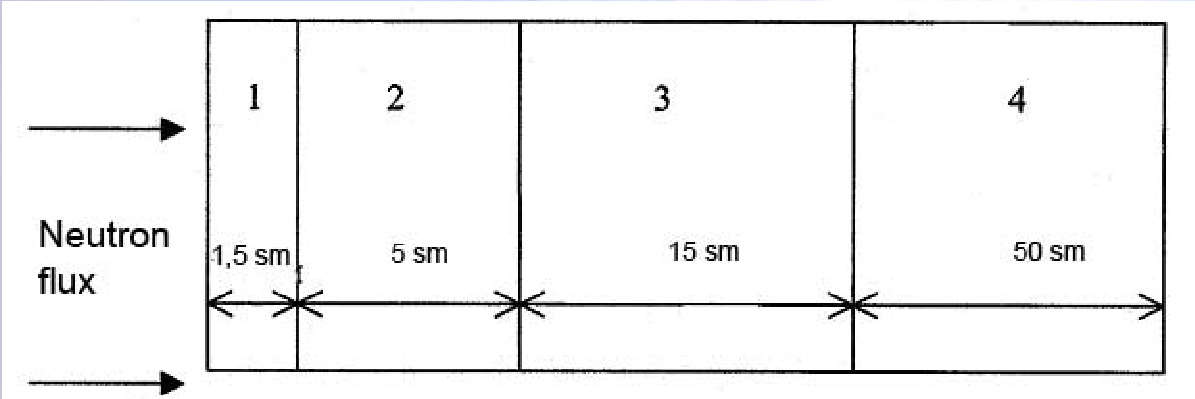
We analyzed two alternatives of compact fusion power units:

- With blanket containing fission materials, which are not dangerous from the point of view of nonproliferation;
- With “pure” blanket.

Both types of blanket must contain Li-material components for Tritium breeding.

For power unit with transmutation blanket the following geometry of plasma core has been accepted: $R_0 = 2$ m, $a = 1$ m, $k = 1.7$. Blanket with thickness of 25 cm and shield of 50 cm consists of three zones, two of them containing minor actinides.

The version of transmutation blanket for power unit



The composition of calculation's zone

Zone 1 – 50% steel, 50% coolant
Zone 2 – 15% steel, 50% coolant, 35% MA
Zone 3 – 15% steel, 40% coolant, 45% MA
Zone 4 – 75% steel, 25% water.
Coolants: liquid lithium;
liquid lead;
water

Integral characteristics of blanket and fission rate of MA

	Version 2	Version 3
	(Li)	(H_2O)
Fission for 1 D-T neutron		
Zone 2	1,87	0,66
Zone 3	5,17	1,23
Sum	7,04	1,89
Keff	0,96	0,86
Integral characteristics		
The mean specific power of fissions, MW/m^3	211	56,7
Heat power of fission, MW	4627	1243

The variants of main parameters of power units 1,3 GW with transmutation blanket and water cooling system

$a = 1$ m; $R = 2$ m; $k = 1{,}7$; $n_{e20} = 1$; $B_t(R_o) = 3{,}9$ T; $H_{IPB(y,2)} = 1{,}6$

	I	II
I_p, MA	5.00	5.3
β_p	1.2	1.3
τ_E, ms	412	427
P_{NBi}, MW	45.	45.
T_e, keV	6.8	7.1
T_i, keV	7.1	7.5
q_b	7.1	6.8
q_0	2.9	1.4
n_e/n_{GW}	0.638	0.604
l_i	0.585	0.746
I_{bs}, MA	2.542	2.181
W_p, MJ	20.900	22.153
Γ_n, MW/m^2	0.311	0.352
Q	1.217	1.374
f_n, 10^{19}m^{-3}	2.036	2.305
β_N	3.189	3.550
$P_{B\text{-}TI}$, MW	25.429	28.204
P_α, MW	7.818	8.849
P_n, MW	46.587	52.732
$\Delta\Psi_{res}$, Wb	7.297	9.127
I_{NB}, MA	2.459	3.104
f_{bs}	0.5089	0.4142
γ_{NB}, A/W	0.0546	0.0690
E_{NB}, keV	200.	300.
T:D	0.7: 0.3	0.7: 0.3

Calculations show that compact power unit with transmutation blanket is capable to produce more than 1 GW of thermal energy in case of water cooling system and more than 4 GW in case of lithium cooler system. Because there is no production of other transuranium elements under condition of full burnout of MA in blanket so the risk to violate non-proliferation treaty is minimal.

Keeping in the frame of conservative approach to compact configurations physics, development of compact power unit with “pure” blanket presents fundamental interest. At the same time it is significantly more complicated task.

As prototype of a pure blanket the blanket of demo tokamak-reactor DEMO-C has been selected, which ensures conversion of neutron energy to heat, as well as reproduction of tritium. The blanket thickness is 0.75 m. The primary materials of blanket are special steel, ortosilicate of lithium for tritium reproduction, and beryllium for neutron multiplication. Potential heat rating of such blanket at neutron load of 1.3 MW/m^2 is 1.5-2.8 GW.

R= 3m, A= 2, D:T= 0.5:0.5,
HIPB98(y,2) = 2, B=3,9T

	I	II	III	IV	V	VI
Plasma current I_p, MA	10.792	8.746	10.028	11.918	15.384	9.091
Poloidal beta β_p	1.228	1.429	1.324	1.210	1.096	1.324
Energy confinement time τ_E, ms	1328.54	1268.54	1224.15	1189.72	1202.80	1123.30
Average density, n_{e20}, m^{-3}	1.364	1.354	1.363	1.375	1.391	1.136
Elongation, κ	1.7	1.7	1.7	1.7	1.7	1.7
Average electron temperature T_e keV	8.96	6.55	7.96	10.10	13.97	7.128
Average ion temperature, T_i, keV	8.74	6.40	7.78	9.92	13.94	7.023
Safety factor on axis, q_0	2.33	2.09	1.93	1.78	1.17	1.550
n_e/n_{GW}	0.893	1.094	0.960	0.815	0.639	0.883
Thermal plasma energy W_p, MJ	174.76	133.83	164.27	211.54	301.02	134.27
$f_{fast,}$%	6.65	6.45	5.75	5.97	11.345	6.238
Neutron loading Γ_n, MW/m^2	1.6551	1.1431	1.6040	2.2573	3.1929	1.3556
Fusion gain factor Q	10.871	7.509	9.726	11.863	12.587	8.910
Normalized beta β_N	4.655	4.401	4.677	5.075	5.913	4.226
Beam-target interaction $P_{B\cdot TI}$, MW	27.12	20.90	26.875	35.846	50.614	21.991
P_a,MW	93.73	64.74	90.839	127.84	180.83	76.826
Neutron Power P_n, MW	558.54	385.80	541.32	761.83	1077.57	457.82
Bootstrap current fraction f_{bs}	0.7117	0.7449	0.7308	0.6943	0.5559	0.7202
Beam-driven current efficiency γ_{NB}A/W	0.0516	0.0367	0.0412	0.0483	0.0675	0.0420
Neutral beam power P_{NB},MW	20/40	20/40	20/45	20/55	40/60	30/30
Neutral beam energy E_{NB}, keV	400/500	400/500	400/400	400/400	400/100 0	140/500

R= 4m, A= 2, D:T= 0.5:0.5

	I	VI
Plasma current I_p, MA	12.934	16,3
Poloidal beta β_p	1.186	1,2764
Energy confinement time τ_E, ms	2033.15	1932.37
Average density, n_{e20}, m^{-3}	0.9078	0.906
Average electron temperature T_e, keV	10.374	8.857
Average ion temperature, Ti, keV	10.127	8.664
Safety factor on axis, q_0	2.523	2.160
n_e/n_{GW}	0.882	0.959
Internal inductance, 1_i	0.728	0,923
Neutron loading $\Gamma_{\text{п}}$, MW/m^2	1,6551	3,048
Fusion gain factor Q	19.045	39,123
Normalized beta β_N	4.032	5,52
Beam-target interaction PB-TЪ, MW	26.942	36.45
P_a,MW	139.575	278,353
Neutron Power P_n, MW	831.75	1824,61
Bootstrap current fraction f_{bs}	0.7391	0.7508
Beam-driven current efficiency $\gamma_{NB,}$ A/W	0.0660	0.0535
H-mode enhancement factor HIPB98(y, 2)	2	2
Neutral beam power P_{NB},MW	20/31	30/40
Neutral beam energy E_{NB}, keV	400/500	400/500

Calculations show that for power unit with R_0 = 3 m the value of Q ≥10 is attained at P_{NBI} = 60 MW. Ratio of beams with energy of 400 keV and of 500 keV is 20:40, plasma current is 10.8 MA. Fraction of bootstrap-current is 0.71, drift current is 0.29, factor γ_{NB} = 0.052 A/W. Increase of power injection up to 100 MW results in significant plasma current rise (up to 15.4 MA) and comparatively low rise of Q (25%).

In case of power unit with $R_0 = 4$ m with moderate values of β_N and additional heating power, thermal power in blanket reaches 1 GW; in case of more high values for β_N and of additional heating power 75 MW, the thermal power achieves 1.8 GW, neutron flux – 3 MW/m^2. Some skepticism arises on the possibility to realize these parameters. But, at any case, tokamak-reactors with $R_0 =$ 3 m and $R_0 = 4$ m can be used as reactors for the components of fusion reactors testing rather than power units.

The essential point is the electrical power necessary to supply to the toroidal magnetic system. In the table 6 calculations of the power consumed by one of versions of geometry of toroidal magnetic system for R_0 = 2, 3 and 4m are given. In the same table currents in the central part of the toroidal magnet creating a field 3,9T, voltage on TMC, consumption of water for removal thermal output, are presented.

The energy losses in central post of TMS and coolant possibilities of water flow

R (tokamak radius, m)	J (current density, MA/m^2)	I (total current, MA)	ΔU (total voltage, B)	B (toroidal magnetic field, T)	P_h (heat, MW)	S_{H2O} (full cross section of water channels, m^2)	G_{H2O} (total water flow, кg/c)	V_{H2O} (minimum of the needed water velocity, m/c)
2	21,4	39,05	441,6	3,9	88,9	0,249	409	1,65
3	14,25	58,51	441,6	3,9	135,1	0,56	659	1,14
4	11,05	78,1	441,6	3,9	177,8	1,126	818	0,67

From the results of calculation follows, that there are significant margin in possibility of water cooling through parallel channels. But ohmic losses too high, especially for variant R_0=4 m. This define a significant part of skepticism for reliability of power units with high effectiveness, which is necessary for real consumer.

Conclusion

Present base of experimental data, design-theoretical analysis and developed fusion technology permit to conclude:

1. From the physical and technical points of view, it is possible to build compact power unit with transmutation blanket based on a tokamak with A = 2 and with warm electromagnetic system. Cost of such power unit with thermal power of 1.3-4.6 MW and with full cycle of energy conversion will be not more than 10^9 $.

2. There are no physical and technological problems for building of power unit having “pure” blanket with thermal power of 2-3 GW. The problem is achievement of acceptable energy effectiveness and cost of such unit.

With careful optimism, we can consider compact tokamak-reactors with A = 2 as realizable variant for the first generation of fusion power units.