ID: xxx

TOKAMAK WITH REACTOR TECHNOLOGIES CONCEPT

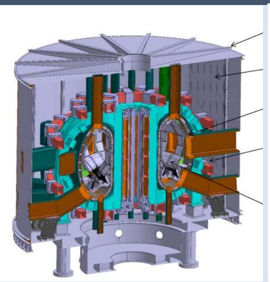
S.V. KONOVALOV[1,2], A.V. KRASILNIKOV[1], D.V. PORTNOV[1], V.M. SAFRONOV[1], V.M. LEONOV[2,1], R.R. KHAYRUTDINOV[2,1], A.S. KUKUSHKIN[2,1], V.E.LUKASH[1,2], I.YU. RODIN[3], E.N. BONDARCHUK[3,1], I.V. MAZUL[3,1], A.B. MINEEV[3,1], E.G. KUZMIN[3,1], A.A. KAVIN[3,1], D.A. KARPOV[3,1], I.E. LYUBLINSKI[4,1], A.V. VERTKOV[4,1], A.A. IVANOV[5], YU.I. BELCHENKO[5], G. DENISOV[6], V.E. SYTNIKOV[7,1], V.S. VYSOTSKY[8,1]

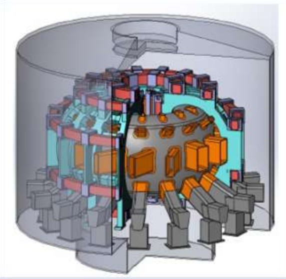
[1]Institution "Project Center ITER", Moscow, Russian Federation, [2]National Research Centre "Kurchatov Institute", Moscow, Russian Federation, [3]Joint Stock Company "D.V.Efremov Institute of Electrophysical Apparatus", St Petersburg, Russian Federation, [4]Joint Stock Company "Red Star", 1a Electrolitnyi proezd, 115230, Moscow, Russian Federation, [5]Budker Institute of Nuclear Physics of Siberian Branch Russian Academy of Sciences, Novosibirsk, Russian Federation [6]Federal Research Center Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russian Federation, [7]"R&D Center FGC UES", JSC, Moscow, Russian Federation , [8]Russian Scientific R&D Cable Institute (VNIIKP), Moscow, Russian Federation

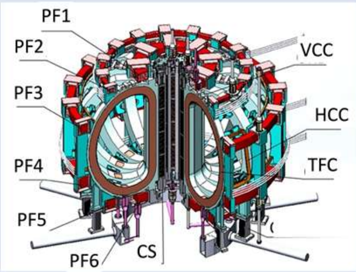
ABSTRACT

Concept of a tokamak with reactor technologies (TRT) is developed to facilitate fast and economically sound transition to the pure fusion reactor as well as to the fusion neutron source (FNS) for the hybrid fusion-fission system. Well controllable steady - state operation and reliable power and particle control in a reactor relevant conditions are principal plasma physics problems to be resolved on the way to both fusion reactor and FNS. Finding optimal solutions to them determines the mission of TRT. To explore wide variety of technically feasible proposals to achieve these goals the experiments should be performed in low activation conditions, i.e. mostly with H and D plasmas. However tritium trace experiments are also foreseen for the TRT research program. TRT electromagnetic system is designed on the base of REBCO high-temperature superconductor providing B_{t0} = 8 T at the machine center. The increased magnetic field will allow achieving the tokamak fusion plasma regimes with Q ~ 1 at moderate machine size (R = 2.15 m, a = 0.57 m) and therefore lower cost. TRT will be able to operate in quasi-stationary (>100 s) regimes with hydrogen, helium, and deuterium plasma and with short (t < 10 s) deuterium-tritium discharges (Q ~ 1) limited by radiation heating of the toroidal field coils. Missions of TRT are: (i) development and integration of the key fusion reactor technologies in one machine; (ii) development and investigation of the quasi-stationary plasma discharges; and (iii) development and investigation of regimes with burning fusion plasma with the domination of alpha-particle core plasma heating during limited by radiation heating deuterium-tritium experiments. The reactor technologies to be tested here include the HTS EMS operating at the extremely high magnetic field; the solid metal and liquid lithium first wall and advanced divertor; the several ten MW, 0.5 MeV-range NBI; 230 GHz, MW-range gyrotrons; 60-80 MHz, MW-range ICRH system; the tritium complex; the remote control technologies; and the reactor-relevant diagnostics. The conceptual design of the main components of the TRT and its expected performance characteristics are presented in the paper

TRT MAIN CHARACTERISTICS

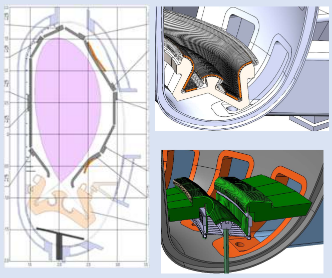






General view of the TRT in cryostat is shown in the left. Double wall vacuum vessel provides radiation shield for all D and limited DT operation scenarios. TRT electromagnetic system (right figure) consist of 16 HTS toroidal field coils (TFC), 6 HTS (LTS –option) Poloidal Field Coils, 4 Central Solenoid (CS) HTS sections, 24 HTS (LTS – option) correction coils (VCC) and 4 HTS horizontal field control coils (HCC). 2 coils to explore separatrix swipping technique can be installed additionaly at the VV bottom.

First Wall and Divertor

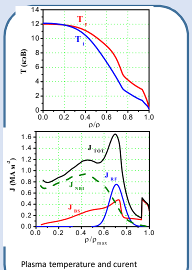


156 FW modules will be arranged in 10 rows as shown in the left figure. TRT should start operation with ITER-like divertor (top right). Than various divertor options are to be explored (for example "swipping" divertor (right-bottom figure).

Li protection (CPS) of the FW and divertor is one of the key targets of TRT Research Plan. Continuous rise of the Li concentration is foreseen.

Ip=5MA, , $n_e = 2{\cdot}10^{20}$ m^{-3} P_{aux} ~ 40 MW – top heat load boundary.

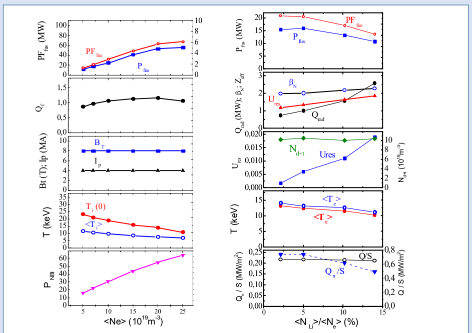
Operation Scenarios



Plasma temperature and curent profiles

Basic H plasma scenario
$N_e = 6.0{\cdot}10^{19}$m^{-3}
$β_N$ =1.4
<Te>/<Ti>=6.2/4.8
I_{NBI} = 2.07 MA (P=20MW)
I_{BS} = 1.18 MA
I_{RF} = 0.75 MA (P=14MW)
P/S = 0.22 MW/m^2

Basic TRT scenarios with H plasmas are focused on the development of the plasma control algorithms. Synergy between EC and NB heating and CD is the key strategy in controlling plasma profiles. Basic scenarios provide necessary heat flux to the PFC to study reactor relevant materials and constructions of the First Wall and Divertor



Fully non inductive stationary DT scenarios at different plasma density (left) and Li concentration (right). P_{fus} and PF_{fus} at the top pannels stand for fusion reactivities without and with allowing for the beam - target reactions, respectively

The presence of Li as a main plasma impurity was found to be tolerable up to the concentration of about n_{Li}~15%

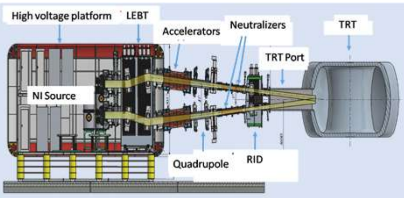
Expected discharge characteristic in TRT allow wide operation window to explore steady MHD stable scenarios with (for DT mixture) fusion gain factor of order unity providing neutron flux to the wall > 0.2MW/m^2, which is sufficient for the fusion neutron source in the fusion-fission hybrid reactor

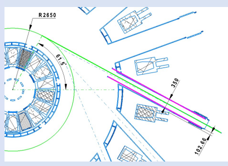
Table 1.TRT main parameters in comparison with other machine and projects
* expected T-14 parameters after adiabatic compression, ** T-trace/ D - T plasma.

		C-Mod	T-14	CIT	Ignitor	DTT	SPARC	TRT	ITER
R_0	m	0.67	0.42*	2.1	1.32	2.11	1.85	2.15	6.2
a	m	0.22	0.12*	0.65	0.47	0.64	0.57	0.57	2.0
A		3.0	3.3	3.2	2.8	3.3	3.2	3.77	3.1
B_0	T	8.0	12.5*	10.0	13.0	6.0	12.2	8	5.3
I_p	A	2.0	1.2*	11.0	11.0	5.5	8.7	4 - 5	15.0
k_{sep}		1.8	1	2.0	1.83	1.8	1.97	1.8	1.85
$δ_{sep}$		0.4		0.25	0.4	0.4	0.54	0.3	0.48
$Δt_{flattop}$	s	1	0.2	5	4	90	10	>100/<10*	1000
$Φ_{tot}$	Wb	8		75	33	33Vs	42	~33	277
$<n_e>$	10^{20} m^3	2 - 8	8*	3	4.8	1.8	1.4	up to 2	1
$τ_E$	s	~ 0.1	0.06		0.62	0.43	0.77	0.33	
P_{aux}	MW	6	3.5	20	24	45	25	up to 40	73
P_{fus}	MW	0	3.5*	800	96	~ 0.01	140	~0.5/ 40**	500
P_{sep}/R	MW/m	~ 10			16	15	15.7	14 / 16**	15
Q		0	1	infinity	9	0	11	0.01/ >1**	10

HEATING AND CD

TRT auxiliary heating and current drive system comprises 25MW NBI with beam energy 300-500keV, 10MW ECRH with 10-12 gyrotrons 230 (260) GHz and ICRH system of ~5MW with frequency range of 60 - 80 MGz.. TRT VV has 3 specially designed equatorial ports to provide tangential neutral beam injection with R_{tg} = R0-a/2 = 1865mm. 6 injectors (2 for each ports) are designed in Budker Institute. Gyrotrons for frequency 230GHz are designed in Applied Physics Institute (Nizniy Novgorod) with use of technologies and experience gained in development of the 177GHz gyrotrons for ITER. EC waves from 12 gyrotrons in TRT should enter the plasma through the one equatorial port. Multi-mirror system in the port should provide online control on the EC power deposition profile. The synergetic effect between NB and EC heating and CD is the most promising in development the algorithms for the kinetic control of the plasma.





2 Beams in the Port, Up to 7MW each for H and ~5MW for D. NBI ports allow tangential injection for best possible CD

SUMMARY

Conceptual design of the Tokamak with Reactor Technologies - TRT revealed that compact (R/a=2.15/0.57) tokamak with high (B_t=8T) magnetic field with HTS REBCO EMS, powerful auxiliary heating/CD complex and advanced strategy in FW and divertor technology development opens the unique possibility to integrate most important technologies both for pure fusion and hybrid fusion-fission reactor in a one single machine. TRT experimental program with H, He and D plasmas is aimed to develop the stationary operation regimes attractive for the reactor, i.e. with reliable controllability of the plasma parameters including their radial profiles and keeping plasma wall interaction at the constant tolerable level..

ACKNOWLEDGEMENTS

The work was supported by State Atomic Energy Corporation "Rosatom", agreement N^{0}313/1671-D from 05/09/2019.