TRT DIAGNOSTIC AND PLASMA CONTROL COMPLEXES CONCEPTUAL DESIGN ON THE BASE AND WITH DRIVE OF THE ITER FUSION TECHNOLOGY DEVELOPMENT IN RUSSIA

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Russia's responsibilities and cooperation within the ITER Project

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JSC TVEL
Bochvar Inst
JSC "CMP"
JSC VNIIKP
Kurchatov Inst

TF Nb_3Sn (19,3%*) and PF NbTi (20%) Conductors

Efremov Inst

SN, FDU, DC Busbar & Instrumentation (100%)

JSC "GCMP"

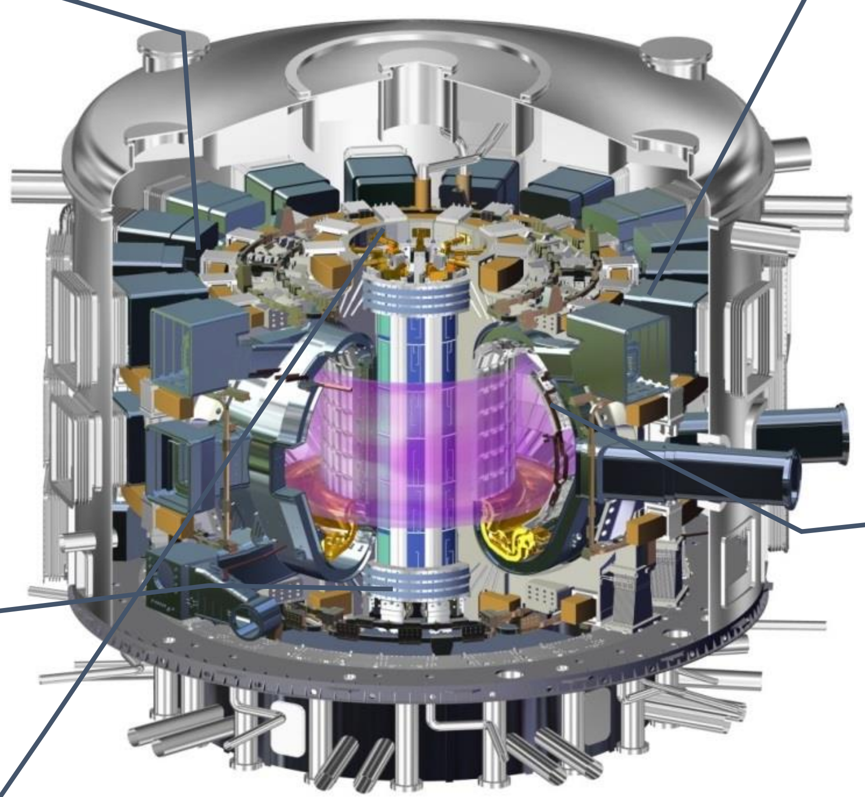
Port Plug Test Facility (100%)

Efremov Inst

Dome (100%) and Plasma Facing Component Tests (100%)

Efremov Inst
JSC "SNSZ"

Poloidal Field Magnet № 1 (100%)



23 (+6) ITER systems (9,09 % of the machine construction cost)

Upper Ports (100%)

Efremov Inst

170 GHz EC Gyrotrons (33%)

IAP RAS
JSC Gycom

Seven (+6) Diagnostic systems for plasma parameters investigation and control

Lower Port Plug (08), Upper Port Plug (02, 07, 08) and Equatorial Port Plug (11) (25%)

ITER-Center
Fusion Center
Kurchatov Inst
JSC VNIIA
JSC NIITFA
JSC "Luch"
Ioffe inst
Budker Inst
SRC TRINITI

Blanket First Wall (40%), Blanket Module Connections (100%)

Efremov Inst
Dollezhal Inst
JSC PSZ

Over 30 major Russian research institutions and industries participate in developing and fabricating ITER components

8 major Russian universities educate students and postgraduate students for the ITER Project

First Wall plasma facing material R&D

Due to change of the first wall material from Be to W RF DA organized cooperation of Russian institutions [3] (Lavrentyev Institute of hydrodynamics SB RAS, “Budker institute SB RAS, JSC “Efremov institute” JSC “TRINITI”, MEPhI) for development and study of the **B_4C coating (50-1000 μm) on W** first wall prototypes (water and passively cooled) for use in the ITER first wall conditions.

Other plasma facing coatings (**TiB_2, BN, SiC, etc**) are also under studies for TRT

Research of the properties important for use in ITER (adhesion, sputtering, redeposition, etc.) are started in the number of irradiation installations, including:

- **Tsefei-M up to 60kV, 2.5GW/m^2 electron beam** facility in **Efremov institute**,
- **QSPG plasma gun (0.2-3.0 ms, v = (1-3)*10^5 m/s, density= 10^{22}-10^{23} m^{-3})** in **JSC TRINITI**
- **laboratories** in **MEPhI**
- **material studies installations** in **Budker institute**

TRT missions and design

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The missions of the

high magnetic field (B=6-8T),

high temperature superconducting (HTS, REBCO),

compact (R=2.15m), classical (R/a=3.8),

quasi-stationary (>100sec) **TRT** (T > 10 keV, n ~ 10^{14} cm^{-3}) [4] are to provide:

- development of **quasi-stationary discharge scenarios** in a plasma with reactor relevant characteristics (maintaining the quasi-stationary current, temperature, density profiles of the main plasma, optimization of the plasma parameter profiles on its periphery for diminishing the plasma-wall interaction, including mitigation of the ELM instabilities, optimization of the divertor operation, disruption mitigation technologies development, etc.);
- development of the **quasi-stationary noninductive current drive technologies**;
- **plasma technologies and materials development** for effective first wall and divertor operation;
- development of the **integrated methods of plasma control**.

Conceptual designs of the TRT diagnostic and plasma control complexes were developed in 2021-2024 (see special issues of Plasma Physics Report Vol.48, No.8 and No12, 2022 and Vol.50, No.4, 2024 and [4-6], respectively).

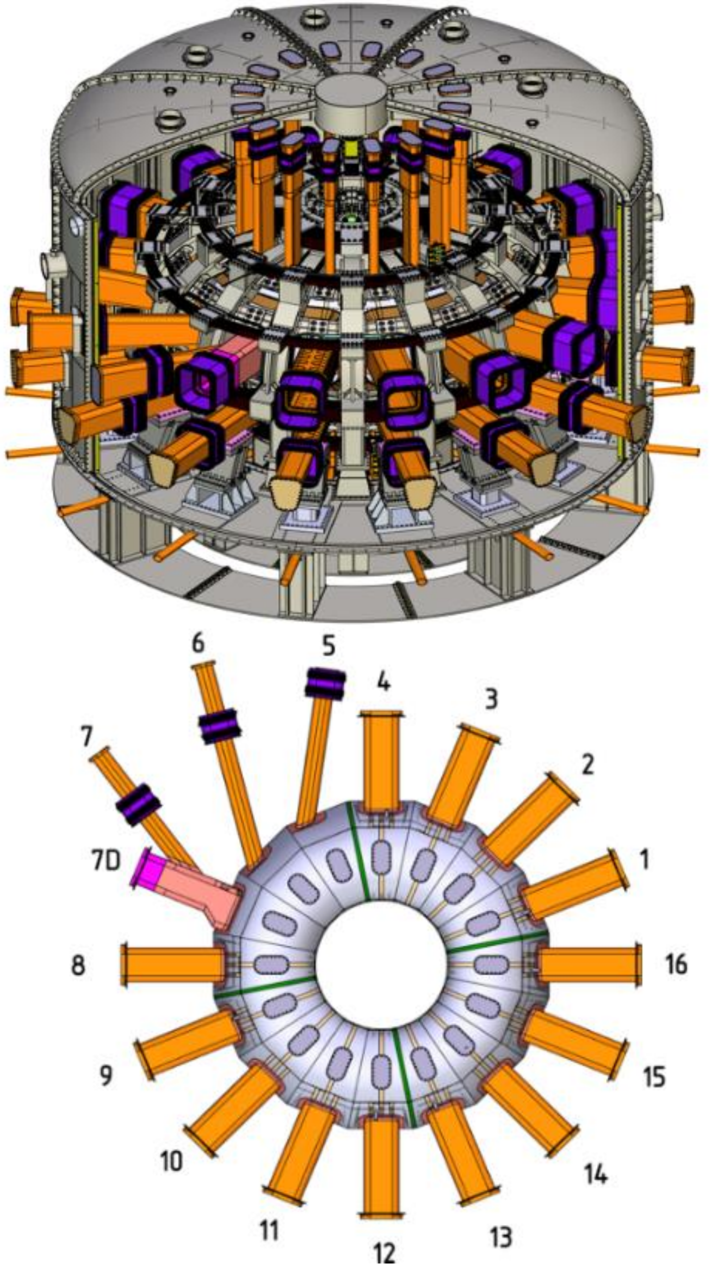


FIG. 1. TRT conceptual design with port numeration for diagnostic and plasma control systems distribution.

TRT technological platform *and cooperation*

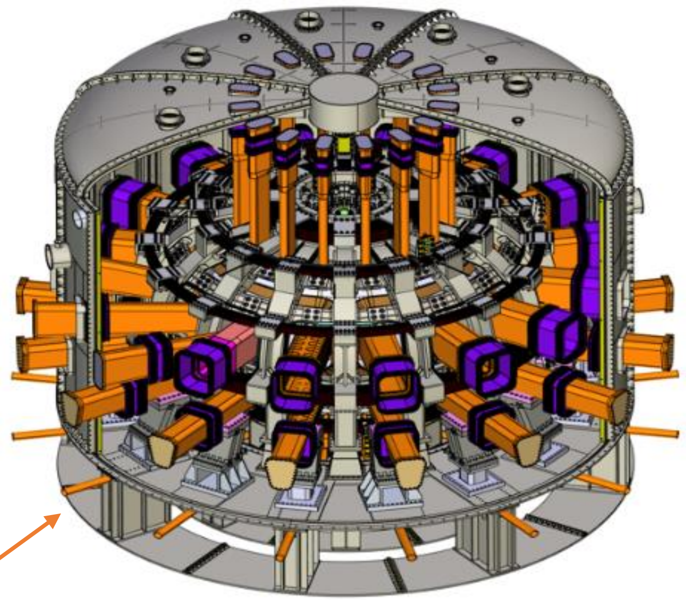
HTS EMS, and so High (6-8T) magnetic field
SuperOкs, Kurchatov inst, TRINITI, Efremov inst

Metal covered by B_4C and Li first wall
Efremov inst, ITER-Center, TRINITI, Budker inst, Inst Gydrodinemic, ITAM, MePHI, Dollezhall inst.

Innovative NBI with energy 0.5 MeV and total power ~20 MW
Budker inst.

Correction coils, fiders, power supply systems etc.
TRINITI, Efremov inst.

230 GHz gyrotrons of 1 MW each (t > 100 s)
IAP RAS, JSC Gycom



Components of experimental brider and hybrid blanket modules
Dollezhall inst., Efremov inst.

Innovative 5 MW ICRH at 45-80 MHz and current drive by few MW Helicons and Low hybrid
Ioffe inst., Efremov inst.

Tritium complex
TRINITI

Innovative divertor
Efremov inst.

Remote control technologies
Kurchatov inst., ITER-Center, TRINITI

Reactor–relevant diagnostics
ITER-Center, Kurchatov inst., TRINITI, Budker inst., Ioffe inst., IAP RAS

Quasi-stationary current driving technologies
Kurchatov inst., TRINITI, Budker inst., Ioffe inst., IAP RAS

Joint information technology platform arrangement [28] is creating to provide the remote design and remote participation in fusion researches in Russia

Auxiliary heating and current drive TRT systems

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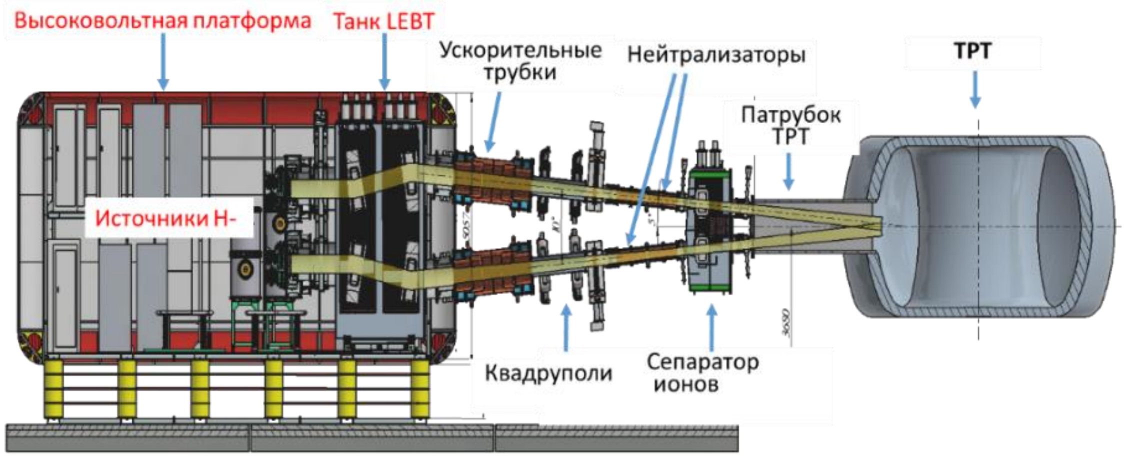


500 keV D- NBI at TRT (Budker institute)

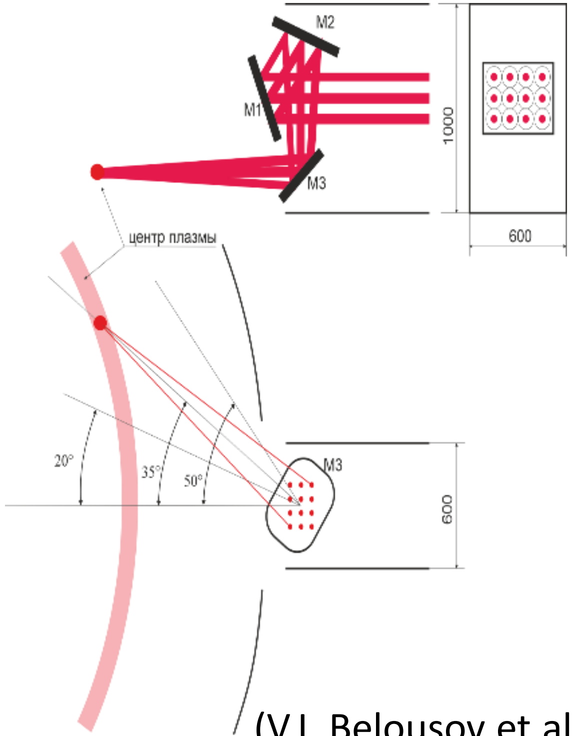
~ 7 MW (H) or ~ 5.7 MW (D) to each of three ports.
(Yu.I. Belchenko et.al. : Plasma Phys. Reports №11, 2021)

Injector innovations:

- **Ion source and acxellerator axis**
- **Plasma and photon neutrallizer**
- **Energy recuperation for efficiency 80%.**

ICRH (~5 MW at frequency 45-80 MHz)
and few MW helicon current drive at 1-1.2 GHz
(V.L. Vdovin, D-IIID, KSTAR, T-15MD)
and 5 MW 4.6 GHz low hybrid CD

ECRH: 10MW, >100 s, 230GHz
~12 gyrotrons – IAP RAS



(V.I. Belousov et.al..: Plasma Phys. Reports №12, 2021)

Unique auxiliary heating system complex will provide
self-consistent control of plasma profiles including $I_p(r)$

2. TRT RESEARCH PROGRAM (2)

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TRT research program is aimed at **development, studies and further development** of :

- the quasi-stationary discharge scenarios in a reactor relevant plasma simultaneously providing safe stationary plasma – wall (divertor) interaction and non-inductive CD with robust plasma control.
- Synergetic use of powerful heating/CD (NBI, ECRH, ICRH, helicons/LHCD), plasma fueling and magnetic control systems to provide a wide range of the algorithms for effective and robust plasma control.
- Disruption mitigation and ELM control technologies.
- Usage of the Be or covered by B_4C W or liquid Li first wall components are under experimental analysis now.
- Several advanced divertor designs.

Fast ion behavior in plasma with fusion characteristics will be important part of the program. High magnetic field, ~20 MW, 500 keV deuterium and hydrogen injection in combination with ICRH (minority and three ion schemes) and ECRH are providing relatively unique possibility to study at TRT the not only DD and trace tritium DT fusion but also the **efficiency of fusion in the number others fuel mixtures such as: p+^{9}Be (2% in plasma), p+^{11}B (2%), D+^{6}Li (0.2%), D+^{9}Be (2%), D+^{11}B (2%), and especially D+^{3}He (0.1-10%) and D+^{7}Li (1.8%) = n+^{4}He+^{4}He (σ=2*10^{-1} b at 200 keV, Q=15.1 MeV).**

Essential part of the program will be **technological studies of breading and hybrid blanket components behavior**.

2. TRT RESEARCH PROGRAM (stage approach)

According to current plans **the initial phase of research program (6-10 years) consists of six stages**:

1) integrated commissioning with plasma,
2) short discharges with maximum magnetic energy, with first wall inertial cooling, limiters and disruption mitigation system,
3) long pulses of plasma with reactor parameters with low-Z covered plasma facing components,
4) Li technologies for first wall and advanced divertor,
5) experiments with trace tritium,
6) full size technological experimental program for pure and hybrid reactor. Strong cooperation in domestic experiments is expected with ITER partners and especially with BEST project.

3. CURRENT STATUS OF TRT DIAGNOSTIC COMPLEX

- The TRT diagnostic complex is being developed [7] to provide: plasma characteristics measurements and generation the required signals for plasma and machine controls to meet TRT missions [4] and research program [8] during long quasi-stationary discharges.

- Based on the **TRT 3D model** (shown in Fig.1), the **Open - MC** neutron transport calculations were performed [9] for model with TRT related material containment.

  The results of DT neutron flux distribution in TRT horizontal and vertical cross sections calculated for nominal ($n=10^{14}$ cm^{-3}, T=10 keV) TRT 50%D + 50%T plasma parameters are shown in Fig.2.

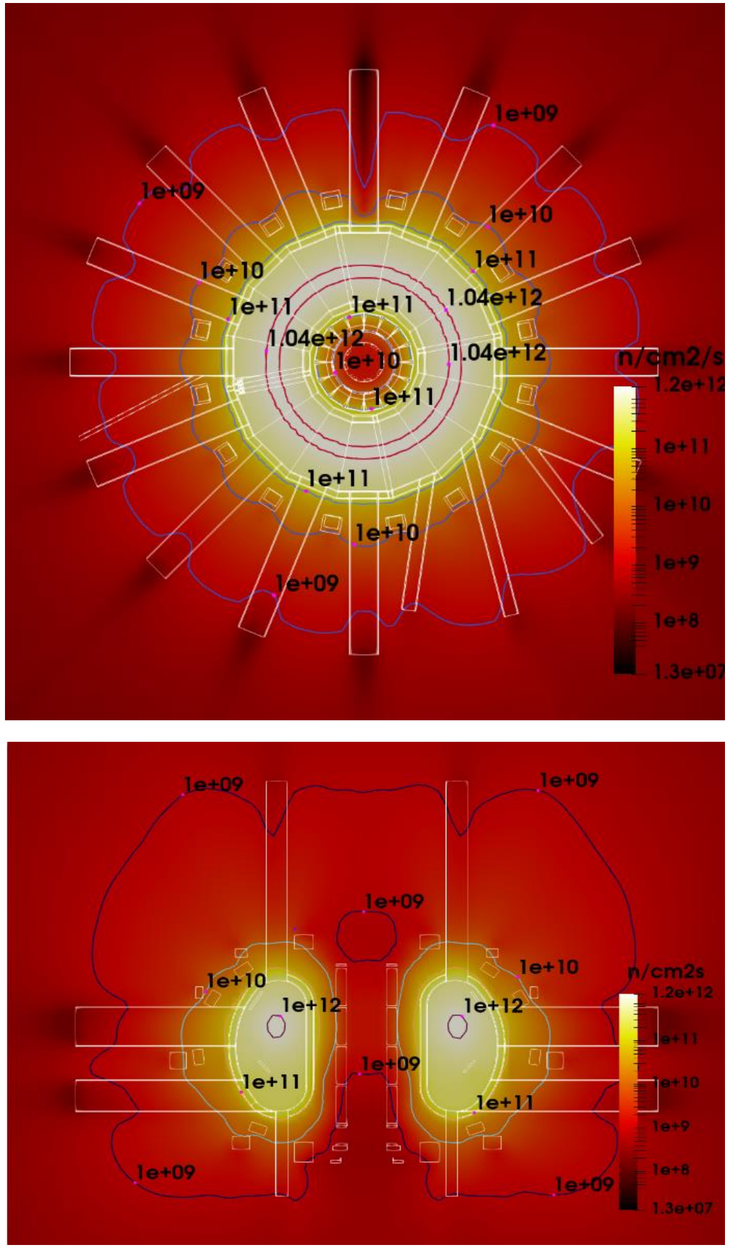

FIG.2. DT neutron flux distribution in TRT horizontal and vertical cross sections calculated for nominal ($n=10^{14}$ cm^{-3}, T=10 keV)TRT 50%D+50%T plasma parameters.

3. CURRENT STATUS OF TRT DIAGNOSTIC COMPLEX (ITER experience)

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Russian scientific centers are responsible for development and manufacture of **7 (+6) diagnostic complexes, 5 port plugs and 4 Port plug test facilities** for ITER.

RF ITER diagnostic complexes are:

- Neutral particle analyzers (**Low energy NPA, High energy NPA**,); **Diamond fast charge exchange atom spectrometer, diamond and scintillator neutron spectrometers and ©-ray spectrometer);**
- **Thompson scattering system** with interfaces for **Laser induced fluorescence**;
- **high field side reflectometry** and **refractometry**;
- **H_{α}(and impurity) - spectroscopy**,
- **Charge exchange resonance spectroscopy**,
- **vertical neutron camera with U-238 fission chamber counters and diamond compact spectrometers**,
- **Divertor neutron flux monitors with the numbers of U-235 and U-238 fission chambers.**

3. CURRENT STATUS OF TRT DIAGNOSTIC COMPLEX
(DNFM and diamond neutron and fast atom spectrometers experience)

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- Designs of ITER DNFM with two units containing three U-235 and three U-238 of various sensitivities are shown in Fig.3. Fission chambers were specifically designed for the harsh conditions and wide range of ITER fusion power measurements from 100 kW up to 700 MW with time resolution of up to 1 ms and with high (~99.9%) availability target for ITER scenarios control with maximum fusion power.
- The prototypes of developed for use in Vertical neutron camera and NPA collimator in equatorial port 11 compact CVD diamond neutron and fast atom spectrometers are shown in Fig.4 and 5. The results of energy calibrations of the fast atom CVD diamond spectrometer before its successful application in the EAST experiments are shown in 5.

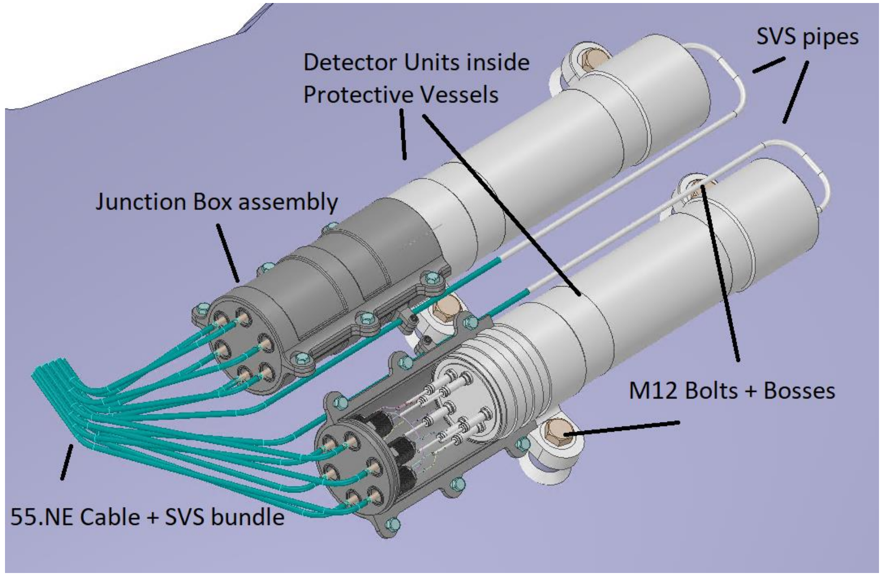

FIG.3. ITER Divertor neutron flux monitor. design.

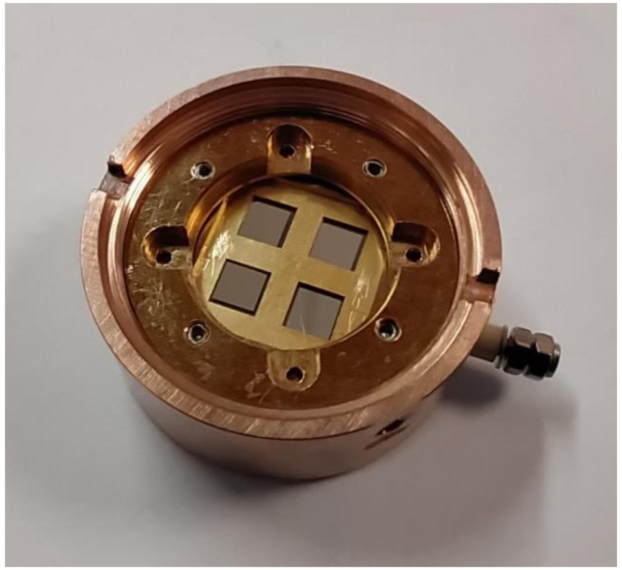

FIG.4. Prototype of ITER fast atom and neutron spectrometer with 4 CVD diamonds

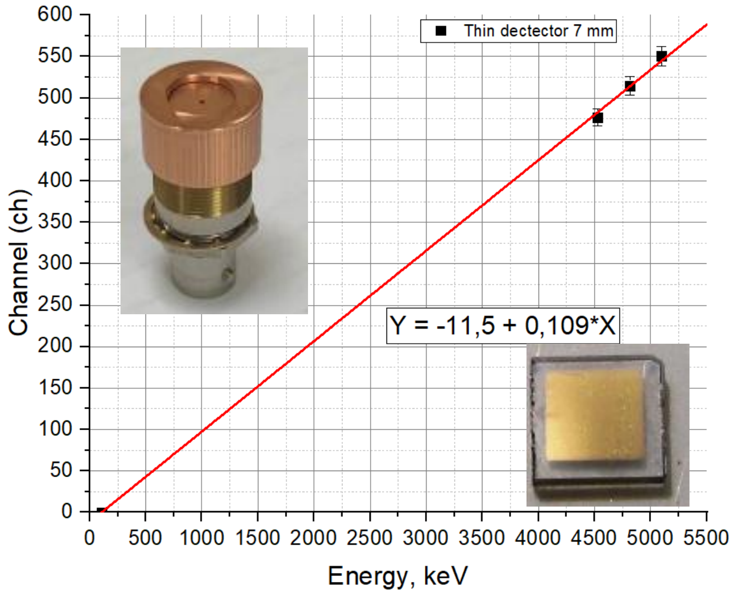

FIG.5. Results of CVD diamond detector (in inserts) fast atom energy calibration

3. CURRENT STATUS OF TRT DIAGNOSTIC COMPLEX
(CVD diamonds synthesis for Compact spectrometer)

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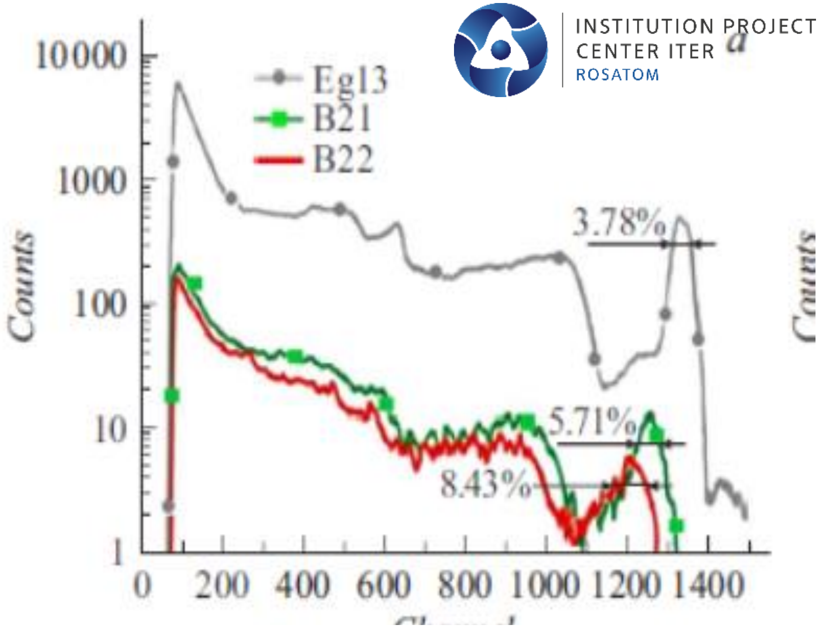
- CVD diamond for detectors **have being grown in Project center ITER** on Boron doped high pressure high temperature diamond in microwave plasma reactor ARDIS-300. Back contact is substrate of B-doped HPHT diamond and front contact was made of Ti as shown in Fig.5 insert.

- **Highest purity and crystal quality** of the growing CVD diamond provide:
  detector charge collection efficiency 97% and 97%, and energy resolution <3% and 0.8% under 14.7 MeV neutron and 5.5 MeV alpha-particle irradiation, correspondingly, as shown in Fig.6.



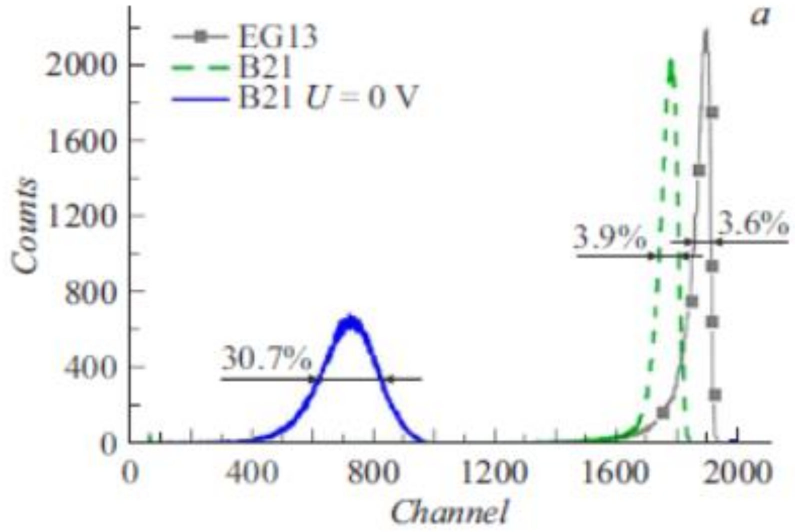


FIG.6. Pulse height spectra of two CVD diamond detectors (B21 and B22) in flux of 14.7 neutron (left) and 5.5 MeV ^{241}Am alpha-source in atmosphere (right) shown in comparison with "Element-6" etalon CVD detector (Eg13).

3. CURRENT STATUS OF TRT DIAGNOSTIC COMPLEX

The allocation (option 1) of the preliminary designed TRT diagnostic complex [10] currently containing **30 diagnostic systems** shown in Table 1.

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- Equipment of the Electromagnetic diagnostics is placed in many ports. Disruption mitigation system, Pellet injectors, Helicons, lost ion probe, divertor and technological diagnostics are still under consideration.

TABLE 1. STATUS OF DIAGNOSTIC [10] AND PLASMA CONTROL SYSTEMS ALLOCATION IN TRT PORTS*.

Port	Equatorial	Upper	Divertor
1	Multichannel neutron collimator [11], Neutron flux monitors [12], Neutr. activation syst, Hard x-ray monitor, g-ray spectrometers and collimators [13]		
2	Test blanket modules		
3	ICRH system [4, 14]		
4	Test blanket modules	Reflectometer, Refractometer	
5	NBI heating and current drive [5]		
6	NBI heating and current drive, Diamond fast atom spectrometers [15]		
7	NBI heating and current drive Diagnostic NBI (port 7D) [16]	CXRS, NPA, Diamond fast atom spectrum.	
8	CXRS [17], MSE [18], BES, Z_{eff}, Laser for Thompson scattering [19], Tangential NPA [20]		
9	Thompson scattering, BES, H_a-monitor, Impurity lines spectrometer, IR-thermography, first wall diagnostic		
10			
11	ICRH system		
12	Reflectometer [21], MSE, EC-emission measurements	IR-divertor thermography, Reflectometer	
13	TS laser dump, TS in divertor, H_a-monitor, Fast video-range camera, Neutron flux monit, Neutron active. syst.		
14	Radiation (bolometry, SXR, XUV) tomography, NPA, Hard X-ray monitor	Radiation tomography, refractometer	Radiation tomography
15		Reflectometer	
16	ECRH system [6]		TS in divert.

3. CURRENT STATUS OF TRT DIAGNOSTIC COMPLEX (allocation based on DNBI diagnostics)

The number of measurements of crucial for plasma control profiles of TRT characteristics ($T_i(r)$, v_i (r), $J(r)$, $Z_{eff}(r)$, etc.) will be done by **CXRS, MSE, BES and NPA** diagnostics using **60-80 keV Diagnostic neutral beam injector** which will be allocated in equatorial perpendicular port 7D. Allocation of these systems on TRT is presented in Fig.7.

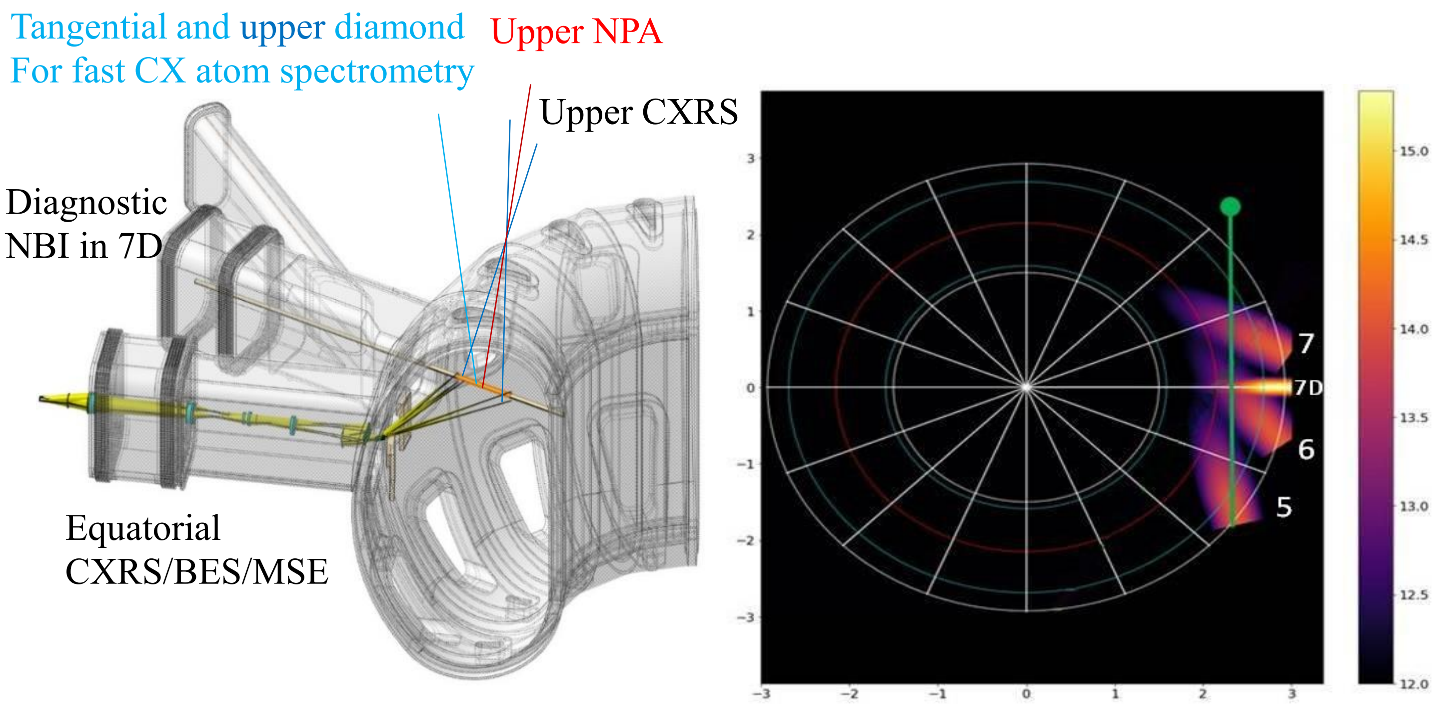
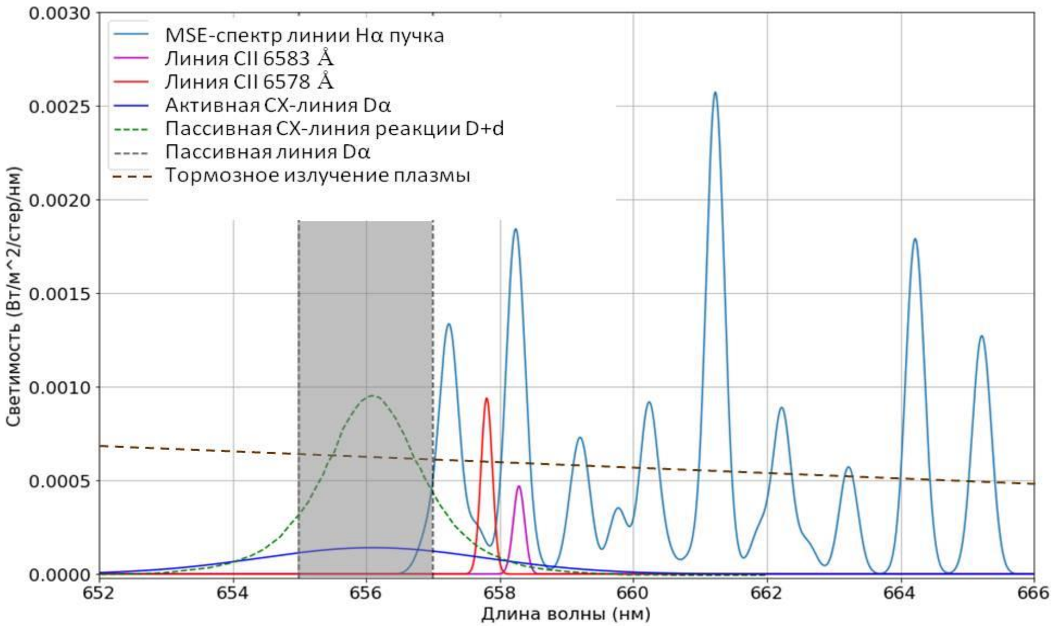


FIG.7. Left: Allocation of Diagnostic NBI in equatorial port 7D, CXRS in equatorial and upper ports, tangential in port 7 and vertical (upper port 8) Diamond fast ion spectrometers and vertical NPA in upper port 8.
Right: Results of NBI and DNBI atom density calculation in TRT plasma equatorial cross section and CXRS/BES/MSE line of sight from equat. port 8.



MSE-lines H_α DNB for E_0 =100 keV (light blue line) in port №8 + CXRS line D_α (blue line), passive D_α (gray box), passive charge exchange d_0+d (green dot line), C^{1+} lines (red & rose), bremstr. (brown dot line) for n_e=2·10^{19} m^{-3}.

3. CURRENT STATUS OF TRT DIAGNOSTIC COMPLEX.

(Example of Radial Neutron Camera integration (1 option))

The integration of the Multichannel neutron collimator inside the TRT equatorial port 1 (first option) with results of the neutron flux density calculation inside collimator and in its detectors positions are presented in Fig.8.

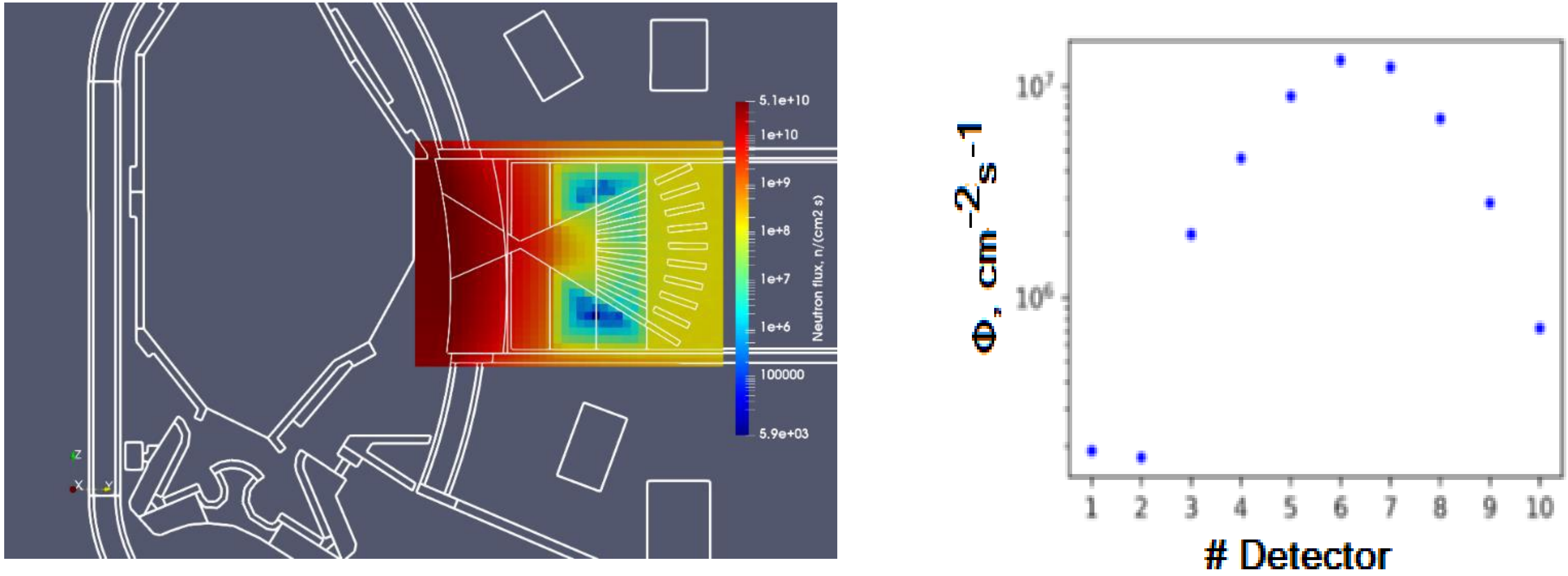
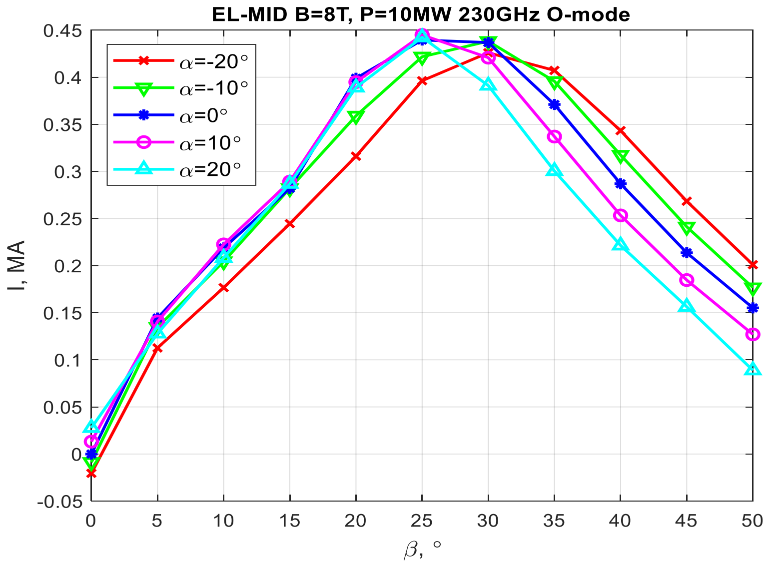


FIG.8. Results of neutron flux density calculation inside (left) of integrated in TRT equatorial port 1 multichannel neutron collimator and in its detector position (right).

The most challenging requirement to all diagnostics is operation during long quasi-stationary TRT discharges with corresponding data acquisition systems, time and spatial resolutions required for plasma control.

4. TRT PLASMA CONTROL COMPLEXES CONCEPTUAL DESIGN

- The most powerful and efficient control tool will be be the six 500 keV NBIs (D/H) with total power 20 MW. Injection angle will not be changeable ($R_{inj}=R_0$-a/2) and plasma kinetic control will be provided by changing of the beam energy and power and synergism with ICRF waves, ECRH, pellet injection, etc. Optimal current drive will be reached in density range 0.5-1*10^{14} cm^{-3}
- ECRH system containing ten-twelve 1 MW long pulse gyrotrons with frequency 230 GHz (specially being developed for TRT 8 Tesla magnetic field). Efficiency of ECRF wave system for current drive in TRT upon the injection angel and ECRH power is shown in Fig.9.



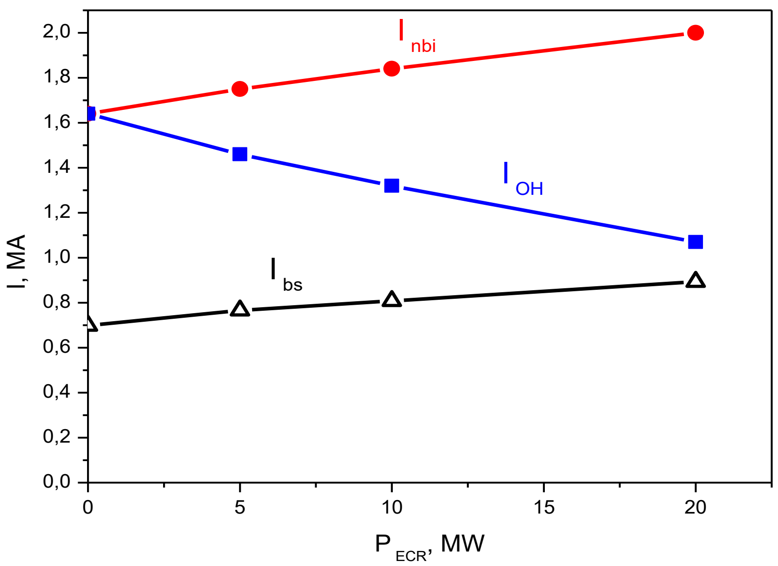


FIG.9. a) Value of ECRF wave driven current at P_{ECRH}=10 MW, B_t = 8T, 230 GHz, depending upon injection angles (α – with respect to equatorial plane, β_t^0– with respect to perpendicular direction in equatorial plane, b) plasma currents upon P_{ECRH} (fixed wide ECRF wave absorption profile at ρ~0.4, P_{NBI}= 20 MW)

For better profile control two independently rotating mirrors (for 5 and 5 MW) are considered for application in TRT

Important that two major TRT heating methods provide strong synergetic tools not only for heating and current drive total efficiency and profile control but also for the bootstrap current value and its profile control altogether with plasma fueling methods and in particular fueling pellet injection.

4. TRT PLASMA CONTROL COMPLEXES CONCEPTUAL DESIGN

(NBI & ICRF heating and CD synergism, Helicon and LH current drive)

- Application of ICRF wave heating and current drive in frequency range 45-80 MHz with power up to 5 MW is planned at TRT.

  Two multi strip ICRH antennas currently allocated in equatorial ports 3 and 11.

  Special interest will be devoted to experimental studies of the possibility to increase fusion rates in ICRH + D^+ NBI into deuterium plasma discharges with $^3He^{2+}$ and wall impurity minorities ($^9Be^{4+}$, $^7Li^{3+}$, $^{11}B^{5+}$) exploring minority, and three ion scheme mechanisms.

- Off-axial generation of noninductive plasma current is planning by

  - few MW helicon waves with frequency 1000 - 1200 MHz and
  - 4.6 GHz low hybrid waves are also under consideration (up to 1 MA LHCD at RF power of 6 MW is predicted).

4. TRT PLASMA CONTROL COMPLEXES CONCEPTUAL DESIGN
(Plasma – FW interaction, disruption mitigation)

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- Three+ options of the first wall: Beryllium, covered by low Z material (B_4C) Tungsten and liquid Lithium are under analysis for TRT.

- Several advanced divertor options are under planning for studies.

  - Start operation with ITER-like Tungsten divertor with neon gas puffing.

  The broad enough parameter space of ITER-like TRT divertor operation exists for plasma current of the order of 4 MA.

  - In addition to neon gas puffing the possibility of the separatrix swiping is also included into the TRT preliminary project.

  - The corner divertor with neon gas puffing is the another TRT divertor option. SOLPS-ITER calculations demonstrate possibility to diminish ion and electron temperature at separatrix down to 1 eV having Z_{eff} ~ 2.4 by 10^{19} s^{-1} neon gas puffing that simplify transfer to detachment regime.

- For disruption mitigation at TRT it is planned to apply the low-Z impurity injection, preferably from first wall material (Be, B).

5. SUMMARY

- TRT Research program focused on:

- achieving and optimizing of the quasi-stationary (>100 s) fusion reactor relevant plasma regimes with the development of quasi-stationary noninductive current drive and bootstrap current formation,

- development of technologies for optimization of stationary plasma - wall interaction and advanced divertor operation.

- Fusion efficiency of the number fuel mixtures will be studied in experiments with combination of NBI, ICRH & ECRH.
- Operation of pure fusion tritium breading and hybrid, fusion-fission, experimental blanket modules will be studied.

- Preliminary design and first option of port allocation of ~30 TRT diagnostic systems were performed.

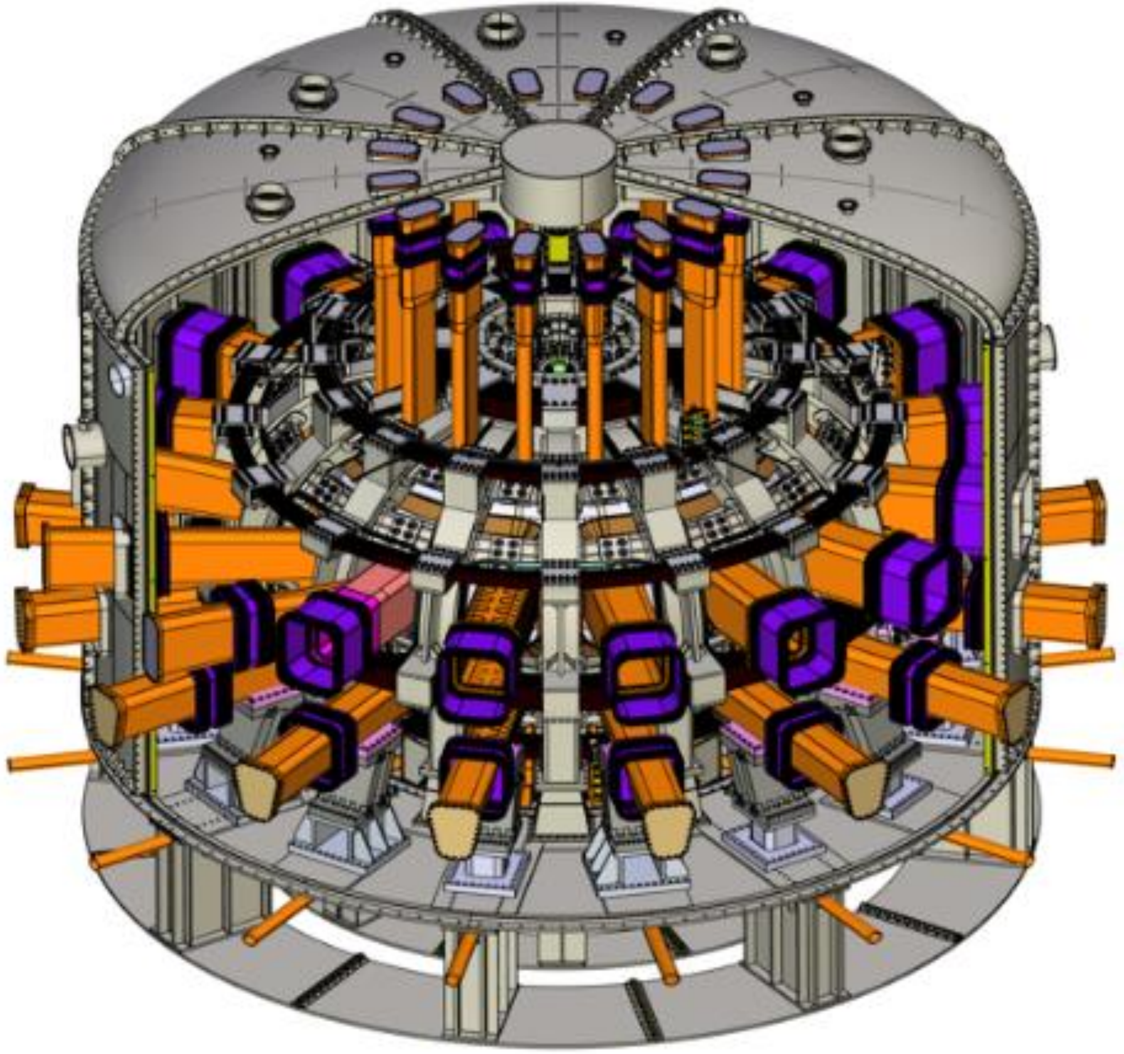
- Developed during conceptual and preliminary design the TRT plasma control complex includes:

- Six heating and current drive 500keV deuterium / hydrogen neutral beam injectors of total power ~20 MW,
- ECRF wave heating and current drive complex on the base of twelve 230/170 GHz gyrotrons,
- ICRF wave heating and current drive complex operating with two antennas in frequency range 45-80 MHz,
- Helicon or low hybrid wave off-axis current drive system,
- ELM pace making and mitigation pellet injection system,
- Disruption mitigation system, based on low-Z (Be, B) impurity injection,
- Options of advanced divertor with neon gas puffing and separatrix swiping.

- TRT Research program is open for close cooperation with the ITER Project and with ITER partners domestic experiment.

Thank you

for Your attention



REFERENCES

- [1] Sakharov A.D. and Tamm I.E. Private communication (1950).
- [2] Krasilnikov A.V., Abdyuhanov I.M., Aleksandrov E.V., et. al., Nuclear Fusion 55, 104007 (2015)
- https://doi.org/10.1088/0029-5515/55/10/104007.
- [3] Cherepanov D.E., Burdakov A.V., Vyacheslavov L.N., et. al., Physics of Atomic Nucleai , v.87, p.S99 (2025).
- [4] Krasilnikov A.V., Konovalov S.V., Bondarchuk E.N., et. al., Plas. Phys. Rep. 47, 1092 (2021).
- [5] Belchenko Yu.I., Burdakov A.V., Davydenko V.I., et.al., Phys. Rep. 47, 1151 (2021).
- [6] Belousov V.I., Denisov G.G., Shmelev M.Yu., Plas. Phys. Rep. 47, 1158 (2021).
- [7] Kashchuk Yu.A., Konovalov S.V., Krasilnikov A.V., Plas. Phys. Rep. 48, 1339 (2022).
- [8] Leonov V.M., Konovalov S.V., Zhogolev V.E., et.al., Phys. Rep. 47, 1107 (2021).
- [9] Portnov D.V., Vysokikh Yu.G., Kashchuk Yu.A., Rodionov R.N. Plasma Physics Reports, Vol.47, 1285 (2021).
- [10] TRT Diagnostic complex published by 29 papers in special issues of Plas. Phys. Rep. 48, n.8, 12 (2022) and 50, n.4 (2024).
- [11] Nemtsev G.T., Rodionov R.N., Khafizov R.R., et.al., Plas. Phys. Rep. 48, 1345 (2022).
- [12] Kormilitsyn T.M., Kashchuk Yu.A., Rodionov R.N., et.al., Plas. Phys. Rep. 48, 1352 (2022).
- [13] Shevelev A.E., Khilkevitch E.M., Bakharev N.N., et.al., Plas. Phys. Rep. 48, 1369 (2022).
- [14] Baev V.M., Getman D.V., Gubin A.M., and Subbotin M.L., Plas. Phys. Rep. 47, 1169 (2021).
- [15] Artem’ev K.K., Krasilnikov A.V., Kormilitsyn T.M.and Rodionov N.B., Plas. Phys. Rep. 48, 1360 (2022).
- [16] Davydenko V.I., Ivanov A.A., and Stupishin N.V., Plas. Phys. Rep. 48, 838 (2022).
- [17] Serov S.V., Tugarinov S.N., Serov V.V., et. al., Plas. Phys. Rep. 48, 844 (2022).
- [18] Zemtsov I.A., Neverov V.S., Nemets A.R., et. al., Plas. Phys. Rep. 50, 470 (2022).
- [19] Mukhin E.E., Tolstyakov S.Yu., Kurskiev G.S., et. al., Plas. Phys. Rep. 50, 406 (2022).
- [20] Afanasyev V.I., Melnik A.D., Mironov M.I., et. al., Plas. Phys. Rep. 50, 524 (2022).
- [21] Vershkov V.A., Petrov V.G., Subbotin G.F., et. al., Plas. Phys. Rep. 48, 875 (2022).
- [22] Mazul I.V., Giniyatulin R.N., Kavin A.A., et. al., Plas. Phys. Rep. 47, 1220 (2021).
- [23] Putrik A.B., Krasilnikov A.V., Titishov K.B., et. al., IAEA Fusion Energy Conference, TEC-MLT, (2025).
- [24] Vertkov A.V., Zarkov M.Yu., Lyublinskii et.al., Plas. Phys. Rep. 47, 1245 (2021).
- [25] Buzhinskij O.I., Otroschenko V., Barsuk V., J. Nucl. Mater. v.390-391, p.996 (2009).
- [26] Kukushkin A.S., Pshenov A.A., Plas. Phys. Rep. 47, 1238 (2021).
- [27] Molchanov P.F., Kudrevatykh P.S., Shtyrkhunov N.V., at.al. Plas. Phys. Rep. 50, 1461 (2025).
- [28] Portone, S.S., Mironova, E.Y., Semenov, O.I. *et al.* Phys. Atom. Nuclei **86** (Suppl 1), S24–S32 (2023).
- https://doi.org/10.1134/S1063778823130082