ENGINEERING-PHYSICAL TOKAMAK T-15MD AND STEADY-STATE INJECTION

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This paper presents the main parameters and design of proposed T-15MD tokamak. The installation is meant for demonstration of the tokamak two-component operating mode and for steady state operation problems-solving with a plasma current drive (CD) at a level of about 1 MA. Injection of hydrogen neutral beams with a power up to 8 MW is chosen as the main method for non-inductive CD. For an electron temperature increase it is supposed to use ECH power up to 6 MW at a frequency of 110 GHz. Parameters of an ion source IVIS KS with a power of 3 MW which is under development for the T-15MD and the main characteristics of the NB injectors are described. Results of preliminary calculations of the tokamak plasma parameters are presented.

As a result of teamwork of researchers from different countries the direction of movement to construction of a power thermonuclear reactor is chosen now. The Russian Federation, being the active participant of international project ITER, is interested in expansion of base of experimental works on controlled thermonuclear fusion (CTF).

The accelerated development of world nuclear power engineering intensifies problems of its raw maintenance and recycling of wastes. Attraction to the decision of these problems of the controlled thermonuclear fusion is one of the opportunities actively discussed today by foreign and Russian experts. Introduction of CTF in nuclear power is possible by its inclusions in a cycle of nuclear fuel production ("breeding") for traditional nuclear power, and also by "reburning" its wastes - minor actinides. Both directions become technically possible, if into a contour of fast (14 MeV) neutrons utilization ("blanket") of the CTF reactor to enter fissible materials, that is to use the CTF reactor as a thermonuclear source of neutrons (TSN or a "hybrid reactor"). In that way the important step to practical application of CTF can be done.

For expansion of research subjects in support of nuclear and thermonuclear power, in Russia it is necessary to have compact tokamak with a flexible ITER-like configuration of a magnetic field, with extended ($k \leq 2$) divertor plasma, with an ability to control the shape and parameters of a plasma in real time. Installation should be equipped by a complex of additional plasma heating and current drive (P_{aux} 10-15 MW), providing simultaneous achievement of high plasma temperature ($T_i \sim T_e \sim$ 5-9 keV) and density ($n_e \sim 10^{20}$ m^{-3}), and also allowing to control plasma profiles at full non-inductive current drive. Reliable realization of such operating modes is the primary goal of the offered project - Engineering-Physical Tokamak (EPT - T-15MD) [1].

Based on a level of possible financing and available resources, T-15MD will be the installation of a modern level constructed within the nearest 5-6 years. Such project can become the center of researches in Russia under program of CTF on the basis of tokamaks, uniting scientific and technical potential of various collectives of the country and providing a wide spectrum of researches within 10 years.

Program T-15MD includes studying possible ways of economic efficiency increase of a thermonuclear reactor, including its work in the two-component mode necessary for TSN. The wide program of works in modes with the improved parameters of plasma (raised times of energy and particles confinement and high β_N) and demonstration of a stationary mode ($t > t_{skin}$) of the plasma discharge is considered.

The discharge start and the plasma current rise will be carried out by standard induction way, by means of magnetic reversal of the central solenoid. After achievement of the current nominal value (or even a little bit earlier) transition to non-inductive current drive should be provided. Quasi-stationary regime is necessary and is the major from the point of view of transition to large-scale thermonuclear power. In case of T-15MD it corresponds to pulse duration of 5-10 s at a level of the plasma current ~1 MA and requires application of powerful systems of the plasma heating and current drive, and also divertor for removal of power entered into the plasma. Injection of fast hydrogen atoms with energy 75 keV and ECR heating at frequency 110 GHz are chosen.

Experimental program T-15MD will cover a wide range of researches on CTF including the following problems:

- Achievement of high values of β_N at simultaneous maintenance of the plasma high density and temperature as a way to cost reduction of the CTR.
- Realization of the improved plasma confinement regimes with internal and external transport barriers.
- Investigation of realization ability of modes with high values of β and n_e in steady state discharges with completely non-inductive plasma current.
- Divertor optimization and investigation of peripheral plasma influence of on global characteristics of the plasma discharge.
- The real time control over stability, equilibrium, heating and confinement of the high-temperature plasma.
- Investigation of the plasma interaction with various materials, including graphite, tungsten and lithium.

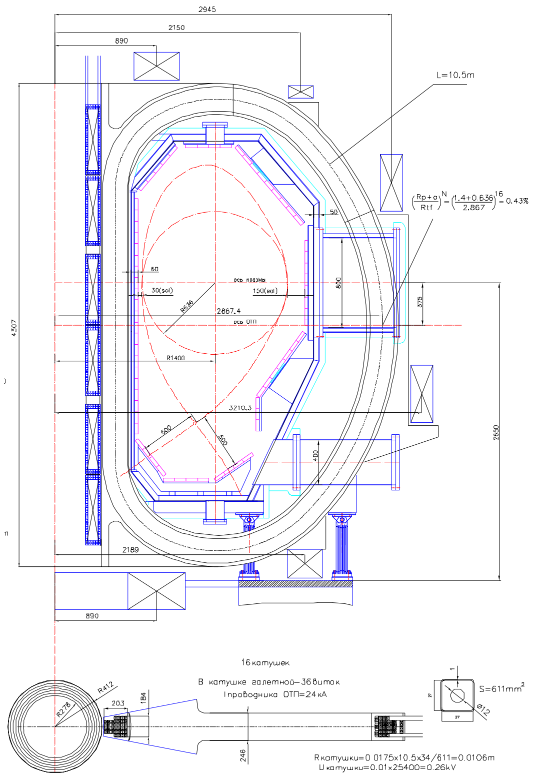

Fig.1. T-15MD configuration

Fig.1 presents one variant of T-15MD configuration. For today a final decisions on the exact design and sizes of the installation sub-assemblies aren't still made. However it is accepted, that the toroidal magnetic field on the vacuum chamber axis should be of 2 T, the plasma current should reach 2 MA. The tokamak major radius is chosen in interval R = 1.4-1.5 m, aspect ratio ~ 2.2, elongation ~ 1.8.

The main system for the plasma heating and current drive in T-15MD will be the neutral beam (NB) injection system with power up to 8 MW at particles energy 75-80 keV. The system consists of 4 injectors, each injector has two quasi-stationary hydrogen ion source IVIS-CS each with power of 3 MW in the ion beam. After the ion beam neutralization resulting beam of fast atoms will have 1 MW power, therefore each injector should provide neutral power input into the tokamak of 2 MW.

Preliminary calculations of achievable plasma parameters in a case of the NB injection heating and also for combined heating NB + ECR were performed. Some important results are shown in Figs.2-4.

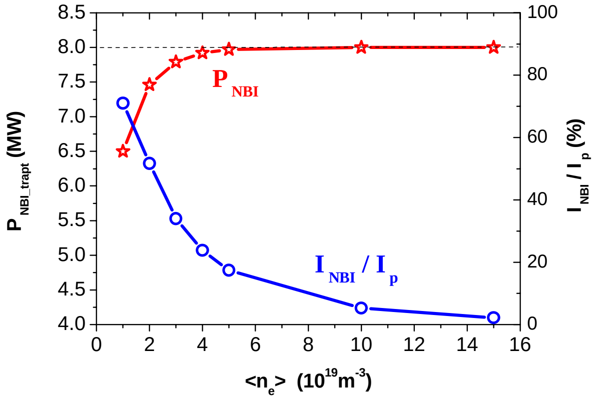

Fig.2. Dependence of absorbed by the plasma injected beam power and generated non-inductive current fraction on the average plasma density.

Fig.2 and Fig.3 presents the results for injection of 8 MW hydrogen atoms with energy 80 keV in hydrogen plasma in a case of toroidal field 2 T and the plasma current 2 MA.

From Fig.2 one can see that injected power is completely absorbed by the plasma at density above $5*10^{19}$ m^{-3}. The generated non-inductive current fraction decreases rather quickly with growth of the plasma density, however at density of $2*10^{19}$ m^{-3} it is at a level of 1 MA.

Distributions of the absorbed injection power over relative plasma radius for different average plasma densities (in units of 10^{19} m^{-3}) are shown in Fig.3. At moderate values of the average plasma density injected NB power is absorbed in internal areas of the plasma column and only when the plasma density exceeds

$10^{20}m^{-3}$, strong absorption of the beam power on the column periphery begins.

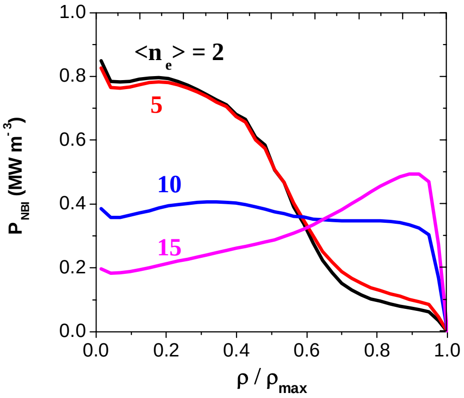

Fig.3. Distributions of the absorbed beam power over relative plasma column radius for different average plasma densities (in units of 10^{19} m^{-3})

Operational regimes with close to completely non-inductive plasma current created mainly due to NB injection and bootstrap-effect represent particular interest. In this case the long-pulse mode of T-15MD operation is possible, despite of not too big capacity of magnetic flux in an inductor.

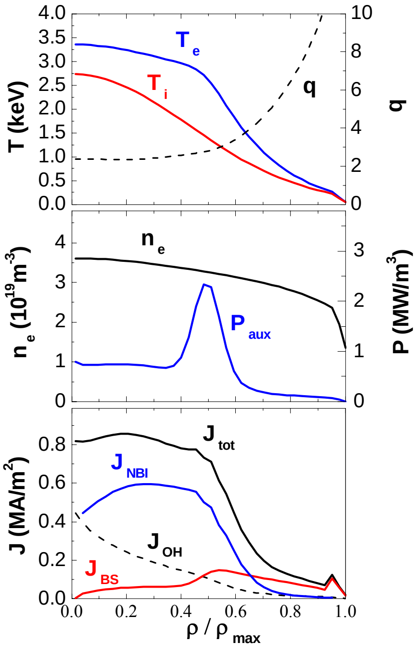

Fig.4. Plasma parameters profiles in the long-pulse mode of the T-15MD operation

One of variants of such mode is presented in Fig.4 where the plasma total current equal to 1 MA and the plasma average density at a level of $3*10^{19}$ m^{-3} are chosen at which the NB power absorption and current generation are still high. For increase of electron temperature and improvement of conditions for the plasma current generation by the beam, ECR power at a level of 7 MW is additionally entered approximately in the middle of the plasma column radius. The toroidal field, as well as in the previous calculations, is of 2 T.

In this mode the beam generated current fraction is I_{NB} ~ 60 %, the bootstrap current is I_{BS} ~ 22 %, the rest is an ohmic current which has maximum in the central part of the plasma column. In all column the plasma electron temperature is slightly above an ion temperature.

Installation T-15MD will use three existing injectors from installation T-15, described in work [2], and one more new. Series of ion sources IVIS with working parameters 60 kV/60 A/1 s (Fig.5) [3] had been prepared for work in the T-15 neutral beam injection system.

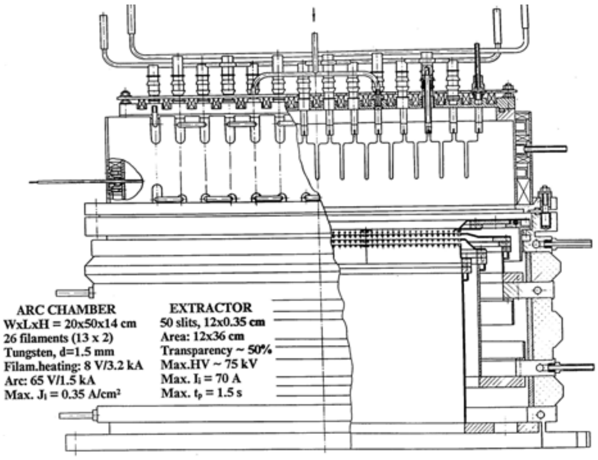

Fig.5. Ion source IVIS for T-15 injectors.

All NBI components, namely neutralizer, residual ions deflecting magnet, ion dump, and movable NB calorimeter, can work in steady-state regime when NB power of 3 MW is producing. The increase of injection pulse duration up to 10 s and more requires modernization of the ion source because of three principal causes:

- Use of DC heating of tungsten filament cathodes leads in a case of long-pulse operation to their overheat;
- Source arc chamber is made of stainless steel and its cooling was calculated for work with the pulse duration of no more than 5 s.
- Electrodes of ion-optical system (IOS) which provides extraction and formation of ion beam with small divergence angle at a level ±1÷1.5°

are multi-slot grids with peripheral cooling that limits pulse duration to 1.5 s.

Modernized ion source IVIS-CS for application in the T-15MD injectors is under development, in which:

- The design of the cathode block is changed for three-phase AC heating of cathode groups. “Old” arc chamber with new cathode block has been tested with increased up to 5 s arc pulses;
- New arc chamber is designed with configuration similar to Japanese “Kamaboko” [4] with the case made of copper and cooling which provides steady state work at power up to 150 kW (Fig.6);
- The design of multi-aperture (with shaped round apertures) three-electrode IOS with internal cooling channels is under development. The transparency of such electrodes is less, than in multi-slot systems, and is about 35 %. New IOS is to be mounted in former high-voltage ceramic insulation unit of the IVIS source which should provide extraction of hydrogen ion beam with a current of 40 A.

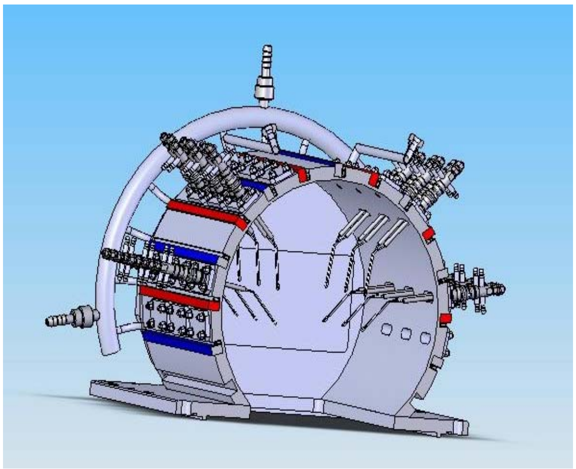

Fig.6. Arc chamber of IVIS-CS.

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