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Maintenance of stationary stage of VNS JUST-T for transmutation of minor actinides

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Carried out investigations are devoted more precise elaboration of some aspects of concept of compact tokamak JUST-T as a volumetric neutron source (VNS) for minor actinides transmutation. The main problem of tokamak as VNS is an achievement and a maintenance of flat top stage of operation providing required neutron loading on inner wall of blanket. As shown earlier [1] the proposal of use of spherical tokamak with major radius R=2 and aspect ratio A=2 allows to use some advantages of as both spherical tokamaks (large elongation, increase of safety factor q_{95} and normalized beta β_N) and modern large devices (SN configuration with elongation $\kappa_{95} \approx 1.7$). Use of CS situated inside of the central toroidal rod allows to ramp plasma current up to the level of $I_p \sim 2.5$ MA. The required flux storage in the solenoid (~ 6 Vs) can be provided by means of the solenoid discharge from maximum current to zero one. The solenoid with zero current is either switched off until the next discharge or even removed from the irradiation zone. An idea of application of tangential neutral beam injection became very fruitful for attaining the stated aims of tokamak JUST-T. Non-inductive stage including slow plasma current ramp up to desired value in skin times (thousands seconds) can be achieved by using of tangential NBI. Thus NB is suggested to use both for plasma heating and current drive. First of all the use of NBI provides for further ramping up to desired value of plasma current which is defined by required level of neutron loading. Further on flat top stage of operation the obtained plasma current is non-inductively maintained by bootstrap current and current drive due to NBI. The goal of this exploratory work is to study the influence of energy E_b of injected beam of deuterium on obtained parameters of plasma on steady stage. An analysis of the integrated system is necessary to simultaneously find the best beam and plasma parameters. The inversely proportional dependence of total collision cross-section $\sigma(E_b)$ of beam particle energy E_b effects on spatial profile beam absorption and source of generation of fast ions $\dot{n}_f$ arising due to processes of charge exchange, electron impact ionization and ion impact (including impurities) ionization. The beam deposition profile $H(r)$ plays an important role in determining the current profile and the beam-driven current efficiency η_{CD}. The efficiency of CD increases with the growth of particle energy E_{NB} and electron temperature T_e. The dependence of η_{CD} on particle energy is shown in Fig.1.

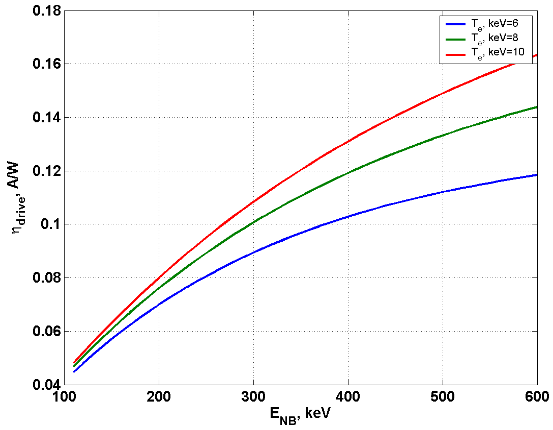

Fig. 1. The efficiency η_{CD} on particle energy E_{NB}

The results were obtained for spatial uniform plasma with different temperatures. The further analysis were performed on the base of the results of numerical simulations obtained by use of code DINA [2] for non-inductive stage of plasma current ramp up with achievement of steady state of operation. The modelling was carried out for a flat density profile (n_b/n_0)~0.9.

Mono energetic neutral beams with energy in interval (140÷400 keV) were applied in scenarios (I-IV). The processed data are presented in Table.

	I	II	III	IV	V	VI
Plasma current I_p, MA	4.827	5.007	5.299	5.691	5.047	5.159
Poloidal beta β_p	1.177	1.214	1.276	1.306	1.330	1.381
Minor radius *a*, cm	100.42	100.42	100.42	100.42	100.42	100.42
Major radius R, cm	202.18	202.18	202.18	202.18	202.18	202.18
Energy confinement timeτ_E, ms	407.48	411.64	427.11	453.48	414.79	422.88
Average density, $\bar{n}_{e20}$, m^{-3}	1.0072	1.0091	1.011	1.011	1.009	1.009
Elongation, κ	1.7	1.7	1.7	1.7	1.7	1.7
Electron temperature on axis $T_e(0)$, keV	15.043	18.188	22.134	25.57	21.083	22.688
Ion temperature on axis $T_i(0)$, keV	15.966	20.432	26.115	30.638	23.581	25.018
Average electron temperature $\bar{T}_e$, keV	6.474	6.753	7.136	7.627	6.814	6.967
Average ion temperature $\bar{T}_i$, keV	6.878	7.122	7.493	7.957	7.054	7.139
Safety factor on axis, q_0	5.369	2.886	1.371	1.142	1.344	0.974
$\bar{n}_e/n_{GW}$	0.661	0.638	0.604	0.563	0.633	0.619
Internal inductance, l_i	0.475	0.585	0.746	0.871	0.716	0.792
Thermal plasma energy W_p, MJ	20.001	20.900	22.153	23.709	20.935	21.319
f_{fast}, %	12.343	17.485	25.631	32.576	25.731	30.255
Neutron loading Γ_n, MW/m^2	0.246	0.311	0.352	0.373	0.297	0.298
Fusion gain factor Q	0.967	1.217	1.374	1.462	1.164	1.169
Normalized beta β_N	2.978	3.189	3.550	3.909	3.531	3.752
Beam-target interaction P_{B-TI}, MW	18.885	25.429	28.204	28.416	23.002	22.391
P_α, MW	6.198	7.818	8.849	9.400	7.480	7.507
Neutron Power P_n, MW	36.932	46.587	52.732	56.015	44.576	44.737
Bootstrap current fraction f_{bs}	0.5791	0.5089	0.4142	0.3411	0.4433	0.3922
Beam-driven current efficiency γ_{NB},A/W	0.0451	0.0546	0.0690	0.0833	0.0633	0.0689
Toroidal magnetic field $B_t(R_0)$, T	3.9	3.9	3.9	3.9	3.9	3.9
H-mode enhancement factor $H_{IPB98(y,2)}$	1.6	1.6	1.6	1.6	1.6	1.6
Neutral beam power P_{NB},MW	45.	45.	45.	45.	20/25	20/25
Neutral beam energy E_{NB}, keV	140.	200.	300.	400.	140/400	140/500

The most interesting for JUST-T concept results were presented in Figs. 2 and 3. Increasing particle energy leads to increasing plasma current and especially CD (more than two times in considered interval of energy). It might be explained by both the efficiency increase of current drive from particle energy and the growth of plasma temperature due to displacement of profile of absorption for more energetic atoms in the direction of plasma centre. The displacement of neutral beam deposition $H(r)$ leads to increasing of thermal energy confinement time.

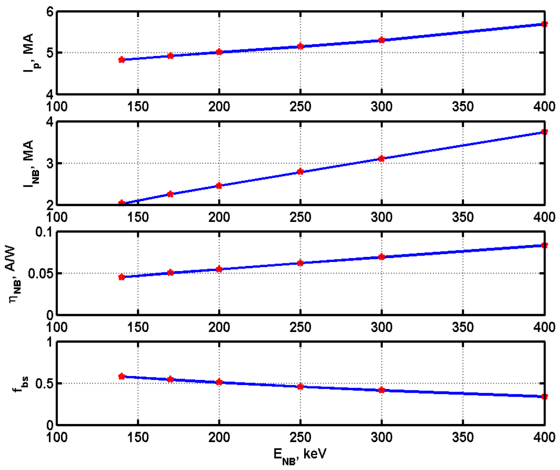

Fig. 2. The dependence of plasma current I_p, current drive I_{NB}, efficiency η_{CD}, portion of bootstrap current f_{bs} on energy E_{NB} of particles injected in plasma

When energy of particle E_{NB} grows the bootstrap current portion f_{bs} tends to be lowered. This fact likely occurs due to the more peaked plasma temperature profile. Although maximising η_{NB} is desirable, there are other important effects to be considered. For instance, high-beta magneto hydro dynamic (MHD) stability evidently requires a broad current profile. This can be easily achieved by flattening deposition profile $H(r)$ albeit at the cost of η_{NB}.

The more peaked profiles of temperature were obtained with growth of energy. The beam-target interactions $P_{B\text{-}TI}$ contributes to the total fusion power as well to the neutron production. Its contribution is a half of the total neutron load Γ_n.

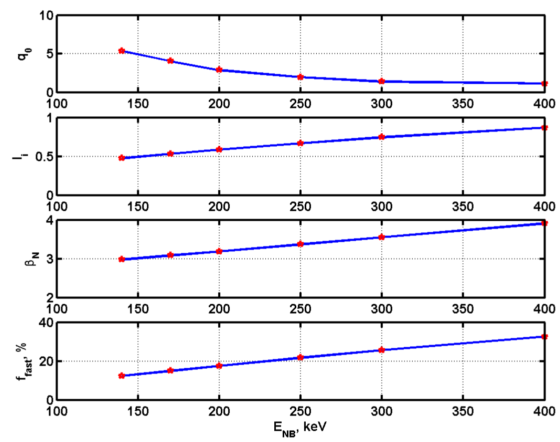

Fig. 3. The dependence of safety factor q_0, internal inductance l_i, normalized beta β_N and portion of fast ion f_{fast} on energy E_{NB} of particles injected in plasma

The increase of pressure of fast ion is obtained with the growth of particle energy. The non-thermal distribution of injected fast ions n_f may drive micro instabilities in tokamak plasma. It is possible that the fast ions n_f could be very rapidly slowed. It results in formation of hollow radial current profile observed in [3] with non-monotonic safety factor profile. For particle energy $E_{NB} \geq 400$ keV the q_0 on magnetic axis becomes smaller than q=1 and the sawtooth oscillations is occurred. For particle energy E_{NB}≥400 keV the q_0 on magnetic axis becomes smaller than q=1 and the sawtooth oscillations is occurred. The JUTS-T concept is supposed to avoid the steady-states with the reversed safety profile and with plasma sawtooth phenomenon. To provide the fulfillment of these requirements we need to apply both neutral beams with energies 140 keV and 500 keV (see V and VI in Table). This would greatly reduce the beam-driven current efficiency. We include only the thermal ion and electron pressures in beta. We assume that the super thermal ions have no effect on the beta limit for the thermal plasma. A power of less energetic neutral beam is greatly become weak when it penetrates into plasma. The obtained radial profiles of bootstrap current j_{bs}, current drive j_{CD} and the plasma current j_p are shown in Fig. 4.

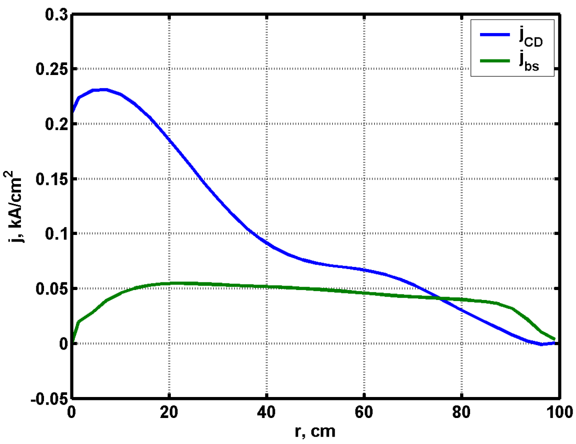

Fig. 4. The density profiles of bootstrap current and CD

Less energetic NB is absorbed and generates CD mostly at the peripheral plasma. More energetic beam penetrates plasma center to supply required CD and monotonic current profile there. The portion of bootstrap current f_{bs} is about 0.4. The efficiency of CD is $\gamma_{CD} \sim$ 0.06 A/W. The carried out calculations have shown possibility of tangential NBI to provide fully non-inductive current drive in steady-state tokamak with $f_{bs} + f_{CD} \approx 1$. The obtained β_N is close to scaling $5 \cdot l_i$ which is the upper MHD limit for no wall RWM excitement. The average plasma density $n_e \sim 1 \cdot 10^{20}$ cm^{-3} is far from the Greenwald limit.

1. E.A. Azizov, V.N.Dokuka, R.R. Khayrutdinov, "Achievement and Maintenance of Stationary Stage of VNS JUST-T for Transmutation of Minor Actinides", 30th EPS Conference on Controlled Fusion and Plasma Physics, P-4.169, St Petersburg, Russia, July 7-11, 2003
2. R.R. Khayrutdinov, V.E. Lukash "Studies of Plasma Equilibrium and Transport in a Tokamak Fusion Device with the Inverse-Variable Technique", Journal Comp. Physics, v. 109, 193 (1993)
3. Fujita et al., "Formation and sustainment of tokamak equilibrium with a current hole in JT-60U", Phys. Rev. Lett. 87, 2450001 (2001)