FEASIBLE SCENARIO OF STARTUP AND BURNUP OF FUSION PLASMA IN AMBIPOLAR D-T REACTOR

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This paper describes startup of an ambipolar D-T reactor with fusion power 1400 MW and power gain factor Q=10 using pulse (7–9 s duration) D-atomic injectors with the energy of 80 keV. Total power of the atomic injectors is 56 MW.

I. INTRODUTION

The startup and burnup scenario is proposed for a fusion ambipolar D-T reactor, which parameters are estimated and described in Ref. 1, but power gain factor Q is decreased from 20 to 10 (similar to ITER). The idea of this reactor is based on the tandem mirror concept (Refs. 2–4). Fusion plasma is created in a solenoid of the length of L_s=75 m; the plasma diameter is D_{sp}= 2 m, the plasma density at plateau is n_{plat}= 1.5×10^{14} cm^{-3}, $<n>$= $0.78n_{plat}$. The vacuum magnetic field B_{sv} = 2 T, the mirror field B_m= 14 T. The reactor is completely axisymmetric with double end mirrors with the length of $L_{mirrors}$= 2×14 m. The plasma diameters in double end mirrors are D_{bp} = 1.8 m (at barriers) and D_{plp}= 1.1 m (at plugs). The vacuum fields are B_{bv}= 1.68 T (at barriers), B_{plv}= 4.3 T (at plugs); three mirror fields are B_{max} = 14–13.6–14.4 T. Fusion power is 1400 MW. Total nuclear power is 1800 MW.

II. STARTING THE DOUBLE END MIRRORS

The reactor startup consists of the following stages.

Stage 1. Filling of the trap (solenoid and mirrors) with plasma by means of the plasma sources with circular geometry which are installed in the end magnetic fields and with gas discharge provided in annular channels (with diaphragms). The plasma is injected into a solenoid through the double end mirrors and their end expanding fields. The initial solenoid plasma has the density n_{sw} = 10^{13} cm^{-3}, and temperature $T_{s0} \approx$ 50 eV. At such plasma temperature, the ion mean path is λ_d = 4.6 m << L_s. The solenoid plasma is gas-dynamic, the plasma confinement time $\tau_{gd} \approx R_sL_s/2v_{i\,sound}$= 3.8 ms. Power of plasma-sources is 2×6 MW. Plasma stream from these sources decreases 5–10 times ~50 ms after they are turned on.

In experiments with a large solenoid it was found that the line-tying of the solenoid plasma to the annular plasma-sources at ends creates MHD-stability.

Stage 2. Starting the electron barrier mirrors after starting the annular plasma-sources ~20 ms later. Turning on barrier electron cyclotron heating (BECH) system with power 2×67.5 MW for heating the barrier electrons with the density $n_{eb} \approx 10^{13}$ cm^{-3} up to 360 keV. At energy content 2×4.7 MJ, the heating time is ~70 ms×3. High value of the parameter $\beta_\perp$= 0.7 and such ratio of the plasma pressure components $p_\perp = 1.8p_{||}$ are necessary for MHD-stabilization by conducting walls.

Ion reverse pumping from the thermal barriers at parametric resonances is turned ~50 ms after BECH start.

Stage 3. Starting the plug mirrors simultaneously with the BECH-system. It is proposed to use the pulse D-atomic injectors E_j =80 keV and I_j = 2×150 A. In the initial warm plasma with the density $n_{sw} = 10^{13}$ cm^{-3} with inclined injection ≈100% D^+ ions are captured from the atomic beams into the magnetic field. Life-time of the captured ions in the plugs is

$$\tau_p \approx \tau_d^{i/i} = 2.45\times10^{11}\,\frac{\sqrt{\mu}}{n\Lambda_i}\,E_{i-keV}^{3/2}\,. \qquad (1)$$

The energy loss-time due to heating of electrons is

$$\tau_{\varepsilon l}^{i/e} = 10^{13}\,\frac{\mu}{n\Lambda_{ei}}\,T_{e-keV}^{3/2}\,. \qquad (2)$$

The electrons are well heated by the fast captured ions and do not hinder accumulation of the hot ions. Average energy of the confined ions decreases with time

$$\langle E_i\rangle = E_j\,\frac{\tau_{\varepsilon l}^{i/e}}{t}\left(1-\exp\left(-\frac{t}{\tau_{\varepsilon l}^{i/e}}\right)\right). \qquad (3)$$

The electron temperature is determined from the energy balance

$$T_{e-keV}(t)=\left\{\frac{1}{c}\frac{\Lambda}{\mu}n\times10^{-13}E_{j-keV}\,\tau_{\varepsilon l}^{i/e}\left[1-\frac{\tau_{\varepsilon l}^{i/e}}{t}\left(1-\exp\left(-\frac{t}{\tau_{\varepsilon l}^{i/e}}\right)\right)\right]\right\}^{2/5},\ \text{where } c\approx\frac{2}{5}+\frac{5}{2}\frac{t}{\tau_p}. \qquad (4)$$

The designed plasma density in the plugs is $n_p = 5\times10^{13}$ cm^{-3}, with the ion energy $\langle E_i\rangle \approx 72$ keV (3) and the electron temperature $T_{ep} \approx 6.76$ keV (4) and $\beta_\perp = 0.65$ ($p_\perp = 2.4p_{||}$), is achieved in $\Delta t \approx 80$ ms. About 30 ms after plugs startup, the plasma stream from the plasma sources decreased 5-10 times.

III. STARTING THE CENTRAL SOLENOID AND HEATING OF ITS PLASMA

Stage 4. Starting the central solenoid after starting the plugs ~16 ms later. By this time the hot plasma with the density $n_p=10^{13}$ cm^{-3}, the ion energy $\langle E_{ip}\rangle=77$ keV (3) and the electron temperature Tep ≈ 5.12 keV (4) is accumulated and heated in the plugs.

It is proposed to use the pulse D-atomic injectors $E_j = 80$ keV and $I_j = 400$ A for the solenoid. While the plasma is accumulated in the plugs up to the density $n_p=5\times10^{13}$ cm^{-3}($T_{ep} \approx 6.76$ keV) and later on, the solenoid initial warm plasma and the hot plasma being accumulated will be confined in the solenoid by the ambipolar barriers and will be heated. Also in the solenoid plasma, 100% D-atoms are captured as D^+ ions into the solenoid magnetic field from the injected atomic beams. The injected hot ions heat the electrons and the initial ions.

After capturing of the hot ions in the solenoid with the density 10^{13} cm^{-3} during a period of 74 ms, the plasma is created with the density $n_s= 2\times10^{13}$ cm^{-3}, the ion temperature T_{is} ~25 keV and the electron temperature T_{es} ≈4.65 keV (4). The confining ambipolar barriers φ_c [5, 6] are

$$\varphi_c=\left(\frac{T_{ep}}{T_{es}}-1\right)\varphi_b-T_{ep}\ln\left(\frac{n_s}{n_p}\sqrt{\frac{T_s}{T_p}}\right). \qquad (5)$$

At the thermal barrier the potentials φ_b=112 kV and φ_c = 42 kV are formed. The longitudinal particle confinement time $\tau_{p||}$ [7, 8] is

$$n\tau_{p//}=3.12\times10^{11}G\left(R_{ps}/2\right)\frac{\sqrt{\mu}}{\Lambda_i}T_{is-\mathrm{keV}}^{3/2}\frac{\varphi_c}{T_{is}}\exp\left(\frac{\varphi_c}{T_{is}}\right)\frac{1}{1+T_{is}/2\varphi_c}. \qquad (6)$$

At the mirror parameter G ≈2.5 and $n_s= 2\times10^{13}$ cm^{-3}, the time is $\tau_{p||} = 5.9$ s.

The electron cyclotron heating in the plugs (PECH) is turned on and maintained for controlling the electron temperature in the plugs. Then during ≥4 s the plasma is accumulated in the solenoid up to the density 5×10^{13} cm^{-3}, the electrons are heated up to T_{es} ≈18 keV (4), and the ions are heated up to 30 keV. The electron temperature in the plugs is controlled by the PECRH system. The ion confinement time is increased up to $\tau_{i||}$ ~15 s (T_{ep} = 36 keV, φ_c = 100 kV). This plasma relaxation time is ~2 s. During this period the atomic injection of the fast ions goes on, which compensates particle and power losses. As a result, after relaxation the near-equilibrium deuterium plasma with the temperature of T_s= 24 keV is created.

Then it is necessary to decrease the current of the plug pulse atomic injectors and to turn them off after the stationary plug injectors are turned on.

IV. CREATION AND BURN-UP OF FUSION PLASMA IN THE SOLENOID

Stage 5. Introduction of tritium and burn-up of the fusion plasma. Tritium pellets are shot into the solenoid deuterium plasma and turn into ions, which are heated within a period <1 s. The created plasma relax within ~ 0.3 s to the state of $n_s=10^{14}$ cm^{-3}, $T_s \approx 12$ keV.

At the same time, the confining ambipolar barriers φ_c= 100 keV are adjusted (the electron temperature in the plugs T_{ep}~26 keV). About ~1 s after the start of the tritium introduction, the pulse solenoid atomic injectors are turned off. The confinement parameter calculated from (6) is $n\tau_{p||}= 8.3\times10^{16}$cm^{-3}s. The end potentials which confine the electrons in the solenoid φ_e= 260 kV are calculated based on the plasma quasi-neutrality. Longitudinal energy confinement time $\tau_{\varepsilon||}$ is determined by the relationship [9]

$$\frac{\tau_{\varepsilon//}}{\tau_{p//}}=\frac{3T_s}{\varphi_e+\varphi_c+T_s}. \qquad (7)$$

From (7) we determine the parameter $n\tau_{\varepsilon||} = 4.9\times10^{15}$ cm^{-3}s, which considerably exceeds the value of $n\tau_L(1-\alpha_\varepsilon)^{-1}=2.74\times10^{14}$ cm^{-3}s, where $n\tau_L$ is the Lawson parameter, α_ε is the relative loss of hot α-particles from the solenoid. This results in self-ignition of the D-T plasma before its relaxation. The plasma is heated by the α-particles, and the plasma temperature grows. At temperatures 15 keV and 20 keV (at φ_c= 100 kV) the parameter $n\tau_{\varepsilon||}$ is equal to 2.36×10^{15} and 6.2×10^{14} cm^{-3}s, respectively. These parameters also considerably exceed the values of $n\tau_L(1-\alpha_\varepsilon)^{-1}$.

In this fusion plasma burning regime, the plasma temperature increase is

$$\Delta T_s \approx \frac{n_s \varepsilon_\alpha}{12} \int \langle \sigma_f v \rangle \, dt \, . \qquad (8)$$

For ΔT_s=20 keV–12 keV the heating time is Δt= 1.5–2 s.

V. CONSUMMATION OF REACTOR STARTUP

Stage 6. Transition of the reactor to the stationary regime (PECH-power increases. As a result, the temperature in the plugs reaches $T_{ep} \approx 77$ keV, the stationary plug atomic injectors are turned on, and a fuel is added). Increase of plasma parameters in the solenoid: $n_s = 1.5\times10^{14}$ cm^{-3}, T_s = 25 keV, β_s = 0.8. High value of the parameter β_s is necessary for MHD-stabilization of the plasma by conducting walls in a long shallow rippled solenoid. The FLR effect is sufficient to suppress higher modes and to make the first mode a rigid spatial structure. Optimization of scenario is necessary. Fig.1 presents magnetic system of the reactor from Ref.1.

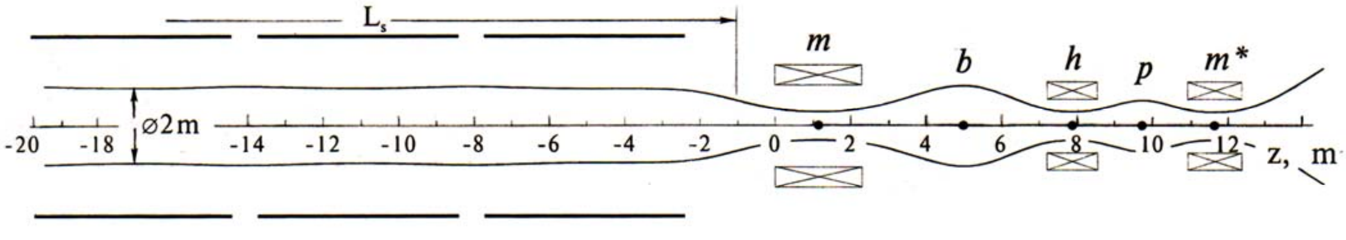

Fig.1. Superconducting magnet system of reactor (one half). Letters “b” and “p” denote thermal electron barrier and plug, respectively.

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