# DISCHARGE INSTABILITY AT EARLY STAGE OF PLASMA COLUMN FORMATION IN TOKAMAKS

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In our paper we study the breakdown physics and current rump in tokamaks in wide range of parameters in 0D model. It is shown that the current-voltage curves has the S-shape. If the loop voltage is greater than critical value than discharge goes from low-current stage to high-current stage. If voltage is less than critical value there are both dumping and steady-state oscillations with large amplitude. The breakdown voltage increased versus gas pressure and decreased versus minor plasma radius.

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## INTRODUCTION

The study of breakdown physics and current ramp-up in tokomaks is still far from completion. Meanwhile, the issue is of great importance because of its practical applications. Knowing the location of plasma column formation is crucial for development of tokamaks and minute description of current ramp-up.

The stage of transition from the avalanche breakdown to plasma column formation in case of plasma being generated in the region of either closed or non-closed magnetic surfaces remains the most obscure. Currently the plasma column formation and current ramp at this stage is analyzed within the homogeneous (0D) model when the transverse column dimension, $a$, as well as the major radius $R$ are derived from the avalanche breakdown condition and considered constant throughout the entire stage [1].

General consideration leaves no hope that the region where the breakdown conditions are satisfied coincides with the cross section of the quasineutral plasma column after the column has been formed and remains invariable during the startup. In particular, this is conditioned by heterogeneity of breakdown dynamics across vessel's cross section, necessity to sustain the equilibrium conditions along the minor radius, etc. In the present paper we discuss the possible paths to overcome these difficulties.

However, we first want to study the properties of this 0D model, i.e. analyze the regularities induced by the bulk processes accompanying current ramp during the early stage of plasma column formation.

## EQUATIONS FOR QUASINEUTRAL PLASMA

In this paper we apply the approach developed in [1,2] following the original notation. The energy balance equations for electrons and ions in 0D approximation are written in the form

$$\frac{3}{2}\frac{d}{dt}(n_e T_e) = P_{OH} - P_\Delta - P_{ion} - \frac{3}{2}\frac{n_e T_e}{\tau_E} \qquad (1)$$

$$\frac{3}{2}\frac{d}{dt}(n_e T_i) = P_\Delta - P_{cx} - \frac{3}{2}\frac{n_e T_i}{\tau_E} \qquad (2)$$

Particle balance: ions $n_e$ ($10^{20}$ m$^{-3}$) and neutrals $n_0$ ($10^{20}$ m$^{-3}$) respectively:

$$\frac{dn_e}{dt} = 10^{20} n_0 n_e S_i - \frac{n_e}{\tau_p} \qquad (3)$$

$$V_V \frac{dn_0}{dt} = \frac{n_0 V_p}{\tau_p} - 10^{20} n_0 n_e S_i V_p \qquad (4)$$

Circuit equation for plasma current $I_p$ (MA):

$$L\frac{dI_p}{dt} + R_{pl} I_p = U \qquad (5)$$

where $L$ is column inductance and $U$ is the loop voltage.

In (1-5) the following notations are applied: $V_p$ is the volume of plasma region, $V_v$ represents the vacuum chamber volume, $T_e$ и $T_i$ are the electrons and ions temperatures respectively [keV], $P_{OH}=I_{pl}^2 R_{pl}/V_p$ describes ohmic heating specific power [MW/m$^3$], $R_{pl}$ is plasma column resistance [μΩ], $R_{pl}=\eta 2R/a^2$, $\eta=1.65\cdot 10^{-3}\ \ln L/T_e^{1,5}$, [μΩ·m]. $P_\Delta$ is equilibration specific power between electrons and ions in plasma, i.e. $P_\Delta=0,24\ (T_e-T_i)/T_e^{1,5} n_e^2$.

$P_{ion}$ is neutral gas ionization specific losses: $P_{ion}=1,6\cdot 10^{18} n_o n_e S_i W_i$, $W_i=0,03$ keV.

$$S_i = 2\cdot 10^{-13}\sqrt{\frac{T_e}{R_y}}\exp\left(-\frac{R_y}{T_e}\right)\cdot\left[6+\frac{T_e}{R_y}\right]^{-1}$$ - neutral gas ionization rate (m$^3$/s), $R_y$ = 0,0136 keV. $P_{cx}$ describes charge exchange specific losses [MW/m$^3$]. $P_{cx}=2,4\cdot 10^5 n_e n_o (T_i-T_o) T_i^{0,327}$, $T_o=2,59\cdot 10^{-5}$ keV. $\tau_E$, $\tau_P$ are the energy and particles confinement times. For simplicity we put $\tau_E=\tau_P$.

## DISCUSSION

The system of equations (1-5) admits a stationary solution. Fig. 1 demonstrates current-voltage characteristic for the gas discharge in KTM tokamak [3] as functions of varying initial pressure of the neutral gas (hydrogen), $R$=1,1 m, $a$=0,2 m, $\tau$=5 ms. It is evident that the current-voltage characteristic has the S-shaped curve similar to that of an arc discharge.

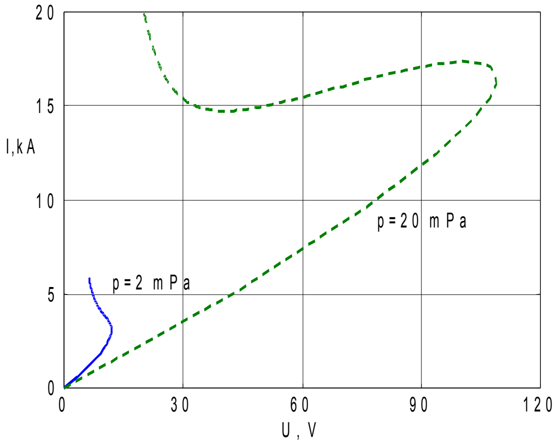

*Fig. 1. Current-voltage characteristic for various pressure of hydrogen*

The voltage required for low-current to high-current stage transition (not depicted) we further refer to as “breakdown voltage – $U_b$”. For the transient solution obtained for a certain initial condition and $U>U_b$ the current grows unrestrictedly with time. In case $U\leq U_b$ the current either reaches a stationary value (Fig. 2) or, at $U<U_b$, the entire system comes to steady-state oscillations (Fig. 3).

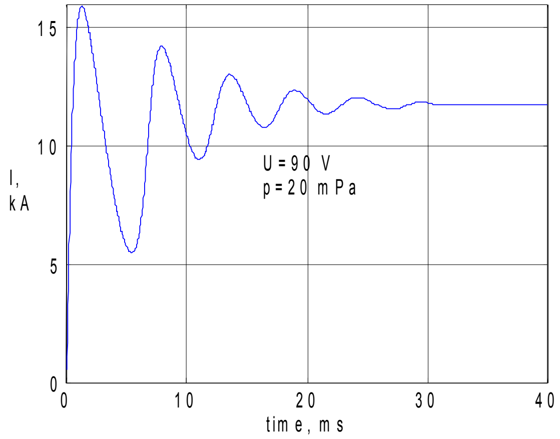

*Fig. 2. The plasma current reaching a stationary value at pre-breakdown voltage*

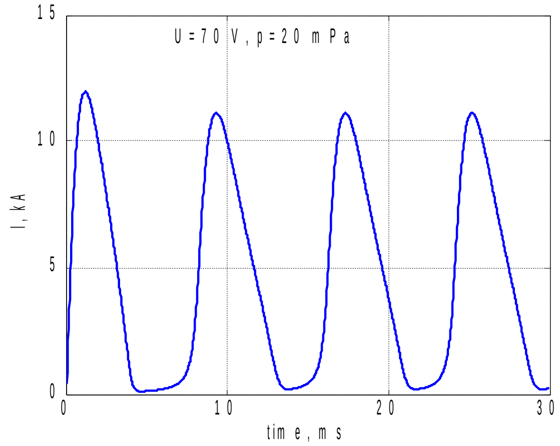

*Fig. 3. The stationary oscillations of plasma current at $U<U_b$*

The phase path of oscillatory motion being the closed cycle to determine the scale of oscillation for parameters which describe plasma column is shown in Fig. 4.

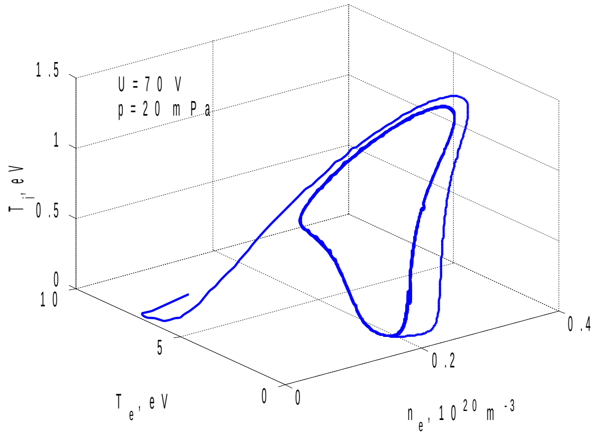

*Fig. 4. The 3D-phase path of plasma parameters oscillations*

The value of breakdown voltage as a function of parameters under consideration represents our major interest. Fig. 5 shows that $U_b$ increases linearly with the gas pressure. An explicit analytical expression for current-voltage characteristic is hard to obtain due to complexity of the system (1-5). However, (1-5) allow simplification if only main terms are considered. The expression to describe $n_e$ and $n_o$ as functions of $T_e$ can be derived from (3,4).

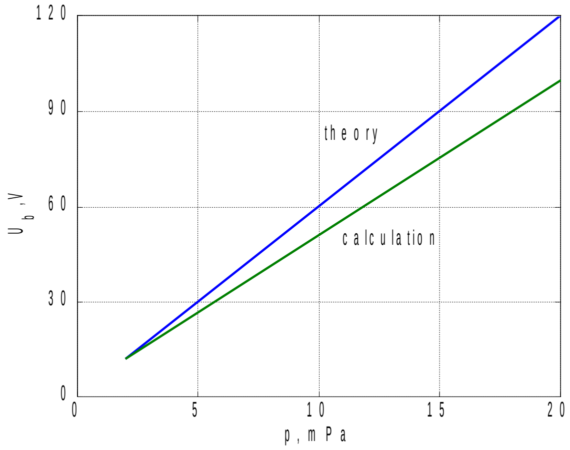

*Fig. 5. Comparison of theory and numerical results for breakdown voltage*

Allowing for the fact that charge exchange represents the major energy loss channel during breakdown and assuming $T_i\approx T_e$ one can find from (1,2) the $T_e$ function of the voltage.

Now (5) provides the $T_e$ dependence of the current. This parametric dependence allows us to find the conditions when $dU/dI_P=0$, i.e. $U_b$:

$$U_b = 10\sqrt{2}\,\frac{\sqrt{RV_V \ln L}}{aT_K^{0,1}}\,n_0^0 \qquad (6)$$

where $n_o^o$ is the initial neutrals concentration, $T_K$~2.4 eV. Otherwise, in units for KTM conditions:

$$U_b=1{,}2\,P/a\ [\mathrm{V}],\ P\ [\mathrm{mPa}],\ a\ [\mathrm{m}] \qquad (7)$$

$$I_b=5\,a\,P\ [\mathrm{kA}] \qquad (8)$$

In Fig. 5 one can see the comparison of numerical simulation results obtained for transient system (1-5) with formula (7) where a fairly good agreement is observed.

Fig. 5 demonstrates pressure dependent linear growth of breakdown voltage similar to that during the avalanche breakdown (high pressure limit [4]). However, the breakdown voltage at quasineutral stage is substantially higher (within an order of magnitude) than the corresponding value at the avalanche.

As it is seen from (6) and (7) $U_b$ is in inverse proportion to the minor plasma radius. The latter was determined rather arbitrarily. In order to overcome this obscurity this value can be estimated from the condition for plasma equilibrium in external poloidal magnetic fields being weak in the breakdown region yet having the finite magnitude.

Solving the Grad-Shafranov equation subject to external poloidal field and a fixed value of current one can find the major radius while the cross section of the plasma column determines the value of the average minor radius, $a$. For KTM conditions this dependence can be well approximated as follows:

$$a(\mathrm{m}) = \sqrt{I(\mathrm{kA})/500} + a_0 \qquad (9)$$

where $a_0$ is an minor quantity. Now the system (1-5) can be expanded with (9).

Numerical analysis of this system has demonstrated that the breakdown voltage is strongly dependent on the minor radius, i.e. on value $a_0$, at small currents. This signifies that a substantial part of the current occurs in the region of non-closed magnetic surfaces so these currents are to be taken into consideration, i.e. the situation is similar to that during halo-current [5].

## CONCLUSIONS

1. Bulk processes at early stage of plasma column formation cause S-shape current voltage characteristic and jump from low current regime to high current regime.
2. At more large neutral gas pressure pre-breakdown regime is unstable and causes regular plasma parameter oscillations with large amplitudes.

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## НЕСТІЙКІСТЬ РОЗРЯДУ НА РАННІЙ СТАДІЇ ФОРМУВАННЯ ПЛАЗМОВОГО ШНУРУ В ТОКАМАЦІ

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В роботі розглядаються закономірності формування розряду в токамаці у широкому діапазоні змінення параметрів в однорідній моделі. Показано, що вольт амперна характеристика розряду має S - подібний характер. При напрузі, яка перевищує критичну величину, розряд переходе у сильнострумову стадію, при менших напругах реалізуються або затухаючі, або незатухаючі коливання великої амплітуди. Напруга пробою зростає разом з тиском газу й зменшується з ростом малого радіусу шнуру.

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## НЕУСТОЙЧИВОСТЬ РАЗРЯДА НА РАННЕЙ СТАДИИ ФОРМИРОВАНИЯ ПЛАЗМЕННОГО ШНУРА В ТОКАМАКЕ

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В работе рассматриваются закономерности формирования разряда в токамаке в широком диапазоне изменения параметров в однородной модели. Показано, что вольтамперная характеристика разряда носит S-образный характер. При напряжениях, превышающих критическую величину, разряд переходит в сильноточную стадию, при меньших напряжениях реализуются либо затухающие, либо незатухающие колебания большой амплитуды. Напряжение пробоя растет с ростом давления газа и падает с ростом малого радиуса плазменного шнура.