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SOLUTION EXPLORATION OF PLASMA INITIATION AND CURRENT RAMP–UP SCENARIO IN A-SSTR

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Fully ECCD and PFC supported ECCD plasma initiation and current ramp up scenarios in the A-SSTR are analyzed analytically and numerically. Necessary conditions and operational limits for plasma initiation and current ramp up are obtained. The analytical dependencies for scenario optimization are discussed. Results of the time dependent self consistent transport simulations for both types of scenarios in the A-SSTR are performed. The advanced scenario is proposed to achieve plasma parameters, necessary for further NBCD current ramp up in the A-SSTR.

Keywords: Plasma, Tokamak, Steady-state Operation, ECCD, NBCD, Ionization, Current Ramp-up, Numerical Simulation

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定常トカマク炉 A-SSTR の初期プラズマ生成および プラズマ電流の立ち上げシナリオの考察

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（2000年 1 月 4 日受理）

中心ソレノイドコイルを排除した非誘導電流駆動方式による定常炉、改良型 A-SSTR を対象に立ち上げシナリオの検討を実施した。主要な課題は初期プラズマの生成から 500kA~1MA（定格プラズマ電流の 5~10%）程度までプラズマ電流を立ち上げることの可否である。ソレノイドコイルを排除しても 1Vs に満たない僅少の磁束供給は期待できることから、完全非誘導方式による場合と僅少の磁束供給が期待できる場合の両ケースについて立ち上げシナリオの検討を実施した。

磁束供給を考慮する場合、改良型 A-SSTR においては最大初期励磁の磁束は 0.4Vs である。ここでは 4V を 0.1 秒間プラズマに与えた。この場合、3MW の ECH 予備電離･加熱の条件の下に 10ms 程度で放射損失ﾊﾞﾘﾔｰを乗り越え、また初期のﾄﾞﾘﾌﾄ電流は閉じた磁気面を形成できる程充分な電流値の得られることが示された。更に、加熱ﾊﾟﾜｰは直接プラズマ電流と連動していないため、プラズマの MHD 安定性の条件$\beta_p \varepsilon <1$ を満足することが容易であることも明らかになった。

一方、立ち上げ初期においてポロイダルコイルシステムによる磁束供給がない場合でも初期プラズマの生成が可能であることが示された。この場合、外部から操作できるパラメータは加熱入力ﾊﾟﾜｰのみであるため、立ち上げシナリオの構築は容易ではない。輸送方程式と条件$\beta_p \varepsilon <1$ の両方を満足する温度、密度および電流を刻一刻設定することで初期プラズマの生成シナリオを構築した。この場合も ECH 予備電離･加熱のﾊﾟﾜｰは 3MW である。

更に、初期プラズマの生成からプラズマ電流 2.0MA 程度まで ECH によって立ち上げる場合の必要となる時間の算出も行い、結果は約 2000 秒となった。

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1. Introduction

The CS(Center Solenoid Coil)-less current ramp-up scenarios with NBCD (Neutral Beam Current Drive) has been considered for A-SSTR design earlier [1]. The NBCD is effective at the phase when plasma is already ionized, density is sufficiently high ($n \sim 10^{19} m^{-3}$) to absorb the NB, toroidal current is enough $I_p \sim$ 1-2 MA to create closed magnetic surfaces, to avoid orbital losses of the fast ions and to make possible plasma equilibrium control by PFC (Poloidal Field Coil) system.

Here we consider a few possible scenarios of plasma breakdown, ionization and establishing of the parameters when NBCD and PFC control become effective. To provide this in the CS-less configuration of the A-SSTR it is possible to use $\Delta\psi \sim 0.4$ Vs of the magnetic flux, created by PFC for the Townsend breakdown as well as up to $P_{EC,max} \sim 5$ MW of the EC (Electron Cyclotron) heating and current drive for EC breakdown and current ramp-up.

2. PFC supported plasma initiation

The breakdown is possible if the ionization rate exceeds the losses. For breakdown provided by externally applied voltage this condition is determined by the Townsend avalanche process.

The PFC system of A-SSTR could provide voltage U = 4 V/turn within Δt = 0.1 s which could be used for the Townsend avalanche breakdown [2]. The minimal voltage necessary to provide the breakdown depends on the prefill gas pressure p_0 (Torr) and the amplitude of the stray field [2]:

$$U_{min}(V) = 2.5\ 10^4 \pi R\ p_0/\ln(510\ p_0\ L), \qquad (1)$$

where the connection length $L \approx 0.25\ a_{eff} B/B_v$. In A-SSTR the stray field is $B_v \leq 0.005$ T, the plasma minor radius $a_{eff} \approx 1.5 - 2$ m, the plasma major radius $R \approx 6$ m, B = 11 T. So, the connection length $L \geq 1000$ m. The dependence of the minimal voltage per turn (1) is presented in Fig.1. It is clear that A-SSTR PFC system could provide the necessary conditions for plasma breakdown if the prefill gas pressure is in the range $4\ 10^{-6} - 1.5\ 10^{-5}$ Torr. This corresponds to the range of plasma density after the complete plasma ionization:

$$n = 6332\,\delta\, p_0 = 0.127 \div 0.475 \times 10^{19}\, m^{-3}, \qquad (2)$$

for $\delta \equiv V_{tot}/V_p = 5$, where p_0 is a pressure of the prefill gas in Torr, δ is the ratio of the total pumping volume to the plasma volume. This is shown in Fig. 2.

To estimate the toroidal current $I_p = \int e\, n\, V\, dS$ at the end of the break down phase (when the electron density n reaches 10% of the initial neutral gas N_0: $n/N_0 = 0.1$) we use the electron drift velocity along the field lines [3]:

$$V_E = 35\, U/(2\pi\, R\, p_0),$$

where V_E is in m/s, U is in V, R is in m and p_0 is in Torr. So, the maximal plasma drift current for Townsend breakdown could be estimated as:

$$I_p = 0.0177\, Ua^2k/R = 0.0125\, U, \qquad (3)$$

where the plasma current I_p is in MA. Thus and , the plasma elongation κ=1.8, after the Townsend breakdown phase for U = 4 V, I_p = 0.05 MA. This current is enough to create the poloidal magnetic field $B_p = 5 \times 10^{-3}$ T, which marginally compensate the stray fields. So, for further plasma ionization with the PFC assistance we shall consider plasma in a tokamak configuration with closed magnetic surfaces.

The breakdown time necessary for ionization from $n/N_0=\xi$ to $n/N_0=0.1$ for $p_0 > 1.5\sim2/(510L) \approx 3\sim4\times10^{-6}$ Torr $\tau_B = \ln(1/10\xi)\, 2\pi R/9000\, U$ [3]. For the preionization of $\xi = 3\times10^{-7}$ $\ln(1/10\xi) = 15$, and R = 6 m in the case of A-SSTR the breakdown time is:

$$\tau_B = 0.063/U = 0.063\, \Delta t/\Delta\psi, \qquad (4)$$

Thus, for the PFC provided flux of $\Delta\psi = 0.4$ Vs, $\tau_B \ll \Delta t$.

For the prefill gas pressure $p_0 < \approx 3\sim4\ 10^{-6}$Torr the breakdown time exponentially increases [3].

To simulate further plasma ionization after the breakdown process we use the ASTRA code [4]. Plasma evolution is described in the 1.5D approximation by the system of 1D transport equations for the magnetic surface averaged electron density n, ion and electron temperatures T_i, T_e, poloidal flux:

$$\partial n/\partial t = \mathrm{div}(D\,\nabla n) + nNS_i, \qquad (5)$$

$$1.5\partial nT_i/\partial t = \mathrm{div}(n\,\chi_i\nabla T_i + 2.5\,D\,T_i\nabla n) + Q_{ei} - Q_{iN}, \qquad (6)$$

$$1.5\partial nT_e/\partial t = \mathrm{div}(n\,\chi_e\nabla T_e + 2.5\,D\,T_e\nabla n) + \\ + Q_{OH} - Q_{ei} - Q_H - Q_C + Q_{EC}, \qquad (7)$$

$$\partial\psi/\partial t = 2\,\pi\,R\,c\,(j - j_{BS} - j_{CD})/\sigma_{\|} \qquad (8)$$

with self consistent 2D plasma internal equilibrium calculations. In eqs. (5)-(8) we just show the processes, taken into account. In ASTRA code all variables are properly averaged over the magnetic surfaces with proper metric coefficients [4]. Here we used the standard nomenclature D, χ are plasma particle and heat diffusivities, Q_{OH} describes the Ohmic heating, Q_{ei} is the electron/ion equipartition term, $Q_H = nN(S_dE_d + S_iE_i + S_rE_r)$ is the Hydrogen dissociation, radiation and ionization losses, S_i and S_r are the ionization and induced radiation intensities, $Q_C = n_CnQ_C(T_e)$ describes the Carbon radiation losses, Q_{iN} describes the ion heat sinks and sources, connected with ion-neutral interaction.

The neutral gas distribution N, T_n is calculated using the 1D slab layer kinetic approach taking account of the particle conservation low, correspondent to full particle recicleing:

$$N_0V_{tot} = \langle n\rangle V_p + N_a(V_{tot} - V_p) + N_a\langle N/N_a\rangle V_p, \qquad (9)$$

which gives boundary conditions for the neutral gas N_a:

$$N_a = (N_0\,\delta - \langle n\rangle)/(\delta - 1 + \langle N/N_a\rangle),$$

where brackets denote the plasma volume averaging.

We consider also external circuit equation:

$$L_{ext}dI/dt - R_{\Omega}(I_0\text{-}I_p) = U_{ext}, \qquad (10)$$

where L_{ext} is plasma external inductance, R_{Ω} is plasma resistivity, I_0 is noninductive current.

At the initial phase of the discharge development, the plasma passes from the configuration without closed magnetic surfaces and rotational transformation to the tokamak configuration. So, the codes which are usually used for the selfconsistent simulation of the external equilibrium are useless at this phase. We do not simulate here the external equilibrium self consistently, supposing that plasma occupies the whole vacuum vessel at the initial phase and after the tokamak equilibrium formation the A-SSTR PFC system could provide the proper plasma shape and equilibrium. Our results are not sensitive to the detailes of the external equilibrium. And possibility of plasma control could be easily checked using the plasma evolution scenario we obtained.

At the ionization phase, we start with $n_e/N_0 = 0.1$, which corresponds to equal collision rate with charged and neutral particles.

The initial value of plasma current for PFC supported ionization is assumed to be the same as at the end of the previous breakdown phase $I_p = 0.05$ MA.

We describe plasma transport at this phase with the model, similar to ref. [5].

At the initial phase, the processes ionization and charge exchange are dominant. So, the minimal EC power $P_{EC,min}$, required for complete plasma ionization ($n_e/N > 0.95$) is determined by the ionization, radiation and charge-exchange losses on the residual gas and impurities, rather than plasma transport.

For low temperature (T = 2-4 eV) pure hydrogen plasmas minimal losses $Q_H + 1.5\,(T_i + T_e)\,n\,N\,S_i$ could be approximated by the function:

$$Q_L = 550\, n\, N\, (T - 0.002),$$

where Q_L is in MWm^{-3}; n, N are in $10^{19}m^{-3}$, T is in keV. Maximal losses correspond to the maximum of the product nN. From the particle conservation low this maximum could be estimated as $nN = 0.25\, N_0^2\delta$. So, for the lower limit for the input power, necessary for plasma ionization we obtain the following estimation:

$$P_{H,lim} = 0.55\,(10^5 p_0)^2\,(T - 0.002)\,V_p\,\delta = 1375\,(10^5 p_0)^2(T - 0.002),.$$

For low external power $P_{EC} \sim P_L$(2.5-2.1 eV) time of ionization increases.

Presence of impurities implies the absolute lower limit on the power, necessary for ionization. Maximum of the Carbon radiation corresponds to T = 5 eV and maximum density n:

$$P_{C,lim} = 0.036\,(10^5 p_0\delta)^2 V_p n_C/n = 450\,(10^5 p_0)^2 n_C/n,$$

but these losses could be dramatically reduced if the input power is enough to keep the temperature at 8-10 eV after passing nN maximum correspondent to 50% of ionization.

For input power less than $P_{C,lim}$ plasma temperature after the ionization can not exceed 5 eV. So, the maximum Carbon contamination of the A-SSTR plasma, correspondent to the minimum of the pressure, permitted by Townsend conditions $p_{0,min} = 0.5x10^{-5}$ Torr and maximum available ECRH power of $P_{EC,max} = 5$ MW:

$$n_C/n_{lim} = P_{EC,max}/450(10^5 p_{0,min})^2 = 4.45\ 10^{-2} \qquad (11)$$

For Carbon contamination of n_C/n =0.2% we consider, this limitation implies the required power of 230 kW or maximum pressure of $2.3x10^{-5}$ Torr for $P_{EC} = 5$ MW.

It is also clear that maximal additional current caused by external voltage is:

$$\Delta I_p = \Delta\psi/L_{ext} = 0.04 \text{ MA}.$$

So, total current after the PFC supported ion complete plasma ionization is $I_p = 0.09$ MA.

So, we can summarize the results of the PFC supported breakdown and ionization consideration as follows.

The minimum voltage necessary for breakdown, is connected with the prefill gas pressure and stray fields values $U = U(p_0, B_v)$.

For the case of prescribed U, B_v there is a restricted pressure range, where the breakdown is possible.

Plasma density after the breakdown and ionization is determined by the prefill gas pressure: $n \sim p_0$.

Minimum power, required for ionization is determined by p_0 and plasma contamination: $P \sim p_0^2 n_Z/n$.

Total drift current at the breakdown phase $I_{p,1} \sim U \sim 0.05$ MA enables the plasma ionization in a tokamak configuration.

Further PFC supported current ramp-up provides the additional current $I_{p,2} \sim \Delta\psi/L_{ext} = 0.04$ MA. So, in this case it is possible to provide the average current ramp-up speed of 0.9 MA/s.

Plasma temperature after the ionization above the power threshold is determined by the transport model.

So, the prefill gas pressure could be varied in the range, described above together with EC power to choose the optimal parameters for EC supported current ramp-up phase considered in Sec.4.

As it is shown in Sec.4 the ramp-up is faster for maximal electron temperature and minimal density. So, for further consideration we chose as optimum the minimal prefill gas pressure, permitted by Townsend conditions for U = 4 V, provided in A-SSTR by the PFC system:

$p_0 = 5x10^{-5}$ Torr.

We also notice, that the applied power should not be too high to avoid the appearance of the internal separatrix. It was provided in our calculations by P_{EC} = 3 MW.

The results of the ASTRA simulation of the external voltage supported ionization is shown in Fig.3 with U = 4 V, P_{EC} = 3 MW.

The starting point t = 0 corresponds to the condition of the end of the breakdown with n/N_0 = 0.1 and plasma drift current of 50 kA. The delay of the start of ionization in respect of the time of the voltage application is τ_B = 0.063/U = 16 ms. From the residual gas N and plasma density <n> behavior, we can conclude that the ionization itself takes about 2.5 ms. During this period the applied power P_{EC} is spent mostly to compensate the Hydrogen radiation and ionization losses P_H similar to fully ECCD supported ionization, displayed in Fig.4 of the next section.

After the ionization phase, the plasma temperature starts to increase together with plasma current. The plasma current ramp-up speed is relatively high at this phase dI_p/dt = 0.4 MA/s up to the end of the application of external voltage after 0.1 s. After this the current ramp-up speed reduces to $dI_p/dt \sim$ 1 kA/s. And further ramp-up proceeds with the inductive time scale t ~ L_{ext}/R_{Ω}. Further discharge development is discussed in Sec.4.

3. ECH supported plasma initiation

The plasma initiation with the ECRH was studied both experimentally and theoretically [6,7,8,9]. The theoretical model [8,9] gave reasonable quantitive agreement with the experimental data [6,7]. So, the model could be used for predictive analysis for the A-SSTR.

In this case as it was for Townsend breakdown, the ionization is possible when the particle and energy sources exceed the losses. To define the conditions and process dynamics we start transport simulations from the phase of Coulomb collisions domination (n/N > 0.1), but closed magnetic surfaces do not exist. Plasma transport and equilibrium at this phase could be describe as in ref.[8,9].

At the phase of the absence of the magnetic surfaces we solve 0D analog of the system of 1D transport equations eqs.(5)-(7):

$$dn/dt = - n/\tau + nNS_i, \qquad (12)$$

$$1.5dnT_i/dt = - 1.5\ n_iT_i/\tau + Q_{ei} - Q_{iN}, \quad (13)$$

$$1.5dnT_e/dt = - 1.5\ n_eT_e/\tau + Q_{OH} - Q_{ei} - Q_H - Q_C + Q_{EC}, \quad (14)$$

together with the particle conservation low (9) and current density:

$$j = j_D + j_D, \quad (15)$$

where:

$$j_D = 2\ c\ p/RB_v. \quad (16)$$

is the drift current density [9]. Here we use the following definitions:

$Q = P/V_p$ is an average power density; $\tau = a/(v_x + v_s/k)$ is the confinement time, $k = b/a$ is a ratio of the vertical and transversal vessel sizes (~plasma elongation), $v_x = 2\ p\ c^2/B_v^2\ \sigma\ R$ is the transversal electric drift velocity, $v_s = C_sB_v/B$ is a transversal component of the flux along the field lines, C_s is the ion sound speed, B is the toroidal magnetic field.

We also take into account the plasma pressure limit caused by equilibrium:

$$4\ \pi\ p\ /B_v^2 = R/a. \quad (17)$$

Thus, the toroidal current $I_p = \int j_D\ dS$ in absence of the driven current ($j_{EC} = 0$), could be established at the maximal level of:

$$I_p = c\ k\ a\ B_v/2 \quad (18)$$

If EC system drives extra toroidal current, the limit (18) could be overcome and closed magnetic surfaces could be formed.

Unfortunately there is no theoretical consideration of the smooth transition between the equilibrium without closed magnetic surfaces, considered above, and tokamak configuration. So, we use the above consideration up to the moment, when plasma induced poloidal field B_p compensate the stray field B_v and $\beta_p\varepsilon < 1$. For further current ramp-up we apply equations (5) - (8) with the same transport model [5] using the achieved plasma parameters as initial conditions.

The results of the discharge initiation with EC only are performed in Fig.4. As it is seen from the residual gas N and plasma density <n> behavior the ionization takes the same time 2.5 ms as it was in the PFC supported ionization for the same applied power of 3 MW and the prefill gas pressure of $5x10^{-6}$ Torr.

Drift plasma current limit for $B_v = 0.005$ T of A-SSTR corresponds to $I_{p,lim} = 0.07$ MA. At the phase without closed magnetic surfaces the plasma current is established fast with the confinement time scale $\tau \sim 20$ ms. After the formation of the closed magnetic surfaces it grows slowly with the inductive time scale $L_{ext}/R_\Omega >> \tau$.

Further discharge development with closed magnetic surfaces in a tokamak configuration proceeds the similar way for both types of the discharge initiation.

4. ECH SUPPORTED CURRENT RAMP-UP

The optimal power value for the current ramp-up by external source correspond to the maximum current ramp-up speed $dU/dP_{EC} = 0$. In the case of $dT/dP \neq 0$ this condition reduces [10] to $d\{R_\Omega(W/\tau_E - I_p/\eta)\}/dT = 0$, or:

$$P_{EC,opt} = (3 + 2\gamma)I_p/\eta(1+2\alpha) - I_pU, \qquad (19)$$

where W is the total energy content, $\tau_E \sim T^\alpha$ is the energy confinement time, $\eta \sim T^\gamma$ is the EC current drive efficiency. Thus, the condition (19) would determine the optimal P_{EC} scenario with the maximum speed of the current ramp-up. For the specific case of Bohm diffusivity:

$$\tau_E \sim a^2k/D\ (=a^2kB/63T),\ \alpha = -1. \qquad (20)$$

If we consider ITER power scaling low for the energy confinement time in the H and L modes [2]:

$$\tau_{EH} = 0.0503\ I_p^{0.91}\ R^{2.05}\ \varepsilon^{0.57}\ \kappa^{0.72}\ B_o^{0.15}\ n_{19}^{0.44} A_i^{0.13}\ P^{-0.65},$$

$$\tau_{EL} = 0.023\ I_p^{0.96}\ R^{1.95}\ \varepsilon^{-0.06}\ \kappa^{0.64}\ B_o^{0.03}\ n_{19}^{0.4} A_i^{0.2}\ P^{-0.73}, \qquad (21)$$

we could find out, substituting $1.5nT/\tau_E$ for P, that $\alpha \sim -2.5$.

So, according to (19) there is no maximum and higher P_{EC} gives higher ramp-up speed. Thus, we should choose the scenario with the maximal P_{EC} permitted by natural restrictions. There are a few restrictions which could reduce the optimal current ramp-up speed, the maximal available power:

$$P_{EC} < P_{MAX,0} \ (= 10 \text{ MW}) \tag{22}$$

beta limit $(\beta_p + l_i/2)a/R < 1$, which gives in the dimensional units:

$$P_{EC} < P_{MAX,1} = 0.024\ (R/a-1/4)I_p^2V_p/a^2k\tau_E, \tag{23}$$

where P_{EC} is in MW, I_p is in MA, a is in m, V_p is in m^3, τ_E is in seconds, and the condition, dependent on the distributions of the driven current and plasma resistivity. The point is that if driven current is too peaked in comparison with the plasma resistivity and $I_{CD} > I_p$ as it is at the noninductive current ramp-up phase, the negative Ohmic current could create locally negative total current which in turn cause the appearance of the internal separatrix and discharge disruption. So, this restriction could be in brief expressed like the limitation on the safety factor inside plasma:

$$q < \infty \tag{24}$$

From the other hand to provide the current ramp-up (dI/dt > 0) the driven current value should exceed the plasma current $I_0 > I_p$. This implies the lower limit for the input EC power:

$$P_{EC} > I_p/\eta. \tag{25}$$

Let us substitute the ECCD efficiency dependence:

$$\eta = C_1T_e/n, \tag{26}$$

with $C_1 \sim 0.01$ A/W, T_e is in keV, n is in $10^{19}m^{-3}$. We should note here that accurate expression for C_1 depends on the specific ECCD system parameters. Since they are no specified yet, we will use the simplified parametrization (26) obtained for the ITER EC system from the results of ray-tracing calculation [11].

It is clear, that for the high ECCD efficiency high electron temperature low density scenarios are preferable. So, we propose the low density high electron temperature scenario of the current ramp-up with ECCD (for plasma currents from $I_p \sim 50$ kA to $I_p > 0.5$ MA.

We choose the minimal prefill gas pressure permitted by Townsend conditions ($p_0 = 5\mathrm{x}10^{-6}$ Torr). After the ECRH supported plasma ionization we start programmed ECCD taking account of restrictions (22)-(24).

Low density causes high shine through losses of NBI. Low current could cause the disruption in the case of high pressure of the suprathermal ions when $\varepsilon\beta_p > 1$. So, we increase plasma current up to $I_p = 2$ MA by the ECCD and after this we use the gas puffing to increase density up to the values, necessary to reduce the NBI shine through losses. At this time ECCD efficiency drops so that the ECCD becomes much smaller than the total plasma current $I_{EC} << I_p$. But the skin time of the current decay is much larger than the confinement time. So, after the puffing we receive enough high density without strong changes in plasma current. Thus, we could start further NBI supported inductiveless current ramp-up.

The results of the 1.5D transport simulations of the optimal EC current ramp-up scenario with the ASTRA code are shown in Fig.3. We used here transport model similar to ref. [5] with the L-mode confinement scaling.

At low plasma current $I_p < 0.35$ MA the increase of EC power was limited by the restrictions described above. So, we increase P_{EC} step-wise from 3 MW to 5 MW during this phase. The ECCD current at this phase is $I_{CD} = 1.2\ I_p$ and bootstrap current is $I_{BS} \sim 0.5 - 0.3\ I_p$. For current $I_p >$ 0.35 MA it is possible to use the whole available power $P_{EC} = 5$ MW which provides the current ramp up speed of ~ 1 kA/s and $I_{CD} = 1.2\ I_p$. The fraction of the bootstrap current drops with the plasma current (to about 5% at $I_p = 2$MA).

For the L- and H - mode confinement with $\tau_E \sim I_p$ and CD efficiency $\eta \sim T$ there exists a positive feedback loop: the higher current is, the higher temperature is reached, the higher EC current could be driven, etc. So, the electron temperature and EC current grow together with the plasma current.

Let us derive the simple relation, which enables to estimate and optimize the necessary parameters for the current ramp-up phase. From the steady state energy balance equation depends on plasma parameters as follows: $T \sim G_1\, n^{0.4}\, P^{0.3}\, I_p$, where G_1 is a constant, determined by magnetic field and geometry and profile effects. Substituting this dependence in the expression for the EC driven current we obtain:

$$I_{CD} = C_1 PT/n = C_1 G_1 P^{1.3} I_p/n^{0.6}$$

So, the current ramp up speed $dI_p/dt = R_\Omega(I_{CD} - I_p)/L_{ext}$ taking account of plasma resistivity dependence $R_\Omega \propto Z_{eff}/T^{3/2}$ could be estimated as:

$$dI_p/dt \sim (C_1G_1P^{1.3}/n^{0.6} - 1)\, Z_{eff}/P^{0.45}n^{0.6}I_p^{\,0.5}\,. \qquad (27)$$

This simplified expression should be corrected in the low current range taking account of the bootstrap current.

It is clear from eq. (27) that for each density there exists a power threshold for ECCD current ramp up. Below this threshold ECCD ramp-up is impossible. It is also clear that the ramp-up speed decreases with increase of plasma current.

The upper limit for the fully EC current ramp-up speed is determined by the runaway electrons $E < 0.06\ E_{Dr}$ [10] taking account the Dricer field dependence $E_{Dr} \propto n/T$:

$$L_{ext}dI_p/t < U_{Dr} \sim n^{0.6}/P^{0.3}I_{p.} \qquad (28)$$

So, eqs. (27), (28) determined the operational space where fully ECCD supported current ramp-up is possible. More detailed studies of the operational space limits by 1.5D calculations are necessary after any specific ECCD system would be proposed for A-SSTR.

5. CONCLUSIONS

We analyzed here the possibility of fully ECCD and PFC supported ECCD plasma initiation and current ramp up in the A-SSTR tokamak. The analysis is carried out analytically and by the time dependent self consistent plasma transport simulations with the ASTRA code.

Necessary conditions and operational limits for plasma initiation and current ramp up are obtained.

Two different types of scenarios with and without PFC support are performed. It was demonstrated that 5 MW of EC power could provide plasma initiation and current ramp-up speed of about 1 kA/s.

To reduce the NBI shine through losses and the influence of the suprathermal particle pressure on the equilibrium stability *the advanced scenario is proposed.* It is proposed to increase plasma current to 2 MA using the ECCD only in the low density high temperature plasma, After this the density could be increased (T_e reduced) by gas puffing in the transport time scale, i.e. much faster than skin time of plasma current reduction, and NBCD current ramp-up could be started.

The requirements to the ECCD system should take into account of the possibility of EC current profile control. This could enable to avoid the disruptions ($q(r<a) >> 1$) caused by appearance of the internal separatrix due to peaked Ohmic currents and optimize the current ramp up speed.

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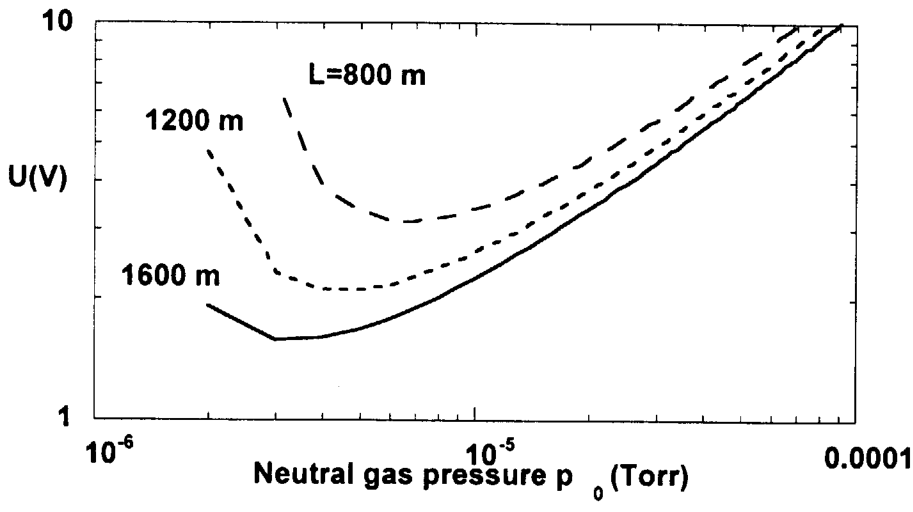

Fig.1 Minimal voltage for Townsend breakdown as a function of the prefill gas pressure p_0.

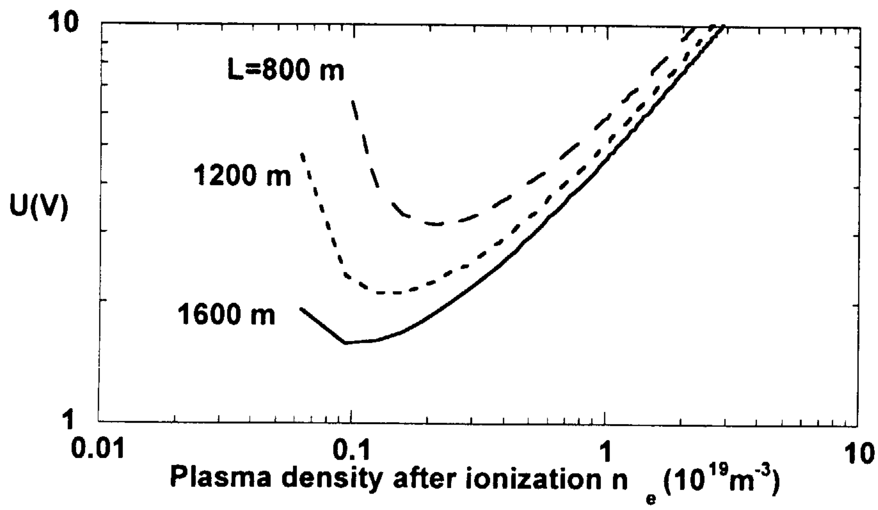

Fig.2 Minimal voltage for Townsend breakdown as a function of the final density after plasma ionization in 20% of pumping volume ($\delta = 5$).

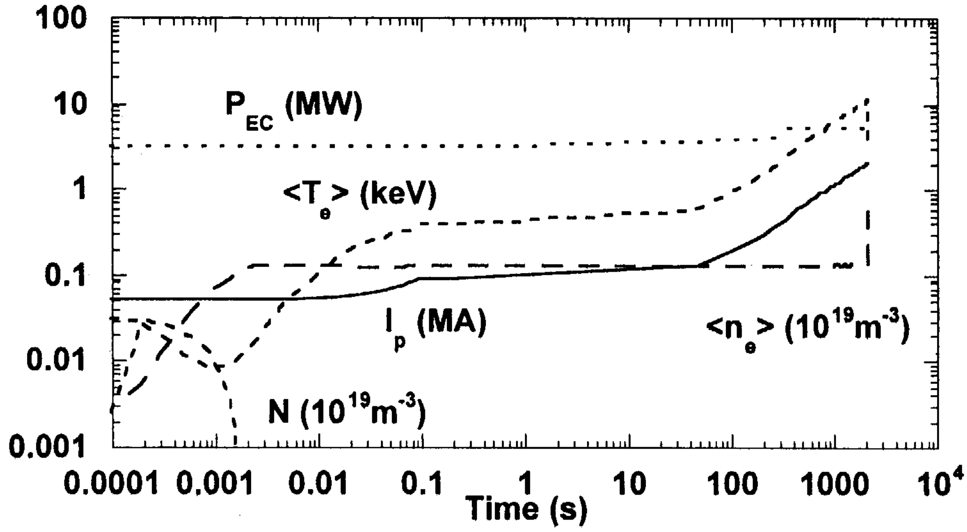

Fig.3. PFC supported ECCD current ramp-up scenario I_p(Time). Loop voltage U_{ext} = 4 V was applied until 0.1 s. EC power P_{EC} was changed from 3 MW to 5 MW. $\langle n_e \rangle$ is the volume averaged plasma density, N is the residual gas density, and $\langle T_e \rangle$ is the density weighted electron temperature.

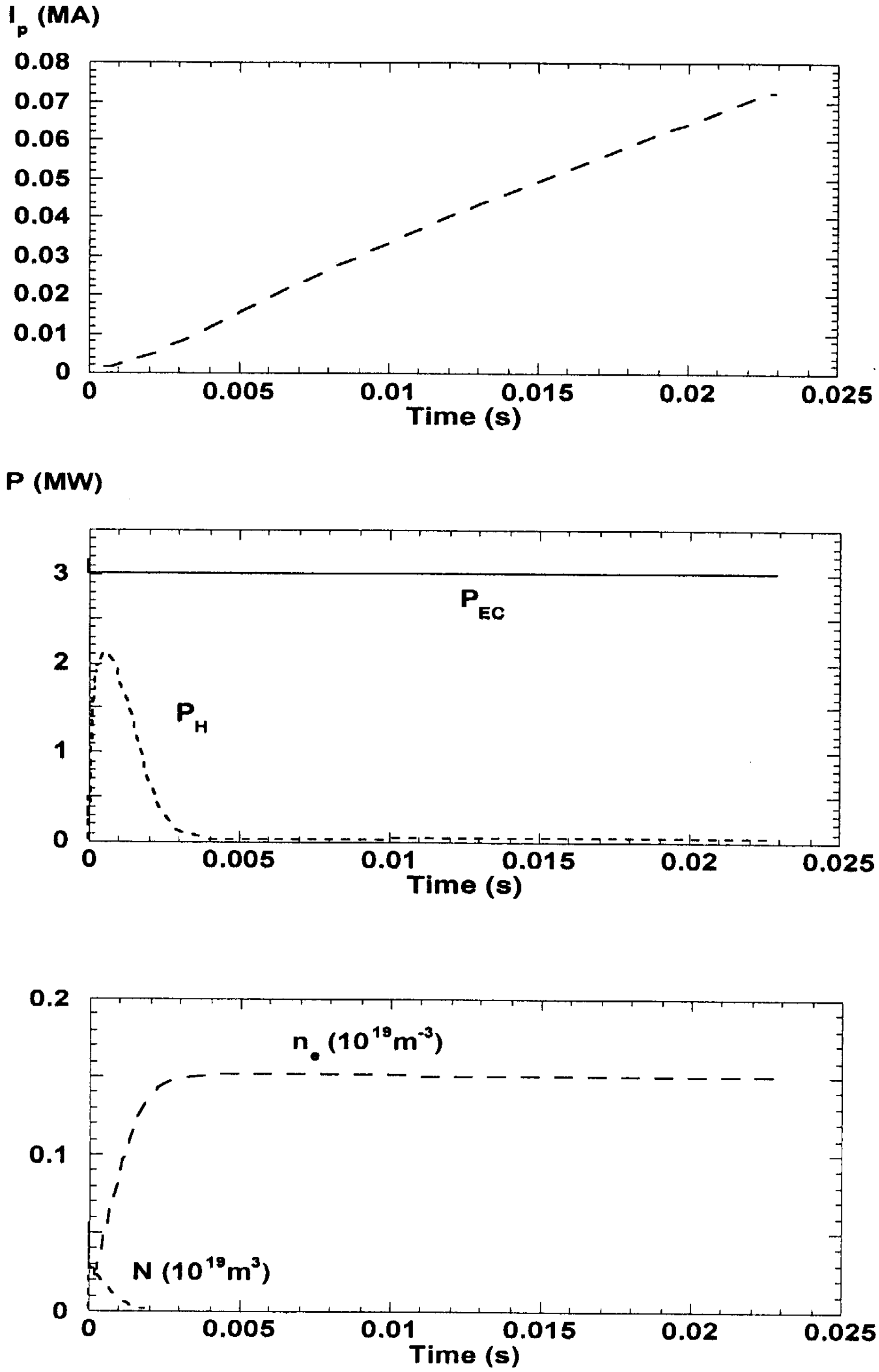

Fig.4 Full EC supported plasma initiation at the phase of the absence of closed magnetic surfaces (I_p < 0.07 MA). I_p is the total plasma current. P_{EC} and P_H are the absorbed EC power and volumetric energy losses due to radiation and ionization, $\langle n_e \rangle$ is the volume averaged plasma density, N is the residual gas density.

国際単位系 (SI) と換算表

表 1　SI 基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表 2　SI と併用される単位

名称	記号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

$1\ \mathrm{eV} = 1.60218 \times 10^{-19}\ \mathrm{J}$
$1\ \mathrm{u} = 1.66054 \times 10^{-27}\ \mathrm{kg}$

表 5　SI 接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

表 3　固有の名称をもつ SI 組立単位

量	名称	記号	他の SI 単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m \cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー，仕事，熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表 4　SI と共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

$1\ \text{Å} = 0.1\ \mathrm{nm} = 10^{-10}\ \mathrm{m}$
$1\ \mathrm{b} = 100\ \mathrm{fm}^2 = 10^{-28}\ \mathrm{m}^2$
$1\ \mathrm{bar} = 0.1\ \mathrm{MPa} = 10^5\ \mathrm{Pa}$
$1\ \mathrm{Gal} = 1\ \mathrm{cm/s^2} = 10^{-2}\ \mathrm{m/s^2}$
$1\ \mathrm{Ci} = 3.7 \times 10^{10}\ \mathrm{Bq}$
$1\ \mathrm{R} = 2.58 \times 10^{-4}\ \mathrm{C/kg}$
$1\ \mathrm{rad} = 1\ \mathrm{cGy} = 10^{-2}\ \mathrm{Gy}$
$1\ \mathrm{rem} = 1\ \mathrm{cSv} = 10^{-2}\ \mathrm{Sv}$

(注)

1. 表 1 － 5 は「国際単位系」第 5 版，国際度量衡局 1985 年刊行による。ただし，1 eV および 1 u の値は CODATA の 1986 年推奨値によった。
2. 表 4 には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. bar は，JIS では流体の圧力を表わす場合に限り表 2 のカテゴリーに分類されている。
4. EC 閣僚理事会指令では bar，barn および「血圧の単位」mmHg を表 2 のカテゴリーに入れている。

換　算　表

力	$N(=10^5 dyn)$	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　$1\ \mathrm{Pa \cdot s}(\mathrm{N \cdot s/m^2}) = 10\ \mathrm{P}$(ポアズ)$(\mathrm{g/(cm \cdot s)})$

動粘度　$1\ \mathrm{m^2/s} = 10^4\mathrm{St}$(ストークス)$(\mathrm{cm^2/s})$

圧力	MPa(=10 bar)	kgf/cm^2	atm	mmHg(Torr)	$lbf/in^2(psi)$
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	$J(=10^7 erg)$	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal ＝ 4.18605 J (計量法)
　＝ 4.184 J (熱化学)
　＝ 4.1855 J (15 °C)
　＝ 4.1868 J (国際蒸気表)

仕事率　1 PS (仏馬力)
　＝ 75 kgf·m/s
　＝ 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

(86 年 12 月 26 日現在)

SOLUTION EXPLORATION OF PLASMA INITIATION AND CURRENT RAMP-UP SCENARIO IN A-SSTR