Plasma Current Ramp-up by the Vertical Field and Heating Power in the CTF Device

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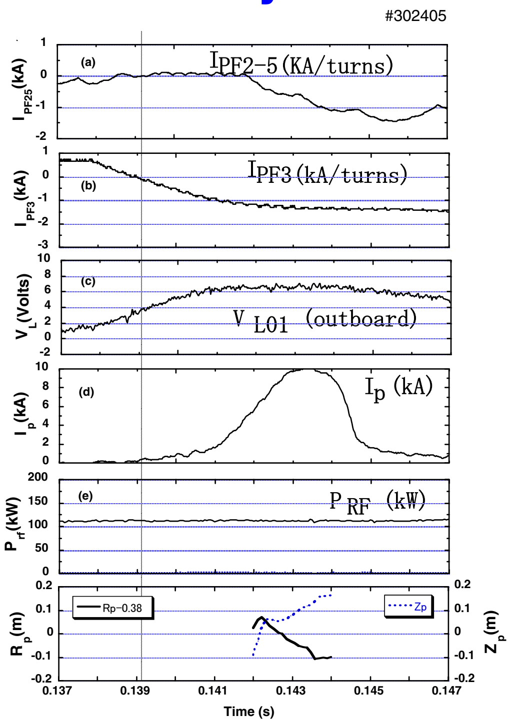
4. Summary

1. Recent progress of CS-less operation in Japan

[1] In TST-2 spherical tokamak, the plasma current up to 10 kA has been achieved by the vertical field and ECRH.



O. Mitarai, Y. Takase A. Ejiri, S. Shiraiwa, H. Kasahara, T. Yamada, S.Ohara, TST-2 Team, K. Nakamura, A. Iyomasa, M. Hasegawa, H. Idei, M. Sakamoto, K. Hanada, K. N. Satoh H. Zush), TRIAM Group and N. Nishino

"Plasma Current Start-up by ECW and Vertical Field in the TST-2 Spherical Tokamak"
Journal of Plasma and Fusion Research **80 No.07 (2004) RC0083**

[2] Recently, in the CS-less operation without any inner VT coil, the plasma current up to 110 kA has been achieved by ECRH and vertical field in JT60-U. (Takase, Mitarai, Ide, Suzuki et al) Model calculation predicted 140 kA.

2. Formula for calculation

[1] Plasma circuit equation with vertical field and divertor coils

(for initial start-up phase)

$$L_p \frac{dI_p}{dt} \quad R_p(I_p \quad I_{CD} \quad I_{BS}) \qquad M_{PV}\frac{dI_V}{dt} \quad M_{Psh}\frac{dI_{sh}}{dt} \quad M_{Pdiv}\frac{dI_{div}}{dt}$$

$I_{CD} \quad \frac{-_{CD}}{nR_o} P_{CD},$ $_{CD}$ = 1.25x10[19] [Am^{-2}W^{-1}], $f_{BS} \quad I_{BS}/I_p \quad C_{BS}\sqrt{\quad} \quad _p$

C_{BS} = 0.6, $R_p \quad {}_{NC}\frac{2 \; R}{a^2}$

[2]. Equivalent plasma circuit method (for overall knowledge)

$_{div}$ = I_{div}/I_p and $_{sh}$ = I_{sh}/I_V, $\quad B_{VE} \quad B_{zoV}I_V \quad B_{zosh}I_{sh} \quad B_{zodiv}I_{div}$

$$L_{peff}\frac{dI_p}{dt} \quad R_{peff}I_p \quad \frac{M_{PV} \quad M_{Psh} \;\; _{sh}}{B_{zoV} \quad B_{zosh} \;\; _{sh}} \frac{dB_{VE}}{dt} \qquad L_{peff} \quad L_p \quad M_{Pdiv} \quad \frac{M_{PV} \quad M_{Psh} \;\; _{sh}}{B_{zoV} \quad B_{zosh} \;\; _{sh}} B_{zodiv} \quad _{div}$$

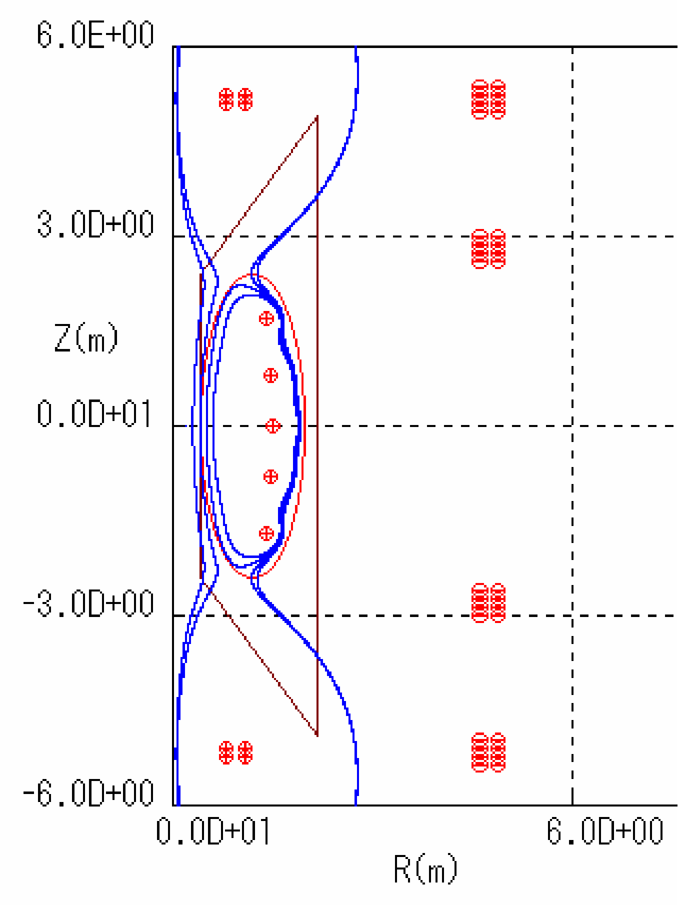
L_p =0. 580x10^{-6} H, L_{peff} =0. 595x10^{-6} H.

[3]. Separate coil current method (for second, divertor coil activation phase)

$$L_p\frac{dI_p}{dt} \quad R_{peff}I_p \quad \frac{M_{PV} \quad M_{Psh} \;\; _{sh}}{B_{zoV} \quad B_{zosh} \;\; _{sh}}\frac{dB_{VE}}{dt} \quad M_{Pdiv} \quad \frac{M_{PV} \quad M_{Psh} \;\; _{sh}}{B_{zoV} \quad B_{zosh} \;\; _{sh}} B_{zodiv} \frac{dI_{div}}{dt}$$

Poloidal coil layout in CTF and simple magnetic surface for I_p=10 MA.

The total current of the divertor coil is +72 MA, and the total current of the shaping and vertical field coil are -8 MA, respectively



2.3. 0-D particle and energy balance equations with control algorithm

$$\frac{dn_T(0)}{dt} = (1 + \ _n)\, S_T(t) - (1 + \ _n)\, n_D(0)n_T(0)\overline{<\ v>_{DT}(x)} - \frac{n_T(0)}{\ _T^*}$$

$$\frac{dn_D(0)}{dt} = (1 + \ _n)\, S_D(t) - (1 + \ _n)\, n_D(0)n_T(0)\overline{<\ v>_{DT}(x)} - \frac{n_D(0)}{\ _D^*}$$

$$\frac{dn\ (0)}{dt} = (1 + \ _n)\, n_D(0)\, n_T(0)\overline{<\ v>_{DT}(x)} - \frac{n\ (0)}{\ ^*}$$

$$\frac{dT_i(0)}{dt} = \frac{1 + \ _n + \ _T}{1.5\ e\ (f_D + f_T + 1/\ _i + f\ )\, n_e(0)}\left[P_{EXT}/V_o + \overline{P}\ + \overline{P}_{oh} - \left\{\overline{P}_L + \overline{P}_b + \overline{P}_S\right\}\right]$$

$$- \frac{T_i(0)}{(f_D + f_T + 1/\ _i + f\ )\, n_e(0)}\left[\left\{1 + \frac{1}{\ _i\,(1 - (1 + \ _n)Zf_{imp})}\right\}\frac{dn_D(0)}{dt} + \left\{1 + \frac{1}{\ _i\,(1 - (1 + \ _n)Zf_{imp})}\right\}\frac{dn_T(0)}{dt} + \left\{1 + \frac{2}{\ _i\,(1 - (1 + \ _n)Zf_{imp})}\right\}\frac{dn\ (0)}{dt}\right]$$

Confinement time

$$\ _{IPB(y,2)}[s] = \ _{HH}\, 0.0562\, A_i^{0.19}\, I_p^{0.93}[MA]\, \bar{n}_{19}^{0.41}[x10^{19}m^{-3}]\, R^{1.97}[m]\ \ ^{0.58}[m]x\ \ ^{0.78}\, B_t^{0.15}[T]\, /P_{HT}^{0.69}[MW]$$

$$\ _{NA}[s] = 7.1\ \ 10^{-22}\, \bar{n}\left[cm^{-3}\right] R^{2.04}[cm]\, a^{1.04}\, [cm]\sqrt{q(a)}$$

[1] $\ _E = \min\{\ _{NA},\ \ _{IPB98}\}$ **(First part)**

[2] $\ _E = \ _{IPB98}$ **(Second part)**

[3] $1/\ _E^{\,2} = 1/\ _{NA}^{\,2} + 1/\ _{IPB98}^{\,2}$ **(Not in use here)**

(1) External heating power (Mainly preprogram in this study)

$$P_{EXT}(HL)\ [W] = M_{HL0}(t) x 10^{6}\ \overline{P}_{thresh} - \left(\overline{P}_{oh} + \overline{P} - \overline{P}_{b} - \overline{P}_{s}\right) V_{o}$$

with H-mode power threshold $M_{HL0}=15$

$$\overline{P}_{thresh}\ [MW] = 2.84\ \overline{n}^{0.58}\ [10^{20}\ m^{-3}]\ B_t^{0.82}\ [T]\ R^{1.0}[m]\ a^{0.81} / A_i$$

(2) Current drive power (PI control T_{int}=5 sec)

$$P_{CD}(I_p) = 100x10^{6} G_{PCD} \left\{ e_{IP,n} + \frac{1}{T_{IPint}} \bullet_{i=0}^{n-1} e_{IP}(i\ \ T)\ \ T \right\}$$

$$e_{IP}(t) = \left(1 - \frac{I_p(t)}{I_{po}(t)} \right)$$

The actual heating/current drive power P_{CD} is determined by the maximum value $P_{CD} = \max\{P_{EXT}(HL), P_{CD}(I_p)\}$

(3) Fueling control (PID control T_{int}=3 sec, T_d=0.01~1 sec)

$$S_{DT}(t) = S_{DT0} G_{SDT}(t) \left\{ e_{Pf}(n\ \ T) + \frac{1}{T_{DTint}} \bullet_{i=0}^{n-1} e_{Pf}(i\ \ T)\ \ T + \frac{T_{DTd}}{T} \left(e_{Pf}(n\ \ T) - e_{Pf}((n-1)\ \ T) \right) \right\}$$

$$e_{Pf}(t) = \left(1 - \frac{P_f(t)}{P_{fo}(t)} \right)$$

Table 1. CTF assumed plasma parameters

Major radius:	R= 1.2 m	Enhancement factor:	$_{HH}$=0.6 ~2.2 (IPB98(y,2))
Minor radius:	a = 0.8 m	Peak electron density:	n(0) ~ 3.6 x10^{20} m^{-3}
Aspect ratio:	A = 1.5	Greenwald density limit1:	n_{GW} ~ 6.8x10^{20} m^{-3} (for I_p = 10 MA)
Toroidal field:	B_t = 2.5 T	Peak temperature:	T_i(0) ~ 15 keV
Elongation:	= 3	Effective ion charge:	Z_{eff} ~ 1.3
Internal inductance	$_i$ = 0.5	Confinement time	$_E$ ~ 0.6~0.7 s
Plasma current:	I_p ~ 10 MA	Fusion power	P_f=300 MW
Temperature ratio:	$_i$ = T_i / T_e= 0.95		
Density profile:	$_n$ = 0.5		
Temperature profile:	$_T$ = 1.0		

Plasma inductance (= 3) L_p ~ 0.589 H

Mutual inductance between PF3 coil and plasma: M_{PV} = 6.08x10^{-6} H/A, B_{zoV} =1.33x10^{-6} T/A

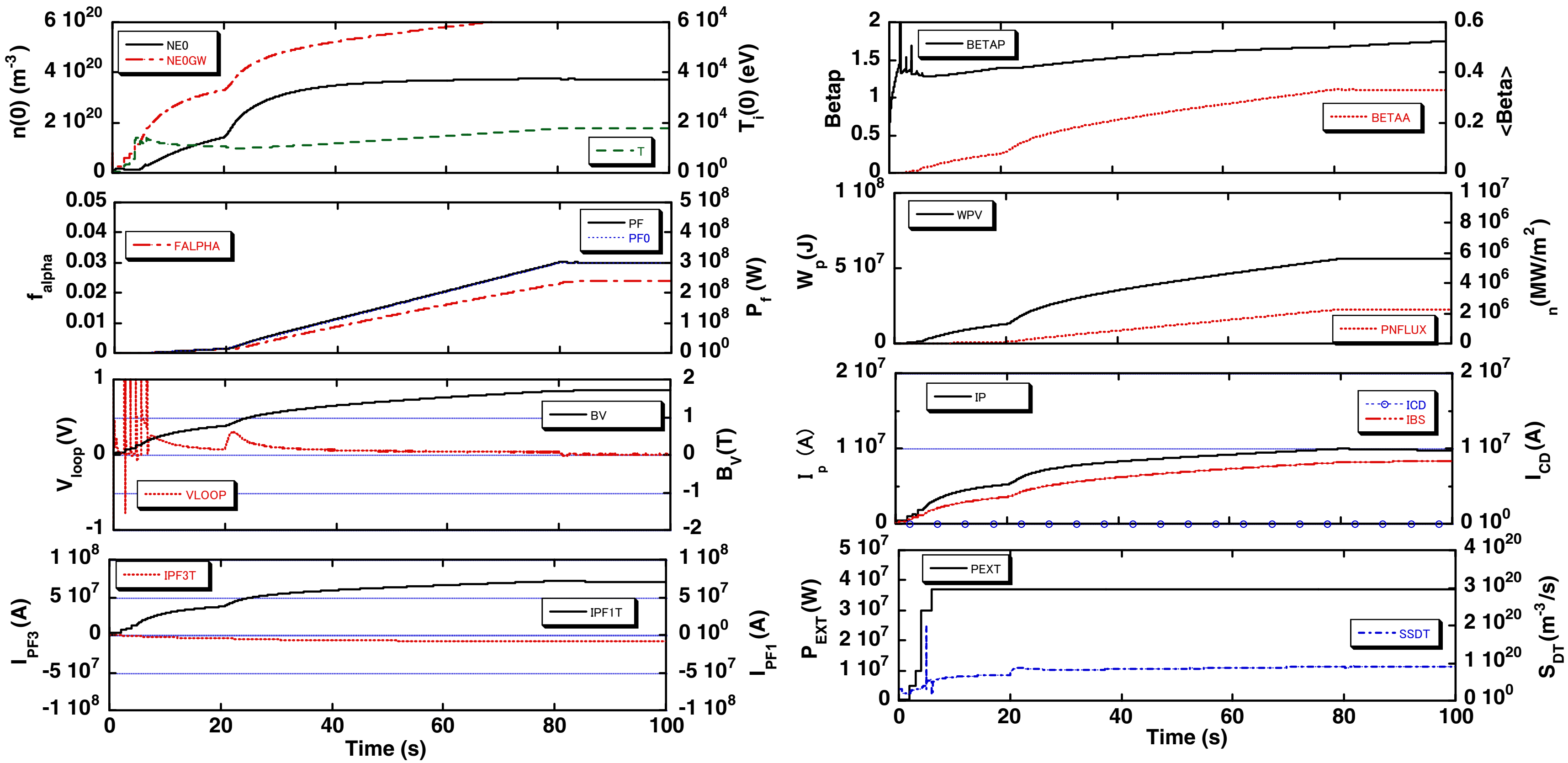
Mutual inductance between PF2 coil and plasma: M_{Psh} = 2.91x10^{-6} H/A, B_{zosh} = 0.631x10^{-6} T/A

Mutual inductance between PF1 coil and plasma: M_{Pdiv} =0.132x10^{-6} H/A, B_{zodiv} = 0.0272x10^{-6} T/A

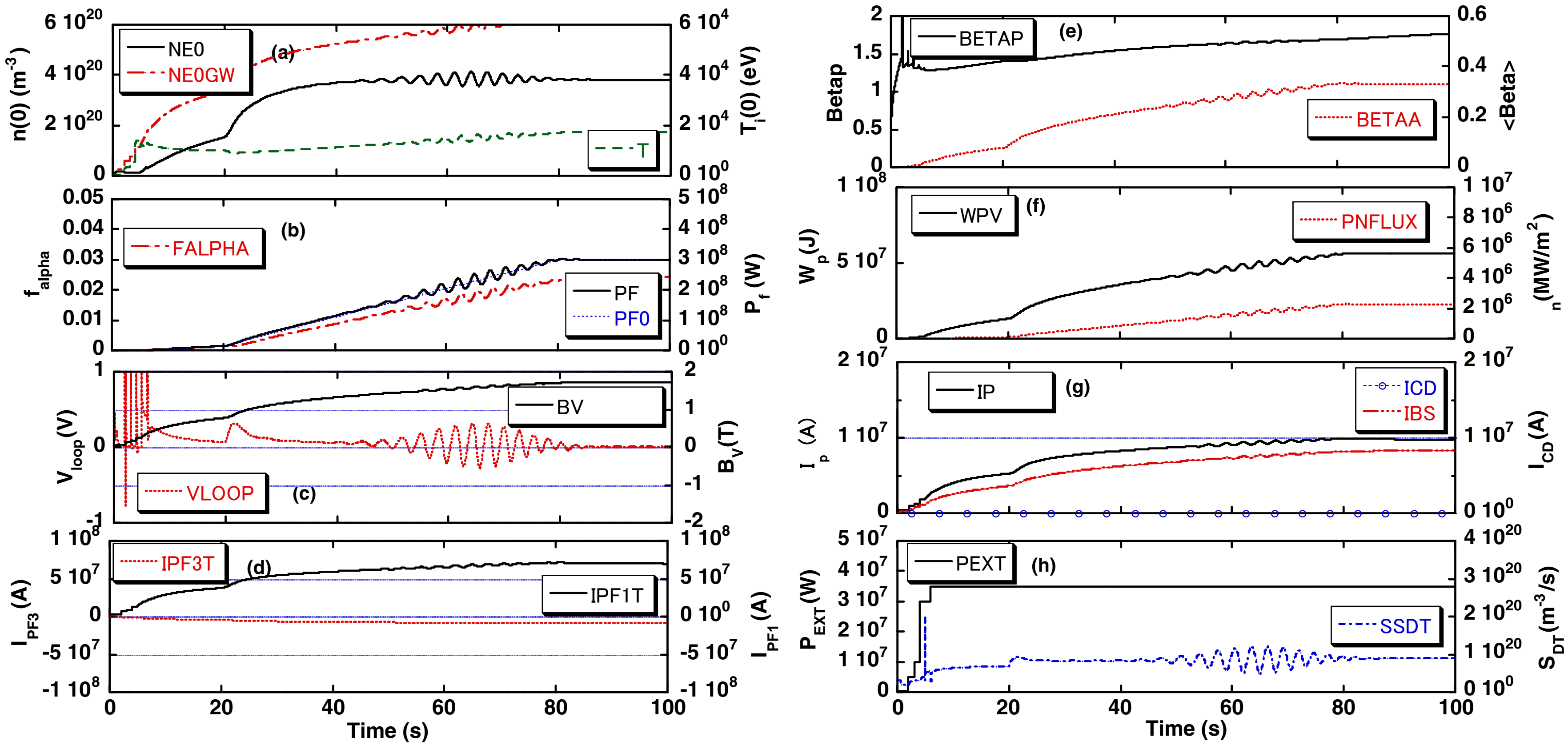
3. Calculated results

3.1. Equivalent circuit model（ $_E$=min{ $_{NA}$, $_{IPB98}$})

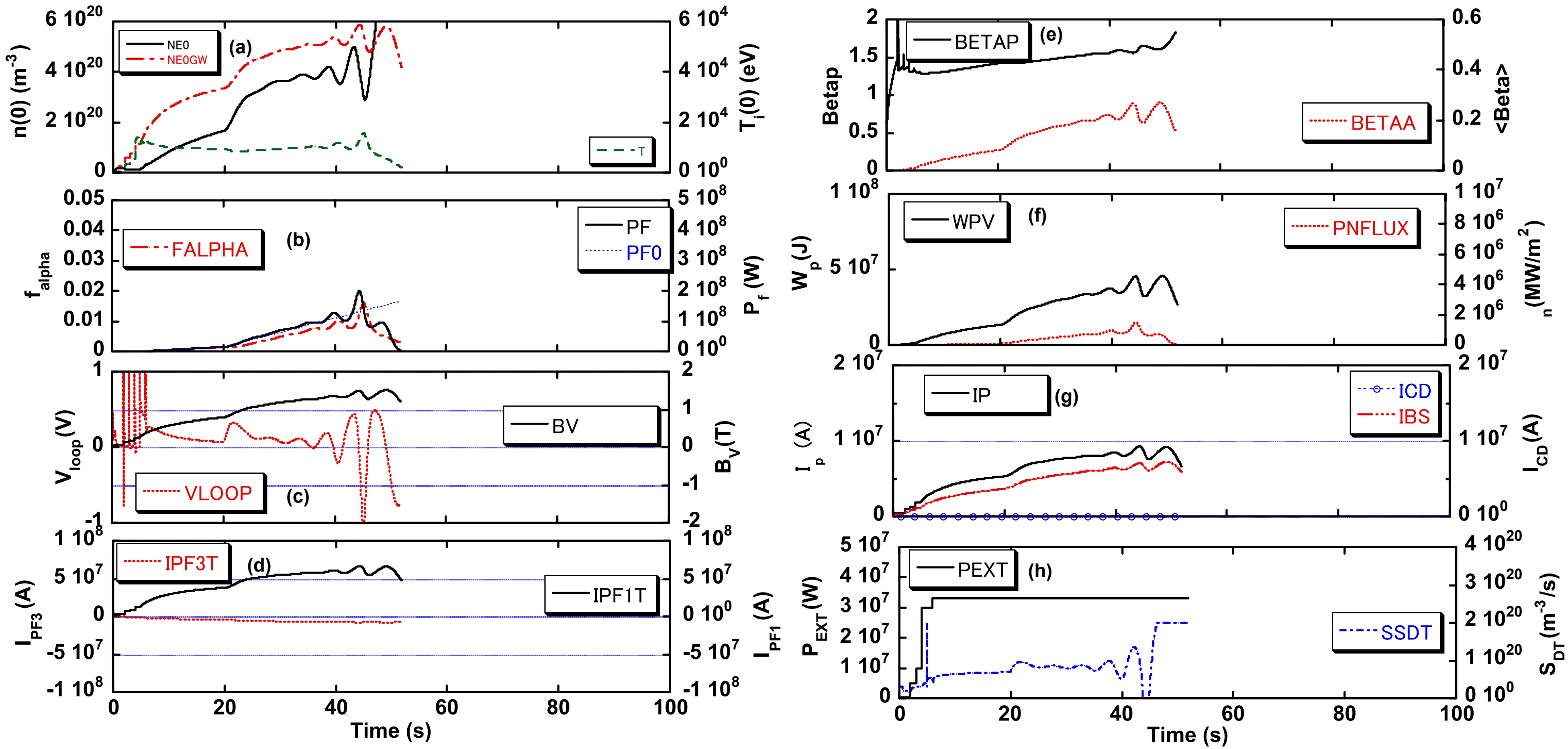
For $_{CD}$ = 0 [Am^{-2}W^{-1}], the external heating power of 37 MW together with the fusion power up to 300 MW increases the plasma current up to 10 MA. As the non-inductive driven current does not exist in this case and the bootstrap current is ~80 % (for C_{BS}=0.6), the plasma current is slowly reduced after peak of 10 MA.



When the heating power is slightly decreased to 35 MW, the operating point can be reached but the oscillation in plasma parameters takes place.

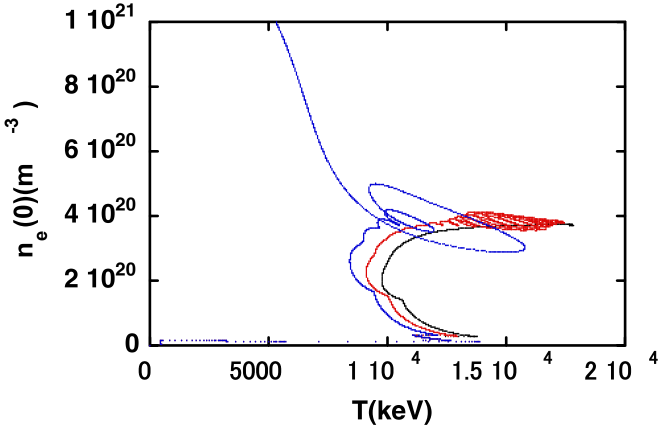


When the heating power is further decreased to 33 MW, the steady operating point cannot be obtained because the plasma parameter oscillation grows and the discharge is eventually terminated.

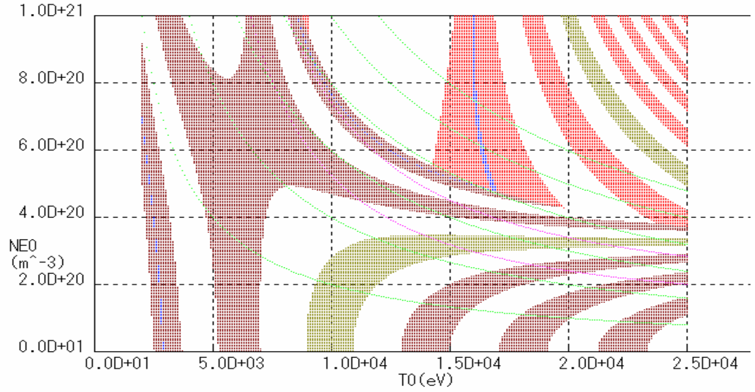


The reason of these oscillations and termination is understood using POPCON.

As the height of the contour line during accessing the operating point is high for NA, it is difficult to reach the operating point with the smaller heating power.



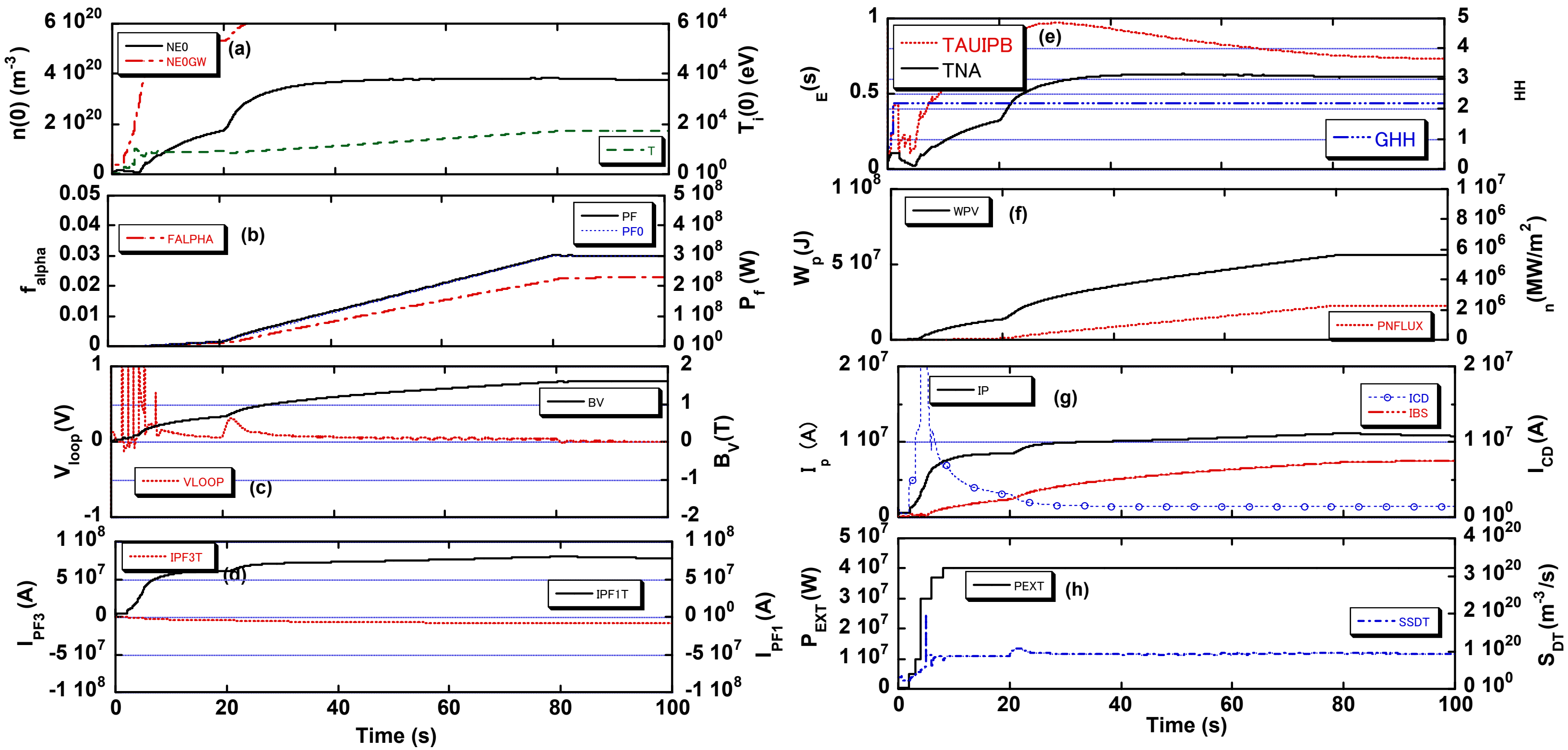
Operation path



POPCON for f_{ash} =0.012

When the non-inductive current drive efficiency with $_{CD}$ = 1.25x10^{19} [$Am^{-2}W^{-1}$] exists, the same plasma current should be obtained by the smaller heating power than 37 MW. However, the discharge is terminated with P_{EXT}=37 MW and needs 40 MW.

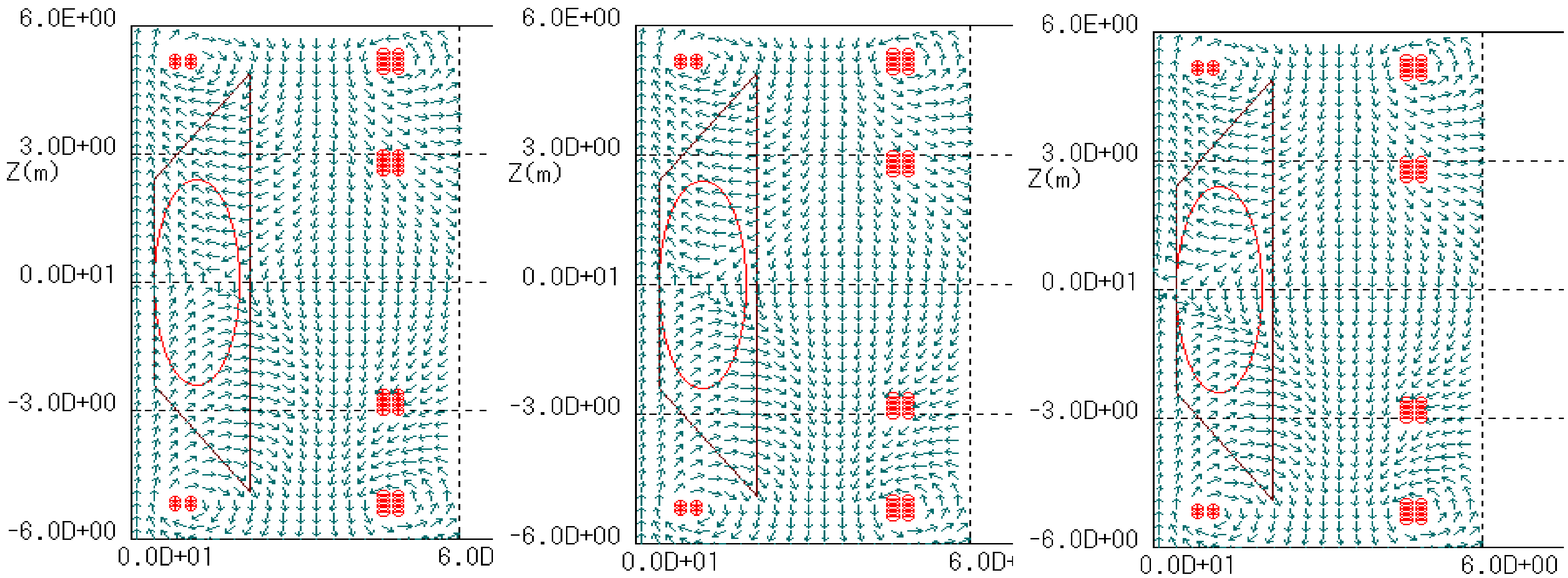
<u>This is in contradiction to our intuition</u>.



Reason: During discharge, the Neo-Alcator scaling is dominant. Therefore, the larger plasma current decreases the confinement time through the Neo-Alcator scaling with $q^{0.5}$ (q is the safety factor), leading to necessity of larger heating /current drive power.

3.2. Separate coil current method with $_E$=min{ $_{NA}$, $_{IPB98}$},

The null point is created when the coil current ratio is maintained. In the outward region of this null point, the normal vertical field for equilibrium is generated. (No vacuum chamber current effect). The null point moves inward with time.



The magnetic field vector in the breakdown phase;
(a) I_{PF1}=+80 kA total, I_{PF2}=-6.4 kA total, and I_{PF3}=0 kA,
(b) I_{PF1}=+80 kA total, I_{PF2}=-6.626 kA total, and I_{PF3}=-0.215 kA total,
(c) I_{PF1}=+80 kA total. I_{PF2}=-6.85 kA total, and I_{PF3}=-0.429 kA total

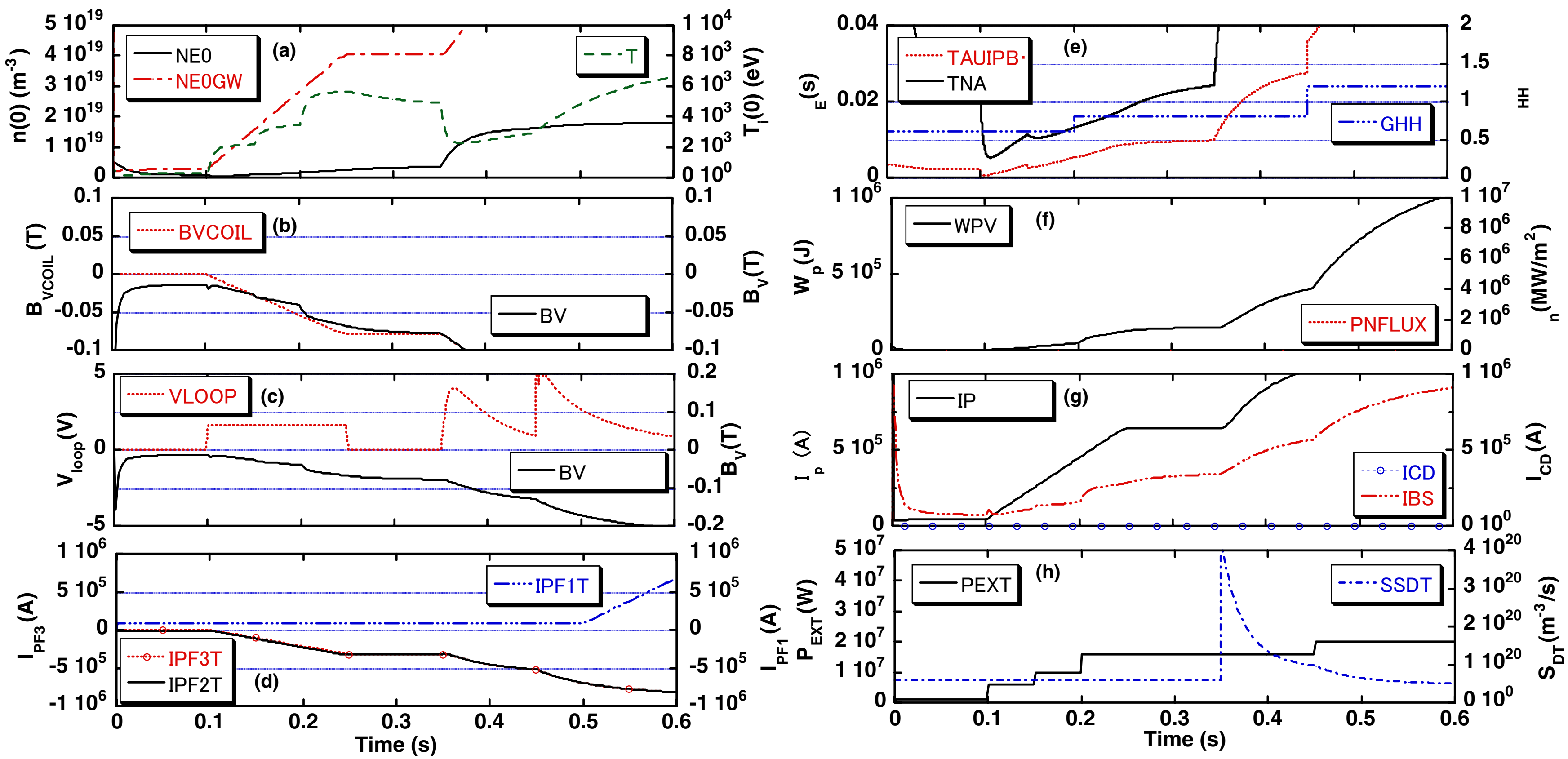
[1] Initial phase controlled by PF1, PF2 and PF3 coils.

The plasma current is ramped up to ~0.67 MA when

I_{PF1}(total) =+80 kA is maintained,

I_{PF2} (total) = -6.4 kA → -320 kA

I_{PF3} (total) = 0 kA → -320 kA

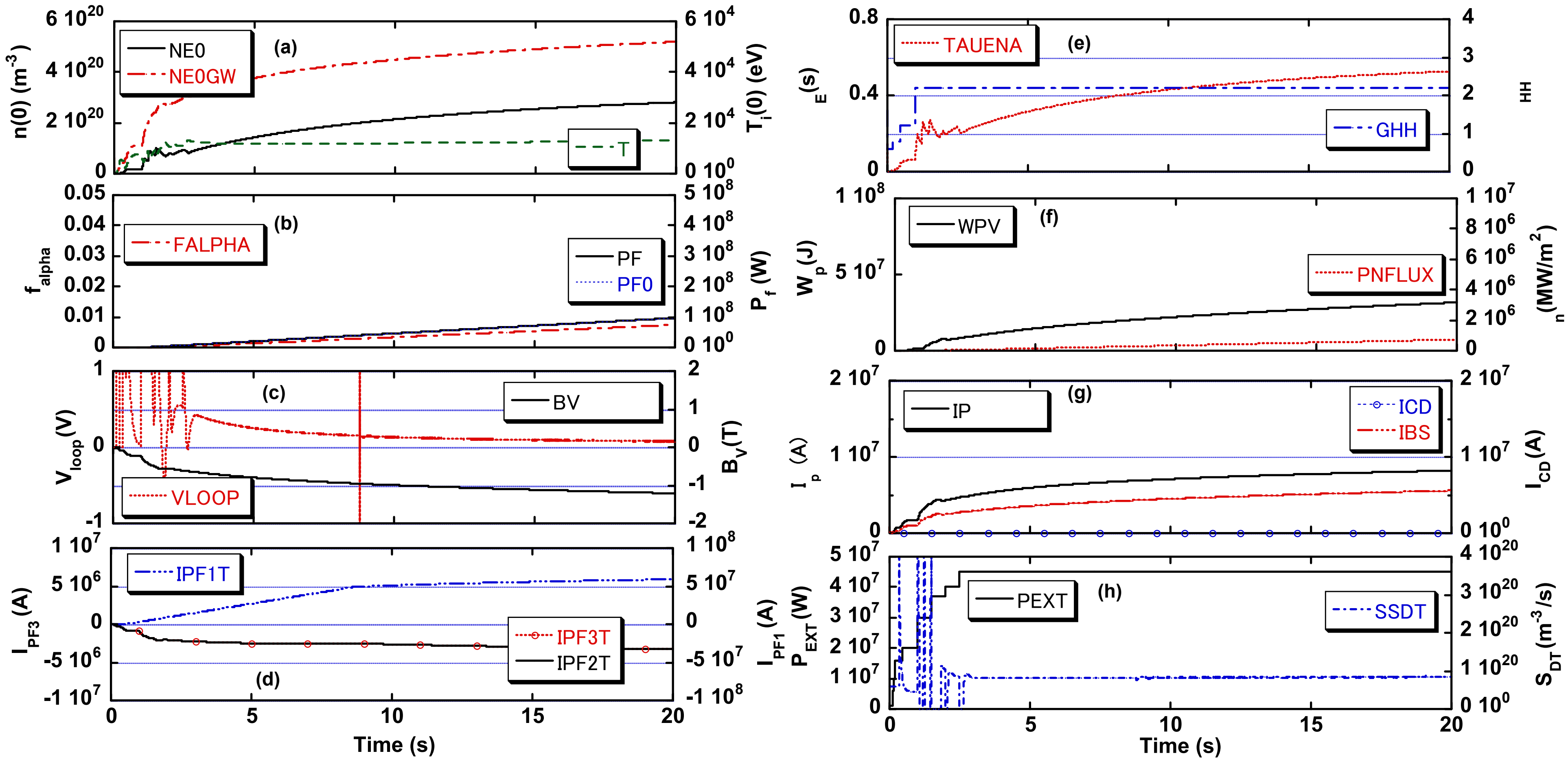


@ Initial phase is determined by IPB(y,2) scaling.

[2] Divertor coil activation phase $_E$=min{ $_{NA}$, $_{IPB98}$},

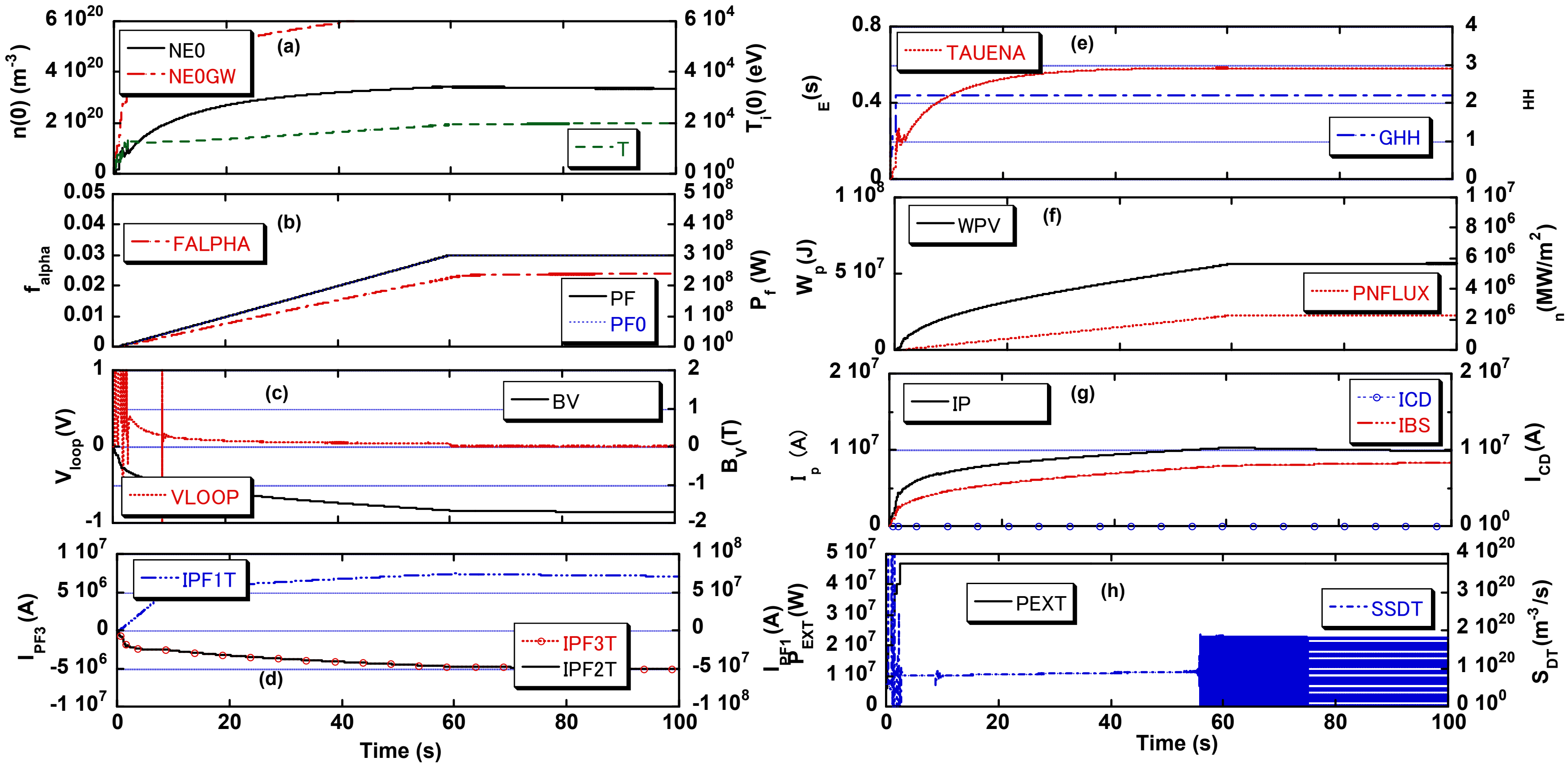
When the divertor coil current I_{div} reaches $_{div}I_p$, it is now set to be proportional to the plasma current with $_{div}$= 1.8. Reverse induction by divertor coil is not large.

Fig. 8



[3] The long time behavior up to 100 s (P_{EXT}= 45 MW, $_{CD}$ = 0 [$Am^{-2}W^{-1}$], $_{E}$=min{ $_{NA}$, $_{IPB98}$},)

The plasma current of 10 MA is finally obtained. **(We should note that the slower ramp rate of the fusion power can reduce the heating power to the operating point with P_{EXT} =43 MW and t_{ramp}=200 sec.)**

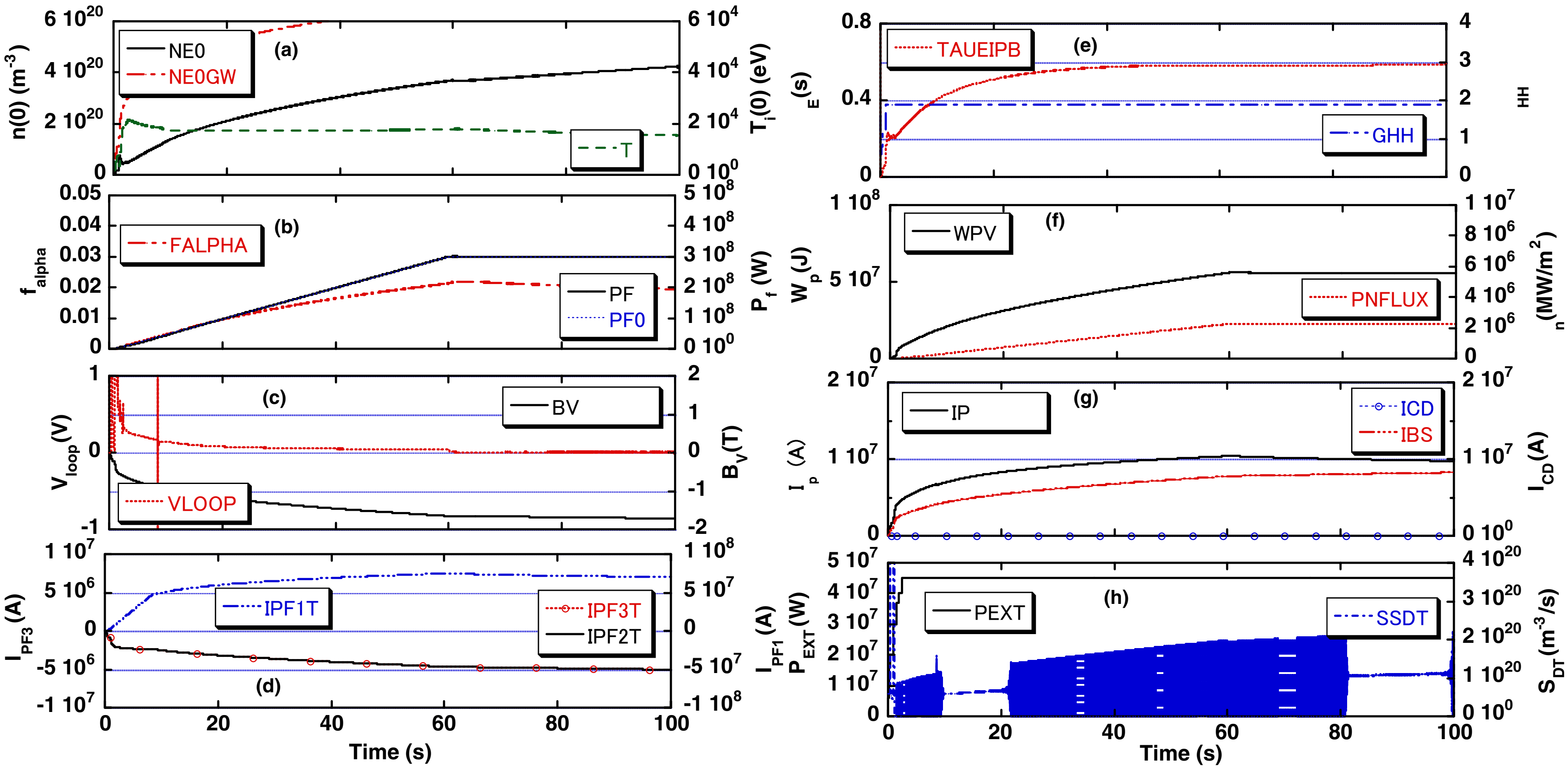


3.3. Separate coil current method with $_E$= $_{IPB98}$

[1] $_{CD}$ = 0 [$Am^{-2}W^{-1}$], P_{EXT}=45 MW, $_{HH}$=1.9, (T_d=0.5 s, T_{int}=3 s)

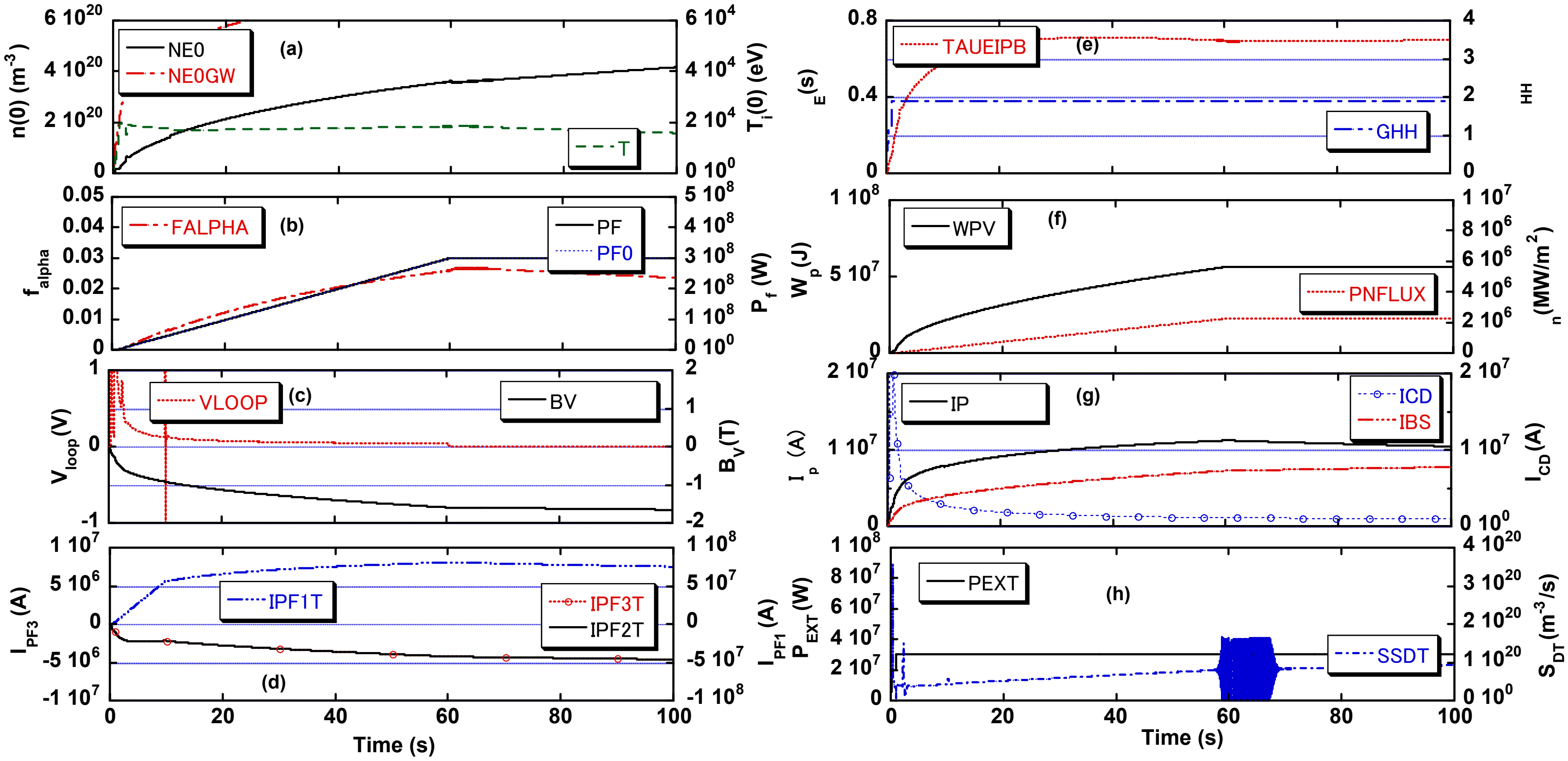
When no current drive exists, 45 MW is needed to obtain 10 MA.

(Note: Density and temperature has no steady state.)



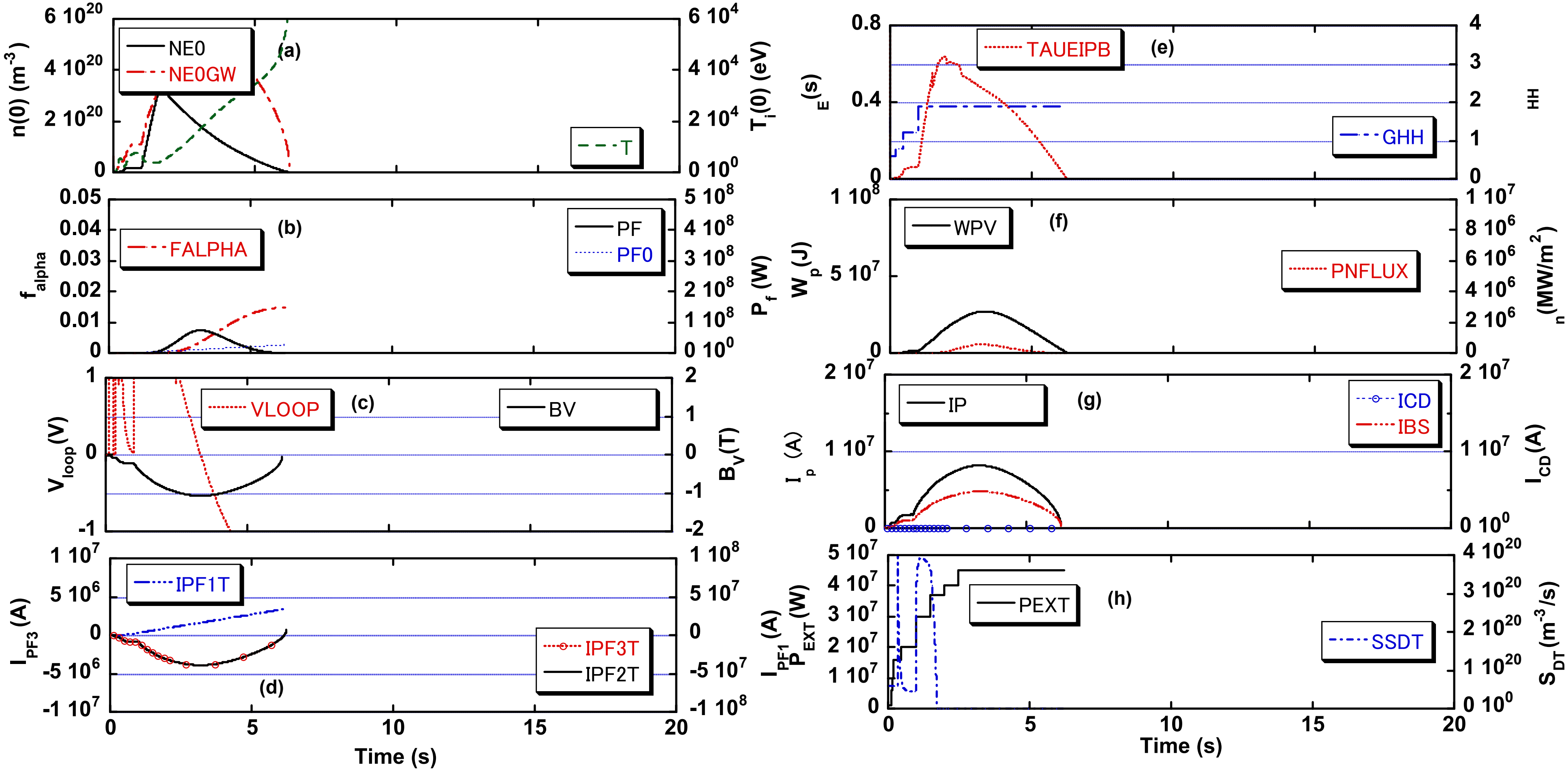
[2] $_{CD}$ = 1.25x10^{19} [Am^{-2}W^{-1}], P_{EXT}=30 MW, $_{HH}$=1.9, (T_d=0.1 s, T_{int}=3 s)

On the other hand, if the current drive capability exists, the heating/current drive power can be reduced to 30 MW for 10 MA ramp-up. IPB(y,2) scaling provides reasonable results with respect to the plasma current.



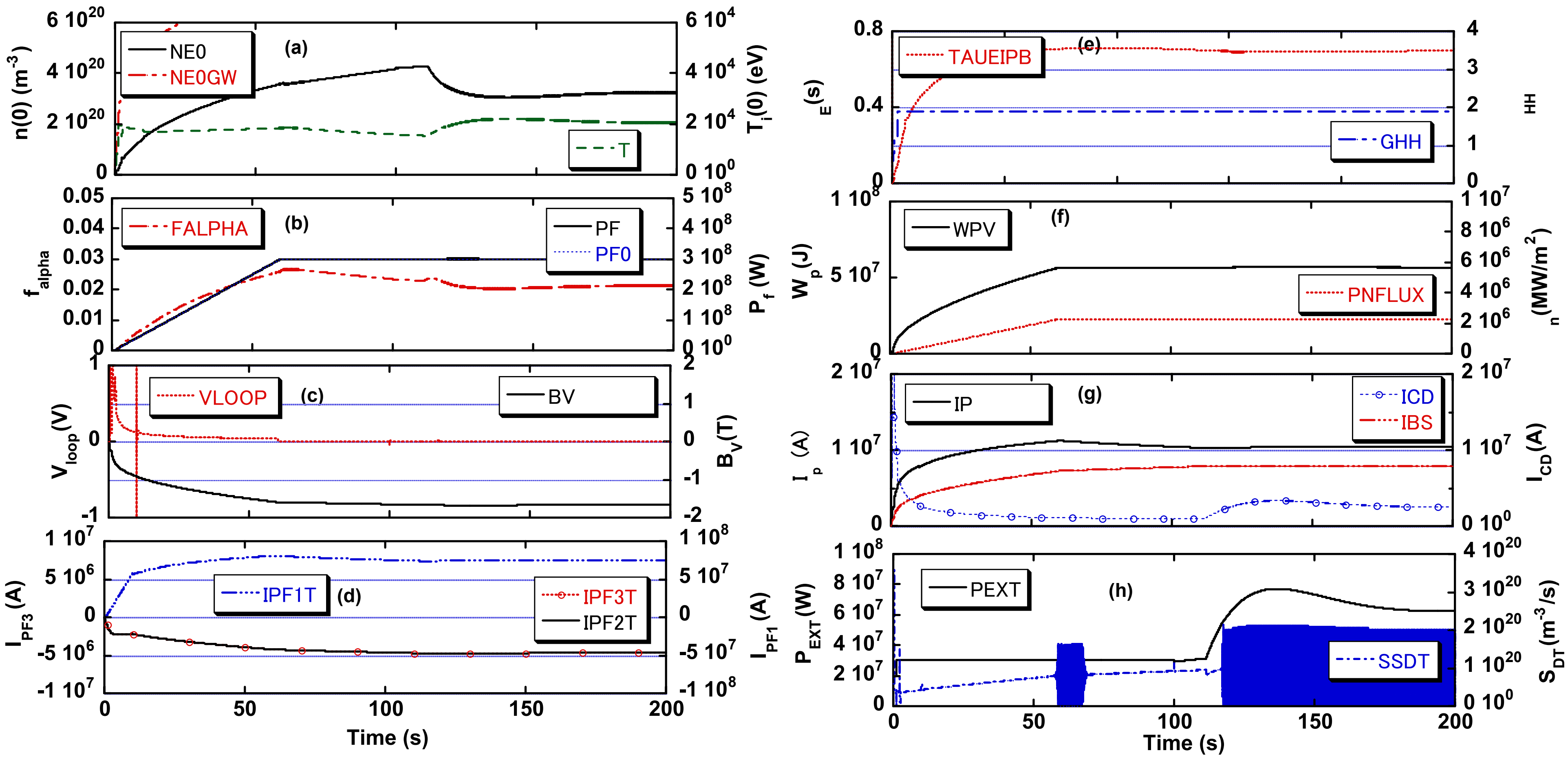
[3] Second phase is unstable for IPB(y,2) scaling. Careful adjustment of the PID parameter in fueling control is necessary.

$_{CD}$ = 0 [$Am^{-2}W^{-1}$], P_{EXT}=45 MW, $_{HH}$=1.9, (T_d=0 s, T_{int}=3 s)



[4] Steady state of 10.5 MA after 100 sec is maintained by the feedback control of the non-inductive drive power.

$_{CD}$ = 1.25x10^{19} [Am^{-2}W^{-1}], $_{HH}$=1.9, P_{EXT}=30 MW to 70 MW, (T_d=0.1 s, T_{int}=3 s)



4. Summary and further issues

[1] The plasma current ramp up to 10 MA is possible with the heating power of 30~45 MW in the CTF device without the central solenoid for these scalings.

[2] It is confirmed that the equivalent circuit equation model and separate poloidal coil circuit model provide the similar results with 0-D equation.

[3] The plasma current of ~600 kA could be obtained in the initial phase by outer poloidal coil activation.

[4] Discharge behaviors based on the minimum selection of the confinement time of NA and IPB provides the contradictory results.

IPB scaling provides the reasonable behaviors except for the second phase. (Careful choice of the derivative time for fueling is necessary in the second phase.)

[5] For steady state operation, more heating/current drive power is required.

Further optimization would be necessary to reduce the power.