Plasma current ramp-up and ignition in the Component Test Facility (CTF)

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O. Mitarai Kyushu Tokai University, Kumamoto, Japan

M. Peng Oark Ridge National Laboratory, USA

Y. Takase University of Tokyo, Japan

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1. Introduction

[1] Lowered-cost and fast approach is required for fusion energy development at present.

@Recent increase in oil price may indicate the shortage of oil in the near future???

@Recent devastating Typhoon and Hurricane are created by the hotter sea water. Is this due to the Green house effect ????

@ "Kumamoto" is now in the "tropical zone", 34~37°C for a long time, therefore "passion fruits" are growing as in Hawaii. Is this due to the Green house effect ????

Different toroidal machine concept from ITER and lower construction cost of compact DT burning machine, capable of fusion material/component testing, ignition and steady state burn operation, is very attractive.

It would enhance a fusion energy development.

We may need "track change" or "additional track".

[2] Advantages in ST

(1) Toroidal field can be reduced with high beta realization.
→ The toroidal beta $<\beta>\sim 39$ % in NSTX may be enough for a reactor.

(2) Compactness can reduce the construction cost, increases the neutron wall loading for material/component test. Construction period is also reduced.

(3) Large neutron wall loading may be suitable to test transmutation waste, which may help fission cycle.

[3] Continued experimental progress is needed for ST

(1) Plasma temperature needs to reach >10 keV as in HA tokamak.

(2) The large plasma current ramp-up has not been demonstrated without CS. (This topics)

(3) The bootstrap current is not large enough yet.

(4) Divertor heat flux is larger than that in HA tokamak.

[4]. Remarkable progress of plasma current ramp-up without CS in Japan

(1) In JT-60U, CS-less operation but with inner VT coil demonstrated the plasma current ramp-up to 600 kA. (ECRH,LHCD+VF-->NBI+VF)

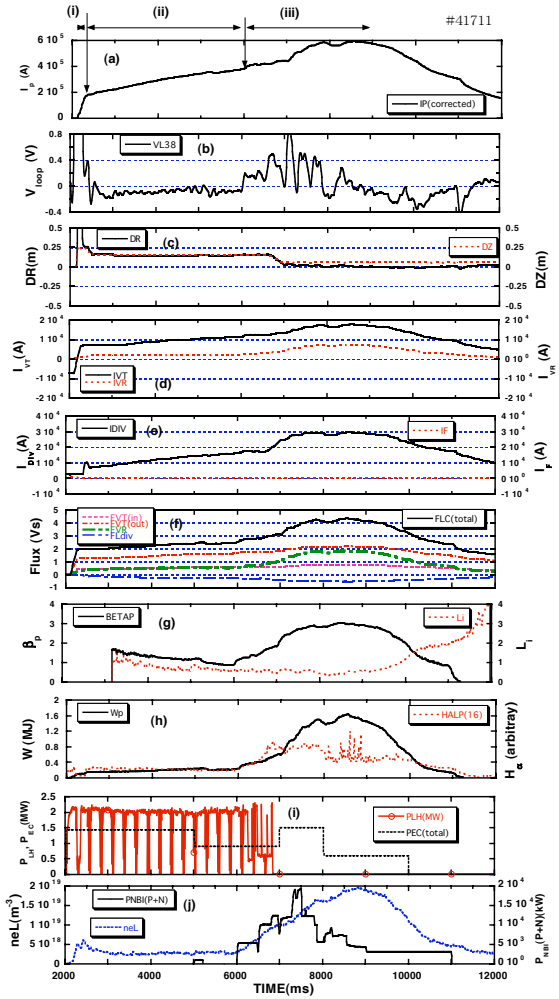


Fig.11 (41711)

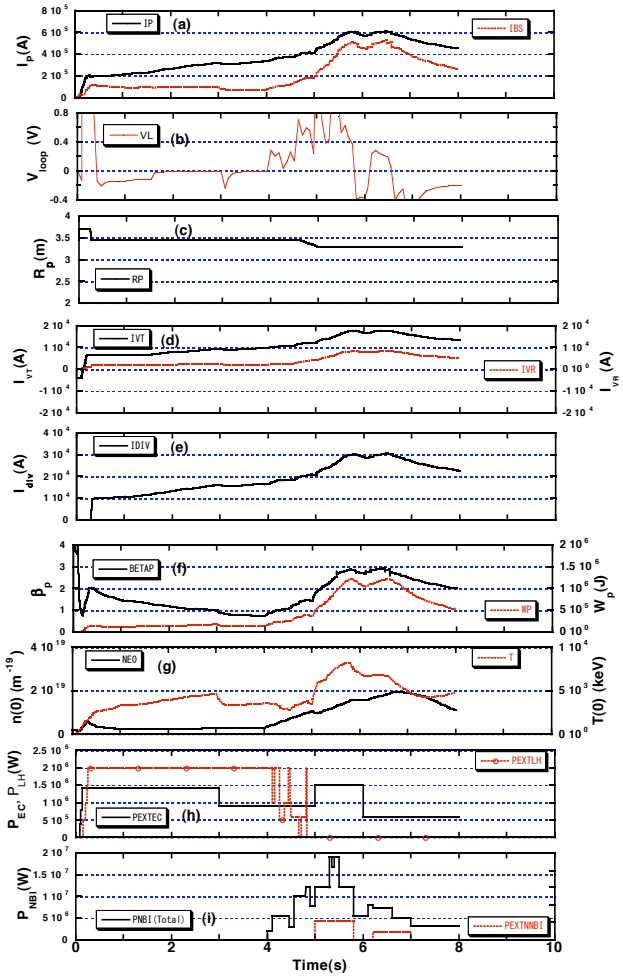


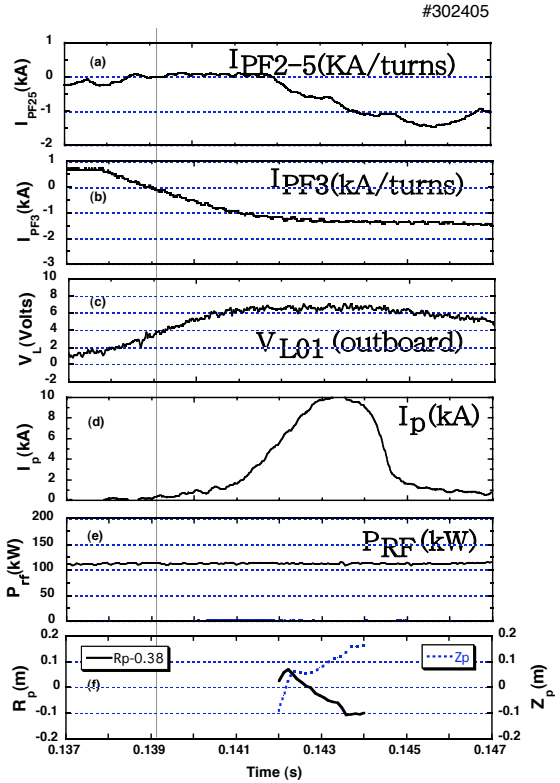
Fig.12 (41711)

1.O. Mitarai, Y. Takase, S. Ide, et al, "Ohmic Transformer-Free Plasma Current Start-up and Ramp up in JT-60U" to be submitted.

2.Takase Y., et al, Journal of Plasma and Fusion Research, 78 (2002) 717

3.Shiraiwa S., Takase Y., Fukuda F., Gao X., Gryaznevich M., Ide S.,, toh S., Kamada K., Maekawa T., Mitarai O., Miura Y., ,et al., Physical Rev. Lett., 92 (2003) p035001-1-4

(2) 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

The steady state current of ~4 kA is driven by EBW.

(3) 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.**

(4) In the Late device (~15% TFC current), ~11 kA plasma current has been achieved with ECW/EBW.

[5] Interesting features of CTF.

Component Test Facility (CTF), whose design is led by M.Peng, is <u>a medium field, steady state ST</u> without CS capable of D-T burning.

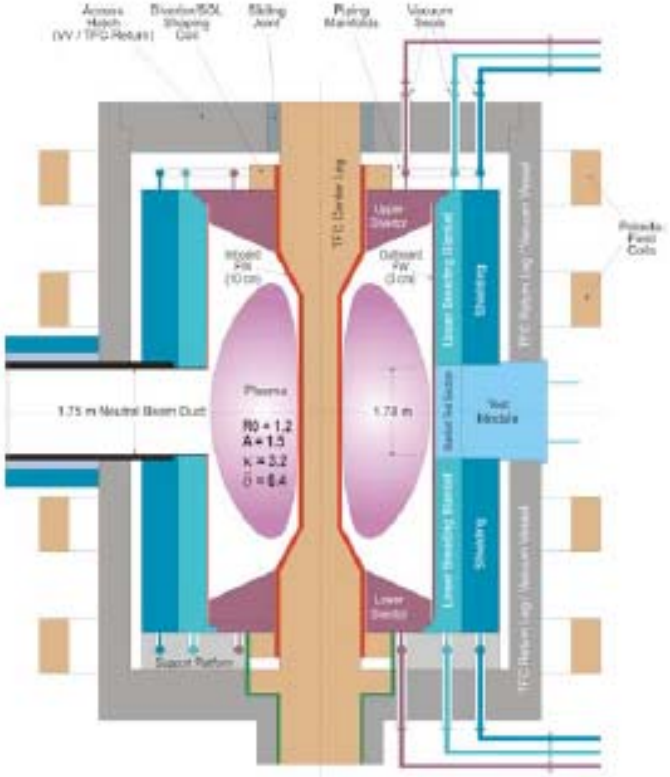


Fig. 9. Vertical cross section view of a CTF configured for full remote handling of all chamber systems.

@ Compact machine: R=1.2 m, a= 0.8 m, A=1.5, I_p= 9~16 MA

@ Medium toroidal field (B_t=2.5 T) by copper coils→ Normal field tokamak

@The cut-off density is n_{cut}= 6x10^{19} m^{-3} for fundamental frequency of f_{ce}=70 GHz. In the low density, ECCD and LHCD may be possible.

@Phased operation:

[1] 75 MW, [2] 150 MW, [3] 300 MW: Large average neutron wall loading ~ 2 MW/m^2

@ Large Greenwald density limit: n/n_{GW}<0.3

@ Relatively low beta: β <34%

@ Relatively low bootstrap current: f_{BS}<0.5

cited from IEEJ05 & PPCF05 (M.Peng)

[6] Purpose of this work

CTF main steady state parameters were calculated using the system code based on the two fluids model. (C.Neumeyer)

(1) to calculate the plasma current ramp-up based on the one fluid model, and related subjects such as ignition and sensitivity analysis,

(2) to calculate the plasma current ramp-up based on the two fluid model, and related subjects, (future work)

on phased CTF operation with fusion powers: [1] 75 MW, [2] 150 MW, and [3] 300 MW.

2. Formula for calculation

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

$$L_p \frac{dI_p}{dt} + R_p(I_p - I_{CD} - I_{BS}) = -\left(M_{PV}\frac{dI_V}{dt} + M_{Psh}\frac{dI_{sh}}{dt} + M_{Pdiv}\frac{dI_{div}}{dt} \right)$$

$$I_{CD} = \frac{\eta_{CD}}{nR_o} P_{CD}, \quad f_{BS} = I_{BS}/I_p = C_{BS}\sqrt{\varepsilon}\beta_p, \quad C_{BS} = 0.6, \quad R_p = \eta_{NC}\frac{2\pi R}{\pi a^2 \kappa}$$

NBI current drive efficiency: (proportional to beam energy)

$$\eta_{CD} = E_{NBI} \times 10^{20} \left[-8.471\times10^{-4} + 1.852\times10^{-3}(T_e(0)/1000)/(1+\alpha_T) - 5.307\times10^{-5}\left\{(T_e(0)/1000)/(1+\alpha_T)\right\}^2 \right]$$

η_{CD} ~ (1.42, 2.12 and 2.78)x10^{19} [$Am^{-2}W^{-1}$]

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

$\alpha_{div} = I_{div}/I_p$=1.8 and $\alpha_{sh} = I_{sh}/I_V$=1,

$$B_{VE} = B_{zoV} I_V + B_{zosh} I_{sh} - B_{zodiv} I_{div}$$

$$L_{peff}\frac{dI_p}{dt} = -R_{peff} I_p - \left\{ \frac{M_{PV} + M_{Psh}\alpha_{sh}}{B_{zoV} + B_{zosh}\alpha_{sh}} \right\} \frac{dB_{VE}}{dt}$$

wirh $$L_{peff} = L_p + \left\{ M_{Pdiv} - \left\{ \frac{M_{PV} + M_{Psh}\alpha_{sh}}{B_{zoV} + B_{zosh}\alpha_{sh}} \right\} B_{zodiv} \right\} \alpha_{div}$$

L_p =0.381x10^{-6} H, L_{peff} =0.396x10^{-6} H.

[3]. 0-D particle and energy balance equations with control algorithm

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

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

$$\frac{dn_\alpha(0)}{dt} = (1+\alpha_n)\, n_D(0)\, n_T(0)\, \overline{<\sigma v>_{DT}(x)} - \frac{n_\alpha(0)}{\tau_\alpha^*}$$

$$\frac{dT_i(0)}{dt} = \frac{1+\alpha_n+\alpha_T}{1.5\, e\, (f_D + f_T + 1/\gamma_i + f_\alpha)\, n_e(0)} \left[P_{EXT}/V_o + \overline{P}_\alpha + \overline{P}_{oh} - \left\{ \overline{P}_L + \overline{P}_b + \overline{P}_S \right\} \right]$$

$$- \frac{T_i(0)}{(f_D+f_T+1/\gamma_i+f_\alpha)\, n_e(0)} \left[\left\{ 1 + \frac{1}{\gamma_i\,(1-(1+\alpha_n)Zf_{imp})} \right\} \frac{dn_D(0)}{dt} + \left\{ 1 + \frac{1}{\gamma_i\,(1-(1+\alpha_n)Zf_{imp})} \right\} \frac{dn_T(0)}{dt} + \left\{ 1 + \frac{2}{\gamma_i\,(1-(1+\alpha_n)Zf_{imp})} \right\} \frac{dn_\alpha(0)}{dt} \right]$$

T_i=T_e provides the severest condition. (one fluid model)
Hot ion mode would be studied in the near future. (two fluid model)

Confinement time: $\tau_E = \tau_{IPB98y2}$

$$\tau_{IPB98(y,2)} = \gamma_{HH}\, 0.0562\, A_i^{0.19} I_p^{0.93} [MA] \bar{n}_{19}^{-0.41} [\times 10^{19}\, m^{-3}] R_o^{1.97} [m] \varepsilon^{0.58} \times \kappa^{0.78} B_{to}^{0.15} [T] / P_{HT}^{0.69} [MW]$$

Helium ash: $\tau_\alpha^*/\tau_E = 4$

Control algorithm

(1) External heating power

$$P_{EXT}(HL)\,[W] = M_{HL0}(t) x 10^6\, \overline{P}_{thresh} - \left(\overline{P}_{oh} + \overline{P}_{\alpha} - \overline{P}_b - \overline{P}_s\right) V_o$$

with H-mode power threshold (Righi) $M_{HL0}=P_{NET}/P_{thresh}=15$

$$\overline{P}_{thresh}[MW] = 1.10\overline{n}_{20}^{1.12}[10^{20}\,m^{-3}]B_t^{0.69}[T]R^{2.35}[m]/A_i^{0.9}$$

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

$$P_{CD}\left(I_p\right) = 1\times 10^8\left\{e_{IP} + \frac{1}{T_{IP\,\mathrm{int}}}\int e_{IP}dt\right\}$$ **with** $e_{IP}(I_P) = 1 - I_P(t)/I_{Po}(t)$

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=0.1 sec)

$$S_{DT}(t) = S_{DT0}\left\{e(P_f) + \frac{1}{T_{\mathrm{int}}}\int_0^t e(P_f)dt + T_d\frac{de(P_f)}{dt}\right\}G_{fo}(t)$$

$$e(P_f) = 1 - P_f/P_{fo}(t)$$

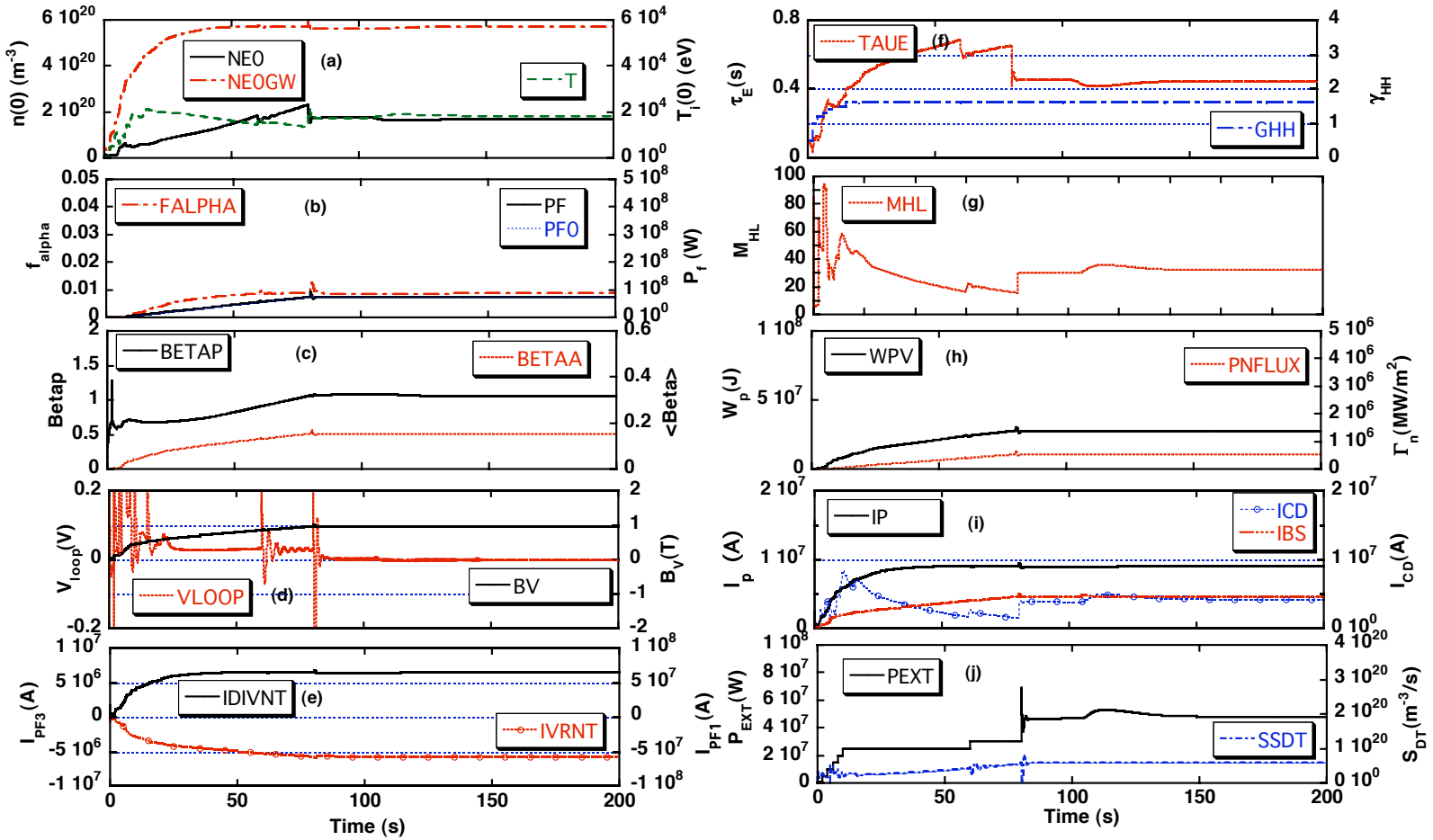
Table 1. CTF plasma parameters calculated in this work

Operation phase		[1]	[2]	[3]	[4] Hot ion mode	[5] Hot ion mode	
Fusion power	P_f	75 MW	150 MW	300 MW			
Major radius	R	1.2 m					
Minor radius	a	0.8 m					
Aspect ratio	A=R/a	1.5					
Toroidal field	B_t	2.5 T (f_{ce}=70 GHz, n_{cut}=6.1x10^{19} m^{-3})					
Elongation	κ	3.2					
Internal inductance	ℓ_i	0.25			ℓ_I = 0.5		
Plasma current	I_p	9.0 MA	12.8 MA	16 MA			
Temperature ratio	T_i/T_e	T_i/T_e=1			T_i/T_e=2		
Density profile	α_n	0.5					
Temperature profile	α_T	1.0					
Enhancement factor	γ_{HH}	1.6	1.5	1.4			
Peak electron density	n(0)	1.69x10^{20} m^{-3}	1.83x10^{20} m^{-3}	2.48x10^{20} m^{-3}	2.0x10^{20} m^{-3}	2.05x10^{20} m^{-3}	
Greenwald factor	$n(0)/n(0)_{GW}$	0.3	0.22	0.24	0.19	0.2	
Peak ion temperature	$T_i(0)$	18.3 keV	25.9 keV	28.3 keV	43.7 keV	41.0 keV	
Effective ion charge	Z_{eff}	1.26	1.27	1.29	1.29	1.3	
Confinement time	τ_E	0.44 s	0.46 s	0.44 s	0.41 s	0.46 s	
Neutron wall loading	Γ_n	0.5 MW/m^2	1.0 MW/m^2	2.1 MW/m^2	2.1 MW/m^2	2.1 MW/m	
Toroidal beta	$<\beta>$	15 %,	23 %	34 %	31 %	31 %	
Normalized beta	β_N	3.3	3.6	4.3	3.9	3.8	
Allowable normalized beta (Lin-Liu)	β_N(Wong)	8.26 (6.4)	8.26 (6.4)	8.26 (6.4)	8.26 (6.4)	8.26(6.4)	
Steady state current drive power	P_{CD}	48 MW	64 MW	84 MW	80 MW	60 MW	
NBI energy	E_{NBI}	110 keV	160 keV	250 keV		500 keV	
Bootstrap current fraction	f_{BS}	51 %	38 %	37 %	33 %	33 %	
He ash fraction	f_{ash}	0.87 %	1.7 %	2.4 %	2.7 %	2.9 %	
Fusion amplification	$Q_F=P_f/P_{EXT}$	75/48= 1.5	150/64= 2.3	300/84= 3.5	300/80=3.75	300/60 = 5.0	
Double null divertor heat flux for 1 m width	P_{div}	4.0 MW/m^2	6.0 MW/m^2	9.2 MW/m^2	9.1 MW/m^2	7.81 MW/m^2	Radiative plasma mantle of 80 % -->20 cm width

3. Calculated results

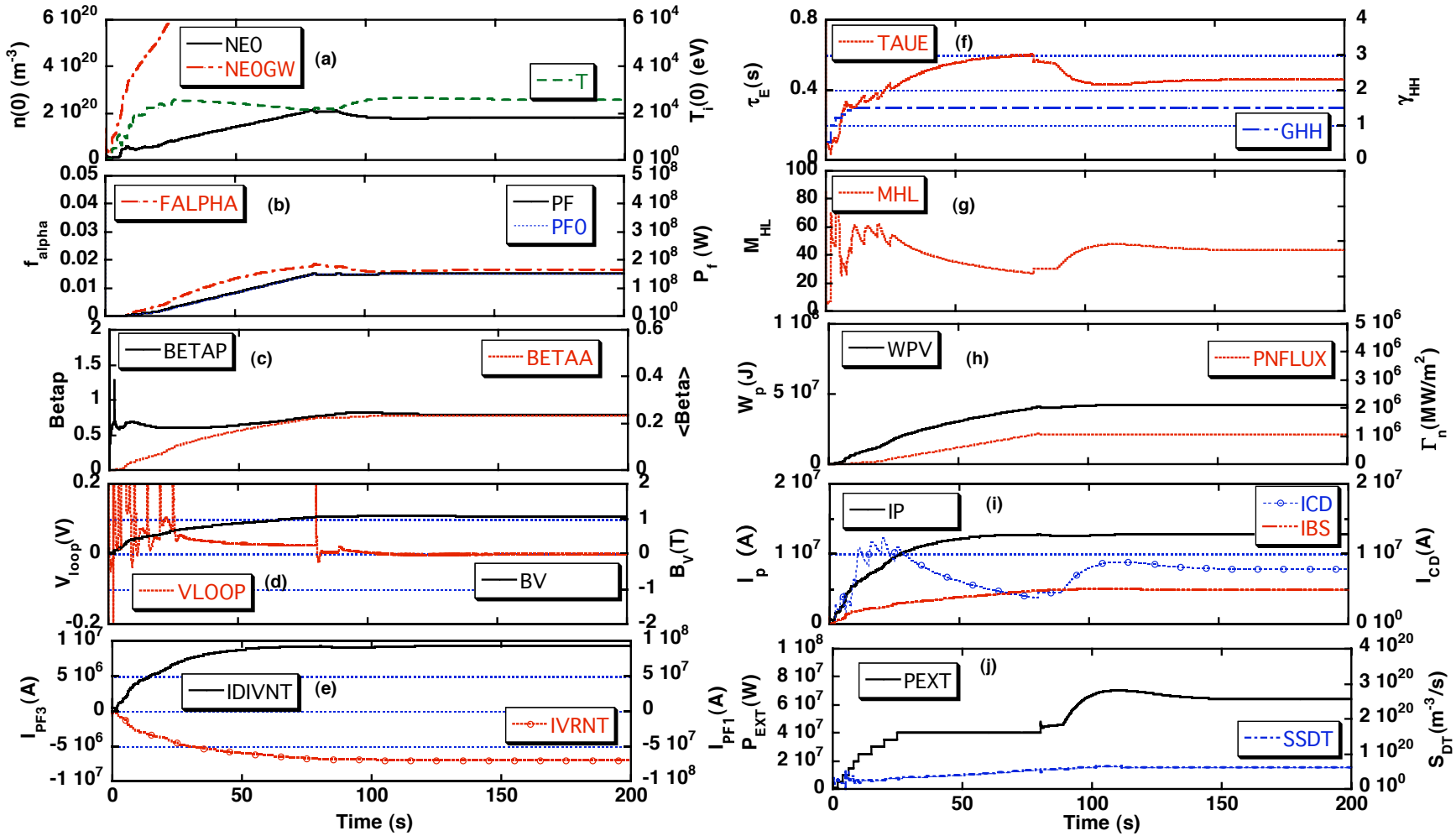
3.1. P_f=75 MW

The external heating power of 25 MW increases the plasma current up to 9 MA. Steady state after 80 sec is maintained by the feedback control of the non-inductive drive power 48 MW. Confinement factor γ_{HH}=1.6.



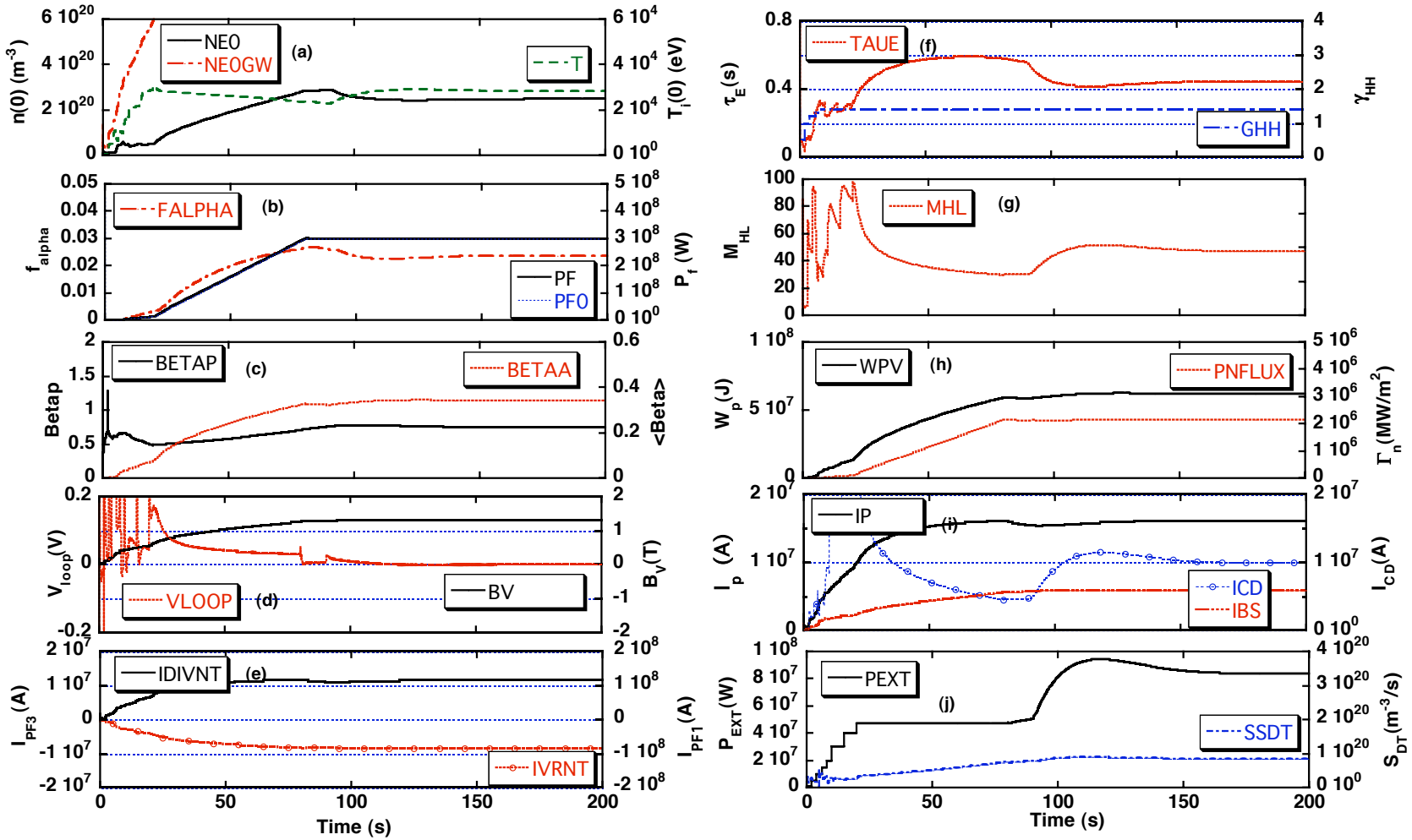
3.2. P_f=150 MW

The external heating power of 40 MW increases the plasma current up to 12.0 MA. Steady state after 80 sec is maintained by the feedback control of the non-inductive drive power 64 MW. Confinement factor γ_{HH}=1.5.

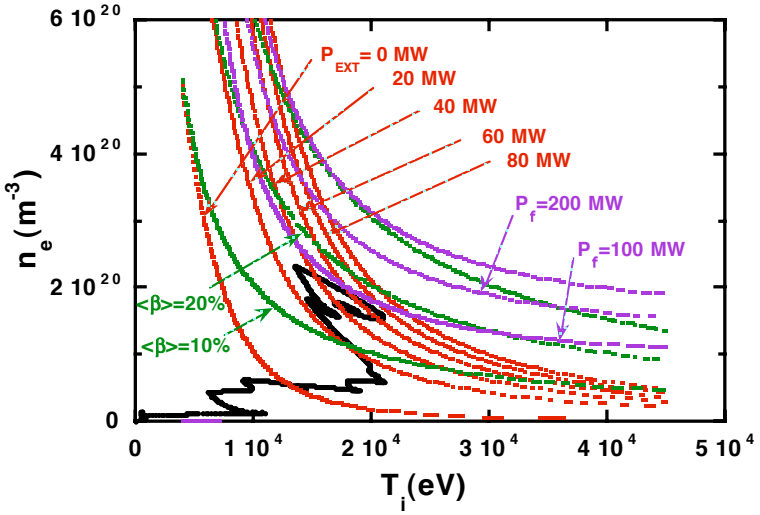


3.3. P_f=300 MW

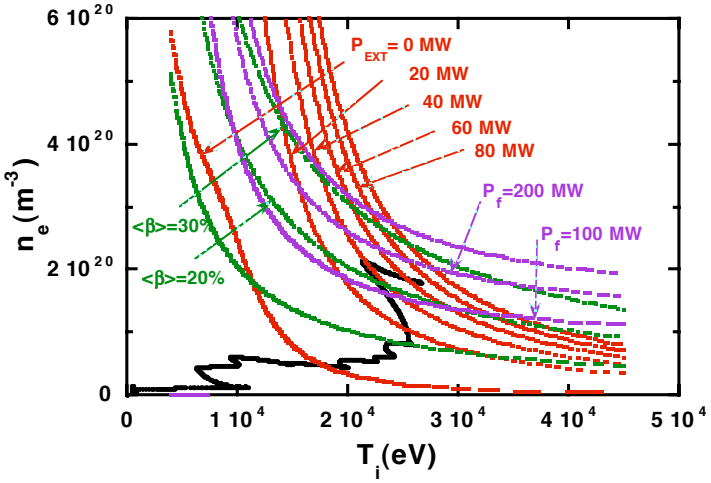
The external heating power of 47 MW increases the plasma current up to 16.0 MA. Steady state after 80 sec is maintained by the feedback control of the non-inductive drive power 84 MW. Confinement factor γ_{HH}=1.4.



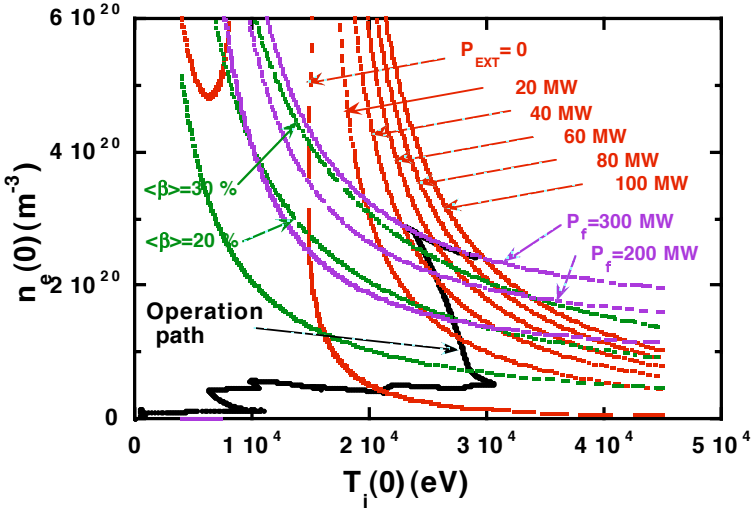
3.4. **Operation path**



P_f=75 MW



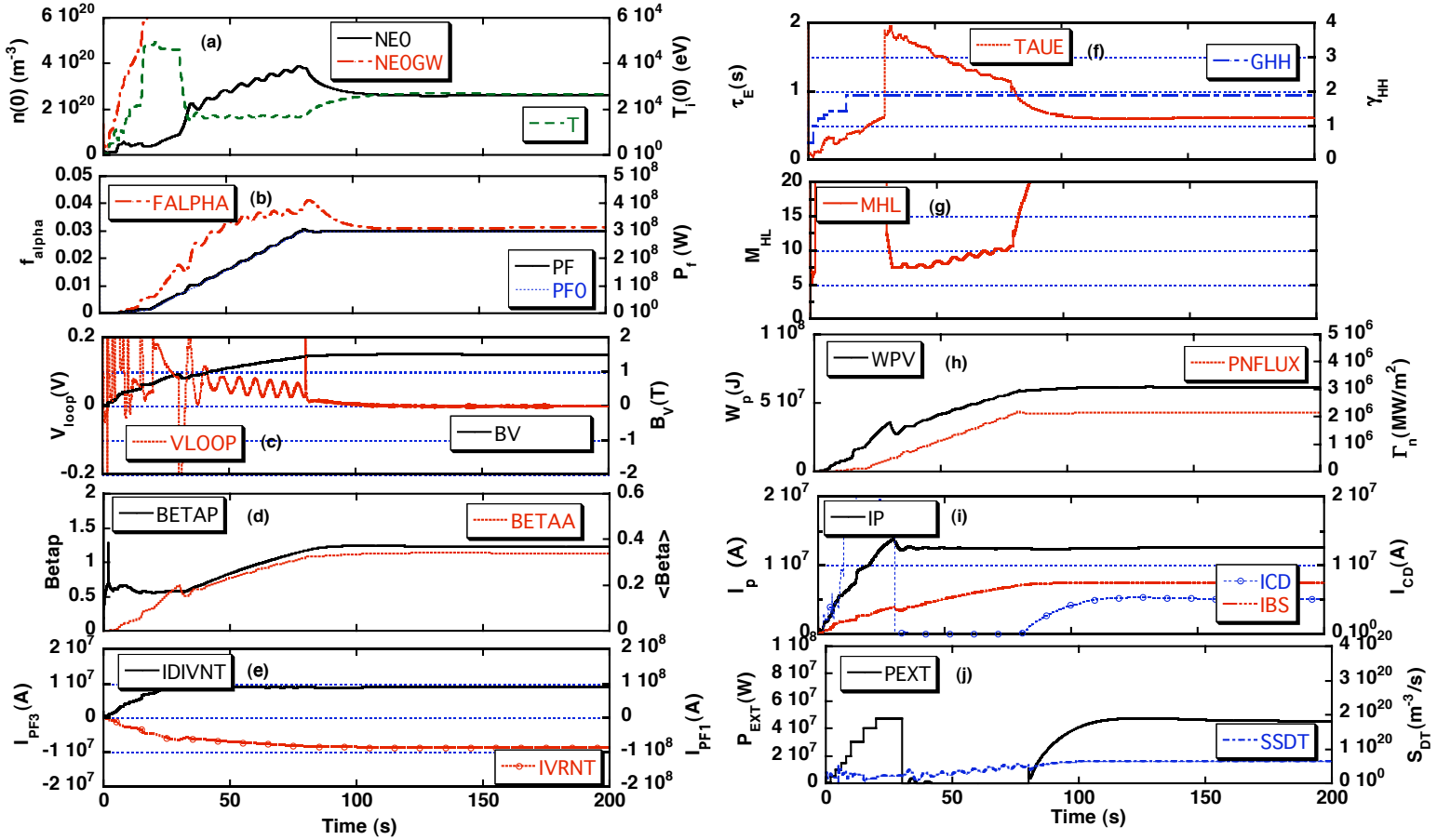
P_f=150MW



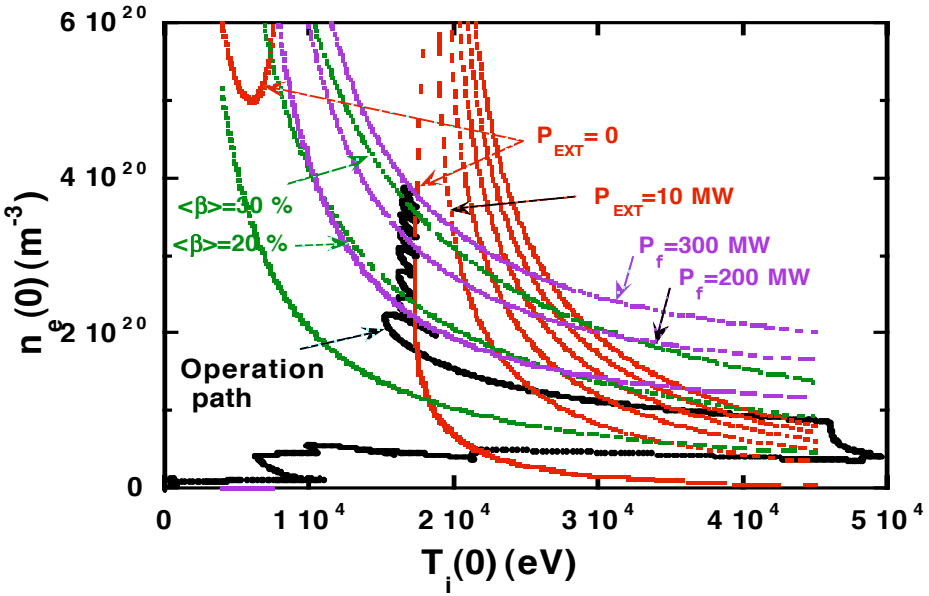
P_f=300MW

3.5. Transient ignition with P_f=300 MW and γ_{HH}=1.9

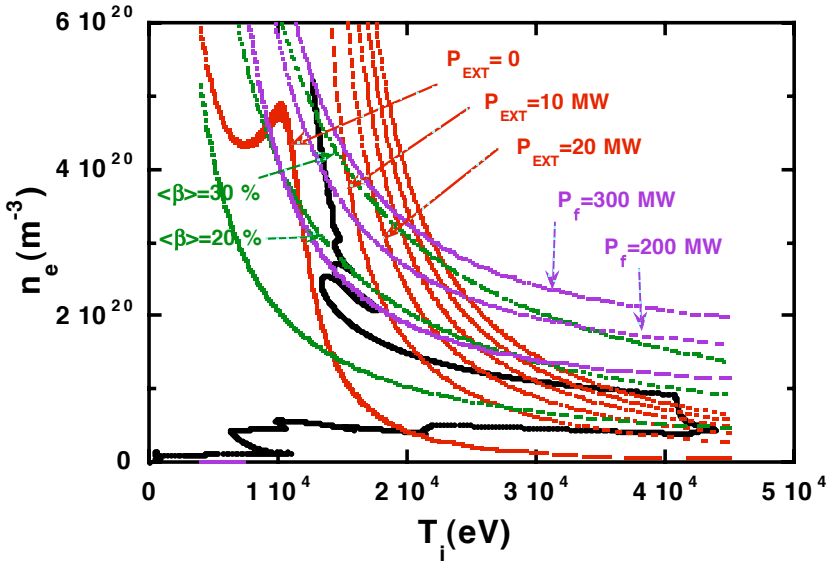
The set value of the H-mode power threshold is M_{HLo}=7.5 and then feedback control of the heating power is switched on at 30 sec. → P_{EXT}=0 MW. The external heating power is zero between 30 and 80 sec. As I_p=12 MA is larger than set value, but it decays and then the current drive power is switched on at 80 s.



Corresponding POPCON



Corresponding operating path during transient ignition phase with γ_{HH}=1.9 up to 7.9 sec.



Ignition regime shrinks at γ_{HH}=1.75

The ignition boundary shape is given by $[P_{ht}\tau_E^2] \propto n^{(1+\alpha-2S)/(1-S)}$ for the confinement time of $\tau_E \propto n^{\alpha}/P_{ht,net}^{S}$.

For IPB98(y,2) scaling with α=0.41 and S=0.69, the ignition boundary is in parallel in the density axis because of $[P_{ht}\tau_E^2] \propto n^{0.03/0.31}=n^{0.1}$, which shows the very week dependence on the density.

4. Analytical expression of the plasma current ramp-up

When an analytical formula is available to estimate the plasma current ramp-up, this type of calculation becomes credible.

4.1. The effective circuit equation including <u>shaping, vertical and divertor coils</u> is given by

$$L_{peff}\frac{dI_p}{dt} = -R_{peff}I_p + C_{PVSH}\frac{dB_{VE}}{dt} \qquad \textbf{(4-1)}$$

$$C_{PVSH} = \left\{\frac{M_{PV} + M_{Psh}\alpha_{sh}}{B_{zoV} + B_{zosh}\alpha_{sh}}\right\} \qquad L_{peff} = L_p + \left\{M_{Pdiv} - C_{PVSH}B_{zodiv}\right\}\alpha_{div}$$

After integration

$$\left[L_p + \left\{M_{Pdiv} - C_{PVSH}B_{zodiv}\right\}\alpha_{div}\right]I_p + R_{peffo}I_p t = C_{PVSH}B_{VE} \qquad \textbf{(4-2)}$$

with

$$B_{VE} = \frac{\mu_o I_p}{4\pi R}\left\{\frac{1}{\mu_o}\left(\frac{\partial L_S}{\partial R}\right) + \frac{\ell_i}{2} + \beta_p - \frac{1}{2}\right\}$$

we have

$$\left[L_p + \left\{M_{Pdiv} - C_{PVSH}B_{zodiv}\right\}\alpha_{div}\right]I_p + R_{peffo}I_p t = \frac{C_{PVSH}\mu_o I_p}{4\pi R}\left\{\frac{1}{\mu_o}\left(\frac{\partial L_S}{\partial R}\right) + \frac{\ell_i}{2} + \beta_p - \frac{1}{2}\right\}$$

then

$$\beta_p = \frac{\frac{2}{3} W_p / V_o}{\frac{1}{2\mu_o}\left(\frac{\mu_o I_p}{2\pi a \ell_\kappa}\right)^2}$$

$$= \frac{4\pi R}{C_{PVSH}\mu_o}\left[L_p + \left\{M_{Pdiv} - C_{PVSH} B_{zodiv}\right\}\alpha_{div}\right] - \frac{1}{\mu_o}\left(\frac{\partial L_S}{\partial R}\right) + \frac{1}{2} - \frac{\ell_i}{2} + \frac{4\pi R}{C_{PVSH}\mu_o} R_{peffo} t \qquad \textbf{(4-3)}$$

The analytical plasma current ramped up by the vertical is given by **($I_p \propto \sqrt{W_p}$)**

$$I_p = \sqrt{\frac{\frac{4}{3}\frac{W_p}{V_o}\frac{(2\pi a \ell_\kappa)^2}{\mu_o}}{\frac{4\pi R}{C_{PVSH}\mu_o}\left[L_p + \left\{M_{Pdiv} - C_{PVSH} B_{zodiv}\right\}\alpha_{div}\right] - \frac{1}{\mu_o}\left(\frac{\partial L_S}{\partial R}\right) + \frac{1}{2} - \frac{\ell_i}{2} + \frac{4\pi R}{C_{PVSH}\mu_o} R_{peffo} t}} \qquad \textbf{(4-4)}$$

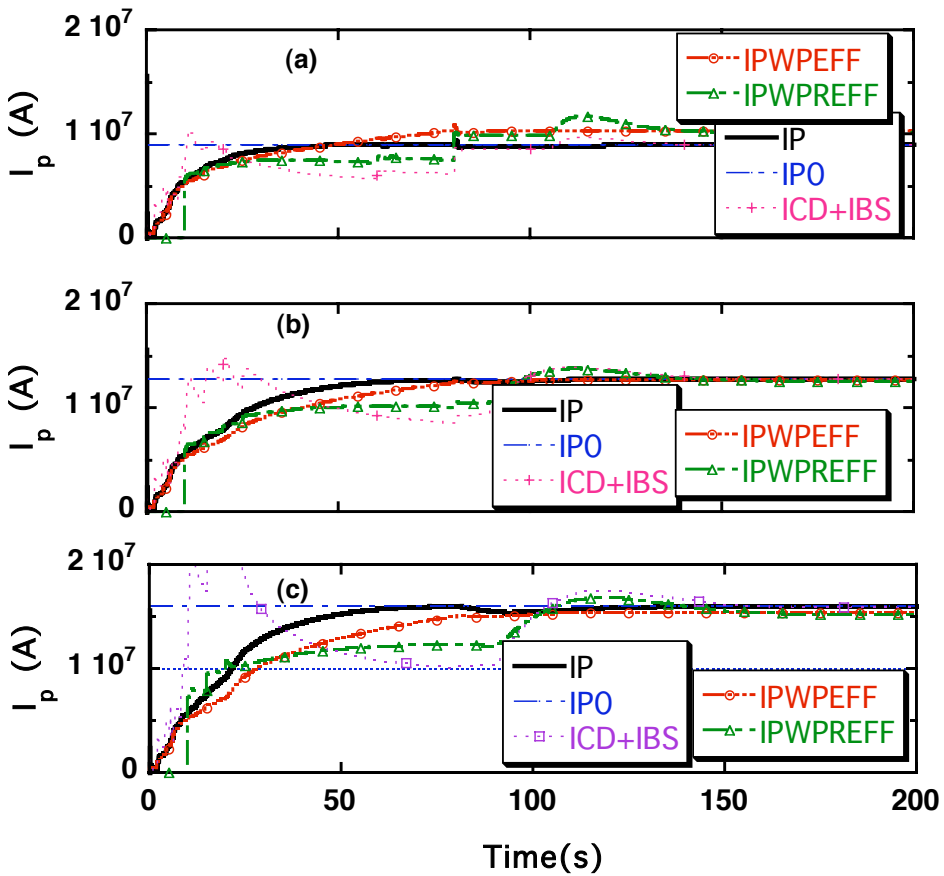
When <u>shaping and divertor coils are not taken into account</u> with $C_{PVSH}=M_{PV}/B_{zo}=\pi R^2$ and $L_{peff}=L_p$ through $\alpha_{sh}=0$ and $\alpha_{siv}=0$, we have the simpler formula

$$I_p(t) = \sqrt{\frac{\frac{4W_p}{3V_o}\frac{(2\pi a \ell_k)^2}{\mu_o}}{3\frac{a(\varepsilon)(1-\varepsilon)}{(1-\varepsilon)+b(\varepsilon)\kappa} + \frac{\varepsilon c(\varepsilon)}{(1-\varepsilon)+b(\varepsilon)\kappa} - \frac{a(\varepsilon)(1-\varepsilon)}{(1-\varepsilon)+b(\varepsilon)\kappa}\frac{\varepsilon d(\varepsilon)}{(1-\varepsilon)+b(\varepsilon)\kappa} + \frac{3\ell_i}{2} + \frac{1}{2} + \frac{4R_{peffo}}{\mu_o R} t}} \qquad \textbf{(4-5)}$$

4.2. Comparison with numerical results

IPWPREFF: $R_{pffo} \neq 0$

IPWPEFF: $R_{peffo}=0$



Analytical result is well fitting to the numerical one.

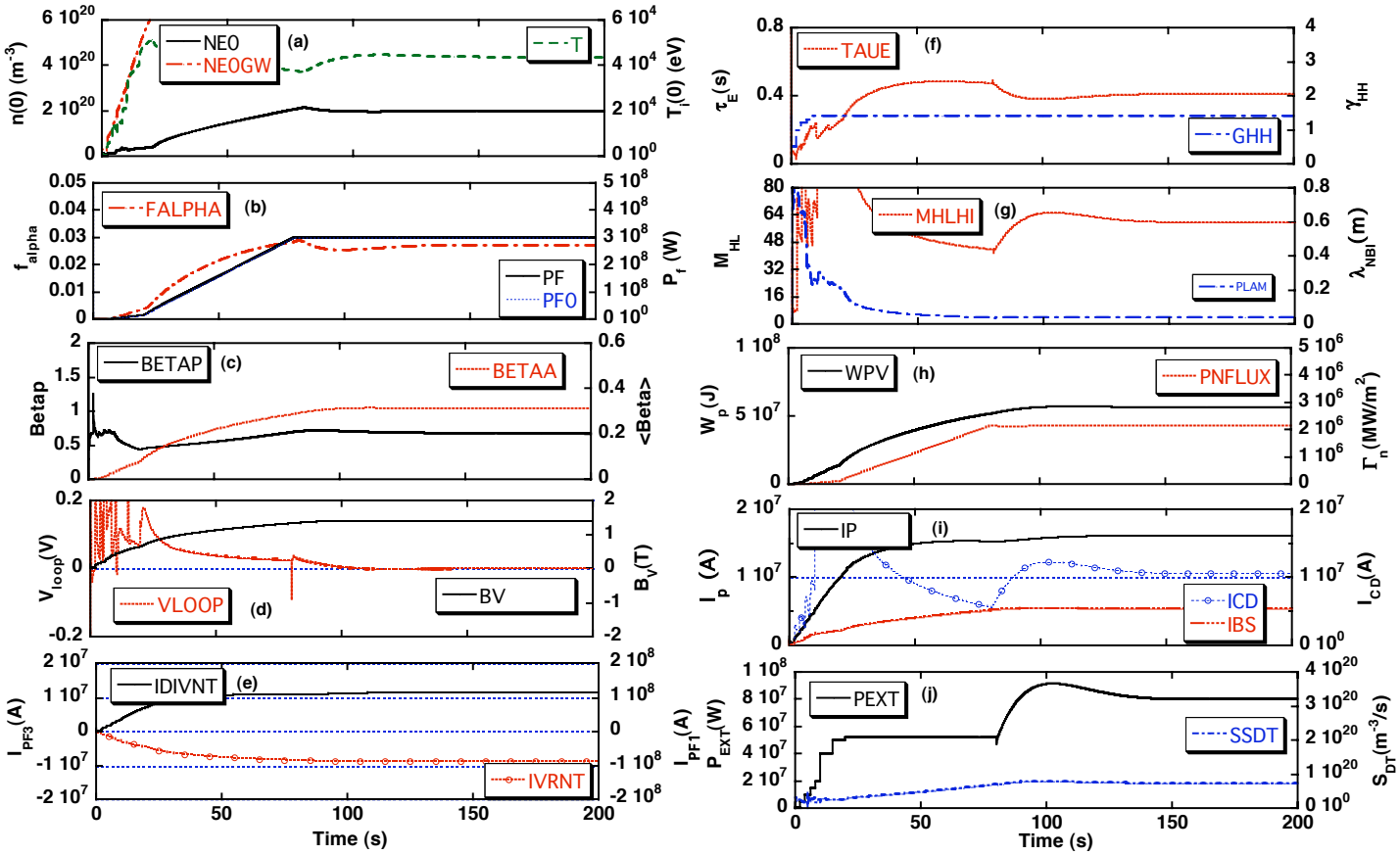
The plasma current is simply determined by the plasma energy W_p.

5. Sensitivity studies

5.1. Larger internal inductance of ℓ_i=0.5 and Hot ion mode of T_i/T_e=2

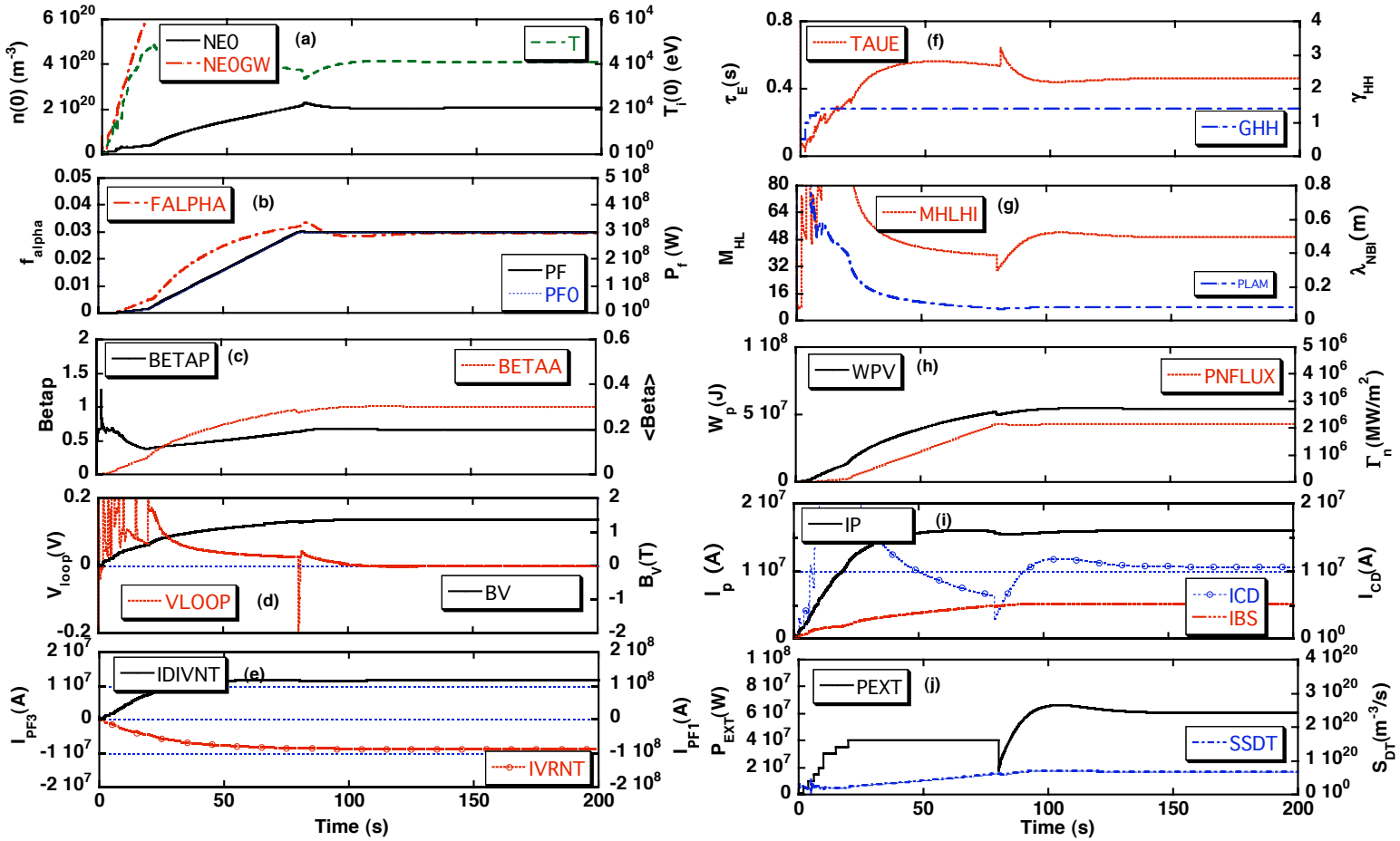
The plasma current is retained at I_p=16 MA by 52 MW and the hot ion mode operation.
Density decreases and temperature increases by Hot ion mode.

(L_{peff}=0.584 μH for ℓ_i=0.5 , P_f=300 MW, Confinement factor γ_{HH}=1.4, 52 MW->80 MW)



5.2. Larger internal inductance, Hot ion mode of T_i/T_e=2 and Higher NBI energy

E_{NBI}=500 keV→ Large current drive efficiency→Reduction of steady state power to 60 MW. (ℓ_i=0.5 , P_f=300 MW, Confinement factor γ_{HH}=1.4, 40 MW-> 60 MW)

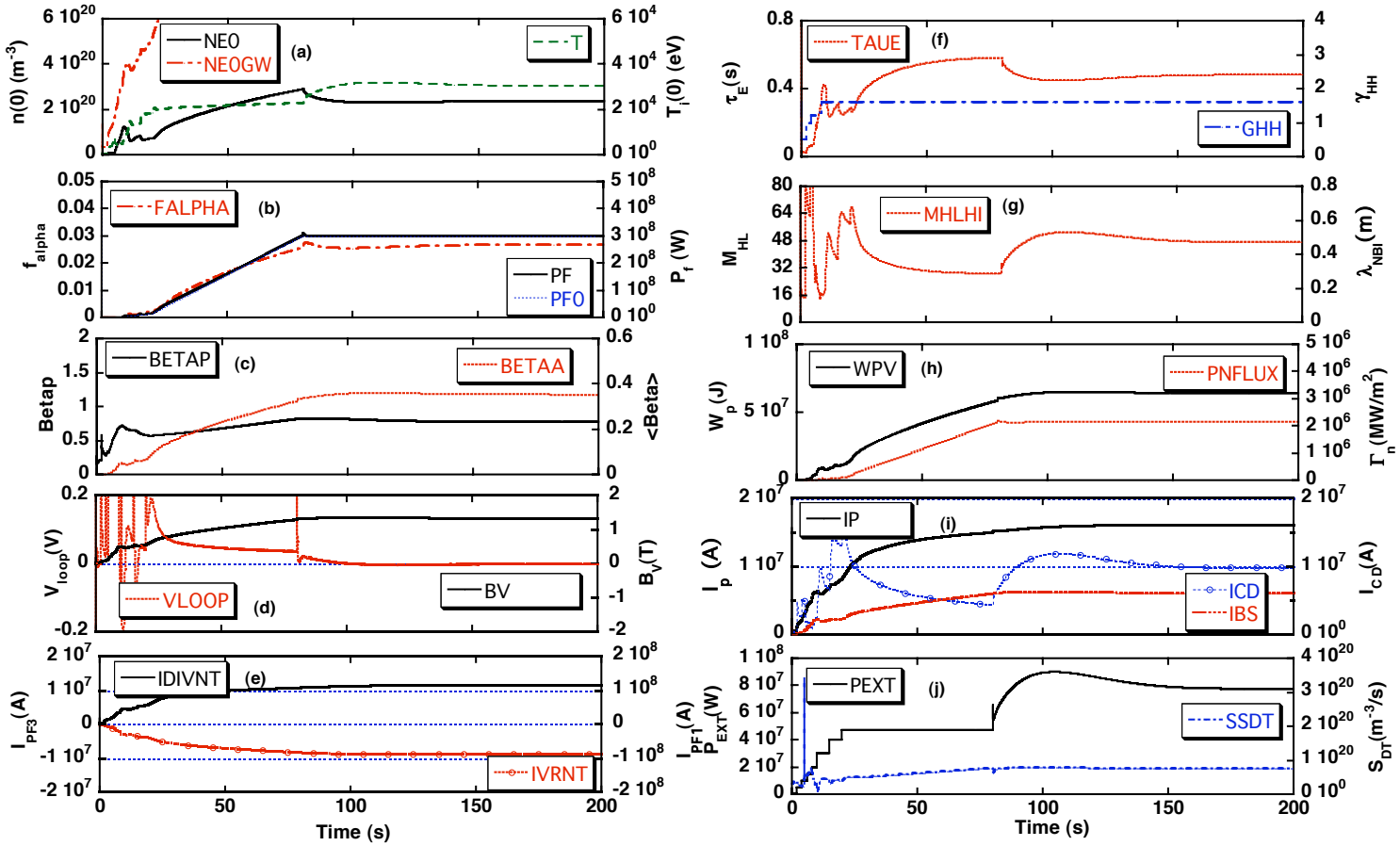


5.3. ESGRB scaling (Pettey et al)

$$\tau_{ESGRB} = \gamma_{HH} 0.028 A_i^{0.14} I_p^{0.83} [MA] n_{19}^{-0.49} [\times 10^{19} m^{-3}] R_o^{2.11} [m] \varepsilon^{0.3} \times \kappa^{0.75} B_{to}^{0.07} [T] / P_{HT}^{0.55} [MW]$$

The electrostatic gyro-reduced Bohm scaling with no beta dependence does not provide the better performance like a big machine due to large R dependence.

(It needs larger confinement factor γ_{HH}=1.6 for P_f=300 MW, ℓ_i=0.25, and I_p=16 MA.)



6. Summary and further issues

@ Compact CTF has high neutron performance than ITER.
(GW density limit factor 0.2, Neutron wall loading 1 – 4 MW/m^2
Fusion power 75 – 300 MW)

@For T_i/T_e= 1 plasma,

[1] The plasma current ramp up to 9~16MA is possible with the initial heating power of 22~45 MW in the CTF without the central solenoid, corresponding to the fusion power of 75,150, 300 MW. For steady state operation, more heating/current drive power of ~84 MW is required.

[2] Transient ignition is possible for γ_{HH}=1.9 and I_p=12 MA even in this small machine, which may serve the ignition physics study.

[3] Analytical expression provides almost the same of the numerical results.

[4] Radiative plasma mantle may be needed to reduce divertor heat flux because it is so large.

@The hot ion mode of T_i/T_e= 2 provides better performance.

[1] Larger internal inductance of ℓ_i=0.5 gives 16 MA with 52-80 MW due to the lower density. (cf. 12 MA for T_i/T_e= 1)

[2] When beam energy is doubled, steady state heating/current drive power can be reduced.

[3] Separate power balance equations for electrons and ions should be incorporated.