Fusion Power Rise-up in the Helical Reactor FFHR2m

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0. Motivation

Minimization of the external heating power to access ignition is advantageous to increase the reactor design flexibility and to reduce the capital and operating costs of the plasma heating device in a helical reactor.

We have found that

@lower density limit margin reduces the external heating power,

@minimum heating power is obtained for the longer fusion power rise-up time than 100~300 s.

@ any fusion power rise-up time can be employed in a helical reactor.

1. Zero-dimensional power and particle equations with control algorithm

1.1. How to reduce the external heating power

[1] Feedback controlled external heating power:

which is based on "Sudo density limit" with the net heating power :

$$\gamma_{DLM} n(0) \le n(0)_{\lim}[m^{-3}] = \gamma_{SUDO} \frac{0.25\times 10^{20}}{\gamma_{pr}} \sqrt{\frac{\left\{P_{NET}[W]\times 10^{-6}\right\} B_o[T]}{\bar{a}^2 R[m]}}$$

Density limit margin: $\gamma_{DLM} = [n(0)_{lim}/n(0)] > 1.1$

Minimum density limit margin (set value) : $\gamma_{DL0} = [n(0)_{lim}/n(0)]_{min} = 1.1$

Profile factor: ($\gamma_{pr} = \bar{n}/n(0) = 2/3$ parabolic profile),

Density limit factor: $\gamma_{SUDO} = 1.5$

The external heating power for feedback control

$$P_{EXT}[W] = \left\{\gamma_{pr} \frac{\left[\gamma_{DLM} n(0)[m^{-3}]\right]}{\gamma_{SUDO} 0.25\times 10^{20}}\right\}^2 \frac{\bar{a}^2 R[m]}{B_o[T]} \times 10^6 - \left(P_\alpha - P_B - P_S\right)$$

@ When γ_{SUDO} is large —> P_{EXT} is reduced.

@ When γ_{DLM} is large —> P_{EXT} is increased.

[2] External heating power for the power balance

The power balance equation is

$$\frac{dW}{dt} = P_{EXT} - \left(P_L + P_B + P_S - P_\alpha\right)$$

which is rewritten as

$$P_{EXT} = \frac{dW}{dt} + \left(P_L + P_B + P_S - P_\alpha\right)$$

At the steady state, the plasma energy W is the same for various rise-up times, and ignition gives $P_{EXT}=(P_L+P_B+P_s-P_\alpha)=0$

Long rise-up time: small dW/dt——＞heating power is reduced.

Short rise-up time: large dW/dt——＞heating power is increased.

Ion temperature is obtained by the power balance equation (Ti=Te)

$$\frac{dT_i(0)}{dt} = \frac{1+\alpha_n+\alpha_T}{1.5e\left(f_D+f_T+1/\gamma_i+f_\alpha\right)n_e(0)} \times \left[\left\{P_{EXT}+P_\alpha\right\} - \left\{P_L+P_B+P_S\right\}\right]$$

$$-\frac{T_i(0)}{\left(f_D+f_T+1/\gamma_i+f_\alpha\right)} \times \left[\left\{1-8f_O+\frac{1}{\gamma_i}-f_\alpha\right\}\frac{1}{n_e(0)}\left[\frac{dn_e(0)}{dt}\right] - \left[\frac{df_\alpha(0)}{dt}\right]\right]$$

1.2. Fusion power control

is done by fueling rate, which is determined by PID control of the error of the fusion power

$$\frac{dn_e(0)}{dt} = \frac{1}{1-8f_O}\left[(1+\alpha_n)S_{DT}(t) - \left\{\frac{f_D+f_T}{\tau_p^*} + \frac{2f_\alpha}{\tau_\alpha^*}\right\}n_e(0)\right]$$

Fueling rate is

$$S_{DT}(t) \;=\; S_{DT0}\left\{e_{DT}(P_f) + \frac{1}{T_{\text{int}}}\int_0^t e_{DT}(P_f)dt \;+\; T_d\frac{de_{DT}(P_f)}{dt}\right\}G_{fo}(t)$$

Error of the fusion power: $e_{DT}(P_f) \;=\; 1 - P_f(t)/P_{fo}(t)$

1.3. Helium ash:

$$\frac{df_\alpha(0)}{dt} = (1+\alpha_n)n_e(0)f_D f_T\overline{\langle\sigma v\rangle_{DT}(x)} - \frac{f_\alpha(0)}{\tau_\alpha^*} - \frac{f_\alpha(0)}{n_e(0)}\left[\frac{dn_e(0)}{dt}\right]$$

$\tau_\alpha^*/\tau_E = 3$

1.4. ISS95 Confinement time scaling:

$$\begin{cases} \tau_E[s] = \gamma_{ISS}\ \tau_{ISS95}[s] = \gamma_{LHD} \times 1.6\ \tau_{ISS95}[s] \\ \tau_{ISS95}[s] = 0.079\, \bar{\iota}_{2/3}^{0.4}\, \bar{n}_{19}^{\ 0.51}[\times 10^{19}\, m^{-3}] B_o^{0.83}[T]\, \bar{a}^{2.21}[m] R^{0.65}[m] / P_{HT}^{0.59}[MW] \end{cases}$$

The heating power itself is controlled by the plasma conduction loss

$$\tau_E[s] = \gamma_{HH} \times 0.079\, \bar{\iota}_{2/3}^{0.4}\, \bar{n}_{19}^{\ 0.51}[\times 10^{19}\, m^{-3}] B_o^{0.83}[T]$$

$$\times \bar{a}^{2.21} R^{0.65}[m] / \left\{ \left(P_{NET} - dW/dt \right) 2\pi R \pi \bar{a}^2 \times 10^{-6} \right\}^S [MW] = \frac{C_{op} / \left(2\pi R \pi \bar{a}^2 \right)^S}{\left(P_L \times 10^{-6} \right)^S} = \frac{C_{op}'}{\left(P_L \times 10^{-6} \right)^S}$$

yielding the plasma conduction loss:

$$P_L = \frac{\langle 1.5kTn \rangle}{\tau_E} = \frac{A_L n(0)}{\tau_E} = \frac{A_L n(0)}{C_{op}'} \left(P_L \times 10^{-6} \right)^S$$

where $A_L = \left[1.5e \left\{ f_D + f_T + 1/(T_i/T_e) + f_{alpha} \right\} T_i(0) / \left(1 + \alpha_n + \alpha_T \right) \right]$

The final plasma conduction loss and the confinement time are

- $$P_L = \left[\frac{A_L n(0)}{C_{op}'} \right]^{\frac{1}{1-S}} \left(10^{-6} \right)^{\frac{S}{1-S}}$$

- $$\tau_E = \frac{A_L n(0)}{P_L} = \frac{\left(C_{op}' \right)^{\frac{1}{1-S}}}{\left[A_L n(0) \times 10^{-6} \right]^{\frac{S}{1-S}}}$$

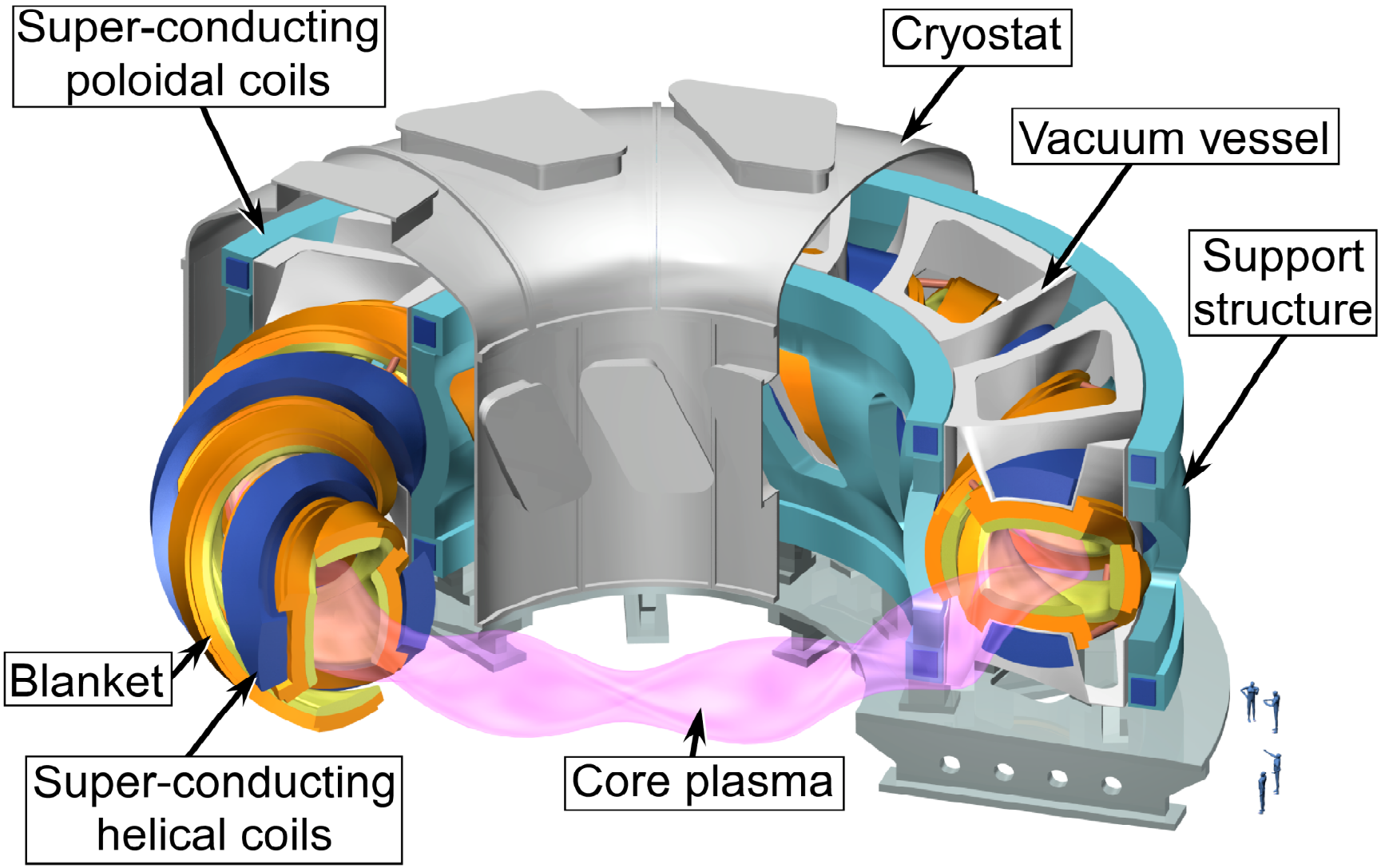


FIG.1 Birds-eye view of FFHR2m helical reactor

		Steady state value
Major radius	R (m)	14.0
Effective minor radius	$\bar{a}$ (m)	1.73
Polarity/Field period	ℓ / m	2/10
Coil pitch parameter	γ	1.15
Magnetic filed	B_o (T)	6.0
Maximum magnetic field	B_{omax} (T)	13.3
Coil magnetic energy	W_c(GJ)	120
Blanket thickness	ΔB(m)	1.2
Rotational transform	$\iota_{2/3}$	0.92
Maximum external heating power	P_{EXT} (MW)	100
Confinement factor over ISS95 scaling	γ_{ISS}	1.92
Confinement time	τ_E (s)	1.9
Helium ash fraction	F_{alpha}	0.034
Oxygen impurity fraction	F_O	0.0075
Effective ion charge	Z_{eff}	1.48
He ash confinement time ratio	τ_α^*/τ_E	3
Fusion alpha heating efficiency	η_α	0.9
Operation density	$n_e(0)$ (10^{20} m^{-3})	2.8
Density limit factor over Sudo scaling	γ_{SUDO}	1.5
Density limit margin in the steady state	$[n(0)_{limit}/n(0)]$	1.27
Ion temperature	$T_i(0)$ (keV)	15.3
Ion to electron temperature ratio	T_i/T_e	1.0
Density profile	α_n	1.0
Temperature profile	α_T	1.0
Beta value	$<\beta>$(%)	3.0
Fusion power	P_f (MW)	1900
Neutron power	P_n (MW)	1520
Bremsstrahlung power	P_B (MW)	57
Synchrotron radiation power	P_S (MW)	3.4
Plasma conduction power	P_L (MW)	282
Electric power output (thermal efficiency)	P_e (MW)	627(33%)
Neutron wall loading	Γ_n (MW/m^2)	1.5
Heat flux to first wall	Γ_h (MW/m^2)	0.06
Heat flux to divertor for 1m wet width	Γ_{div} (MW/m^2)	1.6

Table 1.
Machine and ignition plasma parameters

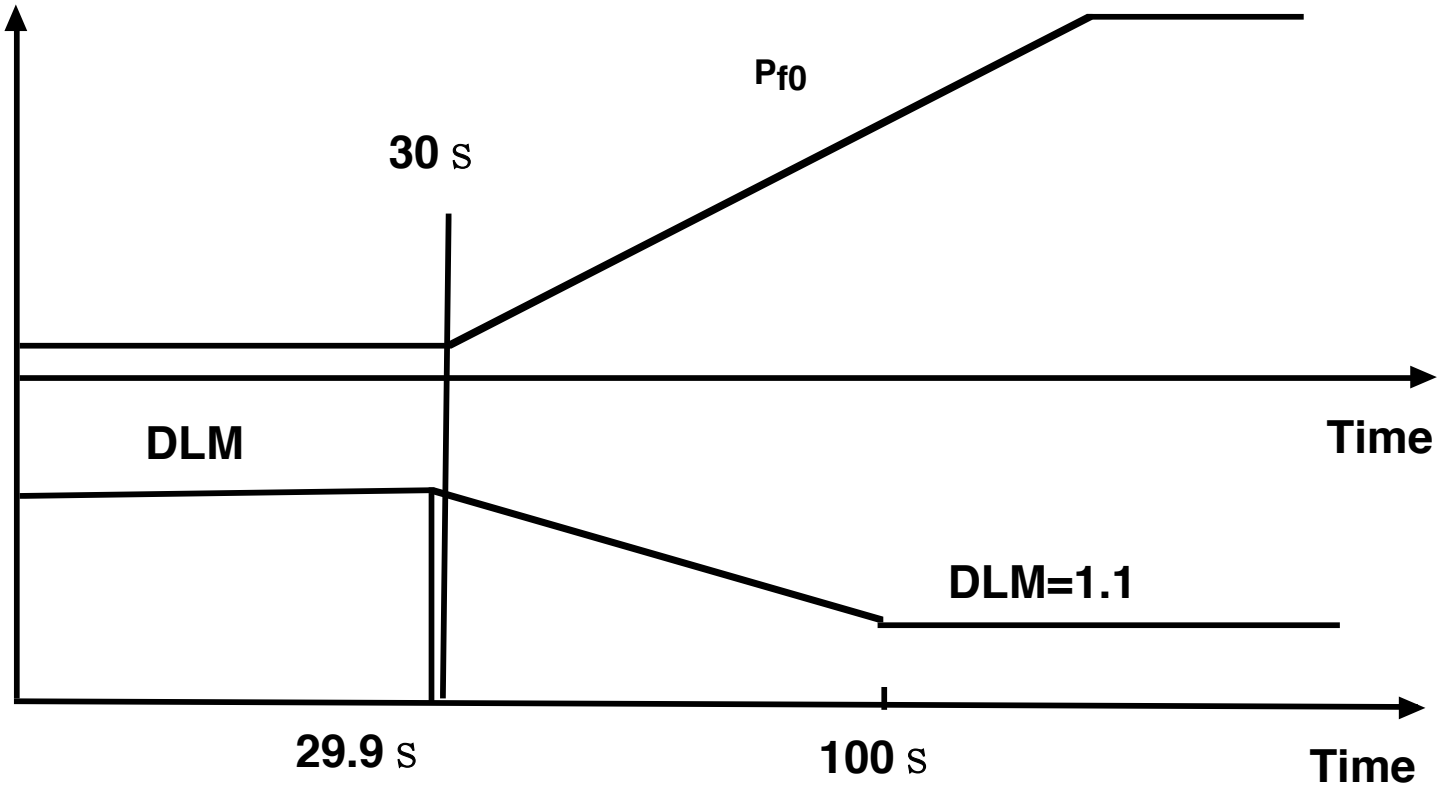
FFHR2m:

R=14m, a=1.73m,
B_o=6.0 T, η_α=0.90,
γ_{ISS}=1.92 (γ_{LHD}=1.2),

α_n=1.0, α_T=1.0,
γ_{SUDO}=1.5

2. Temporal evolutions of plasma parameters

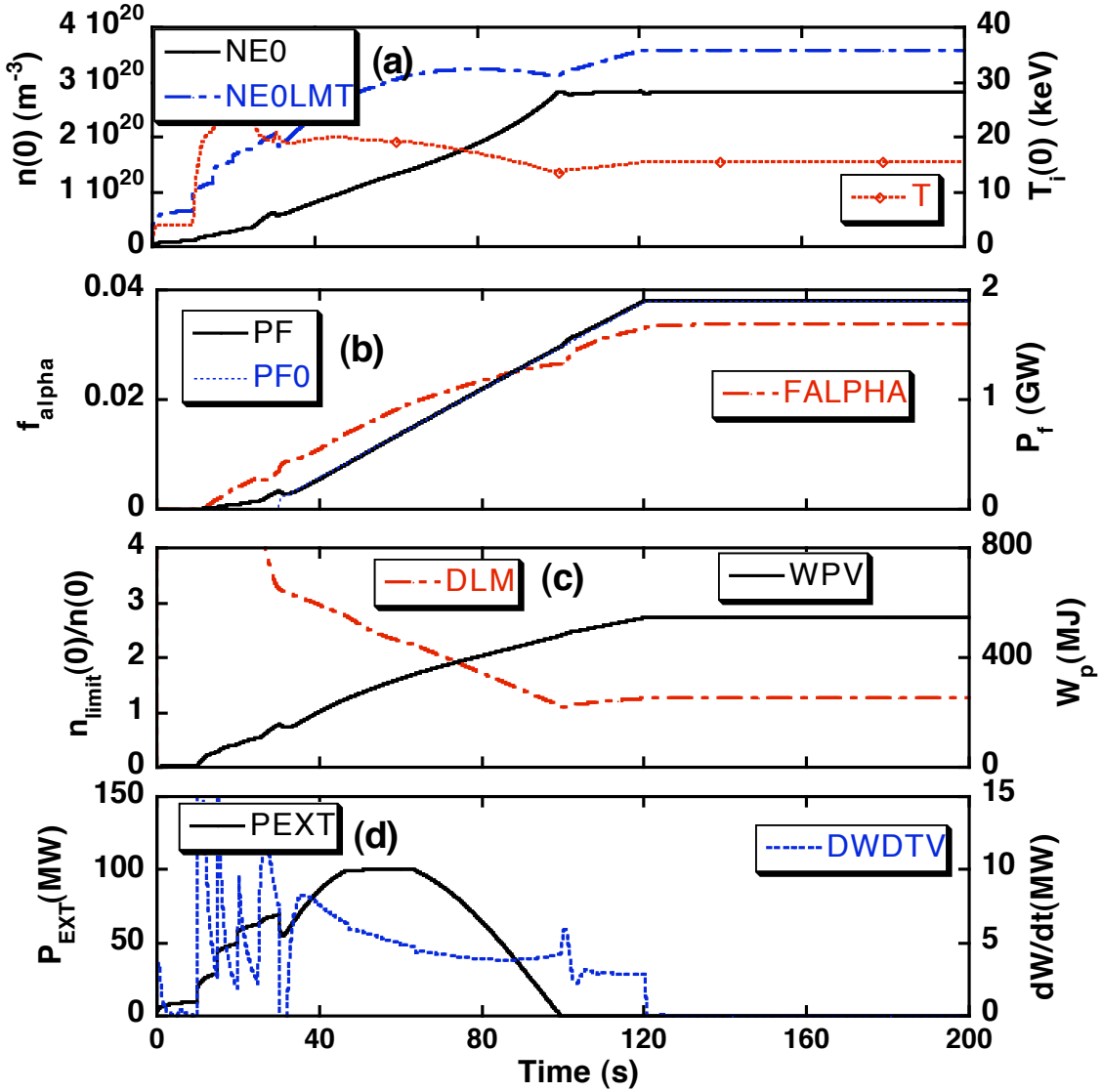
(a) Case-I : Density limit margin changes from the pre-programming phase to feedback phase. --------Time variable DLM effect----------



(a) Case-I

2.1. Initial pre-programming heating power of $P_{EXT\text{-}pre}$=70 MW

[Minimum DLM=1.1 at t_{DLM}=100 s]



When initial preprogramming power is large, --> Density limit margin (DLM) is large.

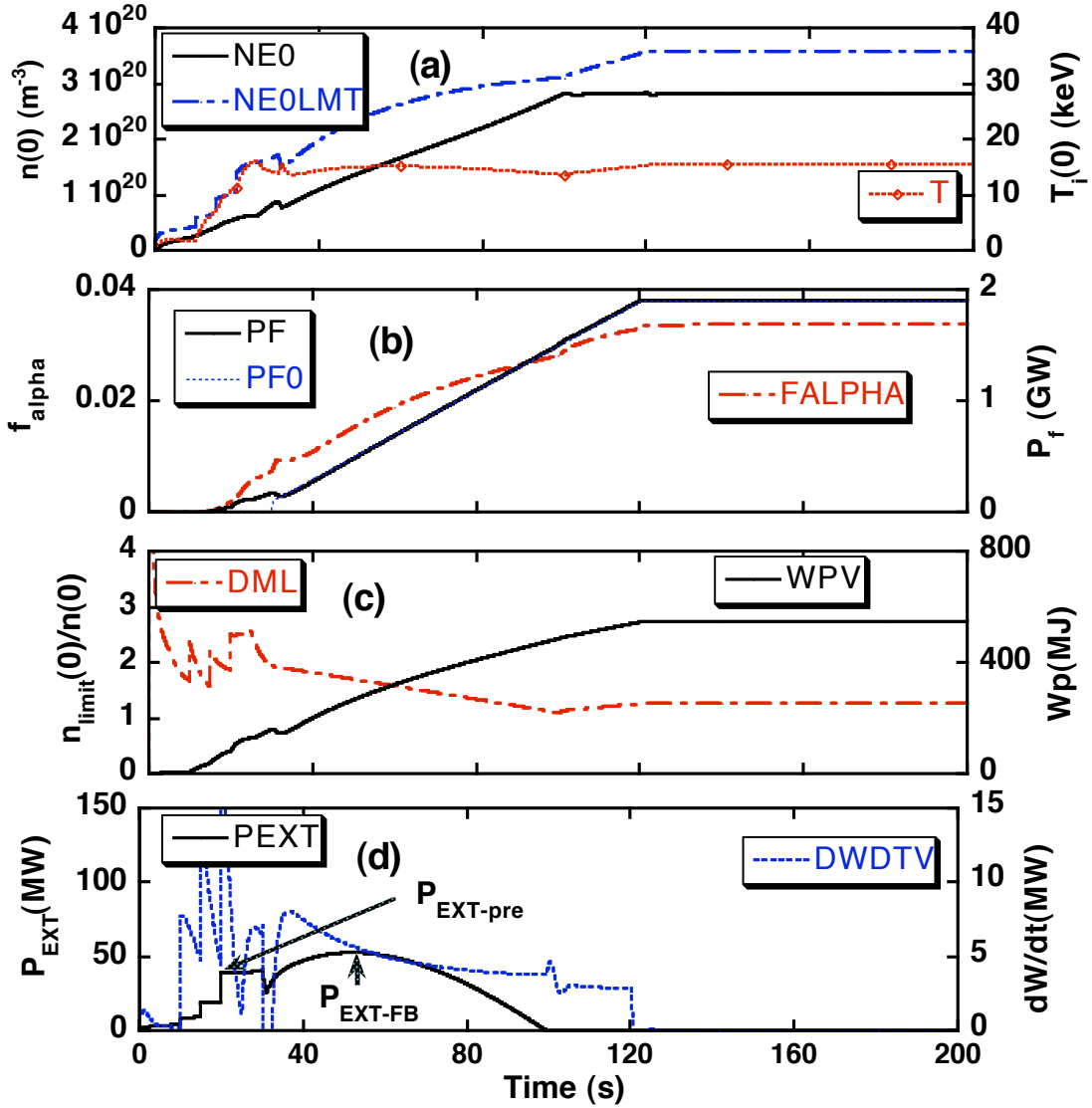
-->Heating power is increased after FB due to the remaining large DLM.

dW/dt＝5∽20 MW

Fusion power rise-up time of t=120 s -> $P_{EXT\text{-}FB}$=100 MW:

2.2. Initial pre-programming heating power is reduced to $P_{EXT\text{-}pre}$=40 MW

the same fusion power rise-up time: t=120 s,



$P_{EXT\text{-}FB}$=53 MW

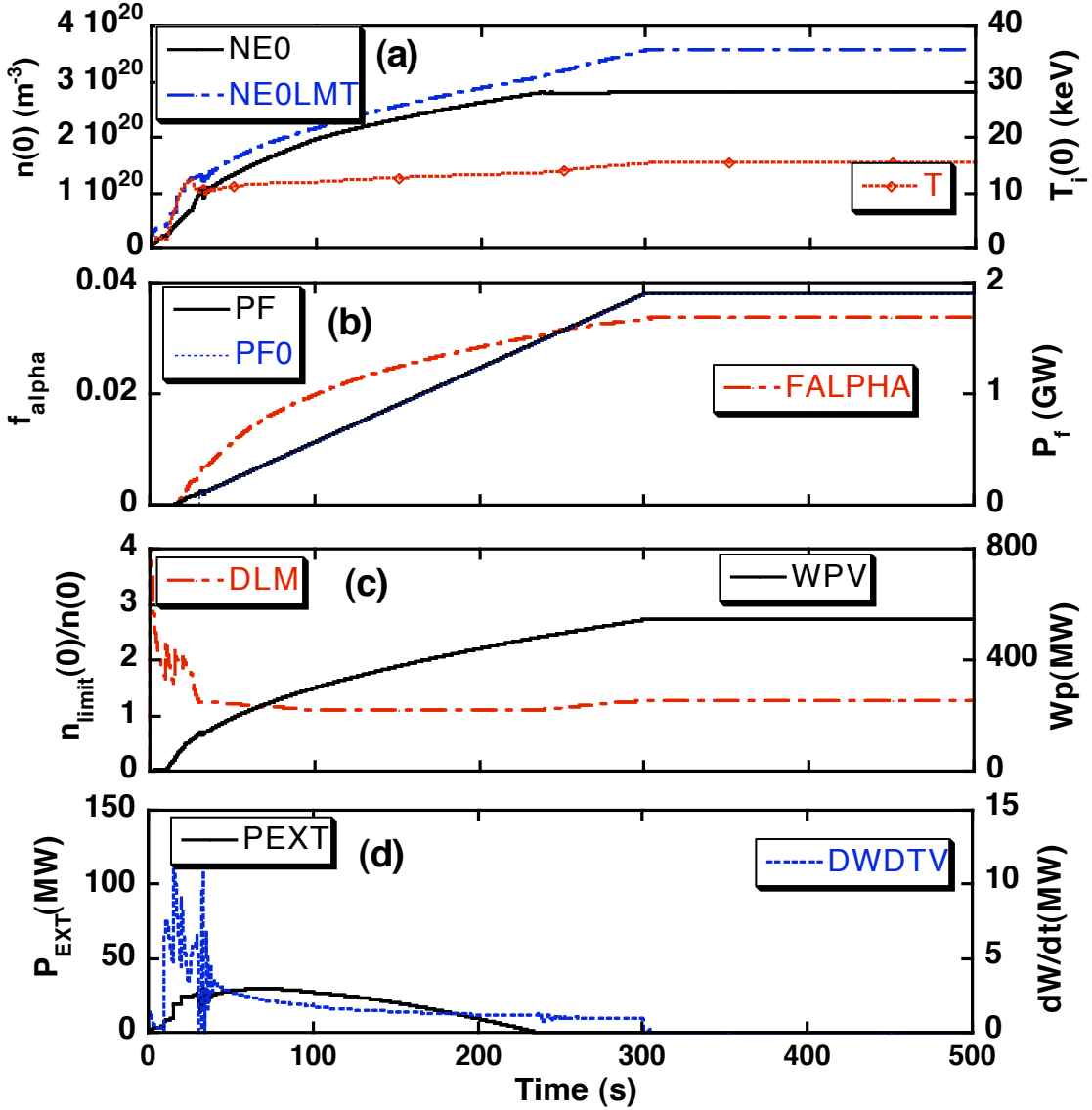
When initial pre-programming heating power is reduced,

-->DLM is reduced,

--> Feedback heating power is reduced.

dW/dt＝5∽10 MW

2.3. Initial pre-programming heating power is reduced to $P_{EXT\text{-}pre}$=25 MW and Fusion power rise-up time is longer as t=300 s,



$P_{EXT\text{-}FB}$=30 MW

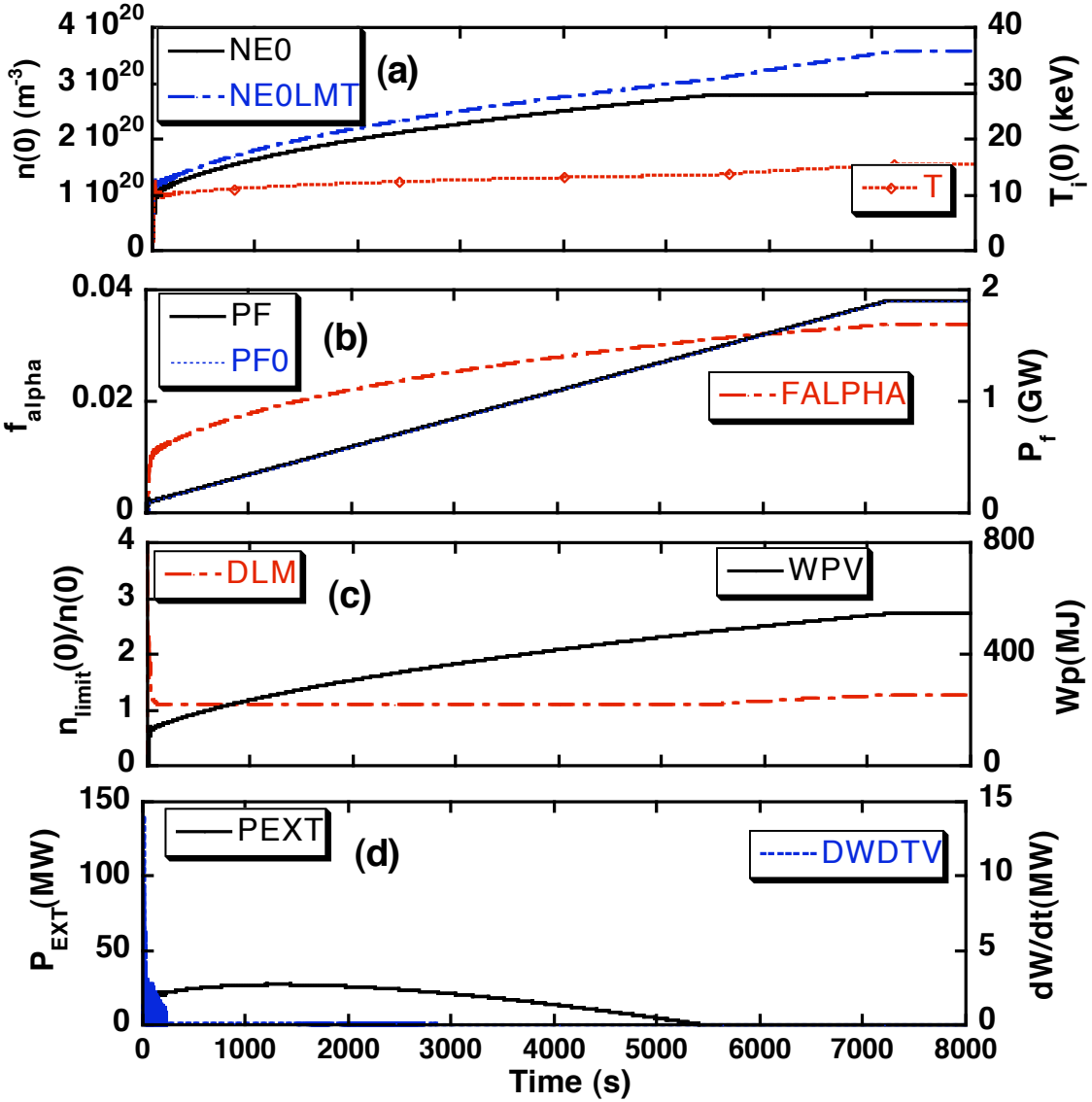
When initial pre-programming heating power is further reduced, and longer rise-up time

→ Smaller DLM

--> Smaller feedback heating power

dW/dt＝3~10 MW

2.4. Initial pre-programming heating power $P_{EXT\text{-}pre}$=25 MW and Fusion power rise-up time is longer as t=7200 s (2 hours),



$P_{EXT\text{-}FB}$=27 MW at 1300 s

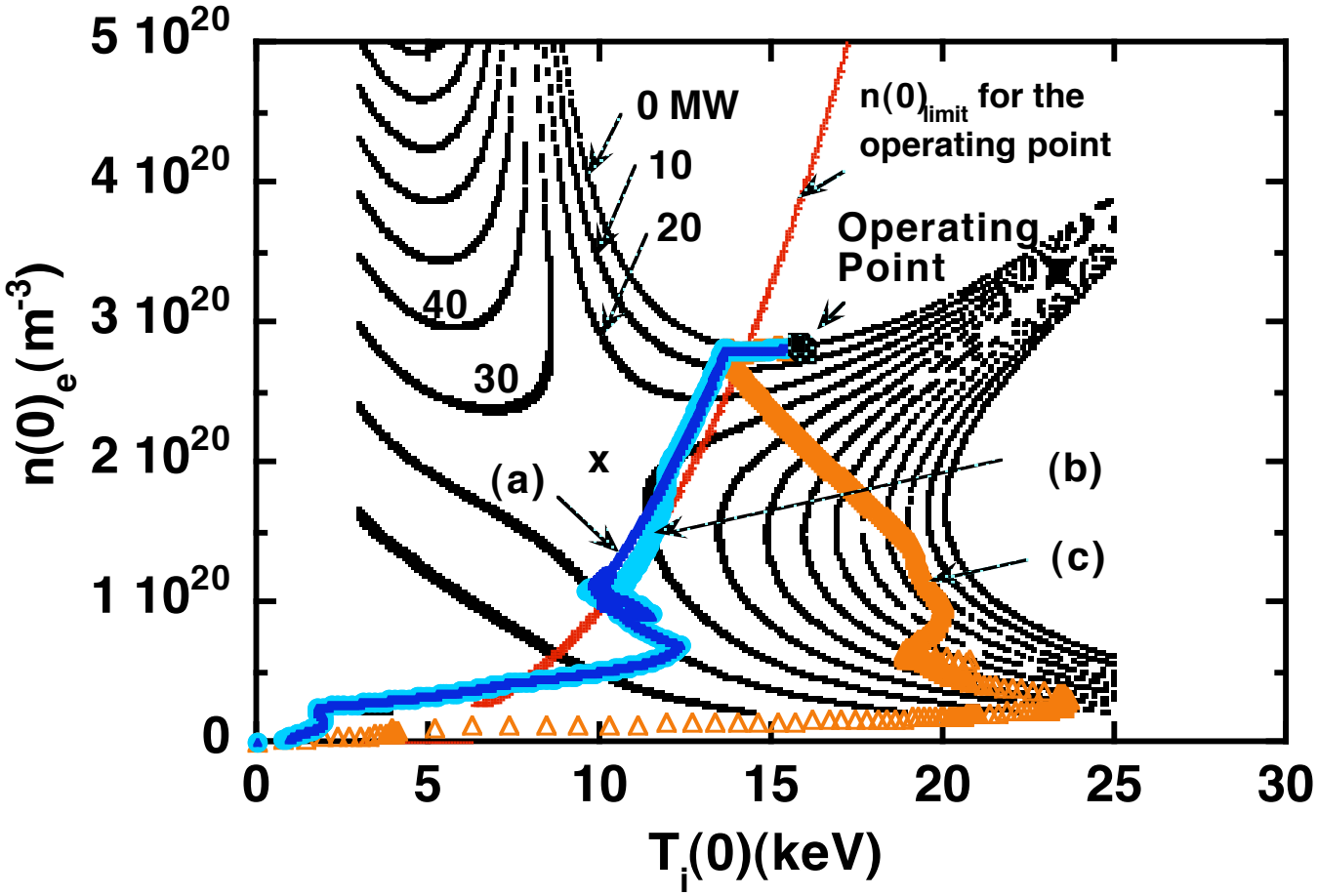
No DLM effect

Power balance determines the minimum heating power

dW/dt=~0 MW

2.5. Operation paths on POPCON

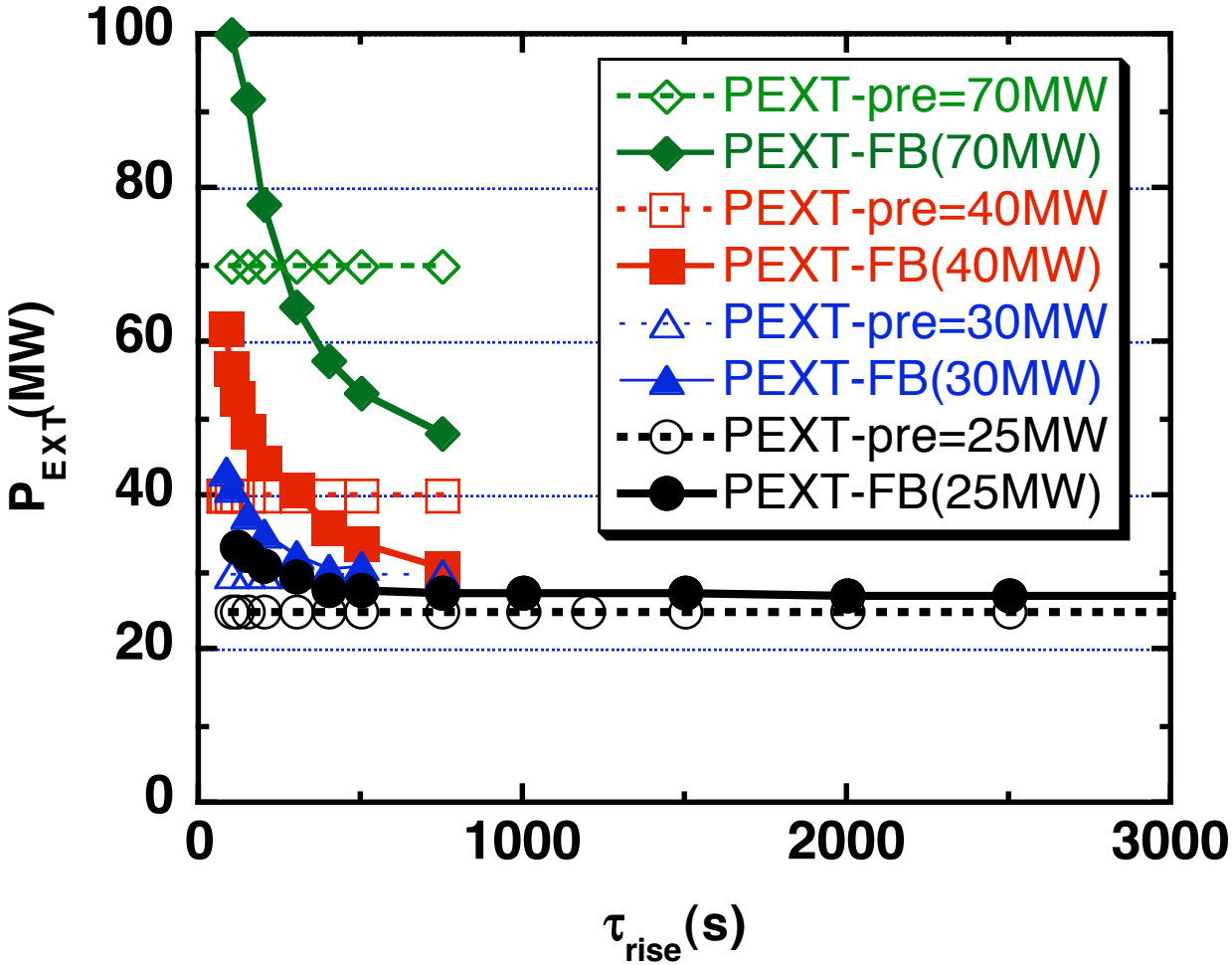
(a) 2 hours rise-up time (b) 300 sec (c) 150 sec



(a) Longer rise-up time
--> Smaller hearing power
--> near the saddle point

(c) Shorter rise-up time
--> Larger heating power

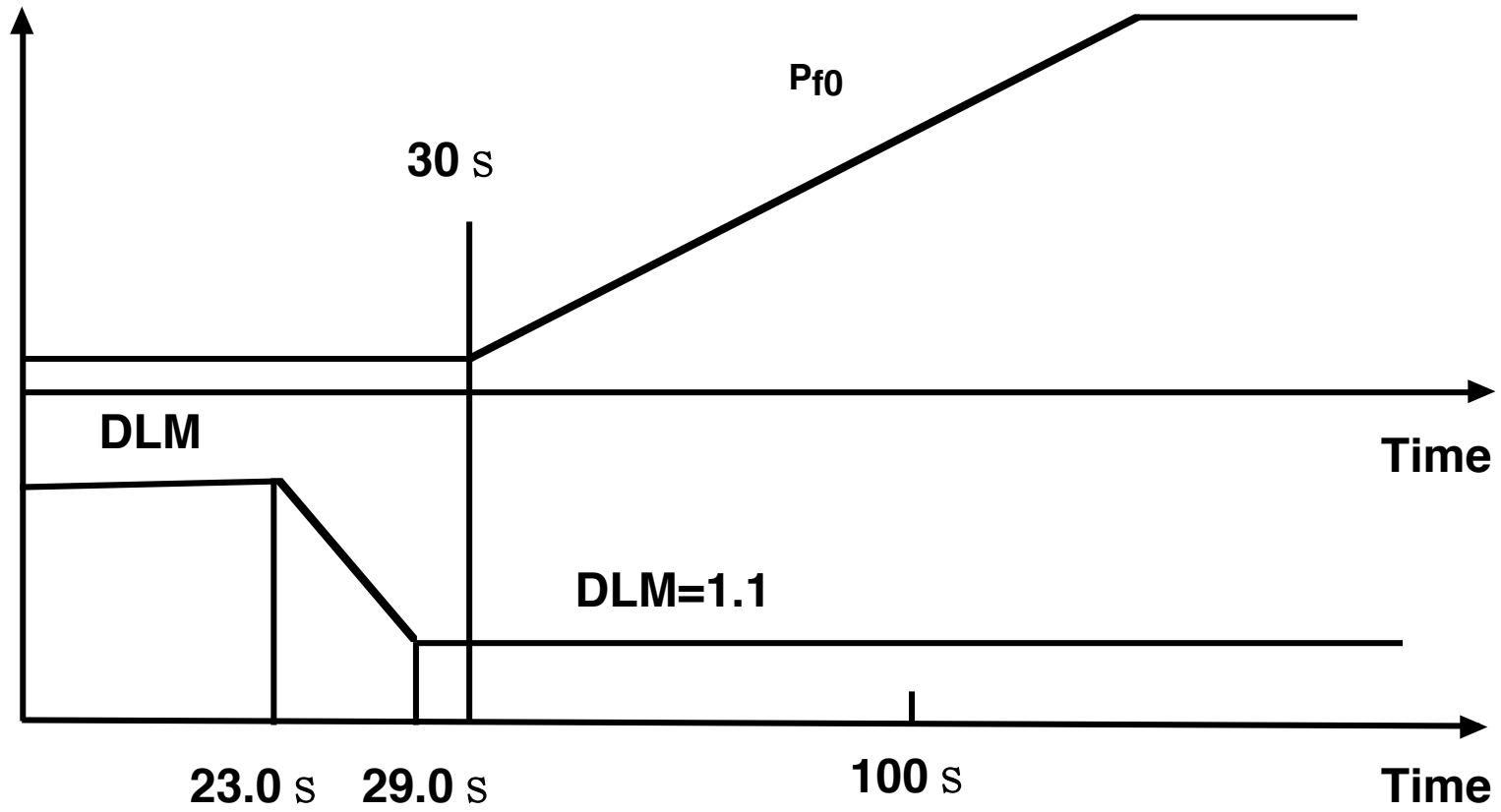
2.6. Fusion power rise-up time vs Feedback controlled heating power for various initial pre-programming heating power



Density limit effect and power balance effect are mixed up due to time variable DLM effect.

3. The dW/dT effect on the heating power

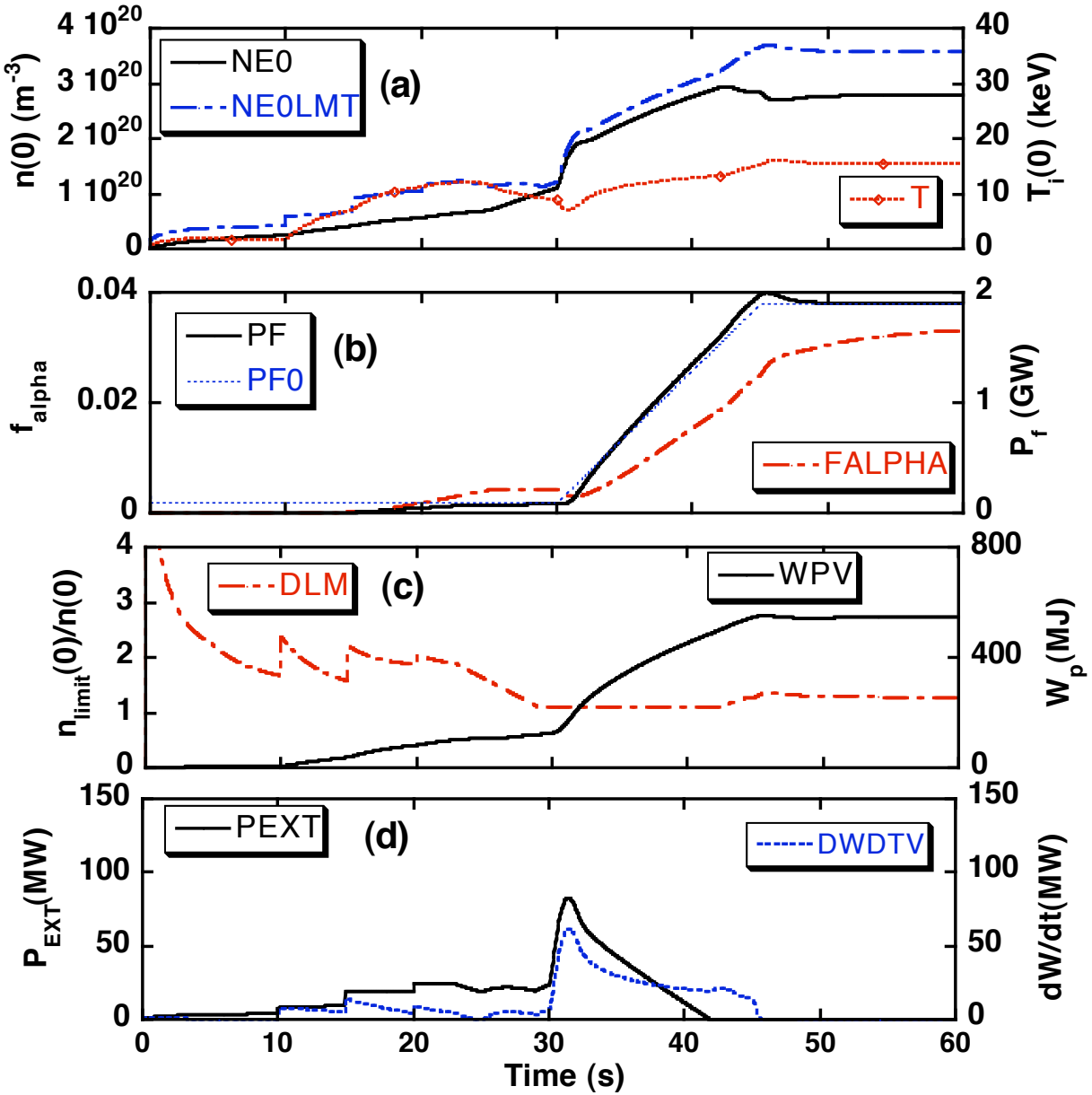
(b) Case-II : Density limit margin is set at constant of 1.1 during fusion power up phase. ------ Time constant DLM effect-------



(b) Case-II

Density limit margin is small during the fusion power rise-up phase.

[1] τ_{rise}=45 s ($\Delta\tau_{rise}$=15 s)



$P_{EXT\text{-}pre}$=25 MW

<u>At t=31.45s</u>

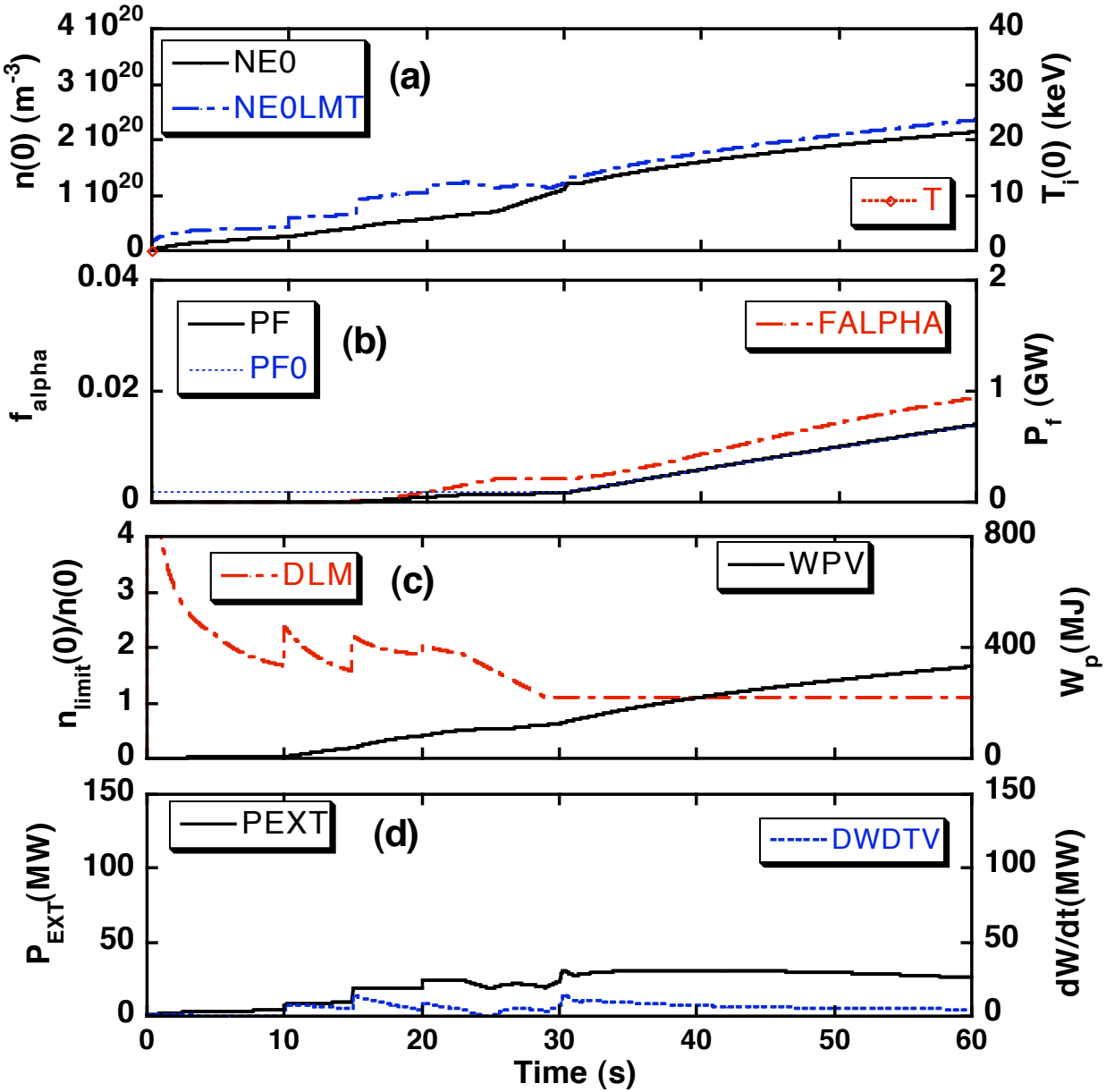
P_{EXT}=82 MW

f_{alpha}=0.003

dW/dt=62 MW
(Main part of the heating power)

POPCON: P_H=20.2 MW

[2] τ_{rise}=120 s ($\Delta\tau_{rise}$=90 s)



At t=39.40 s.

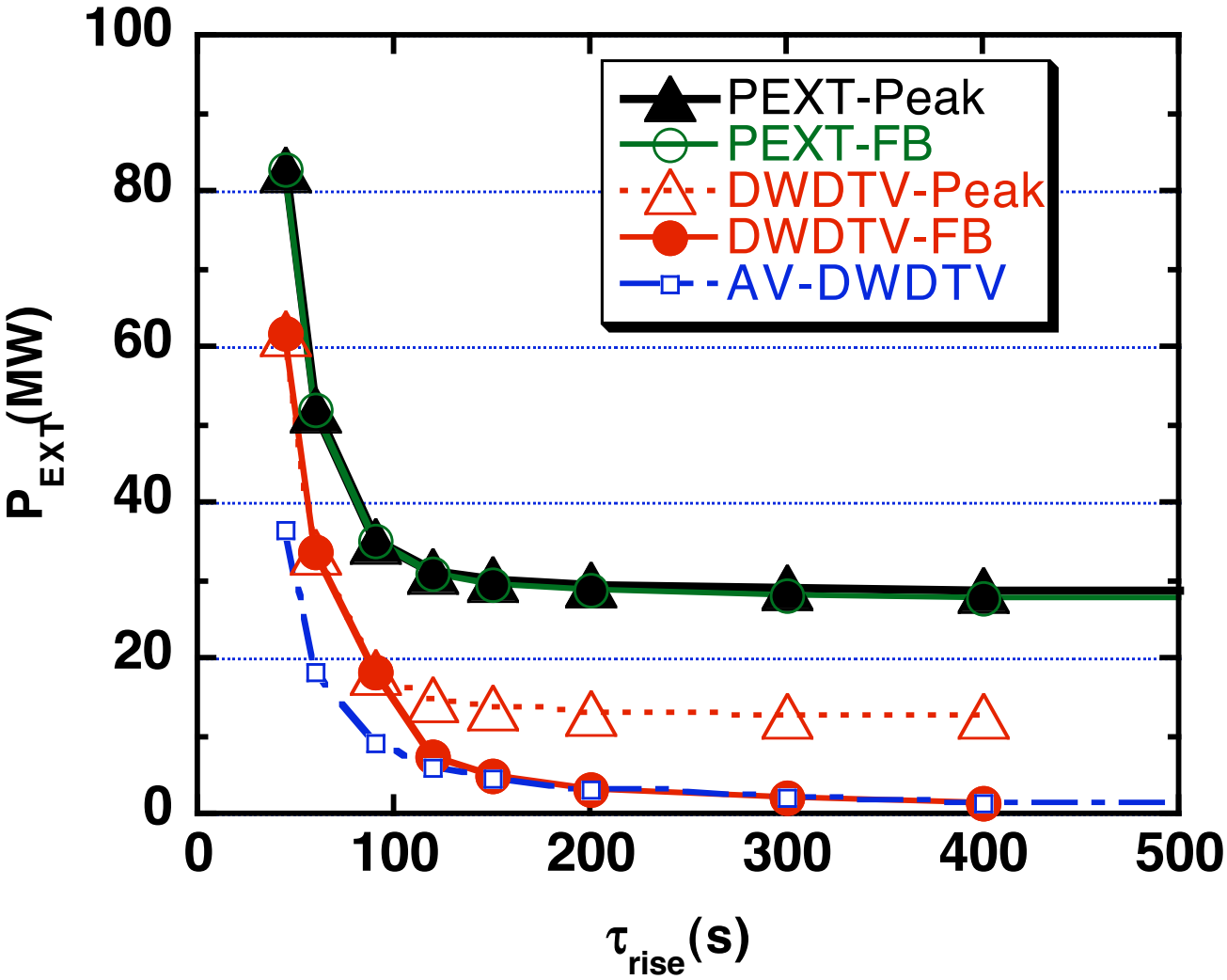
The maximum heating power P_{EXT}=30.8 MW

f_{alpha}=0.0083

dW/dt=7.4 MW

POPCON: P_H=23.4 MW

[3] Fusion power rise-up time vs Feedback controlled heating power for DLM=1.1 during the fusion power rise-up phase (t_{DLM}=29 s~)

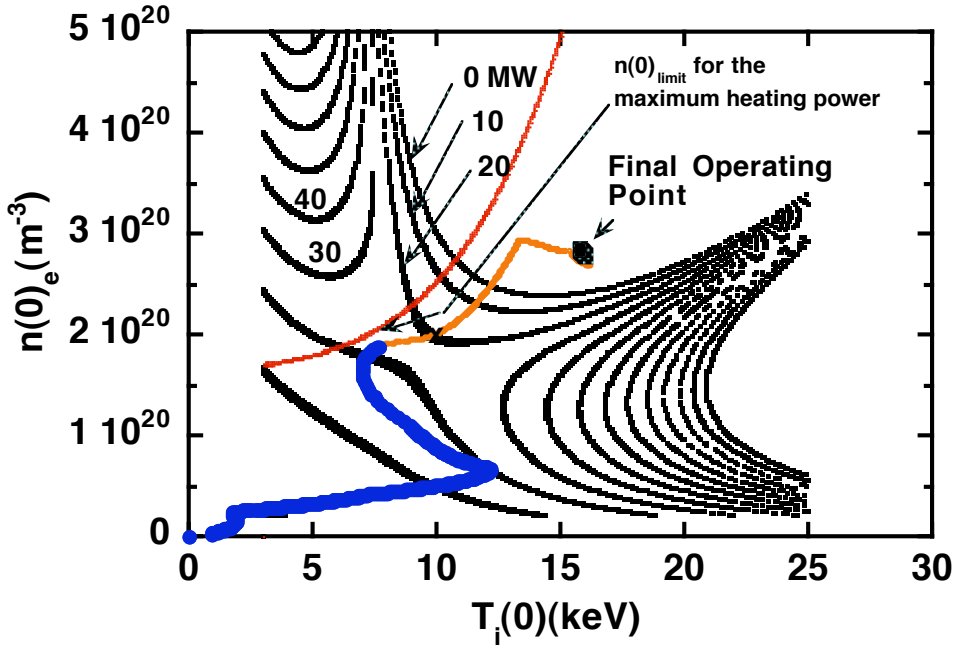


Constant DLM effect

--> Feedback heating power can be minimized for τ_{rise}>100 s.

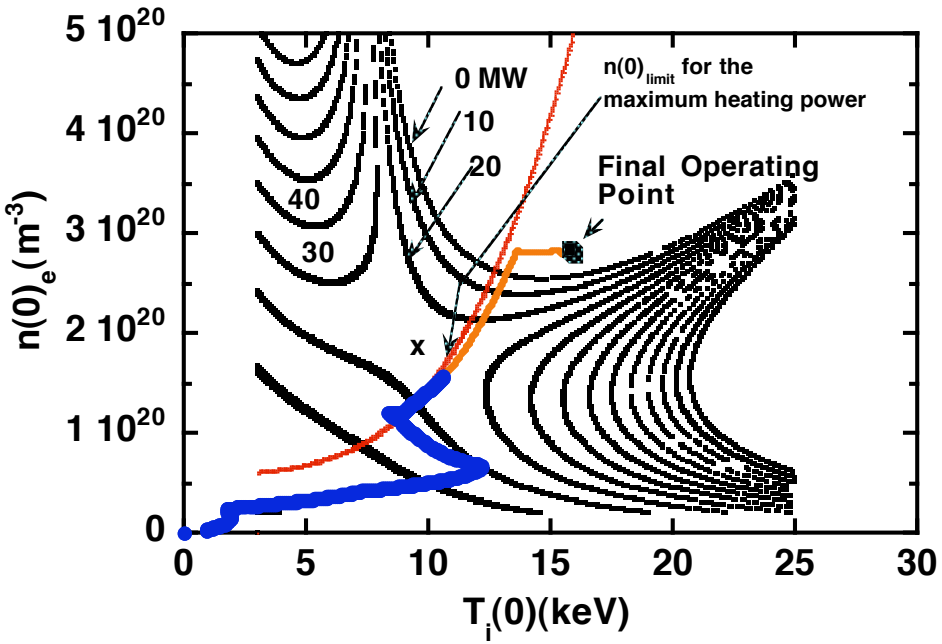
[4] Operation paths on POPCON for the constant DLM=1.1

(a) τ_{rise}=45 s (Δt=15 s) rise-up time



@Smaller He ash fraction
(f_{alpha}=0.003)
@ Long operation path
@ Moved to the lower temperature side by density increase

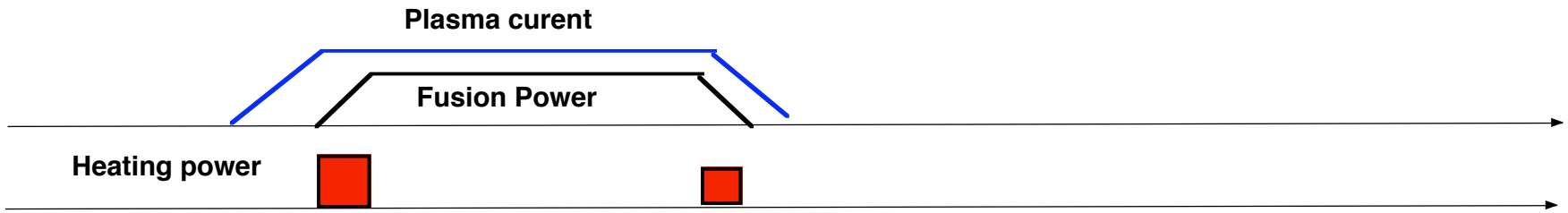
(b) τ_{rise}=120 s (Δt=90 sec)



@Larger He ash fraction
(f_{alpha}=0.008)
@ Shorter operation path
@ Near the saddle point

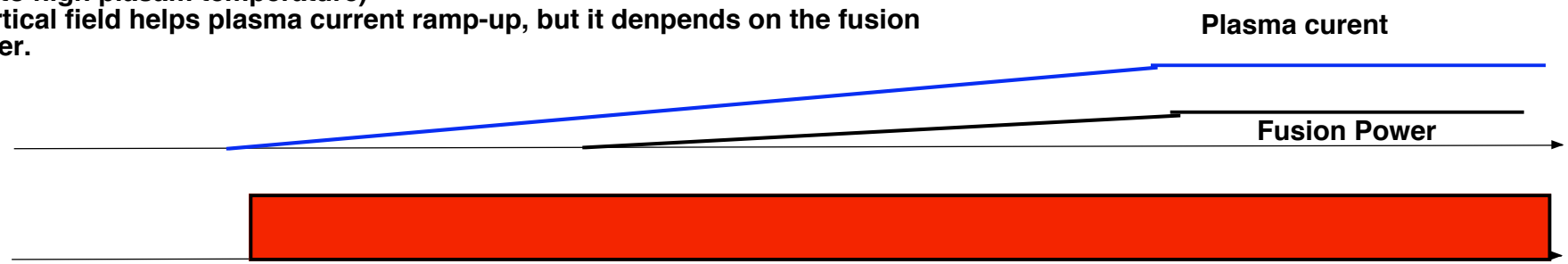
4. Comparison with tokamak

(1) Tokamak+OH (Short rise-up time: limited by OH flux)

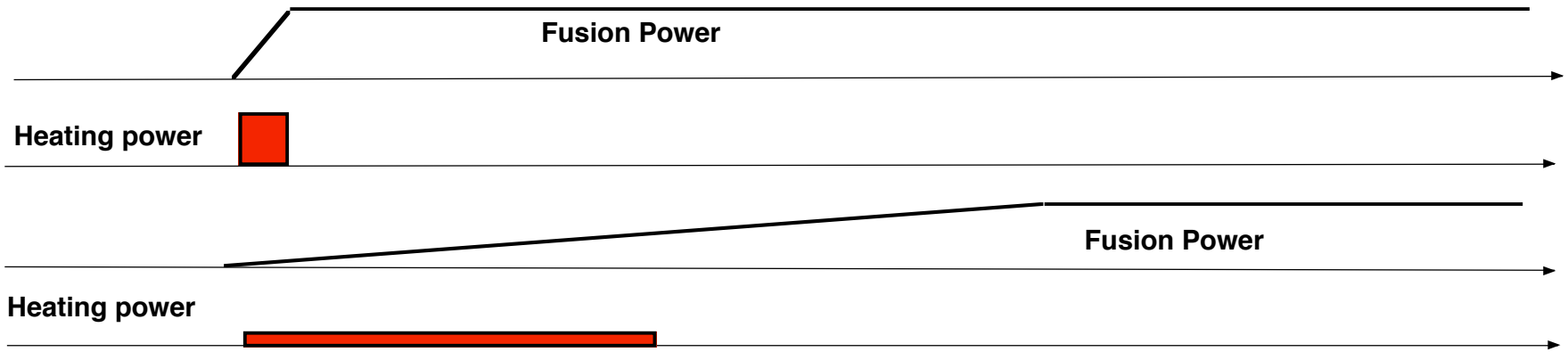


(2) Tokamak+Noninductive (Very long rise-up time, No medium rise-up time)

Non-inductive current ramp-up time is very long due to low plasma resistance due to high plasam temperature)
Vertical field helps plasma current ramp-up, but it denpends on the fusion power.



(3) Helical (Any rise-up time is possible)



5. Summary

1. Density limit margin (DLM) determines the feedback controlled heating power. Lower initial pre-programming power provides the smaller heating power through the lower DLM.

2. Longer fusion power rise-up time >100~300s can further reduce the heating power due to the dW/dt effect.

3. If the larger heating power is prepared, any fusion power rise-up time can be achievable in a helical reactor as a fission reactor, because the poloidal field exists always. This is the advantageous point different from a tokamak system.

4. Shorter fusion power rise-up time provides the longer path to the ignition operating point. Longer fusion power rise-up time gives the shortest path to the ignition operating point due to the dW/dt effect.

POPCON shows a phase space.