Low temperature and high-density ignited operation in FFHR

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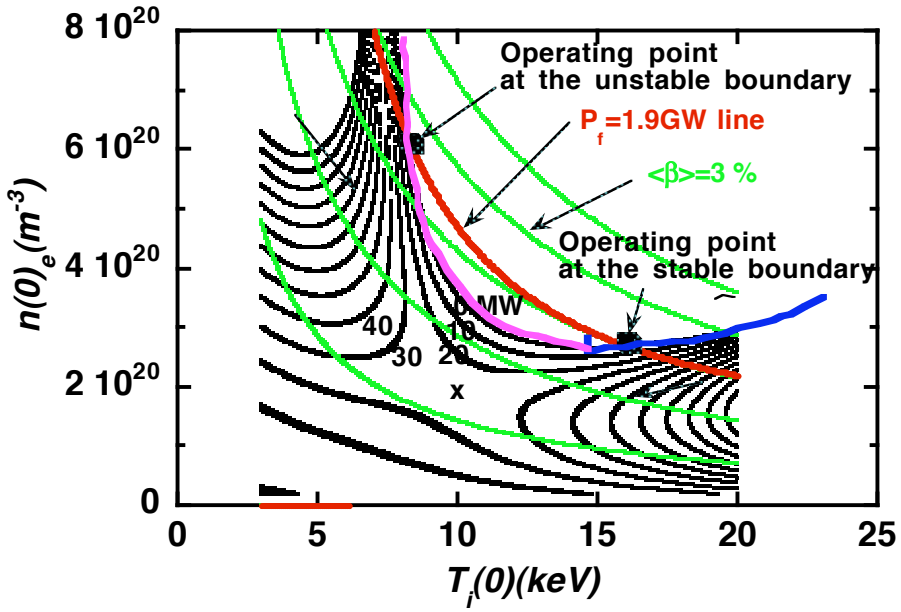
1. Motivation of this study:

For the same fusion power, two operating points exist:

[1] Thermally stable ---- High temperature and low density operation

[2] Thermally unstable ---- Low temperature and high density operation

Recently, super-dense core plasma with $n(0)\sim1.1\times10^{21}$ m^{-3} has been achieved in LHD device with pellet injection experiments. Therefore the low temperature and high-density operation could be a possible operation scenario in FFHR helical reactor.



We have found how to control the unstable operation in FFHR.

So far many stabilization methods had been proposed in ~40 years.

Disadvantages in previous studies:

- Linearization is necessary in many equations.
  Therefore, it is difficult to apply it to 1-D code and a reactor.
- Only stabilization around the steady state unstable operating point has been shown.
  :The access to the unstable operating point from the initial low temperature and density has not been demonstrated.

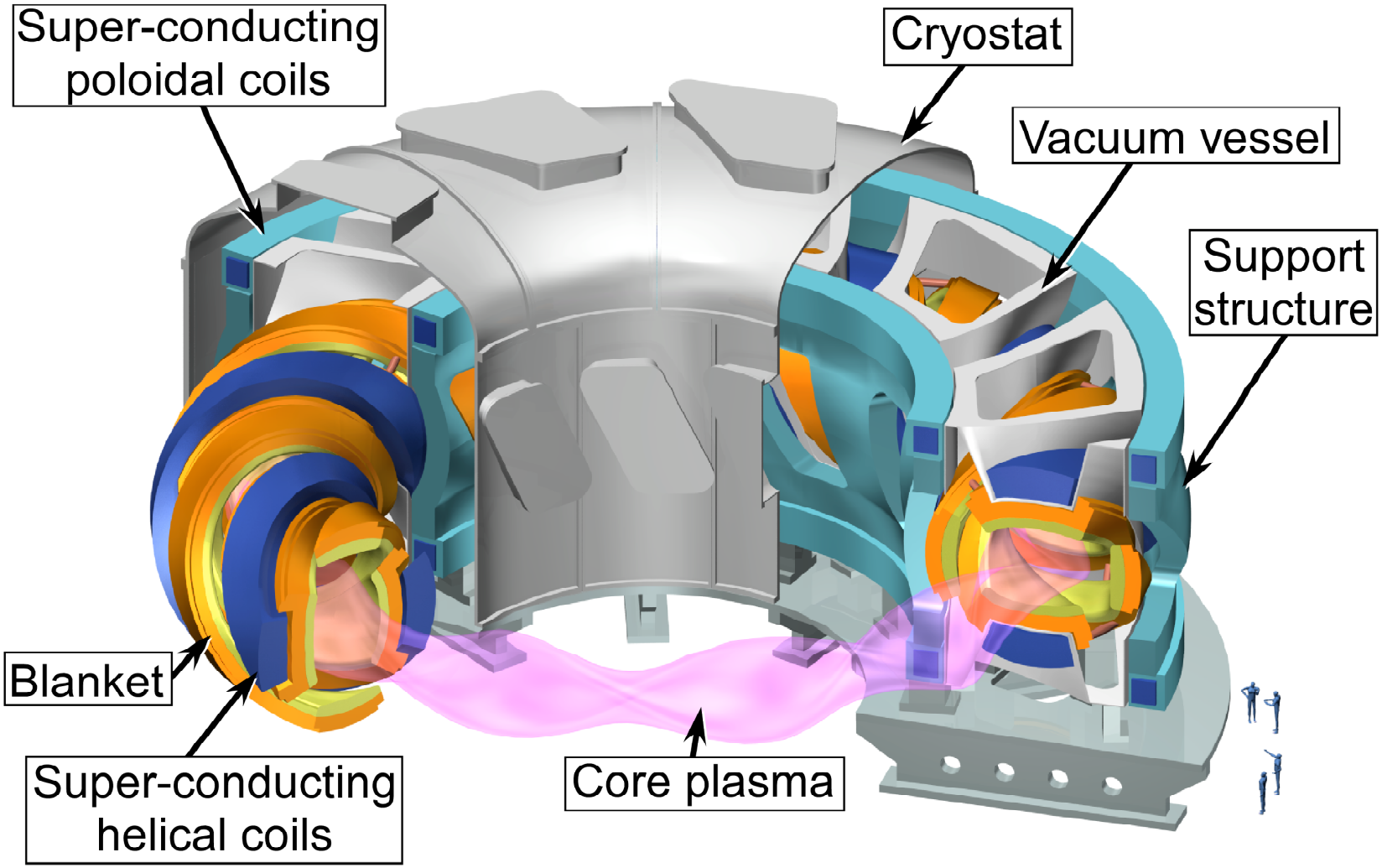
Advantages in this control method:

- simple PID + comprehensive
- no linearization → 0-D and 1-D simulation
- Plasma is treated as a black box → possible implementation in a reactor

In this study we demonstrate

- Pellet injection can control the ignition access and steady state operation in the thermally unstable regime using PID fueling control.
- Control robustness to various disturbances exists to some extent by pellet injection fueling and heating power.
- Comparison with the usual control theory and PID parameter regime
- Smooth fusion power shutdown is possible with pellet injections.
- Failure mode analysis
- Compact FFHR

FFHR (R=14 m, a=1.72 m, B=6 T)



2. 0-D equations and control algorithm

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

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

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

Charge neutrality condition: $n_e(0) = \dfrac{n_D(0) + n_T(0) + 2n_\alpha(0)}{1-8f_o}$

Combined particle balance equations

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

He ash equations

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

Power balance equation

$$\frac{dT_i(0)}{dt} = \frac{1+\alpha_n+\alpha_T}{1.5e\left(f_D+f_T+1/\gamma_i+f_\alpha\right)n_e(0)} \times \left[\left\{P_{EXT}+P_\alpha\right\}-\left\{P_L+P_B+P_S\right\}\right]$$
$$-\frac{T_i(0)}{\left(f_D+f_T+1/\gamma_i+f_\alpha\right)} \times \left[\left\{1-8f_O+\frac{1}{\gamma_i}-f_\alpha\right\}\frac{1}{n_e(0)}\left[\frac{dn_e(0)}{dt}\right]-\left[\frac{df_\alpha(0)}{dt}\right]\right]$$

2.2.Profiles

[1] Thermally stable operation to unstable operation

@Parabolic density profile: α_n=1.0 : $n(x)/n(0) = (1-x^2)^{\alpha_n}$

@Parabolic temperature profile:

α_T=1.0 : $T(x)/T(0) = (1-x^2)^{\alpha_T}$

[2] SDC type operation

$\mathrm{Tanh}(x)=(e^x-e^{-x})/(e^x+e^{-x})=1-2e^{-x}/(e^x+e^{-x})$

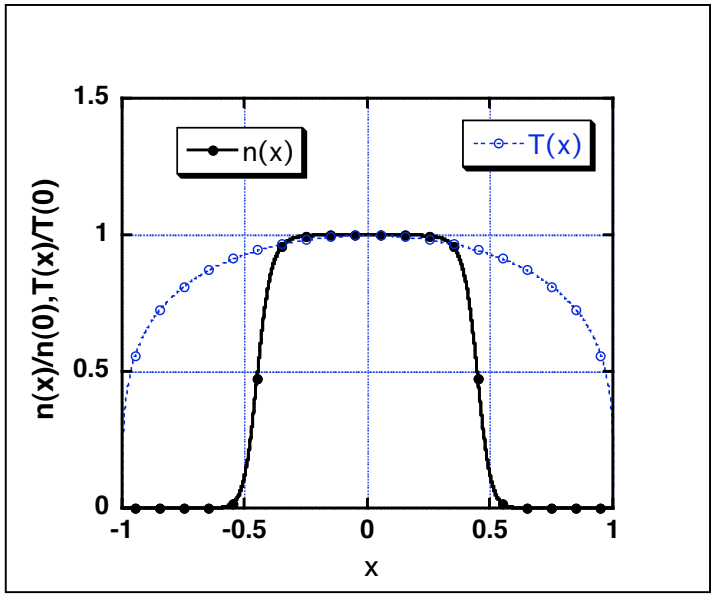
@Box type density profile:

$n(x)/n(0) = 0.5[1-\mathrm{Tanh}(20(x^2 - a_n))]$

$[row/a]_{ITBFM}$=0.45 (a_n=0.2)

@Parabolic temperature profile:

α_T=0.25 : $T(x)/T(0) = (1-x^2)^{\alpha_T}$



2.3. Power balance calculation:

Box type density profile : $n(\rho) = n(0) \times 0.5\left[1 - Tanh\left\{20\left(\rho^2 - 0.2\right)\right\}\right]$

Parabolic temperature profile: $T(\rho) = T(0)\left(1 - \rho^2\right)^{0.25}$

@Volume averaged plasma energy:

$$\bar{W} \,/\, 3kn(0)T(0) = \int_0^1 0.5\left[1 - Tanh\left\{20\left(\rho^2 - 0.2\right)\right\}\right] \times \left(1 - \rho^2\right)^{0.25} 2\rho d\rho$$

$$= \frac{1}{1 + \alpha_n + \alpha_T} \Rightarrow 0.194429$$

@Volume averaged Bremsstrahlung loss:

$$\bar{P}_B \,/\left\{1.488 \times 10^{-38} Z_{eff} n(0)^2 \sqrt{T(0)}\right\} = \int_0^1 \left\{0.5\left[1 - Tanh\left\{20\left(\rho^2 - 0.2\right)\right\}\right]\right\}^2 \times \left(1 - \rho^2\right)^{0.25/2} 2\rho d\rho$$

$$= \frac{1}{1 + 2\alpha_n + 0.5\alpha_T} \Rightarrow 0.172891$$

@Volume averaged alpha heating power :

--> direct integration

2.4. ISS95 scaling (ISS04 scaling is not much different.)

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

2.5. Stabilization by PID fueling control

[1] Continuous fueling

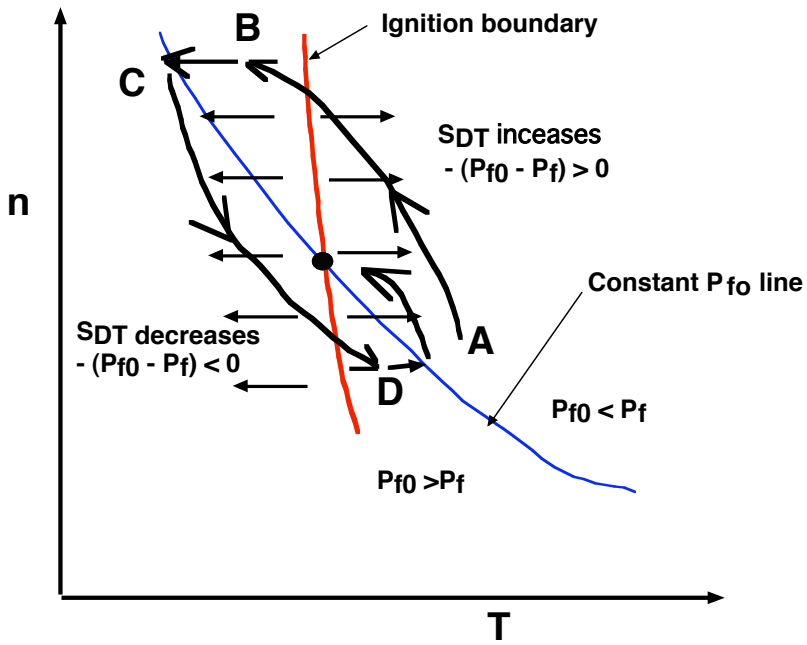
$$S_{DT}(t) = S_{DT0}\left\{e_{DT}(P_f) + \frac{1}{T_{\text{int}}}\int_0^t e_{DT}(P_f)dt + T_d\frac{de_{DT}(P_f)}{dt}\right\}G_{fo}(t) \qquad (1)$$

T_{int} the integration time, T_d the derivative time, [Note: $S_{DT}(t)=0$ if $S_{DT}(t)<0$]

The error the fusion power : $e_{DT}(P_f) = c(1- P_f/P_{fo})$

[1] c=+1 for the stable boundary,

[2] c= -1 for the unstable boundary,



@Stabilization mechanism

1. Cooling by fueling and heating by reducing fueling
2. Operation path movement in the sub-and ignition regime

@ During ignition access, a stable control is possible.

[2] Pellet injection

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

Discrete fueling

$$\begin{cases} S_{DT}(t) = S_{DTpellet} & for\ \ Error(P_f) > 0 \\ S_{DT}(t) = 0 & for\ \ Error(P_f) \le 0 \end{cases}$$

@Plasma Volume V_p=827 m^3 @DT solid molar volumes = 19.88 mm^3/mol

@DT ice particle number density={6.02x10^{23}x2}/19.88 [mm^3/mol]=6.05x10^{28}/m^3

[1]L=12mm: $N_{pell} = \left\{ \pi \left(L_p / 2 \right)^2 L_p \right\} \times 6.05 \times 10^{28} = 82 \times 10^{21} / m^3$

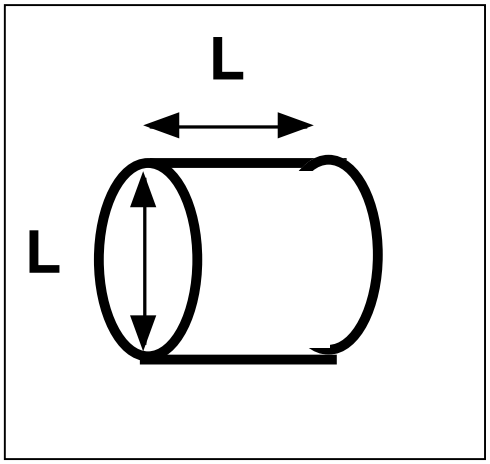
->S_{DTpell}=N_{pell}/V_p=0.990x10^{20} /m^3

[2]L=14mm: N_{pell}=130x10^{21} /m^3

->S_{DTpell}=N_{pell}/V_p=1.57x10^{20} /m^3

[3]L=16mm:

N_{pell}=194x10^{21} /m^3 −> S_{DTpell}=N_{pell}/V_p=2.353x10^{20}/m^3



2.6. Heating power:

In the stable ignition regime, the density limit scaling can be used for the feedback control from ignition to sub-ignition.

$$\gamma_{DLM} n(0) \le n(0)_{\lim}[m^{-3}] = \gamma_{SUDO} \frac{0.25\times10^{20}}{\gamma_{pr}} \sqrt{\frac{\left\{P_{NET}[W]\times10^{-6}\right\} B_o[T]}{\bar{a}^2 R[m]}}$$

as

$$P_{EXT}[W] = \left\{ \gamma_{pr} \frac{\left[\gamma_{DLM} n(0)[m^{-3}]\right]}{\gamma_{SUDO} 0.25\times10^{20}} \right\}^2 \frac{\bar{a}^2 R[m]}{B_o[T]} \times 10^6 - \left(P_\alpha - P_B - P_S\right)$$

In the unstable ignition regime: this cannot be used.

[1] Preprogram is used so far.

[2] PI control of the heating power is newly developed.

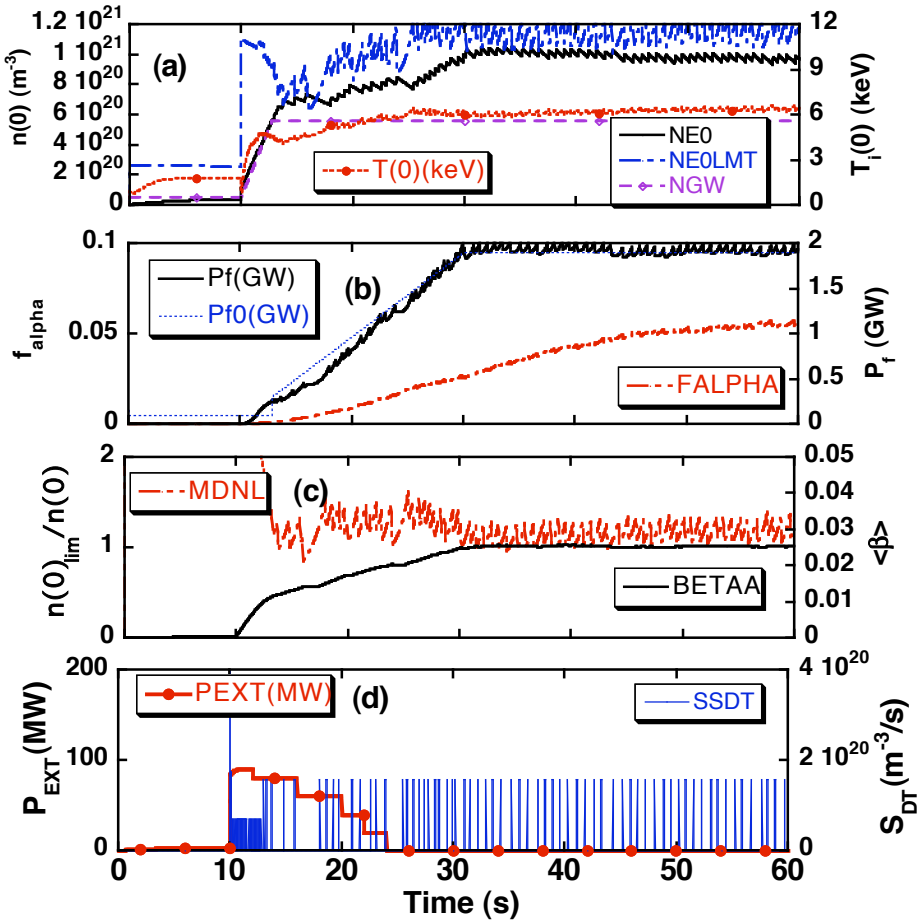
$$P_{EXT}(P_f) = P_{EXTO} \left\{ e_{EXT}(P_f) + \frac{1}{T_{P\,\mathrm{int}}} \int_0^t e_{EXT}(P_f)\,dt \right\}$$

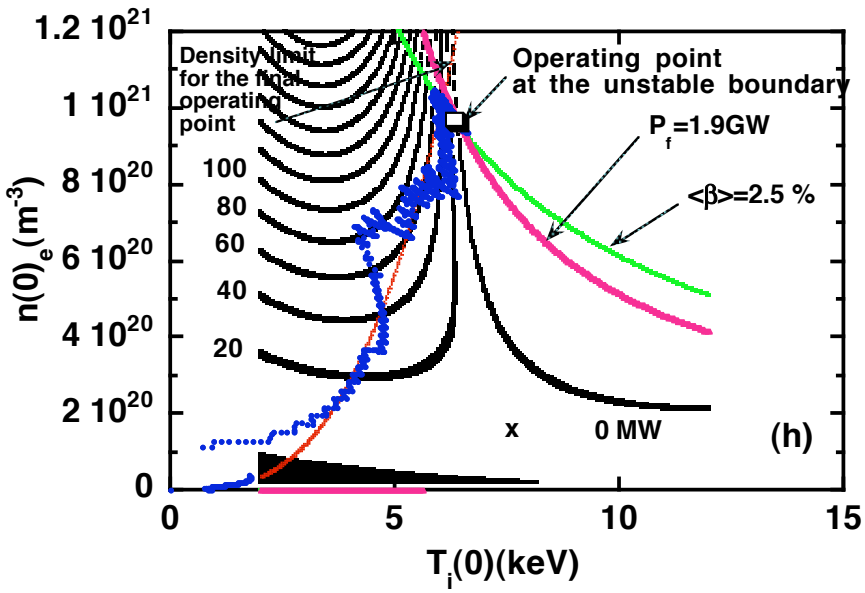
where $e_{EXT}(P_f)=(1-P_f/P_{fimp})$ $P_{fimp}(t)=P_{fo}(t)(1.8/1.9)$, $T_{pint}=15$ s

3. Access to the unstable operation point by pellet injection

3.1. 14 mm pellet size （T_d=0.26s,T_{int}=8s）

It is still possible to control the unstable operating point for $\Delta n \sim 5.0 \times 10^{19} m^{-3}$.





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Between pellet injections, the operating point moves along the constant β line.

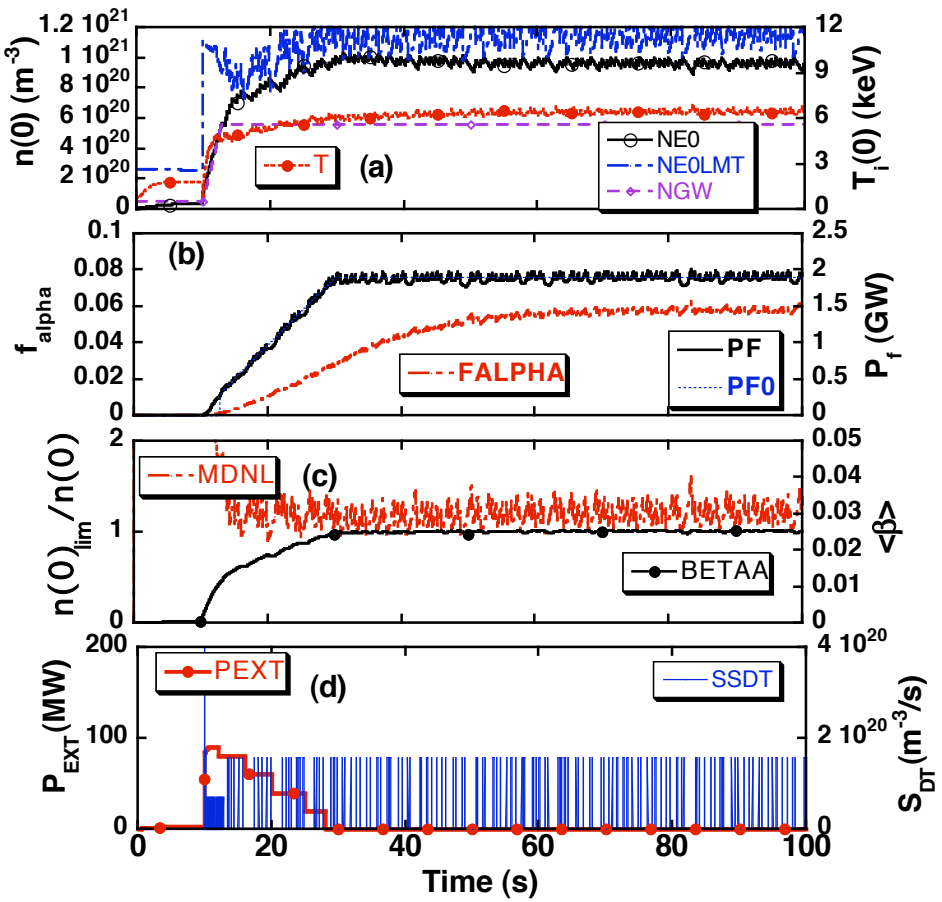
3.2.Comparison of the plasma parameters at the stable and unstable operating point

		Steady state value		
		Stable operating point	Unstable operating point	
		Parabolic profile	Parabolic profile	SDC profile
Major radius	R (m)	14.0		
Effective minor radius	$\bar{a}$ (m)	1.73		
Coil pitch parameter	γ	1.15		
Magnetic filed	B_o (T)	6.0		
Confinement factor over ISS95 scaling	γ_{ISS}	**1.92**		**1.6**
Confinement time	τ_E (s)	**1.9**	**3.9**	**4.7**
Helium ash fraction	f_α	0.034	0.034	0.058
Oxygen impurity fraction	f_o	0.0075		
Effective ion charge	Z_{eff}	1.48		
He ash confinement time ratio	τ_α^*/τ_E	3		
Fuel particle confinement time ratio	τ_p^*/τ_E	3		
Operation density	$n_e(0)$ (10^{20} m^{-3})	**2.8**	**6.0**	**9.6**
Density limit factor over Sudo scaling	γ_{SUDO}	1.5	4.5	5.5
Density limit margin in the steady state	$[n(0)_{limit}/n(0)]$	1.27	1.36	1.59
Ion temperature	$T_i(0)$ (keV)	**15.3**	**8.5**	**6.4**
Density profile	α_n	1.0		Box type
Temperature profile	α_T	1.0		0.25
Beta value	$<\beta>$(%)	**3.0**	**3.6**	**2.5**
Plasma energy	W_p(MJ)	547	634	448
Fusion power	P_f (MW)	1900		
Neutron power	P_n (MW)	1520		
Alpha heating power	P_α (MW)	380x0.9		
Bremsstrahlung power	P_B (MW)	**57**	**181**	**248**
Synchrotron radiation power	P_S (MW)	3.4	0.97	0
Plasma conduction loss	P_L (MW)	**282**	**160**	**96**
Neutron wall loading	Γ_n (MW/m^2)	1.5		
Heat flux to first wall	Γ_h (MW/m^2)	0.06	0.18	0.25
Heat flux to divertor for 0.1m wet width	Γ_{div} (MW/m^2)	**16**	**9.1**	**5.4**

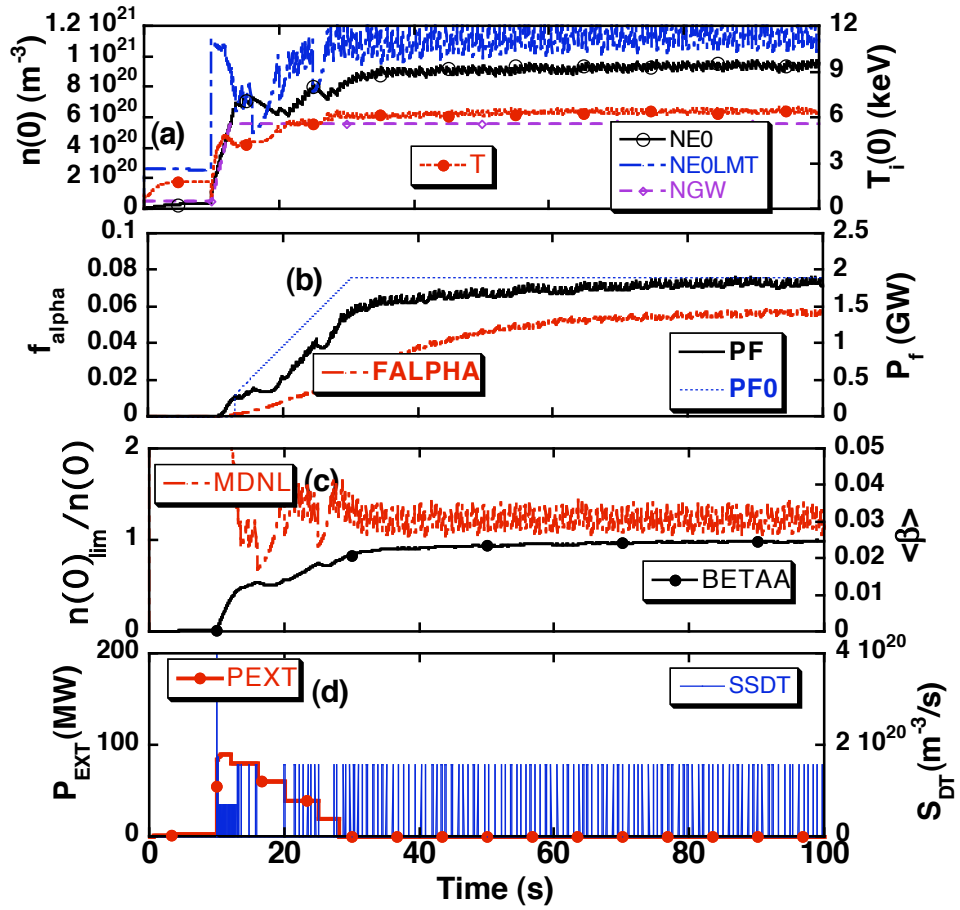
4. PID control parameters

4.1. Long derivative time T_d delays the fusion power, which seems to be contradicted to the usual control theory.

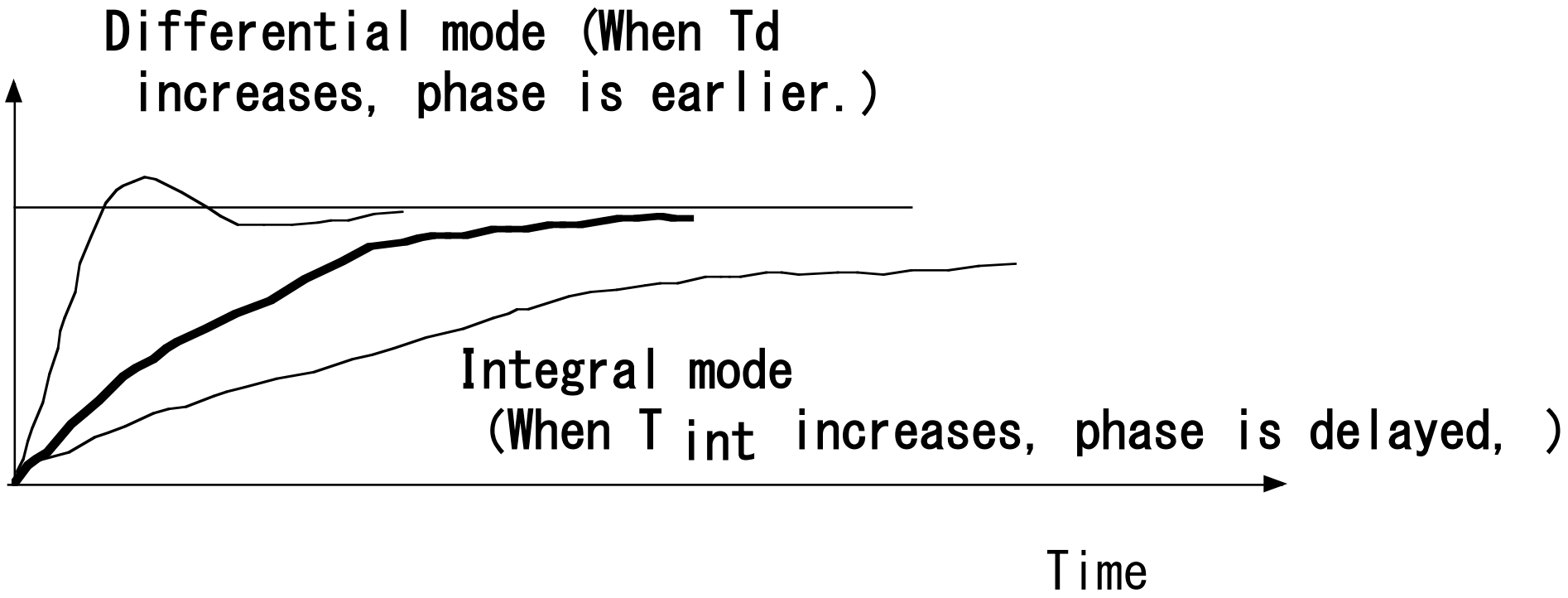
[1] T_d=0.001 s, T_{int}=45 s



[2] T_d=0.39 s, T_{int}=45 s



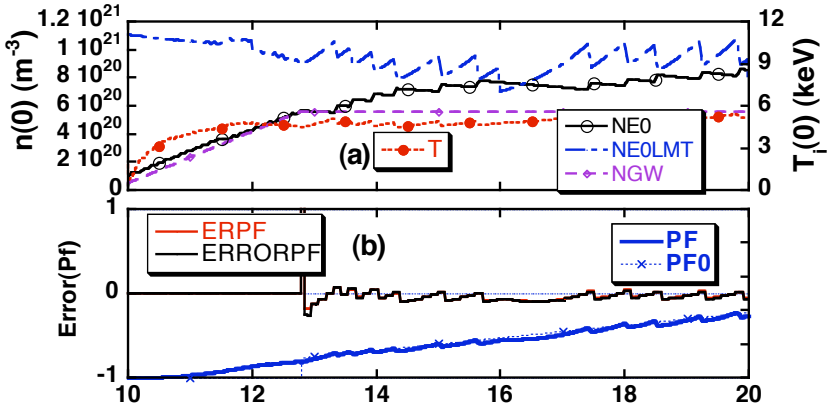
4.2. Usual control theory:



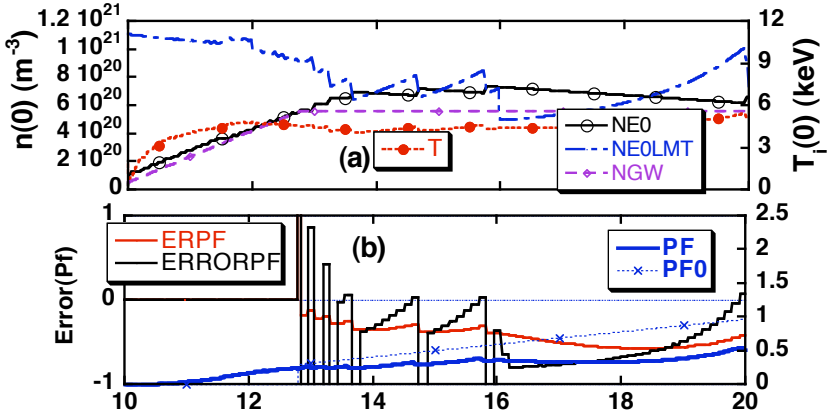
Reason of the contradiction:

(No contradiction to the normal control theory.)

[1] T_d=0.001 s, T_{int}=45 s



[2] T_d=0.39 s, T_{int}=45 s



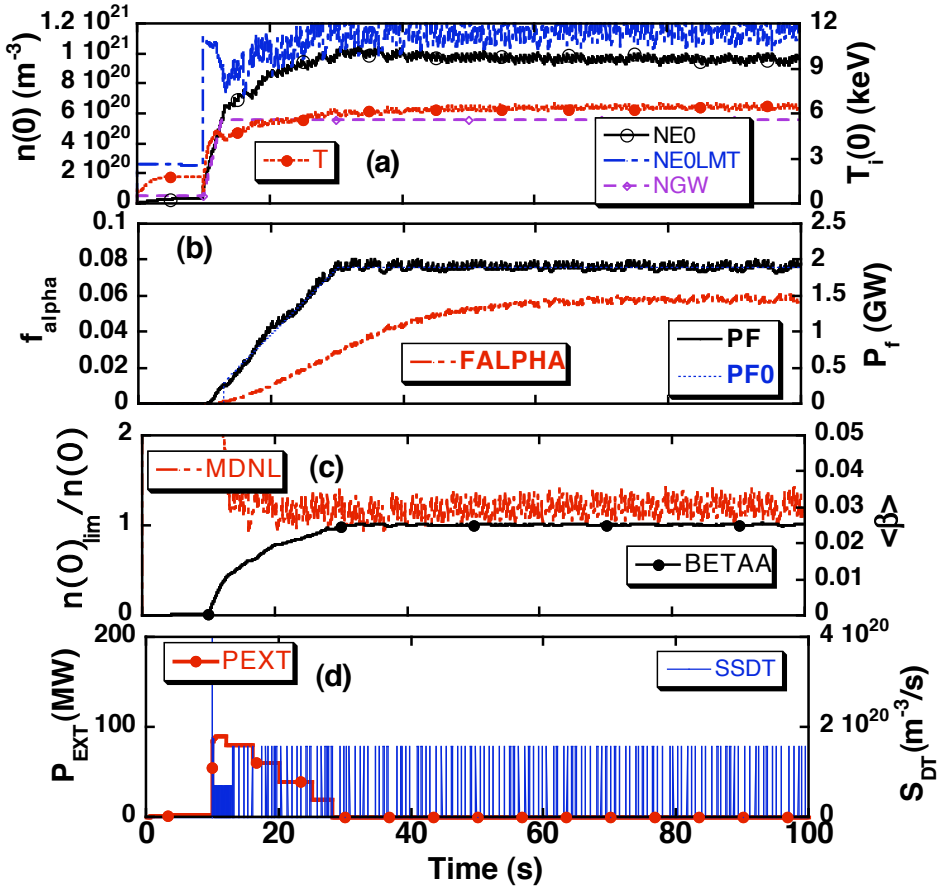
T_d=0.39 s:

To have an early rise-up of the fusion power, fueling is supplied so much in the earlier phase.

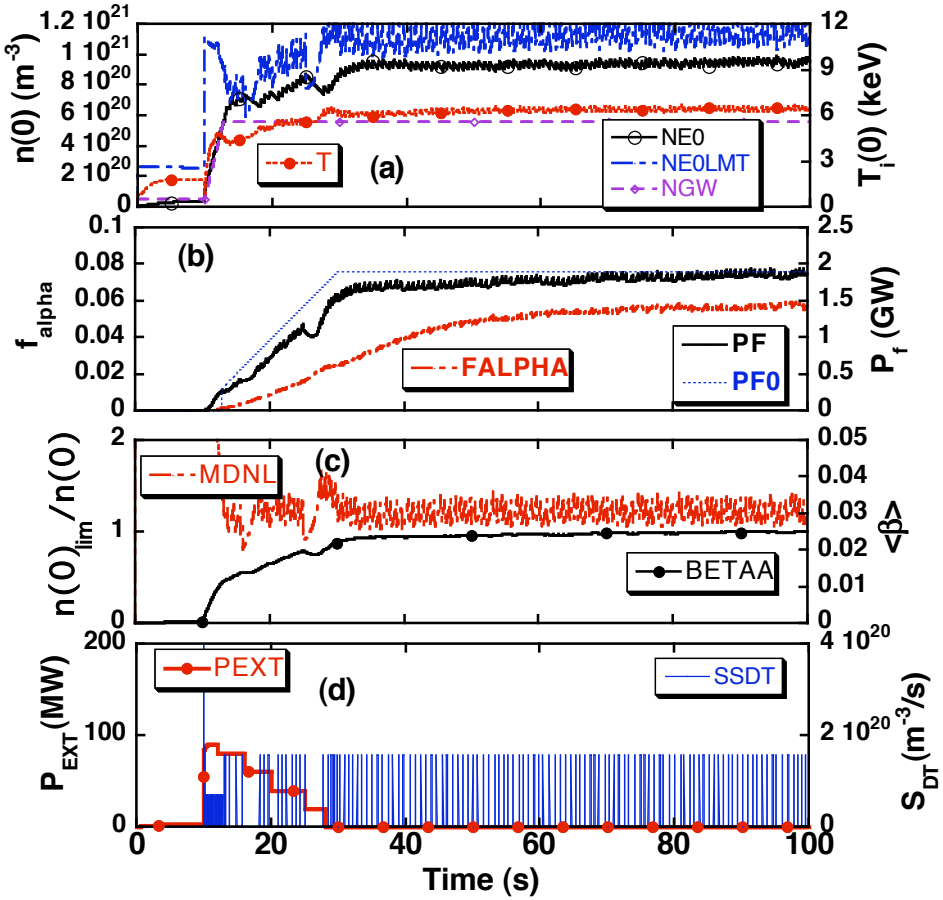
This reduces the plasma temperature, leading to the delay of the fusion power rise-up.

4.3. For the same T_d, the fusion power delays as in the normal control theory when T_{int} is increased.

[1] T_d=0.26 s, T_{int}=1 s

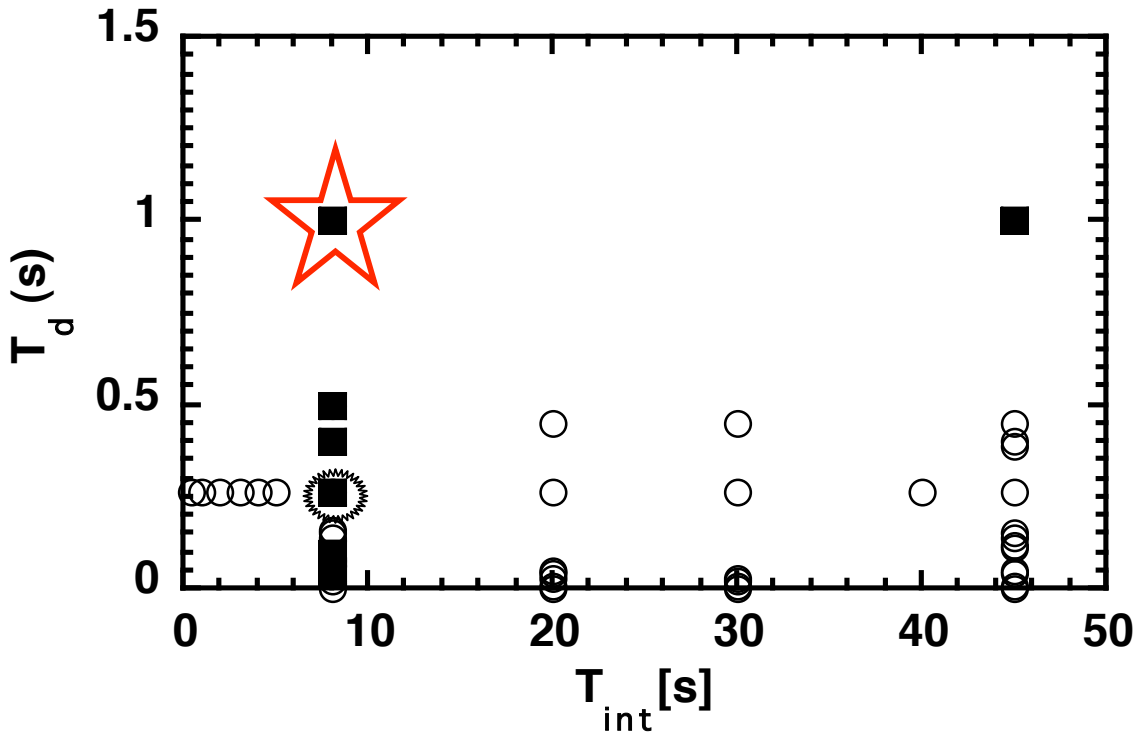


[2] T_d=0.26 s, T_{int}=45 s



4.4. PID control parameter regime for fueling:

T_d and T_{int} regime is quite wide, and expanded by application of the feedback of heating power. It means that it is relatively easy to control this unstable operation by PID control.

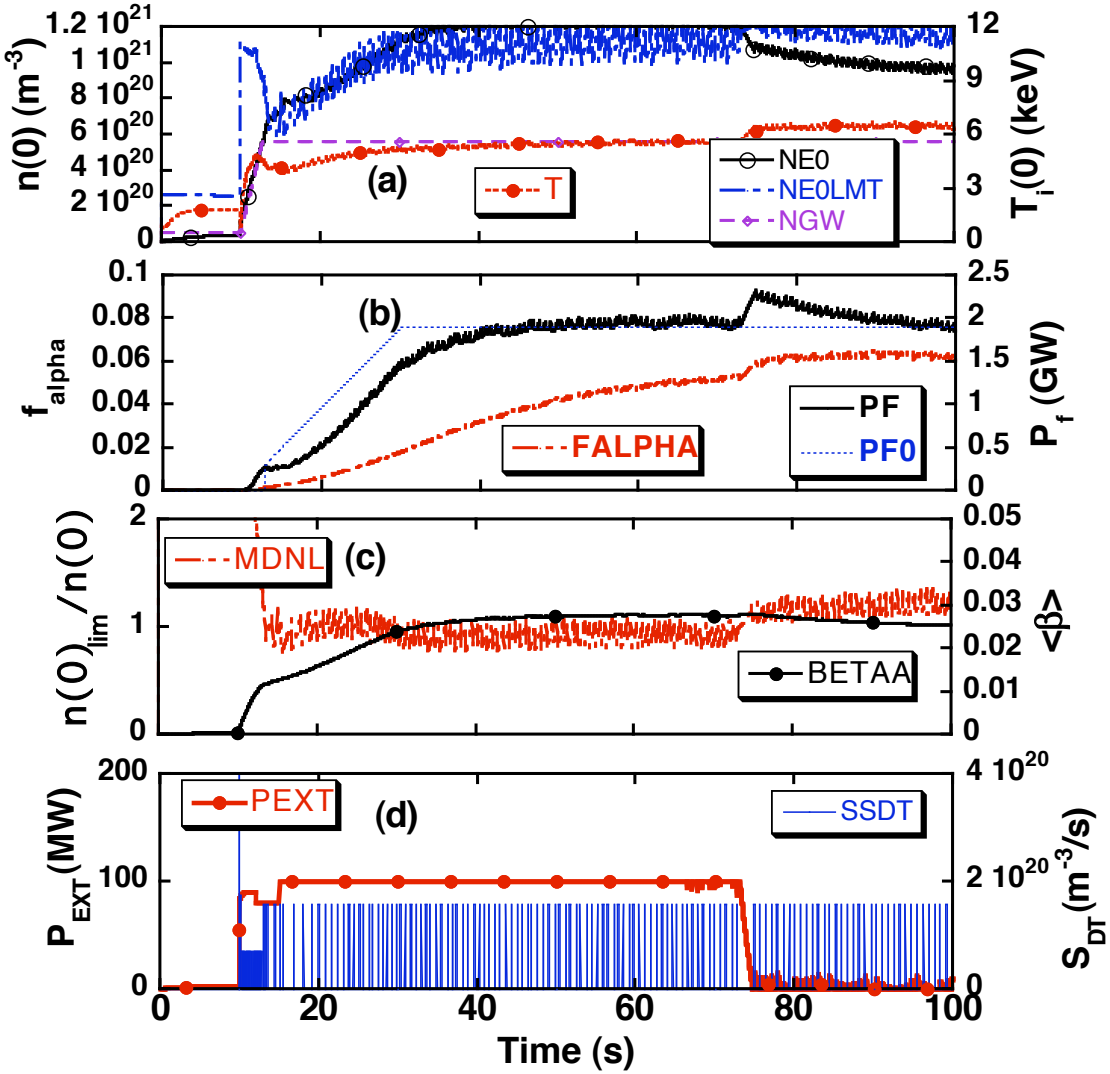


Usually:
T_d=0.26s,T_{int}=8s:

Time step near the calculation time step of T_d=0.02 should not be used.

4.5. Feedback control of the heating power for T_d=1s,T_{int}=8s:

(☆ Just example for large T_d and heating power)



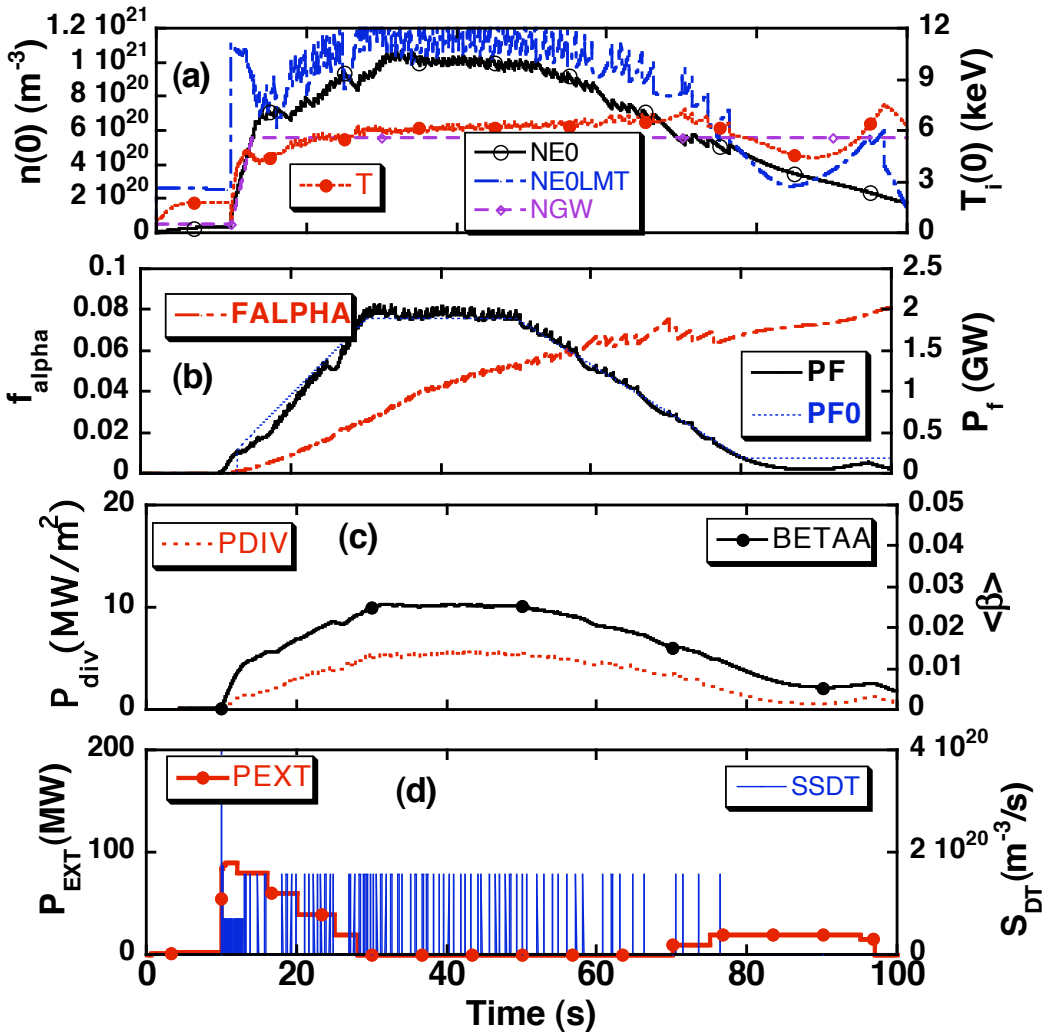
Without the feedback of the heating power, ignition cannot be reached.

The feedback of the heating power helps the fusion power rise-up, and eventually provides delayed ignition.

5. Shutdown phase

5.1. Shutdown phase-1

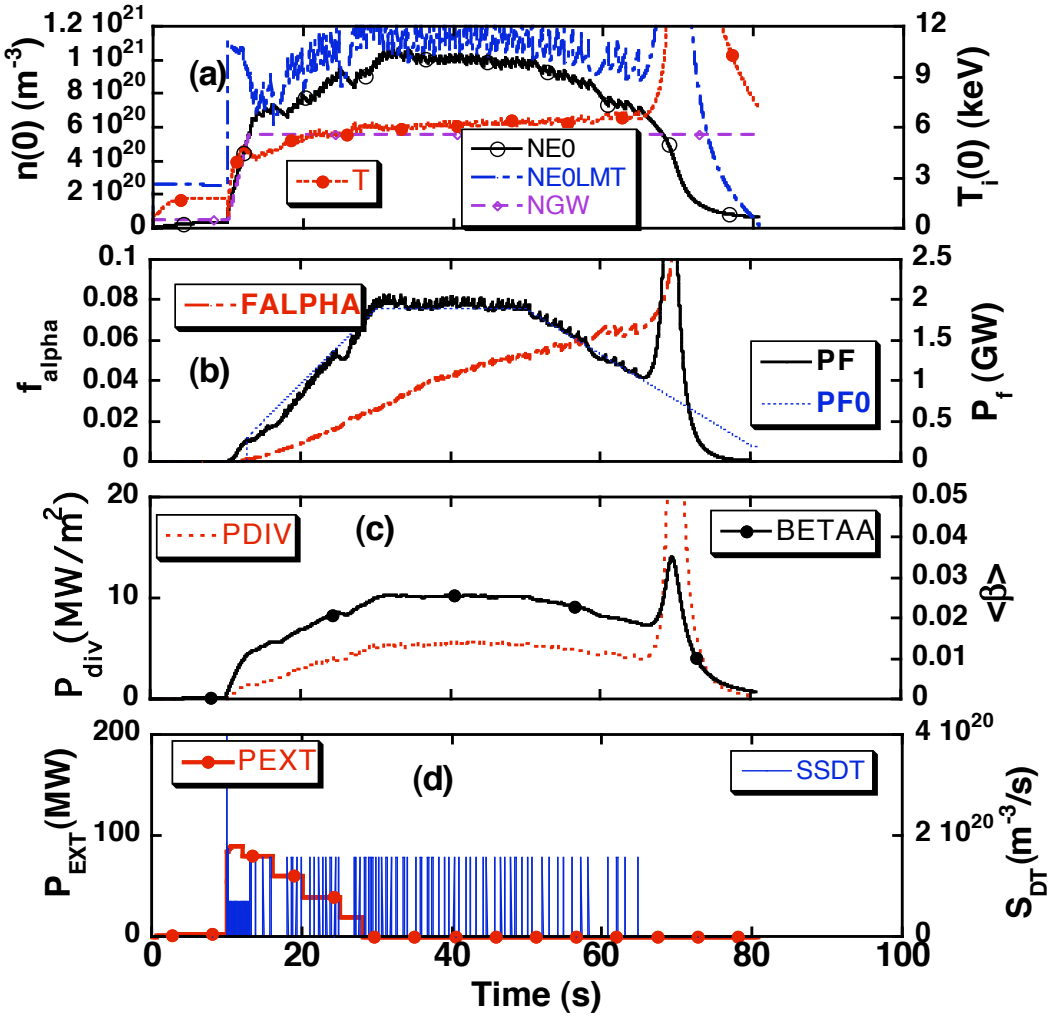
20 MW heating power provides the smooth fusion power shutdown.



Without application of the heating power, the fusion power can be shutdown, but not smoother.

5.2. Shutdown phase-2

If fueling is stopped after 65s, excessive fusion power up to 4.25 GW is observed. Because, the thermal runaway takes place.

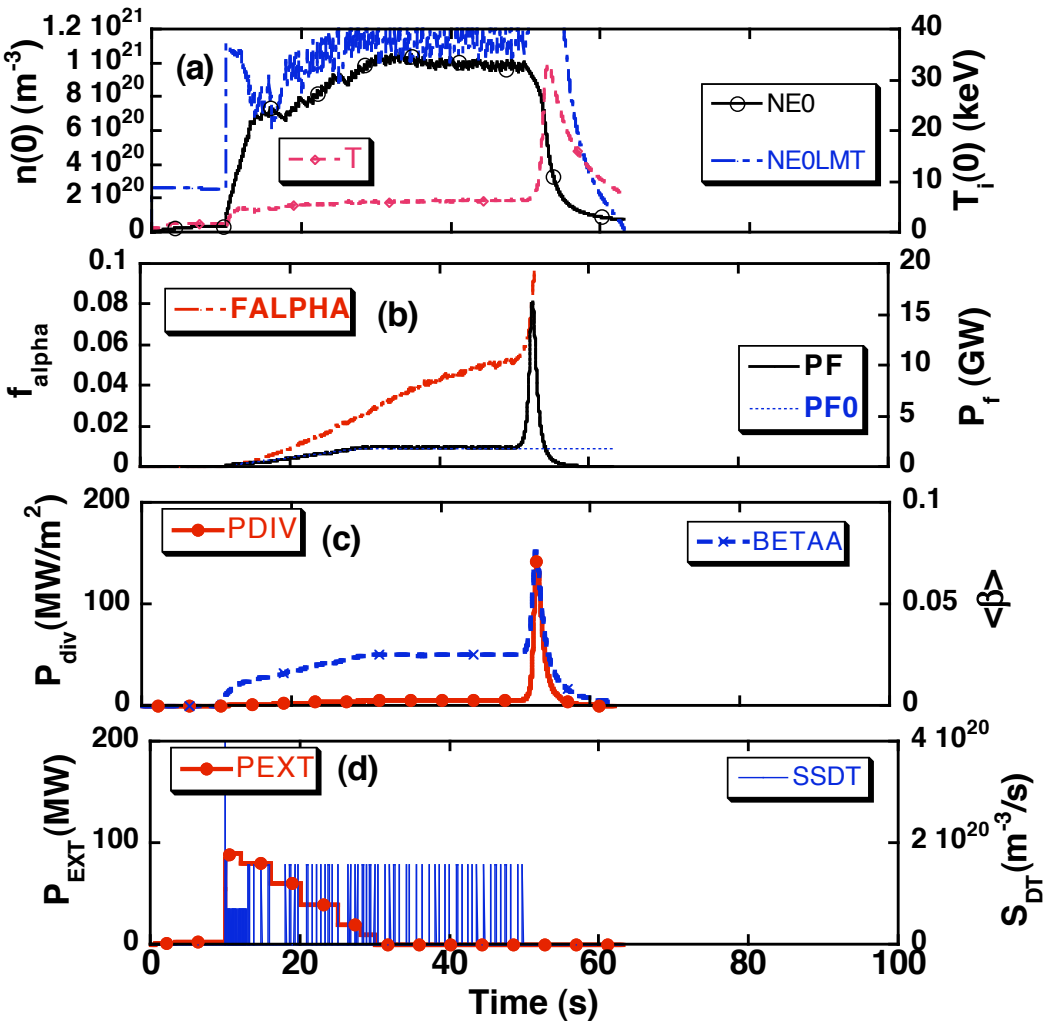


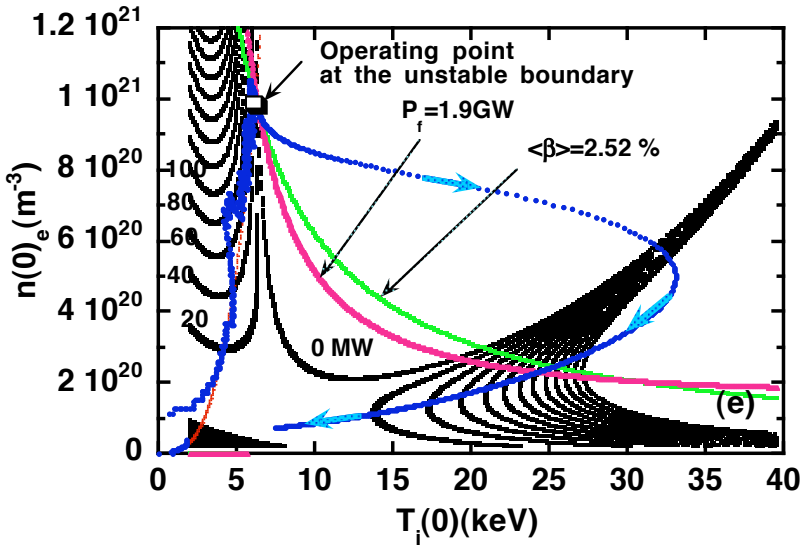
We always need the fueling control for unstable operation.

For forced shutdown, excessive fueling or killer pellet should be used.

6. Failure mode analysis :

6.1. If pellet stops at 50 s during full operation.



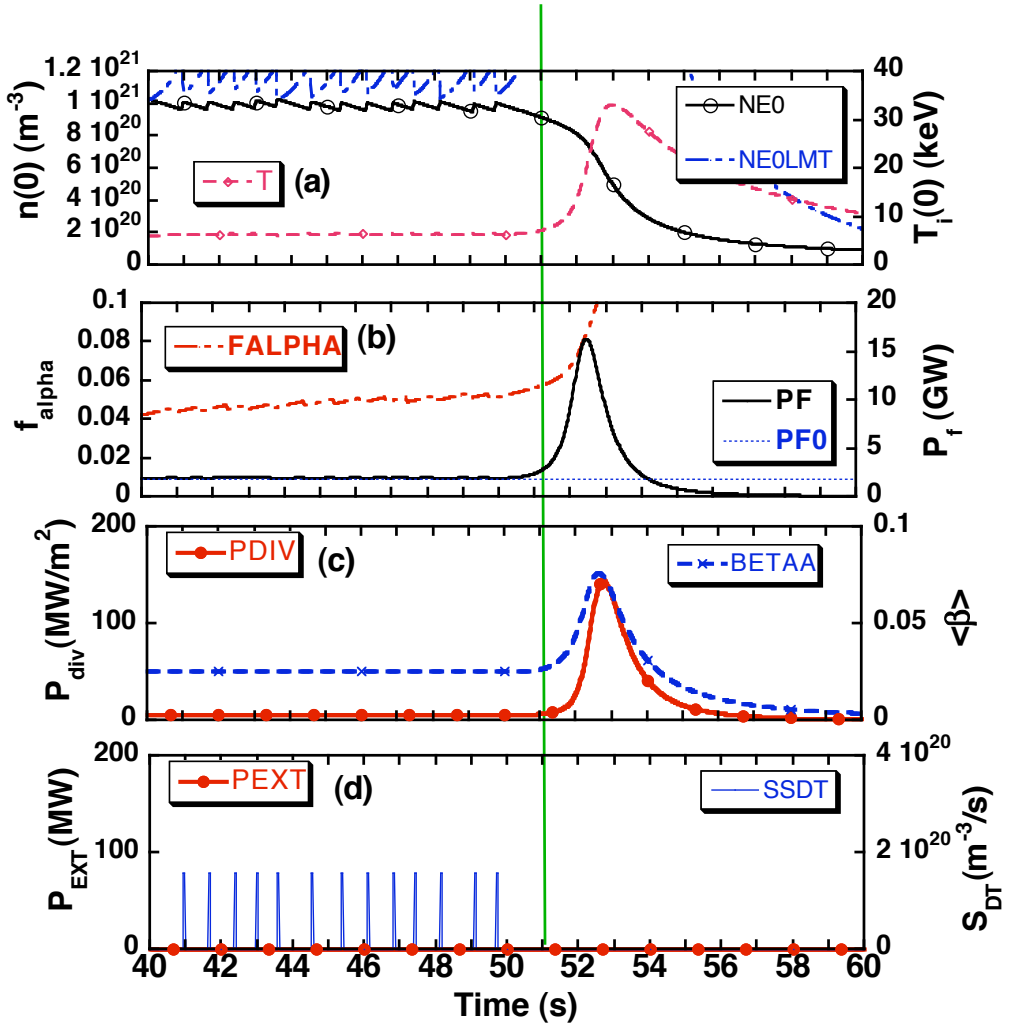


- P_f to ~16 GW
- P_{div} to ~150 MW/m^2
- <β> to ~8%
- T to ~30 keV

Reaching the stable ignition regime.

6.2. Detailed behavior around 50 s.

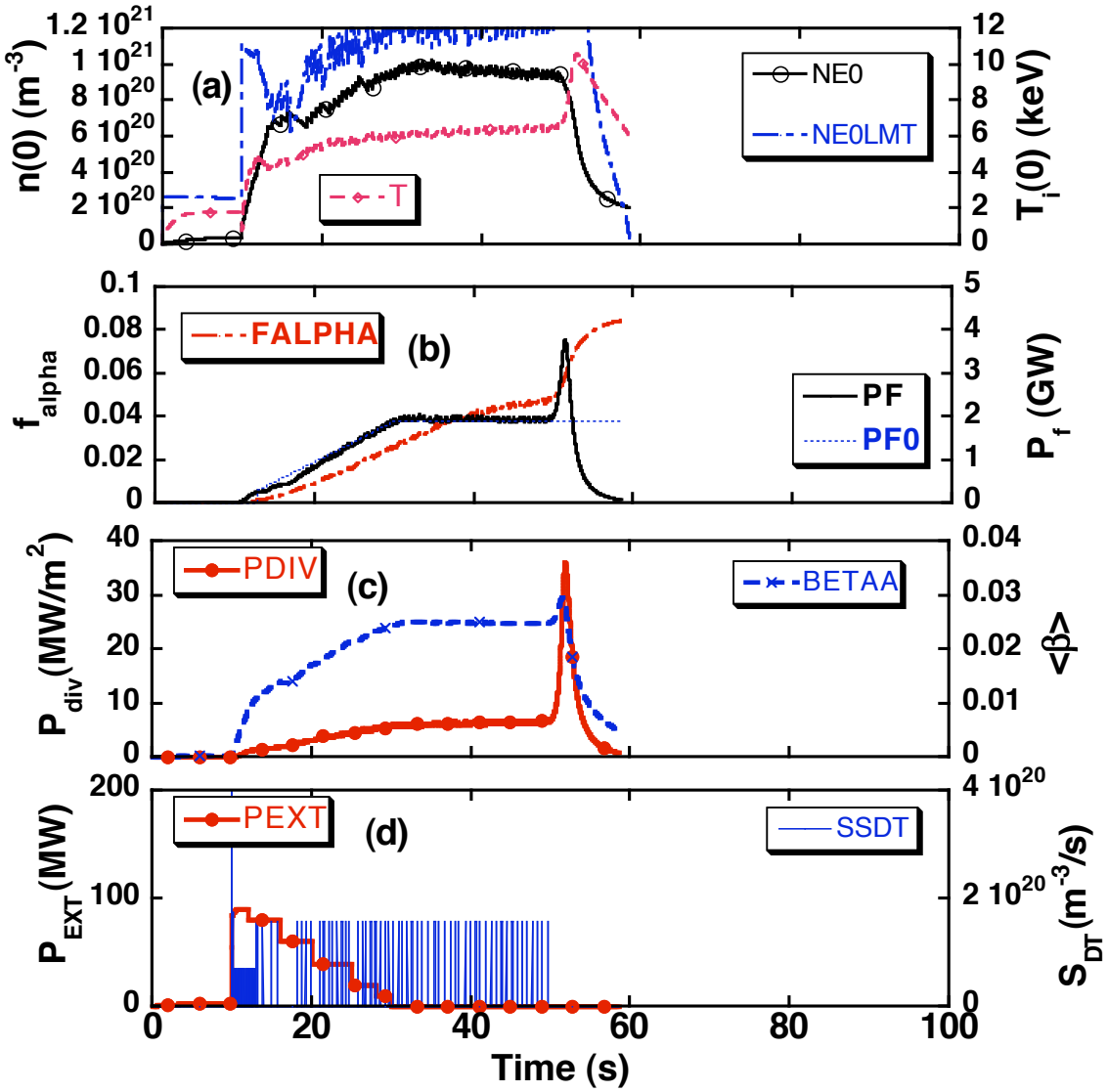
Pellets are regularly injected in the steady state.



If pellet is not injected for 1 s in the steady state, it is a sign of the pellet injection failure.

- **Pellet injection and density monitor are important.**
- **If such failure is detected in the pellet system, the killer pellet should be injected.**

6.3. Possible internal fail-safe function (1): beta limit



Confinement time is assumed to be degraded when beta exceeds the assumed critical value of $\langle\beta\rangle_{CR}$=3%.

$\tau_E=\tau_E'/(1+\{\langle\beta\rangle/\langle\beta\rangle_{CR}\}^{20})$

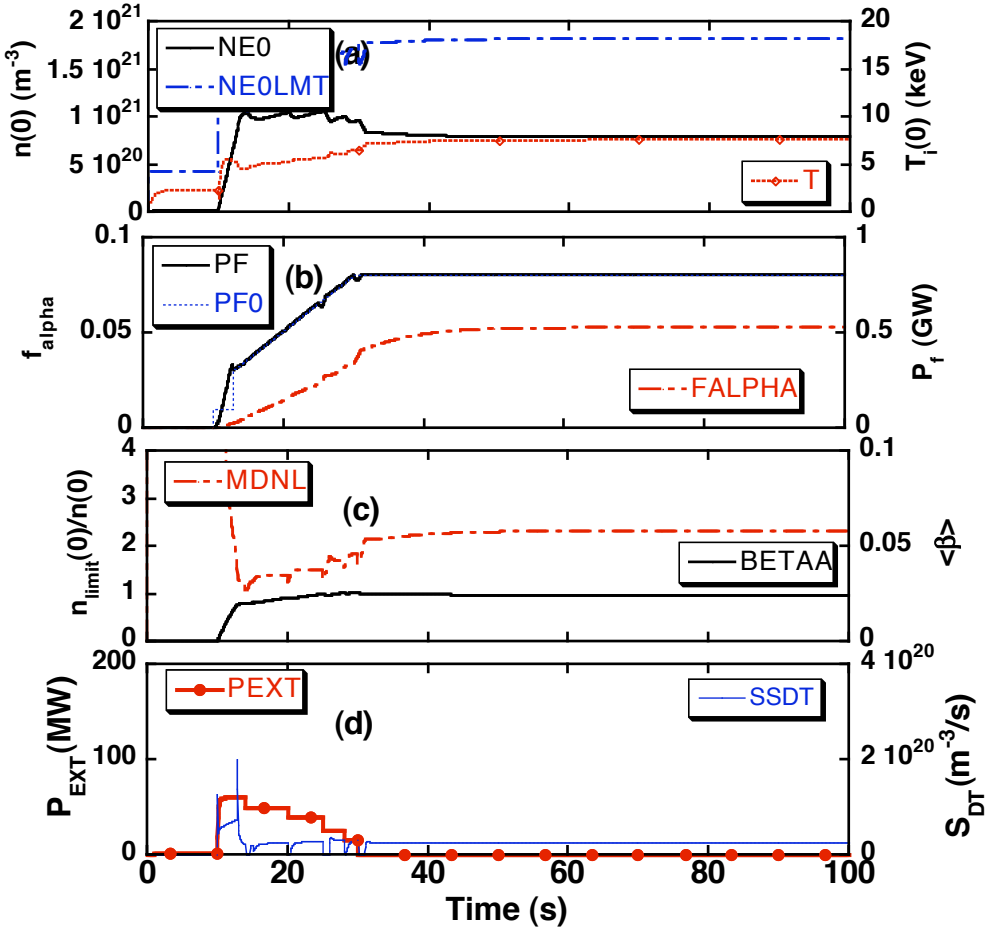
- **P_f to ~4 GW**
- **P_{div} to ~36 MW/m^3**
- **$\langle\beta\rangle$ to ~3%**
- **T to ~10 keV**

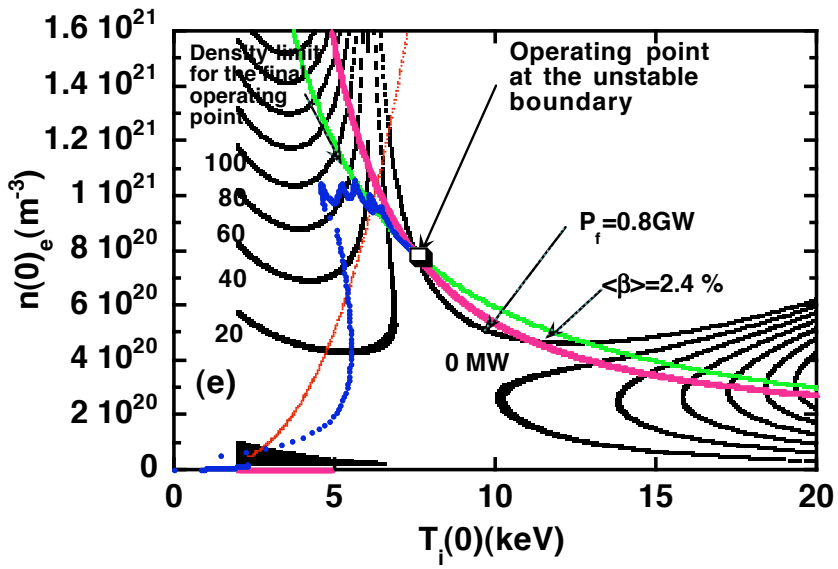
Is this safe enough?

(2) Plasma shift and volume shrinking effect should be taken into account.

7. Compact FFHR（R=8m, a=1.4 m, B=6 T）:Similar size to ARIES-CS

γ_{HH}(ISS95)=1.52,τ_α^*/τ_E=5, τ_p^*/τ_E=3, Density limit=5.5: T_d=0 s, T_{int}=10 s,
P_f=0.80 GW, P_{EXT}=70MW, τ_E=1.8s, P_{div}=8.9 MW/m^2, Γ_n=1.35 MW/m^2, η_α=0.97
n(0)=7.85x10^{20} m^{-3},T_i(0)=7.6 keV, f_α=5.26 %, <β>=2.4 %(at 200s)





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Partial blanket system for fusion power generation experiments.

8. Summary and further issues

[1] It is possible to control the thermally unstable operating point even when the temperature and density change due to pellet injections.
Pellet size of 12 mm ~16 mm pellet are allowed for FFHR.

[2] To ease the pellet injection, the lower temperature (T(0)＜7 keV) is desirable.
The conditions of τ_α^*/τ_E<4～5 and γ_{ISS95}>1.4 are recommended in FFHR.

[3] Control robustness to various disturbances exists to some extent.

[4] PID parameter regime is wide, indicating the easiness of this unstable control. When feedback of the heating power is available, operational regime would be expanded.

[5] Shutdown of the unstable operation is no problem.

[6] Failure mode analysis shows the need of quick response (for example killer pellet), but internal fail-safe function such as beta limit need to be examined in more detail.

[7] Compact FFHR (R~8m, a=1.4 m, B=6T) is possible, which needs more analysis.

Further Issues

1-D simulation should be done as soon as possible to take the profile effect into account during pellet injection.