Feedback control of the heating power to access the thermally unstable ignition regime in FFHR

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Contents:

1. Motivation.
2. Concept for feedback control of unstable regime
3. Calculated results on ignition access
4. Disturbance effect on control when confinement and impurity change:
5. Feedback control and diagnostic systems for low temperature and high-density ignition
6. Summary

1. Motivation:

While the feedback control algorithm of the heating power has been developed for the thermally stable ignition regime, <u>preprogramming alone</u> has been used for the thermally unstable ignition regime so far. This has been one of big issue to be solved in the thermally unstable ignition studies in FFHR.

By analogy of the thermally stable regime, new feedback control algorithm is discovered. It works successfully during ignition access and is robust to various parameter disturbances.

FFHR: Machine parameters

R=15.7m, a=2.5m, P_f=3 GW, η_α=0.98, <B>=4.5T, τ_α^*/τ_E=4, 1.5MeV NBI,

f_c=126 GHz, n_c=1.97x10^{20} m^{-3}

[1] Thermally stable regime: α_n=0.5, α_T=1.0, γ_{ISS95}=1.92

[2] Thermally unstable regime: α_n=3, α_T=1.0, γ_{ISS95}=1.43

2. Concept for feedback control of unstable regime:

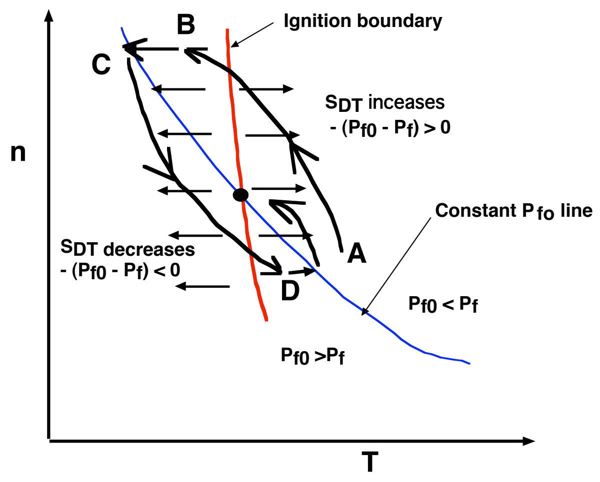
2.1. Feedback control of fueling (published)

Stabilized by PID fueling control

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

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

The error of the fusion power : $e_{DT}(P_f) = c(1- P_f/P_{fo})$
[1] c=+1 for the thermally stable boundary,
[2] c= -1 for the thermally unstable boundary,



@ Stabilization mechanism

1. **Cooling by fueling and heating by reducing fueling**
2. **Operating point rotates to the CCW.**

However, feedback method of the heating power is not discovered yet !!

2.2. Concept for feedback control of heating power:

[1] In the stable ignition regime, the Sudo density limit restricts the operating point to the high-temperature and low-density regime.

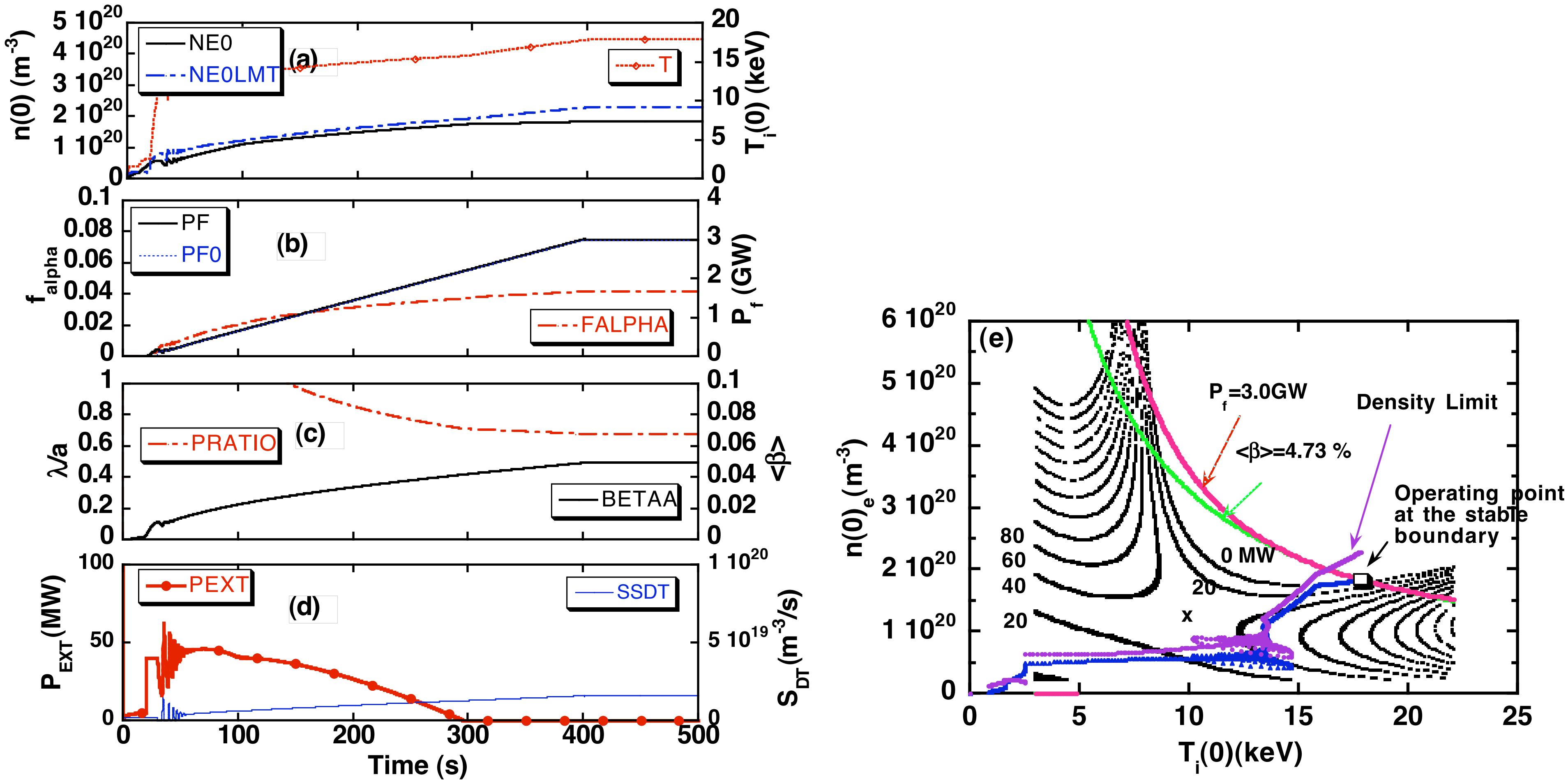
- $$\gamma_{DLM} n(0) \le n(0)_{\lim}[m^{-3}] = \gamma_{SUDO} \frac{0.25\times 10^{20}}{\gamma_{pr}} \sqrt{\frac{\left\{P_{NET}[W]\times 10^{-6}\right\} B_o[T]}{\bar{a}^2 R[m]}}$$

  $$where \quad P_{NET} = P_{EXT} + \left(P_\alpha - P_b - P_s\right)$$

The density limit provides the heating power as

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

Example of feedback control of the heating power in the thermally stable regime

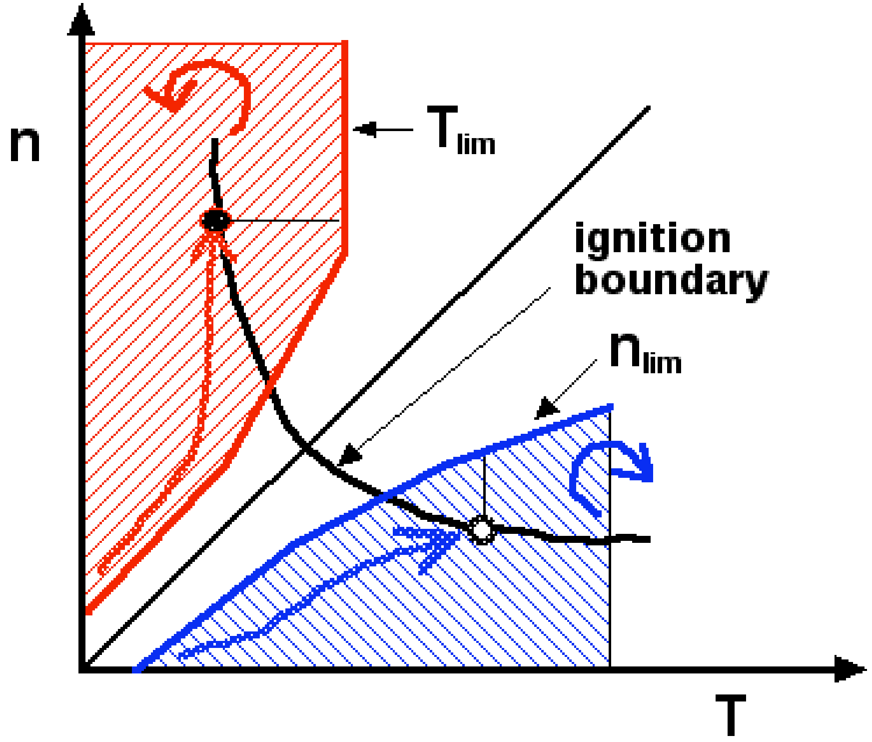


Heating power 40 MW, γ_{ISS}=1.92 (γ_{LHD}= 1.2), B=4.5T, n(0)~1.83x10^{20} m^{-3} < n_c , T(0)~17.8 keV, Γ_n~ 1.5 MW/m^2, <β>~4.9 %, Beam penetration length λ/a~ 0.7 (E_{NBI}=1.5 MeV)

[2] Basic principle of proposed feedback control of the heating power:

The thermally stable and unstable operation regime has an inverse relationship with respect to T-n axis in POPCON. **Analogy of the density limit provides the temperature limit.**

As the density limit restricts the operating point to the low-density regime, **the temperature limit restricts it to the low temperature regime.**



POPCON

@ Artificially posturated temperature limit: (Similar to the density limit)

$$\gamma_{TLM} T(0) \le T(0)_{\lim} = T_c \left[\frac{\left\{ P_{NET}[W] \times 10^{-6} \right\} B_o[T]}{\bar{a}^2 R[m]} \right]^{\alpha_{TC}}$$

Here, T_c and α_{TC} are selected by simulations.

This temperature limit is rewritten as

$$\left[P_{EXT} + \left(P_\alpha - P_B - P_S \right) \right] \times 10^{-6} \ge \left\{ \frac{\gamma_{TLM} T(0)}{T_c} \right\}^{\frac{1}{\alpha_{TC}}} \frac{\bar{a}^2 R[m]}{B_o[T]}$$

Finally, the heating power depends on the measured temperature, and alpha, bremsstrahlung power losses

$$\boxed{P_{EXT} \ge \left\{ \frac{\gamma_{TLM} T(0)}{T_c} \right\}^{\frac{1}{\alpha_{TC}}} \frac{\bar{a}^2 R[m]}{B_o[T]} \times 10^{6} - \left(P_\alpha - P_B - P_S \right)}$$

where γ_{TLM} is adjusted to reduce with the time

$$\gamma_{TLM} = \frac{T(0)_{\lim}}{T(0)} \ge 1.2 \quad , \quad T(0)_{\lim} = T_c \left[\frac{\left\{ P_{NET}[W] \times 10^{-6} \right\} B_o[T]}{\bar{a}^2 R[m]} \right]^{\alpha_{TC}}$$

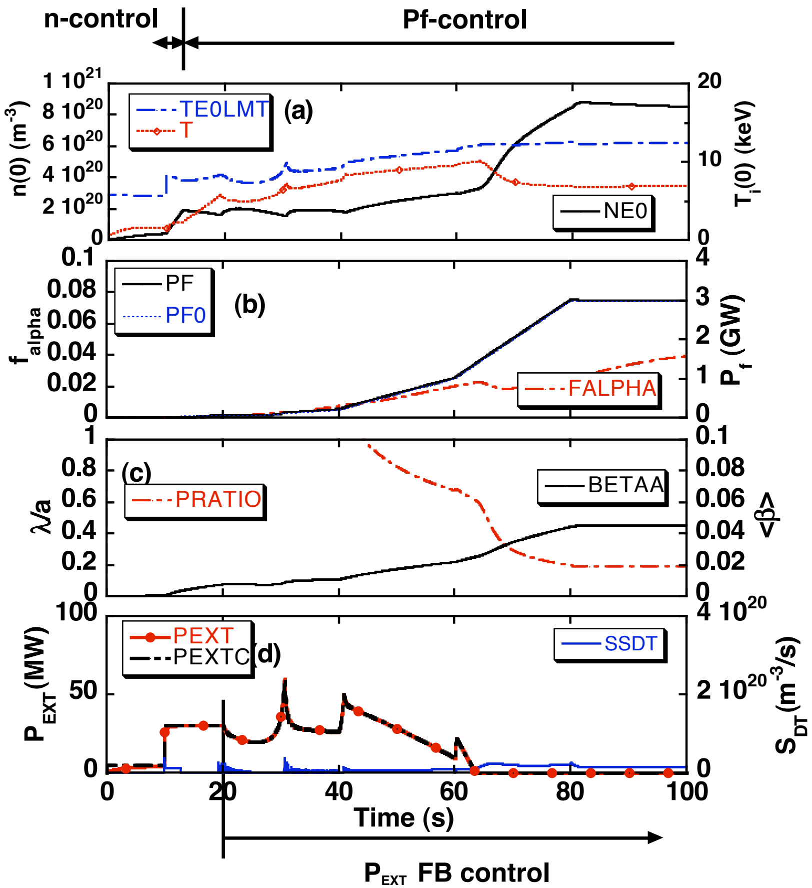
($T_{\lim}$ and T_c are different)

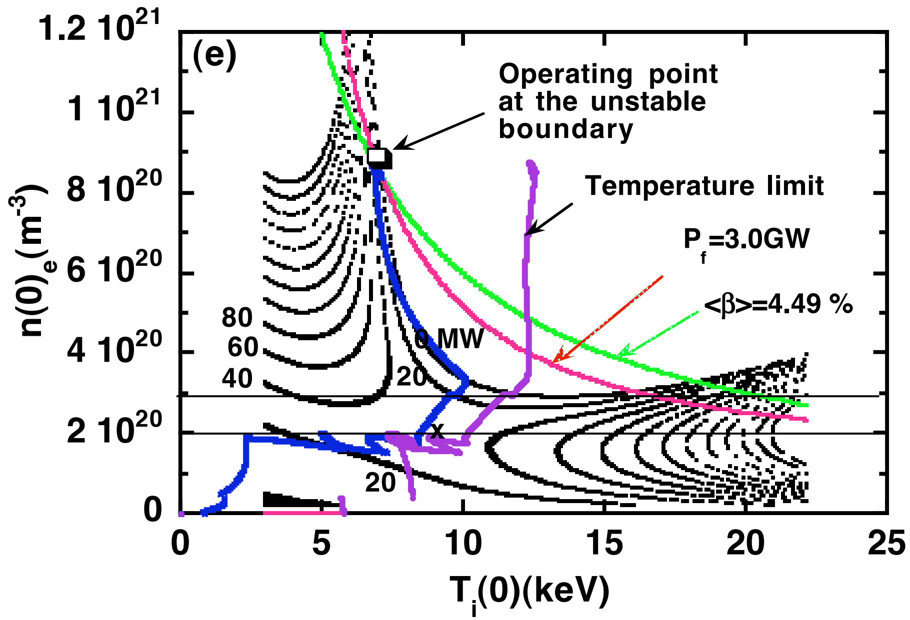
3. Calculated results on ignition access: T_c optimization

[3-1] T_c= 7.7 keV, α_{TC}=0.2 P_{max}=60MW

γ_{ISS}=1.43, B=4.5T, α_n=3, α_T=1.0, E=1.5MeV TanNBI, n(0)=8.40x0^{20} m^{-3}, T(0)=7.1 keV, <β>=4.5 %, P_{div}=12.1MW/m^2 (90° , Δ=0.1m), (T_{int}=10 s, T_{diff}=0 s)

Operating temperature is always lower than the temperature limit.

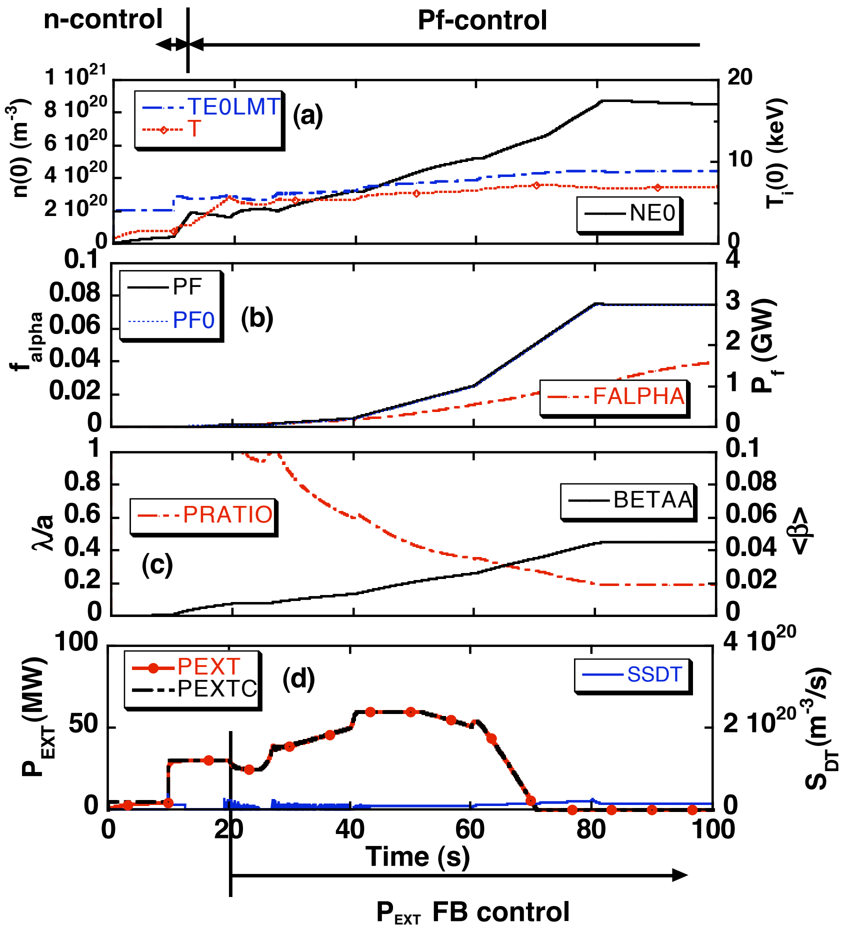


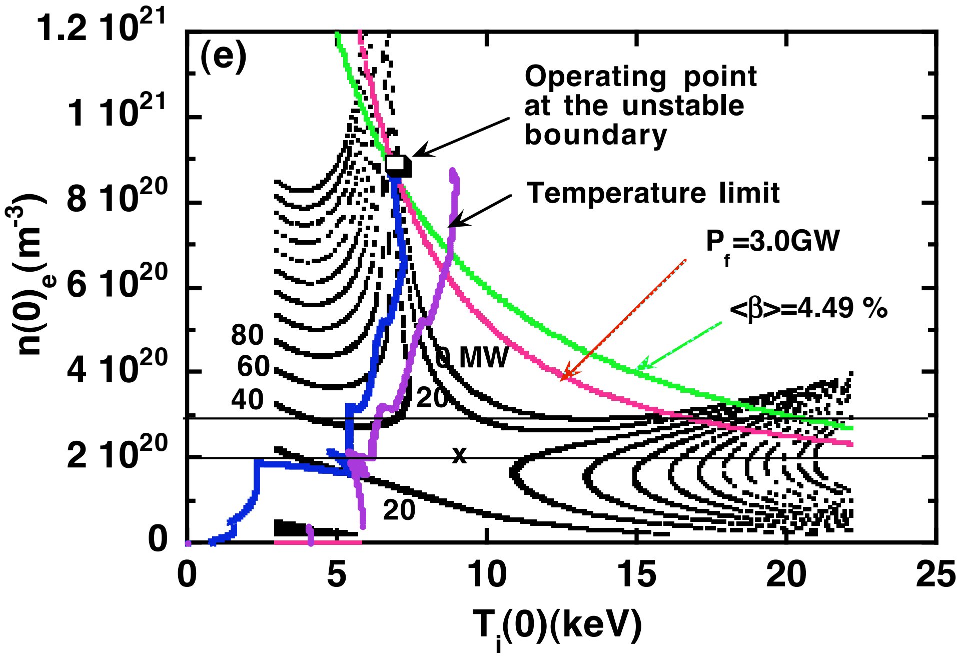


The operating point passes near the saddle point.

[3-2] T_c= 5.5 keV P_{max}=60MW

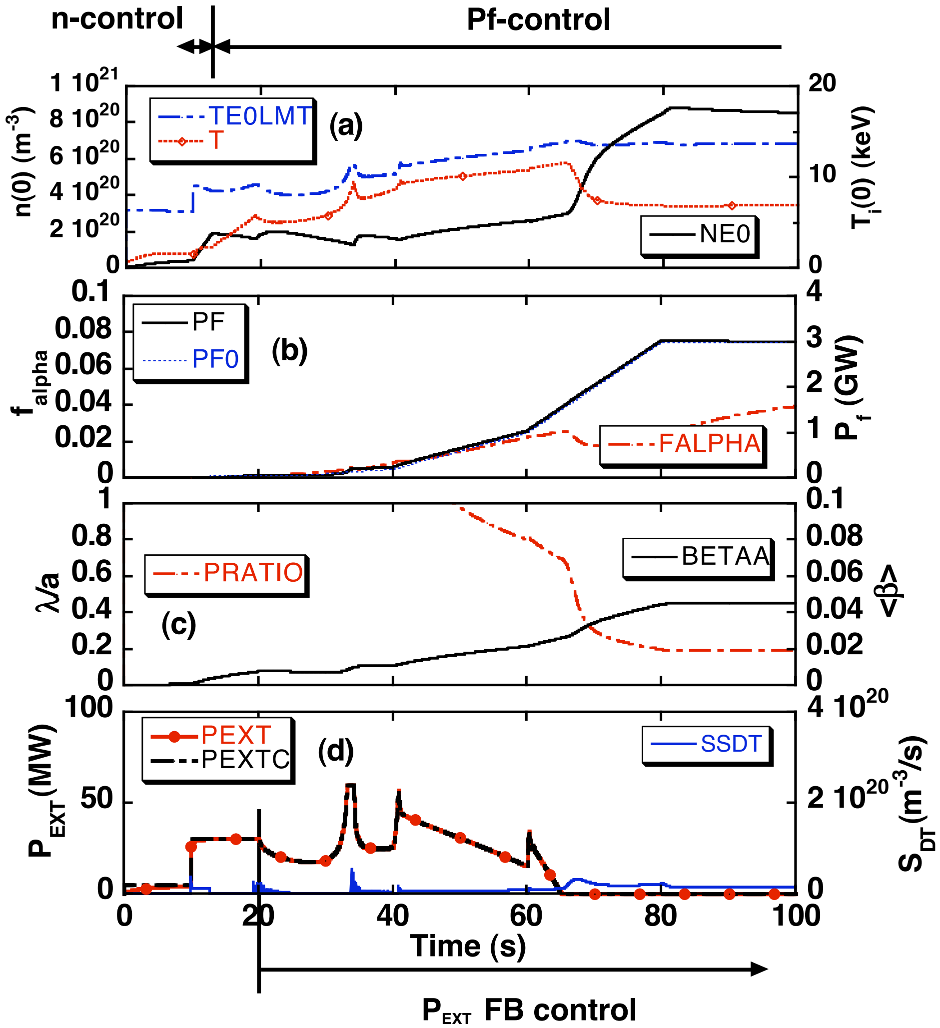
As the temperature limit is lowered, the heating power for ignition access is increased to pass the higher contour map, and the density also increases leading to worse NBI penetration.

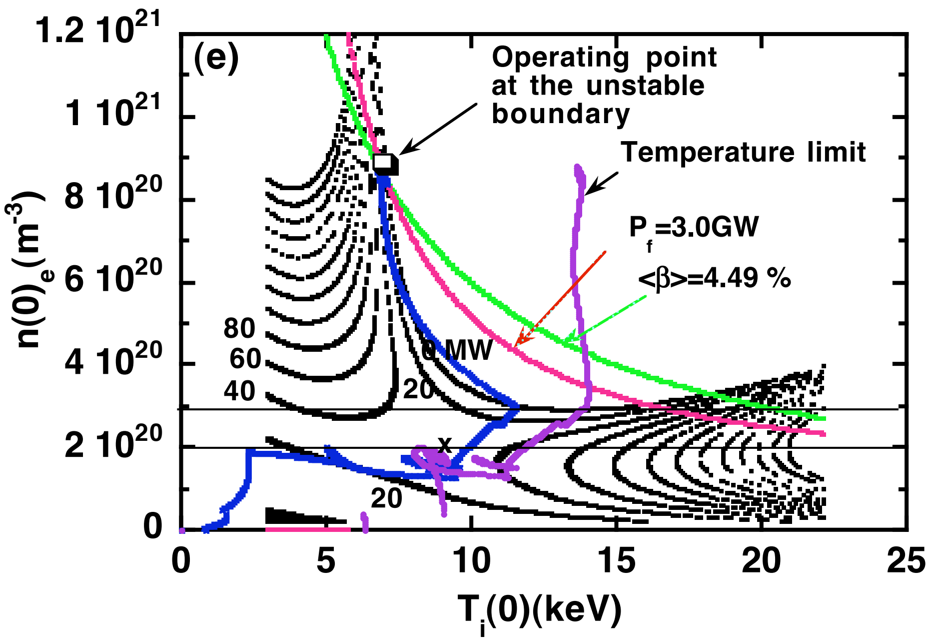




[3-3] T_c= 8.5 keV P_{max}=60MW

As the temperature limit is higher, the operating temperature is increased and the operating point stays longer in the low-density regime favorable for NBI heating. But...



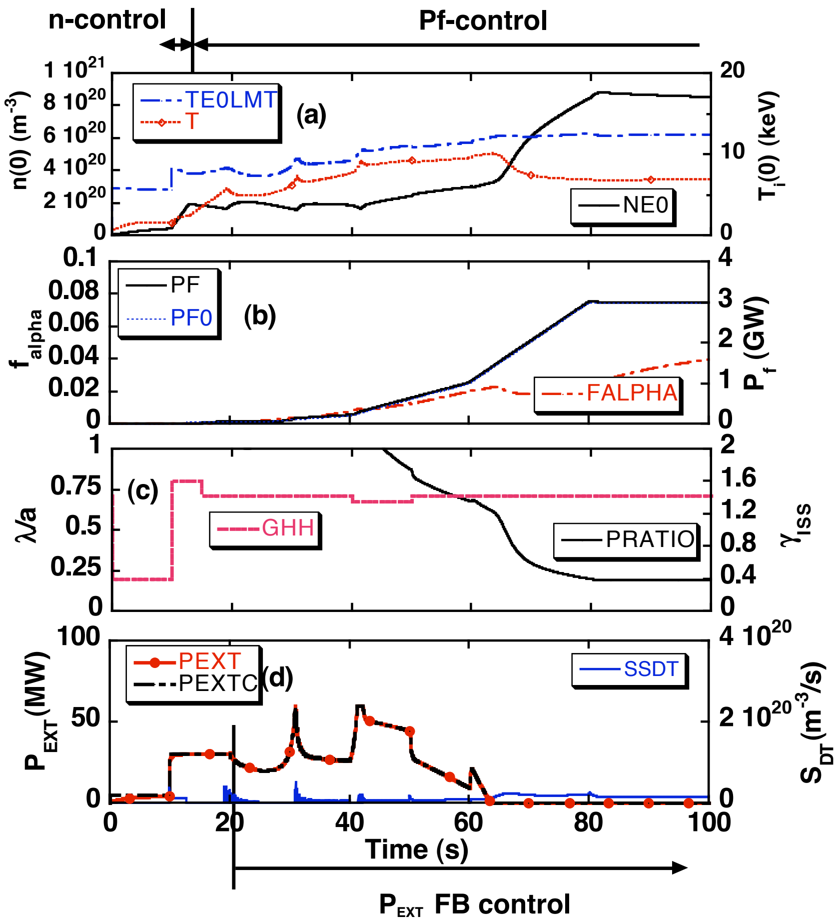


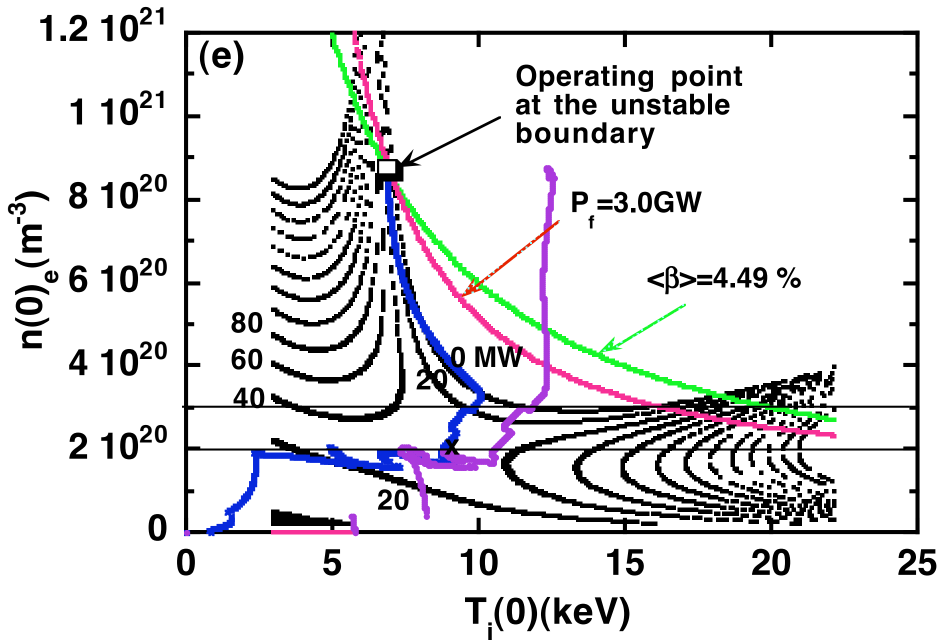
4. Disturbance effect when confinement factor or impurity change:

[4-1] Confinement degradation during 40-50s :

γ_{ISS}=1.43—>1.35 (40-50s) (T_c= 7.7 keV, α_{TC}=0.2)

Heating power is increased during confinement degradation phase.

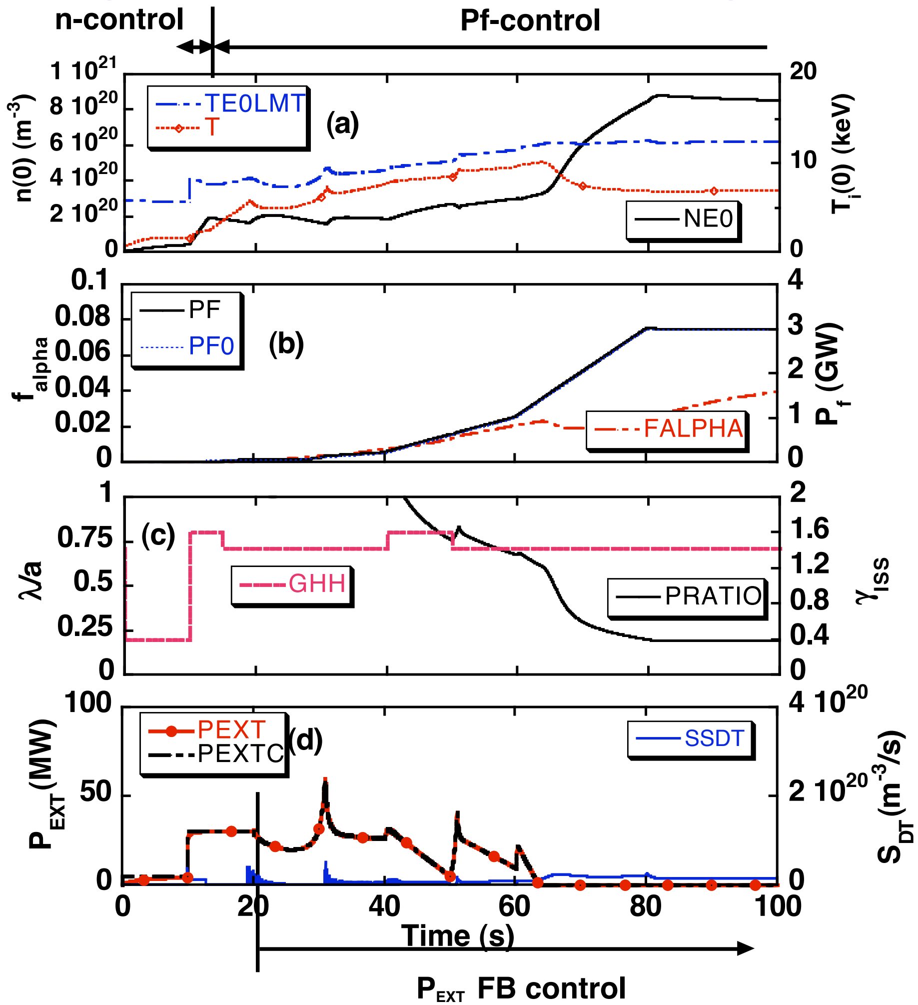


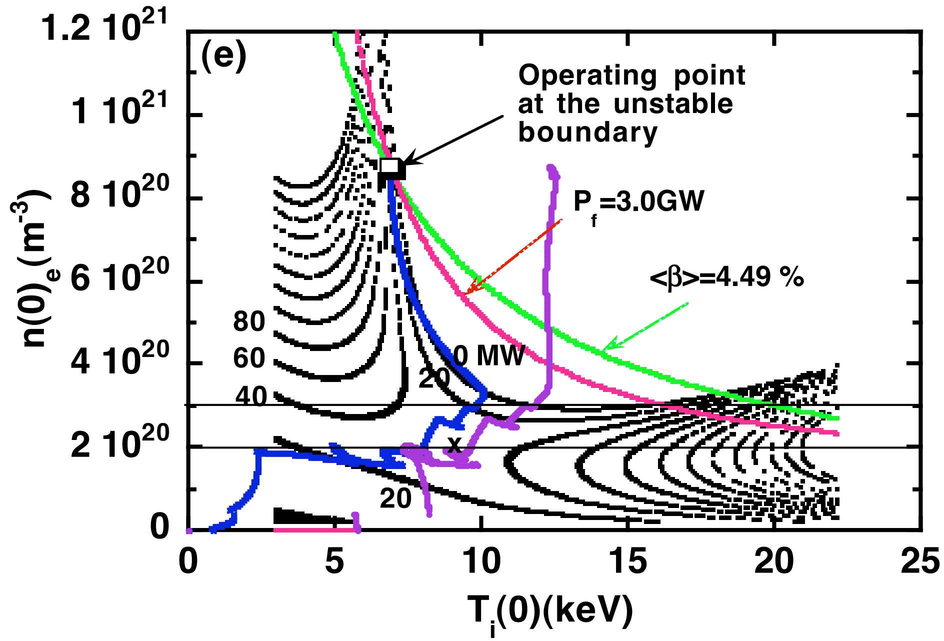


[4-2] Confinement increment during 40-50s

γ_{ISS}=1.43—>1.60 (40-50s), B=4.5T, α_n=3, α_T=1.0E=1.5MeV TanNBI, (T_c= 7.7 keV, α_{TC}=0.2)

Heating power is decreased during confinement improvement phase.



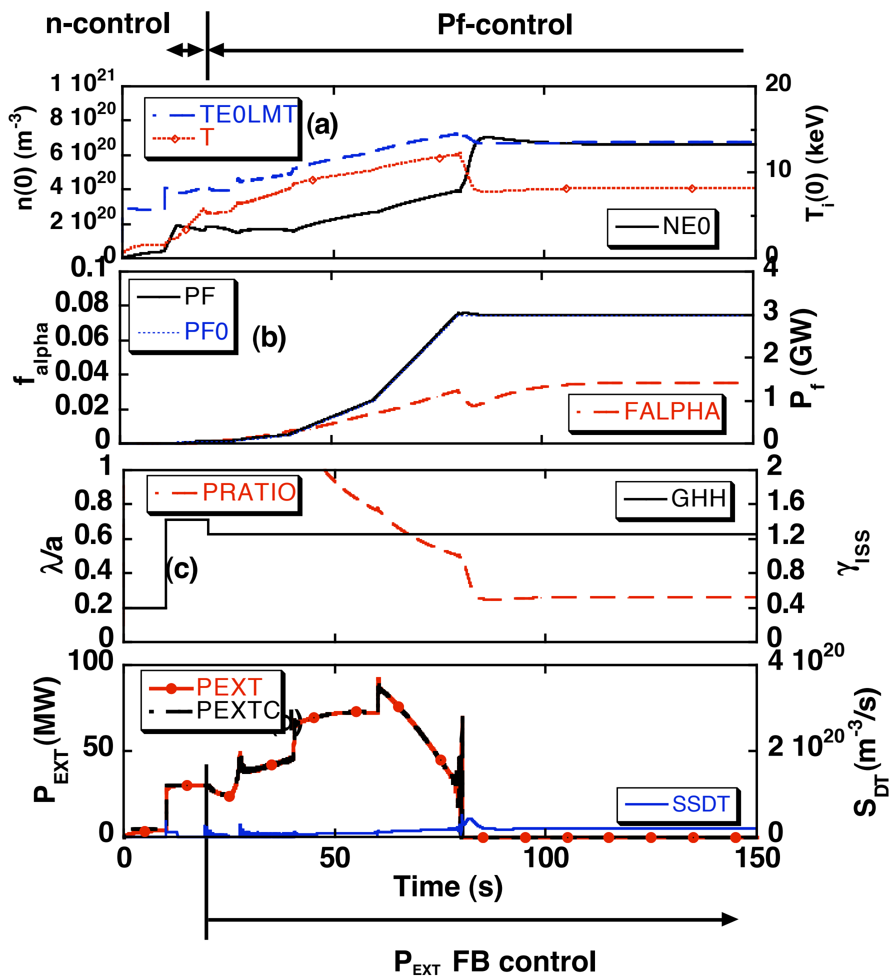


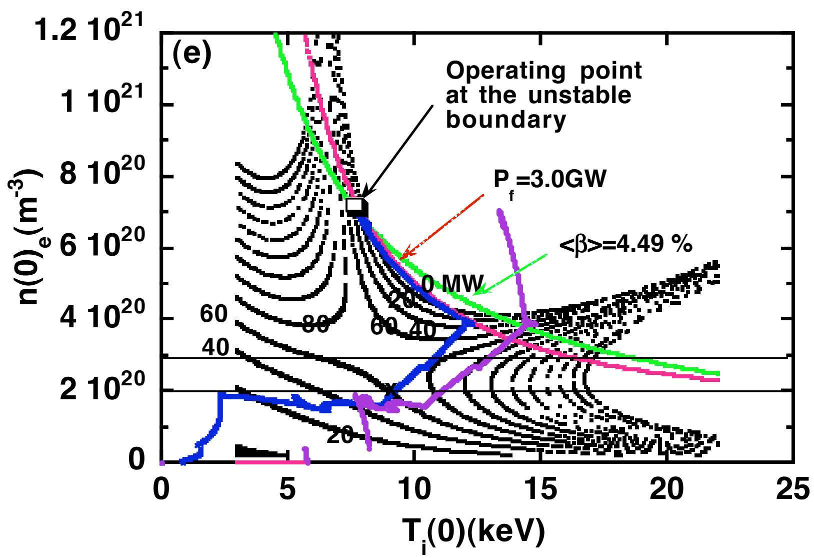
[4−3] Further T_c optimization

Is T_c=7.7 keV optimum for wide parameter regime?

[4-3-1] Lower confinement factor γ_{ISS}=1.25 (T_c=7.7 keV , T_{diff}=0 s)

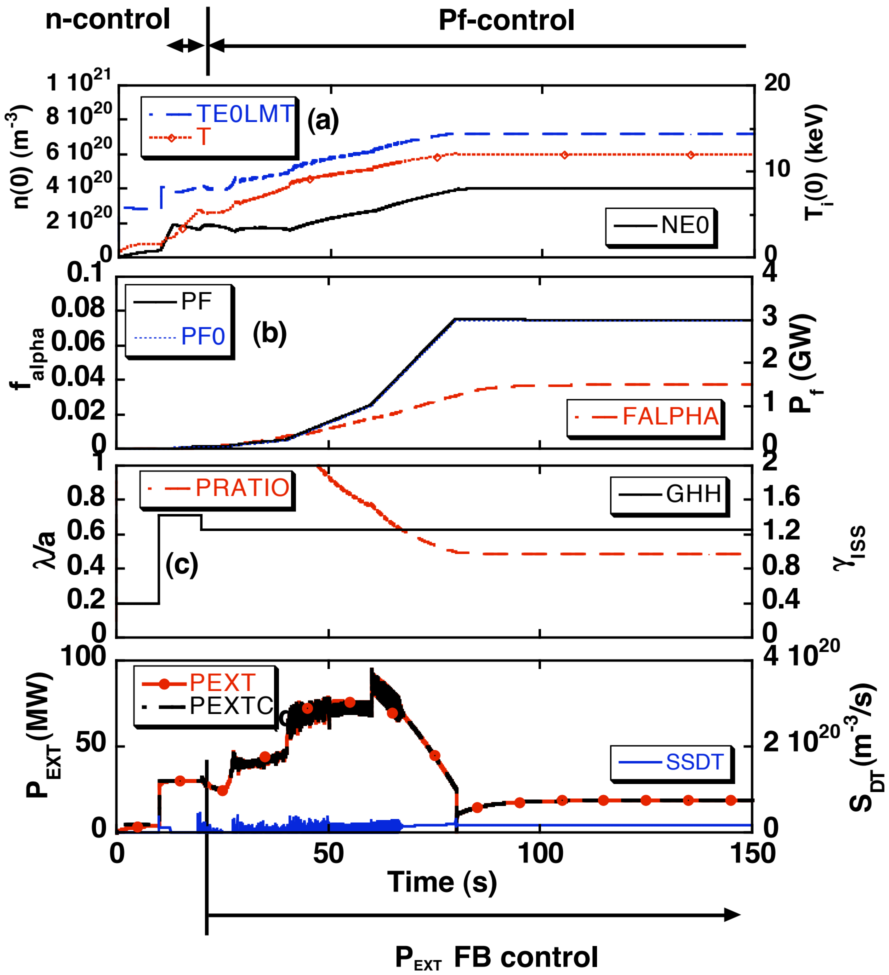
Operating point proceeds to the final one smoothly.

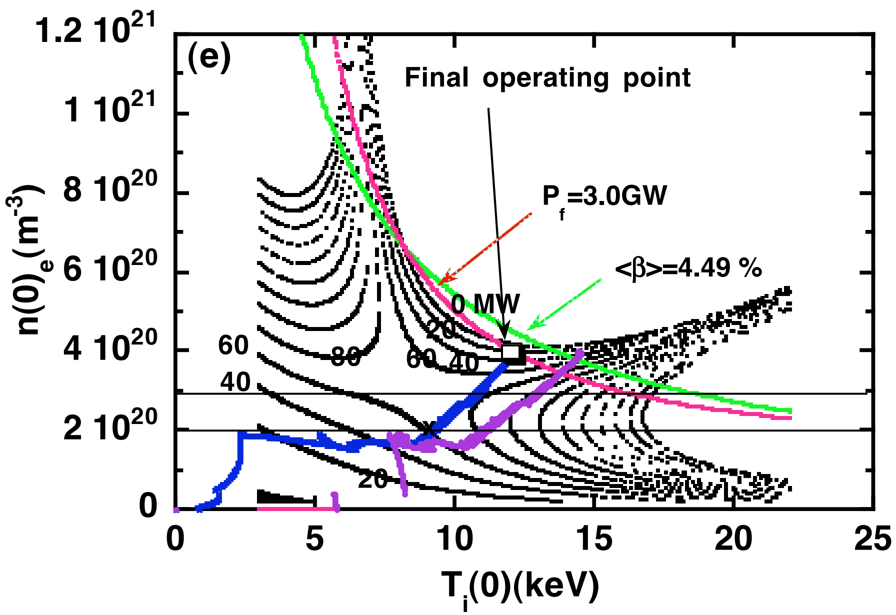




[4-3-2] Finite differential time of T_{diff}=0.13 s (γ_{ISS}=1.25, T_c=7.7 keV)

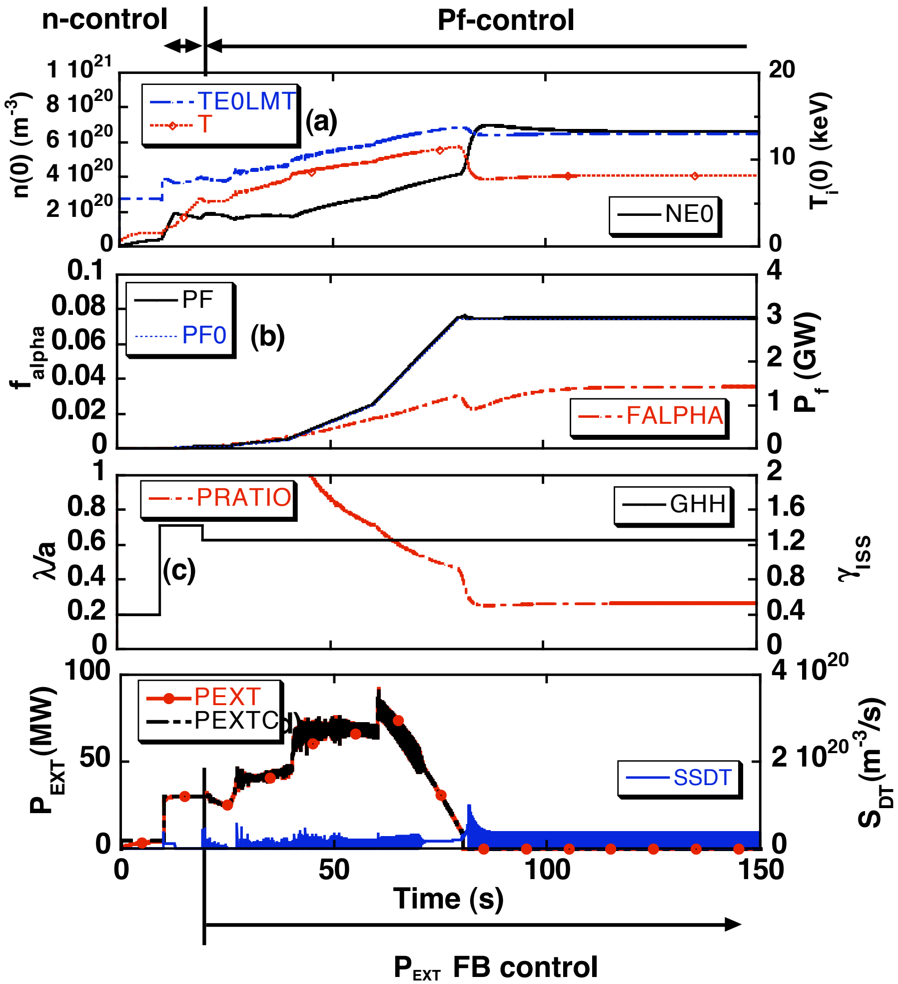
Oscillations on fueling and heating power appear by finite differential time in fueling control. Operating point stops at the highest temperature on P_f= 3GW line by introducing the differential time T_{diff}.

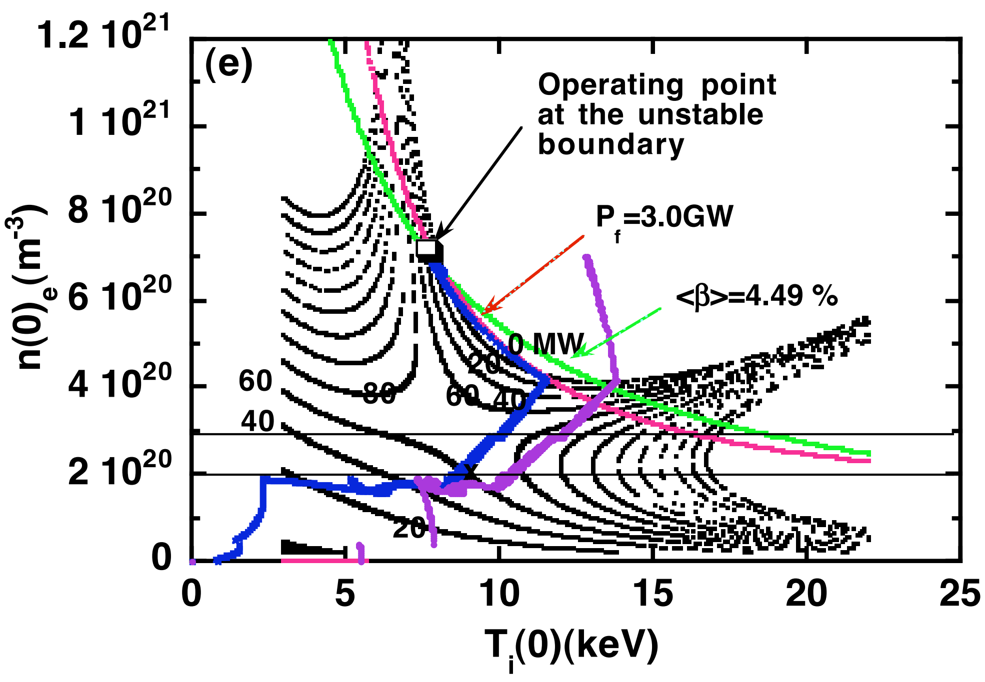




[4-3-3] Lower temperature limit of T_c=7.4 keV (γ_{ISS}=1.25, T_{diff}=0.13 s)

When the temperature limit is lowered, operating point proceeds to the final one smoothly even with the finite differential time. Lower temperature limit drives the operating point to the low temperature regime at the turning point.



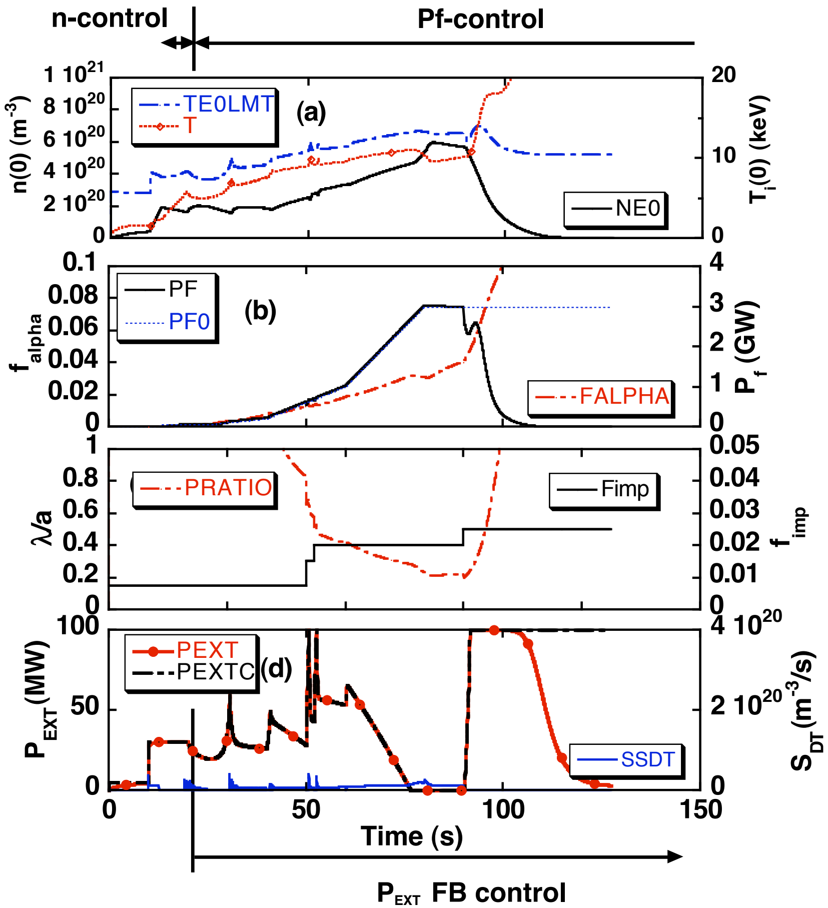


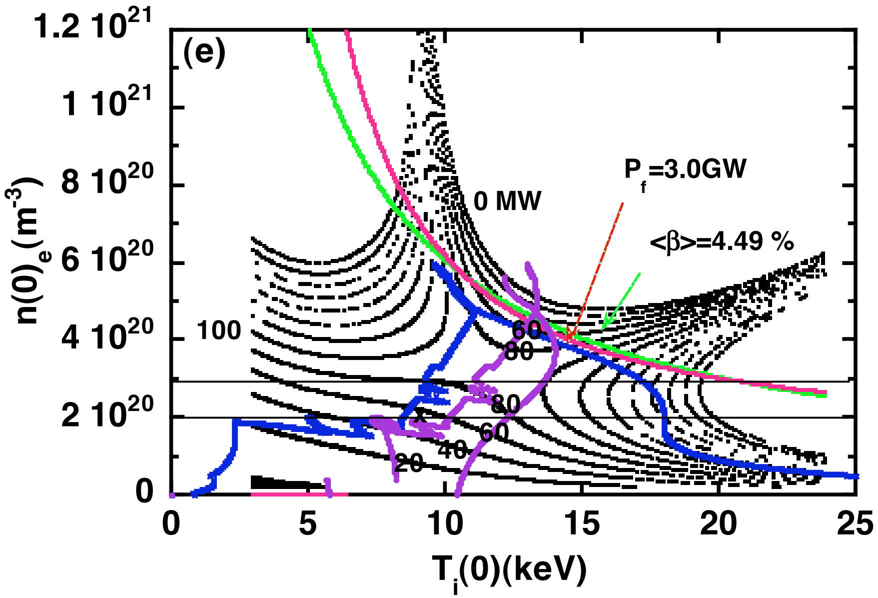
[4-4] Impurity disturbances:

If impurity content is increased during heating phase, feedback heating power is increased. —> Sub-ignition

[4-4-1] Impurity increment to f_{imp}=0.025 (T_c=7.7 keV, T_{diff}=0 s)

Sub-Ignition is terminated.



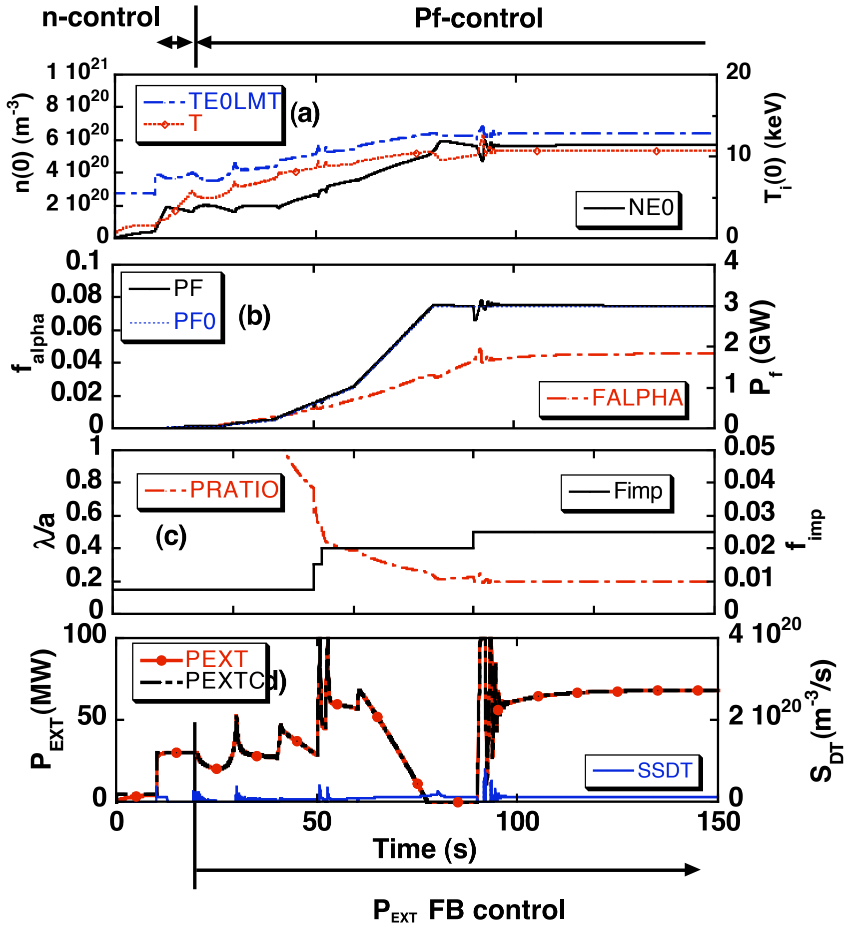


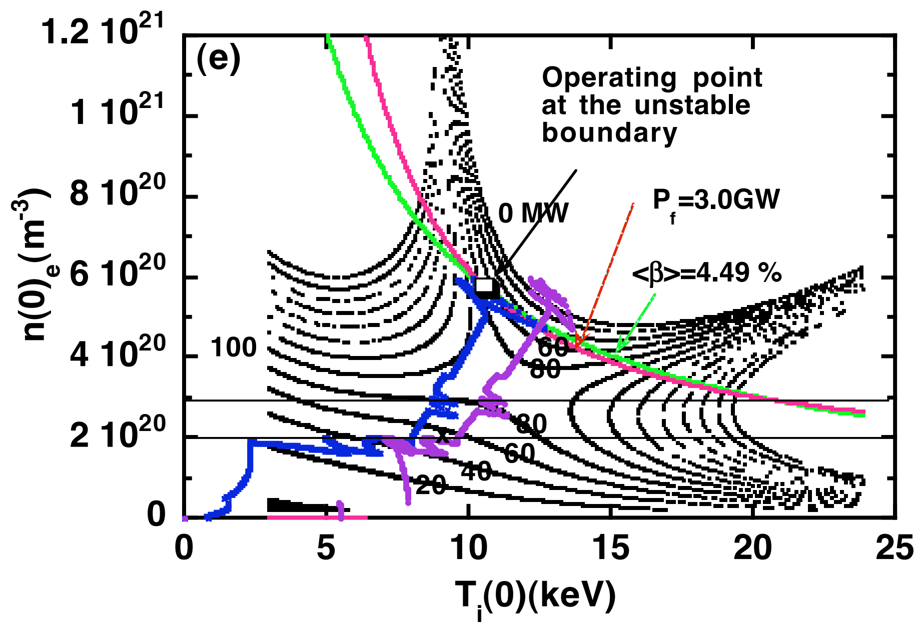
[4-4-2] Lower temperature limit case (T_c=7.4 keV)

(impurity increment to f_{imp}=0.025 ,T_{diff}=0 s)

Sub-ignition is maintained for smaller T_C. Lower temperature limit can keep the operating point on the contour map in the low temperature regime

T_c=7.4 keV can be used for wide parameters.

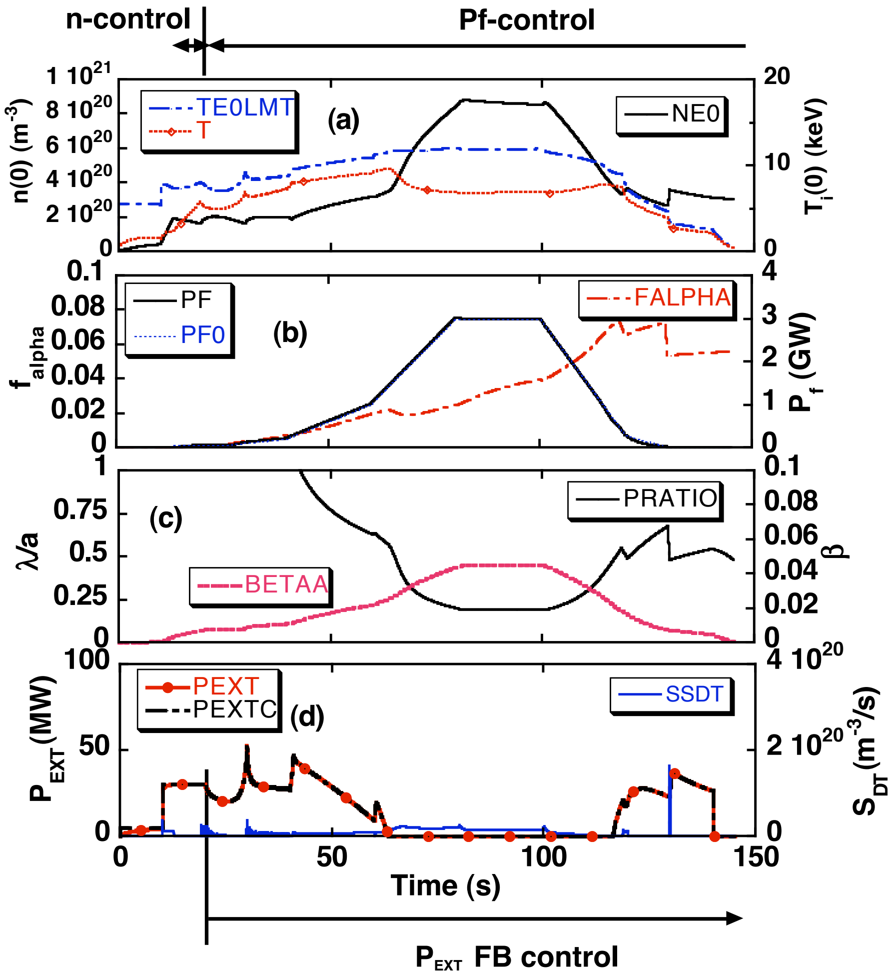


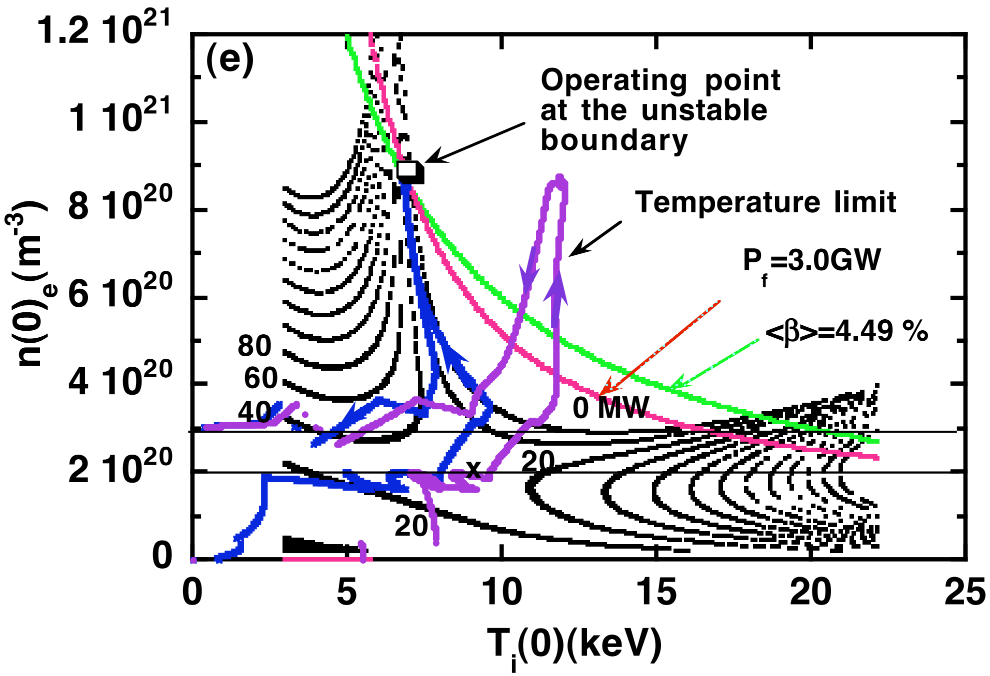


[4-5] Shutdown phase:

[4-5-1] Heating power feedback in all phases. (T_c=7.4 keV, T_{diff}=0 s)

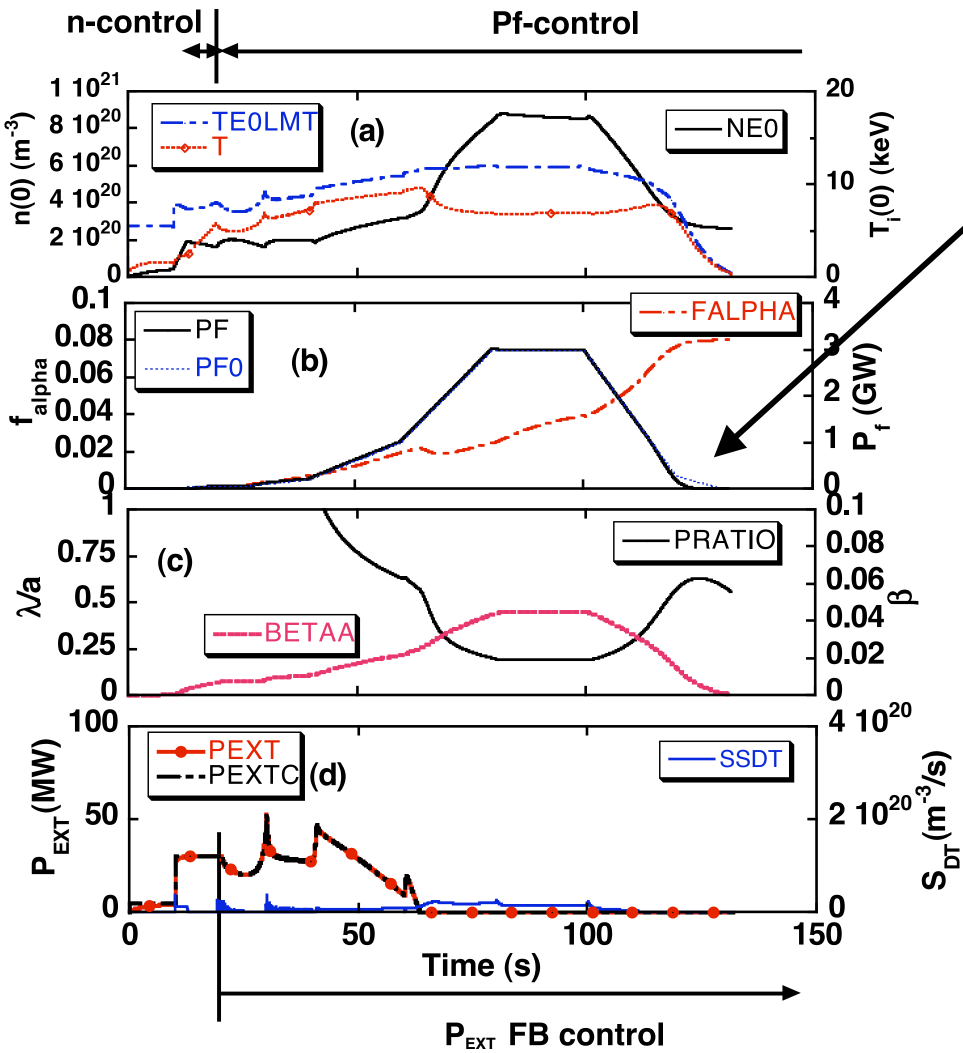
Feedback control of the heating power is applied during the shutdown phase.



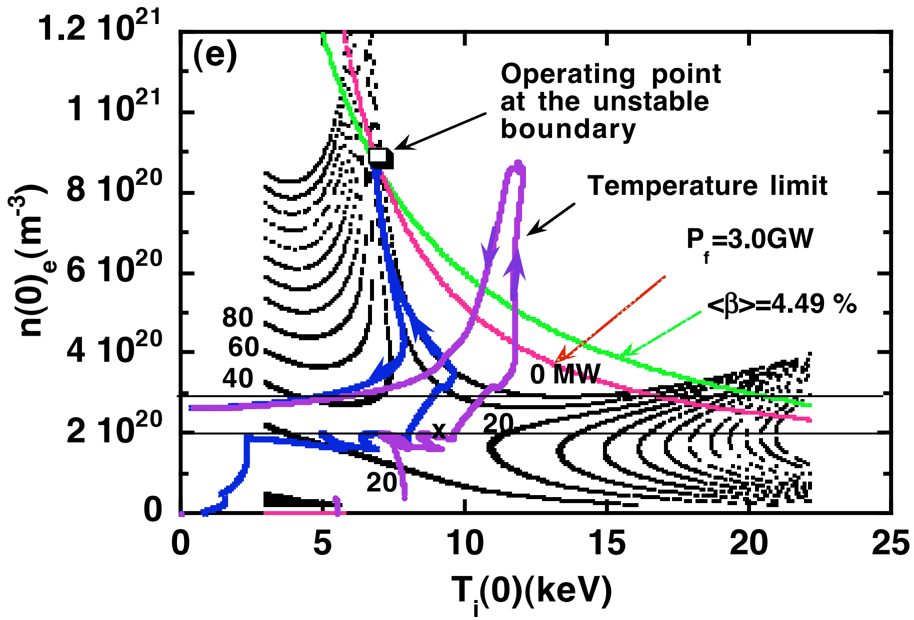


[4-5-2] Heating power is shut off after 110 s. (T_c=7.4 keV, T_{diff}=0 s)

Smooth shutdown has been achieved without the heating power and fuelling.



Fusion power is slightly changed from the set value.



5. Feedback control and diagnostic systems for low temperature and high-density ignition

Temperature measurement is important for feedback control of heating power during high-density ignition access.

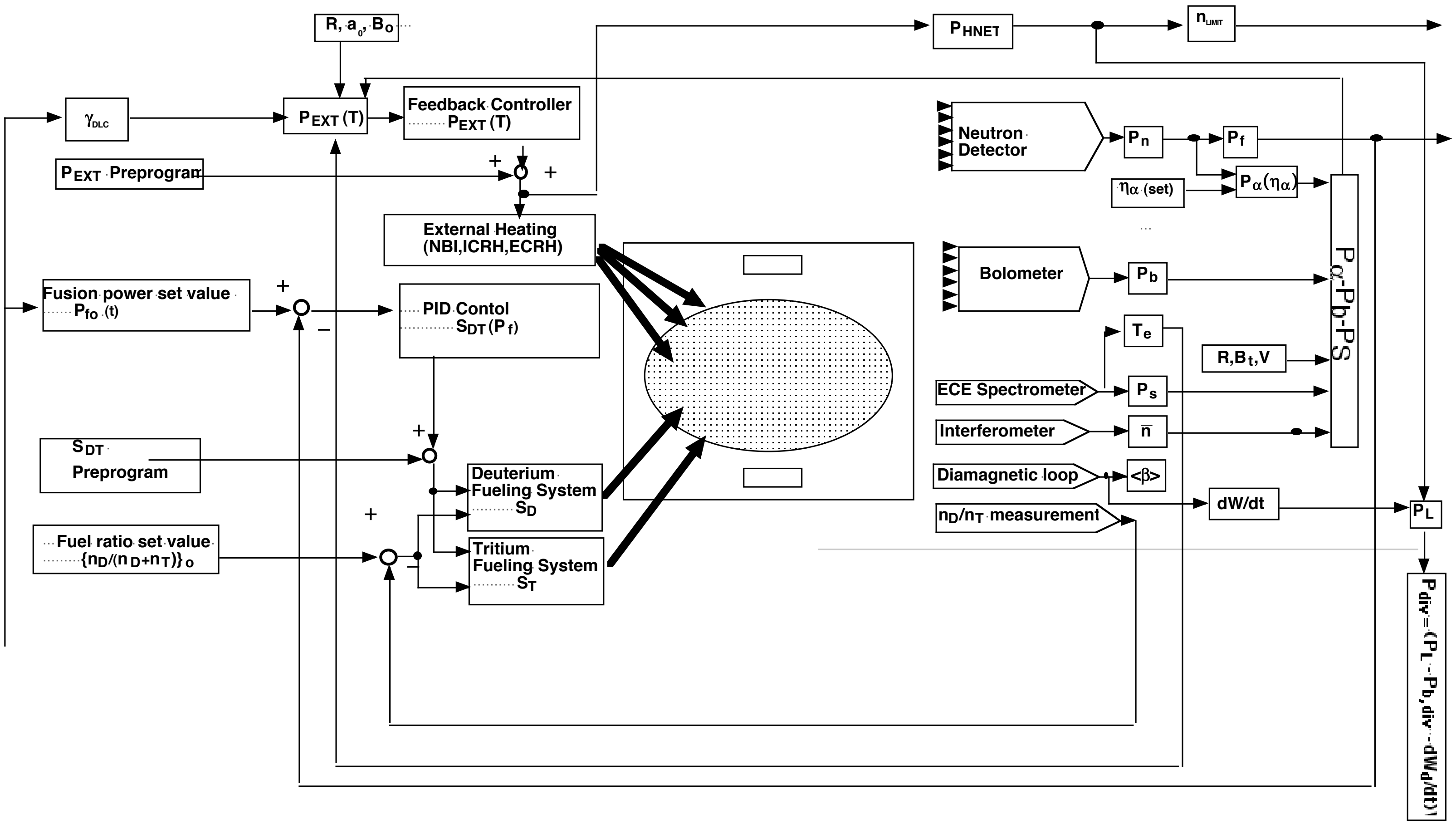


Fig. 1

6. Summary

[1] ●PID fueling control was already developed for the thermally unstable ignition regime.

●Analogy of the density limit gives us the hint that postulated temperature limit restricts the operating point to the low-temperature regime.

The newly discovered control algorithm for the heating power was successfully demonstrated for ignition access to the thermally unstable regime in FFHR.

[2]●Lower T_c tends to increase the heating power and density, and then reduce the penetration ratio of NBI heating.

●Higher T_c tends to stop the operating point if the confinement factor is reduced.

[3] Temperature limit factor of T_c~7.4 keV might be suitable for feedback control for wide parameter regimes.

Feedback control method of fueling and heating power has been developed for thermally unstable operation.