Burn control study using burning plasma simulation experiments in JT-60U

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Introduction

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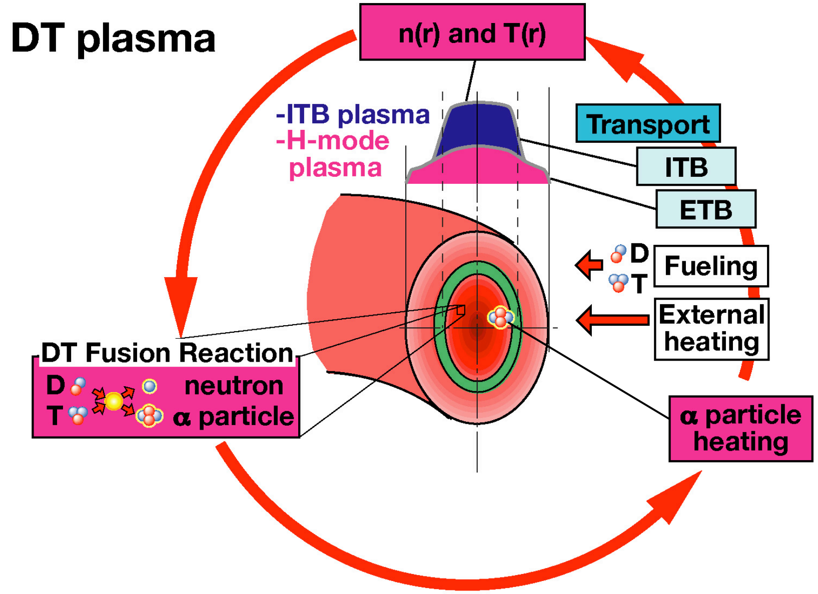
Burning plasmas (DT plasmas)

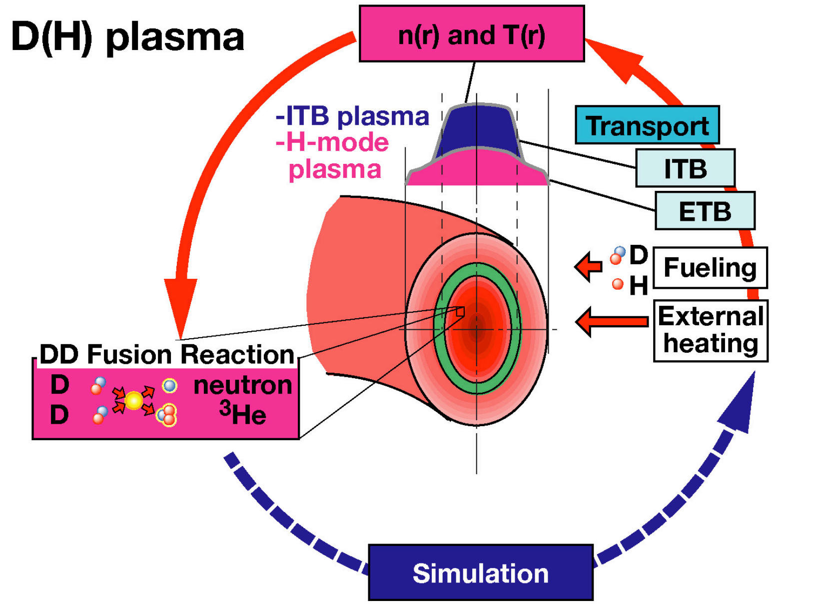
- **Strong linkage** between plasma pressure and heating power through **α particle heating**.
- **Burn control** has to be performed under this linkage involving **various physics**.

This study provides new approach to the burn control study.

➔ **The linkage is experimentally simulated in non burning plasmas.**

Plasma behavior and controllability under the linkage are discussed.





Outline

- Scheme of burning plasma simulation
- Burning plasma simulation experiments
- 0-dimensional calculation
- Discussion and further improvement
- Summary

Scheme of burning plasma simulation

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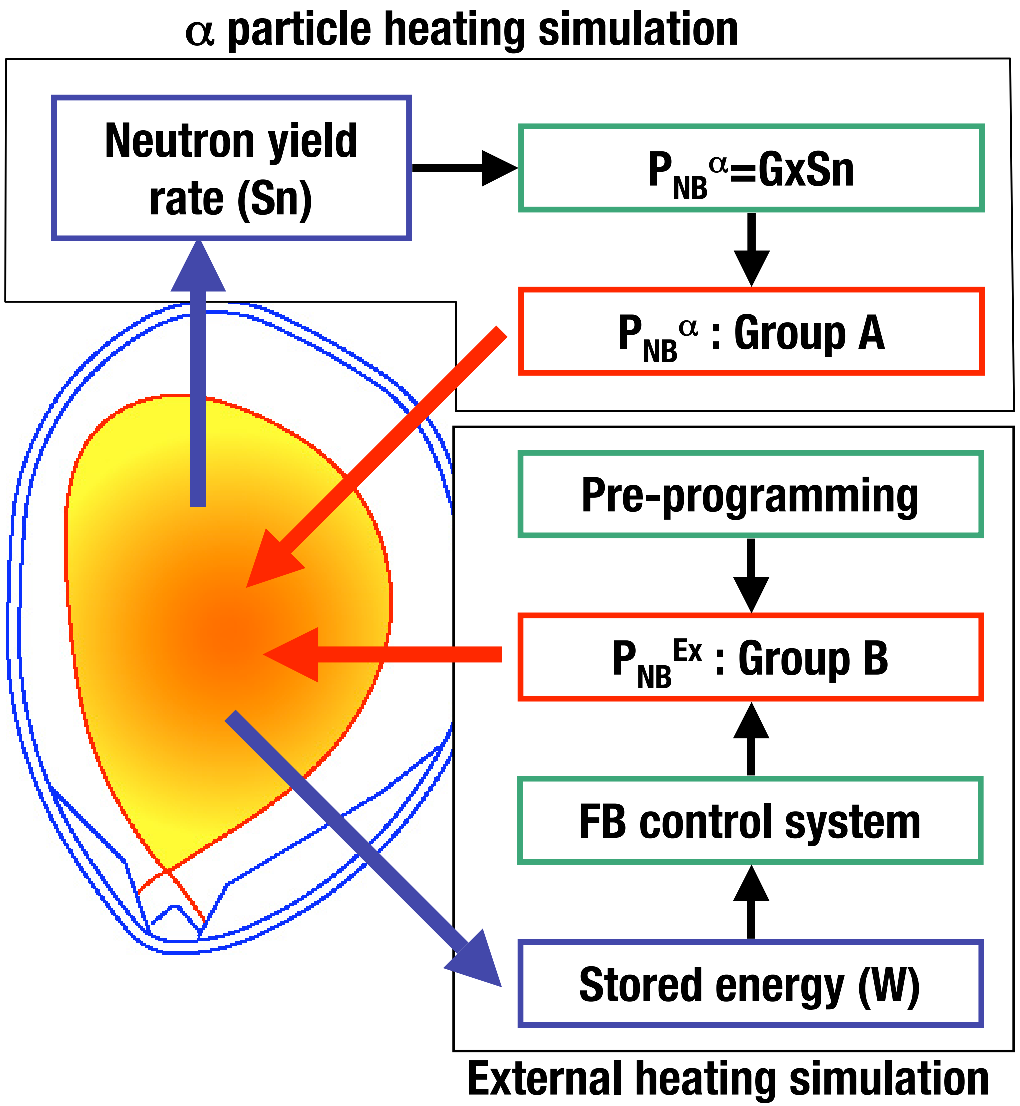

Two NB groups

Group A : α particle heating simulation

$P_{NB}^{\alpha}[MW]=GxSn^{DD}[10^{14}/s]$

Group B : external heating simulation

P_{NB}^{Ex} by pre-programming or stored energy FB control

Equivalent fusion gain for DT corresponding to the same ratio of α particle and external heating

$Q=5P_{NB}^{\alpha}/P_{NB}^{Ex}$

Limitations

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In this burning plasma simulation, there are limitations at present.

- **Different dominant reaction**
  DD : beam-thermal and thermal-thermal
  DT : thermal-thermal
- **Different temperature dependence between $<\sigma v>_{DT}$ and $<\sigma v>_{DD}$**
- **Complicate control for D and T in DT burning plasma**
- **Different heating profile and velocity distribution of α particle heating**
- **No consideration of effects of instability triggered by α particles**
- **No consideration of mass dependence of transport**
- **Stepwise change of $P_{NB}{}^{\alpha}$ ($P_{NB}{}^{\alpha}$ is changed stepwise against Sn, because $P_{NB}{}^{\alpha}$ is controlled by number of NB unit)**

The loop of increases in P_{NB}^{α} and Sn is triggered with G=1.4 in ELMy H-mode plasma

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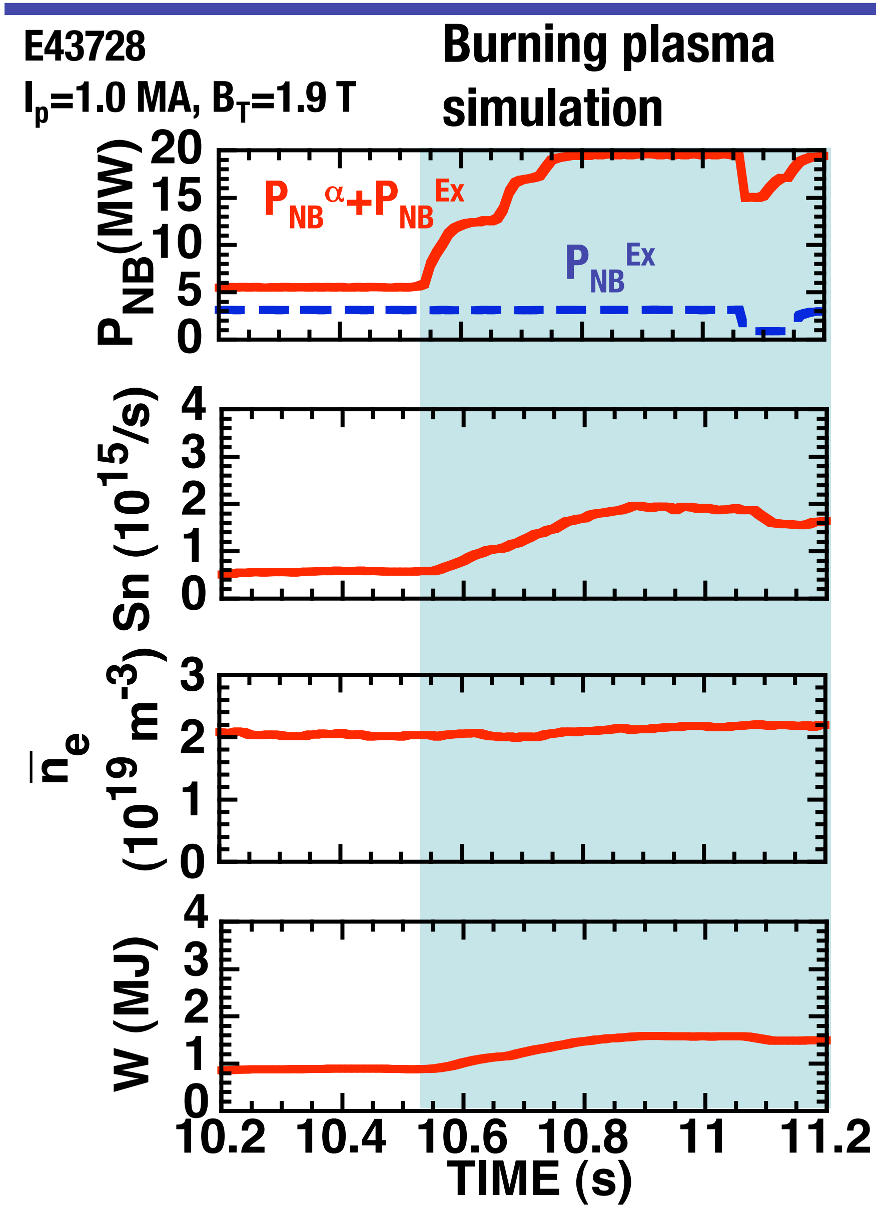

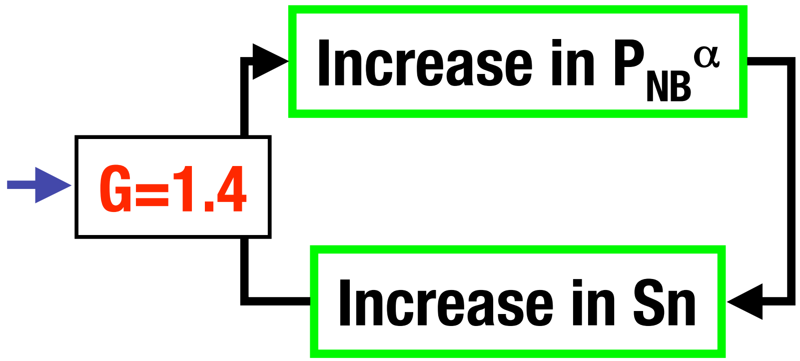

- Constant P_{NB}^{Ex}=3.1 MW. (no burn control)
- P_{NB}^{α} : 2.4 MW (Q=3.8) -> 14 MW (Q=22) with a time scale of 0.2 s.
- Strong linkage between plasma pressure and heating power can be simulated.
- P_{NB}^{α} reaches to the upper limit of the available NB power.

The loop is triggered with G=0.6, although it is not triggered with G=0.35 in reversed shear plasma.

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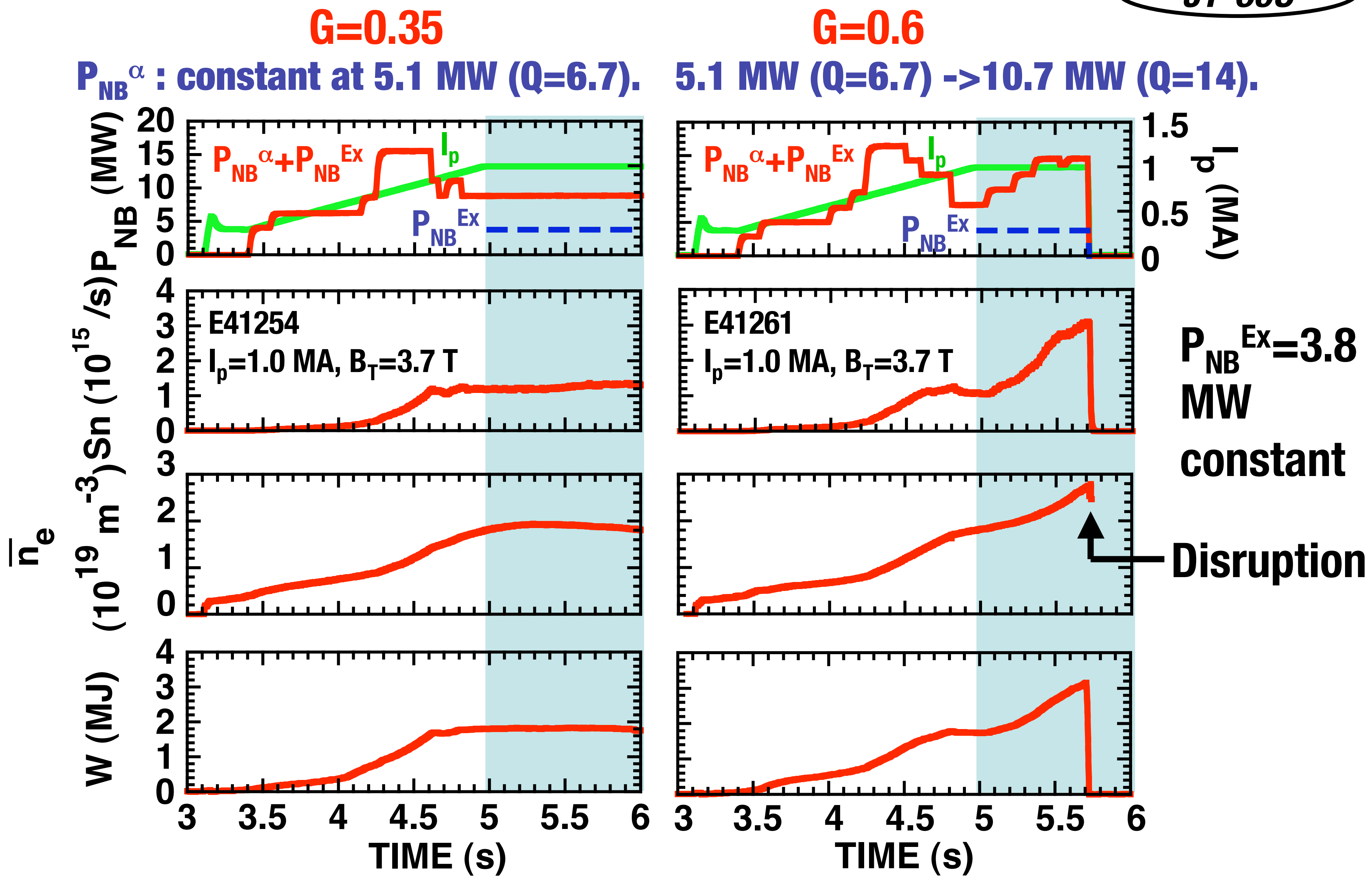

W and Sn are well controlled by P_{NB}^{Ex} in ELMy H-mode / L-mode plasma

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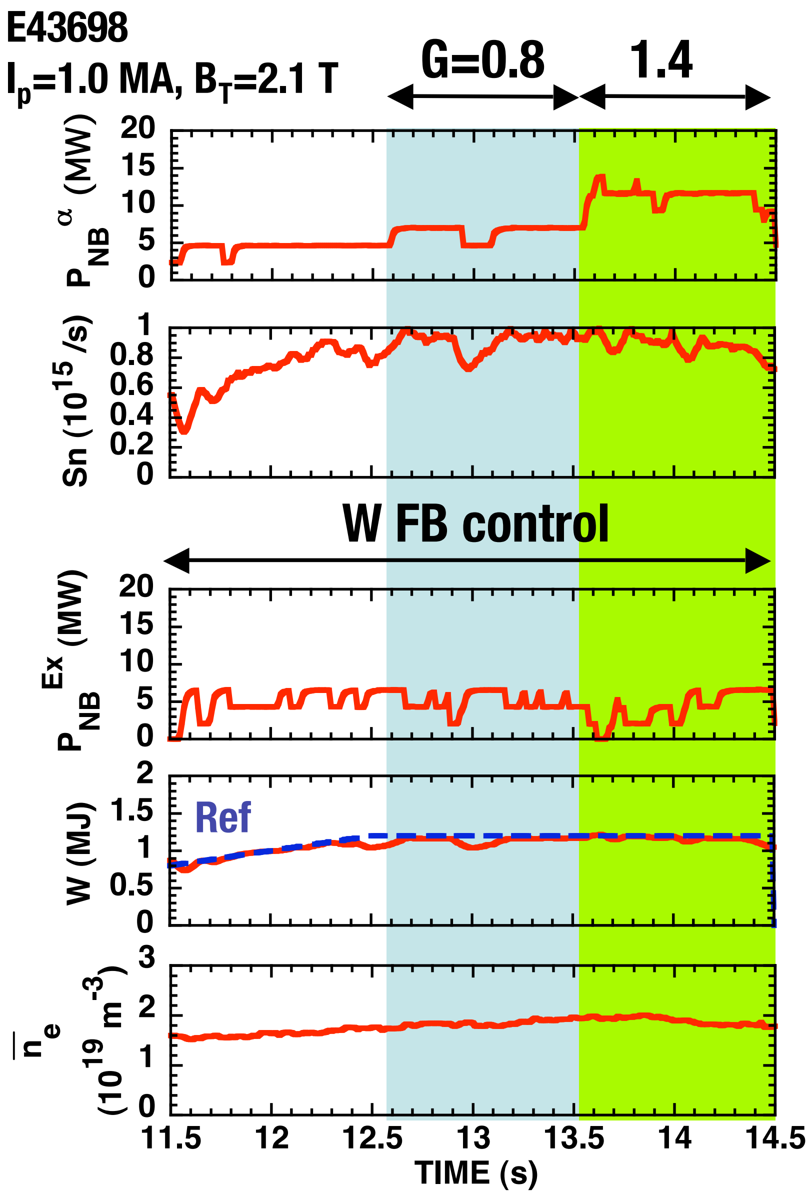

- W is well controlled at a constant value after t=12.5 s by reducing P_{NB}^{Ex} against the increase in P_{NB}^{α}.
- Although the controllability is not lost at t=13.6 s with $P_{NB}^{Ex}=0$, the reduction of P_{NB}^{Ex} to zero indicates that the control margin is not so large in high Q region (Q~30).
- Burn control by external heating will be applied to reversed shear plasma.

0-dimensional model

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Energy

$$\frac{dW}{dt} = -\frac{W}{\tau_E} + P_{NB} - P_{rad}$$

Fast ion (deuterium)

$$\frac{dN_f}{dt} = -\frac{N_f}{\tau_f} + S_{NB}$$

Bulk ion (deuterium)

Center fueling

$$\frac{dN_D^C}{dt} = -\frac{N_D^C}{\tau_D^C} + \frac{N_f}{\tau_f}$$

Edge fueling

(including SOL and divertor)

$$\frac{dN_D^E}{dt} = -\frac{N_D^E}{\tau_D^E} + S_{R+GP}$$

Impurity

$$\frac{dN_{imp}}{dt} = -\frac{N_{imp}}{\tau_{imp}} + S_{imp}$$

Calculation conditions

V=70 m^3, Z=6 (carbon)

Confinement time

$\tau_E = \tau_{E0} P^{-0.69} n_e^{0.41}$ (IPB98 (y,2) scaling)

τ_f : slowing down time

$\tau_D^C = \tau_{D0}^C P^{-1.1} n_e^{0.66}$

$\tau_D^E = \tau_{D0}^E P^{-1.1} n_e^{-0.36}$

(H. Takenaga et al. NF (1999) 1917.)

$\tau_{imp} = \tau_{imp0} P^{-1.1} n_e^{-0.36}$

τ_{E0}=0.2 s, τ_{D0}^C=0.5 s, τ_{D0}^E=0.005 s,
τ_{imp0}=0.005 s,

Neutron yield

thermal-thermal : Maxwell distribution at T

Beam-beam : Maxwell distribution at 60keV

beam-thermal : Maxwell distribution at

$T_{eff}=(n_f T_f + n_D T)/(n_f + n_D)$

$T = W/e(3/2(n_D^C + n_D^E + n_f + n_{imp} + n_e))$

The loop triggered by increasing G well simulates the loop triggered by increasing τ_E.

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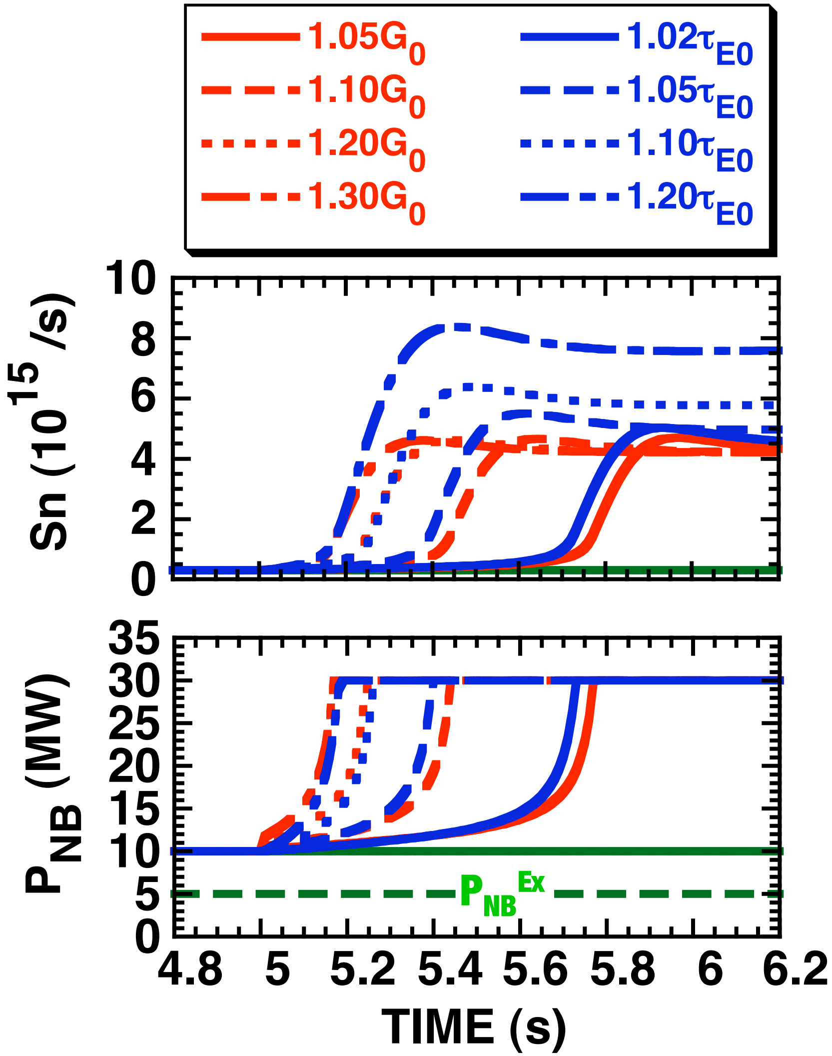

- Constant P_{NB}^{Ex} at 5 MW (no burn control) and Q=5 before t=5 s.
- Sn and P_{NB}^{α} are increased due to increase in G or τ_E. P_{NB} reaches upper limit of 30 MW (Q=25).
- A time scale of increases in Sn and P_{NB}^{α} is smaller for larger increase in G or τ_E.

Red : G is increased at t=5 s
Blue : τ_E is increased at t=5 s

Burn control is effective even with $G=1.2G_0$ at $Q=5$, but is lost with $G=1.12G_0$ at $Q=30$.

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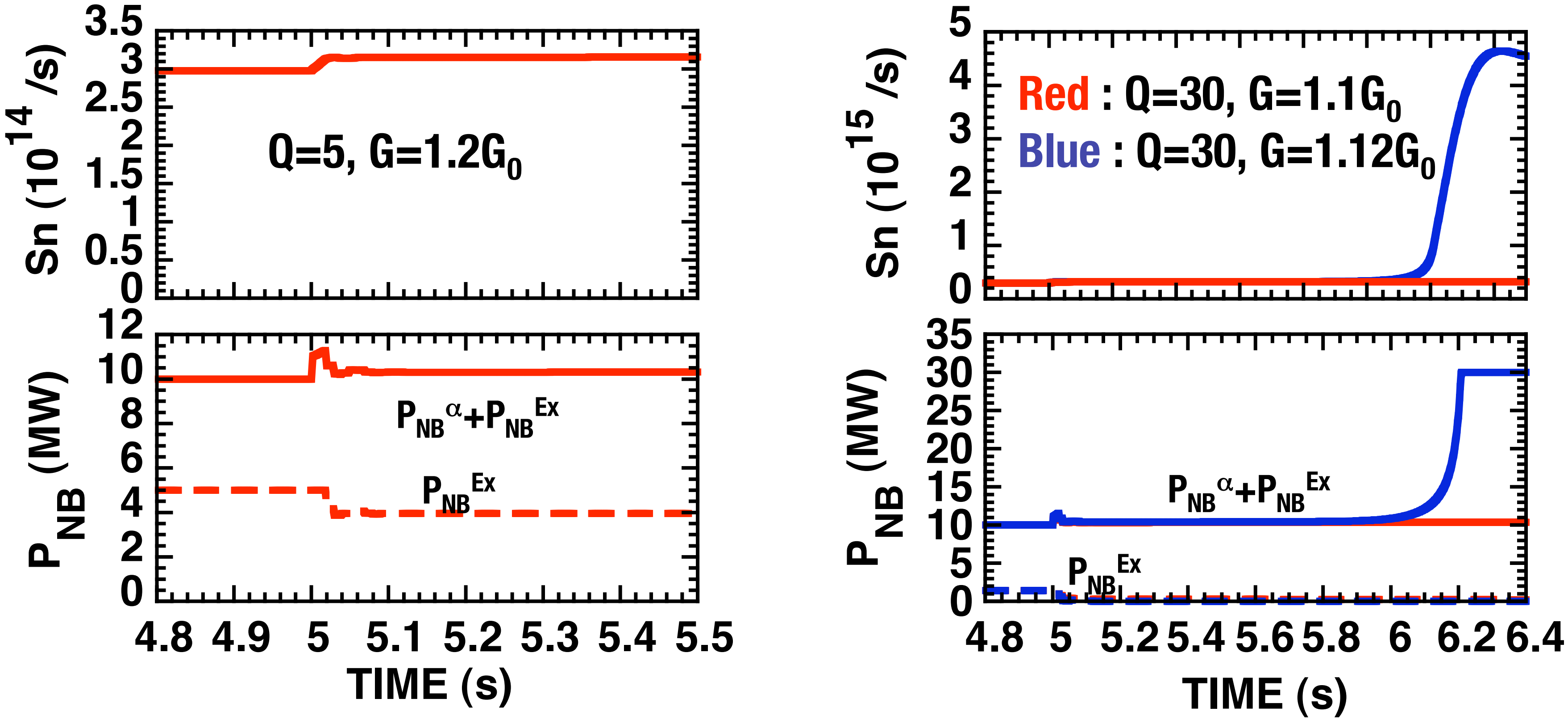
- P_{NB}^{Ex} is controlled at every 10 ms with W FB control (burn control).
- $G=1.2G_0$ at $Q=5$, P_{NB}^{Ex} : 5 MW ($Q=5$) to 3.95 MW ($Q=8$)
- $G=1.1G_0$ at $Q=30$, P_{NB}^{Ex} : 1.4 MW ($Q=30$) to 0.23 MW ($Q=225$)
- $G=1.12G_0$ at $Q=30$, Sn and P_{NB} gradually increase during t=5-6 s and quickly increase after t=6 s. P_{NB}^{Ex} decreases to zero.



Discussion and further improvement

For further improvement,

- Different dominant reaction
  DD : beam-thermal and thermal-thermal, DT : thermal-thermal
  ➔ H beam
- Different temperature dependence between $<\sigma v>_{DT}$ and $<\sigma v>_{DD}$
  ➔ Correction using real time T_i measurement
- Complicate control for D and T in DT burning plasma
  ➔ Simulation using D and H

Planned scheme of burning plasma simulation

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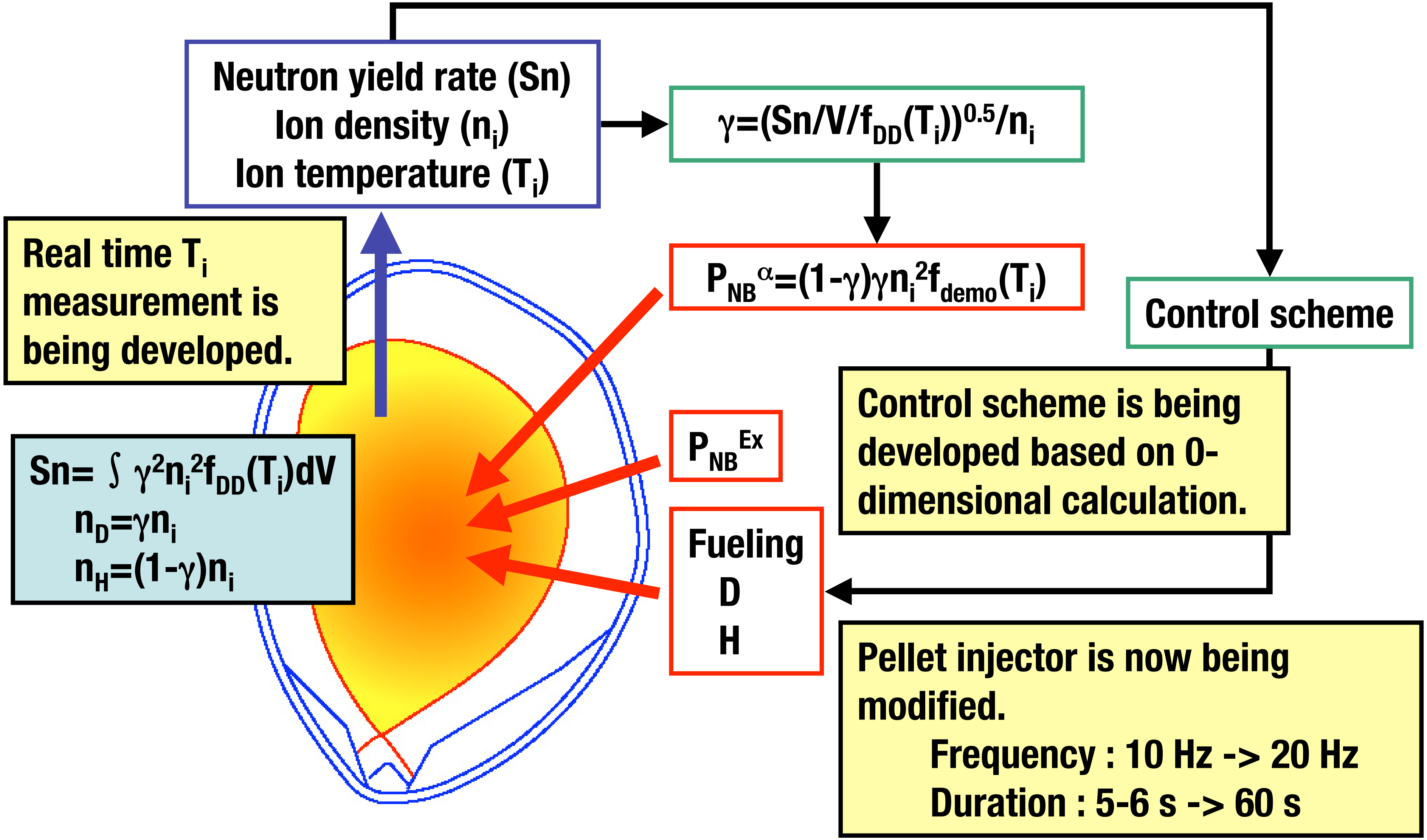

Summary

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- Burning plasma simulation scheme is developed using 2 groups of NB, where one simulates α particle heating and other simulates external heating.
- The loop of increases in neutron yield rate and simulated α particle heating power is triggered by increasing the proportional gain without burn control in the ELMy H-mode and reversed shear plasmas.
- With burn control using the external heating, the neutron yield rate is kept constant in the ELMy H/L-mode plasma.
- Zero dimensional calculation shows that the loop triggered by increasing proportional gain well simulates the loop triggered by increasing confinement.

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