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

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Workshop (W60) on “Burning Plasma Physics and Simulation”
4-5 July 2005, University Campus, Tarragona, Spain
Under the Auspices of the IEA Large Tokamak Implementing Agreement
Introduction

Burning plasmas (DT plasmas)

• Strong linkage between plasma pressure and heating power through $\alpha$ 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

**Two NB groups**

**Group A**: α particle heating simulation

\[ P_{NB}^\alpha = G \times S_n \]

\[ P_{NB}^\alpha \text{ [MW]} = G \times S_n^{DD} \times 10^{14} / s \]

**Group B**: external heating simulation

\[ P_{NB}^{Ex} \text{ by pre-programming or stored energy FB control} \]

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

\[ Q = 5 \frac{P_{NB}^\alpha}{P_{NB}^{Ex}} \]
Limitations

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 $\alpha$ particle heating

- No consideration of effects of instability triggered by $\alpha$ particles

- No consideration of mass dependence of transport

- Stepwise change of $P_{\text{NB}}^\alpha$ ($P_{\text{NB}}^\alpha$ is changed stepwise against $S_n$, because $P_{\text{NB}}^\alpha$ is controlled by number of NB unit)
The loop of increases in $P_{NB}^\alpha$ and Sn is triggered with $G=1.4$ in ELMy H-mode plasma.

- **Constant** $P_{NB}^{Ex}=3.1$ MW. (no burn control)
- $P_{NB}^\alpha$: 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.
- $P_{NB}^\alpha$ reaches to the upper limit of the available NB power.

### Burning plasma simulation

- $I_p=1.0$ MA, $B_T=1.9$ T
- $n_e=1.0 \times 10^{19} \text{ m}^{-3}$
- $W=2.7$ MJ
The loop is triggered with $G=0.6$, although it is not triggered with $G=0.35$ in reversed shear plasma.

$P_{NB}^{\alpha}$: constant at 5.1 MW ($Q=6.7$).

$G=0.35$

$P_{NB}^{\alpha}+P_{NB}^{\text{Ex}}$

$P_{NB}^{\text{Ex}}$

$P_{NB}^{\alpha}$

$P_{NB}^{\text{Ex}}$

$G=0.6$

5.1 MW ($Q=6.7$) $\rightarrow$ 10.7 MW ($Q=14$).

$P_{NB}^{\text{Ex}}=3.8$ MW constant

Disruption

$\bar{n}_e$ ($10^{19} \text{ m}^{-3}$)

$I_p=1.0 \text{ MA}, B_T=3.7 \text{ T}$

$W$ (MJ)

$E41254$

$E41261$

$P_{NB}$

$P_{NB}^{\alpha}$

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

- W is well controlled at a constant value after $t=12.5$ s by reducing $P_{NB}^{Ex}$ against the increase in $P_{NB}^{\alpha}$.

- 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 ($Q \sim 30$).

- Burn control by external heating will be applied to reversed shear plasma.
0-dimensional model

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
\[V=70 \, m^3, \, Z=6 \, (\text{carbon})\]

Confinement time
\[
\tau_E = \tau_{E0}P^{-0.69}n_e^{0.41} \quad \text{(IPB98 (y,2) scaling)}
\]

\[\tau_f: \text{slowing down time}\]
\[
\tau_D^C = \tau_{D0}^CP^{-1.1}n_e^{0.66} \quad \text{(H. Takenaga et al. NF 1999 1917.)}
\]
\[
\tau_D^E = \tau_{D0}^EP^{-1.1}n_e^{-0.36}
\]
\[
\tau_{imp} = \tau_{imp0}P^{-1.1}n_e^{-0.36}
\]
\[
\tau_{E0} = 0.2 \, s, \, \tau_{D0}^C = 0.5 \, s, \, \tau_{D0}^E = 0.005 \, s, \, \tau_{imp0} = 0.005 \, s,
\]

Neutron yield
thermal-thermal : Maxwell distribution at \( T \)
Beam-beam : Maxwell distribution at 60keV
beam-thermal : Maxwell distribution at \( T_{eff} = \frac{(n_fT_f+n_D^CT)}{(n_f+n_D)} \)
\[T = W/e(3/2(n_D^C+n_D^E+n_f+n_{imp}+n_e))\]
The loop triggered by increasing G well simulates the loop triggered by increasing $\tau_E$.

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

Red: G is increased at $t=5$ s
Blue: $\tau_E$ 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 $Q=30$.

- $P_{NB}^{Ex}$ 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
  \( \rightarrow \) H beam

- Different temperature dependence between \( <\sigma v>_{DT} \) and \( <\sigma v>_{DD} \)
  \( \rightarrow \) Correction using real time \( T_i \) measurement

- Complicate control for D and T in DT burning plasma
  \( \rightarrow \) Simulation using D and H
Planned scheme of burning plasma simulation

Neutron yield rate (Sn)
Ion density ($n_i$)
Ion temperature ($T_i$)

$\gamma = \frac{(Sn/V/f_{DD}(T_i))^{0.5}}{n_i}$

$P_{NB}^\alpha = (1-\gamma)\gamma n_i^2 f_{demo}(T_i)$

Control scheme

Real time $T_i$ measurement is being developed.

$Sn = \int \gamma^2 n_i^2 f_{DD}(T_i) dV$

$n_D = \gamma n_i$

$n_H = (1-\gamma)n_i$

Control scheme is being developed based on 0-dimensional calculation.

Pellet injector is now being modified.
Frequency: 10 Hz -> 20 Hz
Duration: 5-6 s -> 60 s
Summary

- Burning plasma simulation scheme is developed using 2 groups of NB, where one simulates $\alpha$ particle heating and other simulates external heating.

- The loop of increases in neutron yield rate and simulated $\alpha$ 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.

Acknowledgments: This work was partly supported by JSPS, Grant-in-Aid for Scientific Research (A) No. 16206093.