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# Ignition Access in the FFHR D-T Helical Reactor

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## Abstract

The temporal evolution of ignition access in the D-T high field helical reactor, FFHR ($R$=20 m, $\overline{a}$=2 m, and $B_o$ ~ 12 T) with the fusion power of ~ 3 GW and the confinement factor of $\gamma_H$=1.5 ~ 2.0 is analyzed by a time dependent zero-dimensional power balance equation with LHD scaling and an H-mode power threshold. It is found that the H-mode power threshold observed in W7-AS should have a hysteresis effect or further be improved to maintain the operating point in the ignition regime. In addition, a lower magnetic field can help ignition access and maintaining the operating point in the ignition regime. To eliminate the complicated L-H transition effects, the L-mode ignition is also pursued using the higher magnetic field $B_o$=15 T.



## Keywords:

ignition, helical reactor, force-free coil, H-mode, LHD scaling


## 1. Introduction

Since the H-mode power threshold scaling has been available, it is now possible to study the ignition characteristics in a stellarator reactor like what is done for a tokamak reactor although the stellarator scaling should be further established in larger experiments. In present experiments, the confinement enhancement factor over the LHD scaling [1] is ~ 1.3, too small for ignition[2]. This difficulty could be overcome by employing a higher magnetic field[3], which could be produced in force-free type helical field coils[4].

Parameter dependence of the ignition access on the magnetic field, confinement factor, the coefficient of the H-mode power threshold, the alpha ash to the energy confinement time ratio, the other scalings and machine sizes should be examined under constraint of an H-mode power threshold. While a high magnetic field makes an empirical density limit higher and an ignited operation regime wider, it makes it more difficult to access ignition and maintain the operating point in the ignition regime due to the higher H-mode power threshold. In this study, the temporal evolution of the ignition access in the D-T high field helical reactor FFHR ($R$=20 m, $\overline{a}$=2 m, and $B_o$ ~ 9 to 15 T) with fusion power around 3 GW and a confinement factor of $\gamma_H$=1.5 ~ 2.0 is analyzed by using the time dependent zero-dimensional power balance equation with LHD and ISS95 scalings [5] and with an H-mode power threshold.

## 2. Formula and Parameters for Calculations

The time dependent equations for zero-dimensional power balance, electron density and alpha ash have been used for ignition analyses[6]. The H-mode indicator is defined by the H-mode power threshold observed in W7-AS [7] as

$$M_{HL} = \frac{\overline{P}_{h,net}\,[\mathrm{MW}]\ V_o\,[\mathrm{m^3}] \times 10^6}{A_{HL}\ \overline{n}\,[10^{20}\,\mathrm{m^{-3}}]\ B_o\,[\mathrm{T}]\ S_o\,[\mathrm{m^2}]} \quad (1)$$

where $\overline{P}_{h,net}$ is the net heating power density given by $\overline{P}_{h,net} = P_{EXT}/V_o + \overline{P}_\alpha - \{\overline{P}_b + \overline{P}_s\}$, $P_{EXT}$ is the external

*Corresponding author's e-mail: omitarai@ktmail.ktokai-u.ac.jp heating power, $\overline{P}_\alpha$ is the alpha heating power, $\overline{P}_b$ is the bremsstrahlung loss, $\overline{P}_s$ is the synchrotron radiation loss, $V_o$ is the plasma volume given by $V_o = 2\pi R \pi \overline{a}^2$ and $S_o$ is the plasma surface, $S_o = 2\pi R \pi \overline{a}^2$, with $\overline{a}$ the effective plasma minor radius, $A_{HL}$ is the coefficient of the H-mode power threshold, $\overline{n}$ is the line averaged density, and $B_o$ is the magnetic field strength.

The density limit[1] for the net heating power density is given by

$$n(0)_{\lim}\,[\mathrm{m}^{-3}] = \gamma_{\lim}\gamma_{pr}\, 0.25\times 10^{20} \sqrt{\frac{\{\overline{P}_{h,net}\ V_o\,[\mathrm{MW}]\}\ B_o\,[\mathrm{T}]}{\overline{a}^2\ R\,[\mathrm{m}]}} \quad (2)$$

where $\gamma_{\lim}$ is the enhancement factor of the density limit, and $\gamma_{pr} = 3/2$ is the profile factor. The fusion power is defined by the birth alpha heating power with $P_f = (\overline{P}_\alpha(\eta_\alpha)/\eta_\alpha + \overline{P}_n)V_o \sim 3.0$ GW where $\overline{P}_n$ is the 14.7 MeV neutron power density.

The following parameters have been assumed. The density and temperature profiles are $\alpha_n = \alpha_T = 1$, the ion to electron temperature ratio $T_i(0)/T_e(0) = 1$, the oxygen impurity content $n_O/n_e = 0.5\%$, the hole fraction $f_H = 0.1$, the wall reflectivity for synchrotron radiation loss $R_{eff} = 0.9$, the alpha particle heating efficiency $\eta_\alpha = 0.7$, and the alpha ash to the energy confinement time ratio $\tau_\alpha^*/\tau_E = 3$.

## 3. Ignition Access in FFHR with LHD Scaling

### 3.1. High field 12 T and low confinement factor $\gamma_H = 1.5$

For a magnetic field of 12 T, it is possible for FFHR to reach ignition with a low confinement factor of $\gamma_H = 1.5$. The temporal evolution of the plasma parameters during the ignition access with $P_{EXT} = 250$ MW is shown in Fig. 1. The initial plasma parameters before the main external heating are chosen arbitrary as $T(0) \sim 1$ keV and $n(0) \sim 3\times10^{19}$ m$^3$ because there is no Ohmic heating. An H-mode transition is assumed to take place from the outset. The plasma temperature increases up to 35 keV in a short time, and then decreases to the final point of $T(0) \sim 21$ keV with an increase in the density by fueling. As the H-mode indicator $M_{HL}$ approaches unity at the final phase of the main heating with the experimentally obtained value of $A_{HL} = 0.024$, $A_{HL}$ should be decreased when the main heating power is reduced to 120 MW so as not to return to the L-mode. The H-mode regime is then expanded at the instant when $A_{HL}$ is decreased; therefore the operating point can access the ignition regime.

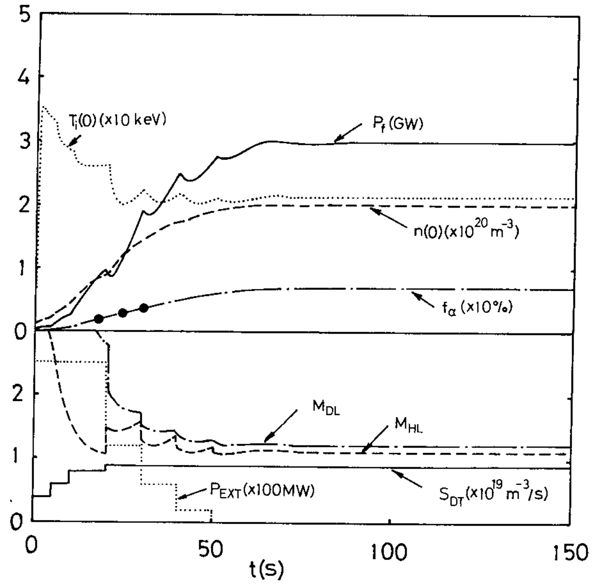


Fig. 1 The temporal evolution of the plasma parameters in FFHR with $B_o = 12$ T and $\gamma_H = 1.5$.

Thus, we have found that $A_{HL}$ value should be a half of the observed value from the outset to access ignition or the hysteresis effect must exist in the H-mode power threshold. The plasma density steadily increases and finally approaches $n(0) \sim 2.04\times10^{-20}$ m$^{-3}$. The operating point is found to exist within the density limit as indicated by $M_{DL} = n_{\lim}(0)/n(0) > 1$. The beta value at the operating point is as low as $<\beta> \sim 0.76\%$. The alpha ash density fraction finally reaches $f_\alpha \sim 7.25\%$.

The operation path in a POPCON plot is shown in Figs. 2(a) to (d) corresponding to alpha ash fractions: $f_\alpha = 2\%$, 3%, 4%, and 7.25%, respectively. It should be noted in Fig. 2(a) that as the contour line of 250 MW exists below the high temperature L-mode regime, it is relatively easier for the operation path to access the ignition regime. The "window to the ignition regime" is seen around 22 keV, and would be closed for a heating power less than $P_{EXT} \sim 230$ MW.

### 3.2. High field 12 T and high confinement factor $\gamma_H = 2.0$

Even if the confinement factor is enhanced up to 2.0, ignition access is not improved due to the H-L transition. As the contour line of 250 MW shifts to the high temperature L-mode regime due to the larger confinement factor, the operating point tends to enter into the high temperature L-mode regime. Therefore, careful operation is necessary not to enter into the L-mode regime during the main heating phase. This can be

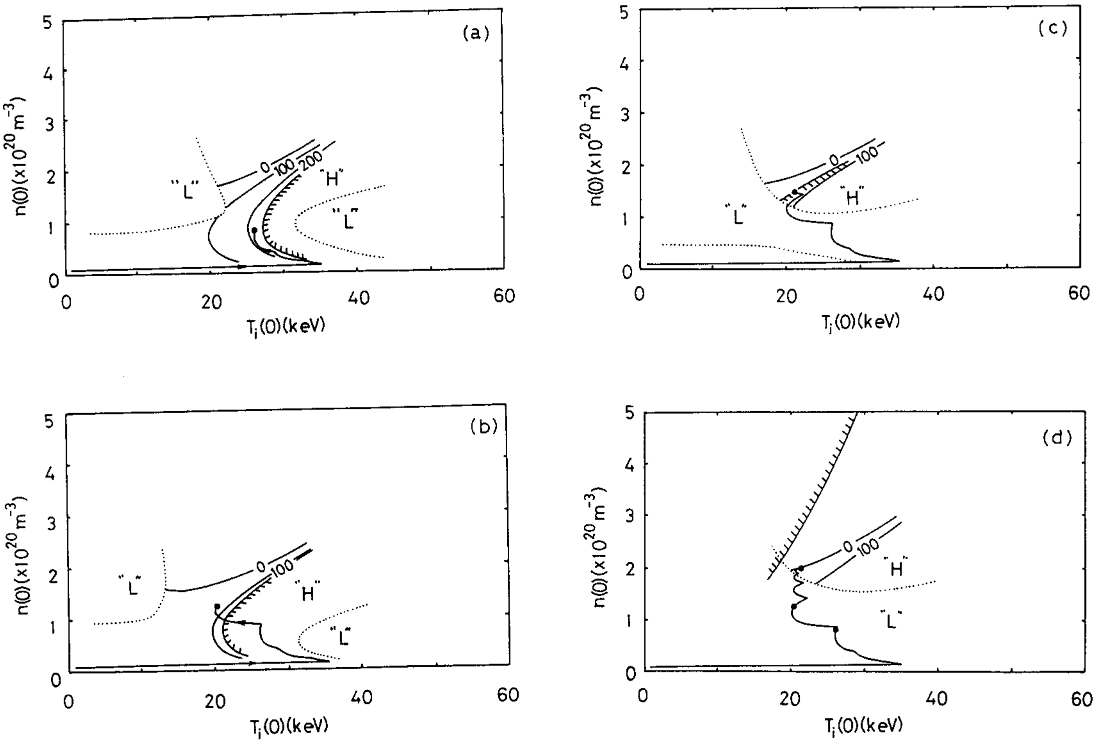


Fig. 2 The operation path (solid line) on POPCON plots corresponding to the solid circles on the $f_\alpha$ trace in Fig. 1 for (a) $f_\alpha$=2%, $A_{HL}$=0.024, and $P_{EXT}$=250 MW, (b) $f_\alpha$=3%, $A_{HL}$=0.008, and $P_{EXT}$=120 MW, (c) $f_\alpha$=4%, $A_{HL}$=0.01, and $P_{EXT}$=60 MW, and (d) $f_\alpha$=7.25%, $A_{HL}$=0.008, and $P_{EXT}$=0 MW.

done by switching off the heating power earlier to reduce the temperature and avoids the H-L transition.

When a long pulse of 250 MW is applied, repetitive fusion power surges are observed due to cyclic H-L-H transitions.

### 3.3. Low field 9 T and low confinement factor $\gamma_H$=1.5

For the lower field of 9 T where the H-mode power threshold is lower, the heating power can be reduced to 200 MW to reach ignition with the low confinement factor of $\gamma_H$=1.5. However, as the ignition boundary is shifted up to the higher density regime, and the operating point is closer to the lower part of the ignition boundary, a "thermonuclear oscillation", as observed in ITER ignition study[6], is found as shown in Fig. 3. These oscillations can be stabilized by increase in the operating density.

### 3.4. Low field 9 T and high confinement factor $\gamma_H$=2.0

When the confinement factor increases up to $\gamma_H$=2, the heating power can be further reduced to 150 MW and the thermonuclear oscillation is no longer

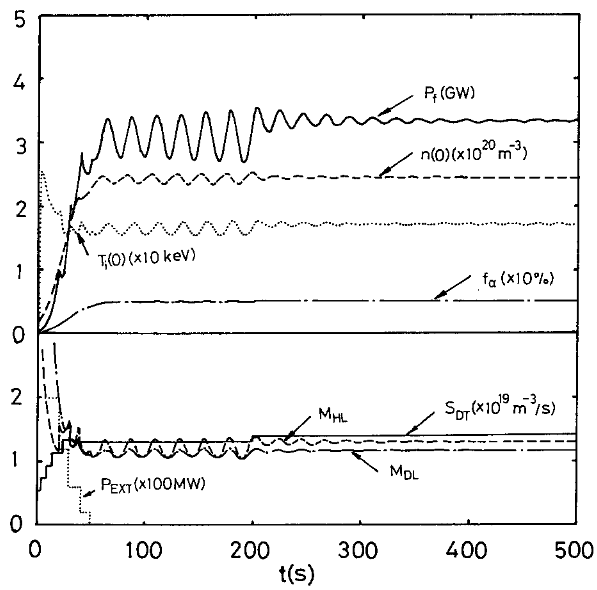


Fig. 3 Ignition access for $B_o$=9 T, $\gamma_H$=1.5, and a heating power of 200 MW. Thermonuclear oscillations are seen up to 200 sec and then stabilized by a slight increase in the density.

observed because the operating point is in the thermally stable higher density ignition boundary.

### 3.5. Higher field 15 T with L-mode operation $\gamma_H = 1.0$

The H-mode operation needs a sophisticated control so as not to enter into the L-mode regime. In the previous POPCON study on FFHR, the L-mode operation with $\gamma_H = 1$ was found to be critically possible with $B_o = 15$ T[3]. This fact was examined with the temporal analysis. As shown in Fig. 4 for $P_{EXT} = 100$ MW, the operating point goes into the L-mode and reaches the ignition regime by increasing the density. This operation scenario has a large advantage over the H-mode operation because an L-H transition is not required.

## 4. Ignition Access in FFHR with the ISS95 Scaling

A somewhat larger confinement factor of $\gamma_H = 1.92$ is necessary over the ISS95 scaling:

$$\tau_{E,ISS95}[\mathrm{s}] = \gamma_H \, 0.079 \, \iota_{2/3}^{0.4} \, \bar{n}_{20}^{0.51} \, [\times 10^{19} \, \mathrm{m}^{-3}] \, B_o^{0.83} \, [\mathrm{T}] \, \bar{a}^{2.21} \, [\mathrm{m}] \, R^{0.65} \, [\mathrm{m}] / P_H^{0.59} \, [\mathrm{MW}] \quad (3)$$

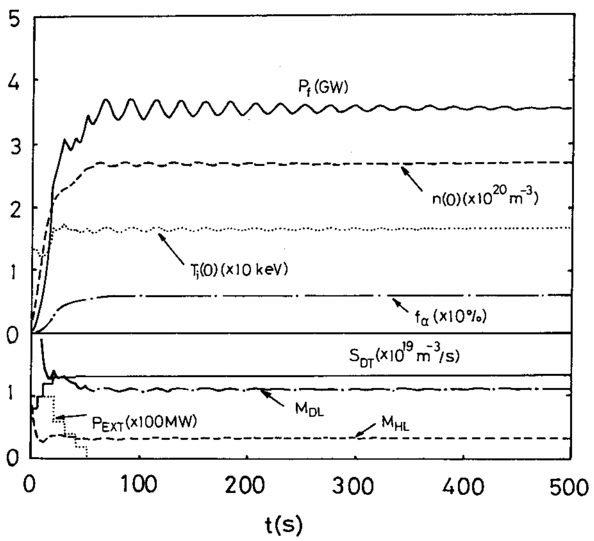


Fig. 4 The temporal evolution of an L-mode operation with $\gamma_H = 1$ and $B_o = 15$ T in FFHR.

for $l = 3$, $\iota_{2/3} = 0.4$, $\gamma_H = 1.5$, $B_o = 12$ T with the other parameters the same as before in order to have similar ignition characteristics as those with LHD scaling, The ignition behavior is not much different from Fig. 1.

## 5. Summary

For $B_o = 12$ T and $\gamma_H = 1.5$, the external heating power of 250 MW is necessary to reach ignition and a hysteresis effect should exist in the H-mode power threshold which opens the window to ignition after the main heating and maintains the operating point in the ignition regime. On the other hand, even when the confinement factor is improved up to 2.0, ignition access is not improved due to the H-L transition in the high temperature regime, and cyclic H-L-H transitions take place for the longer heating pulse. In a lower magnetic field of 9 T, the external heating power can be reduced to 150 MW to reach ignition with $\gamma_H = 2.0$. The L-mode operation with $\gamma_H = 1$ was found to be possible with $B_o = 15$ T.

A somewhat larger confinement factor of $\gamma_H = 1.92$ over ISS95 scaling is necessary for the same ignition performance for $B_o = 12$ T and $\gamma_H = 1.5$.

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