The high density ignition in FFHR helical reactor by NBI heating

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1. Introduction

A high-density and low temperature operation is advantageous to reduce the divertor heat flux via bremsstrahlung radiations and to inject pellets in the FFHR2m helical reactor, however

[1] The first issue:  Thermal instability
   Stabilization of the thermal instability is possible by the PID control based on the fusion power.  Solved!!

   A very high energy NBI system with 5~6 MeV is required for full penetration into high-density plasmas, which might be impossible to construct.
In this work we propose a new operation scenario to use the NBI with the beam energy of \( \sim 1.5 \text{ MeV} \) for both high and low-density operation regimes in FFHR.

@ In the thermally stable low density and high temperature operation, as the density is relatively as low as \( 1.9 \times 10^{20} \text{ m}^{-3} \), NBI with \( \sim 1.5 \text{ MeV} \) can be used.

@ On the other hand, as the high density inhibits the neutral beam penetration, the new operation scenario is required to access the high-density ignition regime by NBI heating with \( \sim 1.5 \text{ MeV} \).

The density is kept at the low value less than \( \sim 4 \times 10^{20} \text{ m}^{-3} \) to ensure the NBI penetration and the operating point passes near the saddle point on POPCON. Above the density, high-density ignition is accessed by alpha heating after turning off NBI using the proposed PID control.
2. NBI penetration length

The NBI penetration e-folding length is calculated by

\[ \lambda(n,T)[m] = \left[ \int_{-\frac{a}{2}}^{\frac{a}{2}} n(x)\sigma_{Yan}(n,T)dx \right]^{-1} \]

where \( \sigma_{Yan} \) is the cross section for the multi-step ionization for NBI [Yanev].

NBI penetration e-folding length for 15.7 m reactors (a=2.5m)

parabolic temperature profile \( \alpha_T=1 \).

peaked density profile with \( \alpha_n=3 \)

square root of parabolic \( \alpha_n=0.5 \)

Half penetration is possible up to \( n(0)=3\sim4\times10^{20} \text{ m}^{-3} \), ensuring NBI heating
NBI penetration e-folding length for 9 m reactor (a=1.5m)

parabolic temperature profile $\alpha_T=1$.

peaked density profile with $\alpha_n=3$

parabolic density profile with $\alpha_n=1$

Half penetration is possible up to $n(0)=3\sim4\times10^{20}$ m$^{-3}$. 
3. 0-D equations, and ignition control algorithm

\[
\frac{dn_D(0)}{dt} = (1 + \alpha_n)S_D(t) - (1 + \alpha_n)n_D(0)n_T(0)\left\langle \sigma V \right\rangle_{DT}(x) - \frac{n_D(0)}{\tau_D^*}
\]

\[
\frac{dn_T(0)}{dt} = (1 + \alpha_n)S_T(t) - (1 + \alpha_n)n_D(0)n_T(0)\left\langle \sigma V \right\rangle_{DT}(x) - \frac{n_T(0)}{\tau_T^*}
\]

\[
\frac{dn_\alpha(0)}{dt} = (1 + \alpha_n)n_D(0)n_T(0)\left\langle \sigma V \right\rangle_{DT}(x) - \frac{n_\alpha(0)}{\tau_\alpha^*}
\]

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

**Combined particle balance equations**

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

\[
\frac{df_\alpha}{dt} = (1 + \alpha_n)n_e(0)f_Df_T\left\langle \sigma V \right\rangle_{DT}(x) - \frac{f_\alpha}{\tau_\alpha^*} - \frac{f_\alpha}{n_e(0)} \left[ \frac{dn_e(0)}{dt} \right]
\]
Power balance equation

\[
\frac{dT_i(0)}{dt} = \frac{1 + \alpha_n + \alpha_{\ell}}{1.5e(f_D + f_T + 1/\gamma_i + f_\alpha)n_e(0)} \times \left[ \left\{ P_{\text{EXT}} + P_{\alpha} \right\} - \left\{ P_L + P_B + P_S \right\} \right]
\]

\[- \frac{T_i(0)}{(f_D + f_T + 1/\gamma_i + f_\alpha)} \times \left\{ 1 - 8f_o + \frac{1}{\gamma_i} - f_\alpha \right\} \frac{1}{n_e(0)} \frac{dn_e(0)}{dt} - \frac{df_\alpha(0)}{dt} \]

ISS95 scaling

\[
\begin{align*}
\tau_E[s] &= \gamma_{\text{ISS}} \tau_{\text{ISS95}}[s] = \gamma_{\text{LHD}} \times 1.6 \ \tau_{\text{ISS95}}[s] \\
\tau_{\text{ISS95}}[s] &= 0.079 \tau_{2/3}^{0.4} n_{19}^{0.51} [10^{19} \text{ m}^{-3}] B_o^{0.83} [T] \bar{a}^{2.21} [m] R^{0.65} [m] / P_{HT}^{0.59} [\text{MW}] 
\end{align*}
\]

External heating power (in thermally stable regime)

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

External heating power (in thermally unstable regime)

Preprogramming now !!
Ignition control

[1] PID fueling control by the fusion power (in thermally stable regime)

\[
S_{DT}(t) = S_{DT0} \left\{ e_{DT}(P_f) + \frac{1}{T_{int}} \int_{0}^{t} e_{DT}(P_f) dt + T_d \frac{de_{DT}(P_f)}{dt} \right\} G_{fo}(t)
\]

The error of the fusion power: \( e_{DT}(P_f) = + (1 - P_f / P_{f0}) \)

\( T_{int} \) the integration time, \( T_d \) the derivative time.

[2] PID fueling control by the density (in thermally stable regime) (for testing control characteristics)

\[
S_{DT}(t) = S_{DT0} \left\{ e_{DT}(n) + \frac{1}{T_{int}} \int_{0}^{t} e_{DT}(n) dt + T_d \frac{de_{DT}(n)}{dt} \right\} G_{fo}(t)
\]

The error of the density: \( e_{DT}(n) = + (1 - n_e(t) / n_{set}) \)

[3] PID fueling control by the fusion power (in thermally unstable regime)

The error of the fusion power: \( e_{DT}(P_f) = -(1 - P_f / P_{f0}) \)
Machine parameters

[1] Commercial reactor FFHR2m2: (Full blanket module)

\[ R=15.7\, m, \quad a=2.5\, m, \quad P_f=3 \, GW, \quad \eta_\alpha=0.98, \quad <B>=4.5T, \quad \tau_\alpha*/\tau_E=4, \, 1.5\text{MeV NBI} \]

Thermally stable regime:  \( \alpha_n=0.5, \quad \alpha_T=1.0, \quad \gamma_{\text{ISS}}=1.92 \sim 1.6 \)

Thermally unstable regime:  \( \alpha_n=3, \quad \alpha_T=1.0, \quad \gamma_{\text{ISS}}=1.43 \sim 1.6 \)

[2] Experimental helical reactor FFHR-C, close to ARIES-CS. (For testing ignition. Partial blanket and shield: the blanket is only placed on the outboard side and the shield is placed in the inboard side).

\[ R=9\, m, \quad a=1.5\, m, \quad P_f=1.1 \, GW, \quad \eta_\alpha=0.98, \quad <B>=7.0T, \quad \tau_\alpha*/\tau_E=4, \, 1.0\text{MeV NBI} \]

Thermally stable regime:  \( \alpha_n=1.0, \quad \alpha_T=1.0, \quad \gamma_{\text{ISS}}=1.92 \sim 1.6 \)

Thermally unstable regime:  \( \alpha_n=3, \quad \alpha_T=1.0, \quad \gamma_{\text{ISS}}=1.4 \sim 1.6 \)
### TABLE I: Plasma parameters at the stable and unstable operating points in FFHR2m2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Stable operating point</th>
<th>Unstable operating point</th>
<th>Parabolic profile</th>
<th>Peaked profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius R (m)</td>
<td>15.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective minor radius a (m)</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polarity/Field period r (m)</td>
<td>2/10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil pitch parameter γ</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume averaged magnetic field B (T)</td>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum magnetic field B_{max} (T)</td>
<td>12.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil magnetic energy W_{c} (GJ)</td>
<td>160</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blanket thickness ΔH(m)</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational transform τ_v,σ</td>
<td>0.92</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum NBI heating power P_{NI} (MW)</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confinement factor over ISS95 scaling n_{95} (Minimum)</td>
<td>1.92 (1.85)</td>
<td>1.43 (1.43)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confinement time ( \tau_c ) (s)</td>
<td>2.3</td>
<td>5.6</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>Helium ash fraction ( \tau_\alpha )</td>
<td>0.041</td>
<td>0.04</td>
<td>0.045</td>
<td></td>
</tr>
<tr>
<td>Oxygen impurity fraction ( \tau_\delta )</td>
<td>0.0075</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective ion charge Z_{eff}</td>
<td>1.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>He ash confinement time ratio ( \tau_\alpha )</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel particle confinement time ratio ( \tau_\delta )</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fusion alpha heating efficiency ( \eta_\alpha )</td>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation density ( \rho(0) ) (10^{23} m^{-3})</td>
<td>1.8</td>
<td>4.5</td>
<td>8.4</td>
<td></td>
</tr>
<tr>
<td>Density limit factor over Sudo scaling ( \rho_{Sudo} )</td>
<td>1.5</td>
<td>7.5</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>Density limit margin in the steady state ( \rho_{lim}/\rho(0) )</td>
<td>1.24</td>
<td>1.75</td>
<td>1.41</td>
<td></td>
</tr>
<tr>
<td>Ion temperature ( T_e(0) ) (keV)</td>
<td>17.8</td>
<td>8.5</td>
<td>7.1</td>
<td></td>
</tr>
<tr>
<td>Ion to electron temperature ratio ( T_e/T_i )</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density profile ( \rho_i )</td>
<td>0.5</td>
<td>3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature profile ( \rho_\alpha )</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beta value ( \beta% )</td>
<td>4.9</td>
<td>5.7</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>Plasma energy ( W_e (GJ) )</td>
<td>1.150</td>
<td>1.352</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>Fusion power ( P_f (MW) )</td>
<td>0.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutron power ( P_n (MW) )</td>
<td>2400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alpha heating power ( P_\alpha (MW) )</td>
<td>600x0.96=588</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bremsstrahlung power ( P_B (MW) )</td>
<td>87</td>
<td>345</td>
<td>348</td>
<td></td>
</tr>
<tr>
<td>Synchrotron radiation power ( P_s (MW) )</td>
<td>4.2</td>
<td>0.9</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Plasma conduction loss ( P_L (MW) )</td>
<td>497</td>
<td>2.40</td>
<td>2.40</td>
<td></td>
</tr>
<tr>
<td>Electric power output (thermal efficiency) ( P_e (MW) )</td>
<td>1000(33%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutron wall loading ( \Gamma_n (MW/m^2) )</td>
<td>1.48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat flux to first wall ( \Gamma_1 (MW/m^2) )</td>
<td>0.056</td>
<td>0.21</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>Heat flux to divertor for 0.1 m wet width (90 degree, ( P_e &gt;2.5x10^{-2} )) ( \Gamma_{w1} (MW/m^2) )</td>
<td>25.0</td>
<td>12.1</td>
<td>12.2</td>
<td></td>
</tr>
</tbody>
</table>
4. Thermally stable ignition regime accessed by NBI in FFHR2m2

During the access to the thermally stable low density and high temperature operation regime, NBI heating has not any problems due to the relatively low-density.

Heating power 40 MW, $\gamma_{\text{ISS}}=1.92$ ($\gamma_{\text{LHD}}=1.2$)
\[ n(0) \approx 1.83 \times 10^{20} \text{ m}^{-3}, \quad T(0) \approx 17.8 \text{ keV}, \quad \Gamma_n \approx 1.5 \text{ MW/m}^2. \]

$\langle \beta \rangle \approx 4.9 \%$

Beam penetration length $\lambda / a \approx 0.7$. 

Operating point at the stable boundary

$P_f=3.0 \text{ GW}$
5. The high-density ignition regime accessed by NBI in FFHR2m2

Density control for NBI: The density linearly increases from $n(0)=2.0 \times 10^{20}$ to $3.0 \times 10^{20}$ m$^{-3}$ by the density control algorithm.

$\gamma_{iss}=1.43, \ B=4.5T, \ \alpha_n=3, \ \alpha_T=1.0, \ \tau_E=4.3 \ s, \ E=1.5 \ MeV \ TanNBI,$

$n(0)=8.37 \times 10^{20} \ m^{-3}, \ T(0)=7.1 \ keV, \ \langle \beta \rangle=4.49 \%, \ \ P_{div}=12.2 \ MW/m^2 \ (90^\circ \Delta=0.1 \ m)$
Sudden increase in the confinement factor near the saddle point brings the operation into a dangerous situation when the density control is used. After 30 s (which is 5 s before the switching to the fusion power control), the confinement factor is artificially increased by a step manner from 1.43 to 1.6.

Fusion power surge to 3.5 GW $\rightarrow$ Unlimited fueling in the Pf-control phase quenches the ignition.
Sudden increase in the confinement factor near the saddle point brings the operation into a dangerous situation when the density control is used.

Limited fueling $S_{DT} < 2 \times 10^{19} \text{ m}^{-3}/\text{s}$ in the Pf-control phase leads to the excessive fusion power such as $\sim 8 \text{ GW}$. $\rightarrow$ (Thermal runaway)
On the other hand, when the confinement factor is suddenly decreased by a step manner from 1.43 to 1.3 (30-35s) near the saddle point during the density control, the discharge terminates.

\[\text{safe shutdown.}\]
The fusion power control should be employed from the initial phase to avoid this dangerous situation (thermal runaway).

\[ \gamma_{\text{ ISS}} = 1.43, \quad B = 4.5 \, \text{T}, \quad \alpha_n = 3, \quad \alpha_T = 1.0, \quad E = 1.5 \, \text{MeV TanNBI}, \]

\[ n(0) = 8.40 \times 10^{20} \, \text{m}^{-3}, \quad T(0) = 7.1 \, \text{keV}, \quad <\beta> = 4.5 \, \%, \quad P_{\text{div}} = 12.1 \, \text{MW/m}^2 \quad (90^\circ \Delta = 0.1 \, \text{m}) \]

Fusion power is carefully controlled to keep the density at the low around \(2 \sim 3 \times 10^{20} \, \text{m}^{-3}\) to ensure the NBI penetration.
This unstable control algorithm is robust to the confinement factor disturbance.

[1] Even when the confinement factor is increased from $\gamma_{\text{ISS}}=1.43$ to 1.6 during 40 to 60 s, the fusion power is well controlled.

$\gamma_{\text{ISS}}=1.43, \cdots \rightarrow 1.6 \ (40-60\text{s}), \quad B=4.5\text{T}, \quad \alpha_n=3, \ \alpha_T=1.0, \quad E=1.5\text{MeV} \ \text{TanNBI},$

Sudden increase in the confinement factor $\rightarrow$ stable operation.
Density increases due to the too much heating power.
When the confinement factor is decreased by a step manner from 1.43 to 1.3 during 40 and 60 s, the fusion power decreases and then the discharge terminates, leading to the safe shutdown. → Proper feedback control method of heating power should be developed

\[ \gamma_{\text{ISS}} = 1.43 \rightarrow 1.3 \text{ (40-45s),} \quad B = 4.5 \text{T, } \alpha_n = 3, \alpha_T = 1.0, \quad E = 1.5 \text{MeV TanNBI}, \]
E=1.0 MeV NBI can also be used in 15.7 m reactor.

$$\gamma_{\text{iss}}=1.43, \ B=4.5 \text{T}, \ \alpha_n=3, \ \alpha_T=1.0, \ E=1.0 \text{ MeV TanNBI},$$

$$n(0)=8.40 \times 10^{20} \text{ m}^{-3}, \ T(0)=7.1 \text{ keV}, \ <\beta>=4.5 \%, \ P_{\text{div}}=12.1 \text{MW/m}^2 \ (90^\circ \Delta=0.1 \text{m})$$

By careful preprogramming, 1 MeV NBI can be used to access the high-density operation.
6. The stable ignition regime accessed by NBI in FFHR-C (R=9m,1.5m)

\[ \alpha_n = 1, \ \alpha_T = 1, \ \gamma_{iss} = 1.8, \ \tau_\alpha^*/\tau_E = 4, \ \gamma_{ISS} = 1.8 \]

\[ P_f = 1.1 \text{ GW} \ (P_n = 1.55 \text{ MW/m}^2), \ \tau_E = 1.7 \text{ s}, \ 1 \text{ MeV TanNBI} \]

\[ n(0) = 3.56 \times 10^{20} \text{ m}^{-3}, \ T(0) = 13.5 \text{ keV}, \ <\beta> = 2.6 \%, \ P_{\text{div}} = 15.2 \text{ MW/m}^2 \ (90^\circ \Delta = 0.1 \text{ m}), <B> = 7 \text{ T} \]

- Reaching ignition is possible but the magnetic field of 7 T (the volume averaged) is needed.
- 1 MeV NBI is enough for heating for the low density and high temperature operation.
7. The high-density ignition regime accessed by NBI in FFHR-C(R=9m,1.5m)

\[ \alpha_n=3, \quad \alpha_T=1, \quad \gamma_{iss}=1.4, \quad \tau_{\alpha}/\tau_E=4, \quad P_f=1.1 \text{ GW} \quad (P_n=1.55 \text{ MW/m}^2), \quad \tau_E=2.16 \text{ s}, \quad 1 \text{ MeV TanNBI} \]

\[ n(0)=9.23 \times 10^{20} \text{ m}^{-3}, \quad T(0)=7.95 \text{ keV}, \quad <\beta>=2.3 \%, \quad P_{\text{div}}=11.0 \text{ MW/m}^2 \quad (90^\circ \Delta=0.1 \text{ m}), \quad <B>=7 \text{ T} \]

1 MeV NBI is enough for high-density ignition access.
8. Summary and further challenge:

We have studied how to use NBI heating in FFHR helical reactors.

[1] From a safe operating point view, the density control should not be used especially near the saddle point on POPCON. It can be used only in the initial phase far from the saddle point.

[2] Fusion power control is important to stabilize the thermal instability, and it should be used before over-passing the saddle point. It should be also carefully preprogrammed to have a low density for NBI penetration. After over-passing the saddle point on POPCON, NBI heating power can be switched off, leading to ignition by alpha heating power. It is also robust to the parameter changes. But the feedback control of the heating power is desirable.

[3] As the NBI energy less than 1.5 MeV would also bring high-density ignition in the FFHR fusion ignition experimental (FFHR-C) and commercial reactor (FFHR2m2), the near term NBI technology could be utilized for proposed helical reactors.

Further big challenge:

To overcome the parameter changes during the ignition access, feedback control of the heating power should be invented.