Ignition access by NBI heating in FFHR

US-Japan Fusion Power Plant studies
2010.2.23-24
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1. Purpose

In a high-density operation, a big issue is what kind of heating system can be used.

Here, we propose the new operation scenario using NBI heating system. In a lower density regime, NBI heating is applied. Once the ignition is accessed, alpha-heating power increases the density and then we approach the final low temperature and high-density ignition point.
## Comparison of the thermally unstable and stable operation

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2. NBI penetration length

[1] Perpendicular injection

Beam flux: \( I_{\text{flux}} = nU \),

\[
\frac{dI(r)}{dx} = -n(r)\sigma_{\text{Yan}}(n,T)I(r)
\]

Solved flux:

\[
I_{\text{pen}}(r) = I_{in}\exp\left(-\int_{-a}^{r} n(r)\sigma_{\text{Yan}}(n,T)dr\right)
\]

Heating power and flux:

\[
P_{\text{NBI}} = I_{b} V_{\text{NBI}} = (nqU_{b}S) V \propto nU_{b} V_{\text{NBI}} = I_{\text{flux}} V_{\text{NBI}}
\]

Absorbed heating power:

\[
P_{\text{abs}}(2a) = P_{\text{in}} - P_{\text{pen}} = P_{\text{in}} \left[ 1 - \exp\left(-2a\int_{-1}^{0} n(x)\sigma_{\text{Yan}}(n,T)dx\right) \right]
\]

Compared to

\[
P_{\text{abs}} = P_{\text{in}} \left[ 1 - \exp\left(-\frac{2a}{\lambda(n,T)}\right) \right]
\]

NBI penetration length:

\[
\lambda(n,T)[m] = \left[ \int_{-1}^{0} n(x)\sigma_{\text{Yan}}(n,T)dx \right]^{-1}
\]

Here, mainly perpendicular injection is considered.
[2] Tangential injection to reduce the shine-through

The density profile along the tangential direction

\[
n(y) = n(0) \left\{ 1 - \left( \frac{\sqrt{R_{\text{tan}}^2 + y^2} - R_o}{a^2} \right)^2 \right\}^{\alpha_n}
\]

\[
T(y) = T(0) \left\{ 1 - \left( \frac{\sqrt{R_{\text{tan}}^2 + y^2} - R_o}{a^2} \right)^2 \right\}^{\alpha_T}
\]

\[
y_{\text{max}} = \sqrt{(R_o + a)^2 - R_{\text{tan}}^2}
\]

Absorbed heating power:

\[
P_{\text{abs}}(2y_{\text{max}}) = P_{\text{in}} \left[ 1 - \exp \left( -2 \int_{-y_{\text{max}}}^{0} n(y)\sigma_{\text{Yan}}(n,T)\,dy \right) \right]
\]
2.2. NBI penetration length using the multi-step ionization
(Yanev formula)

\[
\sigma_{Yan} \left[ \text{cm}^2 \right] = \frac{10^{-16} \exp(S_1)}{E_{NBI}} \left( 1 + \frac{n_\alpha}{n_e} Z_\alpha (Z_\alpha - 1) S_{Z_\alpha} + \frac{n_{Be}}{n_e} Z_{Be} (Z_{Be} - 1) S_{Z_{Be}} \right)
\]

\[ S_1 = \]
\[ + \left\{ A_{111} + A_{112} (\ln T_e) \right\} \]
\[ + \left\{ A_{121} + A_{122} (\ln T_e) \right\} \{ \ln (n_e / n_o) \} \]
\[ + \left\{ A_{131} + A_{132} (\ln T_e) \right\} \{ \ln (n_e / n_o) \} \]
\[ + \left\{ A_{211} + A_{212} (\ln T_e) \right\} \{ \ln E_{NBI} \} \]
\[ + \left\{ A_{221} + A_{222} (\ln T_e) \right\} \{ \ln E_{NBI} \} \{ \ln (n_e / n_o) \} \]
\[ + \left\{ A_{231} + A_{232} (\ln T_e) \right\} \{ \ln E_{NBI} \} \{ \ln (n_e / n_o) \} \]

\[ S_{Z_\alpha} = \]
\[ + \left\{ B_{111q} + B_{112q} (\ln T_e) \right\} \]
\[ + \left\{ B_{121q} + B_{122q} (\ln T_e) \right\} \{ \ln (n_e / n_o) \} \]
\[ + \left\{ B_{211q} + B_{212q} (\ln T_e) \right\} \{ \ln E_{NBI} \} \]
\[ + \left\{ B_{221q} + B_{222q} (\ln T_e) \right\} \{ \ln E_{NBI} \} \{ \ln (n_e / n_o) \} \]
\[ + \left\{ B_{311q} + B_{312q} (\ln T_e) \right\} \{ \ln E_{NBI} \} \]
\[ + \left\{ B_{321q} + B_{322q} (\ln T_e) \right\} \{ \ln E_{NBI} \} \{ \ln (n_e / n_o) \} \]

*****HHHHHHHHHHH (Yanev)***********************

A211=2.30E-01 : A212=-1.15E-02 : A221=-2.55E-03 : A222=-6.20E-04 A231=1.32E-03 : A232=3.38E-05

He impurities :
B111=-2.36 : B112=1.85E-01 : B121=2.5E-01 : B122=-3.81E-02
B211=8.49E-01 : B212=-4.78E-02 : B221=6.77E-02 : B222=1.05E-02
B311=-5.88E-02 : B312=4.34E-03 : B321=-4.48E-03 : B322=-6.67E-04
2.3. NBI penetration length for $E_{NBI}=1$ MeV (planned for ITER)

In a high density operation we assume the peaked profiles: $\alpha_n=3$, $\alpha_T=1$, He impurity, $Z_{eff}=2$

\[ n(x) = (n(0)-n_{B0}) (1-x^2)^3+n_{B0} : \quad n(0)=2 \times 10^{20} \text{ m}^{-3}, \quad n_{B0}=1 \times 10^{19} \text{ m}^{-3} \]
\[ T(x) = (T(0)-T_{B0}) (1-x^2)^3+T_{B0} : \quad T(0)=8 \text{ keV}, \quad T_{B0}=100 \text{ eV} \]

Penetration length is sensitive to the impurity.

$\lambda = 1.37 \text{ m (} Z_{eff}=2), \quad \lambda = 1.78 \text{ m (} Z_{eff}=1.5) \]
2.4. Density dependence of the penetration length

Yanev paper: NBI heating needs $\lambda/a > 0.25$.

To reach $\lambda = a = 1.5\,\text{m}$

@ For 1 MeV :
\[ n(0) \leq 2.4 \times 10^{20}\,\text{m}^{-3} \]

@ For 2 MeV :
\[ n(0) \leq 3.8 \times 10^{20}\,\text{m}^{-3} \]

To reach $\lambda = a = 2.5\,\text{m}$

@ For 1 MeV :
\[ n(0) \leq 1.4 \times 10^{20}\,\text{m}^{-3} \]

@ For 2 MeV :
\[ n(0) \leq 2.4 \times 10^{20}\,\text{m}^{-3} \]
2.5. Surveyed parameters:

[1] R=15.2 m commercial reactor: \( a_{\text{eff}} = 2.51 \text{m}, B_0 = 4.5 \text{T}, \eta_\alpha = 0.98, \tau_p*/\tau_E = 3, \tau_\alpha*/\tau_E = 4, \)

Fusion power: 3.0 GW

ISS95 scaling: In the thermally stable regime: \( \gamma_{\text{ISS}} = 1.92 \ (\gamma_{\text{LHD}} = 1.2) \)
In the thermally unstable regime: \( \gamma_{\text{ISS}} = 1.6 \ (\gamma_{\text{LHD}} = 1.0) \)

[2] R=9 m experimental reactor, \( a_{\text{eff}} = 1.5 \text{ m}, B_0 = 6.0 \text{ T}, \eta_\alpha = 0.98, \tau_p*/\tau_E = 3, \tau_\alpha*/\tau_E = 4, \)

Fusion power: 0.8 ~ 1.1 GW

ISS95 scaling: In the thermally stable regime: \( \gamma_{\text{ISS}} = 2.16 \ (\gamma_{\text{LHD}} = 1.35) \)
In the thermally unstable regime: \( \gamma_{\text{ISS}} = 1.6 \ (\gamma_{\text{LHD}} = 1.0) \)

Magnet stored energy \([160 \text{ GJ}(9/16)^3 = 28 \text{ GJ}]\) is smaller than ITER
3. \( R=15.2 \text{ m commercial reactor (} P_f=3 \text{ GW}) \)

[3-1] \( 15.2/2.51 \text{m, } \) Stable regime, \( \alpha_n=0.5, \alpha_T=1, \gamma_{ISS}=1.92, B_o=4.5T \)

\( n(0)=1.83\times10^{20} \text{ m}^{-3}, T(0)=18.0 \text{ keV}, \langle \beta \rangle=5.03\%, f_\alpha=5.0 \%, Z_{eff}=1.5, \tau_E=2.28 \text{ s}, \Gamma_n=1.53 \text{ MW/m}^2, \Gamma_{\text{div}}=26 \text{ MW/m}^2 \) (10cm width at the right angle to the magnetic field line)

High temperature, low density operation of \( n(0)<2\times10^{20} \text{ m}^{-3}, 1 \text{ MeV NBI is enough for heating.} \)

@\( E_{\text{NBI}}=1\text{MeV} : \lambda=1.78 \text{m, } \lambda/a=0.71 \)
Thermally unstable regime ($\alpha_n=3$, $\alpha_T=1$, $\gamma_{ISS}=1.6$, $B_o=4.5T$)  

$E_{\text{NBI}}=2\text{MeV}$: $n(0)=2.5\sim 4\times 10^{20} \text{ m}^{-3}$,  
$P_f=3.0 \text{ GW}$: $n(0)=9.25\times 10^{20} \text{ m}^{-3}$, $T(0)=6.8 \text{ keV}$, $<\beta>=4.73\%$, $f_\alpha=5.4 \%$, $Z_{\text{eff}}=1.53$, $\tau_E=6.0 \text{ s}$,  
$\Gamma_{\text{div}}=9 \text{ MW/m}^2$, $\Gamma_n=1.5 \text{ MW/m}^2$, $\Gamma_{\text{heat}}=0.26 \text{ MW/m}^2$,  

Ignition access during the density control of $n(0)=2.5 \sim 4\times 10^{20} \text{ m}^{-3}$.  

2MeV, 50 MW  
@$4\times 10^{20} \text{ m}^{-3}$:  
2MeV : $\lambda=1.42\text{m}$, $\lambda/a=0.57$
[3-3] Lower NBI energy:

\[ E_{\text{NBI}} = 1.5 \text{ MeV, } n(0) = 1.5 \sim 2.72 \times 10^{20} \text{ m}^{-3} (t = 35 \text{s}) \]

Shine-through power
Early switch off of the NBI heating power: if the second density is reduced.

\[ E_{\text{NBI}} = 1.5 \text{ MeV}, \quad n(0) = 1.5 \sim 2.3 \times 10^{20} \text{ m}^{-3} (t=35s) \]
Tangential injection:

$E_{\text{NBI}} = 1.5 \text{ MeV}, \ n(0) = 1.5 \sim 2.3 \times 10^{20} \text{ m}^{-3} (t=35\text{s})$

$\Rightarrow$ Reduction in the shine-through power.

$\Rightarrow$ Single NBI energy system may be enough
[3-6] $E_{\text{NBI}}=1.0$ MeV perpendicular injection may be possible:

$$n(0)=1.5 \sim 2.45 \times 10^{20} \text{ m}^{-3}(t=35\text{s})$$

It may be possible to use 1MeV NBI injection at $2.45 \times 10^{20} \text{ m}^{-3}$:

1 MeV: $\lambda/a > 0.5-0.6$

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Operating point at the unstable boundary
$\beta=4.73\%$

$P_f=3.0\text{GW}$

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"SSDT"
4. R=9m experimental reactor (R=9.0 m, a_{eff}=1.5m)

Thermally stable regime with $\alpha_n=1$ and $\alpha_T=1$: $E_{\text{NBI}}=1.0$ MeV

Minimum fusion power $P_f=0.8$ GW, $B_0=6.0$ T, $\gamma_{\text{ISS}}=2.16(\gamma_{\text{LHD}}=1.35)$, $\tau_p^*/\tau_E=3$, $\tau_\alpha^*/\tau_E=4$, $\eta_\alpha=0.98$, Density limit factor of 1.5, $n(0)=3.0 \times 10^{20}$ m$^{-3}$, $T_i(0)=13.6$ keV, $f_\alpha=3.7\%$, $<\beta>=2.9\%$ (at 200s) $\tau_E=1.98$ s, $\Gamma_{\text{div}}=11.1$ MW/m$^2$ (10cm width at the right angle to the magnetic field line), $\Gamma_n=1.1$ MW/m$^2$, $\Gamma_{\text{heat}}=0.054$ MW/m$^2$

As the density is lower than $3.0 \times 10^{20}$ m$^{-3}$, 1MeV NBI is enough. $P_{\text{EXT}}=30$ MW
[4.2] Thermally unstable regime with the peaked profile of $\alpha_n=3$ and $\alpha_T=1$, $\gamma_{\text{ISS}}=1.6$ ($\gamma_{\text{LHD}}=1$), $B_0=6.0$ T, $\tau_p*/\tau_E=3$, $\tau_{\alpha}*/\tau_E=4$, $\eta_\alpha=0.98$.

Density is linearly increased to $n(0)=4\times10^{20}$ m$^{-3}$.

Fusion power $P_f=1.1$ GW: $n(0)=9.38\times10^{20}$ m$^{-3}$, $T_i(0)=7.8$ keV, $f_\alpha=3.7\%$, $<\beta>=3.1\%$ (at 200s), $\tau_E=2.2$ s, $\Gamma_{\text{div}}=10.8$ MW/m$^2$, $\Gamma_n=1.5$ MW/m$^2$, $\Gamma_{\text{heat}}=0.16$ MW/m$^2$.

During the density control lower than $4\times10^{20}$ m$^{-3}$, NBI is injected. $P_{\text{EXT}}=30$ MW, $1$ MeV: $\lambda/a > 0.6$.
[4.3] Thermally unstable regime with the peaked profile of $\alpha_n=3$ and $\alpha_T=1$: $\gamma_{\text{ISS}}=1.6$ ($\gamma_{\text{LHD}}=1$), $E_{\text{NBI}}=1.0$ MeV

$P_f=1.1$ GW, Density is increased between $n(0)=2\sim 5\times 10^{20}$ m$^{-3}$:

As density is increased, then shine-through power is reduced.

$P_{\text{EXT}}=25$ MW, Temperature is always lower than 10 keV.

$1$ MeV: $\lambda/a=0.3$
[4.4] Failure mode analysis of unstable operation:
The fusion power $P_f=0.85$ GW: When the fueling is stopped accidentally, the fusion power surge usually takes place. However, if the fusion power is small as 0.85 GW, fusion power surge does not happen.

It is possible to make a fueling failure mode experiments in the experimental reactor. Safe shutdown takes place in the lower fusion power range.
5. Summary

[1] Heating issue for the high-density and low temperature operation has been solved. NBI with 1~2 MeV can be injected during the lower density operation. After entering the ignition regime by NBI during the density control, alpha-heating would increase the density using the thermally unstable control algorithm.

[2] In a R=15.2 m commercial reactor, 1.5~2 MeV NBI with 50 MW could be enough for ignition access. However, as 1 MeV can be used in the thermally stable regime, various sensitivity studies on 1 MeV NBI injection in the high density operation should be undertaken.

[3] It is possible to access ignition in the smaller R=9m experimental reactor. 1 MeV NBI is enough for access to the thermally stable and unstable operation regimes. Failure mode experiment on fueling stop is possible in this experimental reactor.

Further issues

[1] Failure mode analysis on fueling should be undertaken more actively.

[2] Further sensitivity analyses should be done for NBI heating with 1 MeV.