Study on Plasma Startup Scenario of Helical DEMO reactor FFHR-d1

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Motivation

• Primary design parameters of helical DEMO FFHR-d1 was fixed and core plasma design at its steady-state has been advanced.

• On the other hand, plasma start-up scenario needs to be examined.

• So far, systematic analysis was conducted using 0-D model proposed by Prof. Mitarai.
  - Proposal of start-up scenario by means of feedback control of fuelling amount and heating power by fusion output.
  - Possibility of reduction in the required maximum external heating power by extending start-up time was shown

• To confirm these results, analysis using a quasi 1-D particle balance model is conducted.

Solve density evolution by diffusion equation:

\[
\frac{\partial n}{\partial t} = D \frac{\partial^2 n}{\partial r^2} + \left( \frac{D}{r} + \frac{\partial n}{\partial r} - V \right) \frac{\partial n}{\partial r} - \left( \frac{V}{r} + \frac{\partial V}{\partial r} \right) n + S
\]

Assuming \( D(r) = D \propto \left( \frac{P_{\text{abs}}}{n_e} \right)^{0.6} B^{-0.8}, V=0 \) based on LHD experimental result.

Assuming gyro-Bohm-type parameter dependence

\[
\frac{\partial p(r)}{\partial t} = \frac{1}{\tau_E} \left( \gamma_{\text{DPE}} \hat{p}(r) P_{\text{abs}}^{0.4} B^{0.8} n(r)^{0.6} - p(r) \right)
\]

Confinement improvement \( \gamma_{\text{DPE}} \) is evaluated from heating power deposition profile. \( \hat{p}(r) \) is normalized pressure profile of LHD experiment using for extrapolation.
Model for pellet fuelling

- Assuming pellet fuelling and density source term \( S(r) \) is calculated from the pellet deposition profile and the volume enclosed by magnetic surface.
- The scale-up of the result of the finite-beta equilibrium calculation by VMEC for the extrapolated experimental profile is used.
- Pellet deposition profile is estimated by NGS model.
  \[
  \frac{\partial r_p}{\partial t} \propto f_{\text{abl}} T_e^{1.64} n_e^{1/3} r_p^{-2/3}
  \]
- Assuming adiabatic change of temperature at pellet injection.
Reproduce gyro-Bohm-type parameter dependence 
\( (W_p \propto n_e^{0.6}) \) observed in LHD experiment.
Analysis step for plasma start-up

- Considering the robustness of plasma control and the simplification of pellet fueling system, a simpler control method is preferable.
  - Begin with continuous pellet injection with a constant interval.

- As a first step, pellet injection condition which enables steady-state, self-ignition operation is examined.
  - Start with the plasma profile considered as a candidate of FFHR-d1 (extrapolation from LHD experimental data).
  - Try to find a path to self-ignition by “a series of quasi-steady-state”.
Example of calculation result

based on LHD #115787@3.9s
($R_{ax} = 3.55\text{m}, \gamma_c = 1.2, B_{ax} = 1.0\text{T}$)

Assuming perfect absorption of alpha heating power ($\eta_\alpha = 1.0$).

Simple fuelling cannot sustain plasma

\[ P_{\text{aux}} = 60 \text{MW}, \ 2 \times 10^{22}\text{particles/pellet} \]

- large fuelling: immediately exceeds edge density limit
- small fuelling: cannot sustain fusion output
- intermediate: cannot reach ignition condition

• Deeper penetration allows wider operation region.

• Fusion power strongly depends on the pellet injection interval (there is only a small window).

Application of feedback control

- Applying the same feedback control method as 0D model by Prof. Mitarai.
- PID control of fuelling amount by the deviation of fusion power from the target value:

\[ S_{DT}(t) = S_{DT0} G(t) \left( e_{DT} + \frac{1}{T_{int}} \int_0^t e_{DT} dt' + T_d \frac{de_{DT}}{dt} \right) \]

\[ e_{DT} = 1 - \frac{P_{fus}(t)}{P_{fus,target}(t)} \]

- Considering discrete fuelling amount: (0.4, 0.8, 1.2, 1.6, 2.0) × 10^{22}/shot
- No control of heating power is considered at present.

$P_{\text{fus}} = 3\text{GW}$ can be sustained with small perturbation.

PID control after $t = 2\text{s}$ with fixed interval of 200ms.

- Perturbation of fusion power is only a few %. 

$P_{\text{fus}}$ can be changed in ignition region

PID control after $t = 2s$ with fixed interval of 200ms
$P_{\text{fus}}$ can be changed to sub-ignition region with appropriate heating power.

PID control after $t = 2$ s with fixed interval of 200 ms
Summary and Future work

- Start-up scenario of helical DEMO FFHR-d1 is studied with quasi-1D particle balance model based on the DPE method (Gyro-Bohm-type parameter dependence).
- If pellet fuelling to the core region ($\rho \sim 0.3$) is possible, fusion power can be controlled by a relatively simple way, i.e., change in the size or injection interval.
- Optimization of start-up scenario is being conducted:
  - Detailed examination in the case of shallow deposition
  - Establishment of feedback control method of heating power
- Refinement of physics model is also needed:
  - Effect of the heating power deposition profile
  - Change in the plasma geometry with the increase of beta