Study of NBI plasma start-up assisted by seed-plasma generation using non-resonant microwave heating in Heliotron J


1 Institute of Advanced Energy, Kyoto Univ., Uji, Kyoto 611-0011, JAPAN
2 Graduate School of Energy Science, Kyoto Univ., Uji, Kyoto 611-0011, JAPAN
3 National Institute for Fusion Science, Toki, Gifu 509-3292, JAPAN
4 e-mail: kobayashi@iae.kyoto-u.ac.jp
5 28th IAEA Fusion Energy Conference, 2021/May/10-15, Online

Background & Objectives

- Rapid/robust plasma startup is common issue in Torus devices.
- In LHD and W7-X, plasma startup by NBI alone has been demonstrated ([0. Kaneku, N, 1999 and W. Ott, N, 2002]).
- In Heliotron J, due to limit of NBI pulse width (~0.2c) and device size (Edge-t=2.2m), plasma initiation by NBI alone has not been achieved yet.
- NBI plasma startup method can be established using pre-ionization technique with non-resonant and low power microwave injection ([Kobayashi, NF, 2001]).

Characteristics of seed plasmas have been investigated ([Kobayashi, PPCF 2020]):
- Existence of MeV-class high energy relativistic electrons produced by non-resonant heating is essential to produce the seed plasma.
- Seed plasma density more than ~1 x 10^19 m^-3 was formed, resulting a rapid startup (f < 50 ms) in the low NBI power (5-15 kW) condition.
- Steady-state condition ([Kobayashi, NF, 2001]) is used condition to explain the mechanism.

In this study, we clarify role of the pre-ionization in the assistance of NBI startup.
- Separate physics of plasma startup until burn through and plasma expansion without consideration of boundary effects of open magnetic field lines discussed in Tokamak startup.
- Studied experimentally characteristics of seed plasmas on NBI startup.
- Compared 0-D model analysis developed in previous work ([Hada, ISIJ2015]).

Heliotron J device and apparatus

- Key: L=2.0T, 1.8T helical coil.
- Relativistic electrons are well confined in vacuum magnetic field.
- BNI: 300A, 17cm (16 cm, 17 cm)
- 2.45 GHz; 20 kW (TE10 mode)
- Gas: D2 (ppm), H2 (ppm)
- Temperature of relativistic electrons with ion energy (eV, GeV)
- Three sets of scintillator LaF3(Ca)
- Energy calibration by °C/Cr

Typical waveform of plasma startup by NBI

1. Seed plasma generation phase
- 13 kW, 2.45 GHz O-mode w/o pre-ionization
- Density of ~10^19 m^-3
- Observed strong radiator (7GHz) instability.
- Switch on time (~10-20 s)
- Expected MeV high energy electrons
- Significant CIII intensity, but low OV
- Balance between CIII and OV generation.
- Density evolution by NBI:
  - Inducing T_e upwards, radiation barrier
  - Occurred burn-through for low T_e, imp.
  - Observed edge AXUV intensity rapidly
- Plasma expansion within 10 ms
- Apparatus of D, C
- Gas fueling introduced to ~190 ms increase, m_e > 1 x 10^19 m^-3
- Advancement successful startup

2. NBI startup phase
- Balanced NBI (25A/4.1MW)
- Increase in CHL OV intensity with increasing T_e
- Relativistic electrons are well confined in vacuum magnetic field.
- BNI: 300A, 17cm (16 cm, 17 cm)
- 2.45 GHz; 20 kW (TE10 mode)
- Gas: D2 (ppm), H2 (ppm)
- Temperature of relativistic electrons
- Three sets of scintillator LaF3(Ca)
- Energy calibration by °C/Cr
- Likely L-mode transition (40ns)
- Fast heat and diffusion of electrons with decay time (ms)
- Three sets of scintillator LaF3(Ca)
- Energy calibration by °C/Cr
- NBI: 25A/4.15MW
- Pre-ionization: ~0.04-0.06 m_e
- Temperature, m_e > 1 x 10^19 m^-3
- Rapid heat of electron around 100 ms
- Thermal electron generation by NBI
- Heat and diffusion of electrons with decay time (ms)
- Three sets of scintillator LaF3(Ca)
- Energy calibration by °C/Cr

Critical seed plasma density for rapid startup

- Dependence of m_e on target plasma production.
- No additional fueling during 2.45GHz launch.
- Clear critical density for rapid (~300 ms) NBI startup.
- Even in the condition that the density close to critical condition, gas-wall condition affects NBI plasma startup.

0-D model analysis for NBI startup reveals role of seed plasmas

0-D model analysis for NBI startup

- Solve time derivative particle/energy balance Eqs.
- Particle balance Eq.
  - Beam ion (H2)
  - Molecules (H2, D2)
  - Molecular ions (H+D, H+D+2)
  - Alphas (H, D)
  - Bulk ions (H, D, D+2)
- Energy balance Eq.
  - Bulk ions
  - Bulk electrons
  - Assumption of \( n_e = 5 \times 10^19 \) by conduction term
  - \( \frac{dn_e}{dt} = 0 \)
- Calculation, \( m_e = 1 \times 10^{19} m^-3 \)

Comparison to Experimental result

- \( m_e = 0.04 - 0.06 m_e \)
- Rapid heat of electron around 100 ms
- Thermal electron generation by NBI
- Heat and diffusion of electrons with decay time (ms)

Power flow channels between successful and unsuccessful start-up cases

- Experimentally observed MeV class electrons & Electron acceleration simulation support stochastic acceleration
- We studied NBI start-ups assisted by pre-ionization using non-resonant 2.45 GHz microwave heating in Heliotron J.
- Developed 0-D model analysis to understand physical process.
- Physical processes of the rapid NBI start-up are summarized as follows:
  - Beam ions are produced by collisions with seed plasmas to heat electrons sufficiently.
  - Electron heating promotes dissociation/limitation of deuterium molecules, molecular ions and alphas.
  - Increase in electron density produces fast heat and heat electrons further.
  - In successful start-up cases, these processes act as a positive feedback loop.
  - Resulting the electron temperature causes radiation barrier for low T_e, imp.
  - The knowledge for NBI startup with pre-ionization will be useful to realize NBI plasma startup in the low absorption power case such as the perpendicular or divertor NBI.

Summary

- Developed 0-D model analysis to understand physical process.
- Physical processes of the rapid NBI start-up are summarized as follows:
  - Beam ions are produced by collisions with seed plasmas to heat electrons sufficiently.
  - Electron heating promotes dissociation/limitation of deuterium molecules, molecular ions and alphas.
  - Increase in electron density produces fast heat and heat electrons further.
  - In successful start-up cases, these processes act as a positive feedback loop.
  - Resulting the electron temperature causes radiation barrier for low T_e, imp.