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

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S. Kobayashi, K. Nagasaki, K. Hada[1], T. Stange[2], K. Tokuhara[1], S. Ohshima, H. Okada, T. Minami, S. Kado, H. Ohgaki, T. Kii, H. Zen, Y. Nakamura[1], A. Ishizawa[1], Y. Suzuki[3], M. Osakabe[3], T. Murase[3], Y. Kishimoto[1], S. Konoshima and T. Mizuuchi

Institute of Advanced Energy, Kyoto Univ., Uji, Kyoto 611-0011, JAPAN, [1] Graduate School of Energy Science, Kyoto Univ., Uji, Kyoto 611-0011, JAPAN
[2] Max-Planck Institute for Plasma Physics, 17491 Greifswald, Germany, [3] National Institute for Fusion Science, Toki, Gifu 509-5292, JAPAN
e-mail: kobayashi@iae.kyoto-u.ac.jp

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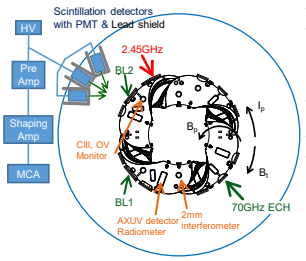
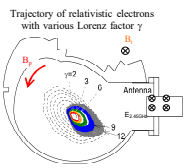
Background & Objectives

- Rapid/robust plasma startup is common issue in Torus devices.
- In LHD and W7-AS, plasma startup by NBI alone has been demonstrated [O. Kaneko, NF, 1999 and W. Ott, NF, 2002].
- In Heliotron J, due to limit of NBI pulse width (<0.2s) and device size (R/a=1.2/0.17m), 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, 2011].
- 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 4×10^{18} m^{-3} was formed, resulting a rapid start-up within 10 ms was achieved even in the low NBI power (0.3 MW) condition.
  - – Stochastic acceleration [Laqua, PPCF 2014] is one candidate to explain the mechanism.
- In this study, we clarify role of the pre-ionization in the assistance of NBI start-up
  - – Configuration of Heliotron J is formed w/o toroidal current,
  - ➢ Separate physics of plasma start-up until burn through and plasma expansion without consideration of boundary effects of open magnetic field lines discussed in Tokamak start-up
  - – Studied experimentally characteristics of seed plasmas on NBI start-up
  - ➢ Compared 0-D model analysis developed in previous work [Hada, ISHW2015].

Heliotron J device and apparatus



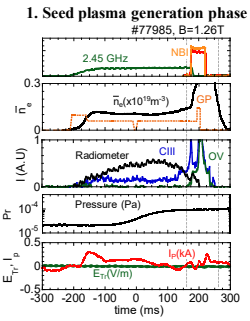
- R/a=1.2/0.16m,
- L/M=1/4 helical coil
  - ➢ Relativistic electrons are well confined in vacuum magnetic field.
- NBI: 30kV-0.8MW x 2Unit (Co, Ctr)
- 2.45 GHz: 20 kW-1sec (TE10 mode)
- Gas: D_2 (puff), H_2 (NBI)



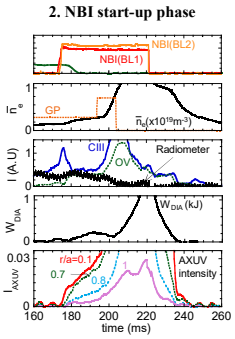
✓ Three sets of scintillator $LaBr_3$(Ce)
✓ Energy calibration by ^{60}C, ^{137}Cs

Typical waveform of plasma startup by NBI

1. Seed plasma generation phase



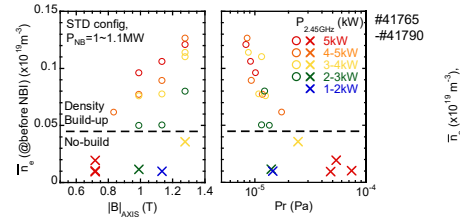
2. NBI start-up phase



- 13 kW, 2.45 GHz O-mode w/o resonances
- Density of ~ 10^{18} m^{-3}
- Observed strong radiometer (70GHz) intensity,
  - ➢ Synchrotron radiation (τ ~10^{-3})
  - ➢ Expected 3 MeV high energy electrons
- Significant CIII intensity, but low OV
  - ➢ Bulk electrons w/ energy of 30 eV < E < 80eV
- Almost zero E_{Tr}, small (< 300 A) toroidal I_p
  - ➢ Limited effect of E_{Tr} on pre-ionization
  - ➢ Small current formation by microwave

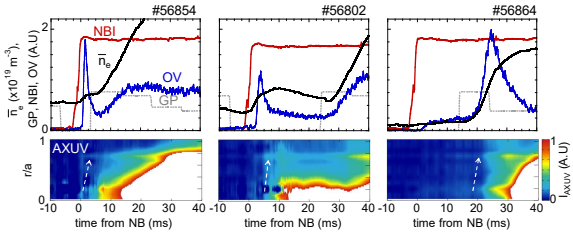
- Balanced NBI (25kV-0.3MW)
- Increase in CIII, OV intensity w/ increasing n_e
  - ➢ Density avalanche by NBI
  - ➢ Indicating T_e exceeds radiation barrier
  - ➢ Occurred burn-through for low Z imp.
- Observe edge AXUV intensity rapidly
  - ➢ Plasma expansion within 10 ms
  - ➢ Appearance of W_{DIA}
- Gas fueling intensified at t = 193 ms increase n_e more than 1×10^{19} m^{-3}
  - ➢ Achieved successful start-up

Critical seed plasma density for rapid start-up



✓ Dependence of B and $P_{2.45GHz}$ on target-plasma production
✓ No additional fueling during 2.45GHz launch
  ➔ Clear critical target density for rapid (<50ms) NBI startup.
  ➔ Target-plasma density increases with increasing B and $P_{2.45GHz}$
✓ Even in the condition that the density close to critical condition, gas/wall condition affects NBI plasma startup.

Gas fueling with proper timing promotes plasma expansion in low n_{seed} case



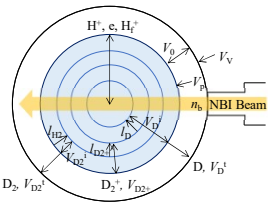
✓ In case of medium seed plasma density (n_{seed}) conditions,
  ➔ Plasma expansion can be seen even no additional gas fueling.
✓ In low n_{seed} condition, expansion was observed after additional gas fueling.
  ➔ If a sufficient seed plasma exists, the early gas fueling can promote plasma expansion with short time after NB.

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

0-D model analysis for NBI start-up

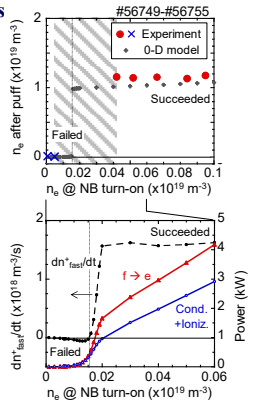
Solve time derivative particle/energy balance Eqs.

- Particle balance Eq.
  - ✓ Beam ion (H_1^+)
  - ✓ Molecules (H_2, D_2)
  - ✓ Molecular ions (H_2^+, D_2^+)
  - ✓ Atoms (H, D)
  - ✓ Bulk ions (H^+, D^+)
- Energy balance Eq.
  - ✓ Electrons (e)
  - ✓ Bulk ions
- Assumptions of
  τ_E, τ_p: 5 ms (by conduction term)
  τ_{fast}: 100 ms
- Calculate n_e up to ~ 1×10^{19} m^{-3}

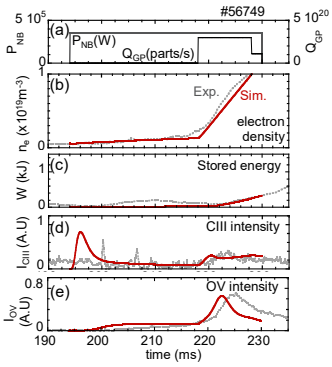


Critical seed density

- Well reproduces relation between critical density condition and n_{seed}
- dn^+_{fast}/dt just after NB injection is key parameter to decide the start-up after puff
  - ✓ If dn^+_{fast}/dt is positive, start-up is succeeded.
  - ✓ Heating power P_{heat}(f→e) overcoms P_{loss} by conduction & ionization.
  - ✓ Around critical density condition, P_{heat} increases exponentially.
  - ✓ In higher n_{seed} case, P_{heat} linearly increases with n_{seed}

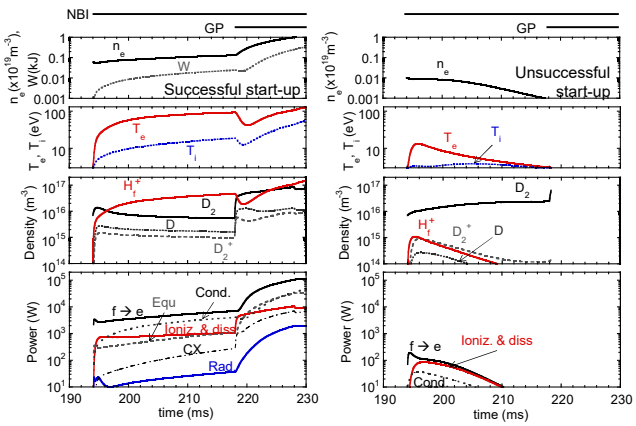


Comparison to Experimental result



- NBI: 25kV-0.35MW
- n_{seed} = 0.06×10^{19} m^{-3}, T_{seed} = 3 eV
- Well reproduces experimental observations
- Overestimation of CIII intensity at initial phase is due to assumption of T_{seed} and carbon density (set to be zero)
- Even after additional GP, n_e W_{DIA} can be reproduced well.

Power flow channels between successful and unsuccessful start-up cases

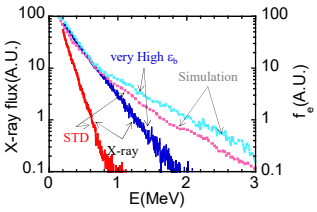


- n_{seed} of 0.06×10^{19} m^{-3}
- Rapid evolution of T_e heated by H_1^+
- Increased P_{Heat} (f → e) with time (and n_e as well)
- Promotion of electron heating leads dissoc/ioniz of D_2, D_2^+ & D.
- As a result, n_e increase promotes H_1^+ production and P_{Heat} (f → e) furthermore.
  - ➢ Positive feedback loop in case of significant n_{seed}
  - ➢ T_e exceeding radiation barrier
  - ➢ Successful start-up
- T_e is determined by balance between P_{Heat} (f → e) and conduction term.

- n_{seed} of 0.01×10^{19} m^{-3}
- H_1^+ density & T_e decreased 1ms after NB
- Not promoted dissociation of D_2
- Stop calculation since T_e < 3 eV
- Even if additional gas fuelling was not applied and NBI pulse width was extended, T_e did not increase, resulting start-up failed.

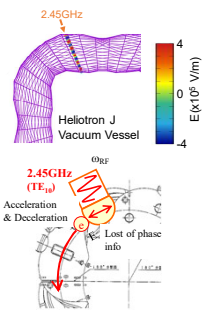
X-ray spectrum measurement reveals existence of MeV class electrons & Electron acceleration simulation support stochastic acceleration

- Experimentally observed MeV class electrons by scintillator
  - ➔ Support stochastic acceleration
  - Roughly consistent to electron acceleration simulation
  - ⇔ Difference in energy spectrum if E > 1MeV for high ε_b case
  - ⇔ For STD case, difference in slope of spectrum
  - ➢ Measured X-ray is emitted when the electrons collide with inner components in vacuum vessel.



Developed numerical calculation for electron acceleration by non-resonant microwaves

- ✓ Add acceleration term in orbit following calculation
  - Accel/Decel by E-field of microwave
- ✓ Simplified E-field spatial distribution
  - Emitted by rectangular antenna
  - Consider E-field in toroidal direction
  - Standing wave with f = 2.45 GHz
- ✓ Relativistic effect for mass of electrons
- ✓ Randomly distributed initial position
- ✓ Energy loss term only by orbit loss, collision with wall
  - Synchrotron rad. is thought to be negligible if E < 4 MeV, being proportional to E^4
  - Ignored collisions with background electrons/neutrals



Summary

- We studied NBI start-up assisted by pre-ionization using non-resonant 2.45 GHz microwave heating in Heliotron J.
- Developed 0-D model analysis to understand physical processed
  - Physical processes of the rapid NBI start-up are summarized as follows:
  1. Beam ions are produced by collisions with seed plasmas to heat electrons sufficiently
  2. Electron heating promotes dissociation/ionization of deuterium molecules, molecular ions and atoms,
  3. Increase in electron density produces fast ions and heat electrons furthermore.
     - ➢ In successful start-up cases, these processes act as a positive feedback loop
     - ➢ Resulting the electron temperature exceeds radiation barrier for low Z impurities.
- The knowledge for NBI start-up with pre-ionization will be useful to realize NBI plasma start-up in the low absorption power case such as the perpendicular or deuterium NBI.