ICRH start-up for further X3 ECRH in W7-X: minority scenario

V.E. Moiseenko on behalf of W7-X, U-2M, LHD and LPP-RMA contributors

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OUTLINE

- Opportunities to create high performance plasma with no 2nd harmonic ECRH;
- Minority ICRF plasma production scenario;
- U-2M experiments <u>with</u> minority pressure control;
- LHD experiments;
- Conclusions and future plans;
- W7-X experimental proposals.

Two promising scenarios, involving ICRH, for X3 ECRH in W7-X

- ECRH X3 damping is proportional to nT^2:
  target plasma with sufficiently high n_e and T_e required
- Two possibilities with ICRH for plasma start-up and reaching required plasma target:
  1) ICRH => ECRH X3
  2) ICRH => NBI => ECRH X3
- ECRH X3 at LHD couples to plasma with $n_e \sim 2 \times 10^{19}$ m^{-3}, $T_e \sim 600$ eV [T. Shimozuma et al, Nucl. Fusion **55** (2015) 063035] N-NBI start-up, P-NBI sustain)
- For NBI, the ‘ideal’ is the plasma with full ionization. Lower ionization degree will result in longer start-up.
- For W7-X a 1.7 T scenario is proposed which includes plasma production in helium atmosphere with a hydrogen minority at the cyclotron frequency of hydrogen f= 25 MHz.

Which plasma density is needed for fast NBI start-up?

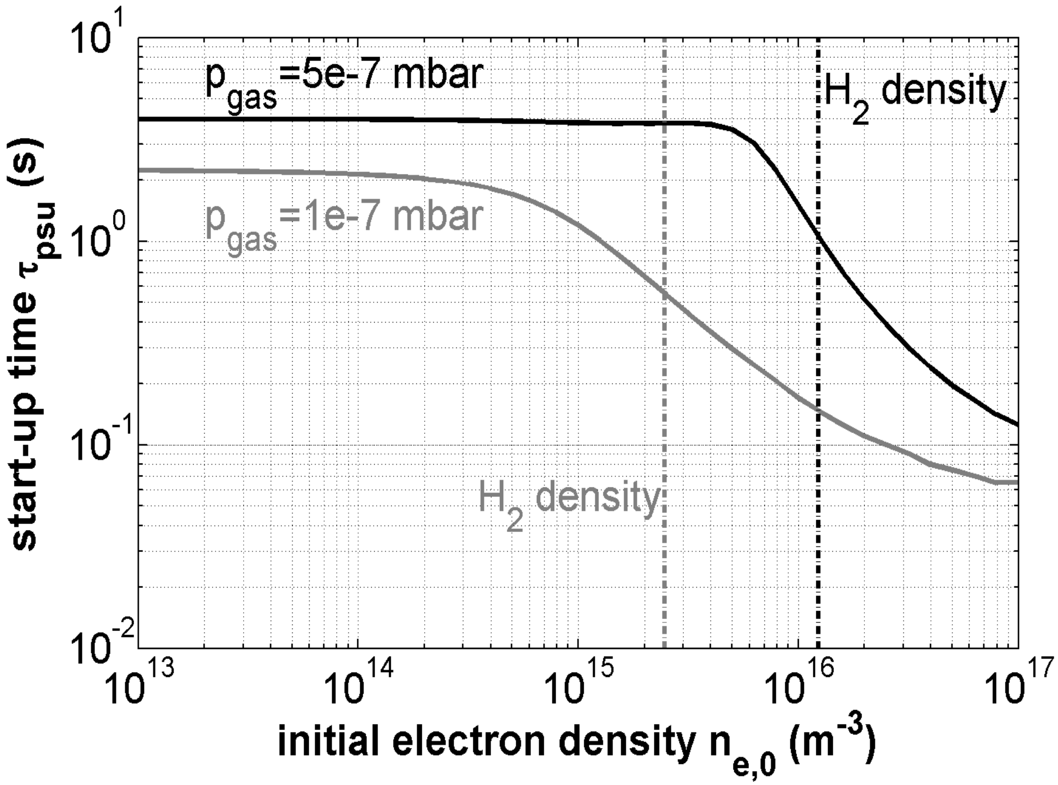


Figure 10. Start-up time (criterion: $T_e > 15\,\mathrm{eV}$) in dependence on the initial electron density, $n_{e,0}$, (the initial ion density was set equal to the electron density). The vertical lines indicate the initial neutral gas density during the simulation.

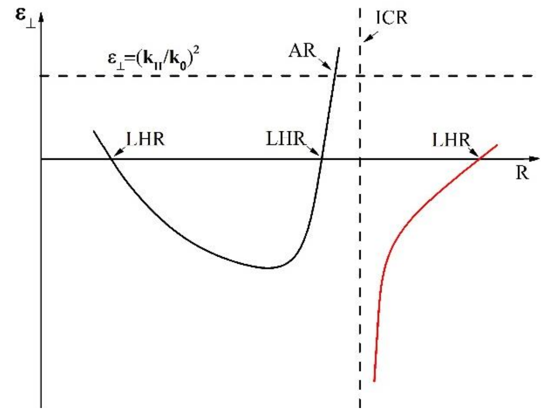
Gradic D. et al. Assessment of the plasma start-up in Wendelstein 7-X with neutral beam injection //Nuclear Fusion. – 2015. – V. 55. – №. 3. – P. 033002.

Max. NBI armor tolerance time is 0.5 s (S. Lazersson). 0.1s NBI shine-through provides low armor temperature.

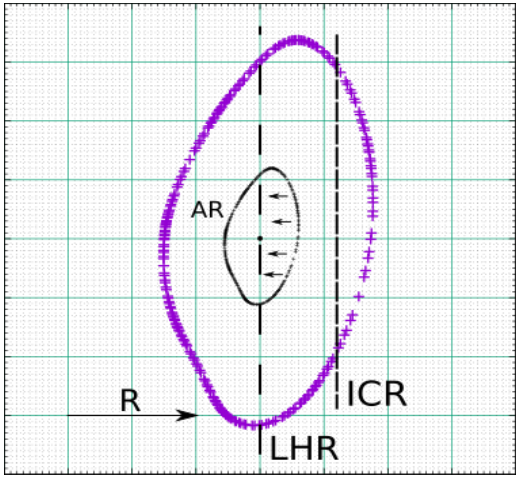
Conclusion: plasma density of $10^{17} m^{-3}$ is sufficient.

Minority ICRF plasma production scenario

- Plasma is produced by ionization by electron impact;
- Electron plasma component is heated by the slow wave;
- At low plasma densities it is heated by SW directly excited by the antenna. Since the power needed is low, good antenna coupling to the SW is not necessary;
- At higher densities, the fast wave excited by the antenna converts to the SW at the Alfven resonance layer. The SW propagates towards the lower hybrid resonance layer, where it is fully absorbed.



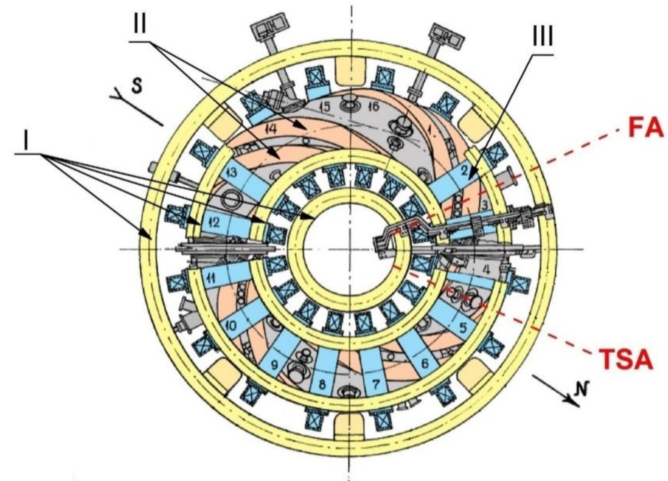
Sketch of $\varepsilon_\perp$ behavior along the major radial chord.



Sketch illustrates FMSW conversion into SW in the presence of a minority inside the plasma column.

V.E. Moiseenko, Yu. V. Kovtun, T. Wauters et al.
J. Plasma Phys. 86 (2020) 905860517

Uragan-2M



Scheme of Uragan-2M. I – Poloidal field coils; II – Helical field coils; III –Toroidal field coils numbered 1-16, FA – Frame antenna; **TSA – Two-strap antenna (W7-X – like).**

Uragan-2M:
B=0.5 T, 0.7 T tried.
Tore major radius 1.7 m
Vessel minor radius 0.34 m
K-1 generator 0.5 MW, 3-10 MHz;
K-2 generator 0.3 MW, 3-10 MHz

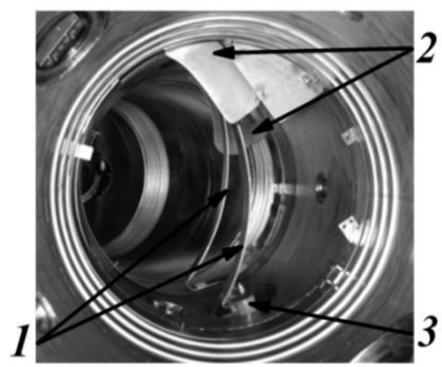
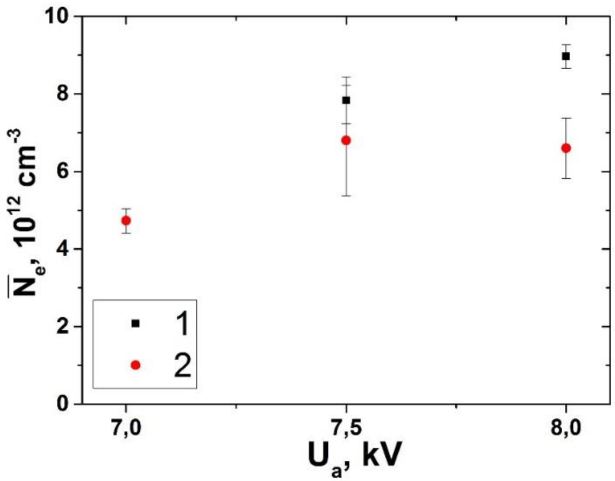


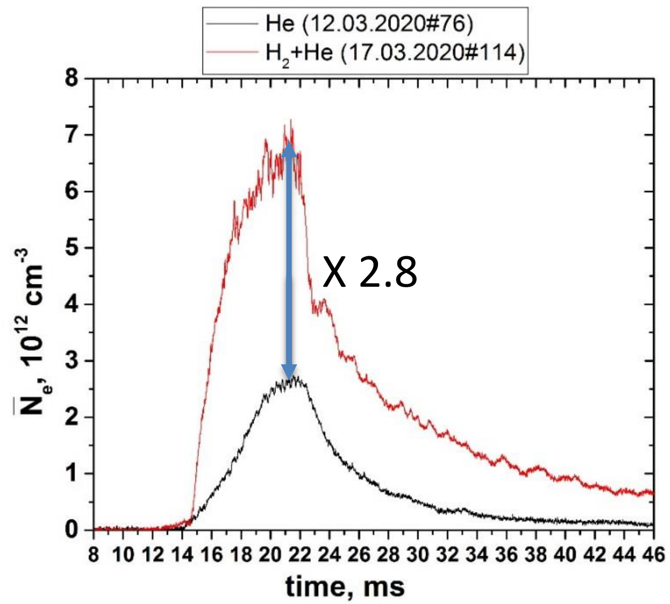
Photo of the antenna inside the U-2M device (a) and the antenna unit electric scheme (b). 1– straps, 2 – limiters from both sides of antenna, 3 – fluoroplastic isolator covered with a quartz tube

V.E. Moiseenko, Yu. V. Kovtun, T. Wauters et al.
J. Plasma Phys. 86 (2020) 905860517
A. V. Lozin, Yu. V. Kovtun, V.E. Moiseenko et al.,
Probl. At. Sci. Technol. Ser.: Plasma Phys. 6, 10 (2020).

Plasma start-up in helium–hydrogen mixtures.

He+H_2 discharge





Higher density is achieved in He/H2 mixtures at 20x lower prefill pressure.

1 – Working gas 14%H_2+86%He, p = 8.3×10^{-3} l
f = 4.9 MHz, B_0 = 0.341 T.
2 – Working gas 25%H_2+75%He, p = 5.4×10^{-3} l
f = 4.9 MHz, B_0 = 0.346 T.

Time evolutions of average plasma density for
He (**p = 0.106 Pa**, B_0=0.344 T)
and mixtures 25%H_2+75%He (**p = 5.4×10^{-3} Pa**, B_0=0.346 T).
(U_a = 7,5 kV, f = 4.9 MHz)

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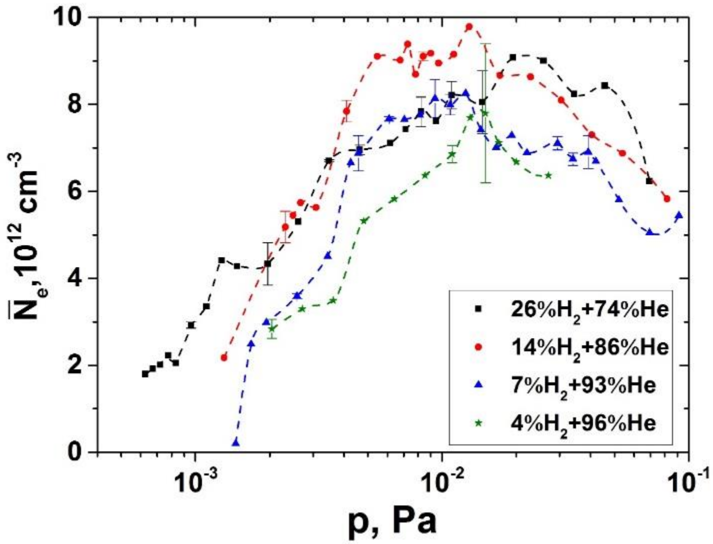
Maximum average plasma density



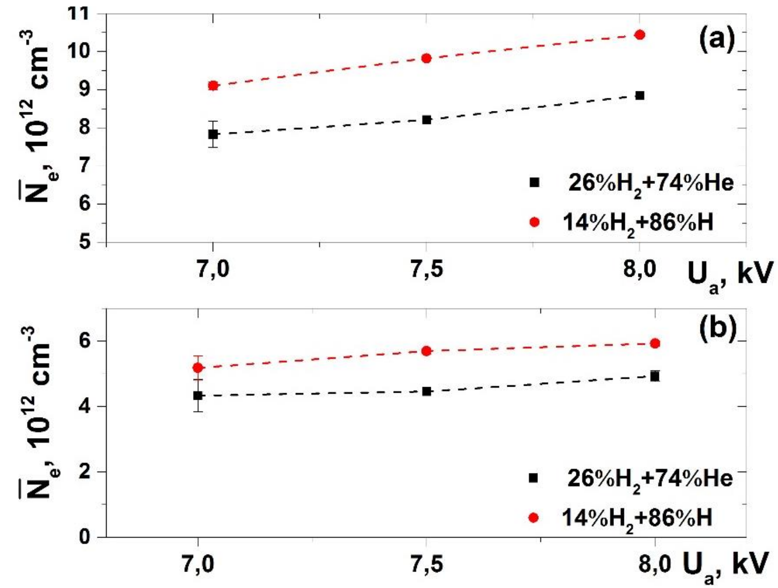
Maximum average plasma density as a function of the pressure (U_a = 7 kV, f = 4.9 MHz)

26%H_2+74%He, B_0=0.34 T.

14%H_2+86%He, B_0=0.35 T,

7%H_2+93%He, B_0=0.35 T,

4%H_2+96%He, B_0=0.344 T,



Maximum average plasma density as a function of the anode voltage on the generator K-1.

14%H_2+86%He, B_0=0.35 T, f = 4.9 МГц (p = 8.4×10^{-3} Pa, (a), p = 2×10^{-3} Pa, (b))

26%H_2+74%He, B_0=0.34 T, f = 4.9 МГц (p = 8.2×10^{-3} Pa, (a), p = 2.3×10^{-3} Pa, (b))

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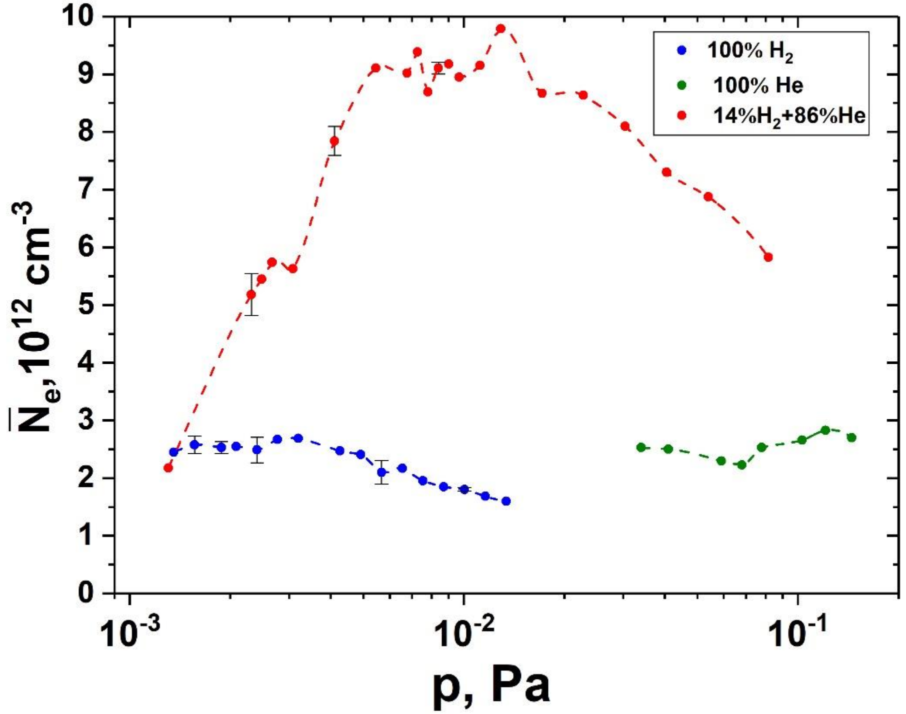
Maximum average plasma density in helium–hydrogen mixture and pure gases



Maximum average plasma density as a function of the pressure (U_a = 7 kV, f = 4.9 MHz)

14%H_2+86%He, B_0=0.35 T,

100%H_2, B_0=0.324 T,

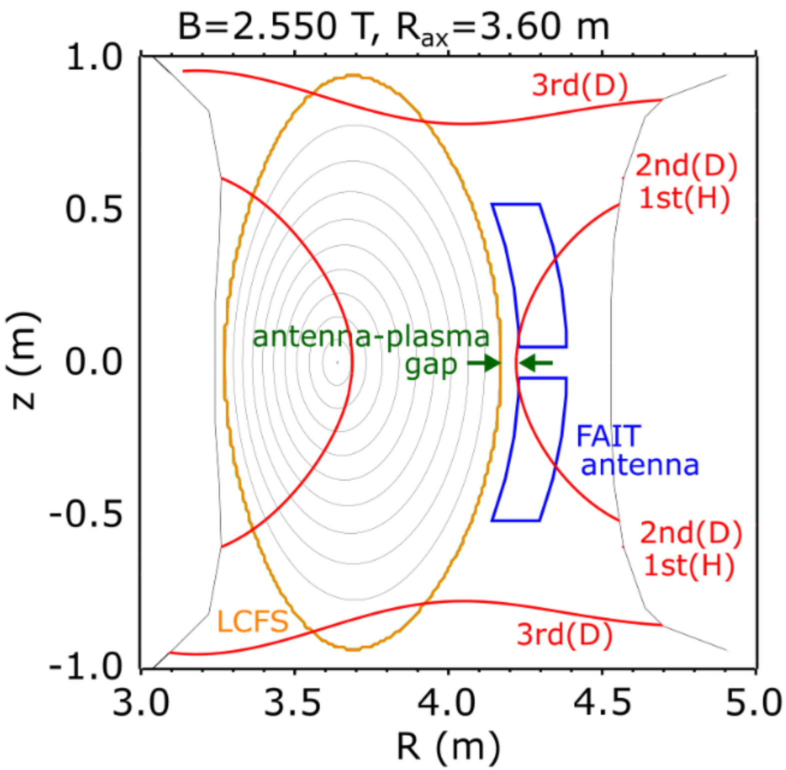
100%He, B_0=0.326 T,

Plasma production at LHD in ICRF in hydrogen minority regime

- Proponent: V.Moiseenko (KIPT), host researcher: S.Kamio with participation of LHD, Uragan and W7-X teams members.
- The motivation is to extend possibilities of stellarator research at different magnetic field values using the scenario of ICRF target plasma production => NBI heating (and X3 ECRH).
- The background is made at Uragan-2M by successful plasma production in He with H minority by ICRH using W7-X like antenna.
- The goal is to research RF plasma production in LHD in the ion-cyclotron frequency range and to collect information needed for the W7-X plasma production scenario at 1.7 T magnetic field. Other goals are to make a background for prospective scenarios for LHD at high (3.9 T) magnetic field and studying physics of RF plasma production.

Experimental details

Experimental conditions:
(Rax, Bt) = (3.6 m, 2.55 T)
Plasma-antenna gap (HAS, FAIT)=(9 cm, 7 cm)
P_{ICRF} (HAS, FAIT)=(0.1 MW, 0.1 MW)
Feb. 16, 2021. Shots No. #169772 - #169796 .



The ICRF resonance layers with B_t=2.55 T.

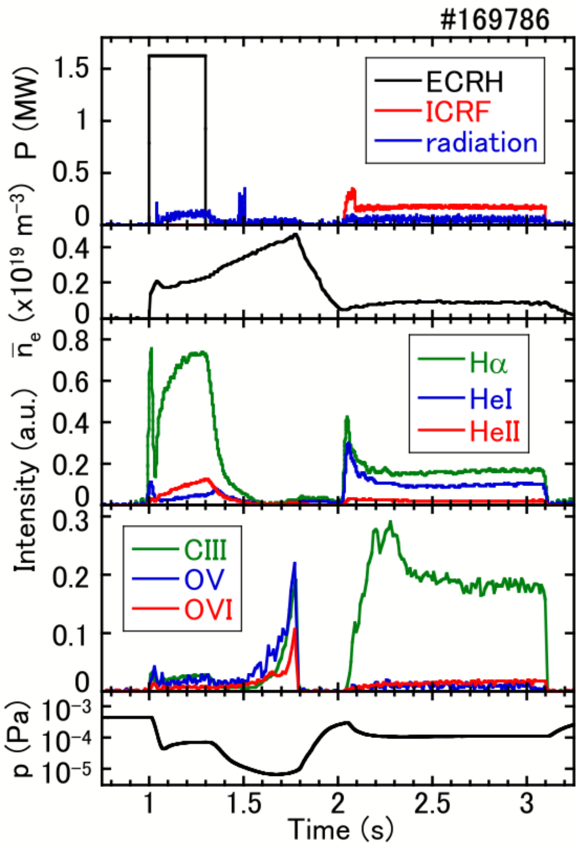
ICRF antennas in the LHD:

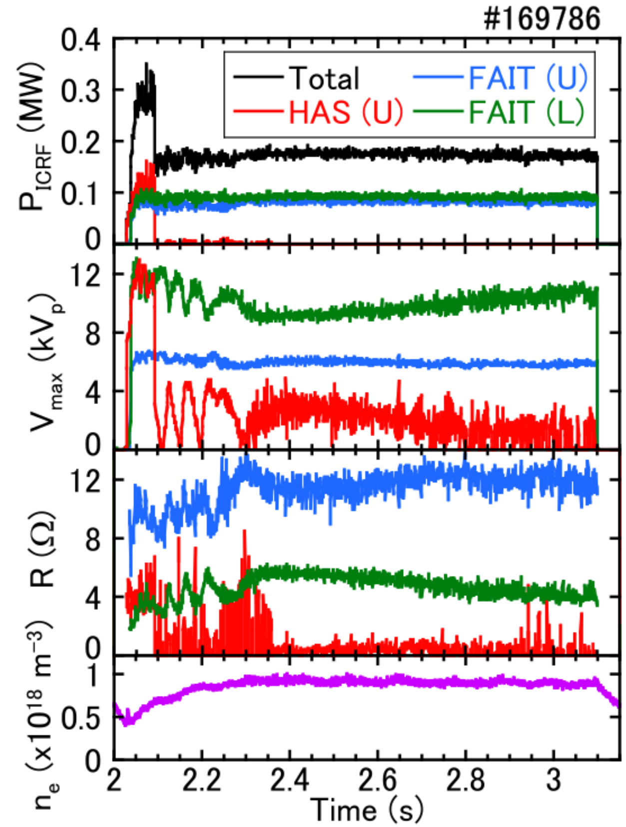
Hand-shake form (HAS) antennas (Upper (U) and lower (L) HAS antennas)

Field-aligned-impedance-transforming (FAIT) antennas (Upper (U) and lower (L) FAIT antennas).

S. Kamio, V.E. Moiseenko, Yu. V. Kovtun et al.
Nucl. Fusion 61, 114004 (2021)

Experimental results. ECRH pre-ionization.



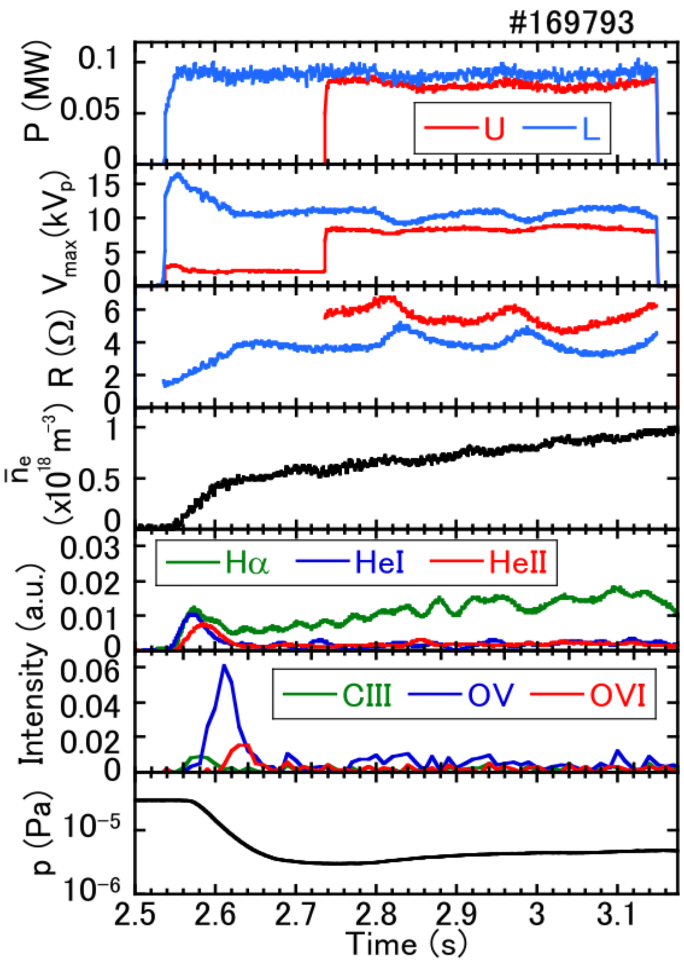


Time evolutions of injection powers P_{ECRH} and P_{ICRF}, radiation power P_{rad}, average electron density $\bar{n}_e$, optical emission intensities of H_α (656.3 nm), HeI (587.6 nm), HeII (468.6 nm), CIII (97.7 nm), OV (63 nm), and OVI (103.4 nm), and neutral gas pressure *p*. The working gas content is ~ 75% He + 25% H_2

Time evolutions of RF powers P_{ICRF}, (total, and individual for antennas HAS (U), FAIT (U and L)), maximum voltages at coaxial line $V_{\max}$, loading resistances (including vacuum loading resistance) *R*, average electron density $\bar{n}_e$.

S. Kamio, V.E. Moiseenko, Yu. V. Kovtun et al. Nucl. Fusion 61, 114004 (2021)

Experimental results



Time evolutions of ICRF power $P_{\rm ICRF}$, (antennas FAIT U and L), maximum voltage at the coaxial line $V_{\rm max}$, loading resistances (including vacuum loading resistance) R, average electron density $\bar{n}_{\rm e}$, optical emission intensities of H_α (656.3 nm), HeI (587.6 nm), HeII (468.6 nm), CIII (97.7 nm), OV (63 nm) and OVI (103.4 nm), and neutral gas pressure p. Working gas content is ~ 81% He + 19% H_2.

S. Kamio, V.E. Moiseenko, Yu. V. Kovtun et al. Nucl. Fusion 61, 114004 (2021)

Summary and future work

•The minority scenario for plasma production in ICRF is described and tried experimentally;

•U-2M experiments demonstrate the reliable plasma production within this scenario and impressive gain from the optimization efforts;

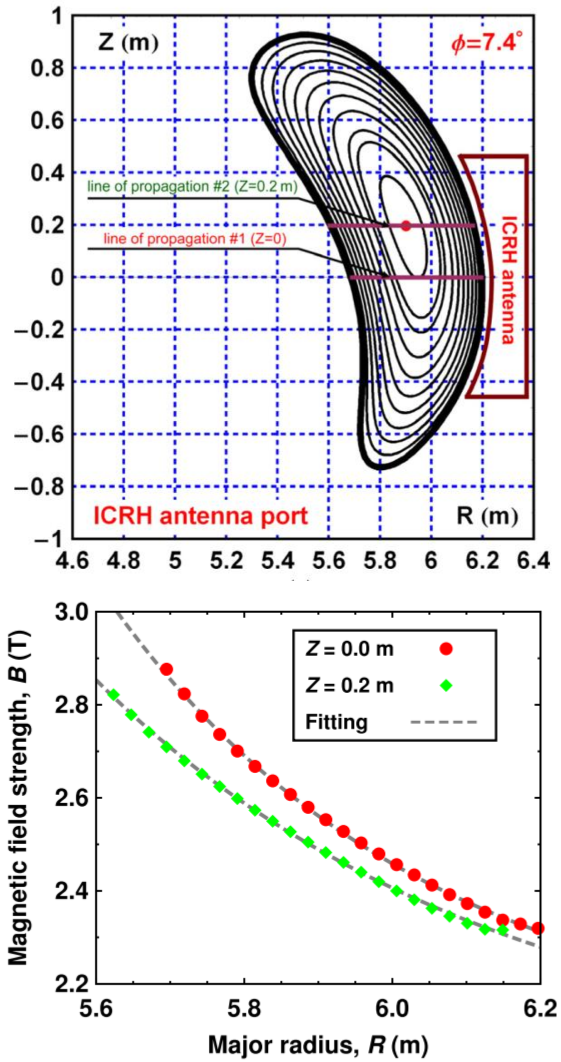
•First experiments at LHD result in successful plasma production at very low, even <100kW, ICRH power which are quite promising;

•The above experiments are the base to confirm earlier formulated proposal for usage the minority scenario for plasma production in ICRF at W7-X at 1.7 T magnetic field;

•The future work may include more detailed studies at LHD and attempts to heat produced plasma both at LHD and U-2M.

•High minority concentrations and usage deuterium instead of helium is of interest.

W7-X ICRH Layout



Generator frequency f=25 MHz;
Neutral gas He+H2 minority (~10%);
Pressure p=1e-4…1e-2 Pa.

Case 1. Plasma 1e18…2e19 m^{-3}, full ionization. Apply NBI with pellet injection and gas puff;

Case 2. Plasma 1e18…2e19 m^{-3}, partial ionization. Apply NBI with gas puff;

Case 3. Hot dense RF plasma. Apply X3 ECRH.

J. Ongena et al. Phys. Plasmas 21, 061514 (2014)

W7-X Proposal: Preparatory Operation, B=2.5 T

1. ECRH start-up, ICRH (38 MHz) starts later with overlapping. ECRH leave ICRH alone at the end of the shot. Aim: to find which plasma ICRH can sustain.
2. ECRH start-up, ICRH starts later with time delay. Aim: to find which is the role of pre-ionization for ICRH start-up.
3. ICRH start-up. Aim: to find the operational frame in parameter space (gas pressure, hydrogen percentage, magnetic field…).
4. ICRH start-up. Further NBI. Aim: compare ECRH and ICRH start-ups influence on NBI.
5. ICRH start-up. Repeatability studies.
6. ICRH start-up. ICRH power increase after start-up. Aim: to find which plasma parameters are achievable with ICRH.
7. ICRH start-up with further ECRH heating in O2 mode.

W7-X Proposal: Low Field Operation, B=1.7 T

1. ICRH (25 MHz) start-up. Aim: to find the operational frame in parameter space (gas pressure, hydrogen percentage, magnetic field…).
2. ICRH start-up. Further NBI. Aim: achieve efficient NBI operation.
3. ICRH start-up. Repeatability studies.
4. ICRH start-up. ICRH power increase after start-up. Aim: to find which plasma parameters are achievable with ICRH.
5. ICRH start-up with further ECRH heating in X3 mode.
6. Develop recommendations for ICRH start-up usage.