Plasma current ramp-up with 28 GHz second harmonic electron cyclotron wave in the QUEST spherical tokamak

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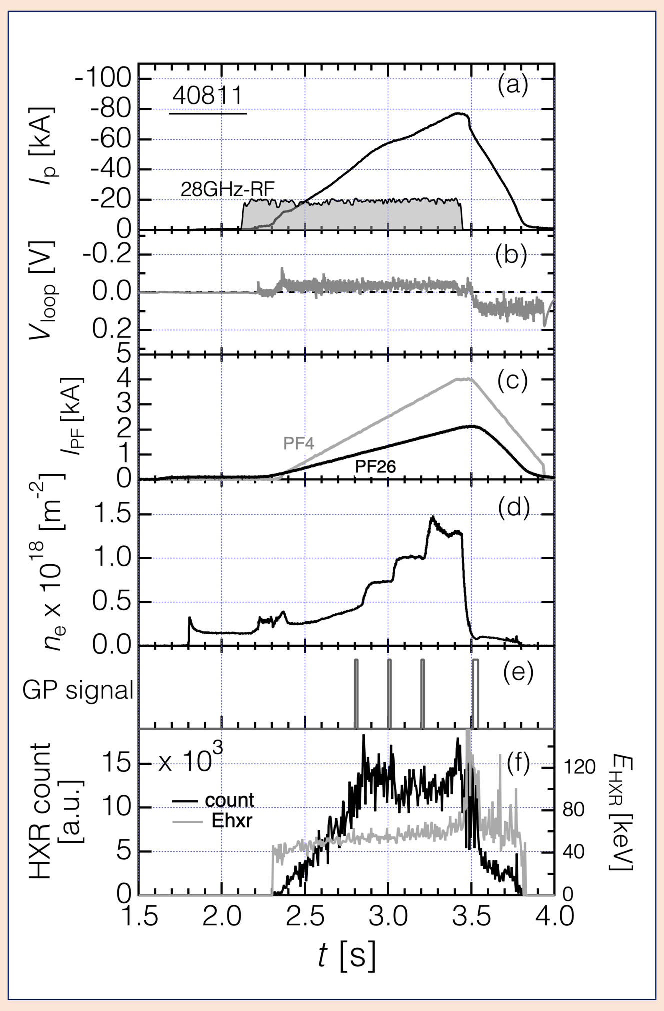
ABSTRACT

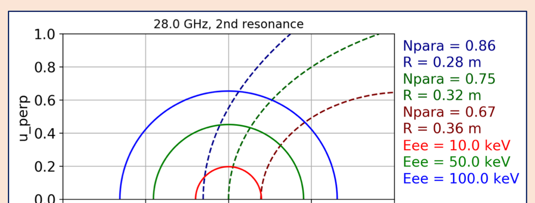
- Through oblique injection of the electron cyclotron wave (ECW), the observation presents that the highest level of plasma current I_p as non-inductive EC ramp-up is attained with small loop voltage, V_{loop} < 0.1 V. The auxiliary ohmic heating (OH) increases I_p by 30-40 %. Energetic electrons have main roles to generate the current and maintain the equilibrium pressure.
- As a result of quasi-normal beam injection and finely adjusted gas fuelling, bulk electrons are heated efficiently, and hence the electron temperature reaches T_e > 500 eV at the density n_e ~ 1 x 10^{18} m^{-3} with the incident RF power of no more than 150 kW.

BACKGROUND

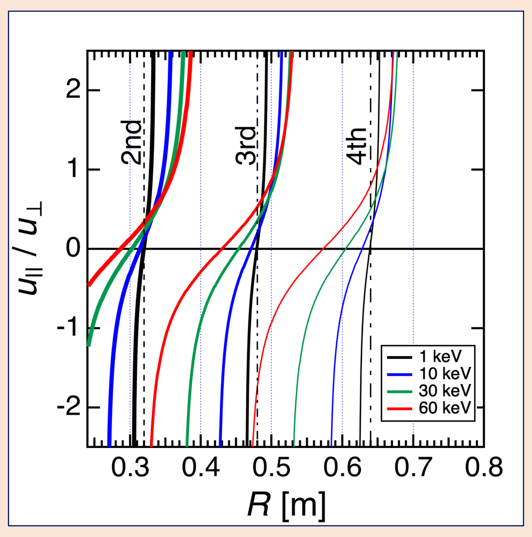
- Plasma current ramp-up experiment by 28 GHz-ECH has been explored in the QUEST spherical tokamak*1,2. Multiple harmonic resonance layers (2nd – 4th) locate in the plasma confinement region.
- Oblique EC wave injection : With high refractive index parallel to magnetic field, $N_{//}$, energetic electrons moving forward along the magnetic field resonate more effectively than those moving backward. Such symmetry breaking is consistent with the results of the current ramp-up experiment (I_p > 70 kA by ECH)*3.



Typical discharge waveforms. Current is ramped up through the 28 GHz-ECH. ECW is injected obliquely as $N_{//}$ = 0.75.



Resonance ellipses and constant velocity circles in velocity space with respect to the second resonance.



Major radial dependence of $u_\parallel/u_\perp$ on particle energy. Particles whose energy of 1 keV (black), 10 keV (blue), 30 keV (green), and 60 keV (red) satisfy resonance conditions at $u_\parallel/u_\perp$

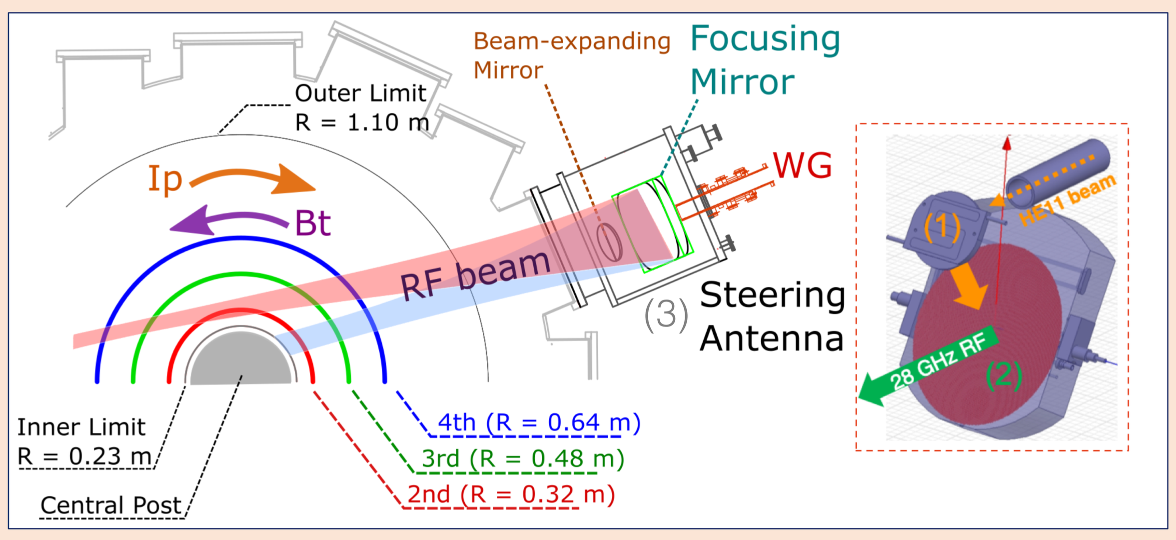
RF INJECTION USING STEERING ANTENNA

STEERING ANTENNA*4

(1) Small convex mirror: HE11 beam → Gaussian beam (expanded).

(2) Large concave mirror: expanded Gaussian beam → focused beam (5-cm waist size at the ECR layer)

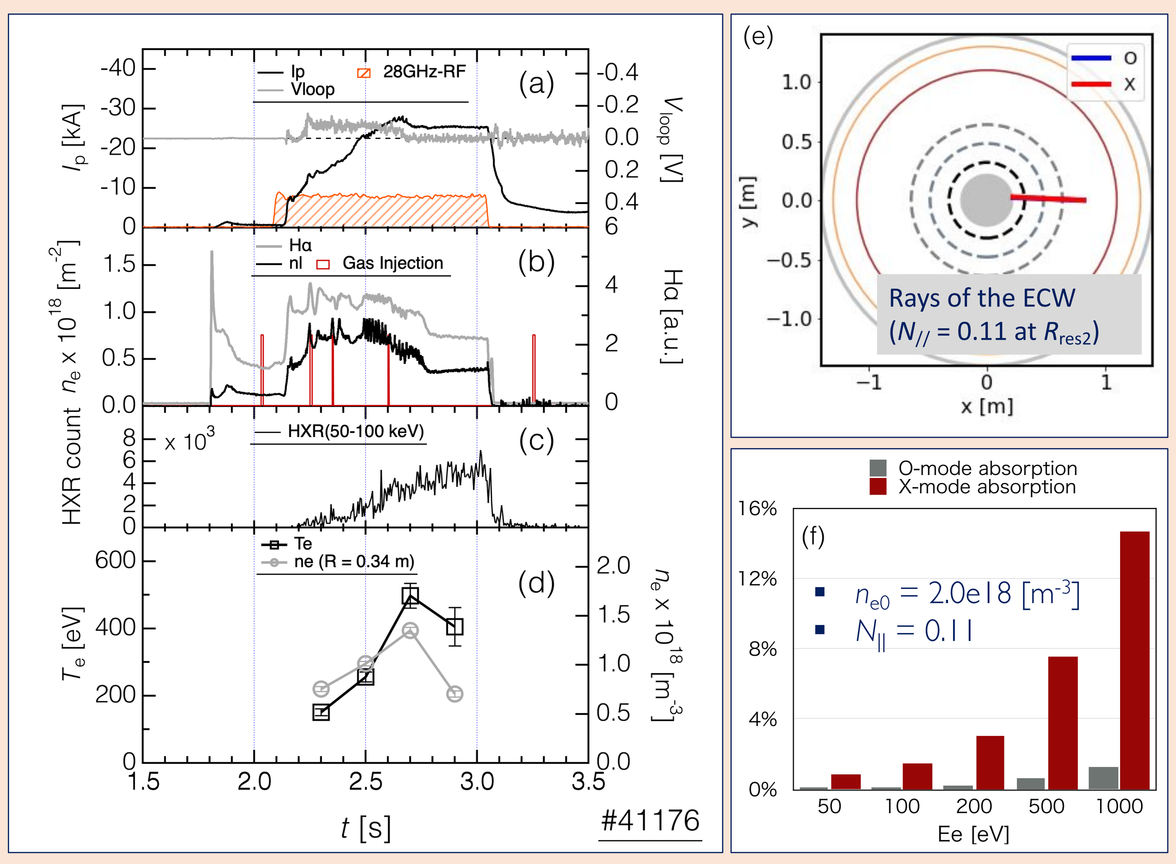
(3) Steering antenna to change the beam direction



A top view of QUEST. The second, third, and fourth harmonic resonance layers are shown by red, green, and blue half circles, respectively.

BULK HEATING THROUGH QUASI-NORMAL ECW INJECTION

- Plasma current is ramped up to I_p ≈ 25 kA. Loop voltage is as low as V_{loop} ≈ 0.1 V measured on the central post, R = 0.18 m
- Hard X-ray (HXR) pulse signal counted by Cadmium Telluride detector is also observed concurrently with plasma ramp-up.
- The RF power is absorbed in both bulk and energetic electrons effectively, therefore moderate current drive and bulk electron heating occur simultaneously.



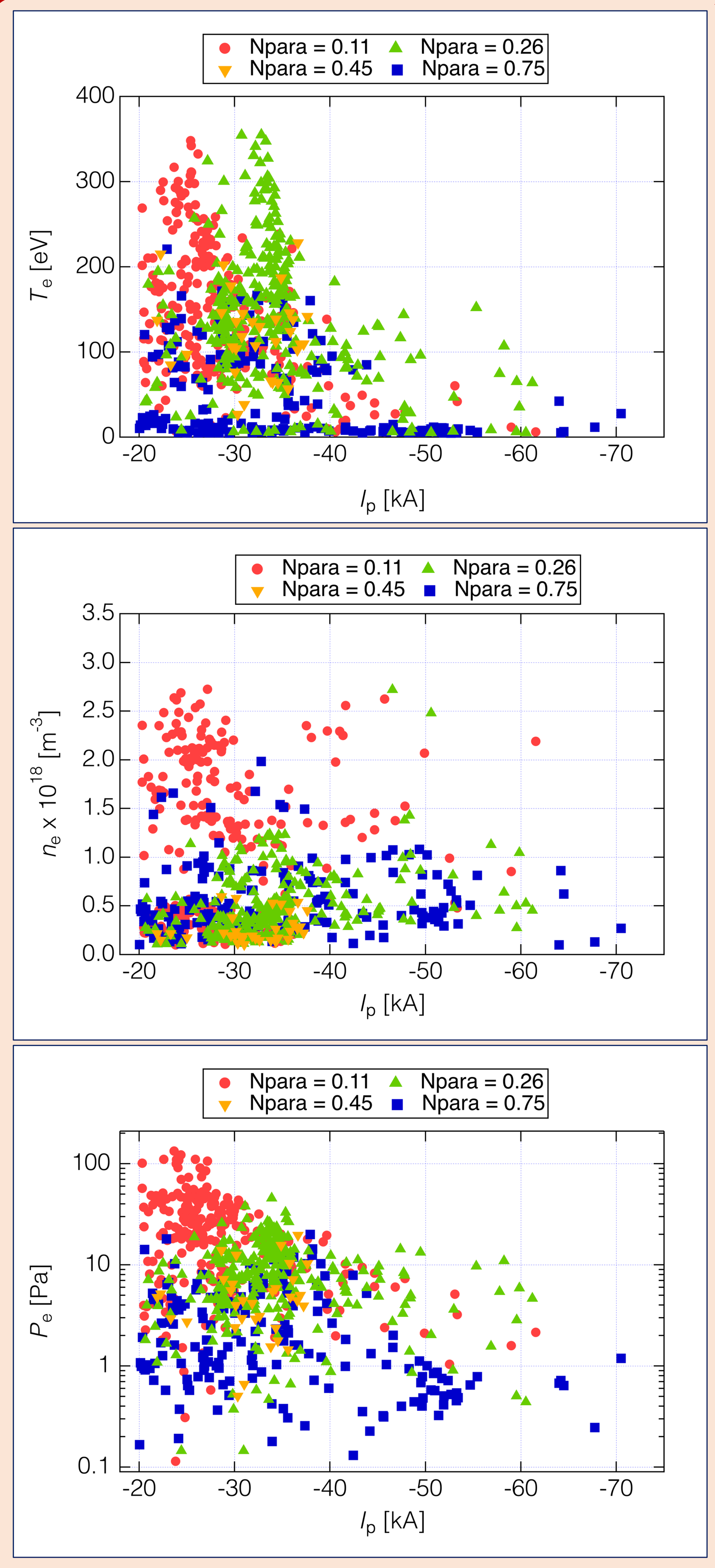
The waveforms of discharge through quasi-normal ECW injection

OUTCOME

ECH CHARACTERISTICS with DIFFERENT $N_{//}$

- ❖ T_e and n_e through the Thomson scattering measurement
- ❖ Data obtained in 2020 (44030 - 45119)
- ❖ Data filtered by
  - ➢ max P_e | (t < 3.0 s) & (T_e > 5 eV) & (|I_p| > 20 kA) & (σ_{Te} < 50 eV) & (n_e > 1×10^{17} m^{-3})

- High T_e with |I_p| < 40 kA + low $N_{//}$
- High I_p, but low T_e with high $N_{//}$
- n_e may weakly depend on I_p
- P_e decreases logarithmically with I_p value
- Energetic electrons own the equilibrium pressure (P_e = 200-300 Pa) when I_p is high

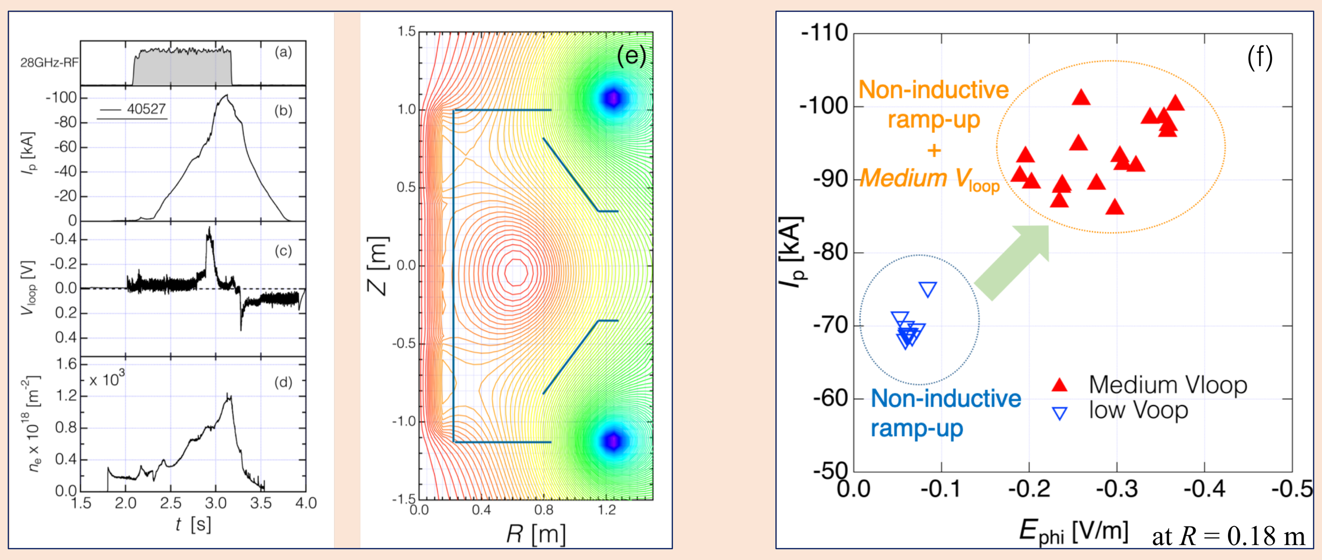


AUXILIARY OHMIC HEATING and MODULATION of LOOP VOLTAGE

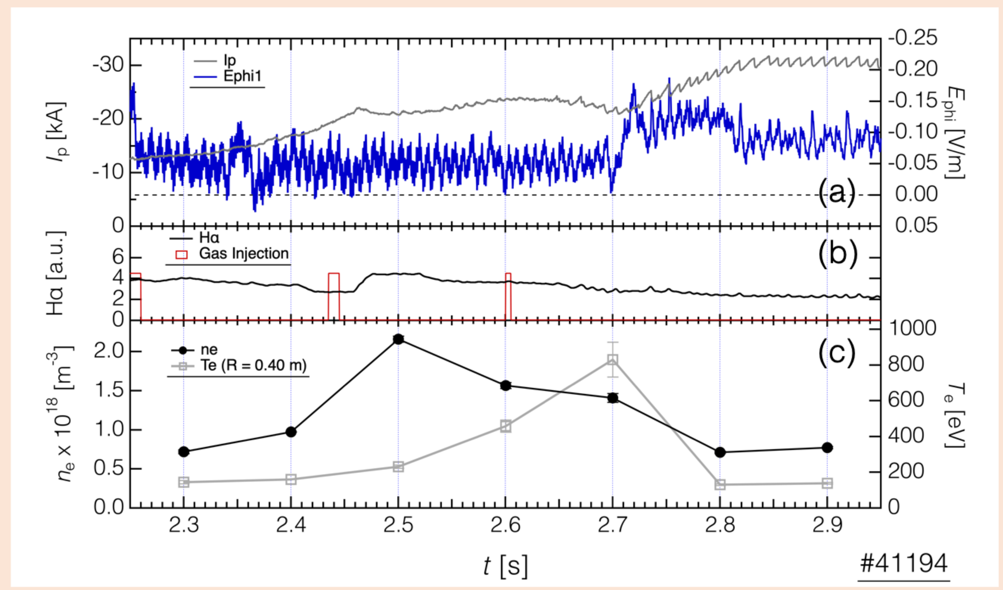
- Oblique ECW Injection:
  - Loop voltage applied after EC current ramp-up
  - I_p > 100 kA achieved
  - I_p increases by 30-40 % with the medium V_{loop} (< 0.5 V)
- Quasi-normal Injection:
  - Modulation of the central solenoid current

  → Change of V_{loop}, thus E_ϕ

  → T_e ≈ 830 eV



Waveforms of the discharge 40527: (a)the 28 GHz-RF power monitor signal, (b)I_p, (c)V_{loop}, (d)line-integrated n_e. (e) Two-dimensional map of magnetic flux surfaces, obtained by an equilibrium reconstruction, with I_p = 100 kA. (f) E_ϕ, measured at R = 0.18 m, vs I_p.



The waveforms of discharge 41194: (a)plasma current I_p, electric field E_ϕ at R = 0.18 m. (b) H_α line emission with gas injection timing. (c) Electron temperature and density measured at R = 0.40 m through Thomson scattering.

CONCLUSION

- The ECH in QUEST, with multi-harmonic resonances in the core region, is characterized by parallel refractive index $N_{//}$ of ECW
- Bulk heating occurs with low $N_{//}$. The highest T_e is obtained with E_ϕ-modulation.
- High I_p is realized with high $N_{//}$, but pressure of bulk electrons decreases obviously. The equilibrium pressure is maintained by the energetic electrons. I_p > 100 kA has been achieved by auxiliary ohmic heatings.

ACKNOWLEDGEMENTS / REFERENCES

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Q-SHU UNIVERSITY EXPERIMENT WITH STEADY-STATE SPHERICAL TOKAMAK