Electron temperature and density profile measurement on the TST-2

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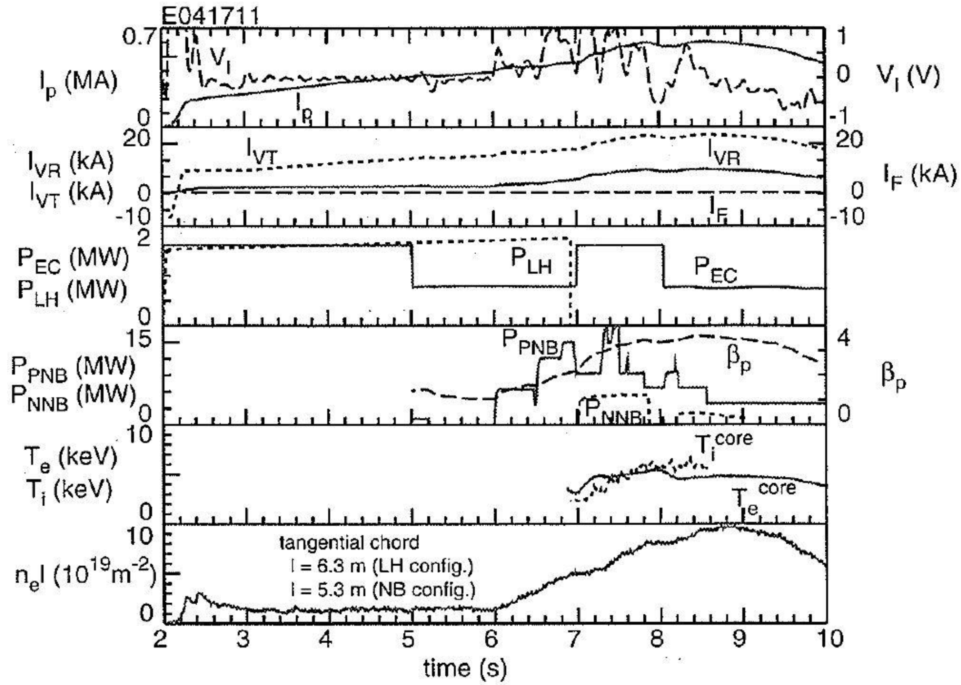
18th International Spherical Torus Workshop (ISTW 2015) and 2015 US-Japan Workshop on ST Plasmas, Princeton, New Jersey, USA, Nov. 3-6, 2015

This work was supported by JSPS Grant-in-Aid for Scientific Research No. 21226021 and by NIFS Collaborative Research Program Nos. NIFS14KOCR001 and NIFS12KUTR078.

Non-inductive current start-up in spherical tokamaks

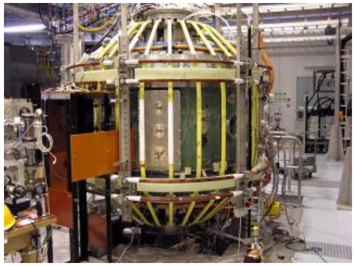
- In spherical tokamaks without central solenoid, non-inductive current start-up is necessary

- Non-inductive experiments have been performed successfully in JT-60U tokamak, by using electron cyclotron wave (ECW) and lower hybrid wave (LHW)



Y. Takase, et al., Journal of Plasma and Fusion Research **78**, 8 (2002).

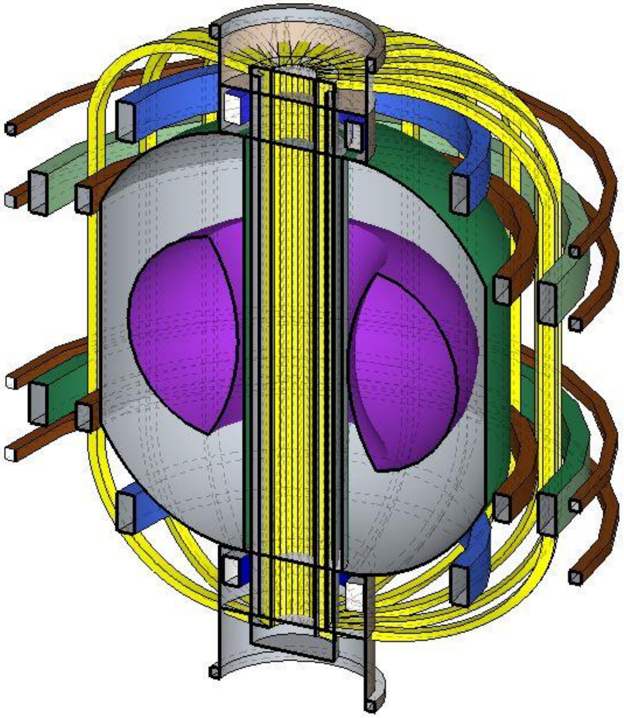
TST-2 spherical tokamak device



- TST-2 has aimed at non-inductive start-up using 100 kW LHW, which has the highest current drive efficiency

<u>Parameters</u>

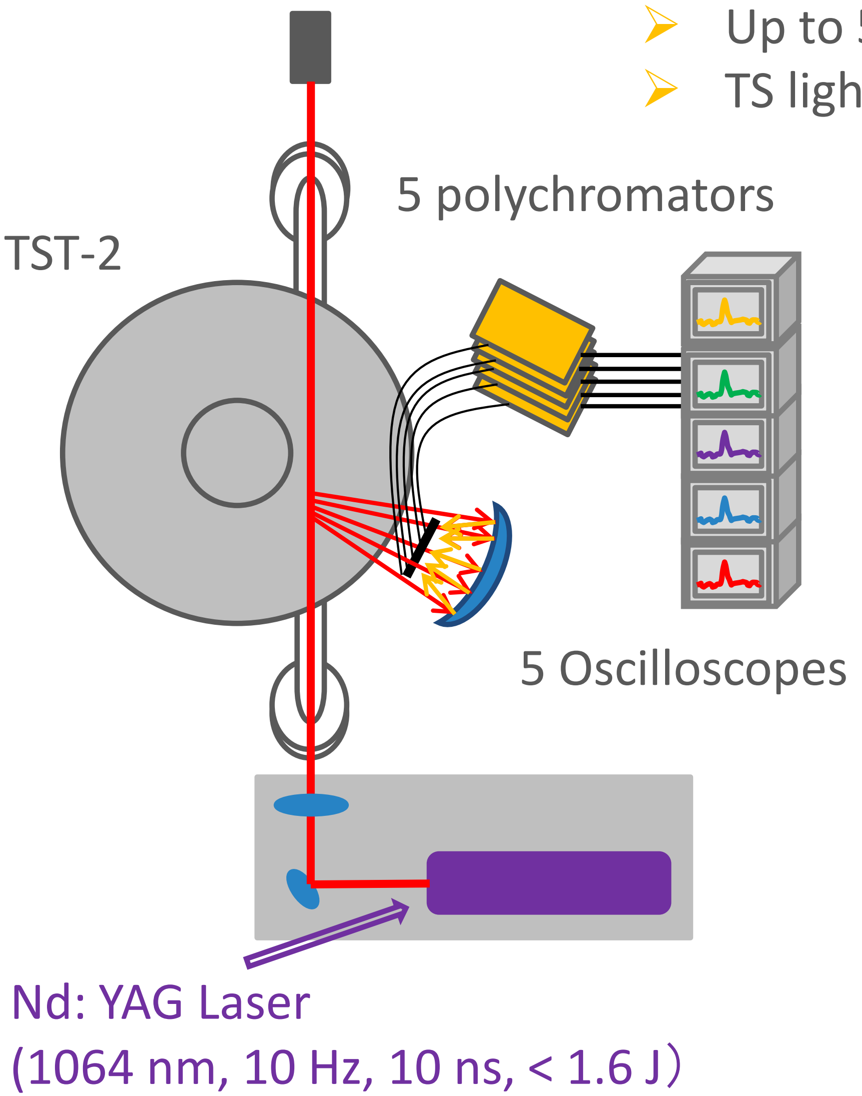
- Size: $R \sim 0.36$ m, $a \sim 0.23$ m
- Aspect ratio: $R/a \sim 1.6$
- Magnetic field: $B_t \leq 0.1$ T (@R = 0.36 m)
- RF power: $P_{LH} \lesssim 100$ kW, $P_{EC} \lesssim 5$ kW
- Plasma current: $I_p \lesssim 25$ kA
- Duration: $t \lesssim 100$ ms

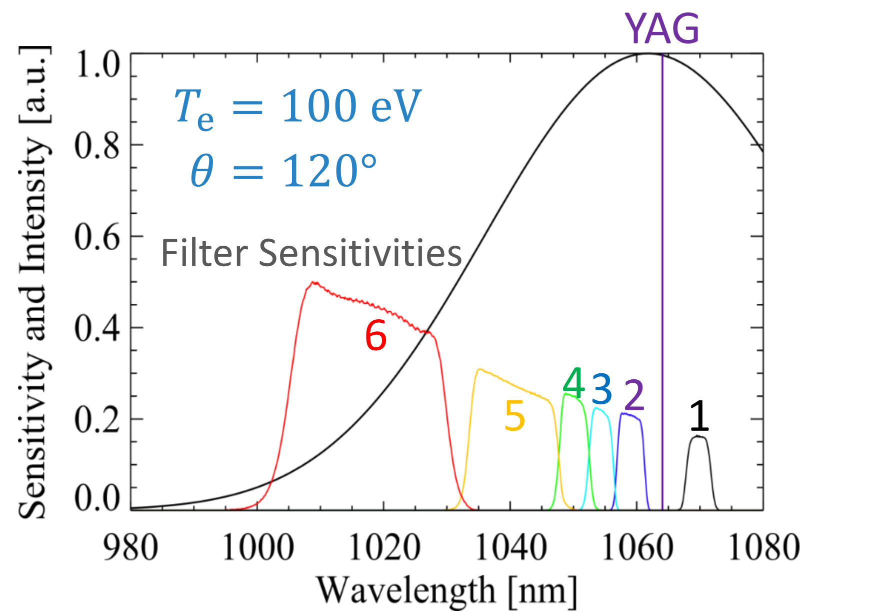


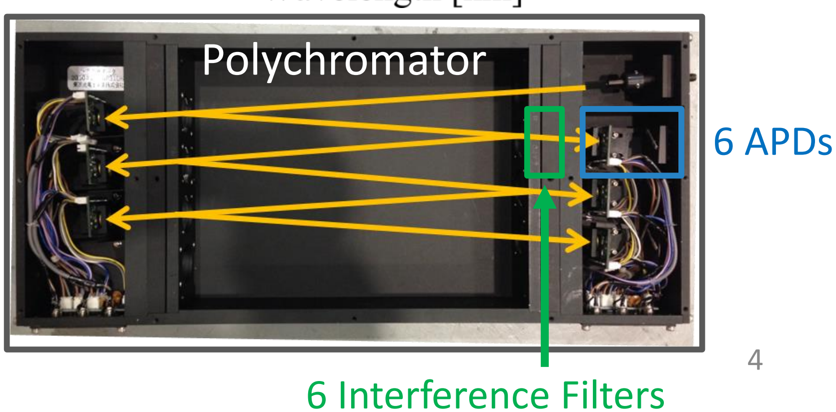
→ It is important to measure electron temperature and density profiles for investigation of the wave and plasma equilibrium

Thomson scattering (TS) diagnostic in TST-2

- Up to 5 spatial points simultaneously (Total 16 CHs)
- TS light from TST-2 plasmas is weak

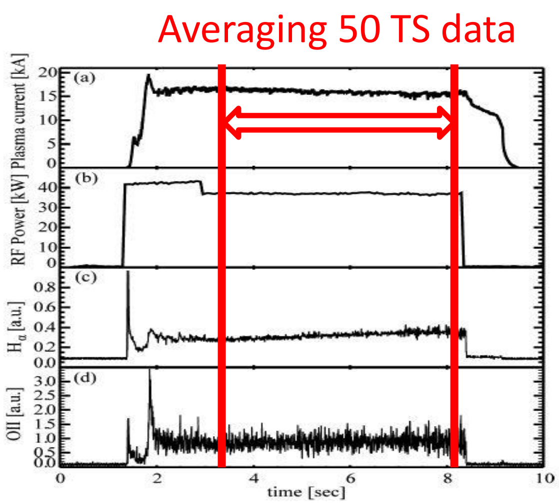


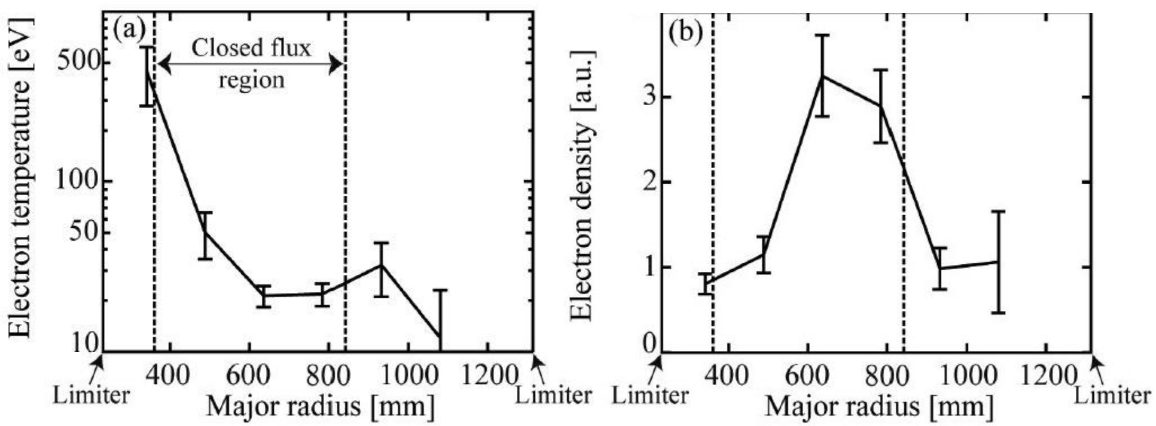




Profile measurement in QUEST

- TS measurements for spherical tokamak plasmas driven by electron cyclotron wave (ECW) were performed in QUEST
- A hollow temperature profile and a peaked density profile were obtained



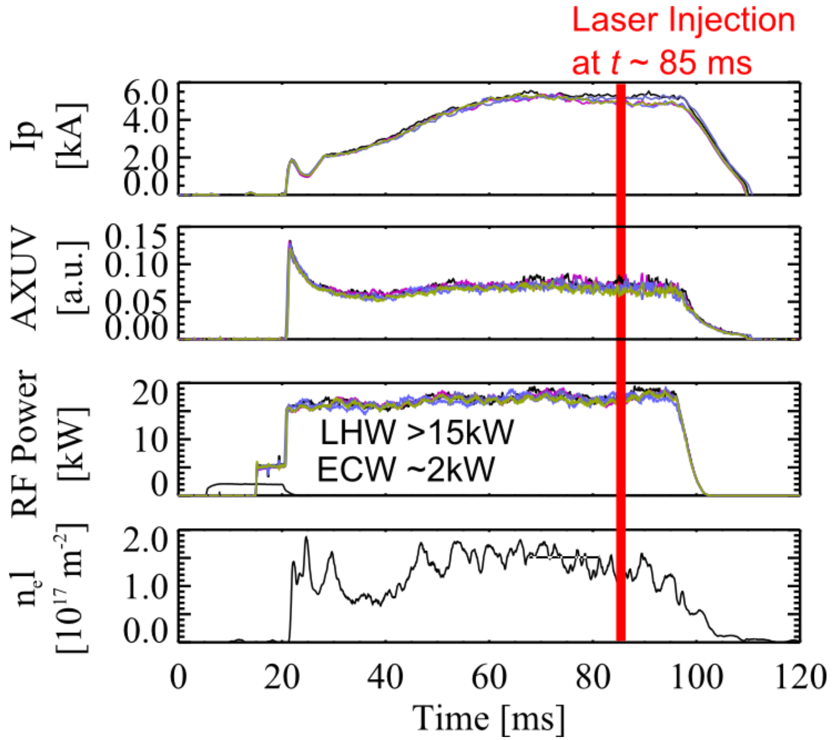


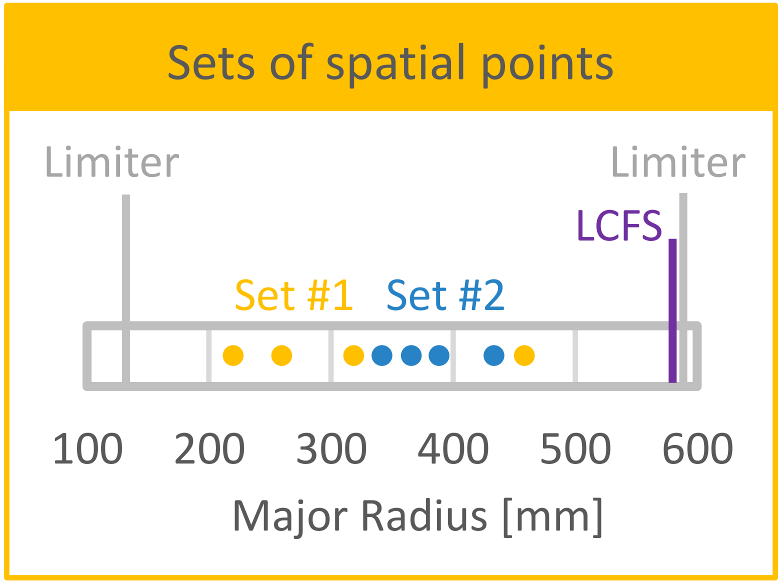
T. Yamaguchi, et al., Plasma Fusion Research **8**, 1302001 (2013).

Similar measurements were performed for LHW-driven TST-2 plasmas

TS measurement for the TST-2 plasmas

- Plasma ignition by ECW and current drive by LHW up to 5 kA
- 10 TS data obtained for 10 reproducible discharges were averaged to increase the measurement accuracy

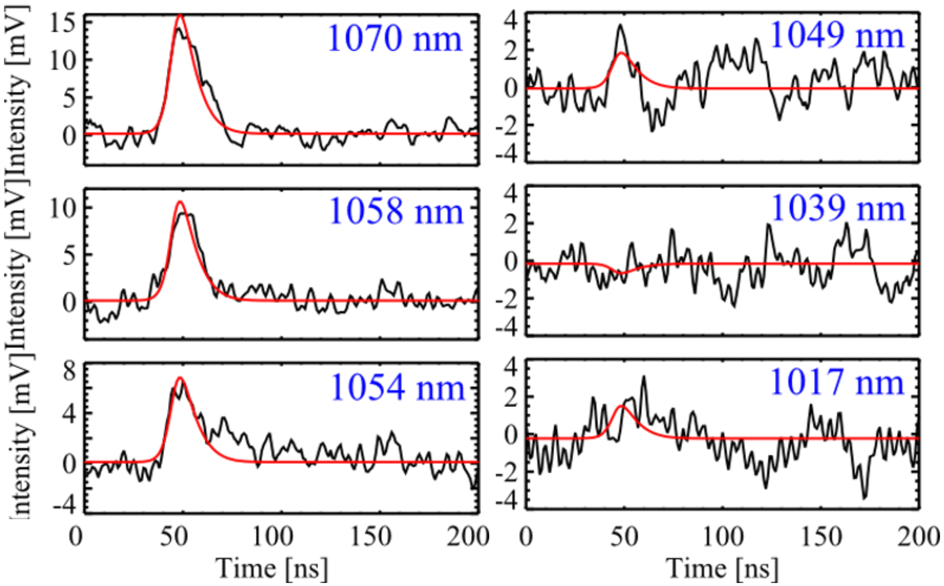


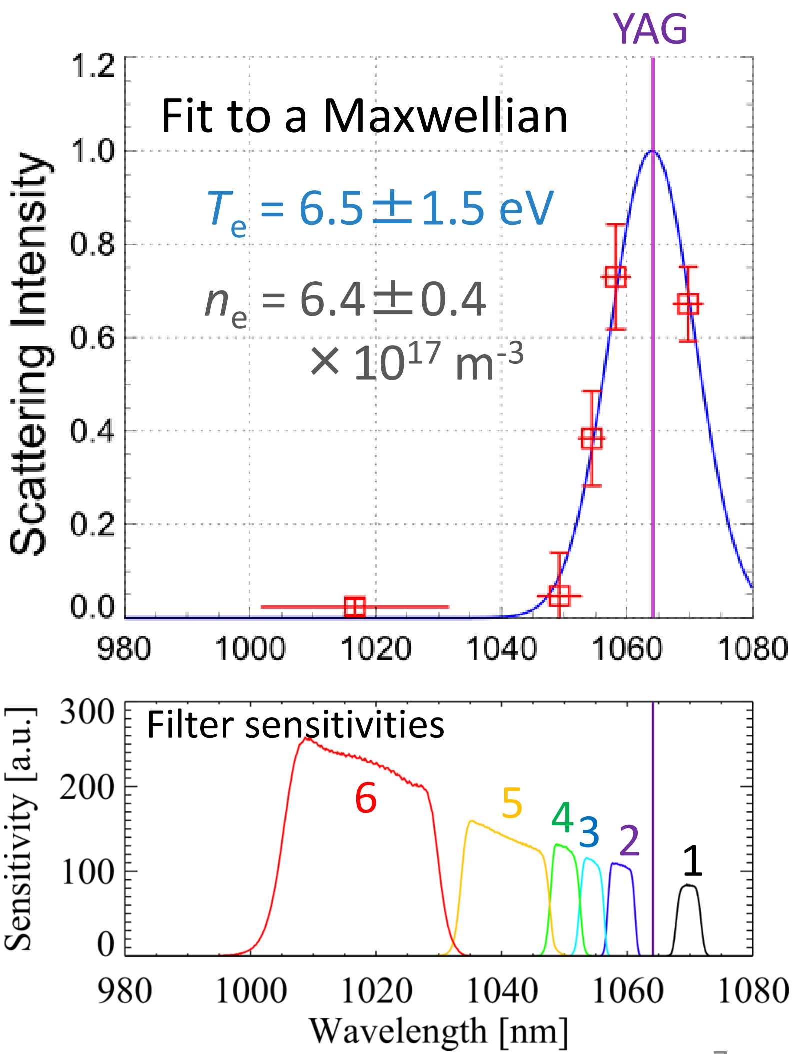


Measurement result (near the plasma center)

- TS signal was detected successfully
- and well-fitted to a Maxwellian with low temperature (< 10 eV)
- Large distortion in bulk velocity was not found

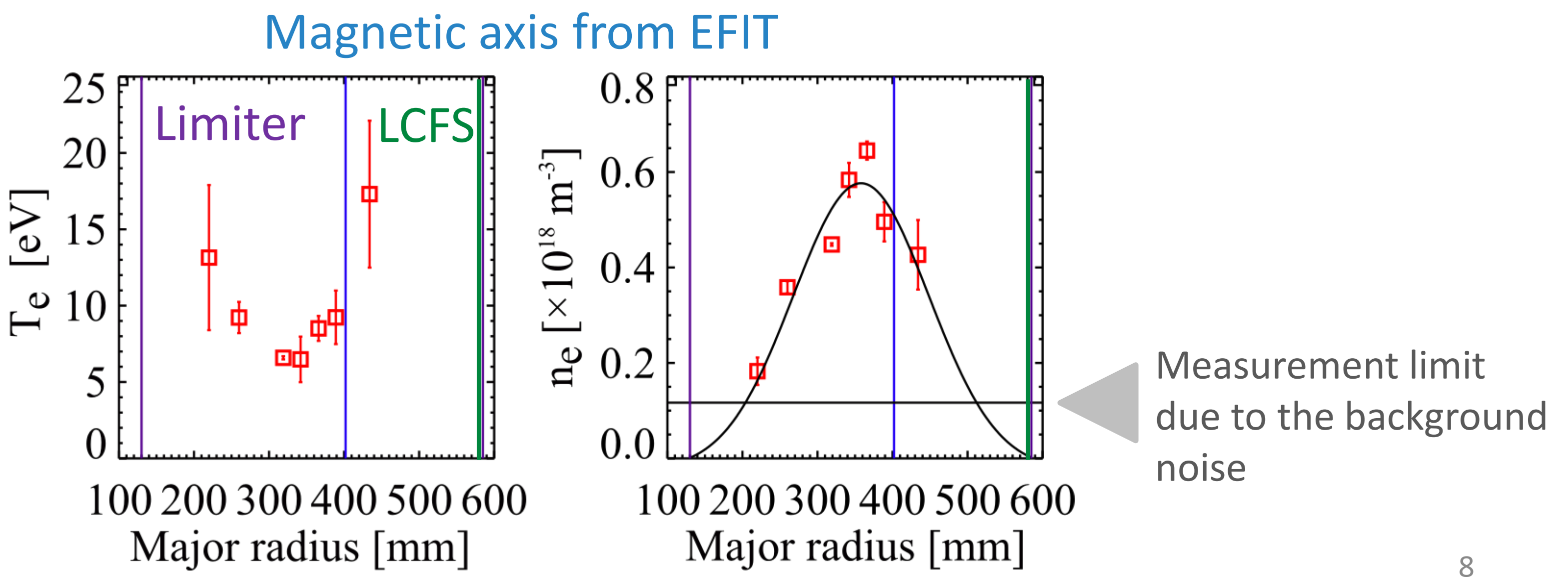
TS signals and the fits (near the center)





Result of profile measurements

- A hollow temperature profile and a peaked density profile were obtained
- The profiles similar to those in QUEST may be caused by a common physical phenomenon in RF-sustained ST plasmas
- The center of the profiles are different from magnetic axis estimated using an equilibrium reconstruction code EFIT



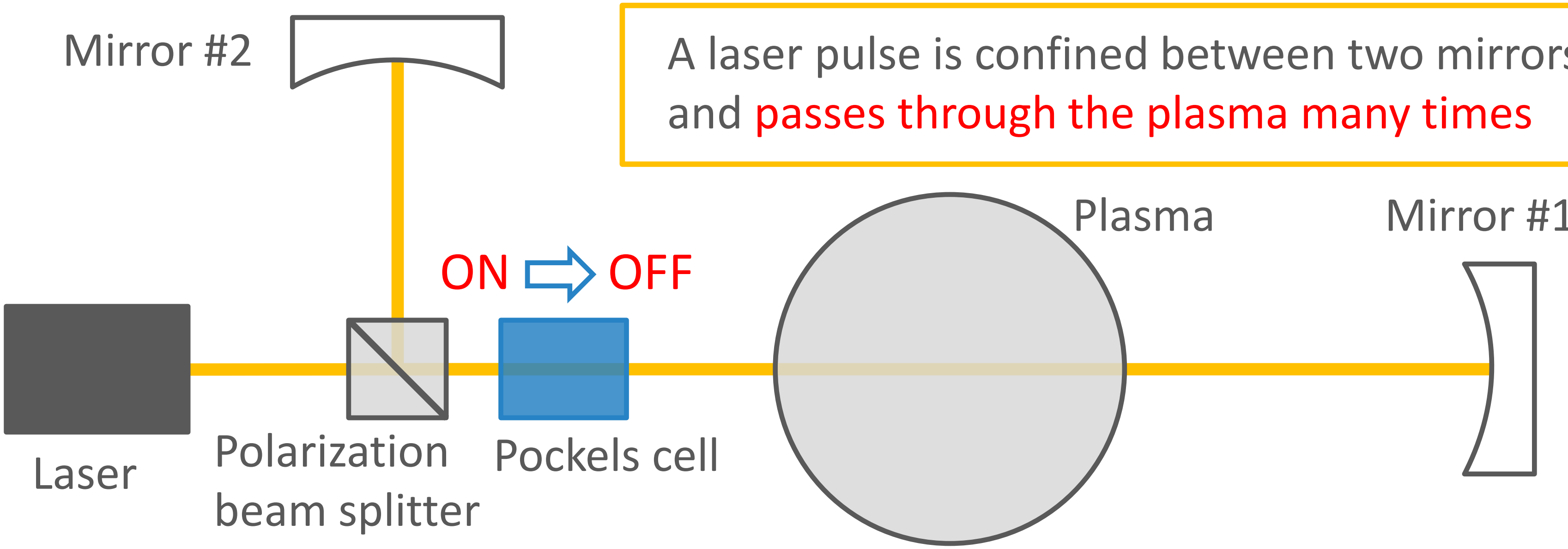
Comparison with other measurements

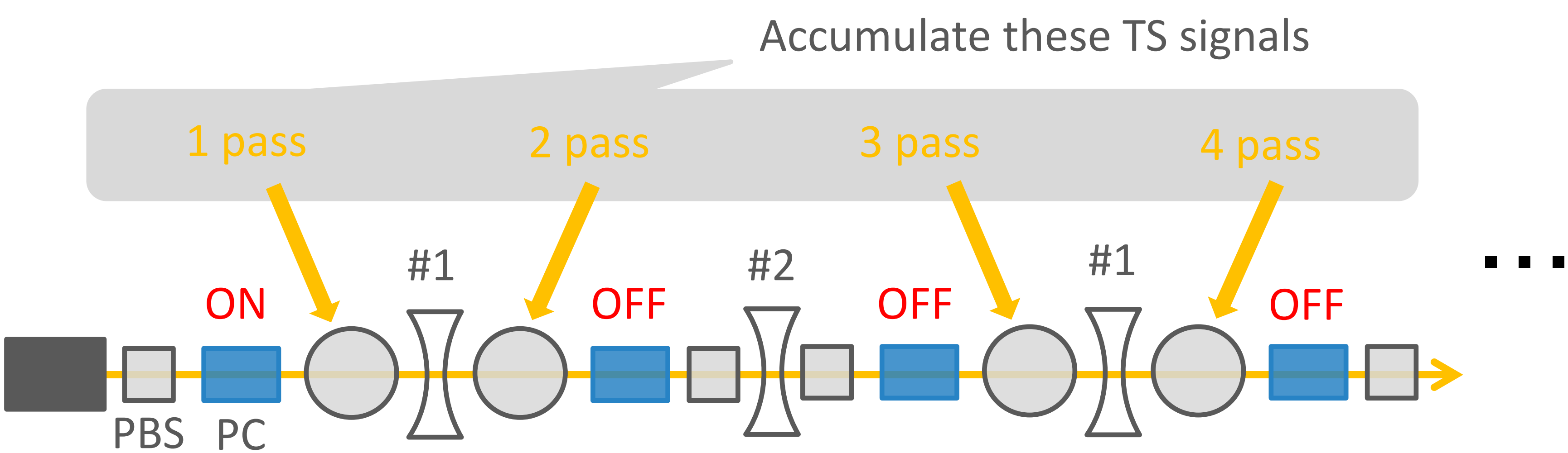
Thomson scattering	Other measurements
① $p_{e,bulk} < 1$ Pa is calculated from $n_{e,bulk}$ and $T_{e,bulk}$ measured by TS	① Total pressure P estimated using EFIT is about 20 Pa at the plasma center
② Electron temperature near the plasma center, $T_{e,bulk} < 10$ eV	② Temperature for fast electrons, $T_{e,fast}$ is 10 keV order from HXR
③ Electron density near the plasma center, $n_{e,bulk} \sim 6 \times 10^{17} \mathrm{m}^{-3}$ ※ $P = n_{e,bulk}T_{e,bulk} + n_{e,fast}T_{e,fast} + n_i T_i$	③ Considering $n_e \cong n_i$ and T_i of 1 eV order from spectroscopy, density for fast electrons, $n_{e,fast}$ is 10^{15} m^{-3} order (less than 1% compared to $n_{e,bulk}$)

Minority fast electrons generated by LHW are dominant in the plasma equilibrium

Coaxial multi-pass TS scheme is utilized to increase TS signal

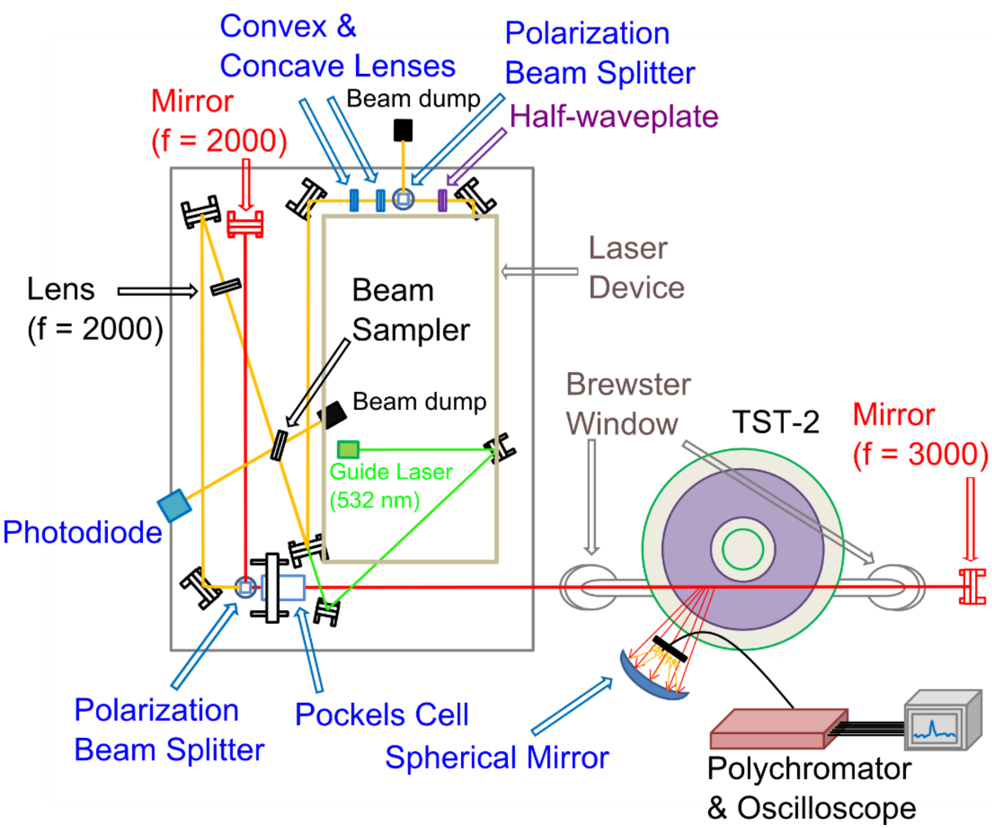
A laser pulse is confined between two mirrors and **passes through the plasma many times**



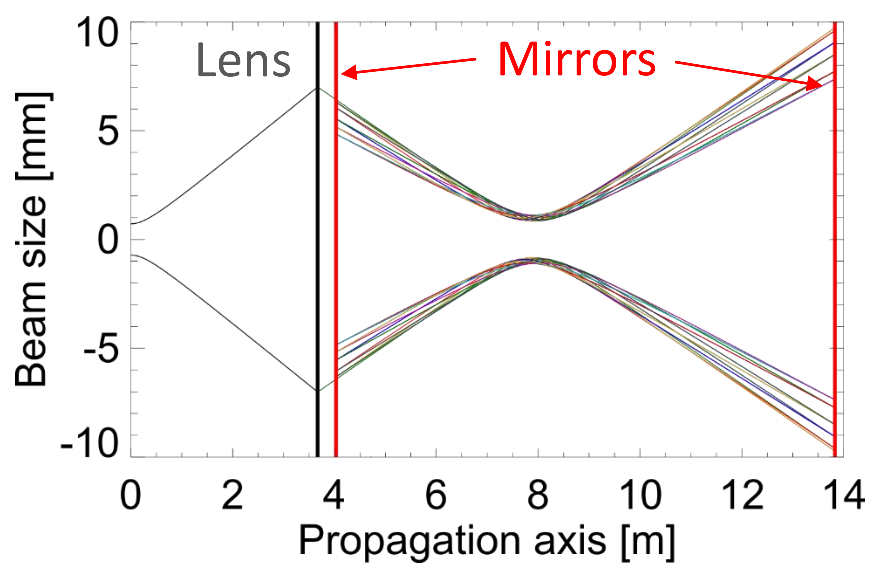


The optical system was designed

- The optical cavity consists of the minimum components to minimize optical loss
- Beam propagation was optimized by calculating quasi-Gaussian beam propagation with the initial value (obtained from beam profile measurement)



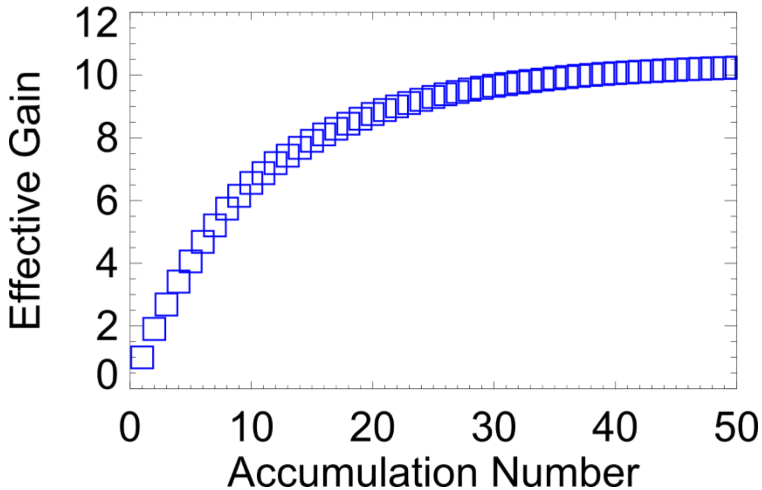
Beam propagation calculated

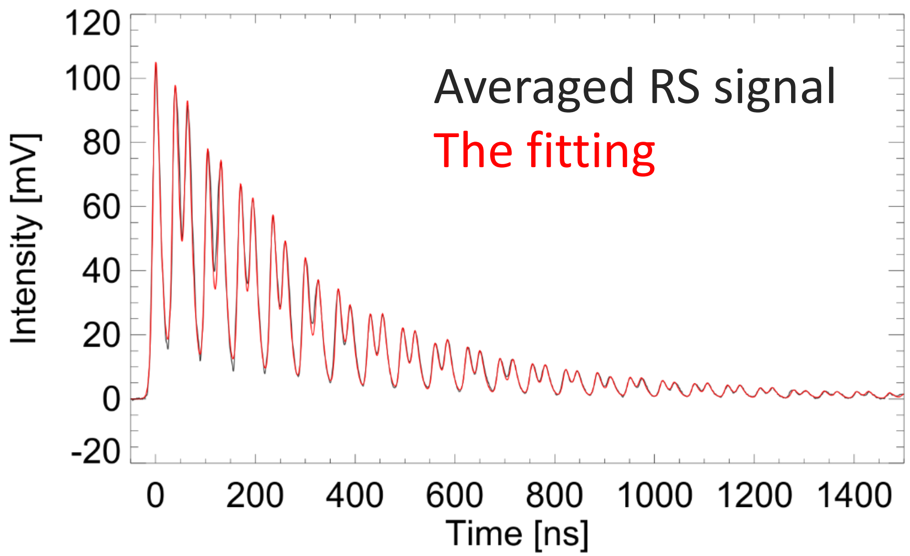


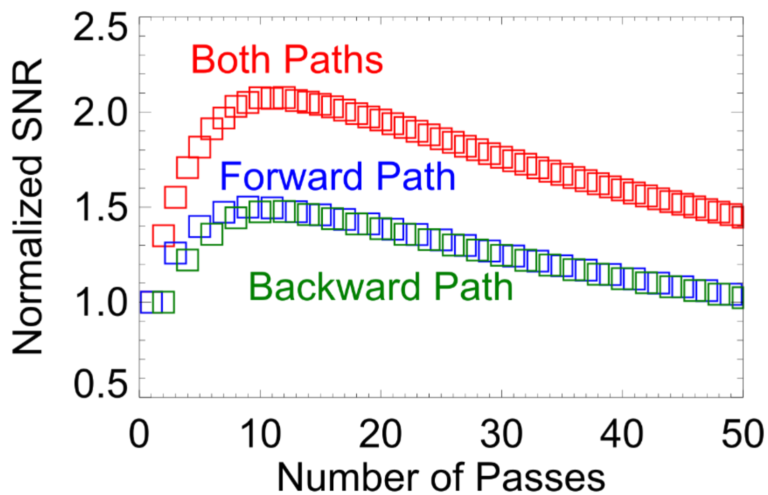
Multi-pass Raman scattering measurement

- More than 50 RS signals were observed
- Effective signal gain reaches up to 10
- SNR can be increased by more than twice <u>when TS signals for both paths are used</u>
  - 90° scattering angle case
  - Isotropic T_e case

⬆ confirmed by double-pass TS

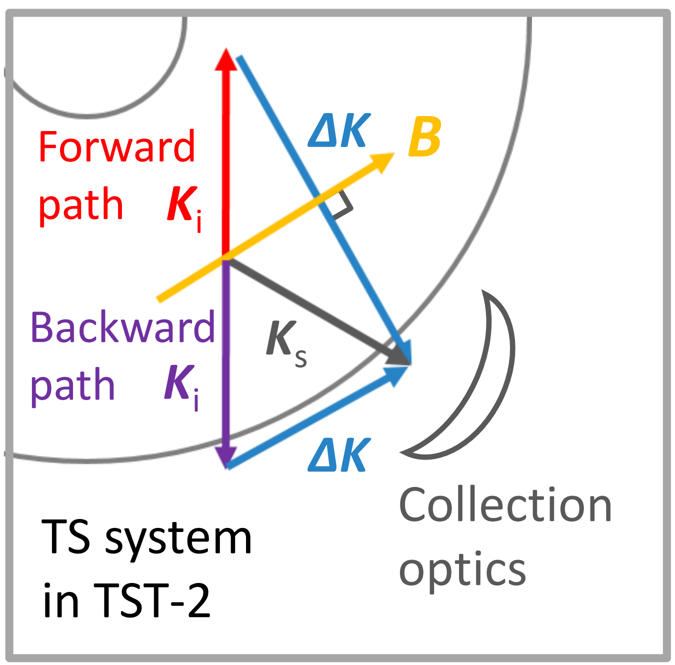






T_e anisotropy measurement using double-pass TS scheme

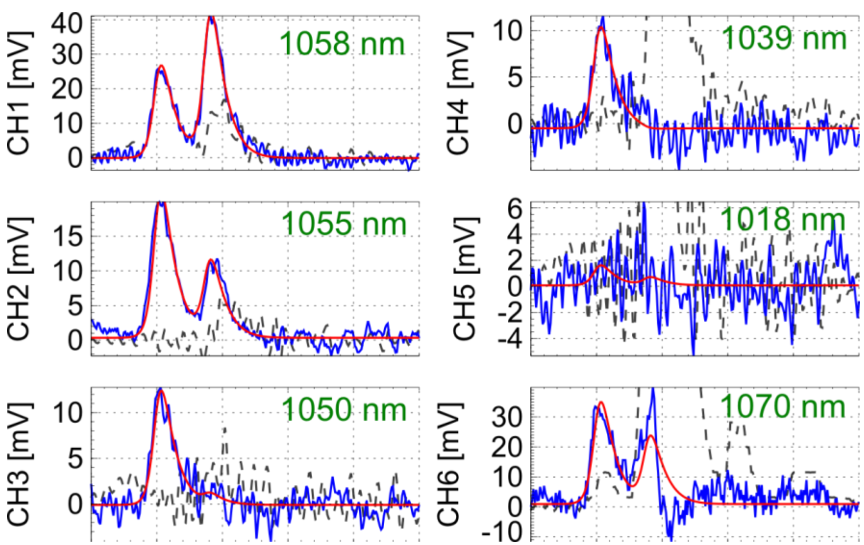
- T_e in the direction parallel to $\Delta \boldsymbol{k}$ (= $\boldsymbol{k}_s$ - $\boldsymbol{k}_i$) is measured in TS diagnostics
- In TST-2, the $\Delta \boldsymbol{k}$ for forward and backward paths are almost perpendicular and parallel to the magnetic field line $\boldsymbol{B}$, respectively
  → The anisotropy can be measured



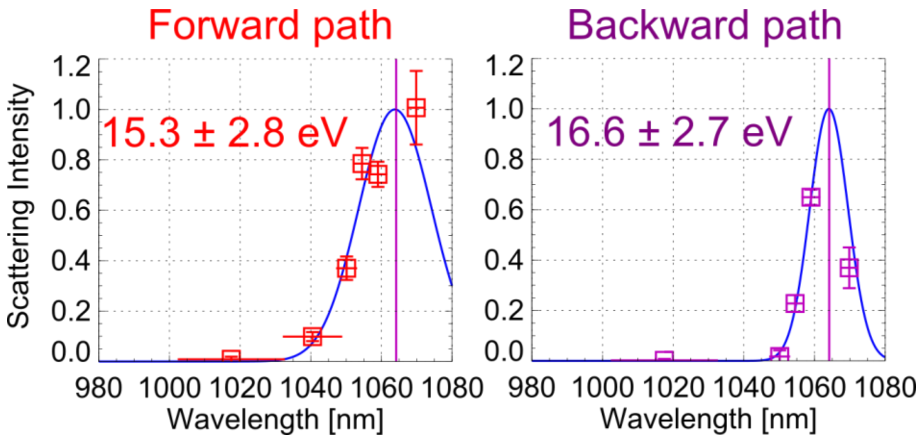
Isotropic T_e was measured by double-pass TS scheme

- Double-pass TS measurement was performed to confirm the T_e isotropy
- Significant anisotropy was not found near the plasma center

Double-pass TS signals
from a point near the plasma center

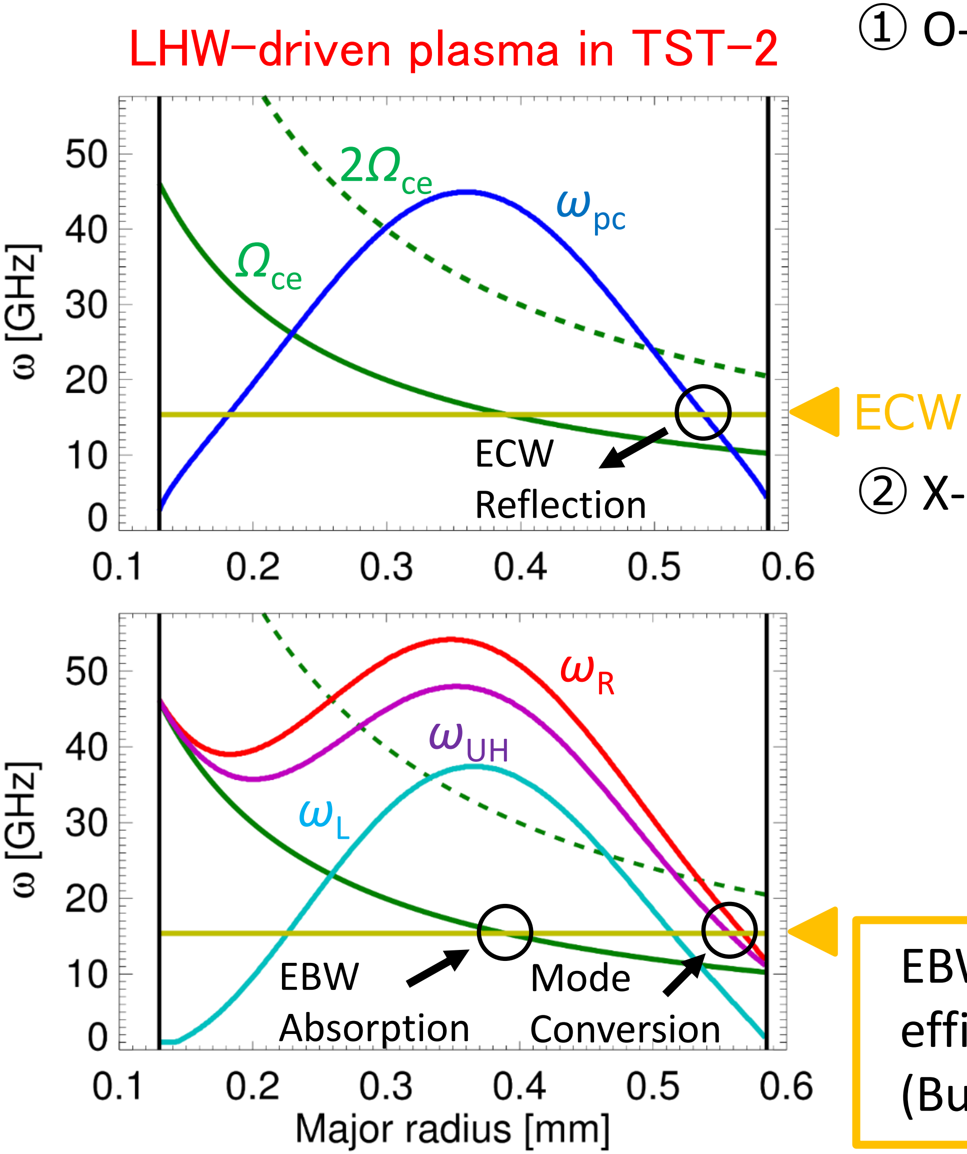


Maxwellian Fits



▶ TS signals for both paths can be used together in the analysis

Additional current drive by electron Bernstein wave (X-B)



① O-mode injection

- Plasma cutoff frequency $\omega_{pc} = \sqrt{\frac{e^2 n_e}{\epsilon_0 m_e}}$
- Electron cyclotron frequency $\Omega_{ce} = \frac{eB}{m_e}$

O-mode ECW cannot propagate to the inside of the plasma

② X-mode injection

- R-cutoff frequency $\omega_R = \frac{\Omega_{ce} + \sqrt{\Omega_{ce}^2 + 4\omega_{pe}^2}}{2}$
- Upper hybrid resonance frequency $\omega_{UH} = \sqrt{\Omega_{ce}^2 + \omega_{pe}^2}$
- L-cutoff frequency $\omega_L = \frac{-\Omega_{ce} + \sqrt{\Omega_{ce}^2 + 4\omega_{pe}^2}}{2}$

EBW converted from ECW with up to 50% efficiency can propagate to the inside (Budden parameter $\eta \sim 0.6$)

Summary

Non-inductive current start-up experiments have been performed in TST-2 spherical tokamak device

① Electron temperature and density profiles for LHW-driven ST plasmas have been measured successfully for the first time

- It was suggested that fast electron is dominant in whole plasma equilibrium

② Multi-pass Thomson scattering system has been developed to increase measurement accuracy

- 10 times larger signal was obtained by applying the multi-pass system
- It is expected that about twice higher SNR is obtained in TS measurement

③ X-B scenario can be applied to TST-2 LHW-driven plasmas, leading to further heating and current drive