Measurement of lower-hybrid waves with microwave scattering on TST-2

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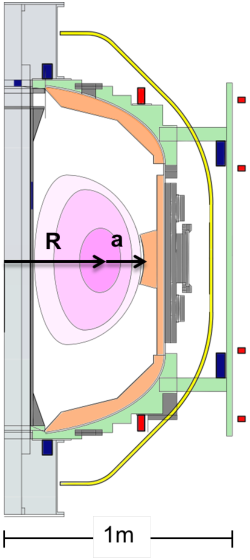
Outline

A microwave scattering diagnostic is being developed to measure the Lower-Hybrid (LH) waves directly and test numerical simulations

- Background
  - Non-inductive plasma start-up with LH waves has been studied on TST-2
  - The current drive efficiency in the actual experiment is much lower than what is predicted by GENRAY-CQL3D
- Microwaves in the range of 12-40 GHz have wavenumber similar to LH waves in TST-2 and suited for diagnosing these waves
- The wave measurements will be compared with numerical simulations to quantitatively understand the current drive physics
- Previous direct LH wave measurements
  - Microwave back-scattering with a reflectometer [Baek 2014]
  - CO_2 laser scattering [Takase 1985]

The TST-2 Machine



- $R = 36$ cm
- $a = 23$ cm

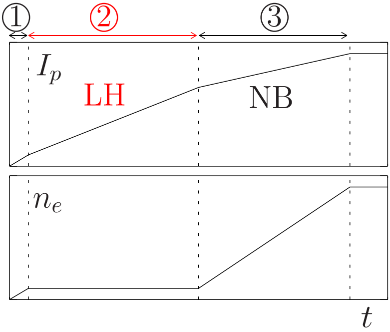
RF non-inductive start-up

- $B_t < 0.15$ T
  (pulse length ∼80 ms)
- $\bar{n}_e < 10^{18}$ m^{-3}
- $I_p < 25$ kA
- RF 400 kW @ 200 MHz

Ohmic (inductive) start-up

- $B_t < 0.3$ T
  (pulse length ∼30 ms)
- $\bar{n}_e < 10^{19}$ m^{-3}
- $I_p < 110$ kA

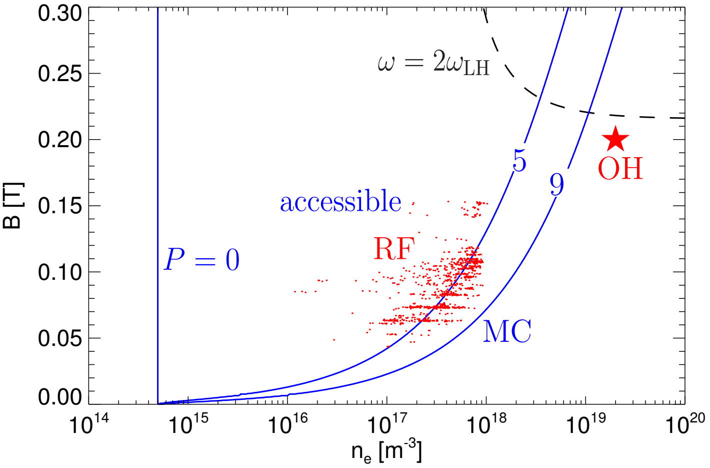
Non-inductive plasma start-up using LH waves is studied on TST-2



1. Plasma initiation (ECH, LH)
2. I_p ramp-up with LH waves
3. Further ramp-up with neutral beam injection

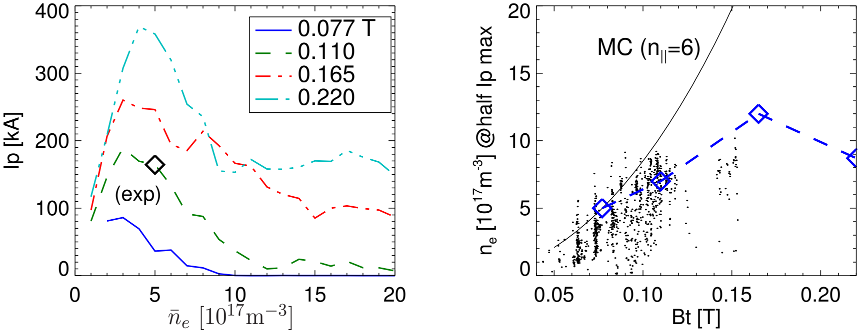
- The LH wave has one of the highest current drive efficiency among rf waves
- Similar scenario tested on JT-60U [Shiraiwa 2004]
- The plasma density must be kept low during I_p ramp-up $\leftarrow$ LH high-density limit

LH waves @200 MHz can access 10^{18} m^{-3} for $n_\parallel = 5$-9



- Density limit low at low field
- $\omega > 2\omega_{\rm LH}$ to avoid parametric decay instability

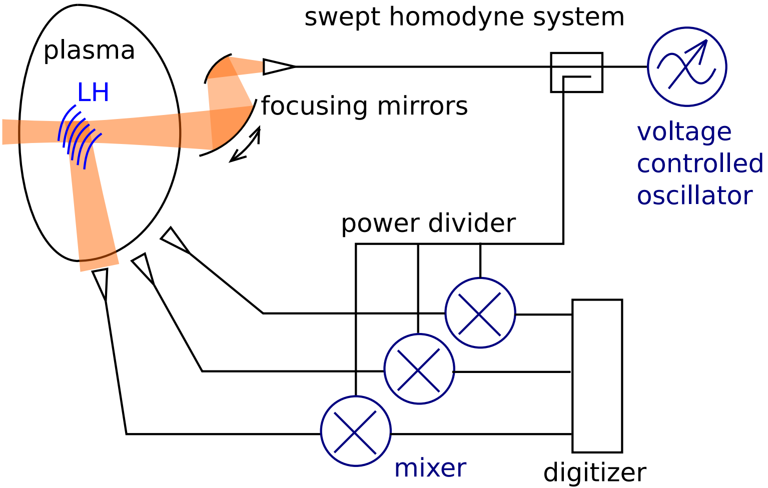
The experimentally achieved plasma current (< 25 kA) is an order of magnitude smaller than simulated



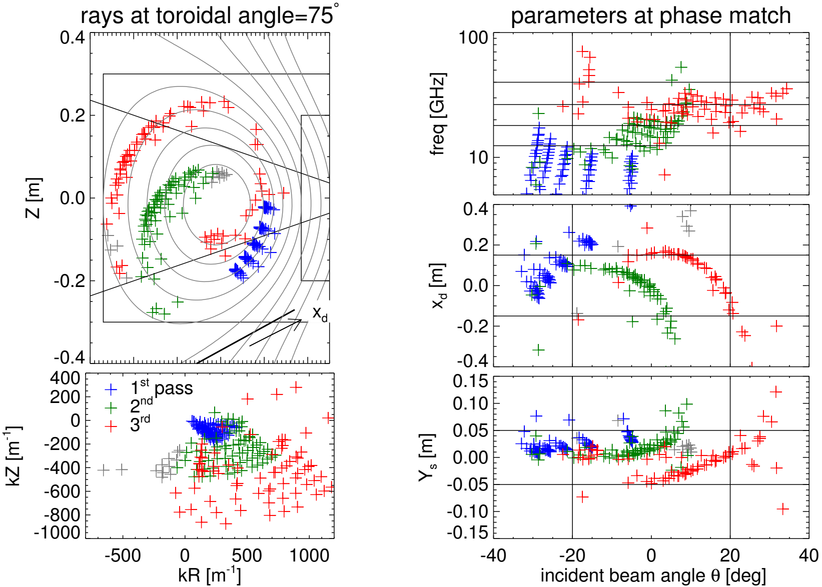
- Simulation by GENRAY (ray-tracing) and CQL3D (Fokker-Planck solver)
- The experimental density limit qualitatively consistent with simulation

Outline

A launched microwave beam can be Bragg-scattered by density fluctuations of the LH waves



Optimum scattering geometry was investigated from the simulated typical wave trajectory on TST-2

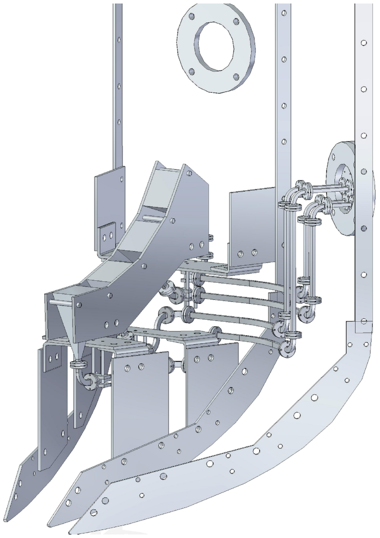


LH waves propagating in a wide range of poloidal cross-section can be detected with a microwave launched from the midplane

- Scan the incident beam angle θ
- Scan the beam frequency
- Detect the scattered light at multiple poloidal locations (x_d)

- The source frequency swept at 1 kHz
  $\rightarrow$ the whole wavenumber spectrum is measured every 1 ms
- Incident beam angle needs to be scanned on a shot-to-shot basis

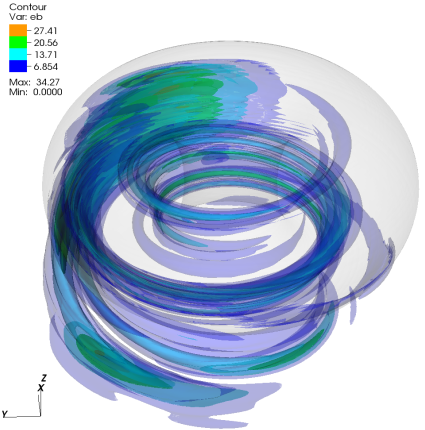
The O-mode microwave scattering system



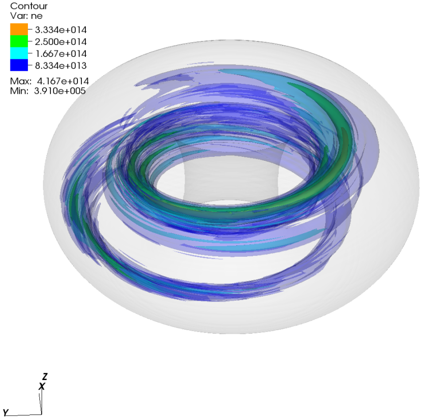
- Microwave bands
  - Ku band (WR-62): 12.4-18.0 GHz
  - K band (WR-42): 18.0-26.5 GHz
  - Ka band (WR-28): 26.5-40.0 GHz
- Incident beam from the midplane horizontal port
- 4-antenna array below the plasma
- Small toroidal tilt to compensate wave k_ϕ

Outline

Full-wave simulation of LH waves was performed with AORSA



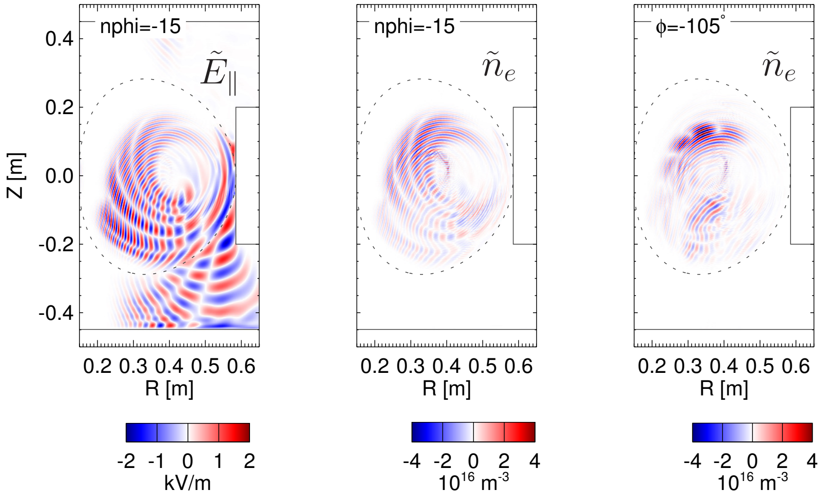
$\tilde{E}_{\parallel}$



$\tilde{n}_e$

- $n_e = 5 \times 10^{17}$ m^{-3}, $T_e = 500$ eV, Maxwellian, $P_{\rm rf} = 1$ MW

The expected signal level is within the detectable range



$$\tilde{\phi} \sim r_e \lambda \tilde{n}_e L$$
$$\sim 2.8 \times 10^{-15}\,\mathrm{m} \cdot 0.01\,\mathrm{m} \cdot 2 \times 10^{16}\,\mathrm{m}^{-3} \cdot 0.05\,\mathrm{m} = 0.03$$

Outline

The microwave scattering system was designed for directly measuring LH waves on TST-2

- The current drive efficiency on TST-2 is lower than what is predicted by GENRAY-CQL3D
- A microwave scattering diagnostics at 12-40 GHz is designed and being fabricated
- The LH fluctuation level estimated with AORSA is within the detectable range

- Future work
  - Detect LH waves
  - Investigate changes in the location of LH waves and their wavenumber spectrum for various parameters
  - Test GENRAY-CQL3D
  - Test full-wave codes (AORSA, TORLH)

References

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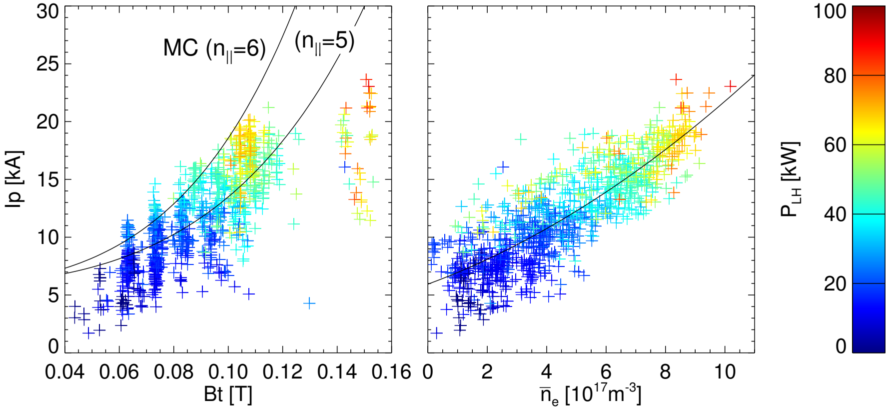
Outline

Strong correlation of plasma current and density leads to upper limit in the driven current at a given magnetic field



- Density limit substantially lower than expected at higher field?

LH accessibility condition

LH $\leftrightarrow$ FW mode conversion condition:

$$\frac{\omega_{pi}}{\omega} = N_\parallel Y \pm \sqrt{1 + N_\parallel^2 (Y^2 - 1)},$$

$$Y^2 = \frac{\omega^2}{\omega_{ce}\omega_{ci}}.$$

In terms of $N_\parallel$,

$$N_\parallel = \frac{\omega_{pi}}{\omega} Y \pm \sqrt{1 + \frac{\omega_{pi}^2}{\omega^2}(Y^2 - 1)}.$$

Launching the wave from the low-density side, the parameter is accessible if

$$N_\parallel > N_a = \frac{\omega_{pi}}{\omega} Y + \sqrt{1 + \frac{\omega_{pi}^2}{\omega^2}(Y^2 - 1)}.$$

Full-wave analysis will be performed

TORLH [Wright 2009]

- Finite Larmor radius code ($k_\perp \rho_L < 1$)
- θ: spectral ansatz
- ψ: finite element
- Coupled with CQL3D [Harvey 1992]

$\rightarrow$ Non-thermal electron distribution

- Weak absorption, multi-pass regime

$\rightarrow$ Full-wave effect may be important