Investigation of drift wave excitation: motivation & requirements

- **Fusion relevant: pressure gradients and magnetic field curvature**
  - Numerous experiments aimed at controlling drift waves performed in magnetically confined plasmas
  - However, these experiments *do not entirely* show that drift waves are launched, which makes any control of drift waves dynamics questionable!

- **Ultimate goal: controlling drift wave dynamics in a toroidal plasma**

- **Systematic externally-driven drift wave using an electrostatic antenna**
  - Highly reproducible plasma shots
  - Probe coverage of the plasma cross-section (detection)

- **Control parameters: poloidal wave number, magnetic field, antenna position**

- **Local wave dispersion properties and time-series statistics**

- **Direct comparison theory-experiment made possible**
### The TORPEX device

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius</td>
<td>1 m</td>
</tr>
<tr>
<td>Minor radius</td>
<td>0.2 m</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>$B \leq 0.1$ T</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>$\leq 1$ s</td>
</tr>
<tr>
<td>Neutral gas pressure</td>
<td>$10^{-4}$-$10^{-5}$ mbar</td>
</tr>
<tr>
<td>Injected <a href="mailto:power@2.45GHz">power@2.45GHz</a></td>
<td>$P_{RF} &lt; 50$ kW</td>
</tr>
<tr>
<td>Plasma density</td>
<td>$n \sim 10^{16}$-$10^{17}$ m$^{-3}$</td>
</tr>
<tr>
<td>Electron temperature</td>
<td>$T_e \sim 5$ eV</td>
</tr>
<tr>
<td>Ion temperature</td>
<td>$T_i \leq 1$ eV</td>
</tr>
<tr>
<td>Gas</td>
<td>H ($6 \times 10^{-5}$ mbar)</td>
</tr>
<tr>
<td>Ion sound Larmor radius</td>
<td>$\rho_s/a \sim 0.02$</td>
</tr>
</tbody>
</table>
Typical diagnostics: Langmuir probes

- HEXTIP 86-tip probe sampling at 250 kHz
- Poloidal probes with finer spatial resolution
  - $n \propto$ ion saturation current
  - Signals assumed 0 at edge
- Density fluctuation measurements

Field line topology
Drift wave Launching: Experimental Setup

- Four electrodes independently controlled
- Radially moveable antenna
- $\varphi$ = phase shift between adjacent electrodes
- $\omega$ the drive frequency
Synchronous detection of the k-resolved antenna excitation

- The detection of the wave excitation is performed using a digital lock-in technique applied to the probe signals

\[ S_{ref} = \Re(e^{i\omega t}); \text{ reference signal} \]

\[ S_p = A_p \cos(\omega p t + \delta_p) + \sum_{\omega'} A' \cos(\omega' t + \delta') \quad \text{Raw signal} \]

\[ S_T = 2S_{ref}S_p \]

\[ S_T = A_p \left[ \cos(\delta_p) + \cos(2\omega_p t + \delta_p) \right] + \sum_{\omega'} A' \cos[(\omega - \omega) t + \delta'] + \sum_{\omega''} A'' \cos[(\omega + \omega) t - \delta''] \]

\[ S_T = A_p + A'_{\omega=\omega_o} \cos(\delta_{\omega=\omega_o}) \quad \text{Low pass filter to extract the DC term} \]

- The magnitude of the detected signal is the density response
- In-phase and quadrature-phase signals provide the phase
- Phase measurements between probes yield the wavenumbers in the appropriate directions (radial, poloidal, parallel)
- Wavenumbers and density response are obtained as a function of the imposed k-poloidal
Nature of the instability in TORPEX

Largest fluctuations on LFS
*bad curvature* region acts as source

Drift-interchange instabilities

Exploit this to actively couple to the drift wave using a tunable antenna
Examination of the intrinsic dispersion relation (passive)

Spectral analysis shows the drift mode

Starting point for actively controlling drift wave dynamics
Density response modeling

\[
H(\omega) = \frac{\omega}{\varepsilon(\omega, k)} A(k_g) = \omega - k_g V_{E \times B} \varepsilon(\omega, \vec{k}) = (1 + k^2 \rho_s^2) \omega^2 - (\omega^* - \omega_R) \omega - k^2_c c^2
\]

\[
A(k_g) = \frac{\sin\left(\frac{k_g d}{2}\right)}{k_g d} \left[ \cos\left(\frac{k_g D}{2}\right) + \cos\left(\frac{3k_g D}{2}\right) \right]
\]

\[
H(\omega) \Rightarrow H(\omega + i\gamma)
\]

- Examination of the linear density response
- Only the damping term is considered as a free parameter
- Attempt to match the modeled response with the measured response
Antenna radial scan $\rightarrow$ optimization $\Delta R = R - R_0$
Plasma response: real and imaginary parts

"Wave-like" pattern but need to identified this disturbance!
Test: density response vs field reversal

- Toroidal field sign-reversal is consistent with the sign of the excited wavenumber!
- Two possible routes: antenna-induced disturbance or wave?
“Properties” of the antenna-induced disturbances @ optimum radial position

Using array of probes sampling both the poloidal and radial directions: Example
Only the weakly damped peak is the drift wave mode.

Strongly damped disturbances are perhaps due to spontaneous plasma response.
Summary and conclusions

- Design of a tunable antenna in k-poloidal
- Electrostatic wave launching in a toroidal plasma
- Optimization of both frequency and wavenumber
- Testing the nature of the “wave-like” pattern using a model compatible with the dispersion relation supported by the plasma dynamics
- Model includes both the antenna spectrum and the electrostatic dielectric
- Enables the identification of a weakly-damped drift wave mode
- Other modes are strongly damped and not compatible with the dispersion relation
  - Spontaneous plasma response
  - Nonlinear wave interaction (i.e., ExB nonlinearity)
- Future studies: investigation of the density response at zero frequency
  - Modulational instability of the drift wave

<table>
<thead>
<tr>
<th>$\omega$(kHz)</th>
<th>$\delta\omega$(kHz)</th>
<th>Amp(a.u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5.6</td>
<td>1.8</td>
<td>0.58</td>
</tr>
<tr>
<td>7.9</td>
<td>1.3</td>
<td>0.52</td>
</tr>
<tr>
<td>21.2</td>
<td>3.8</td>
<td>0.58</td>
</tr>
<tr>
<td>36</td>
<td>1.5</td>
<td>0.88</td>
</tr>
</tbody>
</table>
Outlook: Future Investigation

Experimental developments

- **Diagnostics development**
  - Laser Induced Fluorescence (LIF) in TORPEX to resolve in ion phase-space the density fluctuations.
  - Fast camera for non-perturbative turbulence imaging,

- **Upgraded EC power control for macroscopic transport studies** (see Mario)

- **Supra-thermal ion beam and detector for investigation of interaction of fast ions with drift (Alfvén) waves** (collab. W.Heidbrink, UCI)

- **Use ohmic transformer to close field lines and explore transition in turbulence character** (see Mario’s Poster)

Theory & Experiment comparison

- **3D, two-fluid simulation using ESEL code adapted to TORPEX** (collab. V.Naulin, Risoe)
First results with fast-framing camera

- Fast-framing camera: Photron Ultima APX-RS.
- 1024 x 1024 pixel, 10Bit resolution, monochrome.
- Max frame rate 250kHz at reduced chip size.
- 2 s of acquisition.

- First images during the Ohmic phase.
- Tangential view of the plasma.
- 8kHz frame rate, 17μs int. time, 416x384 pixel.
Fast ion source and detector for TORPEX


- 100eV-1keV ions energy;
- Low gas load aluminosilicate Li-6 ion emitter;
- 10-30μA beam current (effect Schottky);
- High voltage modulable power supply;
- Light ions to facilitate the ion-electron interactions Li-6;
- Small size (src+det) to minimize perturbations.
Torpex LIF system design

System A

Fresnel Lenses

Laser

Collection volume

\( \varnothing = 12 \text{ mm} \)

Light rays

Scan over 10 cm

Torus cross-section

Fiber Optics

\( \varnothing = 2 \text{ mm} \)

NA = 0.5

\( \eta \sim 99\% \rightarrow \text{no vignetting} \)

Courtesy Y. Andrebe
System B

- Laser
- Collection volume
  - \( \varnothing = 12 \text{ mm} \)
- Light rays
- LFS
- Torus cross-section
  - Scan over 10 cm

Fiber Optics
- \( \varnothing = 2 \text{ mm} \)
- \( \text{NA} = 0.5 \)
- \( \eta \sim 72 \% \)
- Vignetting 50 \%

Lenses

\( \varnothing = 40 \text{ cm} \)
Code validation against *basic* experiments

- Basic experiments can provide more overlap
  - Spatially resolved measurements available
  - Higher flexibility
  - More available control parameters

- Validation scenario
  - Assume general model framework applies
ESEL – TCV SOL comparison

NSTX Gas-puff imaging

Time = 0µs

 Courtesy of R. Maqueda

 Courtesy of A. Nielsen

 Courtesy of J. Horacek

<\Gamma_r^[m^2s^{-1}]>
The ESELTPX code

- Global nonlinear Hasegawa-Wakatani code (collab. V. Naulin, Risø, Dk)
- Derived from ESEL code adding parallel dynamics $\rightarrow$ 3D
- Goal: global experiment-theory comparisons

Density equation:
$$\frac{\partial n}{\partial t} = -\frac{\phi}{B} \frac{n}{B} - \frac{1}{B} \frac{nT}{n} \nabla_\parallel (nV),$$

Vorticity equation:
$$\frac{\partial \omega}{\partial t} = -\frac{\phi}{\omega} - \frac{1}{n} \frac{1}{B} \frac{nT}{n} + \frac{1}{n} \nabla_\parallel (n(U - V)), $$

\[ T = \text{const} \]

ExB advection

Interchange drive

Parallel dynamics

Ions
$$\frac{\partial U}{\partial t} = -\frac{\phi}{B} \frac{U}{B} - \nabla_\parallel \phi - n\nu_\parallel (U - V),$$

Electrons (neglect inertia)
$$0 = \nabla_\parallel \phi - \frac{1}{n} \nabla_\parallel (nT) + n\nu_\parallel (U - V).$$

Dissipation
$$\frac{\partial}{\partial t} \mu = \frac{\partial}{\partial t} - \mu_\perp \nabla_\perp^2 - \mu_\parallel \nabla_\parallel^2$$
Proof of principle: initial-value problem

- Start with density blob in the center
- Identical setup apart from parallel density diffusion

**without** parallel diffusion

**with** parallel diffusion

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Status ESELTPX

- Pseudo 3D and full 3D variant under development

- Significant improvement of the code structure
  - Data and run management

- Progress on implementation of advective parallel dynamics and sheath boundary conditions
  - Run test configurations (parallel outflow, ...)

- Problems
  - Time step much reduced if parallel advection included
  - Formulation of sheath boundary conditions

- No results for experiment-theory comparison yet
Sign-up for preprints