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Development of the synthetic diagnostic for the ultra-fast swept reflectometer

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1. Motivation:
   Role of turbulence in plasma confinement

2. Ultra-fast swept reflectometer
   Diagnostic capabilities for turbulence measurements

3. Synthetic diagnostic
   Project progress
1. Motivation: 
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2. Ultra-fast swept reflectometer 
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Confinement is limited by turbulent transport

Plasma in a tokamak must be:

- hot and dense at the core
- cool at the edge

$\rightarrow$ gradients $\rightarrow$ turbulence

Turbulence should be understood, predicted and reduced for a better confinement

**Objective:**
Investigate turbulence during confinement changes

$\delta T$ in the ASDEX Upgrade tokamak with GENE code [genecode.org]
L-H transition – crucial issue for fusion

low confinement (L-mode) $\rightarrow$ high confinement (H-mode)

- Transport of heat and particles reduced
- Drift velocity $\vec{v}_{E \times B} = \frac{\vec{E} \times \vec{B}}{B^2} \propto E_r$
- Increase of the radial electric field creates $E \times B$ shear flow
- Shear flow suppresses turbulence

$E_r \propto E_r$

[F. Wagner, PRL1982]

[E. Viezzer, PPCF 2014]
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• **UFSR** developed at CEA for Tore Supra and WEST tokamaks, transferred to ASDEX Upgrade (2013–2016) supported by EUROfusion

• 50–102 GHz X-mode

• Acquisition 2Gs/s

• Sweep time 1 μs

[F. Clairet, RSI 2017]
Turbulence properties measured by UFSR

- Density profiles with 1 µs resolution
- 1D wave propagation simulation → radial wavenumber spectra
- Density fluctuation (turbulence level)
- Frequency spectra up to 400 kHz
- Correlation length and time

- 2D effects to be considered

[A. Medvedeva, IRW 2015]
Background flow \((E_{r0})\) evolution during I-phase

Proxy for radial electric field:

\[
E_r \approx \frac{\nabla p_e}{en_e} = T_e \frac{\nabla n_e}{en_e} + \frac{\nabla T_e}{e} = E_{r0}
\]

[F. L. Hinton, RMP 1976]

\(E_{r0}\) minimum (at \(\rho_{pol} = 0.98\)) deepens during I-phase from \(-5\) to \(-20\) kV/m
Turbulence and $E_{r0}$ oscillate during I-phase

- Deep negative values of $E_{r0}$ appear between the turbulence bursts
- Crash of $E_{r0}$ happens together with the turbulence increase

Established I-phase might be explained by edge instabilities causing a fast relaxation of pressure (turbulence and flow in phase)

Edge coherent modes appear in the pedestal region and might play a role

[A. Medvedeva, PPCF 2017]
Edge instabilities appear during I-phase

In the pedestal region $0.95 < \rho_{pol} < 1$ the fluctuation amplitude decreases, the spectra become narrower during the I-phase and in H-mode due to the radial electric field shear.

FFT $(A(t)e^{i\Phi(t)})$

Edge coherent modes

[A. Medvedeva, 45th EPS 2018, PPCF accepted]
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   Project objectives and progress
Spontaneous organisation of a set of regularly spaced weak transport barriers: ExB staircase predicted by GYSELA

Project at the crossroads between theory, simulation and experiments
- Turbulence map simulated with gyrokinetic code
- Finite Difference Time Domain 2D code for wave propagation
- Reproduce frequency and wavenumber spectra, correlation length and time
- Compare with turbulence code
Turbulence map simulated with gyrokinetic code

Low collisional plasma → gyrokinetic description

- flux-driven → mimic experiments
- self-consistent interplay btw core, edge & simplified SOL model
- global description: kinetic ions & adiabatic or kinetic trapped electrons
- self-organised $E_r$ well

Density map from GYSELA, $10^{19}$ m$^{-3}$

RMS of $\delta n/n$ [in %]

Normalised radius $\rho$

$E_r \sim \nabla p / ne$

Experimental

[GYSELA SOL & limiter]

$[G. \text{ Dif-Pradalier}]$
Finite Difference Time Domain 2D code

• Finite Difference Time Domain 2D full wave code for wave propagation [Yee 1966, Da Silva 2014]

![Diagram showing finite difference grid with labels for Ey, Jy, Hz, Ex, Jx]

Soft source: \( H_z(kdx, y, ndt) = H_z(kdx, y, (n - 1)dt) + e^{j\omega(ndt)} e^{-\frac{(y-y_0)^2}{\sigma^2}} \frac{A_0}{\sqrt{\varepsilon_0\mu_0}} \)

Measured signal: \( E_n^y(x_s, y_s) = A_0^* e^{j\omega_0 ndt} + a_1^* e^{j(\omega_0 ndt - \phi)} \)

Calculation speed (Python+C): 1000 x 1000 x 5000 points 10min for \( F_0 \)

\[ dt = \frac{1}{40f_0} = 5 \cdot 10^{-13} s, \quad dx = 2cdt \]
Further development: sweep simulation

Sweep: \[ \omega_0 \rightarrow \omega = \omega_0 + v_\omega t \]

Source: \[ e^{i(\omega_0 t + v_\omega t^2 + \Delta \varphi(t))} \]

+ Mimic real reflectometer
  - Optimised calculation speed
  - 1 \(\mu\)s sweep 2 000 000 points \(\rightarrow\) 70 hours
    0.01 \(\mu\)s sweep 20 000 points \(\rightarrow\) 1 hour
    \[ F_{\text{beat}} \approx 400 \text{ MHz} \rightarrow 40 \text{ GHz} \]

- Difficulties of signal extraction
Sign inversion of the spectra asymmetry during I-phase can be explained by a sawtooth-like cutoff layer.

Further application:
- modes’ size, flow detection, turbulence level and wavenumber spectra,
- correlation analysis.

Experiment

2D code application
Synthetic diagnostic: outlook

- Create 2D full wave code
- Couple with GYSELA turbulence maps
- Parallel calculation for (F,t) – 10 min each
- Optimise calculation speed by sweeping of frequency
  - Integrate 2D code to the loop method of wavenumber/turbulence level analysis
  - Add functions for correlation analysis
  - Reproduce spectra for various turbulence scenarios for ASDEX Upgrade and WEST data, compare with GYSELA and GENE
Conclusions

- First studies of the electron density and density fluctuations dynamics during L-H transitions in ASDEX Upgrade have been performed with a time resolution of 1 μs using 1D wave propagation simulation.

- 2D full wave code is developed for interpretation of ultra-fast swept reflectometer data and coupled with GYSELA and GENE turbulence simulations.

- Synthetic diagnostic is being optimised for further data analysis.
Slow sweep simulation

Ey of probing wave

Z, m

R, m

F_{\text{beat}}

1e2

5000 10000 15000 20000 25000 30000 35000 40000
time points
Loop method for wavenumber spectra

Signal phase fluctuations are induced by density fluctuations: $S_{\delta n}(k) = T(k) \cdot S_{\delta \Phi}(k)$

Density fluctuations level:

$$\left(\frac{\delta n}{n}\right)^2 = \frac{1}{k_{\text{max}} - k_{\text{min}}} \int_{k_{\text{min}}}^{k_{\text{max}}} S_{\delta n}(k) \, dk$$
Density fluctuation dynamics: $k_r$-spectra

- Turbulence level falls towards core
- After L-H transition density fluctuations with small $k_r$ are suppressed in the pedestal region

$$\rho_s = \frac{\sqrt{T_e/m_i}}{\Omega_{ci}}$$

ion-sound Larmor radius