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

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<sup>8</sup>For a list of members, see H.Meyer et al, Nucl. Fusion 57 102014 (2017)



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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

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Plasma in a tokamak must be:

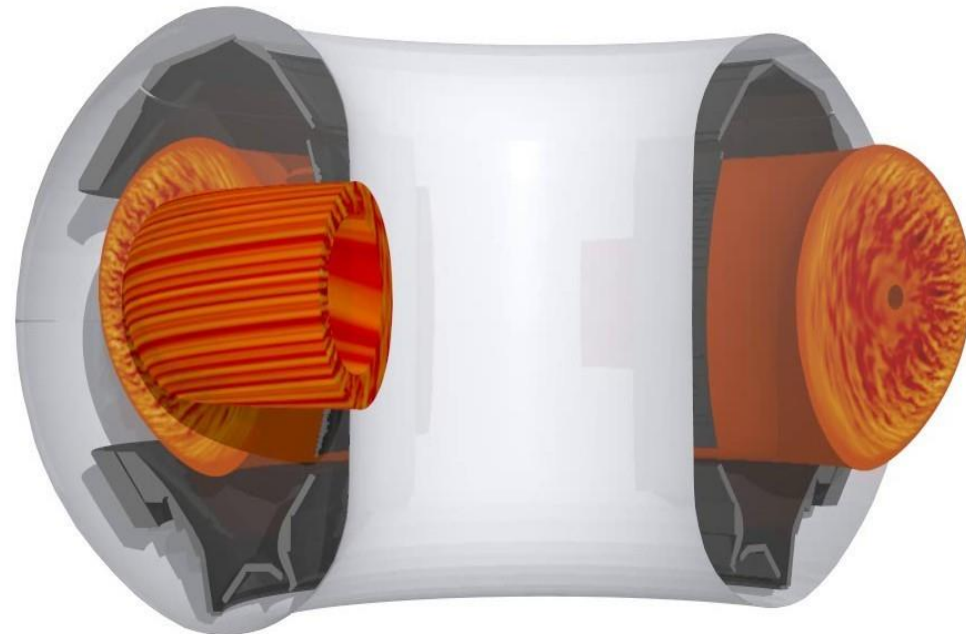
- hot and dense at the core
- cool at the edge

} → gradients → turbulence

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

**Objective:**

Investigate turbulence during confinement changes

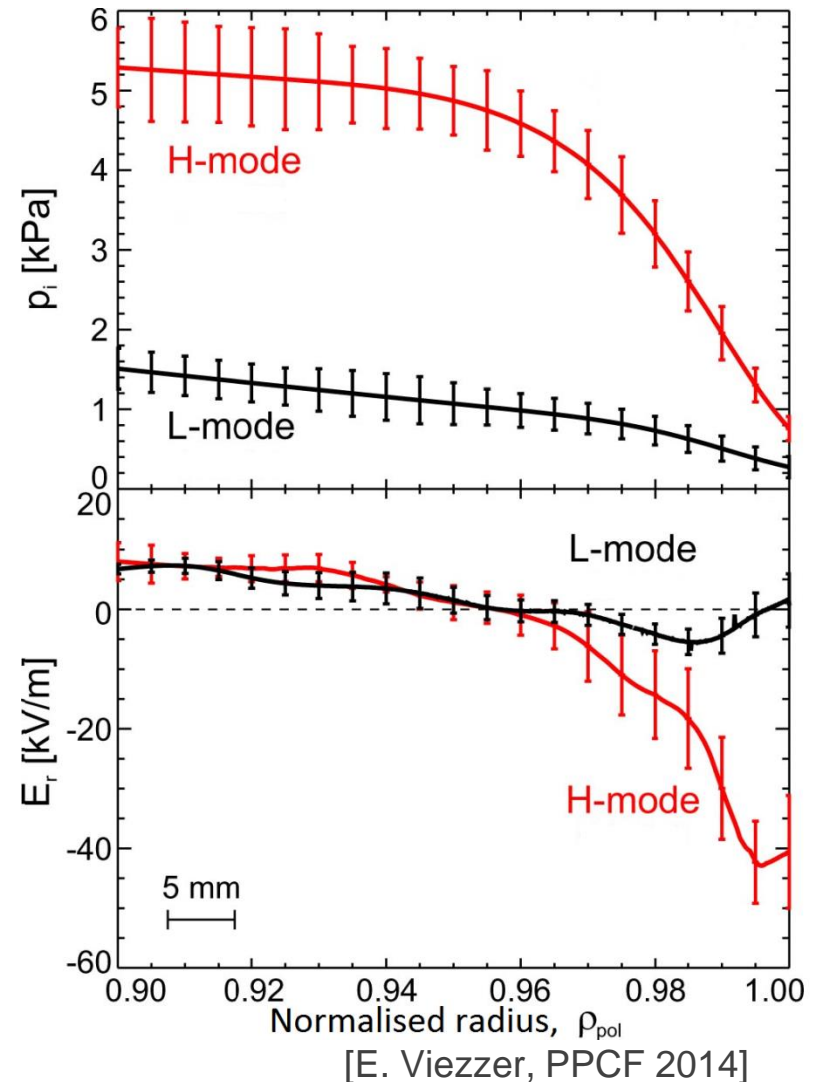
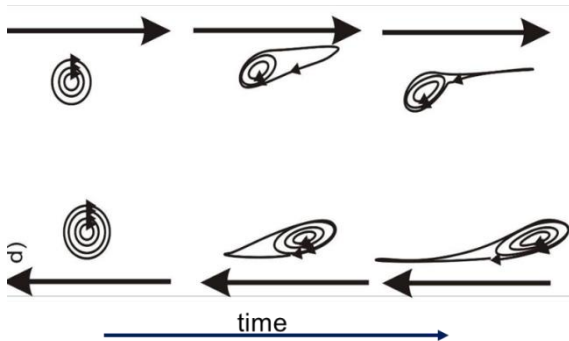


$\delta T$  in the ASDEX Upgrade tokamak with GENE code  
[genecode.org]

low confinement (L-mode) → high confinement (**H-mode**)

[F. Wagner, PRL1982]

- 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**



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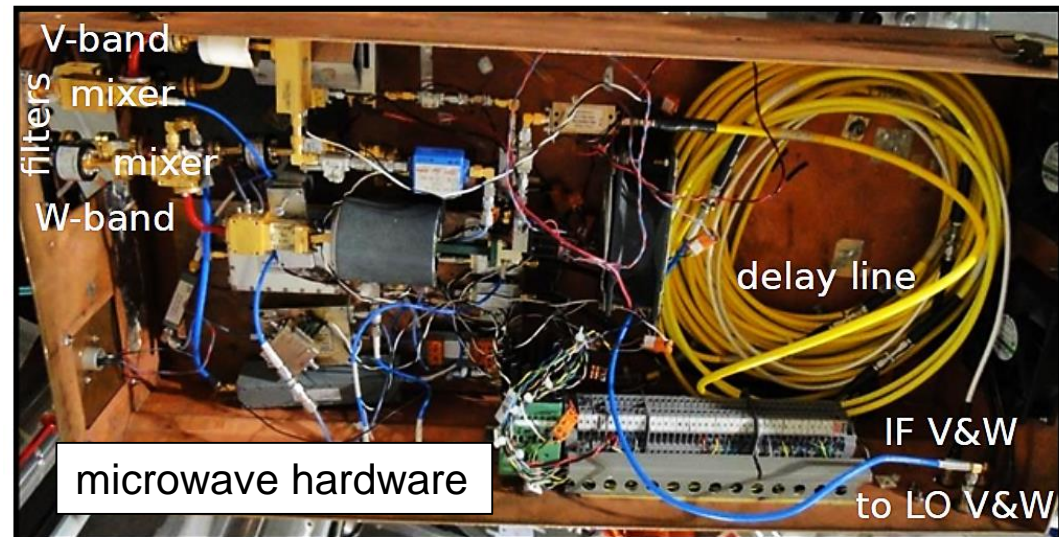
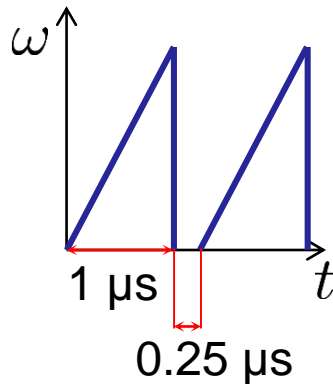
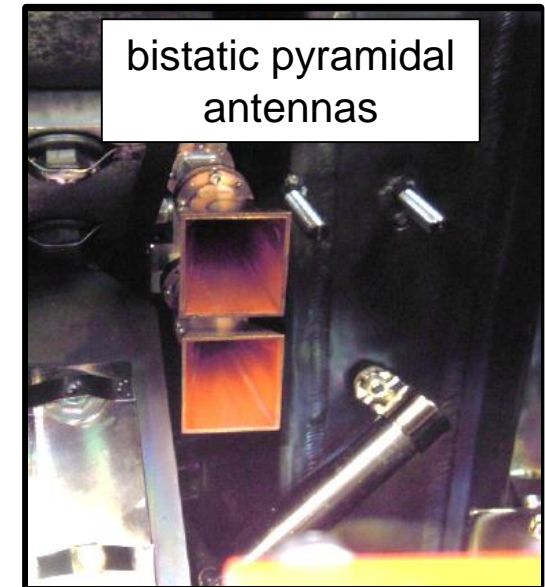
## 2. Ultra-fast swept reflectometer

Diagnostic capabilities for turbulence measurements

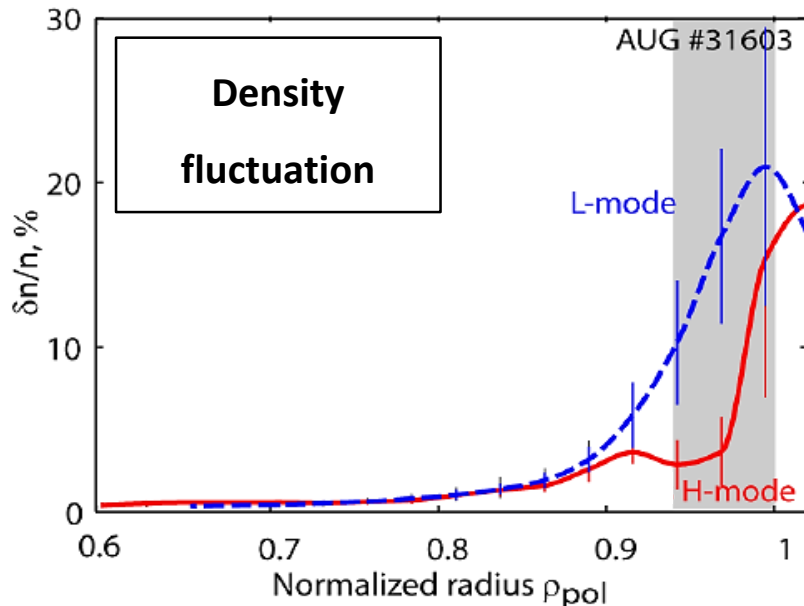
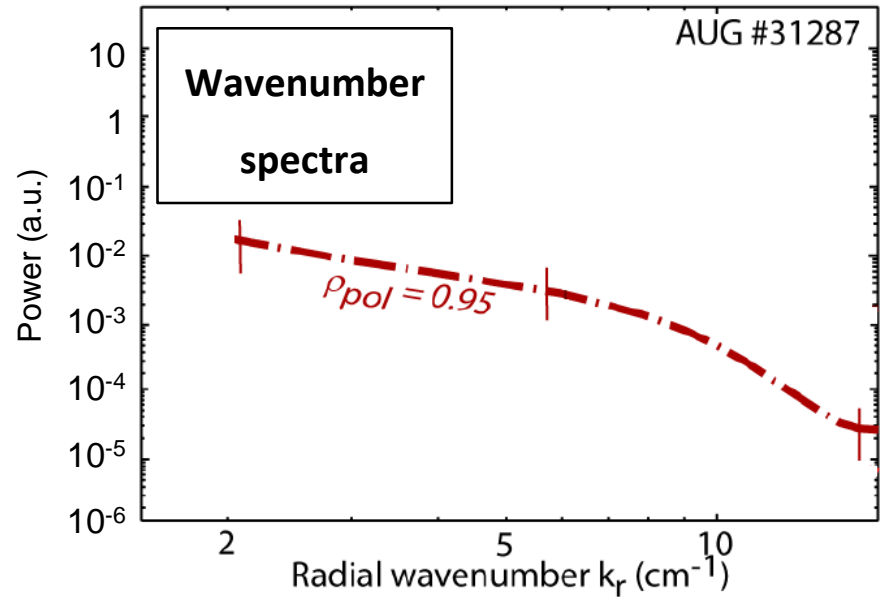
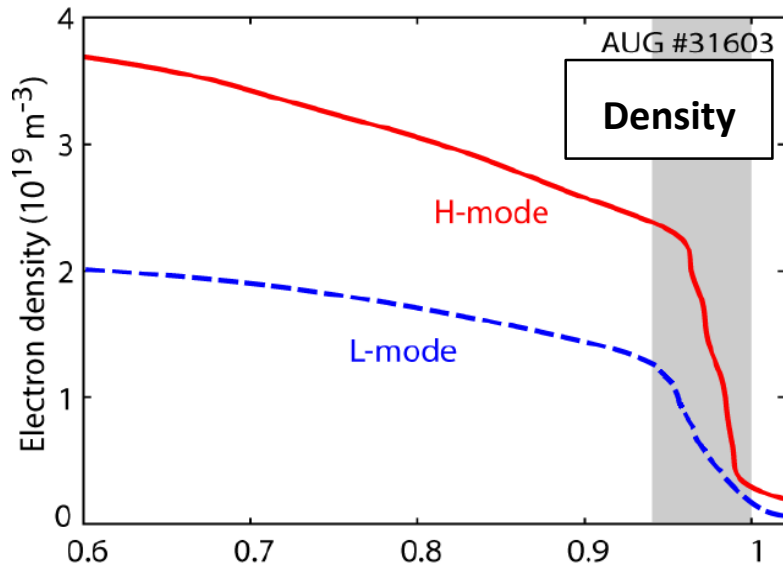
## 3. Synthetic diagnostic

Project progress

- **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  $\mu\text{s}$   
[F. Clairet, RSI 2017]







- Density profiles with  $1 \mu\text{s}$  resolution
- 1D wave propagation simulation  $\rightarrow$  radial wavenumber spectra
- Density fluctuation (turbulence level)
- Frequency spectra up to 400 kHz
- Correlation length and time
- **2D effects to be considered**

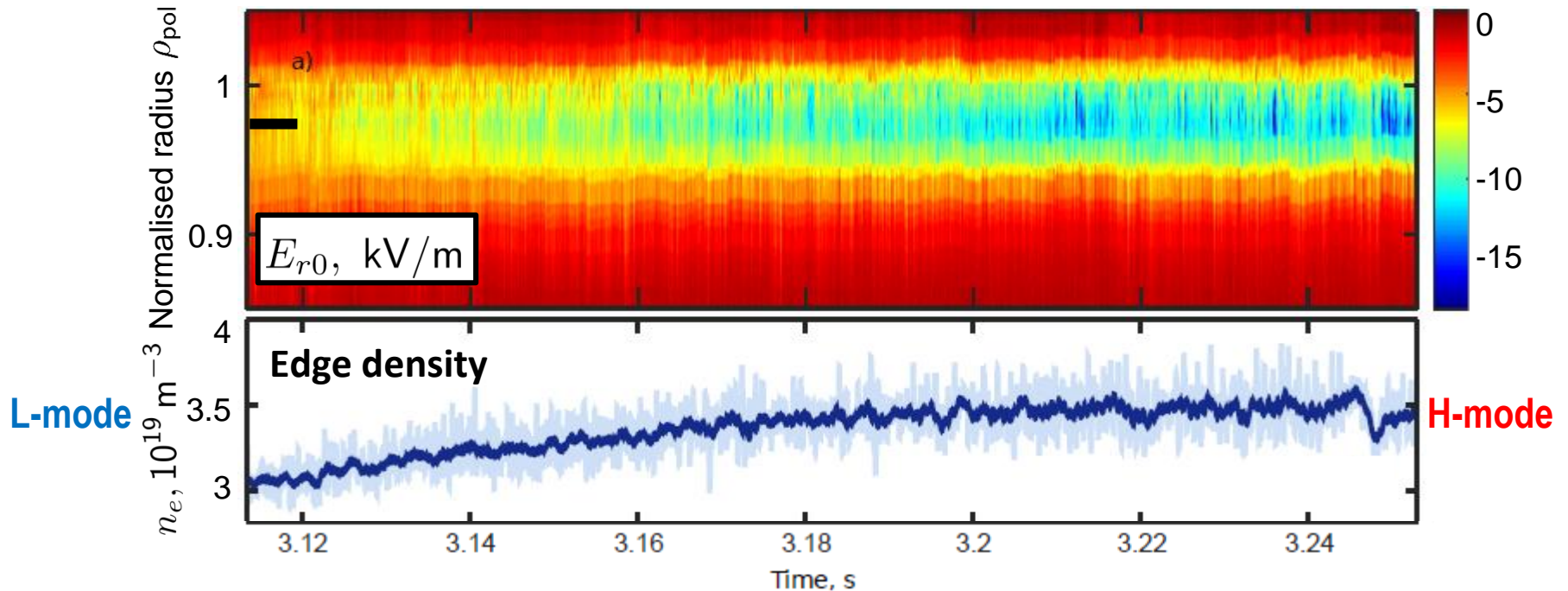
[A. Medvedeva, IRW 2015]

Proxy for radial electric field:

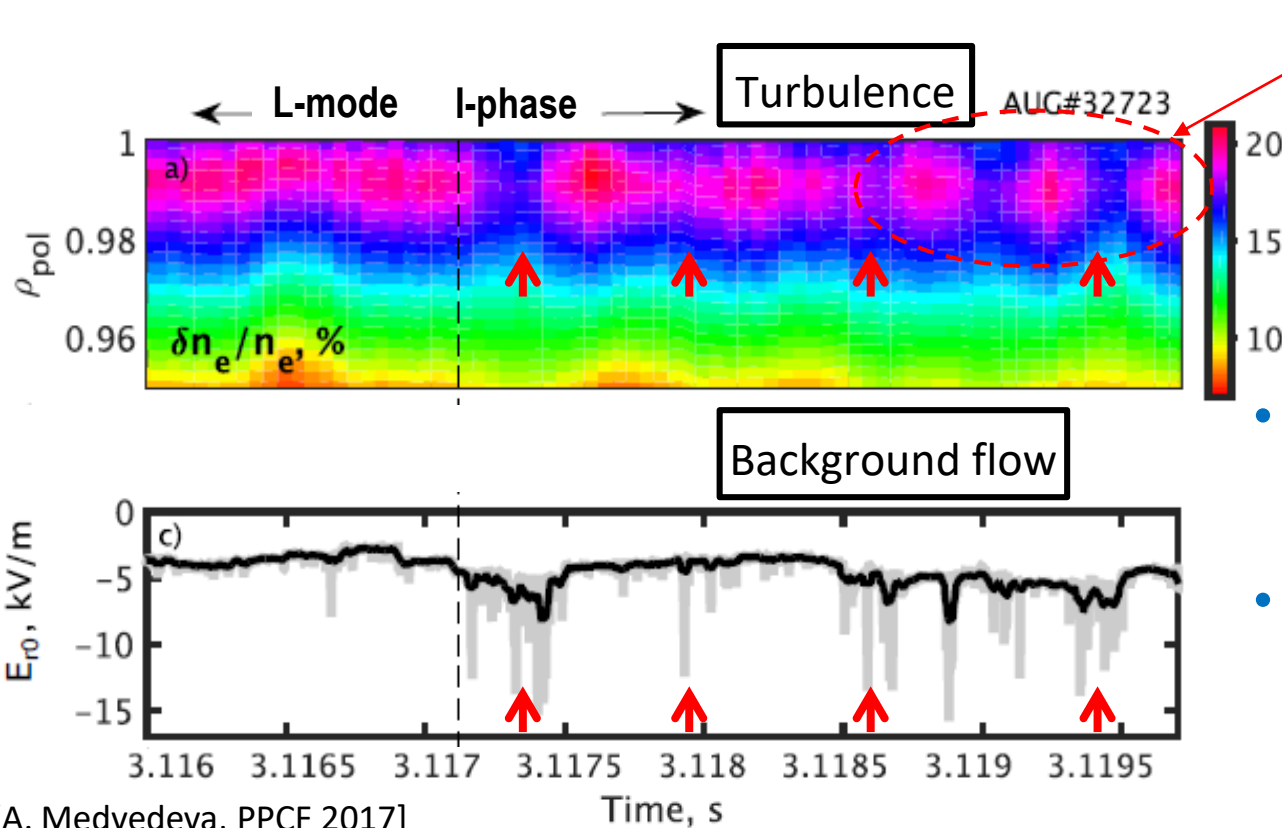
UFSR

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

[F. L. Hinton, RMP 1976]



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

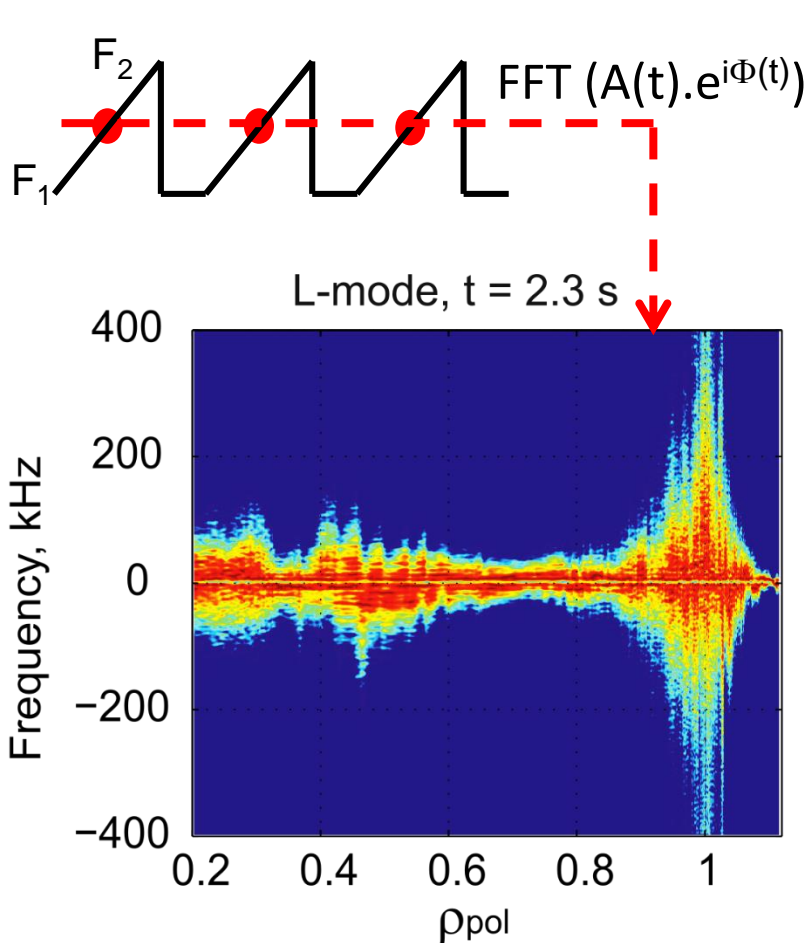


regular oscillations in established I-phase

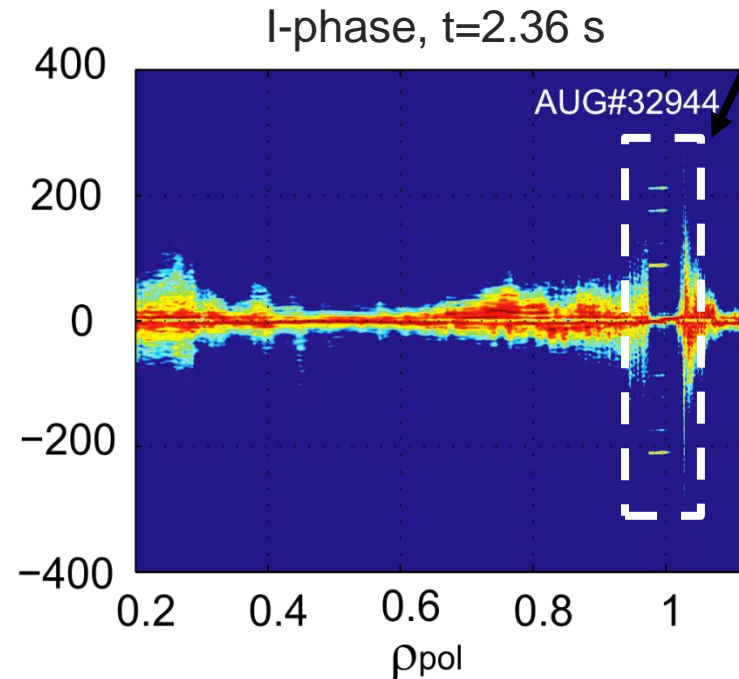
- Deep negative values of  $E_{r0}$  appear between the turbulence bursts
- Crash of  $E_{r0}$  happens together with the turbulence increase

[A. Medvedeva, PPCF 2017]

- 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



Edge coherent modes  
[A. Medvedeva, 45th EPS 2018, PPCF accepted]



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

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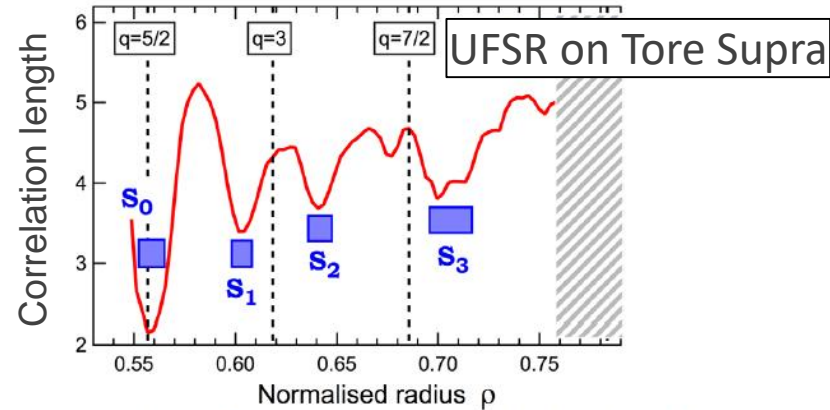
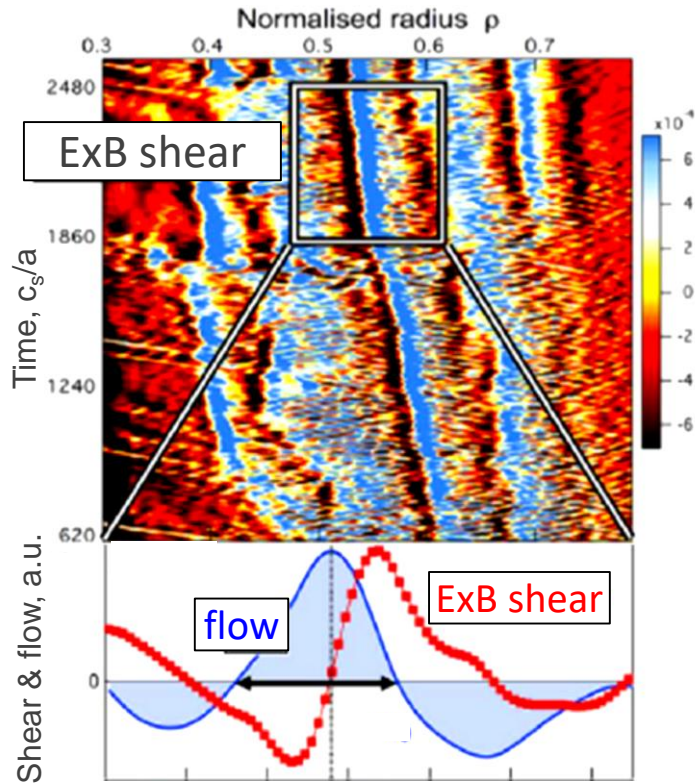
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Diagnostic capabilities for turbulence measurements

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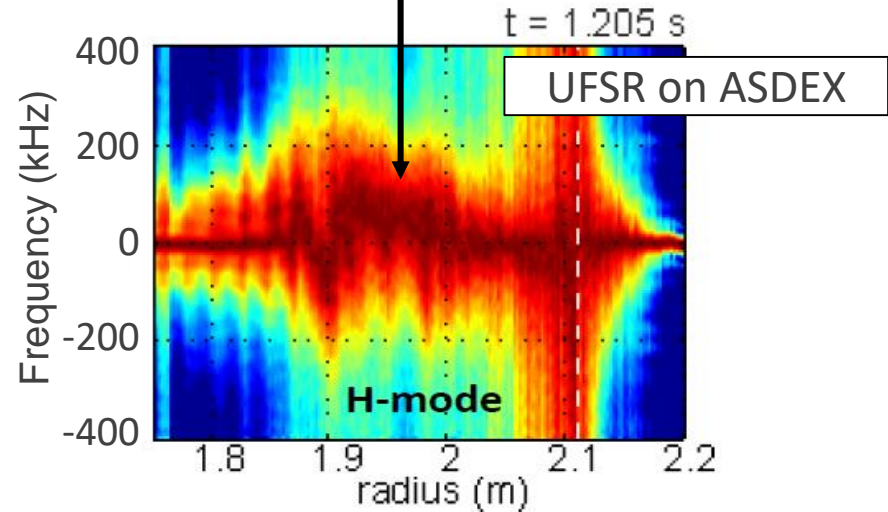
Project objectives and progress

Spontaneous organisation of a set of regularly spaced weak transport barriers:  
ExB staircase predicted by GYSELA

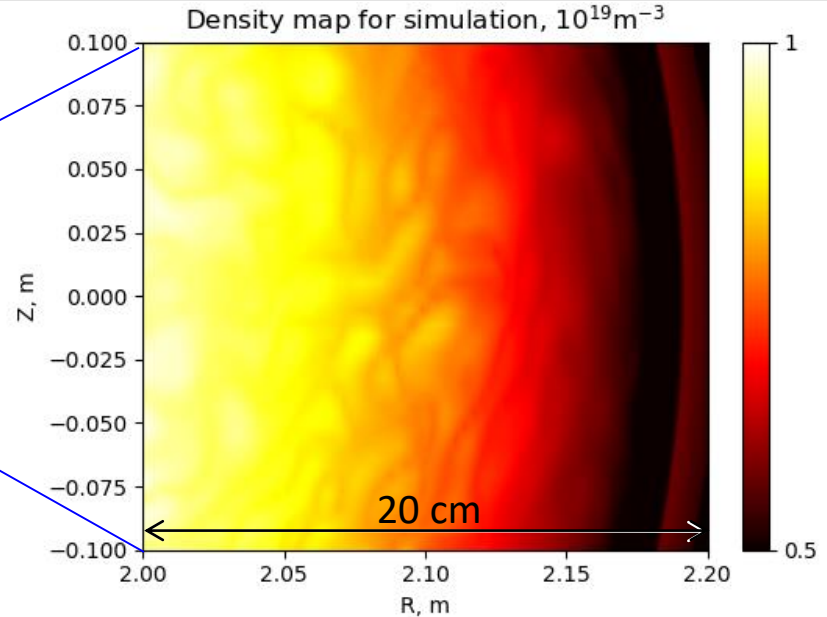
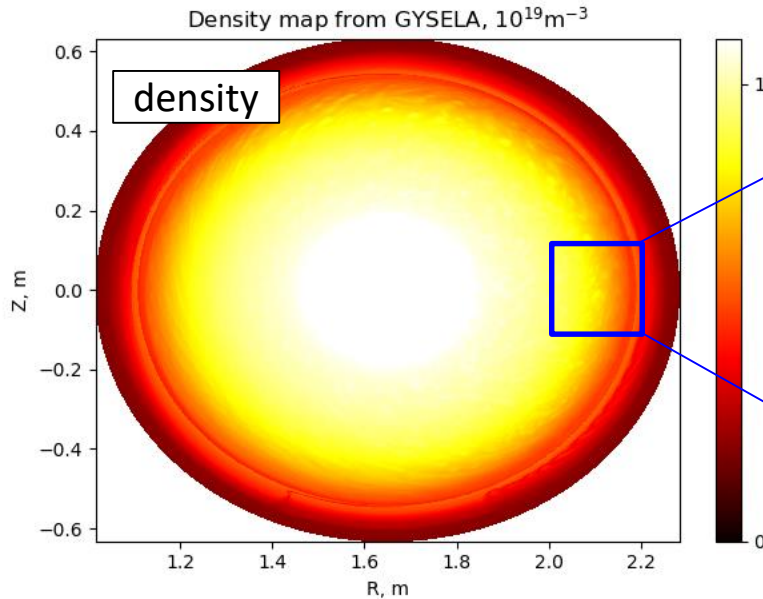


[G. Dif-Pradalier et al., PRL 2015, NF 2017]  
[G. Hornung, NF 2017]

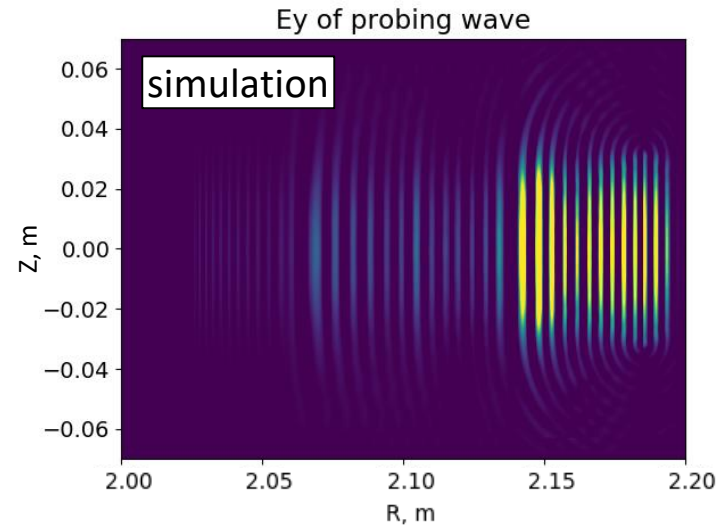
Staircase structure? Flow dynamics?

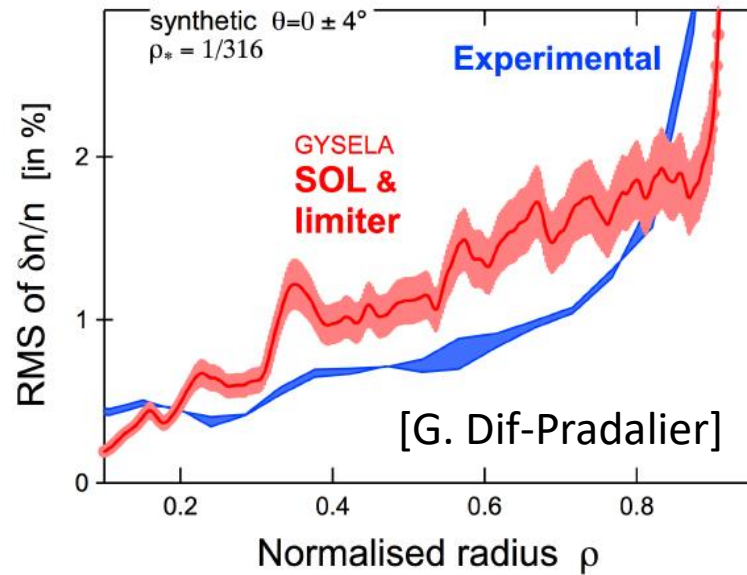
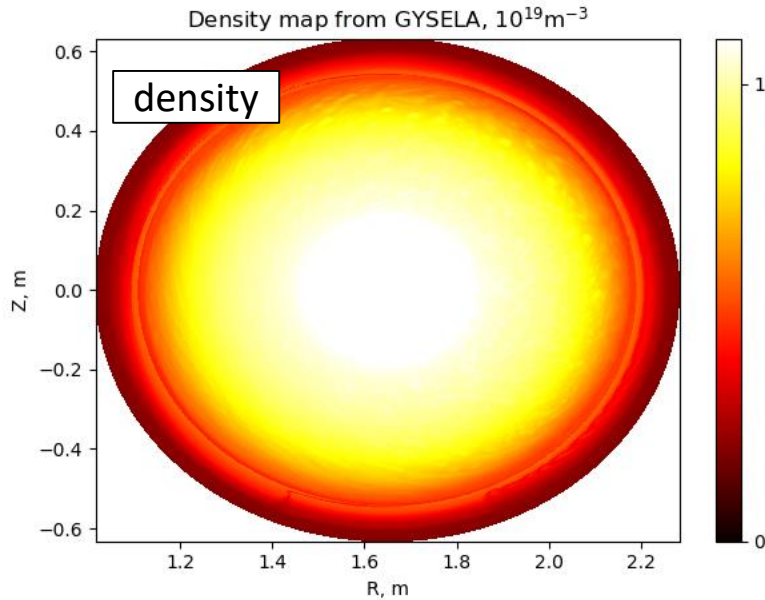


Project at the crossroads between theory, simulation and experiments



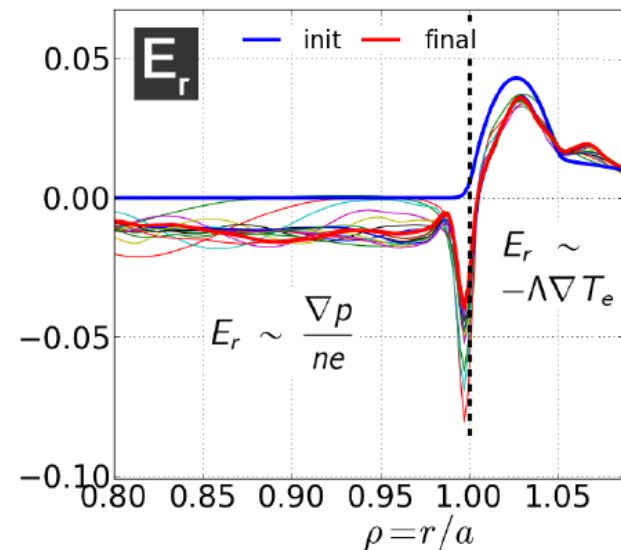
- Turbulence map simulated with gyrokinetic code
- ↓
- Finite Difference Time Domain 2D code for wave propagation
- ↓
- Reproduce frequency and wavenumber spectra, correlation length and time
- ↓
- Compare with turbulence code





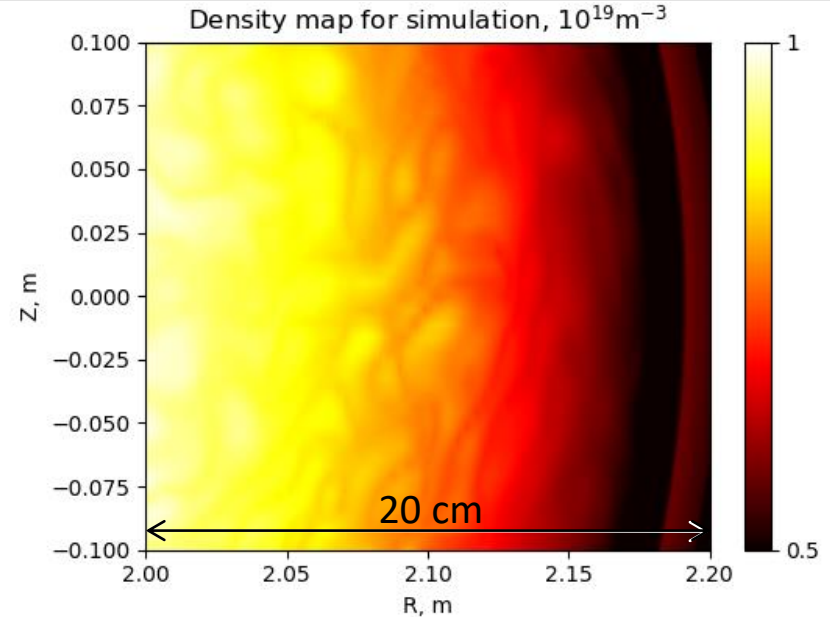
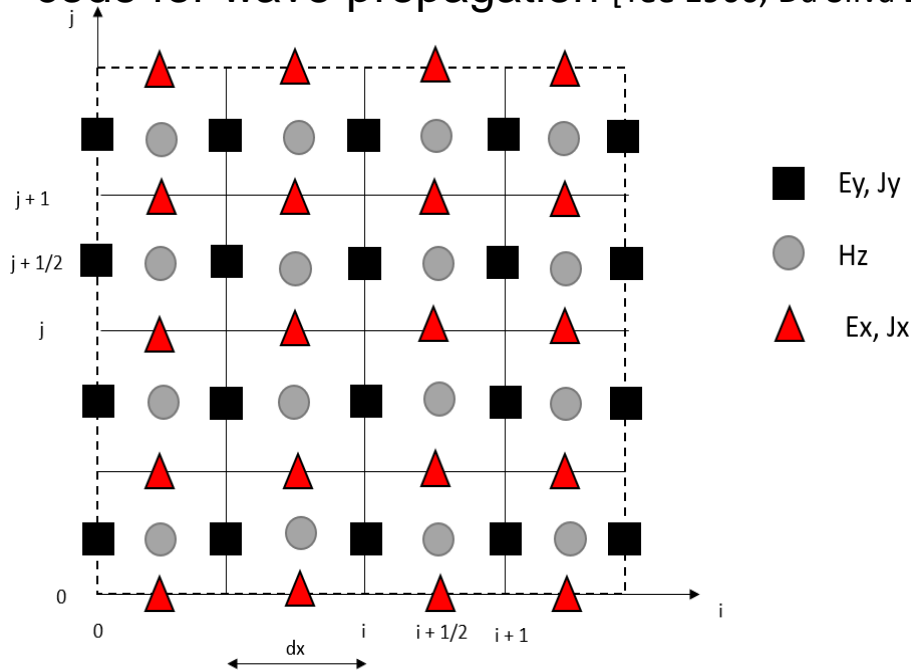
Low collisional plasma  $\rightarrow$  gyrokinetic description

- flux-driven  $\rightarrow$  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





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



$$dt = \frac{1}{40f_0} = 5 \cdot 10^{-13} \text{ s}, dx = 2c dt$$

Soft source:  $H_z(kdx, y, ndt) = H_z(kdx, y, (n-1)dt) + e^{j\omega(ndt)} e^{-\frac{(y-y_0)^2}{\sigma^2}} \frac{A_0}{\sqrt{\epsilon_0 \mu_0}}$

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

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

$x$ 
 $y$ 
 $t$

Sweep:  $\omega_0 \rightarrow \omega = \omega_0 + v_\omega t$

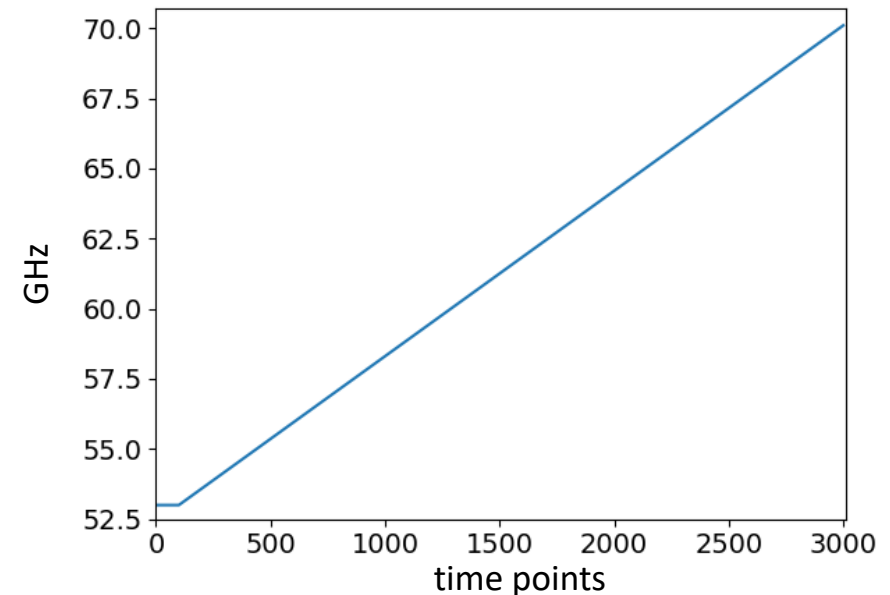
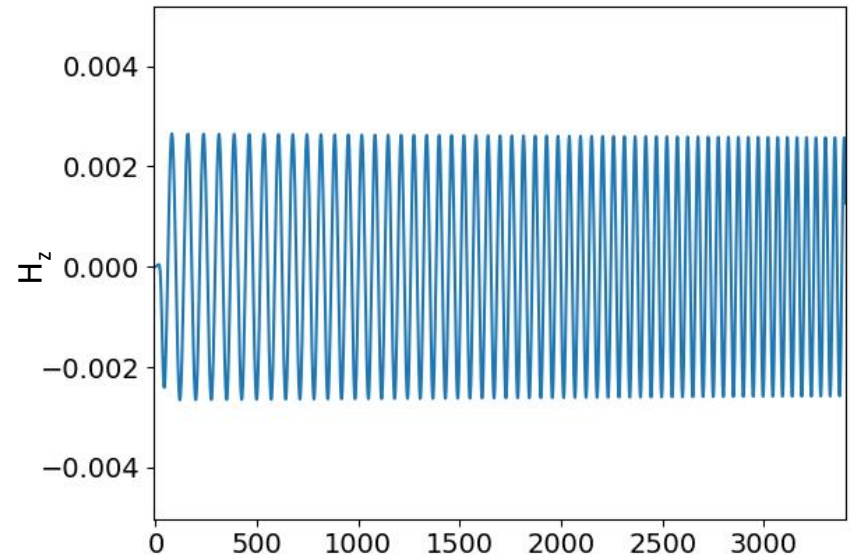
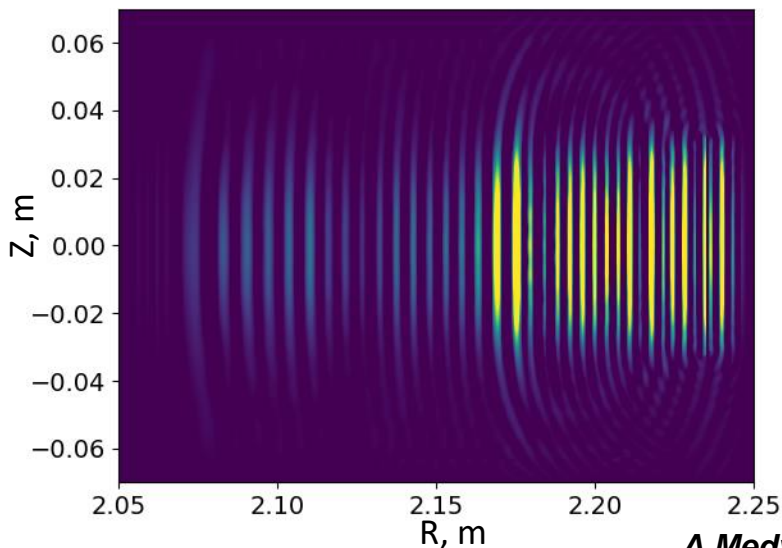
Source:  $e^{i(\omega_0 t + v_\omega t^2 + \Delta\varphi(t))}$

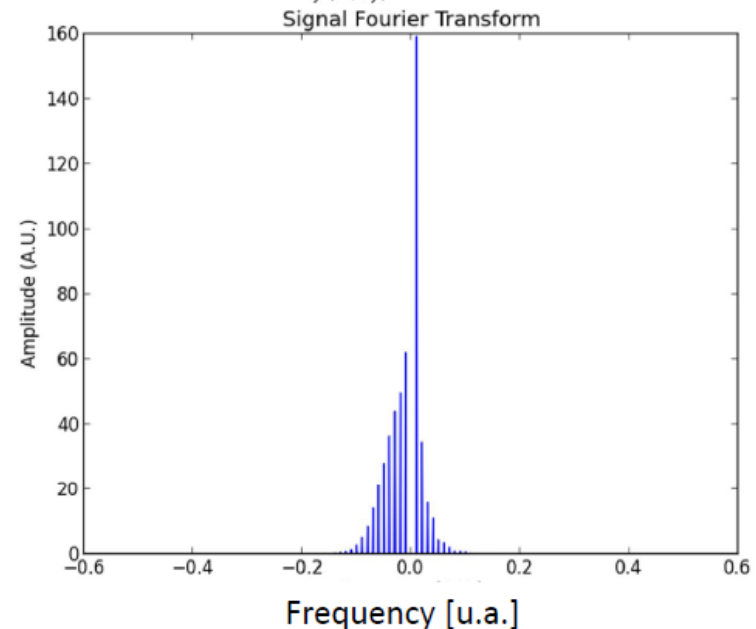
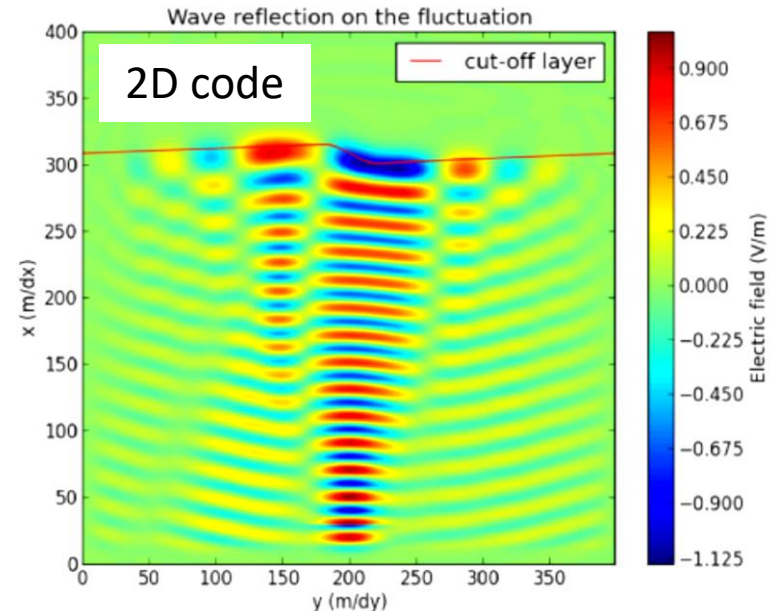
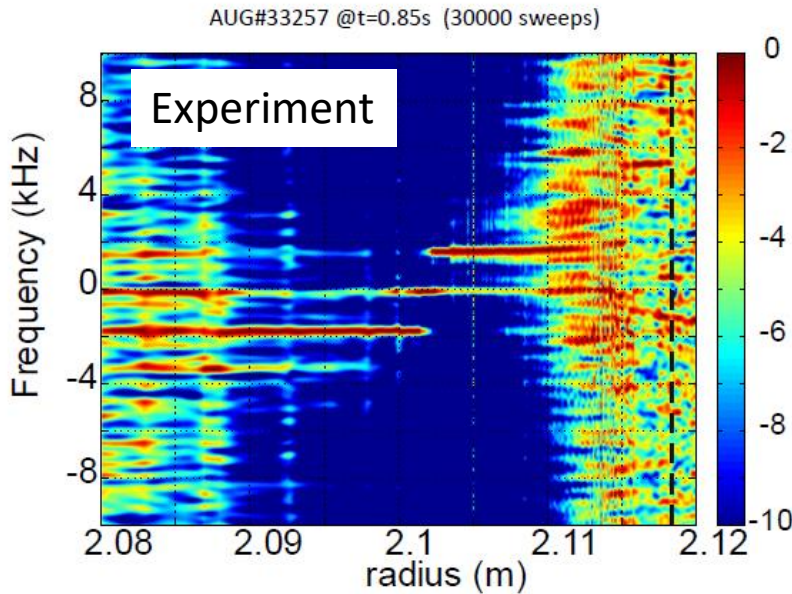
+ Mimic real reflectometer

- Optimised calculation speed
- 1  $\mu\text{s}$  sweep 2 000 000 points  $\rightarrow$  70 hours
- 0.01  $\mu\text{s}$  sweep 20 000 points  $\rightarrow$  1 hour

$$F_{beat} \approx 400 \text{ MHz} \rightarrow 40 \text{ GHz}$$

- Difficulties of signal extraction





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

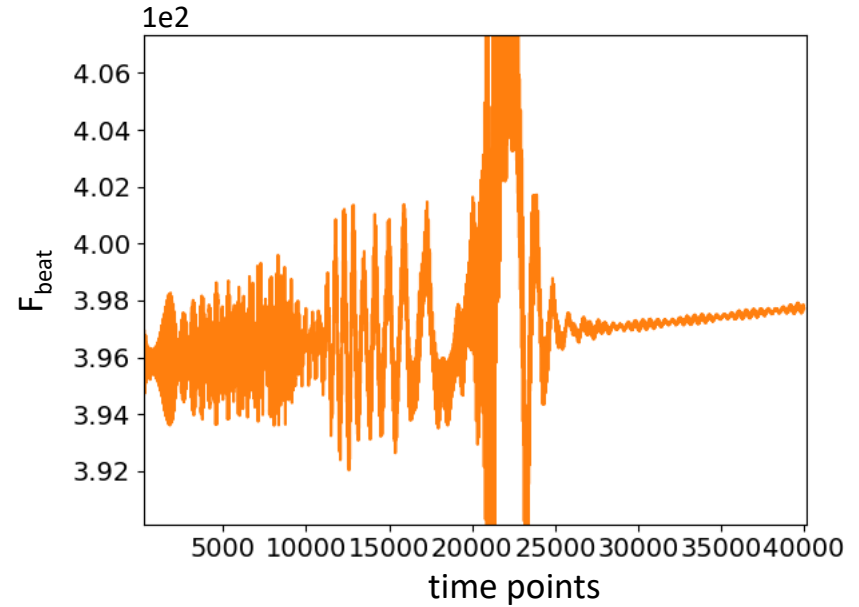
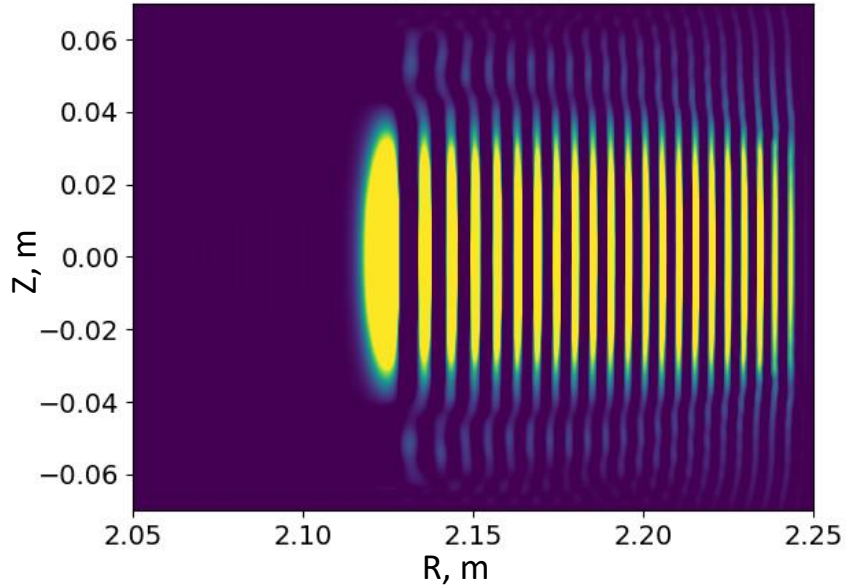
Further application:  
 modes' size, flow detection, turbulence level and wavenumber spectra, correlation analysis

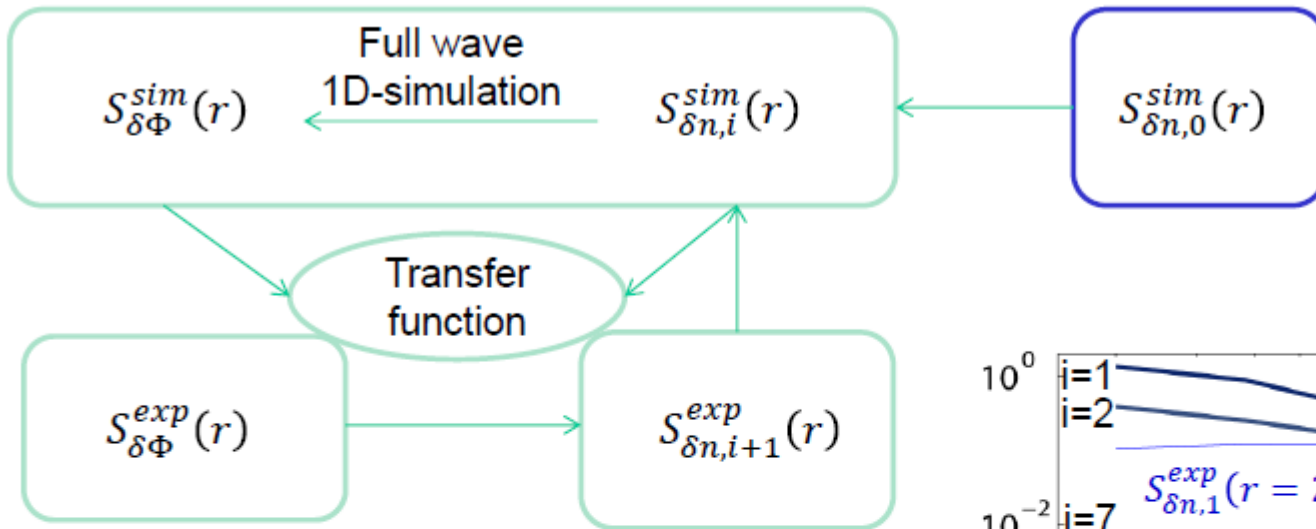
2018

- 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

- 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  $\mu$ s 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.

Ey of probing wave

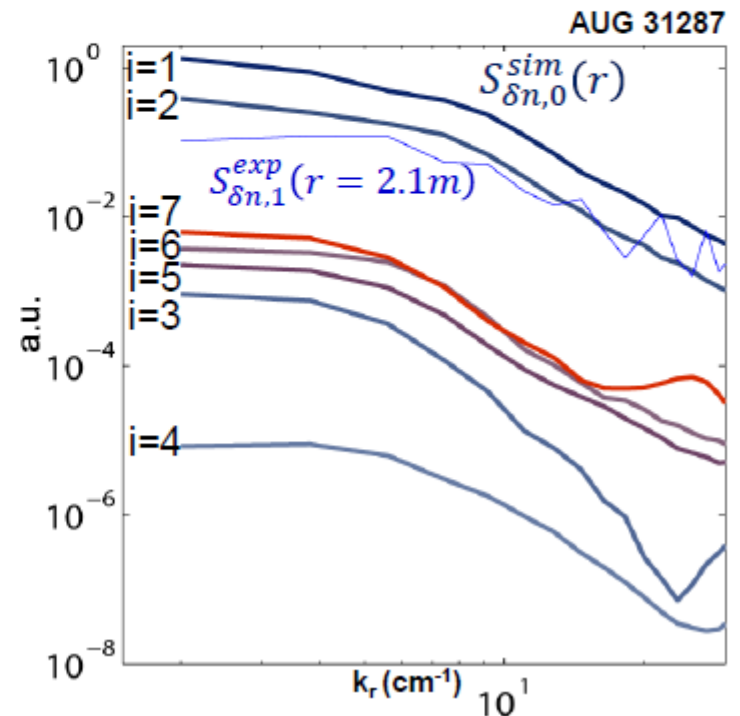


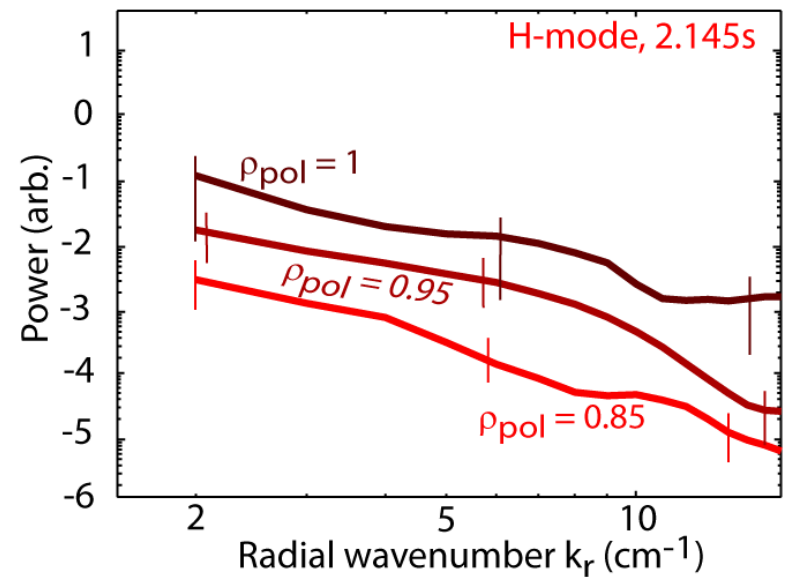
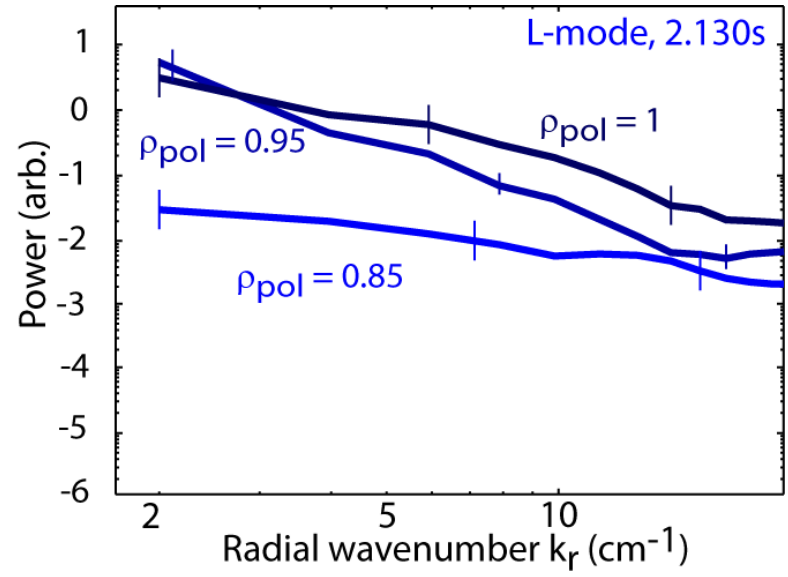
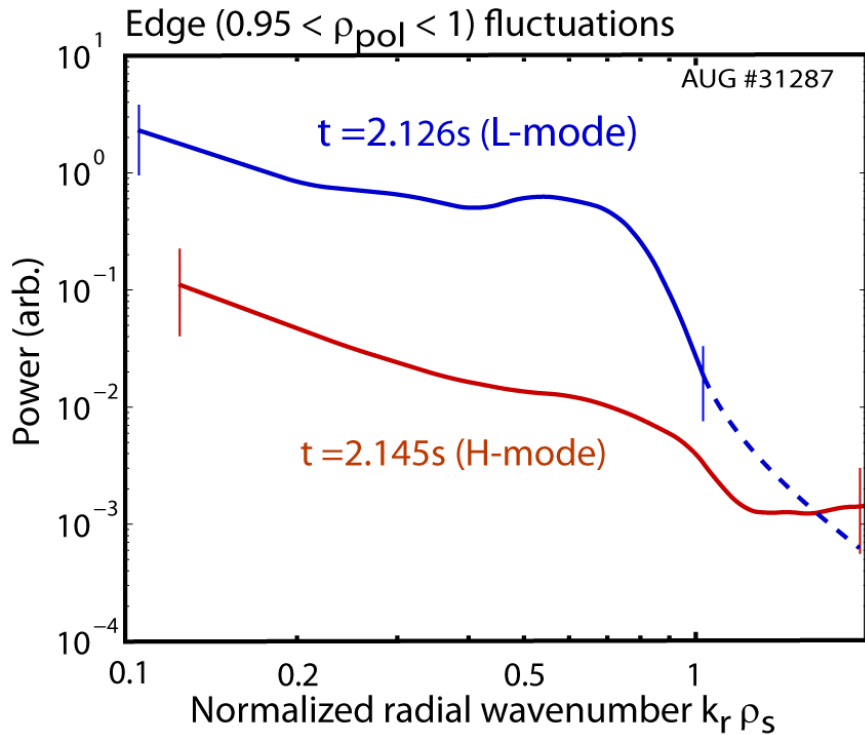


Signal phase fluctuations are induced by density fluctuations:  $S_{\delta n}(k) = T(k) \cdot S_{\delta\Phi}(k)$

Density fluctuations level:

$$\left(\frac{\delta n}{n}\right)^2 = \frac{1}{k_{max} - k_{min}} \int_{k_{min}}^{k_{max}} S_{\delta n}(k) dk$$





- 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