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

A. Medvedeva, F. Clairet, C. Bottereau, R. Marcille, S. Hacquin, G. D. Conway, U. Stroth, S. Heuraux, Guilhem Dif-Pradalier, D. Molina, et al.

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A. Medvedeva[1], F. Clairet[1], C. Bottereau[1], R. Marcille[2], S. Hacquin[1,3], G. D. Conway[4], U. Stroth[4,5], S. Heuraux[6], G. Dif-Pradalier[1], D. Molina[1], A. Silva[7], ASDEX Upgrade team[4], EUROfusion MST1 team[8]

[1]CEA, IRFM, F-13108 Saint-Paul-lez-Durance

[2]Ecole Polytechnique, F-91128 Palaiseau

[3]EUROfusion Programme Management Unit, Culham Science Centre, OX14 3DB

[4]Max-Planck-Institut für Plasmaphysik, D-85748 Garching

[5]Physik-Department E28, Technische Universität München, D-85747 Garching

[6]Institut Jean Lamour UMR 7198 CNRS, Universite de Lorraine, F-54011 Nancy

[7]Instituto de Plasmas e Fusao Nuclear, IST, Universidade Lisboa, Lisbon

[8]For a list of members, see H.Meyer et al, Nucl. Fusion 57 102014 (2017)

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Outline

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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Confinement is limited by turbulent transport

Plasma in a tokamak must be:

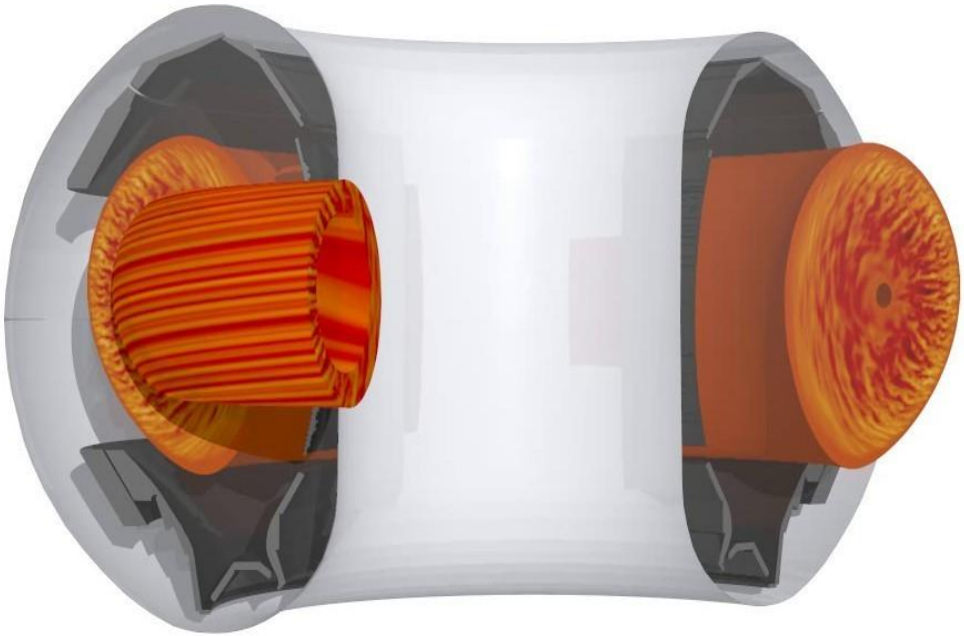
- hot and dense at the core
- cool at the edge

→ gradients → turbulence

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

Objective:

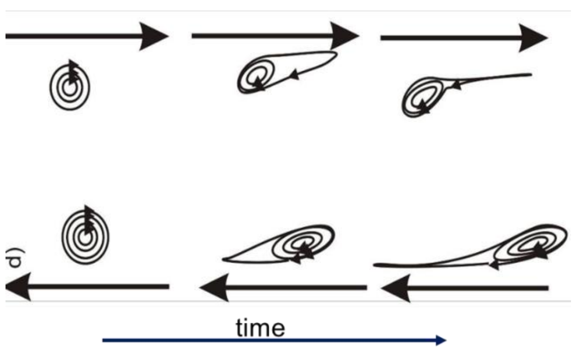
Investigate turbulence during confinement changes

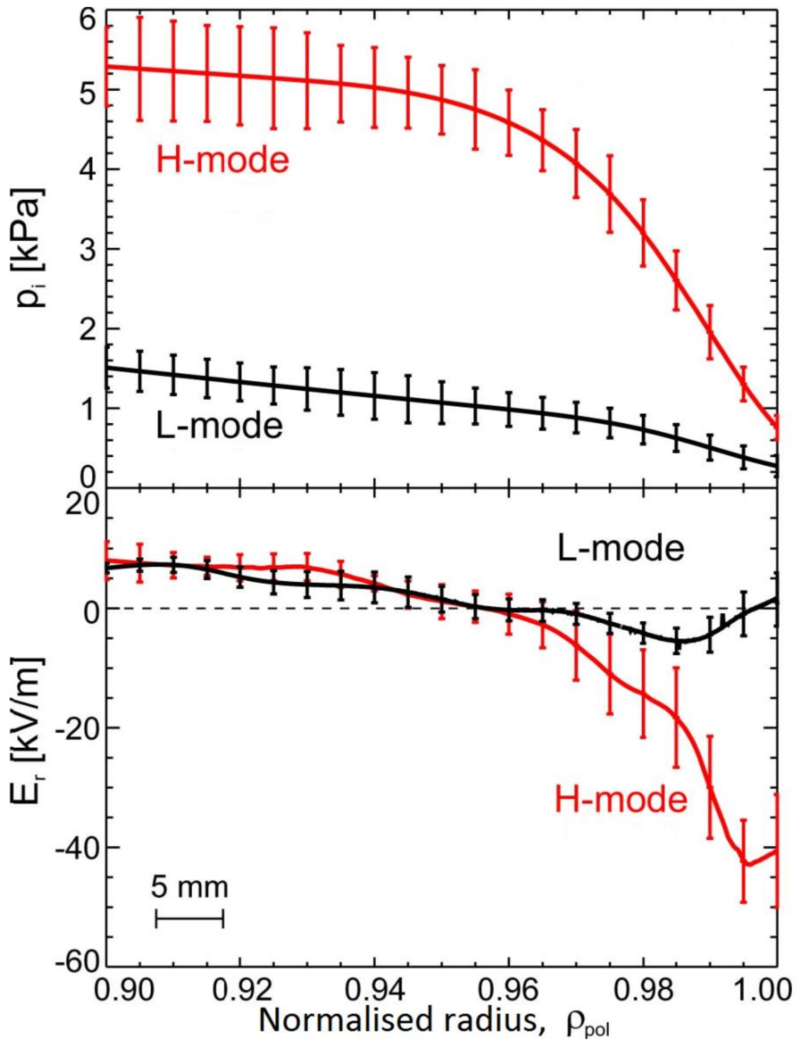


δT in the ASDEX Upgrade tokamak with GENE code
[genecode.org]

low confinement (L-mode) → high confinement (H-mode) [F. Wagner, PRL1982]

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





[E. Viezzer, PPCF 2014]

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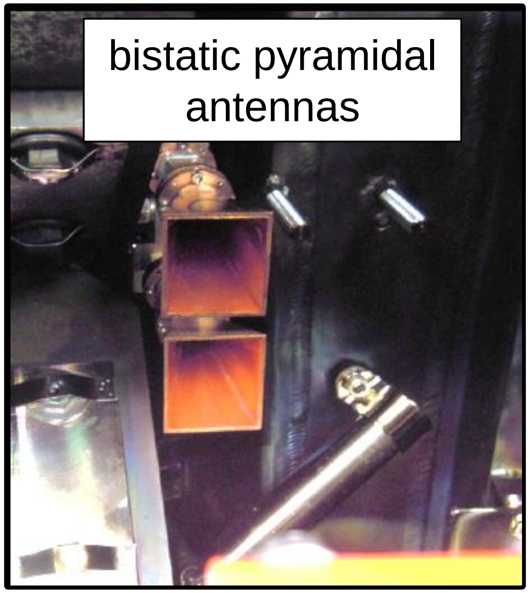
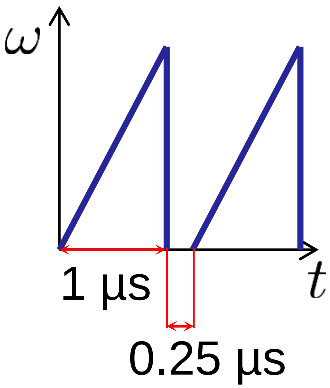
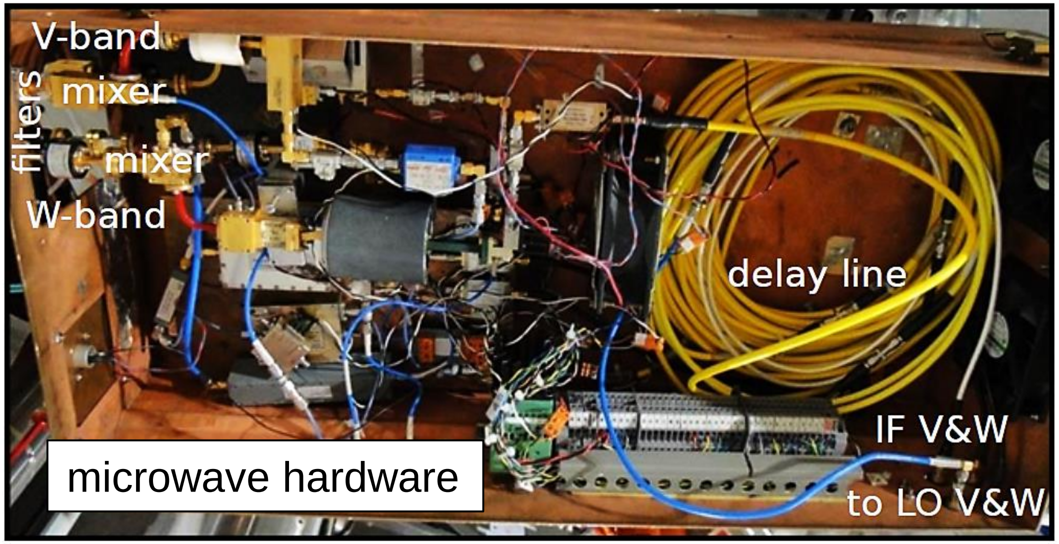
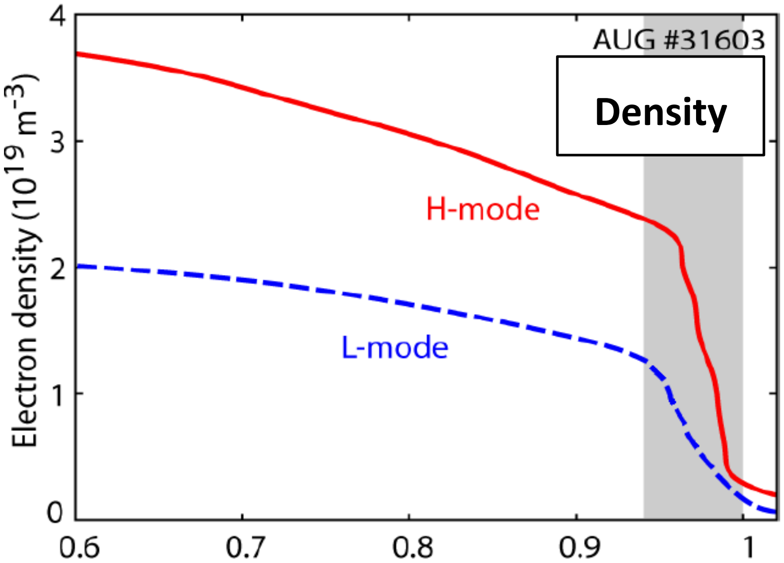
- UFSR developed at CEA for Tore Supra and WEST tokamaks, transferred to ASDEX Upgrade (2013−2016) supported by EUROfusion
- 50−102 GHz X-mode
- Acquisition 2Gs/s
- Sweep time 1 µs
  [F. Clairet, RSI 2017]

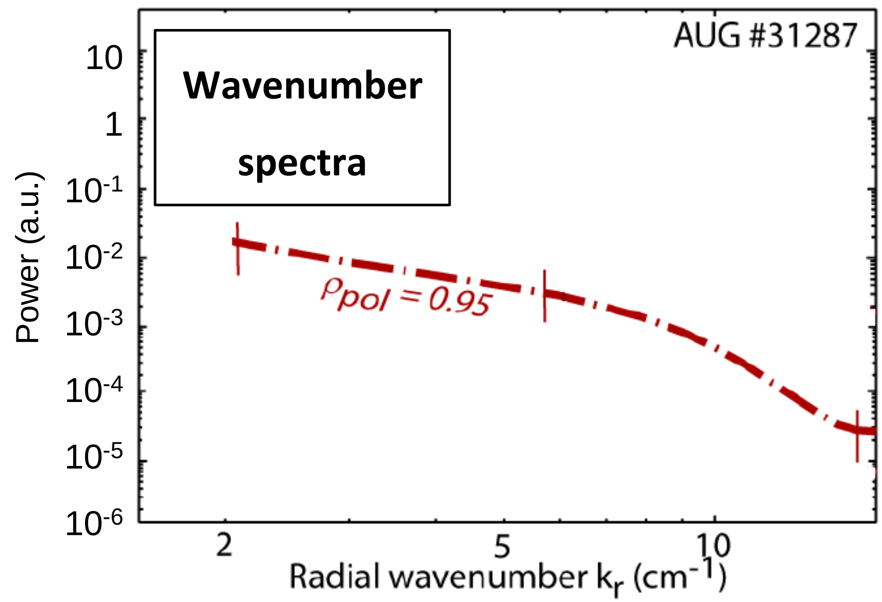


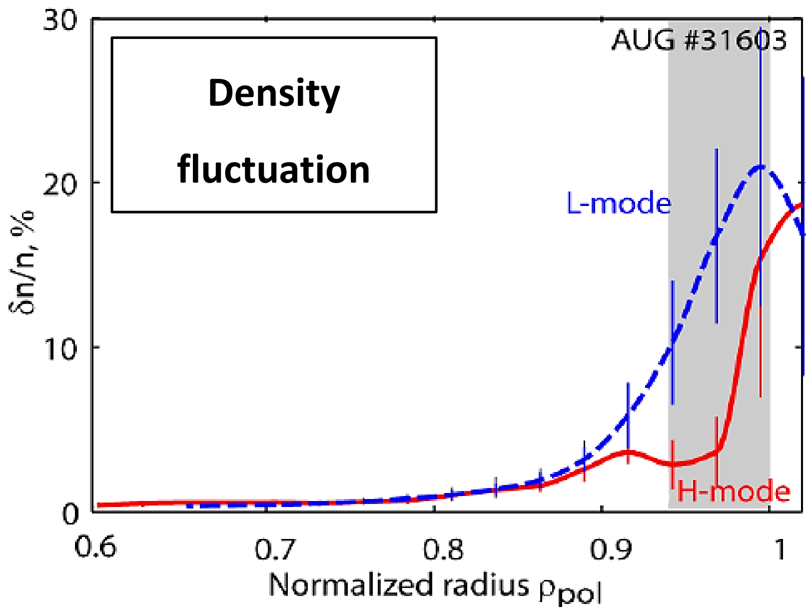




Turbulence properties measured by UFSR







[A. Medvedeva, IRW 2015]

- 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

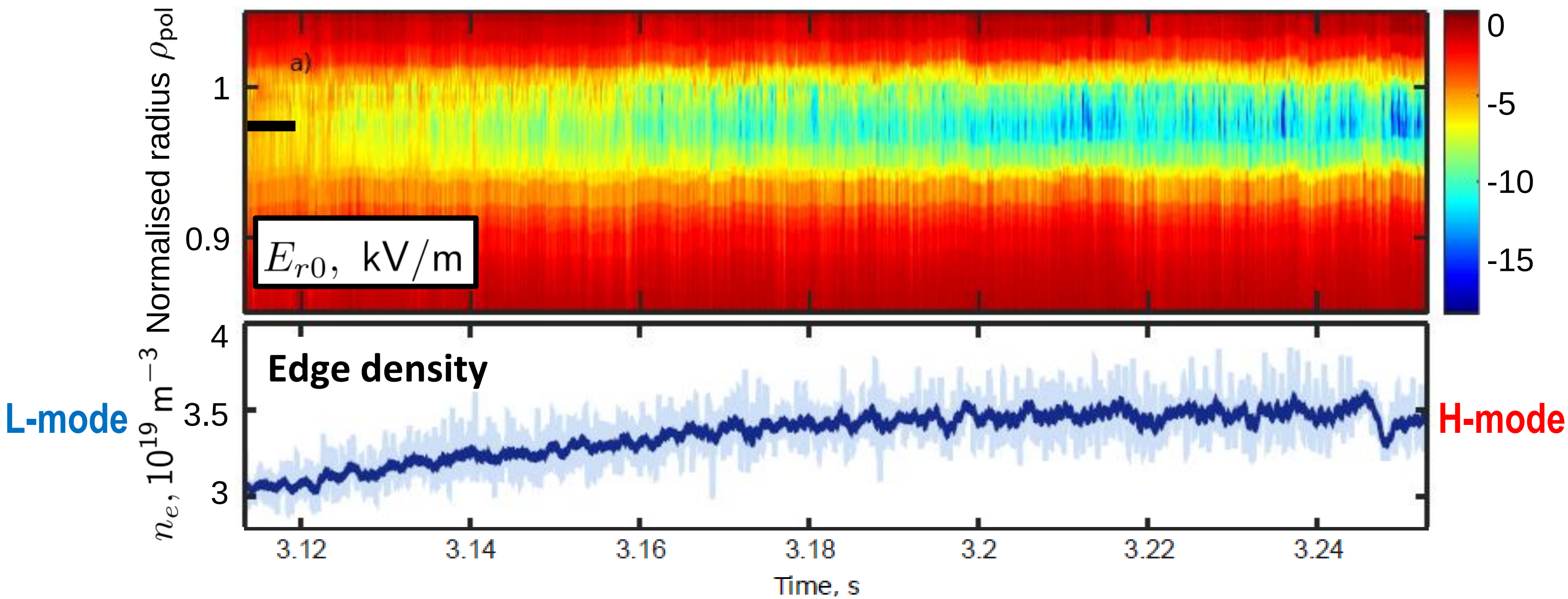
Background flow (E_{r0}) evolution during I-phase

Proxy for radial electric field:

UFSR

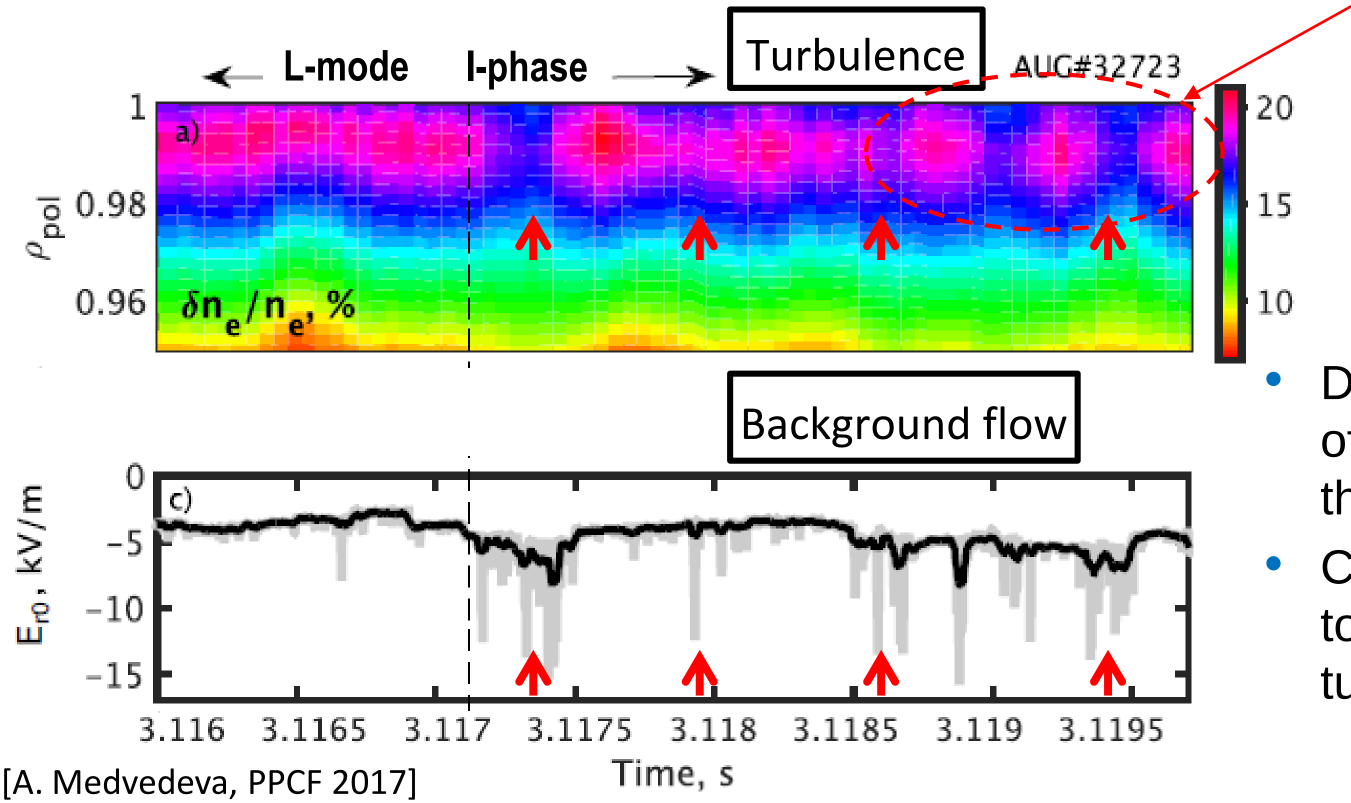
$$E_r \approx \frac{\nabla p_e}{e n_e} = T_e \boxed{\frac{\nabla n_e}{e n_e}} + \frac{\nabla T_e}{e} = E_{r0}$$

[F. L. Hinton, RMP 1976]



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

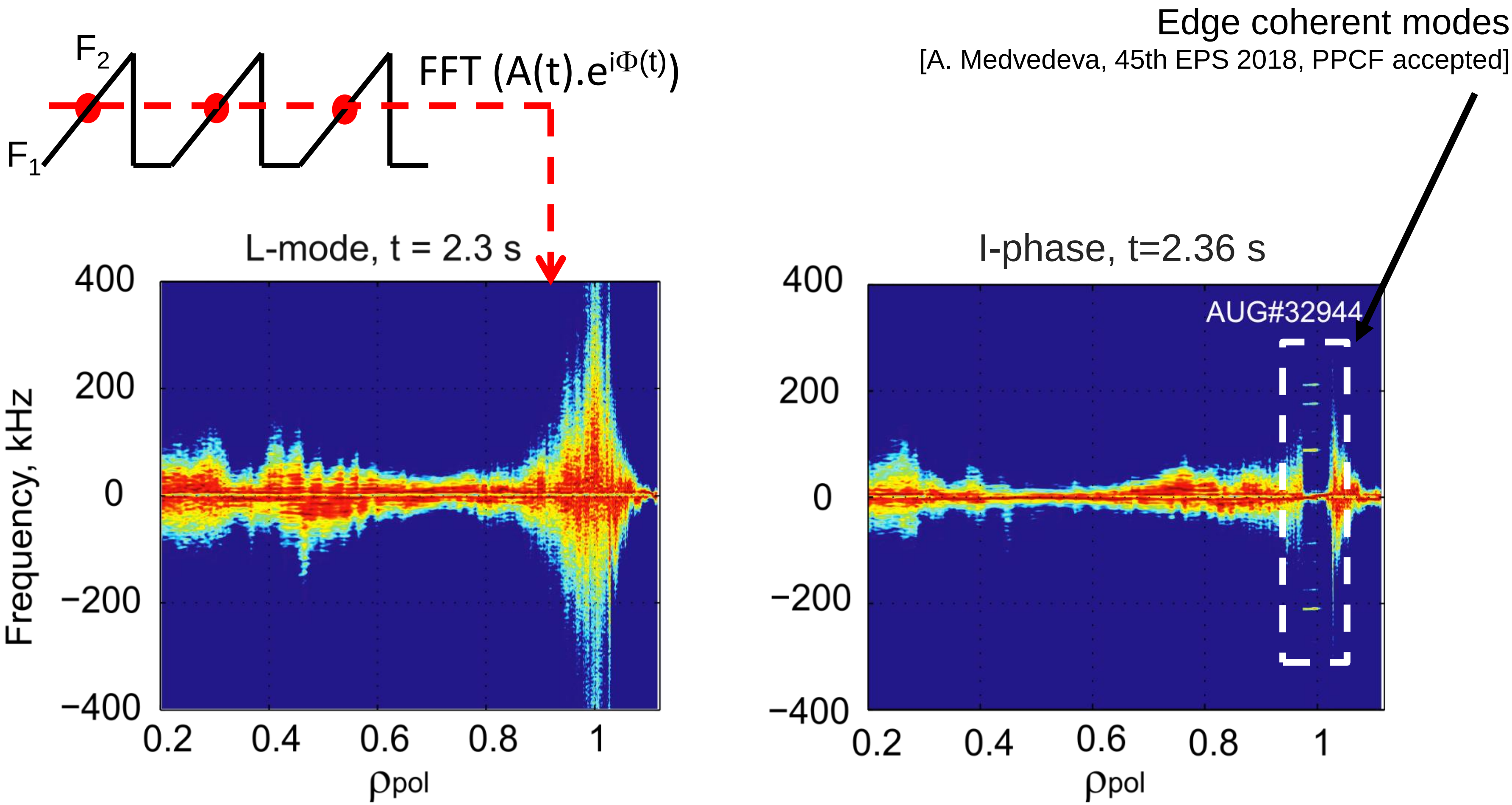
Turbulence and E_{r0} oscillate during I-phase



[A. Medvedeva, PPCF 2017]

- 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



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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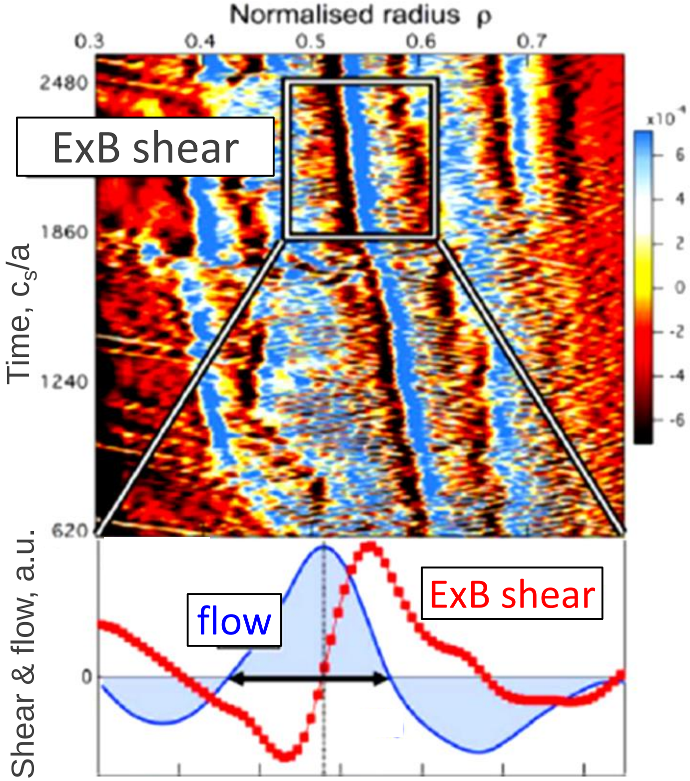
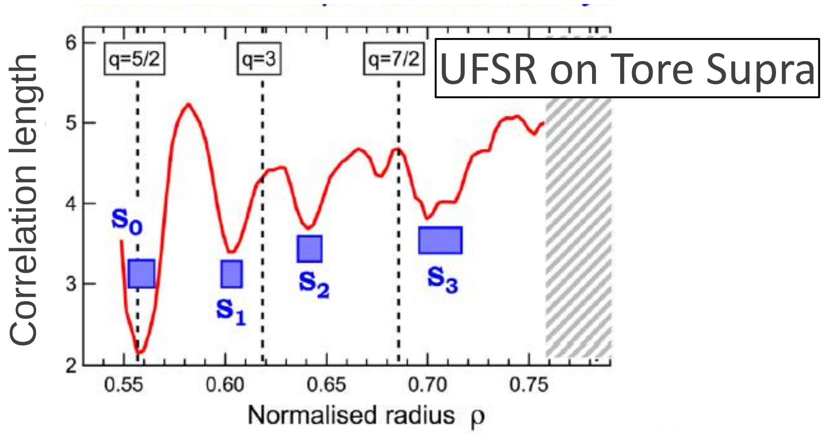
   Project objectives and progress

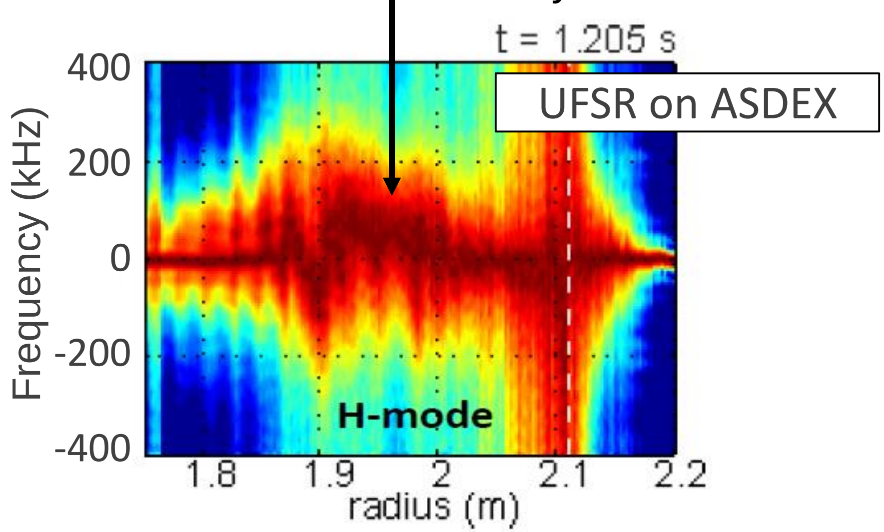
Spontaneous organisation of a set of regularly spaced weak transport barriers:
ExB staircase predicted by GYSELA





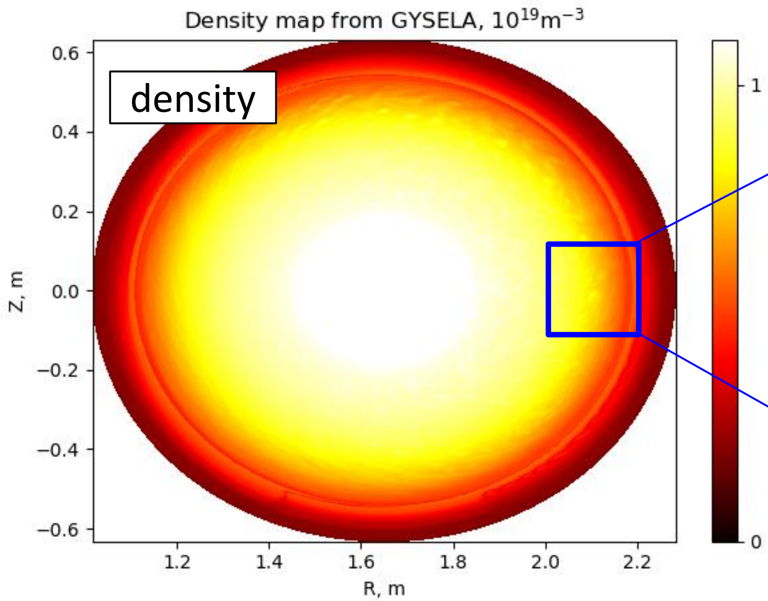
[G. Dif-Pradalier et al., PRL 2015, NF 2017]
[G. Hornung, NF 2017]

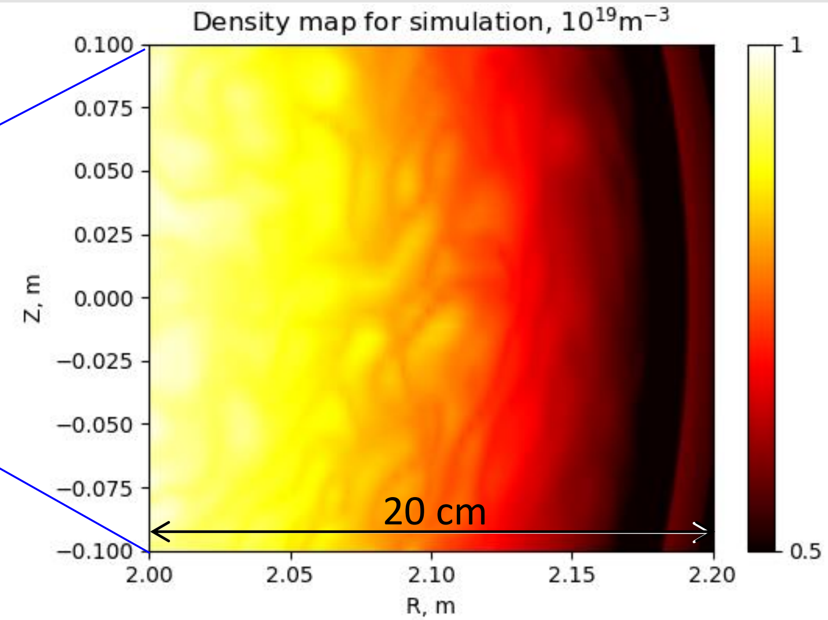
Staircase structure? Flow dynamics?



Project at the crossroads between theory, simulation and experiments

Synthetic diagnostic for UFSR data interpretation





- Turbulence map simulated with gyrokinetic code

↓

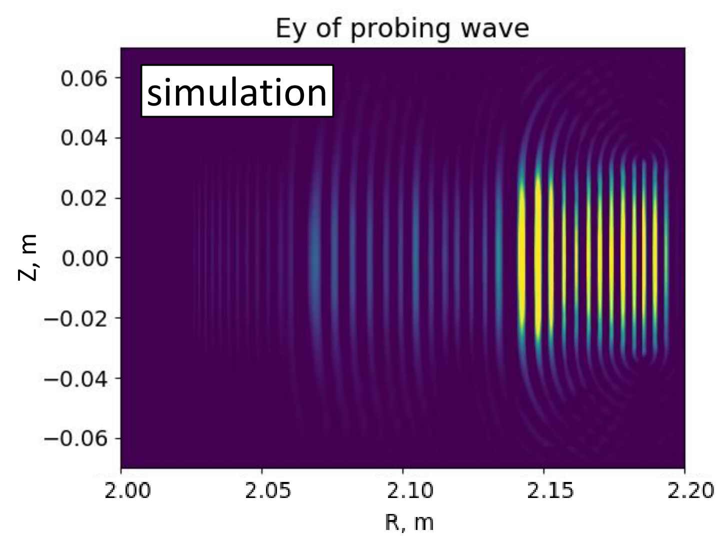
- Finite Difference Time Domain 2D code for wave propagation

↓

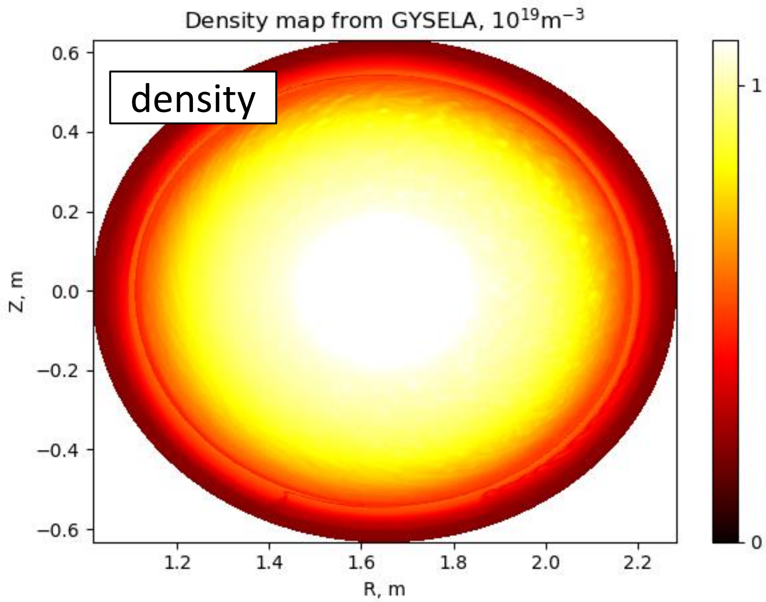
- Reproduce frequency and wavenumber spectra, correlation length and time

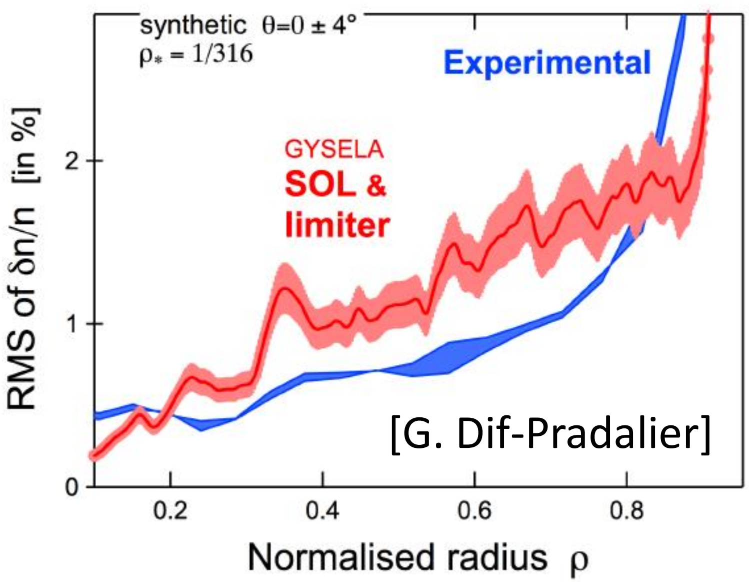
↓

- Compare with turbulence code



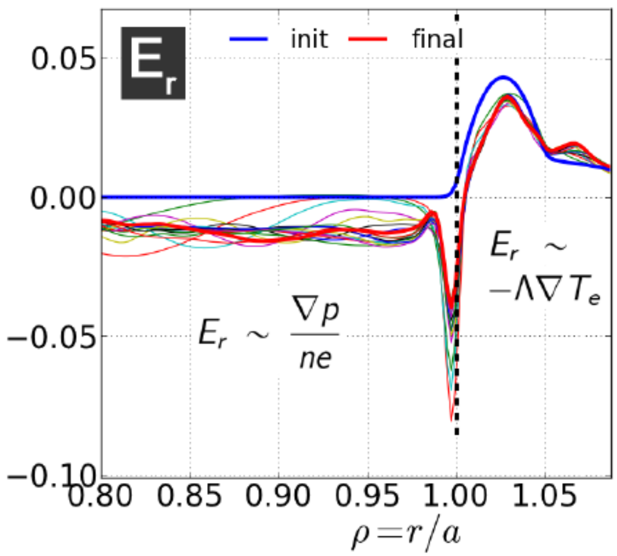
Turbulence map simulated with gyrokinetic code



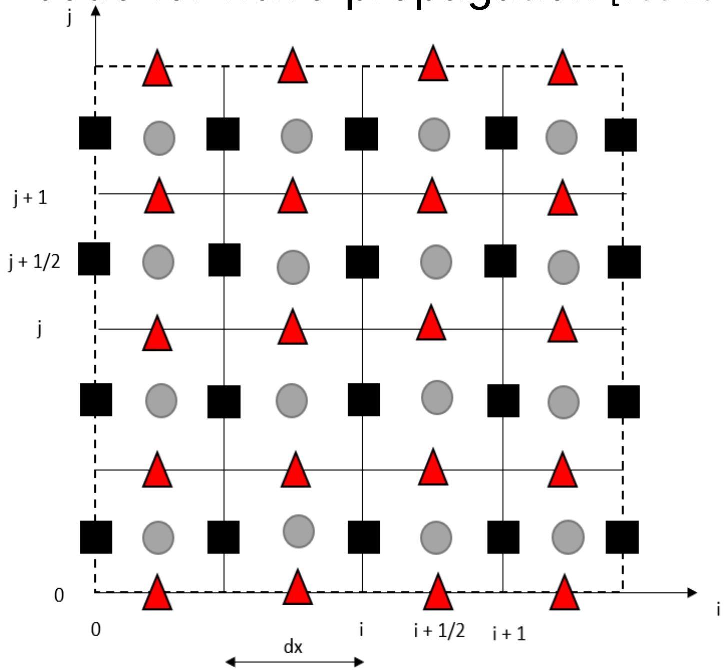


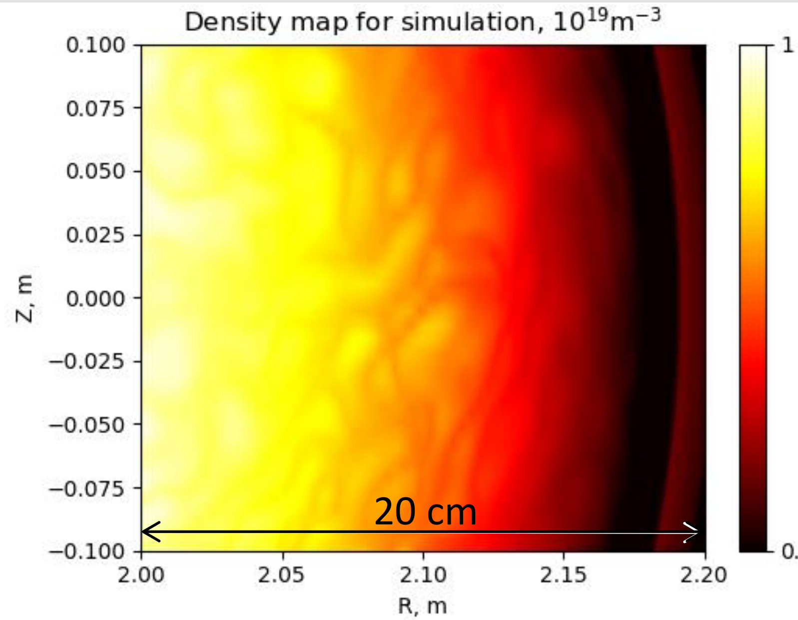
Low collisional plasma → gyrokinetic description

- ❑ 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



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





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

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

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

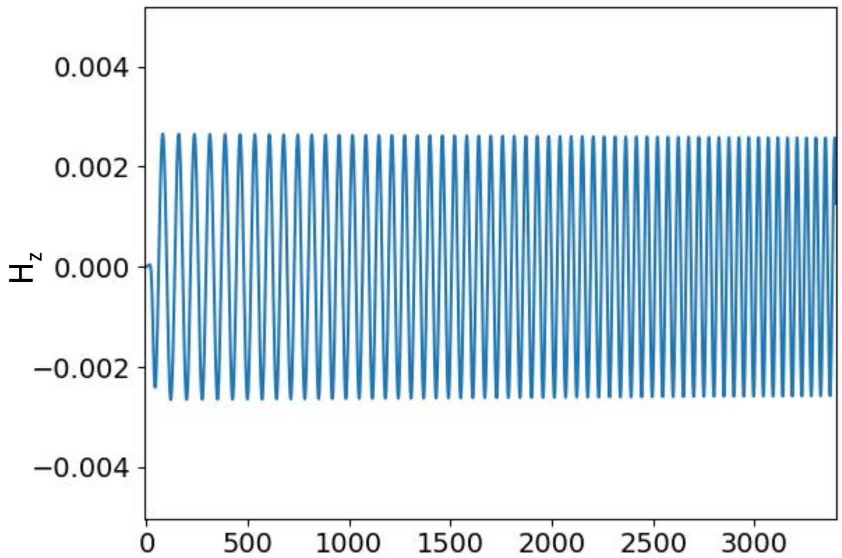
Sweep: $\omega_0 \to \omega = \omega_0 + v_\omega t$

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

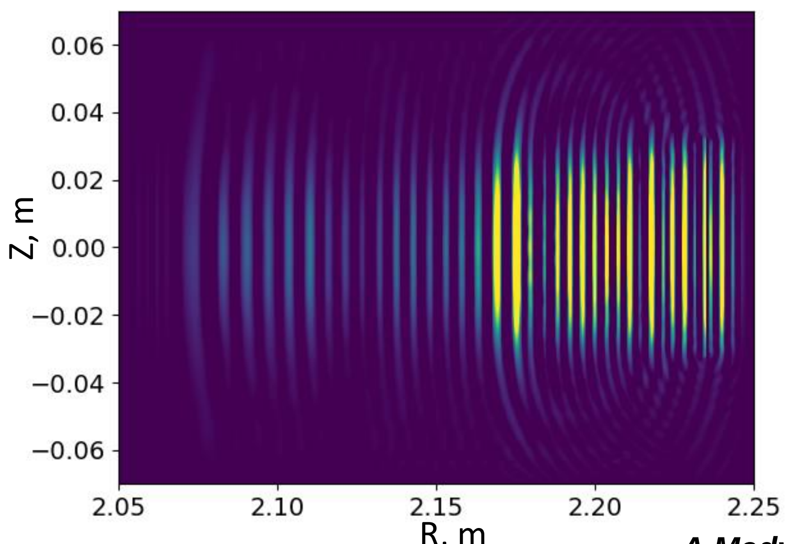
+ Mimic real reflectometer

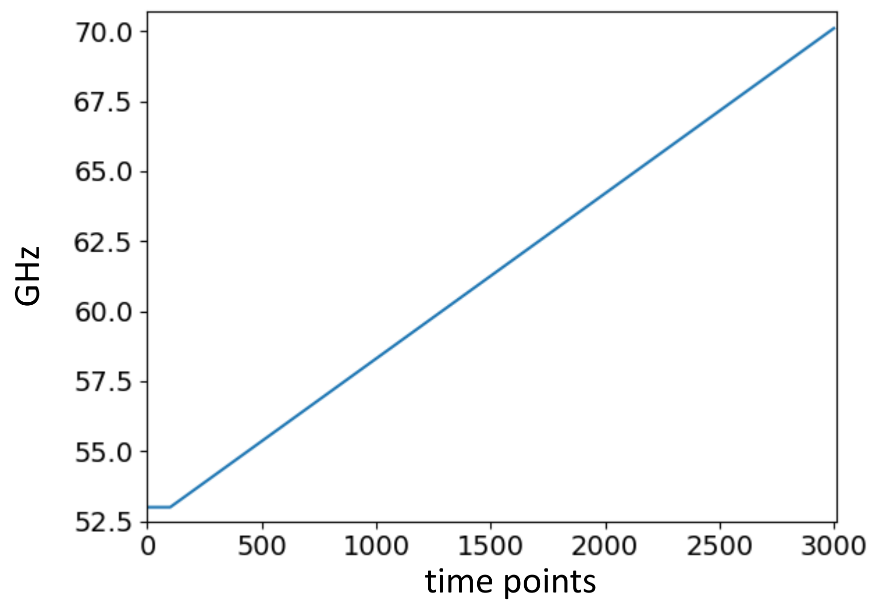
- Optimised calculation speed
- 1 μs sweep 2 000 000 points → 70 hours
  0.01 μs sweep 20 000 points → 1 hour

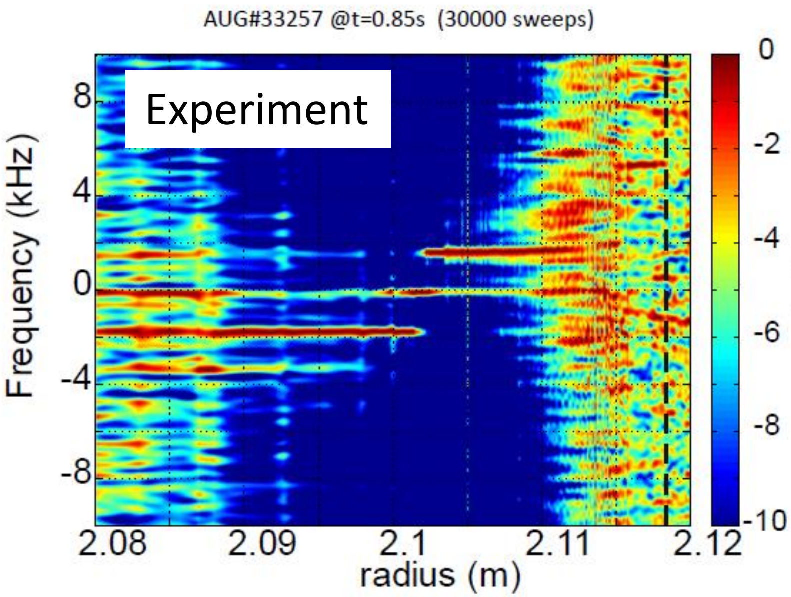
$$F_{beat} \approx 400\ MHz \ \to 40\ GHz$$

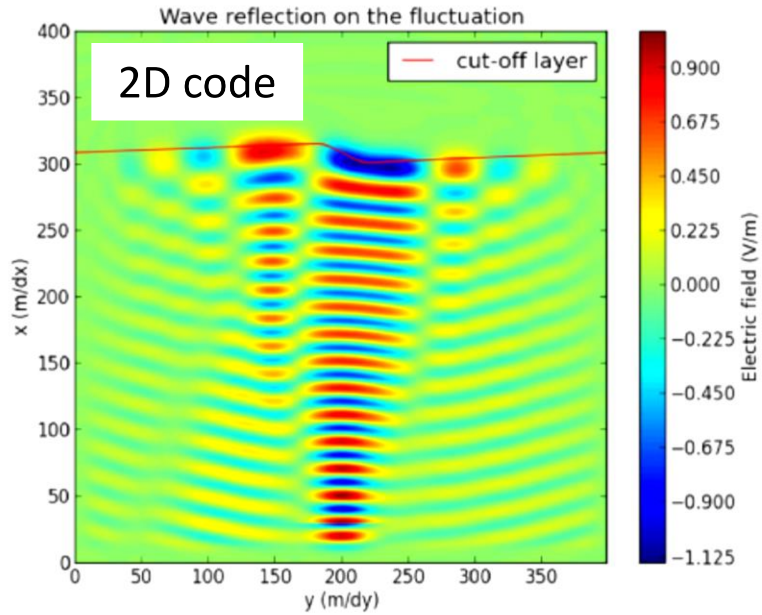


- Difficulties of signal extraction



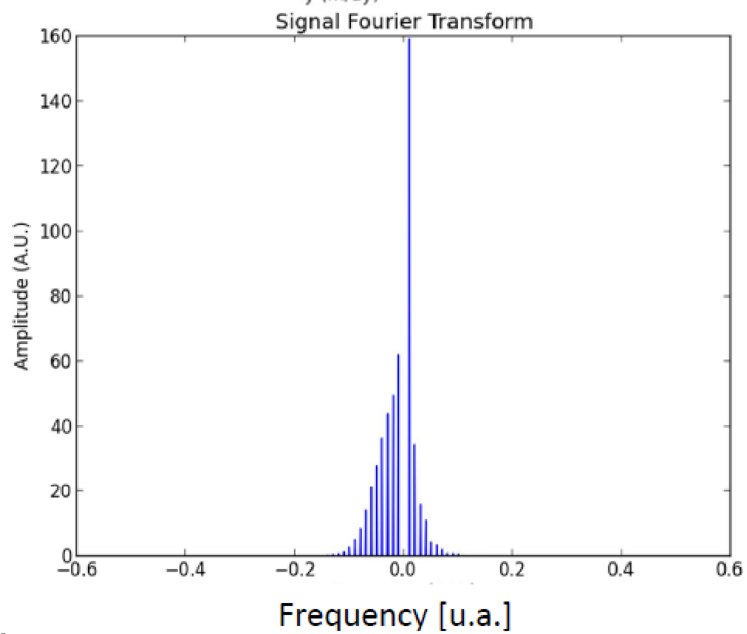






Sign inversion of the spectra asymmetry during I-phase can be explained by a sawtooth-like cutoff layer

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



Synthetic diagnostic: outlook

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

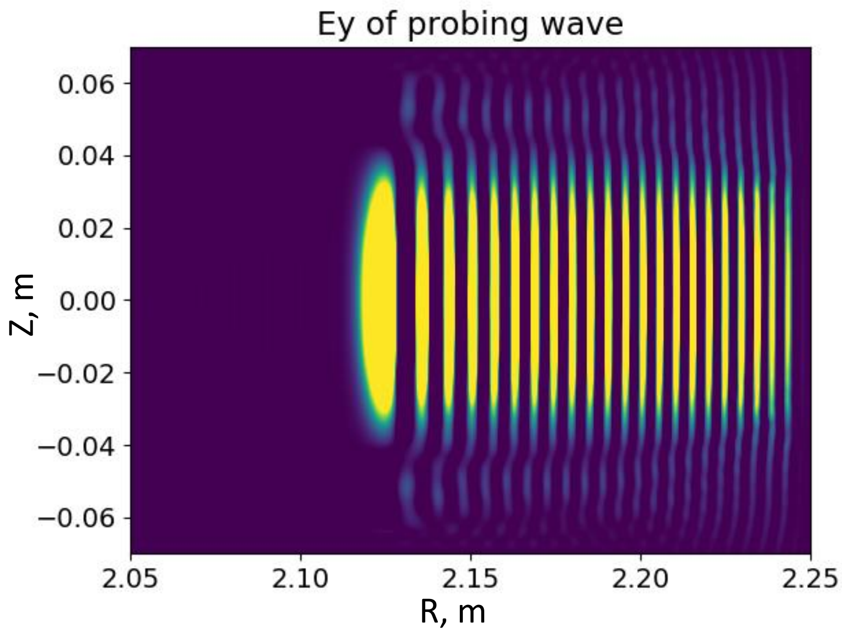
Conclusions

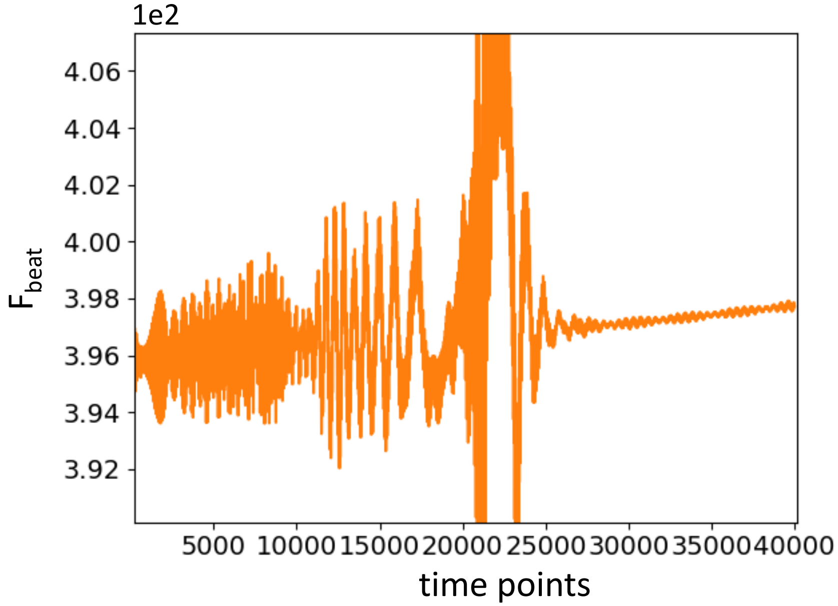
- First studies of the electron density and density fluctuations dynamics during L-H transitions in ASDEX Upgrade have been performed with a time resolution of 1 μs using 1D wave propagation simulation.

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

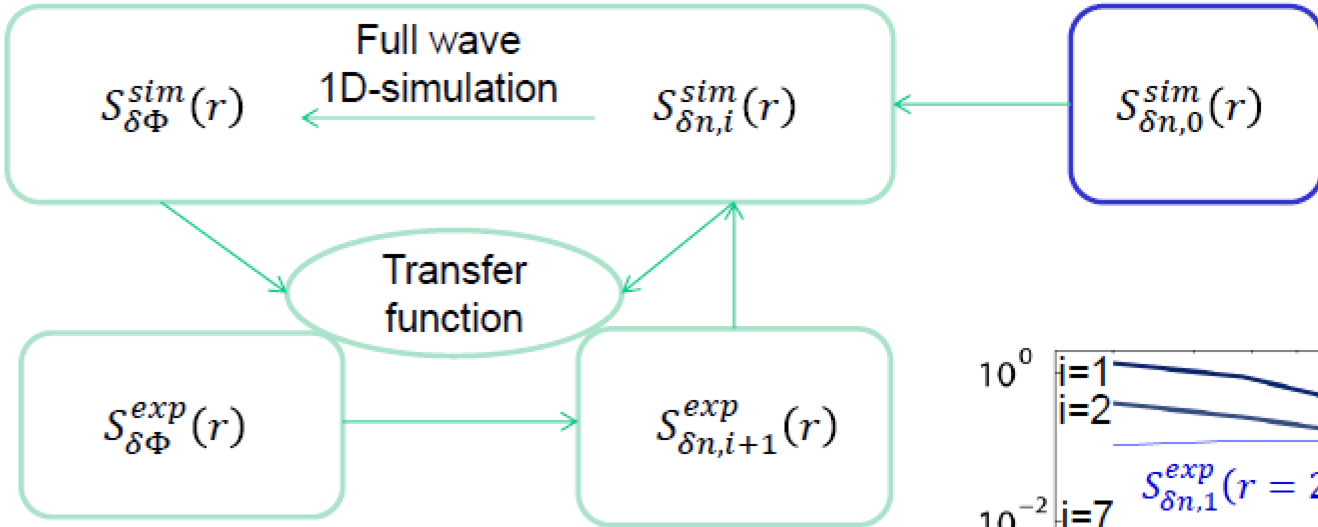
- Synthetic diagnostic is being optimised for further data analysis.

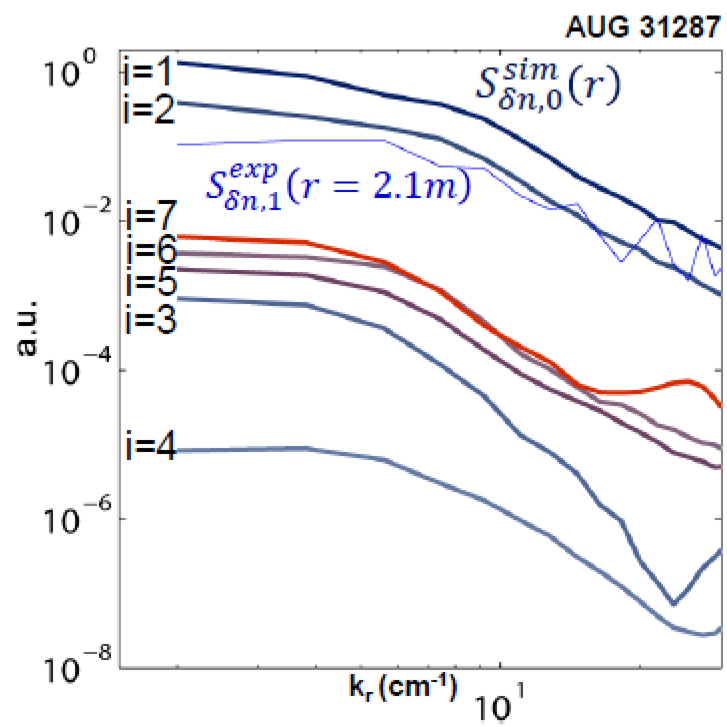
Slow sweep simulation





Loop method for wavenumber spectra



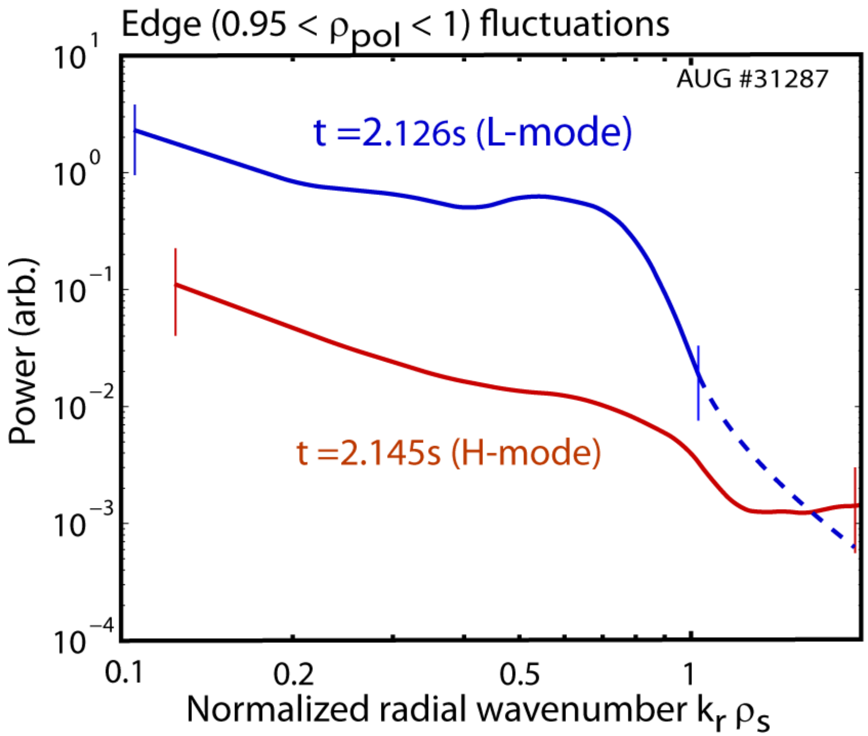


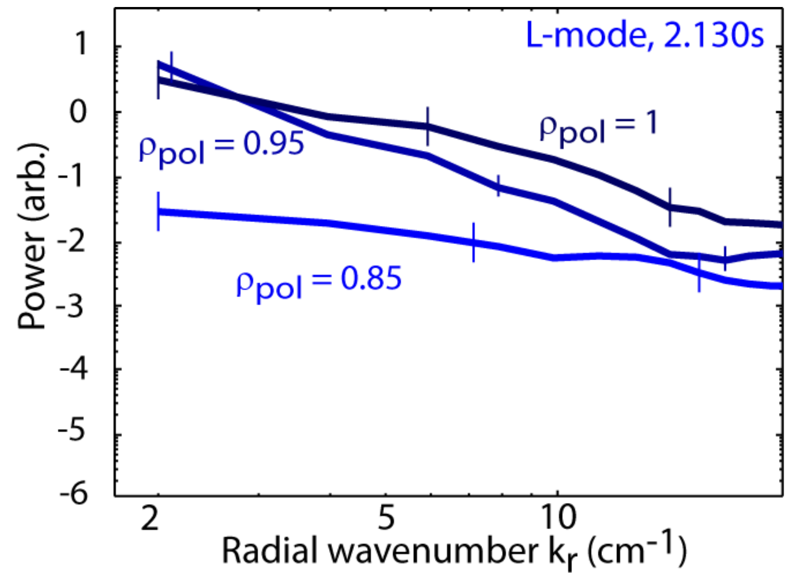
Signal phase fluctuations are induced by density fluctuations: $S_{\delta n}(k) = T(k) \cdot S_{\delta\Phi}(k)$

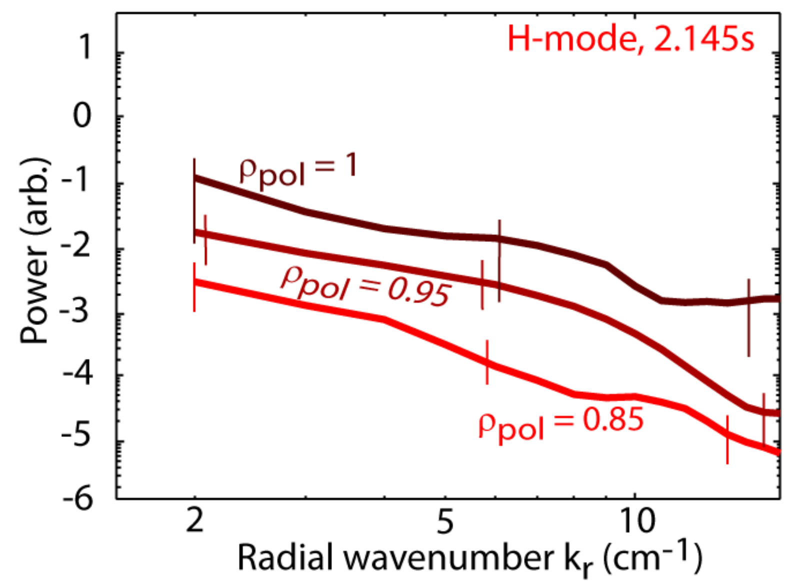
Density fluctuations level:

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

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

A.Medvedeva et al – IRW 2019