Comparative study of multi-scale turbulence at FT-2 by Doppler backscattering and global gyrokinetic modeling

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Outline

1. Motivation of the GAM-turbulence investigation for the isotope study.
2. Successful validation of the global GK code ELMFIRE in the FT-2 tokamak discharge as a groundwork for present investigations.
3. Turbulence parameters by radial correlation Doppler reflectometer.
4. Rotation shearing by GAMs and modulation of the turbulence and diffusivities by GAMs.
5. Experimental investigations of GAM-turbulence interaction in D- and H-discharges.
6. Results of the GK modeling in D- and H-discharges.
7. Conclusions.

Motivation

The isotope effect in tokamak anomalous transport is a longstanding puzzle for physicists. It was first reported almost thirty years ago [J.Hugill & J.Sheffield 1978 *Nucl. Fusion* **18** 15] and since that time observed in many machines.

The typical orbit's widths and typical width of the drift-wave turbulent eddy in tokamak are larger for heavy isotopes. Based on these arguments one could expect growing transport with increasing isotope mass, nevertheless, in numerous experiments an opposite direction of effect was observed [F.Wagner and U.Stroth 1993 *PPCF* **35** 1321; U. Stroth 1998 *PPCF* **40** 9].

The dependence of turbulence long-range correlations, determined, in particular, by the GAM excitation level, on the isotope mass could be responsible [Y.Xu et al. 2013 *PRL* **110** 265005] for the isotope effect in tokamak anomalous transport.

Motivation

GAMs, which are, according to the present day understanding, excited in plasma due to nonlinear interaction of drift waves, in their turn can influence the turbulent fluctuations and anomalous transport. The mechanism GAMs control the turbulence discussed in theory [P.H. Diamond et al. 2005 *PPCF* **47** R35] could be associated with large inhomogeneity of poloidal rotation accompanying GAMs possessing small radial wavelength and huge radial electric field.

This work is devoted to investigation of these effects in the FT-2 tokamak (R = 55 cm, a = 7.9 cm) using a set of highly localized microwave backscattering diagnostics and the global gyro-kinetic (GK) modeling by ELMFIRE code.

Multi-scale benchmarking of experimental FT-2 data and GK simulations

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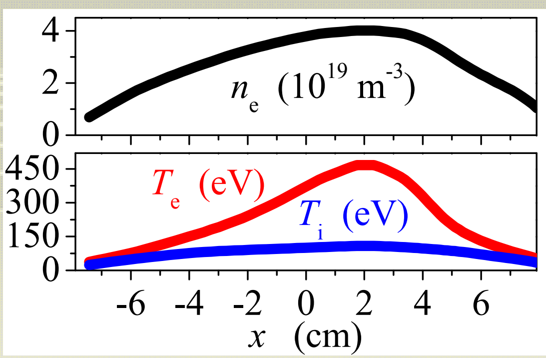
19 kA H-discharge parameters

$B \approx 2.1$ T; $Z_{eff} \approx 3.5$

$n_e(0) \approx 4\times10^{13}$ cm^{-3}

$T_e(0) \approx 470$ eV

$T_i(0) \approx 110$ eV



S. Leerink et al. 2012 *PRL* **109** 165001

E.Z. Gusakov et al. 2013 *PPCF* **55** 124034

E. Gusakov et al. 24 *IAEA FEC* 2012 **CN-197** TH/6-3

Validation of the multi-scale Drift Turbulence Dynamics modeled by full-f Gyrokinetic ELMFIRE-code against measurements in the FT-2 tokamak Ohmic Discharge

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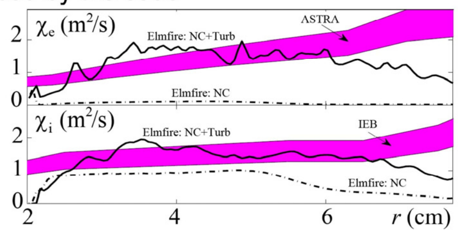
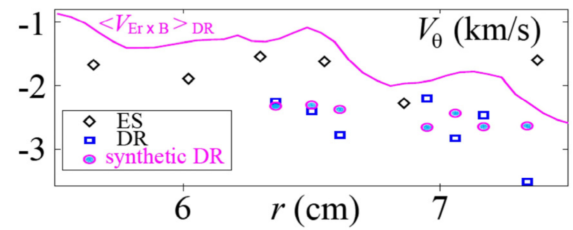
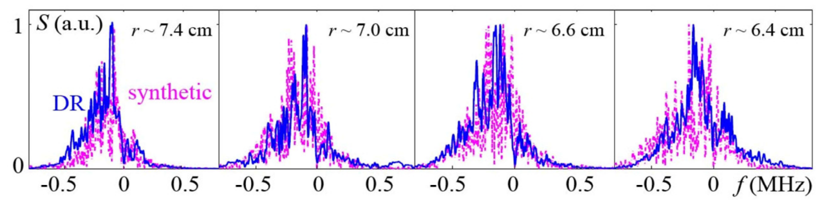
•At the macro-scale electron and ion thermal diffusivities and poloidal rotation profiles are reproduced by the code

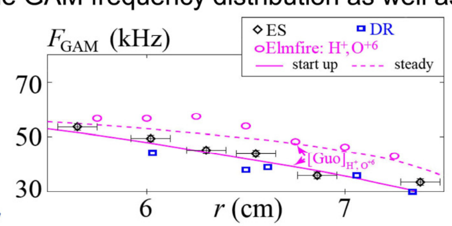


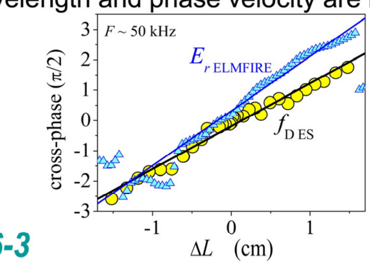


•At the micro-scale the similarity of the Doppler reflectometry spectra provided by the FT-2 experiment and by the Elmfire synthetic diagnostics is demonstrated



•At the meso-scale the GAM frequency distribution as well as its wavelength and phase velocity are reproduced by the code





VTT

Gusakov et al. TH/6-3

X-mode RCDR at HFS. Direct measurements and synthetic approach

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$B \approx 2.1 \rightarrow 1.69$ T

$f_i = 70$ GHz

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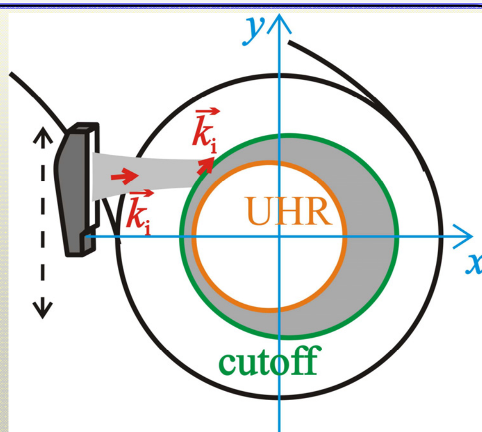
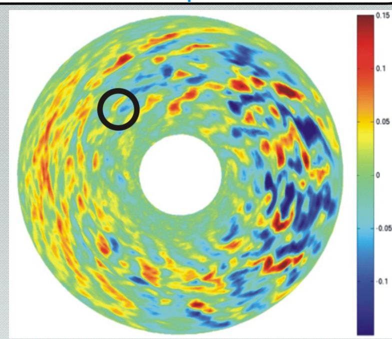


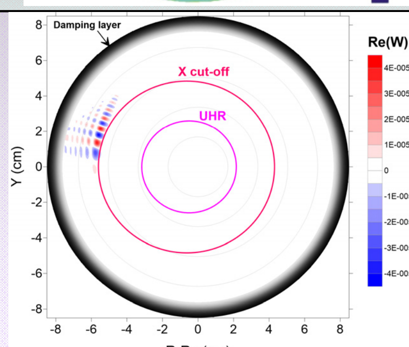
The turbulence snapshot by GK code



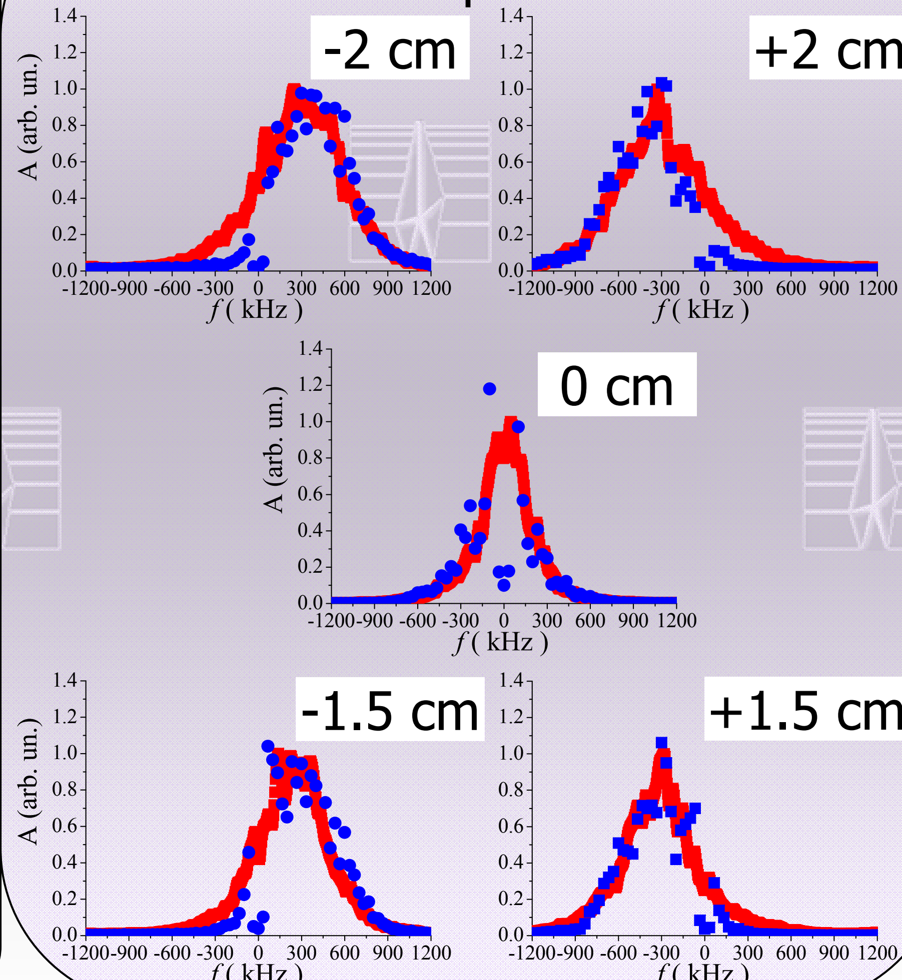
The DR weighting function distribution

$$A_s(\omega) \propto \int \delta n(\omega, \vec{r}) W d\vec{r}$$

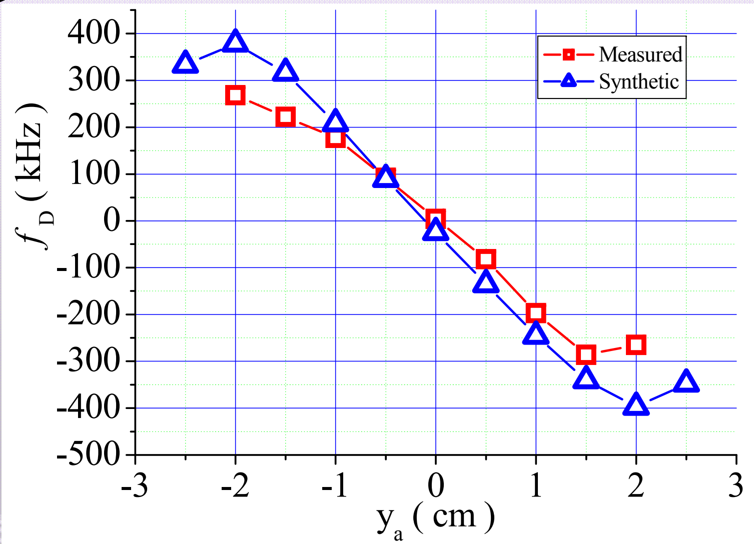
$$W(\omega, \vec{r}) = \frac{1}{n}\left[\hat{\sigma}\vec{E}_a\right]\vec{E}_a^+$$

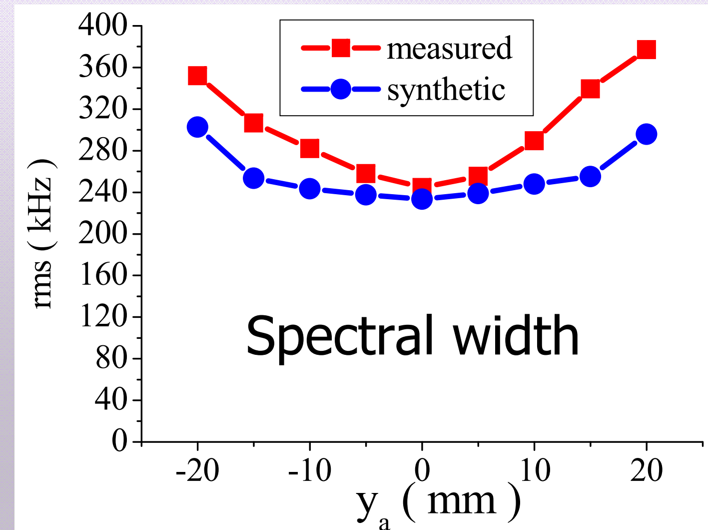


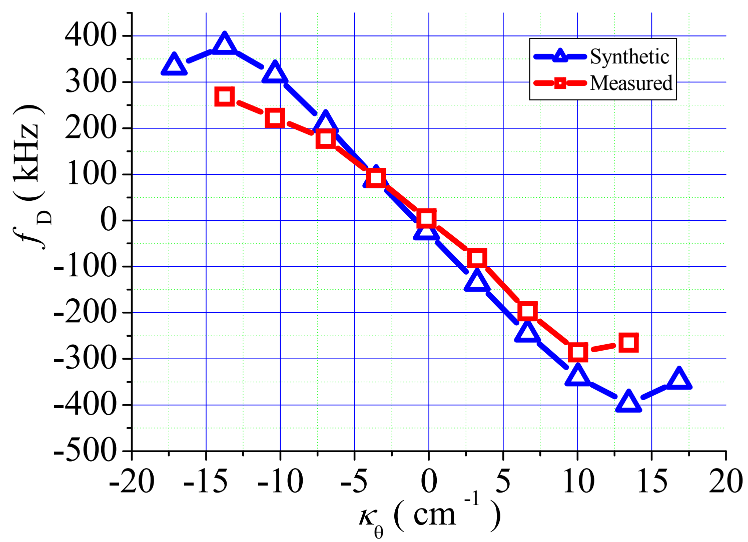
Experimental and synthetic DR spectra

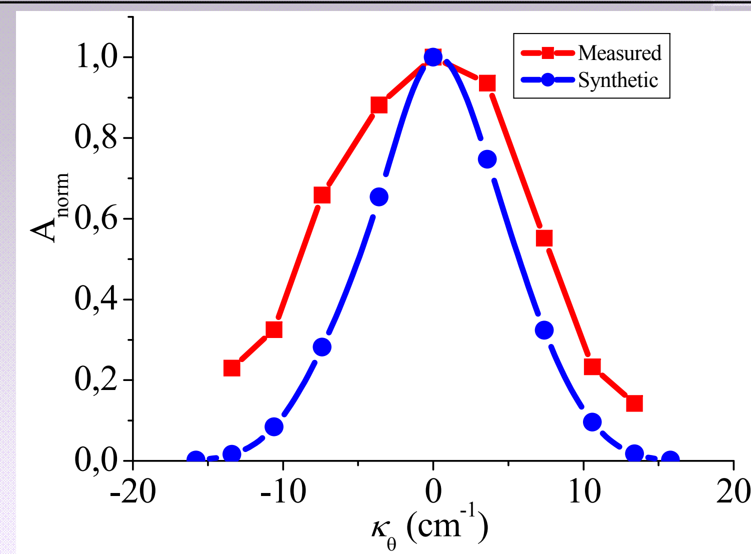


Comparison of experimental and synthetic DR spectra parameters

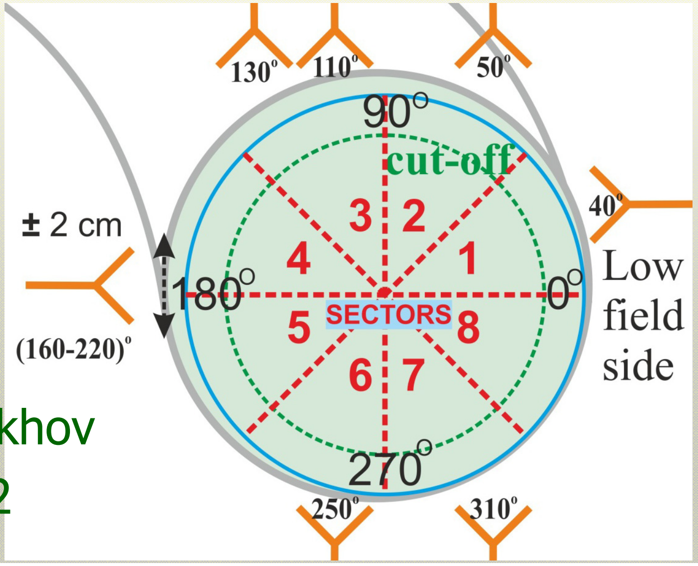








Experiments with O-mode probing to avoid the nonlinear regime



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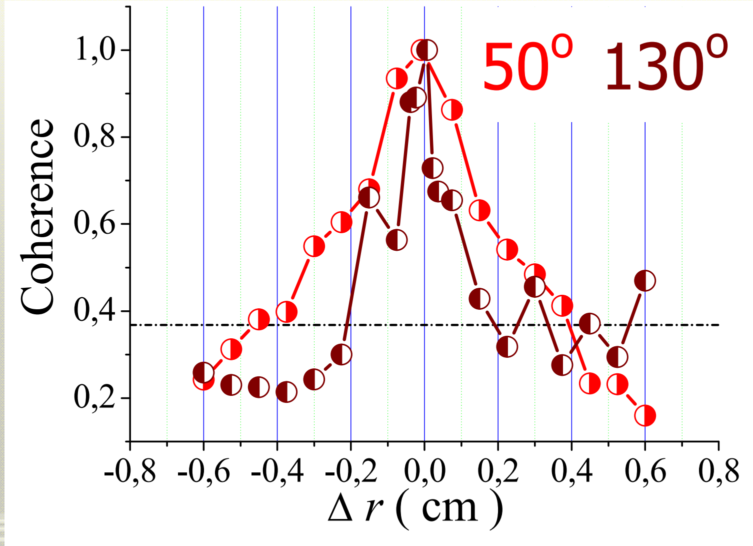

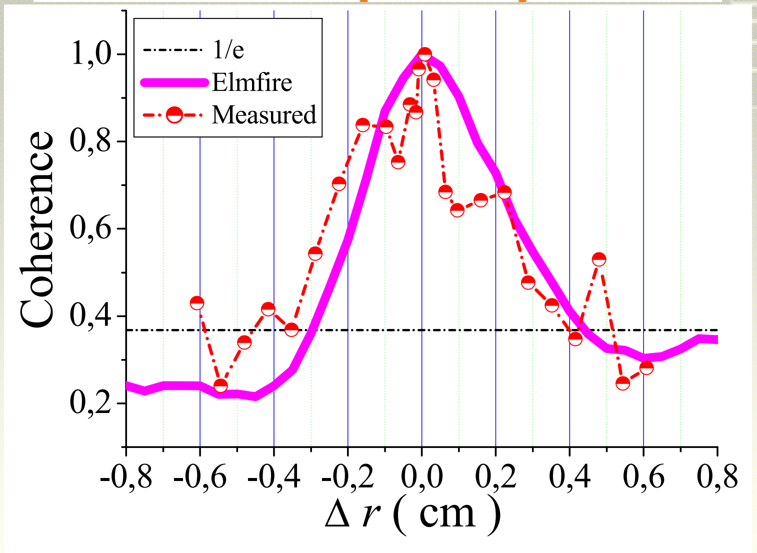

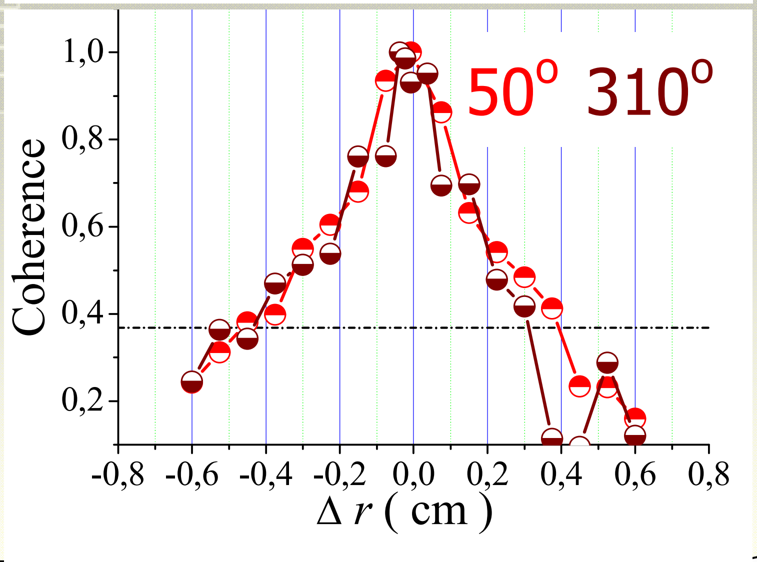

Turbulence radial correlation length poloidal dependence

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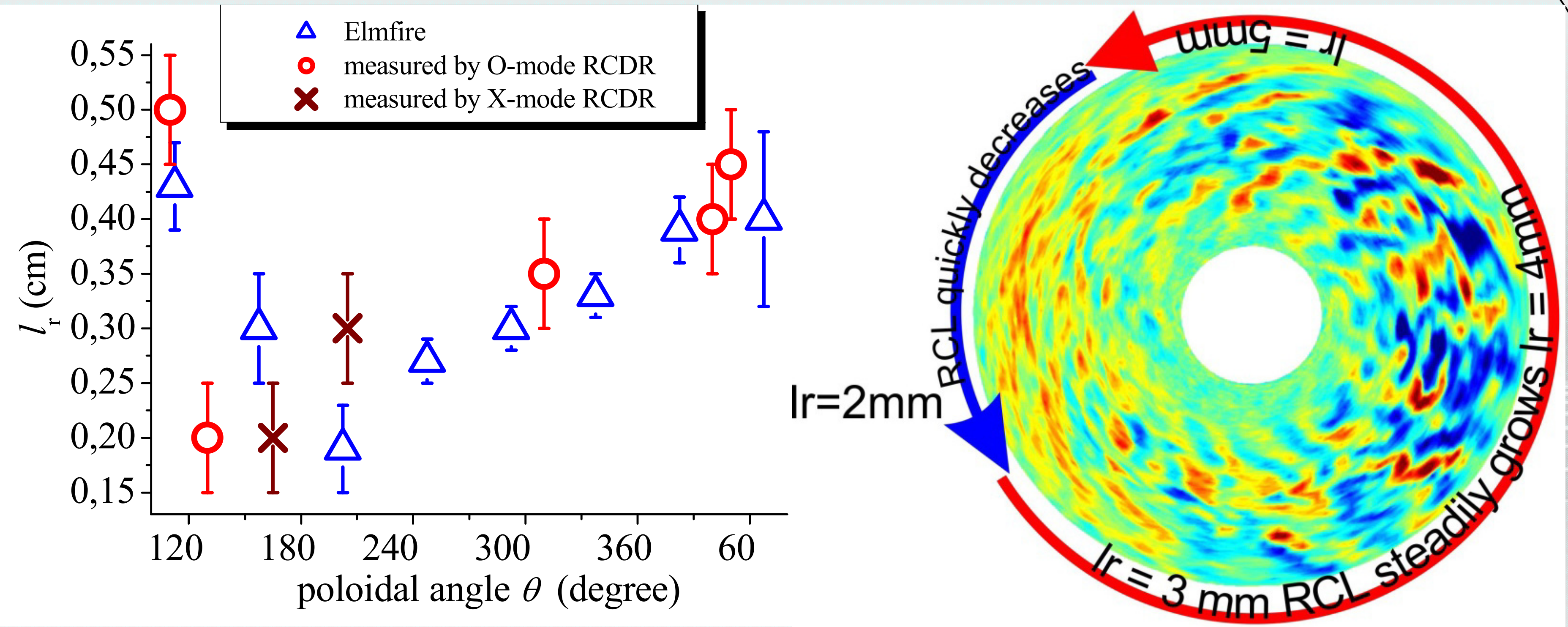
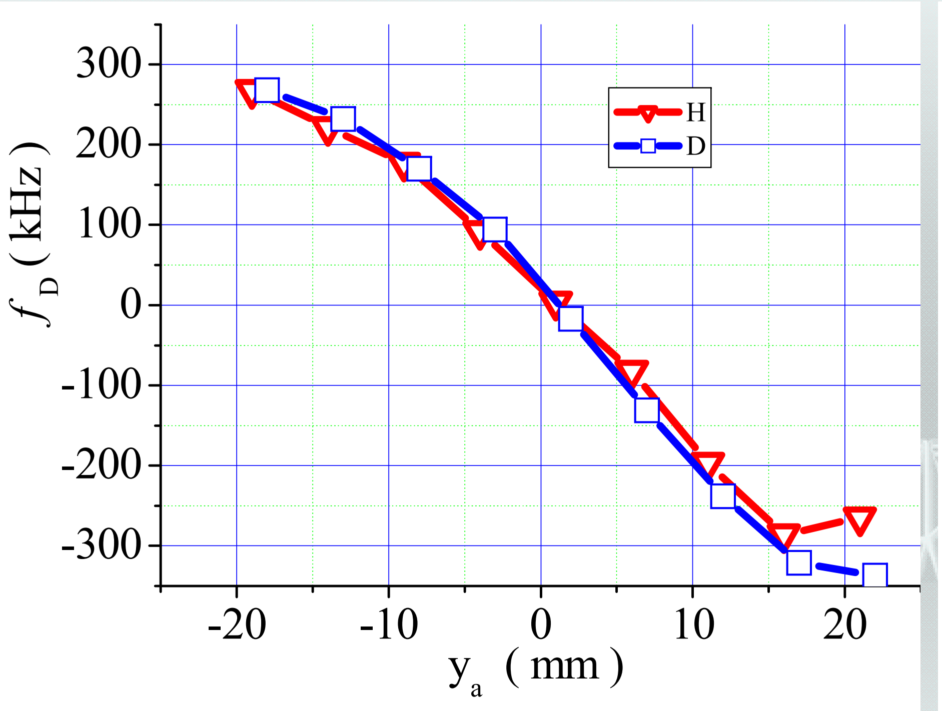
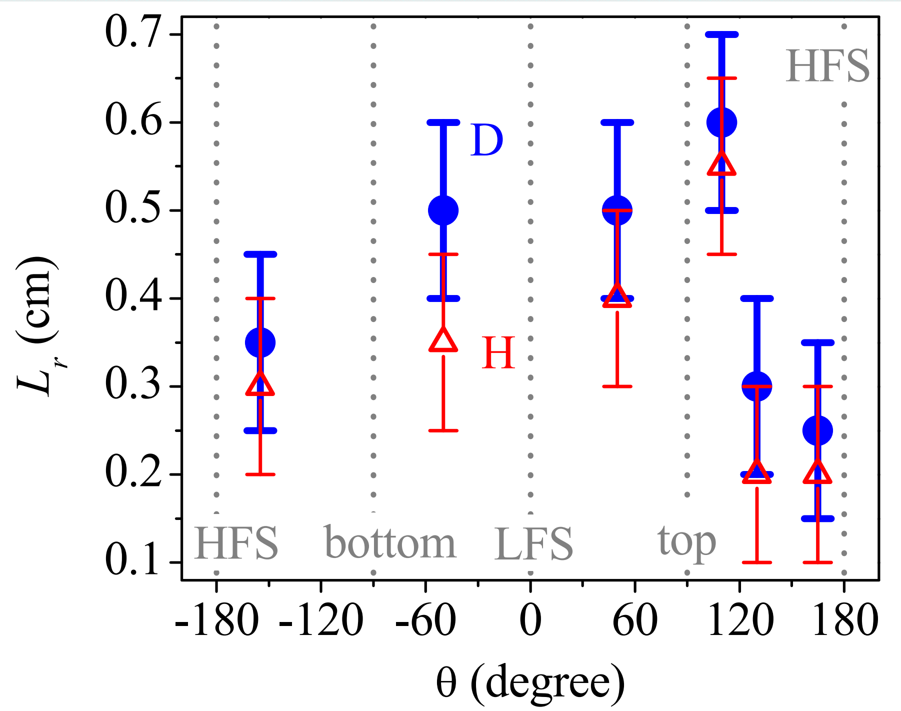


The turbulence radial correlation length both measured by Radial Correlation Doppler Reflectometry and simulated by GK modeling quickly decreases at high field side 120°< θ < 210° and then steadily grows in direction of plasma rotation.

Doppler frequency shift and correlation length in H- and D-discharges

A.Altukhov IRW12





The Doppler frequency shift dependence on vertical antenna position in H & D is similar, however the correlation length in D discharge is usually higher than in the H one.

The electric field variation as provided by Elmfire in agreement with experiment

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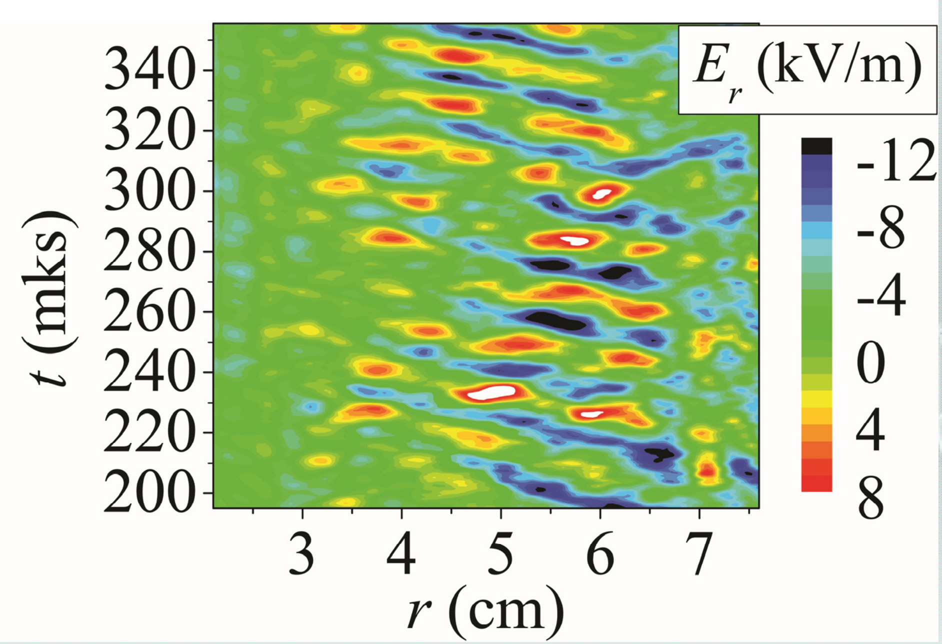
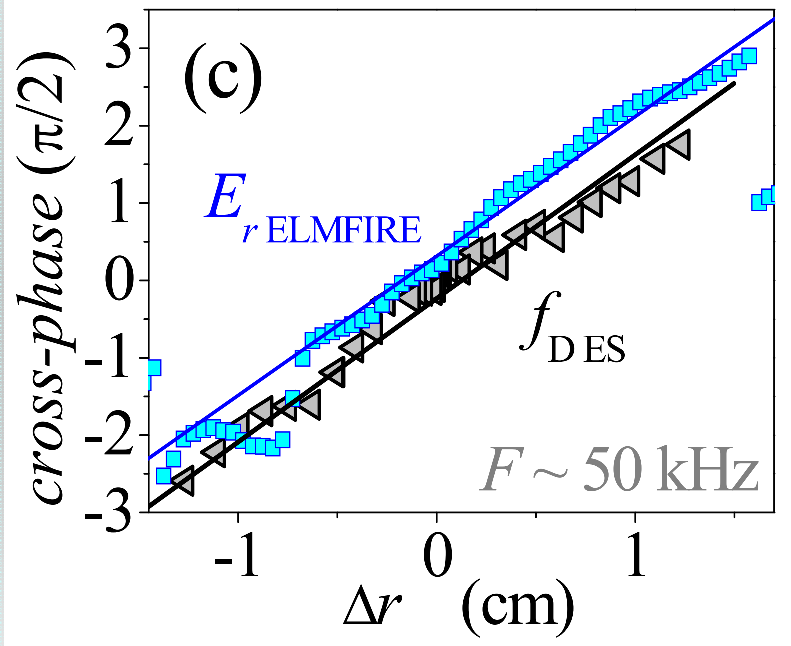
The intensive electric field GAM-wave



Comparison of cross-phases (Elmfire and experiment)



$k_{Gr} \approx 2.6\ \mathrm{cm}^{-1}$

E.Gusakov et al. 2013 *PPCF* **55** 124034

Drift-wave turbulence stabilization condition for GAM rotation shearing

The effective poloidal rotation shearing rate

$$\omega_{\mathrm{eff}} = \left| \tilde{\omega}_{E\times B} H + \bar{\omega}_{E\times B} \right| > \gamma$$

GAM — Mean flow

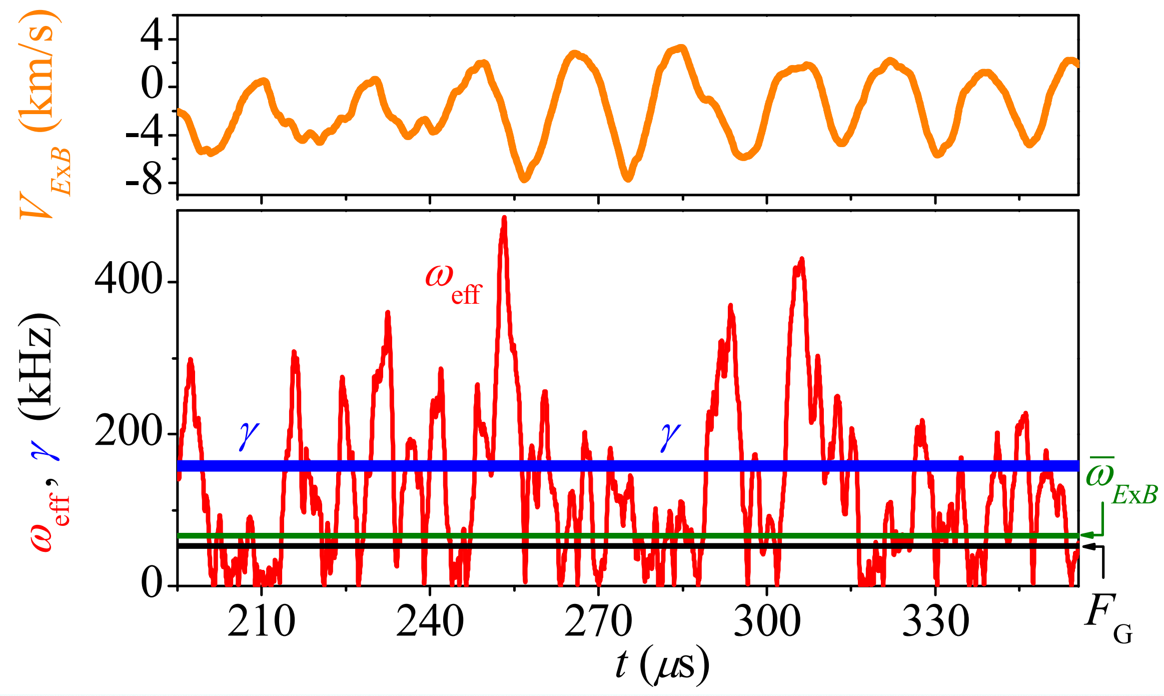
The instability growth rate, or the turbulence inverse correlation time

$$H \equiv \left[(1+3F)^2 + 4F^3 \right]^{1/4} \left[(1+F)\sqrt{1+4F} \right]^{-1}$$

$$F \equiv (2\pi F_G)^2 \gamma^{-2}$$

T.S. Hahm et al. 1999 *PoP* **6** 922

$$H(F_G, \gamma) \approx 0.2$$



A.D.Gurchenko et al. 2015 *EPL* **110** 55001

Effect of strong diffusivity modulation by GAMs in GK simulations

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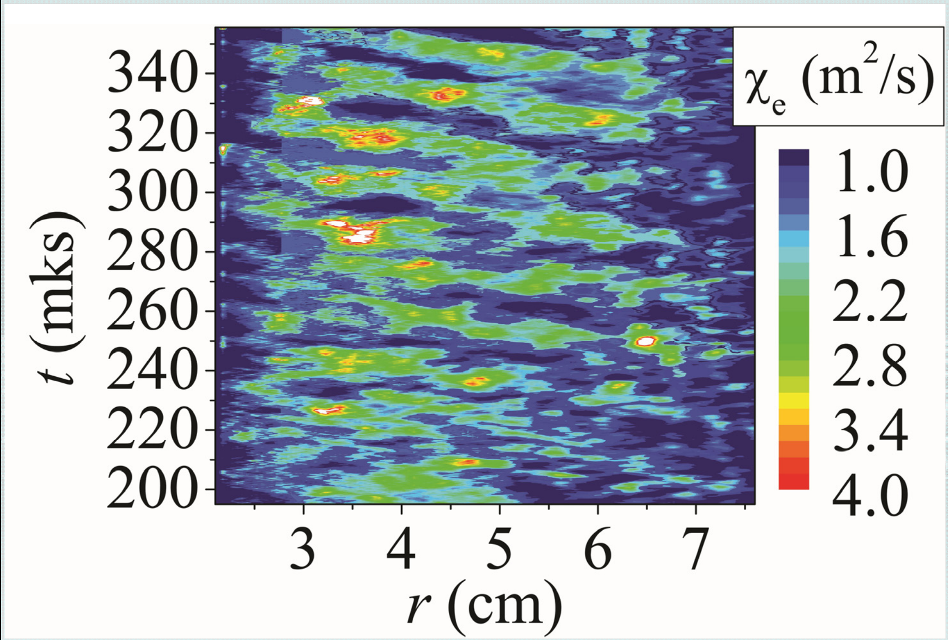
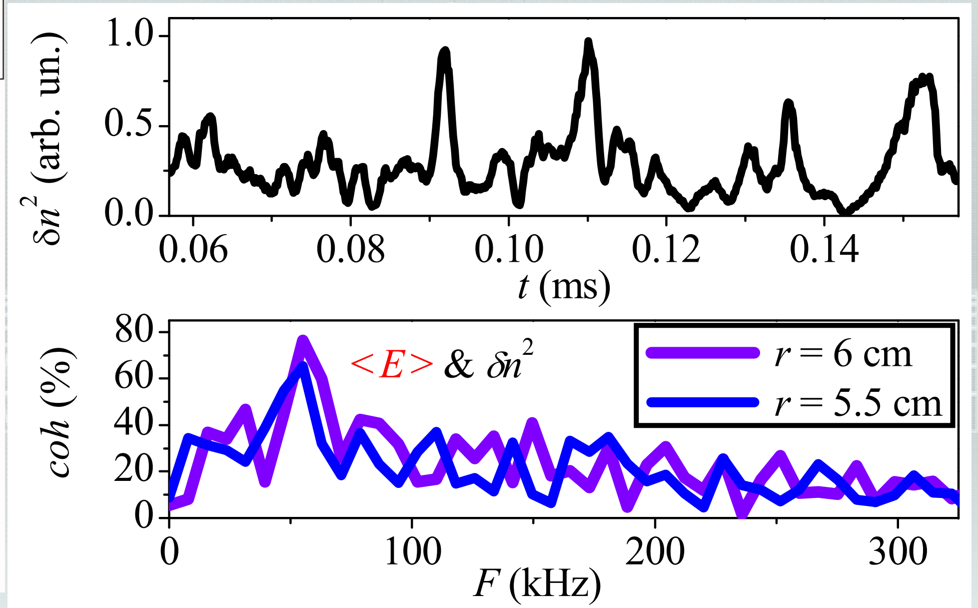
GAM-wave in the thermal diffusivity



The influence of intensive GAMs manifests itself initially in the turbulence level δn^2 modulation



A.D.Gurchenko et al.
2015 *EPL* **110** 55001

High coherence between $<E_r>$ and δn^2 proves the turbulence level modulation by GAMs.

Observations of turbulence level modulation at GAM frequency

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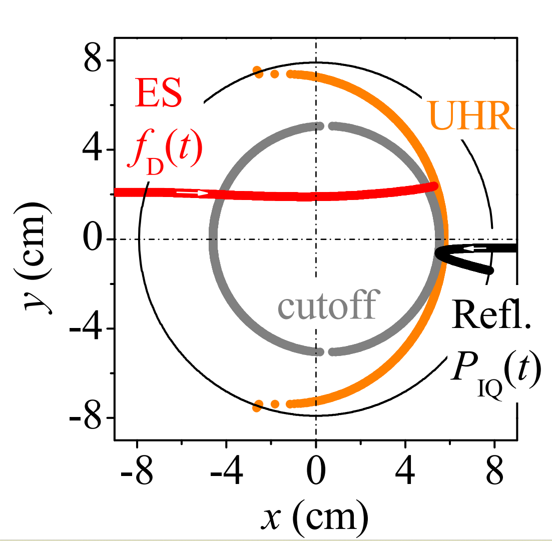
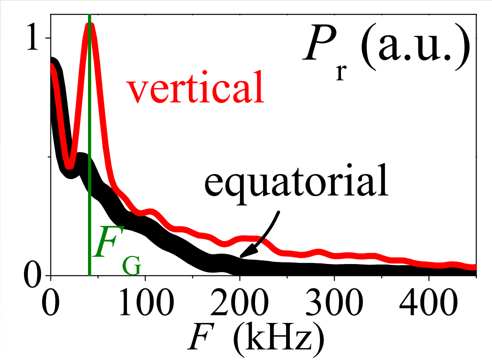
Combined microwave BS diagnostic

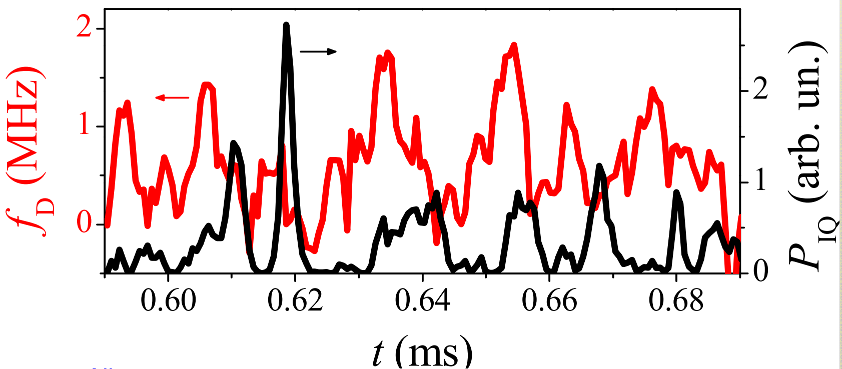


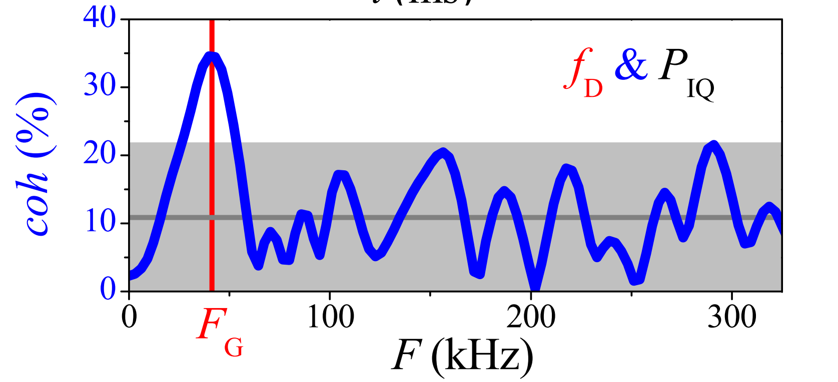


Time traces of f_D- and P_{IQ}-signals:

$f_D(t) = \kappa_\theta V_\theta(t) / 2\pi \sim E_{r\,GAM}$

$P_{IQ}(t) = C^2(t) + S^2(t) \sim \delta n^2$



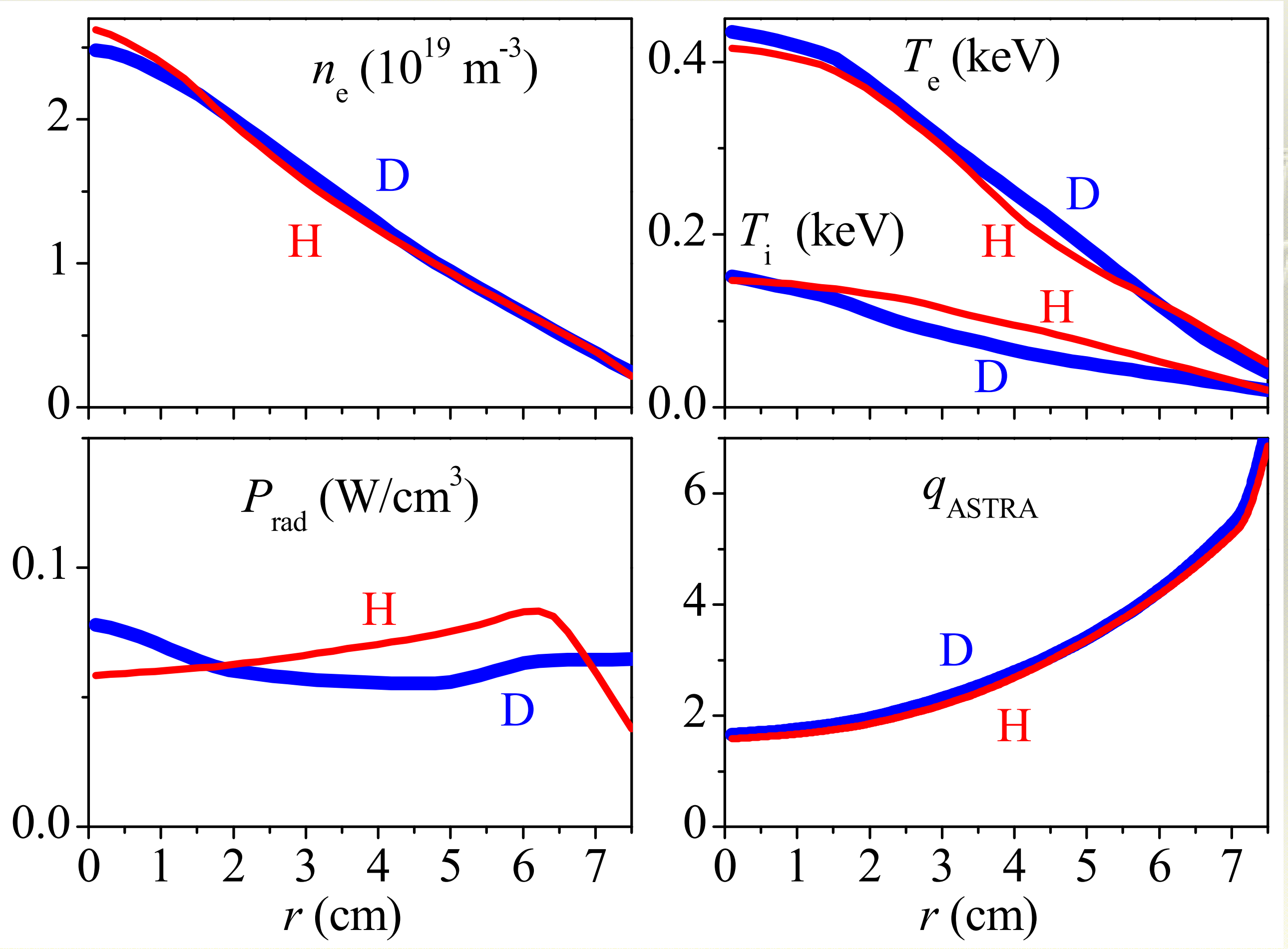


Gurchenko et al. 2015 *EPL* **110** 55001

High coherence between f_D-signal and the total reflectometry power P_{IQ} at GAM frequency proves the turbulence level modulation by GAMs.

Experimental H- and D- regimes for isotope study

A.Gurchenko 42EPS I5.J203



FT-2

R = 55 cm

a = 7.9 cm

27 ms:

19.5 kA

2.25 T

$Z_{eff\,H}$ = 2.8

$Z_{eff\,D}$ = 2.3

GAMs parameters measured in D- and H-discharges

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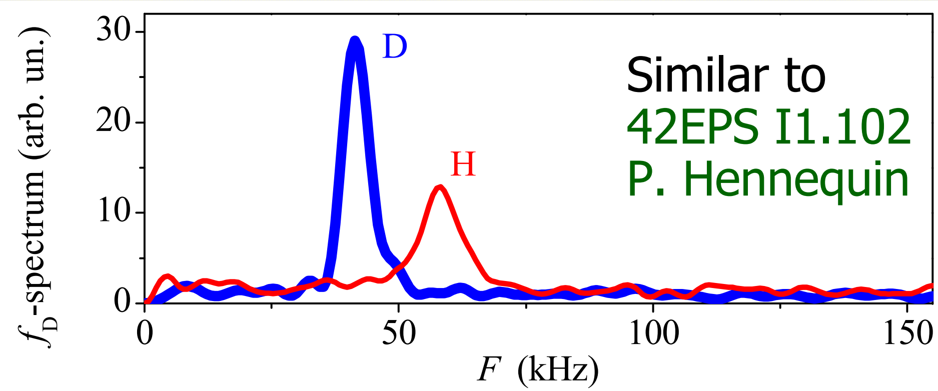
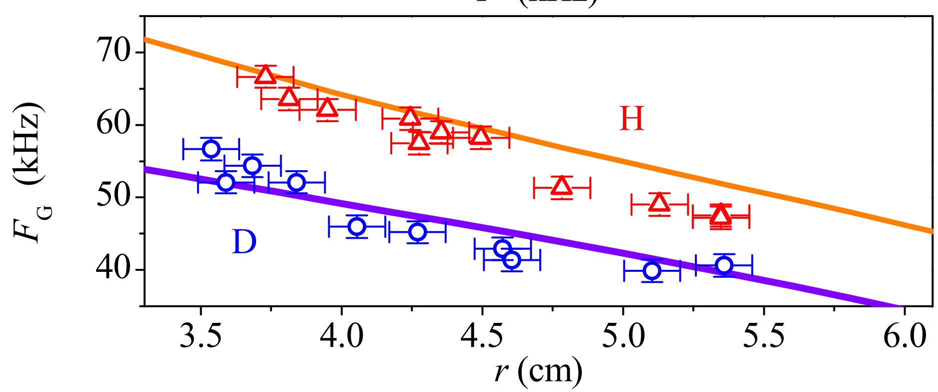
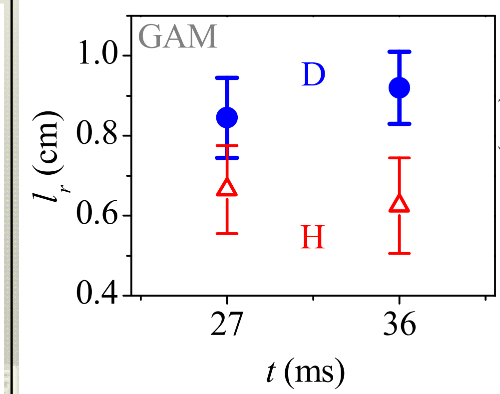
Power spectra of the Doppler ES f_D-signals

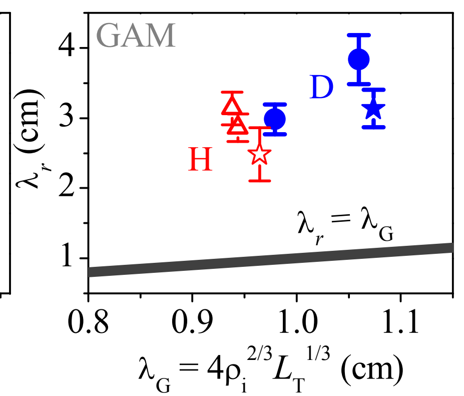




Radial profiles of the GAM frequency

GAMs radial correlation length and wavelength





GAMs here rather correspond to the MHD GAM resonance non-linearly induced by LF beats of the drift-wave turb. The GAM amplitude in this regime is determined not only by the non-linear drive provided by drift-wave turb., but also inverse proportional to the GAM damping rate determined in the edge FT-2 plasma by ion-ion collision frequency.

Turbulence level modulation at the GAM frequency in the experiment

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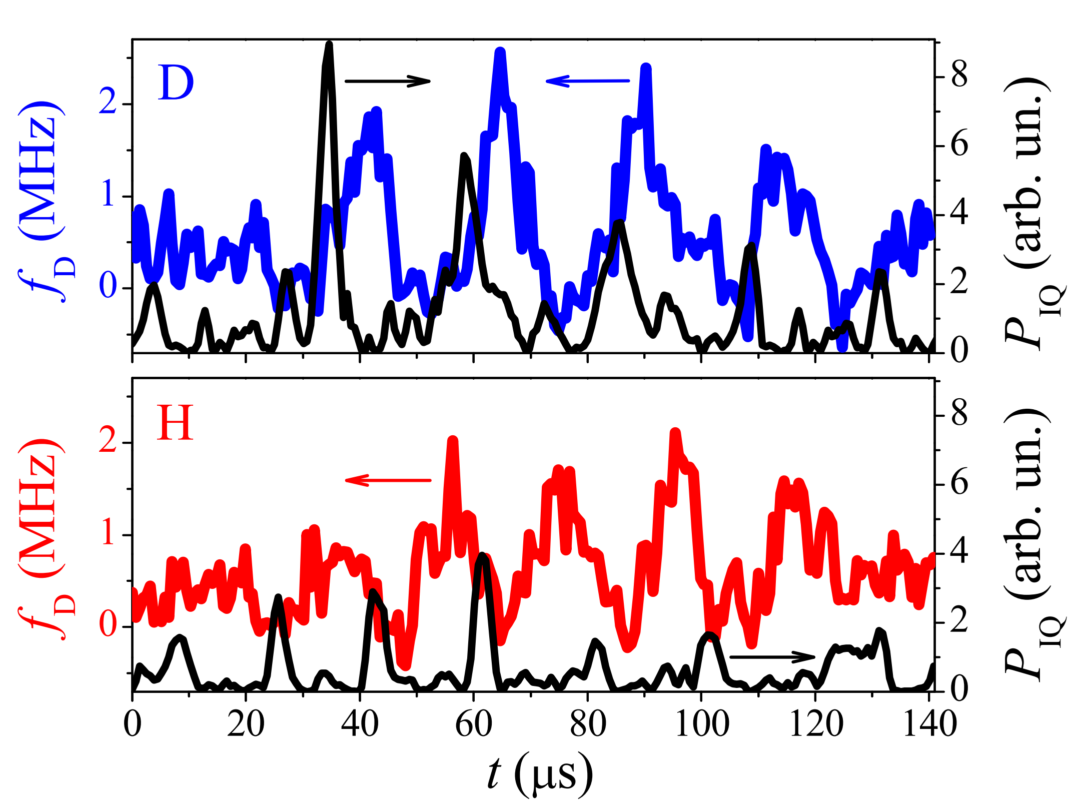
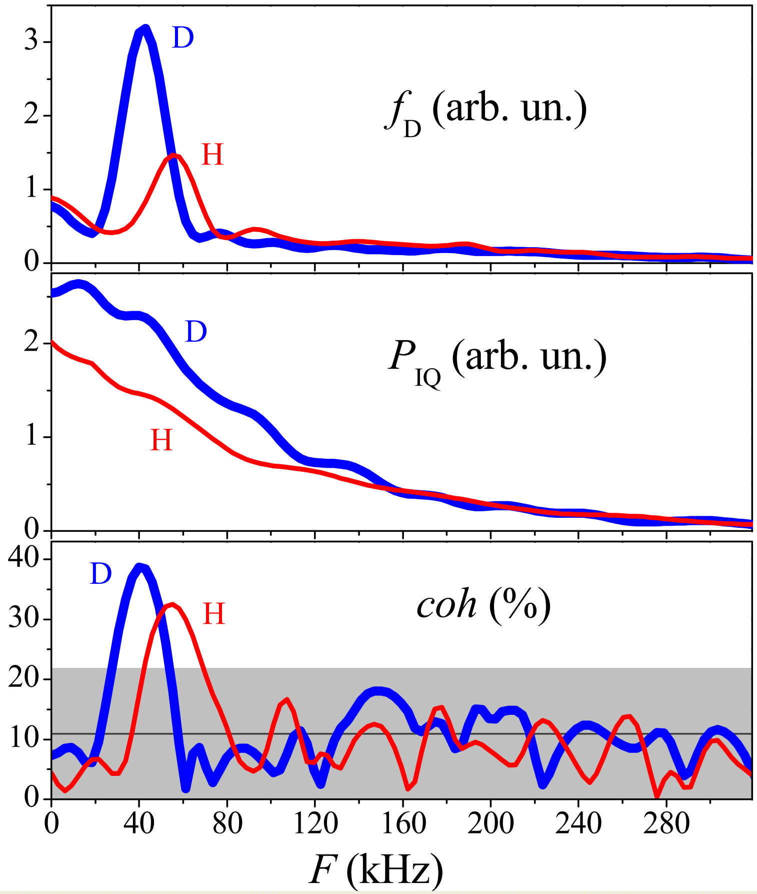
Time traces of f_D- and P_{IQ}-signals at $r \approx 4.5$ cm



To make a more reliable conclusion on the GAM-turbulence interplay a statistical analyses was done



The turbulence level modulation at the GAM freq. is better correlated to the GAMs in D

Weak local anti-correlation of GAM amplitude and electron thermal diffusivity

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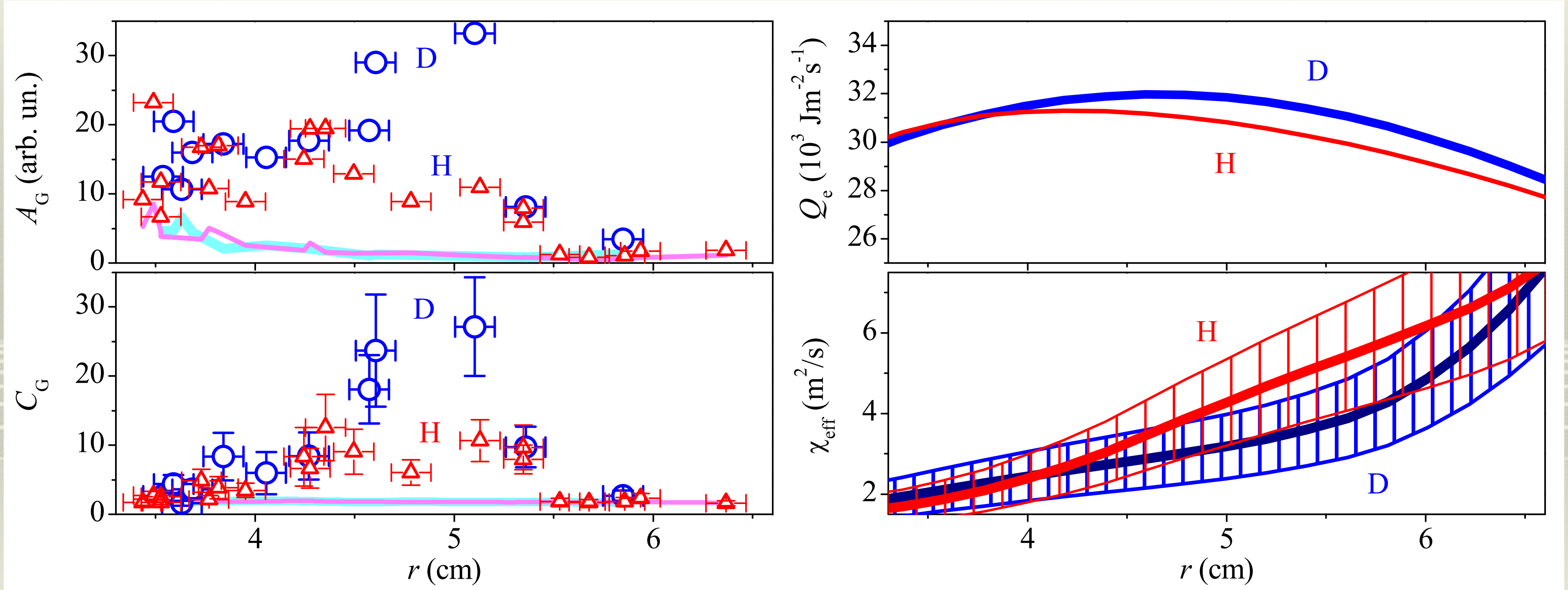

A possible explanation for the higher GAM amplitude in D can be related to its smaller damping due to i-i collisions.

The local anti-correlation effect in GAMs-turbulence interaction

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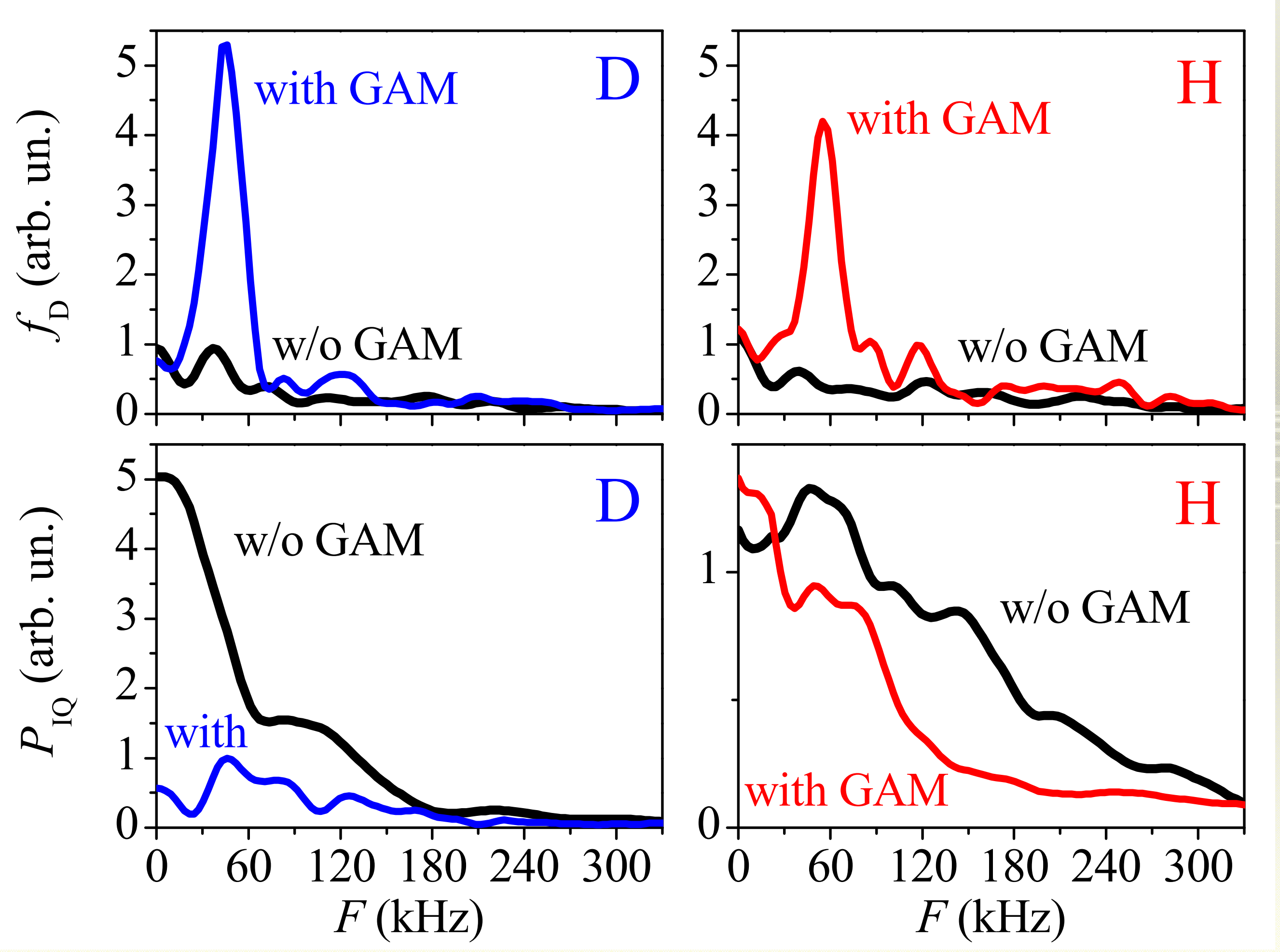
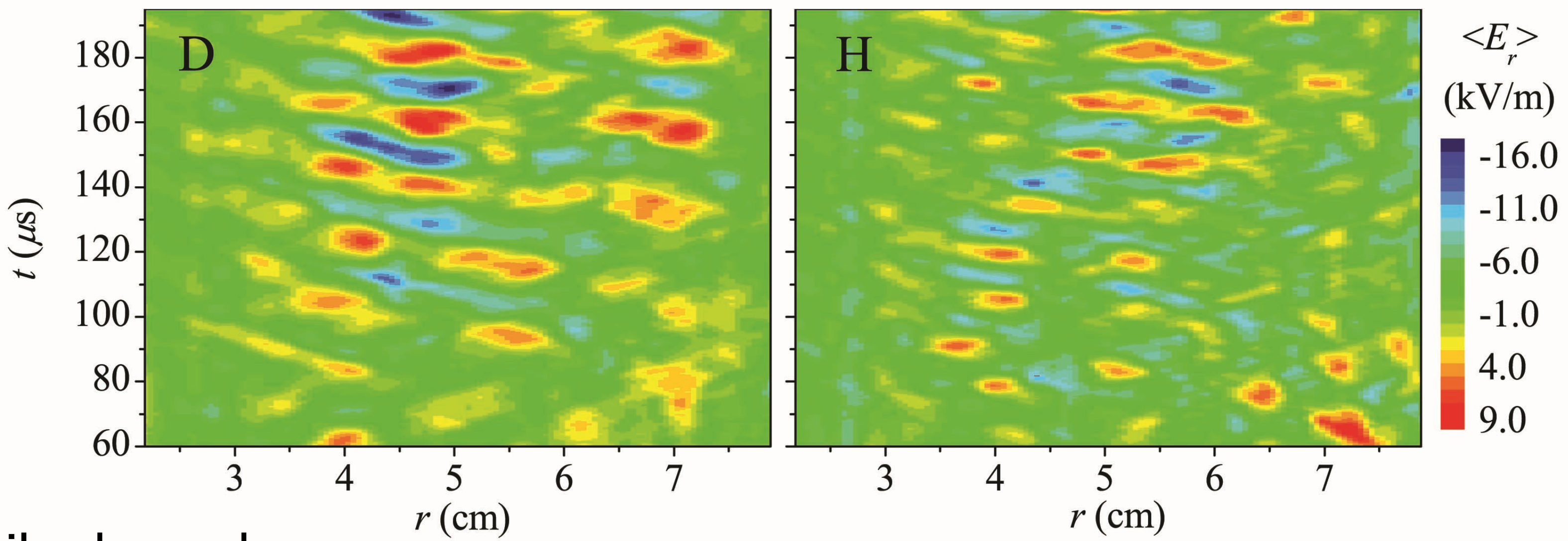
Turbulence in GAM-active and GAM-free periods at $r \approx 4.5$ cm

New f_D- and P_{IQ}-signals were recombined using signals measured in intervals with and w/o GAMs

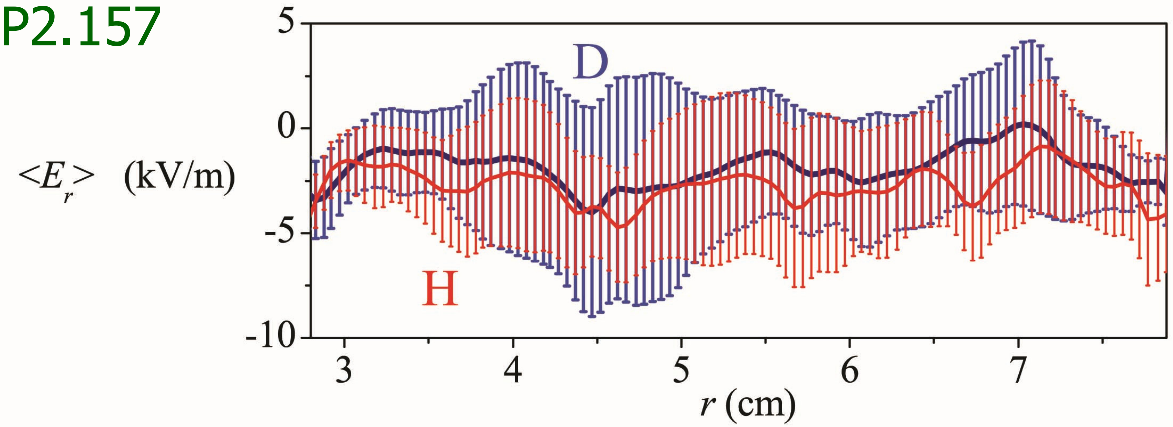


The electric field GAM-waves in D- and H-discharges in ELMFIRE simulations

D-discharge H-discharge



Details shown by
P. Niskala P2.157



Vertical bars indicate the amplitude of $<E_r>$-oscillations averaged over the time.

Time traces of the radial electric field and δn^2 in ELMFIRE simulations

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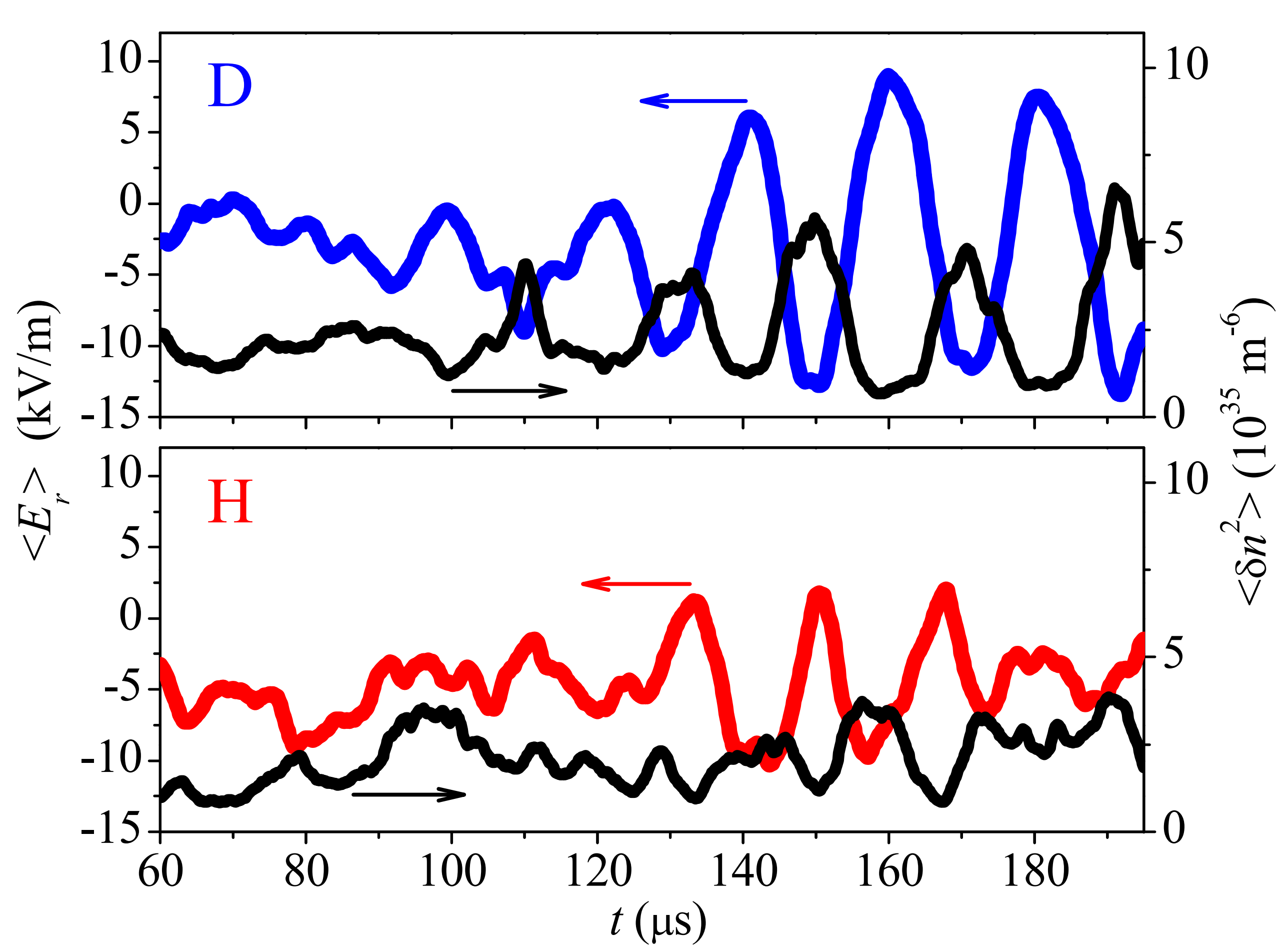
δn^2 calculated after filtering of GAM-oscillations out of $\delta n(t)$ – corresponds not to original GAM, but to the turbulence modulation by it.



$r \approx 4.5$ cm

GAM modulation of the turbulence level in ELMFIRE simulations

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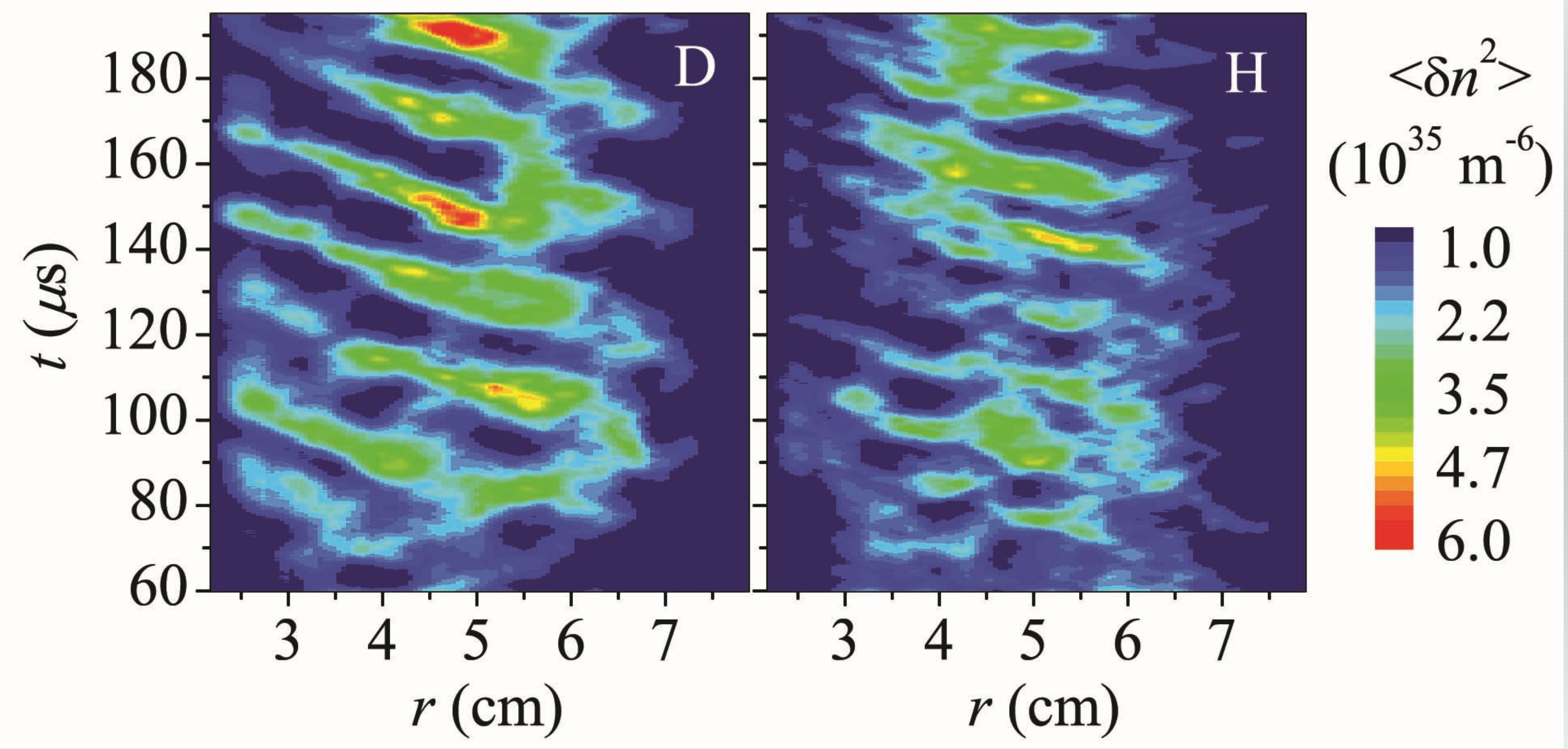
D-discharge H-discharge



The modulation in D looks <u>higher</u> and <u>more coherent</u> than in H, similar to the experiment.

Strong GAM modulation of particle and energy fluxes in ELMFIRE simulations

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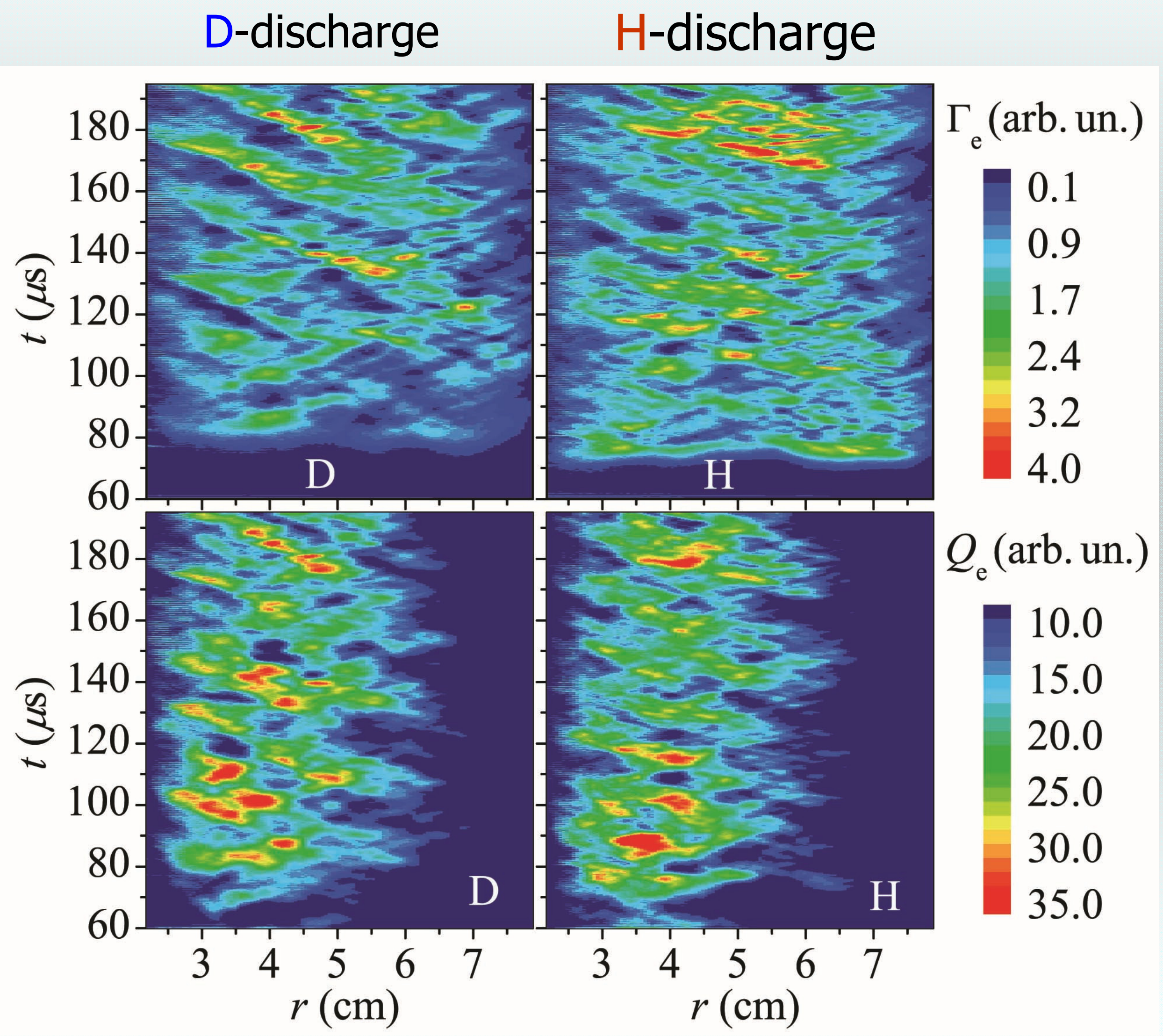
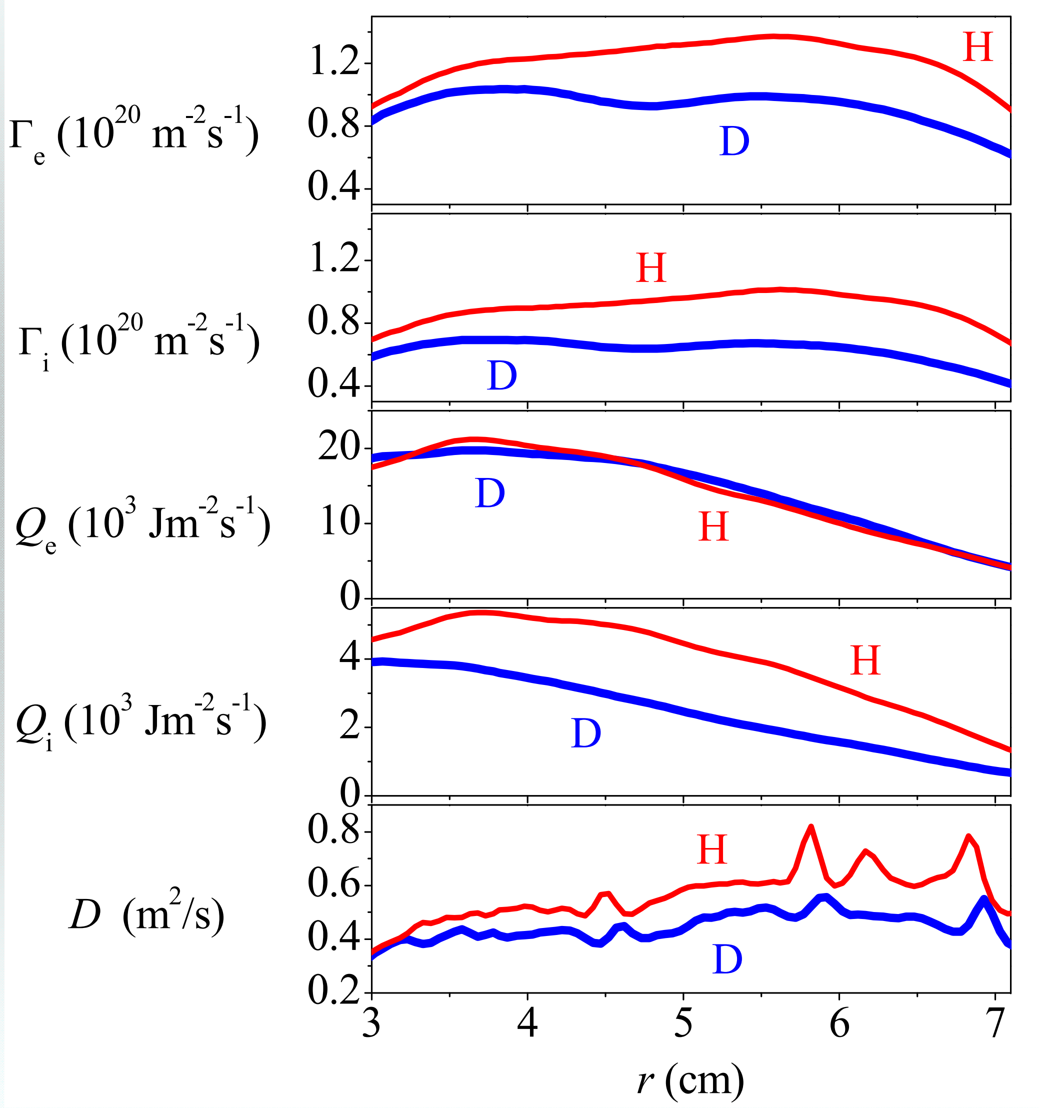


Mean values of fluxes and diffusivity in ELMFIRE simulations



Mean values and modulation amplitudes of the turbulence level

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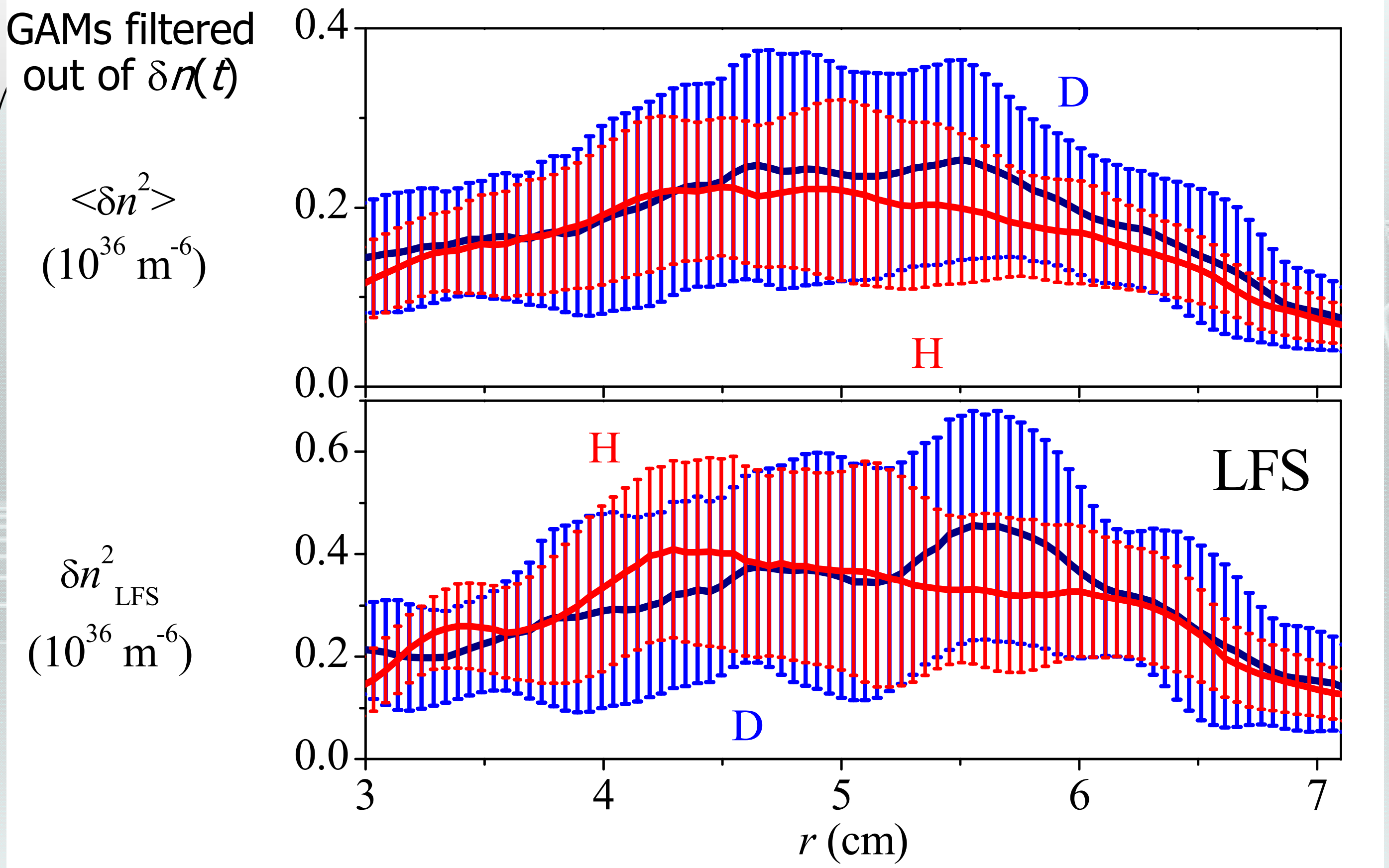

The modest local excess of the δn^2_{LFS} in H at $r \sim 4.3$ cm can be considered as a qualitative confirmation obtained in modeling for the stronger turbulence suppression by more intensive GAMs observed at this r in the experiment.

The higher level of turbulence simulated in D-discharge in comparison with H at the first sight seems to be in drastic contradiction with lower levels computed for particle and ion energy fluxes.

The MHD radial turbulent particle flux in ELMFIRE simulations

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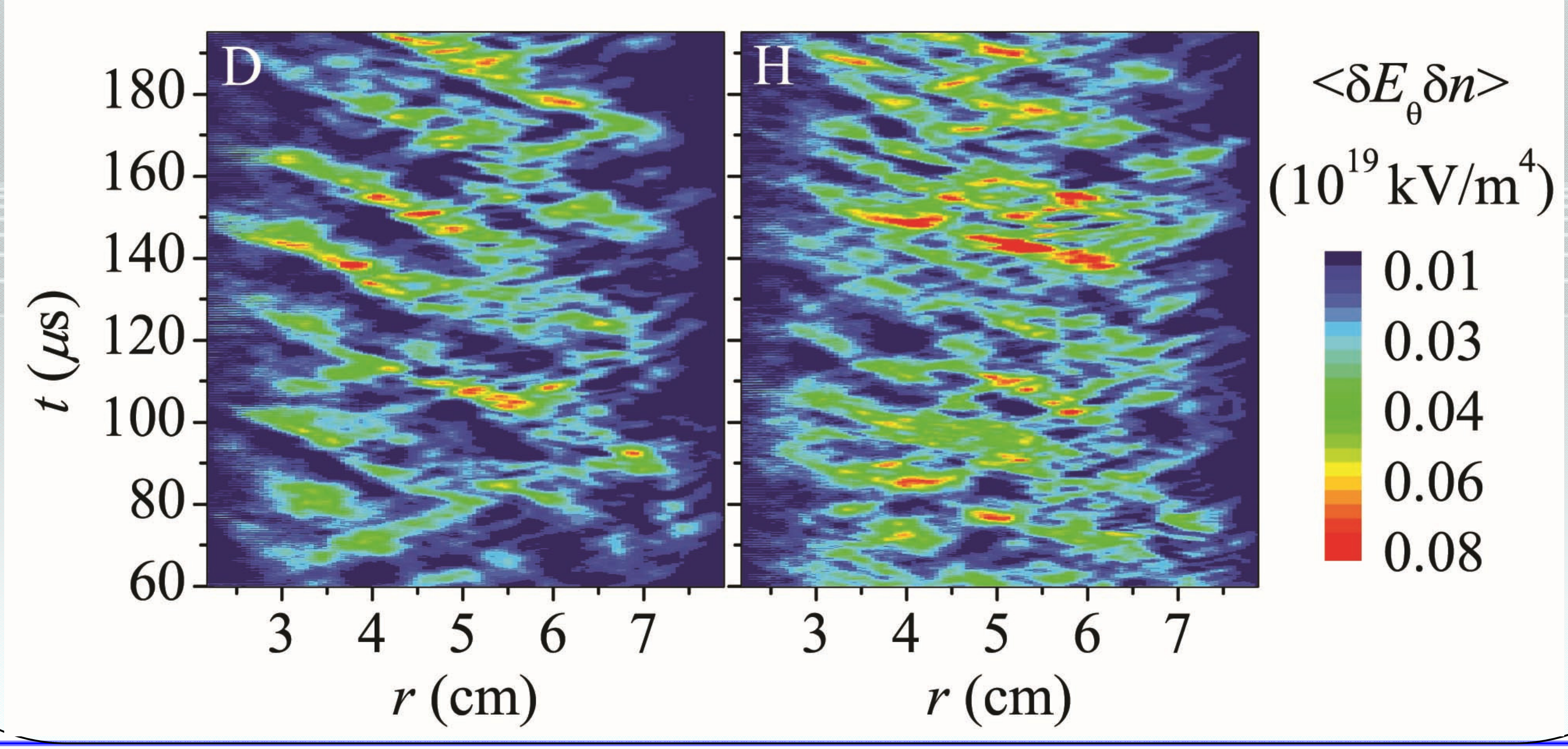
$$\Gamma_t = \frac{\langle \delta E_\theta \delta n \rangle}{B}$$

D-discharge H-discharge



Mean values and modulation amplitudes of δE_θ^2 and the radial turbulent flux

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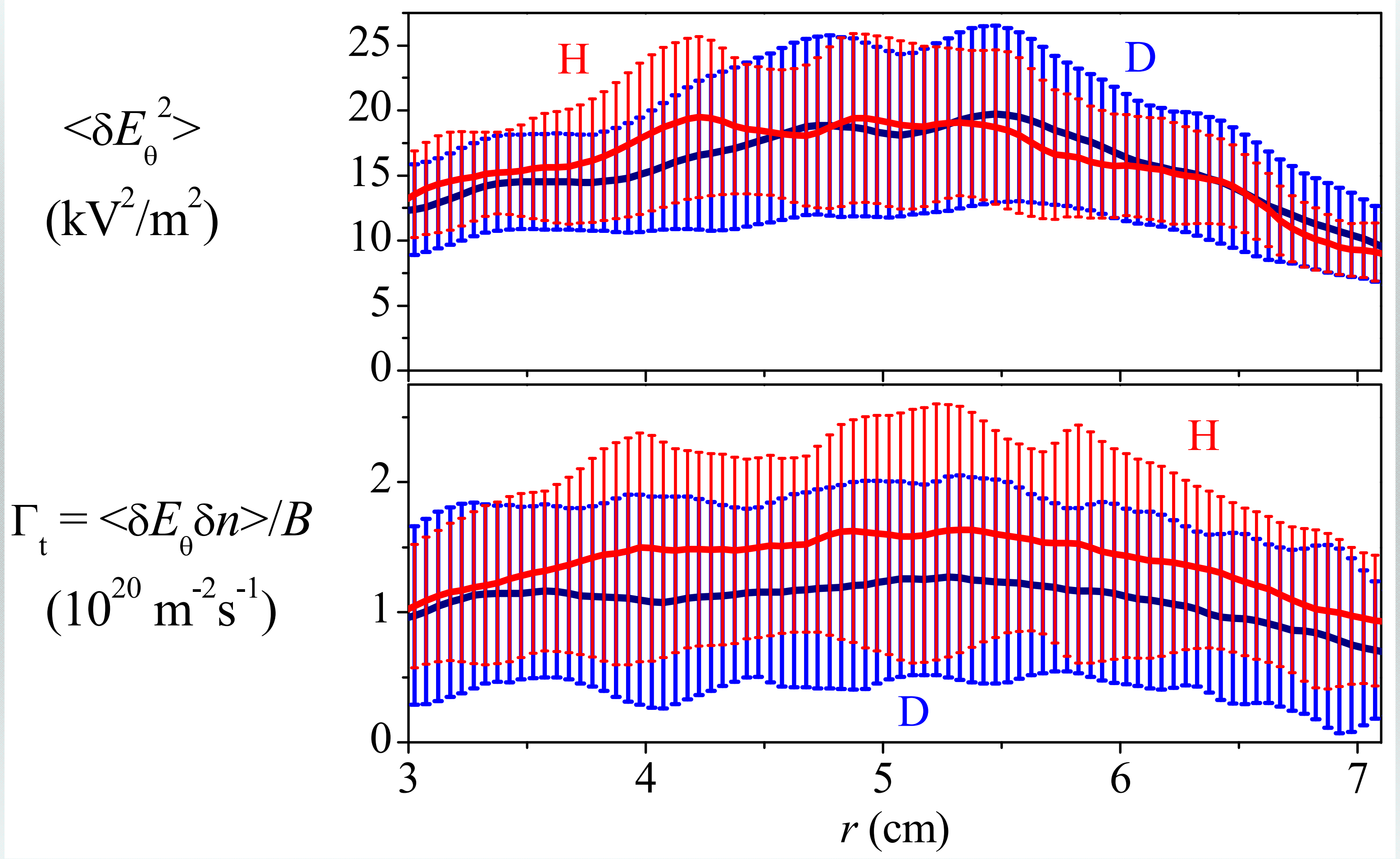

The higher level of Γ_t in H could be explained only by the difference of relative phase of δn and δE_θ in H and D.

Conclusions

Substantial excess of the GAM amplitude, radial wavelength and correlation length in a wide spatial region of D-discharge resulting in stronger modulation of drift-wave turbulence level in comparison with H-discharge is demonstrated by highly localized turbulence diagnostics and the global GK modeling.

The larger turbulence radial correlation length is found in D-discharge in experiment and the stronger modulation of GK particle and energy fluxes as well as of MHD particle flux is shown there by the GK code.

Conclusions

The GK modeling demonstrated comparable level of high frequency density and electric field fluctuations in H- and D-discharges, nevertheless, the mean values of the ion energy and particles flux provided by modeling show the systematic isotope effect at all the radii. The isotope effect is also observed in the mean MHD particle flux, which indicates that relative phase of density and electric field fluctuations in deuterium is closer to $\pi/2$ than in hydrogen.

The obtained results demonstrate productivity of comparative investigation of the anomalous transport phenomena in similar H- and D- discharges using localized diagnostics and global GK modeling and appeal for the further studies focused, in particular, on determination of the drift-wave frequency and wave number domain responsible for the isotope effect.

Comparison of experimental and synthetic X-mode RCDR CCFs

Aalto University
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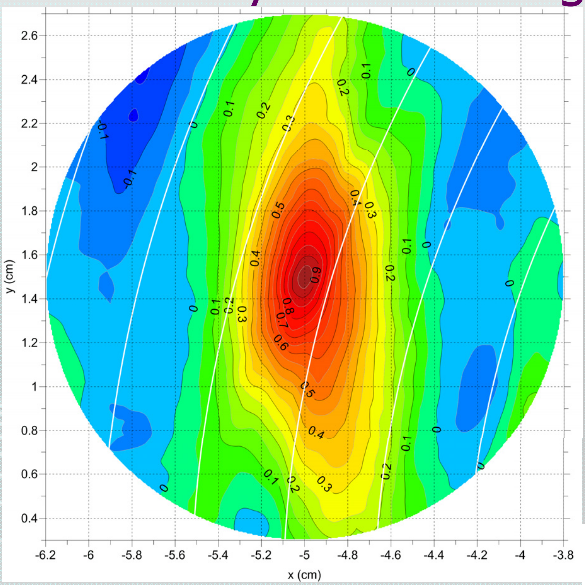
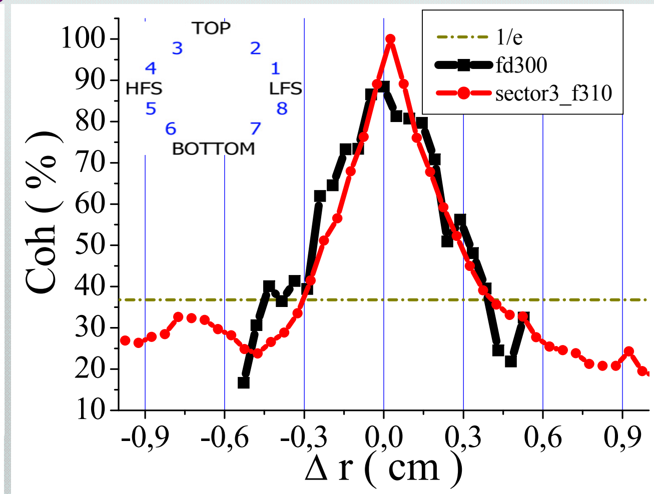
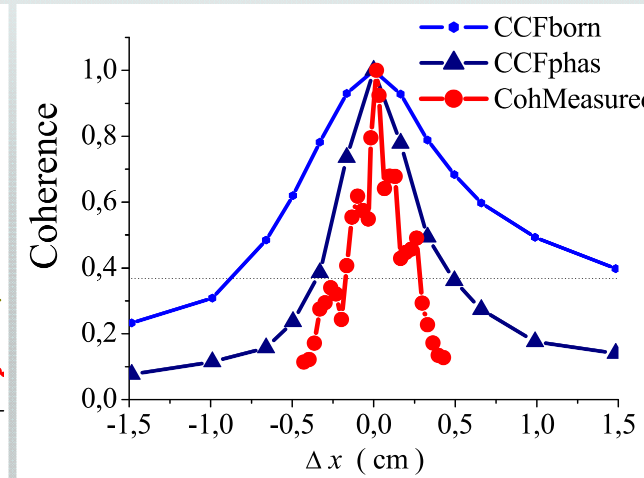
Turbulence two-point CCF by GK modeling



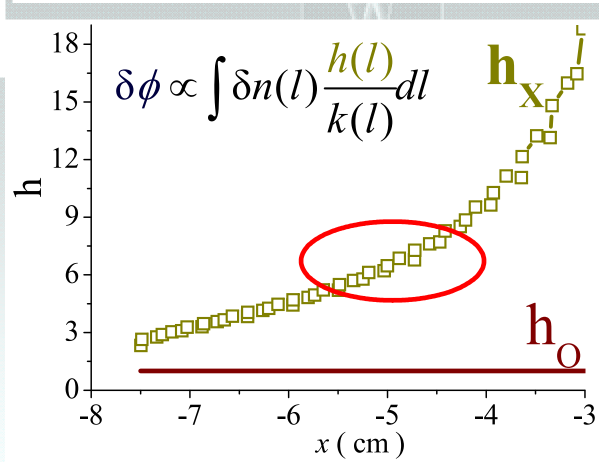
Experimental & GK coherence



Experimental & synthetic coherence



Substantial difference in RCDR synthetic and measured coherences is observed, which is explained by transition of DR to the nonlinear regime



$$CCF_{born} = A_s(f_1) A_s^*(f_2)$$

$$CCF_{phase} = B_s(f_1) B_s^*(f_2); \quad B_s = A_s \exp(i\delta\phi)$$

The modified synthetic DR signal is a product of the Born approximation synthetic signal and the phase factor gained all over the trajectory