EX/11-2Ra

The Isotope Effect in GAM – Turbulence Interplay and Anomalous Transport in Tokamak

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Motivation

GAMs, which are, according to the present day understanding, excited in plasma due to nonlinear three-wave 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.

Dependence of GAM excitation level and, more general, long-range correlations on ion mass could be responsible [Y. Xu et al. 2013 *PRL* **110** 265005] for the isotope effect in tokamak anomalous transport [U. Stroth 1998 *PPCF* **40** 9] which is still unclear.

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.

The turbulence and diffusivity modulation at GAM frequency as provided by ELMFIRE

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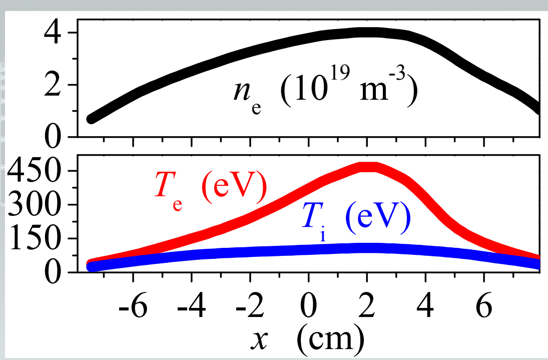
19 kA H-discharge parameters

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

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

$T_e(0) \approx 470$ eV

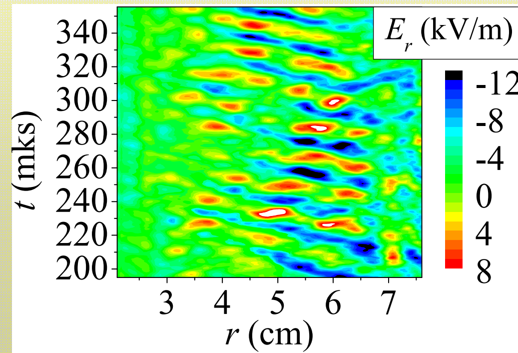
$T_i(0) \approx 110$ eV



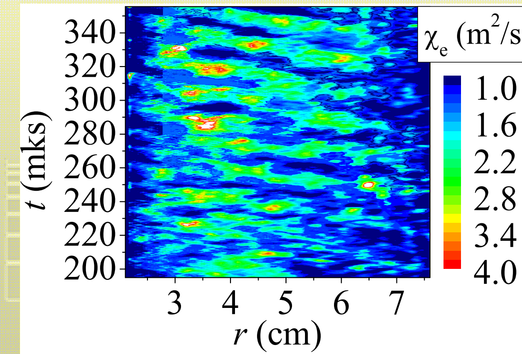
S. Leerink et al. 2012 *PRL* **109** 165001

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

The Electric field GAM wave

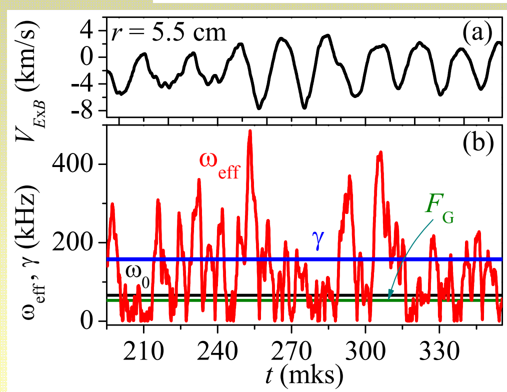


Thermal diffusivity wave



Drift-wave turbulence stabilization condition for GAM rotation shearing

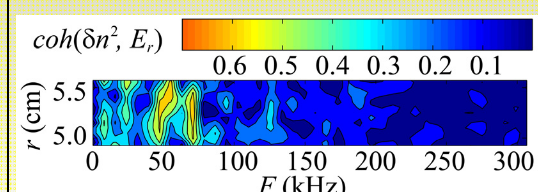
$$\omega_{eff} = \left|\tilde{\omega}_{E\times B} \cdot H + \omega_0\right| < \gamma$$



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

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

High coherence between E_r and equatorial δn^2 at the GAM frequency



A.D. Gurchenko et al. 2014 *41 EPS Conf. PP* **38F** O2.111

Doppler Enhanced Scattering in the UHR and O-mode reflectometer

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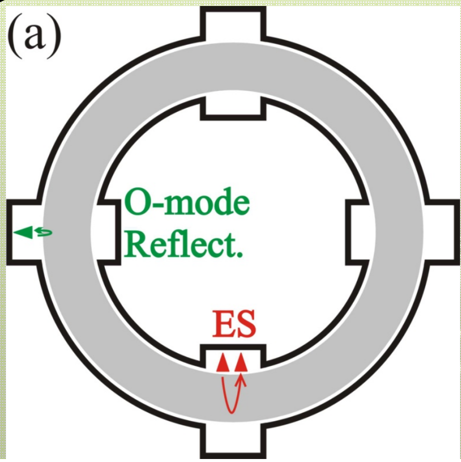
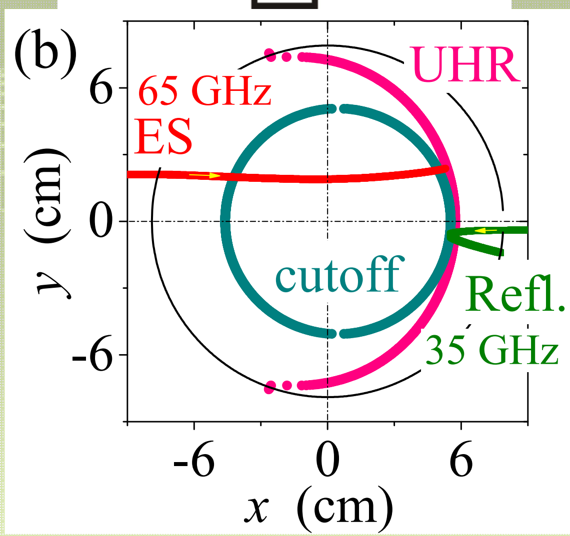


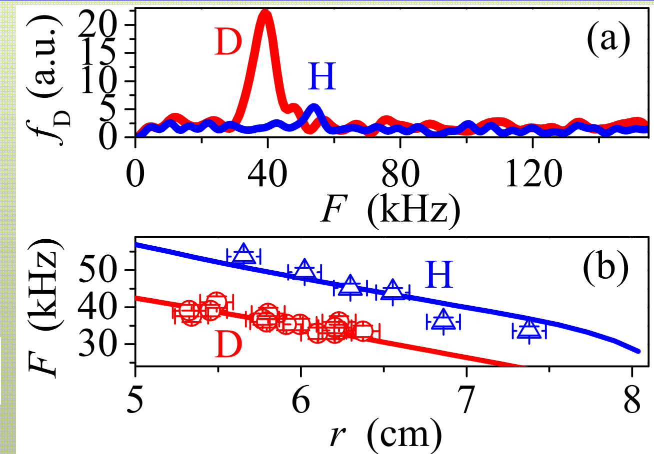


A.D. Gurchenko et al. 2013 *PPCF* **55** 085017

ES: 55-70 GHz

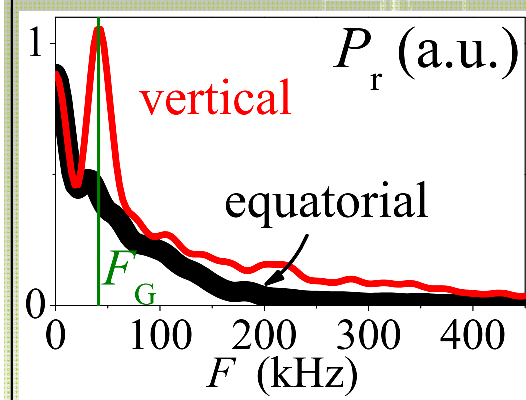
$$f_D(t) = \frac{\int f\,|P_{ES}|\,df}{\int |P_{ES}|\,df}$$

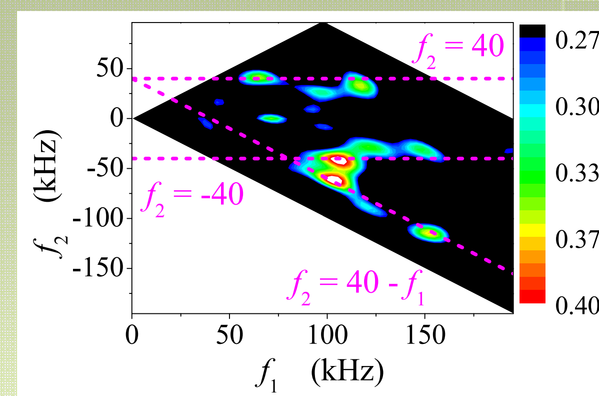
$$f_D(t) = \kappa_\theta V_\theta(t) / 2\pi \sim E_{rG}$$



refl.: 26-37 GHz

$$P_{IQ}(t) = C^2(t) + S^2(t)$$





$$P_r(F) = \langle C(F)C^*(F) \rangle$$

$$b^2(f_1, f_2) \propto \left| \langle P_{IQ}(f_1) P_{IQ}(f_2) P^*_{IQ}(f_1 \pm f_2) \rangle \right|^2$$

The first observations of turbulence level modulation at GAM frequency

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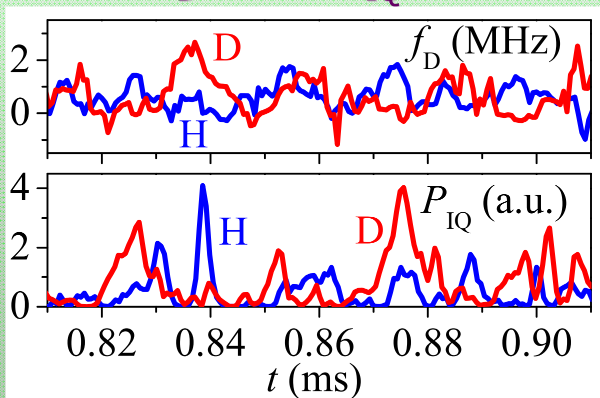
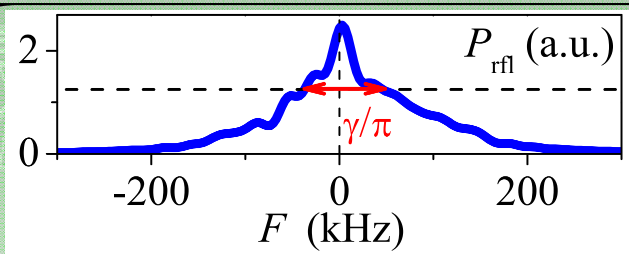
GAM f_D- and P_{IQ}-oscillations with similar periodicity



The amplitude of GAM like oscillations increased in the $f_D(t)$ time trace by a factor of 2 in D-discharge, the shape of P_{IQ}-peaks also became more distinct.



Turbulence inverse correlation time

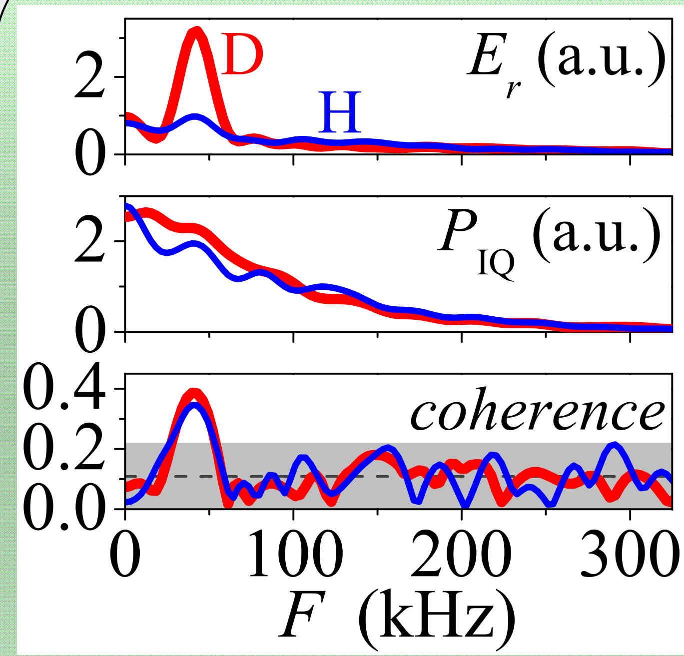
$\gamma \approx 270$ kHz

Effective shearing rate:

$$\omega_{eff} = \left| V_{\theta G} k_{rG} \cdot H + \omega_0 \right| \approx$$

$$\approx \left| 1.7\ \text{km/s} \cdot 2.6\ \text{cm}^{-1} \cdot 0.5 + 50\ \text{kHz} \right| = 271 \pm 42\ \text{kHz}$$

ω_{eff} is very close to the γ, providing the possibility for the turbulence suppression once per the GAM period.



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

Turbulence in GAM-active and GAM-free periods in 19 kA H- & D-discharges

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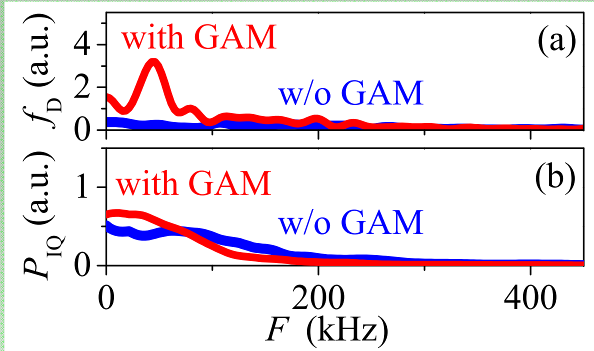
The intermittency of GAMs was taken into account during the integration of the total reflectometer power by selection and recombining of time intervals where GAMs are excited or suppressed. The quality of the selection is seen in power spectra of f_D-signals with and without GAMs. The corresponding P_{IQ} signals were recombined in the timed intervals.

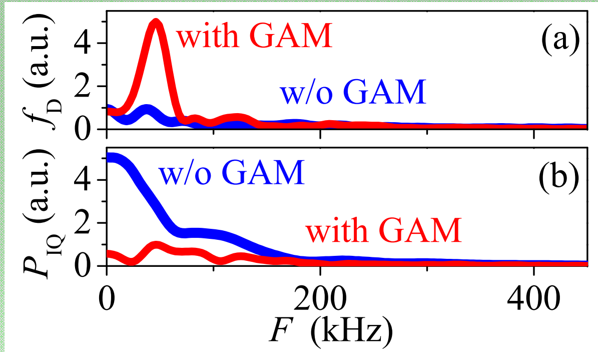
$$\Delta P_{IQ} = \int P_{IQ} dt \Big/ \Delta t$$

Hydrogen



$$\Delta P_{IQ\text{ with GAM}} = 0.8 \Delta P_{IQ\text{ w/o GAM}}$$

Deuterium



$$\Delta P_{IQ\text{ with GAM}} = 0.6 \Delta P_{IQ\text{ w/o GAM}}$$

The turbulence modulation at the GAM frequency results in D-case in strong drift-wave turbulence spectrum suppression during the GAM bursts compared to the GAM-free periods and significant drop of the total reflectometry signal power.

The anti-correlation of GAM amplitude and electron thermal diffusivity

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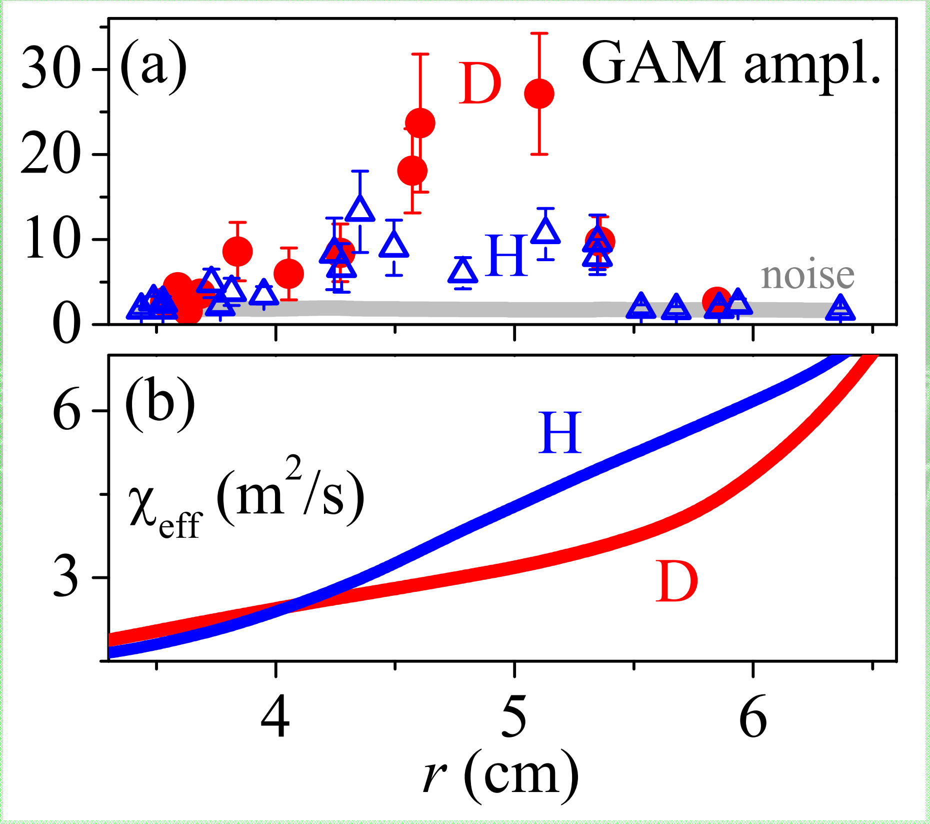

The observed turbulence suppression by GAMs provides an explanation for the anti-correlation of the GAM amplitude and the effective electron thermal diffusivity typical for the FT-2 experiments [A.D. Gurchenko et al. 2013 *40 EPS Conf. PP* **37D** P2.181]. In the case of similar D- and H-discharges the above effect provides a striking example of the isotope phenomenon.

Conclusion (EX/11-2Ra)

It is demonstrated experimentally that the theoretically predicted possibility of GAMs control of the turbulence, associated with the enhanced plasma rotation shearing, manifests itself in modulation of the turbulence level at the GAM frequency. This observation is supported by ELMFIRE full-f global GK modeling demonstrating the modulation of density fluctuations as well as of the heat flux and diffusivity. The experimental effect was enhanced in D-discharge where GAM amplitude increased leading to the fluctuation reflectometry signal suppression during the GAM bursts and to the decrease of the mean anomalous electron thermal diffusivity determined by the ASTRA modeling thus providing an explanation for the isotope effect in tokamak plasma anomalous transport.

Density Fluctuations as an Intrinsic Mechanism to Keep Self-consistent Shape of Pressure Profile

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Motivation

The main goal of the work is to reveal the relation of density turbulence and particle transport with plasma characteristics.

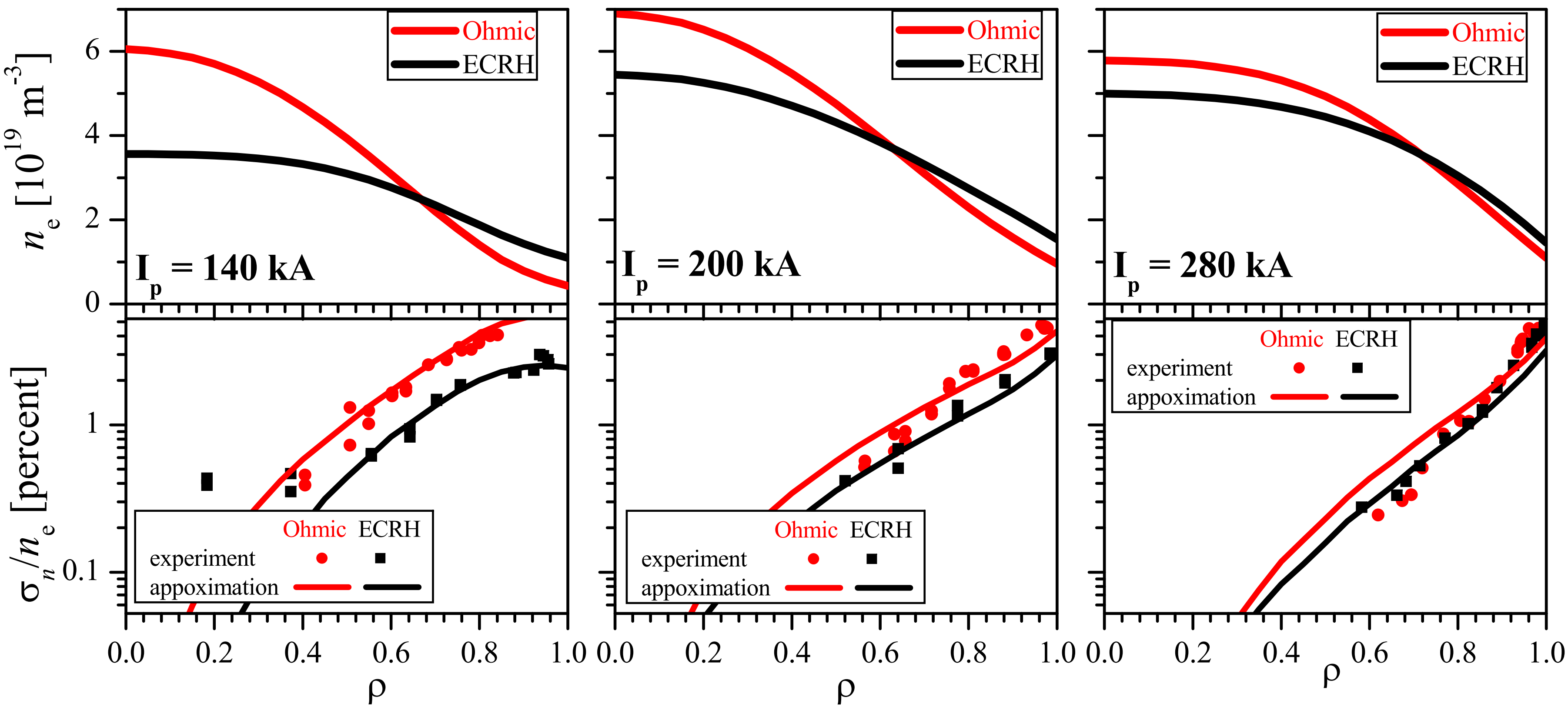
Results

• The **level of the density fluctuations** even **decreases** in ECRH in spite of the **confinement degradation**.

• The density fluctuation level correlates with particle fluxes and formation of the density profile rather than energy confinement.

• The **fluctuation level increases** and **particle transport degrades** when **profiles become more peaked** in comparison with **optimal pressure profile**, causing the fast density decay in OH and "density pump out" in ECRH plasmas.

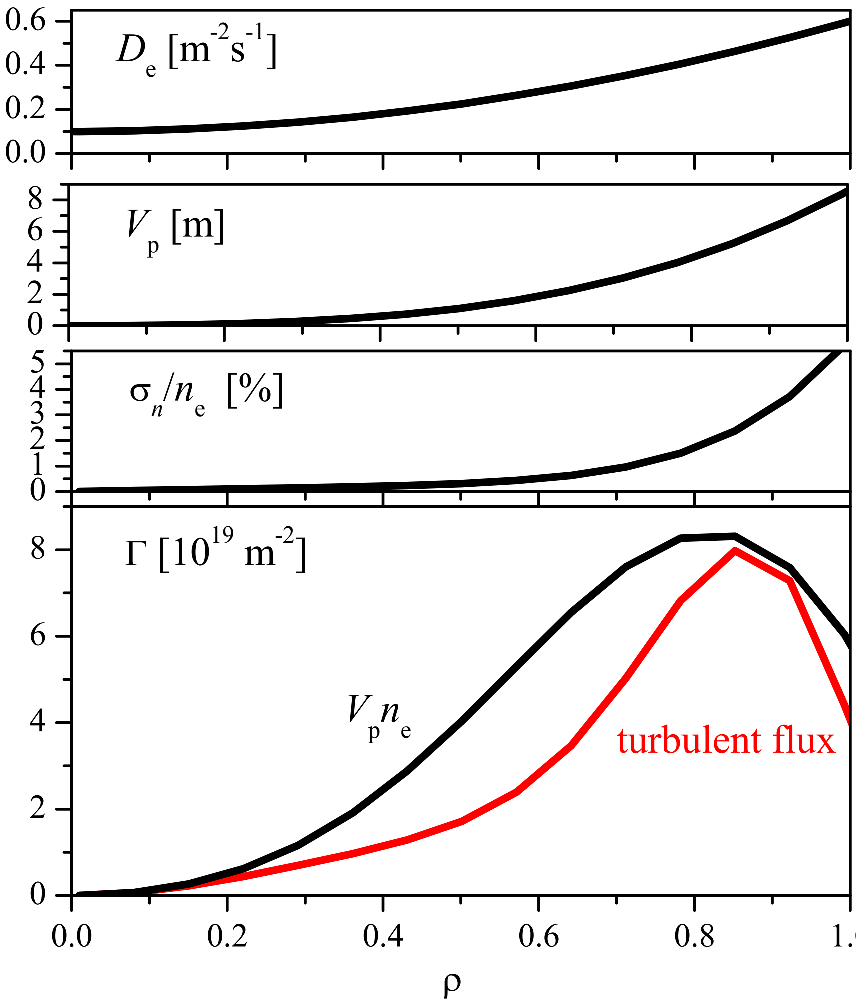
Steady state radial profiles of density fluctuation



- Density fluctuations decreased in ECRH despite the energy confinement degradation.
- The approximation $\frac{\sigma_n}{n_e} \sim 0.2 q_a \cdot \frac{r}{L_n}$ well describes OH and ECRH turbulence level.
- The density fluctuation level seems to be dependent on the density profile shape only, not on the heating power or energy confinement.

Experimental pinch flux and turbulence flux

Does the turbulence level enough to form the density profile?



- Bell-shape of the density profile is believed to be formed by anomalous turbulent pinch flux [B. Coppi and C. Spight 1978 PRL Lett. **41** 551].

- Measurements of plasma pinch [V.A. Vershkov et al. 2013 NF **53** 083014] and density fluctuations allow to compare the experimental inward particle flux $V_p n_e$ with estimated turbulent flux.

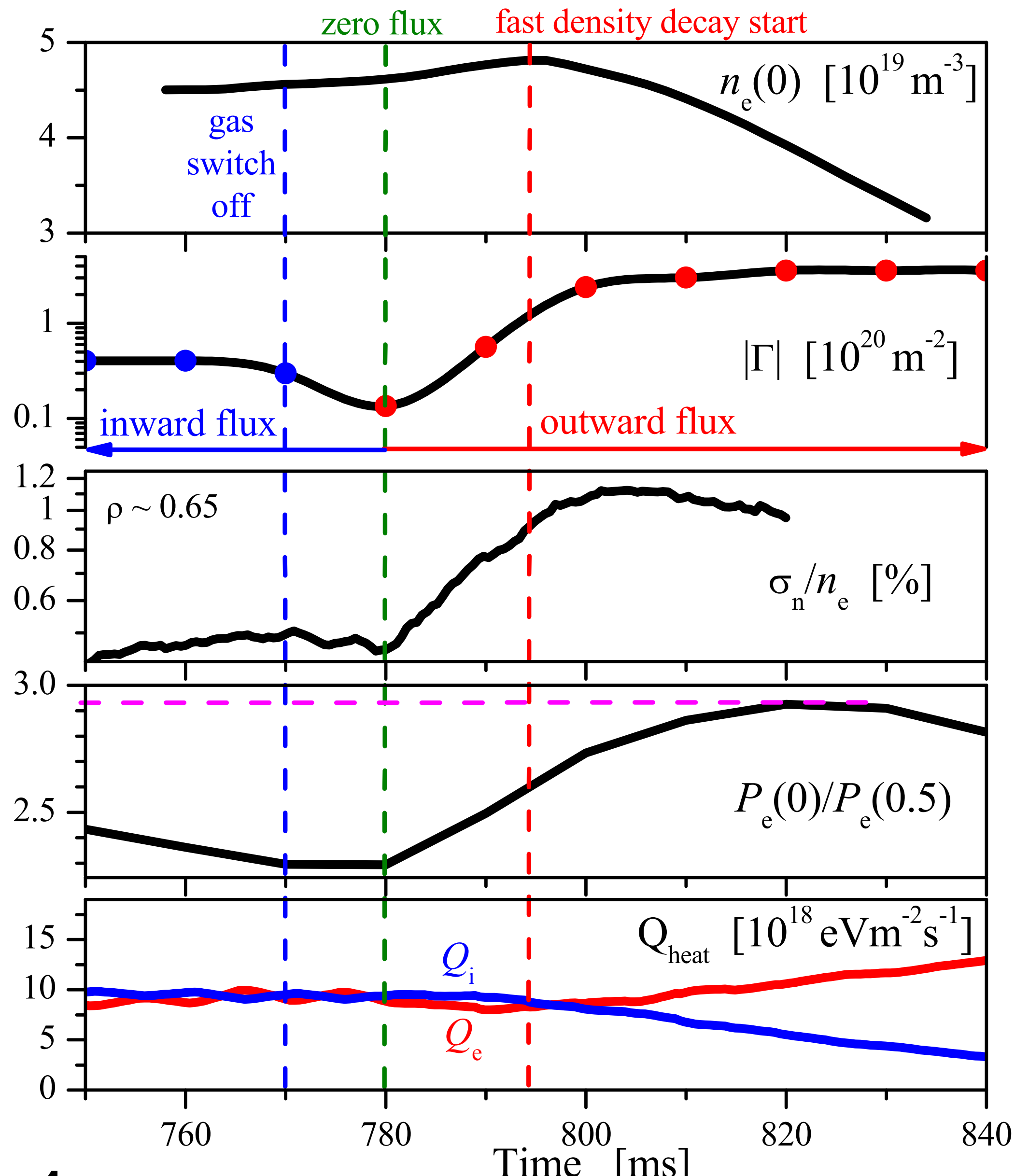
- The maximal turbulent flux was estimated as $\Gamma_{turb} = \langle \delta n_e \delta V \rangle$, where $\delta V = \delta E / B_T \cong \delta\varphi / (\lambda_p B_T)$. It was supposed from probes and HIBP measurements that $\delta n_e / n_e = 0.5 e \cdot \delta\varphi / T_e$.

- Qualitative and quantitative similarity of measured and estimated fluxes was found.

The turbulence level is high enough to provide the anomalous inward particle flux sufficient to form bell-like shape of the density profile.

Turbulence behavior in non-steady OH discharges

Is there the correlation between turbulence level and particle flux?



- The turb. level (at ρ ~ 0.7) reaches the minimum during the density rise when particle flux through the same surface is close to zero.

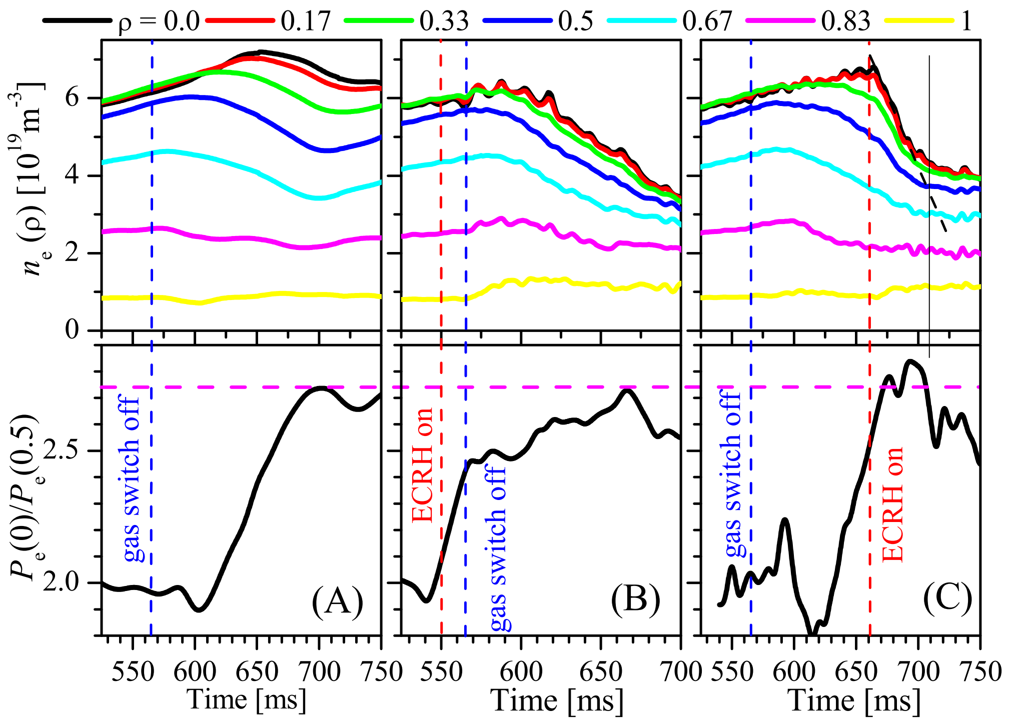
- The turb. minimal level is typical for steady-state discharge with "optimal profile" shape $P_e(0)/P_e(0.5)$ ~ 2.3.

- Both turb. ampl. and fluxes rise if the profile deviates from the optimal one. The linear dependence exists for the turbulence level and the absolute value of the particle flux $\sigma_n/n_e = \sigma_n/n_{\min} + k|\Gamma|$.

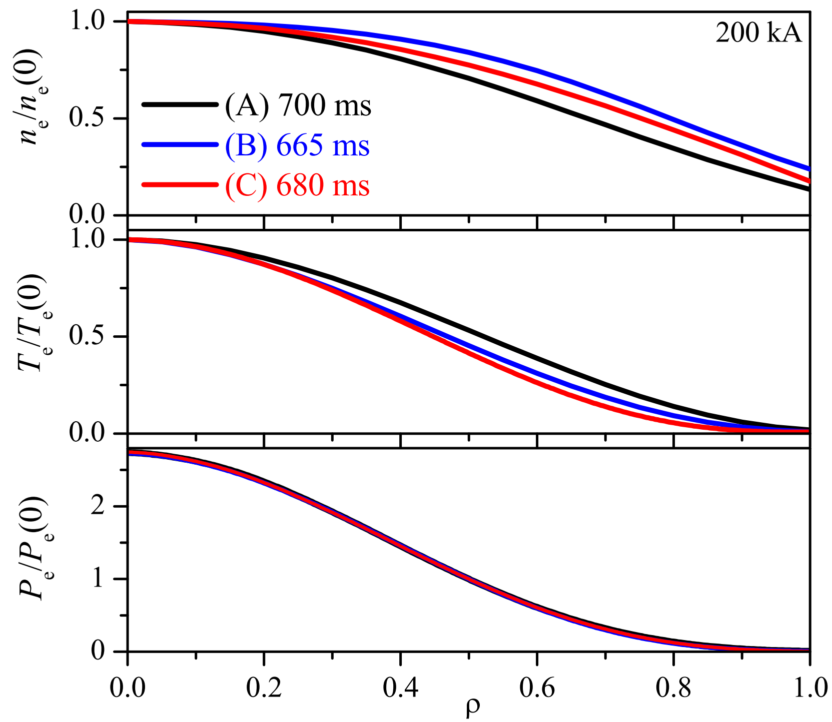
- The density fluctuations have weak relation to heat transport.

Particle transport and marginal pressure profile

Time evolution of density in OH and ECRH



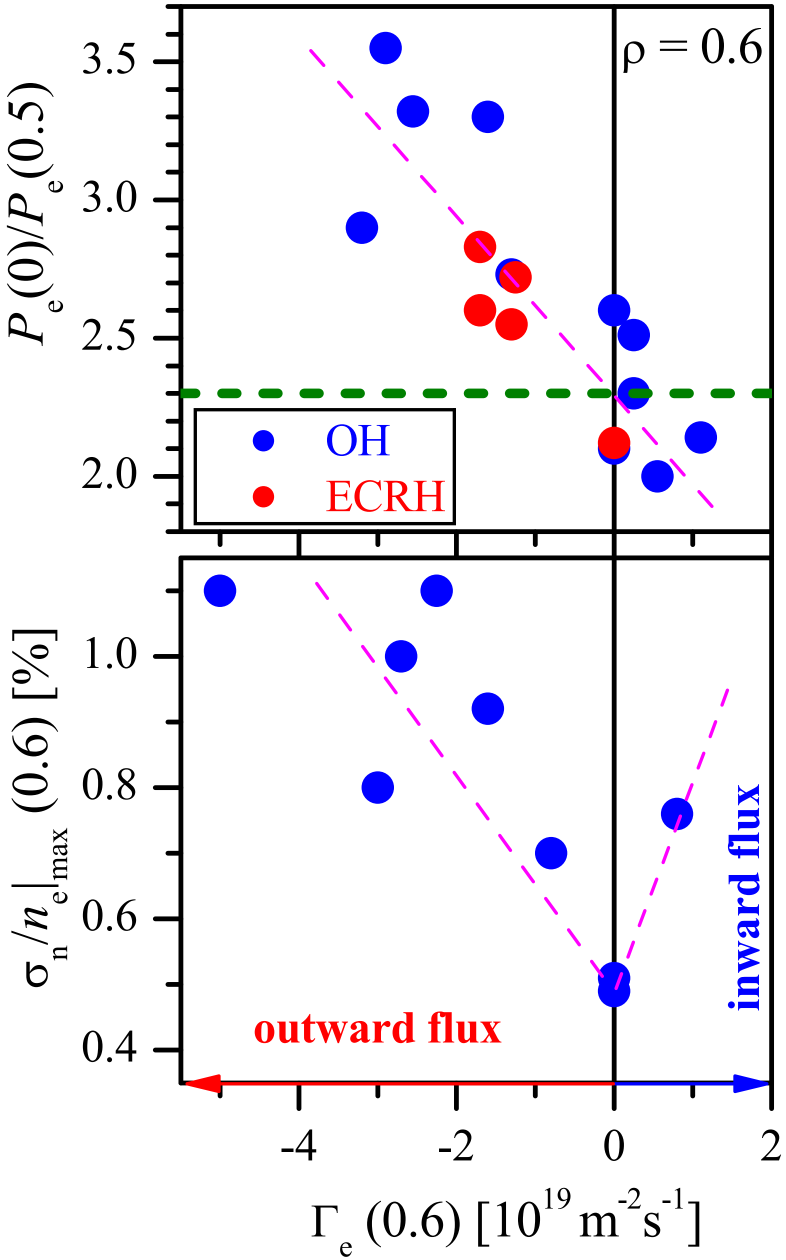
Normalized profiles



- The electron pressure peaking factor $P_e(r)/P_e(a/2)$ at the decay stage approaches the same marginal value ~2.8.
- Moderate ECRH during the density rise (B) could not overcome the peaking factor gap.
- The heating in density decay phase (C) caused immediate pump out.

The temperature and density profiles significantly differs in the density decay phase in considered cases, but marginal electron pressure profiles coincide.

Turbulence, pressure factor and particle fluxes

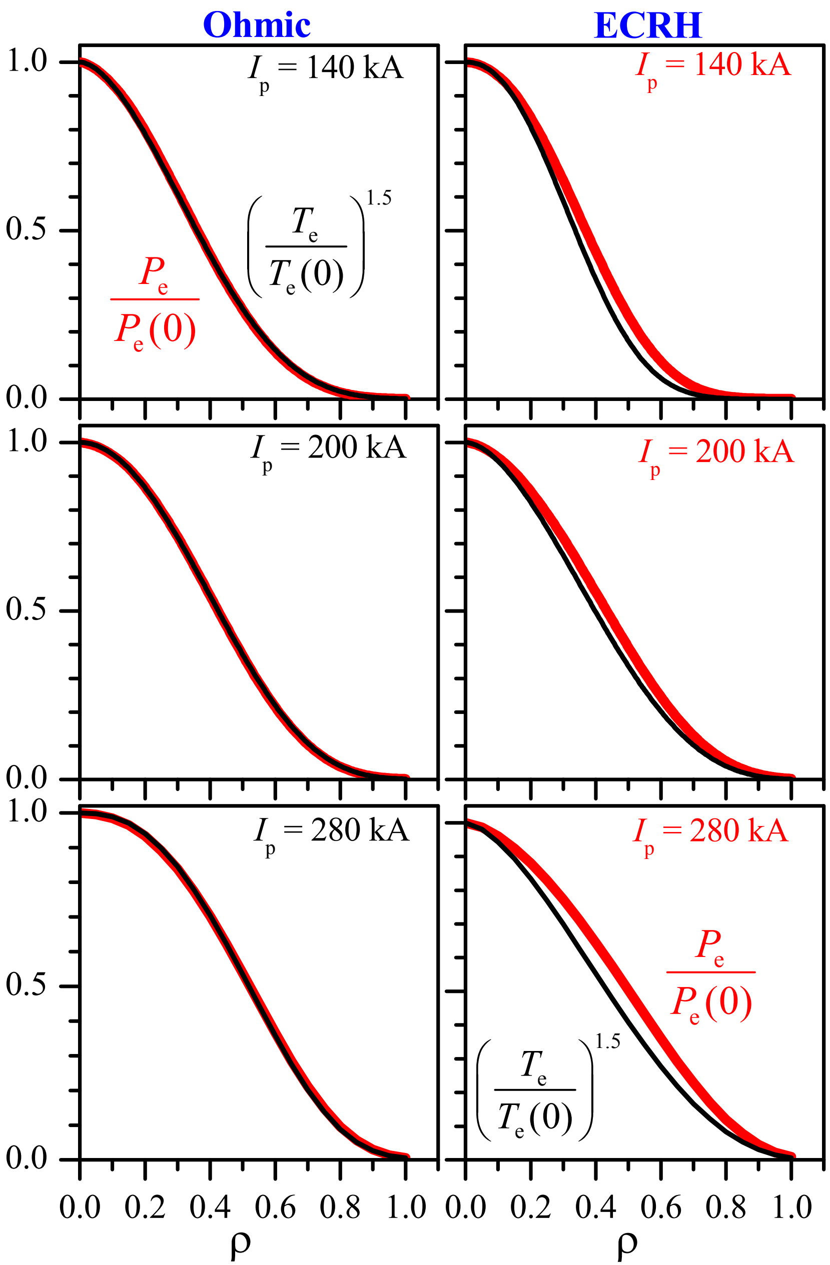


- The minimal turbulence level and zero flux correspond to certain *optimal* density profile with electron pressure peaking factor 2.3.

- The density fluctuation level rises when electron pressure profile deviated from the optimal one in both cases: broadening by gas puffing and peaking by gas switch off or under on-axis ECRH.

- In both cases (inward and outward flux) the direction of induced particle fluxes is aimed to keep electron pressure profile close to optimal one.

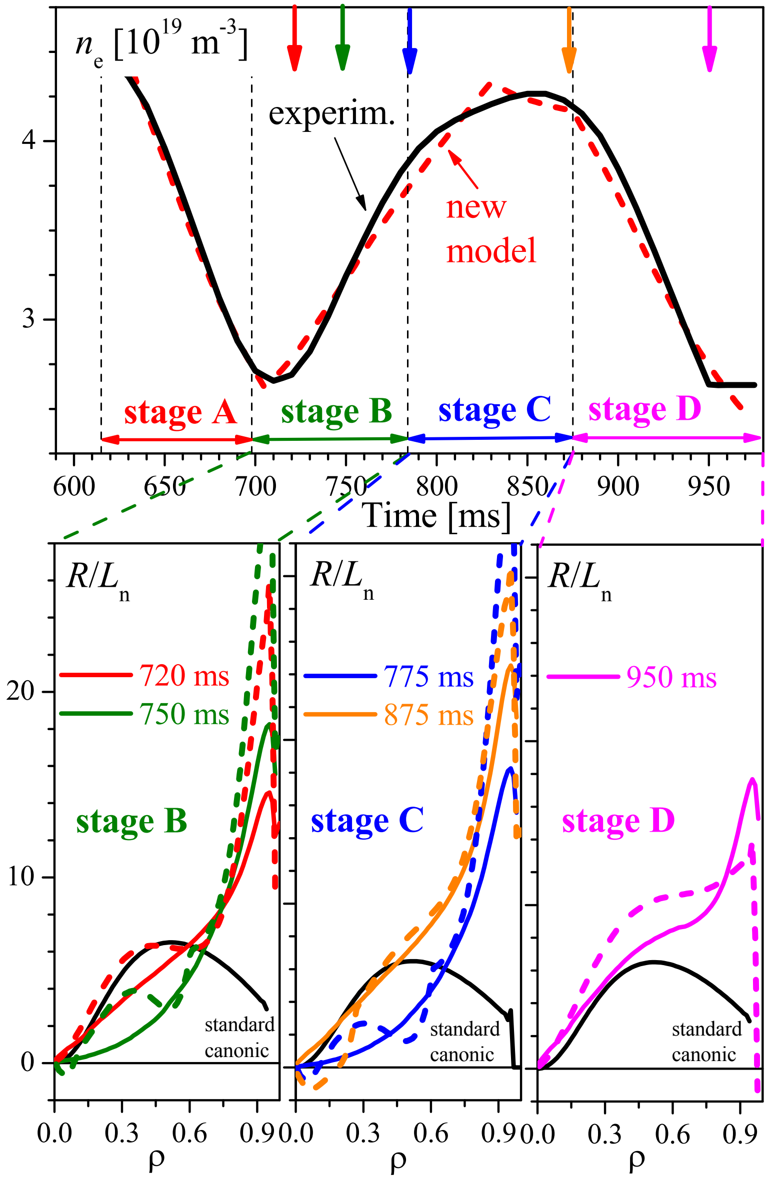
Pressure and current profiles in steady state discharges



- In Ohmic discharges the pressure profiles well coincide with current profile $\sim T_e^{1.5}$ (Spitzer conductivity) at different currents (left column). It suggests $n_e \sim T_e^{1/2}$, as was observed in experiments in ASDEX and holds for T-10.

- The difference between pressure and current profiles in ECRH plasmas may be caused by high particle influx and plasma pressure profile deviation from optimal one due to strong turbulence fluxes.

Simulation of strong gas influx variation in OH discharge with canonic profile transport model



- The difference between R/L_n measured experimentally (solid colored curves) and provided by the canonic profile transport model [Yu.N. Dnestrovskij et al. PPCF **49** 1477] (black curve) was overcome by introducing of the additional term to the standard model (dashed colored curves). This term makes pressure profile stiff if the peaking reaches marginal value $P_e(0)/P_e(0.5)$~2.8.
- Good qualitative agreement is observed between experimental (black solid curve) and simulated (red dashed curve) averaged electron density at different stages of gas-puffing.

Summary (EX/11-2Rb)

• The density fluctuation level is determined by the requirement to keep optimal density and pressure profiles and not related to ionization flux, energy confinement or heating power.

• The turbulence level is minimal in steady-state discharges with small particle fluxes and optimal pressure profile. It rises when electron pressure profile deviated from the optimal one by gas puff switching on/off, additional heating *etc*.

• An optimal pressure profile is close to current profile in steady-state Ohmic discharges in accordance with canonic profile model.

• The marginal pressure profile exists and particle confinement dramatically decreases when plasma reaches this marginal pressure profile.

• The density profile evolution can be simulated both qualitatively and quantitatively by canonic profile transport modeling with strong particle confinement deterioration at the marginal pressure profile.