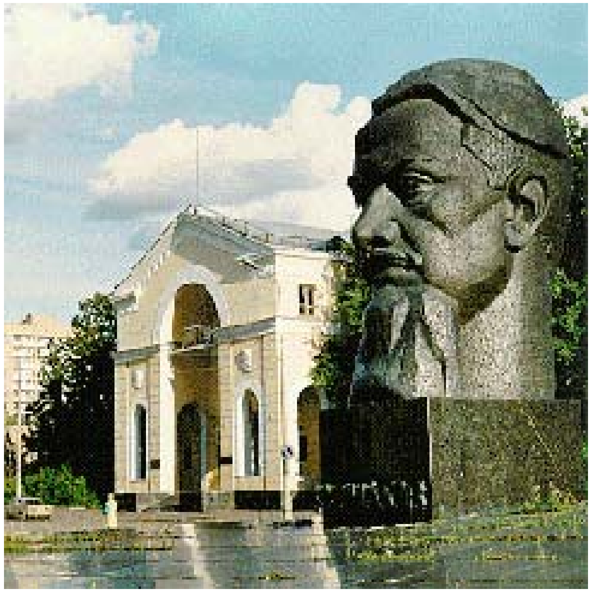

OVERVIEW OF T-10 RESULTS

Presented by:

D.A. Kislov, for the T-10 Team

NFI RRC "Kurchatov Institute", Russia

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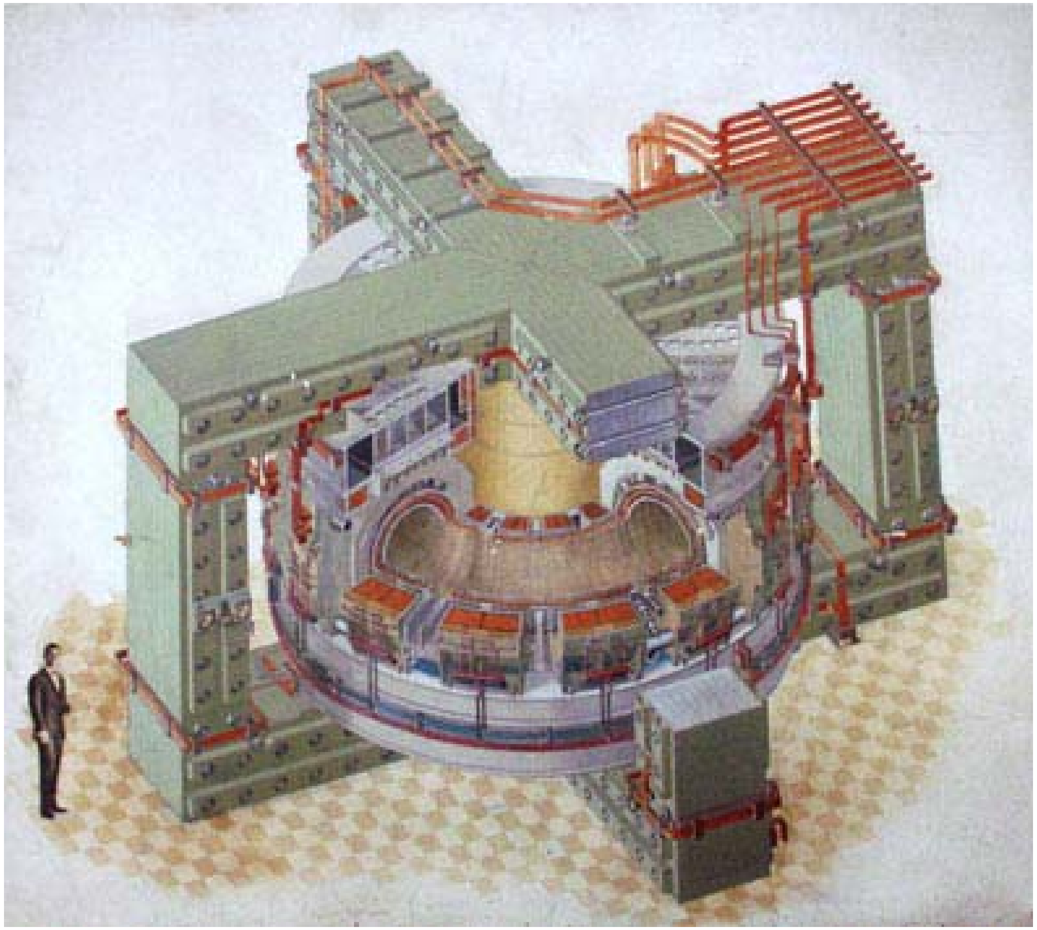
T-10 TOKAMAK



- Operation since 1975
- Circular cross-section,

  $R = 1.5m$, $a_L = 0.3m$,

  B_t up to 2.8T,

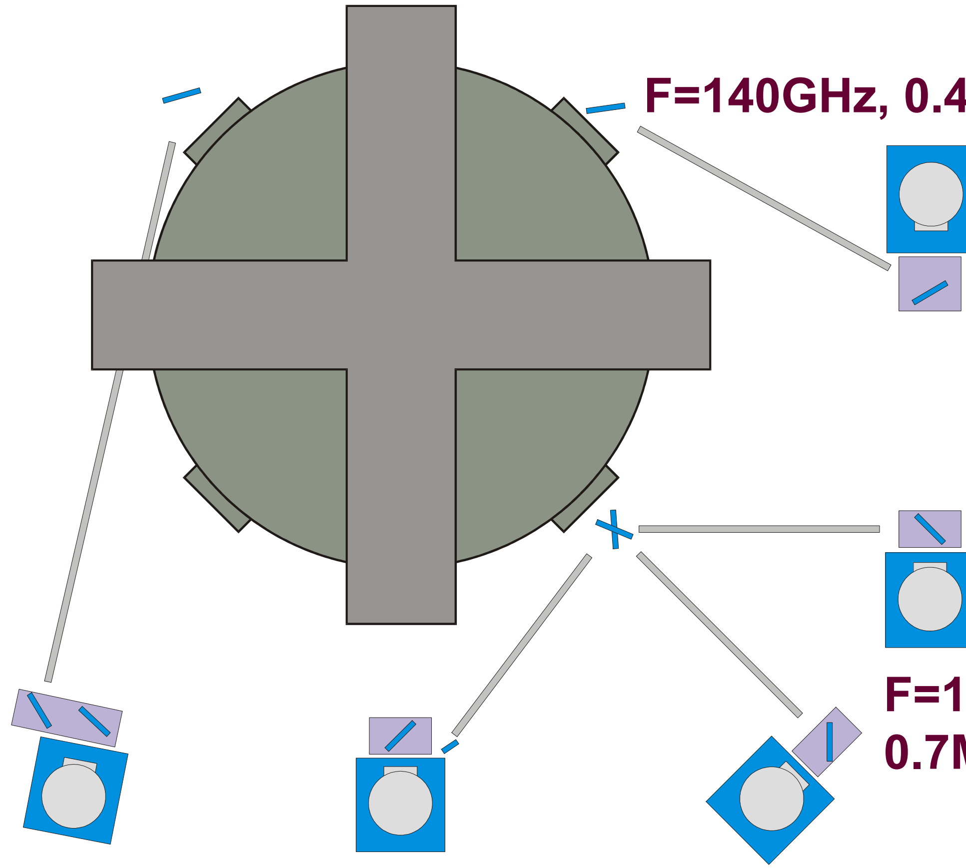
  I_p up to 0.4MA
- Two-frequency ECH system (130 and 140 GHz),

  P_{ECH} up to 3 MW.
- Injection of deuterium and impurity pellets

ECH SYSTEM

- $P_{ECH}(130GHz)=1.4MW$

  $P_{ECH}(140GHz)=1.6MW$
- Second EC harmonic, LFS injection, X-mode
- τ_{ECH} up to 0.4 s
- minimum $w_{ECH} \approx 0.02a$, p_{ECH} up to 25 W/cm^3
- $n_{cut\text{-}off}=1.2*10^{20}$ m^{-3}
- Steerable mirrors (φ_t, φ_θ - var), beam focusing



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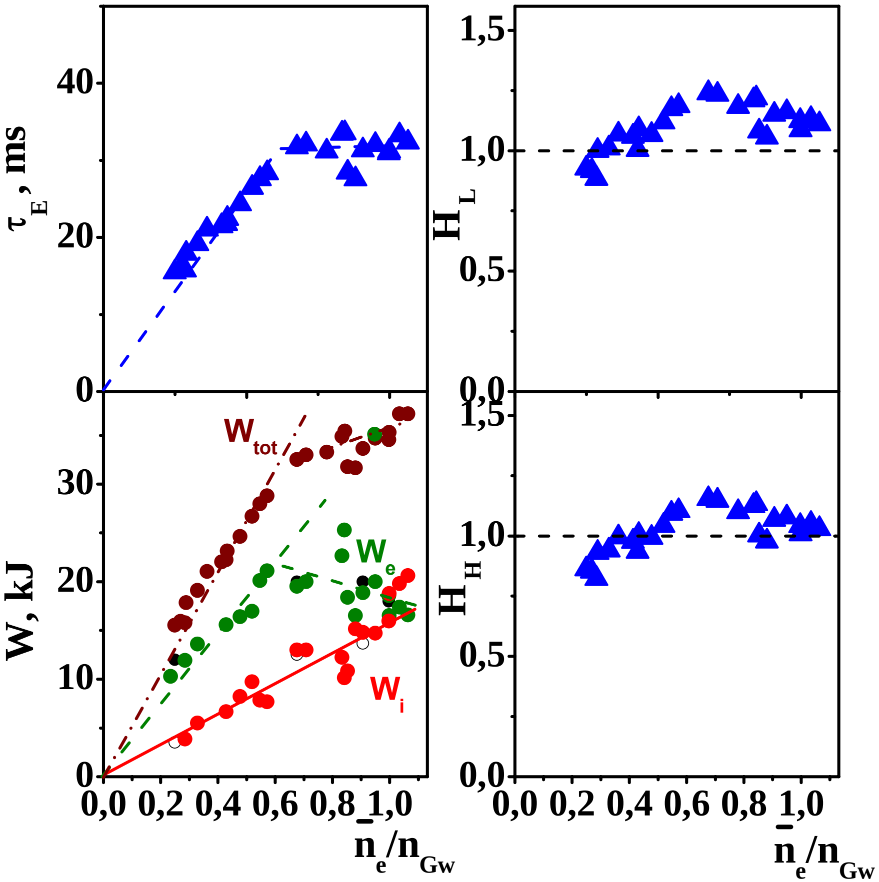
OUTLINE

- Confinement and turbulence studies
  - Energy and particle confinement with ECH
  - Links between confinement and turbulence behavior
  - HFS/LFS turbulence asymmetry
- Effects of pellet injection
  - Improved confinement
  - Fast processes initiated by pellets
- Studies of ITB formation with early ECH
- Sawtooth control by ECCD localized in vicinity of q=1 surface

Energy confinement with ECH



P_{ECH}=0.9MW, $q_a \approx 3.7$

- **$n_e < 0.6 n_{Gw}$: τ_E increases** almost **linearly** with $\langle n_e \rangle$
- **$n_e > 0.6 n_{Gw}$:**

  τ_E growth saturates

  τ_E exceeds L-96th predictions and attains H(IPB98(y,2)) predictions

  (L- and H-mode scaling predictions are similar for T-10 conditions: $\tau_{EH}/\tau_{EL} \approx 2.44 {*} B^{0.12} R^{0.14} A^{-0.64}$, A=5)
- Confinement saturates due to increased electron energy losses

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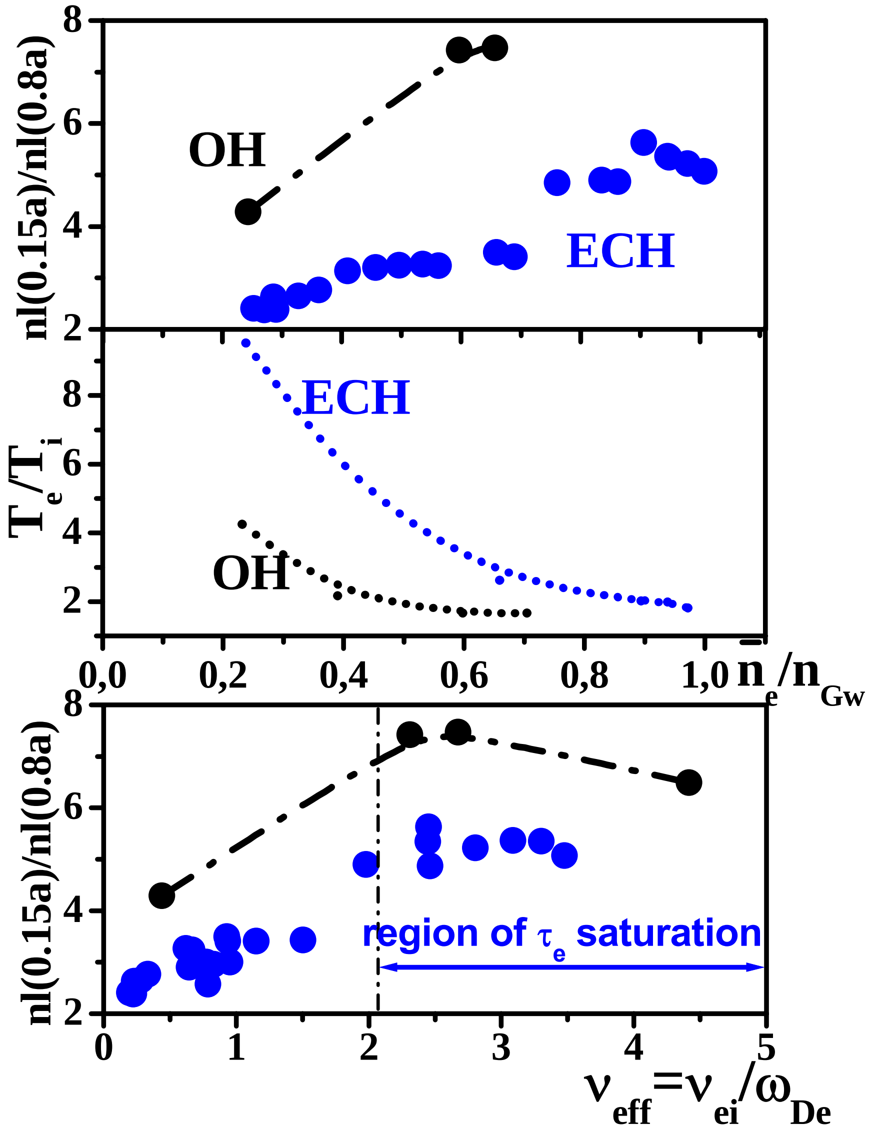
Density peaking with collisionality increasing



- **density peaking** increases with $<n_e>$ growth
- density peaking increases **with $\nu_{eff}=\nu_{ei}/\omega_{De}$,** ($\omega_{De}$ - curvature drift frequency)
- T_e/T_i changes from 10 ($<n_e>/n_{Gw}=0.2$) to 2 ($<n_e>/n_{Gw}=1$)
- **Density pumpout** in the whole ν_{eff} range

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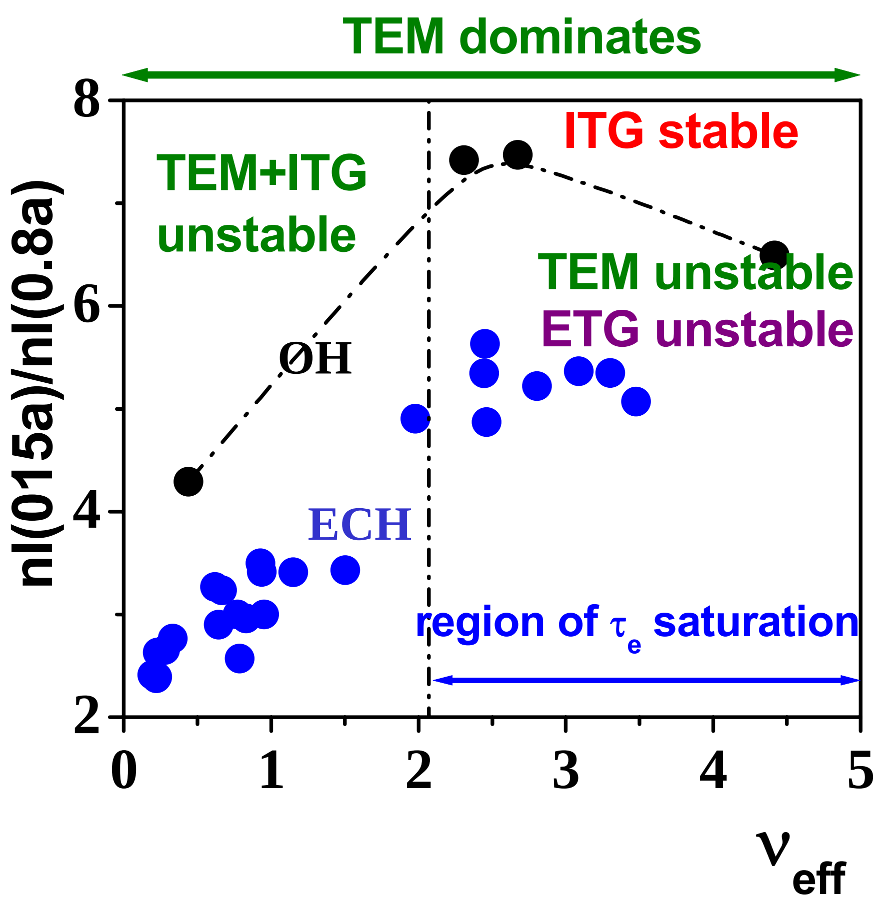
Linear turbulence analysis



- $n_e<0.6n_{Gw}$: **ITG** and **TEM** modes exist
- $n_e>0.6n_{Gw}$: **ITG** stable, **TEM**+**ETG** unstable
- **TEM** dominates in transport
- Density pumpout – **TEM** drive results in outward particle flux
- **TEM** domination – lack of the density peaking at low collisionalities
- Ware pinch increases with ν_{eff} (U_{loop} changes from 0.4 V to 1.2 V)

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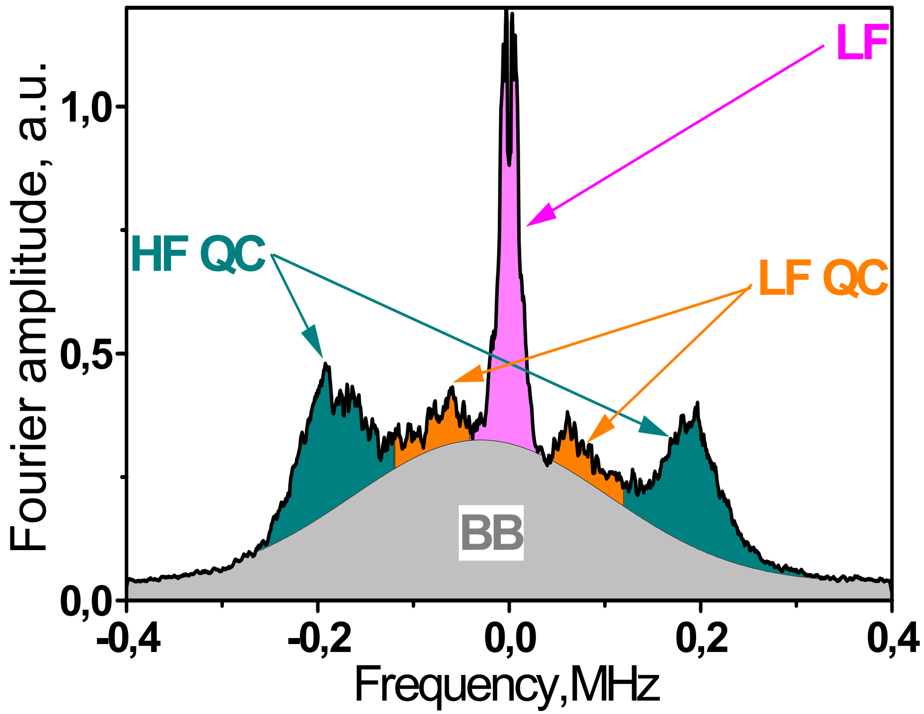
Types of small-scale density fluctuations

Typical reflectometry spectrum



- **Broad Band (BB)** :
  – low coherent fluctuations

Low Frequency Quasi Coherent (LF QC) ($k_\perp \rho_i$~0.3), **High Frequency Quasi Coherent (HF QC)** ($k_\perp \rho_i$~0.7) fluctuations

- features of helical structures from 3D-gyrokinetic simulations

- **Low Frequency (LF)** fluctuations:–"streamers"

Hypothesis: **LF QC** are initiated by **ITG**, **HF QC** - by **TEM**

(radial locations, $k_\perp \rho_i$ values, **LF QC** independence from B_t)

QC type indicate instability responsible for BB

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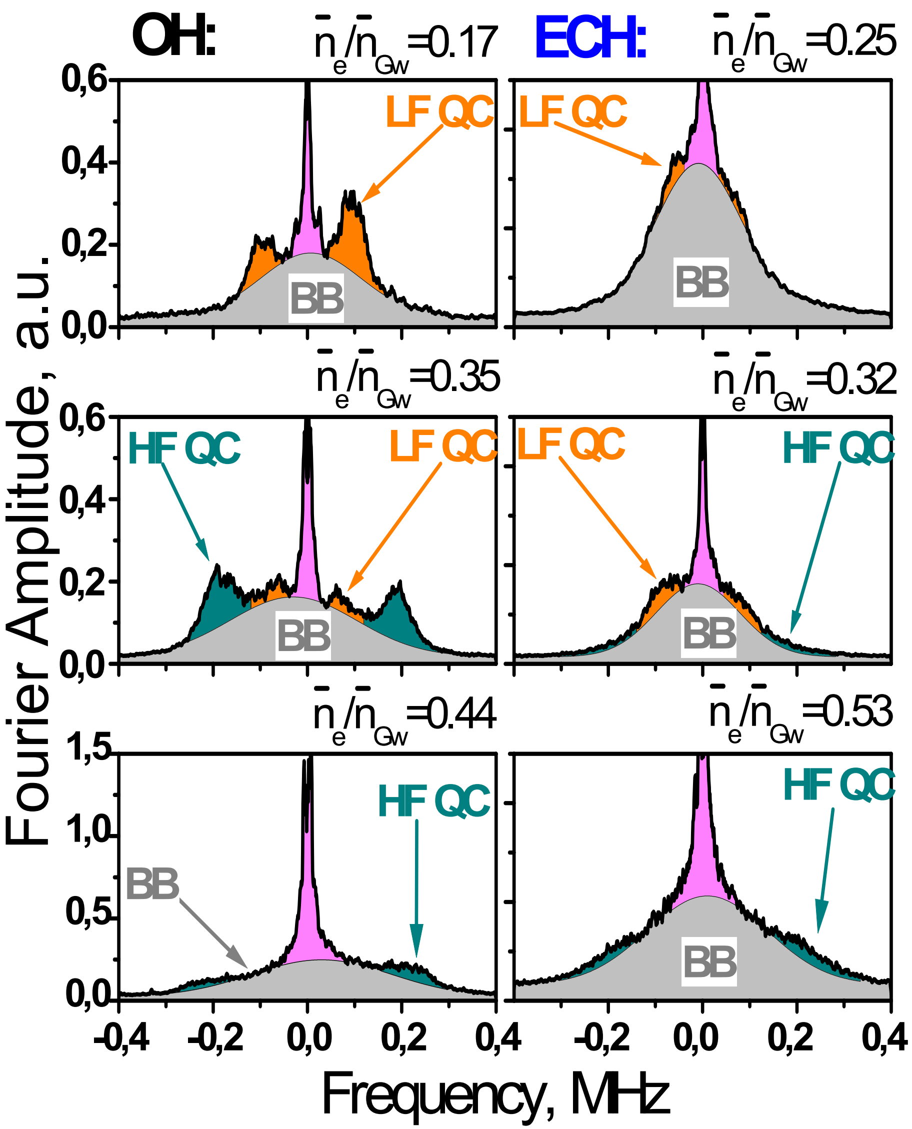
Turbulence evolution with density



- Evolution from **LF QC** at low densities to **HF QC** at high densities
- Turbulence level increases significantly, **QC** maxima decrease with ECH
- general good **agreement between spectrum transformation and turbulence** (**TEM**/**ITG**) **tendencies** in linear calculations:

- **LF QC** decrease with density peaking, disappearance at high densities
- high density: **HF QC** exist

Contradiction: lack of **HF QC** at low density

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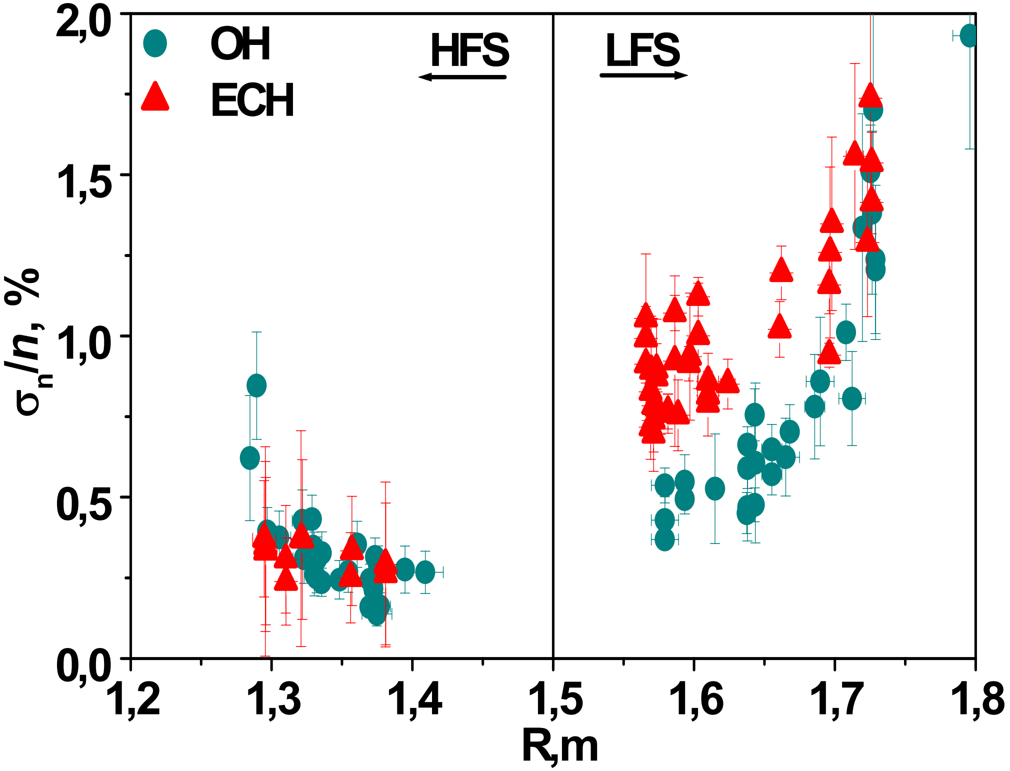
HFS and LFS turbulence asymmetry



VERSHKOV V.A. et al, EX/P4-38.

- **new HFS** correlation **reflectometry** system (extraordinary low-frequency mode)
- all spectrum components are observed in the HFS
- LFS/HFS asymmetry of the density fluctuations amplitude in OH and ECH.
- **ECH: turbulence amplitude increases only in the LFS,**

  HFS - negligible changes,

  LFS/HFS turbulence amplitude asymmetry becomes stronger under ECH

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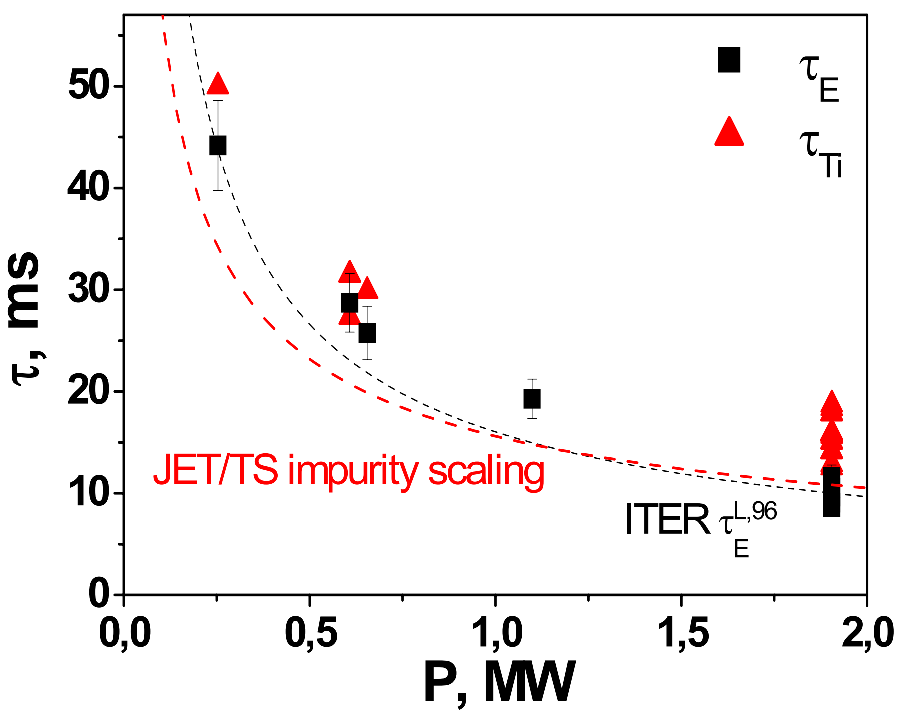
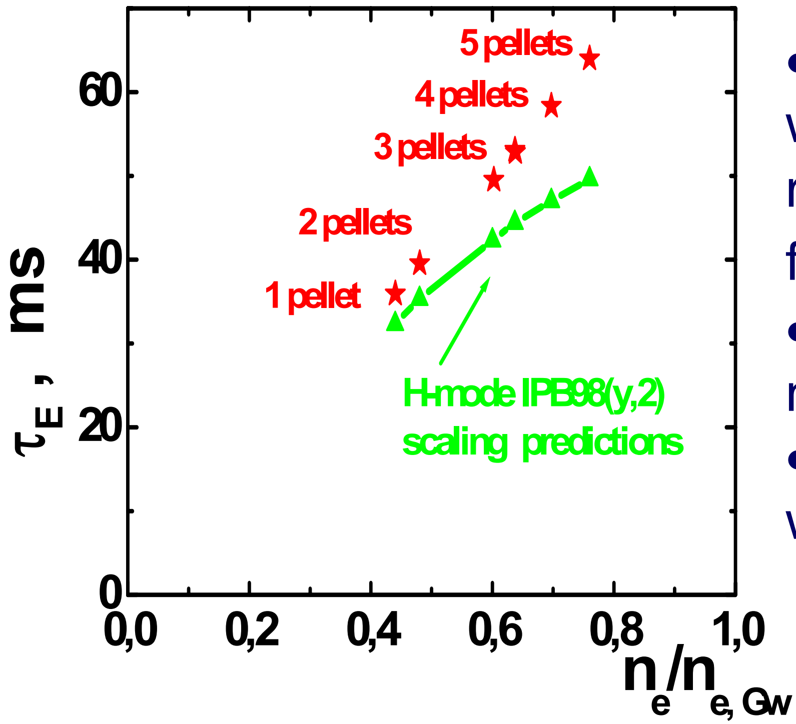
Impurity confinement



- Characteristic times of impurity and deuterium dynamics were measured with pellet injection and fast D_2 puffing
- Characteristic impurity decay times were found to be comparable with τ_E and have similar power and density tendencies
- This suggests dominant role of turbulence convection both in electron and ion channels

VERSHKOV V.A. et al, EX/P4-38.

Repetitive deuterium pellet injection



P_{ECH}=1.4MW (on-axis), q_a≈2.5,

- **improvement of energy confinement** with respect to its "saturated" level in the regimes with gas puffing ($H_H=\tau_E/\tau_{IPB98(y,2)}$ factor attains 1.3 with five pellets)
- peaked density profile, increased neutron yield and $T_i(0)$.
- confinement enhancement decreases with q_a increase

PAVLOV Yu. D. et al, EX/P3-11.

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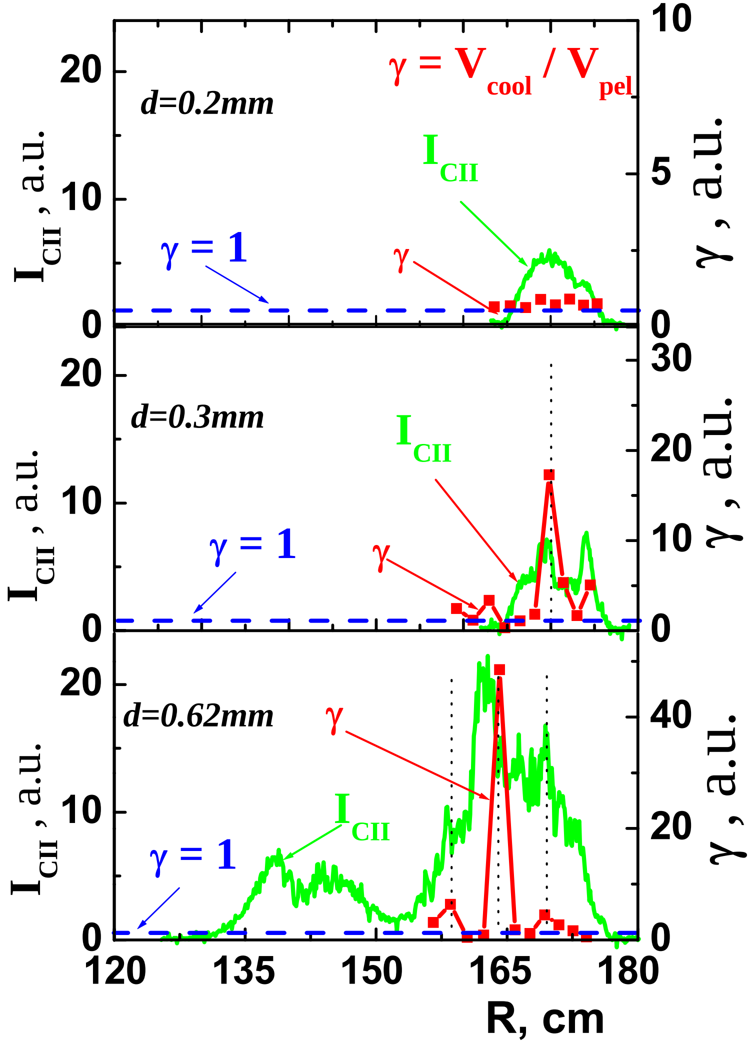
Effects of pellet injection



- local regions with **increased cooling front velocity** correspond to bursts/drops of the pellet ablation rate (I_{CII} ~ ablation rate)
- threshold effect of the pellet size for the observed phenomena
- sawtooth reconnection triggered by pellet
- **hypothesis**: increased cooling front velocity concerned with **MHD events**

SERGEEV V.Yu et al EX/P3-14.

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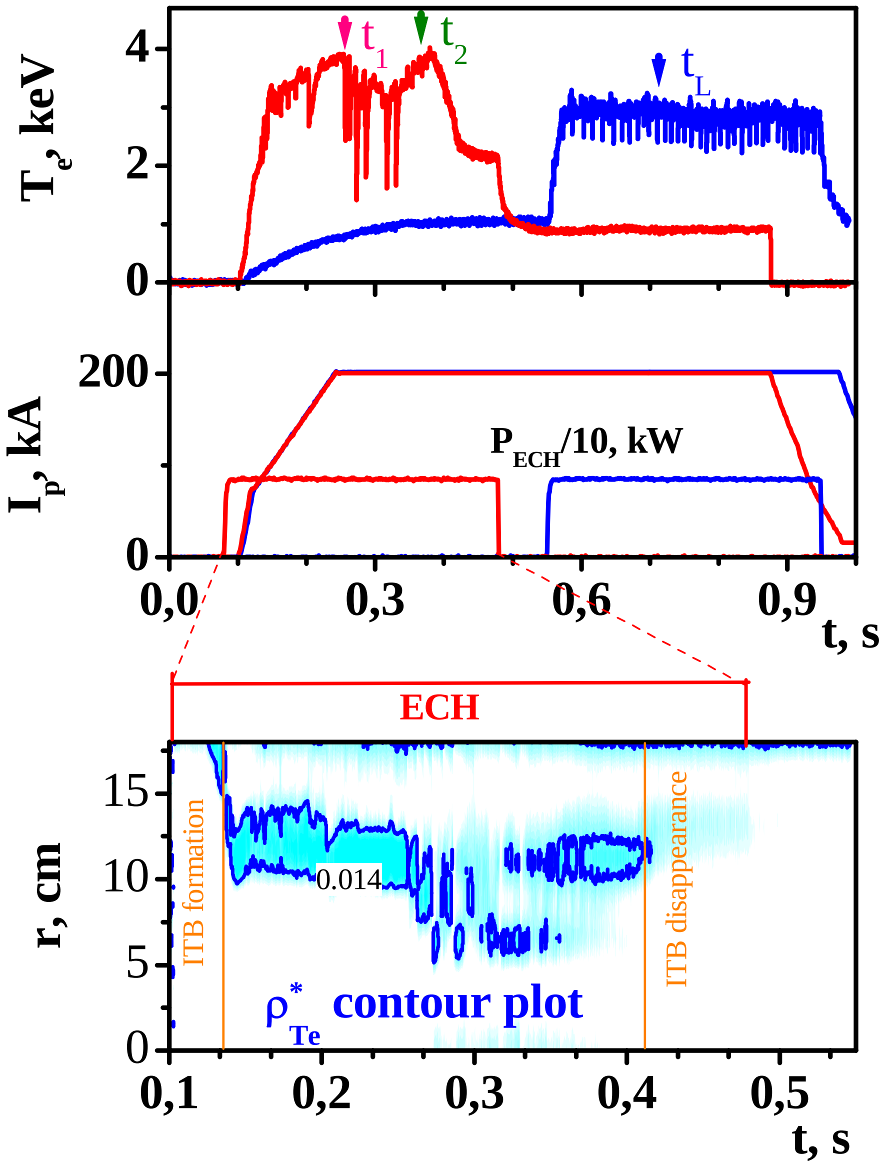
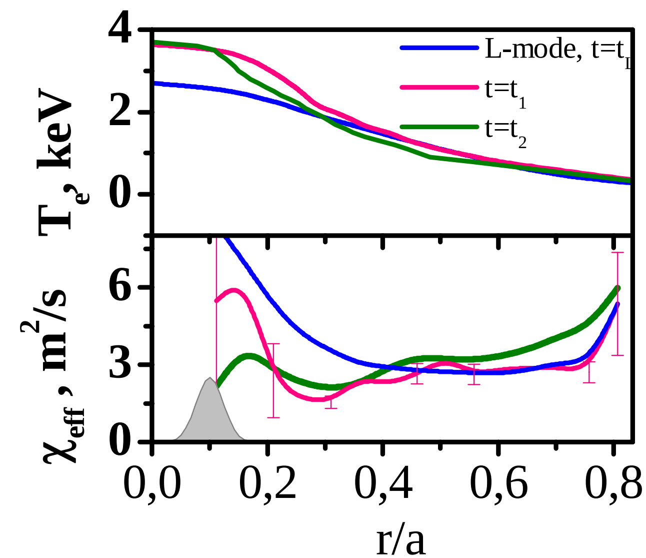
ITB formation with early ECH





- ITB is formed applying ECH during the current ramp up
- χ_{eff} decreases by a factor of ~ 2 in ITB region in relation to L-mode value
- L-mode: $\rho^*_{Te} \leq 0.014$ ($\rho^*_{Te} = \rho_s/L_{Te}$)

  ITB: ρ^*_{Te} = 0.025-0.035

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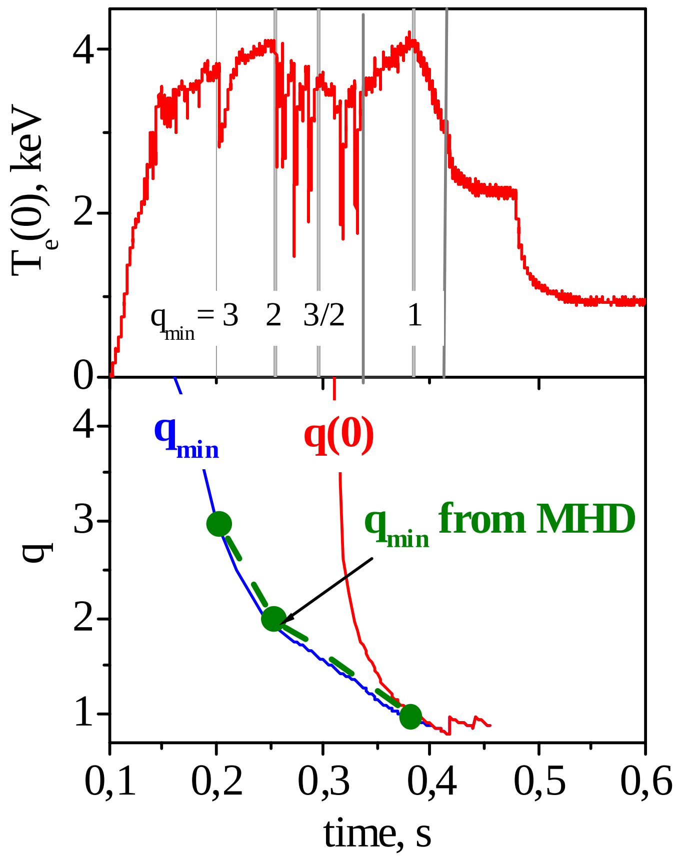
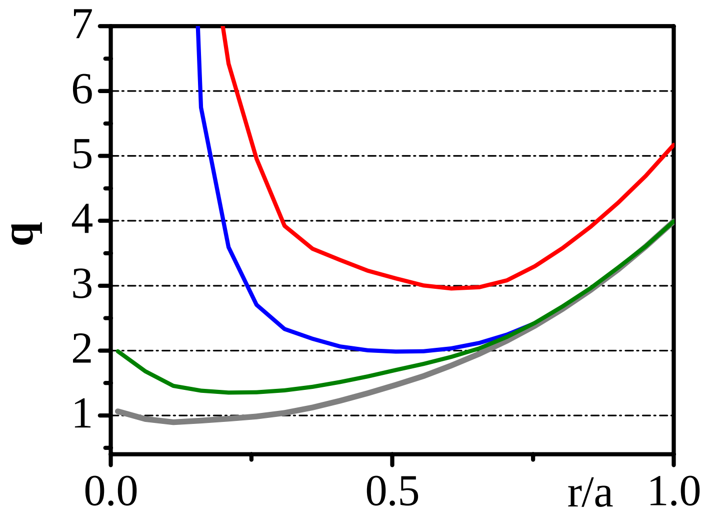
Role of the negative magnetic shear in ITB formation





- q(r) profile evolution from ASTRA code
- ITB is formed in plasma with s<0
- ITB disappears when q_{min} falls below unity

Linear Turbulence Analysis:

S<0 - key ingredient in TEM/ITG stabilization

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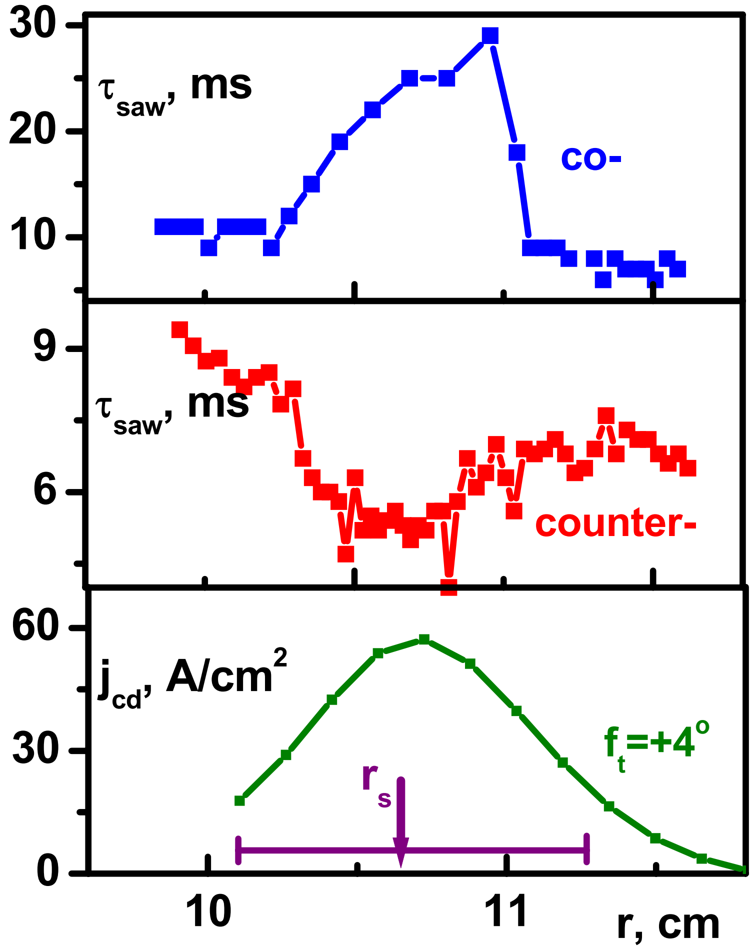
Sawtooth control by ECCD



P_{ECH}=0.4MW, $q_a \approx 3$, $<n_e>=1.5*10^{13} cm^{-3}$

- narrow ECH power deposition ($w_{ECH} \approx (0.03-0.06)a$)
- sweeping of ECCD localization with respect to q=1 surface (HFS)
- considerable **stabilizing effect with co-ECCD** in a narrow region **near q=1 surface**
- **destabilizing effect of counter-ECCD** in the same region **near q=1 surface**
- general good **agreement with critical shear criterion** $\gamma_{eff} > c_r(\omega^*_i \omega^*_e)^{1/2}$ (ASTRA calculations)

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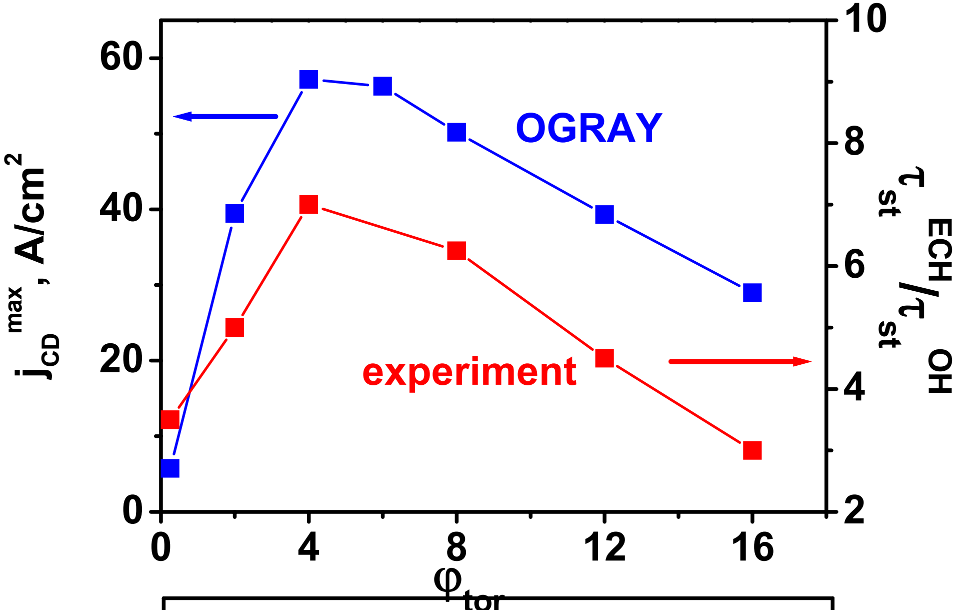
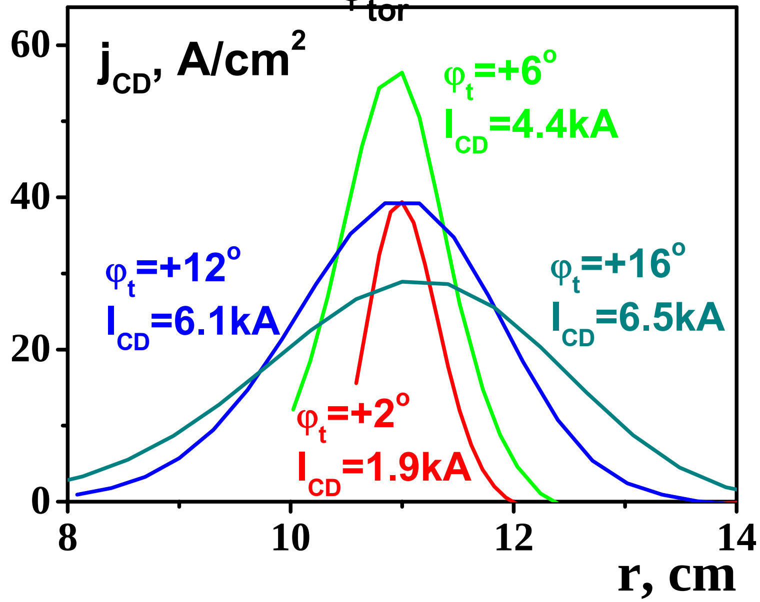
Optimization of $j_{CD}(r)$ profile for sawtooth control





- φ_{tor}= 4-8° (toroidal angle of ECH injection) - the **strongest ECCD effect** on sawtooth stability
- OGRAY code : this range corresponds to the maximum value of j_{CD}^{max}.
- further φ_{tor} increase:
  - I_{CD} increases,
  - j_{CD}^{max} decreases ⇒ weaker ECCD effect on sawtooth stability
- **ECCD effect >> ECH effect** on sawtooth stability in the conditions of the experiment

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SUMMARY

- Essential progress has been made in understanding the **links between confinement and turbulence properties** in T-10 plasma with dominant electron heating.
- Measurements with new HFS reflectometry system demonstrate **LFS/HFS turbulence asymmetry** that strongly increases with ECH power.
- **Improved confinement** has been obtained by repetitive deuterium **pellet injection**. Fast transport and MHD events triggered by pellet injection have been observed.
- **eITB formation** has been observed in reversed shear configuration with **ECH during the current ramp-up**.
- **ECCD** near q=1 was found to be effective **for sawtooth control**. Optimization of the driven current profile has been made.

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T-10 CONTRIBUTIONS

- NEUDATCHIN S.V. et al, EX/P1-8. ITB Events and their Triggers in T-10 and JT-60U
- PAVLOV Yu. D. et al,Transport Barriers and H-mode in Regimes with Deuterium Pellets Injection into T-10 Plasma Heated by ECR EX/P3-11.
- SERGEEV V.Yu et al Interaction of T-10 plasma with Impurity Pellets and Supersonic Gas Jet EX/P3-14.
- KUTEEV B.V. Studies of Dust Dynamics in High Temperature Plasmas EX/P4-13.
- VERSHKOV V.A. et al, Investigation of Different Plasma Components Confinement and Turbulence Characteristics in T-10 Tokamak EX/P4-38.

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