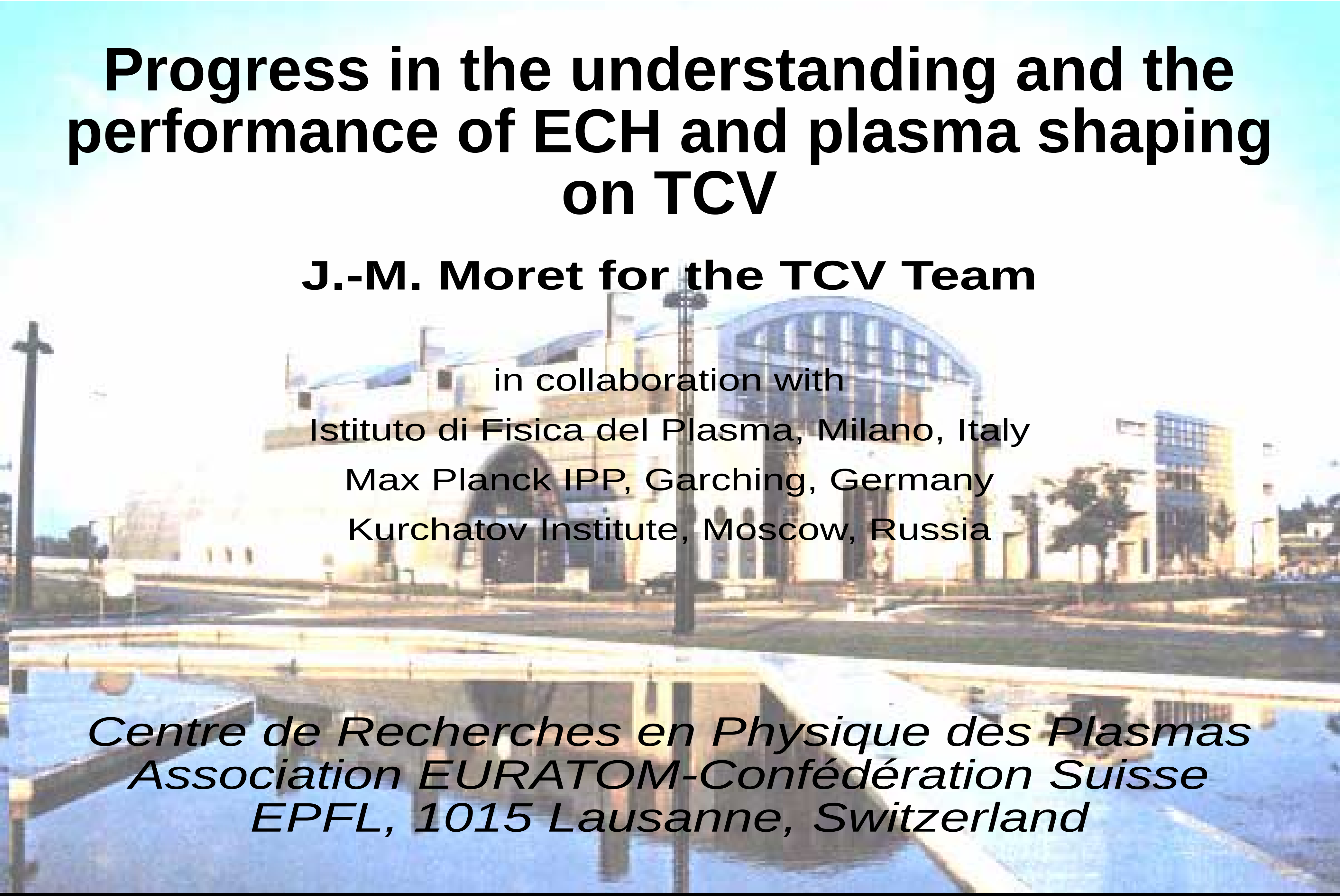


Progress in the understanding and the performance of ECH and plasma shaping on TCV

J.-M. Moret for the TCV Team

in collaboration with

Istituto di Fisica del Plasma, Milano, Italy

Max Planck IPP, Garching, Germany

Kurchatov Institute, Moscow, Russia

Centre de Recherches en Physique des Plasmas
Association EURATOM-Confédération Suisse
EPFL, 1015 Lausanne, Switzerland

Objectives

TCV specificities

- High power density ECH system (4.5 MW)
- Adaptable launching geometry
- Plasma shaping capabilities

$\longrightarrow$Local modifications of plasma pressure and current density

Address tokamak concept improvement

- Increased energy confinement regimes
- Steady state scenarios
- Dominant electron heating (simulate α-heating)

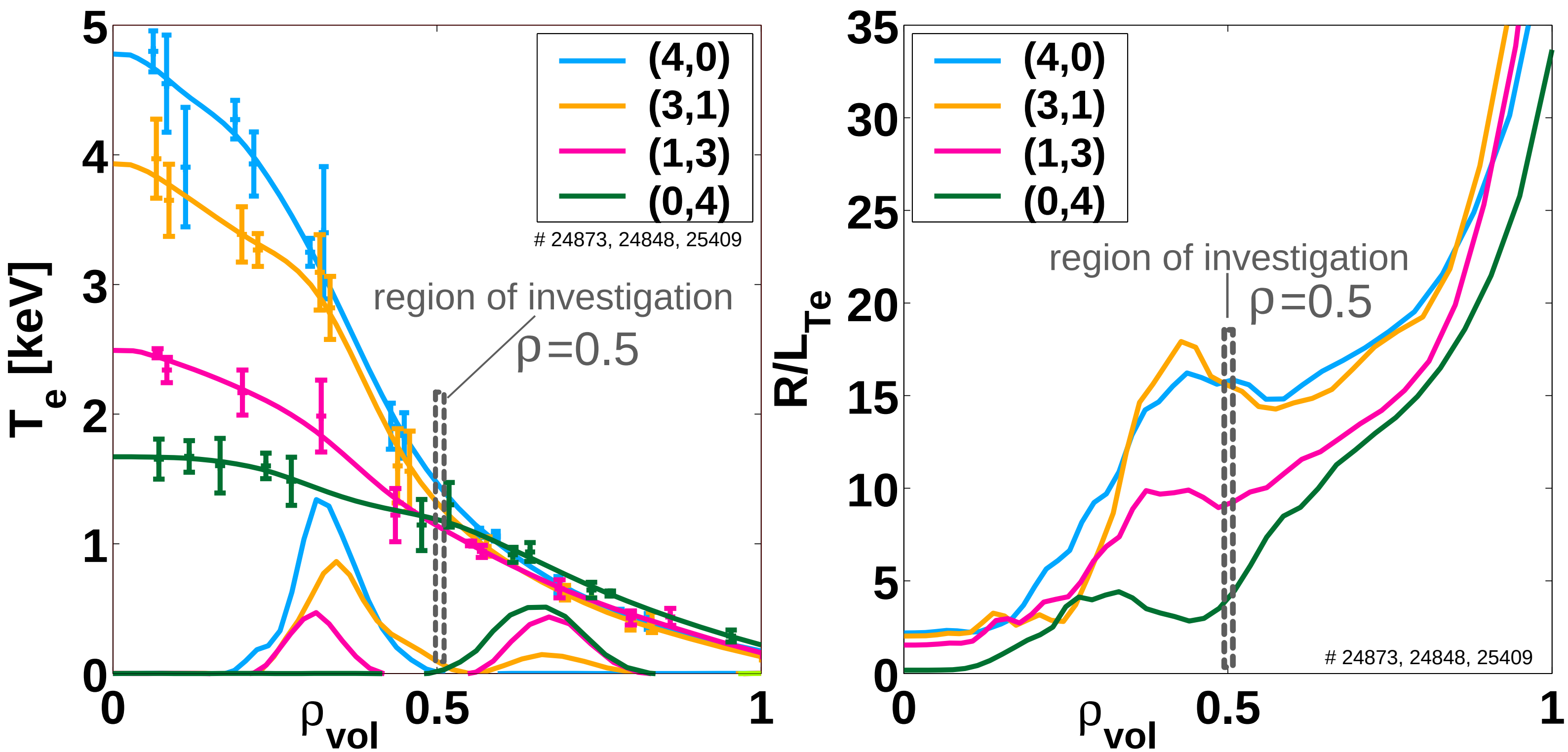
Outline

- Effect of plasma shape on electron transport — Pochelon EX/9-1
- Magnetic shear modulation with ECCD — Cirant EX/6-12
- Electron internal transport barrier formation and control — Henderson EX/3-3
- Third harmonic top-launch ECH — Alberti EX/4-17

Role of the triangularity (δ = -0.2 to +0.4, L-mode) on local electron heat transport over a wide range of $R/L_{T_e} = R\nabla T_e/T_e$

Pochelon EX/9-1

- $P_{ECH}(\rho = 0.35)/P_{ECH}(\rho = 0.70)$ controls R/L_{T_e} at $\rho = 0.5$
- $P_{ECH}(\rho = 0.35) + P_{ECH}(\rho = 0.70)$ controls T_e at $\rho = 0.5$

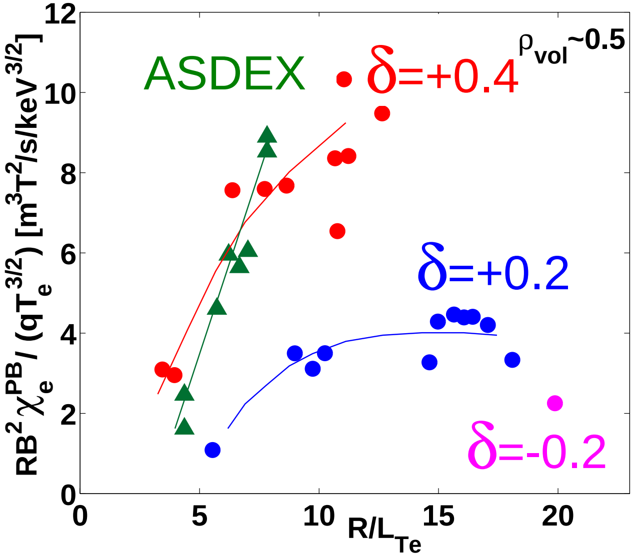


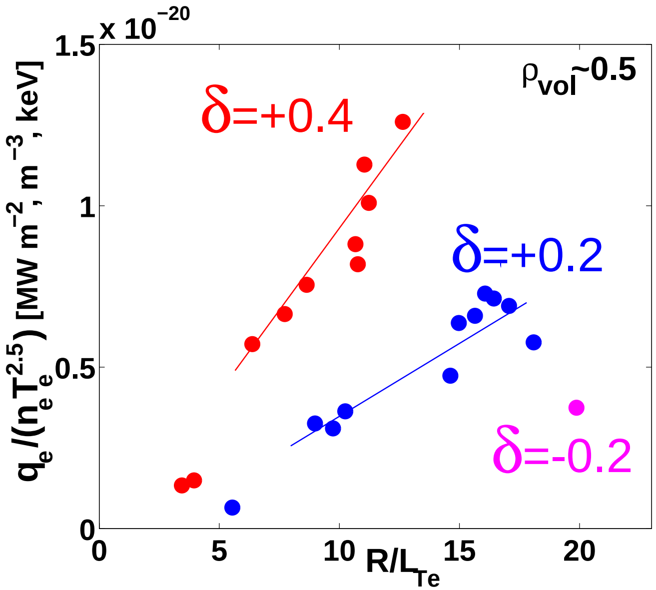
At high R/L_{T_e}

- χ_e saturates and does not follow
  $\chi_e \neq T_e^{3/2}(R/L_{T_e} - R/L_{T_e}^{crit})$
  (ASDEX)

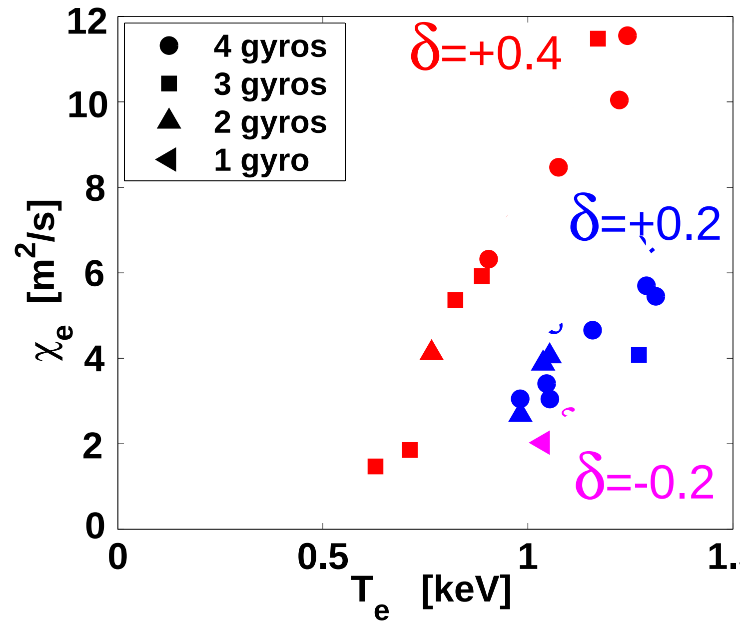
- shape dependence with high diffusivity at positive triangularity

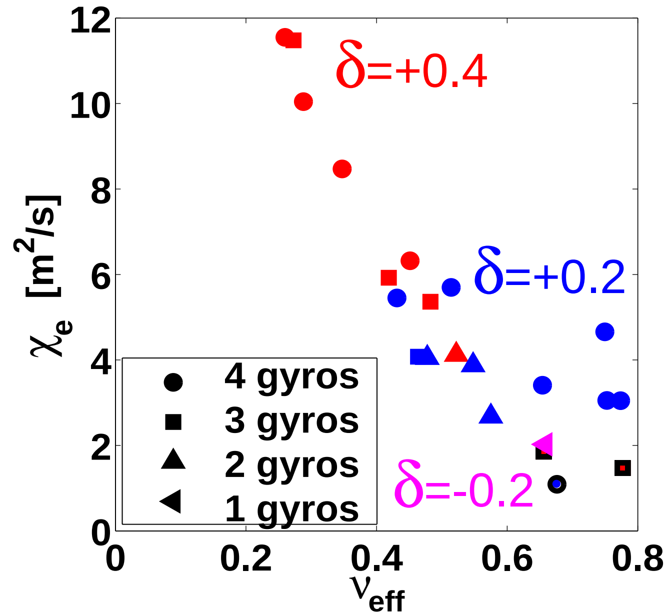
- better with
  $q_e \sim n_e T_e^{5/2}(R/L_{T_e} - R/L_{T_e}^{crit})$





- or $\chi_e \sim f(T_e)$
- Electron heat diffusivity increases with triangularity
- eITB criteria on ρ_s / L_{T_e} obtained at δ = 0.2 but not at δ = 0.4
- triangularity coupled with collisionality (larger Z_{eff} at small δ)
- Local gyro-fluid (GLF23) and global collisionless gyro-kynetic (LORB5) simulations show unstable ITG and TEM (TEM dominate except at low R / L_{T_e})





Magnetic shear modulation with ECCD

Investigate the link between local magnetic shear and electron heat transport

Cirant EX/6-12

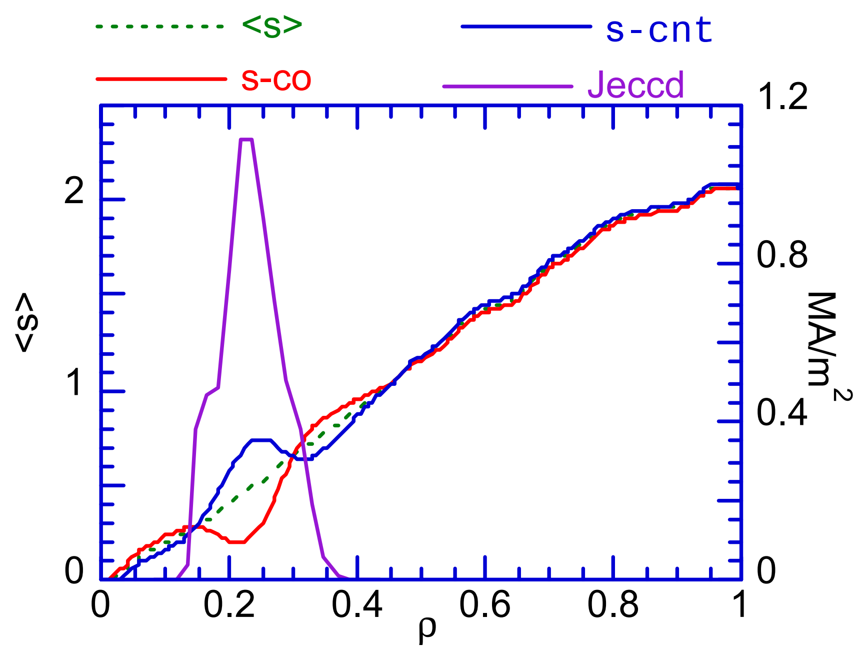
Interleaved co and counter ECCD, off-axis, modulated (5 Hz), at constant total ECH power (0.9 MW)

⟶sign modulation of ECCD locally driven current

⟶change in resistivity

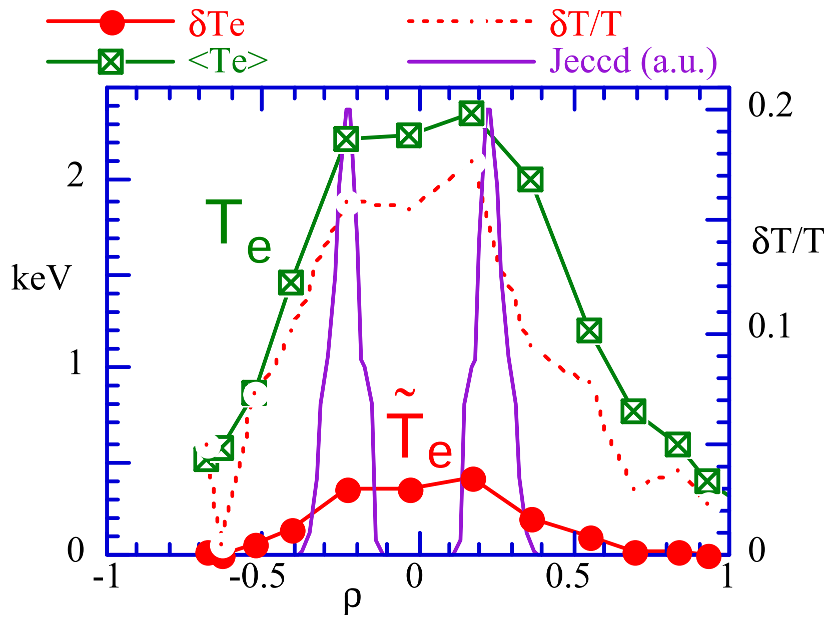
⟶transient current diffusion (modelled with coupled lumped circuits)

⟶local modulation of magnetic shear ($\tilde{s}/s = 60\%$ at ρ_{dep})

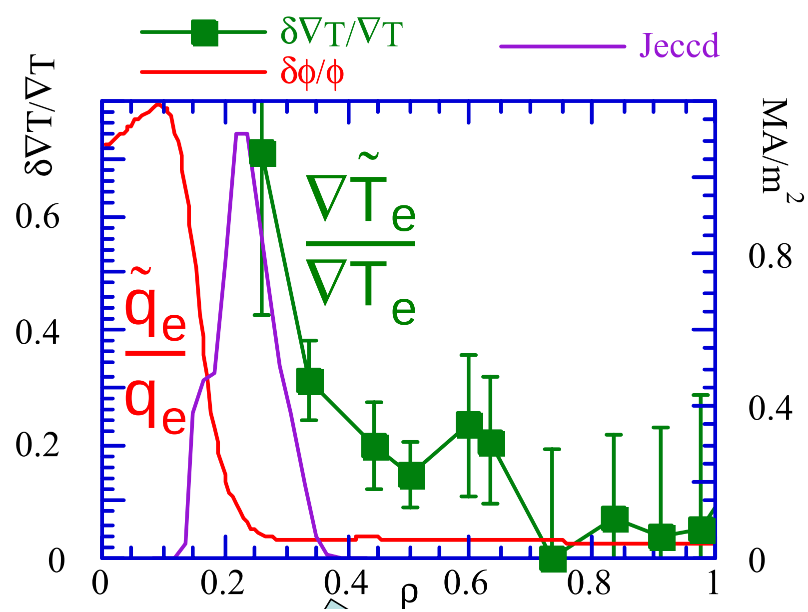


confirmed by l_i, V_{loop} modulation and sawteeth suppression during co-ECCD

Modulation in T_e in spite of constant ECH power



$$\frac{\nabla\tilde{\chi}_e}{\nabla\chi_e} = \frac{\tilde{q}_e}{q_e} - \frac{\nabla\tilde{T}_e}{\nabla T_e} \text{ (60\% at } \rho_{dep}\text{)}$$

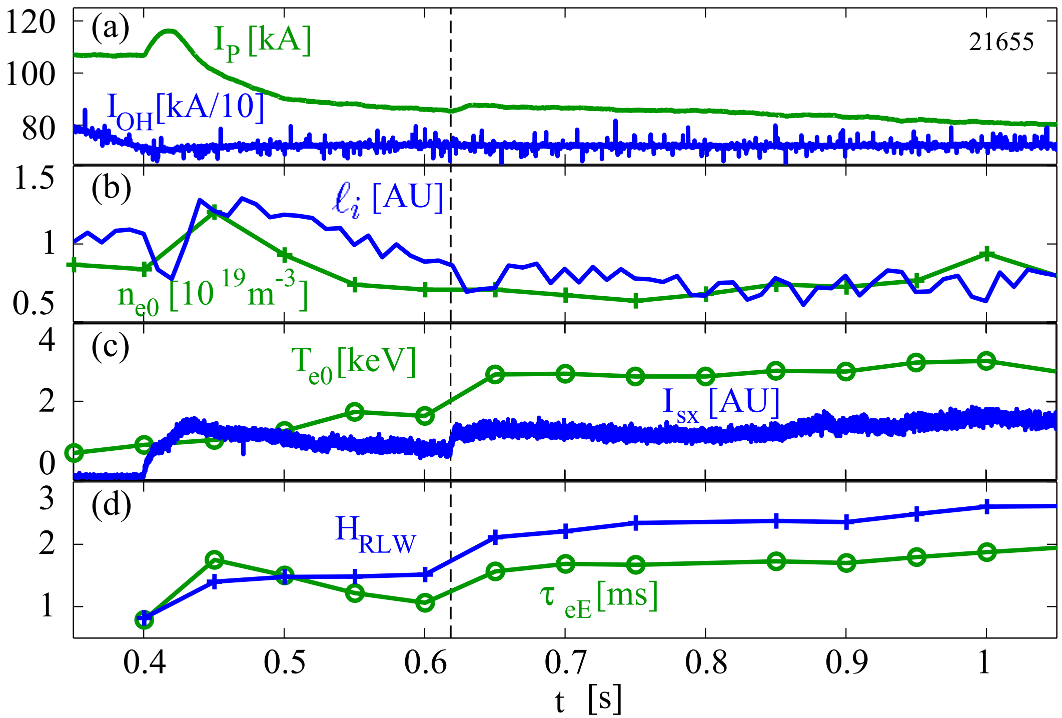


Electron diffusivity decreases with shear by the same relative amount and at the same radial location

Barrier formation and control in steady state scenarios (fully sustained by current drive and bootstrap current)

Henderson EX/3-3

- start with ohmic peaked current density j_Ω
- set $V_{loop} = 0V$, apply off-axis co-ECCD ($\rho = 0.4, 0.9\,MW$)
- after $\tau_{CRT} \cong 0.2s$, peaked j_Ω is replaced by hollow $j_{ECCD} + j_{BS}$
- transition to improved confinement



I_p I_{OH}

n_{e0} l_i

T_{e0} I_{SX}

τ_{Ee} H_{RLW}

Rapid eITB formation

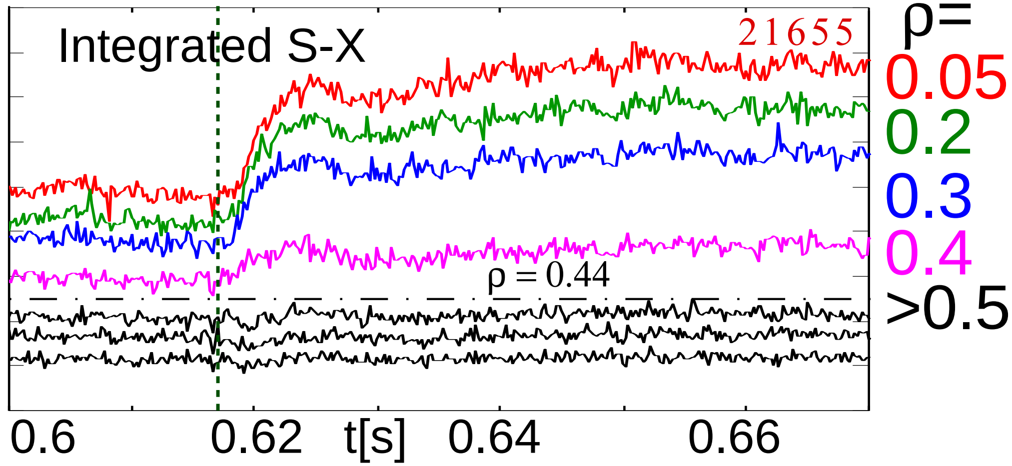
Observed with multiwire X-ray camera, high spatial (1 cm) and temporal (0.05 ms) resolution

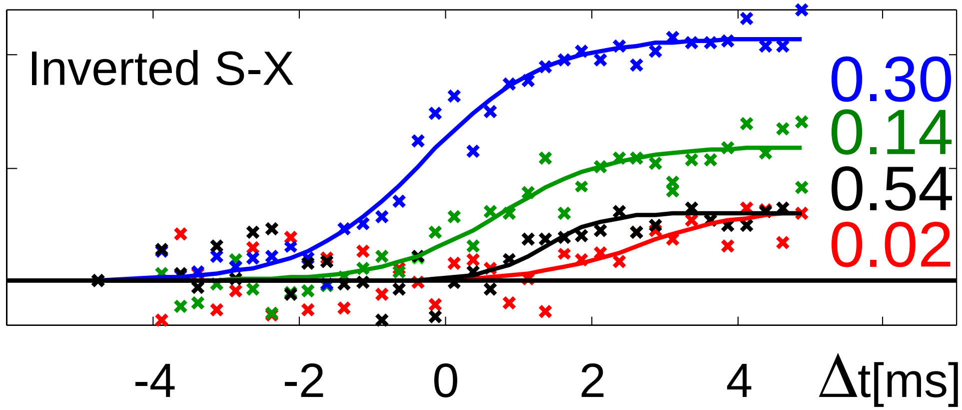
- eITB foot at ρ = 0.44

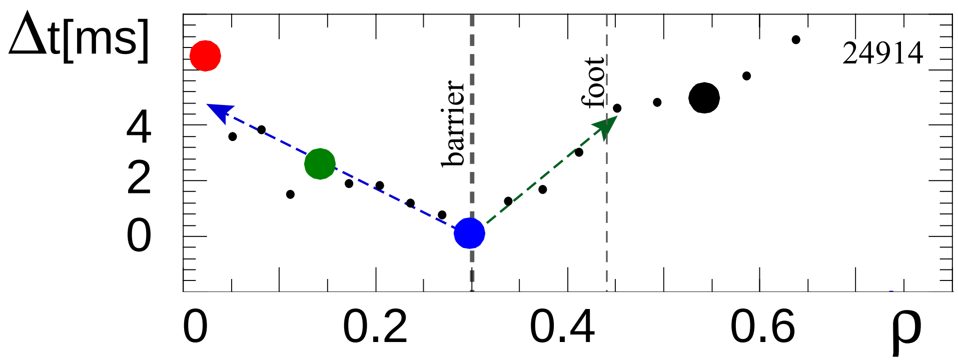
Abel inverted emissivity (constant on flux surfaces)

- eITB formation at ρ = 0.3
- good confinement region expands rapidly

Barrier is very narrow (0.05 in ρ, 1.2 cm)
Barrier formation on a time scale < 1 ms < energy confinement time







Apply on-axis ECH (0.45 MW)

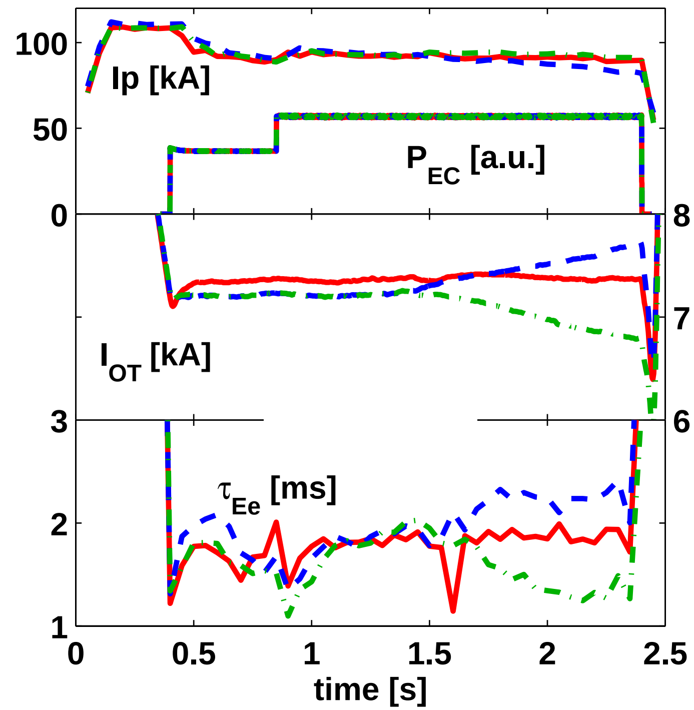
- clear eITB on pressure profile
- τ_{Ee} increases (despite power increase)

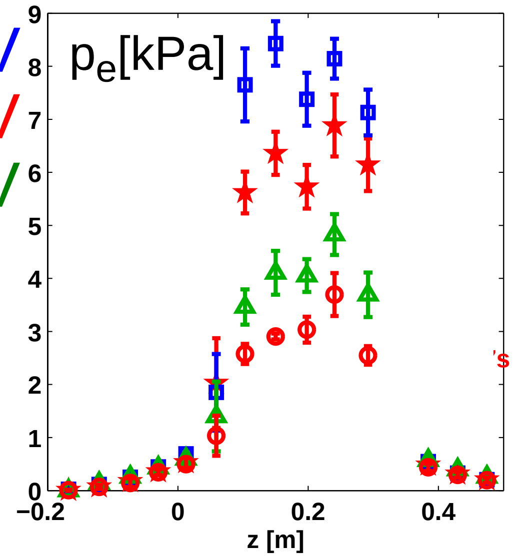
Apply $V_{loop} = \pm 30$ mV

- $P_\Omega = 3$ kW « P_{ECH}
- perturbed the hollow current profile with peaked j_Ω

- with +30 mV, j(0) increasing τ_{Ee} and $p_e(0)$ decreases
- with -30 mV, j more hollow τ_{Ee} and $p_e(0)$ increases

Current profile is the primary cause for confinement increase



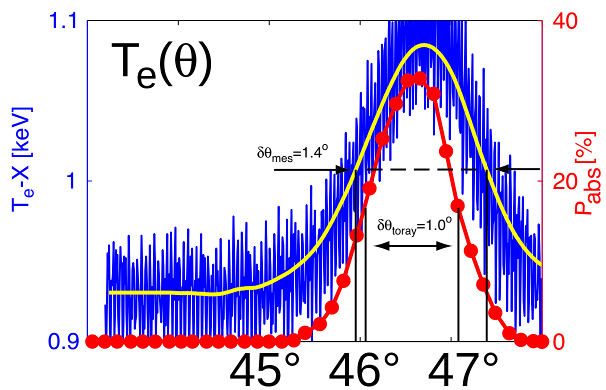


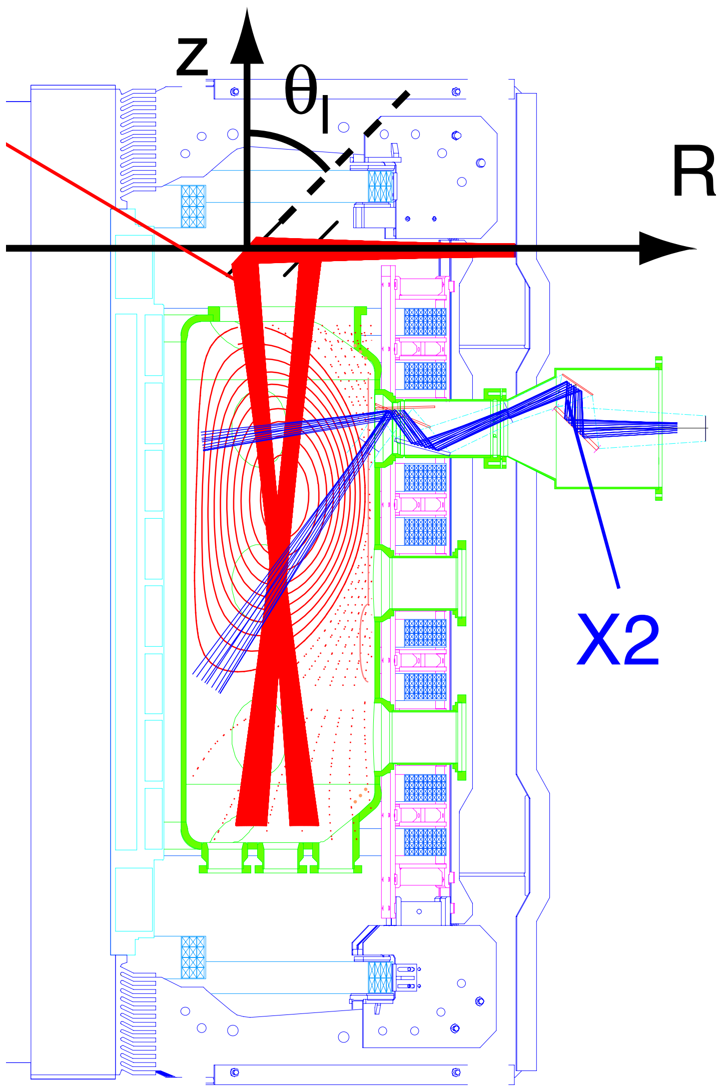
Broaden the operational space with heating well above X2 cut-off density

Alberti EX/4-17

- 3 x 0.5 MW, 118 GHz, 2 s
- top launch grazing incidence to maximise interaction length

Absorption sensitive to launching angle (density gradient refraction, temperature relativistic shift)





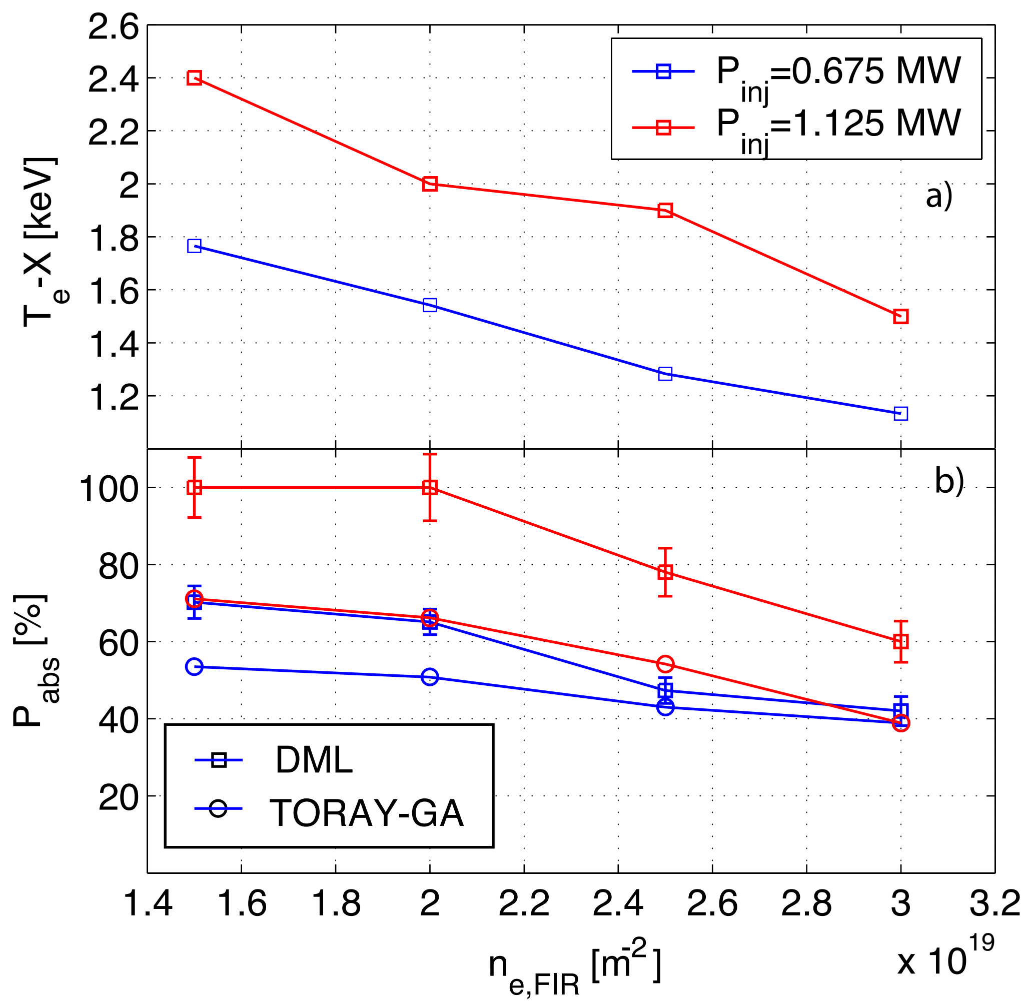
→Real time optimisation of the absorption

Optimised X3-ECH absorption

- measured with the response of β_{DIA} to power modulation

Higher absorption at

- high power (high temperature)
- low density (absorption on suprathermal electrons generated by X3 - difference with TORAY-GA prediction)
- 100% achieved
- comparison between ray-tracing (TORAY-GA) and beam tracing (ECWBG) under way

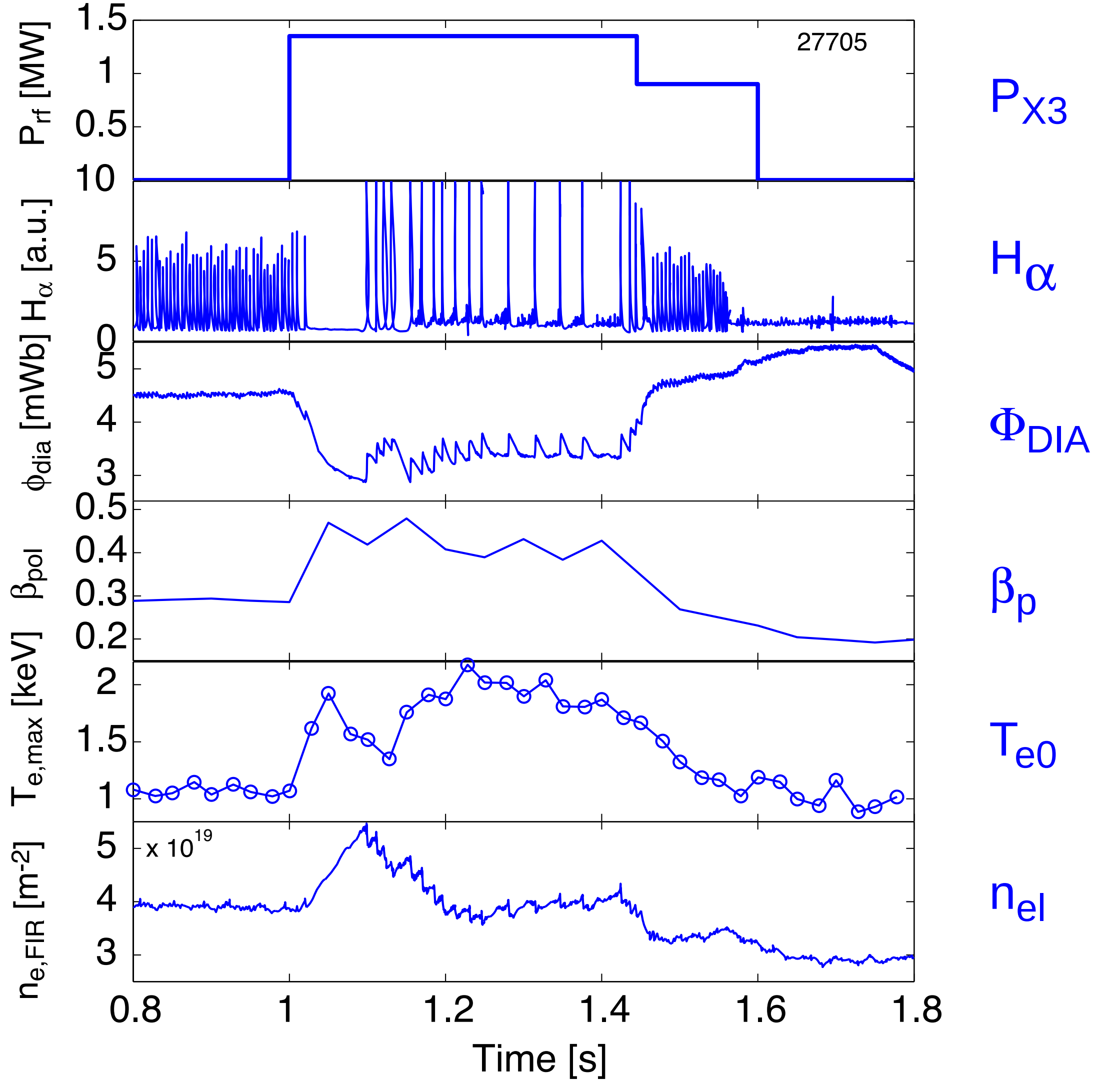


ELMy H-mode with X3-ECH

previous experiments with $P_{X3} \ll P_\Omega$, ELM frequency decreases with power but ELM regime identical to Ohmic H-modes

with $P_{X3} = 3P_\Omega$

- different ELM regime
- ELM frequency much smaller
- Energy loss per ELM increased 10 x
- Minimum power to reach this regime



ECH system of TCV with highly adaptable launching is fully deployed - ideal tool for

Physics understanding

- electron heat transport, role of magnetic shear and shape
- eITB formation

Performances

- steady-state eITB control, high bootstrap fraction
- X3-ECH: real time optimisation of absorption
- ELMy H-mode at high X3-ECH power

TCV contributions

M.A. Henderson	**Rapid eITB formation during magnetic shear reversal in fully non-inductive TCV discharges**	**EX/3-3**
S. Alberti	**Third-harmonic, top-launch, ECRH experiments on TCV Tokamak**	**EX/4-17**
S. Cirant	**Shear modulation experiments with ECCD on TCV**	**EX/6-12**
A. Pochelon	**Effect of plasma shape on electron heat transport in the presence of extreme temperature gradients variations in TCV**	**Oral EX/9-1**