EUROfusion

# Role of $E_r$ on plasma turbulence (OP1 summary presentation)

Compiled by T. Estrada

Contributors: D. Carralero, C. Killer, A. Krämer-Flecken, R. Lunsford, E. Maragkoudakis, N. Pablant, E. Sánchez, A. von Stechow, J.L. Velasco, T. Windisch

GOBIERNO DE ESPAÑA MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

IPP

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# Role of $E_r$ on turbulence: Introduction

In stellarators the radial electric field profile is (mostly) determined by Neoclassical transport:

- Plasma kinetic profiles set the $E_r$ profile, and they all impact the turbulence:
  - ✓ Profile shaping can reduce turbulence (adressed by A. von Stechow and D. Carralero)
  - ✓ $E_r$ directly impacts turbulence in stellarators (not so in tokamaks)
  - ✓ Strong $E_r$ shear can stretch and break turbulent structures, reducing turbulence transport
- Turbulence itself can modify the average plasma flow by sheared zonal flow (ZF) generation, which reacts back on the turbulence and suppresses its own driver

*To disentangle the impact of $E_r$ and kinetic profiles on turbulence is not an easy task, neither in experiments nor in realistic simulations*

# Outline

## Status of understanding after OP1

- **$E_r$ profile validation activities**: cross-diagnostic & NC simulation comparison
- **$E_r$-shear at the edge/SOL boundary**:

  impact on edge turbulence *(impact on SOL transport → adressed by C. Killer)*
- **$E_r$ impact on core turbulence**:

  post-pellet enhanced confinement phase & impurity injection experiments
- **$E_r$ at the magnetic islands**: impact on turbulence *(next presentation)*
- **Gyrokinetic simulations**: linear & non-linear results

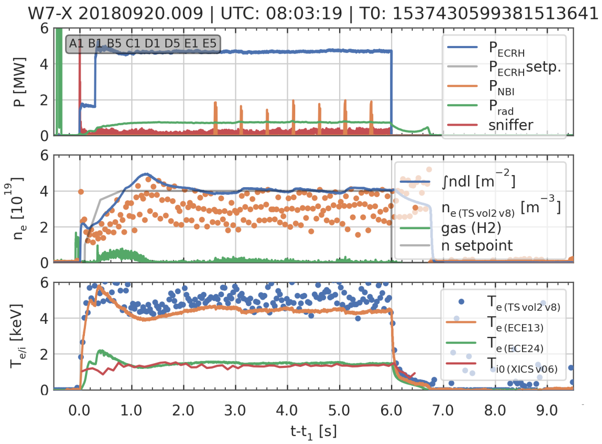
## Open questions and outlook towards OP2

- **Non-linear global simulations**
- **New measurement capabilities for OP2**

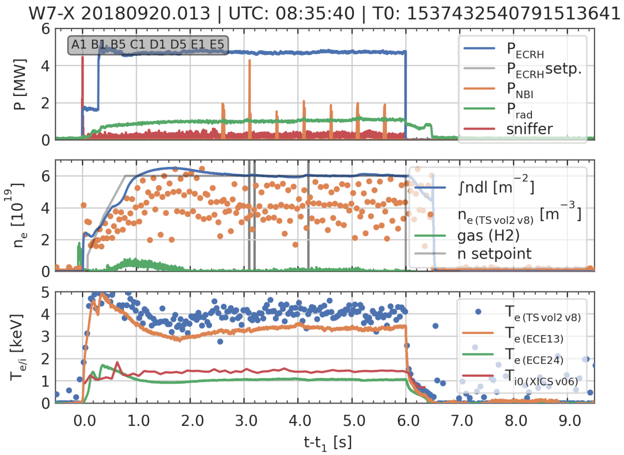
# $E_r$ profile validation: Cross-diagnostic & NC simulation

by the validation group: Windisch, Alonso, Buller, Carralero, Pablant, Smith

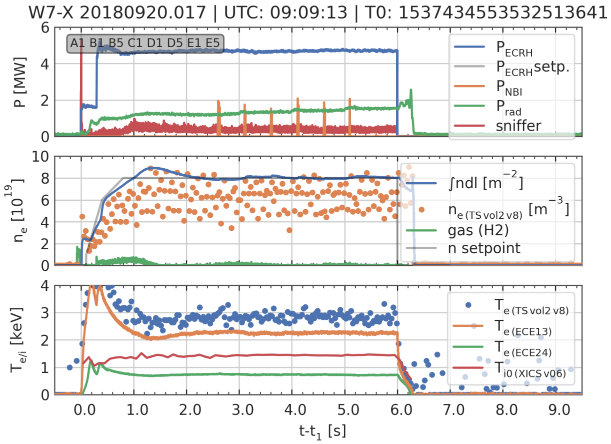
## low density 4 $10^{19}$ $m^{-3}$




## medium density 6 $10^{19}$ $m^{-3}$



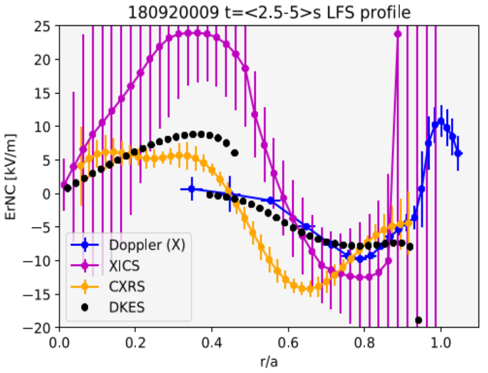

## high density 8 $10^{19}$ $m^{-3}$

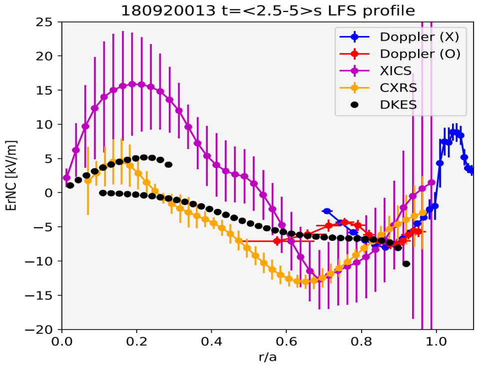


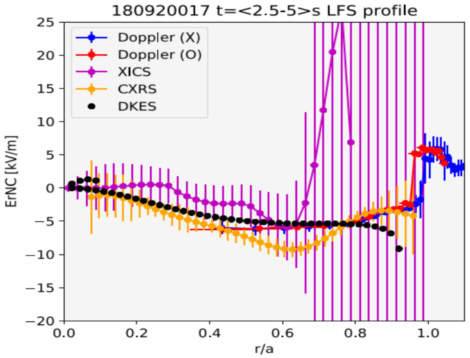
# $E_r$ profile validation: Cross-diagnostic & NC simulation

by the validation group: Windisch, Alonso, Buller, Carralero, Pablant, Smith

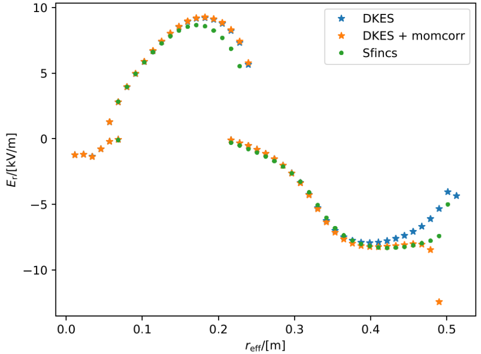
## low density 4 $10^{19}$ $m^{-3}$ | medium density 6 $10^{19}$ $m^{-3}$ | high density 8 $10^{19}$ $m^{-3}$

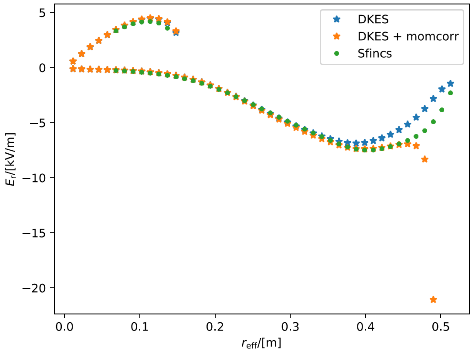


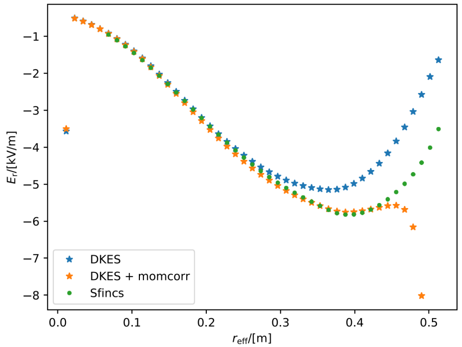




## DKES with momentum correction (mono-energetic collision operator) vs. SFINCS (full collision operator)



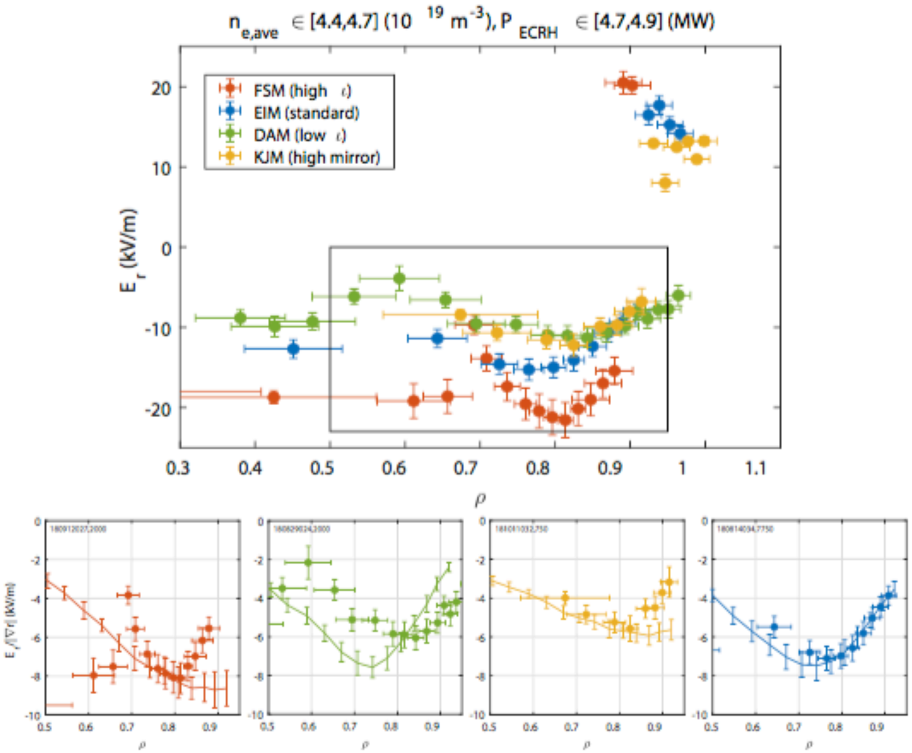



# Er profile validation: measurement vs. NC simulation (I)

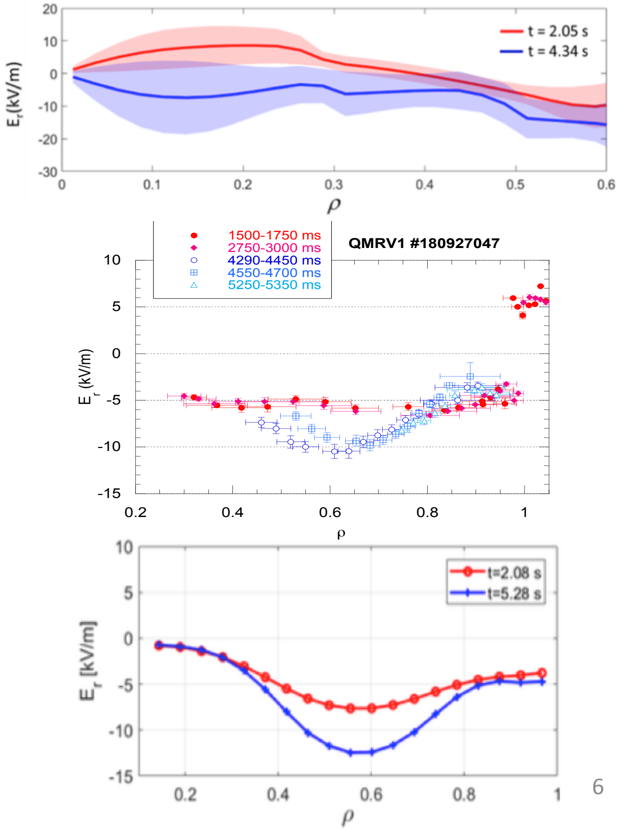
**Comparison** of experimental profiles (DR) and neoclassical predictions obtained using the codes DKES and KNOSOS (J.L. Velasco) for the four most frequent magnetic configurations

D. Carralero et al., NF **60**, 106019 (2020)



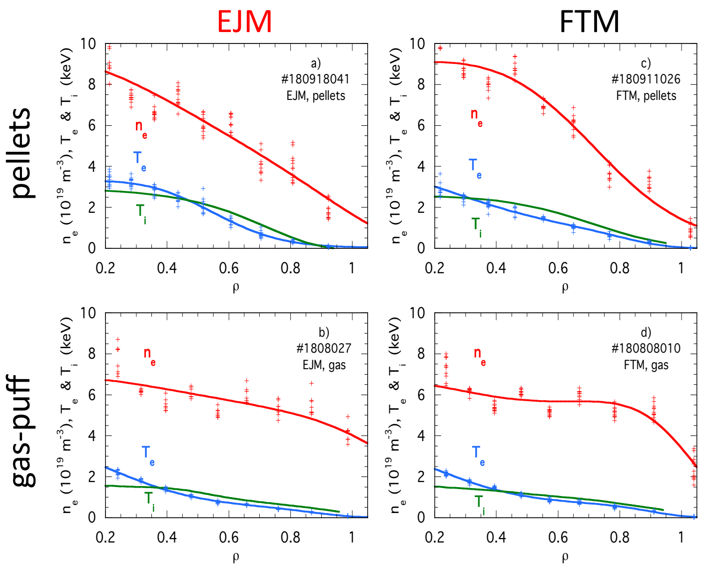

**Comparison** of experimental profiles (XICS and DR) and neoclassical predictions obtained using the code SFINCS

R. Lunsford et al., PoP *to be submitted*

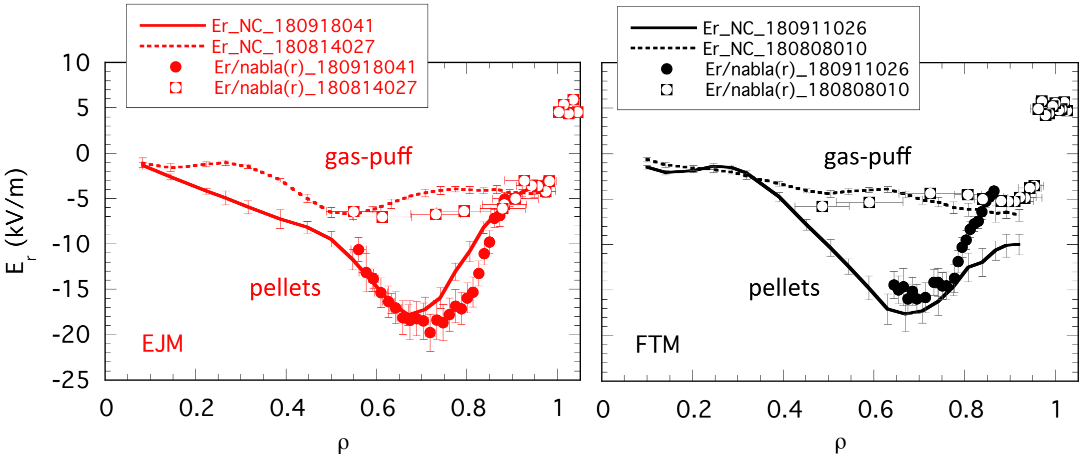


# $E_r$ profile validation: measurement vs. NC simulation (II)






Four experimental programs: **post-pellet & gas fuelled / EJM & FTM** with $n_e \sim 9{\times}10^{19}$ $m^{-2}$ and PECH ~ 5.5 - 6.0 MW




Comparison of experimental (DR) and neoclassical predictions obtained using the codes DKES and KNOSOS (J.L. Velasco) for the four experimental programs

T. Estrada et al., NF **61** (2021) *accepted*

**Considering the diagnostic specific limitations, in general, a reasonable agreement is found when the experimental $E_r$ profiles are compared with the neoclassical predictions**

# Outline

## Status of understanding after OP1

- **$E_r$ profile validation activities**: cross-diagnostic & NC simulation comparison
- **$E_r$-shear at the edge/SOL boundary**:

  impact on edge turbulence *(impact on SOL transport → adressed by C. Killer)*
- **$E_r$ impact on core turbulence**:

  post-pellet enhanced confinement phase & impurity injection experiments
- **Gyrokinetic simulations**: linear & non-linear results

## Open questions and outlook towards OP2

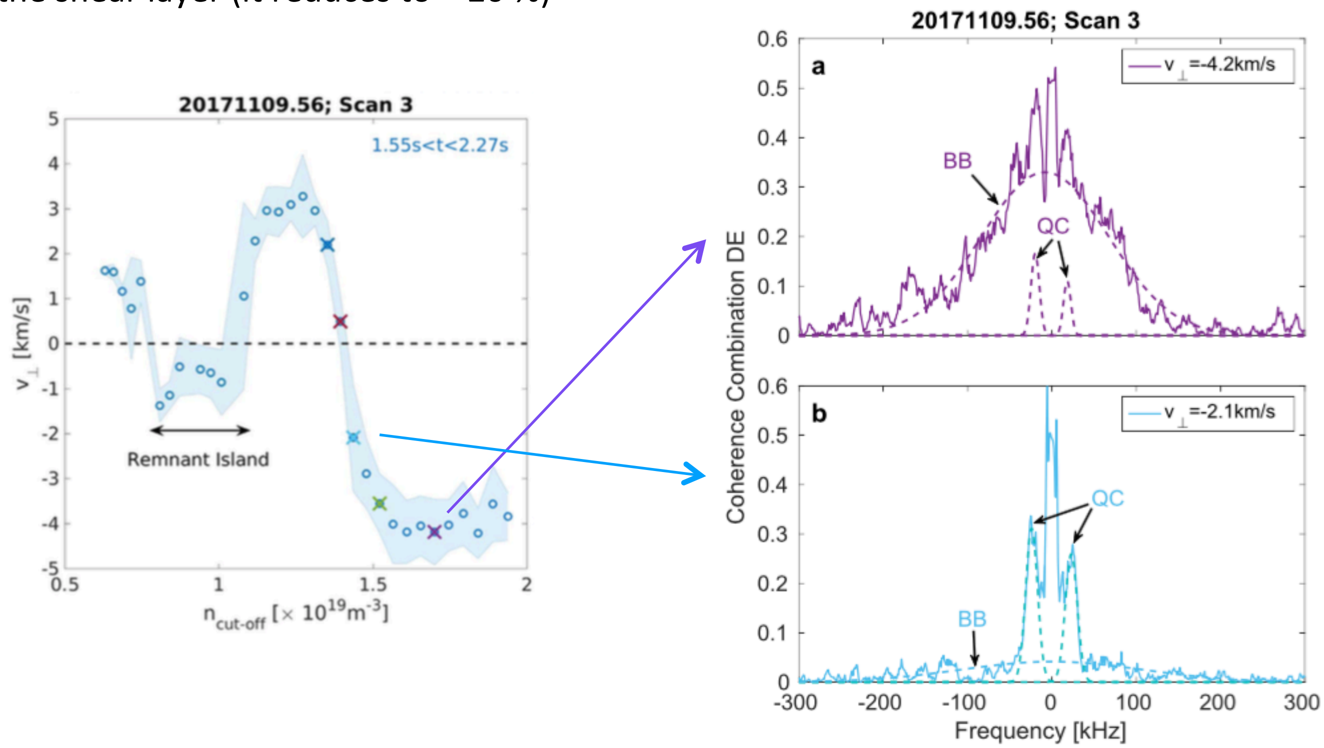
- Non-linear global simulations
- New measurement capabilities for OP2

# $E_r$-shear at the edge/SOL boundary: impact on edge turbulence (PCR)

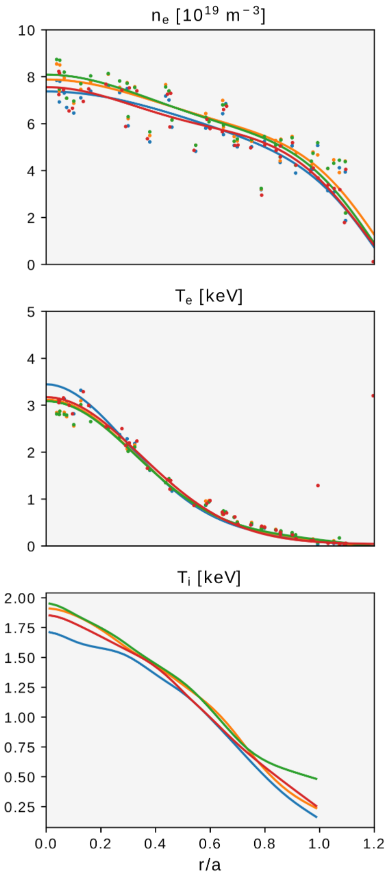
**Impact of the edge $E_r$-shear on the fluctuations**: A. Krämer-Flecken et al., Plasma Sci. Technol. **22**, 064004 (2020)

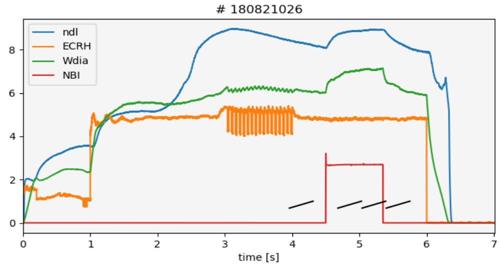
identified as a clear decrease in the broad band turbulence when passing the shear layer

the spectrum has a strong broad band component in the plasma edge (contributes with ≈ 75 % to the spectra) but not in the shear layer (it reduces to ≈ 20 %)



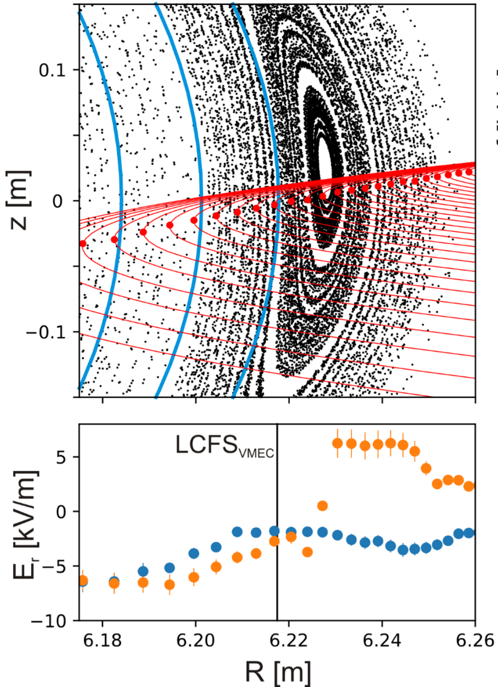
# NBI induced $E_r$-shear reduction at the edge/SOL boundary

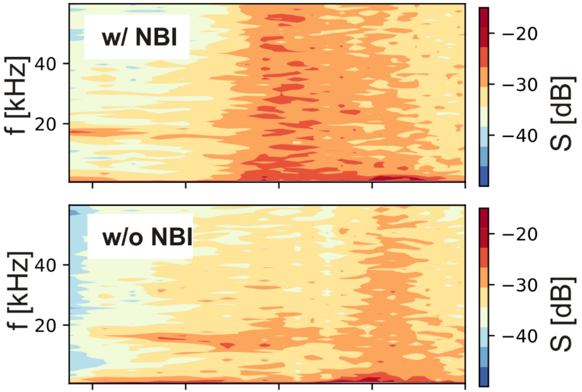


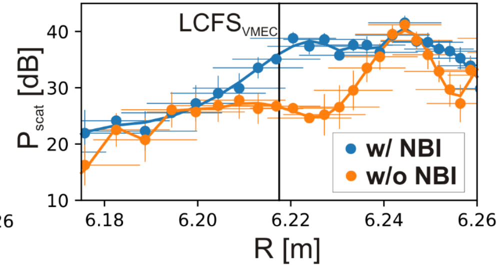




$E_r$ profile in edge/SOL boundary strongly modified during NBI (e.g. fast ions): useful scenario for investigation of $E_r$-shear impact on edge turbulence

T. Windisch



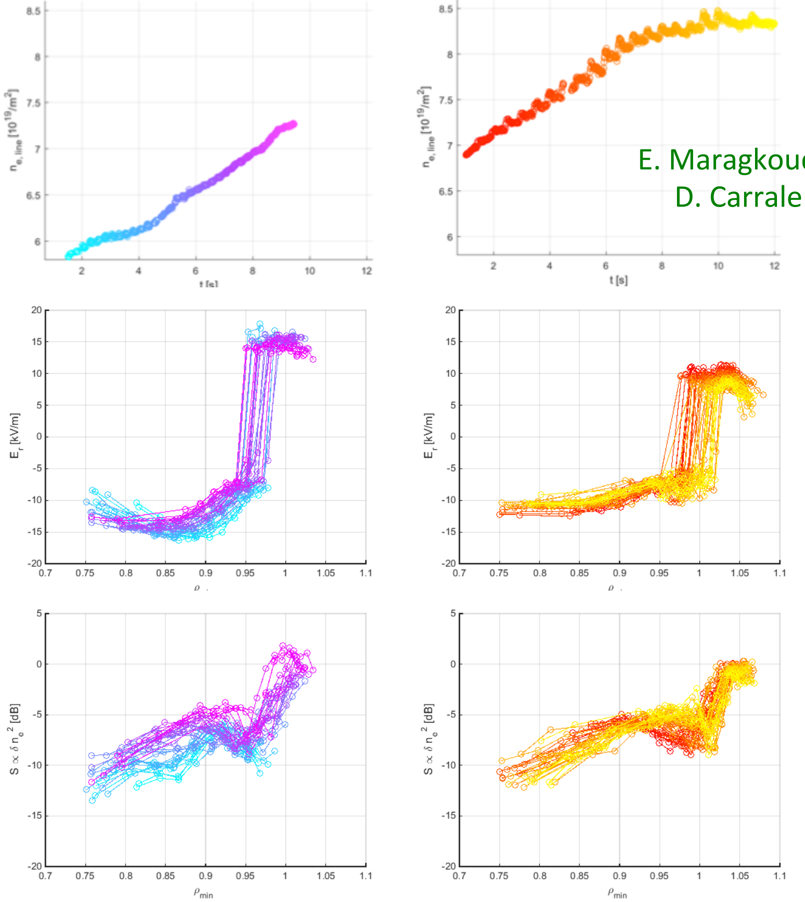



# $E_r$-shear at the edge/SOL boundary: impact on edge turbulence (DR)

#181017033
$P_{ECH}$ = 6 MW

#181018021
$P_{ECH}$ = 4 MW

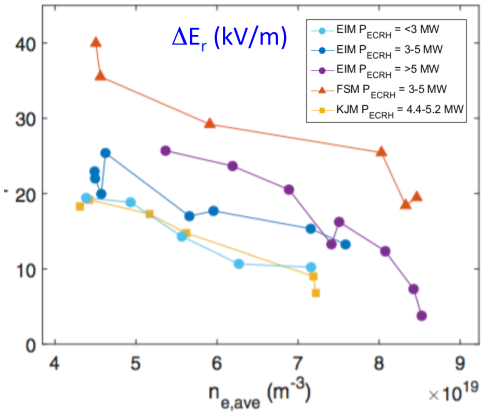


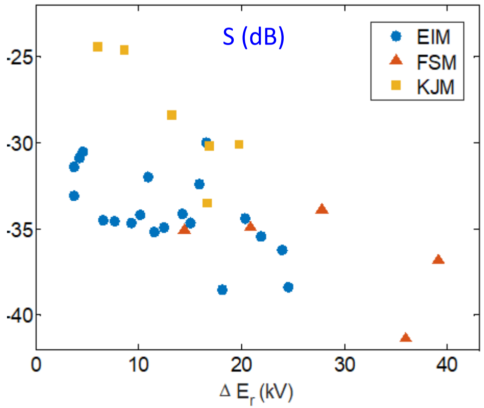

E. Maragkoudakis
D. Carralero

**Impact of the edge $E_r$-shear on the fluctuations**: identified as a local minimum in the fluctuation profile nearby the LCFS

**higher fluctuation level in the high mirror configuration** as compared to the standard and high iota configurations

→ Impact on edge turbulent transport and plasma performance?




**$E_r$-shear at the SOL/edge boundary: impact on SOL transport**
Adressed by C. Killer

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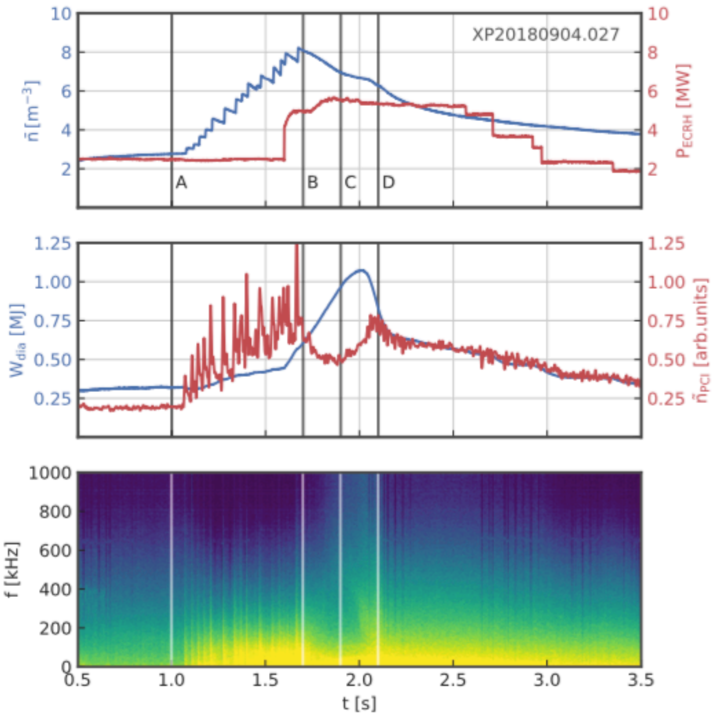
# $E_r$ impact on core turbulence: post-pellet enhanced confinement phase

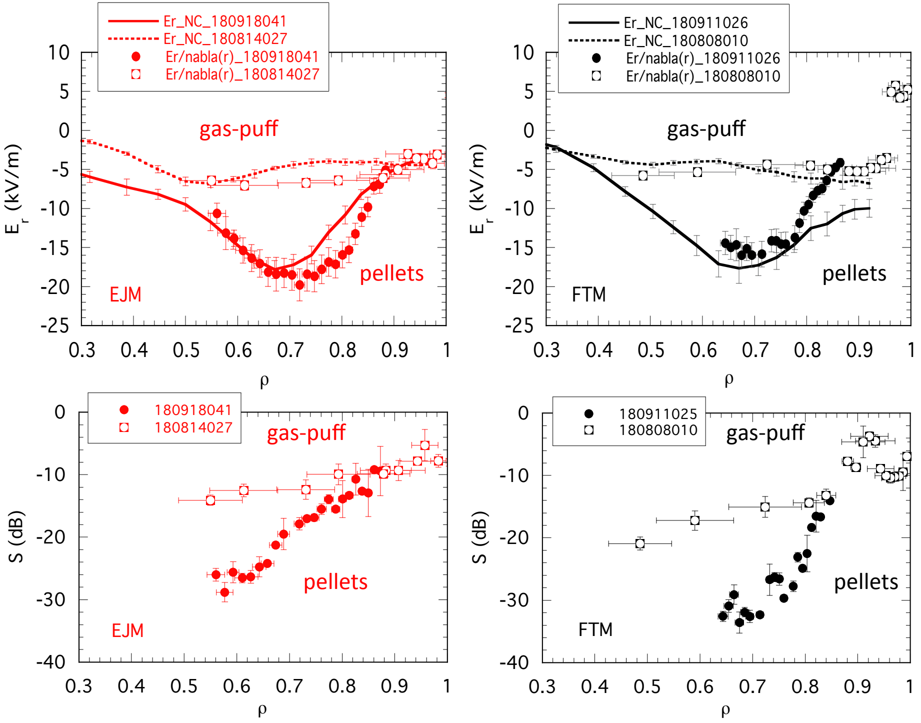
The density fluctuation level decreases during the post-pellet enhanced confinement phase (DR & PCI), in the range $\rho \approx 0.6$-$0.8$, more pronounced in the high iota configuration than in the standard

A pronounced $E_r$-well is measured in the same radial range

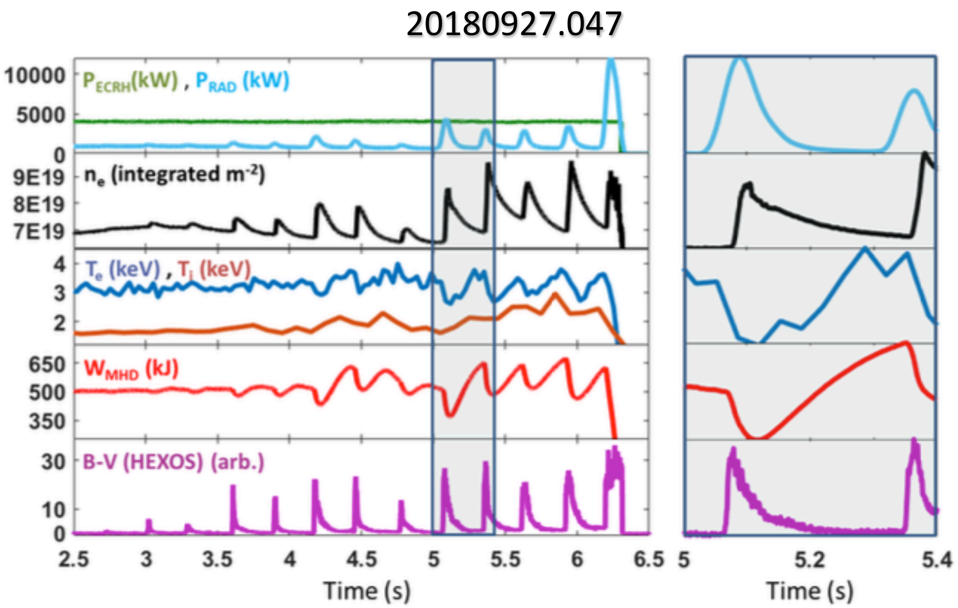
PCI measurements: A. von Stechow et al., PRL *submitted*

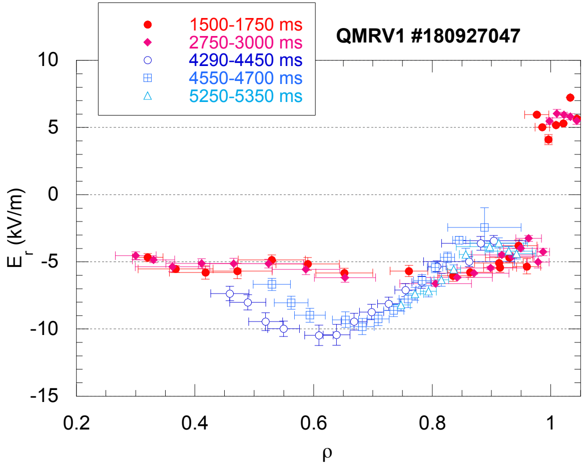


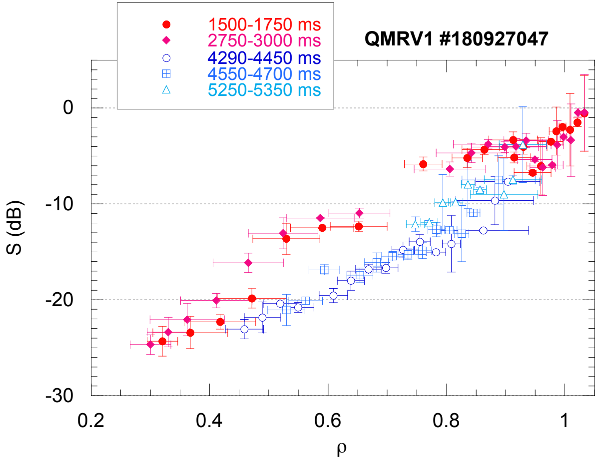

DR measurements: T. Estrada et al., NF **61** (2021) *accepted*



# $E_r$ impact on core turbulence: Boron powder injection experiments




Powder injection modifies kinetic profiles (higher n & T gradients)

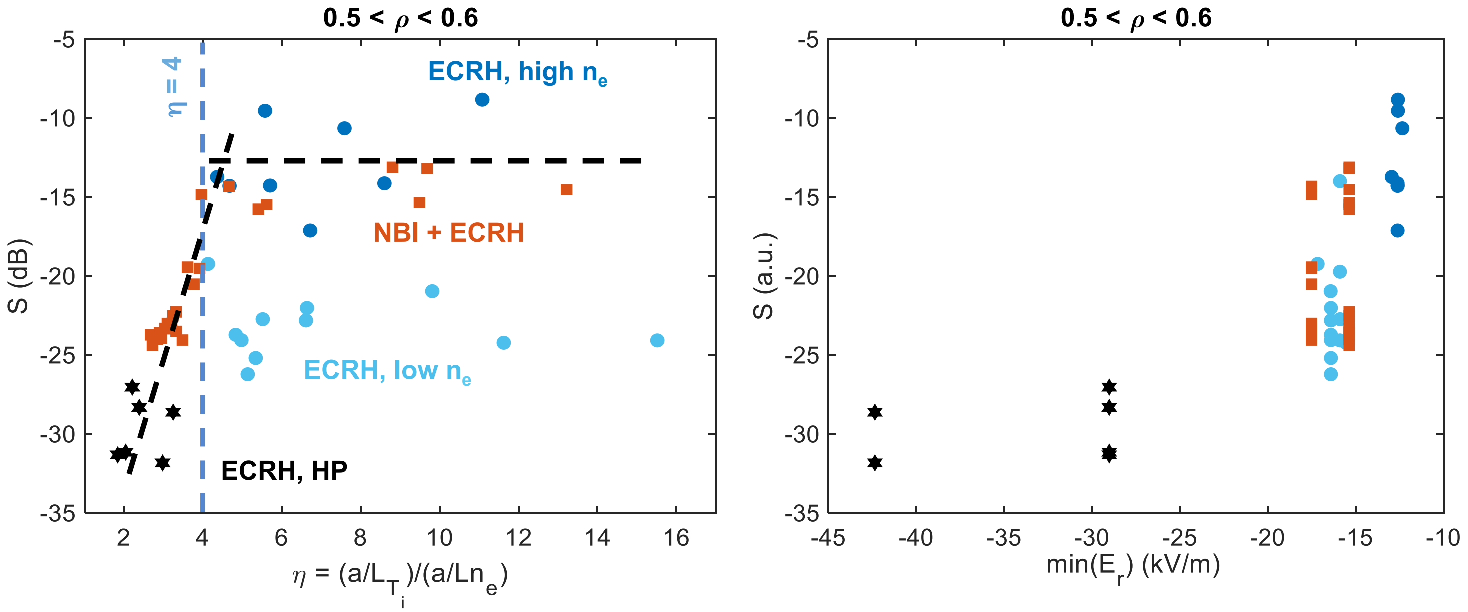
DR measurements (T. Estrada): an increase in $E_r$ and $E_r$-shear and a decrease in density fluctuations is observed between pre-injection (red) and post-injection (blue) phase, in $\rho \approx 0.5 - 0.8$

R. Lunsford, et al. PoP *to be submitted*

# Core turbulence: $E_r$ & profile dependences

DR database provides general relationships between profiles, fluctuations and $E_r$ (D. Carralero):

- in most scenarios **core fluctuations follow η**: $\tilde{n}_e$ increases as η increases and saturates for η > 4
- A relation between the core fluctuations and the $E_r$-well depth is also observed



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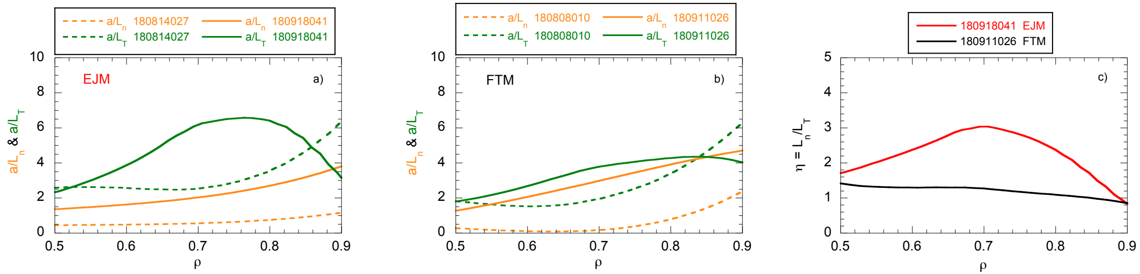
## Open questions and outlook towards OP2

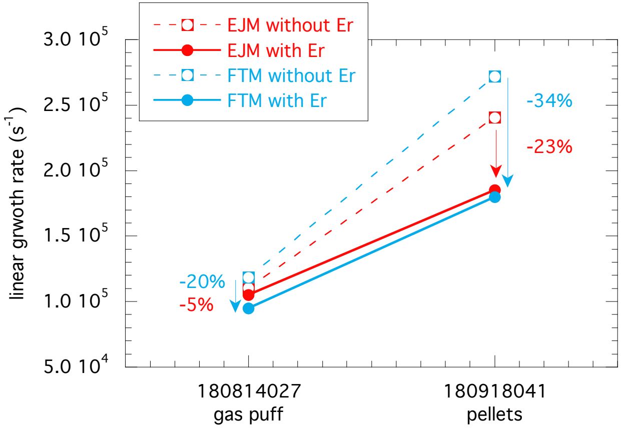
- Non-linear global simulations
- New measurement capabilities for OP2

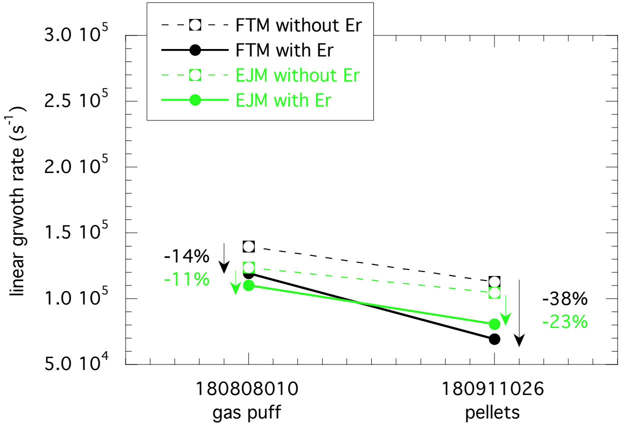
# EUTERPE global linear simulations (I)

Four experimental programs: post-pellet & gas fuelled / EJM & FTM, with $n_e \sim 9\times10^{19}$ $m^{-2}$ and PECH ~ 5.5 - 6.0 MW

- adiabatic electrons
- radial domain 0.65 – 0.75



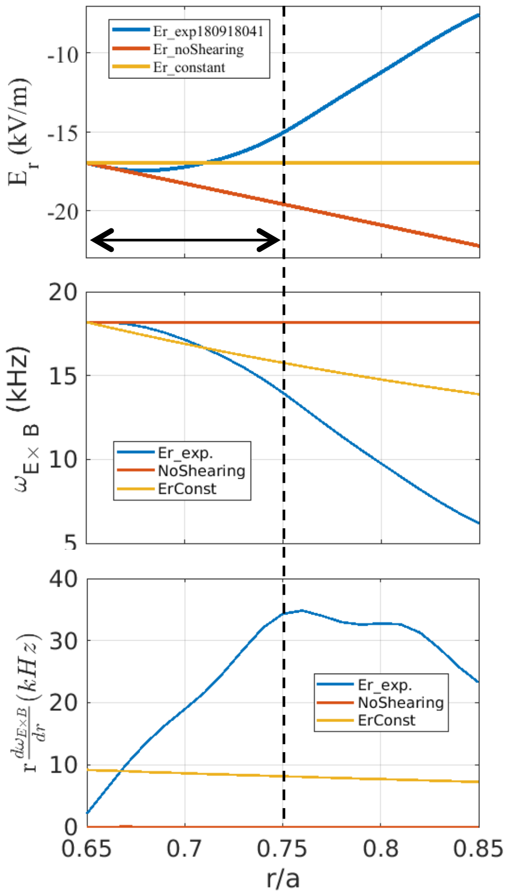

Linear growth rates, γ, for the four experimental programs: in EJM (left, red) and in FTM (right, black), without and with $E_r$ (open and solid symbols). In blue and green, γ obtained swapping the magnetic configurations

E. Sánchez

Stabilizing effect of $E_r$ (and/or $E_r$-shear): T. Estrada et al., NF 61 (2021) *accepted*

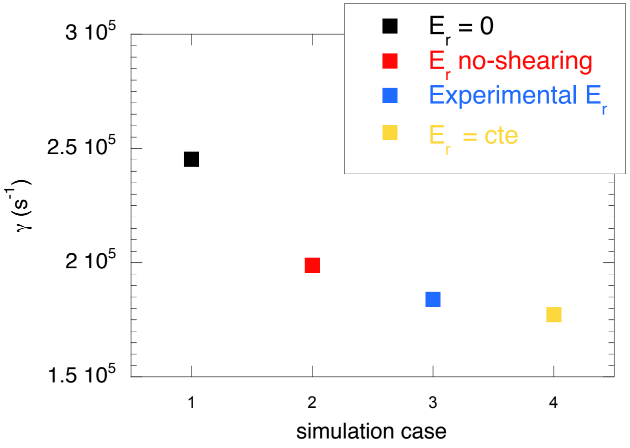
- modest in the gas fuelled plasmas, but significant in the post-pellet plasmas
- larger in FTM (higher magnetic shear) than in EJM for the same profiles

# EUTERPE global linear simulations (II)




## Dominant role of $E_r$ or $E_r$-shear?

Different $E_r$ profiles are considered: $E_r$=0; no-shearing; constant $E_r$ and experimental $E_r$ to disentangle the effect of $E_r$ and $E_r$-shear on the stabilization of ITG driven modes



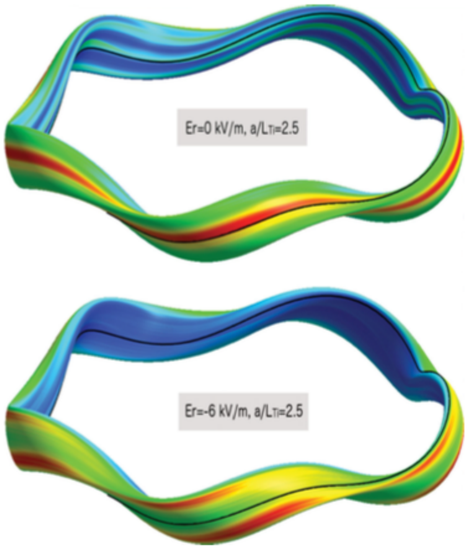

E. Sánchez

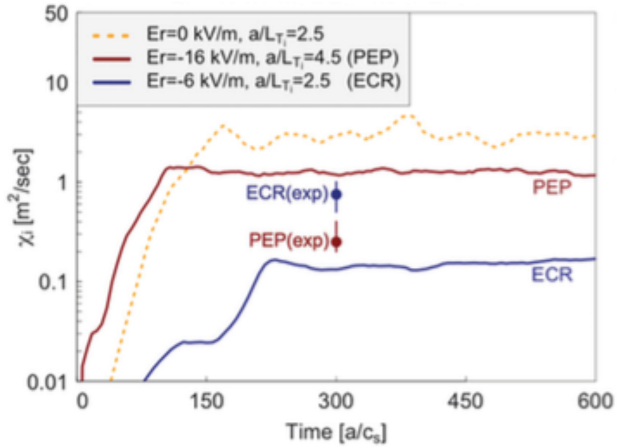
Linear growth rates, $\gamma$, for #180918041, post-pellet phase in EJM configuration with different $E_r$ profiles radial domain 0.65 – 0.75

# GENE local full flux-surface non-linear simulations

Ambipolar $E_r$ produces a displacement of the fluctuations on the magnetic surface towards regions with lower curvature less favorable for turbulence generation → the nonlinear ion heat transport is reduced

P. Xanthopoulos et al., PRL **125**, 075001 (2020)




Simulations at $\rho = 0.63$ with a/Ln = 0 & adiabatic electrons → ITG turbulence

ion heat flux: an order of magnitude reduction with $E_r$

It is not strong enough to compensate for the increase in $\nabla T$ (with $\nabla n = 0$)

**Flux-tube simulations with kinetic electrons**: strong a/Ln reduces ITG in favor of iTEM

How $E_r$ impacts the TEM / iTEM dominated turbulence?

# GENE-3D global non-linear simulations (without $E_r$)

**GENE-3D:** non-linear global simulations with adiabatic electrons (without $E_r$)

- Discrepancies between expectations based on **linear** simulations and the heat fluxes obtained in **non-linear** simulations have been found in W7-X configurations
- **Radially local full flux-surface** simulations overestimates (by a factor of two) the heat fluxes as compared to **global** simulations at the same position → global simulations are needed for quantitative studies

A. Bañón-Navarro et al. PPCF **62**, 105005 (2020)

## Outlook towards OP2

**Non-linear global simulations** with kinetic electrons and $\mathbf{E_r}$ profiles…

impact of $E_r$ and $E_r$-shear on zonal flow response & non-linear saturation of turbulence

work is currently in progress using **GENE-3D** and **EUTERPE**... status?

# New measurement capabilities expected for OP2: PCI & Probes

**Phase Contrast Imaging** A. von Stechow, S. Hansen, J.P. Bähner

**Modelling**:

A synthetic diagnostic that predicts the PCI signal based on outputs form GENE3D and EUTERPE and additional $E_r$ profiles

**Measurement:**

Radial resolution:

- originally planned for OP1 but didn't work due to technical reasons
- plans to implement it for OP2:
  - at least should be able to get an inboard/outboard selection
  - but in the best case have a radial resolution on the outboard side of 0.2 r/a

Using 2 detectors:

- allows to compare line-integrated fluctuations to those at a specific location (either fixed or scanned)
- allows to see the more-or-less local phase velocities and thereby $E_r$ changes

**Probes** C. Killer

a new probe head with:

- a better poloidal resolution of probe pin
- a radial pin array

better insight into the complicated propagation of turbulent structures in the island divertor SOL

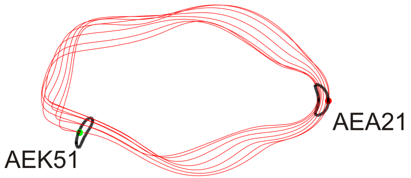
# New measurement capabilities expected for OP2: DR & probes

**Doppler Reflectometry** T. Windisch, D. Carralero, T. Estrada

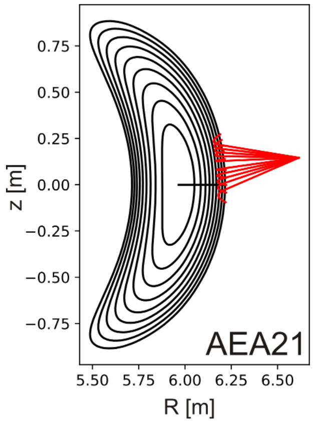
**V-band & W-band DR systems at AEA21:**

upgrade the antenna systems incorporating steerable mirrors:

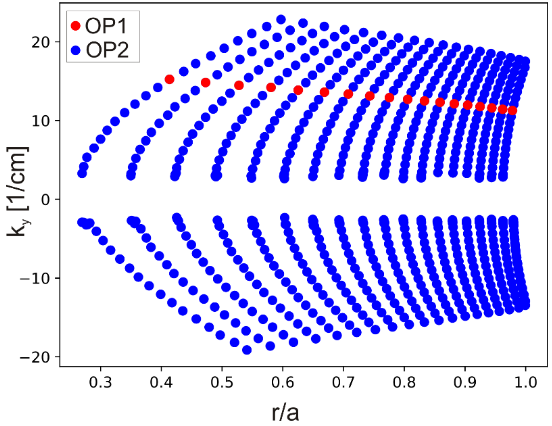
- probing different perpendicular wavenumbers of the turbulence to measure fluctuation wavenumber spectra
- investigate poloidal asymmetries of plasma flows and turbulence on flux surface




beam steering

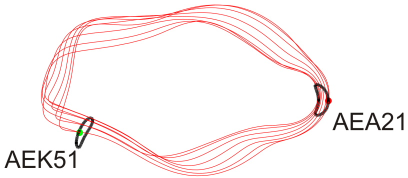



accessible wavenumber domain



# New measurement capabilities expected for OP2: DR & probes

**Doppler Reflectometry** T. Windisch, D. Carralero, T. Estrada, …




**V-band & W-band DR systems at AEA21:**

upgrade the antenna systems incorporating steerable mirrors:

- probing different perpendicular wavenumbers of the turbulence to measure fluctuation wavenumber spectra
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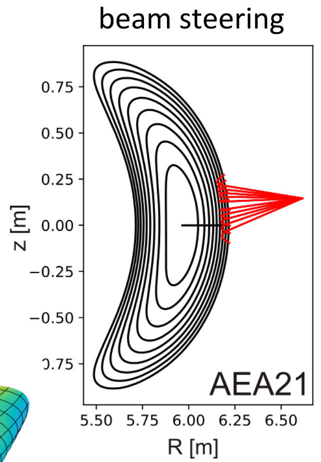


**V-band DR system at AEK51:**

poor performance during OP1.2 mainly due to a misalignment in the in-vessel optics

upgrade the antenna system incorporating a steerable mirror:

- probing different perpendicular wavenumbers of the turbulence to measure fluctuation wavenumber spectra
- investigate poloidal/toroidal asymmetries of plasma flows and turbulence
- long distance correlation as a proxy for ZFs

**New E-band DR system at AEA21:**

- radial correlation measurements (eddy tilting) & E- shear