Wendelstein 7-X

Max-Planck-Institut für Plasmaphysik

Turbulence with profile shaping

A. v. Stechow (IPP) and D. Carralero (CIEMAT)
for the W7-X turbulence topical group, 28.1.2021

HELMHOLTZ
SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

EUROfusion

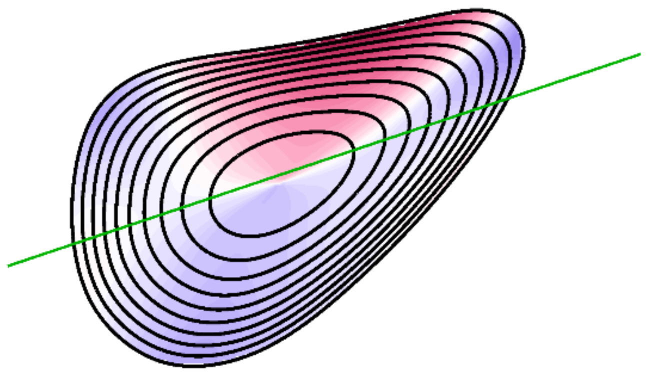
Methods of profile shaping in W7-X

Equilibrium gradient	Control knobs
electron temperature	ECH deposition profile – see TG talk by G. Weir/M. Beurskens from 14.1.2021 edge cooling (particle injection: TESPEL, LBO, Boron dropper)
core density	pellet fueling (entire profile) neutral beam injection (inside half radius)
edge density	edge injections (TESPEL, LBO, Boron dropper) modified particle fueling (e.g. post-NBI)
ion temperature	no direct control (NBI largely ineffective)
electric field (magnitude and shear)	result of neoclassical balance: indirect control by density and heating see TG talk by T. Estrada on 25.2.2021

- our only systematic control knob is ECH power deposition for T_e
- density profile variations are non-stationary and difficult to reproduce consistently
- turbulence observations of “improved confinement“ in OP1: piggy-back measurements with low systematic coverage

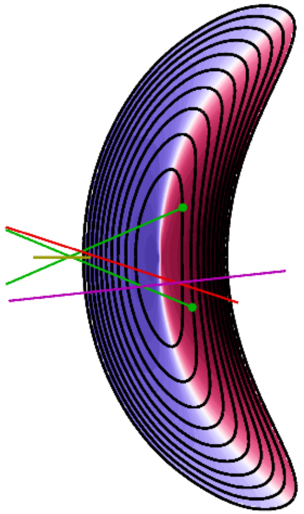
Key core density turbulence diagnostic systems

phase contrast imaging: (roughly) triangular plane



- continuously measures **absolute, line-integrated flucs.**
- **poloidally resolved** ($k \approx$ 2-20 cm^{-1})
- no radial resolution in OP1 (upcoming in OP2)
- signal dominated by largest fluctuations (typ. edge / E_r well)
- typ. result: frequency-wavenumber spectrum $S_{abs}(k, f, t)$

Doppler reflectometer: bean plane



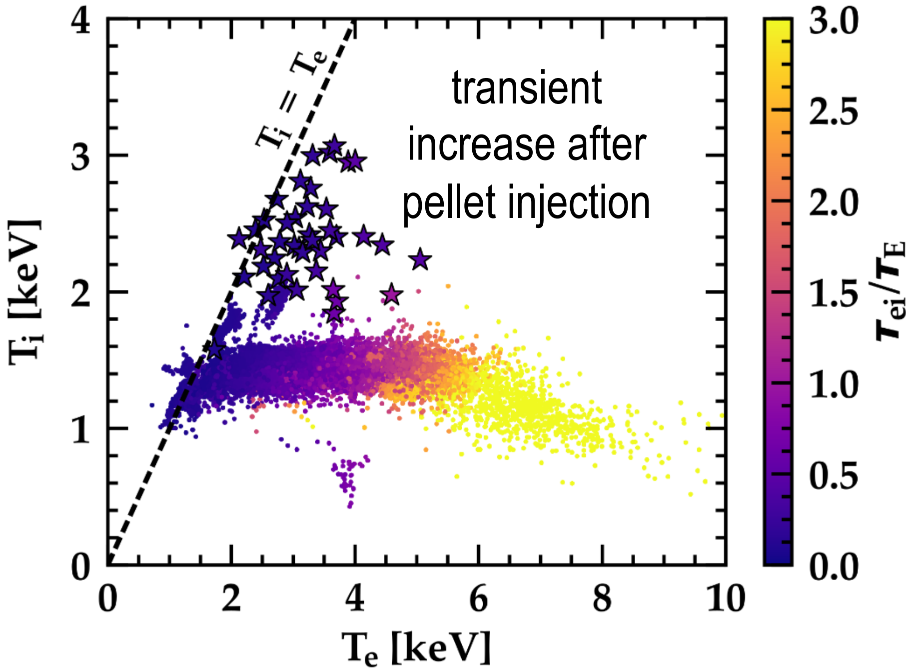
- measures **local fluctuations** at probing frequency (= density)
- **fixed $k_\perp$** (for V-band, $k_\perp \approx$ 7-10 cm^{-1}, $k_\perp \rho_i \sim 1$)
- **radially scanning** ($\tau \approx$ 250 ms), resolution depends on local ∇n
- accessible density range limited by frequency band
- typ. result: radial profile of E_r and fluctuation power $S_{rel}(f, r, t)$

Turbulence codes applied to W7-X

Code	geometry	Capabilities
EUTERPE	global (3D)	multi-species (kinetic electrons+impurities), nonlinear, electric field [E. Sánchez et al., *Journ. Plasm. Physics* **86** 855860501 (2020)]
GENE	flux tube/surface	multi-species (kinetic electrons+impurities), electric field (no shear), EM possible
GENE3D	global (3D)	electric field, kinetic electrons, EM possible, coupling to 1D transport code [A. Bañon Navarro et al., *Plasma Phys. Control. Fusion* **62** 105005 (2020)]
GTC	global (3D)	gyrokinetic PIC, electric field [*H. Y. Wang et al.. Phys. Plasmas* **27** *082305 (2020)*]
stella	flux tube	multi-species (kinetic electrons+impurities), nonlinear [J.M. Garcia-Regaña et al. *Journ. Plasm. Physics* (accepted)]
XGC-S	global (3D)	full-f, electric field [*M.D.J. Cole et al., Phys. Plasmas* **26** *082501 (2019)*]

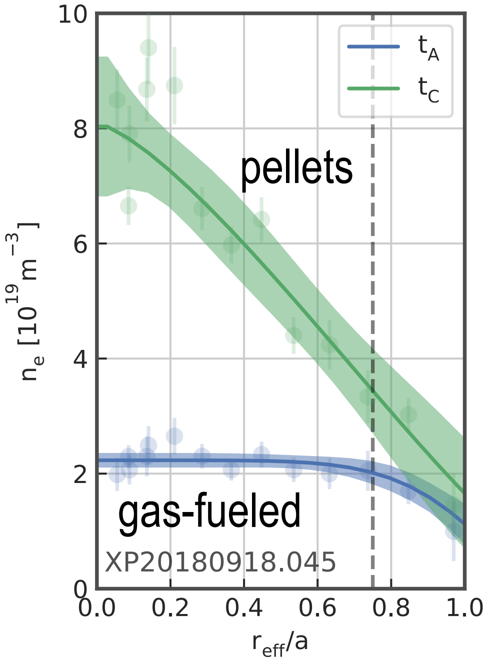
Benefits of density profile control

T_i vs. T_e including peaked density profiles

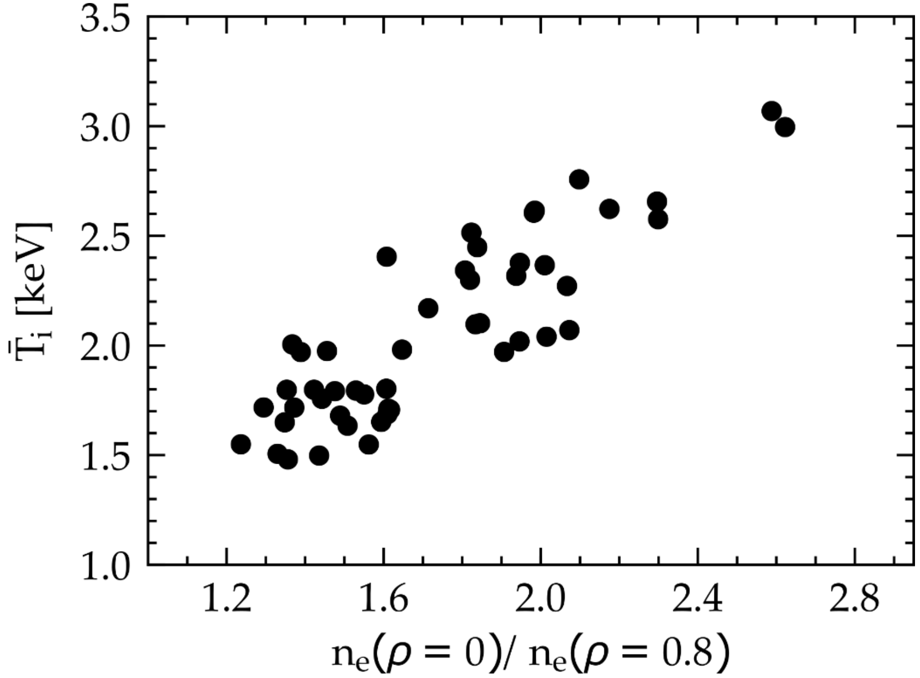


[S. Bozhenkov, EPS 2019, Milan]

sample density profile modification



peak T_i vs. density peaking factor (pellets)

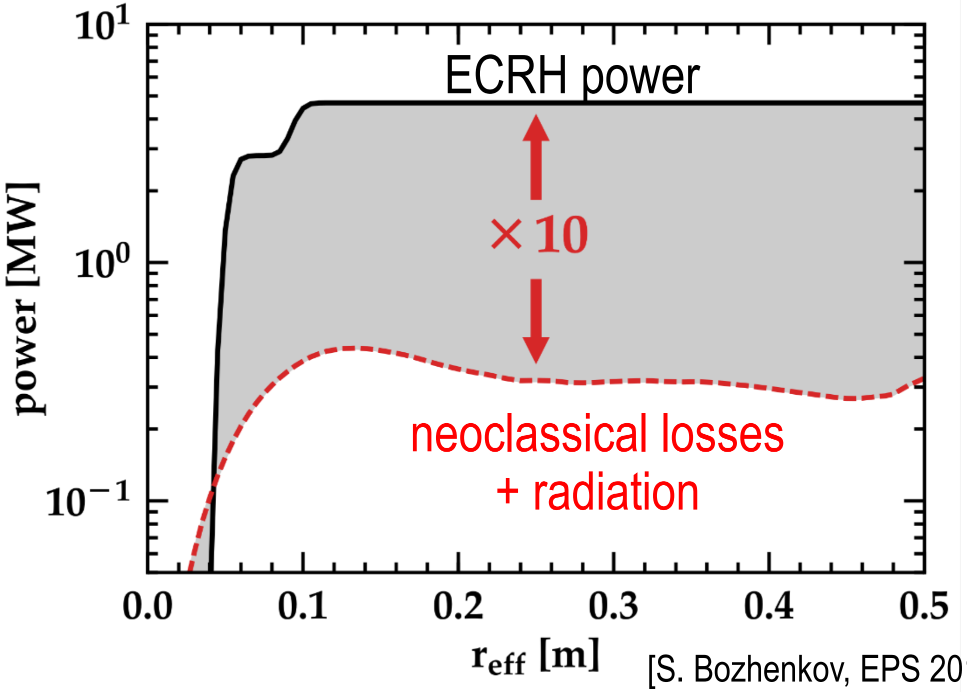


[S. Bozhenkov, NF **60** (2020)]

- **ECRH + flat density profiles:** ion temperature limited to $T_i \lesssim 1.6$ keV in accessible n_e and P_{ECRH} parameter space
  - large shortfall compared to neoclassical expectations (w/ moderate anomalous losses)
- **ECRH + peaked density profiles:** highest W7-X ion temperatures and β achieved **transiently** w/ E_r and shear increase
  - ion temperature maximum scales with density gradient

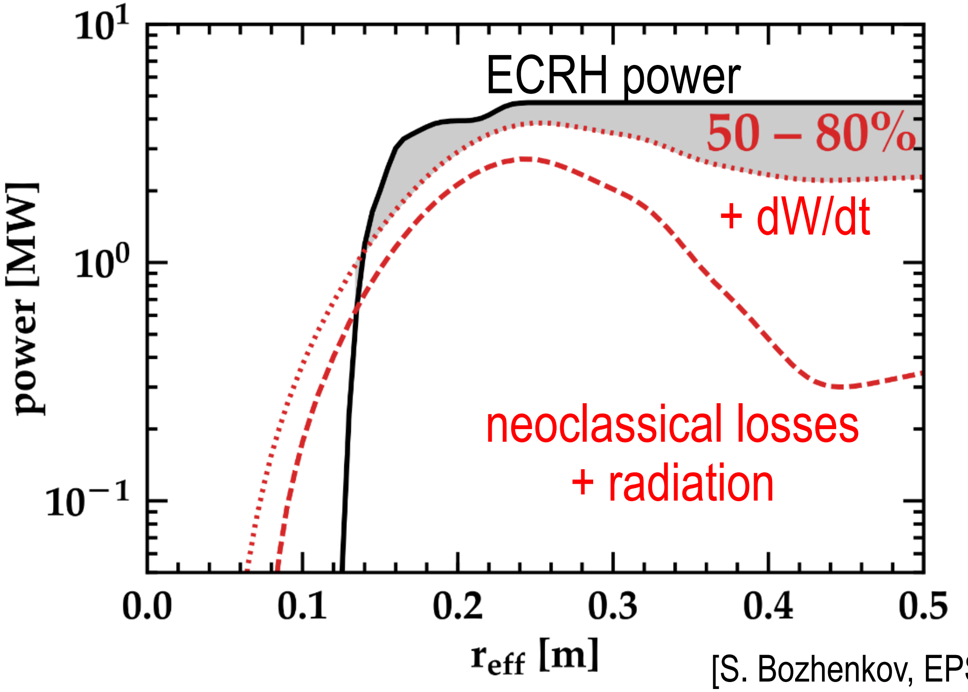
Core density profile control: pellet fueling power balance

power balance for flat density profiles



[S. Bozhenkov, EPS 2019, Milan]

ECRH-heated, pellet-fueled



[S. Bozhenkov, EPS 2019, Milan]

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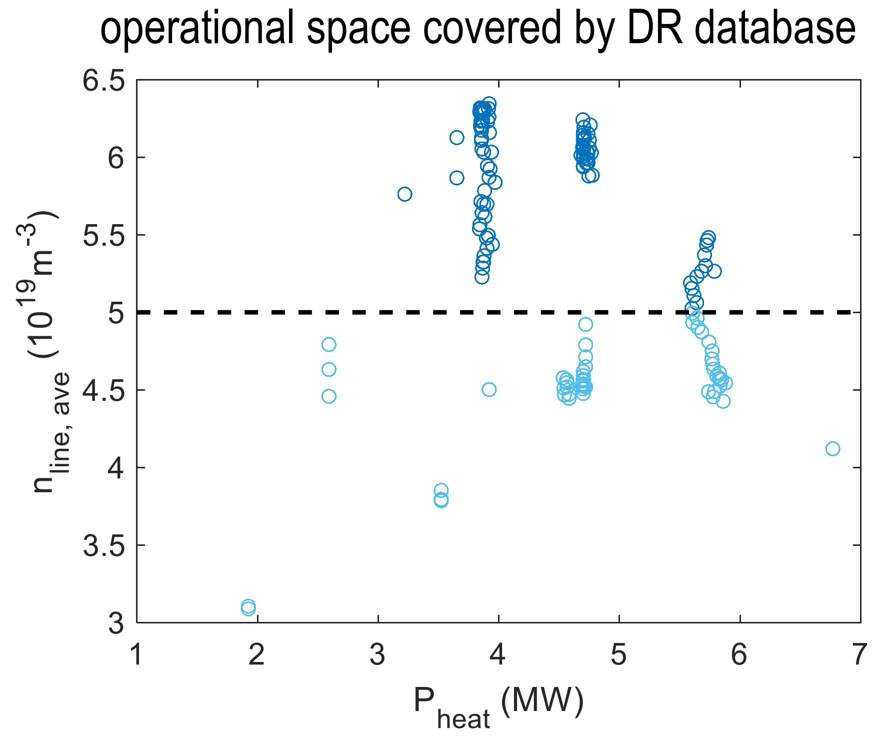
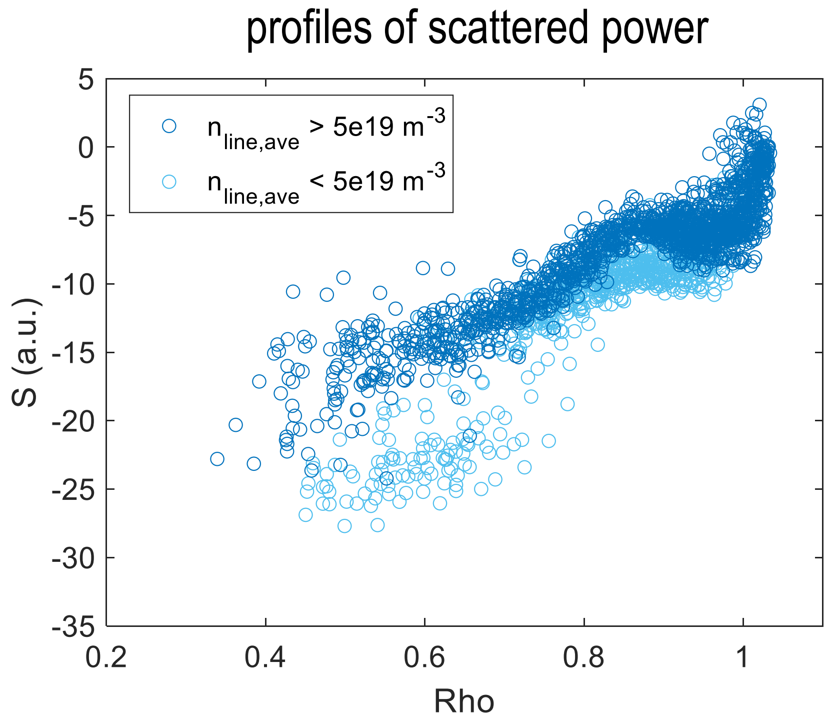
- **ECRH + peaked density profiles:** highest W7-X ion temperatures and β achieved **transiently** w/ E_r and shear increase
  - ion temperature maximum scales with density gradient
- **E_r effects on turbulence:** see talk by T. Estrada on Feb 25 in this TG

Outline

- radially resolved density turbulence regimes in **ECH discharges**
- turbulence during high-performance **pellet fueling experiments**
- core density peaking and turbulence response in **pure NBI discharges**
- **NBI + ECH mix** and density flush-out
- turbulence and impurity transport during **post-NBI edge profile changes**
- edge profile by solid material injections: **massive LBO and Boron dropper**
- summary: **general gradient dependencies**

ECRH discharges, gas puffing



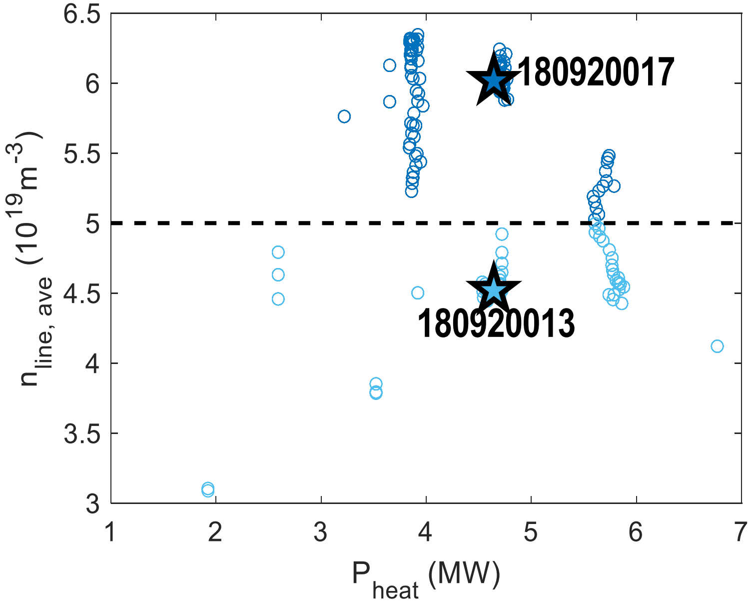


fluctuation profiles from V-band Doppler reflectometer (DR), covering most of OP1.2b operational space:

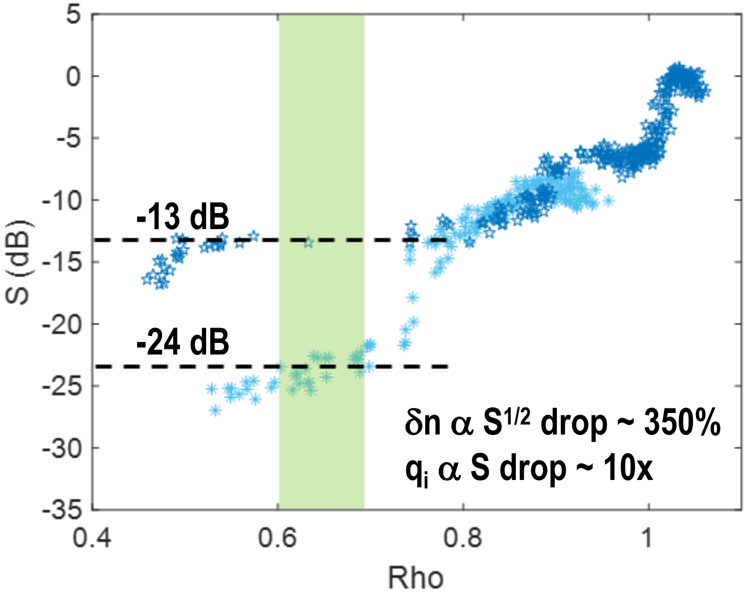
- **generally:** edge region dominates fluctuation power, decreases towards core, **profiles similar**
- **a fraction of the discharges:** strong **suppression of fluctuations towards the core** ($\rho < 0.7$).
- seems to depend on average density, with threshold value $n_{e,ave} \sim 5\ 10^{19}\ m^{-3}$.

Fluctuation suppression in low n_e, ECRH scenarios

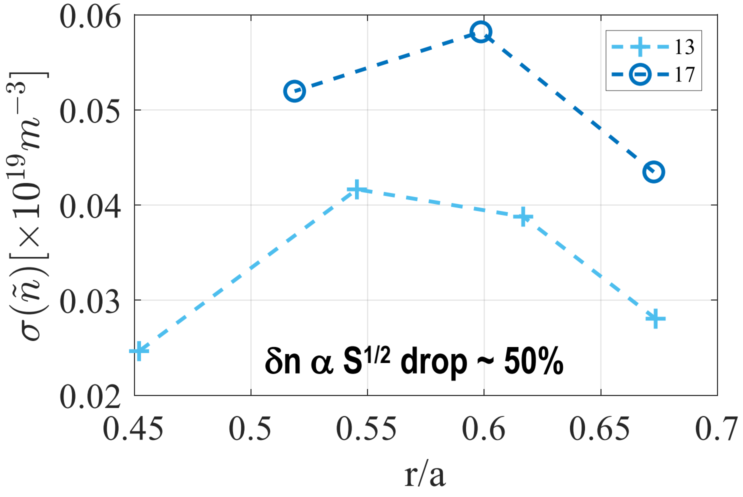
operational space covered by DR database



fluctuation profiles



EUTERPE simulations: fluctuation profiles (non-linear, flux surface, adiabatic electrons)



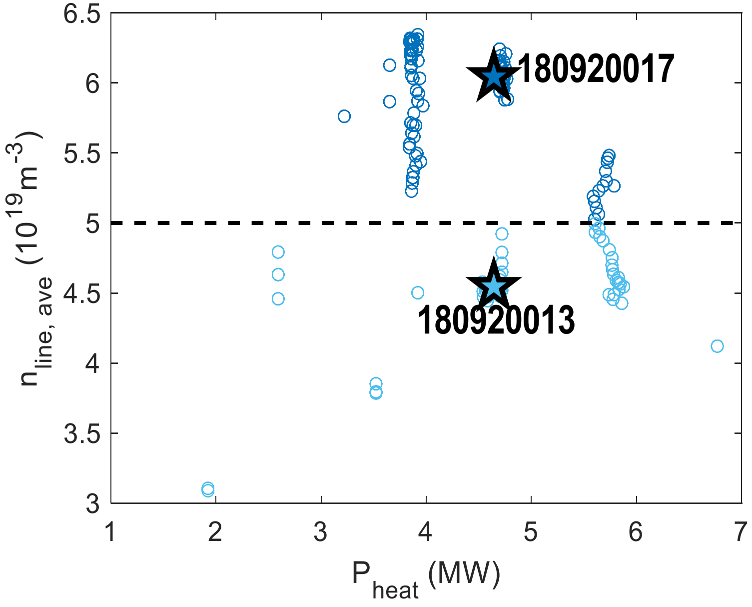
[E. Sánchez, priv. comm.]

two representative shots above and below threshold:

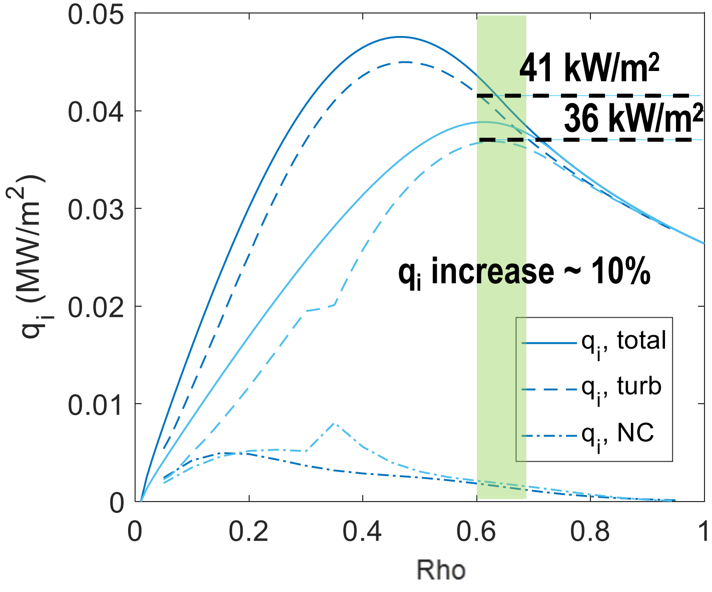
- DR signal power S falls by an order of magnitude at ρ = 0.6-0.7
- corresponds to x3 drop in fluctuation amplitude δn and x10 drop in heat flux q_i
- EUTERPE nonlinear simulations show moderate drop in fluctuations (~50%), but almost no variation in q_i.
- power balance indicates a small decrease (~10%) in turbulent heat flux in the same region.

Fluctuation suppression in low n_e, ECRH scenarios

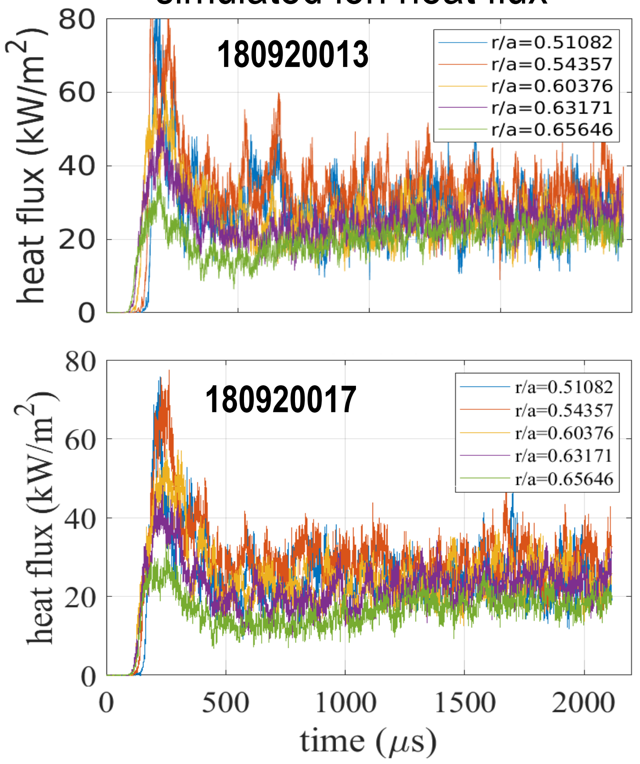
operational space covered by DR database



power balance



simulated ion heat flux



[E. Sánchez, priv. comm.]

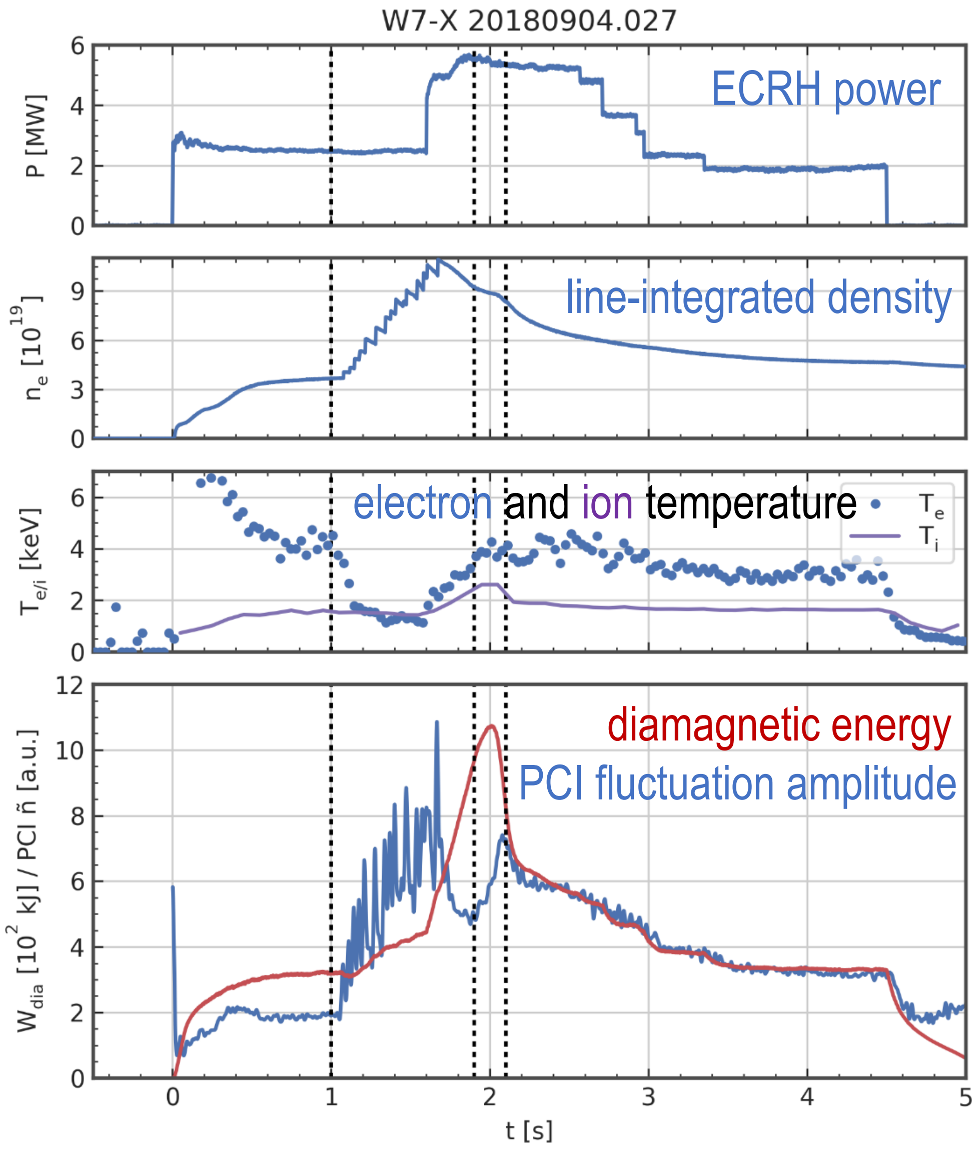
two representative shots above and below threshold:

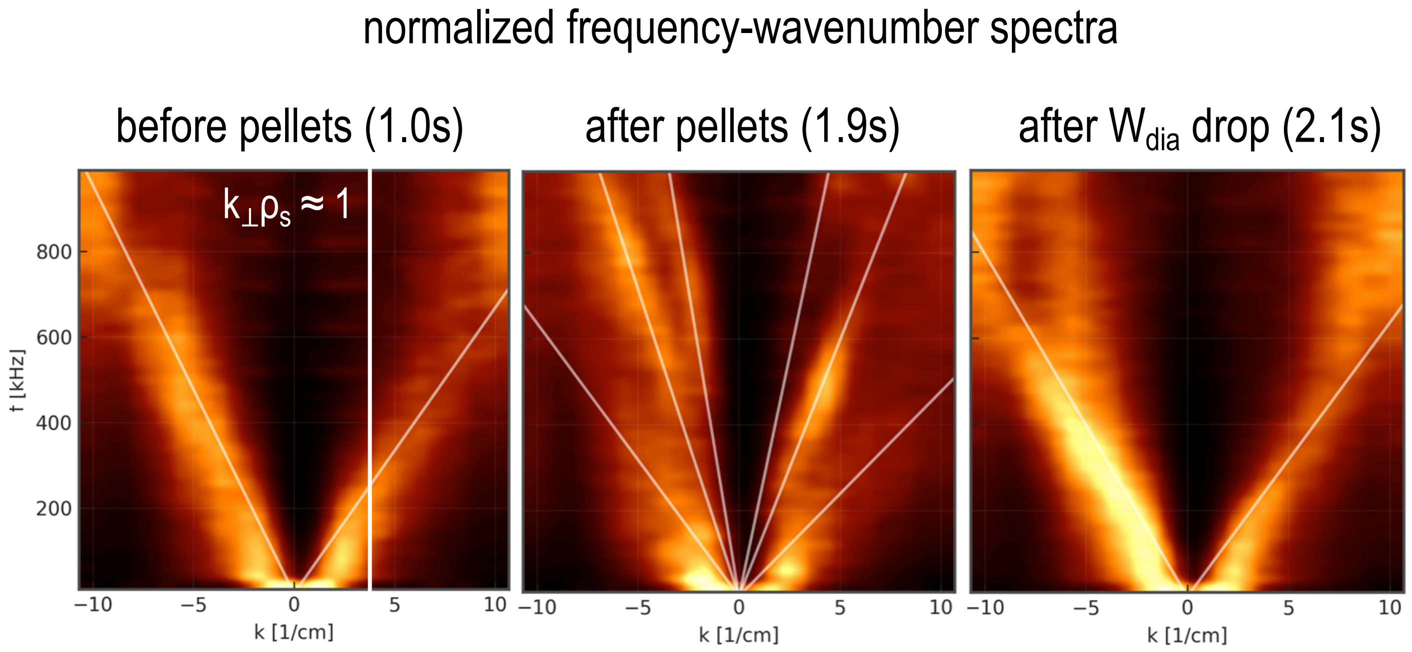
- DR signal power S falls by an order of magnitude at ρ = 0.6-0.7

The observed change in fluctuations in $k_\perp \rho_i$ ~ 1 is not associated to a change in ion turbulent transport.

- power balance indicates a small decrease (~10%) in turbulent heat flux in the same region.

Core density profile control: Pellet fueling (PCI)

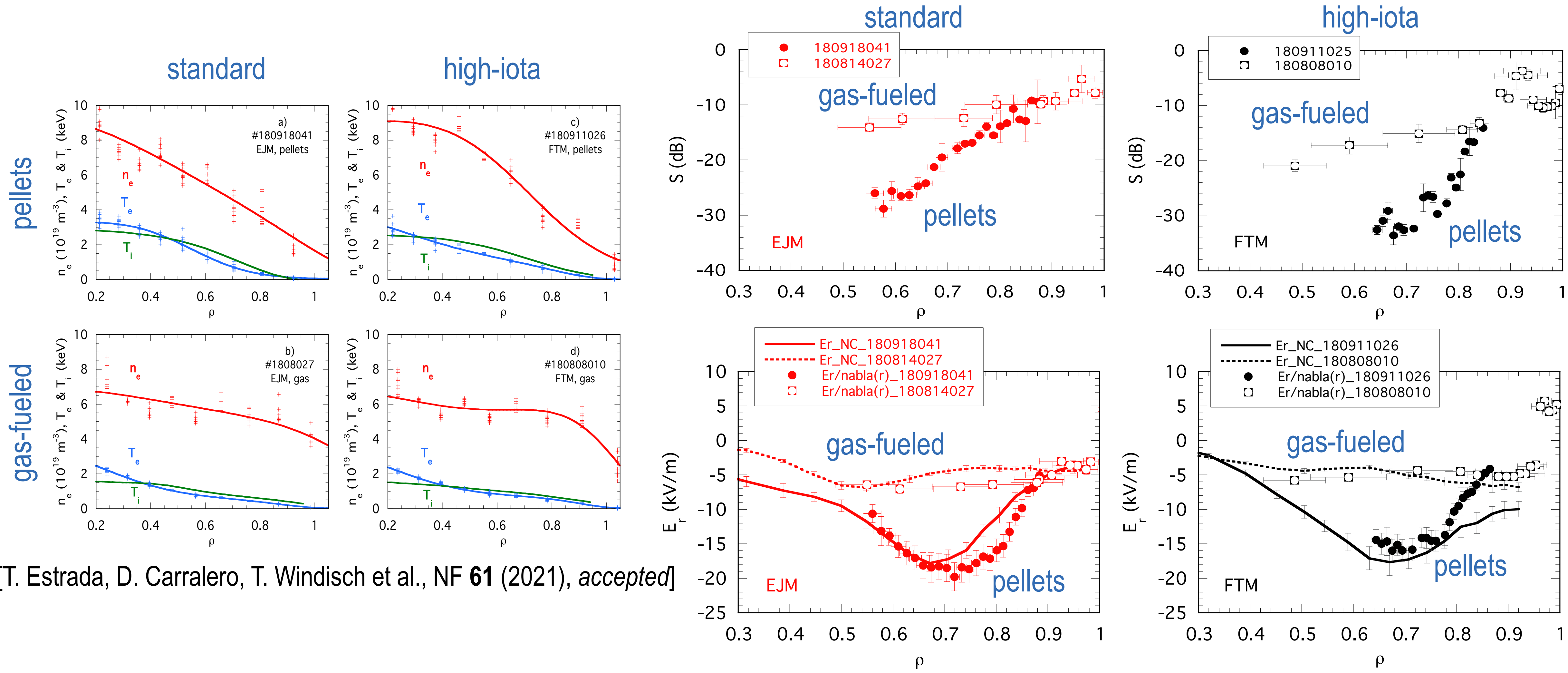




- rapid increase in W_{dia} observed after pellet injection (together with T_e, T_i)
- PCI **fluctuation amplitude significantly reduced** during W_{dia} increase
- during reduced fluctuation phase: **multiple phase velocities observed**
- regular fluctuations and k-f-spectra recovered during W_{dia} drop

[A. v. Stechow *et al.*, Phys. Rev. Lett. (submitted)]

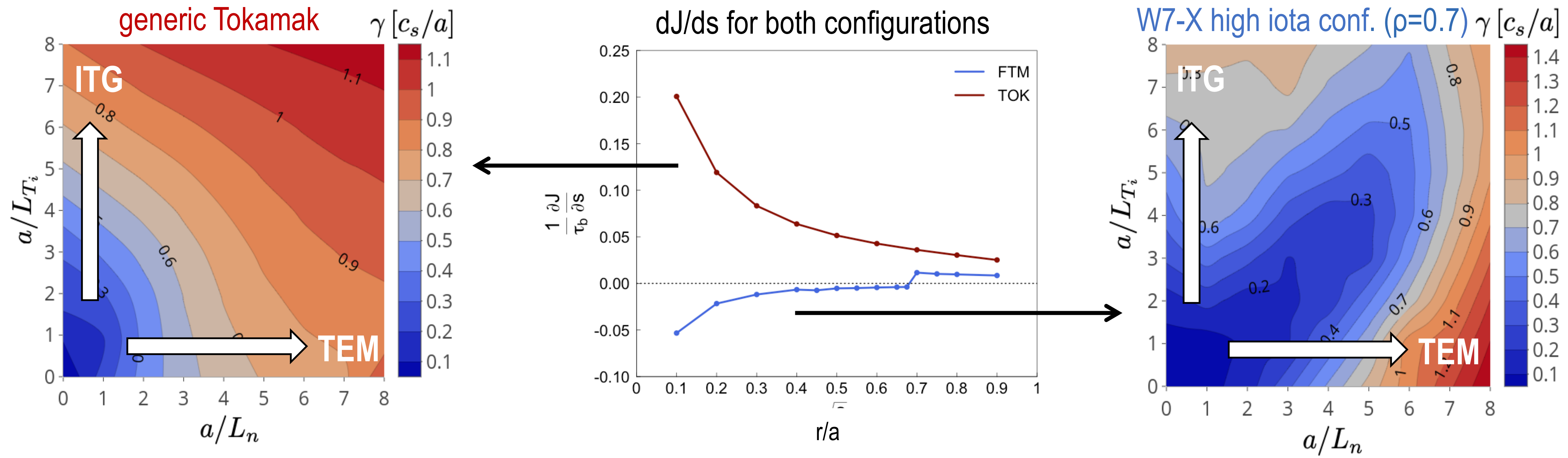
Core density profile control: Pellet fueling (DR)



[T. Estrada, D. Carralero, T. Windisch et al., NF **61** (2021), *accepted*]

- DR Measurements: $\tilde{n}_e$ drops during the post-pellet enhanced confinement phase in the range r ≈ 0.6-0.8
- more pronounced in high iota than standard config.

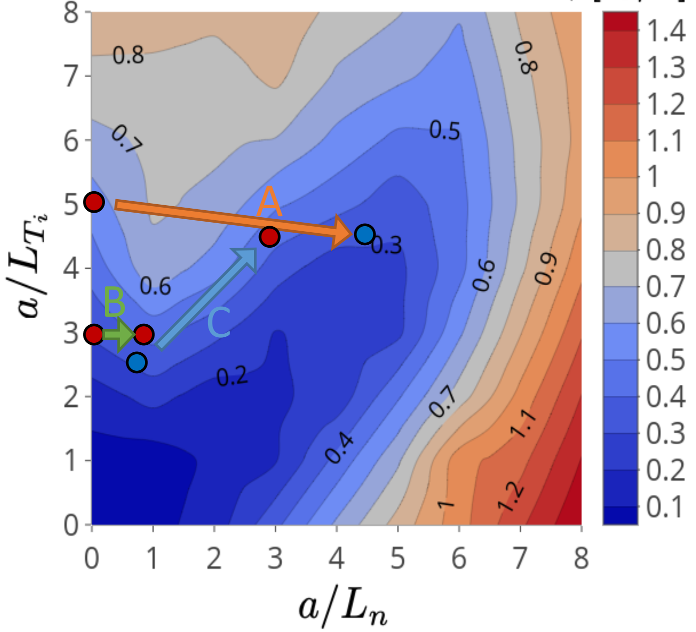
Core density profile control: linear simulations



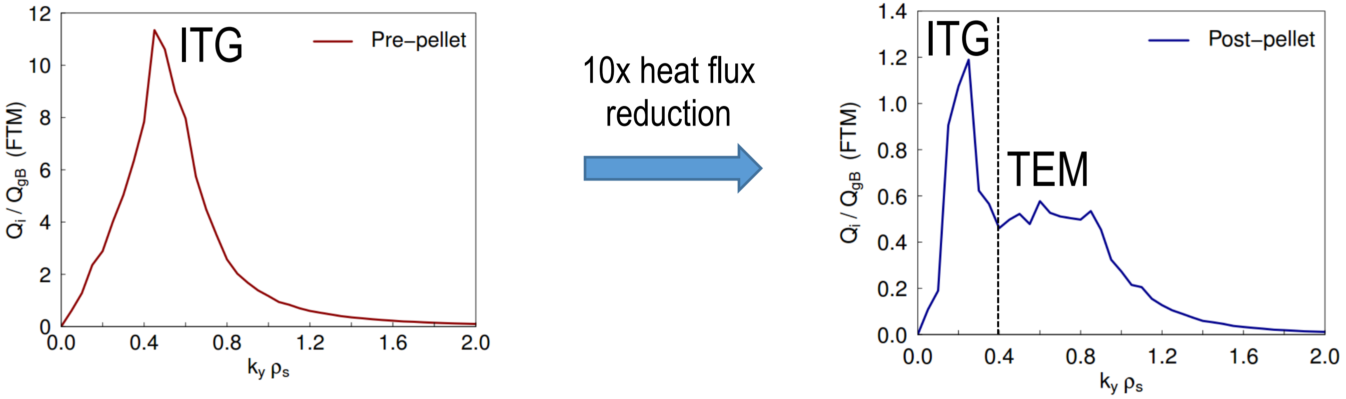
- linear GENE runs for a large set of ∇T and ∇n in different magnetic geometries (w/ T_i=T_e, E_r=0, β=0)
  [Alcusón, Xanthopoulos *et al.*, PPCF **62** (2020)]
- W7-X: **stability "valley" where $a/L_T \approx a/L_n$**
- gyrokinetic model: Stabilty region for W7-X derives from maximum-J property: dJ/ds < 0
  [Proll *et al.*, Phys. Rev. Lett. **108** (2012)] and [Plunk *et al.*, J. Plasma Phys. **83** (2017)]
- with max-J: **(1) ITG stabilizes quickly** with ∇n and **(2) TEM respons weakly** to ∇n
- Linear EUTERPE runs confirm that high iota configuration features higher γ than standard
  [T. Estrada *et al.*, NF **61** (2021), accepted]

Core density profile control: nonlinear simulations

linear growth rates:
(here: H_2, high iota, ρ=0.7)

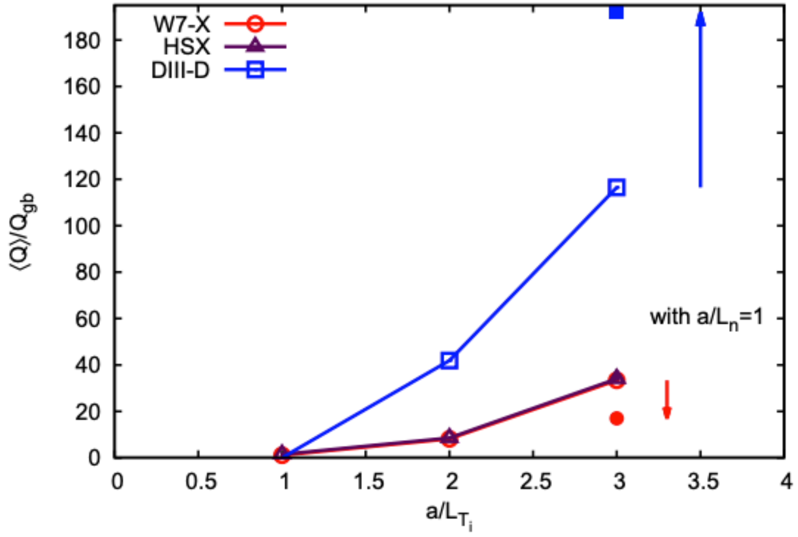


A: nonlinear ion heat flux spectrum (high iota conf., ρ=0.7)



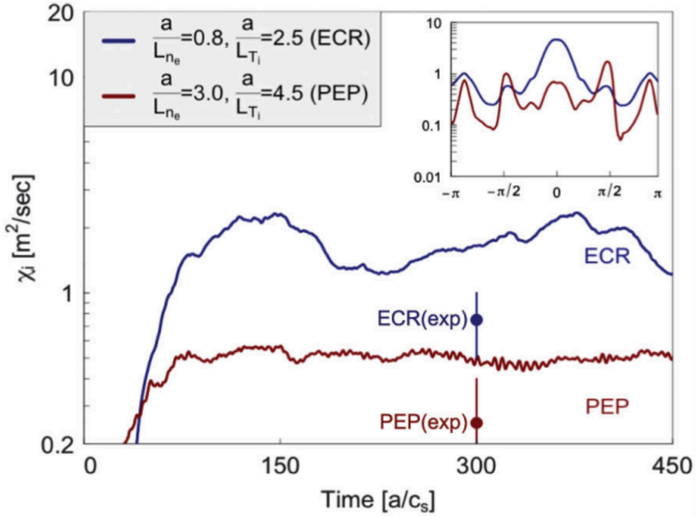
[GENE simulations by P. Xanthopoulos]

B: nonlinear heat flux (high mirror conf., ρ=0.7)



[Proll *et al.*, to be submitted to JPP]

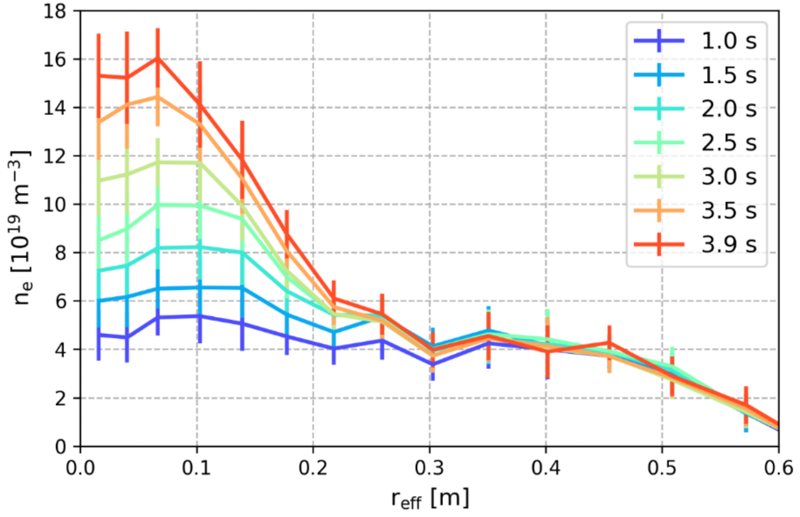
C: ion heat diffusivities (standard conf., ρ=0.63)



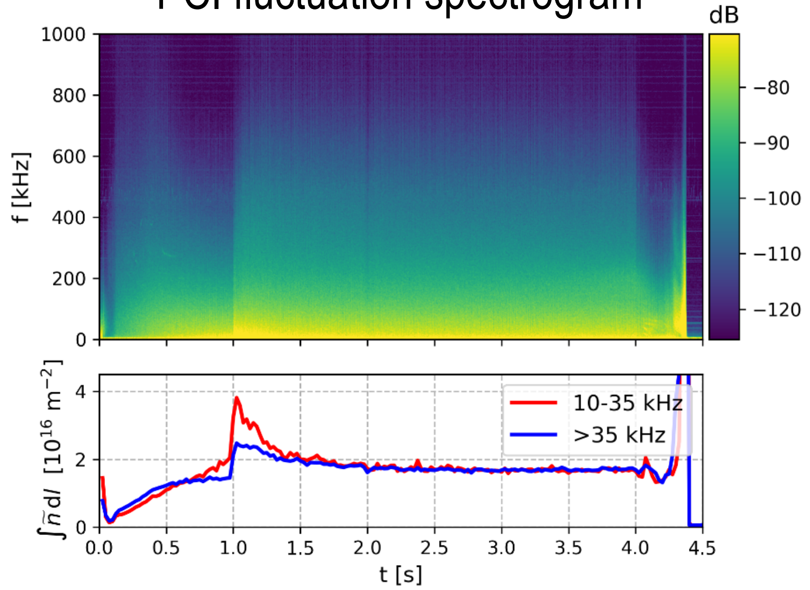
[Xanthopoulos *et al.*, Phys. Rev. Lett. **125** (2020)]

Core density profile control: pure NBI (PCI)

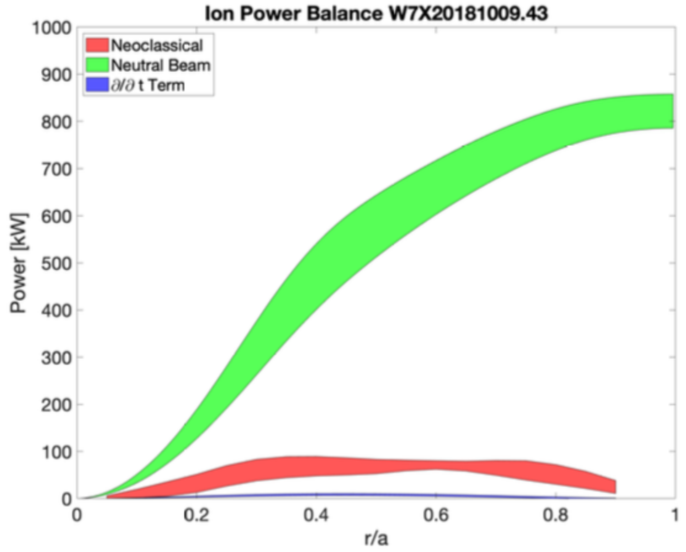
example density profiles (20181009.021)

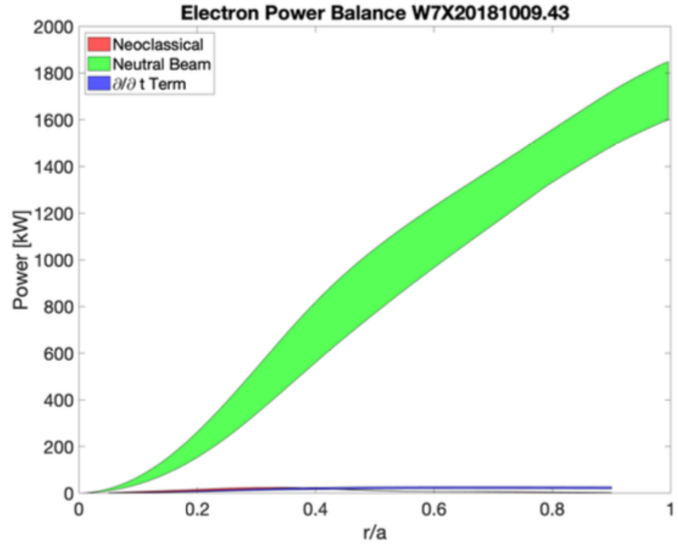


PCI fluctuation spectrogram



BEAMS3D + NEOTRANSP power balance

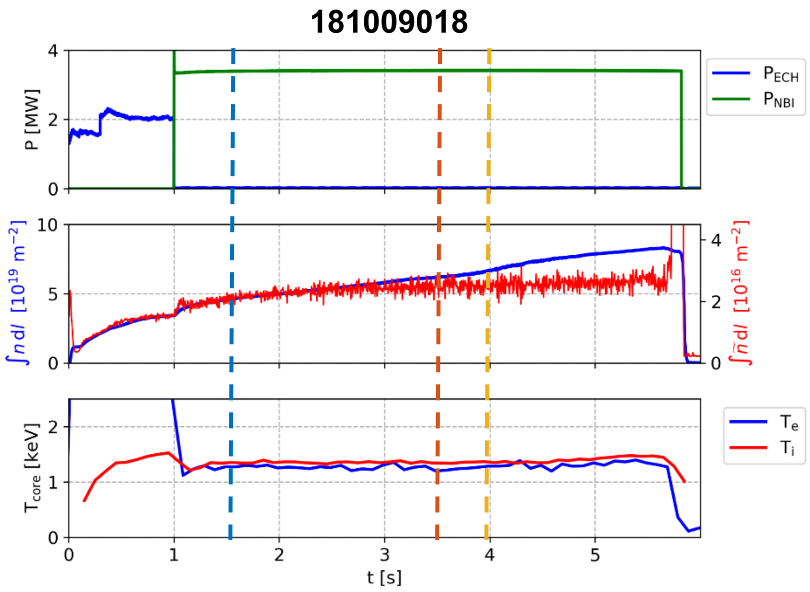


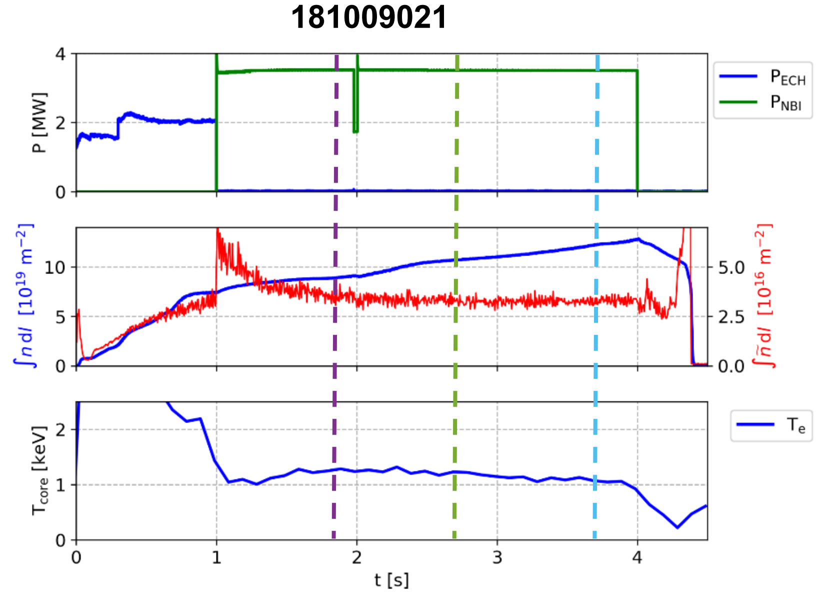


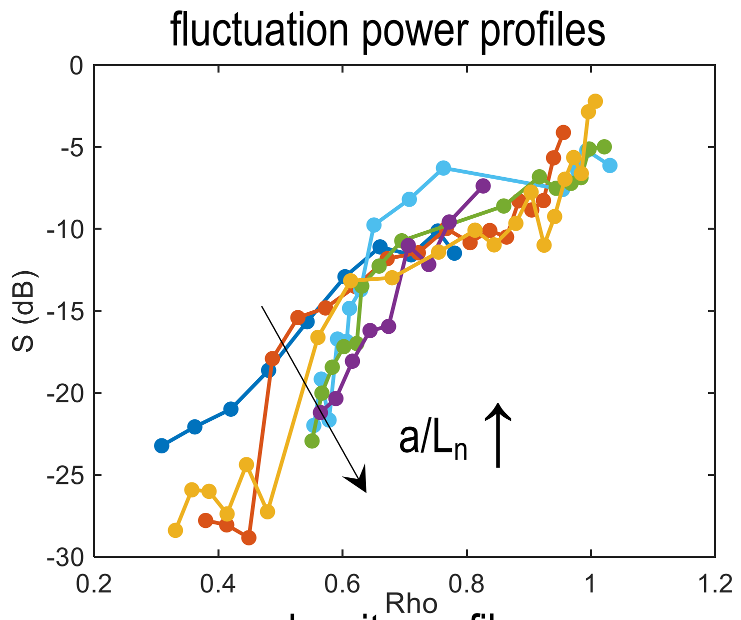
[S. Lazerson *et al.*, in preparation for NF]

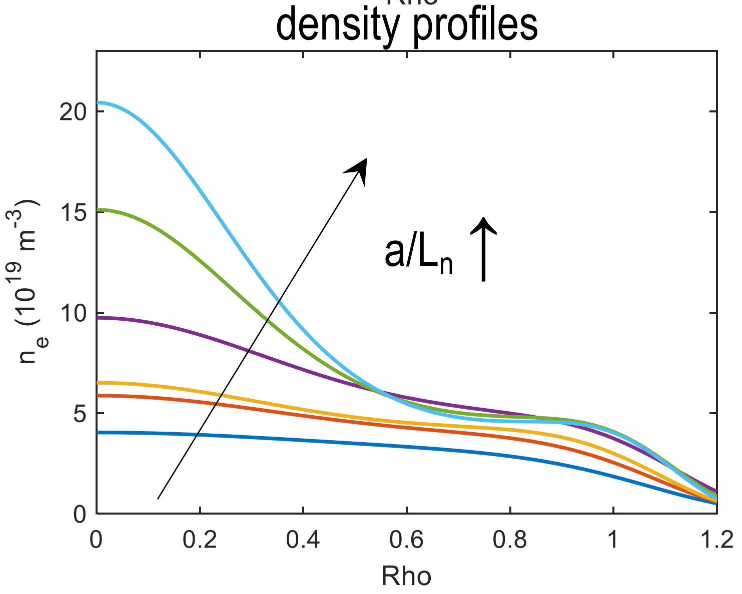
- sharp **increase of density gradient within half radius**
- r/a > 0.5 unchanged from ECH case
- no ion temperature increase
- **power balance shows no time variation**, small neoclassical transport
- **PCI fluctuations largely unmodified** by core gradients
- some programs: intermittent low-f ñ (f < 10 kHz) with peaking

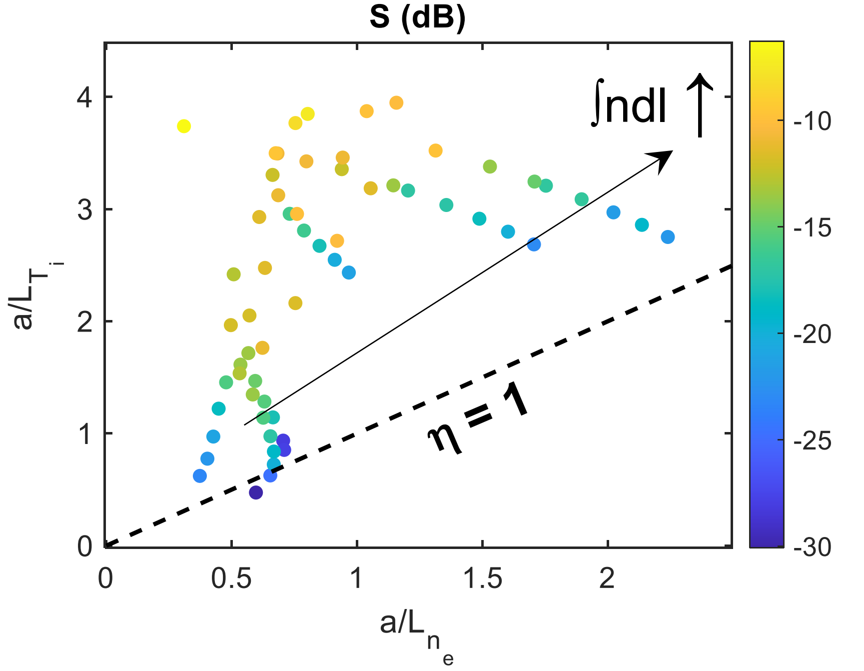
Core density profile control: pure NBI (DR)





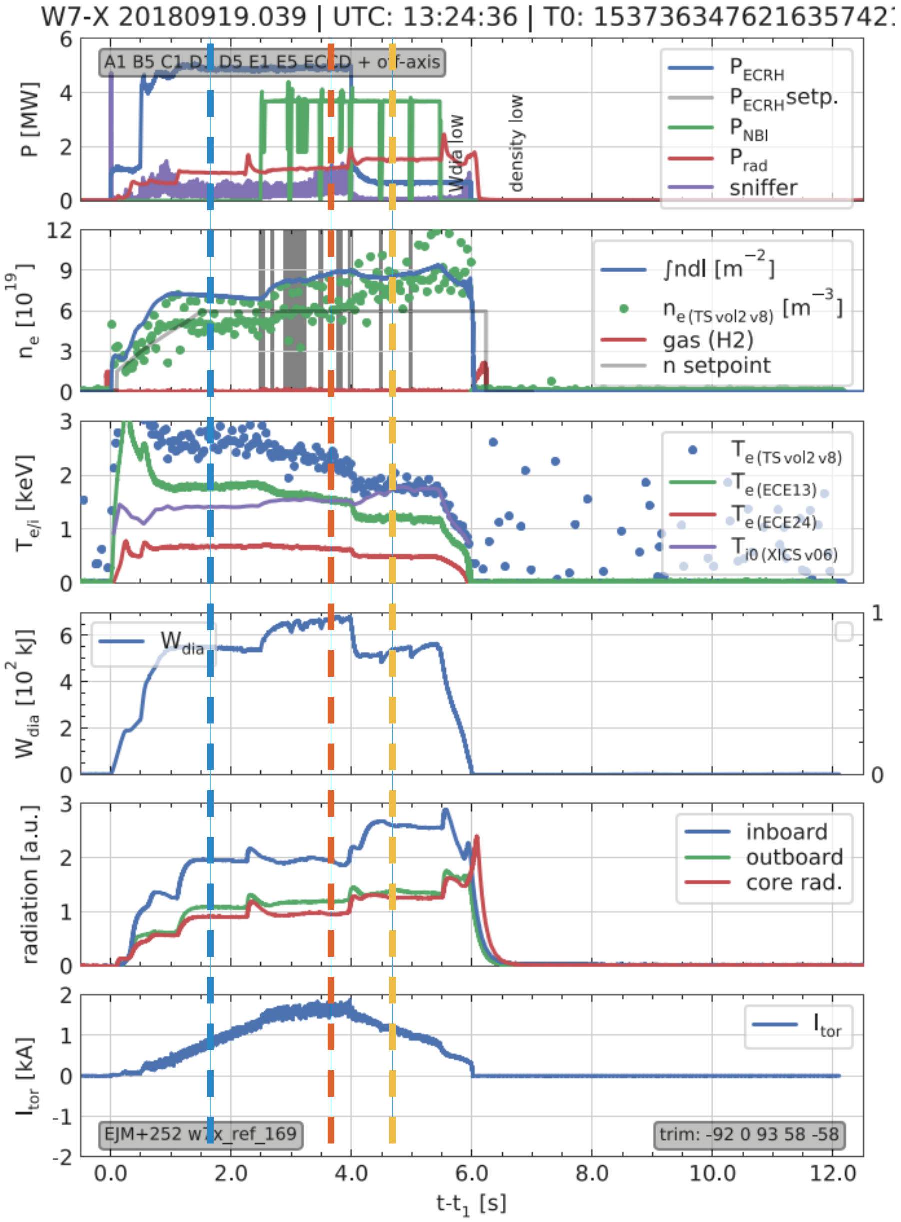


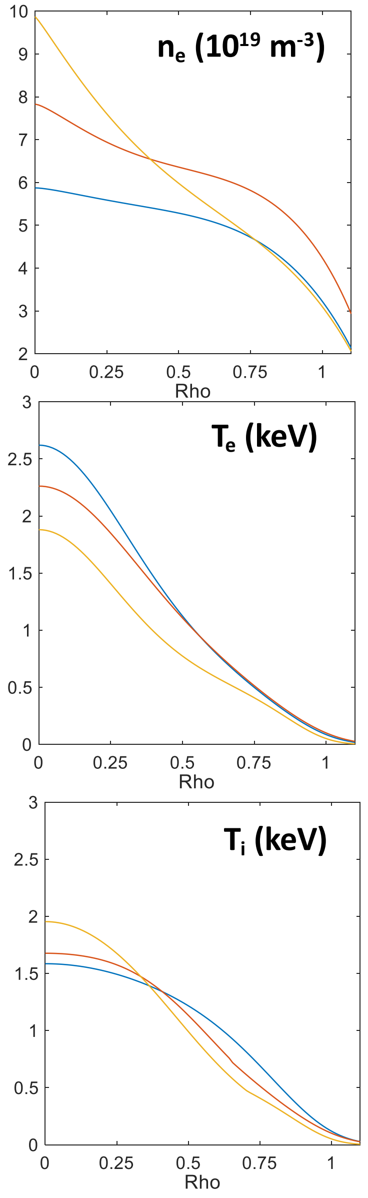


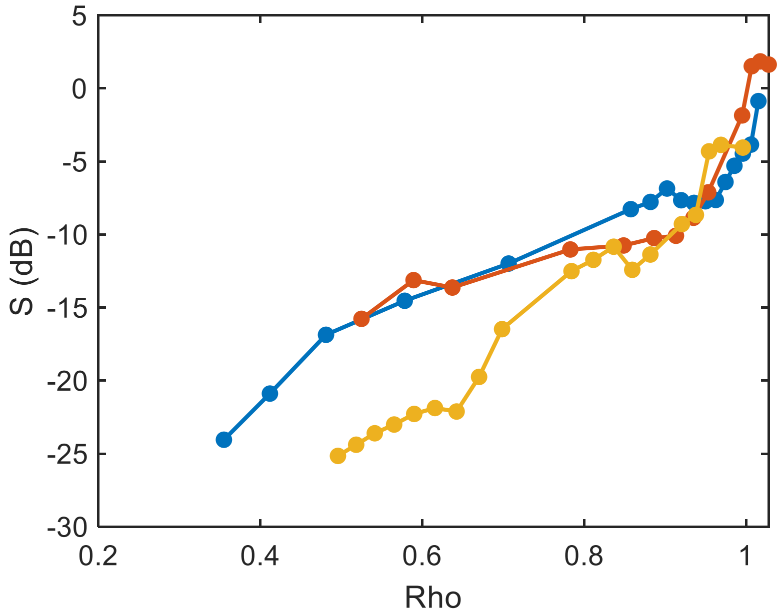


- **drop of core fluctuations** as density gradient increases
- a/L_n increase: $\eta = (a/L_{Ti})/(a/L_n) \rightarrow 1$
- edge unaffected: PCI signal unchanged

Core density profile control: NBI + ECRH

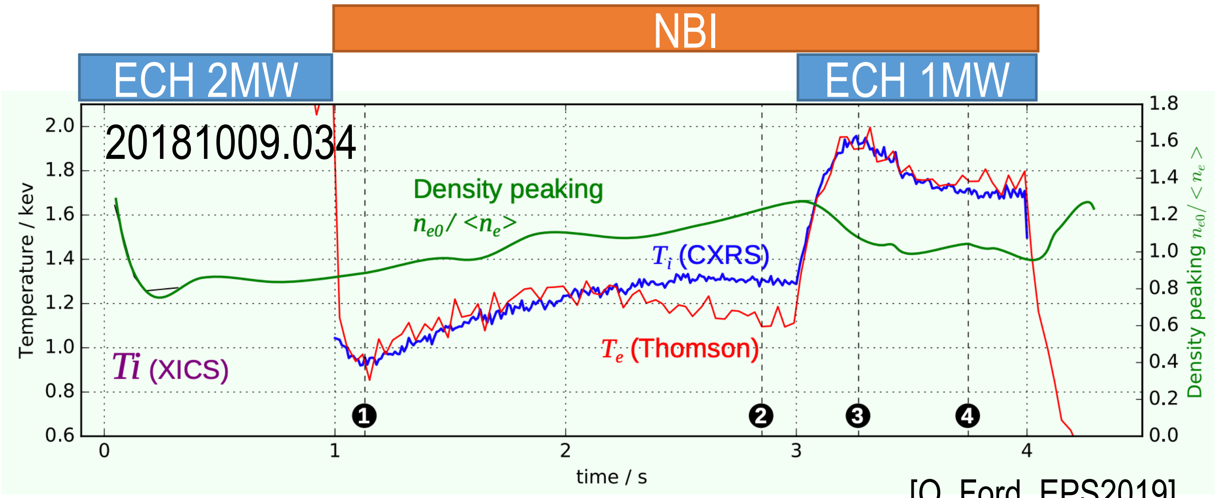




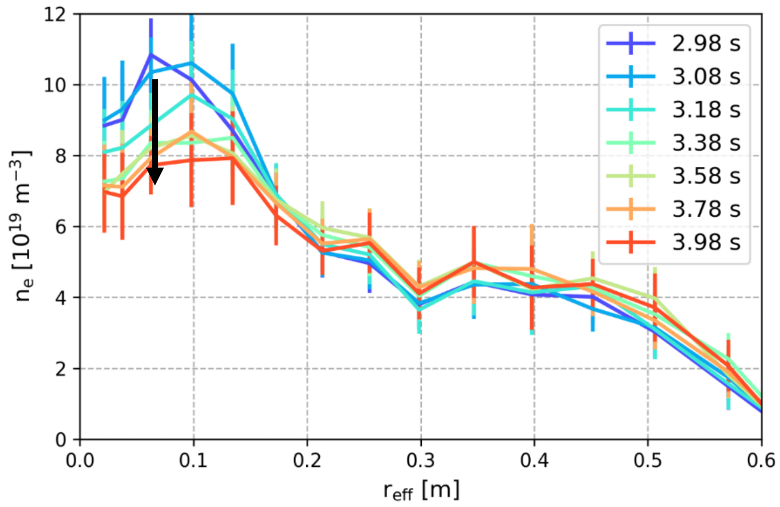


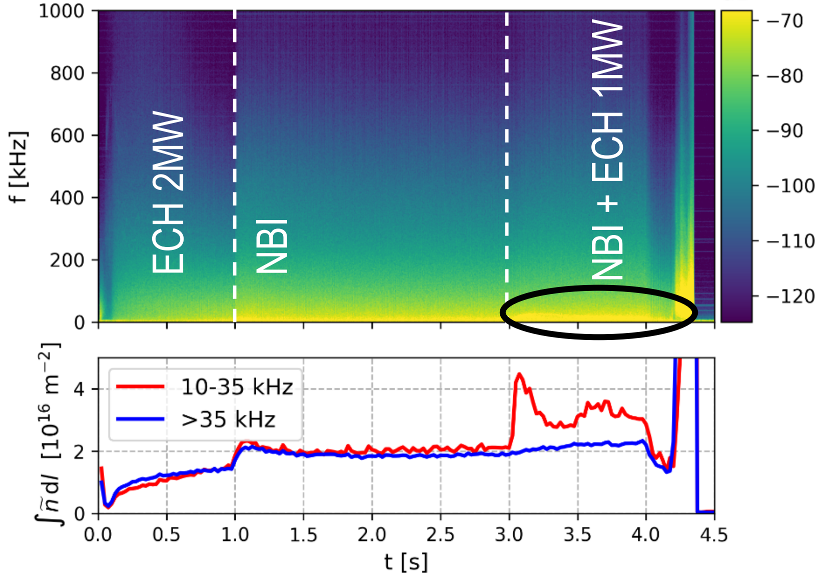
- **first phase:** **typical ECRH** conditions
- **second phase (NBI + 5MW ECH):**
  - slight increase of a/L_{Ti} and overall density
  - $T_{i,core}$ still close to ECRH values.
- **third phase (NBI + 0.7MW ECH):**
  - **a/L_n increased → turbulence suppression**
  - **$T_{i,core}$ ~ 2 keV** is achieved.

Core density profile control: NBI + ECRH



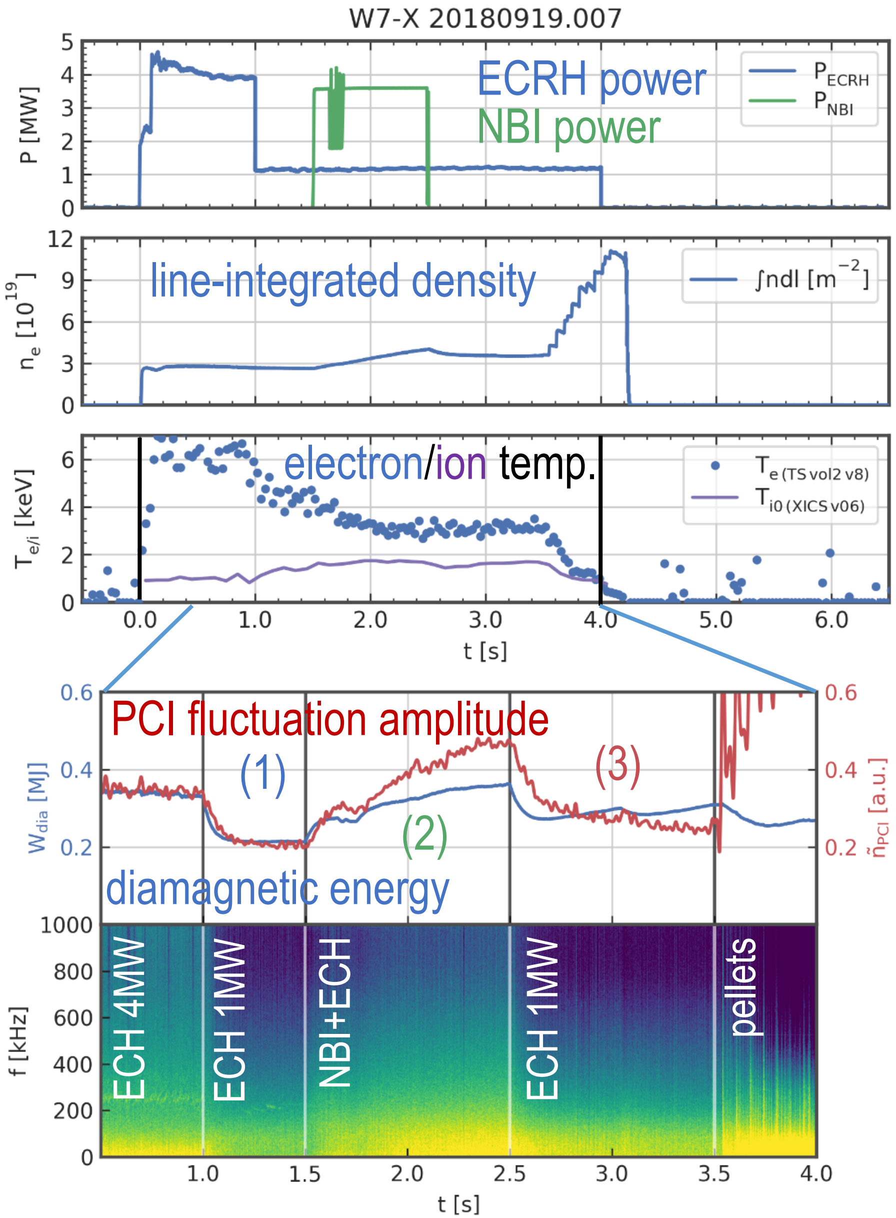
[O. Ford, EPS2019]





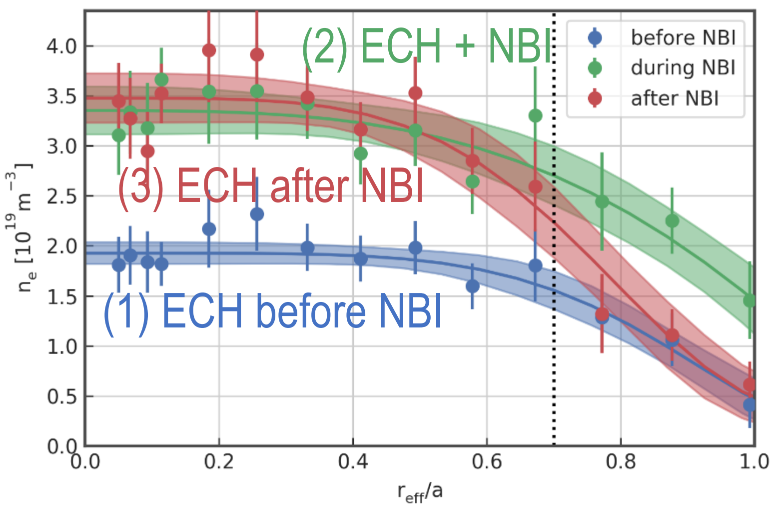
- addition of ECH (1MW O2) to pure NBI plasma: **transient rise in central T_i** to ≈ 2 keV
- **core density reduction** (flush-out?)
- density gradient at ρ ≳ 0.3 remains
- PCI turbulent fluctuations only slightly increased
- low-frequency, **coherent core-localized mode** observed
- turbulence-compatible heating mix, but MHD unstable?

Edge density profile control: modified fueling by NBI

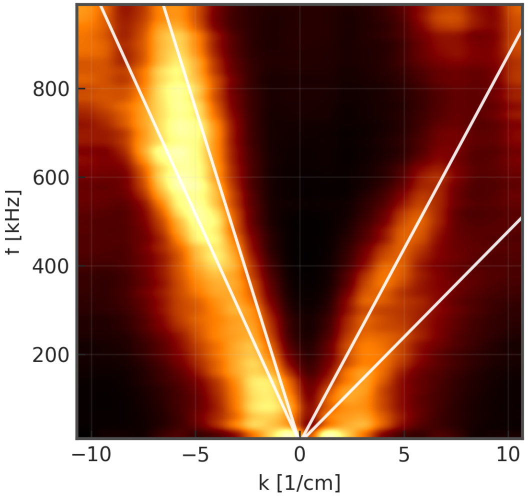


- **NBI + 1MW ECH:**
  - density rise (core + edge), fluctuations increase
- **low ECH power after NBI shutoff:**
  - edge density drops: increased gradient at $\rho \gtrsim 0.5$
  - fluctuations decrease as W_{dia} increases
  - multiple phase velocities in k-f-spectra

density profiles



PCI k-f spectra at (3)



Edge density profile control: modified fueling by NBI

laser blow-off provides radially resolved particle transport measurements

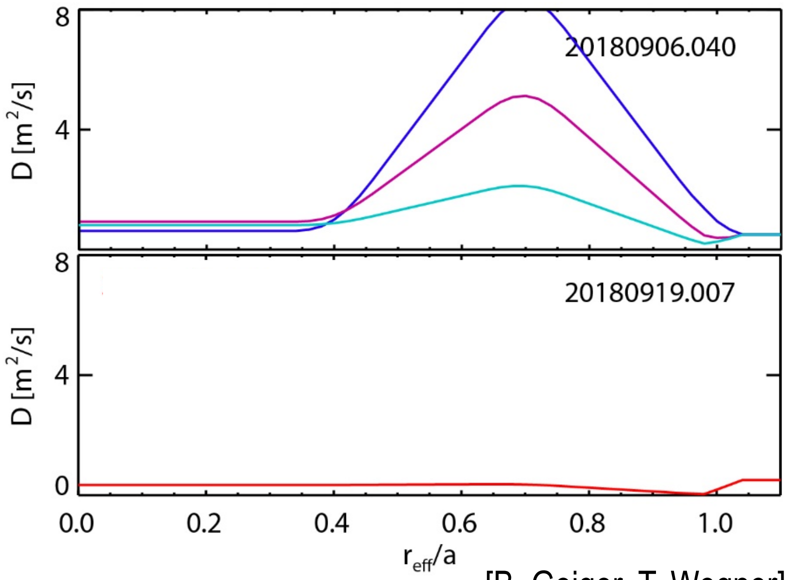
Injection into flat-density ECH-heated plasmas:

- High (>100xNC) anomalous particle diffusion
- Short (50-150 ms) confinement time

Injection after NBI fueling:

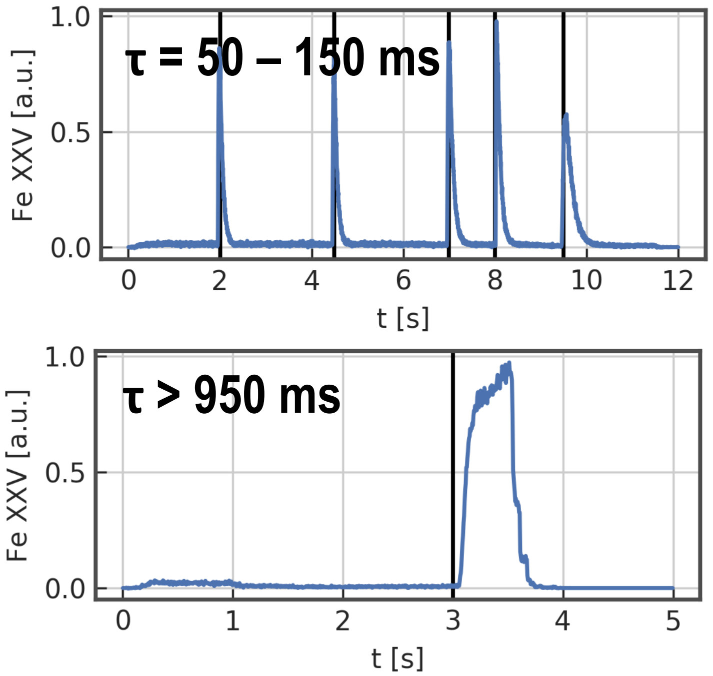
- reduced anomalous particle diffusion
- **extremely long (> 950 ms) confinement time**

NC and anomalous impurity diffusion



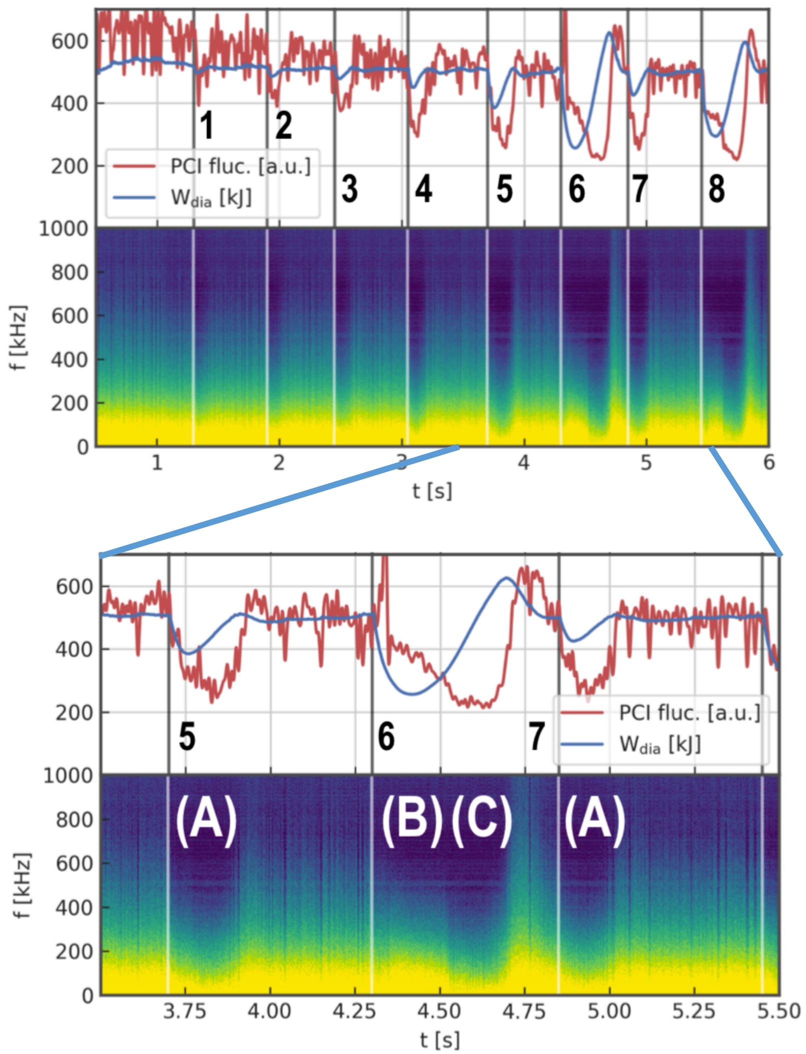
[B. Geiger, T. Wegner]

impurity lifetimes



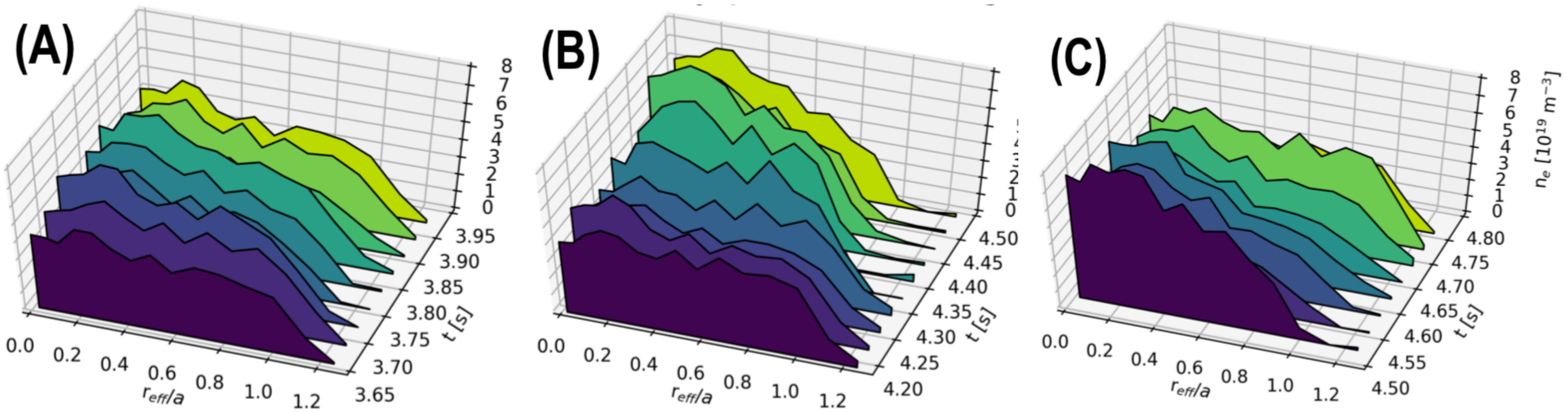
- **Modified density fluctuations are a signature of both reduced heat and particle transport**

Edge density gradient control: LBO



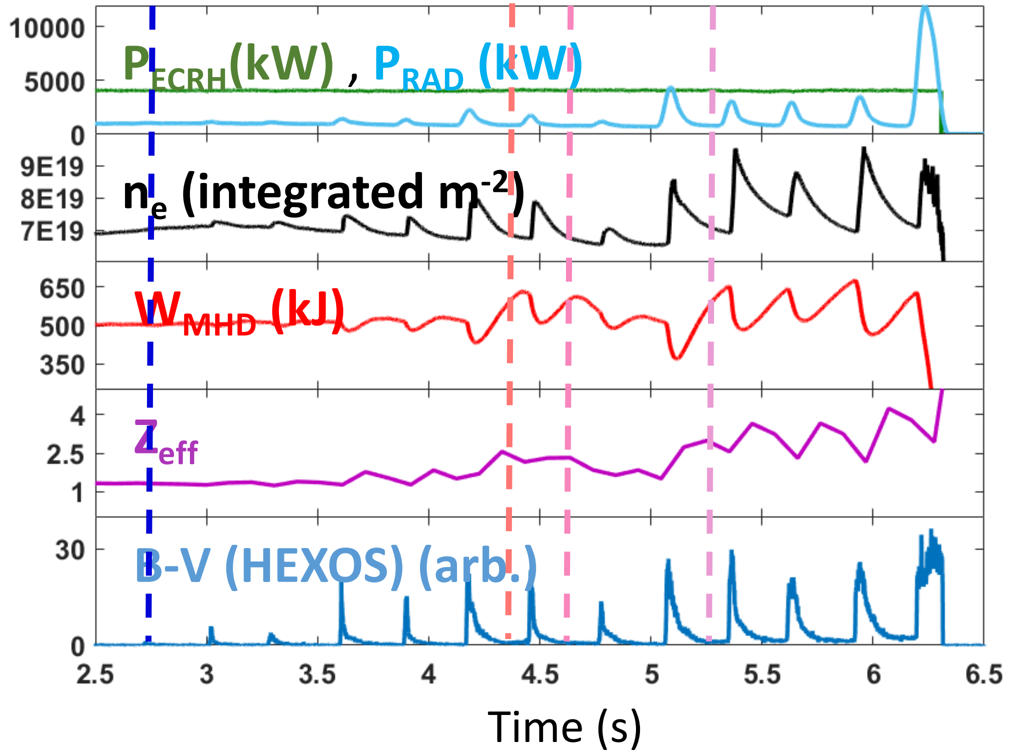
- massive LBO injections temporarily reduce PCI fluctuations
- above threshold mass: **transient W_{dia} and T_i increase**
- time resolved density profiles:
  - plasma shrinks significantly (very high SOL radiation)
  - performance increases with **moderate edge gradients**

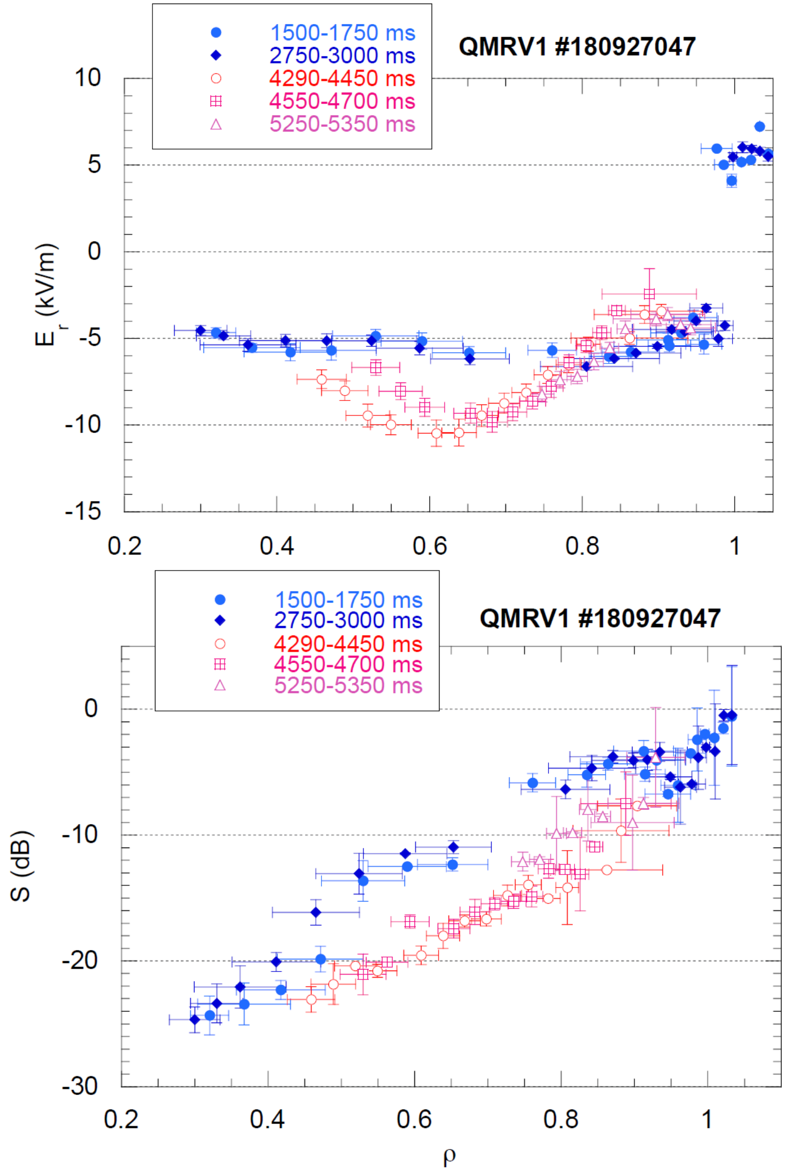
time-resolved density profiles



minor inward shift | total loss of SOL density | SOL "refills"

Edge density gradient control: Boron dropper

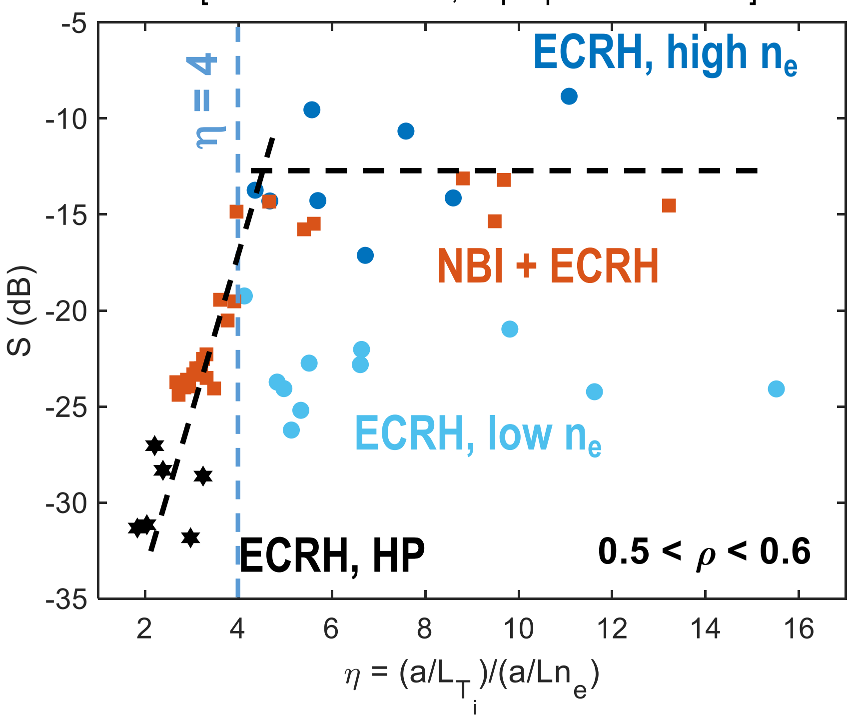


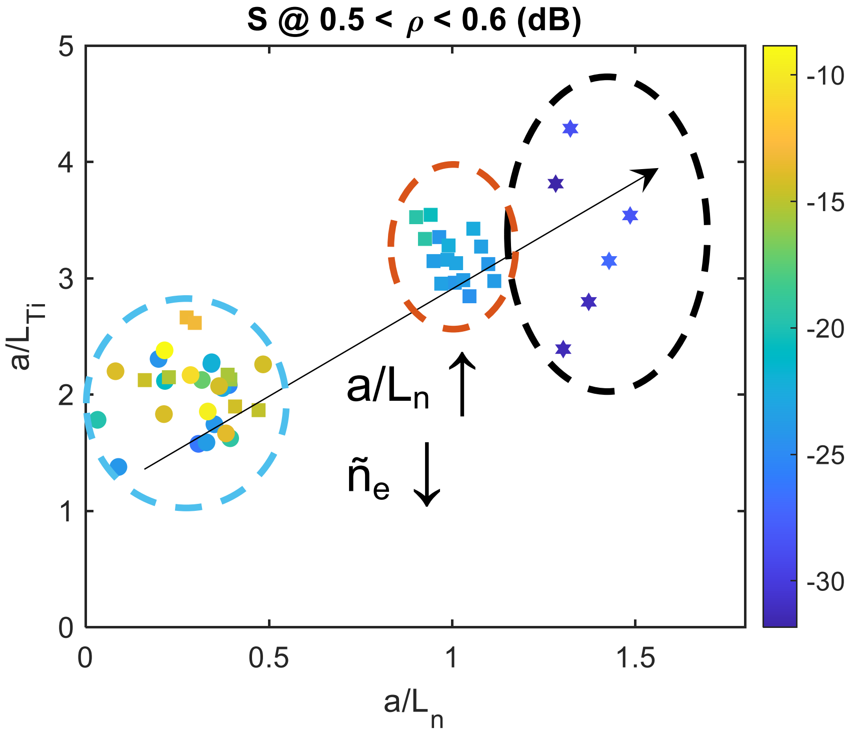


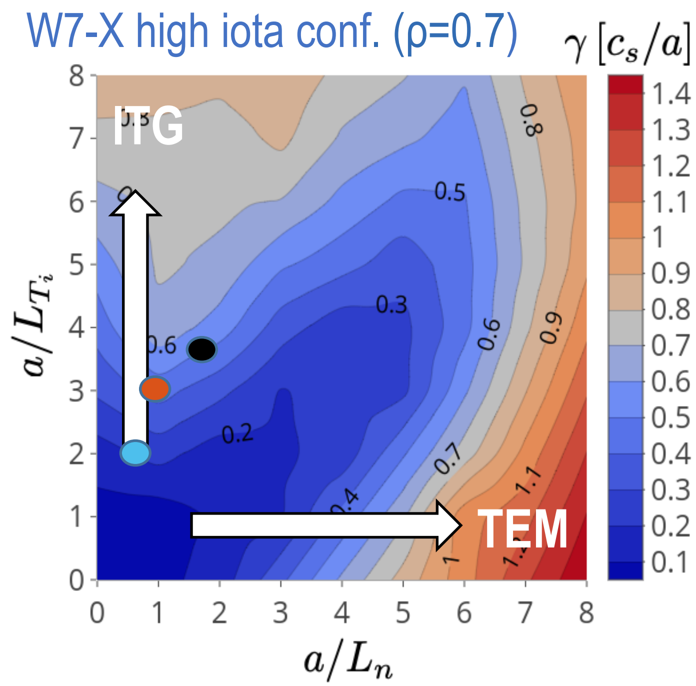
- powder injection modifies kinetic profiles (higher n & T gradients) [R. Lunsford, C. Killer, et al., in preparation for]
- **DR measurements**: increased E_r and E_r shear, decreased $\tilde{n}_e$ observed between pre- and post-injection phase in ρ ~ 0.5-0.8. [T. Estrada, D. Carralero, et al.]
- increase in Z_{eff} may change n_i profiles due to plasma dilution, potentially reducing transport. [See J.M. García-Regaña et al., 9-II-2021]

General profile dependencies

[D. Carralero *et al.*, in preparation for NF]



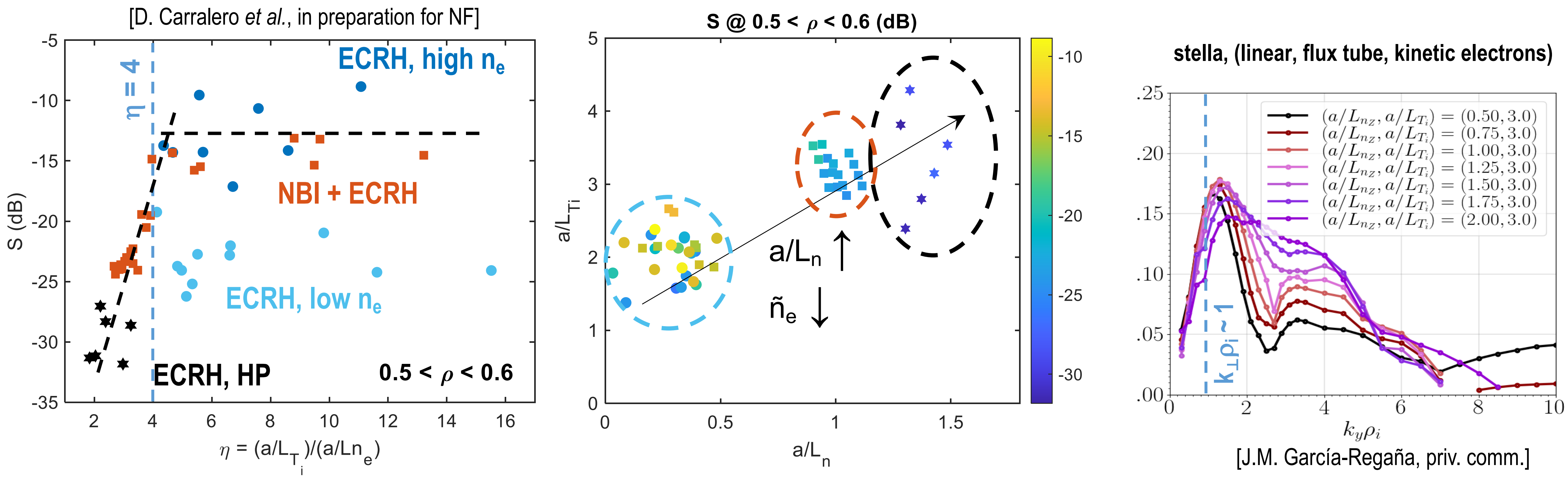




DR database provides general relationships between profiles, fluctuations and performance:

- in most scenarios **core fluctuations follow η**: $\tilde{n}_e$ decreases (mostly) when a/L_n increases and saturates for $\eta > 4$.
- consistent with “stability valley” hypothesis. Comparison of DR data to simulations is complex.

General profile dependencies



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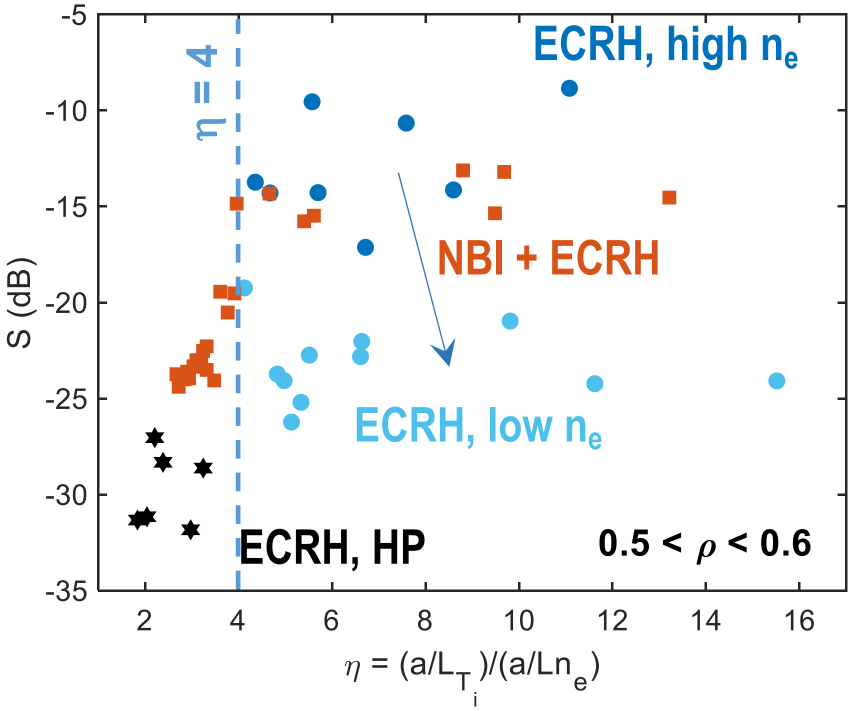
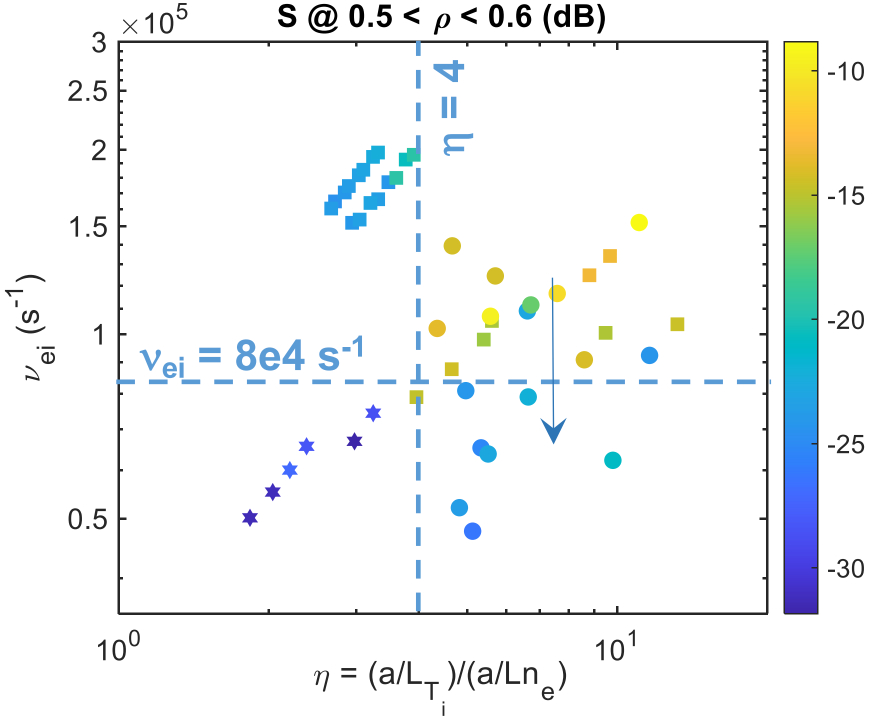
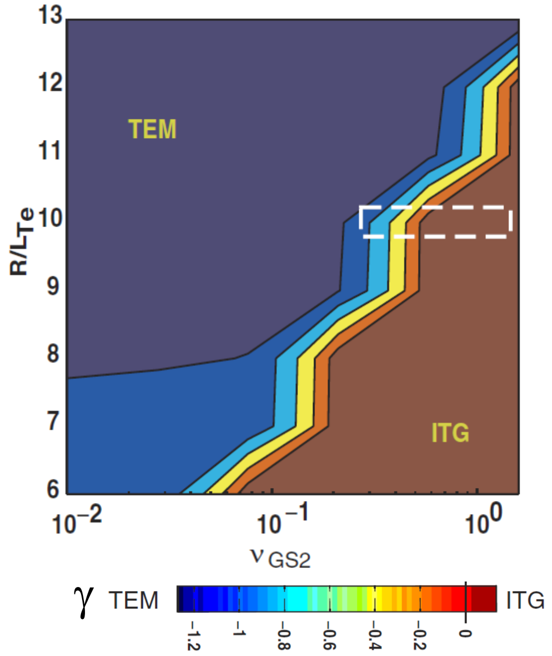




[F. Ryter et al., PRL 95]



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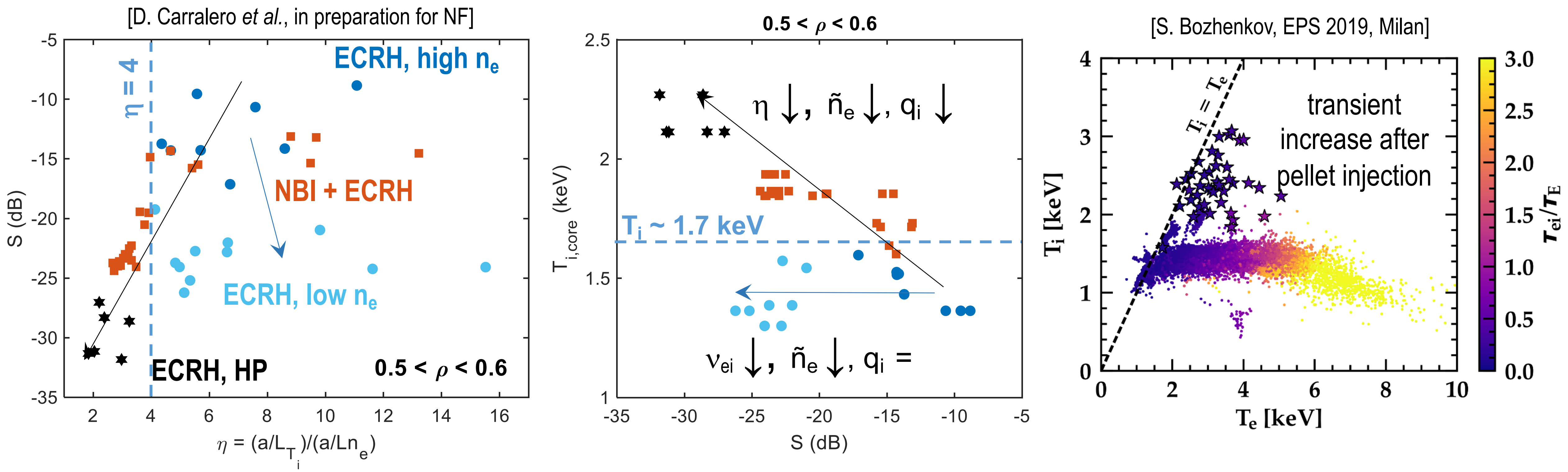

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- consistent with "stability valley" hypothesis. Comparison of DR data to simulations is complex
- for some discharges (low n_e ECRH), **fluctuations drop as ν_{ei} falls** bellow certain value. TEM destabilization?
- **drop in core fluctuations observed whenever T_i limit exceeded**. ν_{ei} suppression does not improve performance.

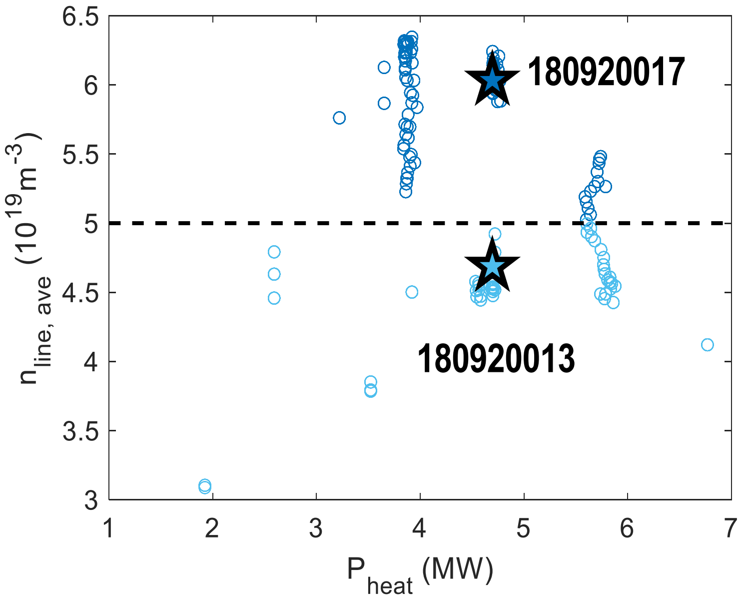
Summary

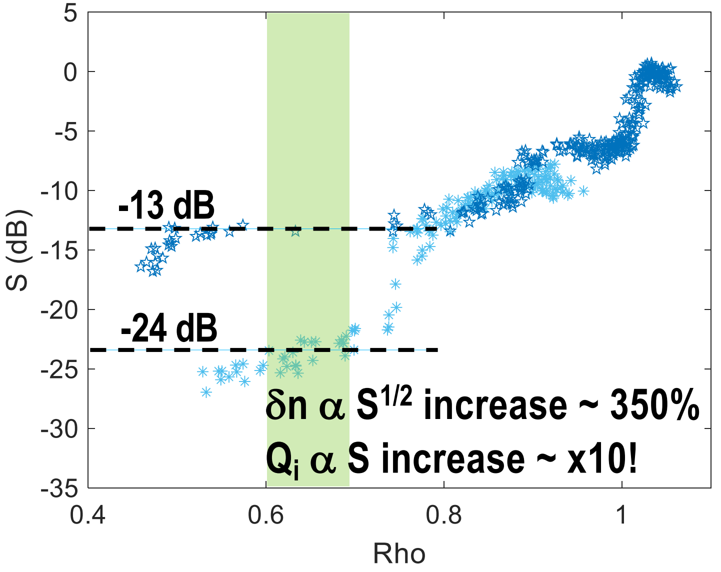
- our only systematic gradient control knob is ECH power deposition for T_e
- increased **density gradients reduce measurements of density fluctuations** in different transient situations:
  high-performance pellets, NBI, massive LBO, boron dropper
- **exceptions to the T_i limit correlate with reduced density fluctuations**
- reasonable agreement with simulations:
  - qualititatively: **reduced η** = $(a/L_{Ti})/(a/L_n)$ **leads to "stability valley"**
  - nonlinear evolution: strongly reduced heat fluxes due to **reduced ITG and weak TEM activity**
- low collisionality appears to reduce fluctuations at $k_\perp \rho_i \sim 1$. Transition to TEM-like turbulence?

- **profile control can reduce density turbulence, which can be an indicator of reduced transport**
- **care needs to be taken when interpreting measurements and simulations!**

Backup slides

Amplitude reduction: Simulations

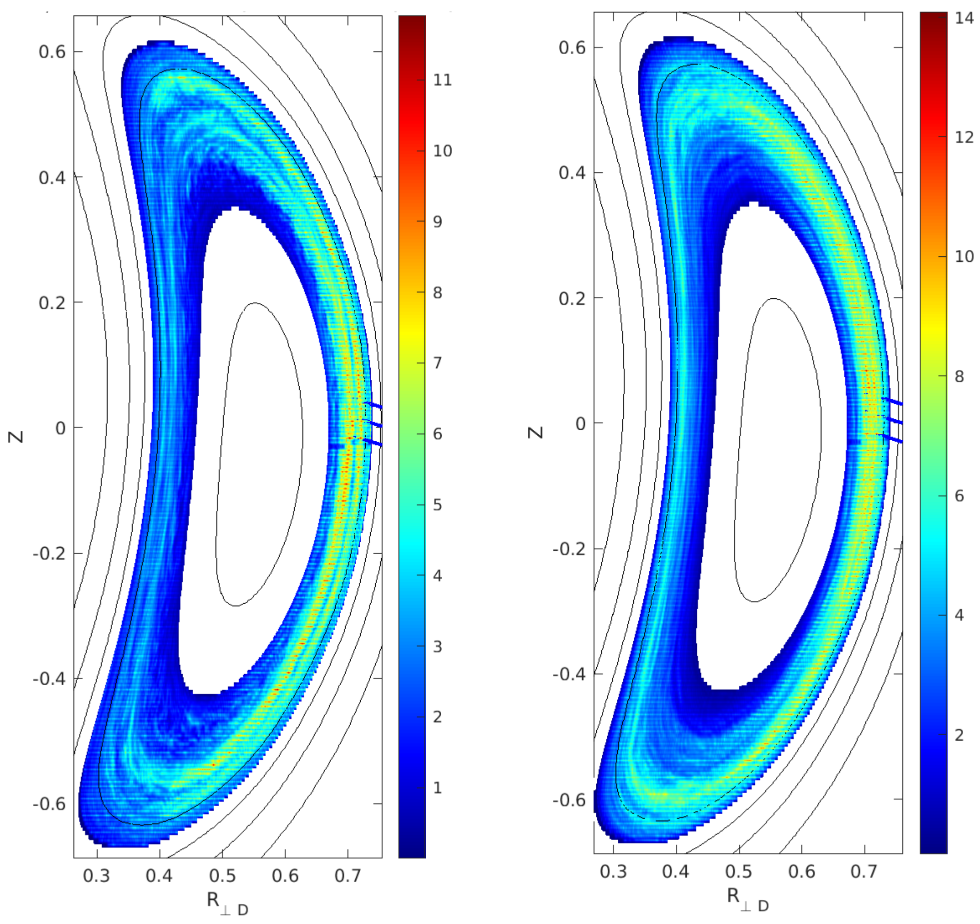


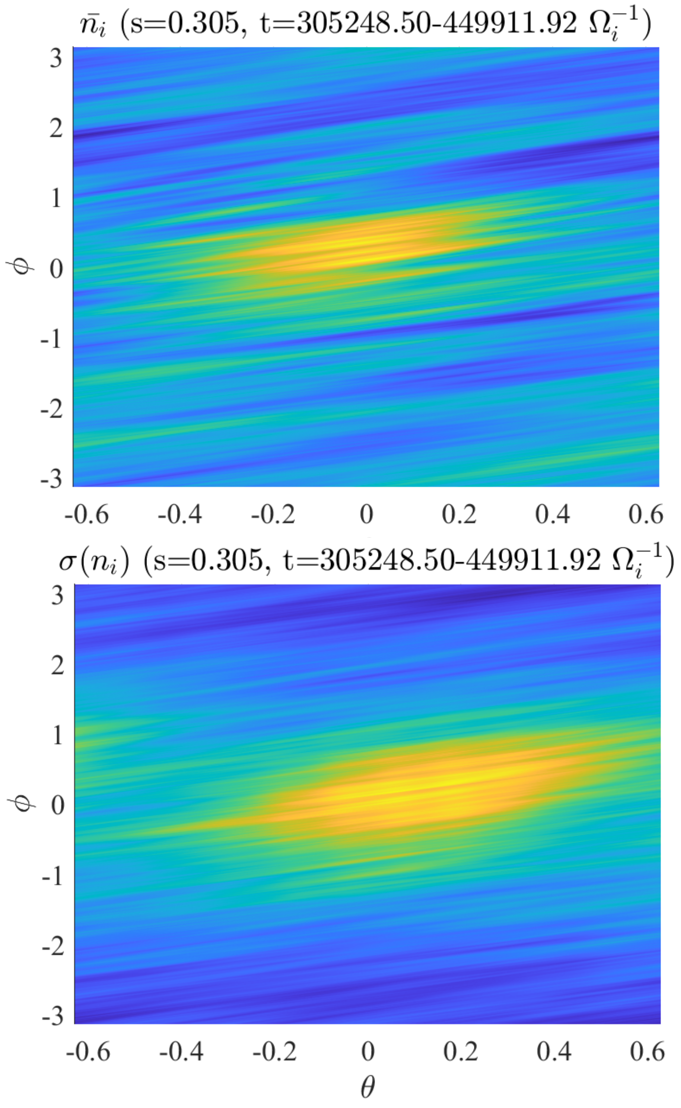


δn α $S^{1/2}$ increase ~ 350%

Q_i α S increase ~ x10!

EUTERPE (non-linear, flux surface, adiabatic electrons)





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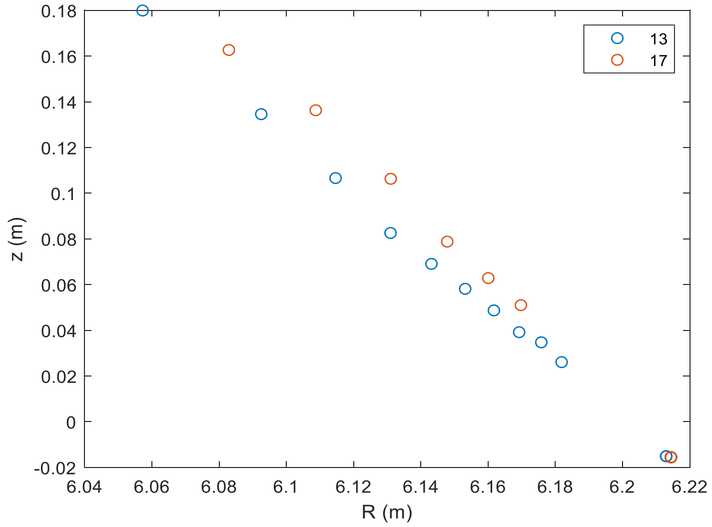
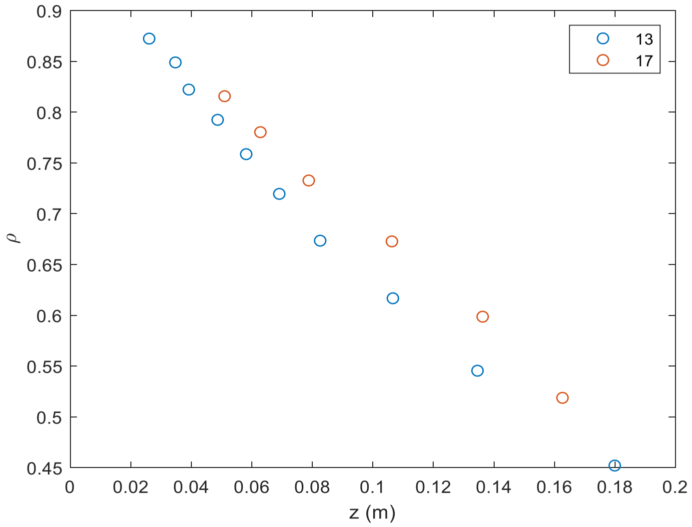
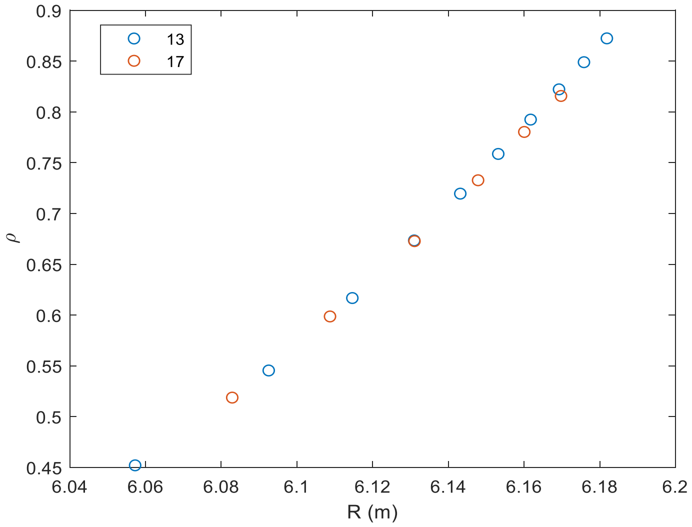
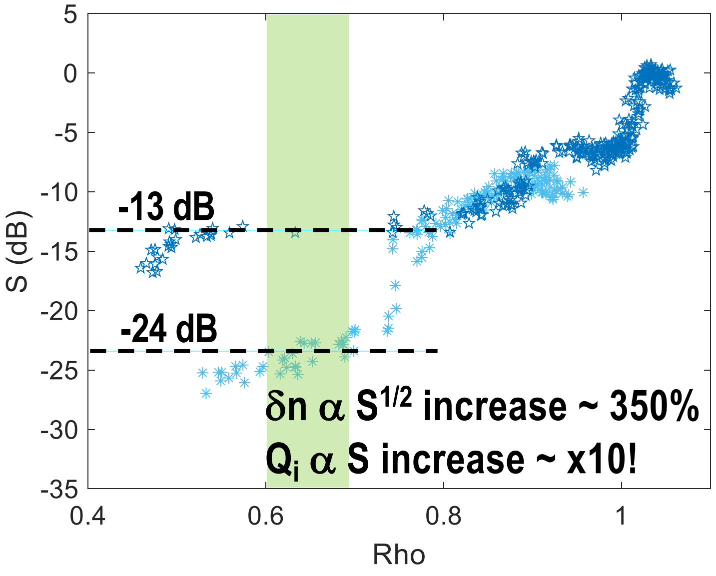
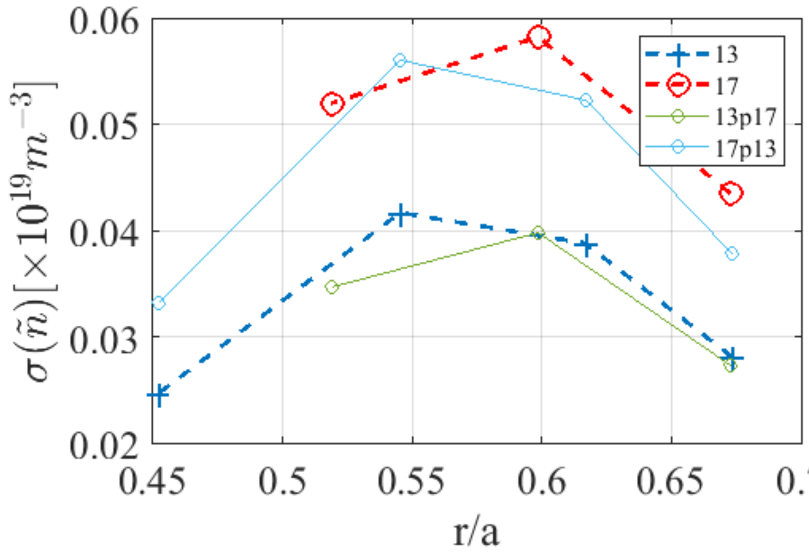
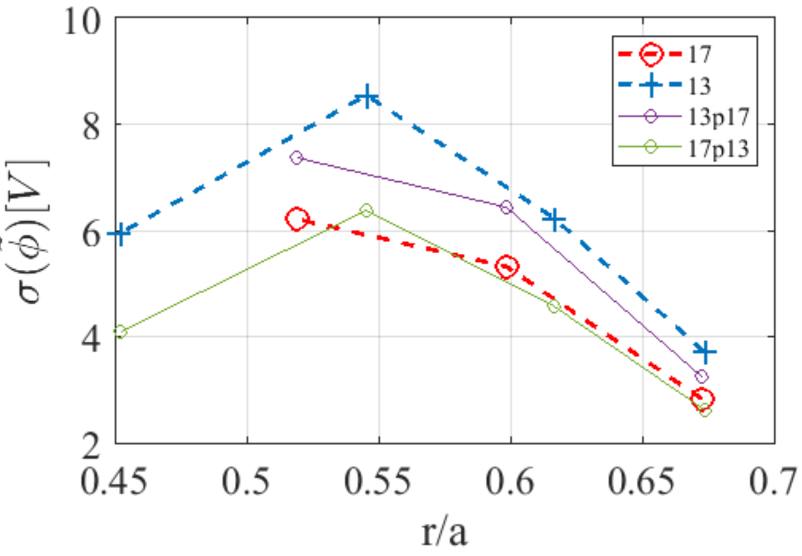






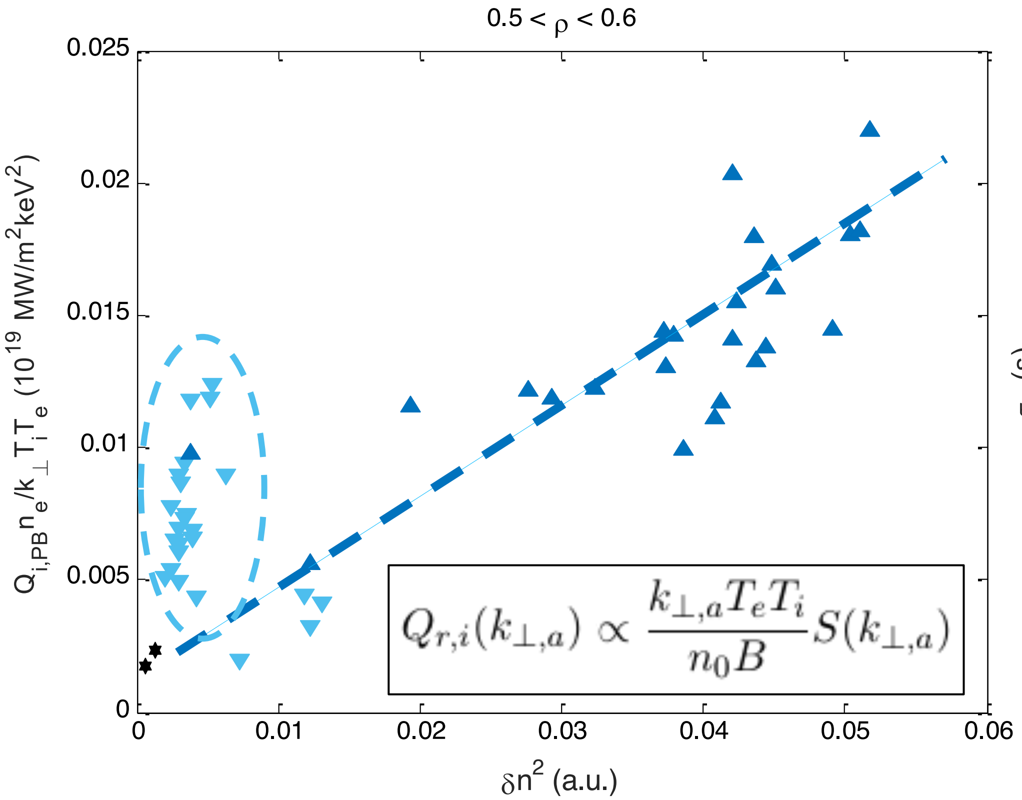


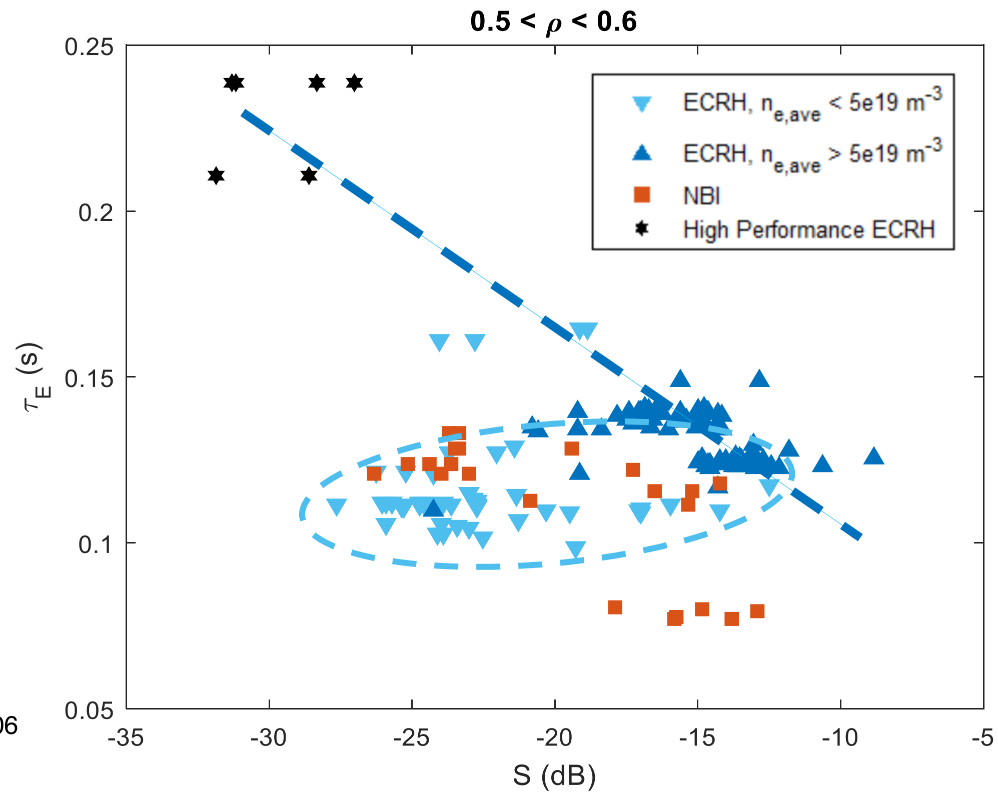




Dashed lines represent the amplitude of fluctuations at the measurement position corresponding to the same discharge. Solid lines represent the amplitude of fluctuations at the measurement position corresponding to the other discharge.

Overview of the results: local/global transport





- **Fluctuations from high density shots** seem to relate to PB-obtained local heat fluxes in the expected way.
- Also seem to be related to τ_E, indicating a link between local core fluxes and global confinement.
- **Reduced fluctuations from low density** shots are not related to any changes in local/global transport.

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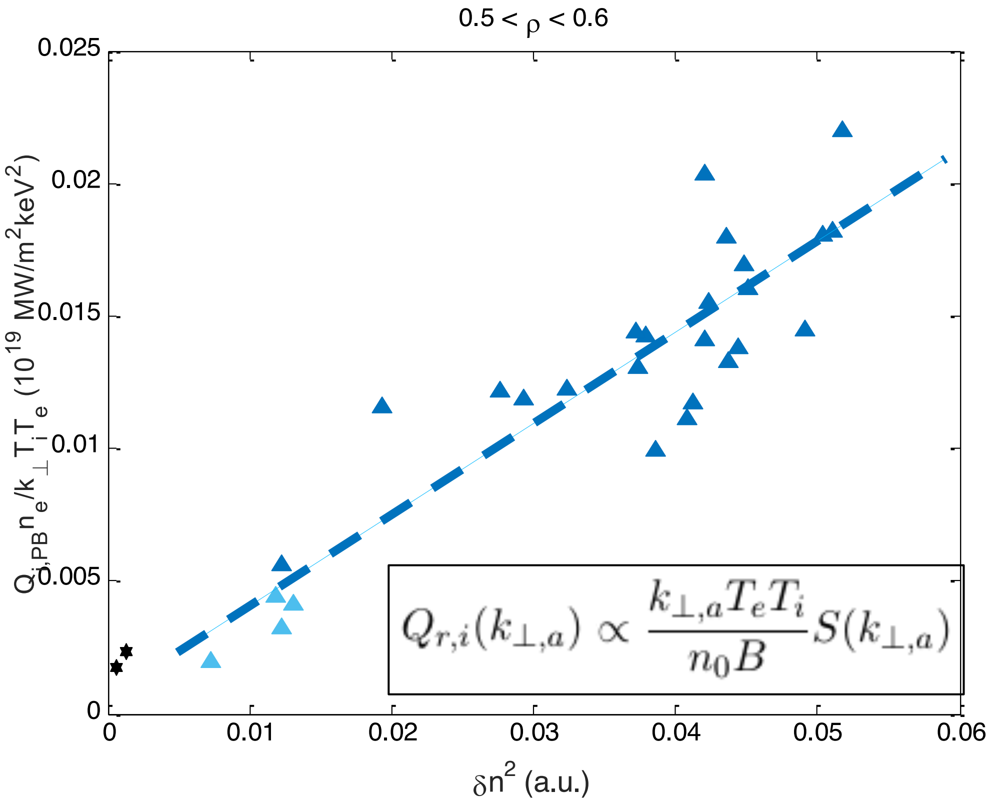

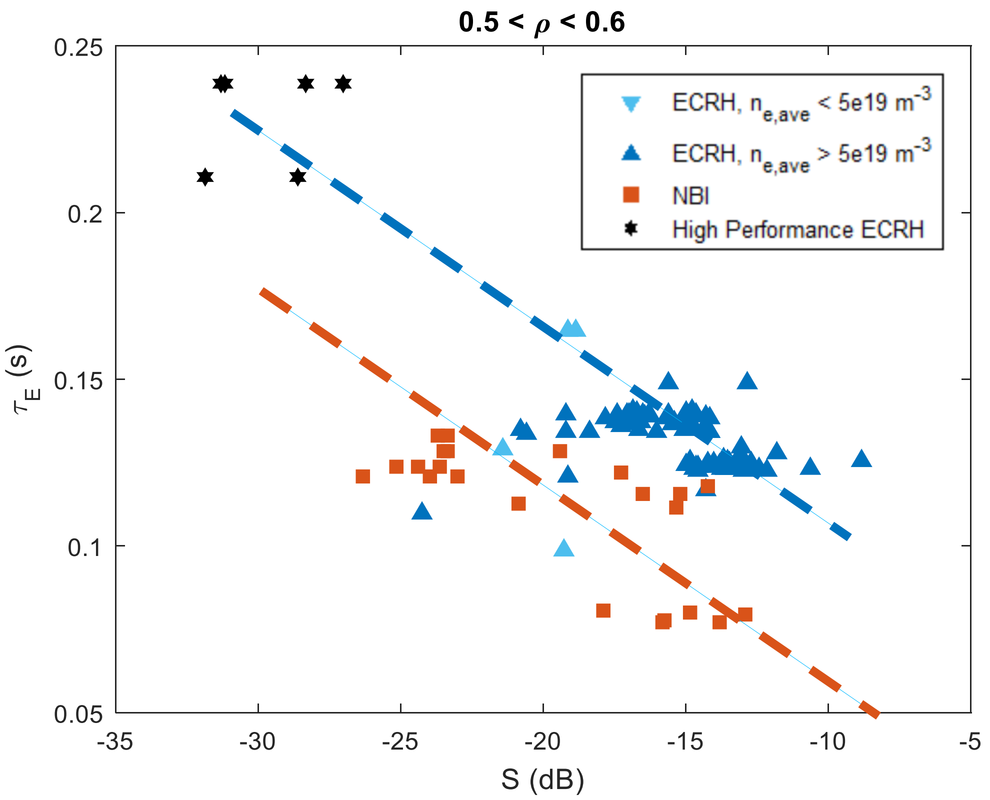

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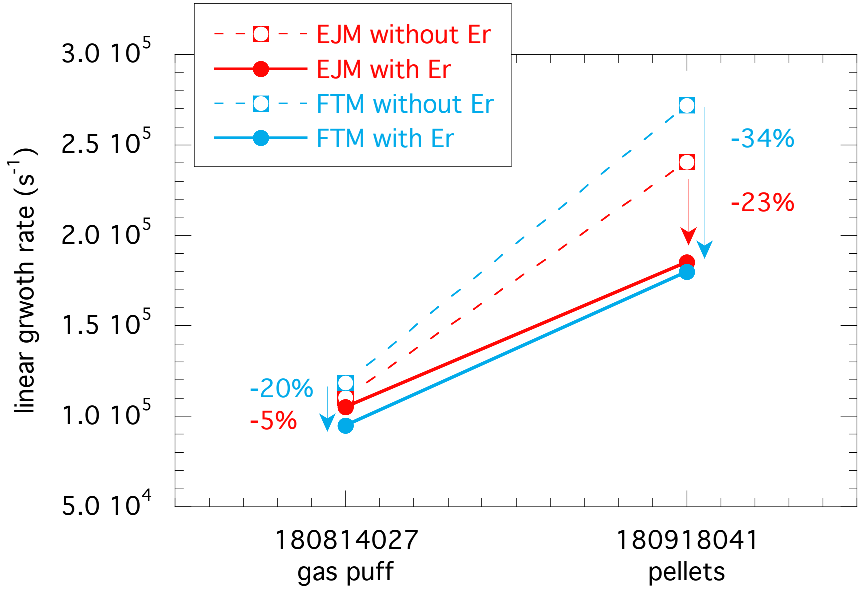
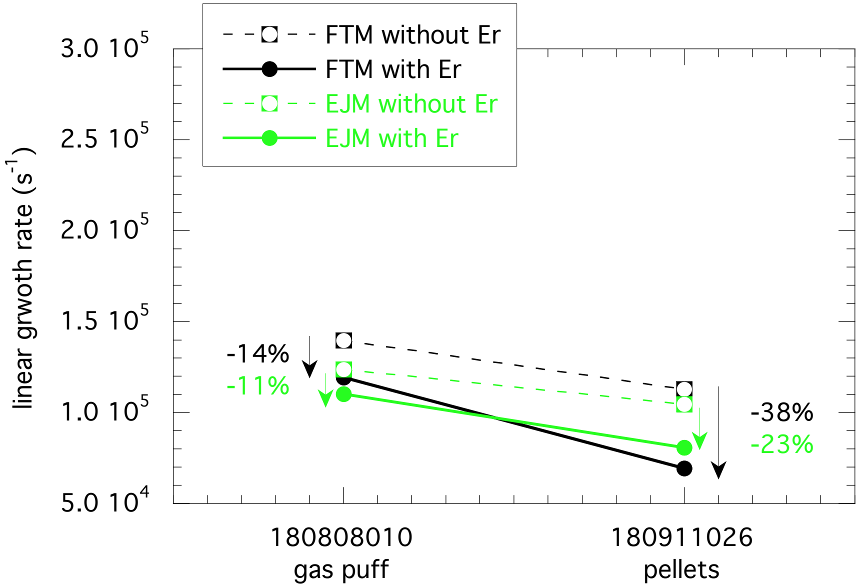
- Also seem to be related to τ_E, indicating a link between local core fluxes and global confinement.
- **Reduced fluctuations from low density** shots are not related to any changes in local/global transport.
- In **NBI shots**, fluctuations and τ_E also seem related, although with a different trend.

EUTERPE global linear simulations

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





Linear growth rates, γ, in EJM (left, red) and in FTM (right, black), without and with Er (open and solid symbols).

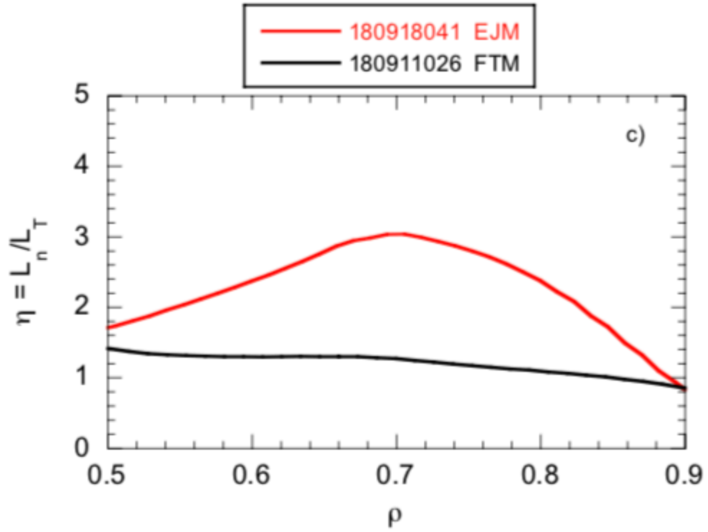
In blue and green, γ obtained swapping the magnetic configurations

E. Sánchez

Post-pellet: lower linear growth rates in FTM than in EJM configuration (in line with lower $\tilde{n}_e$ measured in FTM than in EJM)

The differences are not directly linked to the magnetic configuration itself but rather to the differences in the plasma profiles with lower η in FTM than in EJM

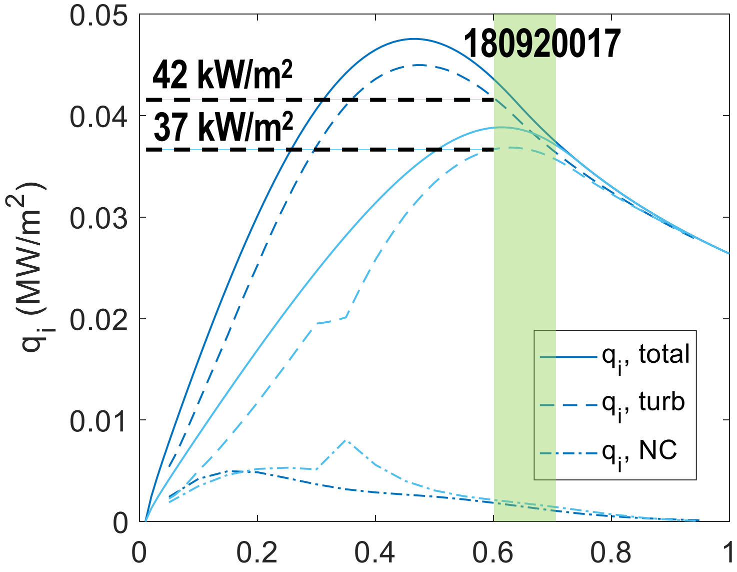
T. Estrada, D. Carralero, T. Windisch et al., NF **61** (2021) *accepted*



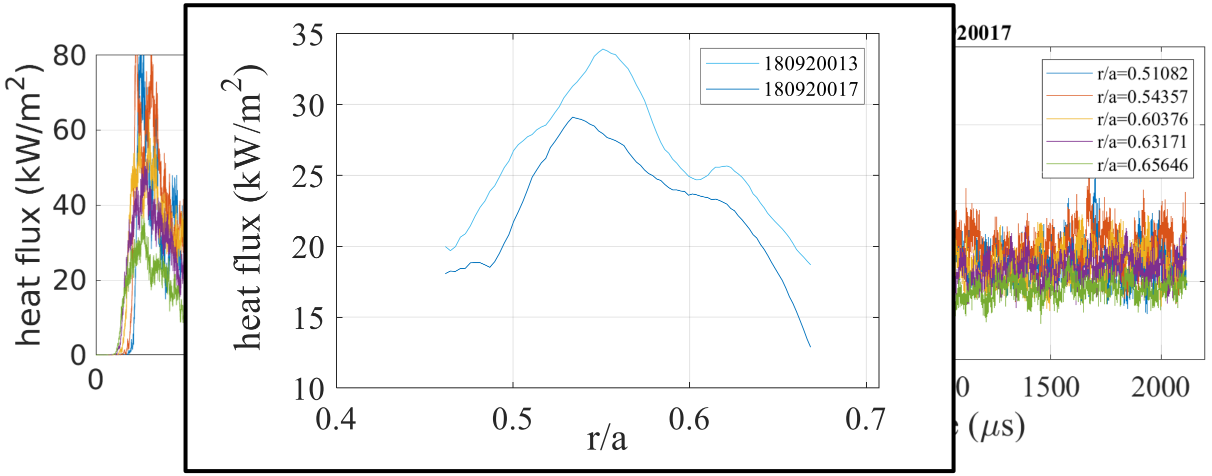
Transport simulations

180920013

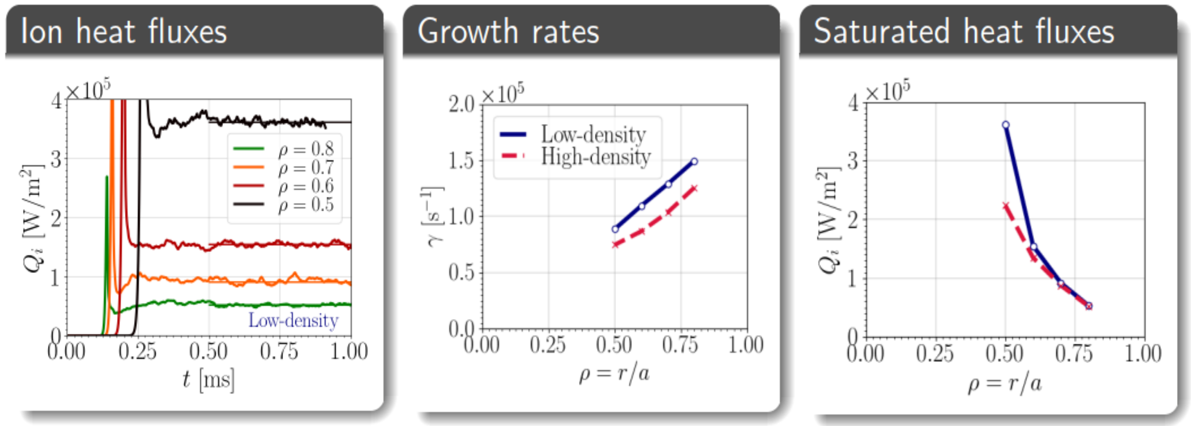
q_i increase ~ 10%



EUTERPE (non-linear, flux surface, adiabatic electrons)



Stella (non-linear, flux tube, kinetic electrons)



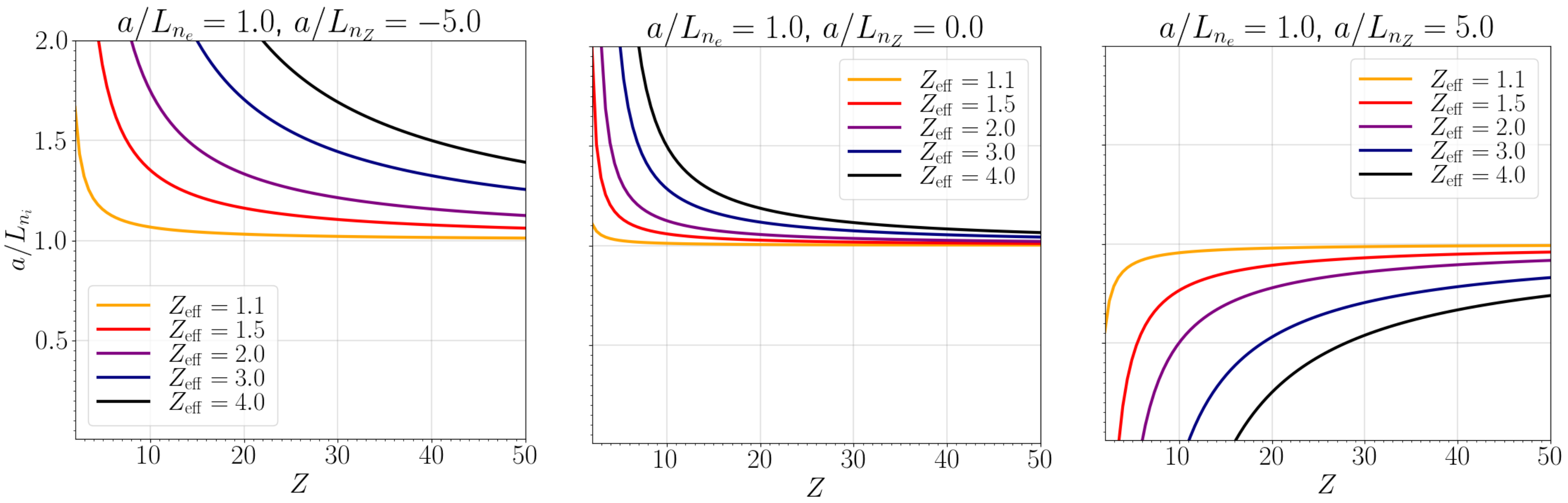
Average q_i as calculated by EUTERPE seems to be in the right order of magnitude.

The comparison between shots goes in the wrong direction for both codes!

The modification of a/L$_n$ by impurities

- Considering a single impurity species, hydrogen as main species and electrons

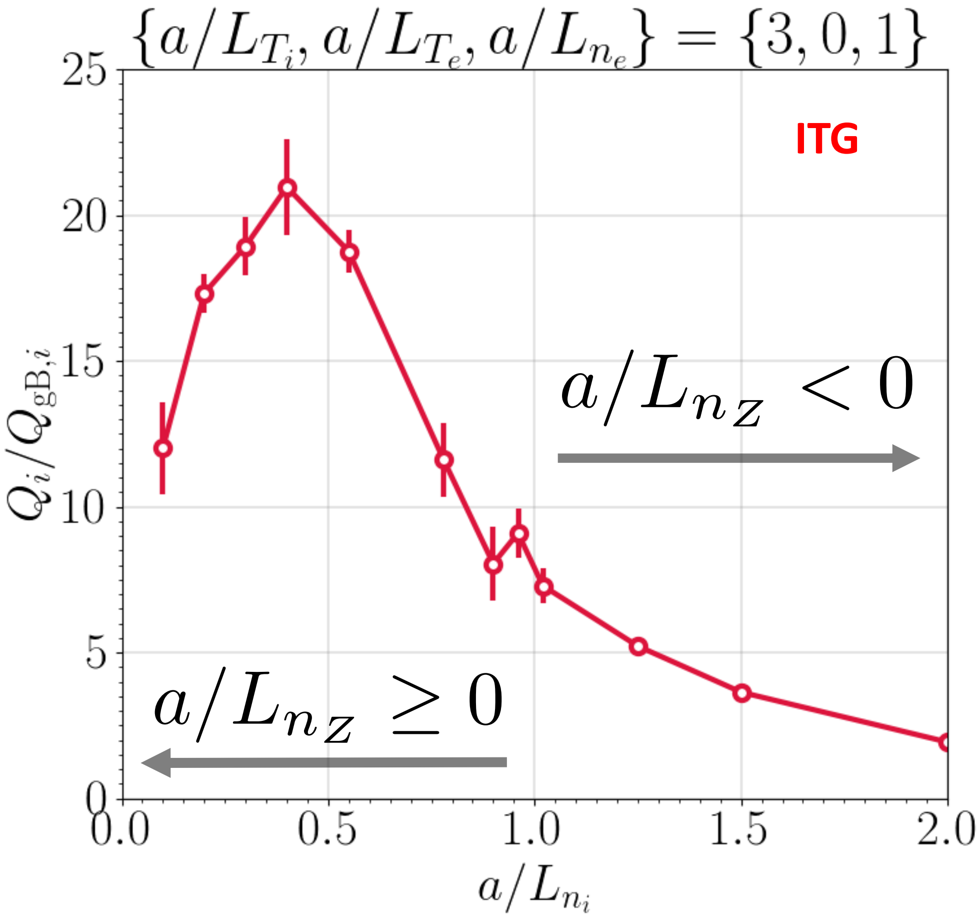
$$n_e\left(\frac{a}{L_{n_e}}\right) = n_i\left(\frac{a}{L_{n_i}}\right) + Z n_Z\left(\frac{a}{L_{n_Z}}\right)$$



- Impurities can perturb appreciably the main ion density gradient, particularly those with low charge.
- The larger the impurity density gradient the stronger the decoupling of n'_i and n'_e.

Q_i ($a/L_{ni} \neq a/L_{ne}$) in the approximation $n_Z = 0$

- **The ion heat flux driven by an ITG can be practically suppressed** at sufficiently strong a/L_{n_i} with respect to its maximum value.



- In experiments:
  - The injection of impurities with TESPEL leads to increase of W_{dia} [Zhang EPS'19]
  - The *Boron dropper* experiments show plasma performance footprints after high Z_{eff} increase [Lunsford APS-DPP 2020]
  - ICRC conditions make a/L_{n_Z} to develop large values for Ar [Langenberg, Impurity TG 2020].

The role of T_e/T_i