EUROfusion

Impurities and turbulence
(OP1 summary presentation)

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Turbulence Topical Group 11th February 2021

Laboratorio Nacional de Fusión Ciemat

Wendelstein 7-X

IPP

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

PPPL

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Outline

1. Consolidated results

- Size of the diffusion coefficient, D_Z
- Scaling of impurity confinement time (τ_I) with Z
- Scaling of D_Z with T_i/T_e
- Gyrokinetic impurity transport simulations

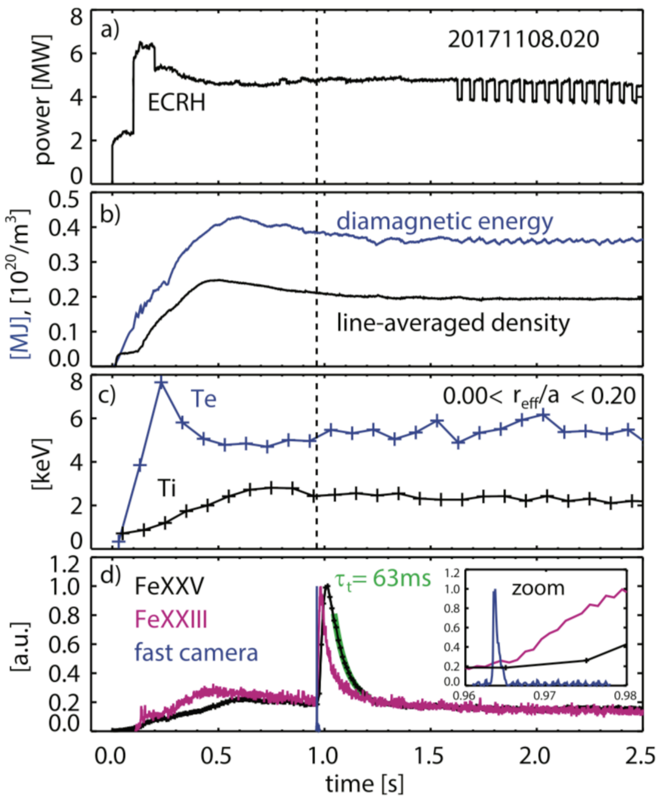
2. Recent results and ongoing work

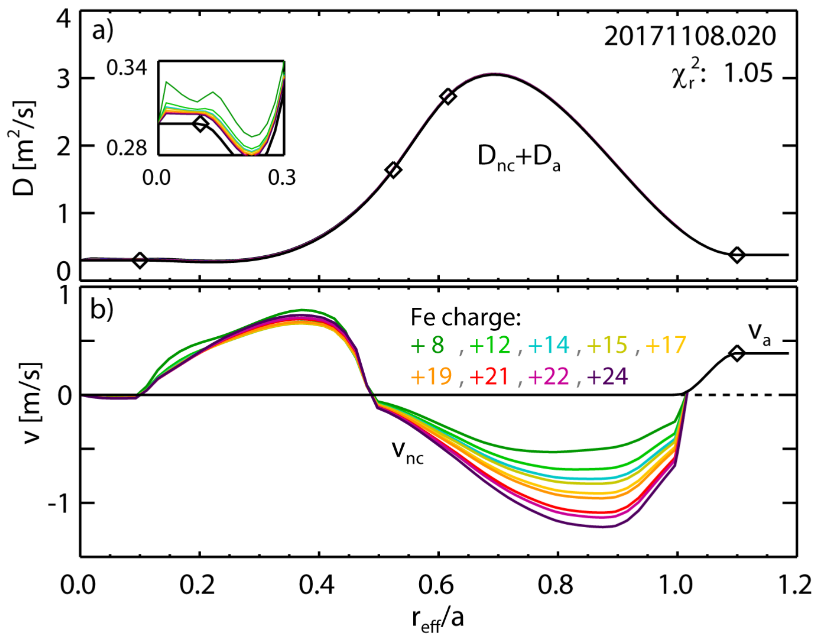
- Impurity profile peaking and accumulation in CIRC
- D_Z in *high* and *low* confinement scenarios
- The role of impurities on turbulence suppression
- Modeling in OP2: TSVV Task *Stellarator Turbulence Simulation*

3. Conclusions and open questions for OP2

Turbulent impurity transport in W7-X: the size of D

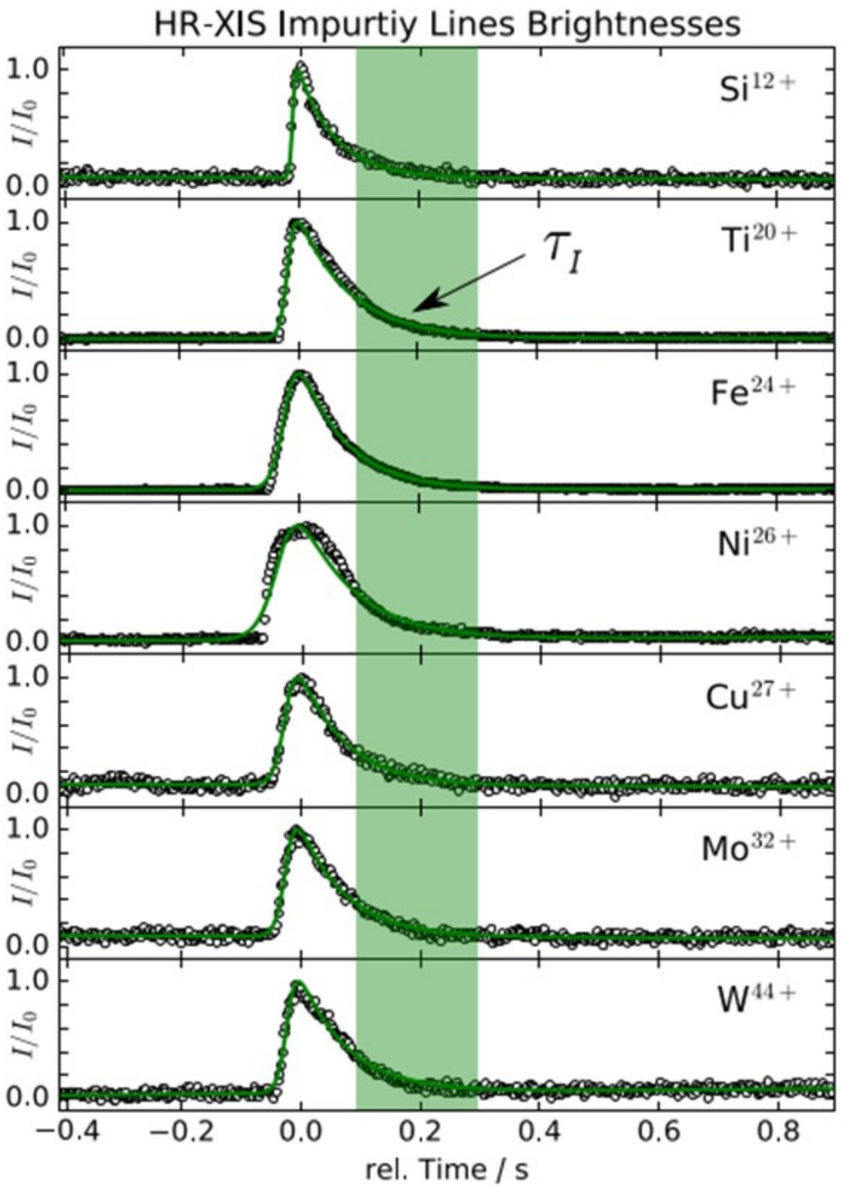
- **Successful operation of the LBO system** at W7-X, allowing good control of injection of Fe at trace concentration [Th. Wegner et al. RSI **89** 2018].
- **Assumption of strong anomalous diffusion needed in STRAHL** to fit the evolution of emission lines in low density plasmas with strong ECRH: $\mathbf{D_{ano} \sim 10^2 \times D_{NC}}$
- **What about other signs of turbulence-driven impurity transport?**

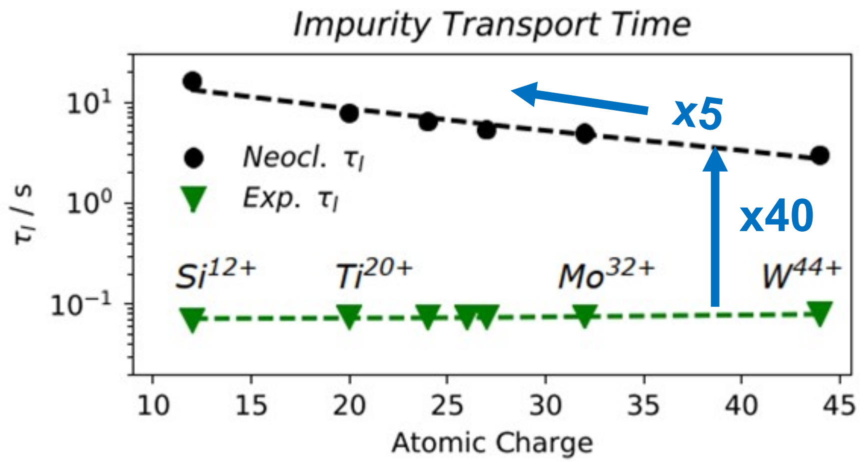




[B. Geiger *et al.* 2019 *Nucl. Fusion* **59** 046009]

Turbulent impurity transport in W7-X: lack of Z-dependence





Anomalous vs. Neoclassic Transport:

- Weak Z-dependence and small transport times
- Neoclassical calculations predict Z-dependence (**x5**) and higher transport times (**x40**)

Open Questions / To Do's:

- Observed in **low density CERC scenarios ⇒ what about** *turbulence suppressed Ion Root Core (CIRC) scenarios?*

[A. Langenberg et al. *Physics of Plasmas* (2020)]

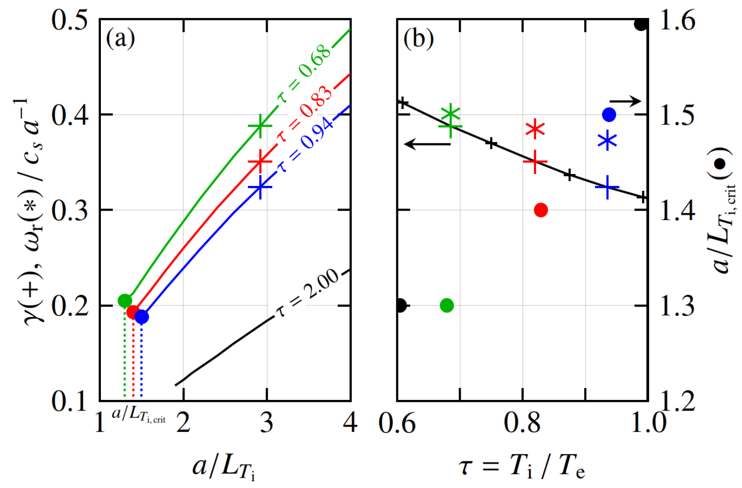
Turbulent impurity transport in W7-X: dependence on $\tau = T_i/T_e$

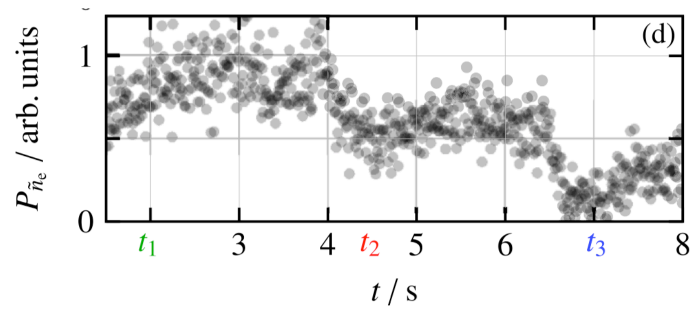
- From a series of time instants during ECRH power scan with different **$\tau = T_i/T_e$** and LBO-injected Fe:

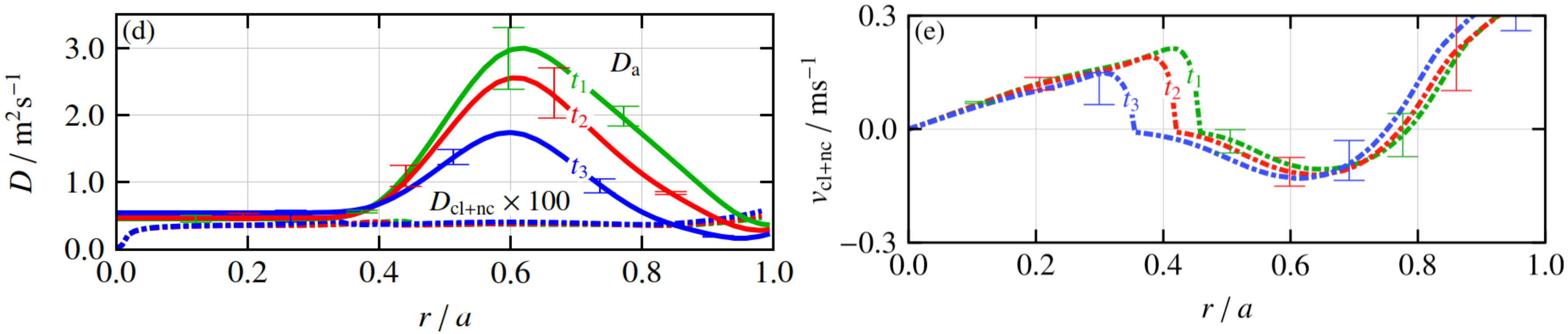
  - **Increasing τ** $\Rightarrow$ Linear stabilization ITG and higher critical gradient ($a/L_{T,crit}$) (from GENE linear simulations).

  - **Increasing τ** $\Rightarrow$ reduction in the normalized fluctuation level (PCI measurements)

  - **Increasing τ** $\Rightarrow$ decrease of diffusion coefficient (D_Z) or, equivalently, enhanced impurity confinement.



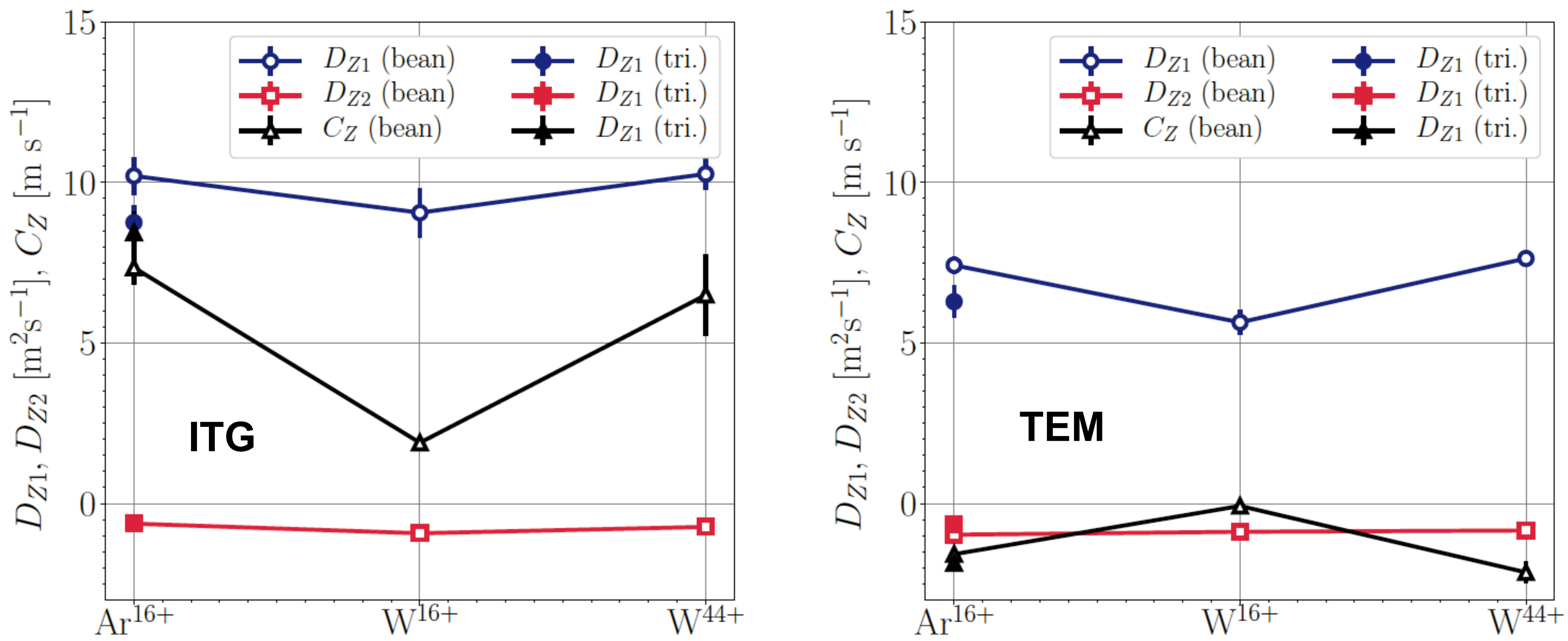




[Th. Wegner et al., NF Letters 60, 2020]

GK simulations: ITG and TEM driven impurity transport

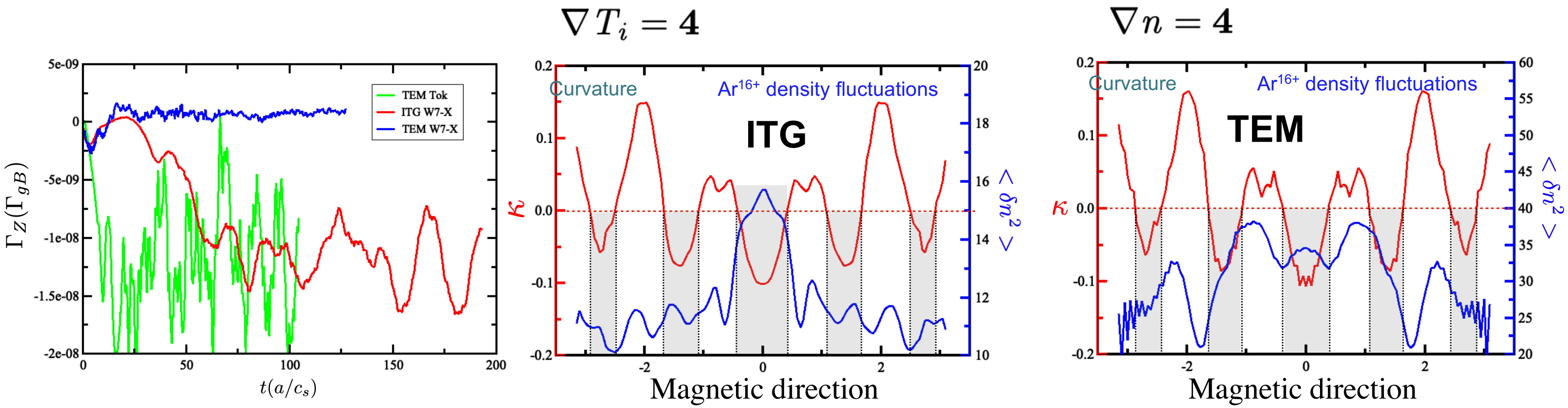
- First turbulent simulations of impurity transport with `stella` [García-Regaña et al. JPP 2021]
- **Dominant weakly Z-dependent ordinary diffusion** (D_{Z1}), negligible thermo-diffusion (D_{Z2}) confirmed for TEM and ITG background turbulence
- In the absence of pressure gradients (C_Z) ⇒ anti-pinch (TEM) and pinch (ITG) contributions.



- **Next:** comparison of nonlinear simulations for specific discharges and comparison against experimental results.

GK simulations: (anti-)pinch and geometry

- Quasilinear theory [Helander&Zocco PPCF 2018] predicts **anti-pinch (C_Z) if impurity fluctuations peak in good curvature regions**.



- GENE simulations applied to validation of numerical simulations with theoretical predictions

  - **For ITG**: C_Z leads to **inward flux** in W7-X as well as in tokamak, δn_Z peaks at bad curvature regions.
  - **For TEM**: C_Z leads in W7-X to **outward impurity flux**, where δn_Z and good curvature regions overlap.
  - Max-J property helps but it is not necessary, similar response found in min-J configs. like low mirror can have similar response [Alcusón et al. ongoing 2021].

- Quasilinear theory generalized including collisions, with minor role for reactor-relevant conditions [Buller&Helander JPP 2020]

GK simulations: (anti-)pinch and geometry

- Quasilinear theory [Helander&Zocco PPCF 2018] predicts **anti-pinch (C_Z) if impurity**

Neoclassical D_Z and τ_I are O(100) **smaller than** experimentally inferred in CERC plasmas.

D_Z scales with T_i/T_e as ITG instability does.

τ_I is practically independent on Z

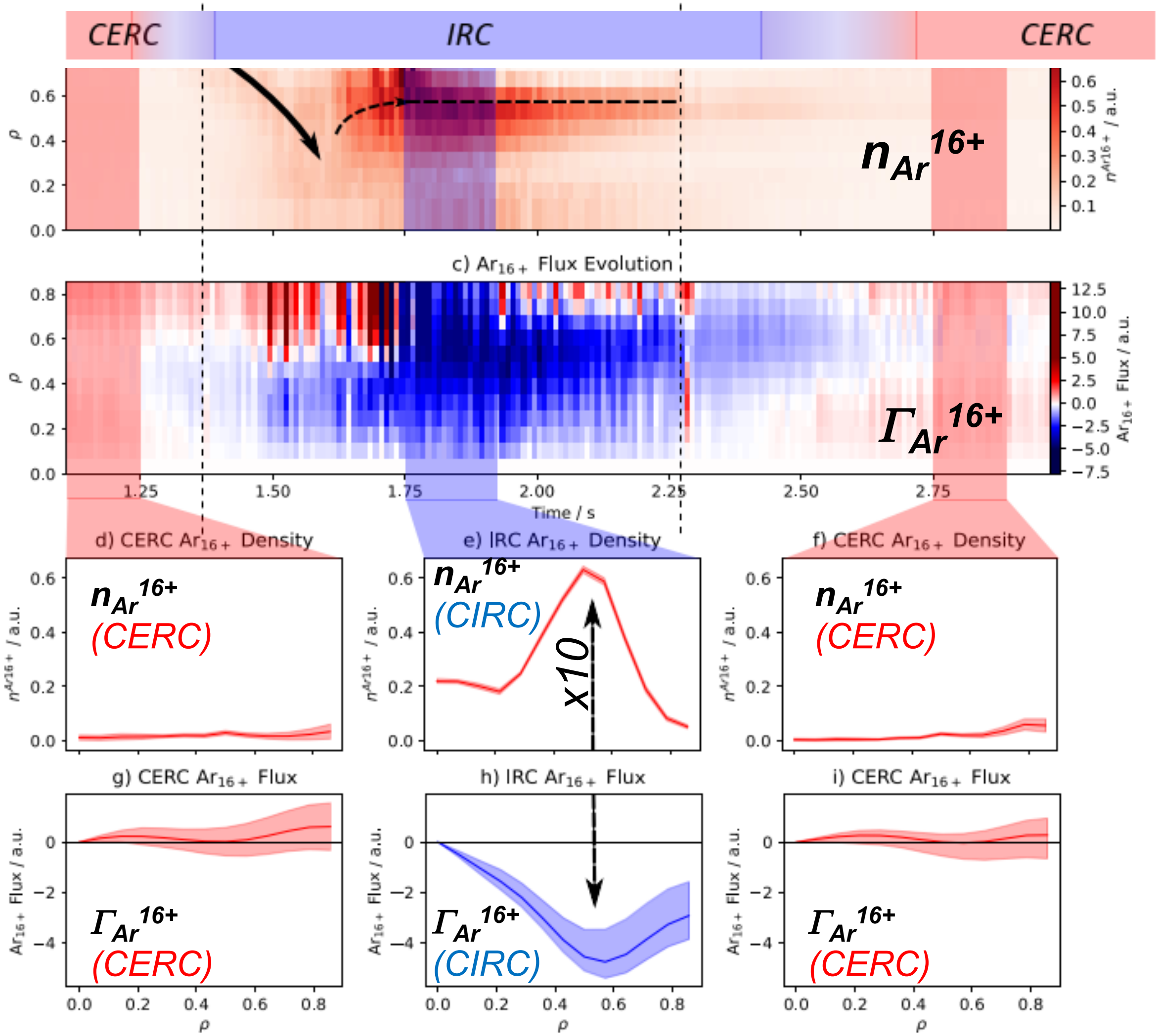
Numerical D_Z reasonably close to experimental values. ITG leads to moderate pinch, TEM does it to weak anti-pinch.

<u>D_Z is determined by turbulence</u>

Convection (**V_Z**) **follows the sign of E_r and depends on Z** (compatible with neoclassical numerical simulations).

Unless V_Z becomes comparable to D_Z, the plasma should develop nearly flat impurity density profiles (peaking factor: $n'_{Z,eq} \sim V_Z / D_Z$)

Impurity confinement in reduced turbulence CIRC scenarios



[A. Langenberg, Th. Wegner, N. Pablant et al. *To be published*]

During electron-ion root transition:

- Significant rise in Ar density n_{Ar}^{16+} (**x10**) with reduced turbulence during pellet injections and evolving *to* ***CIRC.***
- Ar fluxes Γ_{Ar}^{16+} follow E_r evolution from slightly positive to negative Ar fluxes in ***CERC-CIRC*** transition

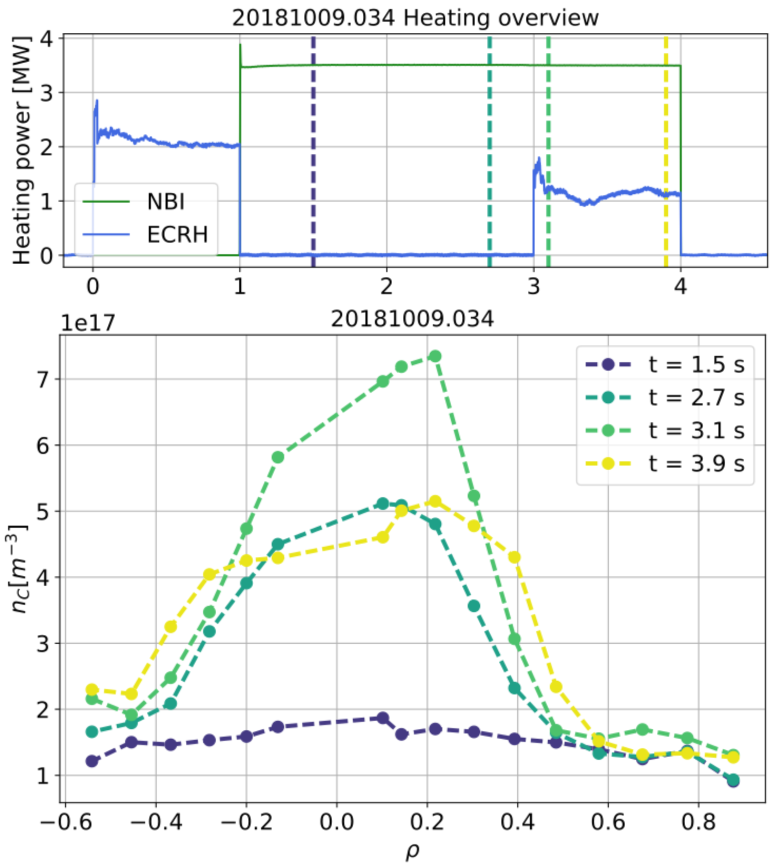
Open Questions:

- Impurity accumulation in steady state ***CIRC*** scenarios?
- Can we disentangle effect of neg. E_r and turbulence suppression?
- Impurity fluxes in other turbulence suppressed scenarios (*pure NBI heated, massive imp. injection*)

Impurity profile evolution and moderation of D_Z

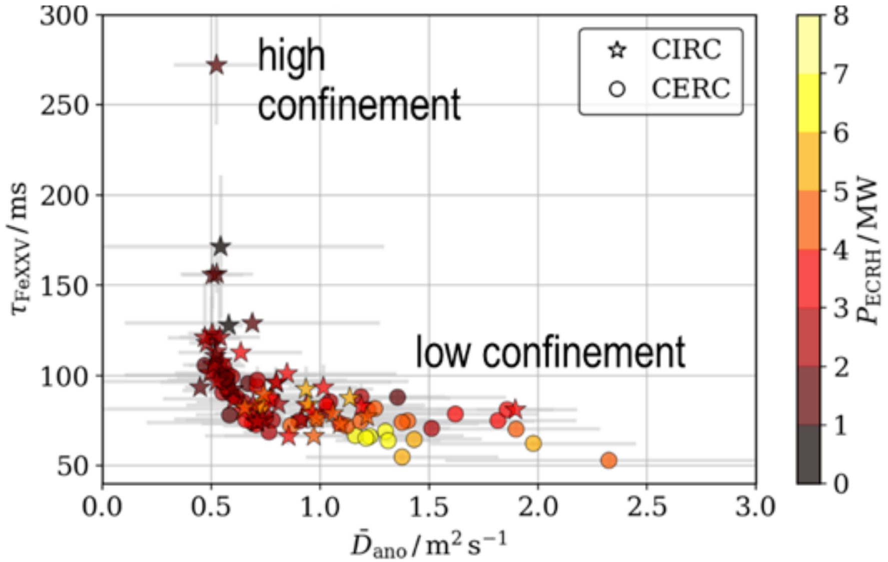
- Sequence of ECRH → NBI →NBI+ECRH Evolution of **Carbon radial profiles from flat to peaked**, indicating a change in the balance between V and D sources.

- **Ongoing: STRAHL simulations to obtain V and D consistent with those profiles** [L. Vano et al. ongoing]



- **Low confinement regime** ⟹ largest D_Z
- **High confinement regime (CIRC)** plasmas ⟹ lower D_Z and longer confinement time, although **still larger than neoclassical**

- **Ongoing: STRAHL V and D vs. GENE simulations** [Th. Wegner et al. to be submitted]



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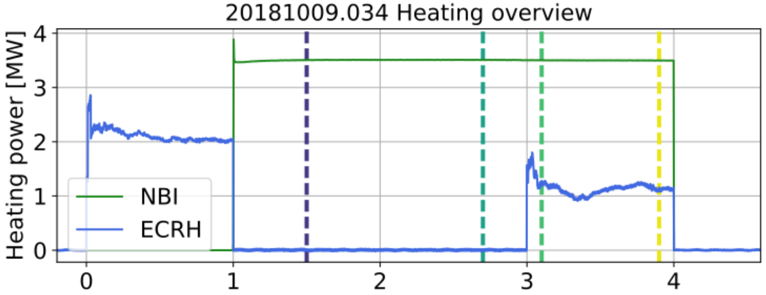

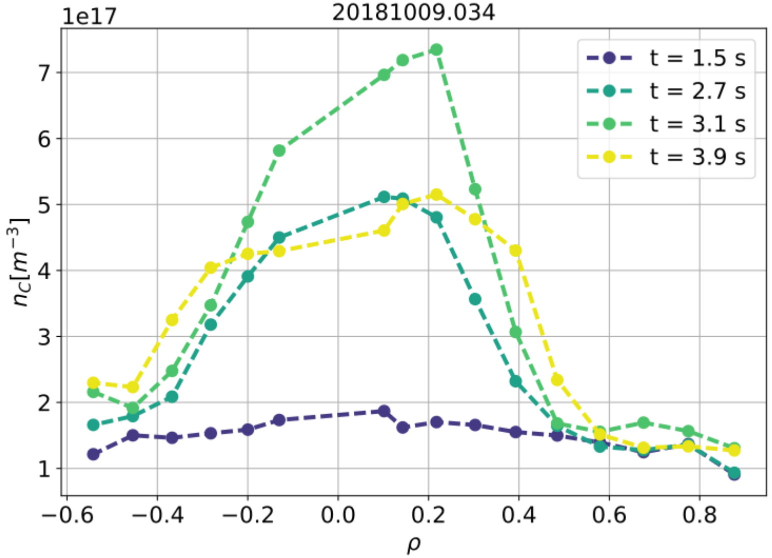

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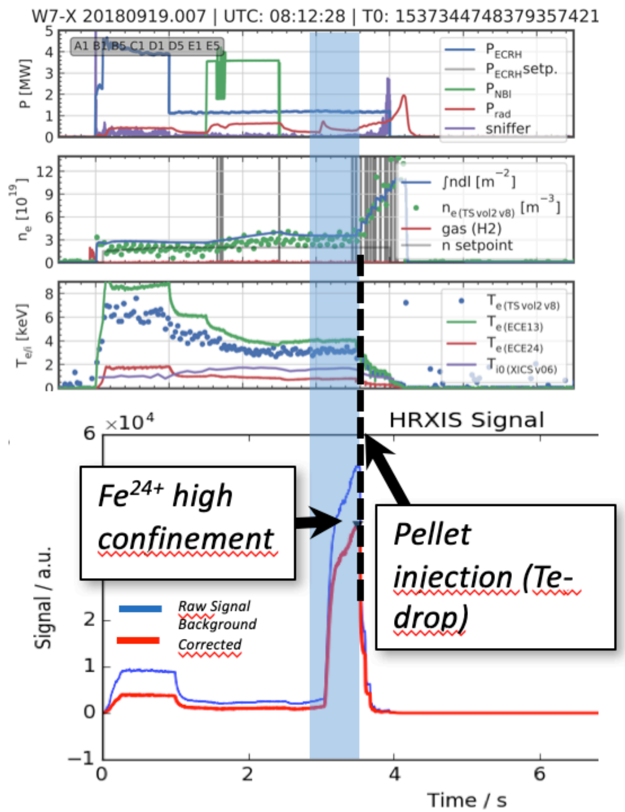
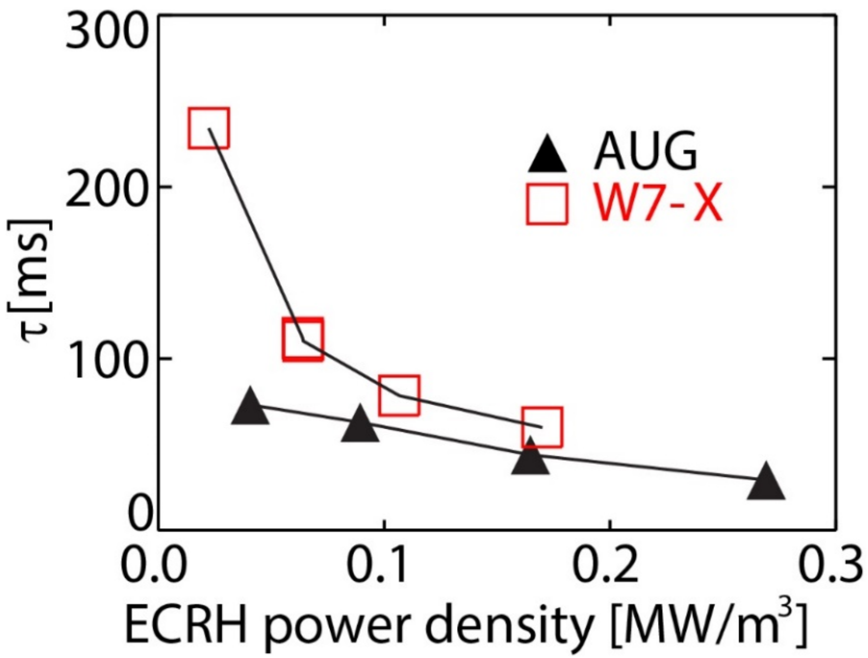
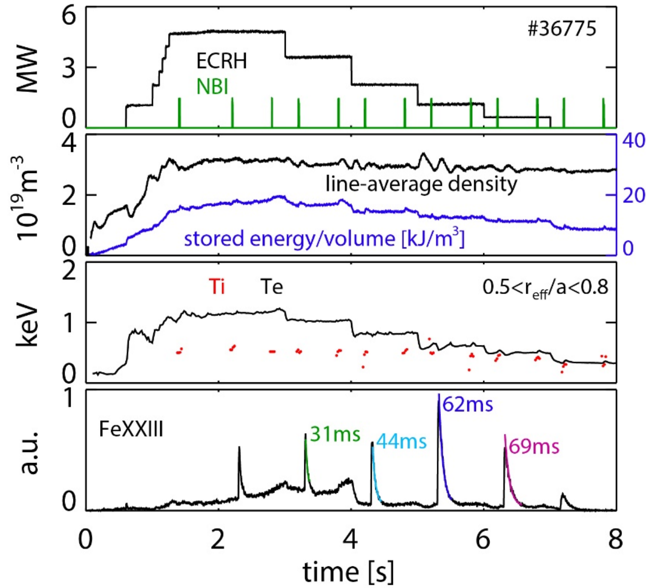


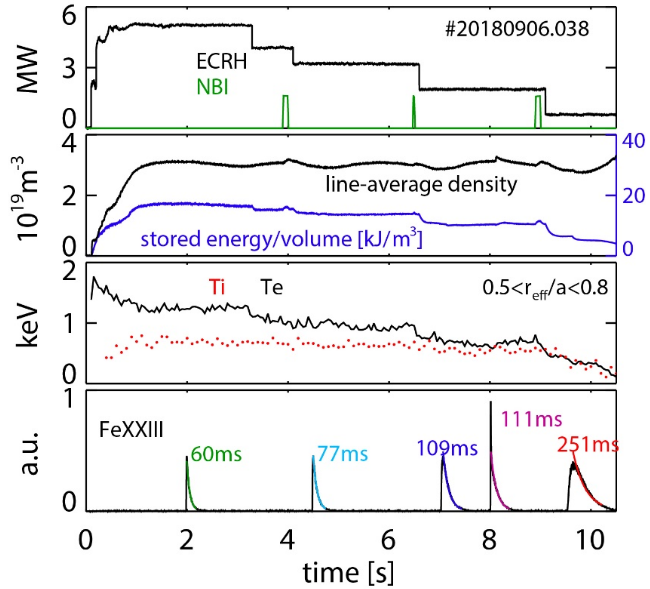
Dependence of D_Z with P_{ECRH} and cross-device comparison

- AUG and W7-X low density hydrogen plasmas with L-mode conditions have been compared.
- LBO injections of iron during ECRH power scan.
- τ_I of Fe^{22+} emission decreases with applied ECRH power in both devices.
- But τ_I differ for the lower values of ECRH power density, where T_i~T_e. **Is the onset of an ion-root in W7-X contributing to increase τ_I?**



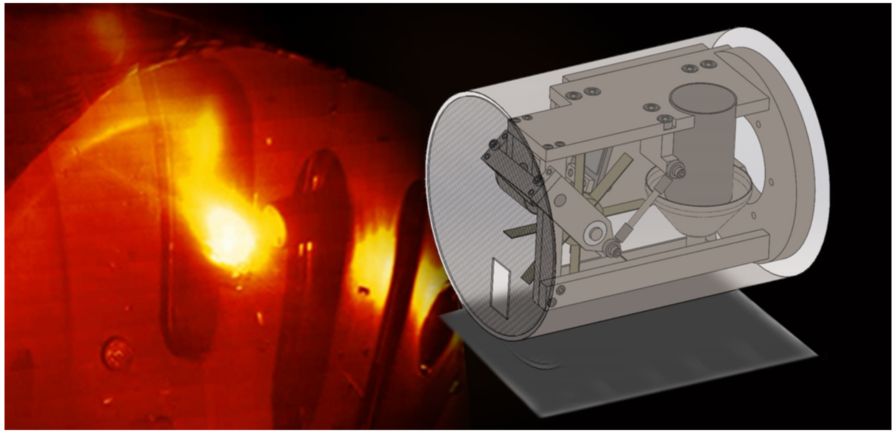
[B. Geiger et al. ongoing work]

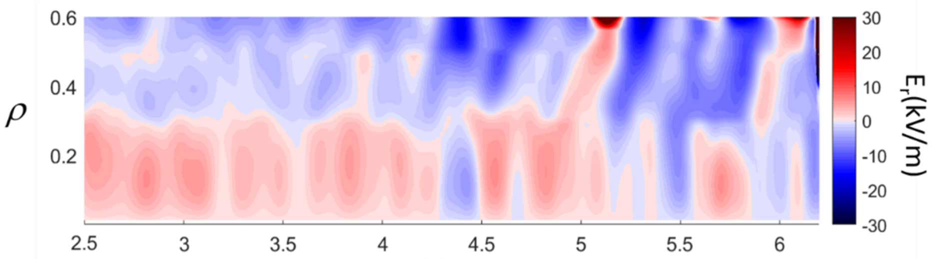


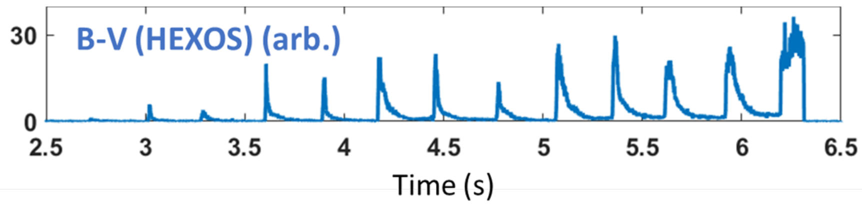


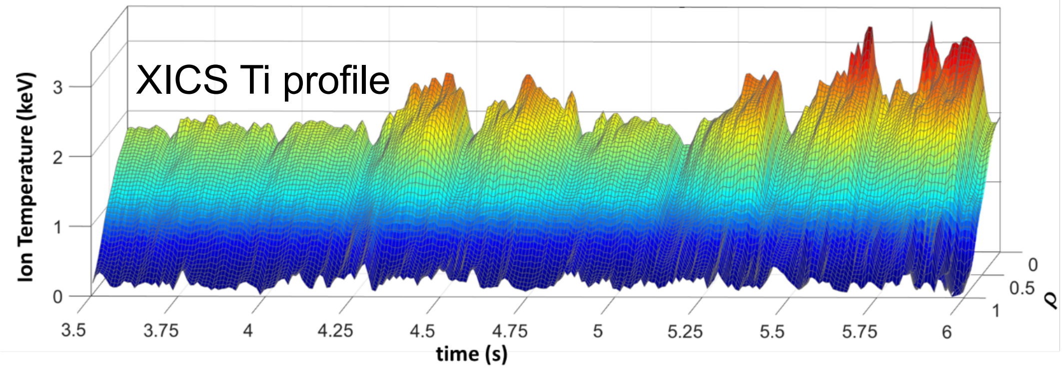
Transient performance elevations: the Probe Mounted Powder Injector (*Boron dropper*)

- PMPI injects 50 ms pulses of B_4C every 350ms at quantities up to 60 mg/pulse to test of supplemental wall conditioning method (inconclusive result)
- Powder well supported by W7-X plasma, strong engagement with PFCs
- Injected pulses result in **steep edge density gradients** possibly **suppressing ITG modes**
- Reduced anomalous transport leads to **elevated core ion temperatures, higher W_{MHD}, increased impurity confinement times**.
- Higher T_i leads to negative core electric field
- Standard confinement returns as density gradient relaxed or new pulse injected







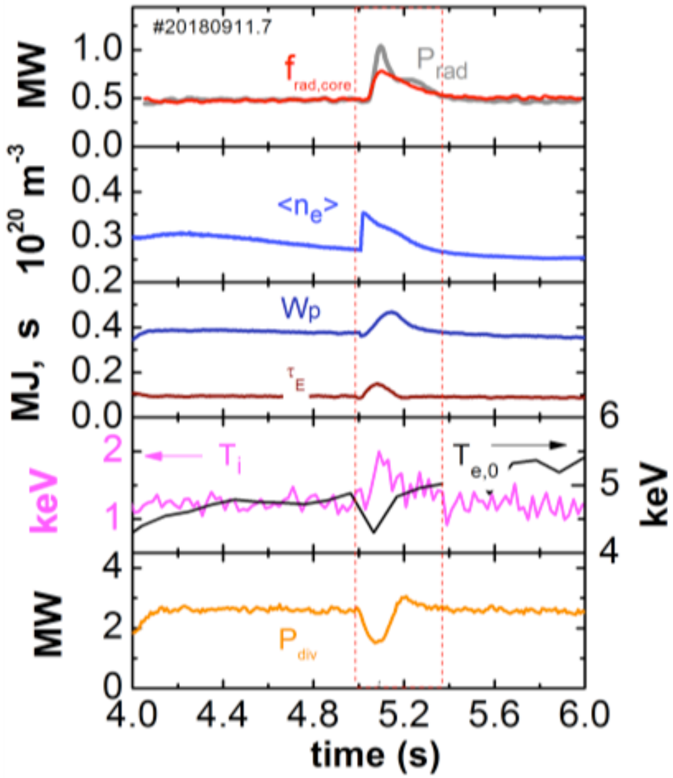


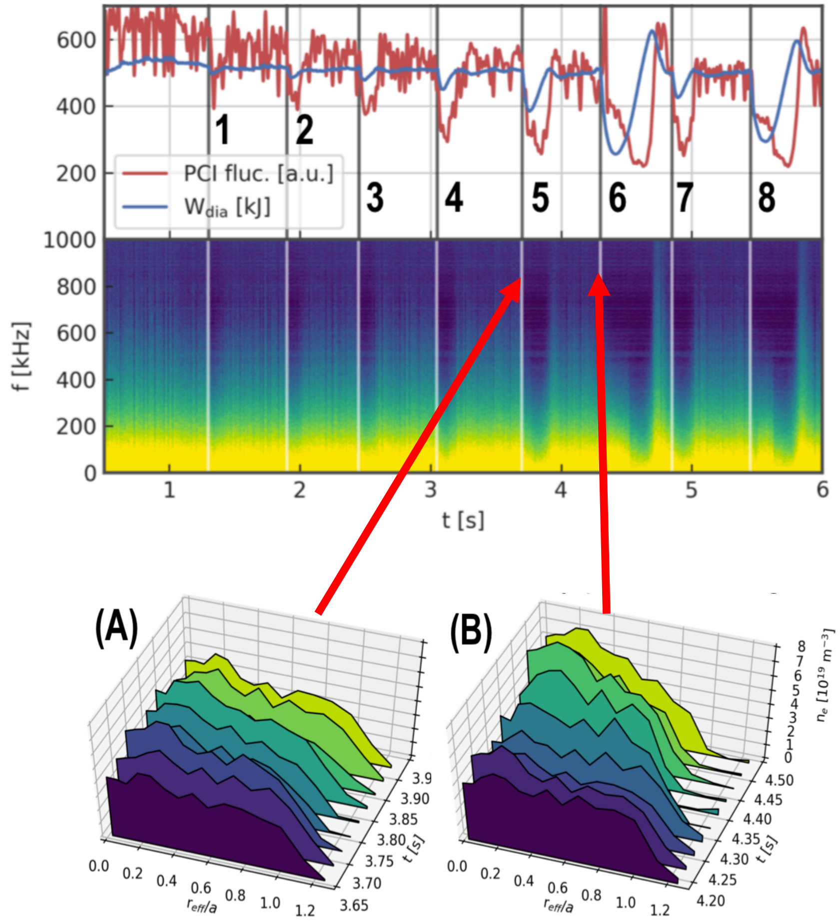
Proposed Future Experimental Plans

1. **Continued PMPI experiments (OP2.0)**
   a) Better transport classification & confirmation of performance boost
2. **Installation of a full IPD system (OP2+)**
   a) Possible in-situ rapid wall reconditioning tool

Transient performance elevations: massive LBO and TESPEL injections

- **Masive LBO injections transiently reduce PCI** fluctuations, increase W_{dia} and T_i
- Preliminary intepretation: plasma density profile schrinks leading to **stabilization of ITG turbulence**.
- Comparable results with TESPEL iron injection [Zhang EPS'19]

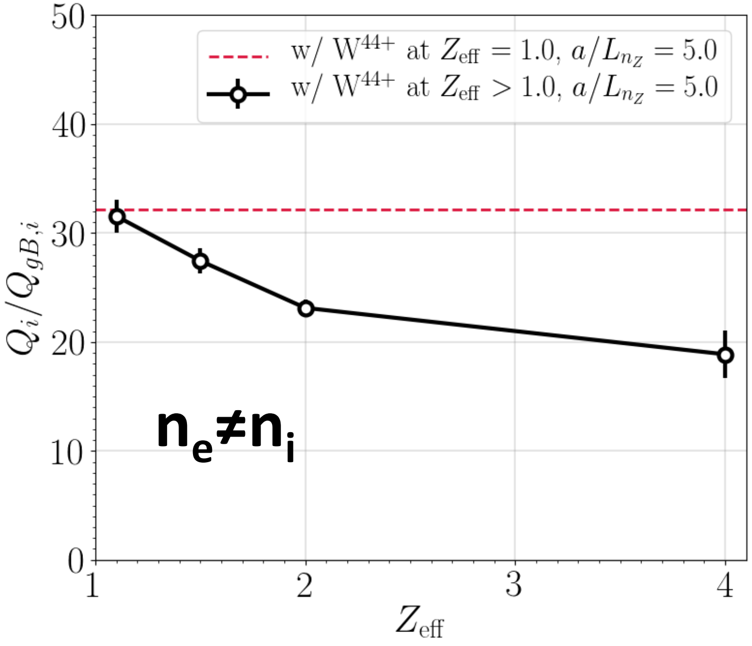




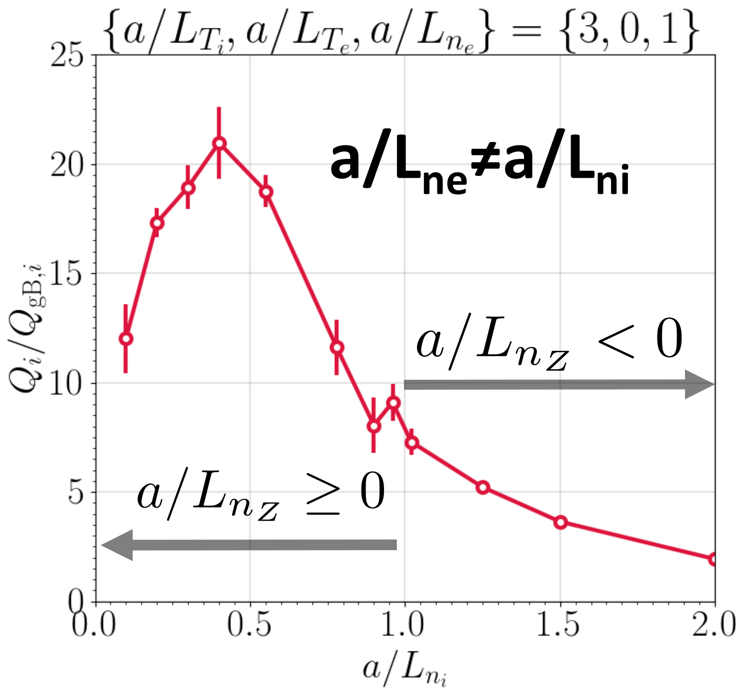
[Z. Huang & Th. Wegner & A. v. Stechow, to be submitted]

Simulating the impact of non-trace impurities on Q_i

- Quasineutrality to lowest order and non-trace impurity concentration $\Rightarrow$ **$n_e \neq n_i$ / $n'_e \neq n'_i$,**
- **`stella`** gyrokinetic simulations have explored the **impact of each effect on the ion heat flux** driven by **ITG** dominated turbulence [García-Regaña, in progress].



Q_i driven by ITG turbulence as a function of the effective charge, assuming W44+ as impurity species leading to **up to 40% Q_i reduction**.



Q_i driven by ITG turbulence as a function of the main ion density gradient, leading to up to a **variation of 90% on the value of Q_i.**

- **Ongoing**: simulations with **`stella`** of low-to-mid Z impurities considering realistic concentration and gradients $\Rightarrow$ key importance of **measured Z density profiles** (**!**).

A final remark on modeling: *Stellarator Turbulence Simulation* TSVV Task

- EUROfusion will coordinate the effort on theory and advanced simulation through a series Theory, Simulation, Validation and Verification (TSVV) Tasks.
- **TSVV#13 Stellarator Turbulence Simulation** within W7-X Work Package.
- Codes: **`stella`**, **`GENE`**, **`GENE-3D`**, **`EUTERPE`** and **`KNOSOS`** (for neoclassical input)

Member	Research Unit	Period	Commitment (ppy/year)
José M. García-Regaña (Task Leader)	CIEMAT	2021-2023	1.0
Edilberto Sánchez	CIEMAT	2021-2023	0.5
José Luis Velasco	CIEMAT	2021-2023	0.5
Michael Barnes	CCFE (Uni. Oxford)	2021-2023	0.5
Félix I. Parra	CCFE (Uni. Oxford)	2021-2023	0.5
Alejandro Bañón-Navarro	MPG (IPP-Garching)	2021-2023	0.5
Jorge Alcusón	MPG (IPP-Greifswald)	2021-2023	0.5
Jörg Riemann	MPG (IPP-Greifswald)	2021-2023	0.5
Josefine H. E. Proll	DIFFER (Uni. Eindhoven)	2021-2023	0.5
ACHs participants[1]	t.b.d.	2021-2023	2.0
Total resources			7.0

D3.3 / D-SUPPORT-OP2.1	**1, 2, 3, 4**	**Dec. 2023**
Motivation: Once the first OP2 campaign has finalized, specific discharges will have to be considered for support of the experimental analyses and the interpretation of the observed turbulence phenomena.		
SMART deliverable: *(S) Theoretical and numerical simulations for W7-X OP2 discharges. (M) This will include activities related (…) validation between numerical and experimental results with the codes stella, GENE, GENE−3D, EUTERPE and KNOSOS (…).*		

- External experts: R. Kleiber (IPP-Greifswald), M. J. Pueschel (Uni. Eindhoven), etc.
- Ph.D. students: A. González-Jerez, H. Thienpondt and F. J. Escoto from Ciemat, A.
- von Boetticher (Uni. Oxford), etc.

Conclusions and open questions

- Transient **reduced turbulence CIRC scenarios** show **radial localization of impurities** instead of flat profiles $\Rightarrow$ V $\gtrsim$ D or changes in the impurity sources
- NBI heated **(CIRC)** plasmas show also **peaking of Carbon** at the core.
- Although not extensively explored, **radiative collapse has been observed.**
- **D_Z**, although **weaker under CIRC** conditions than for CERC regimes, **still much larger than neoclassical** value. **Threshold on D_{ano}/D_{neo} identified**.
- **Impurity injection** at non-trace levels (B-dropper, TESPEL or LBO) induces **transient confinement improvement**
- **Numerical GK simulations match** reasonably well measurements

Conclusions and open questions

- Will accumulation in turbulence reduced steady state conditions happen?
- What changes undergoes the background turbulence that modify the confinement properties of trace impurities? Is it always ITG-driven transport?
- What is the relative weight of the neoclassical, classical and turbulent contributions to V and their parametric dependence?
- If the low D_{neo} is attributed to the neoclassical optimization, how does it compare with other devices?
- Can we take benefit from auxiliary impurity injection to access high performace (ensuring good thermal bulk confinement without intolerable radiation losses)?

Backup slides

Impurity turbulent transport in real experiments: preliminary result

First comparison produce remarkable results comparing the diffusive coefficient by GENE and STELLA with experimental results from *B. Geiger et al. Nucl. Fusion* ***59*** *046009 (2019)* [red curve] for Fe^{26+}.

Simulations: Non-linear, electrostatic, collisionless fluxtube simulation with 3 kinetic species.

Geiger's paper

Z: Fe^{24+}

$a/L_{T_i} \sim 4$

$a/L_n \sim 1$

$T_e = T_i \sim 1keV$

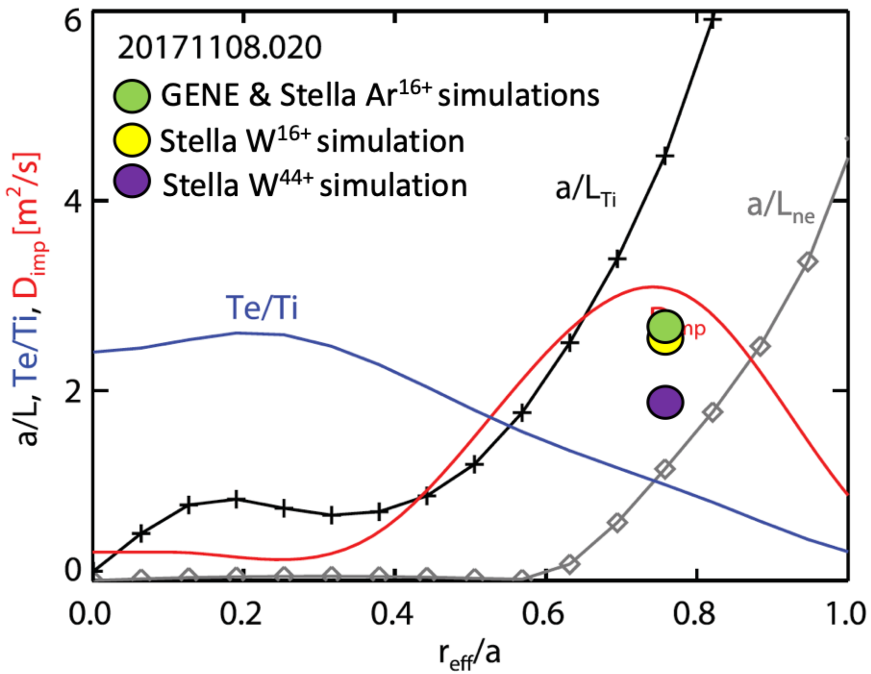
GENE & Stella sims

Z: Ar^{16+} W^{16+} W^{44+}

$a/L_{T_i} = 4 \quad a/L_{n_Z} = 4$

$a/L_n = 0 \quad a/L_{T_Z} = 0$

$T_e = T_i = 1keV$



Non-dedicated simulations: different Z-impurity and small differences in gradients

We know from Langenberg et al PoP 2020 Z, m_Z is not very relevant for D.