Max-Planck-Institut für Plasmaphysik

Gyrokinetic simulations of AUG H-mode, validation & recent advancements

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MAX PLANCK GESELLSCHAFT

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Outline

- **Characterization of an ELM-free ASDEX Upgrade H-mode (K. Stimmel)**
  → M1.3-1.4: “Mode characterization, Single-Scale Simulations”

- **Recent progress on the validation front**
  → M1.5: Validation against as many experiment measurements as possible

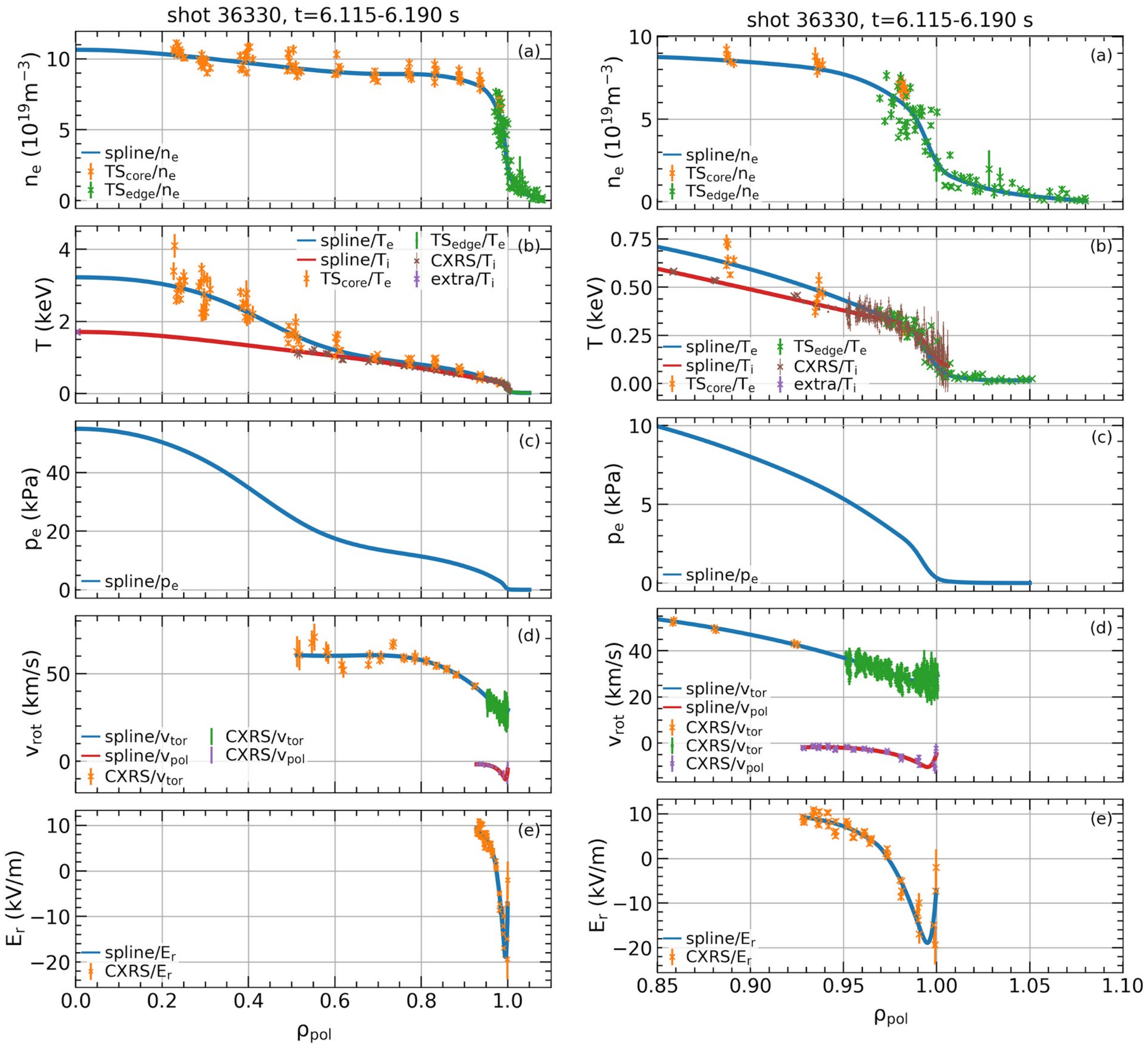
- **A new dilution model in GENE**
  → Possibly facilitating M1.3-M1.5/D1.1 achievements

Gyrokinetic investigation of AUG ELM-Free H-mode #36330

Acknowledgments:
Karl Stimmel (lead investigator), L. Gil, D. Told, M. Cavedon, P. David, M. Dunne, R. Dux, R. Fischer, P. Lauber, A. Kallenbach, F. Jenko, R.M. McDermott, U. Plank, G. Tardini and the ASDEX Upgrade Team

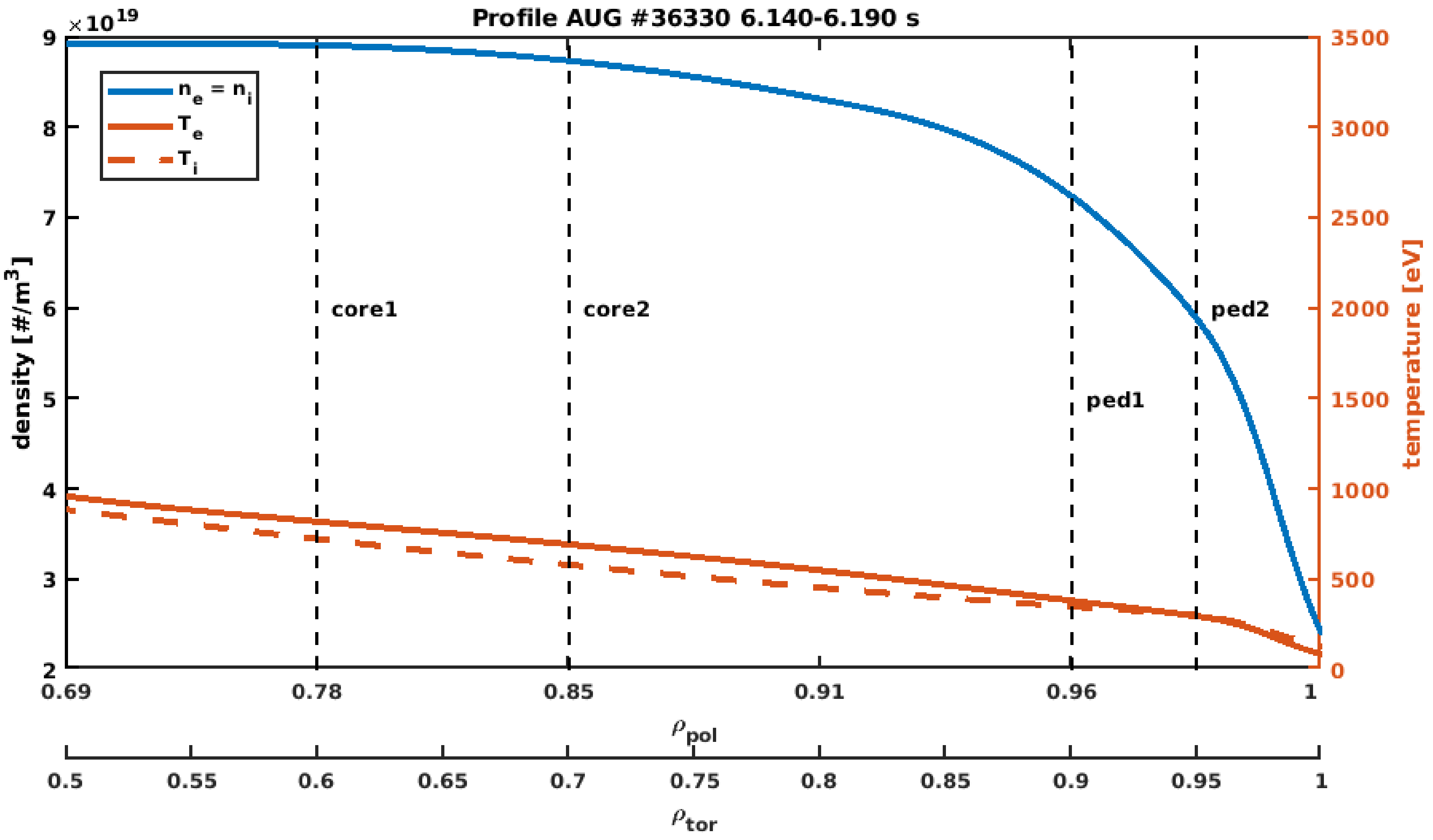
Discharge overview AUG 36330

- Motivation
  - Originally inspired by ECRH ELM-free discharges
    - **Lacked reliable T_i measurements at the time; NBI is required**
  - Well diagnosed ion temperatures, and recently outlined in Kallenbach et al. 2021
- Characteristics
  - Lower single null, favorable ∇B
  - **ELM free** for a few hundred ms from ~6 - 6.2 s
  - ~2.5 MW ECRH, 2.5 MW NBI heating
- Approach
  - Linear/Nonlinear/neoclassical local simulations for radial positions
  - 1 Global electrostatic simulation over the pedestal
  - ExB consistently input from well diagnosed E_{rad} measurement



Discharge overview AUG 36330

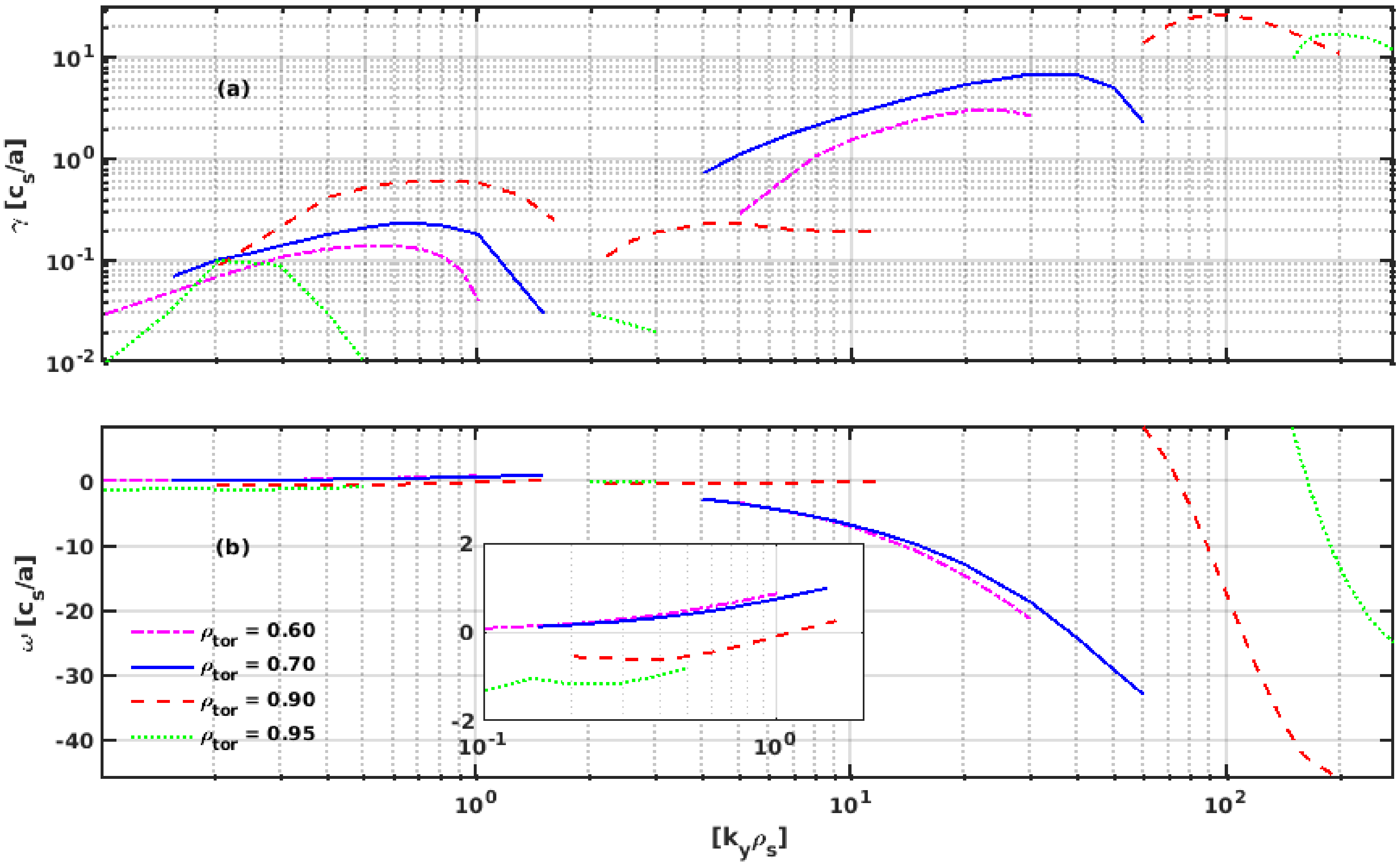
- The 4 radial positions chosen for local simulation



Linear characterization

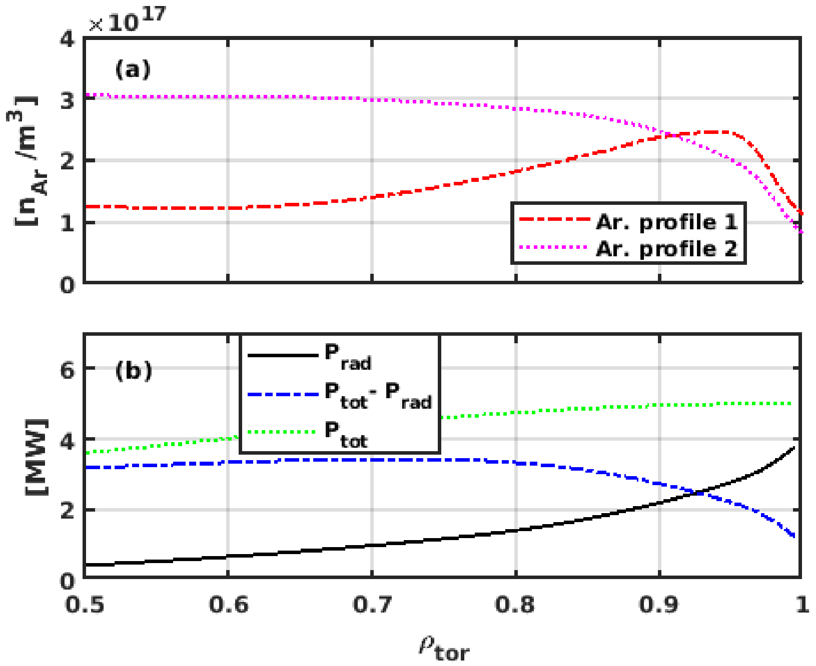
2-species linear local scan:

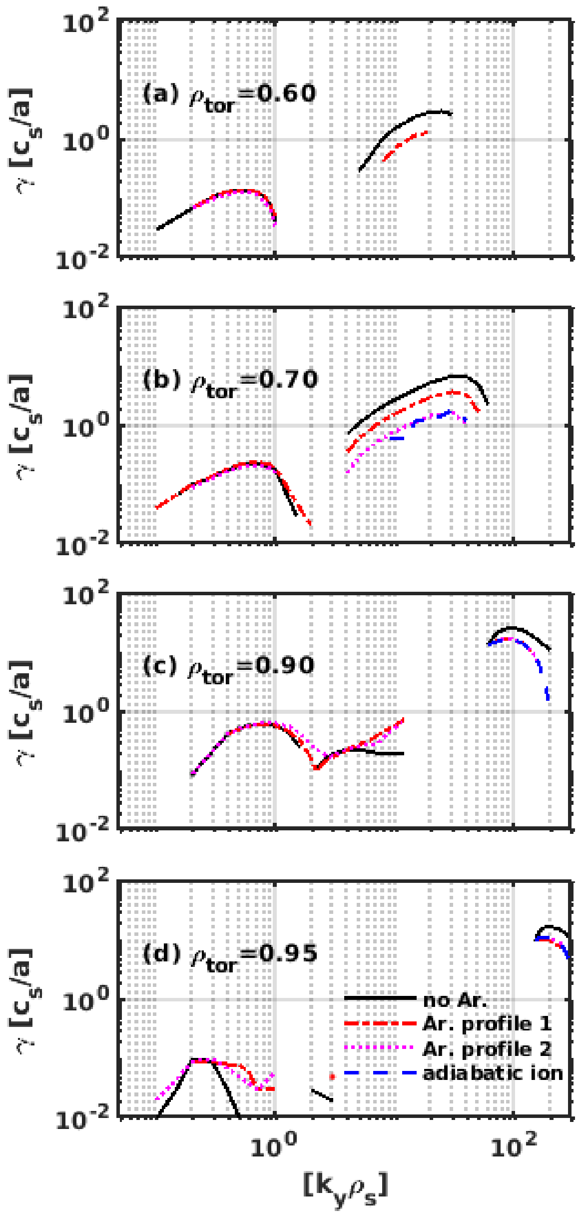
- core characterized as ITG dominated
- pedestal is more complex- ETG/TEM-like dominated



Linear characterization – Argon impact

- 3-species (deuteron, electron, argon ion) linear scans also included
  - Ar. profile 1 is realistic profile, Ar. profile 2 is artificial flat profile to probe effect of argon





- Ion-scale physics captured by two species, but electron scale requires inclusion of argon

- Inclusion of argon is not simply higher or lower growth rate
  - Balance between effect on density gradient (increase heat growth rate) and argon inclusion (tends to decrease growth rate)
  - confirmed nonlinearly

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Nonlinear local

- Extensive nonlinear local simulations performed
- Core simulations match heat flux, pedestal sims do not without global effects
- Ar profile 1 increases heat flux due to gradient increase, while argon profile 2 decreases heat flux since gradient is unchanged

Heat Transport [MW]			ρ_i**-scale**						ρ_e**-scale**	**neo.**	Q_{sum}	
			e.s. channel			e.m. channel						
radial position	ρ_i mod.	ω_{prof}	ion	e^-	Ar	ion	e^-	Ar	ρ_e sum		sim.	TRANSP
$\rho_{\mathrm{tor}} = 0.60$	–	ω_{tor}	2.11	0.82	–	-0.03	0.02	–	0.06*	0.48	3.46±0.14	3.36
	$\omega_{Ti} - 15\%$	ω_{tor}	0.83	0.34	–	-0.01	0.00	–			1.70±0.00	
$\rho_{\mathrm{tor}} = 0.70$	–	ω_{tor}	4.32	1.96	–	-0.05	0.03	–	0.14*	0.56	6.96±0.01	3.44
	$\omega_{Ti} - 15\%$	ω_{tor}	2.38	1.14	–	-0.02	0.02	–			4.22±0.14	
	+ Ar prof. 1	ω_{tor}	4.68	2.09	0.00	-0.05	0.03	0.00			7.45±0.27	
	+ Ar prof. 2	ω_{tor}	3.19	1.43	0.01	-0.04	0.02	0.00			5.31±0.14	
$\rho_{\mathrm{tor}} = 0.90$	–	ω_{tor}	12.68	23.36	–	-0.14	1.40	–	0.03	0.60	37.93±1.29	2.75
	–	ω_{psu}	5.48	9.34	–	0.20	0.92	–			16.57±0.76	
	$\beta_e = 0$	ω_{psu}	2.38	4.53	–	–	–	–			6.91±0.14	
$\rho_{\mathrm{tor}} = 0.95$	–	ω_{tor}	1.88	3.15	–	0.00	0.15	–	0.00	0.88	6.06±0.18	2.22
$\rho_{\mathrm{tor}} = 0.84$ - 0.96	$\beta_e \sim 0$	ω_{tor}	1.38	2.40	–	–	–	–	–	–	3.77±0.19	–
$\rho_{\mathrm{tor}} = 0.84$ - 0.96	$\beta_e \sim 0$	ω_{psu}	0.04	0.08	–	–	–	–	–	–	0.12±0.002	–

Global simulations

- The type of toroidal shear profile used is crucial in pedestal -
  - Using simply toroidal velocity from core in pedestal is incorrect
  - Including a realistic velocity profile reduces heat flux
- Global EM would likely correct discrepancy but is left to future work due to computational cost
- Challenges with pedl. 3 species (comp. cost)
- QCM not clearly observed in any simulations yet

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			e.s. channel			e.m. channel						
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Summary ELM-free AUG H-mode study

- **Linear characterization** of **core ITG**, **pedestal ETG/TEM**
- Nonlinear **core simulations reproduce experimental heat fluxes**
- **Global simulations correct** local heat flux **overprediction** at pedestal top
- **Quasicoherent mode (QCM) not observed**, global nonlinear EM or crossing separatrix (→ TSVV4) may be necessary
- Current work written in manuscript to be submitted to JPP soon
- **Additional analysis** (not shown): linear collisionality, beta scan, quasilinear analysis
- **Future challenges/goals:**
  - Global nonlinear EM simulation
  - 3 species in pedestal
  - Approaching or crossing separatrix (challenging to also get experimental data)

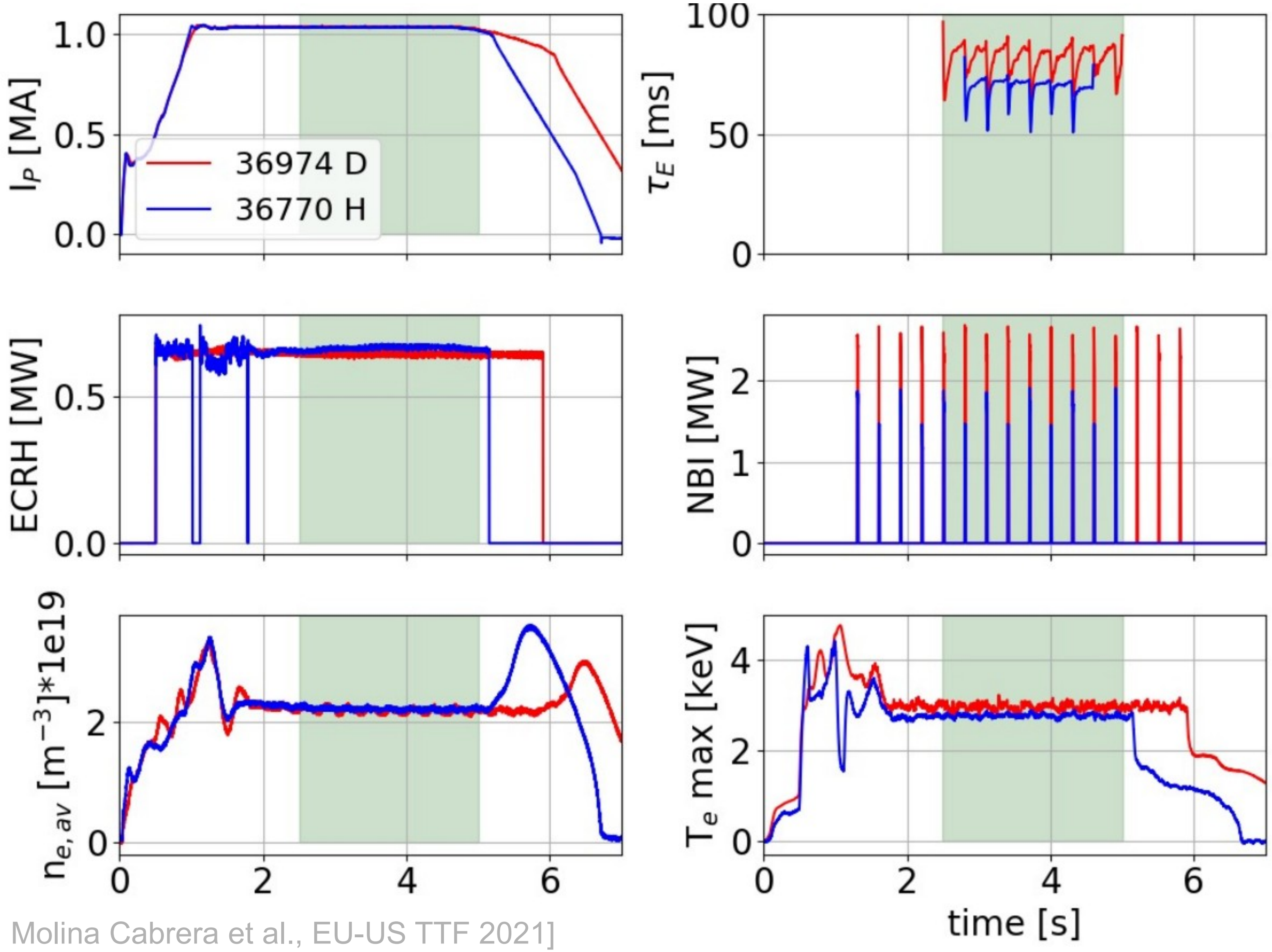
Validation in ASDEX Upgrade Hydrogen & Deuterium L-mode plasmas

Acknowledgments:
P. Molina Cabrera[2,1*], P. Rodriguez Fernandez[1], M. Bergman[2], R. Bielajew[1], G. D. Conway[2], K. Höfler[3,2], C. Yoo[1], A. E. White[1], and the ASDEX Upgrade team

[1]Plasma Science and Fusion Center, MIT Cambridge MA, United States
[2]Max-Planck-Institut für Plasmaphysik, Garching, Germany
[3]Physics Department, Technical University Munich, Garching, Germany

Plasma scenario description

Low-density (n_e = 2.3 $10^{19} m^{-3}$), ECRH heated (650kW) L-mode



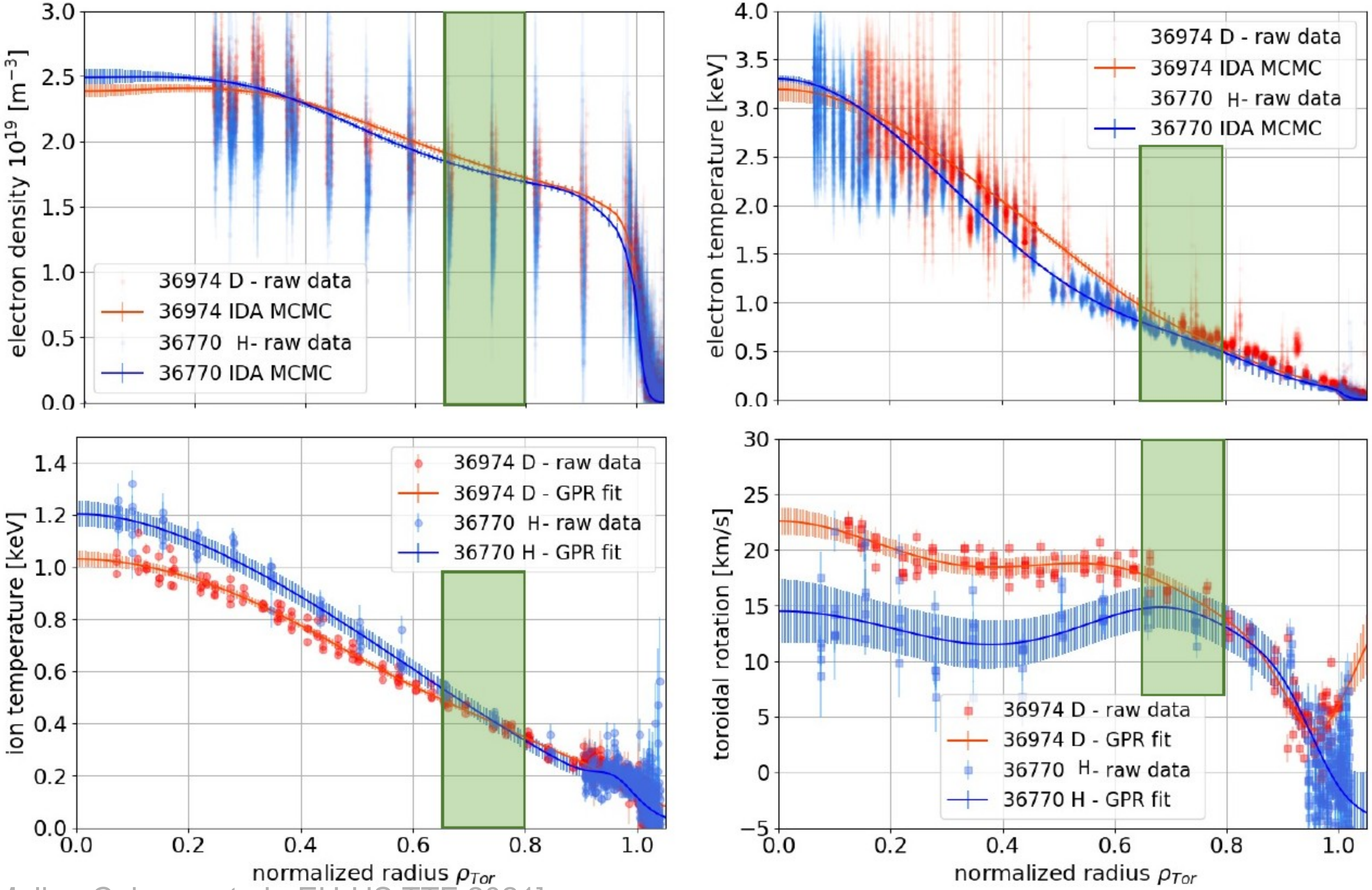
[P. Molina Cabrera et al., EU-US TTF 2021]

- Keep shape, I_P, n_e, and P_{ext} (ECRH) constant and change ion mass.
  - Te, Ti profiles to evolve differently

- Color scheme:
  - Hydrogen = BLUE
  - Deuterium = RED

Profiles and fits with IDA Markov Chain/Monte-Carlo (MCMC)

n_e/P_{ECRH} constant ➢ $T_i(H) > T_i(D)$ and $T_e(D) > T_e(H)$



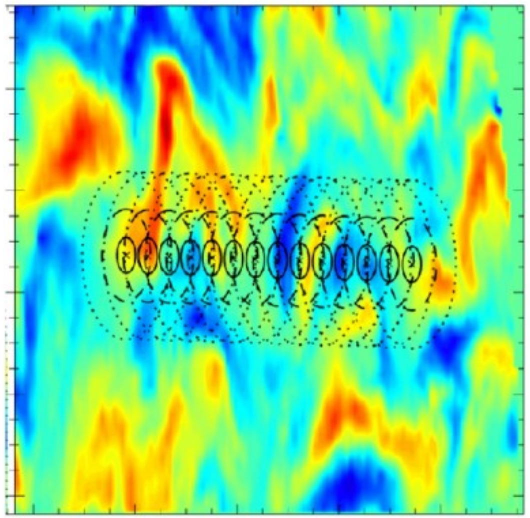
Region of Interest (ROI) where turbulence measurements are available

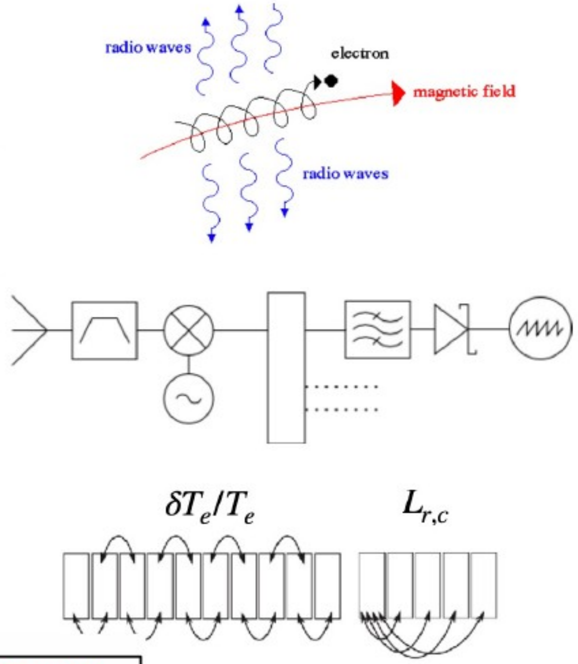
ρ_T 0.65-0.8

[P. Molina Cabrera et al., EU-US TTF 2021]

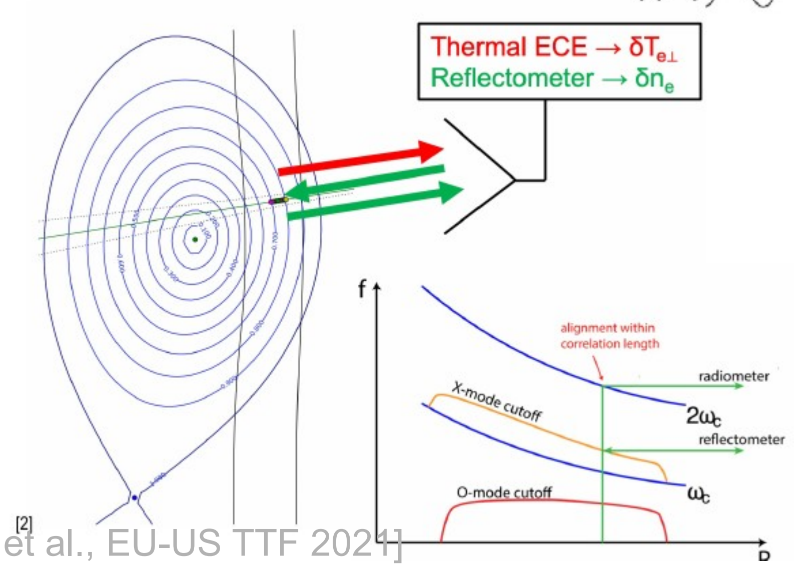
dTe/Te and nT-crossphase diagnostics

GENE dTe fluctuations + CECE geometry





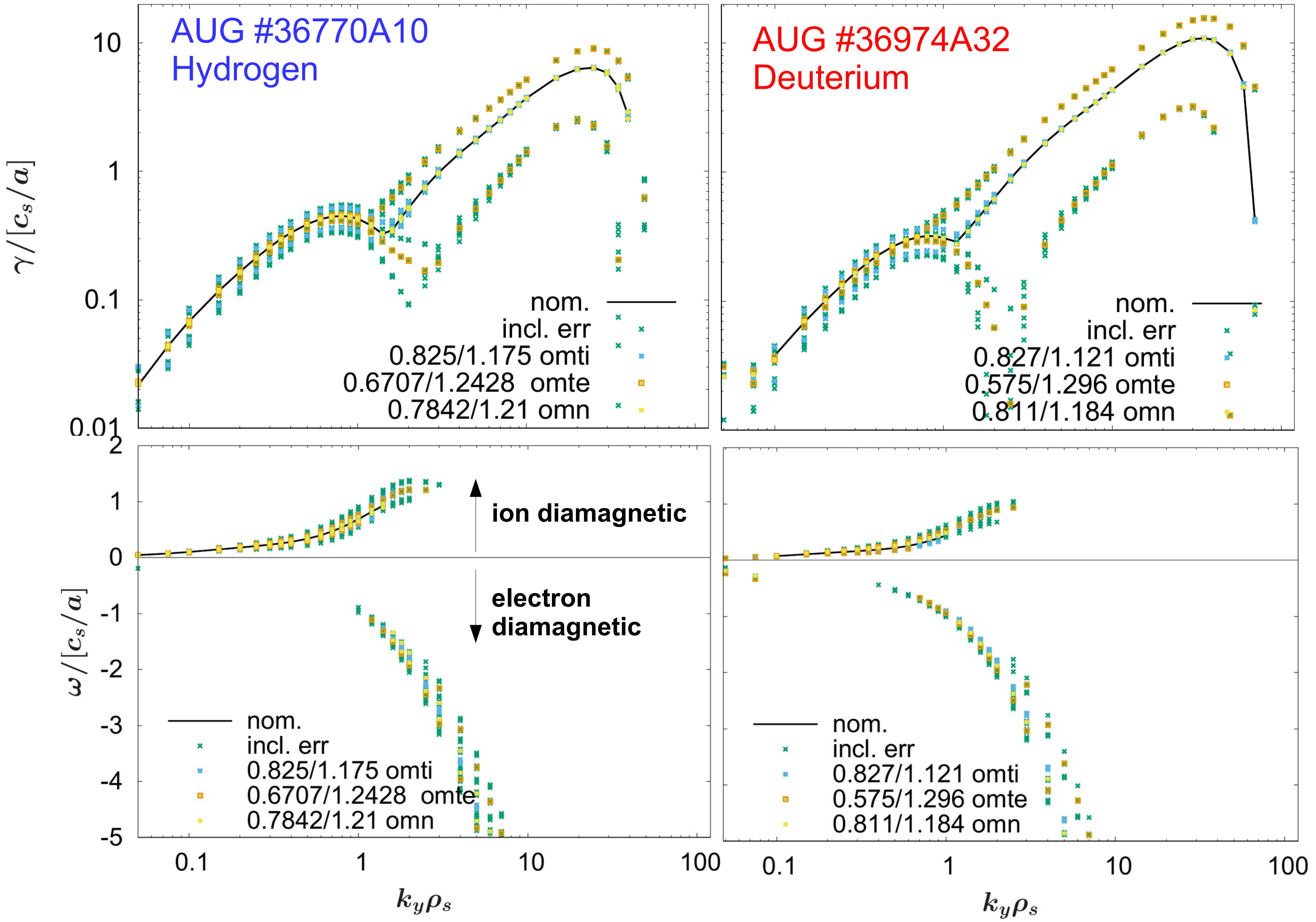
- Electron cyclotron emission ECE allows T_e measurements
- Correlation ECE focus on T_e fluctuations down to 0.1% using cross-correlation
- Measure $dT_e/T_e(f)$, $dT_e/T_e(rms)$, $L_{r,c}$ at $k_\theta \rho_s < 0.4$
- AUG has a 24-ch CECE [1,2]



- Couple reflectometer and CECE into same volume: cross-phase between δn_e and δT_e

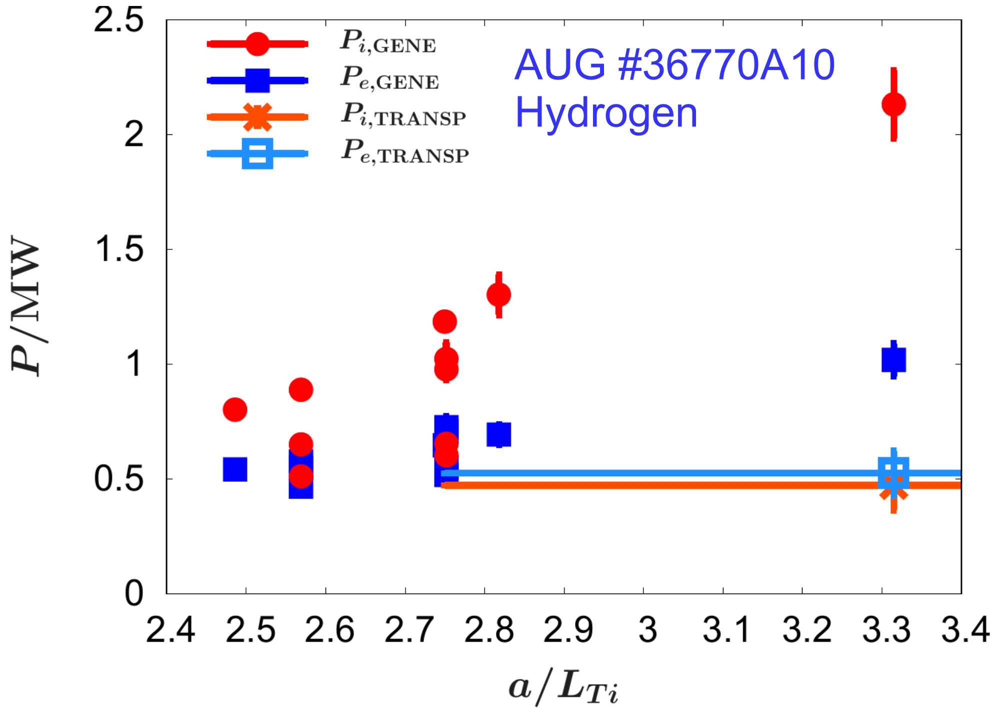
[1] Creely et al., Rev of Sci Instr **89**, 053503 (2018)
[2] Freethy et al., Phys. Plasmas 25, 055903 (2018)
[3] Hillesheim J., Physics of Plasmas **20**, 056115 (2013)
[4] Whie A. E., Phys. Plasmas **17**, 056103 (2010)

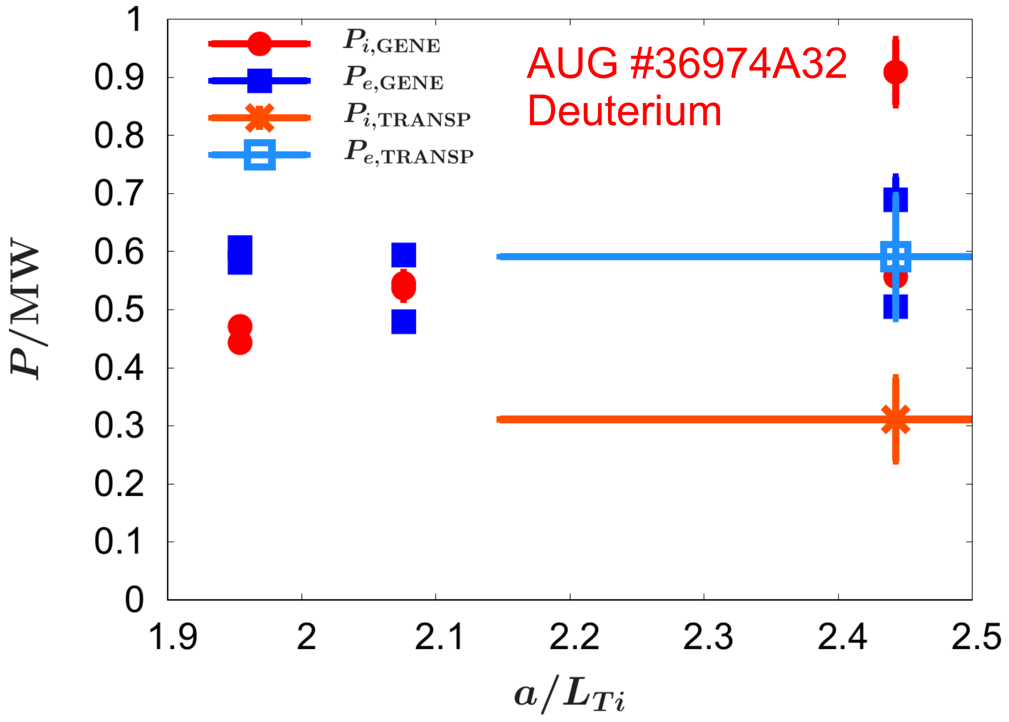
Linear characterization at t=2.45s, ρ_{tor} = 0.75



- Robust ITG on low-*k* ion-scales and ETG on electron scales for both plasmas
- a/L_{Ti} main driver on ion-scales
- Deuterium shows possible transition to dominant TEM at medium-*k* for multiple gradient variations
- Overall ITG/ETG growth rates smaller/larger from H-to-D
- All sims performed with revised IDE equilibria

Nonlinear flux-matching attempts

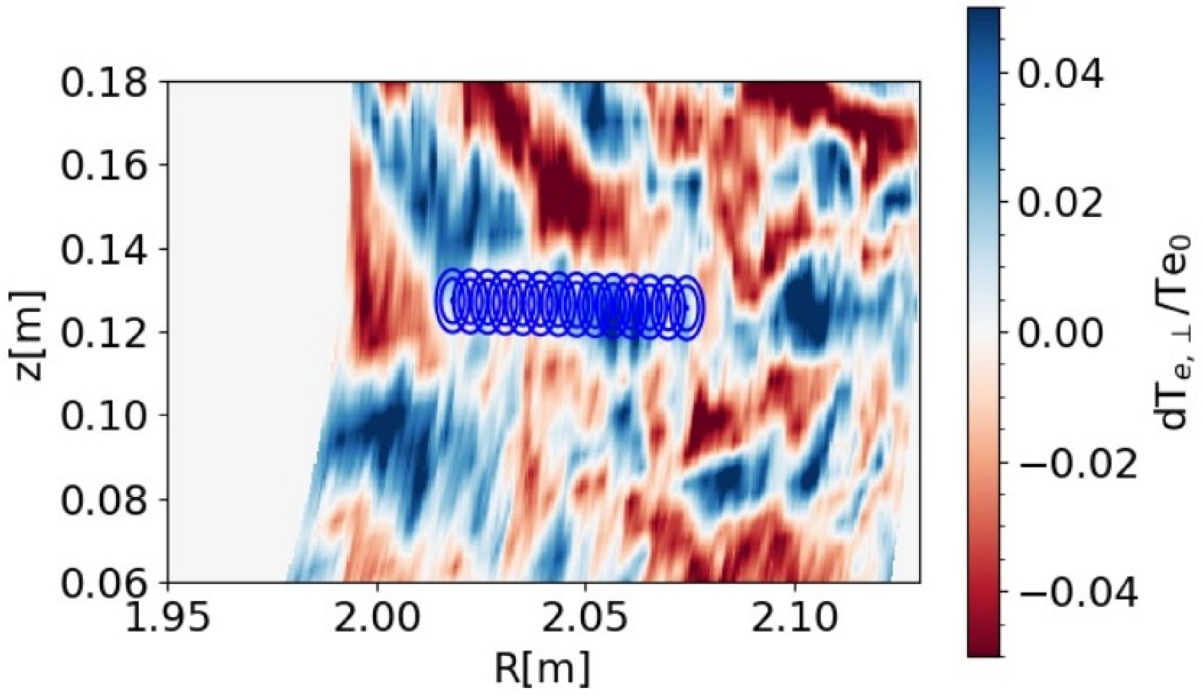




- **Additional scans included above:**
  increased a/L_{Te}, increased/decreased a/L_n, increased ExB shear, 2-species vs. 3-species, increased Z_{eff} (only H)

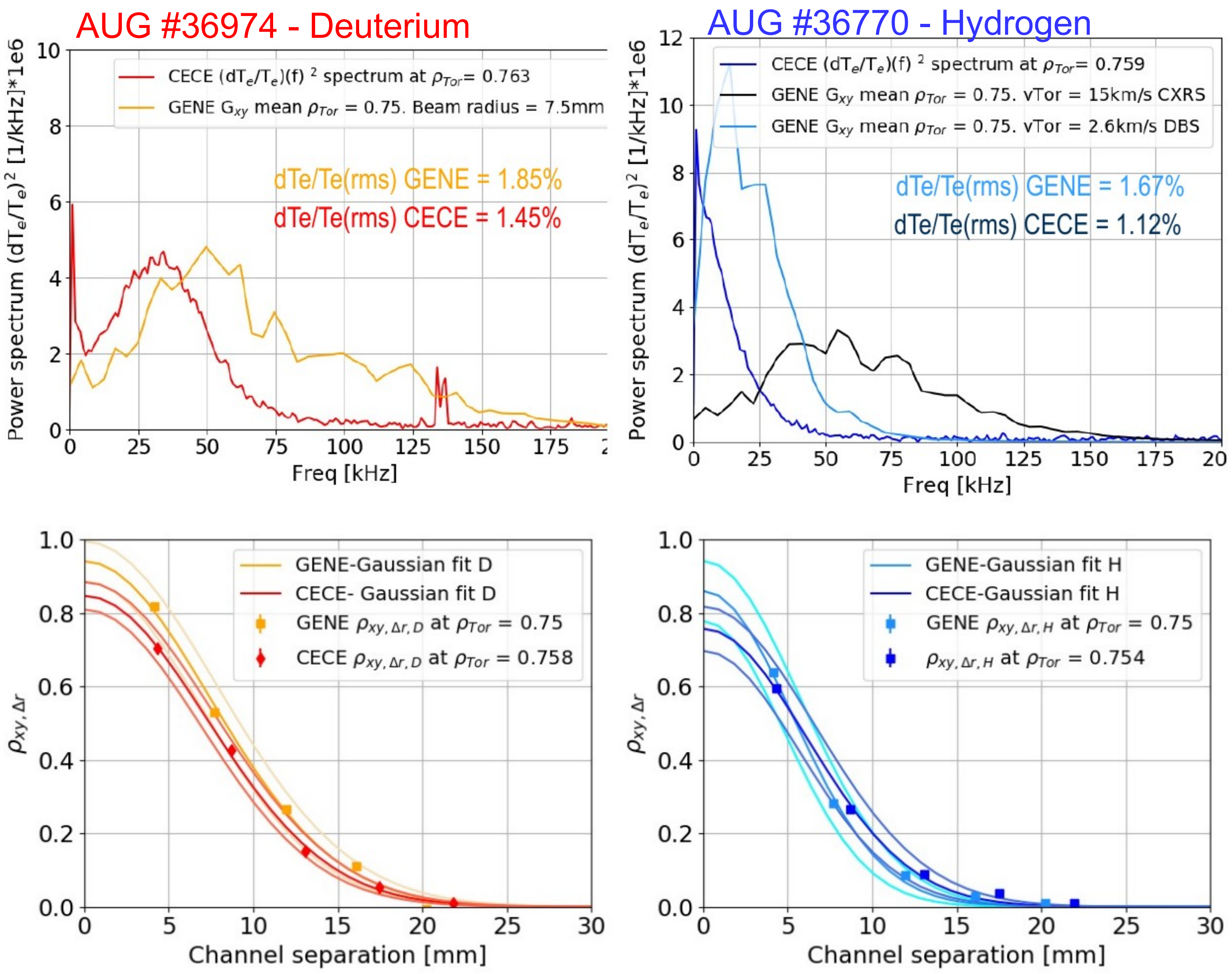
- **Electron heat flux (more relevant to CECE?) well matched while ion heat flux requires lots of variations**

GENE synthetic diagnostics



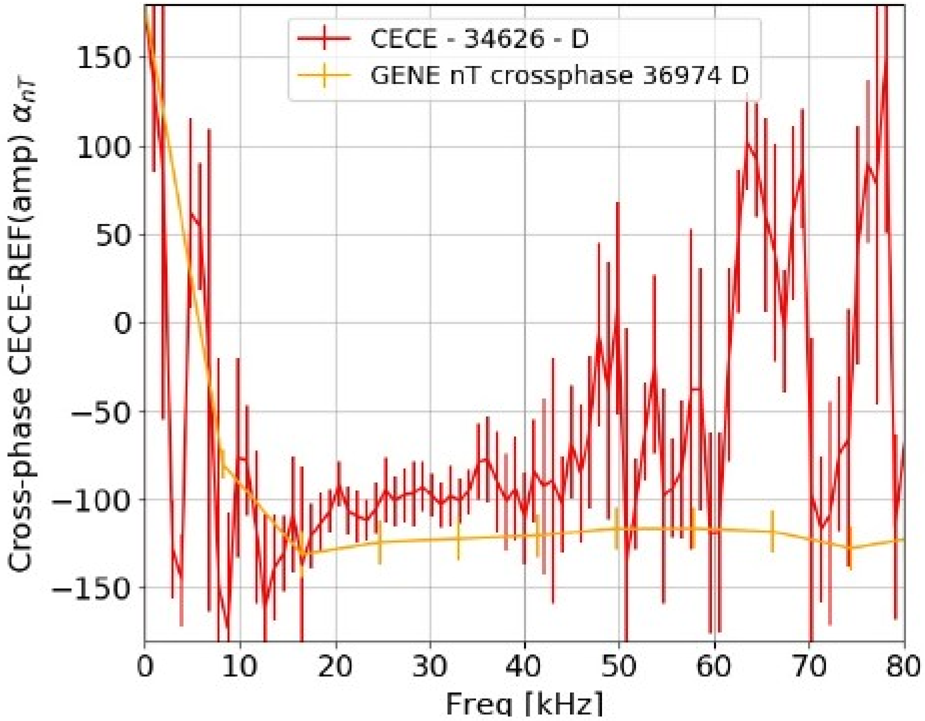
- Interpolate GENE flux-tube data to fine-grained, equidistant time steps
- Apply phase factor for translation from co-moving to lab frame
- Map flux-tube to cylindrical coordinates and extract poloidal cross-section
- Apply spatio (-temporal) filters best matching the diagnostics specifications
- New: Split coordinate mapping (IDL) and filter application (Python) for improved flexibility

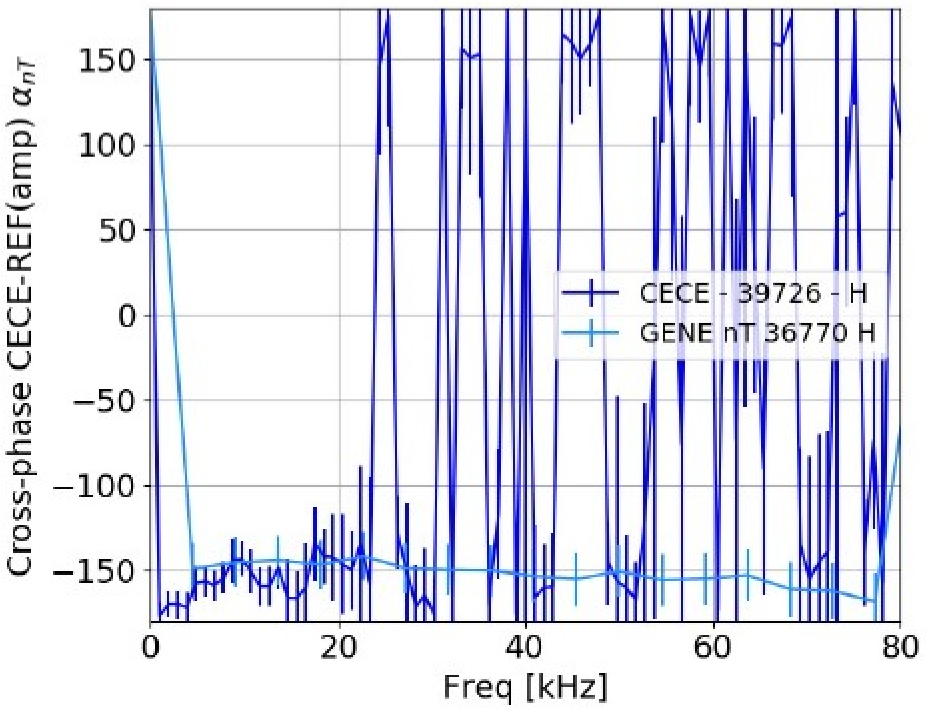
Comparing CECE with GENE



- Found strong impact of background v_{Tor} in H
  - DBS closer to experiment
- GENE $dT_e/T_e(f)$ features power in higher frequencies not found in CECE
- Radial correlations agree within fit uncertainty in both

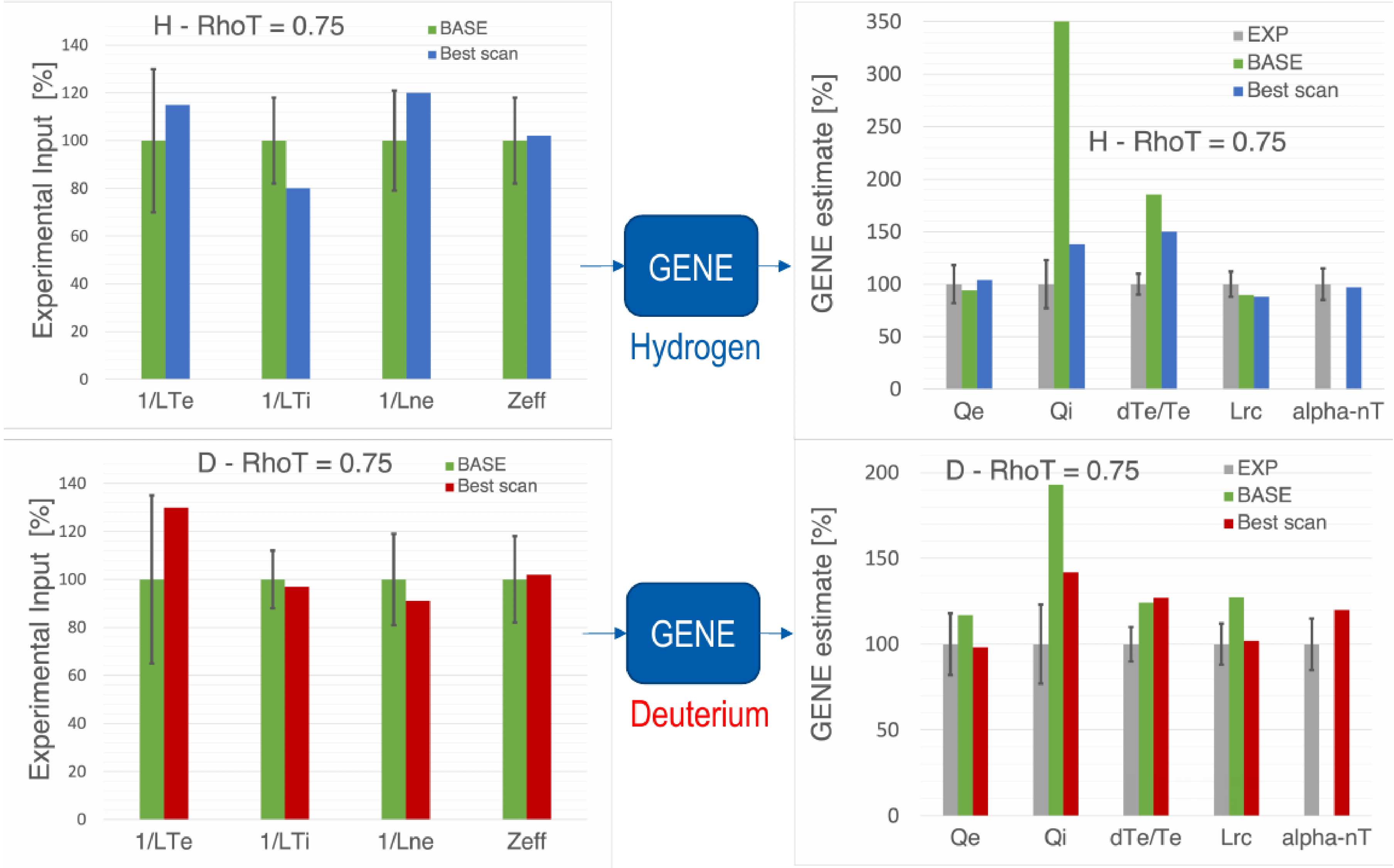
Comparing nT cross-phase with GENE





- **Agreement inside error bars** for both species
- **GENE recovers experimental decrease** in nT cross-phase in H and D

Validation results so far



Gradient scans have brought all quantities within 2 sigma. Qi hardest to match, so far.

Conclusion AUG L-mode validation

- **Significant fluctuation properties changes** observed between H/D:

  dT_e/T_e (D) > dT_e/T_e(H) L_{rc} (D) > L_{rc} (H) α_{nT} (D) > α_{nT} (H)

- **All trends recovered by GENE** - agreement in D between GENE and CECE with new antenna greatly improved from ~66% mismatch reported by Freethy, Görler et al. in 2018 to 25%

- **Ion heat flux overestimated** by GENE (but also TGLF)
  Could be specific to these shots. Model physics or improve profile fit(s)?

- **Next step:** Move from outer-core to very edge (rtor~0.925) → larger T_i uncertainties, detailed error estimates needed / on-going

- **Further AUG validation:** On-going outer-core comparison for **AUG turbulence reference discharge** incl. ECRH scan → edge application further delayed due to unforeseen unavailability of key experimentalists

A dilution model in GENE

A dilution model in GENE

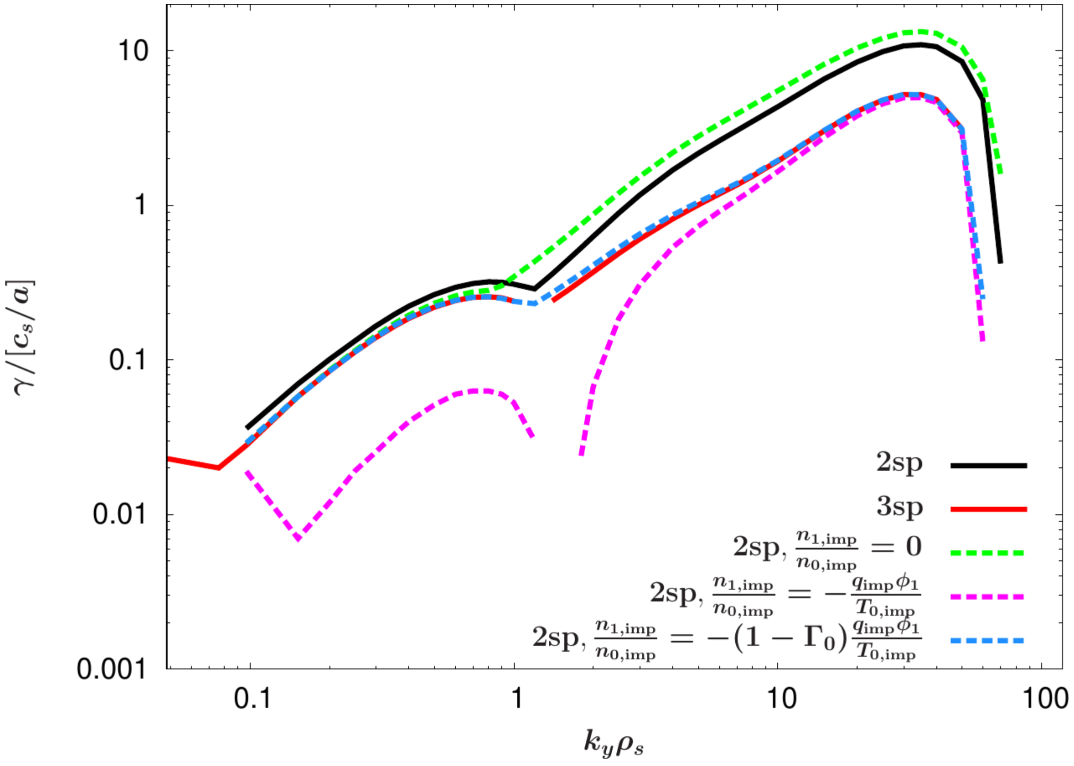
- **Traditionally not considered**
  - ➔ usually, multi-species treatment quite feasible for core treatment
  - ➔ ‘dangerous’ assumption, ions with dynamical effects on bulk ions (e..g., similarities with bulk ions, or resonant fast ions) [Estrada-Mila 2005, Holland 2012, Di Siena 2018], significant impurity transport

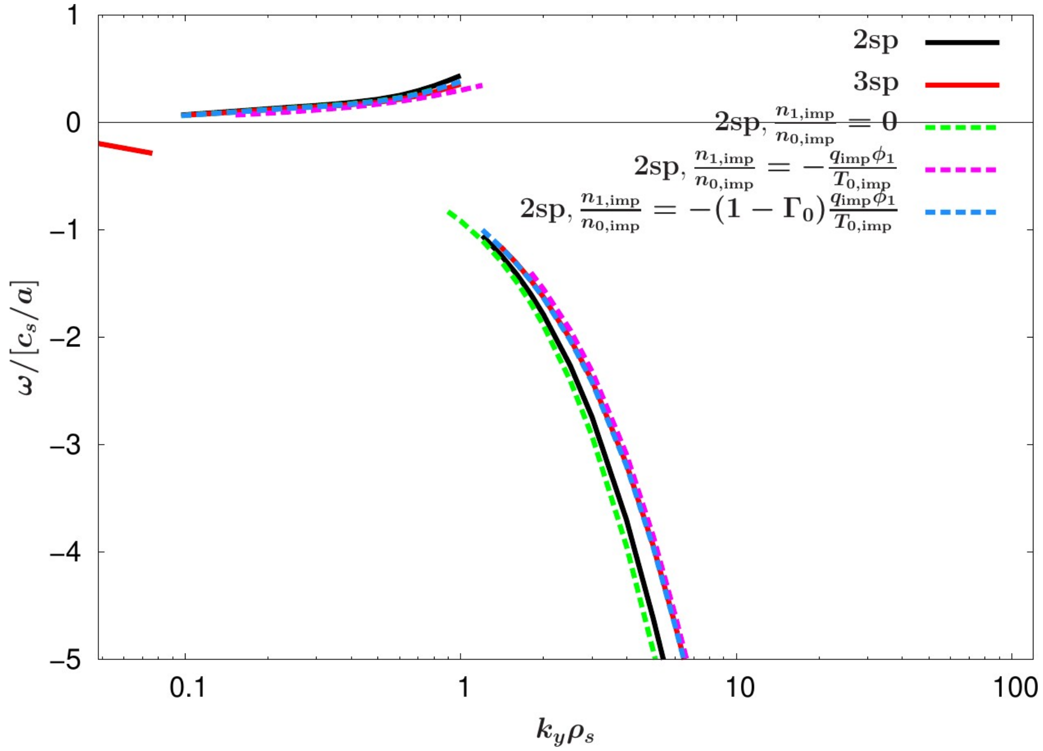
- **Situation changes for non-resonant, insignificant transport impurities**
  - ➔ **capture main effect (dilution) w/o solving GK equation for species may reduce overall computational time dramatically**
  - ➔ **relevant to global simulation, local edge simulations (high resolution) and large parameter scans.**

- **Possible choices:**
  - ➔ Keep only ‘true’ equilibrium effects (e.g., total pressure gradient) and set, e.g., n_1=0
  - ➔ Same as above but assume adiabatic response of dilution species
  - ➔ Same as above but assume f_1=0 only, i.e. keep, for instance, polarization density in Poisson’s equation

A dilution model in GENE

- **Possible choices:**
  - Keep only 'true' equilibrium effects (e.g., total pressure gradient) and set, e.g., n_1=0
  - Same as above but assume adiabatic response of dilution species
  - Same as above but assume f_1=0 only





- Remarkably good agreement for 3rd option → saves 1/3 of runtime

Conclusions

Summary

- **Mode and turbulence characterization in Ar-seeded ELM-free AUG H-mode (K. Stimmel)**
  - Core heat fluxes matched with local simulations, global simulations in ballpark for pedestal turbulence
  - M1.3-1.4: “Mode characterization, Single-Scale Simulations” largely fulfilled for this scenario, refinements required
- **Validation against AUG L-mode isotope scan**
  - Trends captured, good agreement in cross-phases and radial correlation lengths, improved agreement in cross-power spectra
  - Application to very-edge on-going, similarly foreseen for AUG turbulence reference discharge
  - M1.3-M1.4+validation (M1.5) largely addressed → very-edge application needed for fulfillment
- **New dilution model in GENE**
  - Dilution species feature now available
  - May provide access to wider parameter space for dynamically insignificant impurities

Thank you for your attention!

APPENDIX

IDA MCMC profile fit details

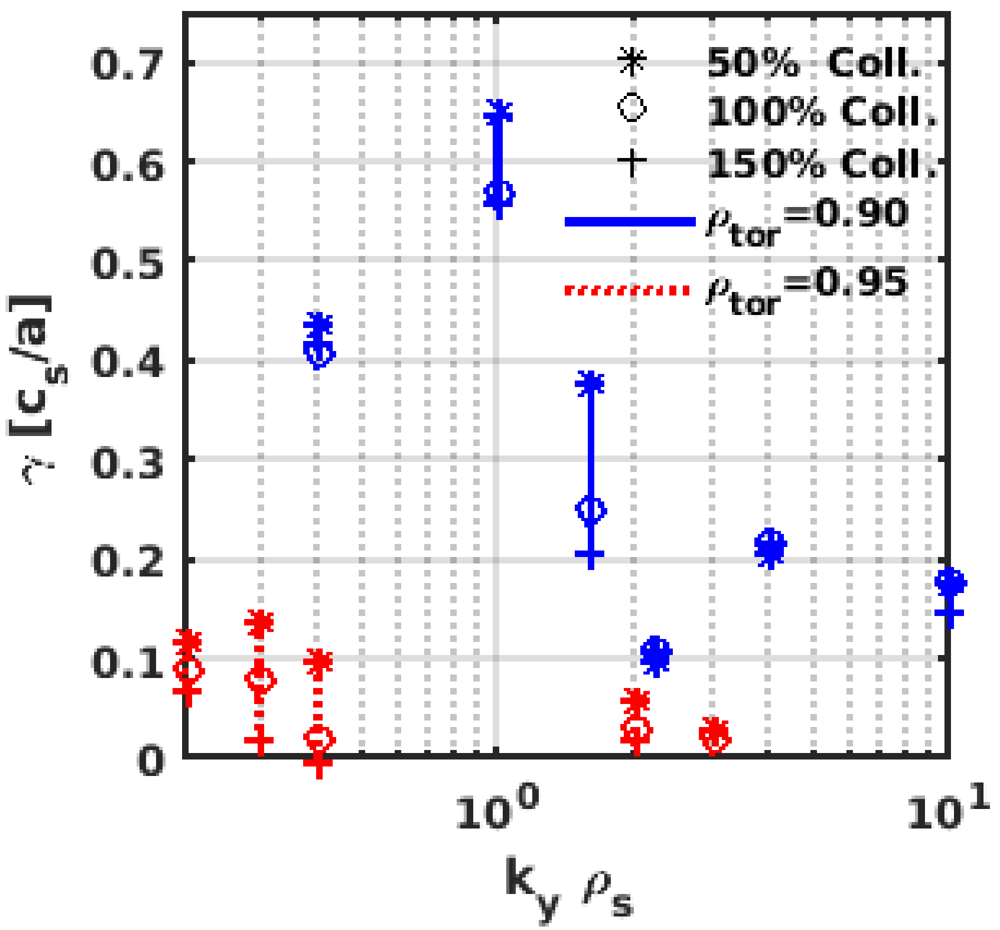
- **Various approaches to profile fitting at AUG**

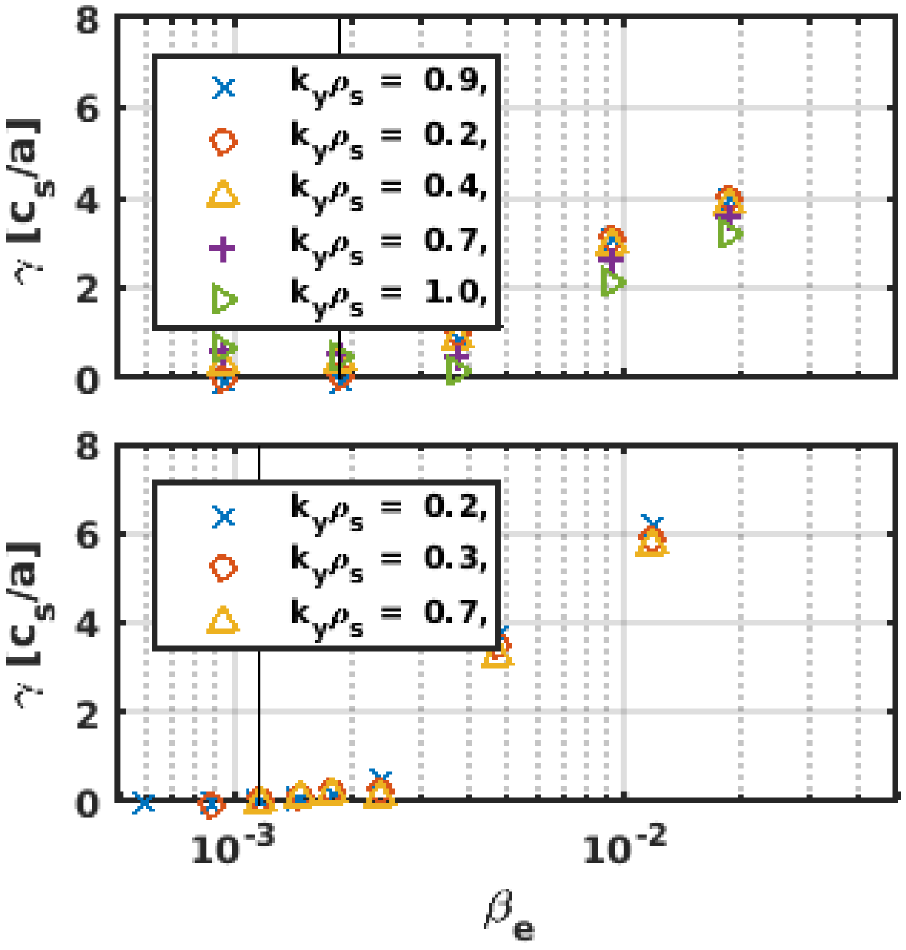
- **IDA[1] takes an integrated approach taking into consideration many diagnostics**
  - Standard available after every discharge may feature large variations in the profile gradients.
  - Error bars are not indicative of profile uncertainty but rather disparity between diagnostics.

- **IDA-MCMC [2] is a more complete sampling of error/fit distribution function, however, very time intensive**
  - Depending on quality of data number of spline points can also lead to large ‘oscillations’ in the profile gradients
  - For this study, used a 8 spline points. Chosen rather arbitrarily, so there’s room to improve.

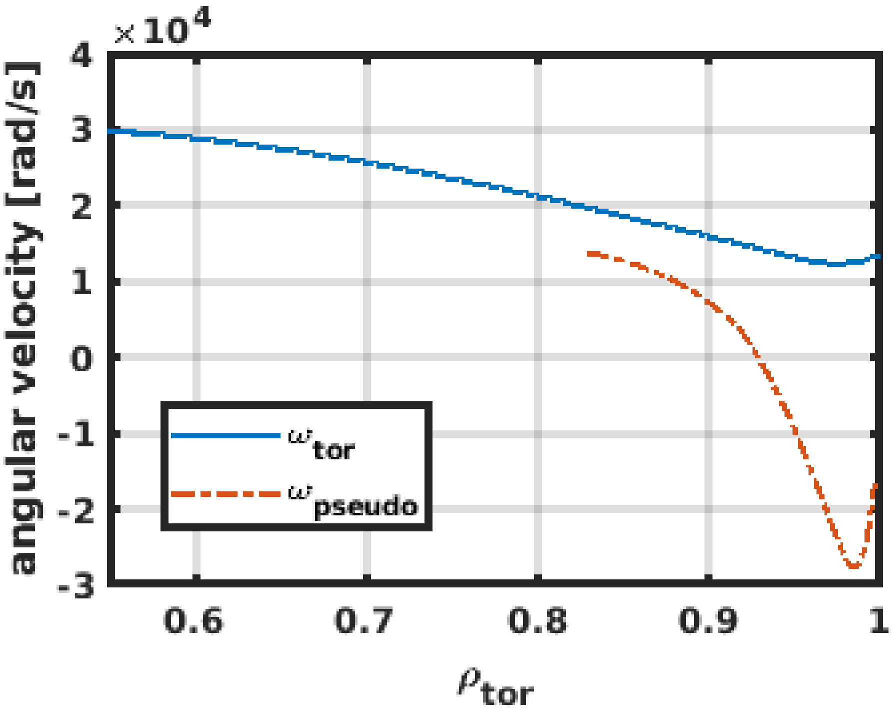
[1] Weisen H, et al. 2020, Journal of Plasma Physics 86 905860501
[2] R. Fischer et al. 2020. Fusion Science and Technology Vol 76, 879-894

Backup: linear scans

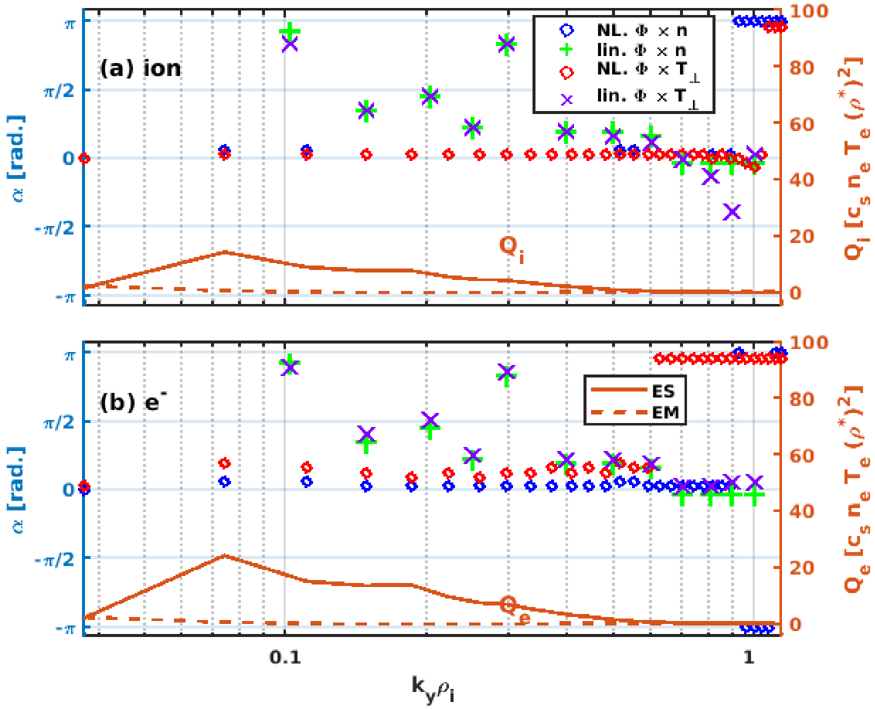




Backup

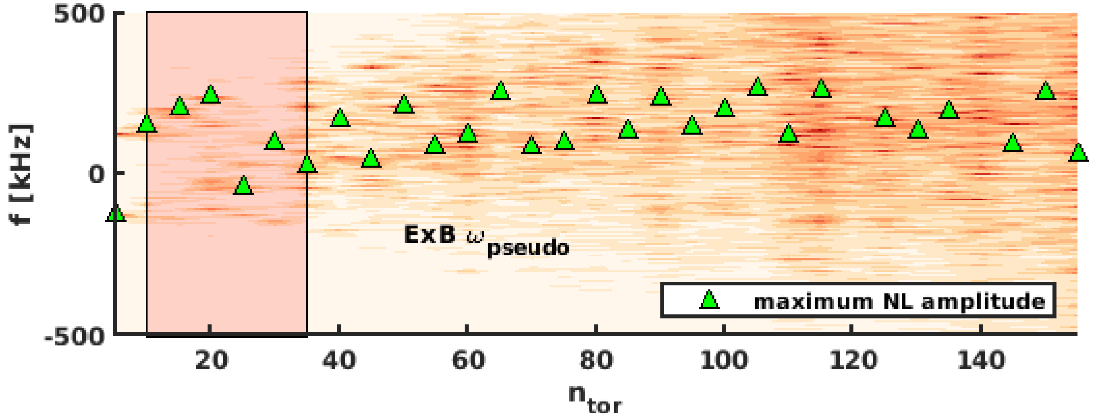


×10^4
angular velocity [rad/s]
ρtor
ωtor
ωpseudo

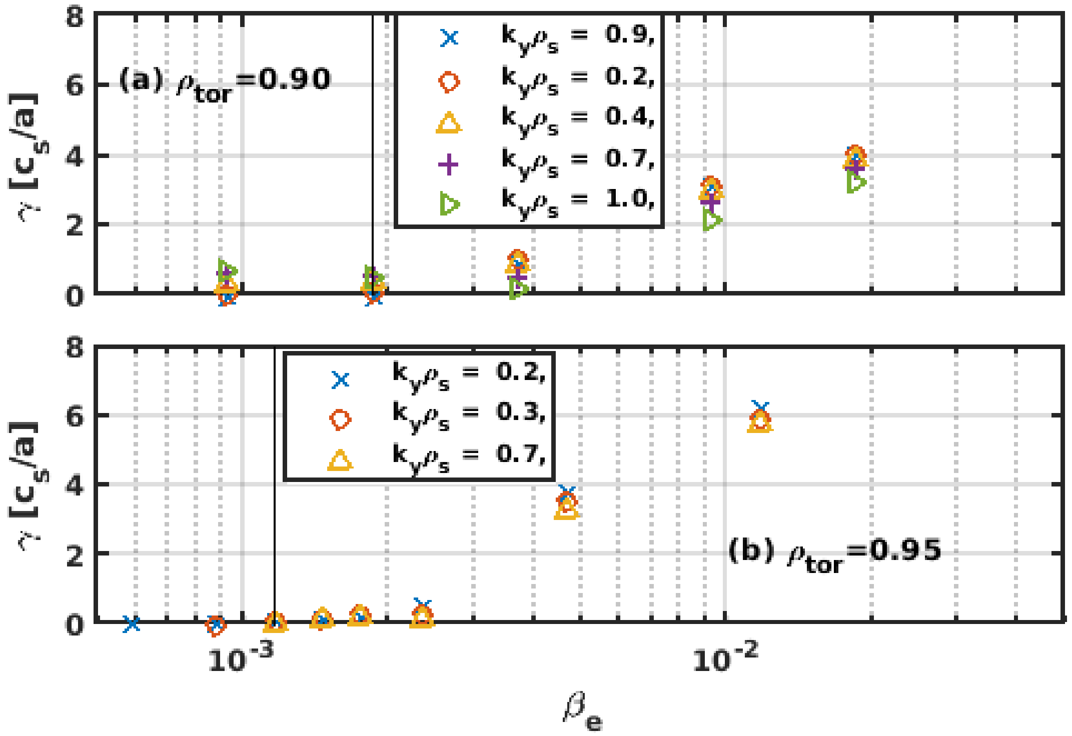


(a) ion
(b) e-
NL. Φ × n
lin. Φ × n
NL. Φ × T⊥
lin. Φ × T⊥
ES
EM
α [rad.]
Qi [cs ne Te (ρ*)2]
Qe [cs ne Te (ρ*)2]
Qi
Qe
kyρi

Backup

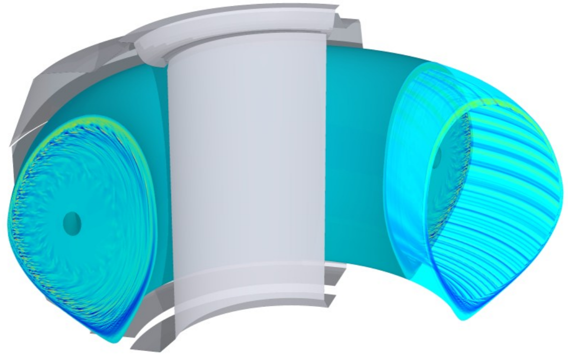


500
0
-500
f [kHz]
20
40
60
80
100
120
140
n_{tor}
ExB ω_{pseudo}
maximum NL amplitude



(a) ρ_{tor}=0.90
$k_y\rho_s$ = 0.9,
$k_y\rho_s$ = 0.2,
$k_y\rho_s$ = 0.4,
$k_y\rho_s$ = 0.7,
$k_y\rho_s$ = 1.0,
γ [c_s/a]
$k_y\rho_s$ = 0.2,
$k_y\rho_s$ = 0.3,
$k_y\rho_s$ = 0.7,
(b) ρ_{tor}=0.95
10^{-3}
10^{-2}
β_e

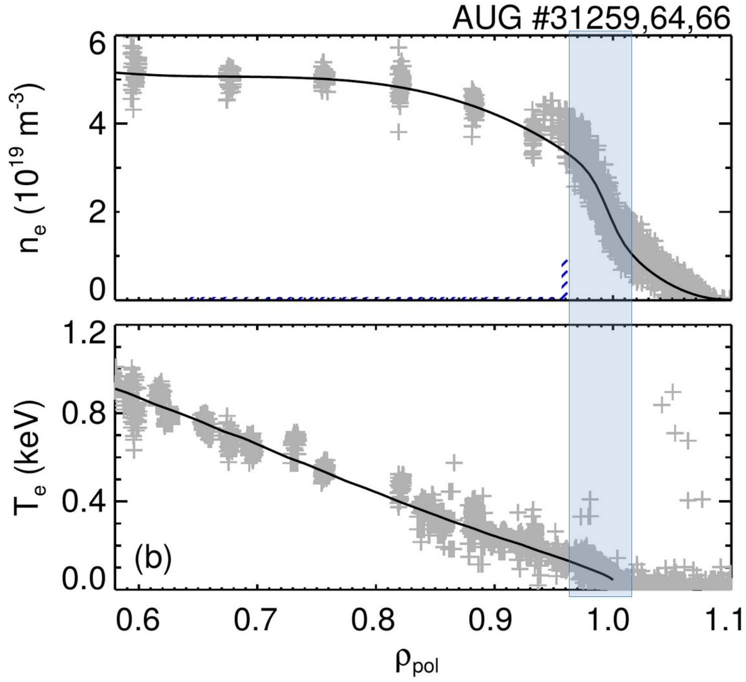
Some challenges on the way to edge/pedestal ...



- **Strongly shaped and varying geometry**
  - → appropriate configuration space discretization / choice of coordinates
  - → X-point treatment? (outlook at end)

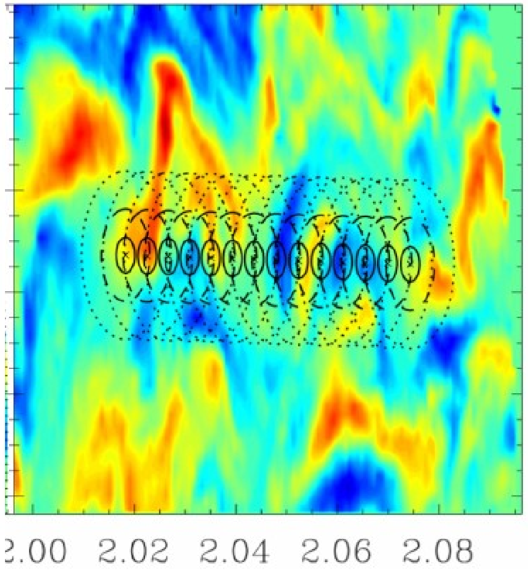
- **3D effects**

- **Steep gradients in density and temperature profiles**
  - → strongly driven turbulence, electromagnetic modes
  - → velocity space discretization challenging
  - → low temperatures ↔ collisionality relevance

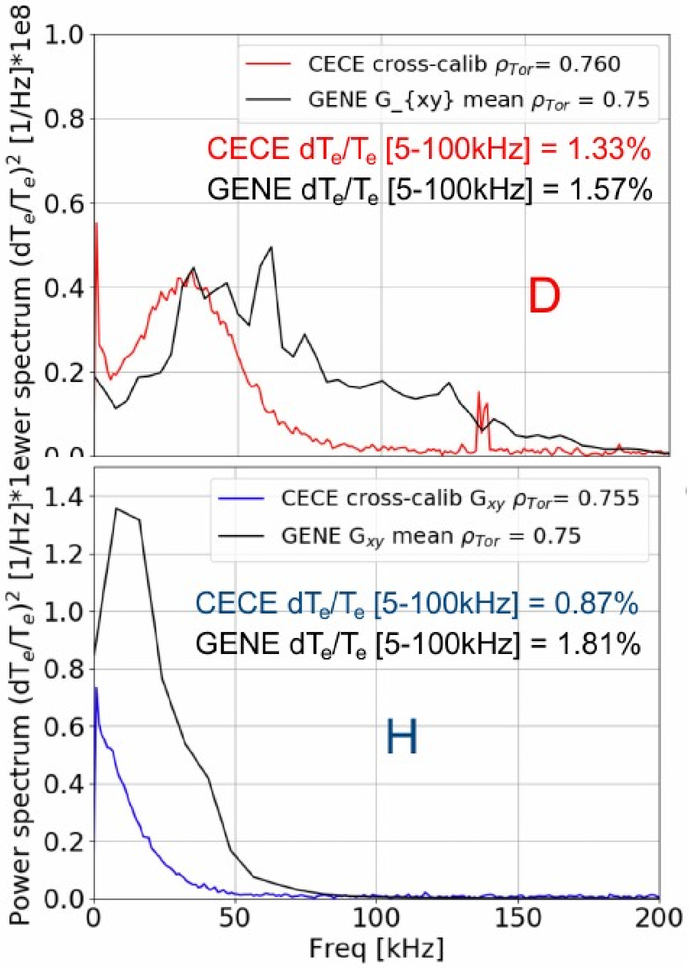


- **Global effects and eventually Breakdown of gyrokinetics?**
  - → *here: take gyrokinetics to extreme & check performance a posteriori* (similar to quasilinear transport modeling)
  - → studies in astrophysics sometimes find breakdown much later than usually expected [D. Grošelj et al., ApJ 847, 28 (2017)]

CECE comparisons in AUG L-mode (D/H)



	Qi [MW]	Qe [MW]	dT/T [%]
Exp. GENE	0. 31 0.41	0.59 0.51	1.33 1.57
Exp. GENE	0.47 0.65	0.53 0.55	0.87 1.81

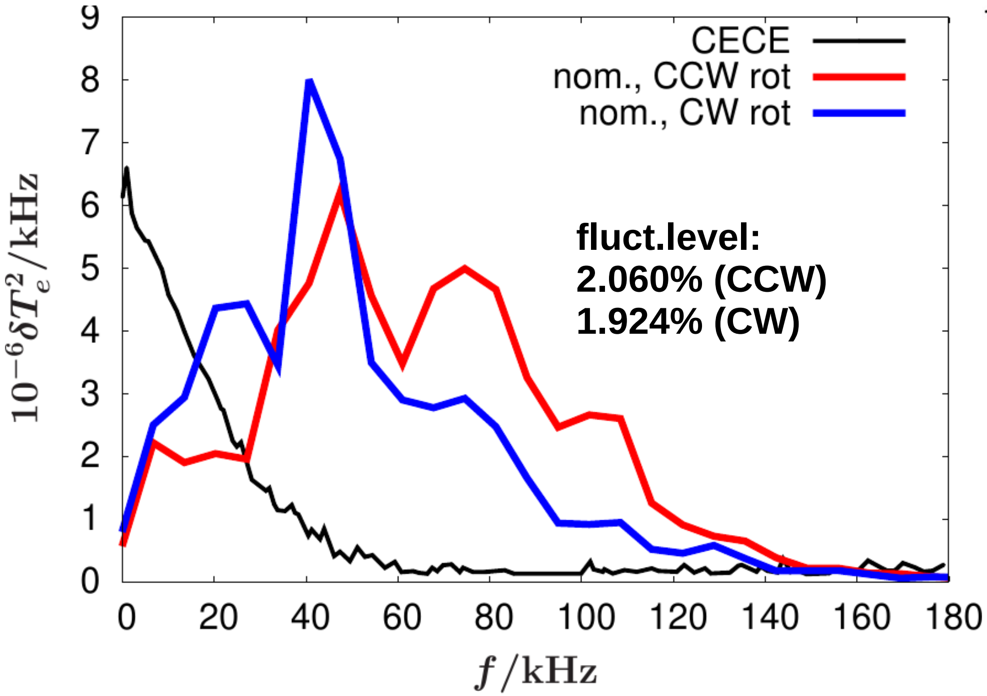


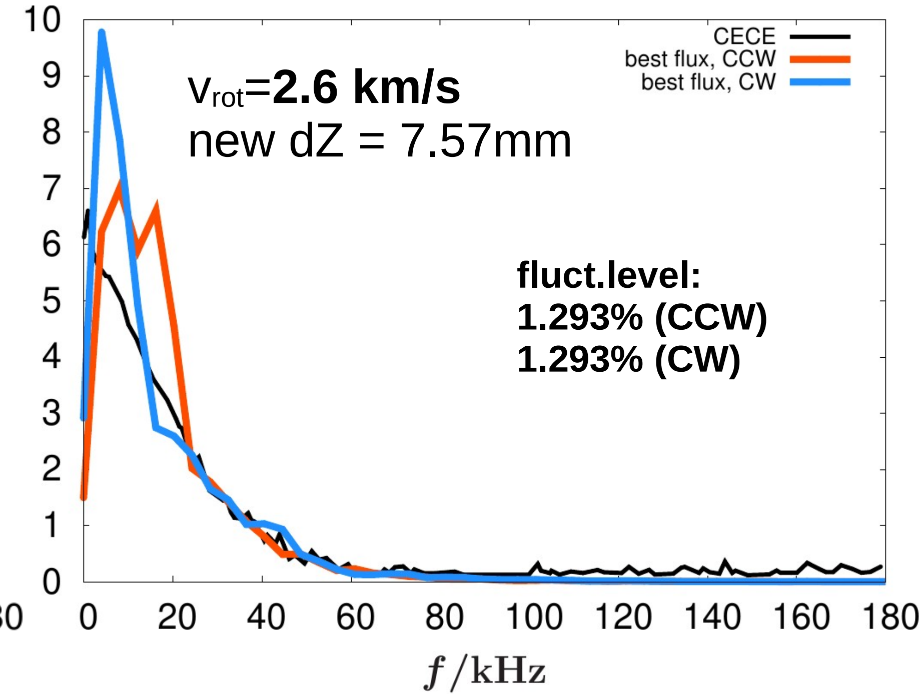
[P. Molina Cabrera, T. Görler et al., EPS 2021]

- $\delta T_e/T_e$ (currently) overestimated but much better agreement than previous work

Sensitivity to toroidal rotation

- **Closer look at Hydrogen plasma – nominal rotation & revised values**





- Toroidal velocity v_{tor} (inferred from DBS) has important role in formation of CECE spectral shape
- In first iteration, rotation induced by beam blips had not been considered