RÉPUBLIQUE FRANÇAISE
Liberté Égalité Fraternité

FRANCE 2030
PROGRAMME DE RECHERCHE
SUPRACONDUCTEURS À HAUTE TEMPÉRATURE ET FUSION

Electron-heated AUG/WEST L-mode plasmas validation

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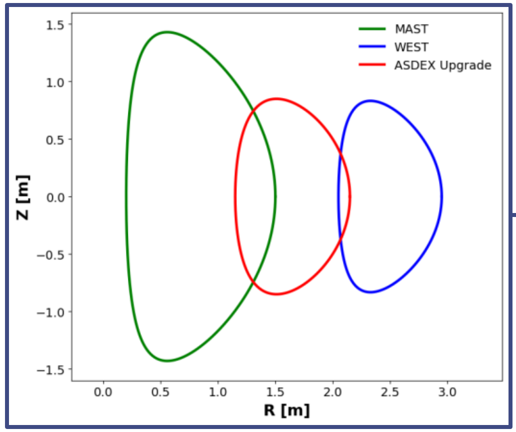
PEPR SupraFusion Workshop

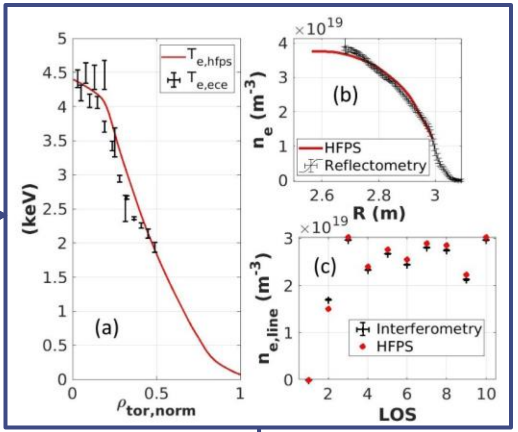
Modeling strategy

FOCUS

1) Identify a **dataset of machine experiments (ASDEX/WEST/MAST?/DIII-D?)**, spanning a wide range of plasma conditions

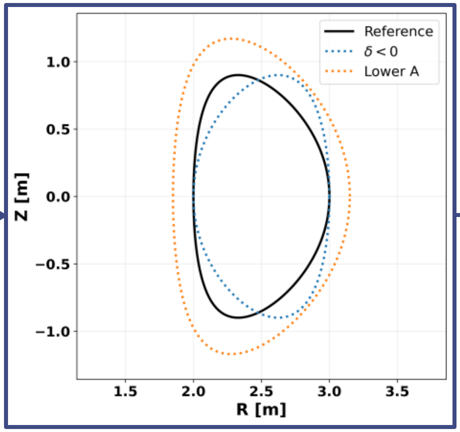
2) Perform predictions with HFPS and validate against experimental measurements

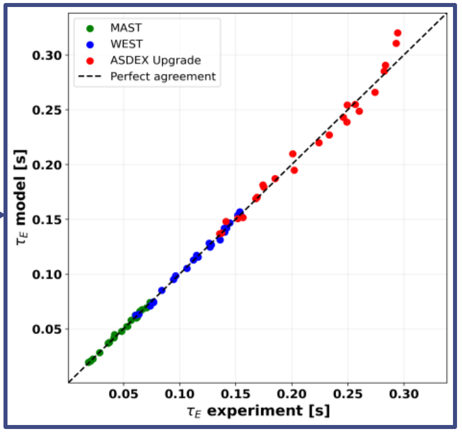




3) **Perform artificial variations of aspect ratio / triangularity** based on this dataset => **decorrelate and interpret the dependences**

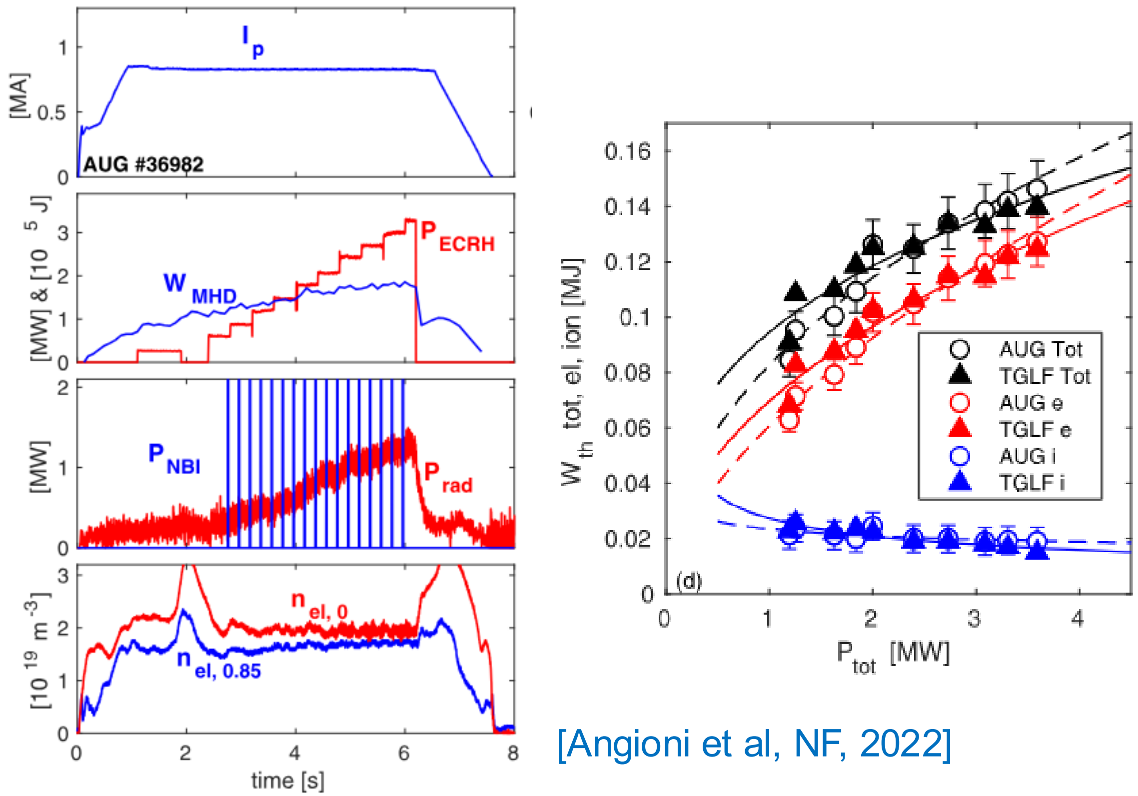
4) Eventually build a refined scaling law explicitly including aspect ratio and triangularity dependences





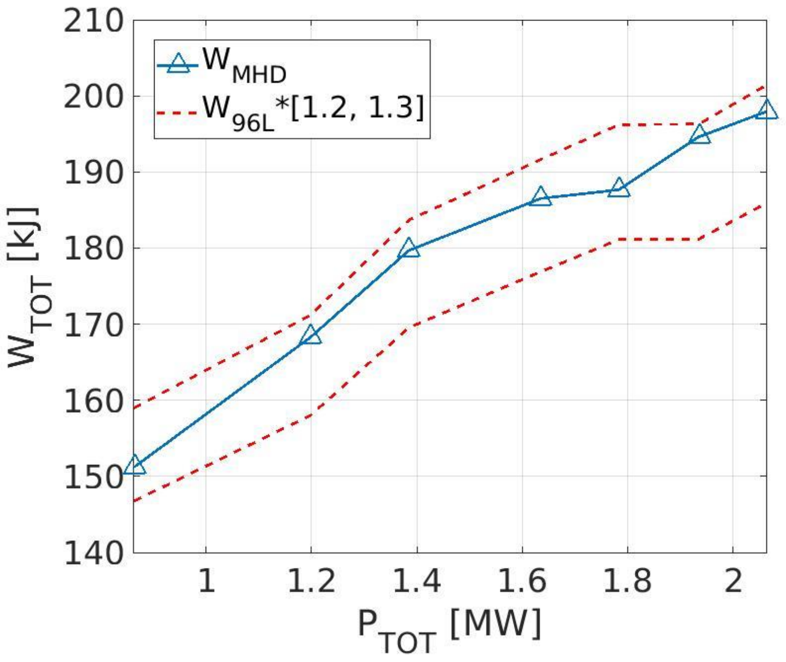
TO START, **electron-heated**, **low beta** to avoid EM modes such as KBMs, **L-mode**, **no/moderate MHD activity** (sawtooth only), **relatively low density**, **well-diagnosed**

ASDEX-Upgrade



[Angioni et al, NF, 2022]

WEST

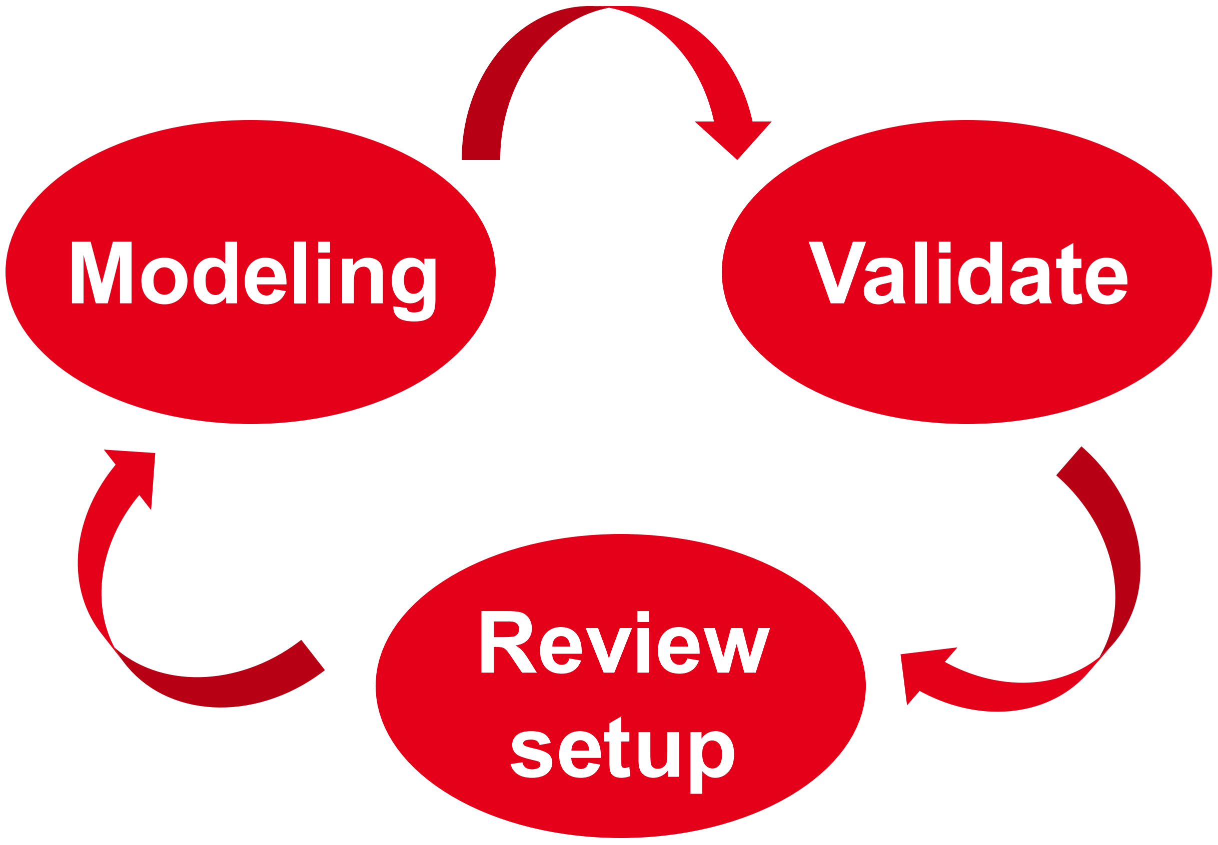


I_P~400 kA, n_{el}~$3.6.10^{19}$ m^{-3}, LHCD-only

Validation of the setup + params

SETTINGS TO BE IDENTIFIED

- Ratio of $T_{i,sep}/T_{e,sep}$
- Impurity self-consistent + Z_{eff} treatment
- Heating self-consistent
- Toroidal rotation
- Model for sawtooth
- Additional core electron heat diffusivity



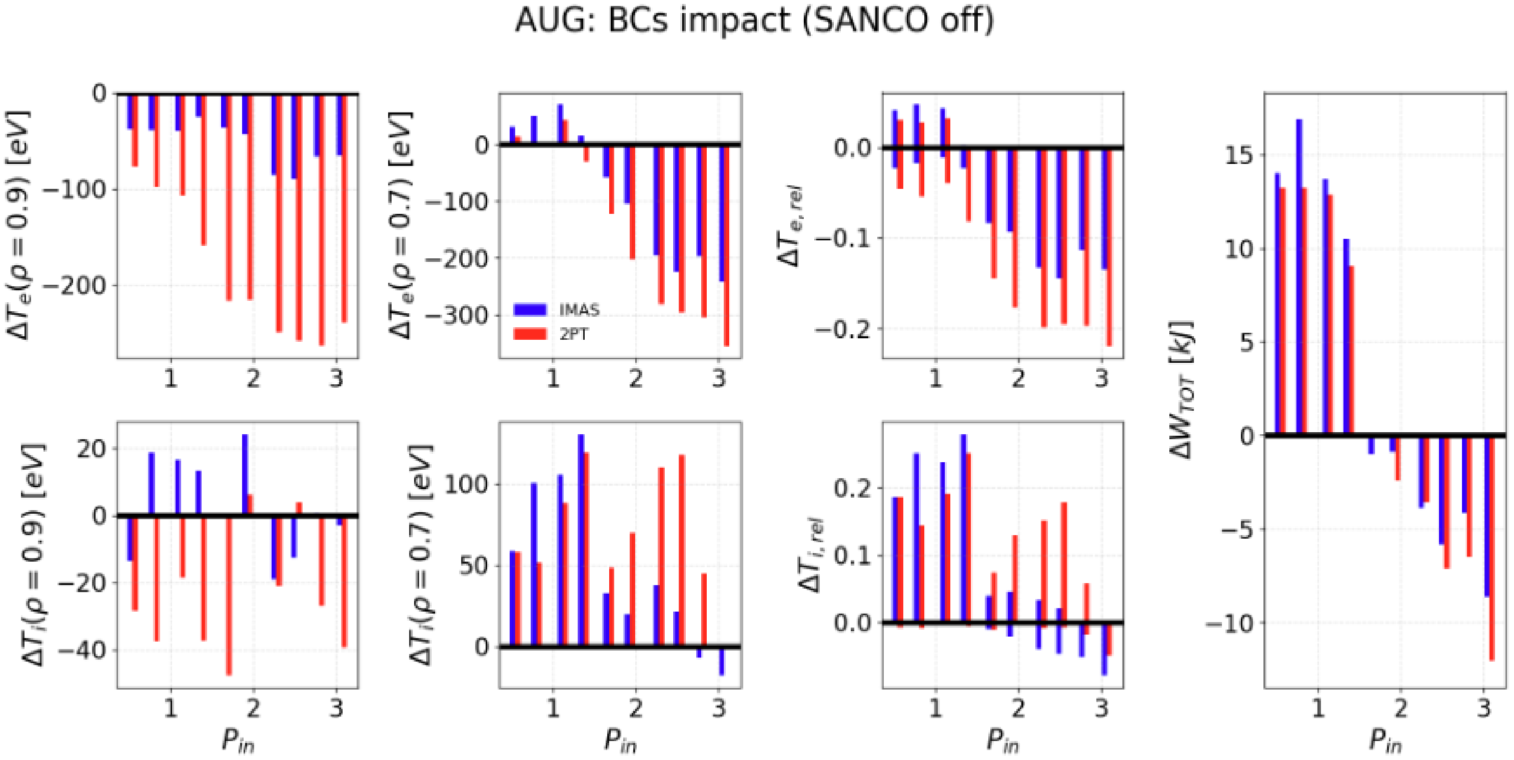
Basic settings

- j, n_e, T_e, T_i predicted + toroidal rotation fixed from IDA?
- BCs ($T_{e,sep}$, $n_{e,sep}$) are taken from the input IDS and T_i/T_e (fixed to 1.5, parametrization or from input?)
- Only one light impurity considered (N) while radiated power is not consistent with the impurity content but directly extracted from IDA and fixed + self-consistent impurity
- Feedback on the line-averaged electron density using a neutral energy of 10 eV
- Heat source is fixed from the IDS input (TORBEAM, LHCD model) + self-consistent
- TGLF-sat2 + Nclass for transport, up to the separatrix
- Continuous sawtooth model (additional diffusion in the q<1 region + enhances resistivity => results in flat q=1) + impact of consistent sawtooth? Or no sawtooth & q<1?

Defining settings for large-scale validation

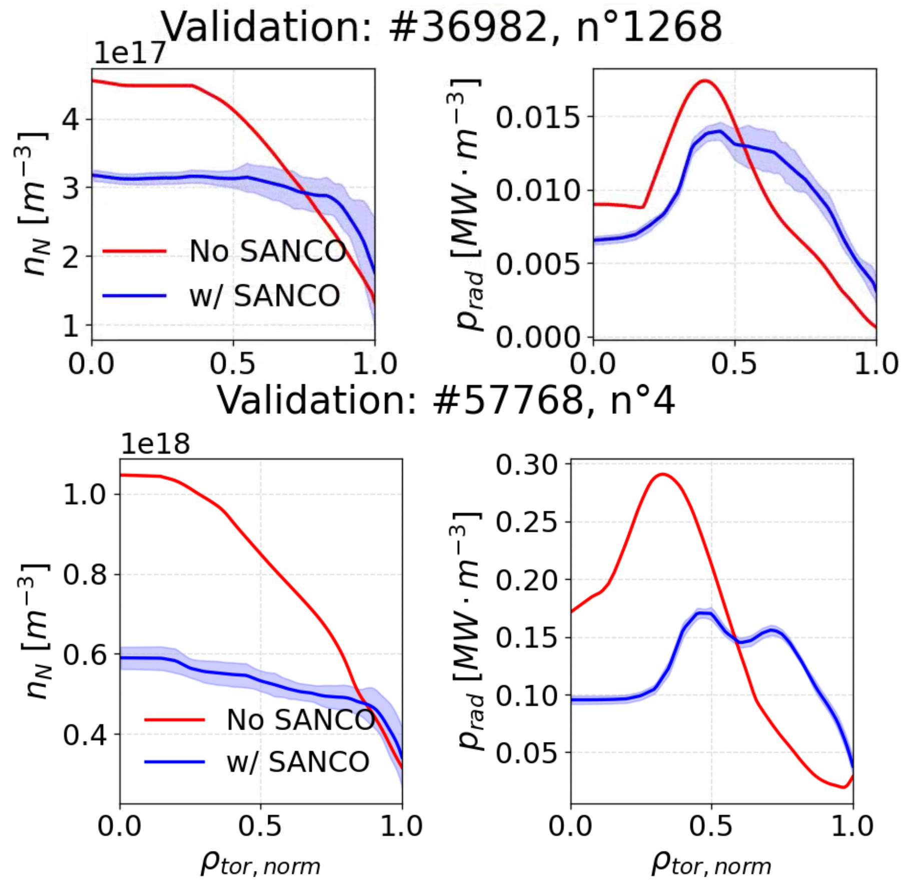
How to constrain T_i/T_e

- AUG edge profiles are relatively well constrained, at least up to 0.9 if not up to the separatrix
- Using AUG to compare IMAS BCs (Ti & Te), & 2pt-model for Te + fixed Ti/Te=1.5 (applicable to WEST)

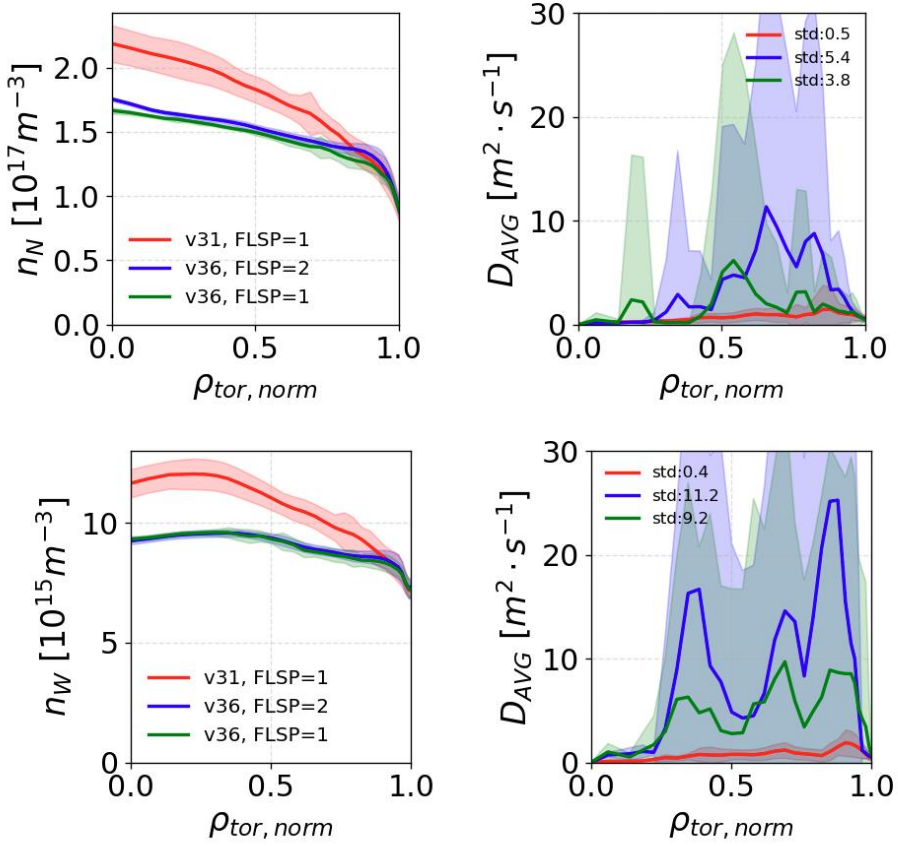


- **IMAS BCs** provide the best agreement at 0.9 and overall
- 2-pt model + fixed Ti/Te is still acceptable as no major difference in stored energy content => **will be used to get consistency between WEST and AUG**

Prediction of impurities consistently with HFPS



Only electron-heated plasmas with low density, no torque => known to yield relatively flat profiles but there seems to be a **disagreement between v34 & 36** on top under investigation

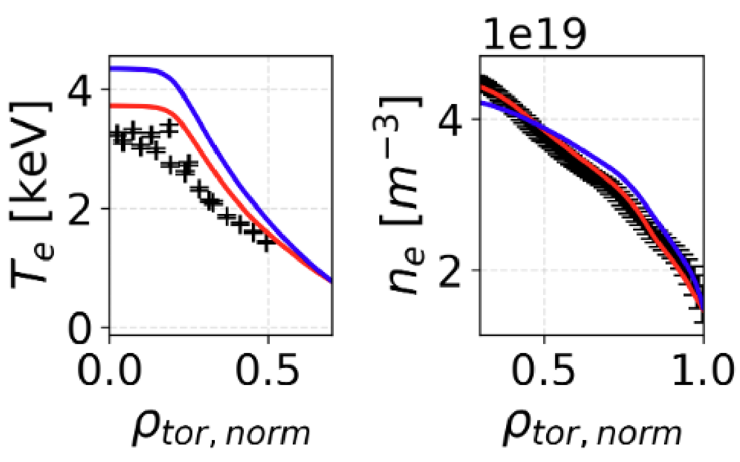


We always predict **flatter impurity profiles** with HFPS **than electron density profiles**

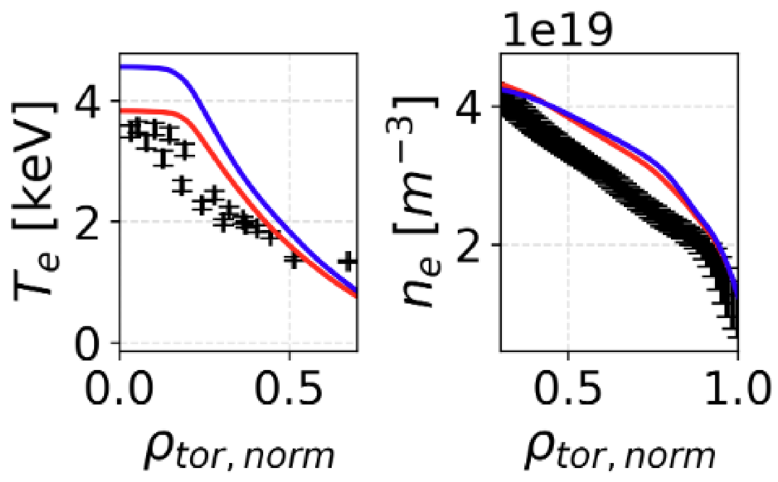
Consequence of flat impurities

- Flat impurity profiles => radiation increased at the edge and decreased in the core which results in core electron temperature differences in WEST as f_{rad}~50%
- With lower impact, the electron density gradients at the edge get always larger due to either increased collisionality (Zeff increases at the edge and reduces in the core) or impurities density gradients themselves (to be analyzed in detail with stand-alone if needed) => lower density peaking

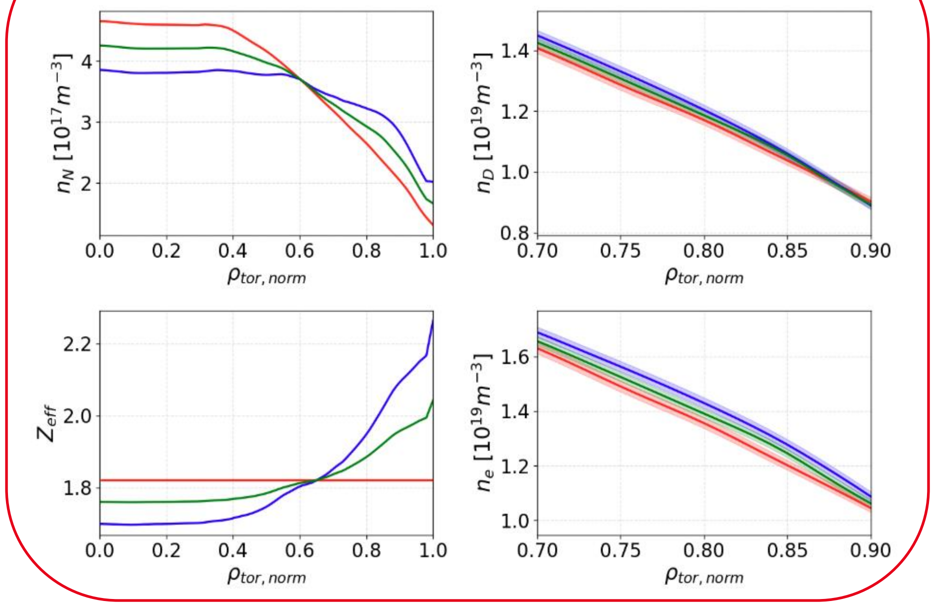
WEST – 57768



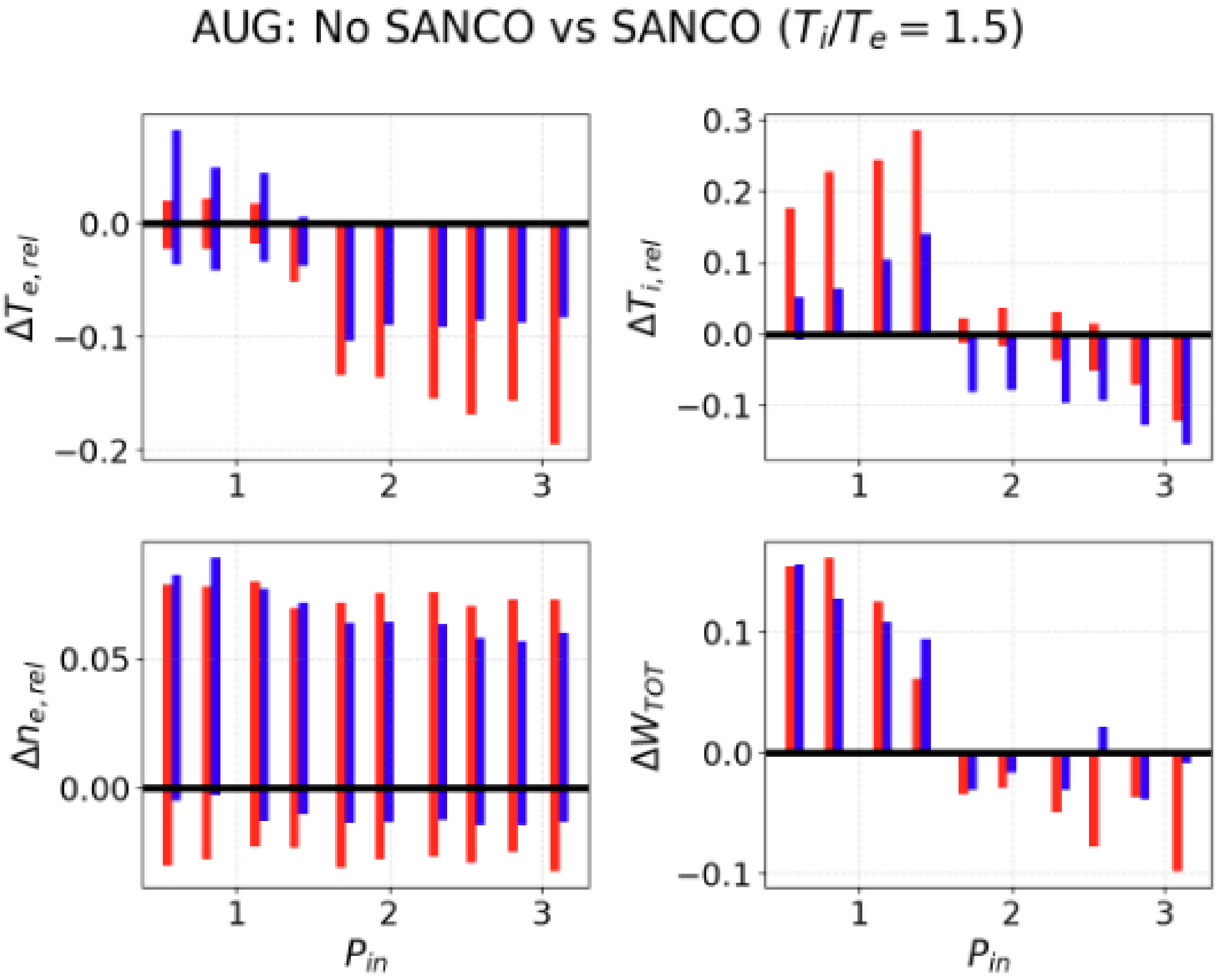
WEST – 62129



AUG – 36982 – t = 2.68 s



Consequence of flat impurities



- Overall, this yields a better agreement in terms of electron temperature and density compared to IDA profiles and therefore better stored energy content
- On WEST, it is rather the opposite. Electron temperature is even more overpredicted as compared to fixed impurity content and this decreases the agreement
- This may illustrate that LHCD profiles complexifies the analysis

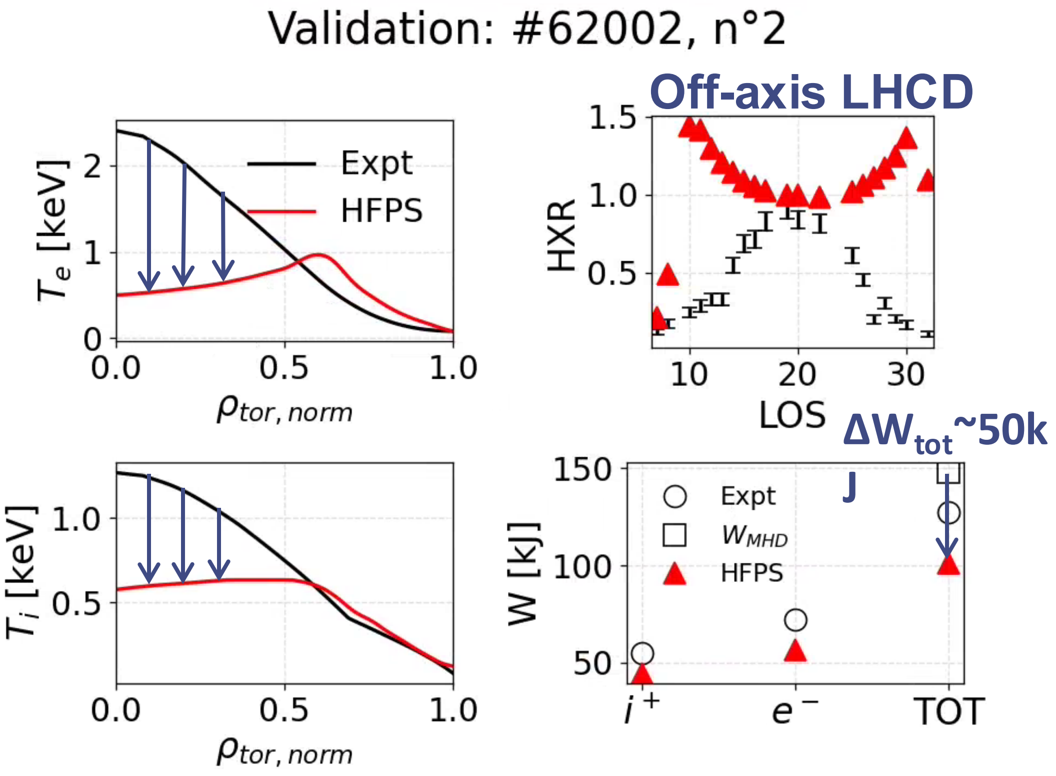
Self-consistent heating

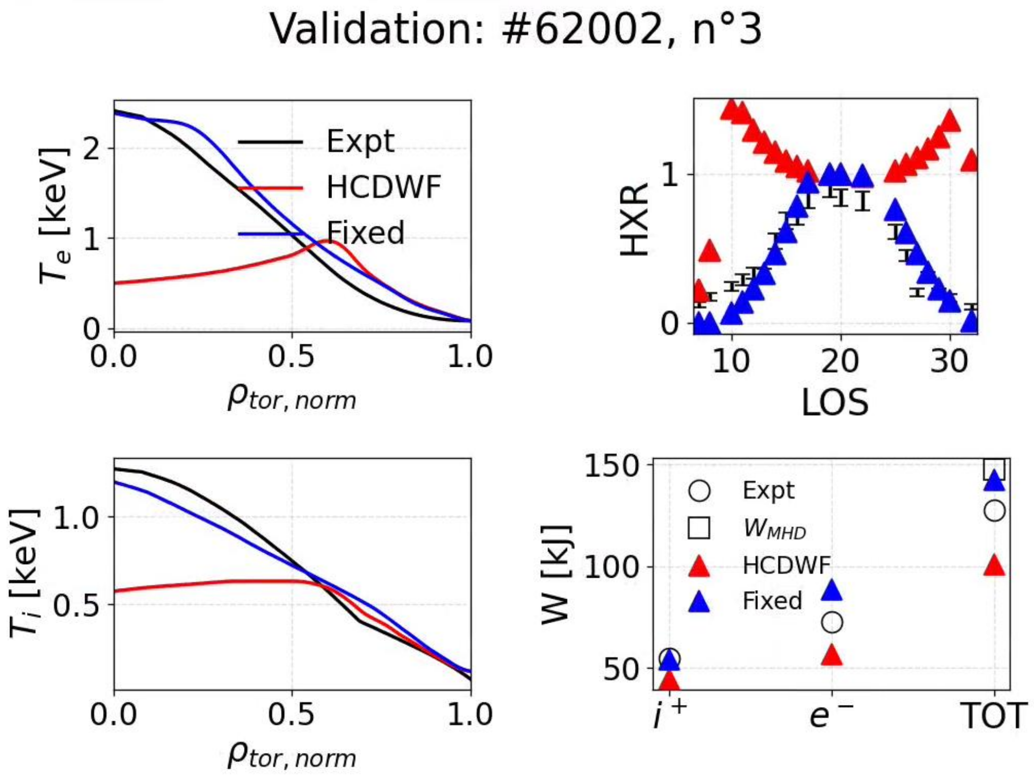
[Morales, NF, 2025]

RADIATIVE COLLAPSE

Partially explained by LHCD off-axis displacement which may be overestimated close to threshold

> Fix LHCD to validated profiles from [Fonghetti, NF, 2025]





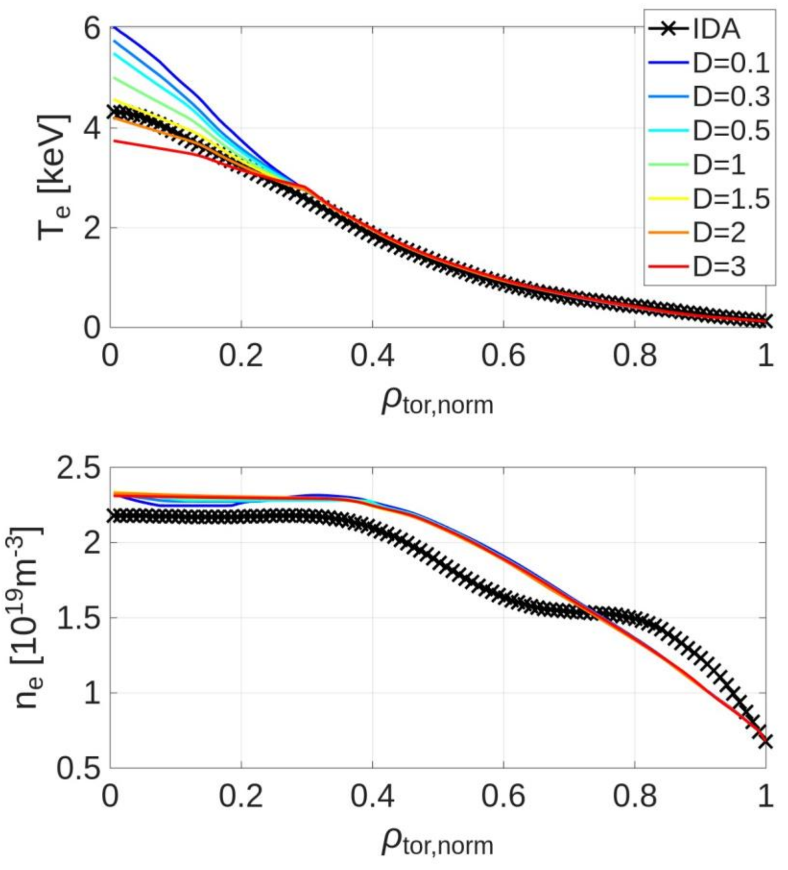
This is obtained when <u>radiations exceed heating</u> in the core and is observed experimentally when P_{LH}/n_e is too low

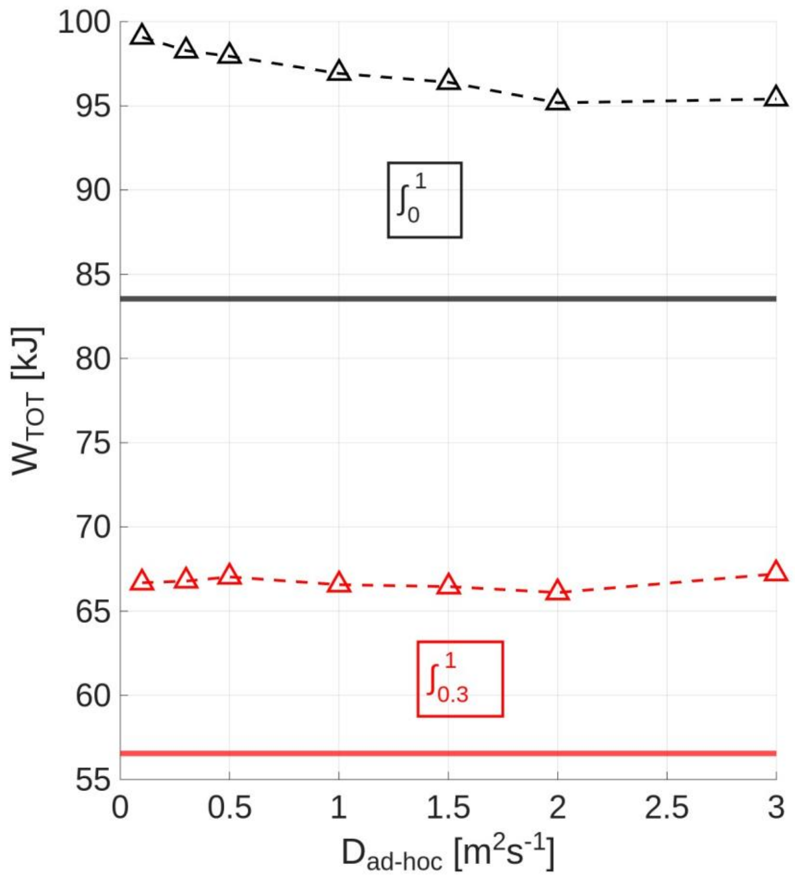
=> here P_{LH}/n_e is close to threshold for 62002

Positive impact on low P_{LHCD} discharges while negligible impact on high P_{LHCD} discharges

Continuous sawtooth model

- Continuous sawtooth is a model which modulates the amplitude of the ad-hoc diffusivity (D below) applied in the q<1 region (heat and particle) and increases resistivity to mimic sawtooth
- Impact only ρ<0.3 region to a low extent (impact on W_{tot} rather low: Δ_{max}~5 kJ)

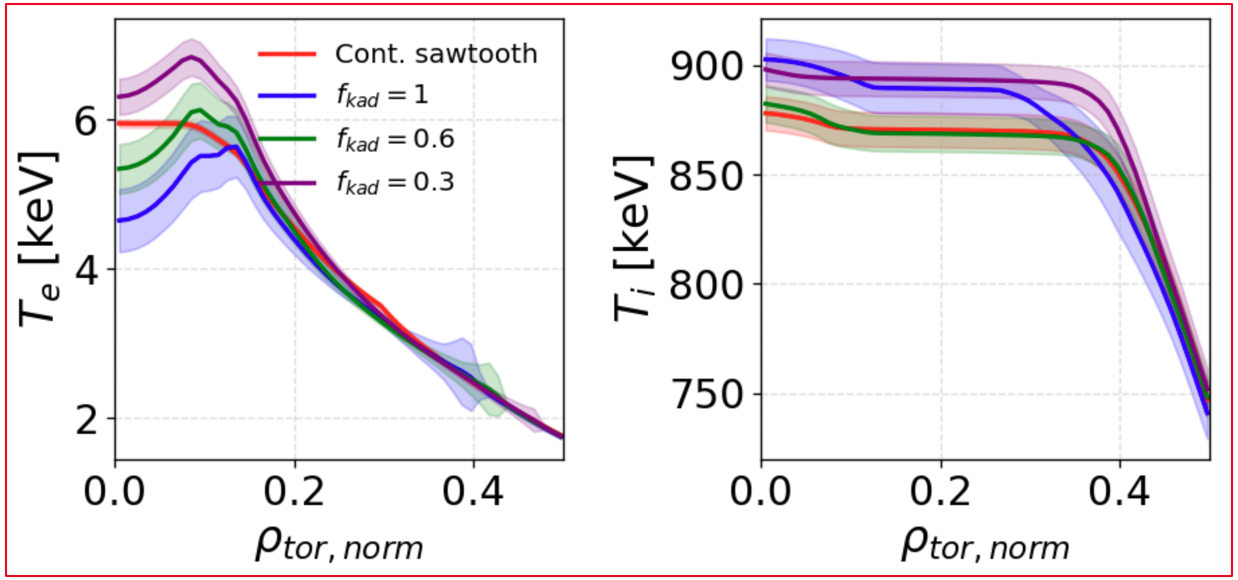




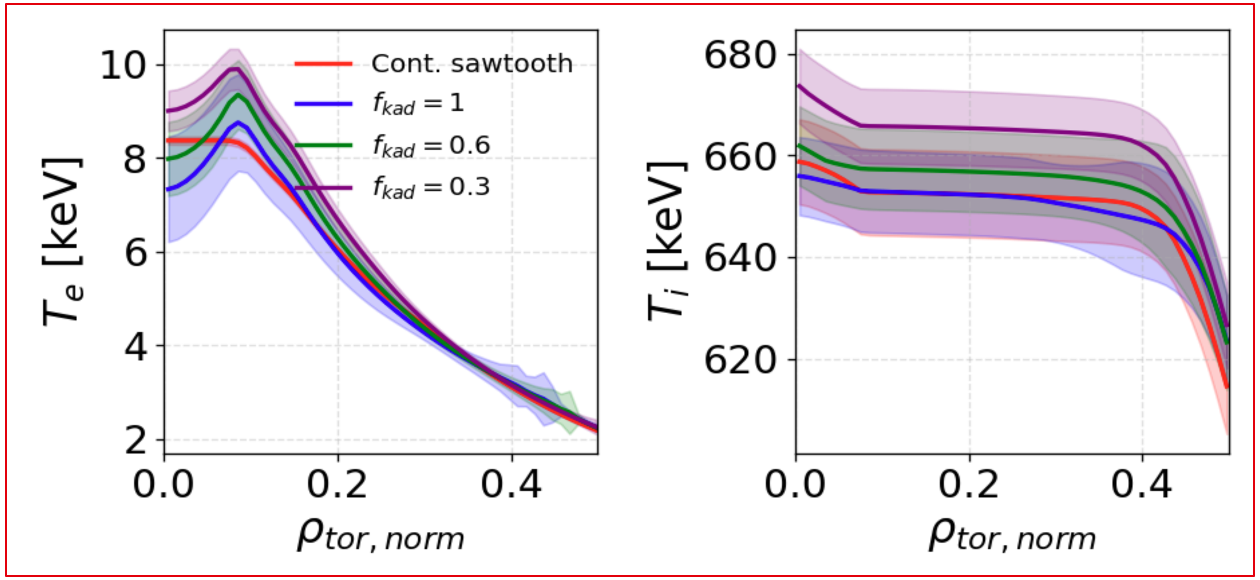
- clamp q=1 in the core and avoid q<1 with large shear configurations
- D has been set to 1m^{2}s^{-1} arbitrarily, to avoid discharge fine-tuning, comes at the price of not perfectly matching within 0.3 the sawtooth averaged profiles

- Kadomtsev model varying the reconnection fraction from 0.3 to 1 + fixing the sawtooth period to experimental observations => the inversion radius matches the experimental one
- **Overall, the predictions tightly match those with the continuous sawtooth model, particularly outside rho = 0.3 which is where profiles are validated**

t = 3.8 s

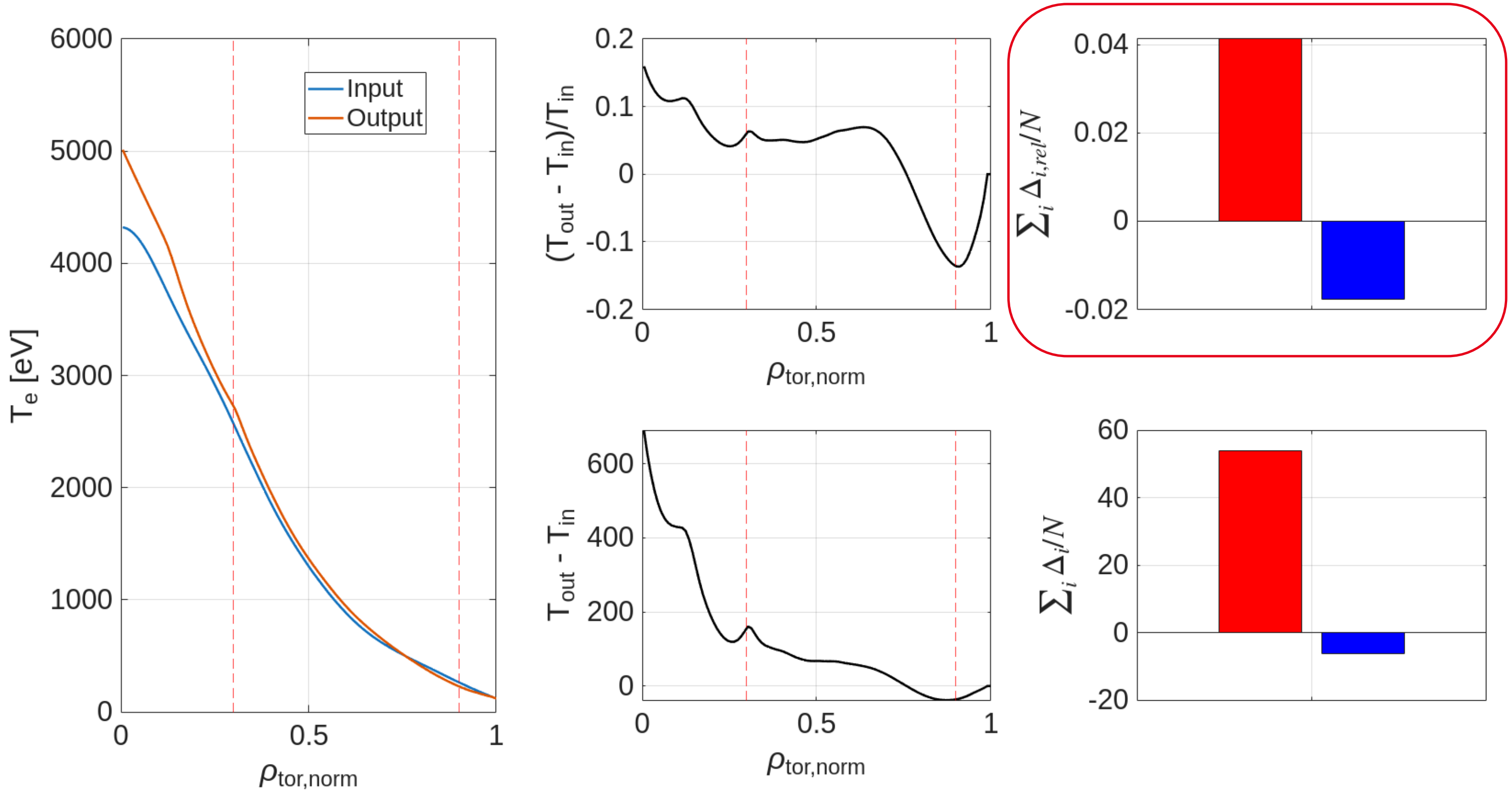


t = 5.8 s



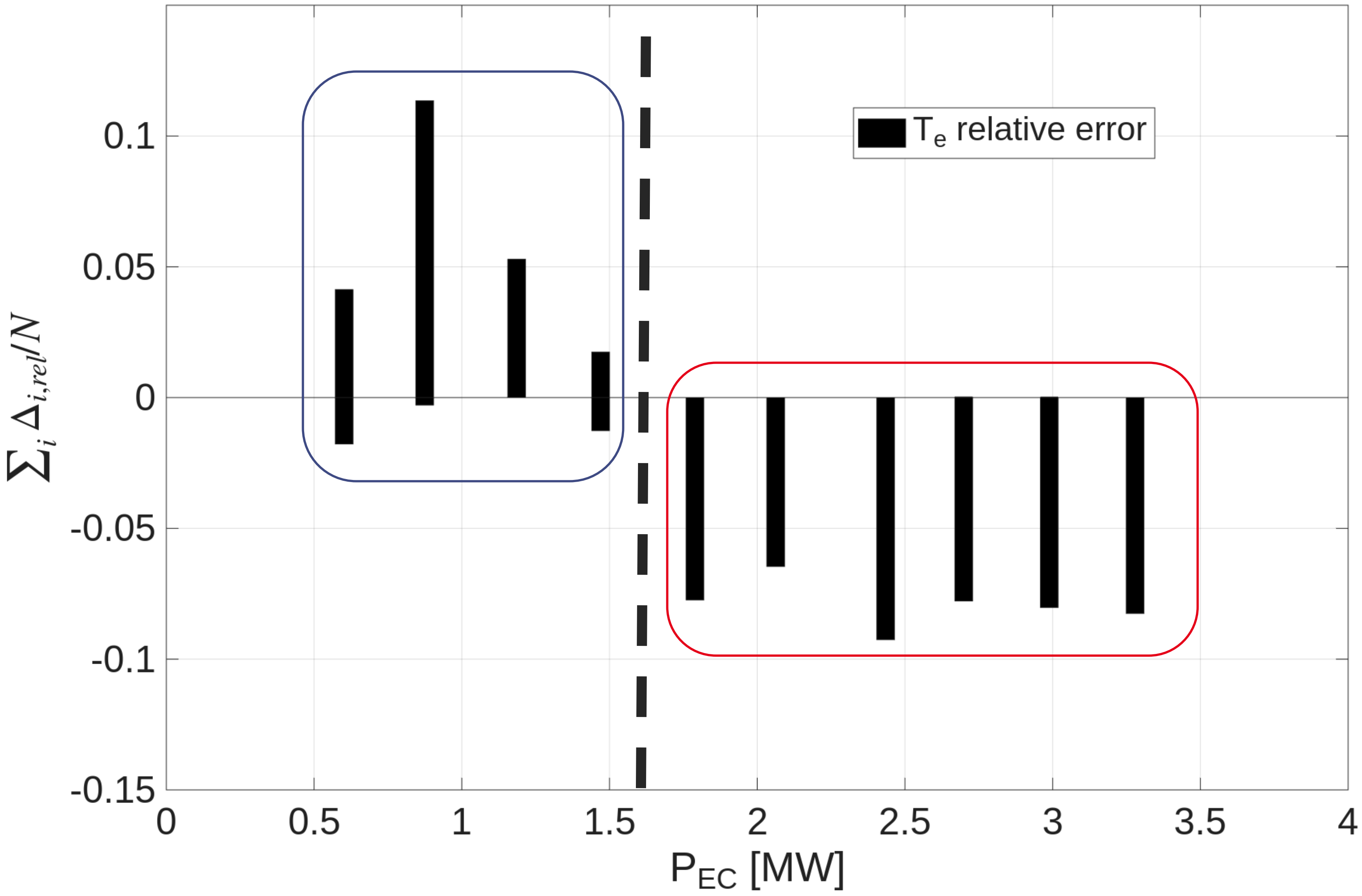
Metrics for profile validation

When going for large database analysis you need metrics to quantify the level of agreement / disagreement, as you cannot compare individually each discharge to expts



- ❑ By using relative errors (top), I put a larger weight on the edge which is maybe not ideal.
- ❑ Does not provide anything on the location of the disagreement + is the value comparable in between shots simulated?

Metrics for profile validation

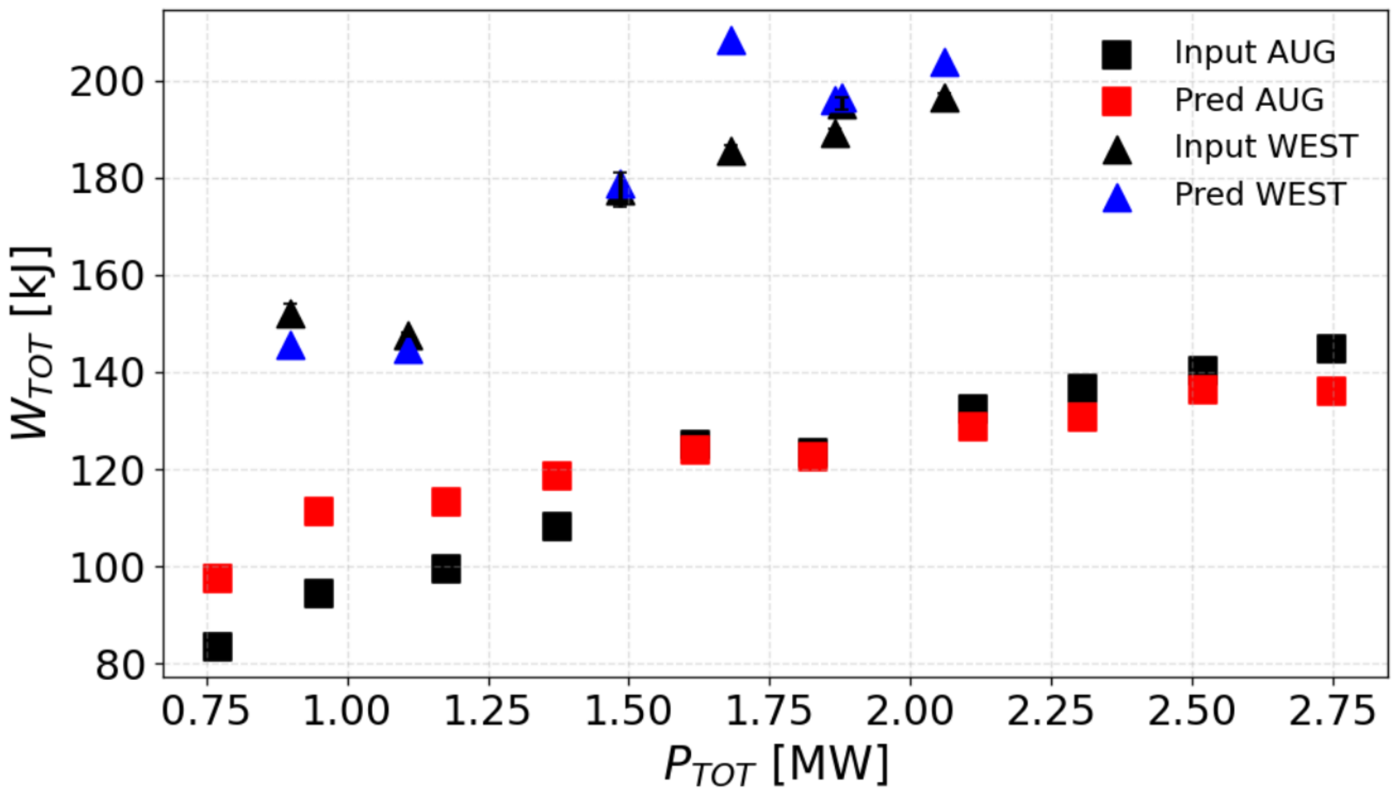


This is quite useful to retrieve previous conclusions as in [Angioni NF 2022] via simple quantities:

If you separate high EC and low EC power, you can see at high EC power the electron temperature is overall underestimated (~10% of underestimation maximum)

+ it would be nice to have the standard deviations to include it in the metric

AUG & WEST W_{TOT} PREDICTIONS



- Average relative errors of 7% for AUG and 4% for WEST (without considering errorbars)
- Trends are reversed between WEST and AUG (in terms of where it overestimates and underestimates) => interesting to **understand why**
  - Auxiliary CD (reversed shear configurations at large LHCD power)? Impact of radiations? Edge properties?

Conclusion

For large-scale validation, several challenges identified:

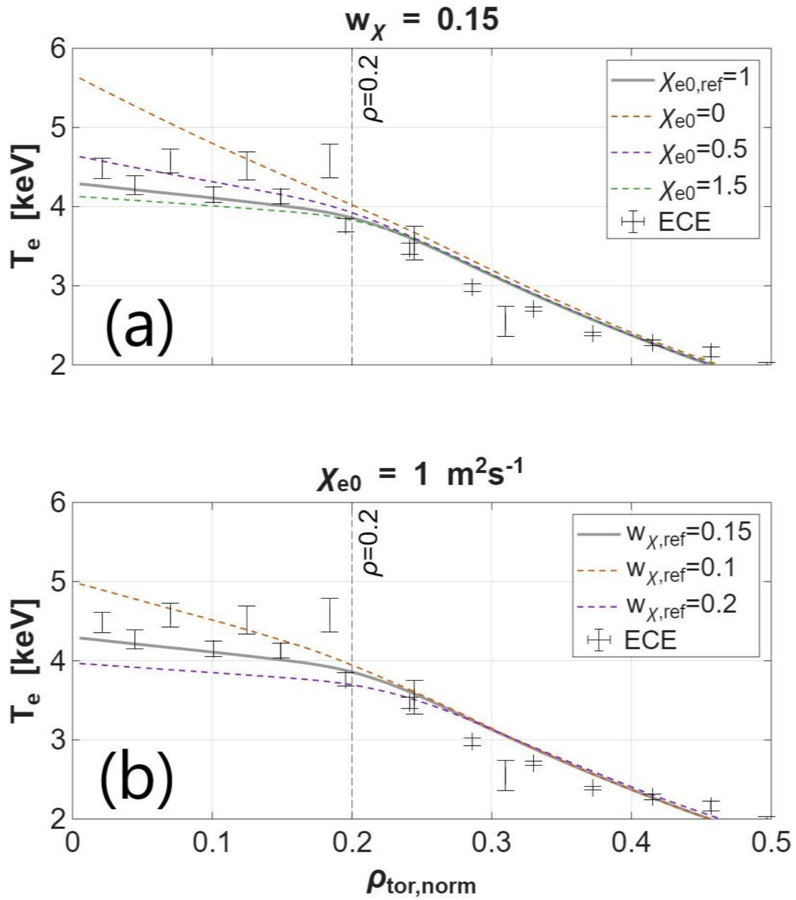
- The overall impact of different BCs on stored energy content is relatively limited and therefore using a consistent approach between WEST & AUG is chosen in the end
- **Self-consistent impurity transport** seems to yield **flat impurity profiles** (any numerical issue from 34- to 36+ to be investigated), inducing large core Te and larger density gradients
- **Continuous sawtooth model** yields same temperature profile outside 0.3 than advanced Kadomtsev and averaged experimental profiles > will be used for all cases
- Core ad-hoc electron heat diffusivity of 1 m^2s^{-1} is required in WEST to avoid overly steep temperature profiles, could originate from overestimation of reversed-shear stabilization in WEST
- Self-consistent LHCD is tricky close to radiative collapses threshold while **imposing hot-branch-like profiles yield better agreement and similar predictions far from threshold**
- **Validation metrics** to be developed to go from single case validation to database identifiable trends

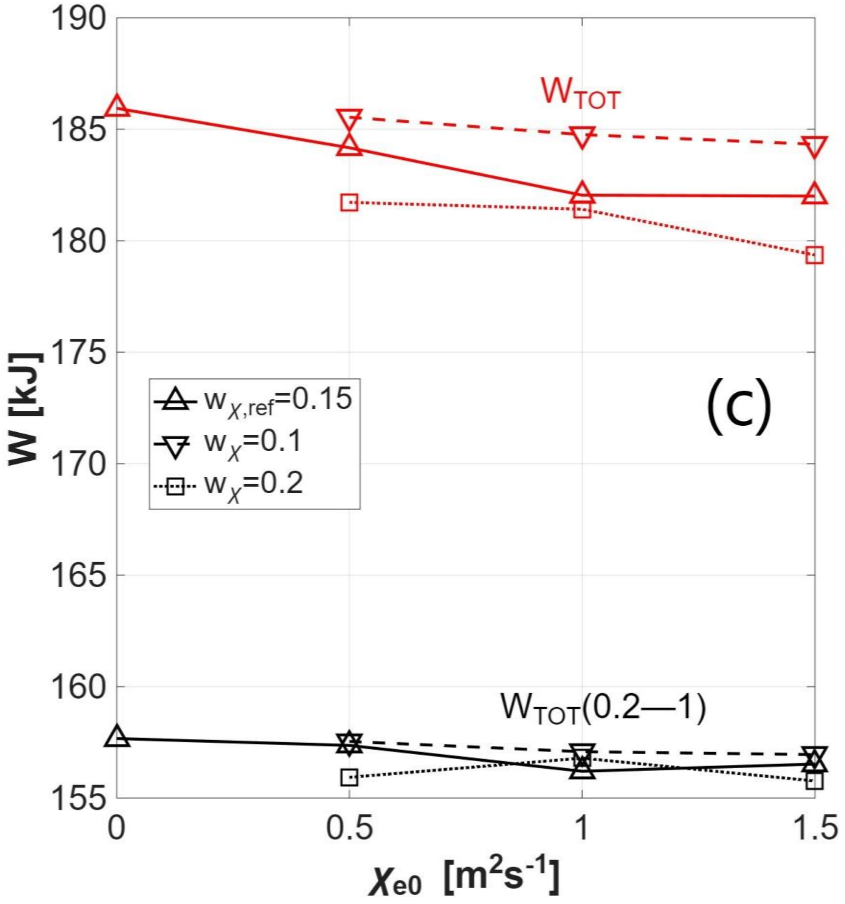
Next step is to populate AUG/WEST to extend validation without any fine-tuning and add DIII-D to see what happens with no machine-tuned parameters

Other presentation material

WEST core turbulence

- No additional diffusion in the core produces overly steep temperature in the core, which can impact in turn LHCD absorption
- This has no impact on the stored energy content outside 0.3 again, and rather low impact in the core
- This underestimation of transport could originate from reversed-shear WEST configuration with off-axis LHCD

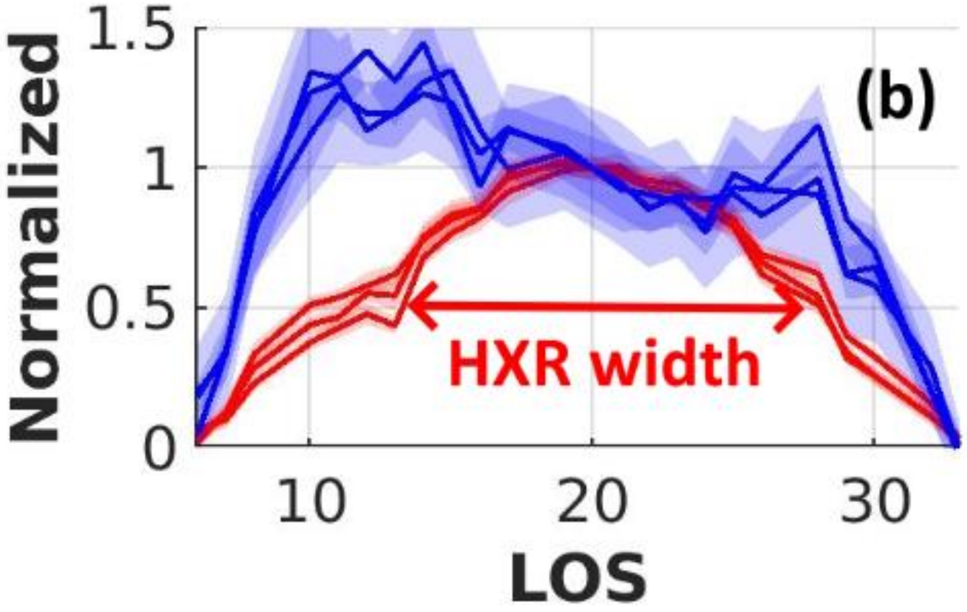




<u>Additional note:</u> AUG diffusion as predicted from TGLF within 0-0.2 also drops to 0 for all cases

Proposal for fixed LHCD strategy

Observed during PhD thesis that HXR profiles remain similar across hot branch (T_e > 2 keV) experiments



>> Take validated 57757 profile

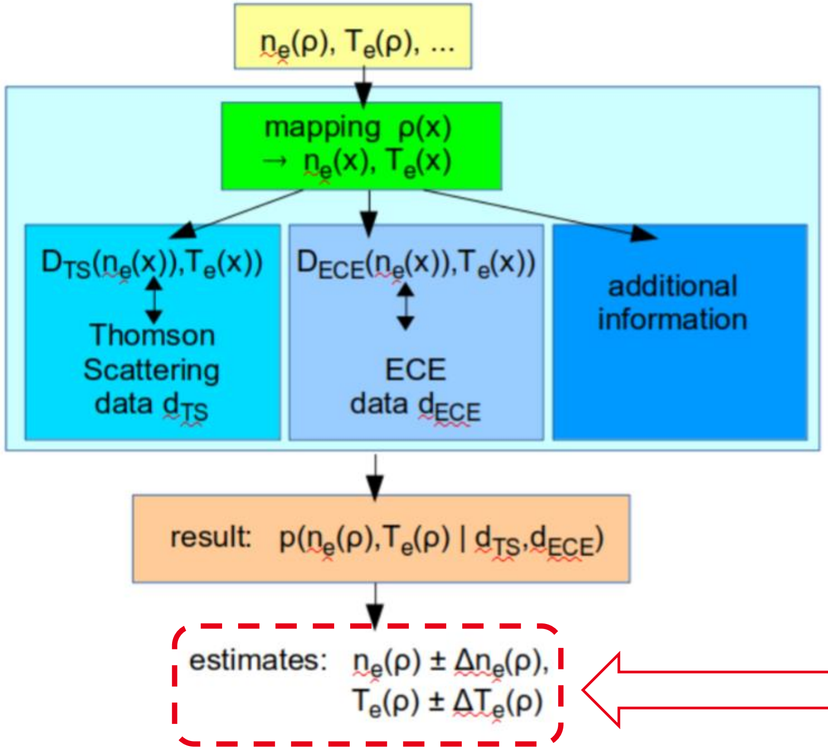
+

- The overall LHCD efficiency is rescaled using a scaling mostly based on W_{MHD}
- Same as performed consistently with Wtot predicted in [Fonghetti, NF, 2025]
- This enables to match Vloop and to capture the impact of current profile variation in between cases

Define a routine for preparing the data

ASDEX-Upgrade

Integrated Data Analysis: Bayesian framework that combines diagnostics with equilibrium and forward models to infer plasma profiles



Fischer et al, ArXiV, 2024

WEST

METIS Data Analysis: Diagnostics with equilibrium infer plasma profiles

Profiles	Methods
$T_e(\rho)$	Eq + ECE
$n_e(\rho)$	Eq + Reflect. + Interf.
$T_i(\rho)$	Neutron flux + sqrt($n_e T_e$)
Z_{eff}	Calibrated Bremmstrahlung
$P_{rad}(\rho)$	Bolometry + $n_W \propto n_e$
$n_N(\rho)$	Quasineutrality + equipartition

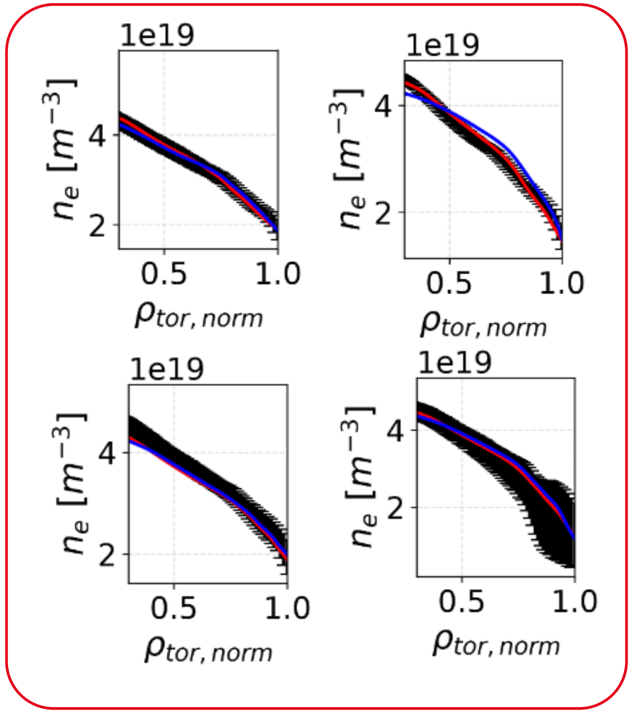
HFPS/IMAS inputs

BCs: reflectometry for ne, 2-pt model for Te

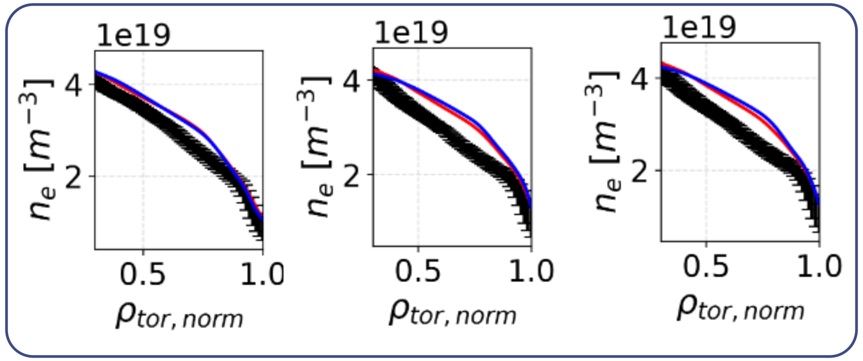
Accurate T_e prediction in AUG & ne prediction in WEST

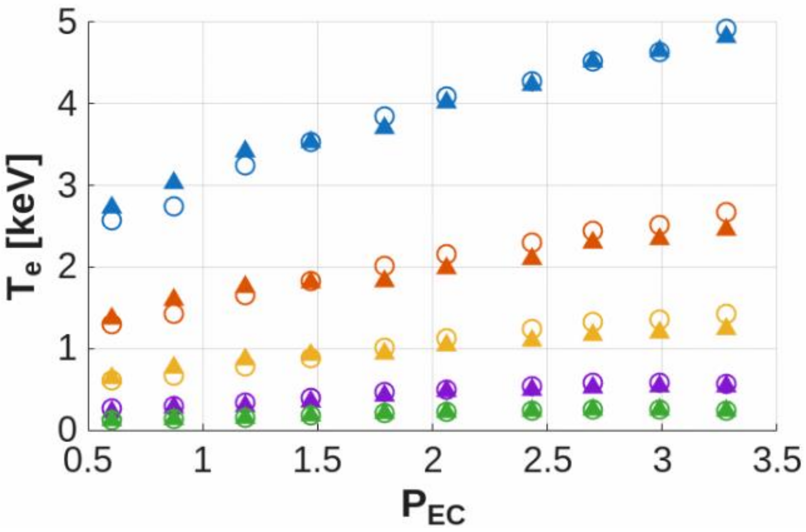
- With BC from input profiles, the e- and i+ temperature predictions are behaving well (except too large core ion turbulence predicted at large P_{EC})
- e- density predictions are very much aligned with reflectometry for C7 pulses though it gets slightly overestimated in C9

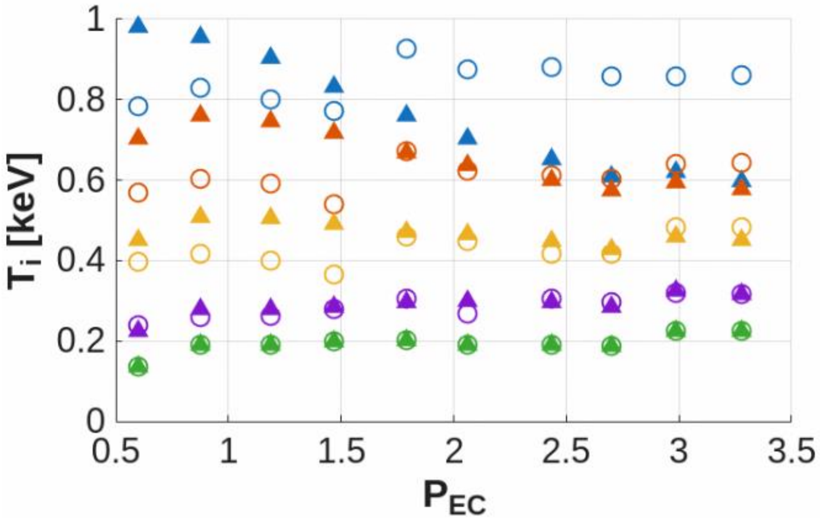
C7



C11







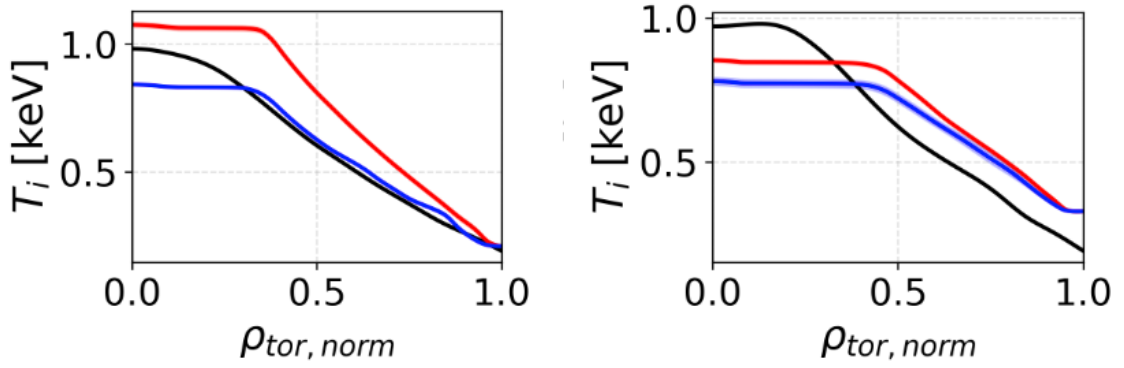
T_i/T_e at the LCFS

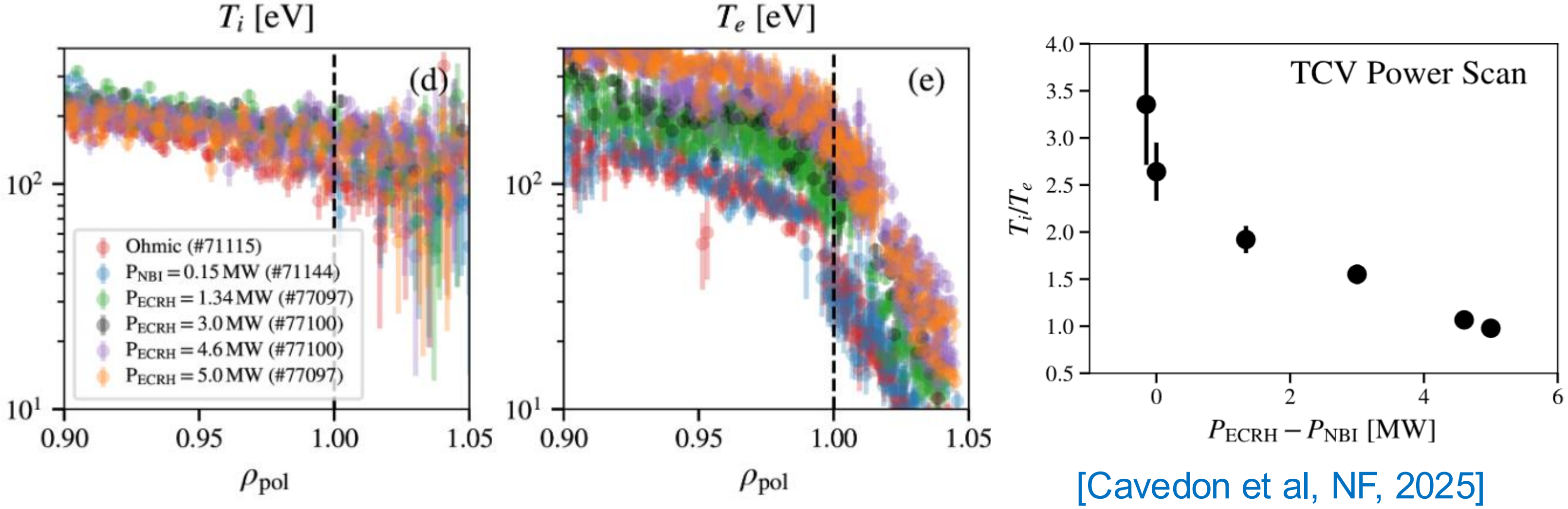
About Ti/Te

- A typical way of constraining is to impose Ti/Te=1.5 ; this do not work at high EC power as Ti is already larger than CXRS fitted Ti
- This in line with a study in TCV showing that T_{sep} (provided by Thomson Scattering) is increasing with the input power while the T_i/T_e ratio is decreasing (though uncertainty on equilibrium)
- It could also be due to T_{esep} which is also highly uncertain (2pt model or IDA)

Any satisfying method (IMAS BCs, 2-pt model and fixed Ti/Te, parametrization, …) and overall impact on predictions ?

P_{EC} increases => $T_{e,sep}$ increases => $T_{i,sep}$ increases

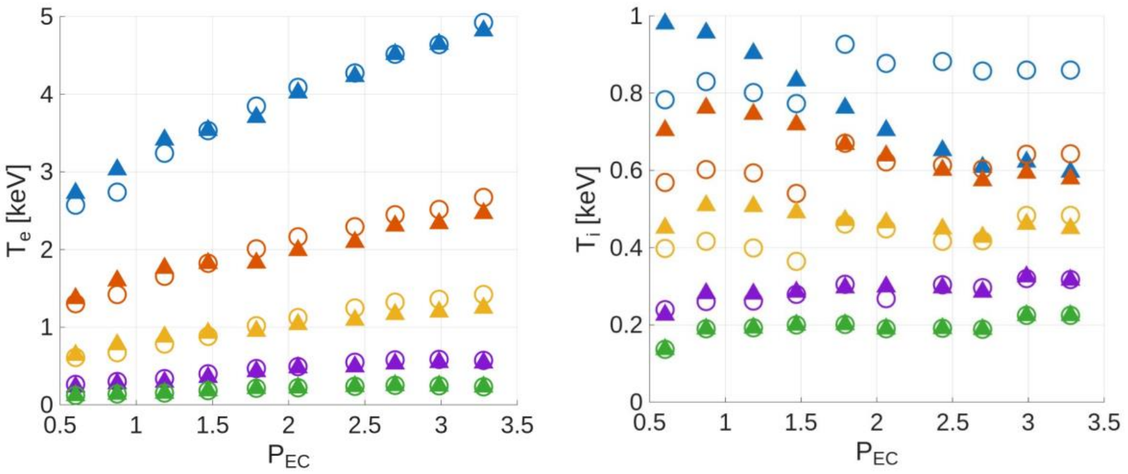


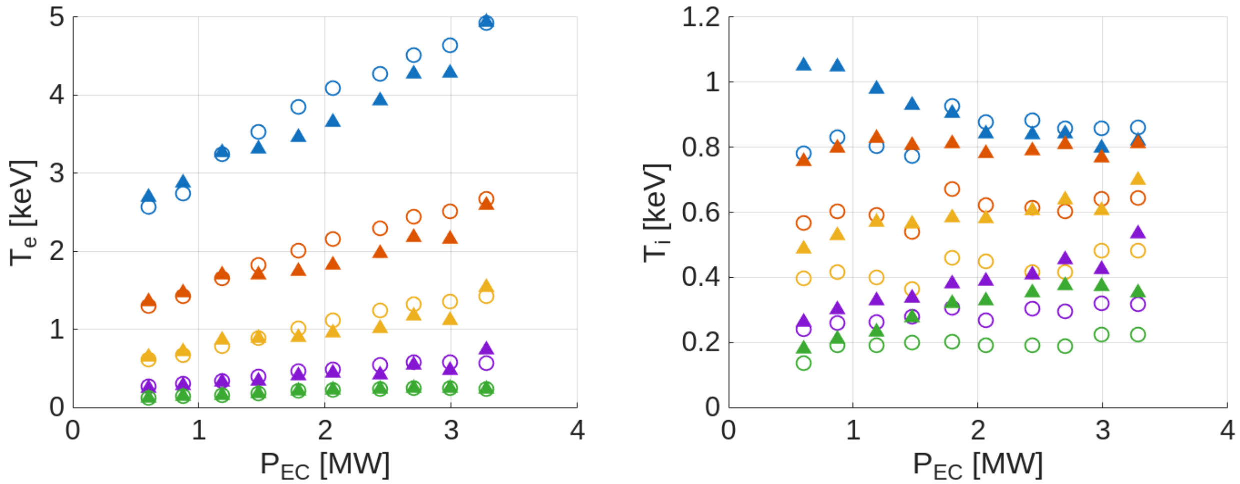


[Cavedon et al, NF, 2025]

Comparison in terms of temperature

BCs (T_e,T_i,n_e) from input profiles → **BCs (T_e,n_e) from input profiles & $T_{i,sep}/T_{e,sep}$=1.5**





T_i/T_e=1.5 leads to such high $T_{i,sep}$ that it impacts in turn electron heat transport...

__**What to do:**__ Compare **1)** T_i/T_e from input profiles + force at minimum T_i=T_e, **2)** Scan constant T_i/T_e, **3)** T_i/T_e from parametrization based on TCV

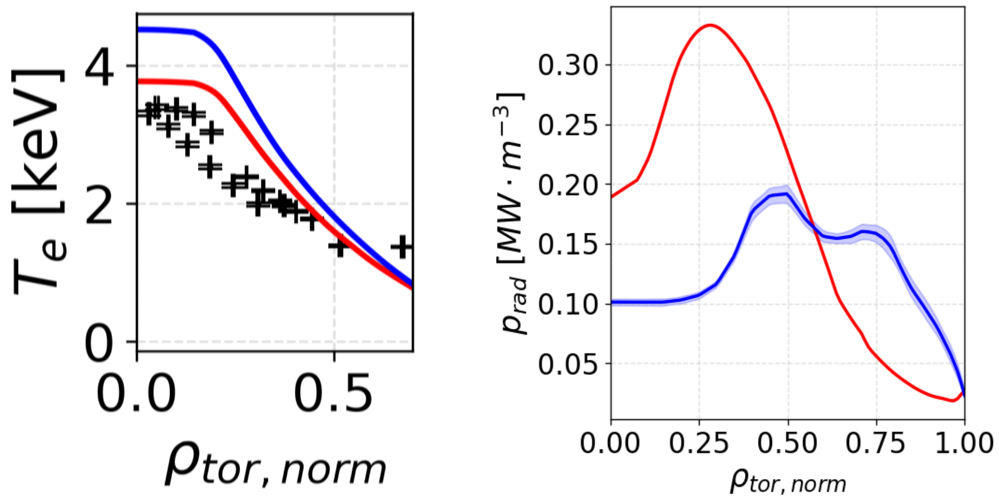
__**Idea:**__ Constant T_i/T_e fails for some cases (large power); parametrization seems hard to trust over a whole db; if T_i is trustable up to 0.9 then the fit provides a satisfying constrain maybe it is better to keep it and just avoid T_i<T_e

Impurities

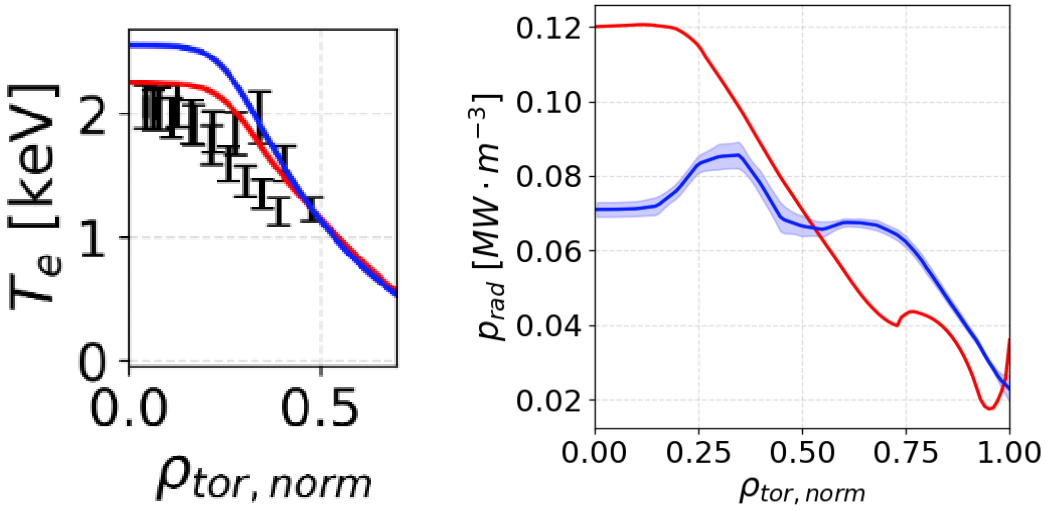
WEST impurities

- In WEST the impact on the electron temperature is much larger as f_{rad} is large => difference in W profiles lead to large differences in electron heat fluxes crossing all flux surfaces
- In particular, both W and electron density profiles (see next slide) are found to be much less peaked => q_{rad} increases at the edge and decreases in the core => T_e increases in the core

62127

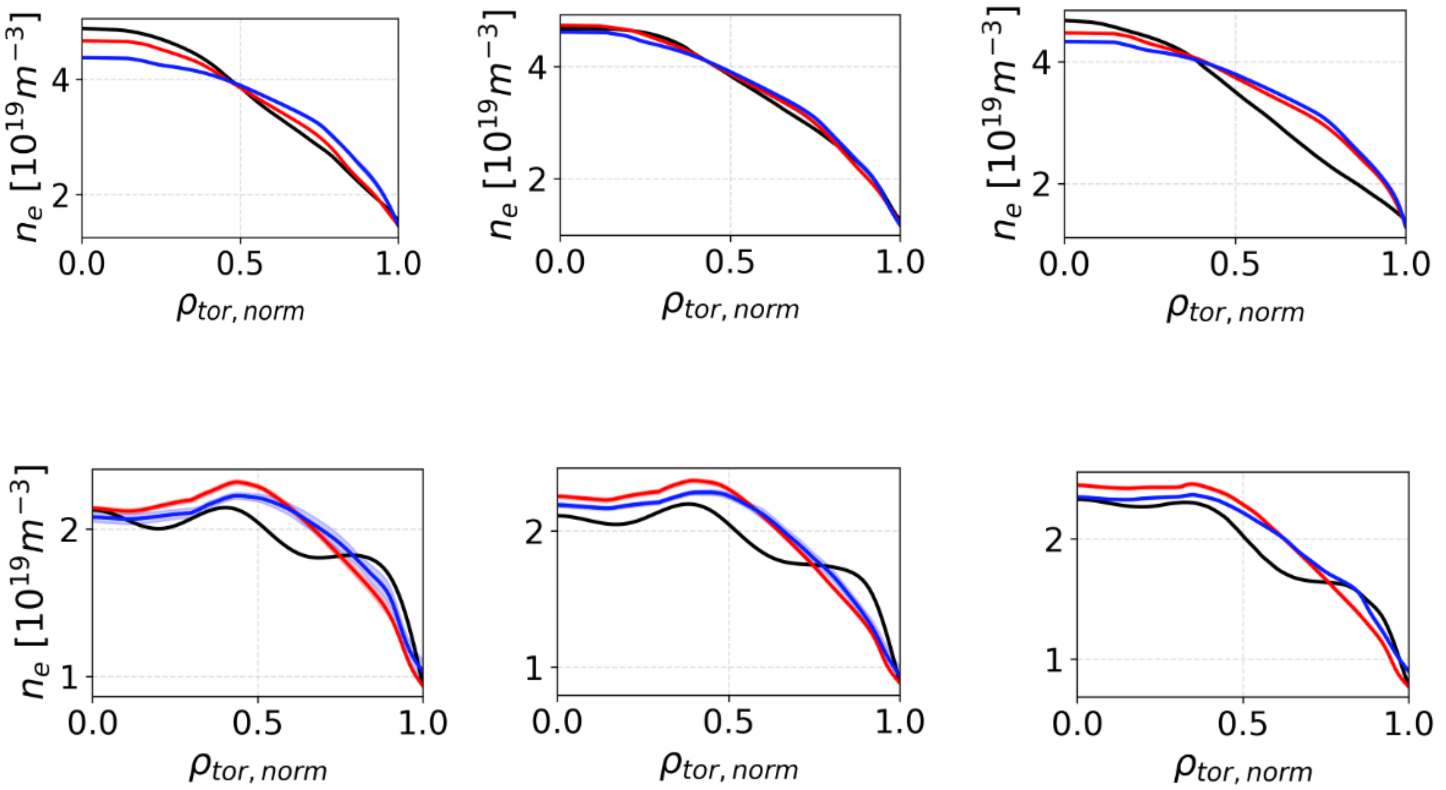


57592



Density peaking overall

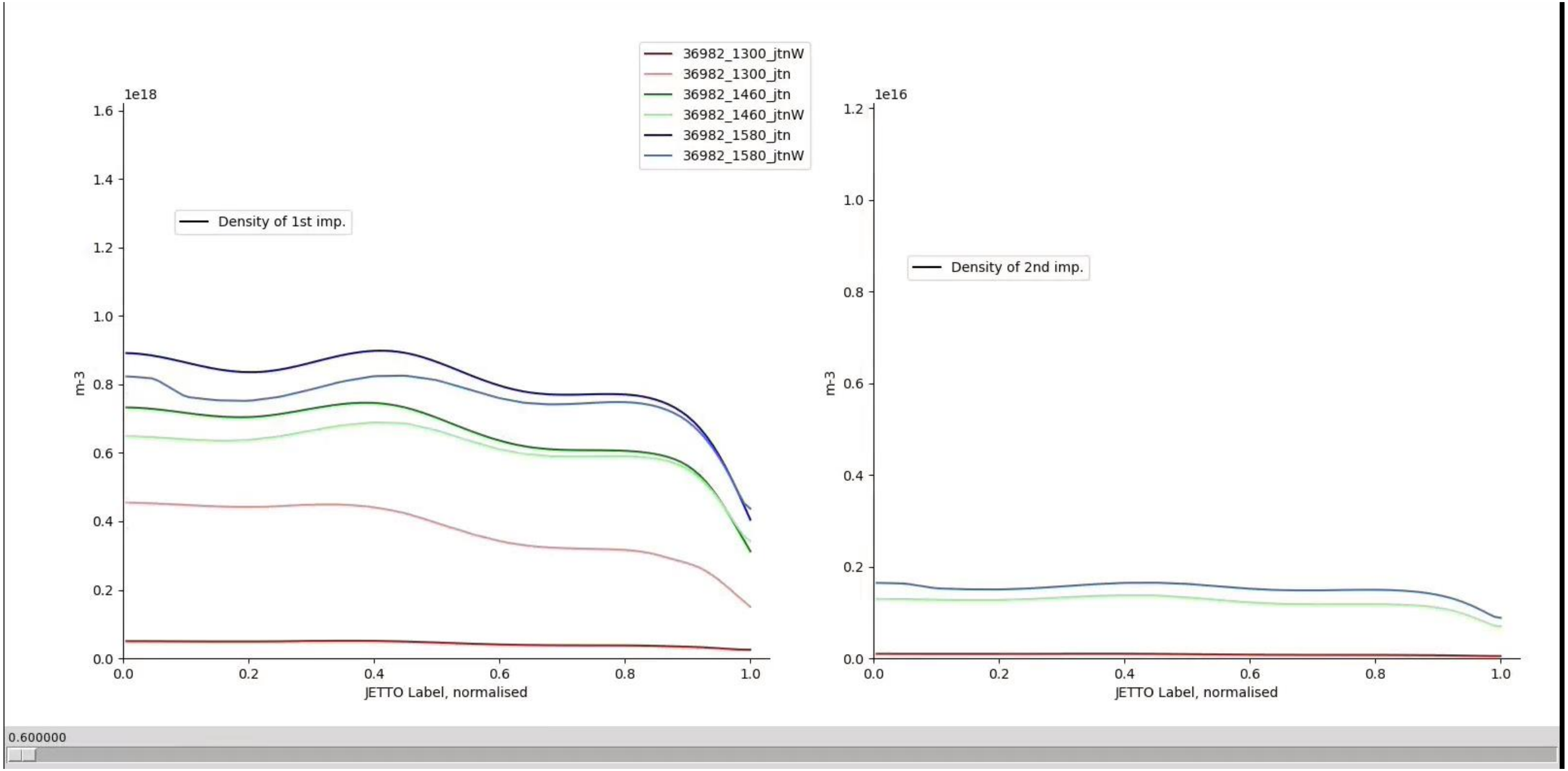
- Whether considering WEST or AUG, n_e, n_n, n_W gradients always get higher at the edge and the electron energy content increases



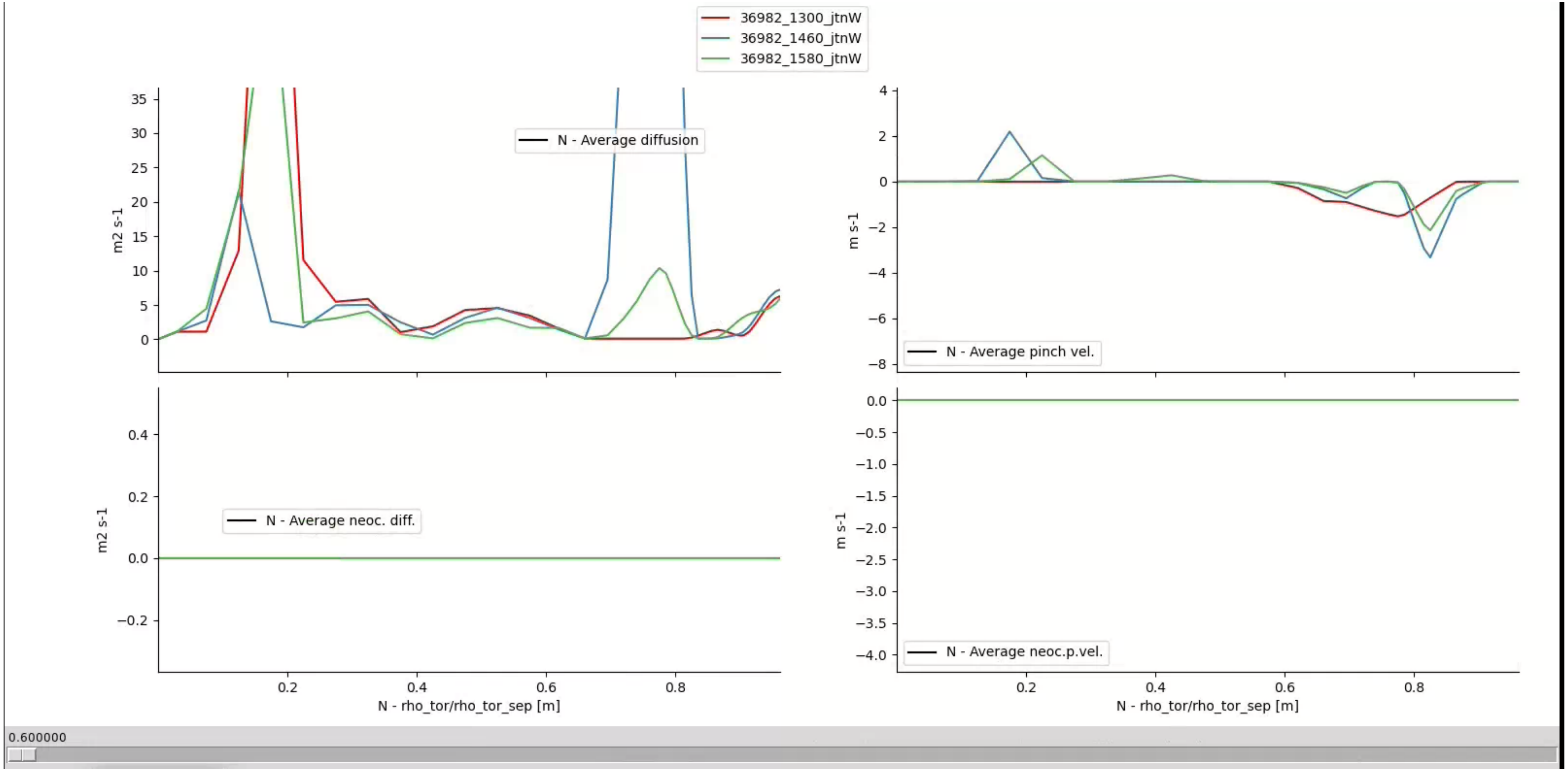
- What is the impact of having flatter N density profile (try different Z_{eff} profiles + fixed transport)

- Are there any numerical artifacts originating from the interaction of all 3 feedback controllers? (How to test?)

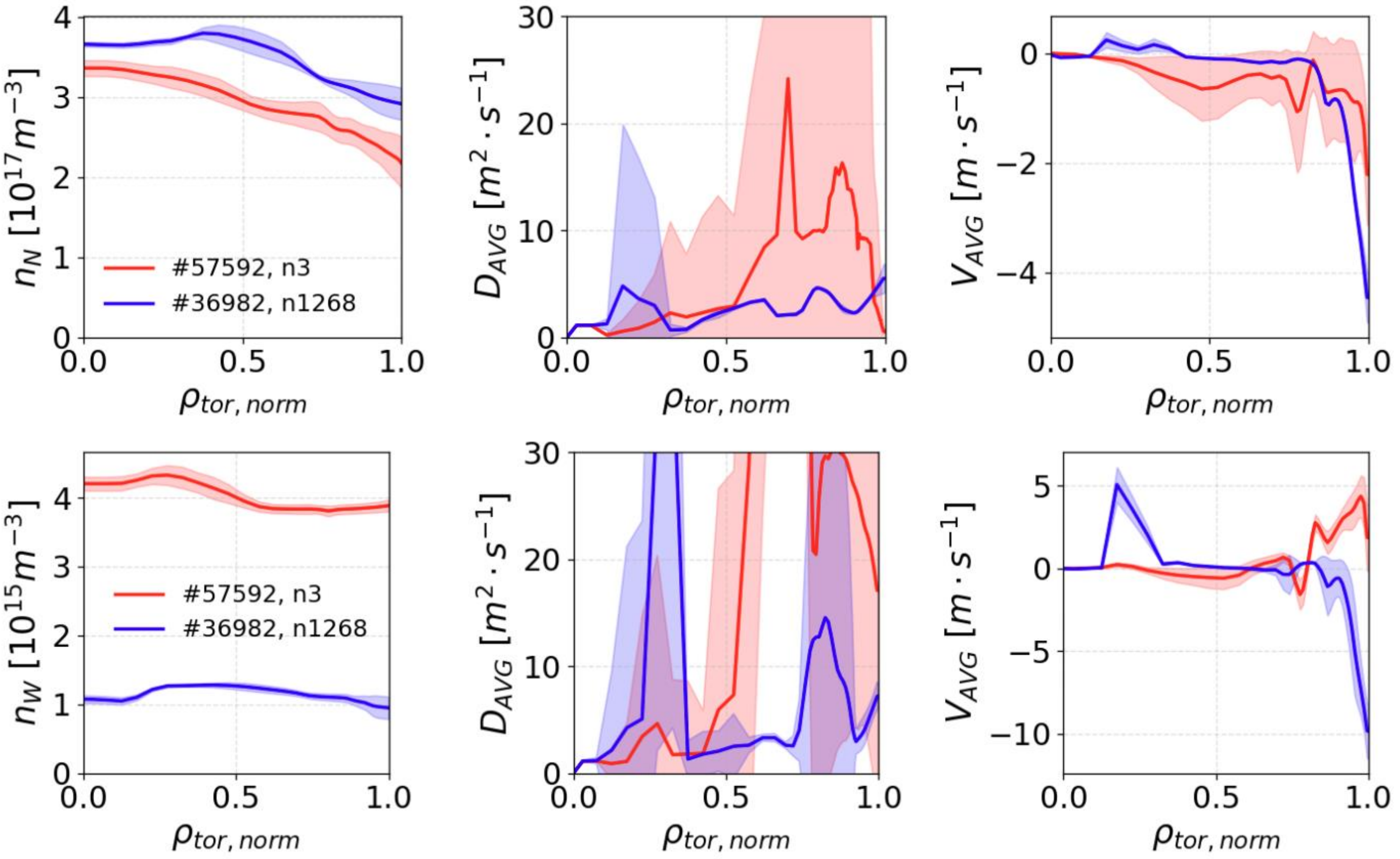
Noisy simulations



Noisy simulations



Issues



The self-consistent prediction of impurities is noisy and predicts diffusion levels (averaged over 2 seconds) that seem way off

This results in (overly?) flat profiles, which in turn overpredicts W radiation off-axis and underpredicts on-axis

This impacts particle transport at the edge (next slide) and core Te and drives the predictions away from measured profiles, particularly at large frad (last slide)

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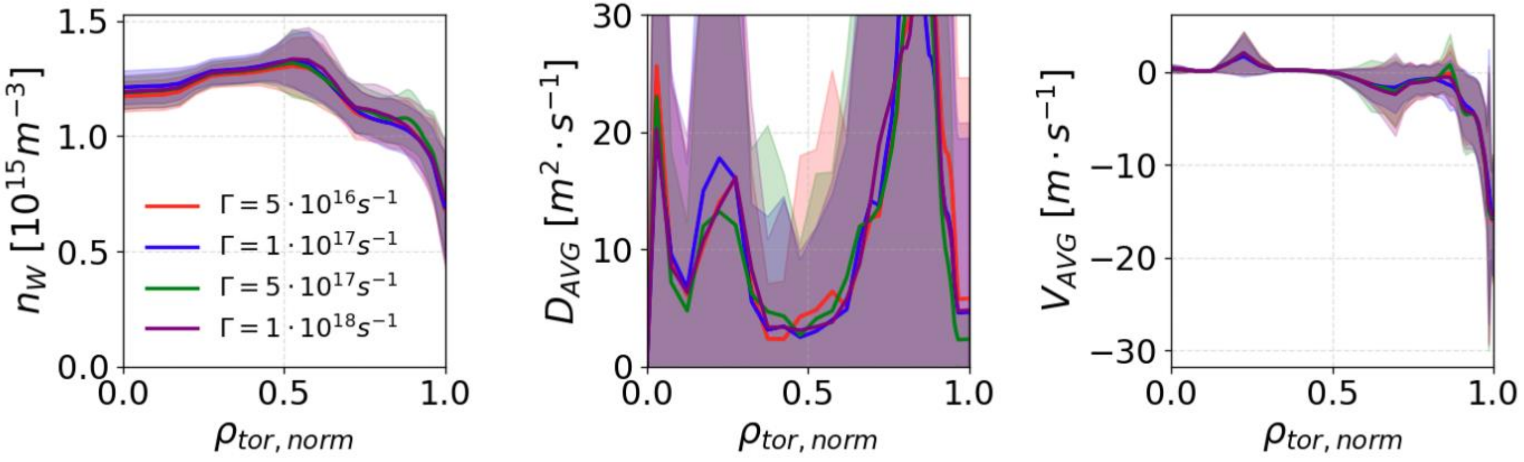
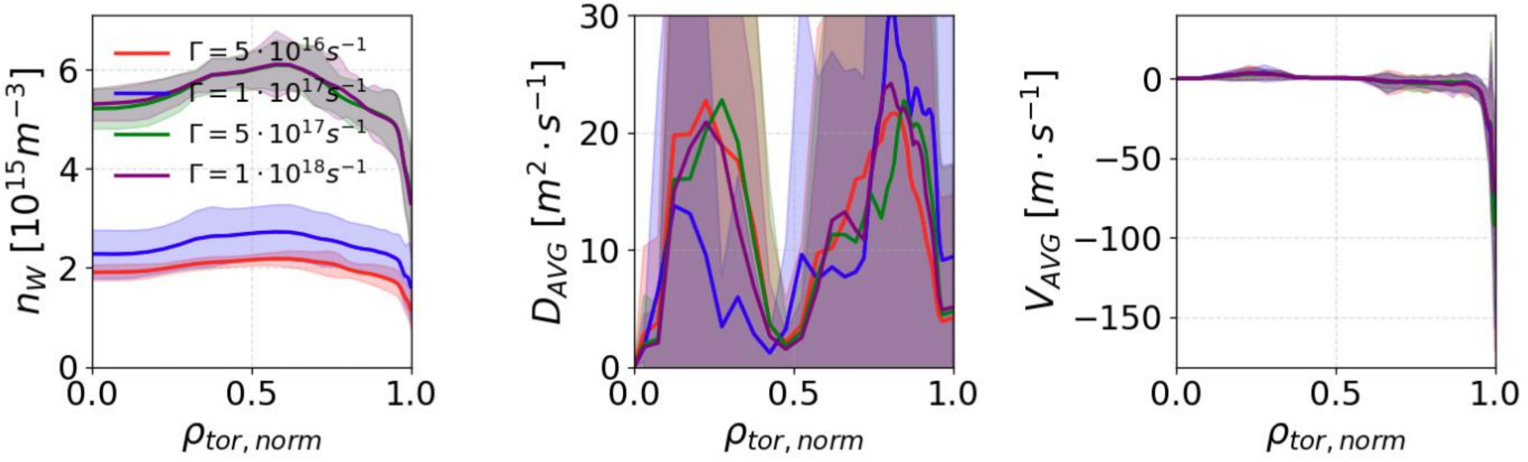
AUG – t = 2.68 s



AUG – t = 6.13 s

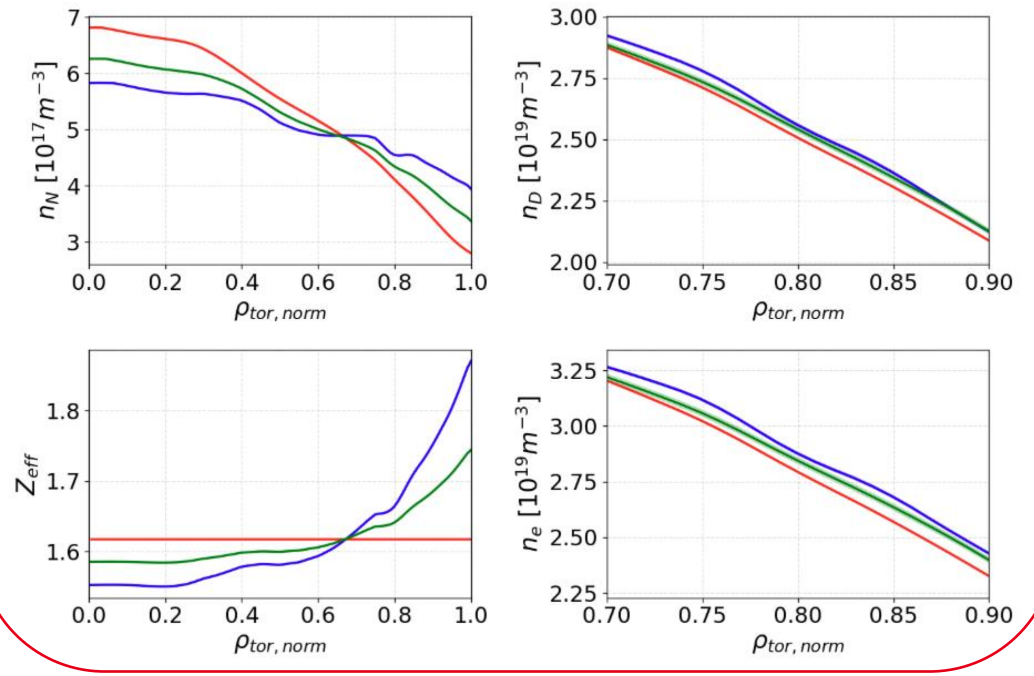


- The large diffusion oscillations do not come from the impurity influxes gains
- Exact same profiles are retrieved with different gains

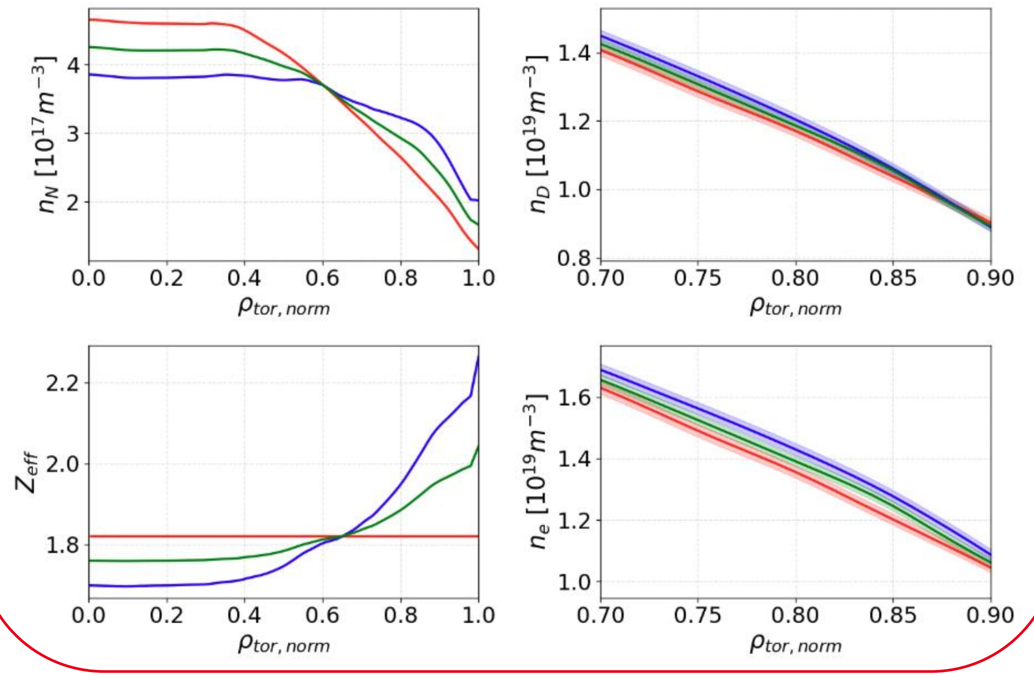
Issues

- Here, I fix the effective charge gradually to the predicted-like profile (removing W contribution) and I therefore get gradually flatter N profiles
- This is correlated with the lower density peaking, reminds of [Angioni, PRL, 2003] -> density peaking decreases when collisionality increases, caused by larger Zeff at the edge (up to ~30%)

WEST - 57592

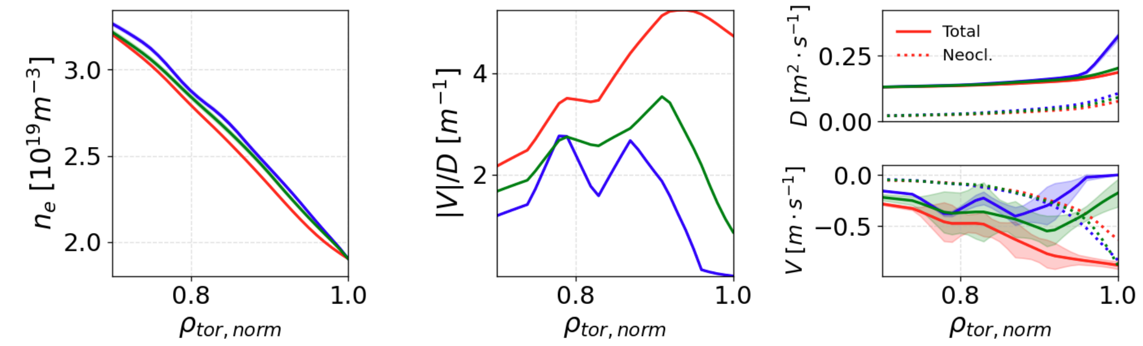


AUG – t = 2.68 s

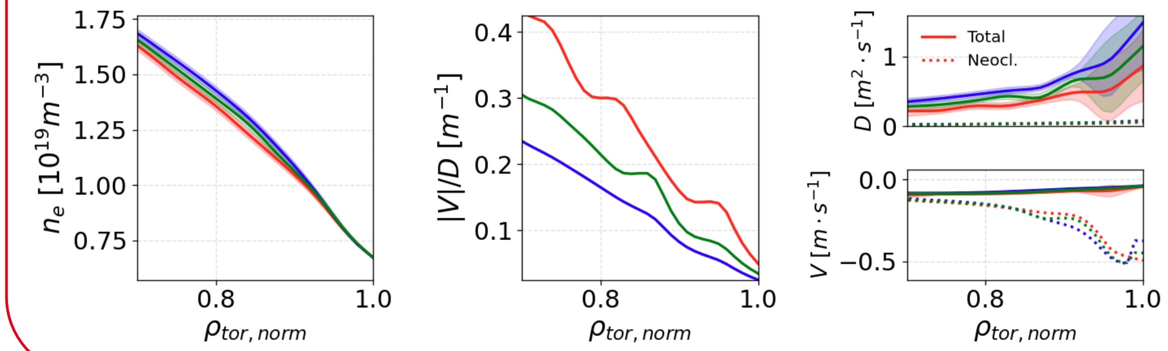


Issues

WEST - 57592



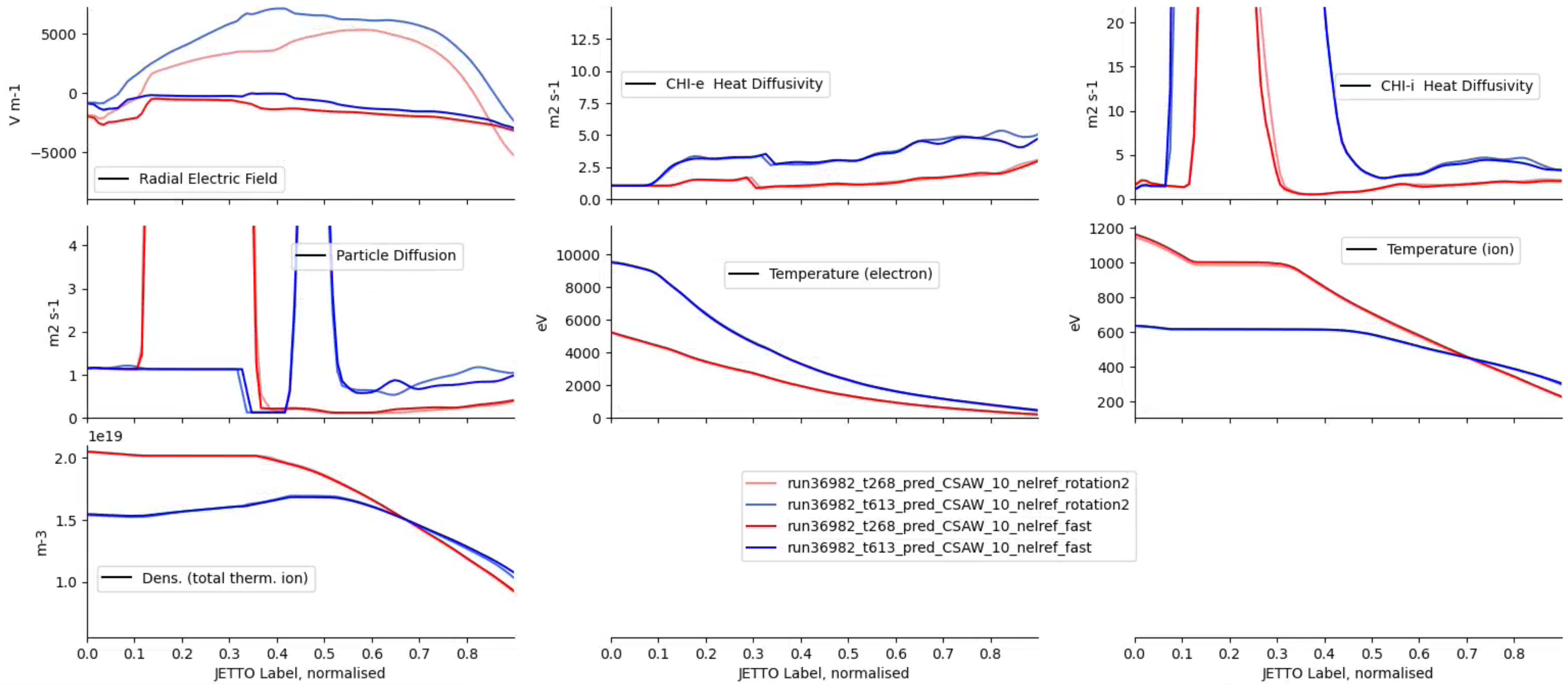
AUG – t = 2.68 s



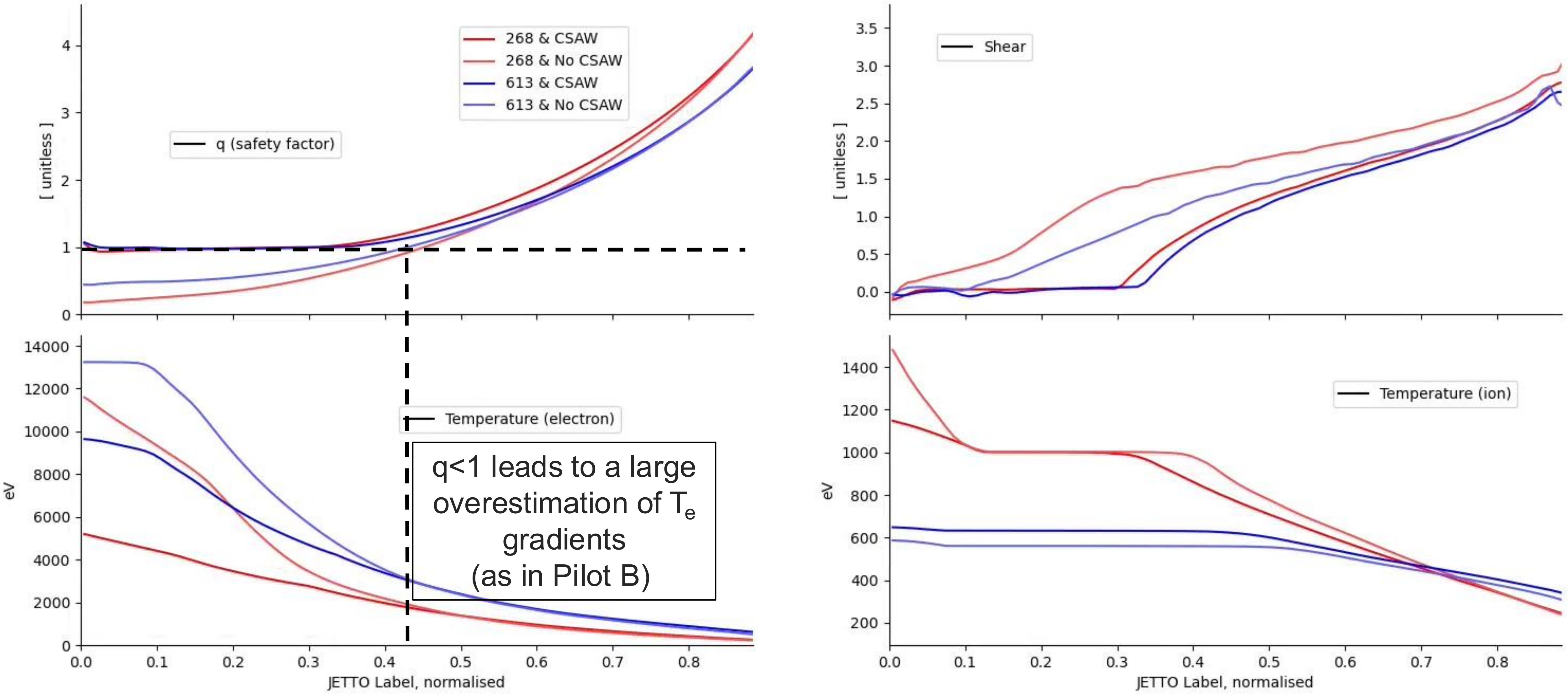
- Quasineutrality effect explains ~25% of the density difference: the model predicts ion density, while ne follows from charge balance
- The remaining 75% is likely due to transport. The larger edge Zeff increases collisionality by up to 30%. This can impact TEM activity and modify the balance between turbulent diffusion and inward particle pinch. What about R/Ln_N ?
- This interpretation should be verified with a stand-alone collisionality scan (see with Emil to install) and by checking the dominant mode frequency at the edge
- Analyzing D and V it seems that there is a difference in the transport between AUG and WEST (or is it D, V splitting method which is arbitrary?)

Toroidal rotation

Adding toroidal rotation impacts the radial electric field and therefore convergence in the sense that at time t you don't have the exact same profiles between both simulations but in the end: same energy content (e-, i+), same profiles and same effective diffusivities => negligible impact as expected



Sawtooth



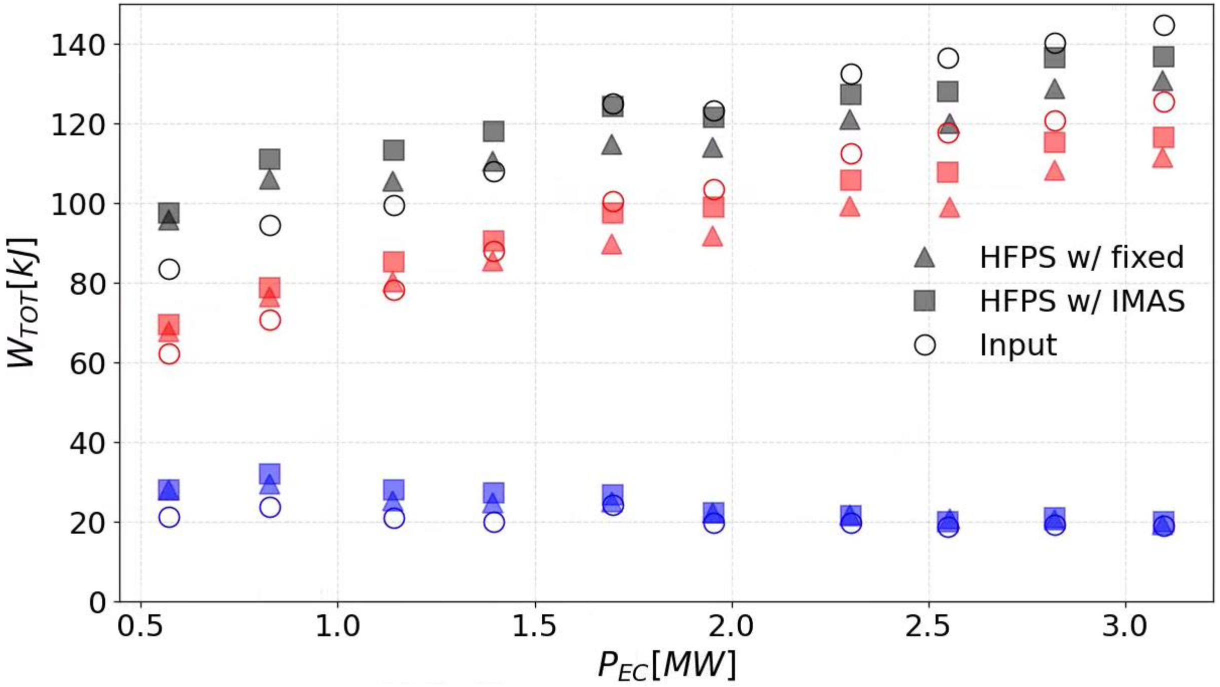
q<1 leads to a large overestimation of T_e gradients (as in Pilot B)

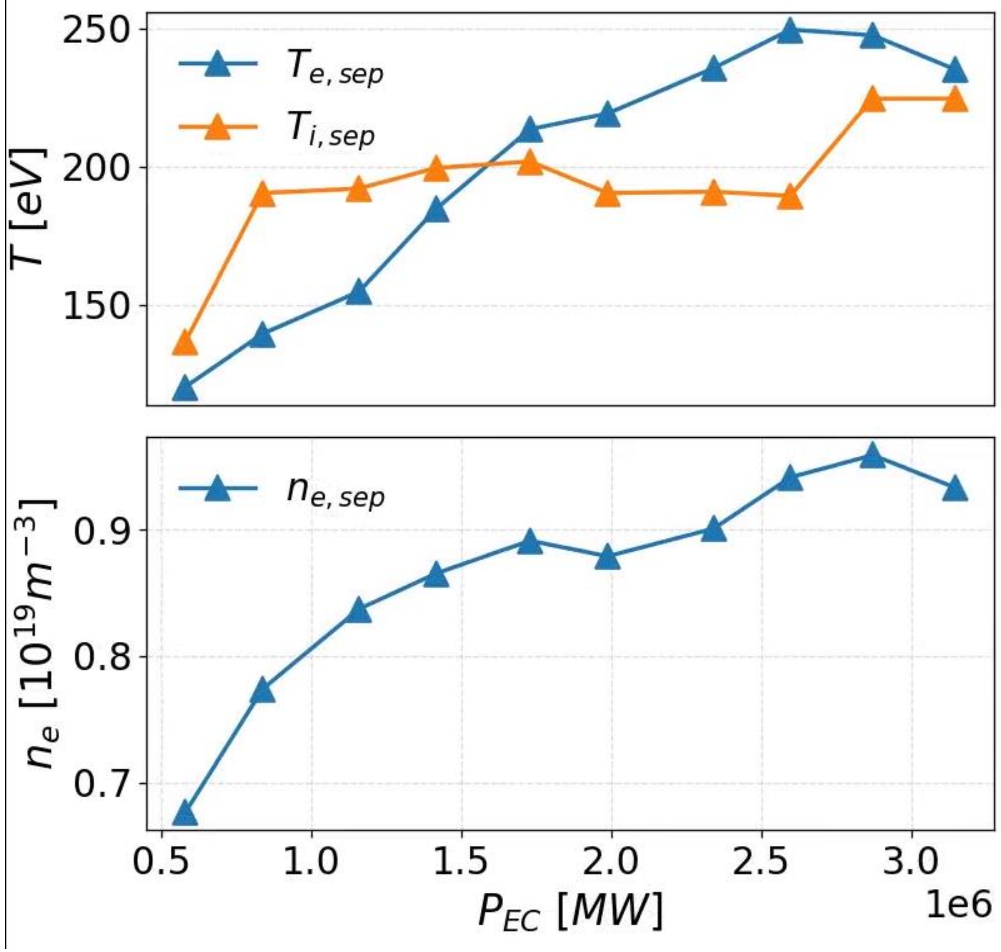
To be done

To do	Status
2-pt model on WEST	Empty IDSs in last campaigns => mail sent to Jamie. For now Te fixed to 80 eV (combination of paper 2023 + SOLEDGE modeling values)
Try parametrization of Ti with Pe based on TCV ?	To be tried and compared to Ti fixed to 1.5 Te + to fixed BCs + to fixed 1.5Te & 2-pt model (as in paper)
Adjust gains for impurity influxes feedback	Gonna take some time as not automatized => it will be performed on few cases to see if we can make simulations less noisy and if it changes the convergence
Answer to why ne profile is matched in C7 but not C11	Started sending mails around in the WEST team to see if it has been observed, characterized, if it is coming from the reflectometers themselves, identifying the main differences between campaigns, …
Self-consistently model for sawtooth	Try an advanced model (Kadomtsev with Porcelli trigger model) to see if we replicate Sawtooth frequency, see if we match inversion radius and then compare to continuous sawtooth to see how it compares
Populate AUG database	Message sent to Ondrej Grover working on large-scale analysis of sepratrix parameters impact on core performances in L-mode discharges of WEST, AUG + eventually coming in IPP ?

Impact of boundary conditions

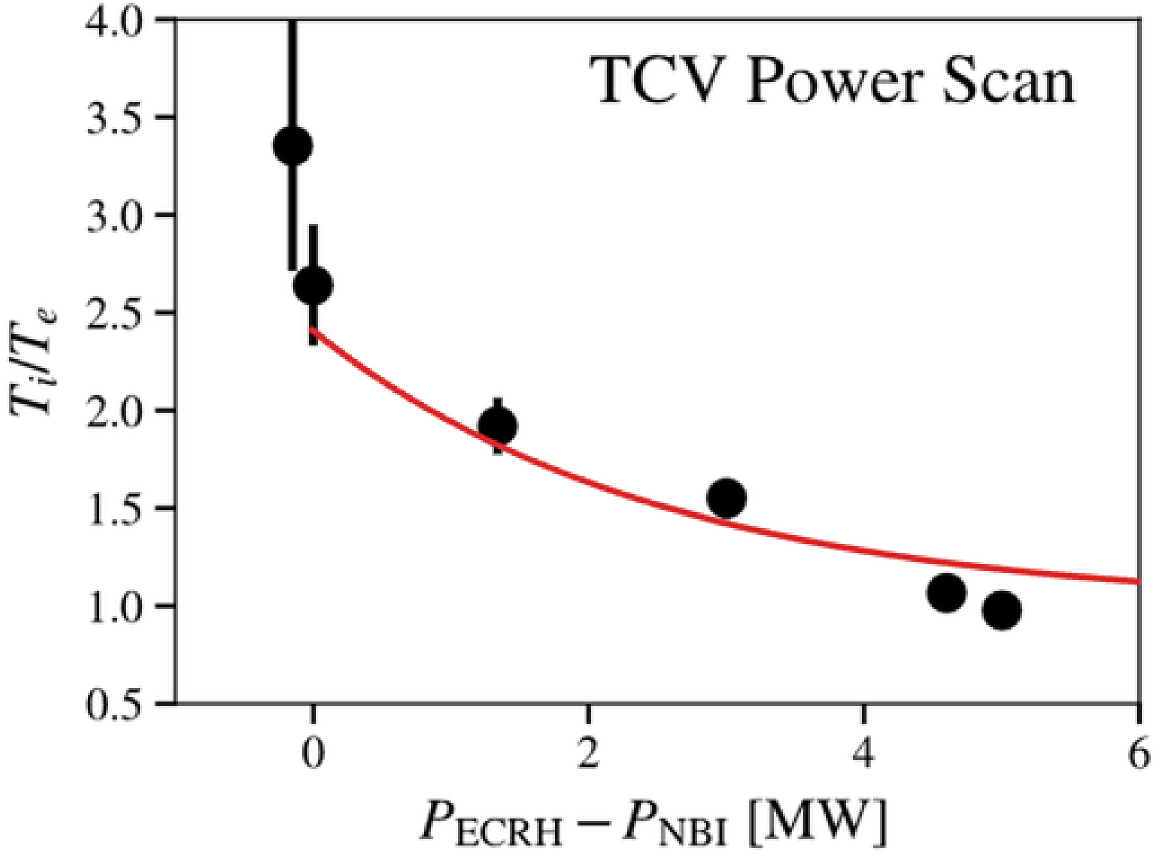
- Usually, $T_i > T_e$ at the separatrix, however here in BCs from IDA, it drops below Te at high input power
- n_{sep} is following nvol/3 which is fine
  - What if **(T_{isep}, T_{esep})** is fixed to **(120, 80)** ?





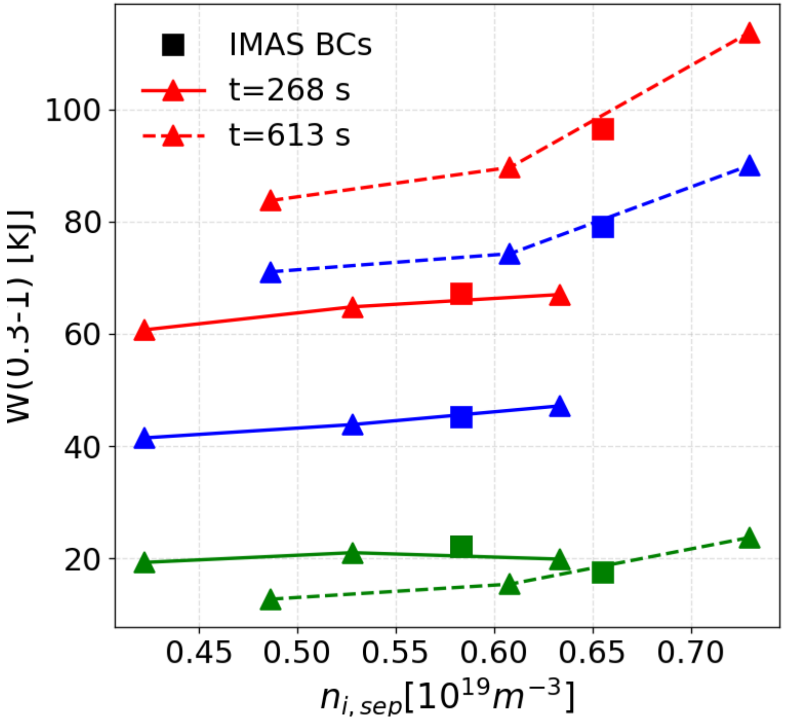
BC choice

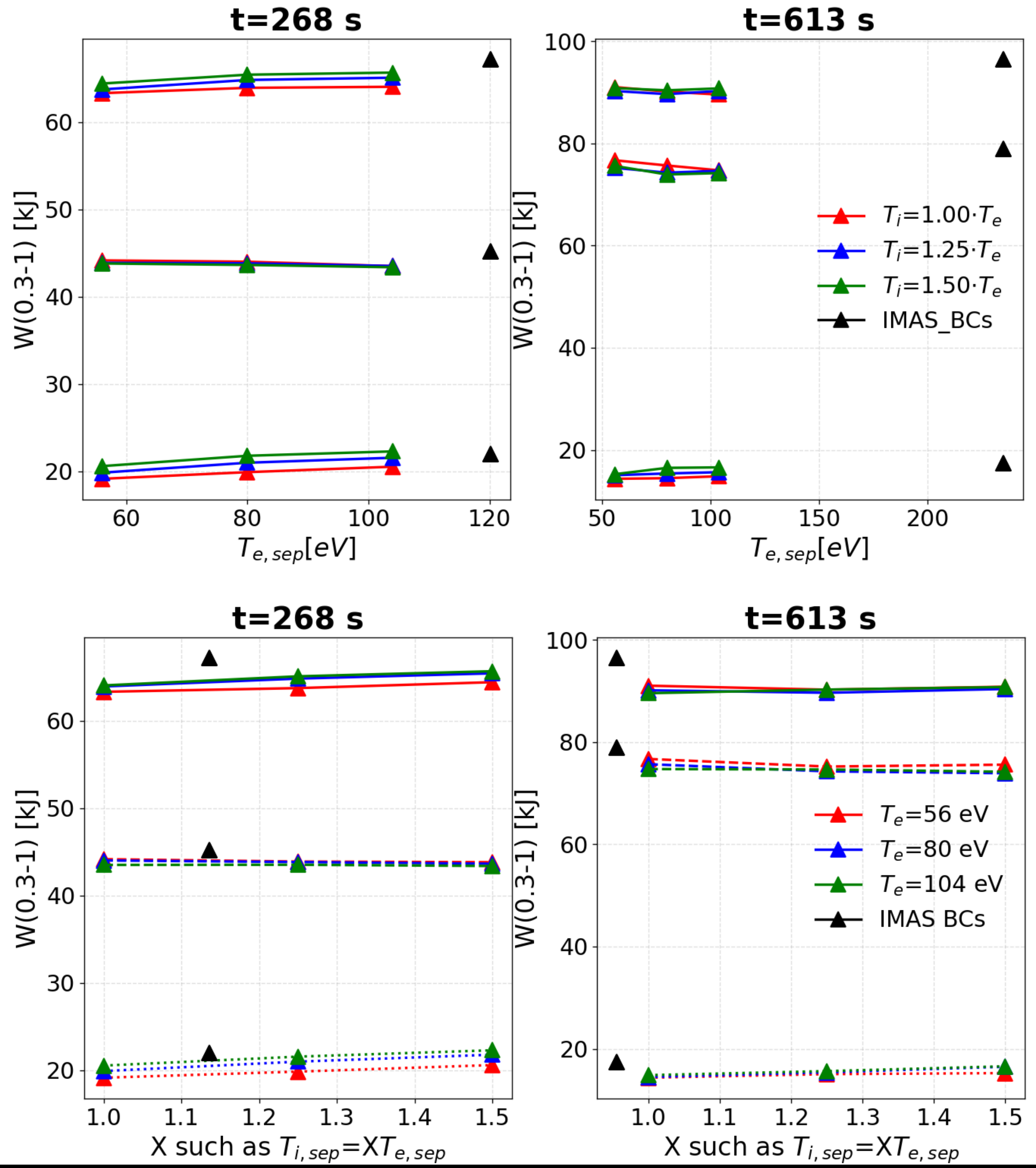
- In TCV, T_i/T_e was observed to decrease with the injected power
- Reported T_i/T_e for Ohmic discharges in AUG are of 2.4
- A **simple parametrization** can be applied to get T_i/T_e depending on the total power applied to the electrons ($P_{TOT}=P_e + P_{OH} – P_{rad}$), $1+1.4(e^{PTOT/3})^2$
- Same parametrization can be applied on WEST, with a $T_{e,sep}$ either originating from 2-pt model or fixed to 80 eV given results from [Bourdelle, NF, 2023]
- $n_{e,sep}$ comes from reflectometry in WEST and provide $n_{i,sep}$ after considerating Z_{eff} while for AUG, it is kept from IDA (close to n_{isep}~$n_{vol}/3$)



BC sensitivity

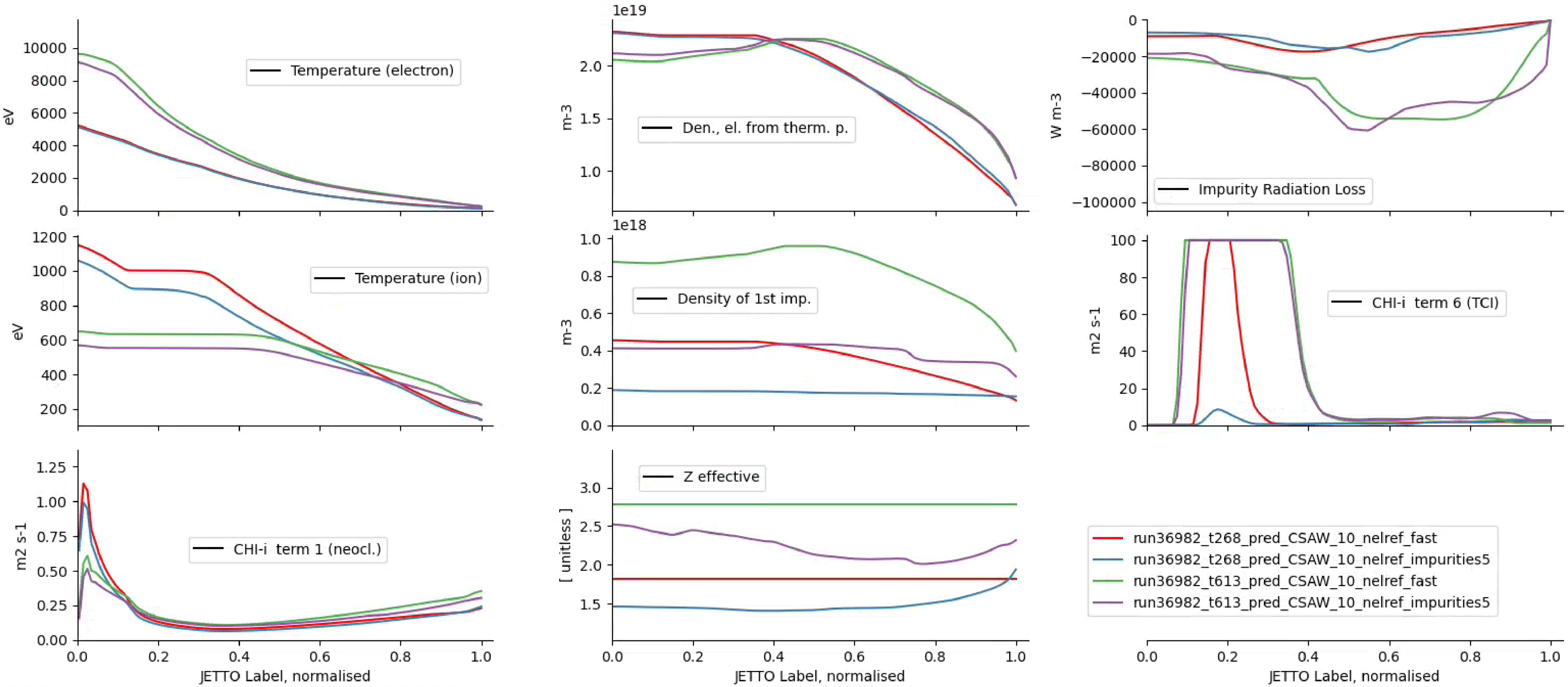
For t=613s, at high nisep, even with 0 neutral influx, target nel is overcome which is why W increases largely





Impact of impurities

When feedbacking n_N with pedestal top (in L-mode...), **large fluctuations** on N source + Z_{eff} gets lower and dilution effect is lost => **Ti decreases** + it is observed that TCI **largely overpredicts ion turbulence in the sh=0 region**, this is concerning + else, relatively low impact and good prediction of Qrad >>> **Feedback on line-averaged n_N**

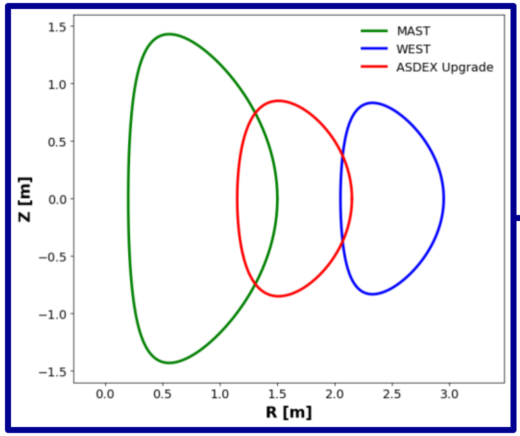


Multi-machine integrated modeling for geometry dependence

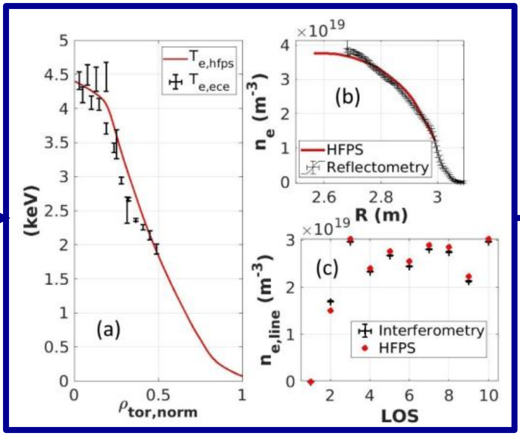
- Tokamak design still relies on energy confinement scaling laws with large uncertainties, especially regarding plasma geometry effects (aspect ratio, triangularity, elongation).
- At the same time, integrated modeling is becoming increasingly reliable, particularly with reduced turbulent transport models, and offers a flexible framework to vary plasma geometry artificially.

Protocol developed to disentangle the impact of plasma geometry on energy confinement:

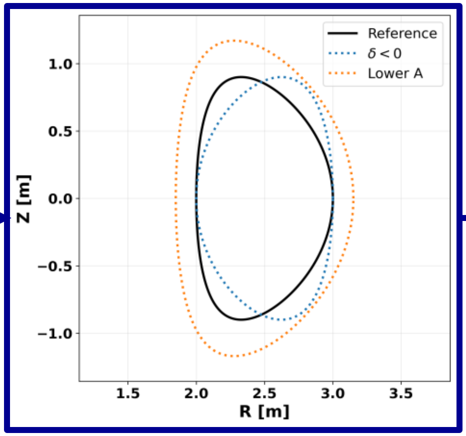
Replicate multi-machine experiments



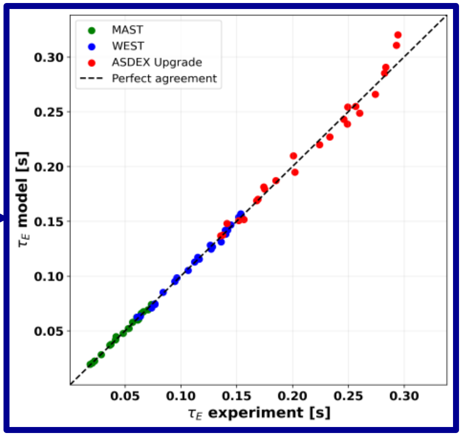
Validate the modeling against measurements



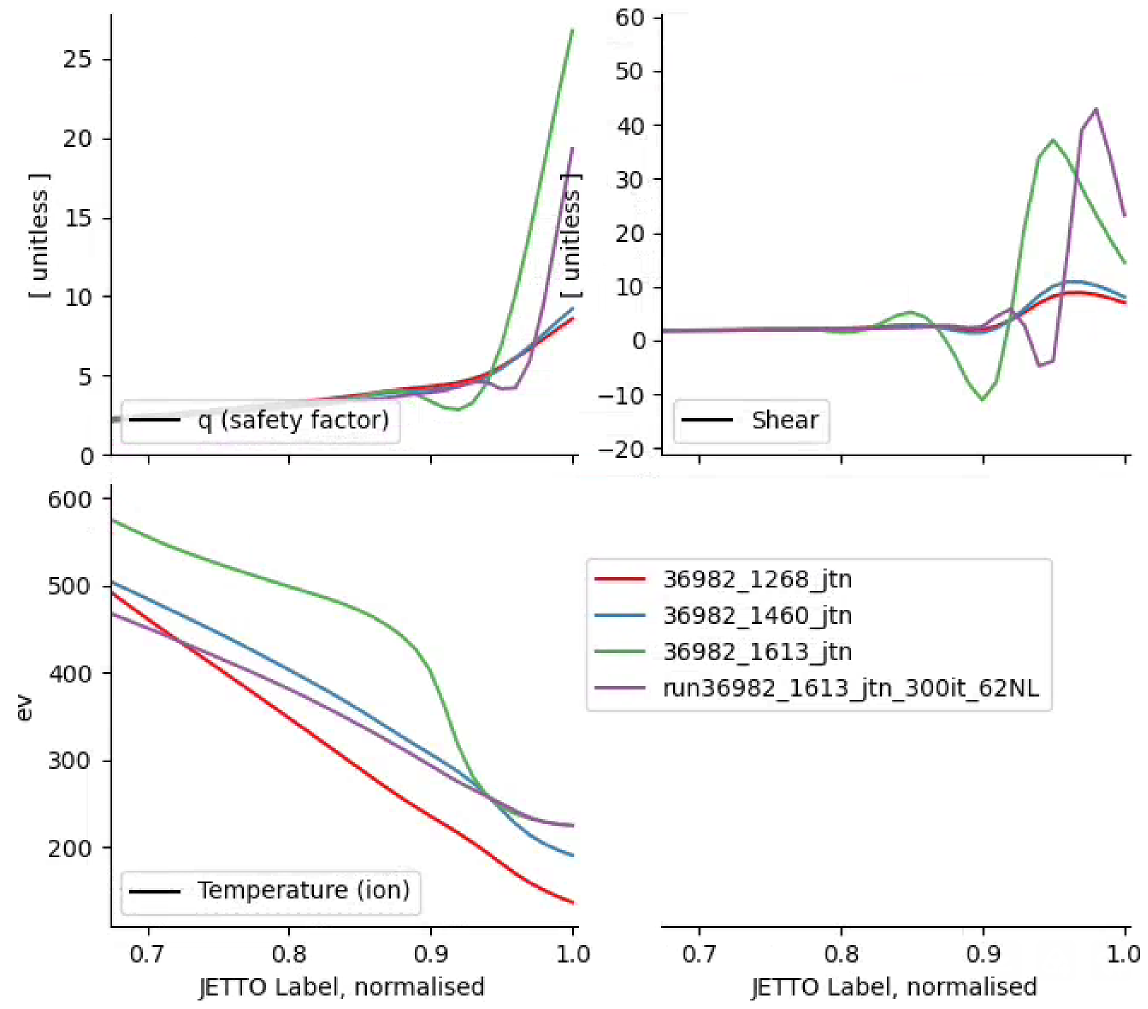
Perform artificial variations of geometry



Provide a refined scaling w/ explicit dependences



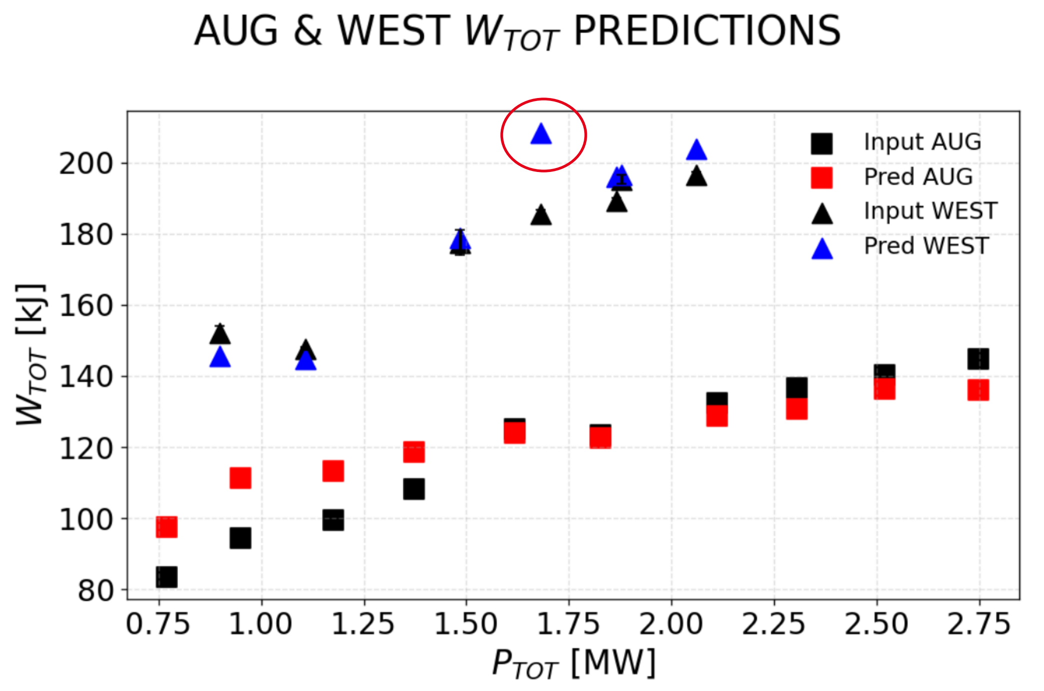
NL = 62 needed

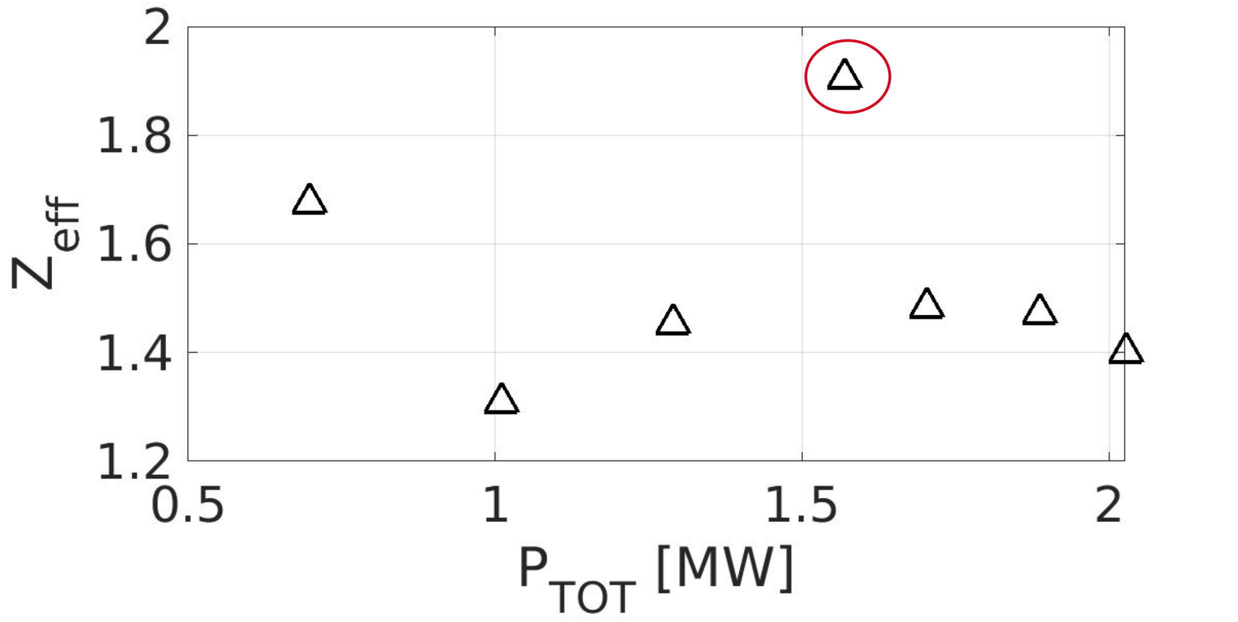


Red, blue, green are 3 cases predicted with NL = 30 (radial 1D grid within ESCO). Not all, but some (high input power), feature large q numerical variations with either high shear or large reversed shear config which yields very large gradients (green)

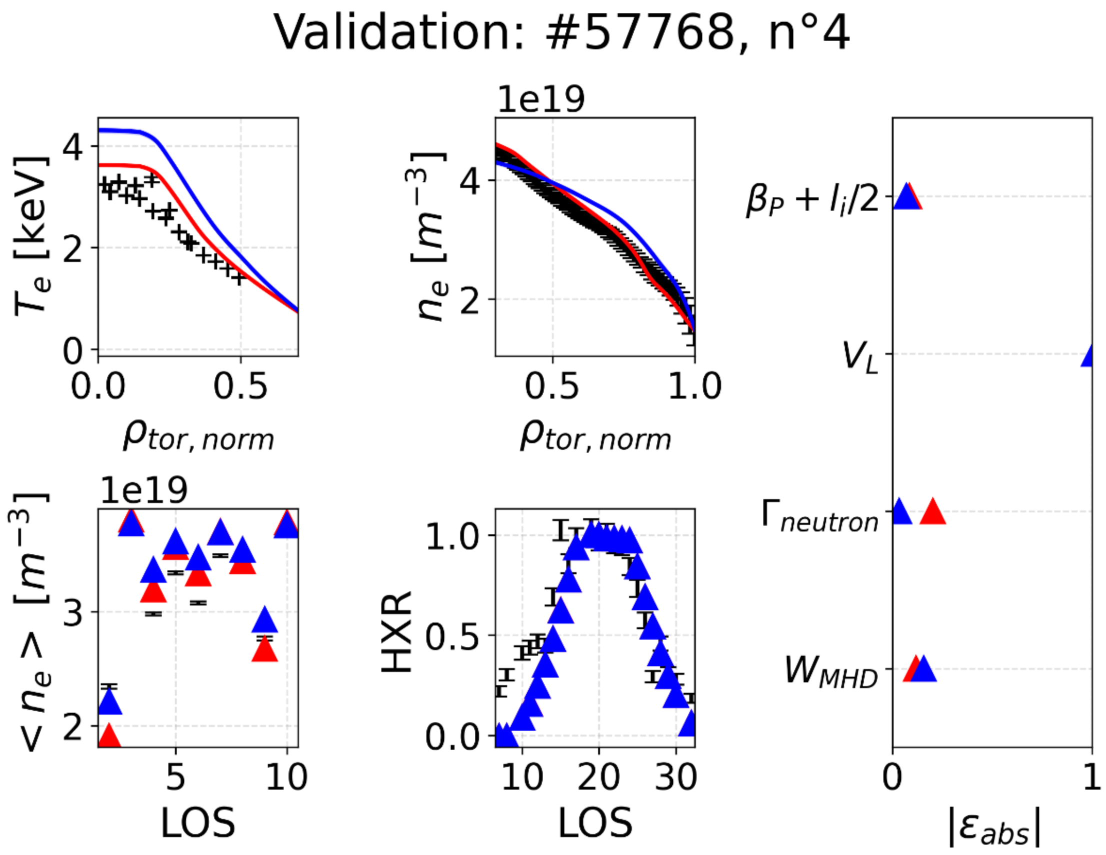
With maximum NL=62 this is mitigated

The most plausible explanation for larger stored energy content compared to other cases is **turbulence stabilization by dilution**

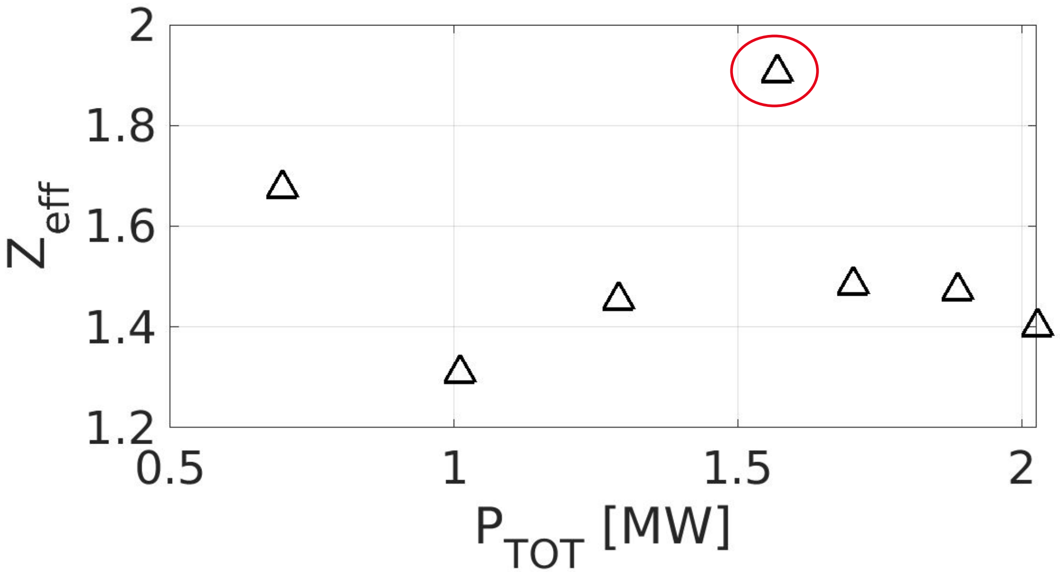


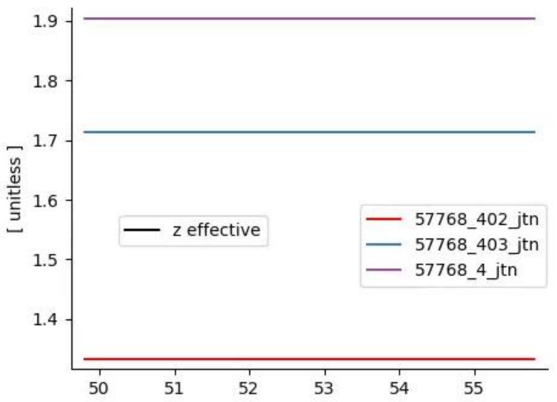


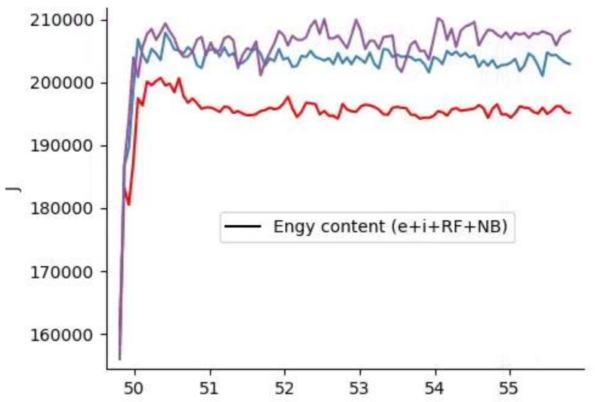
Only notable difference is linked to the effective charge



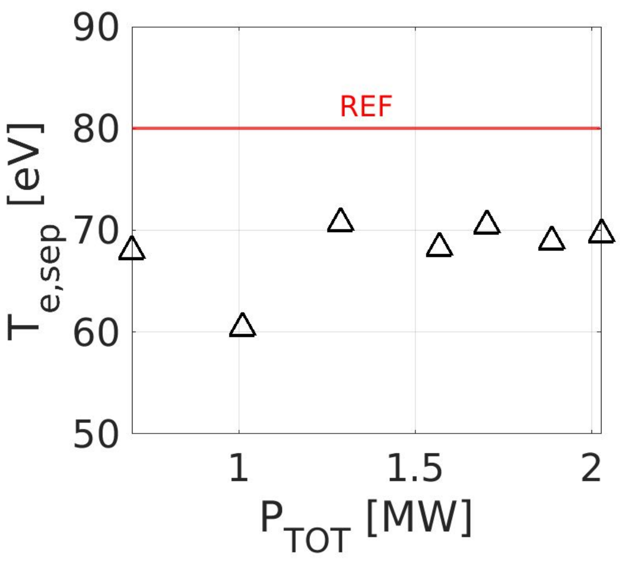
Comparison to diagnostics do not seem too bad

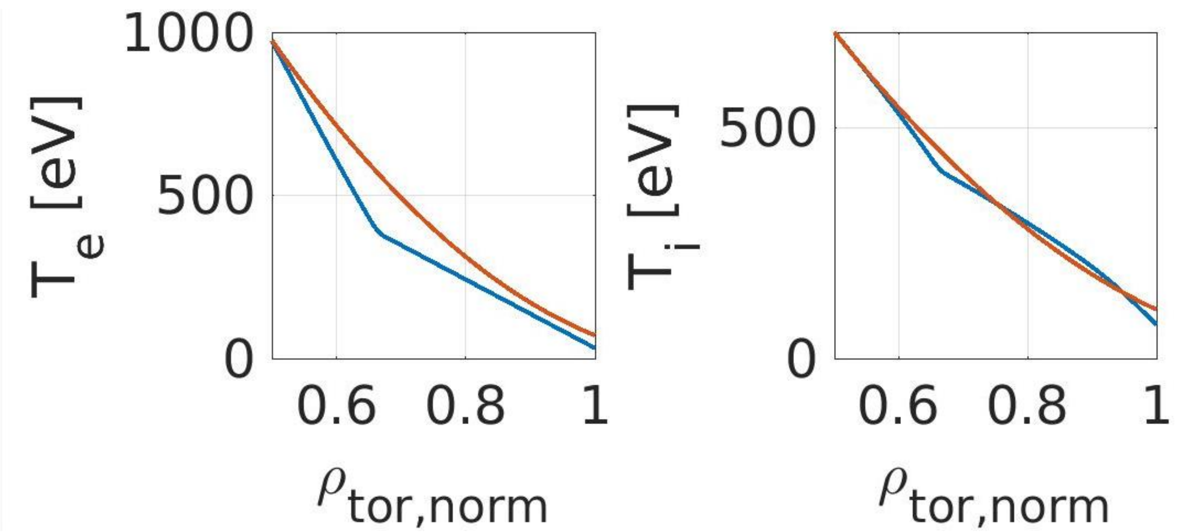






Te,sep in WEST





- All the results were obtained with fixed $T_{e,sep}$ = 80 eV; yet, I now coupled 2pt model and get the following BCs
- Will not change the results but is added in the workflow together with another way of fitting up to the separatrix (from 0.5, gradient linearly decrease down to 0 @ 1.2 & $T_{e,sep}$ imposed)
- Then Ti,sep imposed at 1.5*Te with sqrt(ne*Te) from 0 to 0.5