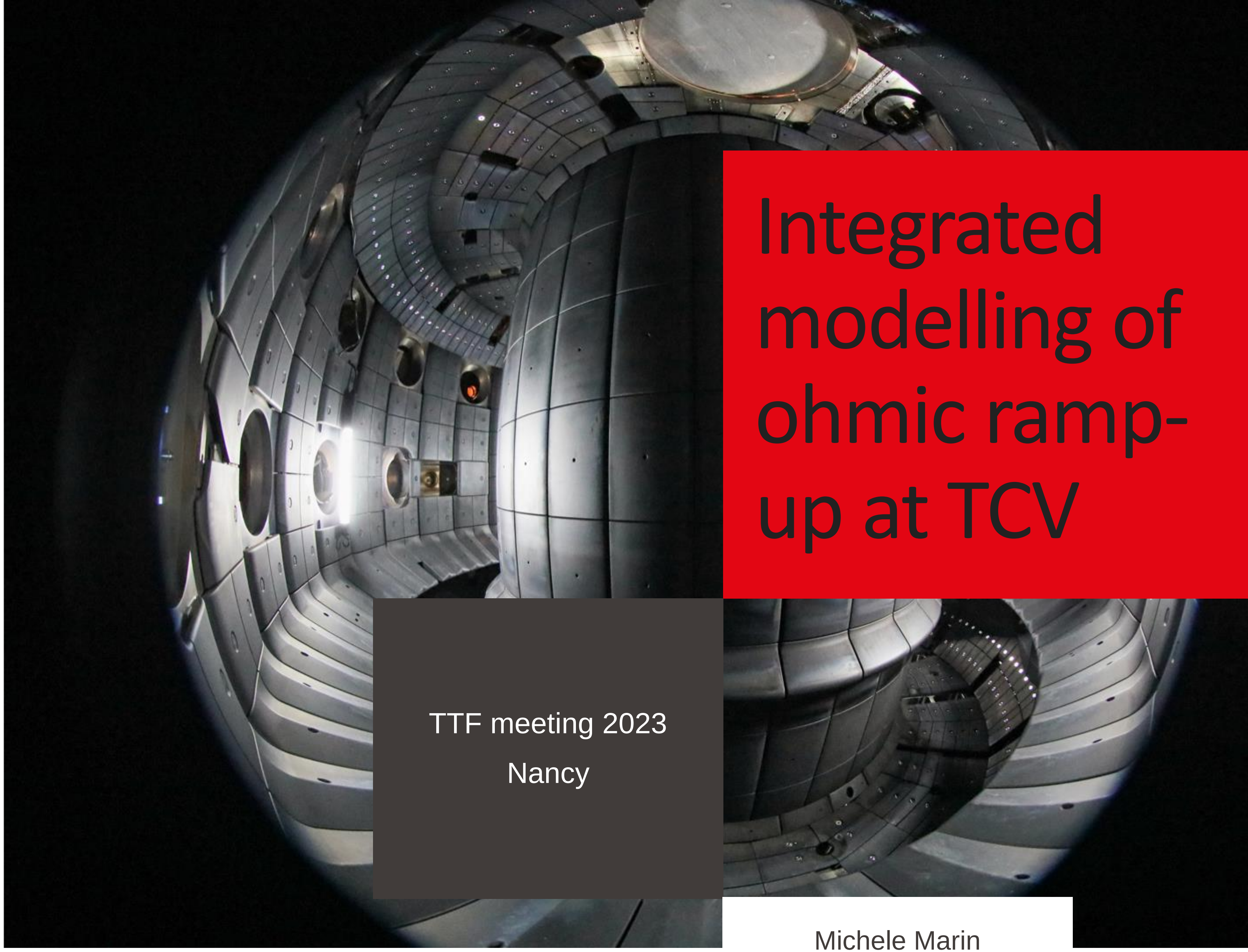

Integrated modelling of ohmic ramp-up at TCV

M. Marin,
Y. Camenen,
O. Sauter,
P. Manas,
L. Simons,
F. J. Casson,
C. Bourdelle
and TCV
collaborators

TTF meeting 2023

Nancy

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Swiss
Plasma
Center

Understanding and controlling the ramp up is crucial to tokamak operation

- Work done within EUROfusion TSVV11 activities

- Focus on validation of integrated modelling
  - Comparison against non-linear gyrokinetic simulations
  - Comparison against experiments

- Ramp up is a critical phase:
  - Need to minimize magnetic flux consumption while avoiding MHD instabilities
  - l_i, V_{loop} and β_N need to be controlled at the same time

Numerous challenges need to be overcome for successful modelling of the ramp up

- Specific conditions: high T_e/T_i, high q, high collisionality, high R/L_n (TCV)
- Numerous physics processes are important (neutral source, sawteeth, turbulence, neoclassical transport etc)

- Large uncertainties on the simulation settings
  - Uncertainties about initial conditions (particularly current profile)
  - Uncertainties about boundary conditions

- State of the art is the simultaneous prediction of j, T_e, T_i

[Fable *PPCF* 2013, Maget *PPCF* 2022, Ho NF 2023]

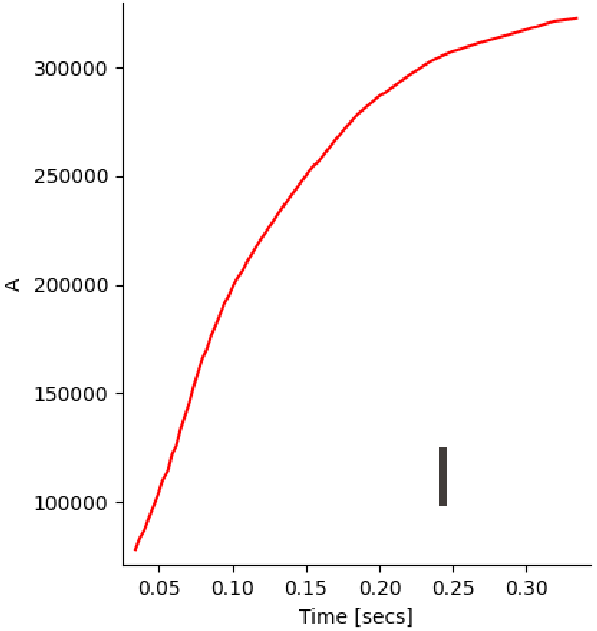
- The predictive channels interact nonlinearly

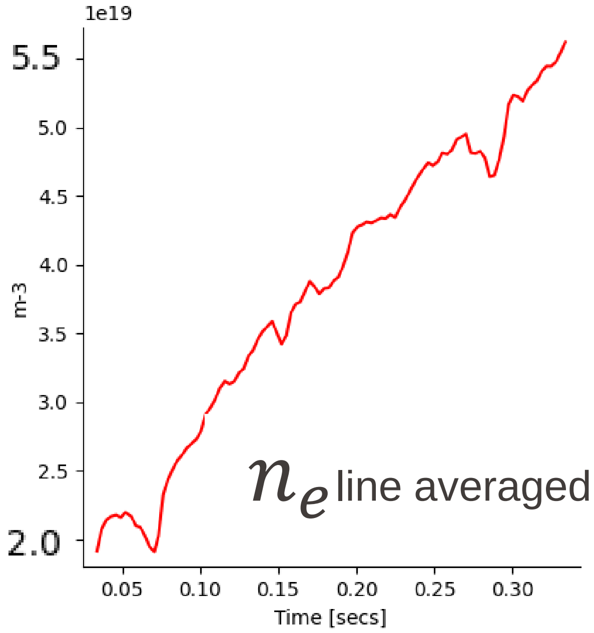
- Aim is to use the same settings for multiple discharges

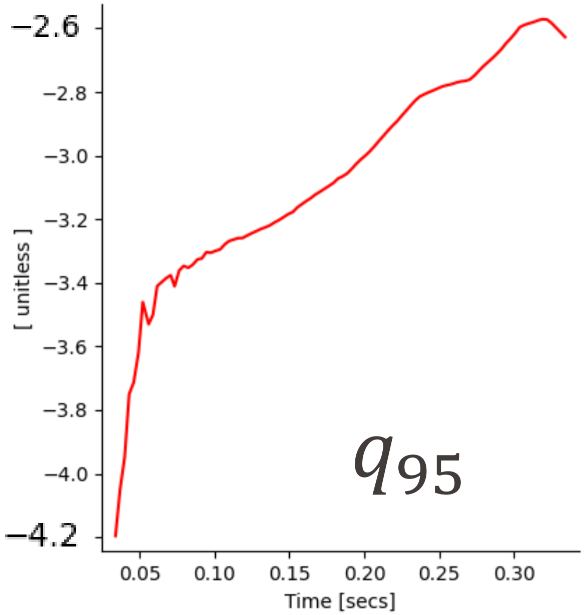
Well diagnosed TCV shot was chosen as reference #64965

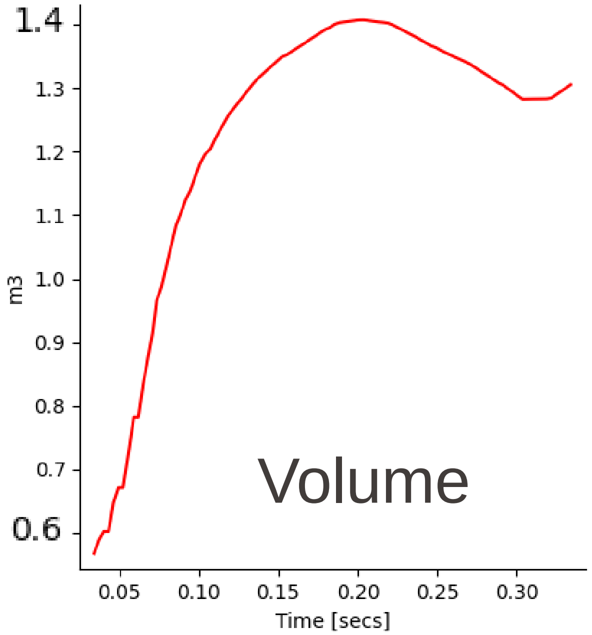
- TCV, Ohmic, L-mode plasma
- Limited (diverted after the modelled interval)
- With electron (Thomson Scattering) and ion (CXRS) measurements during the ramp-up

$t\ [s]$	0.03	0.3
$I_p [MA]$	0.08	0.32
$\kappa\ [-]$	1.0	1.5
$\delta\ [-]$	0	0.2
$n_{e,line\ ave}$ $[10^{19}]$	2.0	5.5
$Z_{eff}\ [-]$	1.2?	1.2
$B_T\ [T]$	1.4	1.4



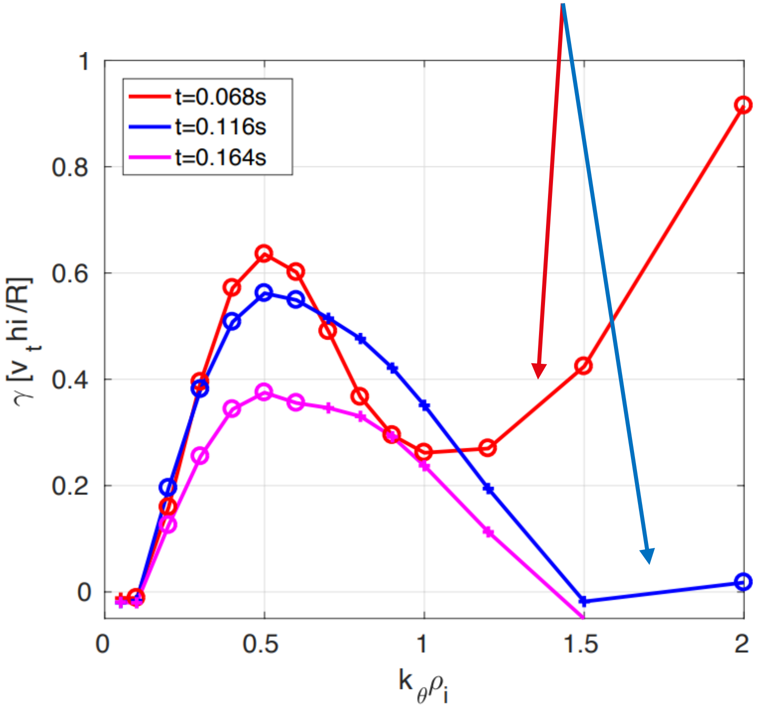






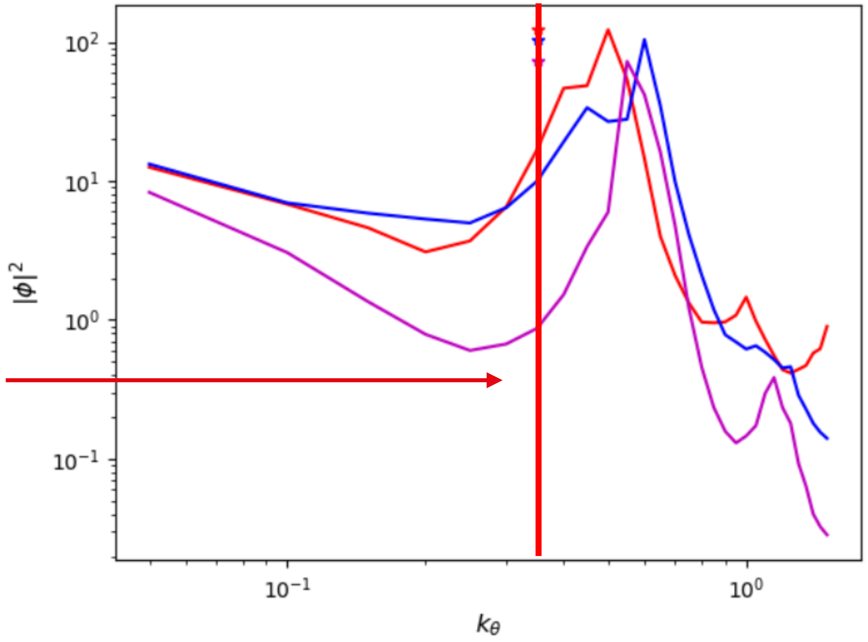
Quasilinear and non-linear gyrokinetic are in qualitative agreement

- Long wavelengths stable
- Fair agreement with quasilinear estimates **[Y. Camenen, this conference]**
- TEM dominated (R/L_n driven) despite of collisionality, especially in the early phase, then transitioning to a hybrid TEM-ITG
- ETG at short wavelength, stabilized when s/q increases



r/a=0.7

$$Max \frac{\gamma}{< k_\perp^2 >}$$



Modelling as self-consistent and predictive as possible

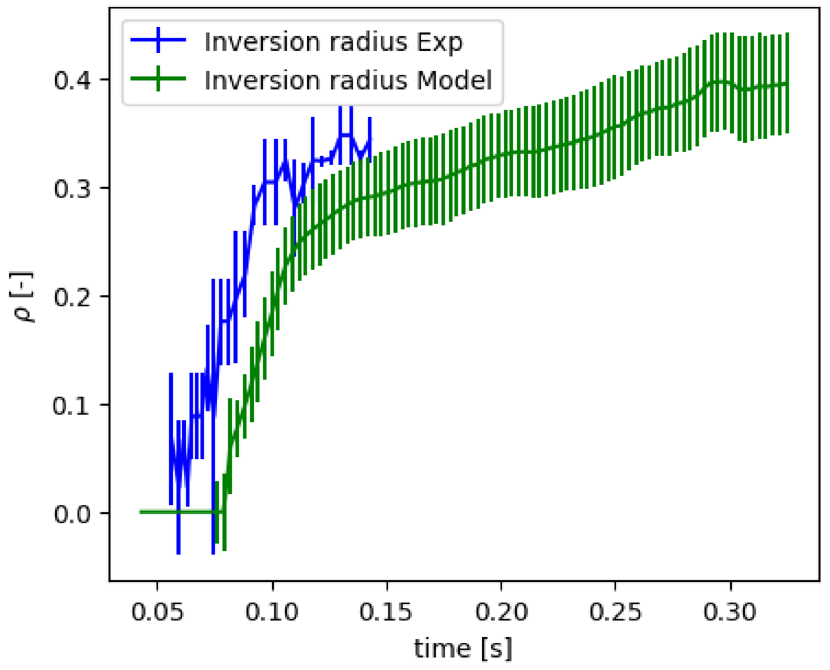
Romanelli M Plasma Fusion Res 2014
Romanelli Jetto Manual 1988
Houlberg W.A. Phys. Plasmas 1997
Challis C.D. Nucl. Fusion 1989
Eriksson L.GNucl. Fusion .1993
Lauro-Taroni L. Controlled Fusion and Plasma Physics
Tamor S. J. Comput. Phys 1981

- Self consistently predict j, T_e, T_i, n_e, n_C
- HFPS, IMAS compatible, equilibrium predicted by ESCO, neutral source by FRANTIC, impurities by SANCO, turbulent transport with QuaLiKiz and TGLF, neoclassical transport with NCLASS
- Boundary shape evolving in time are imposed and extracted by the experimental reconstruction of LIUQE
- Line averaged density from experiment and feedback controlled
- Boundaries at $\rho = 0.99$ for T_e, T_i, n_e, n_C
- Impurity puff constant in time set to roughly match the experimentally measured n_C
- Hollow initial q profile, limit set to $T_i/T_e < 3$

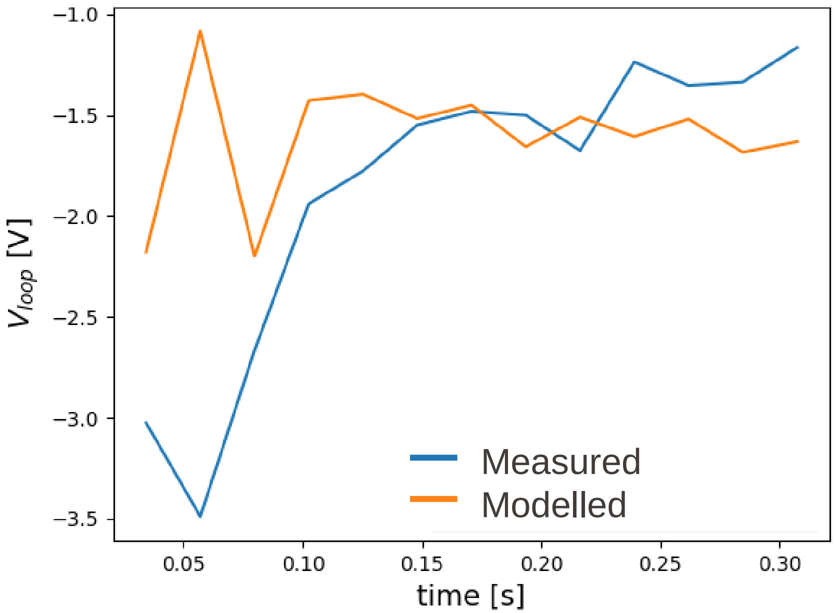
Comparison with the experiment shows fair agreement

- Simulation started at $t = 0.034[s]$, simultaneous with the first HRTS measurement
- Inversion radius for modelling calculate as $q = 1.1$
- V_{loop} noisy but generally underestimated
- Agreement lower for $t < 0.1$, but generally good

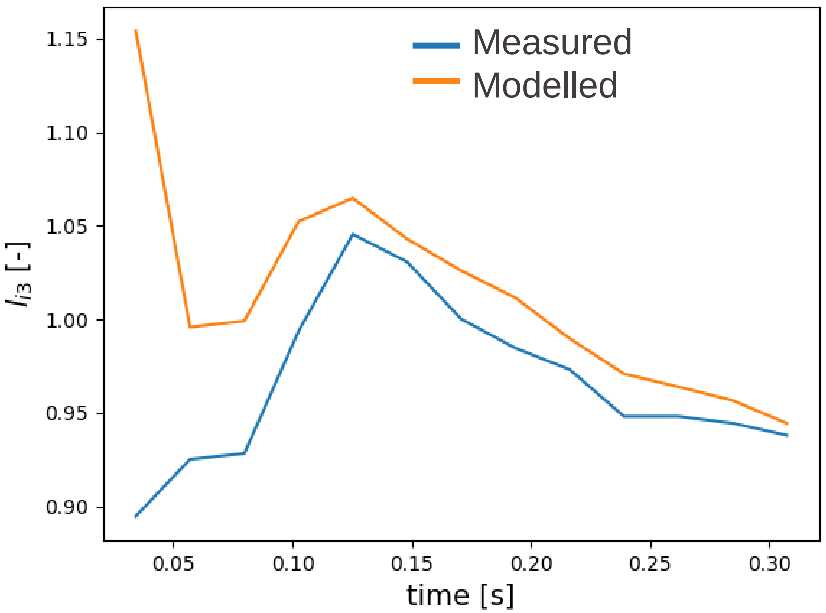
Sawteeth



V_{loop}



li_3



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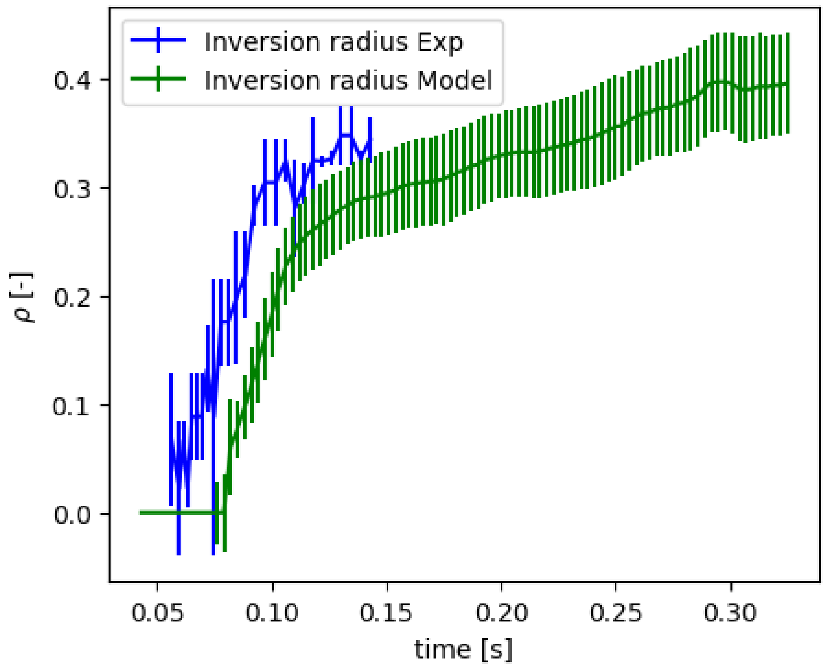
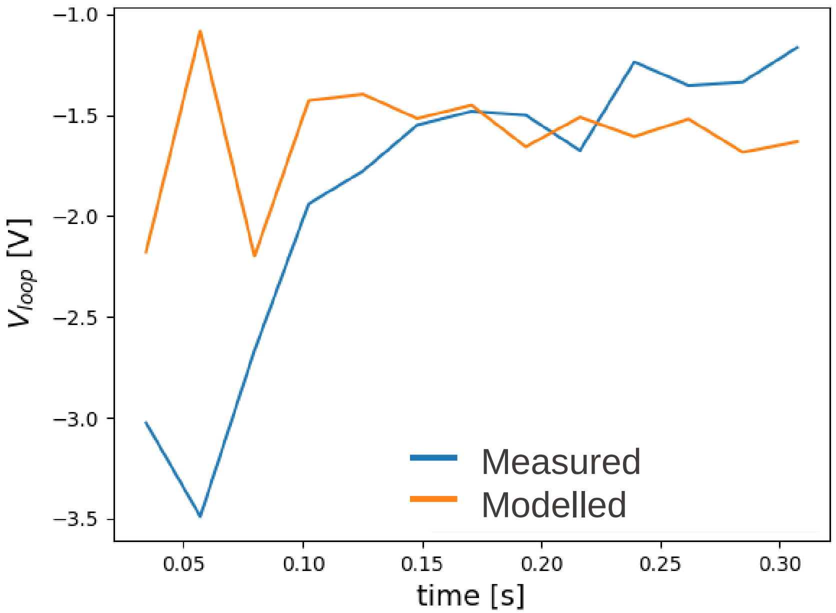
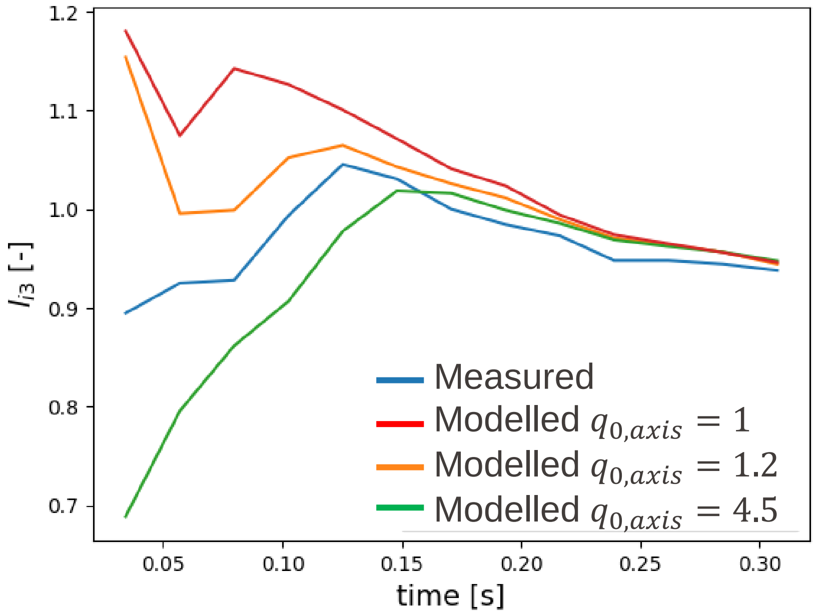
Sawteeth



V_{loop}



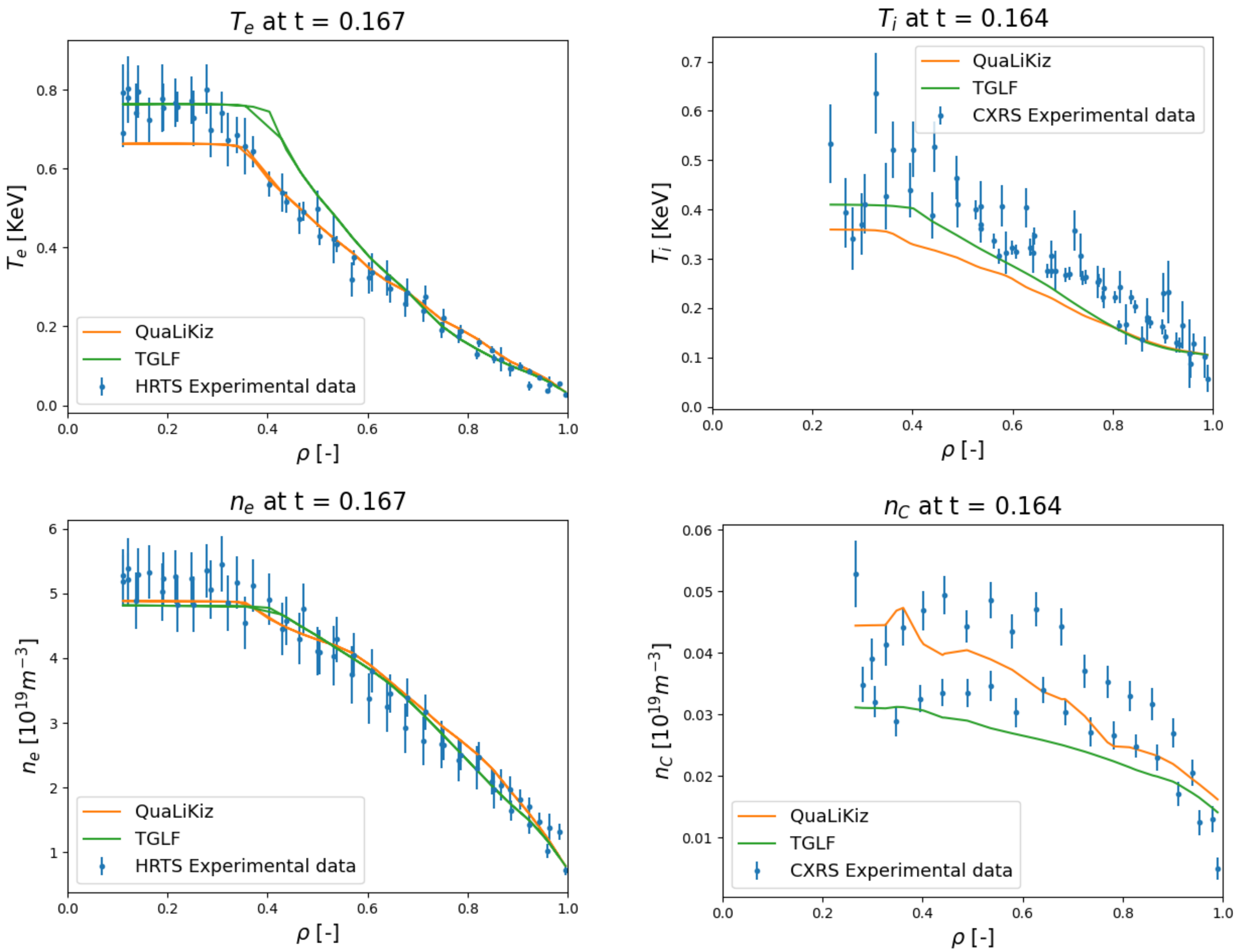
li_3



Most of the disagreement in l_i can be explained by uncertainties the initial conditions

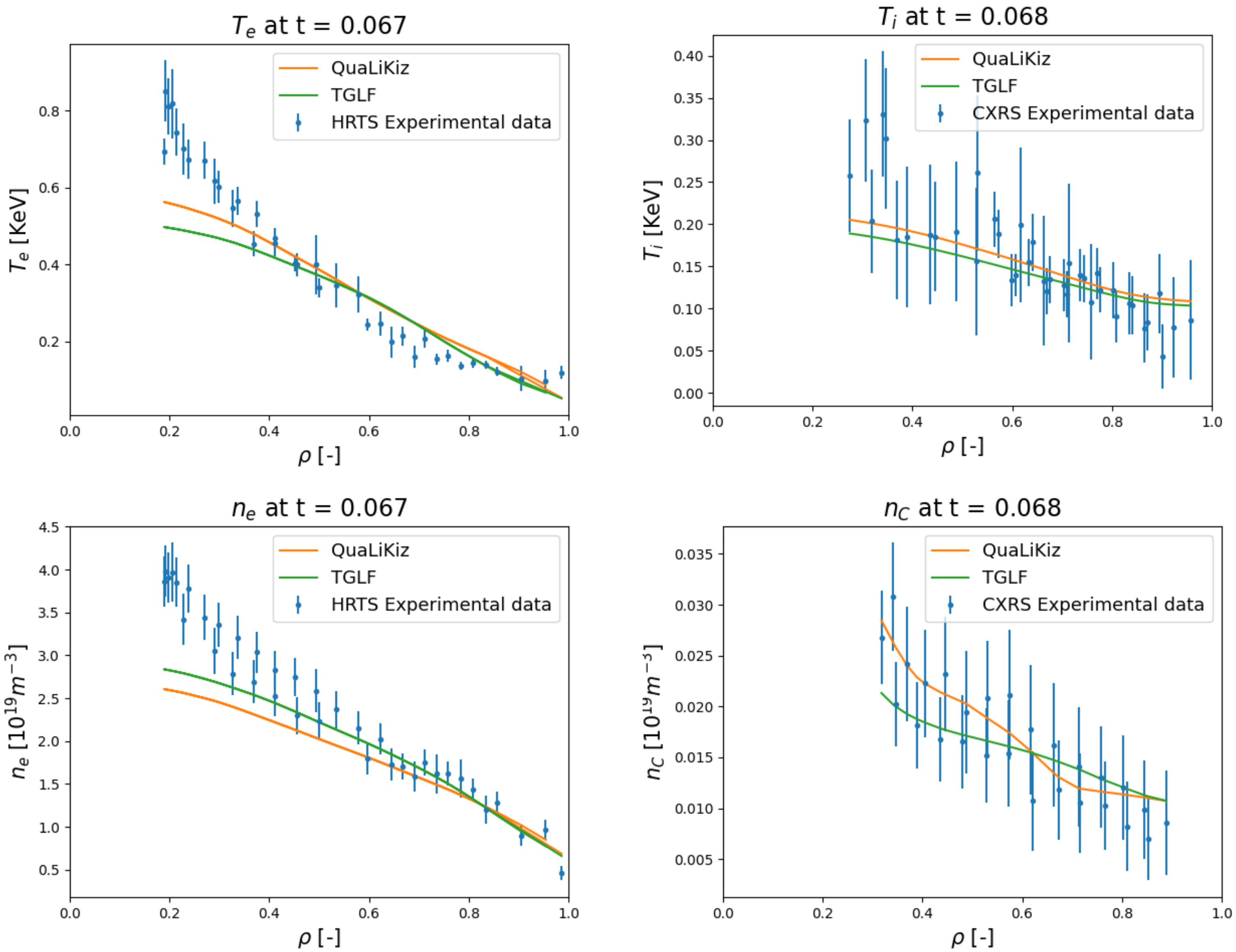
Comparison with the kinetic profiles shows good agreement

- Good agreement is reached on all channels
- Slightly higher T_e, T_i predicted by TGLF (SAT2, no ExB), but n_e generally closer to experiment
- T_i is systematically underpredicted
- Scatter in n_C data (due to miscalibration or misalignment) make comparison more difficult



Fair agreement was obtained during early phase

- Early phase proved to be more challenging
  - Initial conditions more important
  - Larger errorbars for CXRS
- QuaLiKiz predicts transition from TEM to ITG-TEM, especially at inner radii
- Agreement improves after the onset of Sawteeth



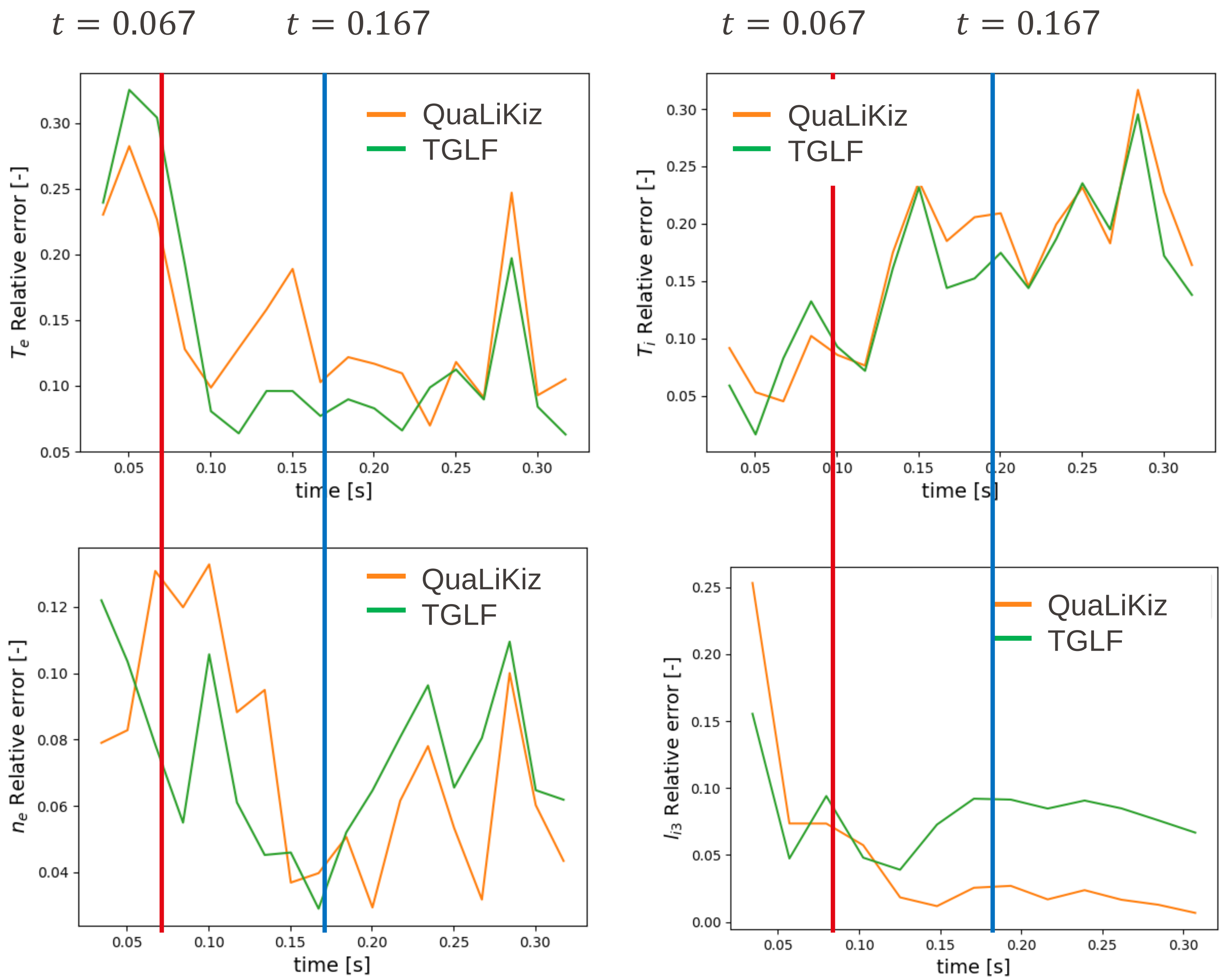
EPFL

A metric was developed to quantify the agreement

- Metric defined as

$$d = \sum_{\rho=sep}^{axis} 2 \left| \frac{d^{\rho}_{fit} - d^{\rho}_{model}}{d^{\rho}_{fit} + d^{\rho}_{model}} \right|$$

- Agreement is generally ~15%
- The chosen time instances are representative of all instances
- No significant difference between QuaLiKiz and TGLF



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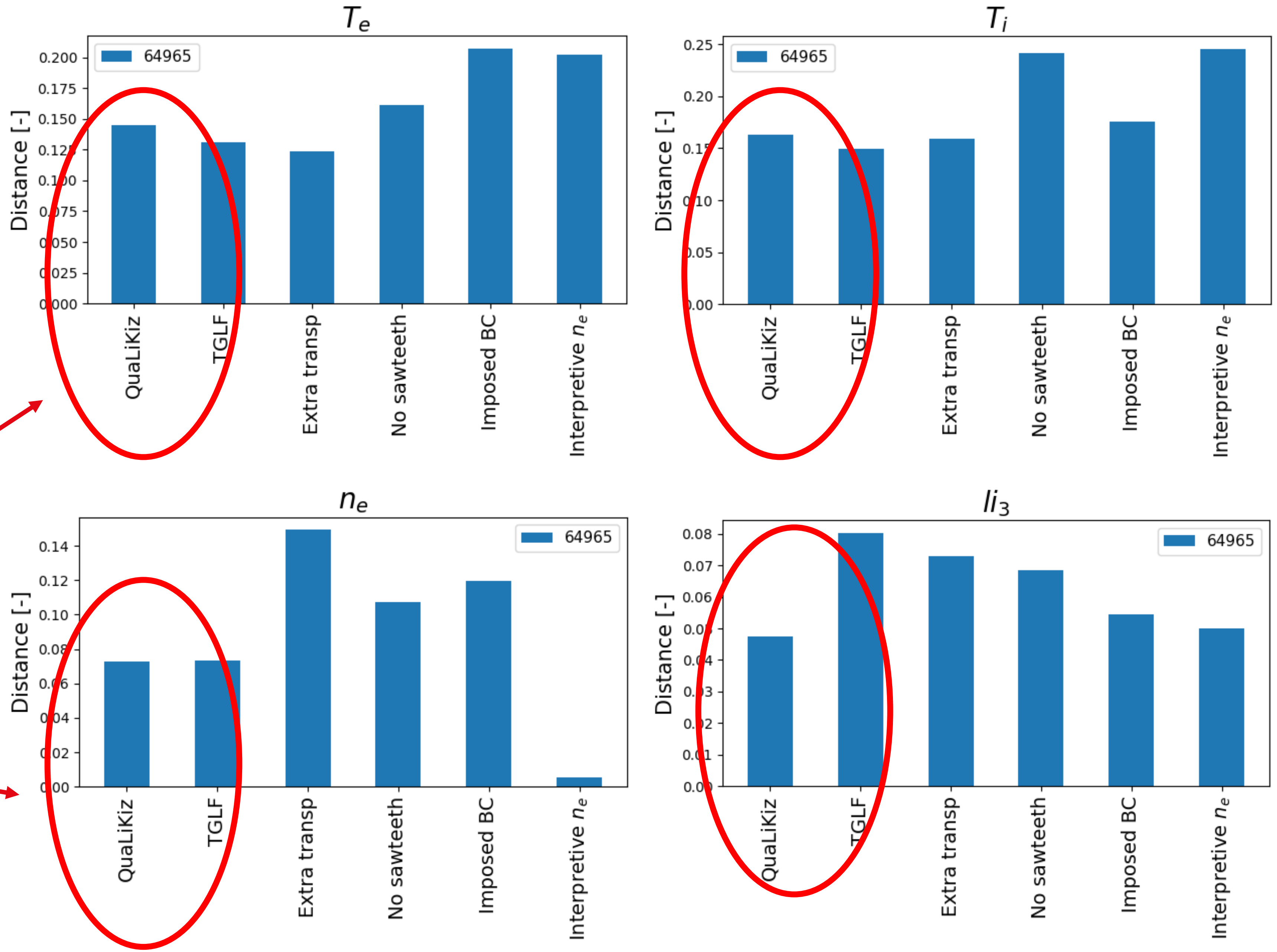
Multiple discharges and variables are compared simultaneously

- Extensive sensitivities were run to explore robustness of settings and physics
- Allows identification of important parameters

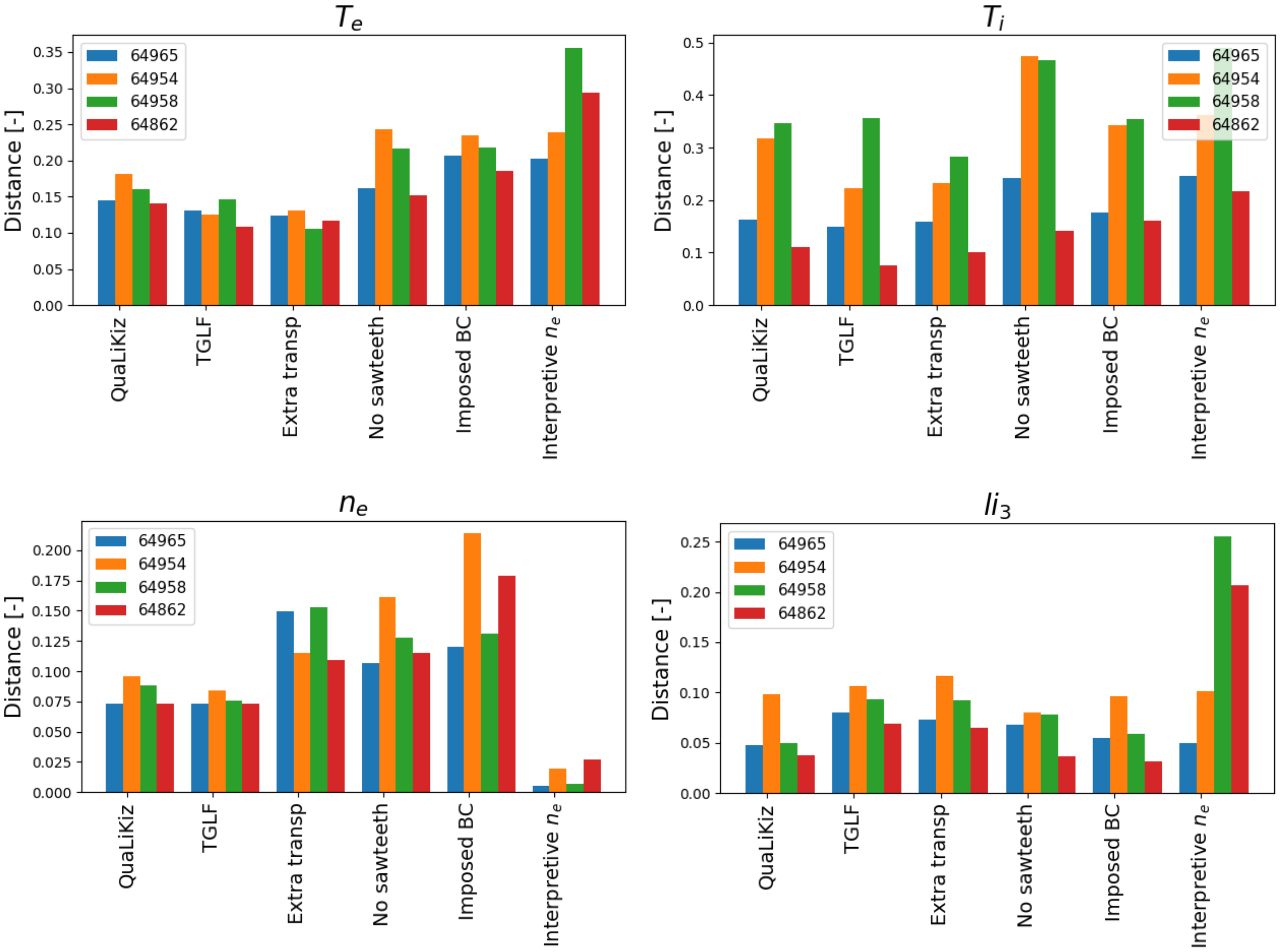


Simulations on previous slide

EPFL

Multiple discharges and variables are compared simultaneously

- Extensive sensitivities were run to explore robustness of settings and physics
- Allows identification of important parameters
- The same settings lead to good agreement over multiple discharges
- Pipeline is in place to include an arbitrary number of discharges



Conclusions

- Multiple TCV ramp-up phases have been reproduced with integrated modelling
- Good agreement with the experimental data was obtained, both on global quantities and profiles evolution
- There is broad agreement between the turbulence predicted by quasilinear and higher fidelity models
  - R/L_n driven TEM dominated plasmas, then transitioning to ITG-TEM
  - $Q_e/Q_i > 1$, especially in early ramp-up phase

- An extensive sensitivity on physical and boundary conditions was performed
- A pipeline leveraging the IDS has been built to enable a larger scale validation exercise

Backup slides

- Power balance
- Turbulence plots
- Turbulence at rho = 0.9
- Figure of merit with experiments
- Early TGLF
- Comparison only QuaLiKiz
- Loc soc?

Power balance qualitatively agrees with standalone nonlinear analysis

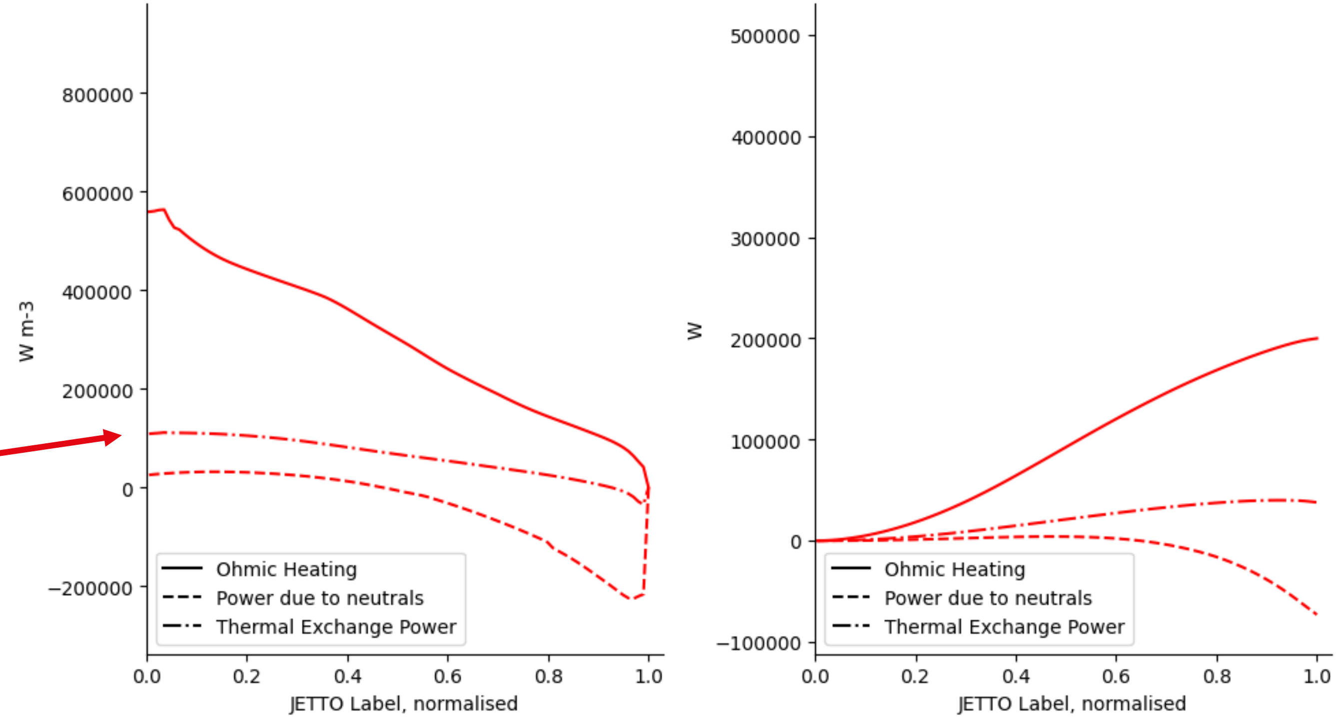
- At the beginning of the discharge Q_i is small
- Competition between ohmic power, ionization and charge exchange
- No charge exchange

From ions to electrons

Sources per unit volume

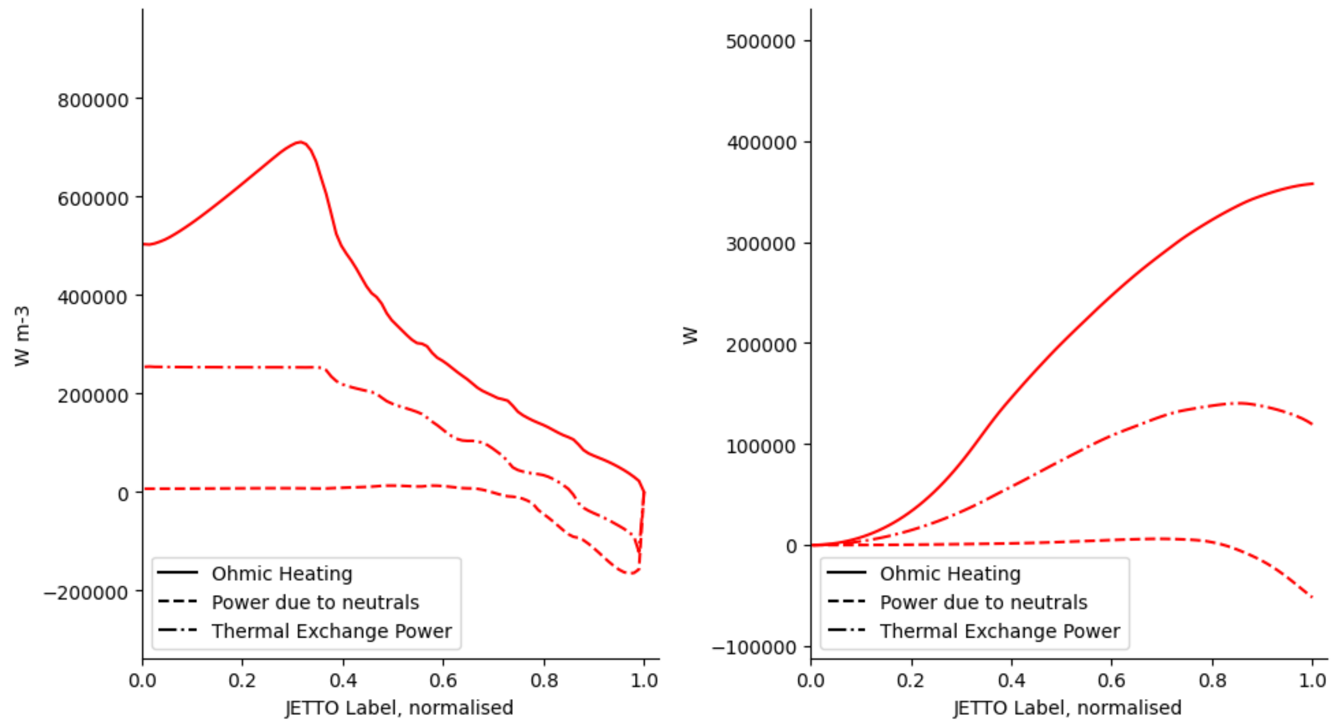
Integrated sources

$t = 0.07\ [s]$



Power balance qualitatively agrees with standalone nonlinear analysis

- At the beginning of the discharge Q_i is small
- Competition between ohmic power, ionization and charge exchange
- Later $Q_i \sim Q_e$



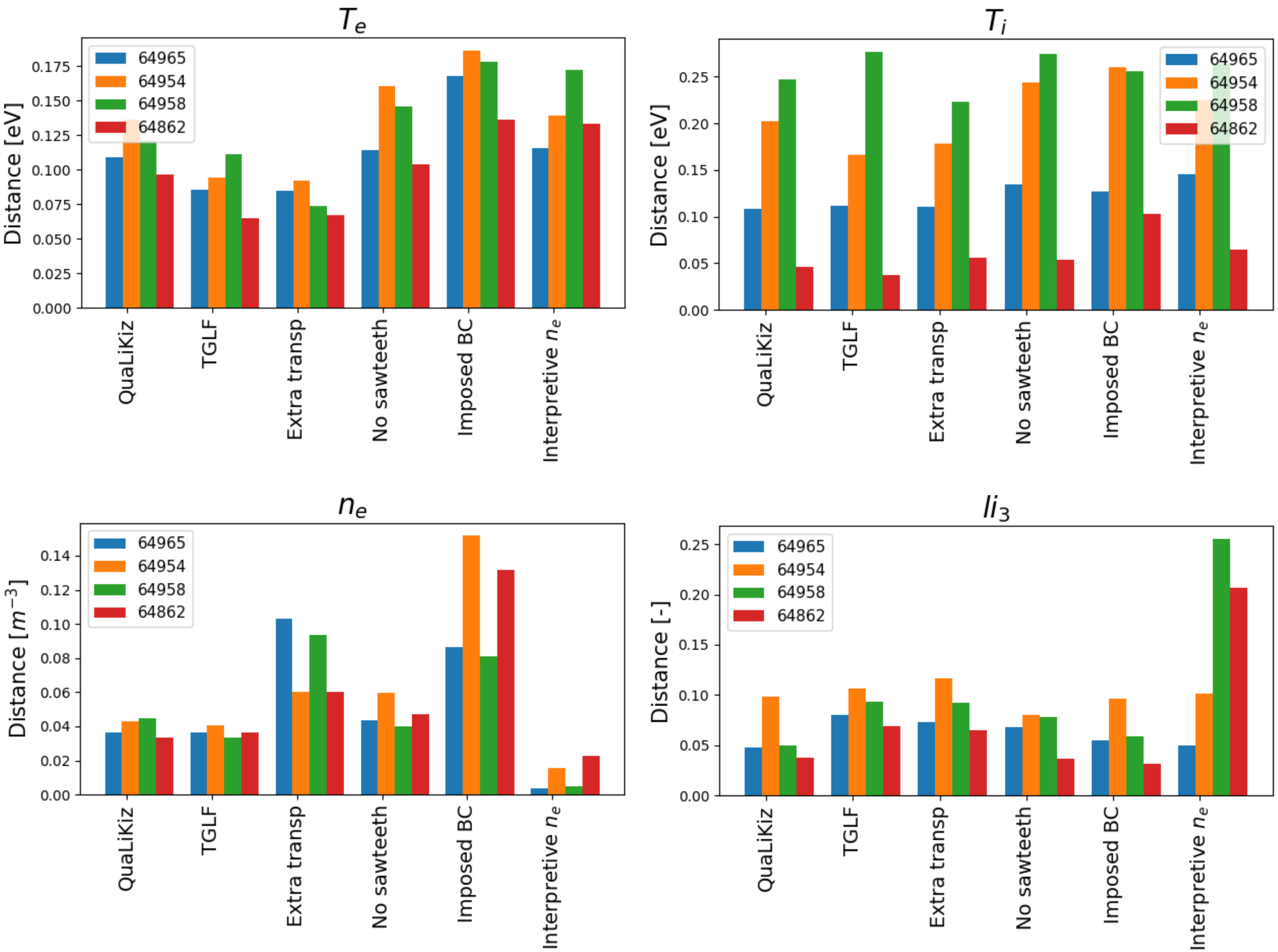
Sources per unit volume

Integrated sources

$t = 0.17\ [s]$

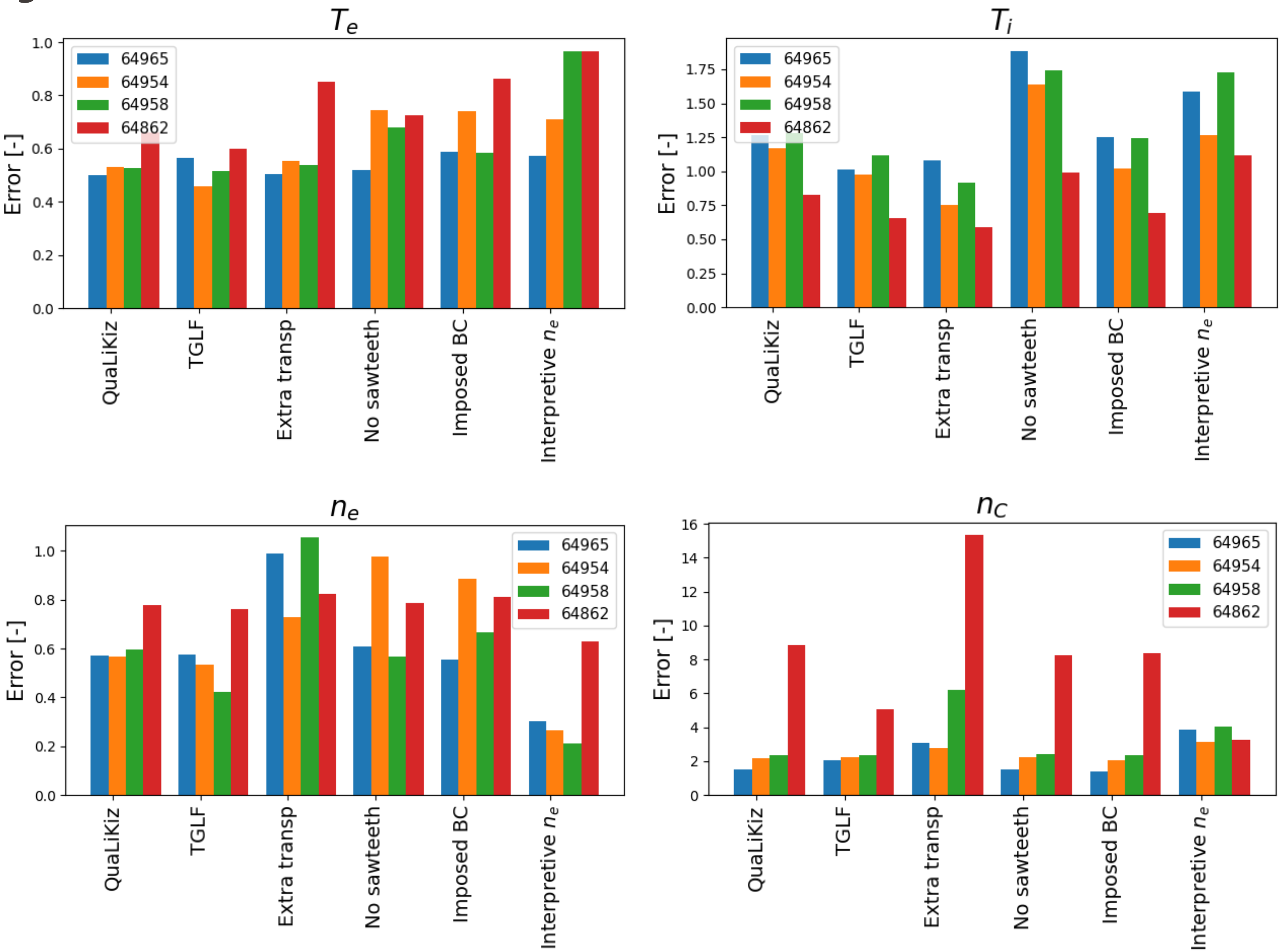
Volume weighted

- $d = \sum_{\rho=sep}^{axis} \frac{2}{V} \left| \frac{d^{\rho}_{fit} - d^{\rho}_{model}}{d^{\rho}_{fit} + d^{\rho}_{model}} \right|$
- Low volumes close to axis weighted less
- Boundary heavily weighted, penalizes changing boundaries even within error
- Non immediately interpretable



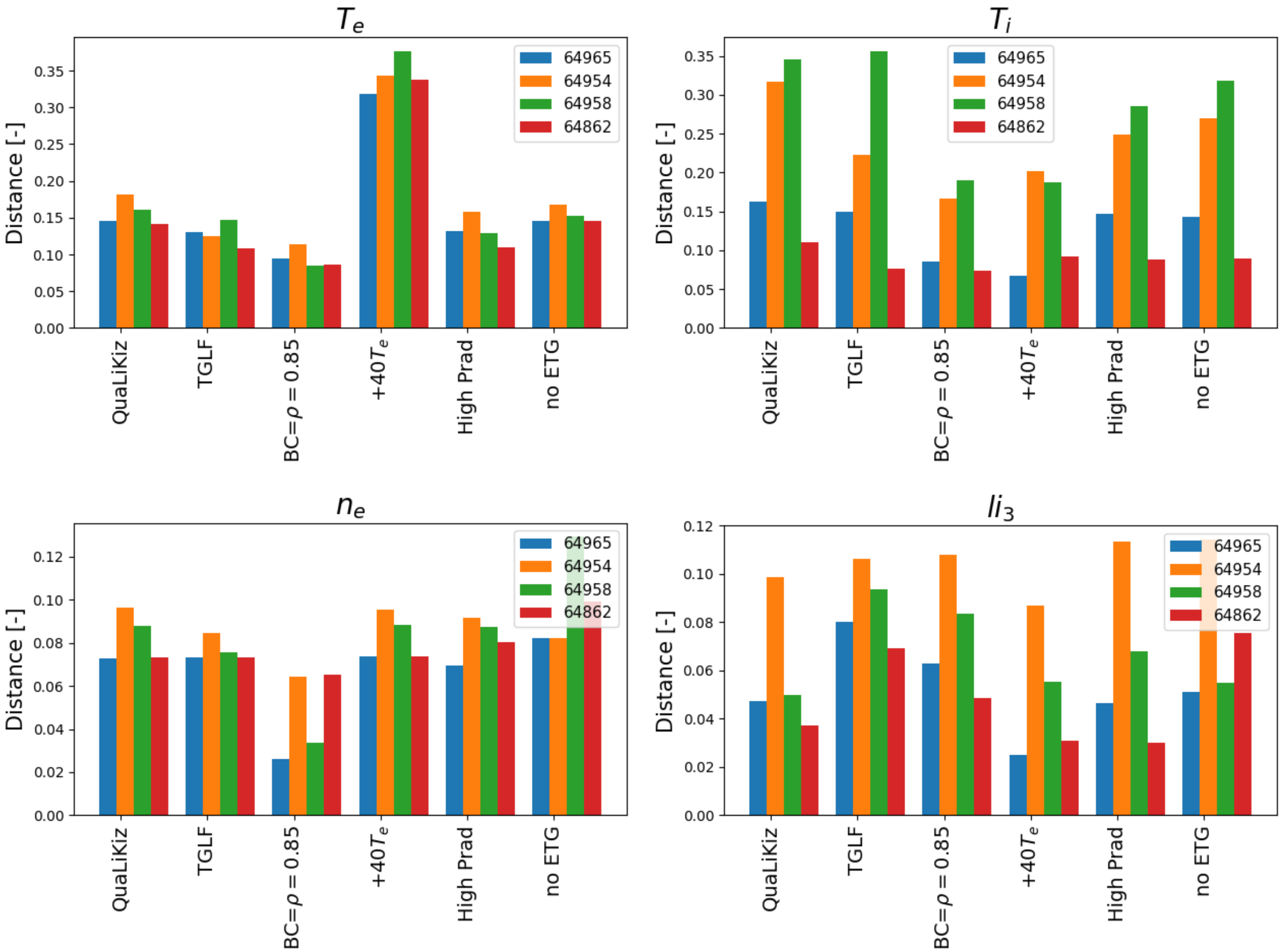
Experimentally weighted

- Takes error-bars into account
- $d = \sum_{\rho=sep}^{axis} 2\left|\frac{d_{fit}^{\rho}-d_{model}^{\rho}}{\sigma_{exp}^{\rho}}\right|$
- Part of the disagreement is due to the poor quality of the experimental data (Ti, nc)



More sensitivities

- High Prad not being important shows stiffness of the profiles
- Agreement is improved consistently with internal boundary conditions
- ETG is not very important
- Even this simple relative distance is skewed to the boundaries

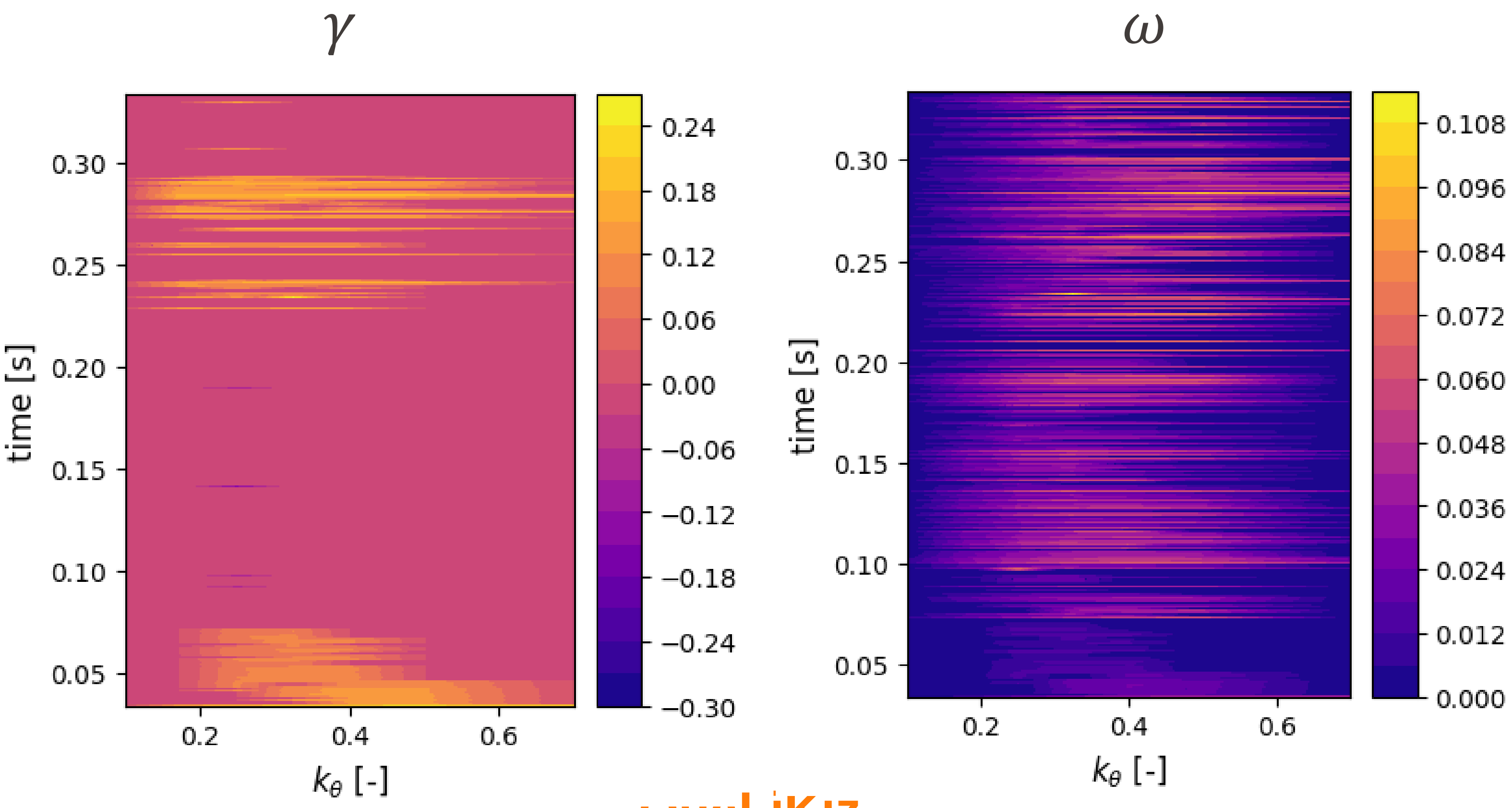


Turbulence from QuaLiKiz at $\rho = 0.5$

- TEM unstable during the early phase, then transitioning to ITG-TEM

- Subdominant modes present but very discontinuous
- ETG is unstable, but does not drive significant fluxes (in integrated modelling)

$\omega > 0$:TEM $\omega < 0$:ITG



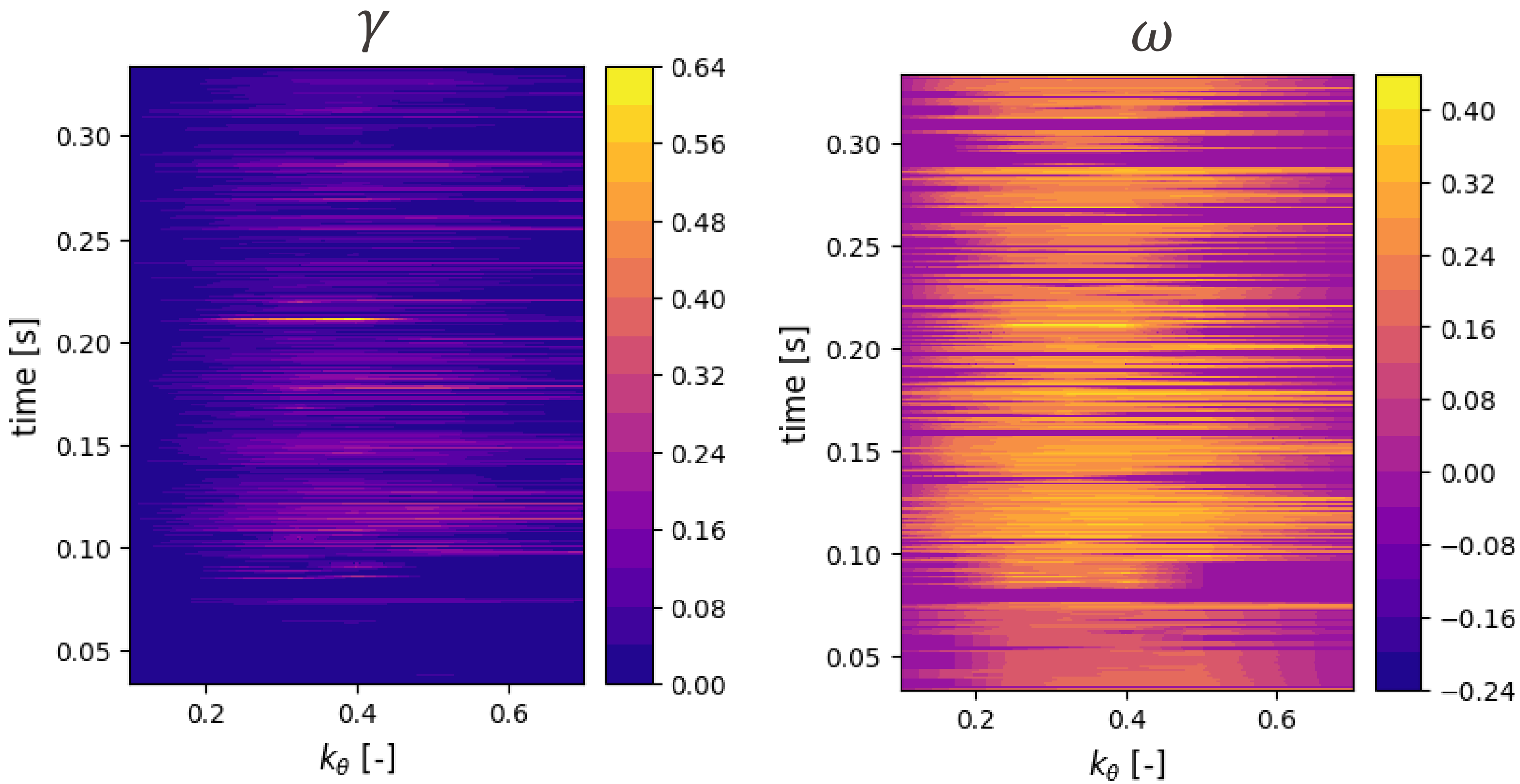
QuaLiKiz

Turbulence from QuaLiKiz at $\rho = 0.7$

- TEM unstable during the early phase, then transitioning to ITG-TEM

- Subdominant modes present but very discontinuous
- ETG is unstable, but does not drive significant fluxes (in integrated modelling)
- TEM remains dominant at $\rho = 0.7$
- Show Qe/Qi from QuaLiKiz

$\omega > 0$:TEM $\omega < 0$:ITG

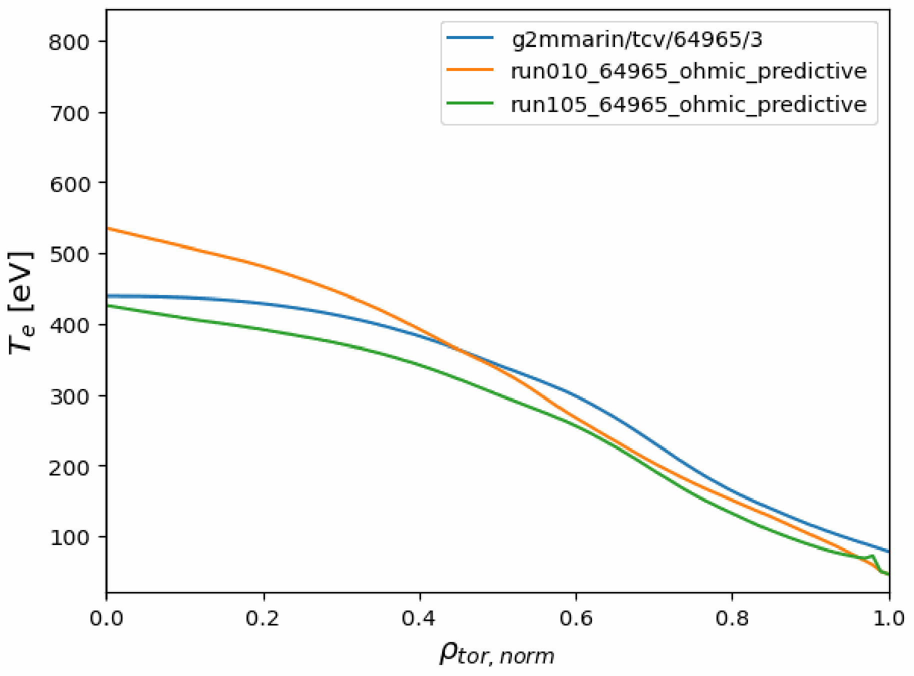


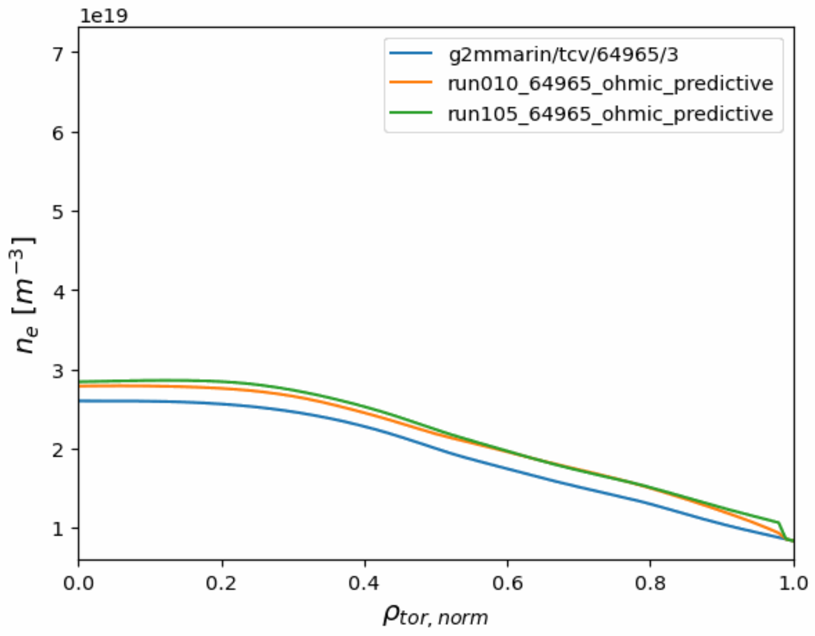
QuaLiKiz

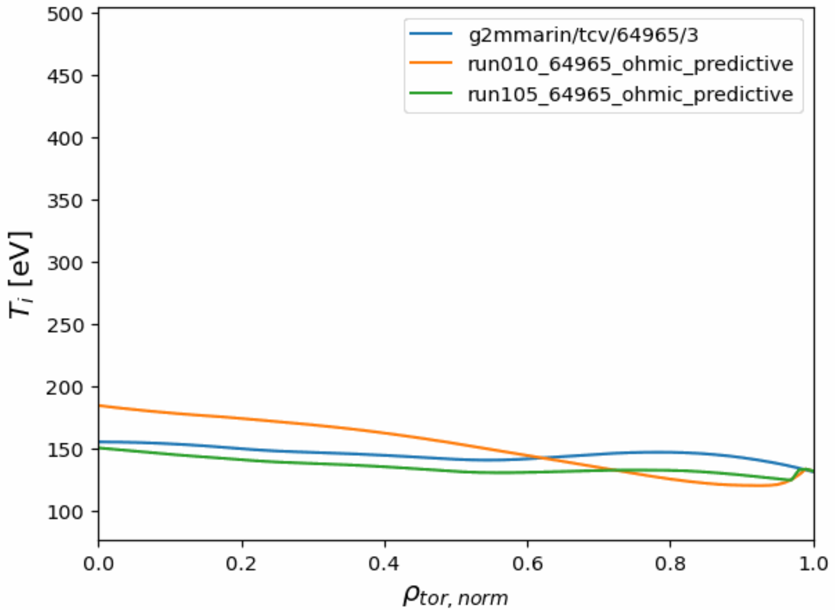
Specific settings

- Limit Ti/Te < 3
- Initial q profile hollow
- Initial Zeff at 1.5, lower close to the separatrix (helps since charge state of C is lower there)
- Limit ne sep < 1.0e19
- Start with Te = 50, smoothly joining with experimental value at 0.1. Helps with ‘blips’
- Impurity escape velocity 200cm/s. Neutral influx varying linearly with ne_ave and Zeff measured
- FRANTIC call frequency=2. Ionization E per atom = 13.6eV, Wall released neutral energy 30eV
- Extra Bohm 0.005
- Kadomstev+Porcelli model for Sawteeth Reconnection and Crash trigger
- Boundary at separatrix for nC. Helps avoid unphysical fluxes at larger concentrations

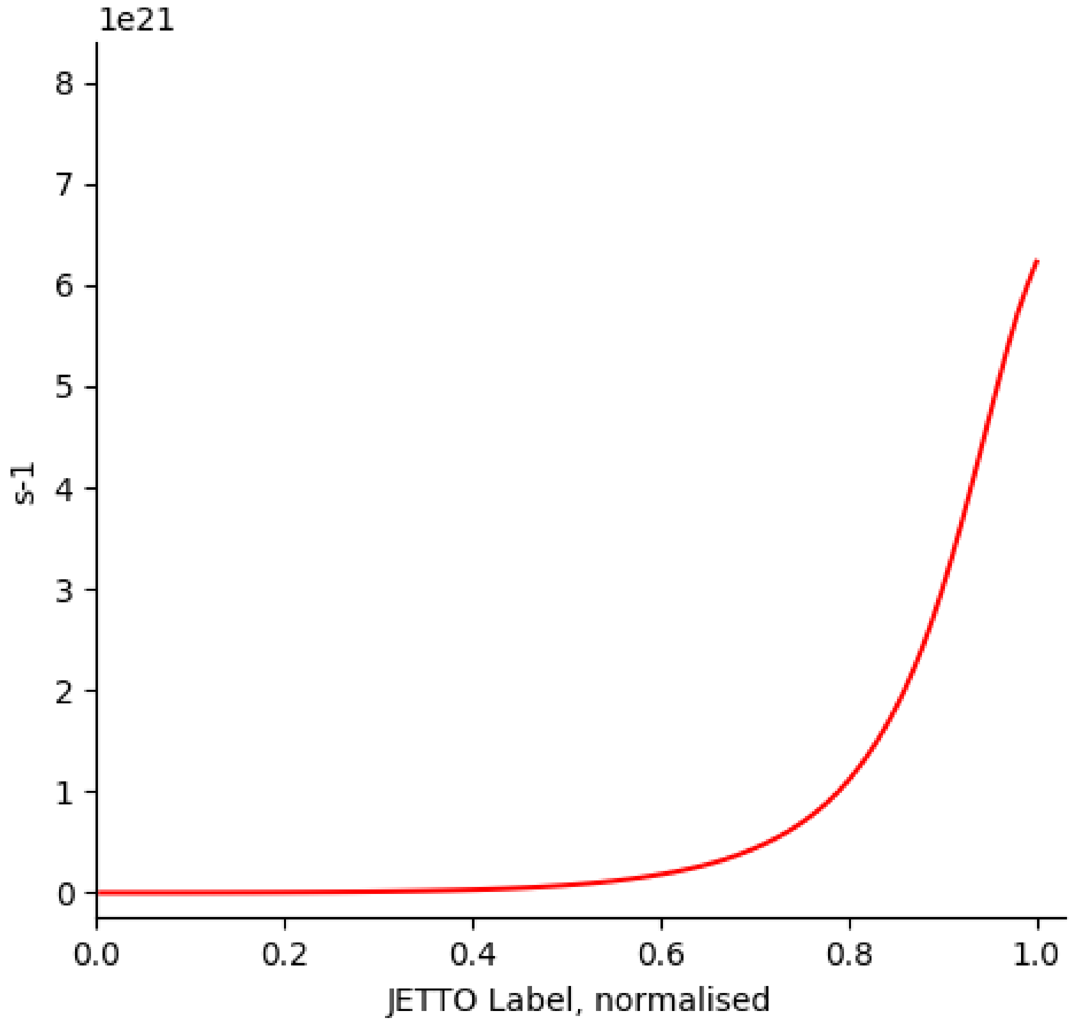
Gifs


g2mmarin/tcv/64965/3
run010_64965_ohmic_predictive
run105_64965_ohmic_predictive
T_e [eV]
800
700
600
500
400
300
200
100
0.0
0.2
0.4
0.6
0.8
1.0
$\rho_{tor,\,norm}$


1e19
g2mmarin/tcv/64965/3
run010_64965_ohmic_predictive
run105_64965_ohmic_predictive
$n_e\ [m^{-3}]$
7
6
5
4
3
2
1
0.0
0.2
0.4
0.6
0.8
1.0
$\rho_{tor,\,norm}$

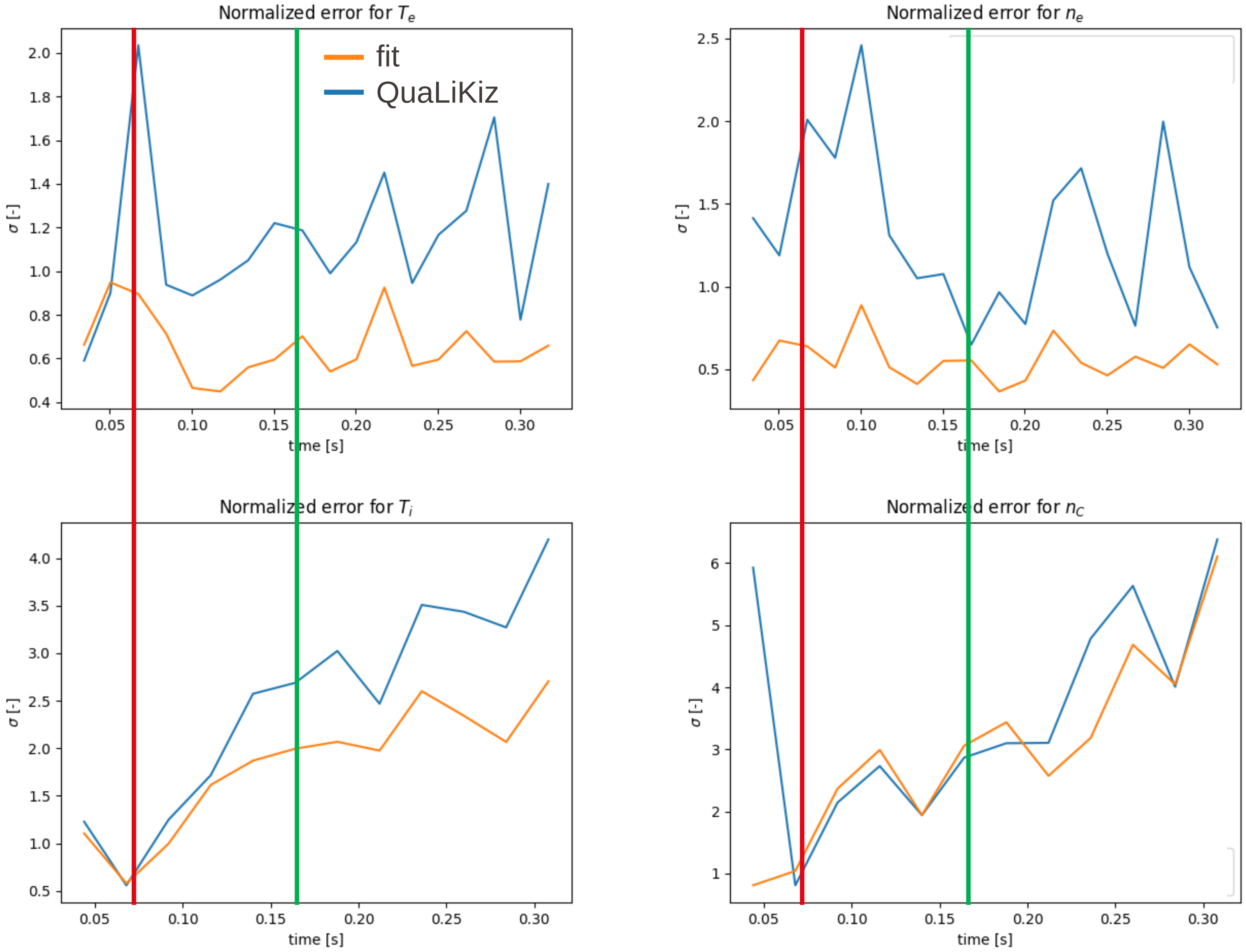

g2mmarin/tcv/64965/3
run010_64965_ohmic_predictive
run105_64965_ohmic_predictive
T_i [eV]
500
450
400
350
300
250
200
150
100
0.0
0.2
0.4
0.6
0.8
1.0
$\rho_{tor,\,norm}$

Particle source



A metric was developed to quantify the agreement

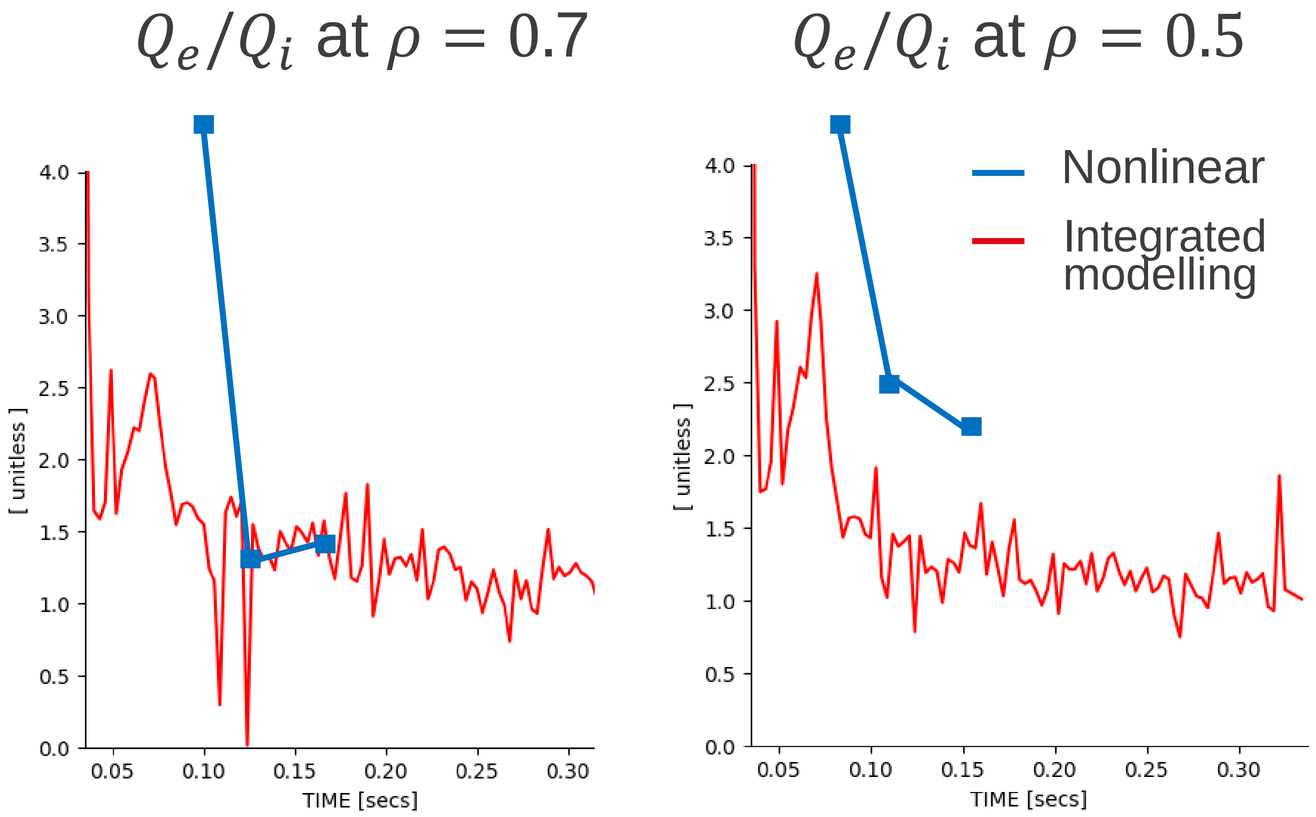
- Agreement is generally good, $d < 2$ for T_e and $d\sim < 2$ for n_e
- The low quality of the data for T_i and n_C is described by the orange lines
- Ratio between blue and orange is a better measure of agreement
- The chosen time instances are representative of all instances



Power balance qualitatively agrees with standalone nonlinear analysis

- At the beginning of the discharge Q_i is small
- Competition between ohmic power, ionization and charge exchange
- Later $Q_i \sim Q_e$
- Q_e/Q_i decreases during the discharge, but is generally lower than the nonlinear results. *Note that 20-30% of Ion flux is neoclassical, and even 60% before 0.1 [s]*
- This is consistent with an underpredicted temperature

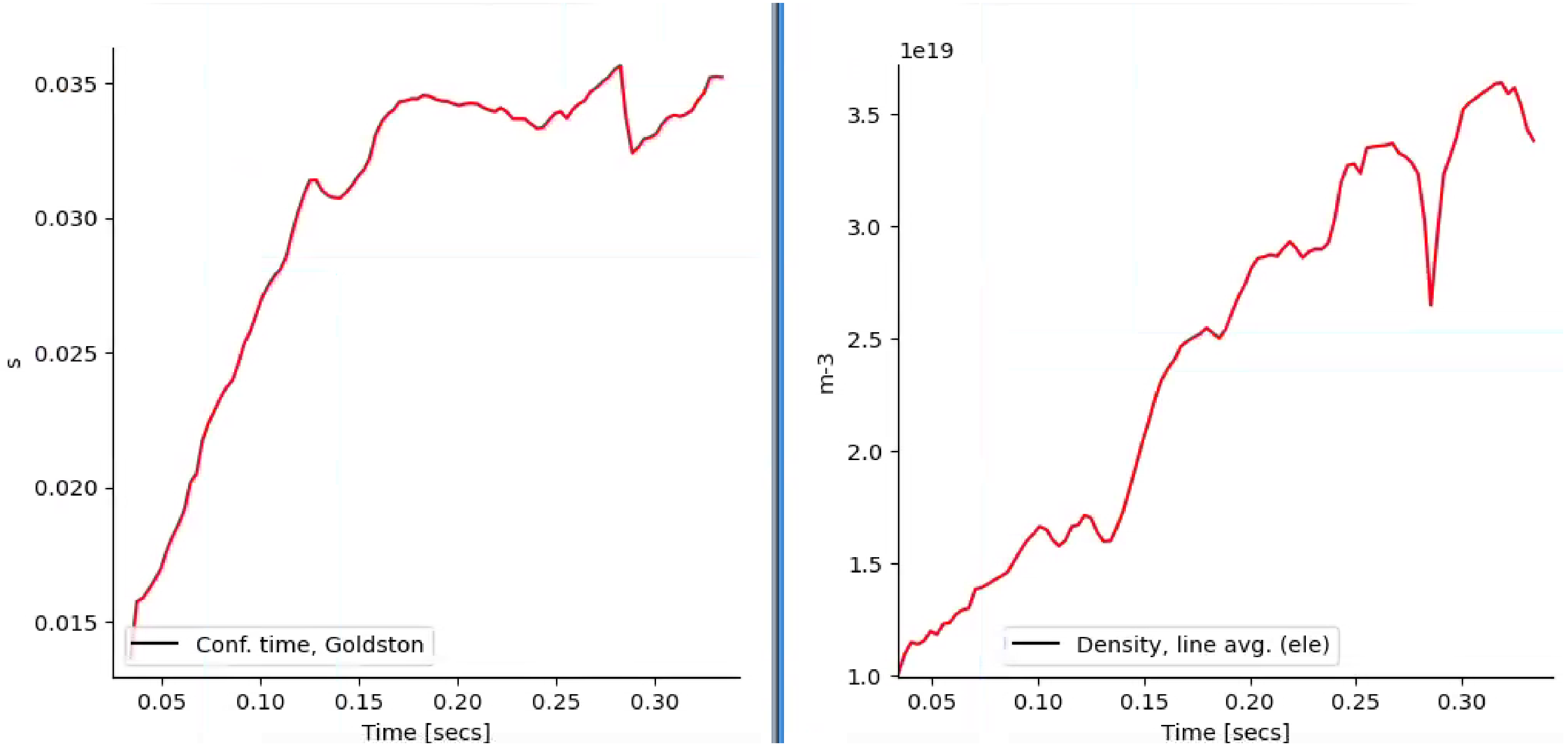
20-30% of Ion flux is neoclassical



Q_e/Q_i at $\rho = 0.7$

Q_e/Q_i at $\rho = 0.5$

LOC SOC?


0.035
0.030
0.025
0.020
0.015
s
Conf. time, Goldston
0.05
0.10
0.15
0.20
0.25
0.30
Time [secs]
1e19
3.5
3.0
2.5
2.0
1.5
1.0
m-3
Density, line avg. (ele)
0.05
0.10
0.15
0.20
0.25
0.30
Time [secs]