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First multi-channel core transport simulations with RAPTOR using a neural network transport model

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Executive summary:

- First combined T_e and T_i simulations with RAPTOR
- Validation of neural network transport model on ITER and JET scenarios
- Faster than realtime simulation capability achieved

1. Motivation for fast turbulent transport models

- Fast and accurate core turbulence transport models needed for
  i) efficient offline tokamak scenario preparation and optimization
  ii) discharge supervision
  iii) realtime trajectory optimization

- No such first-principle-based model currently exists.
  How to combine tractability and accuracy?

Quasilinear assumptions valid when $\frac{\delta n}{n} \sim O(\%)$, as in the confined region [1]
We apply the QuaLiKiz gyrokinetic quasilinear transport model [2,3]

For recent QuaLiKiz validation in ASDEX-U and JET, see:
O. Linder P2.169, S. Breton O4.124, C. Bourdelle P4.167,

- QuaLiKiz needs 10 CPUs for flux calculation at single radial point
- Used in integrated modelling. Not fast enough for realtime applications
- QuaLiKiz large-scale calculations provide training sets for neural network regression which is then realtime capable

2. A proof-of-principle neural network transport model

Multilayer perceptron neural network (NN) for nonlinear regression of precalculated QuaLiKiz output [4]

Reduced 4D Database of QuaLiKiz output from which training and validation sets were chosen

Parameter	Min value	Max value
R/L_{Ti}	2	12
T_i/T_e	0.3	3
q	1	5
$\hat{s}$	0.1	3
$k_\theta \rho_s$	0.05	0.8

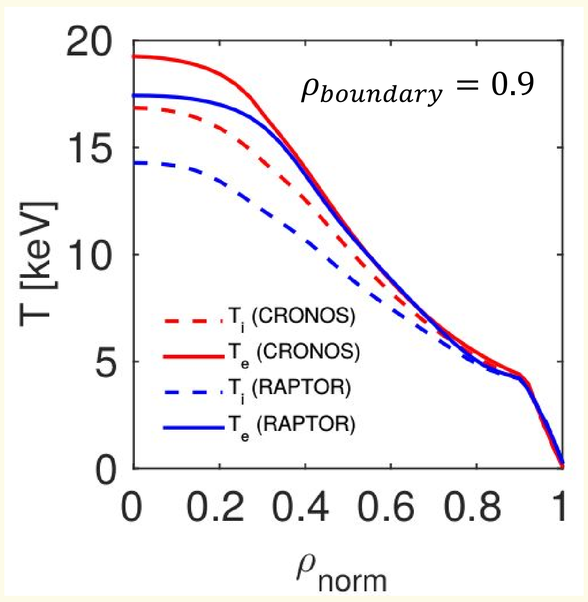
- Includes kinetic electrons. ITG regime
- Dense uniform input grids. ~50000 unstable points used in training sets
- NNs for ion and electron heat flux, electron particle diffusivity and pinch

Extensions to 9D and beyond. See K. van de Plassche P2.182, A. Ho P5.173

3. Applied for first combined T_i and T_e RAPTOR simulations

- QLKNN-kin4D coupled to control-oriented RAPTOR tokamak simulation suite [5]. Analytical derivatives of NN used in implicit solver

- RAPTOR/QLKNN-kin4D ITER hybrid scenario modelling compared to previous CRONOS/GLF23 predictions [6-8]



- RAPTOR upgraded to include simultaneous T_e, T_i, density, and poloidal flux evolution

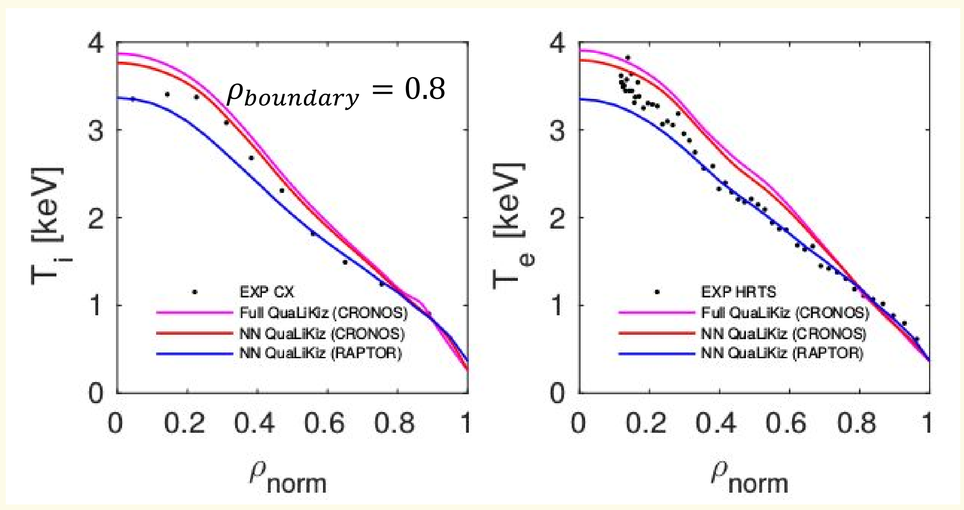
- QLKNN/RAPTOR faster than realtime. 20s to calculate 300 ITER seconds. GLF23/CRONOS took 48 hours. ~4 order of magnitude speedup

4. Validation on JET H-mode discharge

- NN transport model benchmark between CRONOS and RAPTOR for JET baseline H-mode 73324 flattop [9]

- RAPTOR/QLKNN faster than realtime. 2s to calculate 4 JET seconds. CRONOS/QLK took 100CPUh. ~ 5 order of magnitude speedup

- Remaining ~10% RAPTOR vs CRONOS discrepancies to be investigated

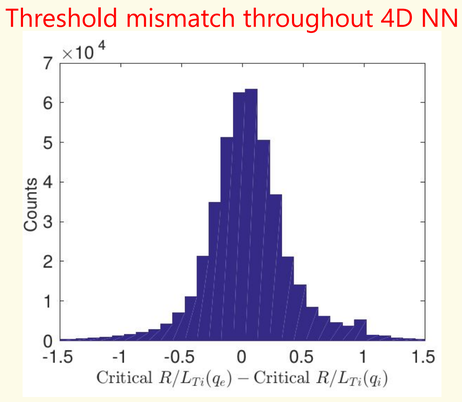


5. Challenge of critical threshold matching

- Neural network fitted to q_e and q_i heat fluxes directly

- Can lead to non-physical states for relatively low ITG threshold mismatch between q_e and q_i due to stiffness

Threshold mismatch throughout 4D NN

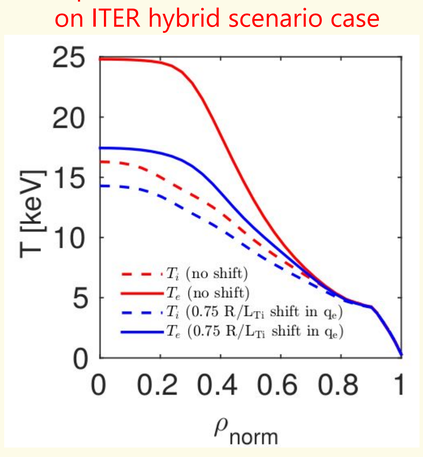


- Bias to q_e NN input R/L_{Ti} an input parameter in RAPTOR

- Needed to avoid $q_e = 0$ for saturated T_i if threshold $q_e(R/L_{Ti}) > q_i(R/L_{Ti})$

- Solution: fit NN to $q_e + q_i$ and $\frac{q_i}{q_e}$. Ensures threshold matching (see K. van de Plassche P2.182)

Impact of threshold mismatch on ITER hybrid scenario case



6. Summary and perspectives

- RAPTOR upgraded: includes T_e, T_i, n, and poloidal flux evolution

- First ever RAPTOR predictive $T_e + T_i$ simulations. JET and ITER validation of proof-of-principle neural network transport model based on QuaLiKiz. Faster than realtime capabilities

- Benchmark with CRONOS. ~10% discrepancies remaining, to be investigated. Full benchmark including n predictions are planned

- Generalize QLKNN transport model to higher dimensions. Apply within RAPTOR for scenario optimization and realtime monitoring

References

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