Fast modelling of turbulent transport in fusion plasmas using neural networks

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Using the QLKNN physics-informed surrogate model for integrated modelling

K.L. van de Plassche (DIFFER), J. Citrin (DIFFER), C. Bourdelle (CEA), Y. Camenen (CNRS), F.J. Casson (UKAEA), V.I. Dagnelie, F. Felici (EPFL-SPC), A. Ho (DIFFER), S. Van Mulders (EPFL-SPC), and JET contributors*

k.l.vandeplassche@differ.nl

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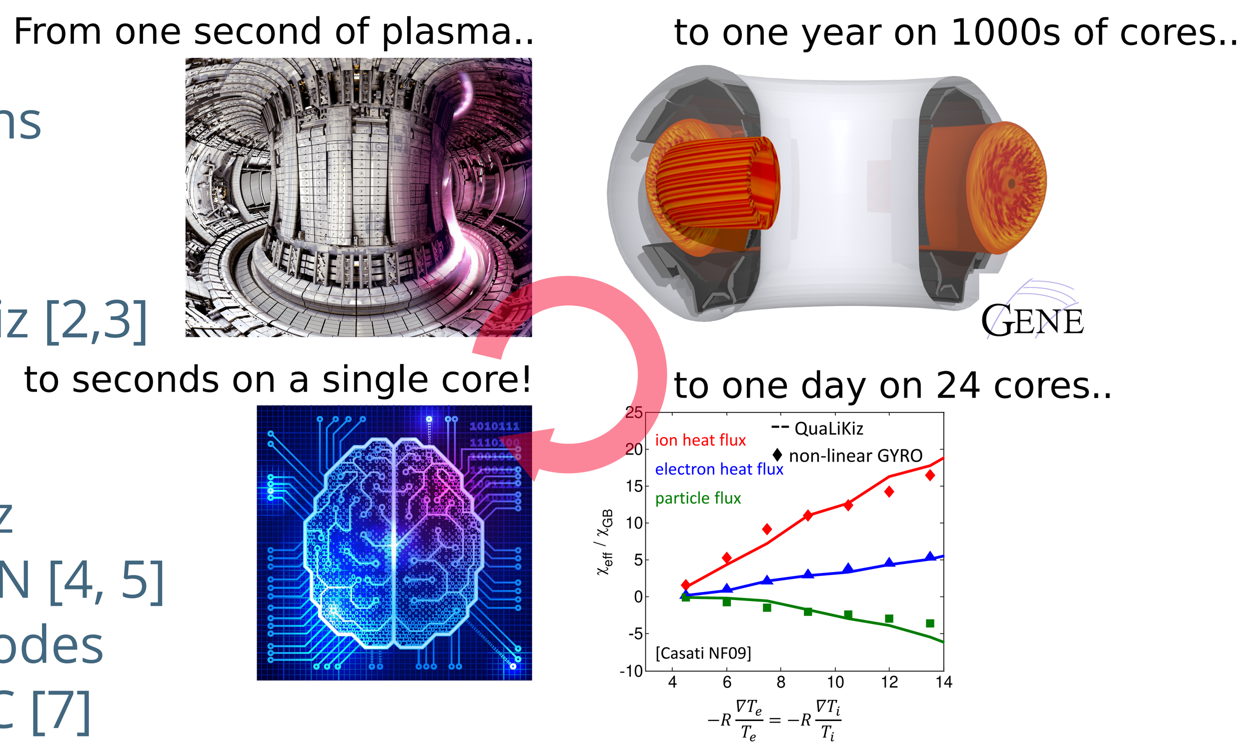
Need for a real-time capable tokamak simulator

High-fidelity gyrokinetic models (e.g. GENE [1]) are too computationally expensive for applications such as:

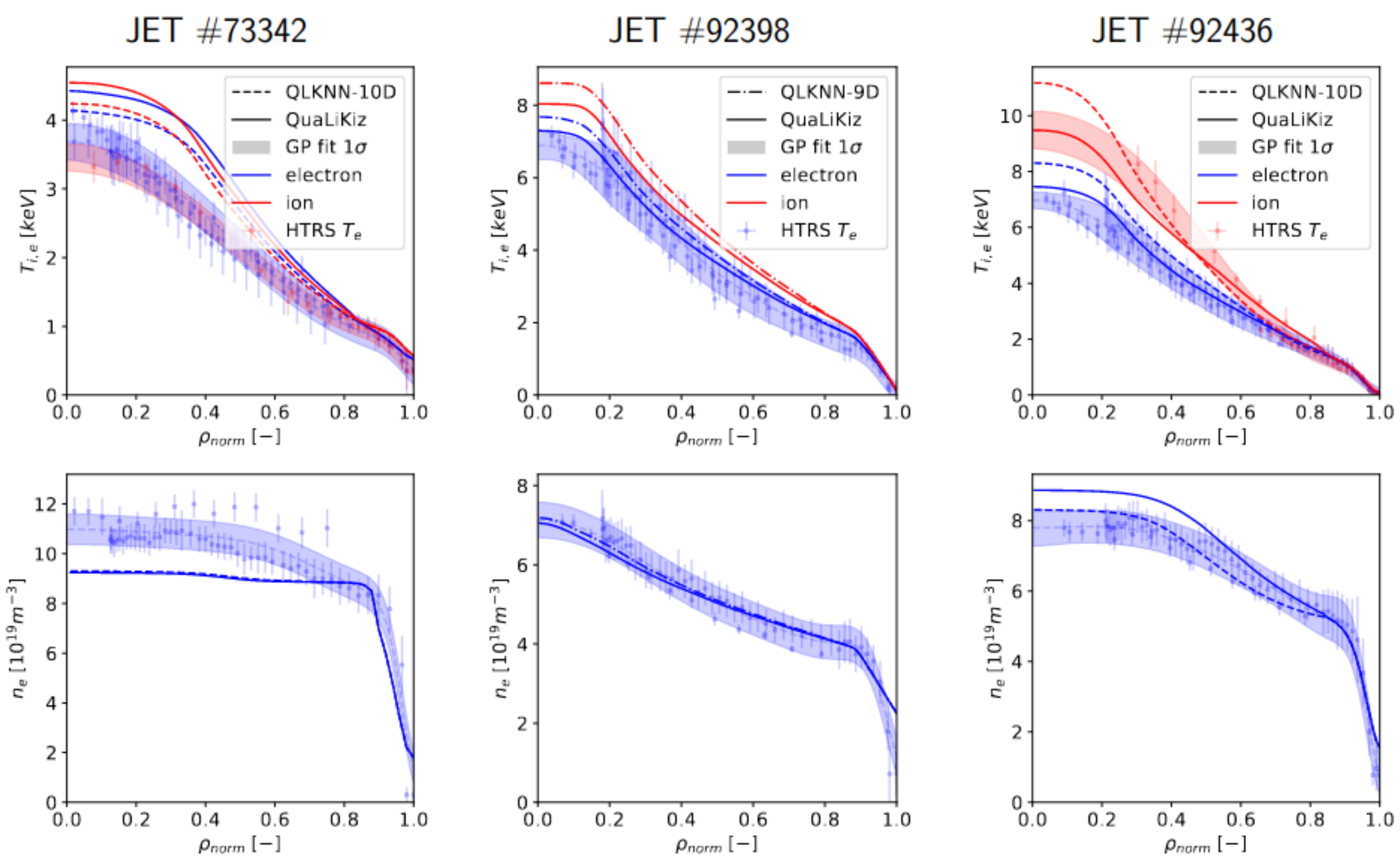
- Routine intershot analysis
- Large-scale reactor design
- Control oriented applications

Enable applications by:

- Use reduced model QuaLikiz [2,3] to generate dataset
- Train Neural Network (NN) surrogate to 'learn' QuaLiKiz mapping, resulting in QLKNN [4, 5]
- Integrate NN in transport codes like RAPTOR [6] and JINTRAC [7]



QLKNN-hyper-10D able to reproduce JET plasmas



- Solve Ψ,T_e,T_i and n_e in JINTRAC and RAPTOR [4]
- Boundary condition of kinetic profiles prescribed at ρ=0.85

Summary and outlook

- Database of ~10^8 turbulent ITG, TEM, ETG heat and particle fluxes over wide parameter space was generated using QuaLiKiz
- Trained surrogate model QLKNN validated in RAPTOR and JINTRAC

Ongoing and future work:

- Creation of next generation QLKNN-hyper surrogate with impurity fluxes and impurity density gradients
- Now in production mode, being applied in wider regimes for JET, WEST, AUG, ITER analysis [9]

Capturing underlying physical system essential

Neural network training methodology chosen to ensure consistency with known physical constraints [4].

Sharp instability thresholds

Only include unstable points in 'goodness' part of cost function

$$C_{good} = \begin{cases} \frac{1}{n}\sum_{i=1}^{n}(QLK_i - NN_i)^2, & \text{if } QLK_i \neq 0 \\ 0, & \text{if } QLK_i = 0 \end{cases}$$

Clip negative heat flux $q_{i,e}$ to zero

Matching thresholds for all transport channels

Use leading-heatflux style fitting. For example for ITG: train on $q_{i,ITG}$ and $q_{e,ITG}/q_{i,ITG}$, D_i,ITG/$q_{i,ITG}$, etc. and multiply the output of the networks.

No spurious positive flux in stable region

Punish positive predictions with extra cost function term

$$C_{stab} = \begin{cases} 0, & \text{if } QLK_i \neq 0 \\ \frac{1}{n}\sum_{i=1}^{n} NN_i - c_{stab}, & \text{if } QLK_i = 0 \end{cases}$$

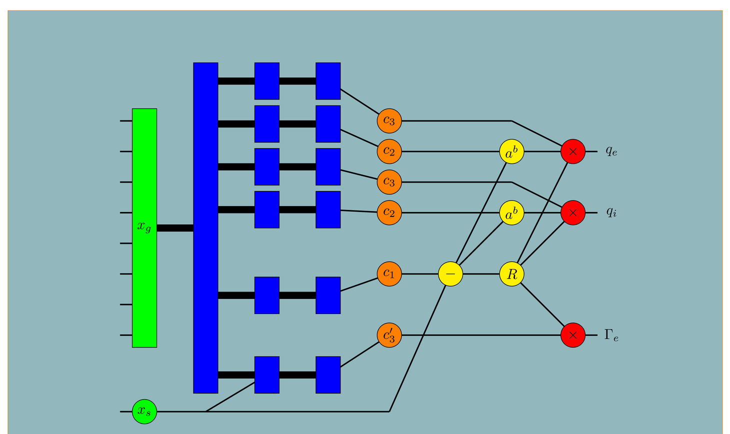
Enforce smoothness

Punish model complexity using a L2 cost function.

$$C_{regu} = \sum_{i=1}^{k} w_i^2$$

Sum costs together

$$C = C_{good} + \lambda_{regu} C_{regu} + \lambda_{stab} C_{stab}$$



Alternatively use network structure: QLKNN-HornNet, see associated paper

Extension to impurity transport ongoing

QLKNN-hyper dataset expanded with including impurity density gradients and their transport fluxes

variable	# points	min	max
$k_\theta \rho_s \leq 1.8$	10	0.1	1.8
$k_\theta \rho_s > 2$	8	3	45
R/L_{T_i}	11	0	16
R/L_{T_e}	11	0	16
R/L_{n_e}	11	-5	5
$R/L_{n_{i,0}}$	12	-15	15
q	8	0.66	10
$\hat{s}$	10	-1	4
r/R	7	0.1	0.95
T_i/T_e	7	0.25	2.5
ν^*	11	1e-5	1
Dilution (n_i/n_e)	4	0	0.3
Total flux calculations	2.8×10^9	$\approx$ 4MCPUh $\approx$ 2TiB netCDF	

- Run impurities in the trace limit using QuaLiKiz
- Improved collision operator with QuaLiK-2.8.1 [8]
- For higher dimensionality, constrain to JET subspace, for example QLKNN-jetexp-15D for JET [5]

References

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