52nd EPS Conference on Plasma Physics (EPS 2026), Edinburgh, Scotland

Modelling of D/T ratio control experiments in JET

K. K. Kirov, P. Fox, M. Lennholm, L. Piron, D. Valcarcel, M. Baruzzo, M. van Berkel, T. Bosman, L. Ceelen, L. Garzotti, B. Kool, J. Mitchell, B. Sieglin, H. Sun, JET contributors and the EUROfusion Tokamak Exploitation Team

United Kingdom Atomic Energy Authority, Culham Campus, Abingdon, Oxon, OX14 3DB, UK
Dipartimento di Fisica "G. Galilei", Università degli Studi di Padova, Padova, Italy,
Consorzio RFX, Corso Stati Uniti 4, 35127, Padova, Italy,
ENEA, Fusion and Nuclear Safety Department, ENEA Frascati, C.P. 65, 00044, Frascati, Italy,
DIFFER—Dutch Inst. for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, The Netherlands
Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands
Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Modelling of D/T ratio control experiments in JET

Outline of the talk

- Motivation
- Numerical tools
- Workflow validation versus JET DTE3 data
  - Particle sources
  - Transport
- Case studies
  - Control D/T ratio with homogeneous D or T pellets
  - Control n_{eL} with mixed D/T pellets
  - Network #1, controlling line integrated density in range and D/T ratio
  - Network #2, controlling D/T ratio and line integrated density
  - Network #3, controlling line integrated density and D/T ratio
- Summary and conclusions

Particle transport modelling for D/T ratio control experiments in JET

Motivation

- D/T ratio need to be controlled in future fusion devices: ITER, BEST, SPARC, STEP
- JET DTE3 featured D/T ratio control experiments

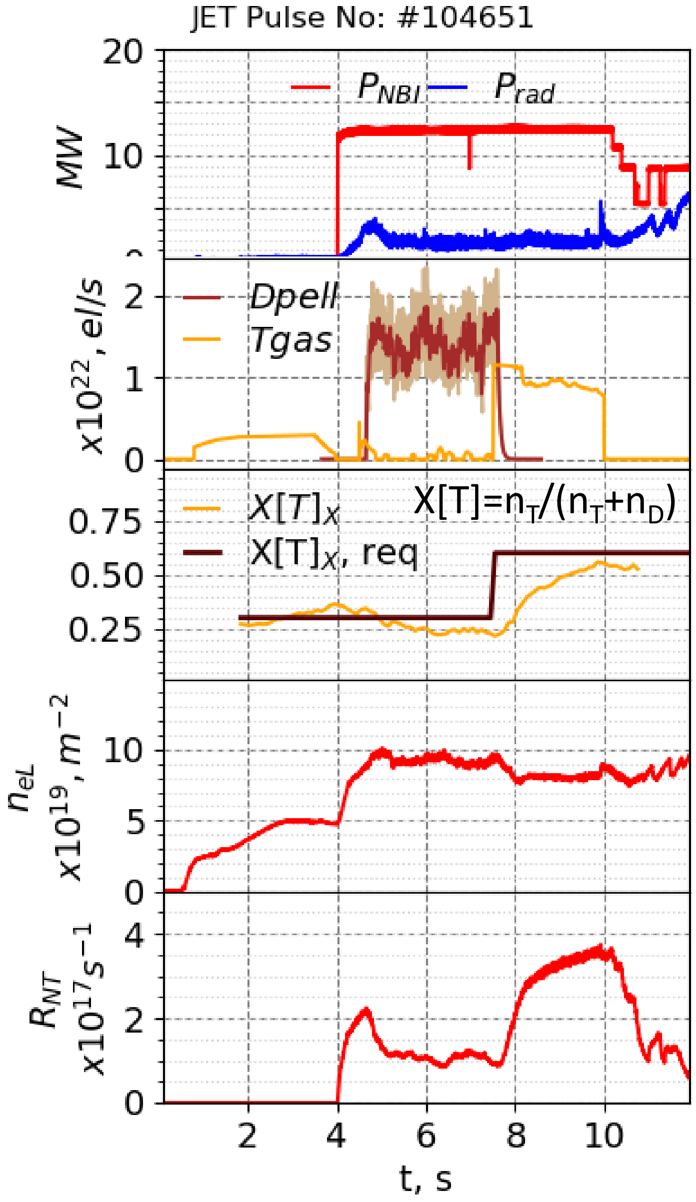
  [Maggi C. et al 2024 Nucl. Fusion 64 112012]
  [Lennholm M.et al 2025 PRX Energy 4 023007]
  [Baruzzo M. et al 2025 30th IAEA FEC2025, Chengdu, China]

- The models used are capable to accurately reproduce the experimental observations for JET DTE3 D/T ratio control experiments

  [K. K. Kirov et al, Nucl Fusion 65 (2025) 106016]

Numerical tools

- JETTO - transport code used in JET, ITER, STEP
- External component to simulate real-time (RT) controllers with JETTO



Particle sources and transport

Sources

- NBI, gas injection, pellets

Transport

- Bohm-gyro-Bohm model

[L. Garzotti et al Nucl. Fusion 43 (2003) 1829]

[K. K. Kirov et al, Nucl Fusion 65 (2025) 106016]

Note, workflow is independent on transport model and can accommodate more advanced modelling approaches

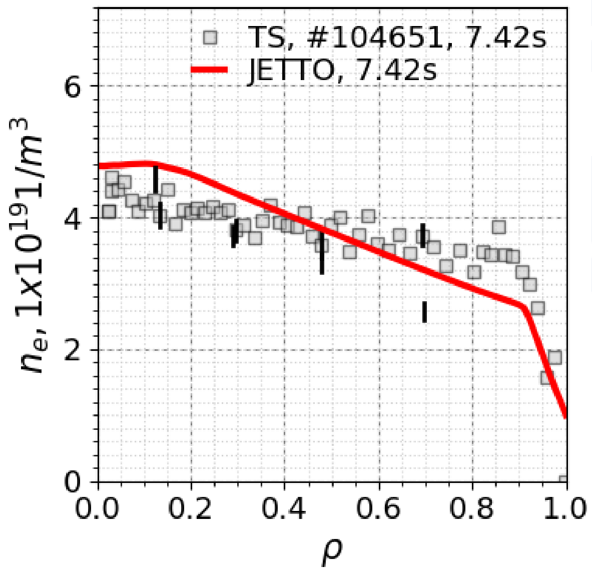
[C. Angioni et al 2009 Plasma Phys. Control. Fusion 51 124017]

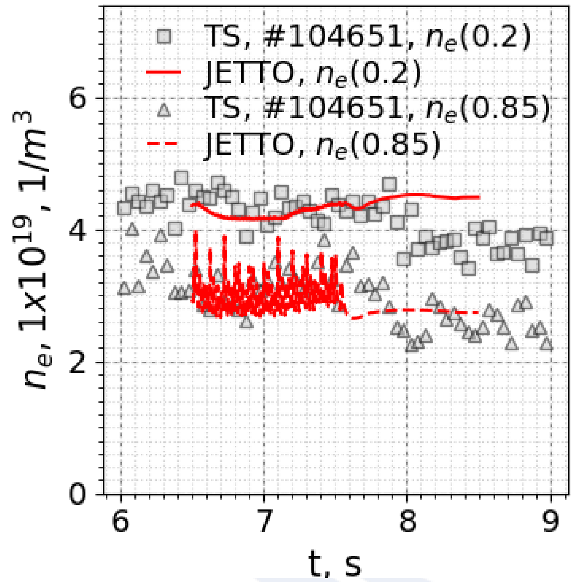
[V. K. Zotta, oral, this conference]

[L. Garzotti, poster, this conference]

Workflow validation

- The new workflow
  - pellets only, JETTO with NGPS, 25ms (40Hz)
  - size, species, composition by external component
  - validated versus experimental observations for JET DTE3 pulse #104651



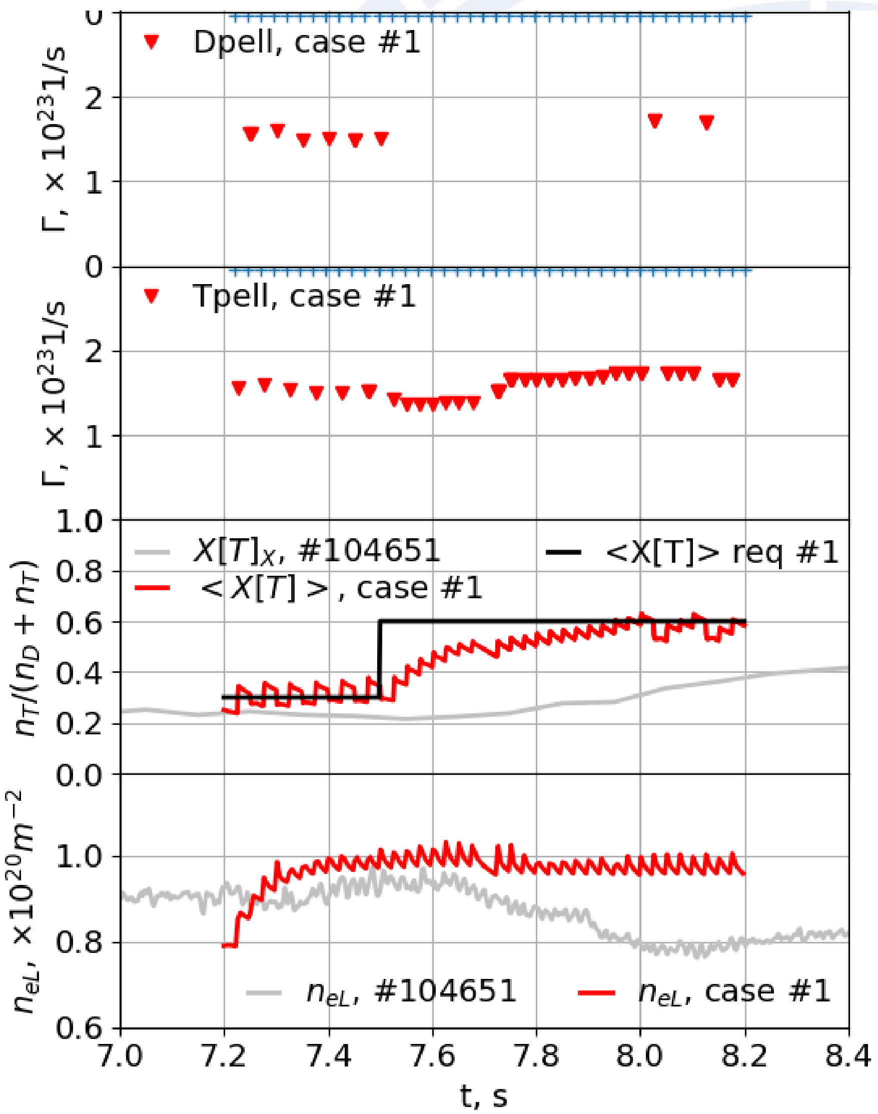


This study reports on simulations of the behaviour of D/T ratio and n_{eL} RT controllers with JETTO
=> Not a predictive transport simulation, but a plasma pulse simulator with RT control of D/T ratio and n_{eL}

Case study: D/T ratio control

D/T ratio control

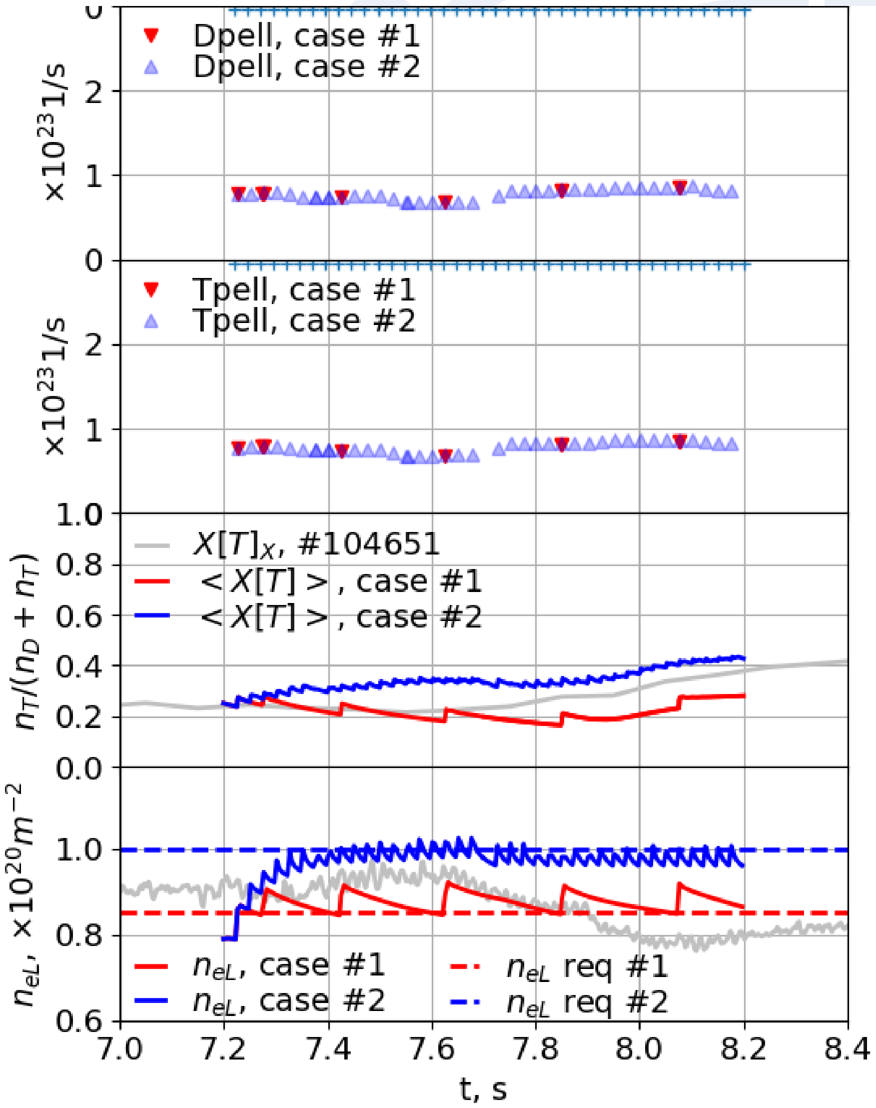
- **Actuator**: pure D or T pellets; **observer**: $\langle X[T]\rangle = \langle n_T\rangle / \langle n_T + n_D\rangle$
- $\langle X[T]\rangle = 0.3$ requested for t<7.5s, then $\langle X[T]\rangle = 0.6$
- Requested $\langle X[T]\rangle$ achieved within 0.5s
- n_{eL} is not controlled, and increase to $\sim 1\times10^{20}\mathrm{m}^{-2}$



Case study: n_{eL} control

Line integrated density control

- **Actuator**: mixed D/T=0.5/0.5 pellets; **observer**: line-integrated n_{eL}
- n_{eL} requested $8.5\times10^{19}m^{-2}$ and $1\times10^{20}m^{-2}$
- D/T ratio is not controlled
- Requested densities are achieved and maintained while D/T ratio remain unchanged
- Note, n_{eL} increase via pellets as actuator, n_{eL} decrease via transport losses



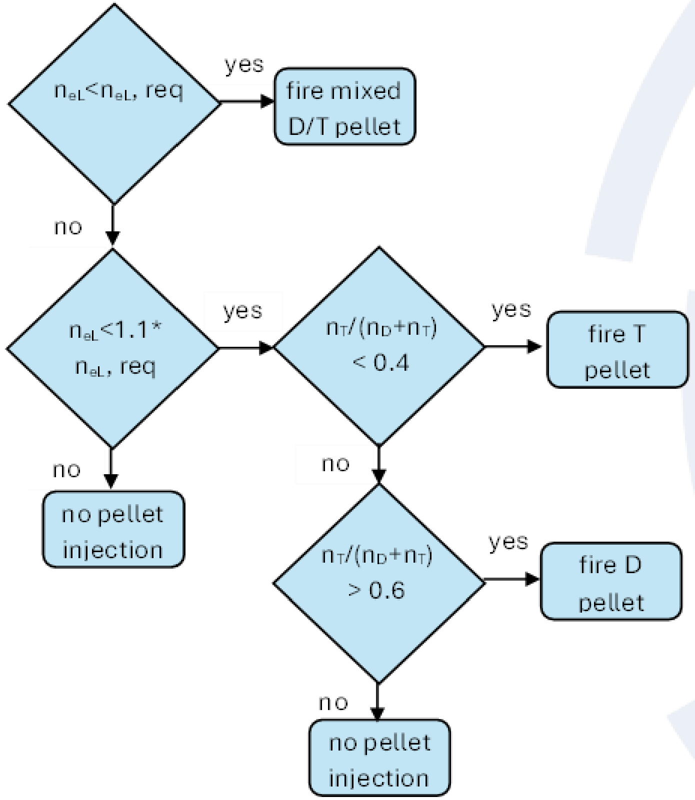
Network #1, controlling n_{eL} in range and D/T ratio

Combining two controllers into a network:

- Actuators are coupled and influence each other
- Prioritisation between the two controlled quantities must be considered
- Test of combined controllers with JETTO with external component for <X[T]> in [0.4, 0.6] and
  - Case 1, n_{eL} req = 8.5×10^{19}m^{-2}
  - Case 2, n_{eL} req = 1×10^{20}m^{-2}

Network #1

- Maintains n_{eL}=1×10^{20}m^{-2} but cannot achieve <X[T]> in [0.4,0.6]
- Lower request, n_{eL}=8.5×10^{19}m^{-2} is achieved on transport time scale



$n_{eL}<n_{eL}$, req

yes

fire mixed D/T pellet

no

$n_{eL}<1.1$* n_{eL}, req

yes

$n_T/(n_D+n_T)$ < 0.4

yes

fire T pellet

no

no pellet injection

no

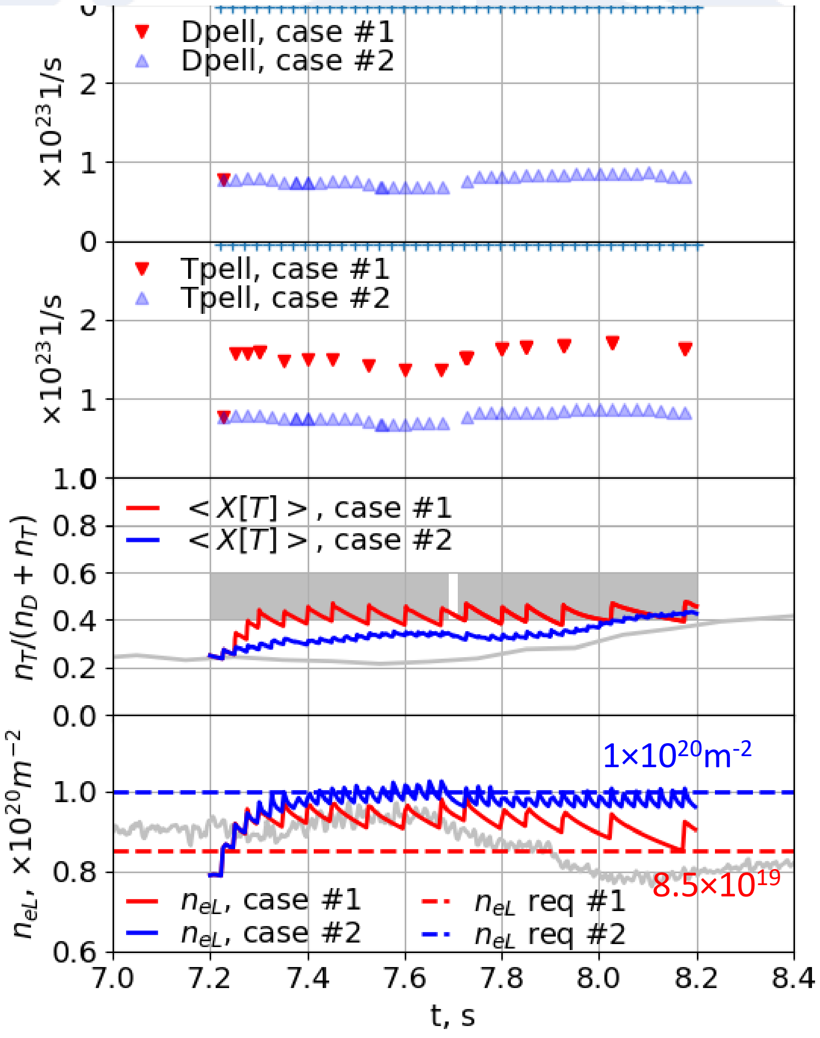
$n_T/(n_D+n_T)$ > 0.6

yes

fire D pellet

no

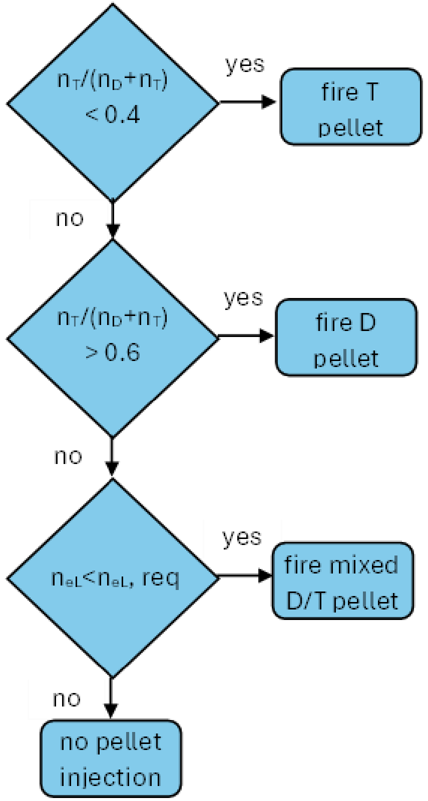
no pellet injection



Network #2, controlling D/T ratio and n_{eL}

Network #2

- Maintains somewhat $n_{eL} = 8.5\times10^{19}$ m^{-2} and better $1\times10^{20} m^{-2}$
- Excellent in controlling <X[T]> in [0.4,0.6]



$n_T/(n_D+n_T) < 0.4$

yes

fire T pellet

no

$n_T/(n_D+n_T) > 0.6$

yes

fire D pellet

no

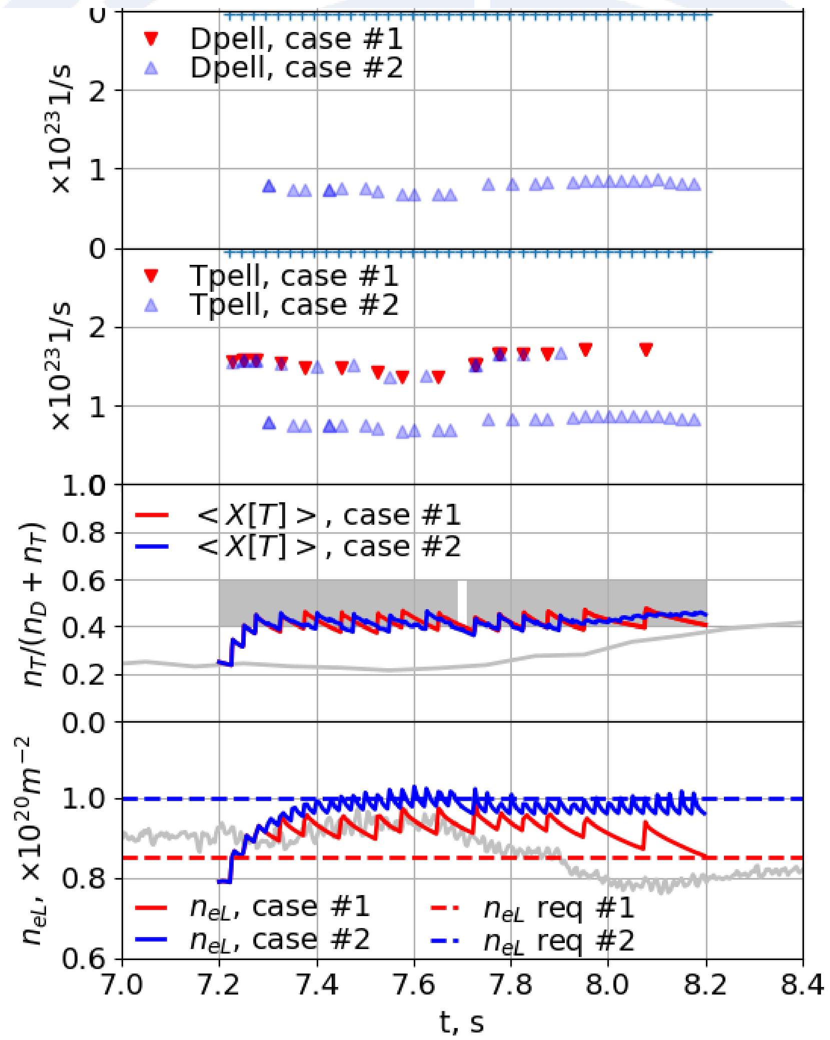
$n_{eL} < n_{eL,\,req}$

yes

fire mixed D/T pellet

no

no pellet injection



Network #2, controlling D/T ratio and n_{eL}

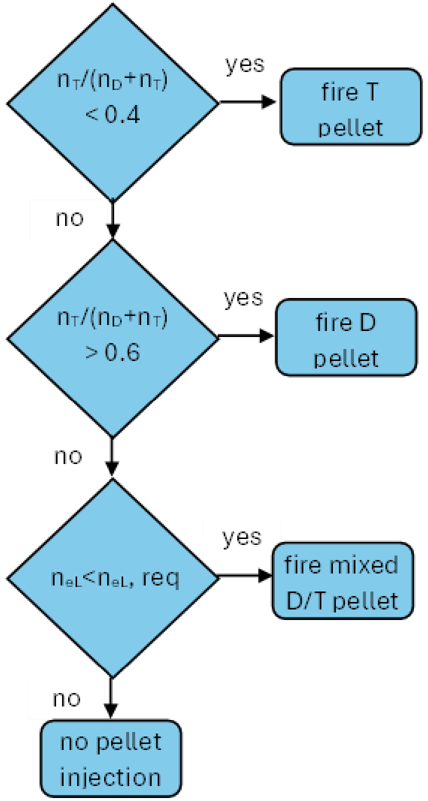
Network #2

- Maintains somewhat $n_{eL} = 8.5\times10^{19}$ m^{-2} and better $1\times10^{20}m^{-2}$
- Excellent in controlling <X[T]> in [0.4,0.6]
- Dynamic response:
  - Case #3, drop n_{eL} request from $1\times10^{20}m^{-2}$ to $8.5\times10^{19}m^{-2}$ and sustain <X[T]> in [0.4,0.6]

  n_{eL} req $8.5\times10^{19}m^{-2}$ achieved slowly

  - Case #4, sustain $1\times10^{20}m^{-2}$ and drop <X[T]> to [0.2,0.3]

  <X[T]> in [0.2,0.3] achieved quickly



$n_T/(n_D+n_T) < 0.4$

yes

fire T pellet

no

$n_T/(n_D+n_T) > 0.6$

yes

fire D pellet

no

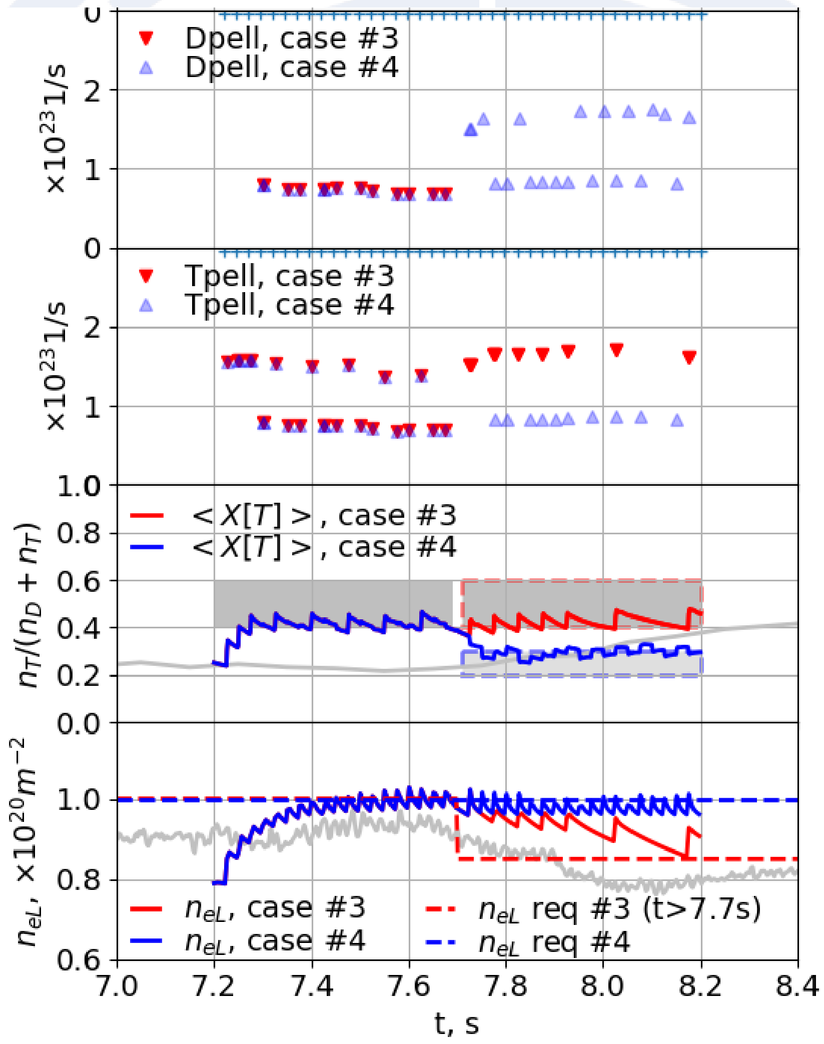
$n_{eL} < n_{eL}$, req

yes

fire mixed D/T pellet

no

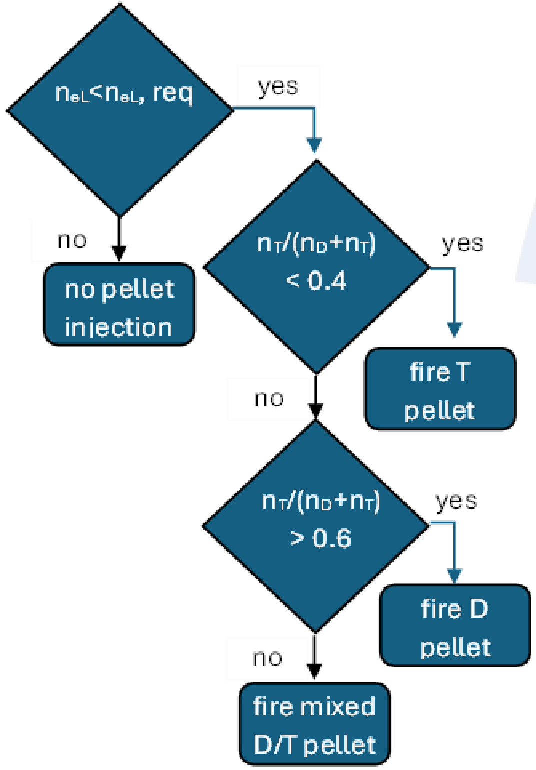
no pellet injection



Network #3, controlling n_{eL} and D/T ratio

Network #3

- Maintains better both requests for n_{eL}: n_{eL}= 8.5×$10^{19}$$m^{-2}$ and 1×$10^{20}$$m^{-2}$
- Controlling <X[T]> in [0.4,0.6] only for higher density request



$n_{eL}<n_{eL}$, req

yes

no

no pellet injection

$n_T/(n_D+n_T)$ < 0.4

yes

fire T pellet

no

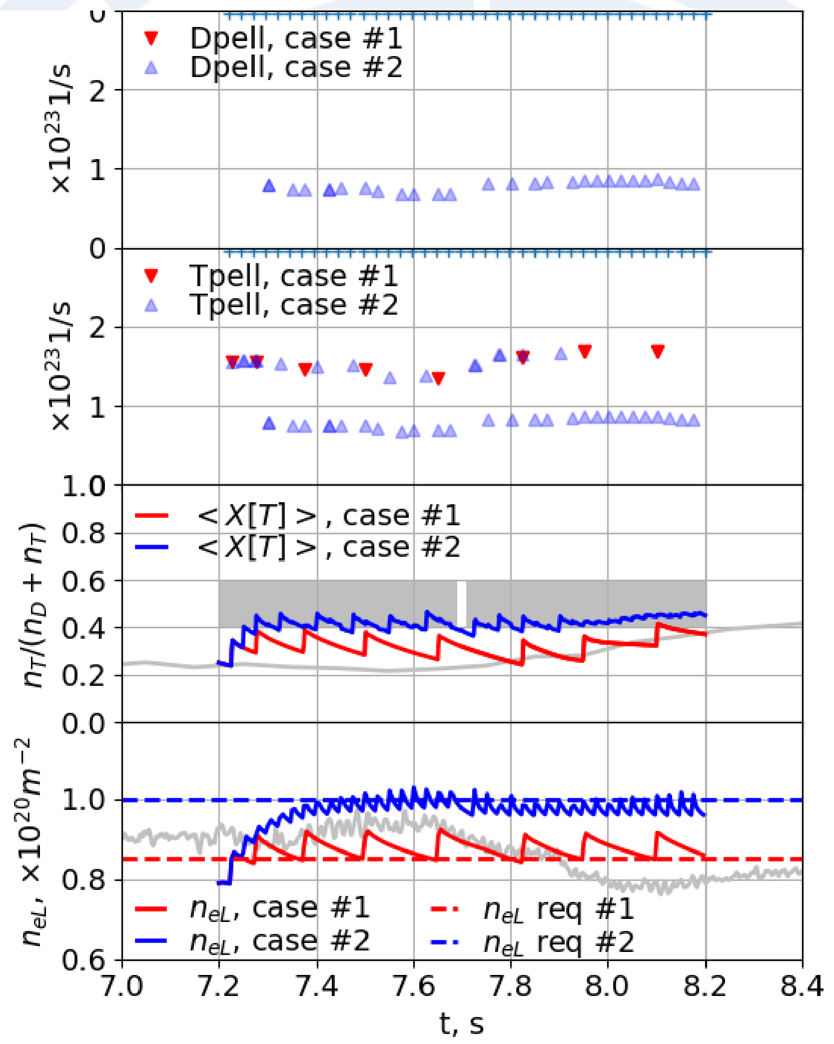
$n_T/(n_D+n_T)$ > 0.6

yes

fire D pellet

no

fire mixed D/T pellet



Network #3, controlling n_{eL} and D/T ratio

Network #3

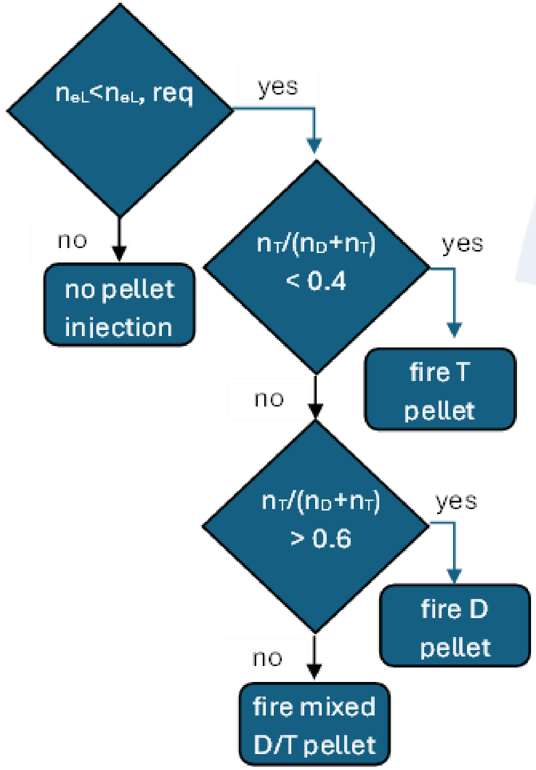
- Maintains better both requests for n_{eL}: n_{eL}= $8.5\times10^{19}m^{-2}$ and $1\times10^{20}m^{-2}$
- Controlling <X[T]> in [0.4,0.6] only for higher density request

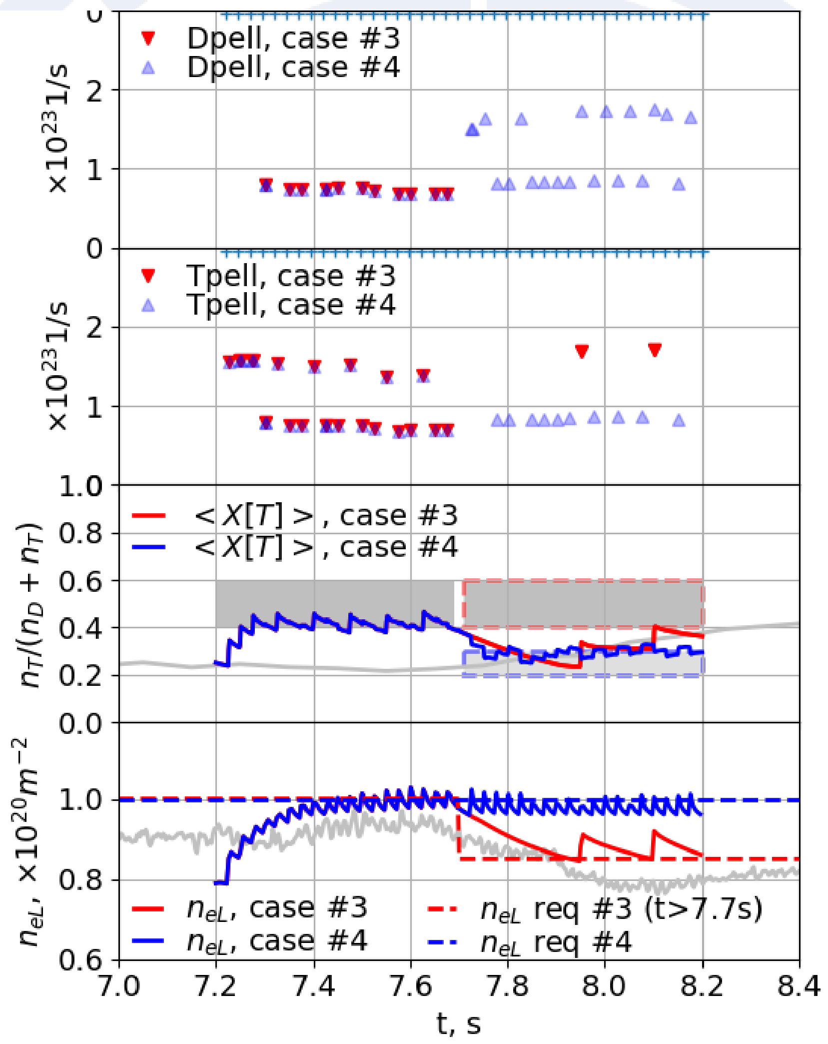
- Dynamic response:
  - Case #3, drop n_{eL} request from $1\times10^{20}m^{-2}$ to $8.5\times10^{19}m^{-2}$ and sustain <X[T]> in [0.4,0.6]

  n_{eL} req $\times10^{19}m^{-2}$ is better but cannot keep constant <X[T]>

  - Case #4, sustain $1\times10^{20}m^{-2}$ and drop <X[T]> to [0.2,0.3]

  <X[T]> in [0.2,0.3] achieved quickly





Summary and conclusions

- The RT networks investigated in this study operate based on two control references: n_{eL} and the D/T ratio, allowing for multiple possible configurations.

- Three configurations were assessed.

- The results demonstrate that not all configurations provide effective RT control within the explored parameter space.

- This finding highlights the necessity of systematically validating RT controllers prior to deployment.

- The workflow proposed in this work provides a robust framework for such validation and is therefore strongly recommended for the evaluation of future control schemes.