

Predictive integrated modelling of a high-radiation fraction electron cyclotron heated STEP plasma scenario

S. Gabriellini¹, F. J. Casson¹, C. Olde¹, E. Tholerus¹, F. Eriksson¹, K. K. Kirov¹, Ž. Štancar¹, H. Meyer²

¹ UKAEA (United Kingdom Atomic Energy Authority), Culham Campus, Abingdon, Oxfordshire, OX14 3DB, UK.

² UK Fusion Energy Ltd, Culham Campus, Abingdon, OX14 3DB, UK

1. Introduction

The Spherical Tokamak for Energy Production (STEP) is a proposed prototype fusion power plant intended to demonstrate net electrical power generation [1]. Among the plasma operating scenarios considered for STEP, this study focuses on a high-radiation-fraction ($f_{rad} = 0.7$) electron cyclotron heated case. This scenario is characterised by the following parameters: a major radius of 4.3 m, an aspect ratio of 1.8, a magnetic field of 3.0 T, plasma current of 21 MA, deuterium–tritium (D–T) fuel mixture, electron cyclotron heating power $P_{ECE} = 150$ MW, fusion power $P_{fus} = 1.8$ GW, normalised beta $\beta_N \approx 4.2$, confinement enhancement factor $H_{98} \approx 1.4$, minimum safety factor $q_{min} > 2$, and radiated power fraction $f_{rad} = 0.7$ using Argon and Xenon impurities, with fuelling provided by D–T pellets.

2. Simulation settings

The integrated modelling framework used in this work is based on the JINTRAC suite of codes, with JETTO as the 1.5D core transport solver [3]. In previous studies, simulations were performed using JETTO in *assumption integration* mode, in which energy confinement is prescribed rather than calculated from first-principles transport models, as described in detail in [2]. In the present work, the flat-top, ramp-up, and ramp-down phases are modelled with different levels of fidelity. The flat-top phase has been refined through the inclusion of the HPI2 [4] pellet model, which accounts for pellet ablation, homogenisation, and drift effects, while the Bohm/gyro-Bohm semi-empirical model has been used for anomalous transport. The ramp-up phase has been analysed at five distinct time points using the coupled JETTO–HPI2–TGLFNN framework. In this approach, TGLFNN—a neural network surrogate of the reduced quasilinear turbulent transport model TGLF [5]—is used to provide a more physics-based description of transport. For the ramp-down phase, the modelling focuses on optimisation under constraints from MHD and vertical stability limits, while ramping down a 21 MA plasma current non-inductively and maintaining a low internal inductance. In this case, the transport assumptions are the same as for the flat-top phase, with future work planned to incorporate TGLFNN. In all simulations presented, impurity transport is modelled using SANCO, although radiation is prescribed independently and remains decoupled from impurities. ESCO is used as the equilibrium solver, with fixed equilibrium boundary. The electron cyclotron heating and current drive (ECH/ECCD) deposition profiles are prescribed as a function of time. When HPI2 is not used, pellet fuelling is controlled via feedback to track a specified Greenwald fraction waveform. The neoclassical transport is computed by NCLASS. The power threshold for H-L transition has been determined with the Martin scaling [6].

3. Pellet injector reliability during the flat-top phase with JETTO-BgB-HPI2

One of the objectives of this study is to assess the impact of missed pellets on STEP plasma scenario parameters. To this end, a pellet injector reliability has been implemented in JETTO

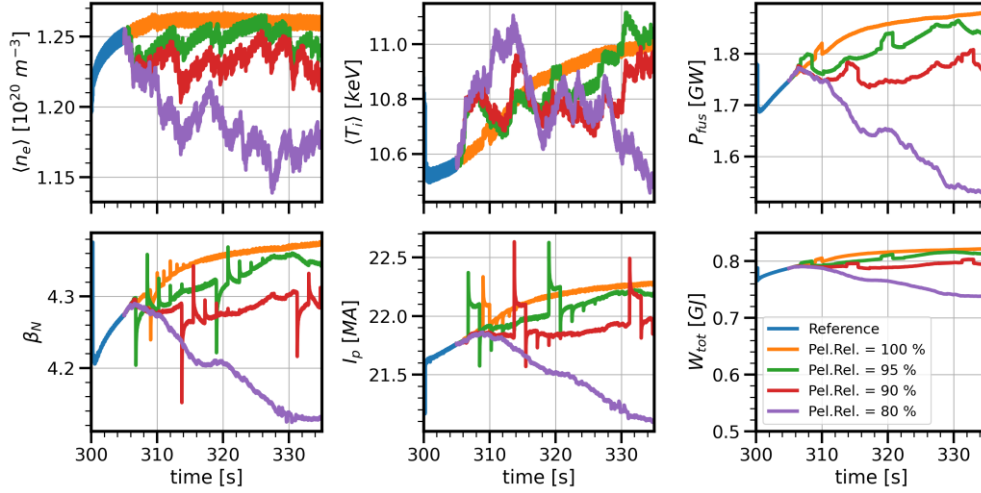


Figure 1. Time traces of the flat-top phase for the line averaged density, volume averaged ion temperature, fusion power, normalised beta, plasma current and total energy, for different values of pellet injector reliability. Spikes in $\beta_N, I_i(3)$ are not linked to the pellet injection but rather to the numeric of equilibrium computation.

using a simple random number generator. For a given reliability (ranging from 0 to 1), a random number is drawn for each injection; if it exceeds the specified reliability, the pellet is skipped. This reliability represents the fraction of requested pellets that are successfully delivered to the plasma. Although estimates of injector reliability for STEP are not yet available, measurements from ASDEX Upgrade (AUG) indicate values in the range of 0.8–0.9 under optimised conditions [7]. In the STEP scenario considered here, a pellet frequency of 15 Hz is required during the flat-top phase to maintain the target density (corresponding to 100% reliability case in Fig. 1). A pellet injector reliability scan was performed for values between 95% and 80%. The results show that at 80% reliability the fusion power decreases by approximately 20%, highlighting the importance of reliable fuelling in a fusion power plant, while key plasma parameters—including density, temperature, stored energy, normalised beta, and plasma current—decrease by less than 10%. Increasing the pellet frequency to 20 Hz at 80% reliability largely recovers the nominal operating conditions.

4. Pellet modelling during ramp-up phase with JETTO-TGLFNN-HPI2

For the ramp-up phase, five time points spanning a range of plasma currents and densities were selected from a reference JETTO–TGLFNN simulation to determine the required pellet frequency using the HPI2 model. At each time, a frequency scan was performed to identify the value needed to recover the target reference density at that time.

Figure 2 shows an example at the start of the ramp-up phase, comparing density profiles before and after pellet injection with the reference case, in which pellet deposition is modelled using a simple Gaussian. The figure also includes the time trace of the line-averaged density, highlighting fluctuations induced by pellet injection at 23 Hz. The corresponding relative density perturbation, $\Delta n_e/n_e$ [%], is also reported. The maximum density variation ($\sim 6\%$) occurs at the beginning of the ramp-up, where both density and plasma current are lowest and the pellet frequency is highest. Such perturbations are associated with an increased likelihood of triggering edge-localised modes (ELMs), which STEP aims to avoid. Consequently, pellet parameters—velocity, mass, and geometry—have been optimised to minimise Δn_e .

Figure 3 presents a summary of the obtained pellet frequencies for all the analysed time points. The lowest frequency (~ 1 Hz) occurs at the lowest line-averaged density, where minimal fuelling is needed to sustain the target conditions. In contrast, to maintain the density of $\sim 3 \times 10^{19} \text{ m}^{-3}$ at different plasma currents requires substantially different pellet frequencies: up

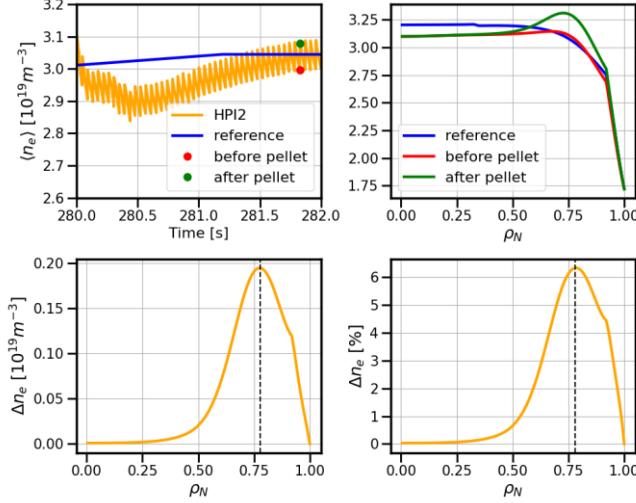


Figure 2. From top to bottom, left to right: time trace of line average electron density for the simple pellet model (blue) and HPI2 (orange); electron density profiles comparison between reference and before/after pellet injection; absolute variation in density; relative variation in density ($\Delta n_e/n_e$).

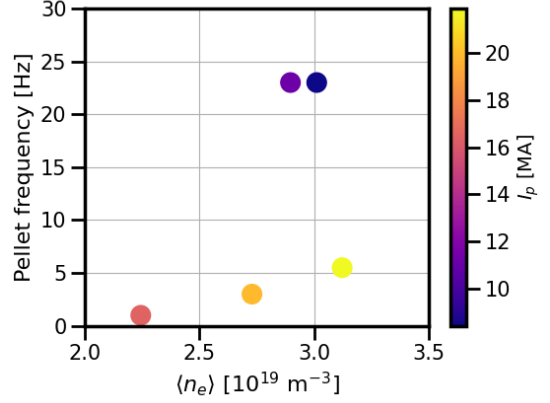


Figure 3. Pellet injection frequency obtained with HPI2 to maintain a certain volume averaged electron density. The colormap represents the plasma current, i.e. different times of the ramp-up phase.

to ~ 23 Hz at low current (~ 6 MA), while at higher current (~ 20 MA) improved confinement reduces the required frequency by roughly a factor of five.

5. Modelling of the non-inductive ramp-down with JETTO-BgB

Identifying a safe pathway for non-inductive ramp-down of the STEP plasma current is essential to avoid severe damage to plasma-facing components. Disruptions at high current ($I_p > 2$ MA) must be avoided, as the associated forces scale with I_p^2 . Several constraints must be satisfied during ramp-down: low internal inductance ($l_i(3) < 0.4$) to ensure vertical stability at high elongation ($\kappa \approx 2.9$); $q_{min} > 2$ to prevent MHD instabilities; electron density below the Greenwald limit ($n_e < n_{GW}$); effective control of exhaust heat fluxes and wall loads; and compliance with radiation limits. The internal inductance target is based on spherical tokamak power plant estimates derived from NSTX experimental data [8], using the relation $\kappa = 3.4 - l_i(3)$. In the present work, the radiation limit is not addressed, as radiation is prescribed and decoupled from impurity transport, as noted earlier; it will be considered in future work. The available actuators for managing the ramp-down are: tailoring the EC current density profile to meet q_{min} and $l_i(3)$ requirements; pellet fuelling to reduce fusion power, alpha pressure and bootstrap current, and also to reduce density, which helps delaying the H–L transition; reduction of radiated power, which further delays the H–L transition and allows more time for plasma current decay. The two-step ramp-down approach developed for the previous STEP design point has been applied here; the resulting time traces are shown in Fig. 4.

- **Phase I: D–T \rightarrow D transition.** The plasma composition is shifted from a 50:50 D–T mixture to pure deuterium by adjusting the pellet source, reducing both alpha heating (P_α) and fusion power (P_{fus}) over ~ 200 s and thereby lowering the bootstrap current. During this phase, the Greenwald fraction is held constant, while the radiation fraction is reduced from 0.7 to 0.2. In addition, the EC power is decreased by 30 MW to further reduce the plasma current, reaching ~ 20 MA by the end of the phase.
- **Phase II: EC power ramp-down.** The EC power is then reduced approximately linearly to lower the temperature, bootstrap current, and total plasma current. The electron density is simultaneously reduced via feedback on the pellet source, tracking a linear decrease in the Greenwald fraction, while the radiation fraction is maintained

at 0.2. Around 1300 s, the ECCD profile is adjusted to control the rise in internal inductance $l_i(3)$ by redistributing current towards the plasma edge, thereby mitigating current peaking caused by induced back-EMF currents.

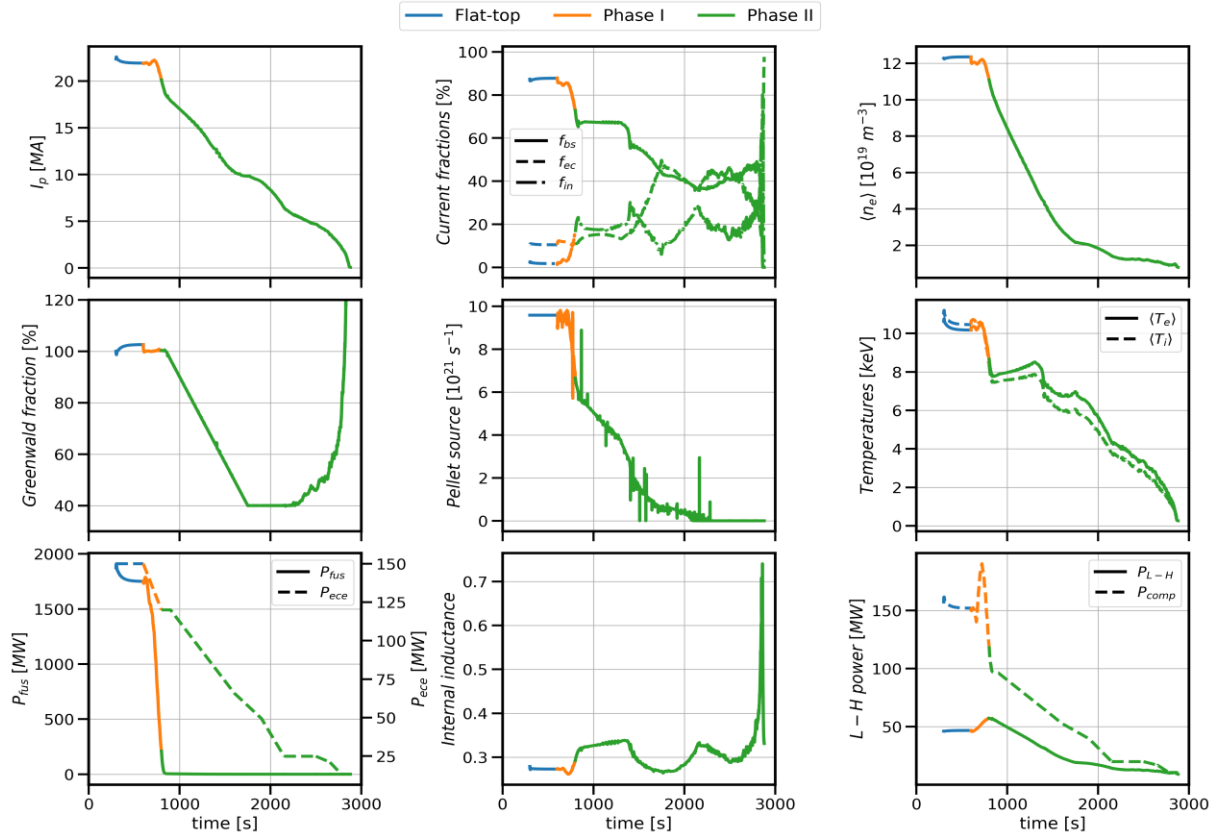


Figure 4. Time traces of the Ramp-Down phase for the plasma current, bootstrap/EC/inductive current fractions, line averaged electron density, Greenwald fraction, pellet source electron and ion temperatures, fusion power, internal inductance, L-H transition power and $P_{comp} = P_{tot} - P_{rad}$.

Modelling of the ramp-down has been performed for this updated STEP design, achieving a reduction in plasma current from ~ 22 MA to ~ 1 MA over approximately 35 minutes. Beyond this point, control of the Greenwald fraction and internal inductance is lost, the plasma transitions to L-mode, and disruptions may occur; however, at such low current levels, their impact is considered acceptable. The long ramp-down duration is primarily due to the long current diffusion times ($\tau_R \sim \mu_0 a^2 / \eta \sim 10^3$ s) and the presence of induced back-EMF currents. These currents arise when the plasma current is reduced rapidly, leading to increased profile peaking and a rise in $l_i(3)$. Consequently, the EC power must be decreased gradually to allow these currents to diffuse and maintain vertical stability.

References

- [1] Meyer H. 2024 Plasma burn—mind the gap. *Phil. Trans. R. Soc. A* 382 20230406, [2] E. Tholerus et al 2024 *Nucl. Fusion* 64 106030, [3] M. Romanelli et al, JINTRAC: A System of Codes for Integrated Simulation of Tokamak Scenarios, Plasma and Fusion Research, 2014, Volume 9, Pages 3403023, [4] F. Koechl, B. Pégourié et al, “Modelling of pellet particle ablation and deposition: the hydrogen pellet injection code hpi2,” EUROfusion Preprint EFDA-JET-PR (12), vol. 57, 2012 [5] G. Staebler *et al* 2024 *Nucl. Fusion* 64 103001, [6] Y R Martin et al 2008 *J. Phys.: Conf. Ser.* 123 012033 [7] *Rev. Sci. Instrum.* 91, 083502 (2020), [8] J.E. Menard et al 2016 *Nucl. Fusion* 56 106023

Acknowledgements: This work has been funded by STEP, a major technology and infrastructure programme led by UK Fusion Energy Ltd, which aims to deliver the UK’s prototype fusion powerplant and a path to the commercial viability of fusion.