PREDICTIVE INTEGRATED MODELLING OF A HIGH-RADIATION FRACTION ELECTRON CYCLOTRON HEATED STEP PLASMA SCENARIO

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STEP PROJECT AND MODELLED PLASMA SCENARIO

- **STEP.** The Spherical Tokamak for Energy Production is a proposed prototype fusion power plant designed to demonstrate net electrical power generation [1].

- **Plasma scenario analysed in this work.** SPP-2 [2]: $R_{geo}\sim 4.3$ m, D-T, 3.0 T / 21 MA, $P_{ECE} = 150$ MW, $P_{fus} = 1.8$ GW, $\beta_N\sim 4.2$, $H^*_{98}\sim 1.4$, $q_{min} > 2$, $f_{rad} = 70$ % (Ar, Xe), DT pellet fuelling.

JINTRAC SUITE OF CODES

- The **JINTRAC [3]** suite of codes has been used for modelling STEP plasma scenarios, as extensively detailed in [4]. Simulations for **Flat-Top** and **Ramp-Down** phase are performed in "assumption integration" mode, in which energy confinement is prescribed. The **Ramp-Up** phase has been modelled using TGLF surrogate neural network (sat1, EM).

- Models coupled to 1.5D **JETTO** transport solver: **ESCO** (equilibrium), **SANCO-ADAS** (impurities), **NCLASS** + **BgB/TGLFNN** (transport models), **HPI2/Continuous pellet** (pellet injection).
- Predicting $j_z, n_D, n_T, T_e, T_i, n_{Xe}, n_\alpha, n_{Ar}$.

PELLET MODELLING DURING FLAT-TOP AND RAMP-UP

- **HPI2** (Hydrogen Pellet Injection) models the pellet ablation and homogenization, based on Neutral Gas and Plasma Shielding (NGPS) model [5], accounting for plasmoid drift and arbitrary pellet injection configurations. Coupled to JETTO it gives the pellet particle source for the particles transport equation. In this scenario and with these assumptions, a pellet frequency of **~15 Hz** is found to be needed during Flat-Top.

- **Pellet reliability studies during Flat-top phase.** A pellet injector reliability model based on a random number generator has been implemented in JETTO to account for missed pellet injections and their impact on plasma parameters.

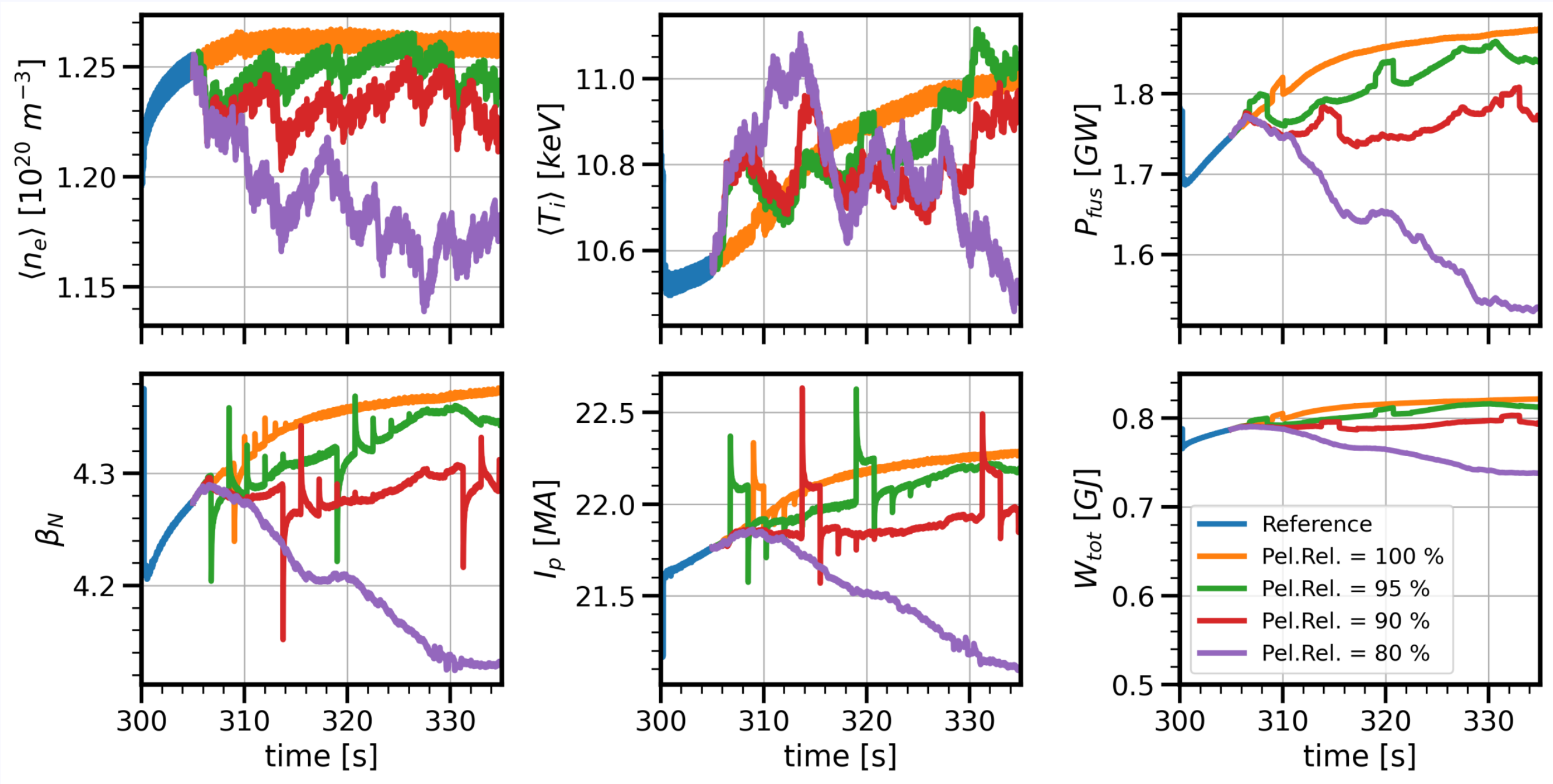


Figure 1. *Time traces of the Flat-Top phase for the line averaged density, volume averaged ion temperature, fusion power, normalised beta, plasma current and total energy, for different values of pellet injector reliability.*

- **Pellet modelling during Ramp-Up with JETTO-TGLFNN-HPI2.** The reference ramp-up simulation, originally performed using the continuous pellet model, has been modelled with JETTO-TGLFNN-HPI2 at five selected time points of the ramp.

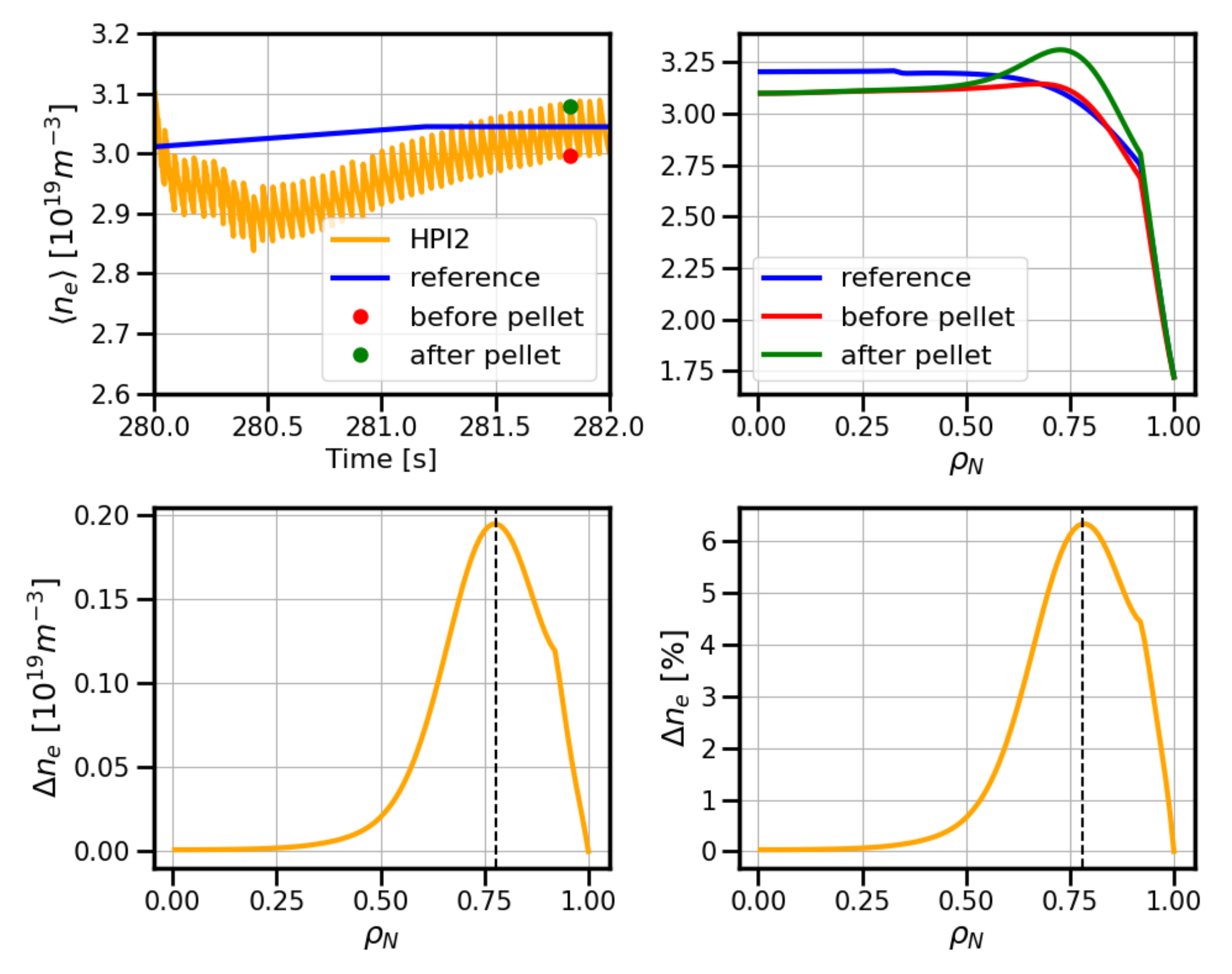


Figure 2. *From top to bottom, left to right: time trace of line average electron density for the continuous pellet (blue) and HPI2 (orange); electron density profiles comparison between reference and before/after pellet injection; absolute variation in density; relative variation in density ($\Delta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

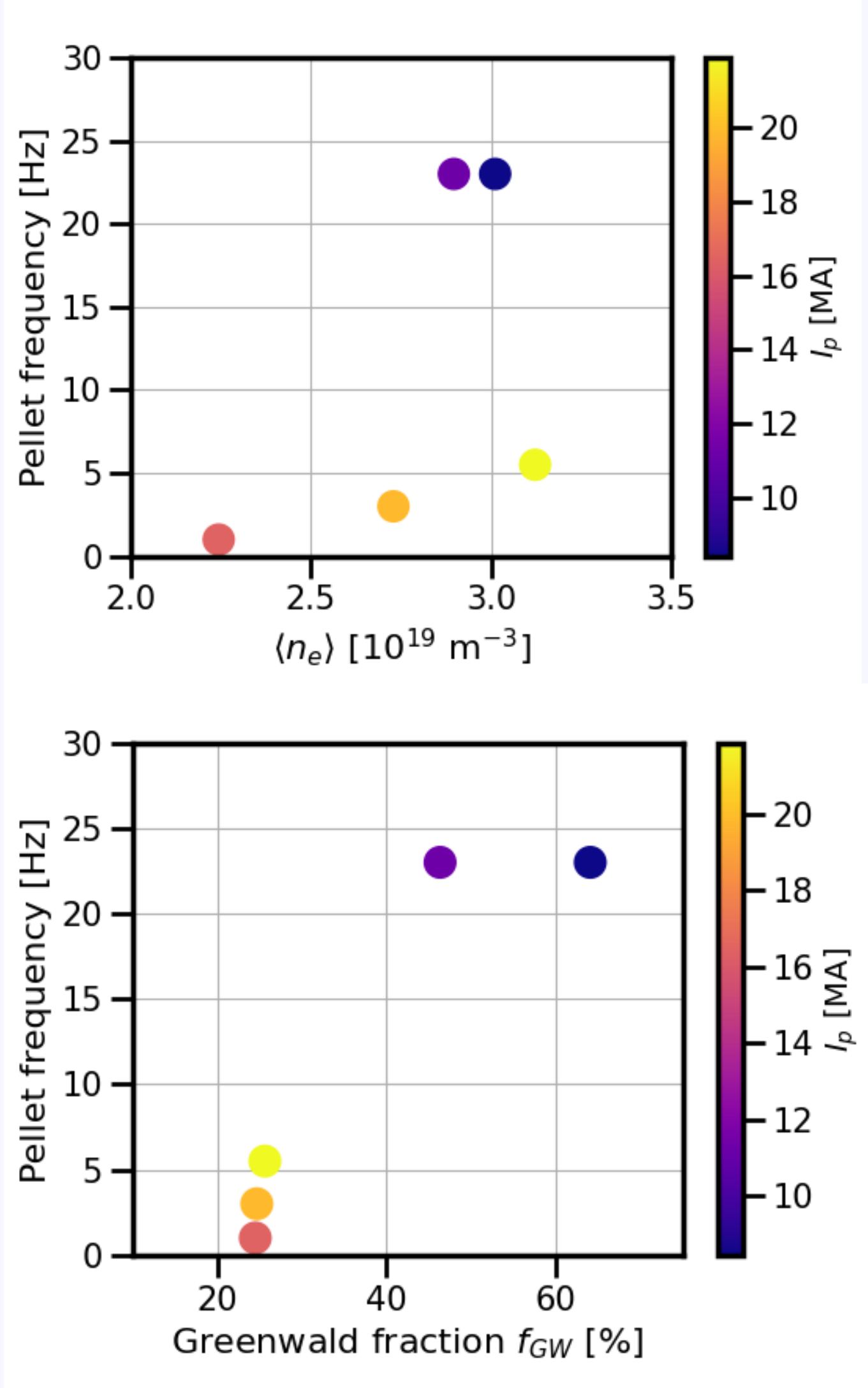


Figure 3. *Pellet injection frequency obtained with HPI2 matching the reference density at five different Ramp-Up times.*

Key takeaways

- Flat-top pellet frequency ~15 Hz.
- At 80% injector reliability the frequency must be increased to ~20 Hz to maintain constant P_{fus}.
- Pellet frequency during Ramp-Up spans from 1 to 23 Hz.
- The $\Delta n_e[\%]$ that can trigger an ELM in a STEP-like plasma is not clear.
- Maximum local $\Delta n_e\sim$ 6 % obtained at beginning of Ramp-Up, at lower current and higher frequency.
- Maximum global $\Delta\langle n_e\rangle\sim 4$ % obtained when density and frequency are the lowest.

NON-INDUCTIVE CURRENT RAMP-DOWN

- **Goal**: establish a safe termination pathway for a STEP high f_{rad} EC heated scenario with JINTRAC integrated modelling.

- **Actuators**: EC power, pellets fuelling rate and mix, impurity seeding fuelling rate.

- **Challenges**: vertical stability, Greenwald density limit, back-EMF induced current, q-profile control, exhaust, radiation limits.

- The two-step approach found for the previous STEP design point has been used:
  - **Phase I: DT->DD transition.** Transition from a 50-50 DT plasma to a pure D plasma by acting on the pellet source mix, bringing $P_{fus} \rightarrow 0$ over ~ 200 seconds. Temperatures stay roughly constant until the P_α is dissipated.

  - **Phase II: EC power ramp down.** EC power is decreased almost linearly to decrease temperature, bootstrap current and overall plasma current. Electron density is decreased by feedback loop acting on magnitude of pellet source, tracking a linear decrease of the Greenwald fraction. Radiation fraction is also decreased (not shown) from 70% to ~28%.

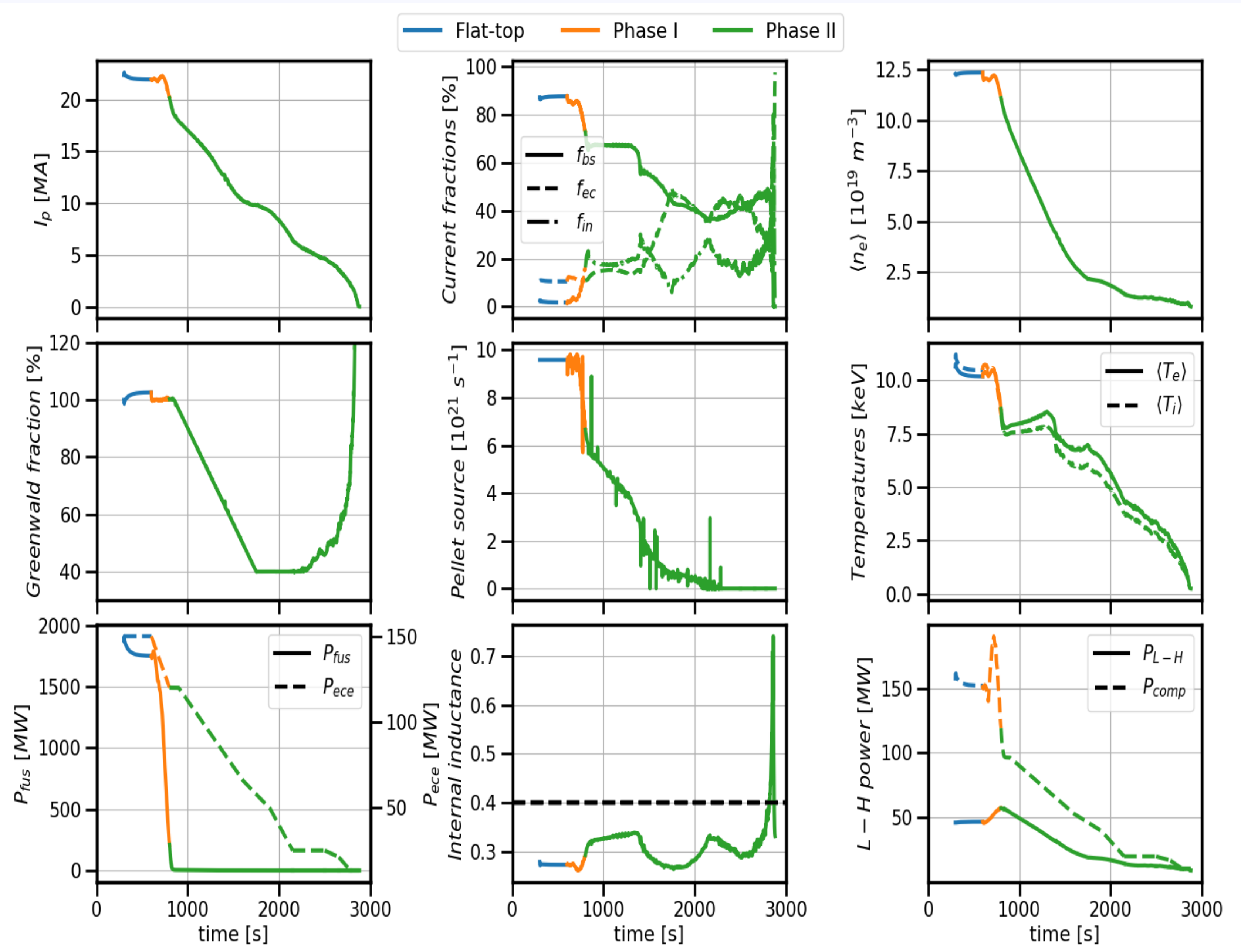
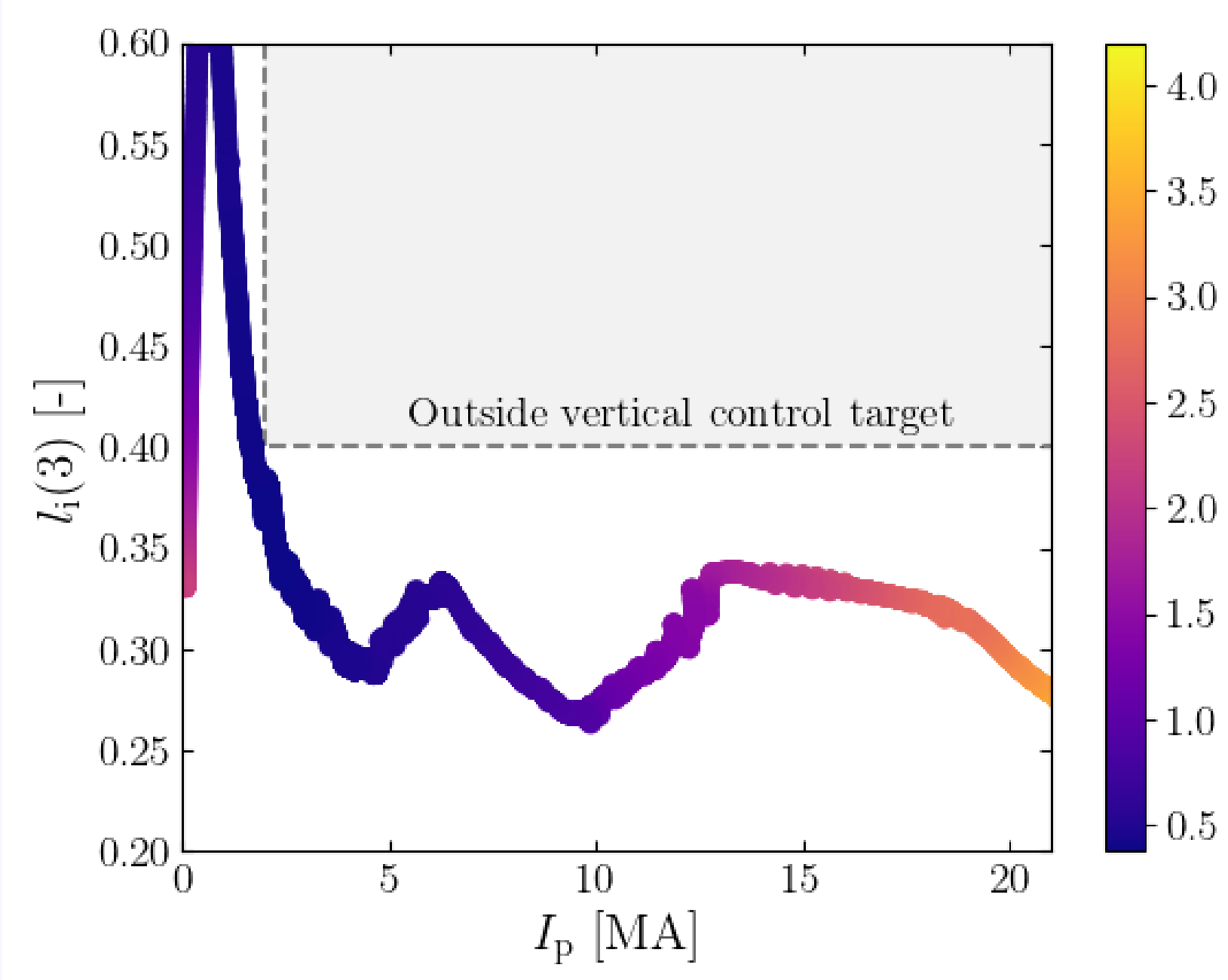


Figure 4. *Time traces of the Ramp-Down phase for the plasma current, bootstrap/EC/inductive current fractions, line averaged electron density, Greenwald fraction, pellet source electron and ion temperatures, fusion power, internal inductance, L-H transition power and $P_{comp} = P_{tot} - P_{rad}$.*

Key takeaways

- Ramp-Down length **~ 35 minutes**: long $\tau_R\sim 10^3\ s$ and back-EMF current.
- **Back-EMF** is challenging, peaks current density and increased l_i.
- **Reducing P_{fus}** early helps reducing pressure and bootstrap current fraction.
- MHD and vertical stability analysis performed: plasma is **stable** down to ~1 MA.
- **Delaying H-L transition** is beneficial to keep l_i under control. Martin's scaling is used [7]:
  - $P_{LH} = C_1\ n_e^{0.717}\ B_t^{0.803}\ S^{0.941}\ (M/2)^{-1}$, compared to $P_{comp} = P_{OH} + P_\alpha + P_{EC} - P_{rad}$.
  - Decreasing n_e and f_{rad} helps delaying H-L transition.
- Controlling **EC deposition location** fundamental to reduce l_i increase → flexible ECCD.
- Greenwald fraction not controlled at the end, disruptions deemed acceptable due to low current.

Figure 5. *Current Ramp-Down trajectory and corresponding $l_i(3)$ and β_N values. The region inside vertical control target is computed via simple fit of NSTX experimental data [5]: $\kappa\sim 3.4 - l_i(3)$.*



Future work

- Radiation computed self-consistently with impurities (Ar, Xe). In this work the impurity transport is computed, but radiation waveform is imposed.
- Improved transport model (TGLF/TGLFNN).
- Investigate exhaust requirements.
- Multi-objective optimisation integrated within JINTRAC to explore other viable paths.

References: [1] Meyer H. 2024 Plasma burn – mind the gap. Phil. Trans. R. Soc. A 382 20230406, [2] Meyer H. 2025, UK STEP towards a fusion power plant plasma, IAEA FEC 2025 [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] E. Tholerus et al 2024 Nucl. Fusion 64 106030, [5] 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 [6] J.E. Menard et al 2016 Nucl. Fusion 56 106023, [7] Y R Martin et al 2008 J . Phys.: Conf. Ser. 123 012033. **Acknowledgements**: This work has been funded by STEP, a major technology and infrastructure programme led by UK Fusion Energy (UKFE), which aims to deliver the UK's prototype fusion powerplant and a path to the commercial viability of fusion.