

Plasma initiation assessment in the Spherical Tokamak for Energy Production

Hyun-Tae Kim¹, Oliver Bardsley¹, Hendrik Meyer², Martin Cox¹, Krassimir Kirov¹, Alexander Petrov¹, Mark Bull¹, Frida Eriksson¹, and STEP team

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

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

Hyun-Tae.Kim@ukaea.uk

1 Introduction

The Spherical Tokamak for Energy Production (STEP) is a programme to design, construct, and operate the UK's first fusion power plant, which is planned for construction in the 2030s. STEP is designed with a large vacuum vessel, as the plasma volume must be sufficient to produce fusion power at the GW level. However, owing to the spherical torus geometry, the central stack space available for the central solenoid is limited, which constrains both the inducible loop voltage and the total available flux in volt-seconds. It is therefore essential to carefully assess the feasibility of plasma initiation and the uncertainties associated with the flux required to complete plasma initiation.

In this contribution, we report on the STEP plasma initiation assessment conducted over the past few years by the STEP plasma initiation group. The assessment tools, based on the Yfactory-DYON workflow, are introduced in Section 2, and the preliminary STEP design is described in Section 3. The operational scenario calculation is presented in Section 4, the predictive modelling results and uncertainty quantification are discussed in Section 5, and the summary and future work are presented in Section 6.

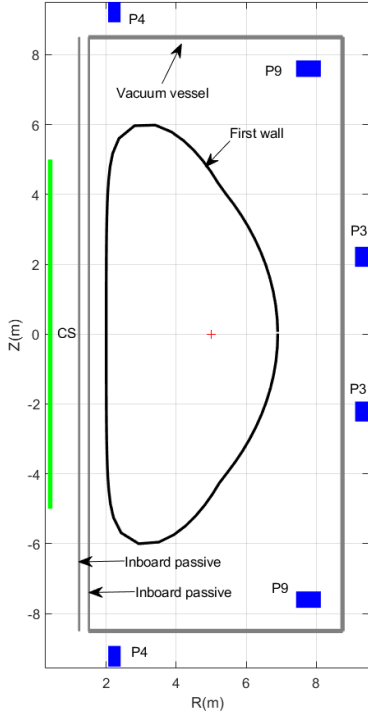


Figure 1: Preliminary STEP design.

voltages directly to the diagnostic outputs. The resulting time-dependent output vector $\mathbf{y}(t)$ tracks critical operational parameters, including the loop voltage ($V_{\text{loop}}(t)$), the vertical magnetic field ($B_z(t)$), and the magnetic field decay index.

In practice, Yfactory is used to optimise magnetic configurations for the critical plasma initiation phase in tokamaks. The algorithm defines a target, time-evolving poloidal magnetic flux (ψ) that satisfies the physical criteria necessary for plasma initiation: namely, a high-quality magnetic null configuration, sufficient loop voltage (V_{loop}), radial force balance, and vertical stability. By inverting the state-space model, Yfactory calculates the precise feedforward current and voltage waveforms required in the poloidal field coils to match this target flux evolution.

2 Yfactory-DYON workflow

2.1 Yfactory code: scenario calculation

The Yfactory code is a specialised computational tool developed to invert a general linear dynamical model using a state-space representation. The primary objective of the algorithm is to determine the optimal state trajectory $\mathbf{x}(t)$ and control inputs $\mathbf{u}(t)$ required to achieve a predefined, time-evolving target output vector $\mathbf{y}(t)$. The underlying system dynamics are governed by the standard linear state-space formulation:

$$\frac{d\mathbf{x}}{dt} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \quad (1)$$

$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u} \quad (2)$$

Within this mathematical framework, $\mathbf{x}(t)$ represents the electrical currents flowing through the magnetic coils and passive structures, while $\mathbf{u}(t)$ denotes the applied coil voltages. The system matrices \mathbf{A} and \mathbf{B} are defined by the intrinsic resistance (R) and inductance (L) of the electromagnetic structures, such that $\mathbf{A} = -R/L$ and $\mathbf{B} = 1/L$. The matrices \mathbf{C} and \mathbf{D} couple these internal currents and

To ensure experimental viability, the algorithm explicitly incorporates realistic engineering constraints and optimisation metrics. It accounts for strict hardware limits, including maximum allowable coil currents, maximum current ramp rates (dI/dt), maximum coil voltages, and maximum voltage ramp rates (dV/dt). To handle these boundaries smoothly, regularisation techniques are implemented as penalty terms that activate when coil currents approach their operational limits: $J = \int \left[\|\mathbf{y}(t) - \mathbf{y}_{\text{target}}(t)\|_{\mathbf{W}(t)}^2 + \mathcal{R}(\mathbf{x}, \mathbf{u}) \right] dt$ where $\mathbf{W}(t)$ represents time-dependent output weightings applied to components of the output vector \mathbf{y} , allowing users to prioritise specific physical objectives during different stages of discharge initiation, and \mathcal{R} denotes the regularisation penalty functions used to enforce the engineering limits. The Yfactory algorithm minimises J and calculates $\mathbf{x}(t)$ and $\mathbf{u}(t)$ such that $\mathbf{y}(t)$ closely matches $\mathbf{y}_{\text{target}}(t)$. An example application of Yfactory to COMPASS-U is given in [1].

2.2 DYON code: plasma initiation prediction

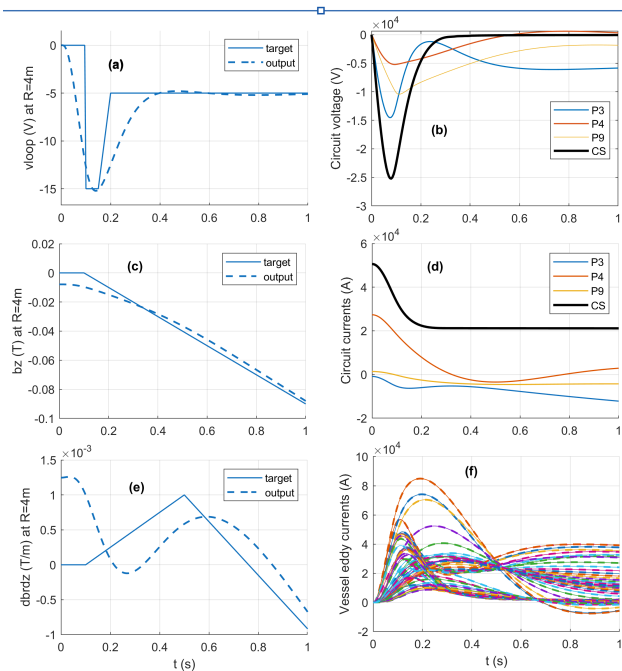


Figure 2: Yfactory calculation for the STEP plasma initiation scenario. Solid lines in (a), (c), and (e) show the target V_{loop} , B_z , and dB_r/dz at $R = 4$ m, respectively. Dashed lines show the corresponding outputs. Panels (b) and (d) show the output circuit voltages and currents, respectively. Panel (f) shows the corresponding eddy currents in the passive structures.

After successful Townsend breakdown, DYON simulates the plasma burn-through phase by solving a coupled system of differential equations. This system comprises the full circuit equations, electron and ion energy balances, and particle balances for both the primary fuel and impurities across each ionisation stage [2]. The capability of DYON’s full electromagnetic simulation to predict operational space for Townsend breakdown and plasma burn-through has been successfully demonstrated on multiple devices [3].

3 Example STEP design and uncertainties

Figure 1 illustrates an example of a variant of the STEP design, focusing on the magnetic coils and passive structures. Note, the STEP parameters used in the modelling of this paper are only indicative and can evolve further. Additional coils are located near the divertor region, but these do not play a major role in plasma initiation and are therefore not included in this study. The passive structures are made of stainless steel, with a nominal resistivity of $7.5 \times 10^{-7} \Omega\text{m}$.

DYON is a comprehensive predictive model for Townsend breakdown and plasma burn-through. It integrates a full circuit equation governing the magnetic coils, passive structures, and plasma current (I_p) with global energy and particle balance equations for neutrals and ions across all charge states, including impurities. A key advantage of DYON is its operational accessibility: it simulates plasma behaviour using only control-room-level input data, namely the operational scenario defined by the coil currents and pre-fill gas pressure. In this study, the time-evolving coil currents calculated by Yfactory serve as the primary input for DYON. From these inputs, DYON computes a two-dimensional, time-varying poloidal flux (ψ) map, enabling a rigorous assessment of the Townsend breakdown criterion along individual open magnetic field lines. This criterion is expressed as:

$$\frac{1}{2} L_{\text{open}} \alpha > 1 \quad (3)$$

where L_{open} is the connection length of a given field line, and α is the Townsend ionisation coefficient, which quantifies the number of impact ionisations produced by a seed electron per metre of travel. The initial plasma volume (V_p) at the onset of Townsend breakdown is a critical parameter that strongly influences the subsequent plasma burn-through phase. Within the DYON framework, the time-evolving V_p is dynamically determined by integrating the volumes occupied by closed magnetic field lines and by open field lines that satisfy Eq. (3).

After successful Townsend breakdown, DYON simulates the plasma burn-through phase by solving a coupled system of differential equations. This system comprises the full circuit equations, electron and ion energy balances, and particle balances for both the primary fuel and impurities across each ionisation stage [2]. The capability of DYON’s full electromagnetic simulation to predict operational space for Townsend breakdown and plasma burn-through has been successfully demonstrated on multiple devices [3].

However, the total resistance of the inboard passive structure could be lower, since additional inboard passive structures are under consideration, including support structures for plasma-facing components, the cavity shield, and the high-pressure shield. The vacuum volume within the first wall is 1145 m^3 , while the vacuum volume calculated from the vessel cylinder is 4136 m^3 . The actual vacuum volume is expected to lie between these values, as hardware components will be installed between the vacuum vessel and the first wall. The effects of uncertainties in inboard resistivity and vacuum volume on plasma initiation are investigated in Section 5.

4 Operation scenario calculation

For inductive plasma initiation, a wide null region should be formed, indicated by small B_z and B_r at $t = 0$ s. At the same time, a sufficiently high V_{loop} should be induced to achieve successful Townsend breakdown and plasma burn-through. When I_p starts to ramp up after successful burn-through, B_z should increase accordingly to keep I_p near the centre of the vacuum space by maintaining radial force balance. The magnetic field configuration should also become concave (i.e. $dB_r/dz < 0$) to ensure vertical stability.

Figure 2 shows how the coil currents for plasma initiation in STEP were calculated. First, the time-dependent targets for V_{loop} , B_r , and dB_r/dz are defined manually. Using these target input data, Yfactory calculates the time traces of the coil currents and voltages so that the outputs closely match the prescribed targets. In this calculation, eddy currents in the passive structures are also taken into account using the STEP hardware design shown in Fig. 1.

5 Prediction of STEP plasma initiation

The operational scenario shown in Fig. 2 is used as direct input to the DYON simulations. Figures 3 and 4 show, respectively, the time evolution of the ψ map illustrating Townsend breakdown and the corresponding temporal evolution of key plasma parameters. The DYON results indicate that inductive plasma initiation in STEP can be successfully achieved under the prescribed conditions. The loop voltage, V_{loop} , reaches a peak value of approximately 15 V at $t \approx 100$ ms; however, Townsend breakdown is initiated significantly earlier, indicating that the V_{loop} required for breakdown is much lower than the induced peak value. The applied loop voltage is also sufficiently high to overcome the radiation barrier associated with deuterium and oxygen impurities, enabling oxygen burn-through (i.e., ionisation up to O^{5+}) at approximately 150 ms. Following successful breakdown and burn-through, the plasma current, I_p , increases steadily, and the magnetic flux surfaces become fully closed by $t \approx 200$ ms.

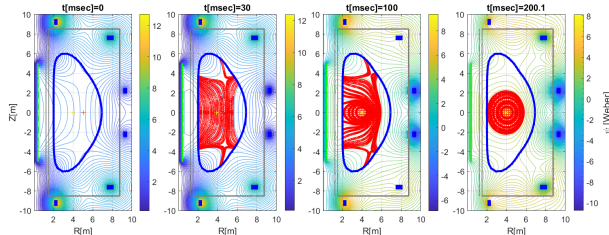


Figure 3: Time evolution of the ψ map and Townsend breakdown in the DYON prediction for STEP. Red lines indicate field lines containing plasma.

consumption. Because the CS current is pre-programmed, a delay in completing plasma burn-through leads to additional CS flux consumption.

In the current implementation of DYON, the radial position of the plasma current centroid is fixed at $R = 4$ m in the reference case. Sensitivity studies performed at $R = 3.5$ m and $R = 4.5$ m show only marginal variations in burn-through duration, indicating that the assumed radial position has a limited influence on the overall initiation dynamics.

The impact of an additional inboard conductor was examined through a scan of the inboard passive conductivity. When the conductivity is doubled, plasma initiation remains feasible; however, the burn-through phase is noticeably prolonged. A further increase in conductivity results in unsuccessful burn-through, suggesting that the doubled-conductivity case lies close to the operational threshold.

The DYON results are not yet final predictions, because the STEP design has not yet been finalised. For example, an additional inboard conducting structure is planned, as discussed above. In the DYON prediction presented here, the volume within the first wall was used as the vacuum volume, representing the minimum value. Including the space outside the first wall would increase the vacuum volume, making plasma burn-through more challenging. The initial oxygen content was assumed to be 1% in the pre-fill gas; however, during first-plasma operation, it could be higher because of wall outgassing. These uncertainties were examined with DYON; Fig. 5 shows the impact of each uncertain parameter on the burn-through delay and central solenoid (CS) flux consumption.

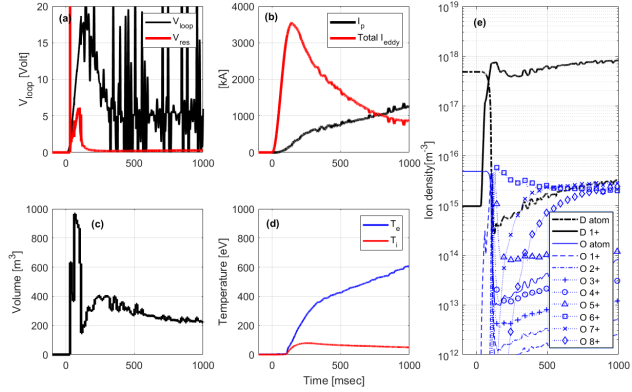


Figure 4: Time evolution of key parameters: (a) total induced V_{loop} (black) and resistive V_{loop} (red), (b) I_p (black) and total eddy current (red), (c) densities of D and O in each charge state, (d) plasma volume, and (e) T_e (blue) and T_i (red).

tional limits—such as maximum current ramp rates, maximum coil voltages, and permissible dV/dt —should be included in future, more comprehensive assessments.

6 Summary and future works

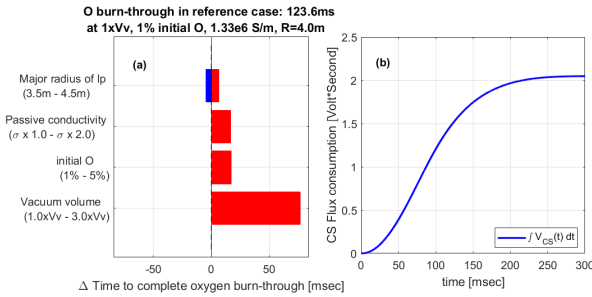


Figure 5: (a) Δ for oxygen burn-through (i.e. ionisation of O^{5+}) for different I_p positions, passive conductivity, initial oxygen content, and vacuum volume. (b) CS flux consumption.

The presence of initial oxygen impurities delays the completion of the burn-through phase, although its overall impact remains relatively modest. This behaviour is likely attributable to the assumptions of low pre-fill gas pressure (1 mPa) and a minimal vacuum volume corresponding to the region enclosed by the first wall. In contrast, the burn-through duration increases significantly with larger vacuum volumes. The total vacuum volume, estimated from the cylindrical vessel geometry, is 4136m^3 . However, since in-vessel components such as blanket structures will occupy substantial space between the first wall and the vacuum vessel, the effective vacuum volume is expected to lie in the range 1145m^3 to 4136m^3 .

Overall, DYON predicts that robust inductive plasma initiation is achievable under the Yfactory operational scenario considered here. It should be noted, however, that the current Yfactory analysis does not fully incorporate engineering constraints. Specifically, only the maximum coil currents have been imposed, while additional limits—such as maximum current ramp rates, maximum coil voltages, and permissible dV/dt —should be included in future, more comprehensive assessments.

In this contribution, we have presented a plasma initiation feasibility assessment for an example of a variant of the STEP design. The operational scenario was calculated with Yfactory, and successful plasma initiation was predicted with DYON. Based on this reference simulation, various parameters—such as effective vacuum volume, initial impurity levels, passive structure conductance, and plasma current position—were scanned and the uncertainties in CS flux consumption were quantified. Further iterations of the Yfactory-DYON workflow will account for the evolving STEP hardware design and engineering limits, and the impact of ECH assistance will also be included in future modelling.

References

- [1] F. Jaulmes et al. *Nuclear Fusion* Accepted (2026).
- [2] Hyun-Tae Kim et al. *Nuclear Fusion* 62 (2022), 126012.
- [3] Hyun-Tae Kim et al. *Nuclear Fusion* 66 (2026), 036043.