PLASMA INITIATION ASSESSMENT IN THE SPHERICAL TOKAMAK FOR ENERGY PRODUCTION

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1. INTRODUCTION

- **STEP project:** Designing and constructing the UK's first prototype fusion power plant with **1.5GW target** for fusion power by 2040, delivering net electricity and tritium self-sufficiency
- **Large vacuum volume** → plasma burn-through challenging
- **Limited centre stack space** → only small Central Solenoid (CS) possible →constrained V_{loop} and magnetic flux in $V{*}s$
- **Essential to evaluate plasma initiation feasibility and uncertainties with validated workflow → Yfactory-DYON**

2. YFACTORY–DYON WORKFLOW

2.1 YFACTORY CODE: SCENARIO CALCULATION [1]

- **Core Function:** The Yfactory code is a specialized computational tool designed to invert a general linear dynamical model using a state-space representation.

$$\frac{d\mathbf{x}}{dt} = \mathbf{Ax} + \mathbf{Bu} \qquad \mathbf{y} = \mathbf{Cx} + \mathbf{Du}$$

- **Primary Objective:** The algorithm's main goal is to calculate the optimal state trajectory ***x(t)*** and control inputs **u(t)** needed to meet a predefined, time-evolving target output vector ***y(t)***.
- **Governing Dynamics:** System dynamics are guided by standard linear state-space equations where ***x(t)*** represents currents in magnetic coils and passive structures, and ***u(t)*** denotes the applied coil voltages.
- **System Matrix Coupling:** ***A = - R/L*** and ***B= 1/L***, while **C** and **D** couple currents ***x(t)*** and voltages ***u(t)*** to diagnostic outputs $V_{loop}(t)$, $B_z(t)$ and decay index n (= $-R/B_z \, dB_z/dR$). ***x(t)*** and ***u(t)*** *are column vectors, and* ***A,B,C,*** *and* ***D*** *are matrices.*
- **Practical Application:** In tokamaks, Yfactory optimizes magnetic configurations for plasma initiation by calculating feedforward current and voltage waveforms in poloidal field coils to track a target poloidal magnetic flux.
- **Engineering Constraints:** The algorithm accounts for real-world hardware limits – such as maximum coil currents, voltages, and ramp rates – by using regularisation techniques as penalty terms when limits are approached.

2.2 DYON CODE: PLASMA INITIATION PREDICTION [2,3]

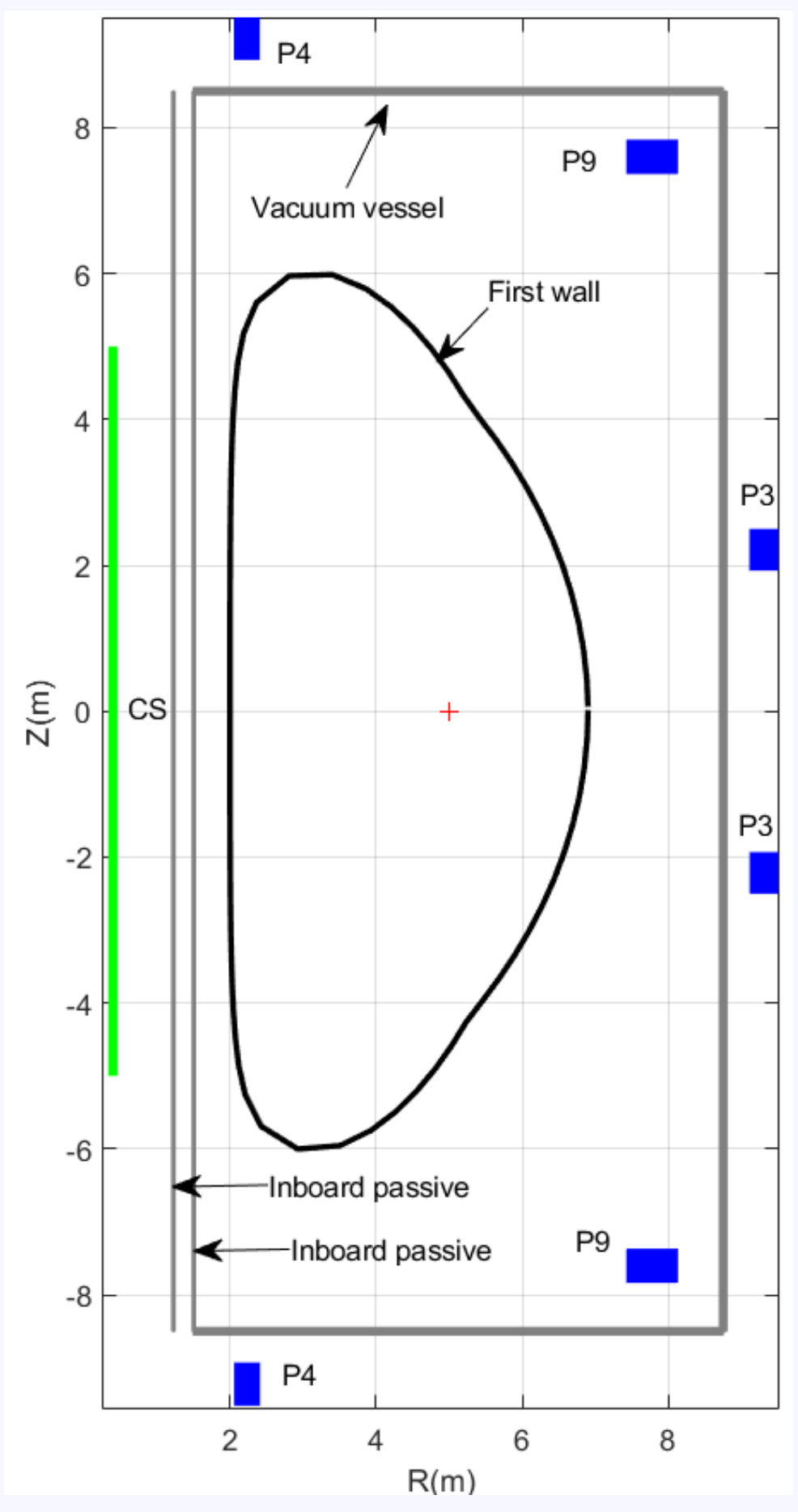
- **Core Function**: DYON is a comprehensive predictive model that simulates Townsend breakdown and plasma burn-through by integrating a full circuit equation with global energy and particle balance equations.
- **Operational Accessibility**: The model is highly accessible because it simulates complex plasma behavior using only control-room-level inputs, specifically the pre-fill gas pressure and the time-evolving coil currents calculated by Yfactory.
- **Breakdown Assessment**: DYON computes a two-dimensional, time-varying poloidal flux map to rigorously evaluate the Townsend breakdown criterion along individual open magnetic field lines.

$$\frac{1}{2}L_{\text{open}}\alpha > 1$$

α : # of ionisation per 1 metre of a seed electron travel

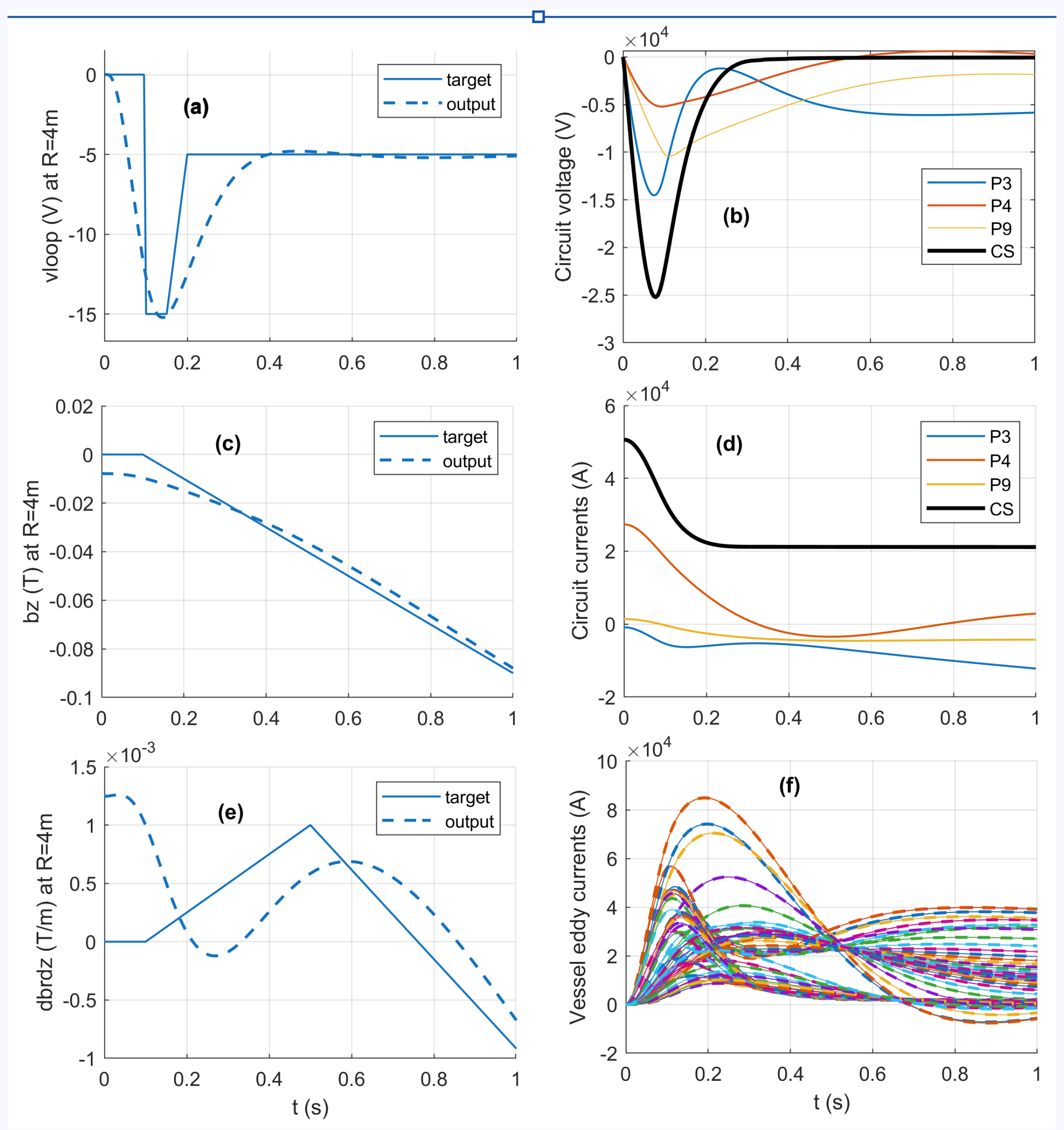
- **Dynamic Volume Tracking**: The initial plasma volume at breakdown onset – which strongly impacts the subsequent burn-through phase – is dynamically calculated by integrating the volumes of closed field lines and qualifying open field lines.
- **Burn-Through Simulation**: After breakdown, the code simulates the plasma burn-through phase by solving a coupled system of differential equations covering circuit physics, electron/ion energy balances, and particle balances for fuel and impurities.

3. PRELIMINARY STEP DESIGN AND UNCERTAINTIES



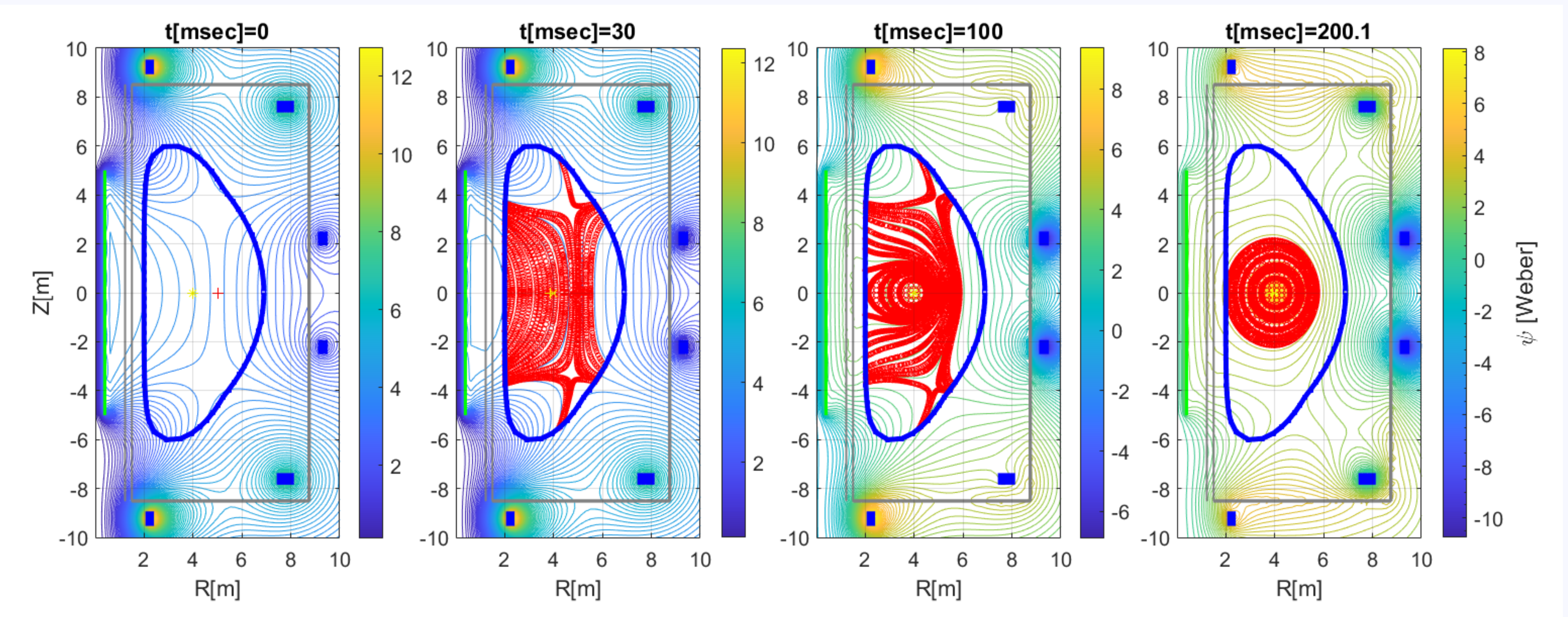
- **Component Scope**: Figure (left) illustrates an example of a variant of the STEP design (Aspect ratio = 2.0), focusing on the magnetic coils and passive structures; additional divertor coils are excluded from this study as they do not significantly impact plasma initiation. Note, the STEP parameters used in the modelling of this poster are only indicative and can evolve further.
- **Material and Nominal Resistivity**: The passive structures are constructed from stainless steel with a nominal resistivity of *7.5e-7 Ohm Metre*.
- **Inboard Resistance Uncertainty**: The total resistance of the inboard passive structure could be lower than nominal because additional internal components – such as plasma-facing support structures, the cavity shield, and the high-pressure shield – are under consideration.
- **Vacuum Volume Range**: The vacuum volume within the first wall is $1145 m^3$, while the volume within the vacuum vessel cylinder is $4136 m^3$.
- **Effective Volume Expectation**: The actual effective vacuum volume is expected to fall between these two values because various hardware components will be installed in the space between the vacuum vessel and the first wall.

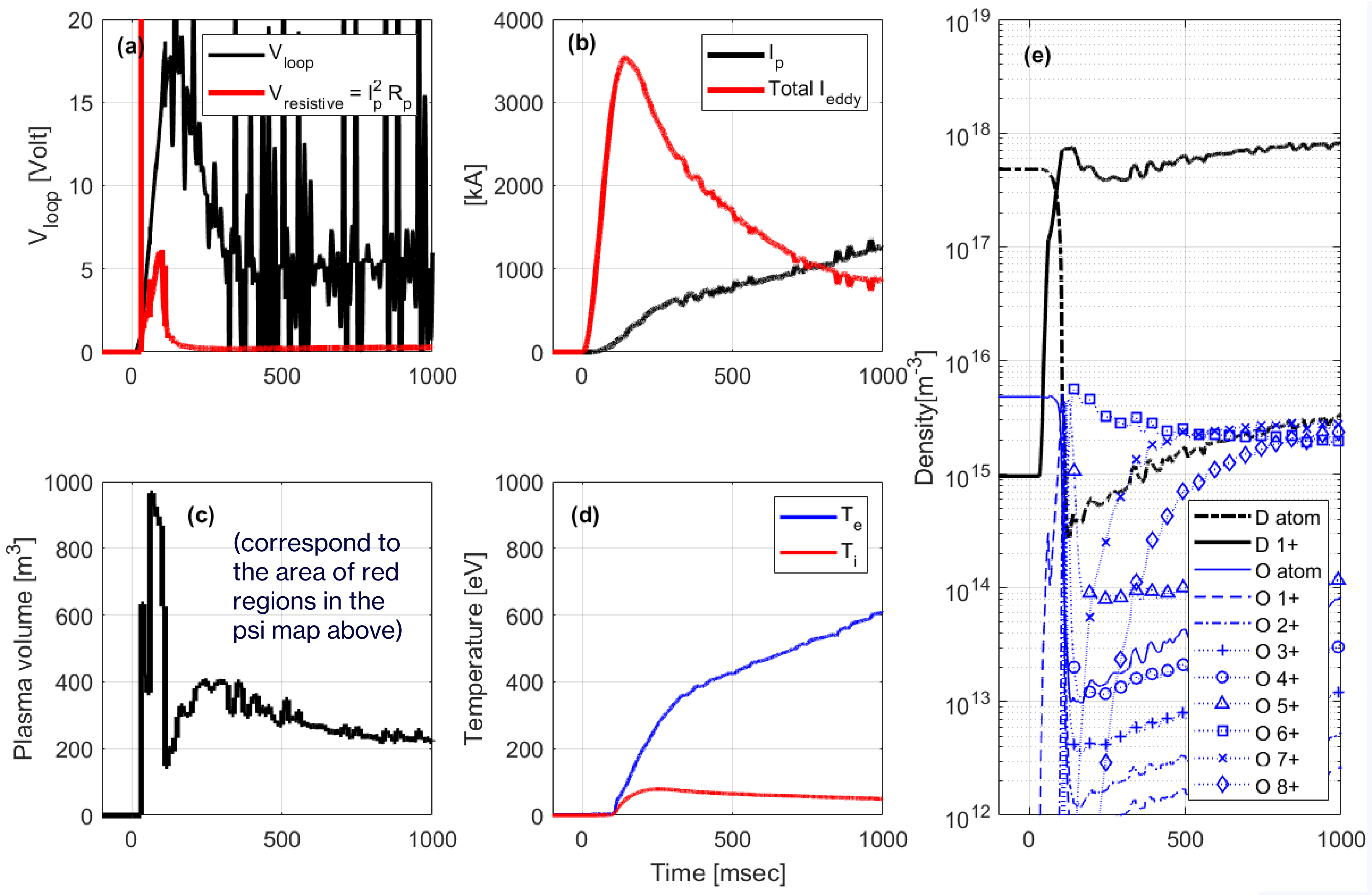
4. OPERATION SCENARIO CALCULATION



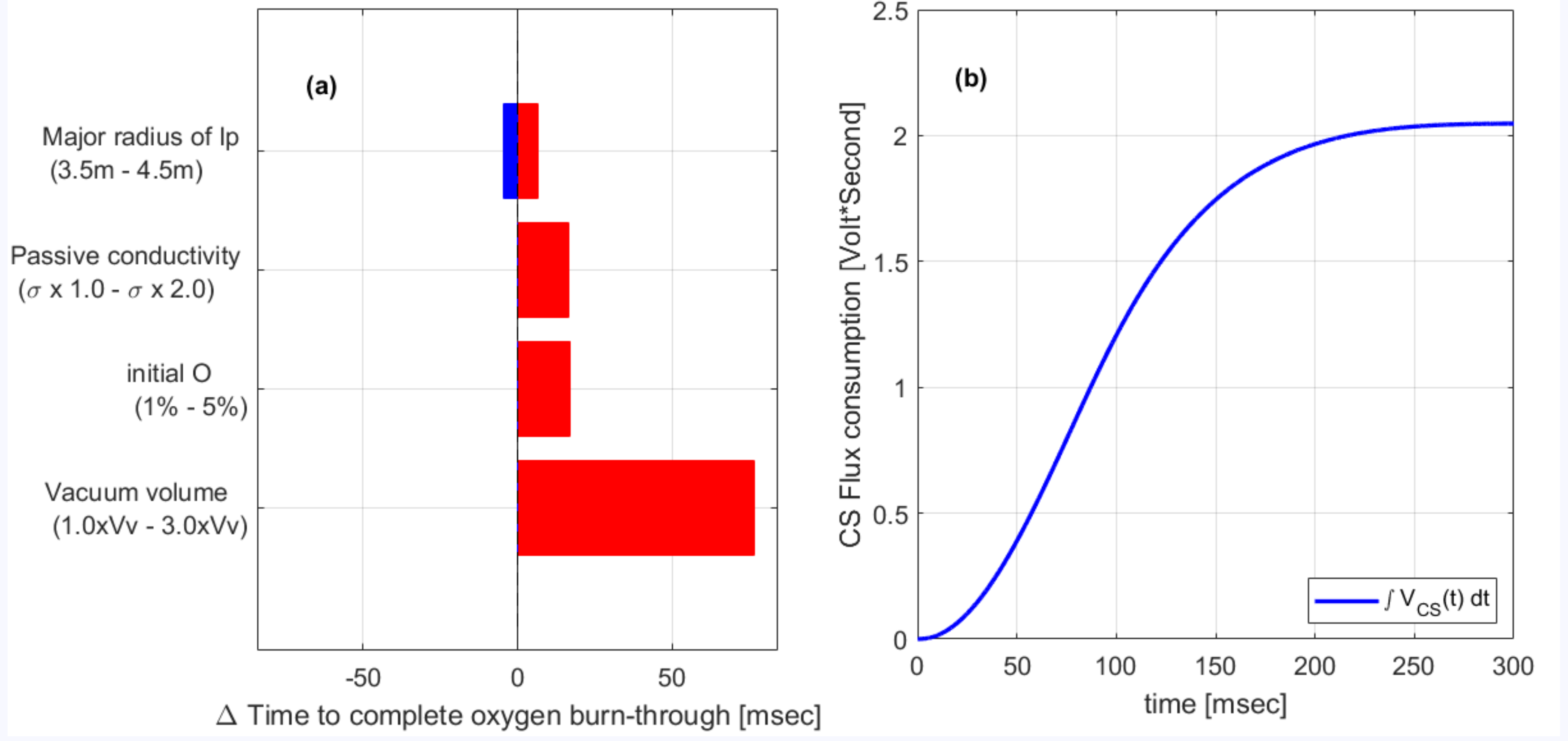
- **Initial Null Configuration:** For successful inductive plasma initiation, a wide magnetic null region – indicated by small B_z and B_r values – must be formed at *t=0 s*.
- **Breakdown and Burn-through requirements:** Simultaneously a sufficiently high V_{loop} must be induced to achieve successful Townsend breakdown and plasma burn-through.
- **Radial Force Balance:** As I_p ramps up following the burn-through phase, B_z must increase to maintain radial force balance and keep the plasma centered in the vacuum space.
- **Vertical Stability:** To ensure vertical stability, the magnetic field configuration must also become concave, satisfying $dB_r/dz < 0$.
- **Target Parameter Input:** The time-dependent targets for operational parameters, specifically V_{loop}, B_r, and dB_r/dz, are initially defined manually.
- **Waveform and eddy current calculation:** Using these manual targets and the STEP hardware design, Yfactory calculates the precise coil current and voltage time traces while factoring in eddy currents in the passive structures.

5. PREDICTION OF STEP PLASMA INITIATION





O burn-through in reference case: 123.6ms
at V_v = $1145 m^3$, 1% initial O, σ=1.33e6 S/m, R=4.0m



- **Simulation Input:** The operational scenario calculated by Yfactory is used as the direct input for the predictive DYON simulations.
- **Feasibility success:** Initial DYON results show that inductive plasma initiation in the preliminary STEP design can be successfully achieved under the prescribed target conditions.
- **Early Townsend Breakdown:** Although the induced V_{loop} reaches a peak value of *15V* at *t=100ms*, Townsend breakdown is initiated significantly earlier.
- **Impurity Burn-through:** The applied V_{loop} is high enough to overcome the radiation barriers of *D* and *O*, successfully completing *O* burn-through (ionisation of O^{5+}) at around *150ms.*
- **Flux Surface Closure:** Following successful breakdown and burn-through, I_p increases steadily, and magnetic flux surfaces become fully closed by *t=200ms.*
- **Caveats:** These DYON predictions are not yet final because STEP hardware design is still being refined, such as the planned addition of an inboard conducting structure.
- **Impact of I_p position:** Sensitivity studies shifting the fixed Ip position from *R=4m* to *R=3.5m* and *R=4.5m* show only marginal variations, indicating its limited influence on initiation dynamics.
- **Inboard Passive Conductivity Threshold:** Doubling the inboard passive conductivity prolongs the burn-through phase while remaining feasible, but any further increase results in unsuccessful burn-through.
- **Modest Oxygen Impurity Impact:** Increasing the initial *O* content from *1%* to *5%* delays the completion of burn-through, though its impact remains modest due to the low prefill gas pressure (*1mPa*) and minimal first-wall vacuum volume used.
- **Vacuum Volume Sensitivity & Flux Consumption:** Larger vacuum volumes significantly increase burn-through duration; because the CS current is pre-programmed, any delay in burn-through directly leads to additional CS flux consumption.

6. SUMMARY AND FUTURE WORKS

- **Feasibility and Verification**: We presented a plasma initiation feasibility assessment for the preliminary STEP design, using Yfactory to calculate the operational scenario and DYON to predict successful plasma initiation.
- **Uncertainty Quantification**: Based on the reference simulation, key parameters – including effective vacuum volume, initial impurity levels, passive structure conductance, and plasma current position – were scanned to successfully quantify uncertainties in CS flux consumption.
- **Future Work and Expansion**: Future iterations of the Yfactory-DYON workflow will be updated to account for the evolving STEP hardware design, stricter engineering limits, and the inclusion of electron cyclotron heating (ECH) assistance modeling.

7. REFERENCES

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

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