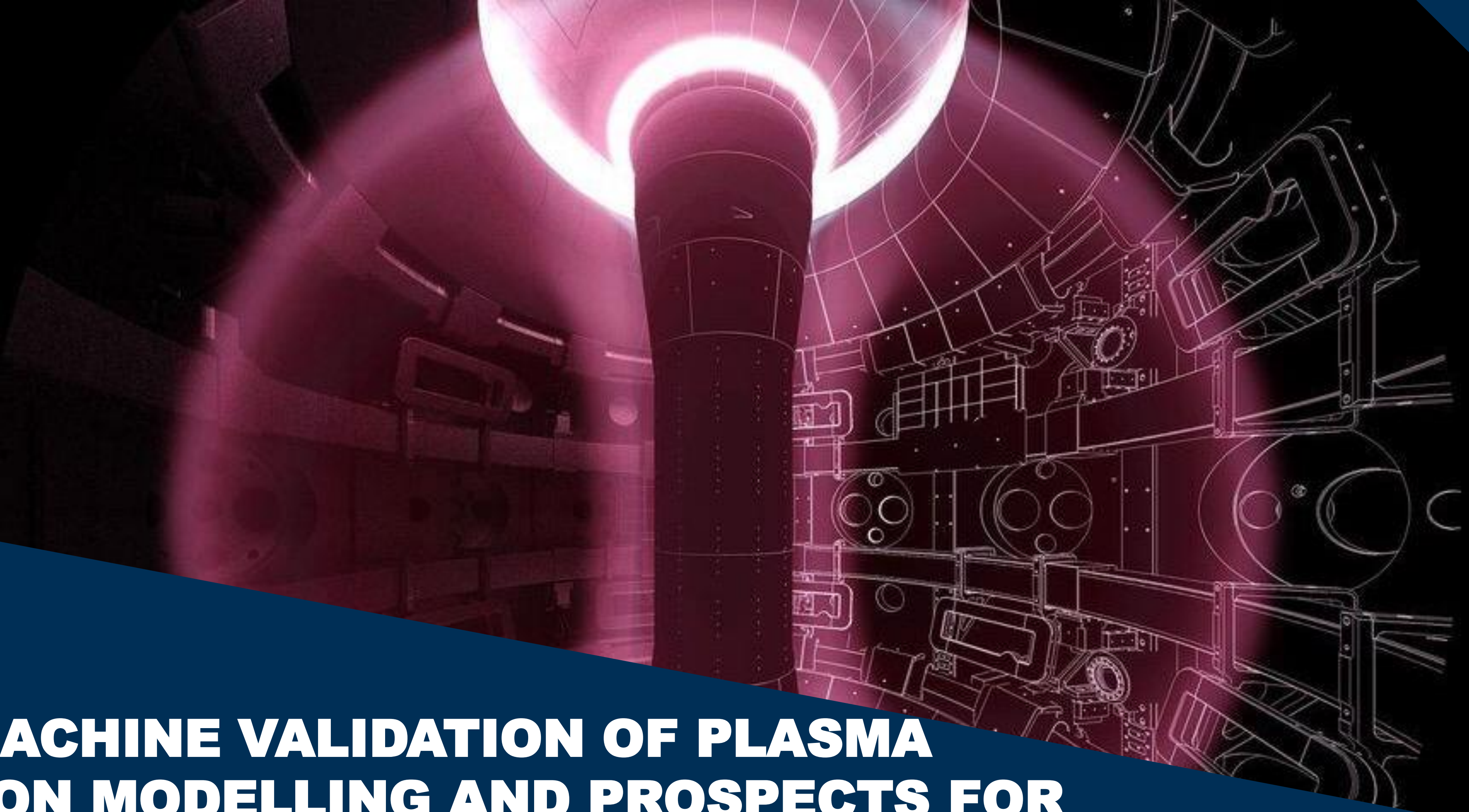

MULTI-MACHINE VALIDATION OF PLASMA INITIATION MODELLING AND PROSPECTS FOR FUTURE DEVICES

30th IAEA Fusion Energy Conference | 13–18 October 2025, Chengdu, China

Hyun-Tae Kim (MAST-U), Runze Chen (EAST), James Yang (DIII-D), Youngsun Lee (KSTAR), Jeongwon Lee (KSTAR), and Hongsik Yoon (VEST), and ITPA-IOS contributors

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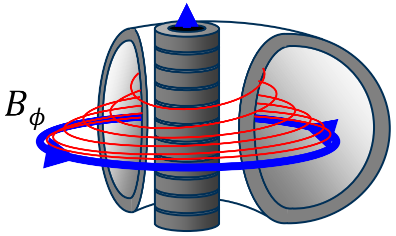
contents

Inductive plasma initiation in tokamaks: Townsend breakdown and plasma burn-through

Gas → (Townsend breakdown phase) → A few % ionisation → (Plasma burn-through phase) → 100% ionisation



$$-\frac{d\Phi_{CS}}{dt} = V_{loop} = 2\pi R E_\phi$$

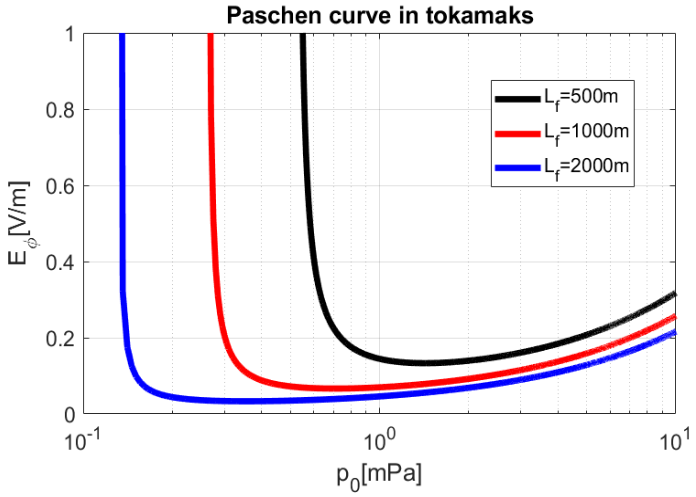
Townsend breakdown in tokamaks: $\alpha L_f > 1$

- α = # of ionisations while an electron traveling in 1 meter $= p_0 A \exp(-\frac{B}{E_\phi/p_0})$

(For Hydrogen gas, A=3.83 and B=93.76)

- L_f = Effective connection length $= 0.25 \times aB_\phi/B_z$

$$E_\phi[V/m] = \frac{93.76 \times p_0[Pa]}{\ln(3.83 \times p_0[Pa] \times L_f\ [m])}$$



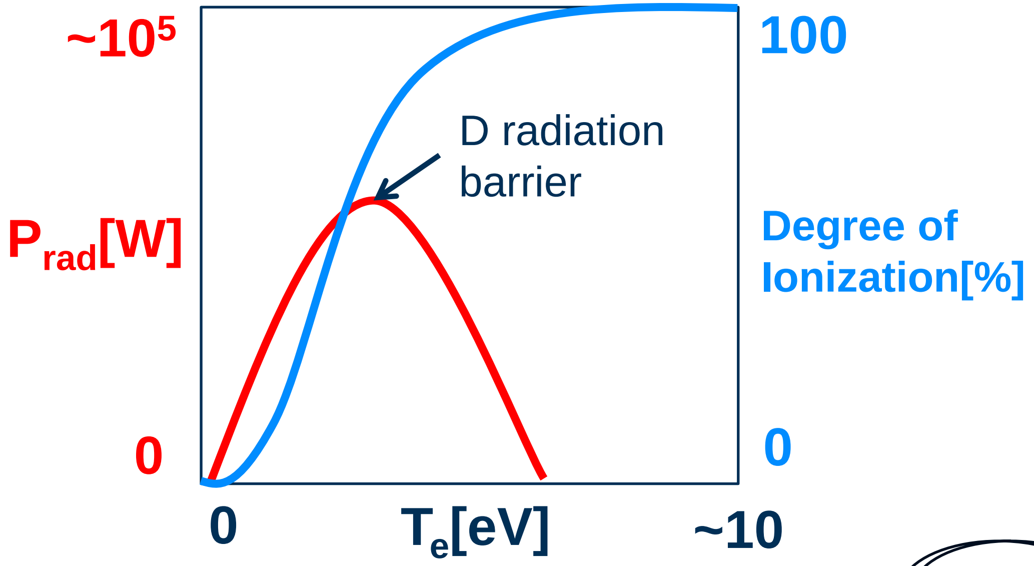
B. Lloyd PPCF 38 (1996) 1627

P. C. de Vries Nucl. Fusion 59 (2019) 096043

Electrons and neutrals exist together in the burn-through phase

- Ohmic heating VS Energy loss from radiation and charge exchange

Radiated power loss $P_{rad} = <\sigma v>_{rad} n_e n_D^{0+}$



Passing the radiation barrier of D and impurities $\Rightarrow P_{rad} \downarrow \Rightarrow T_e \uparrow$

Since $R_p \propto T_e^{-\frac{3}{2}}$, I_p increases with T_e with a constant (or reduced) V_{loop}

Tokamak operation for inductive plasma initiation

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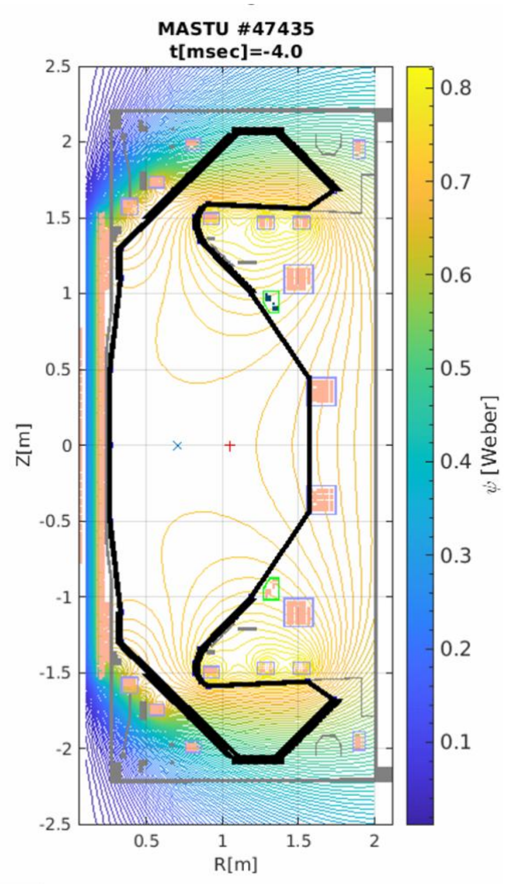
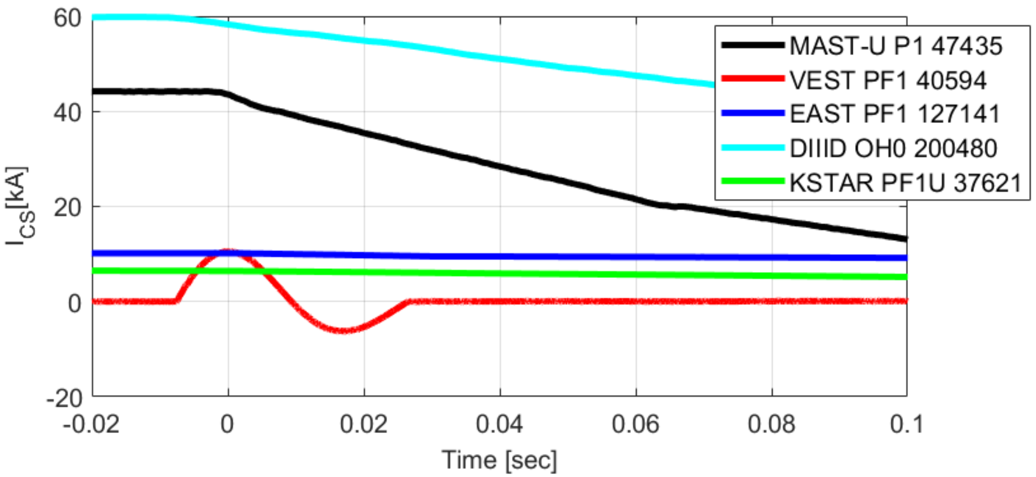
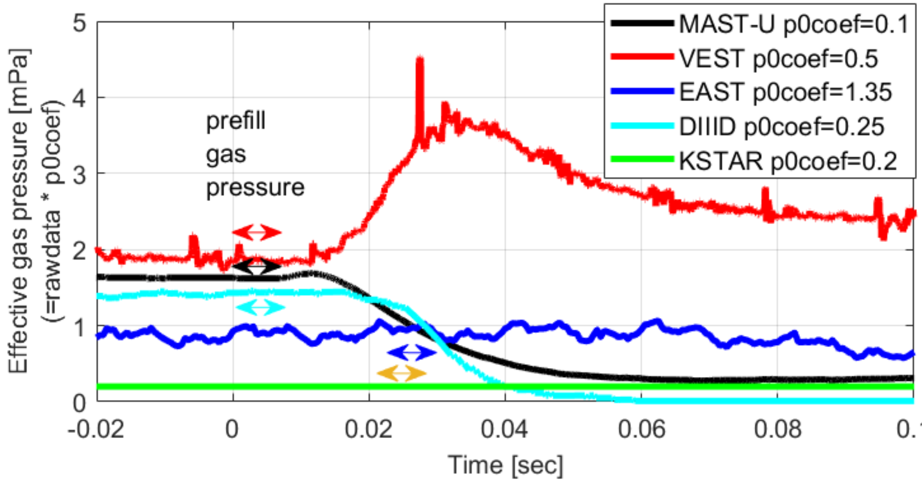
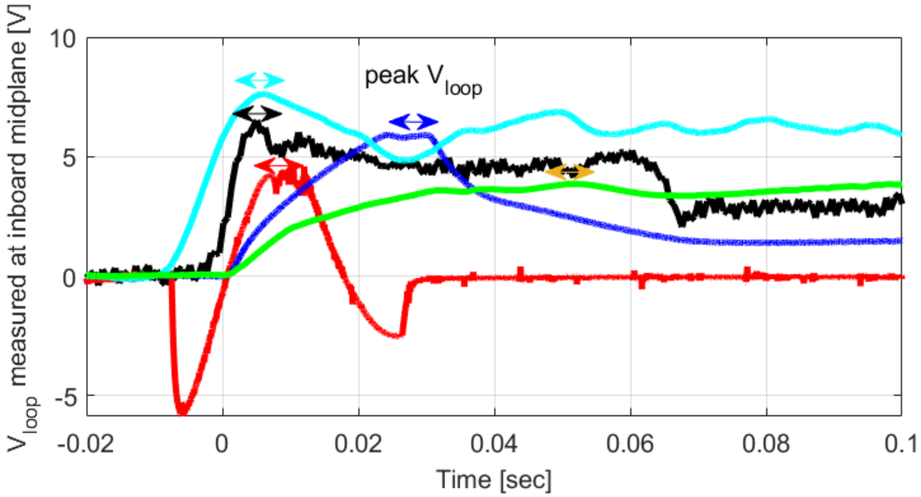
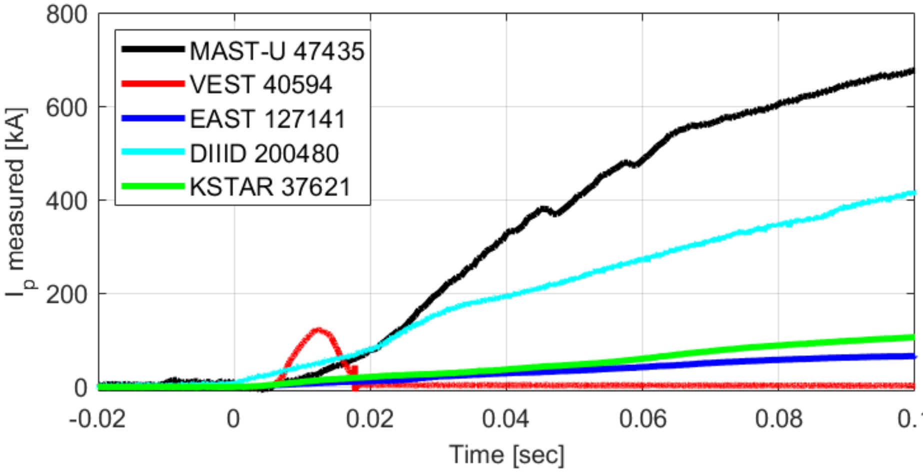


Magnetic field null configuration is required to maximise the connection length.



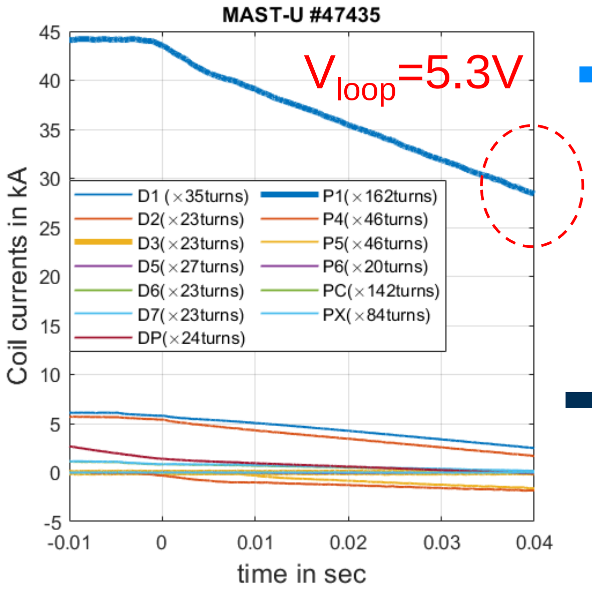




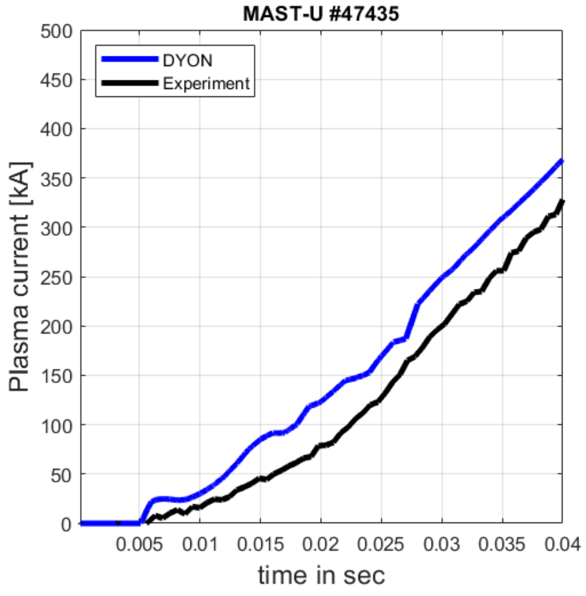


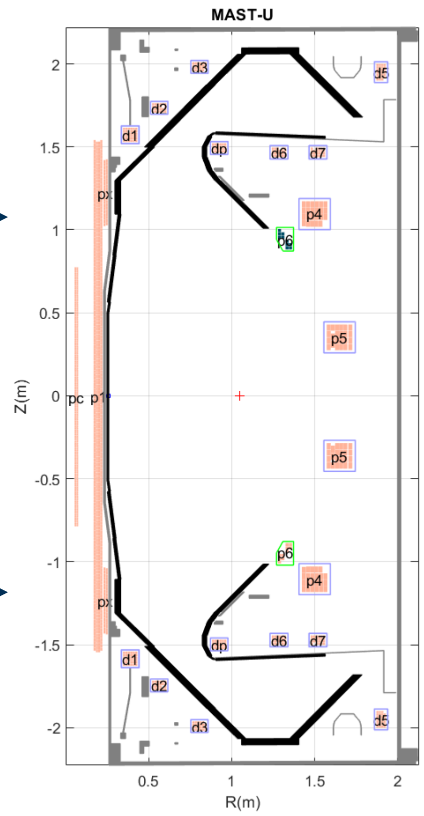
Goal of plasma initiation modelling

p_0 and



DYON





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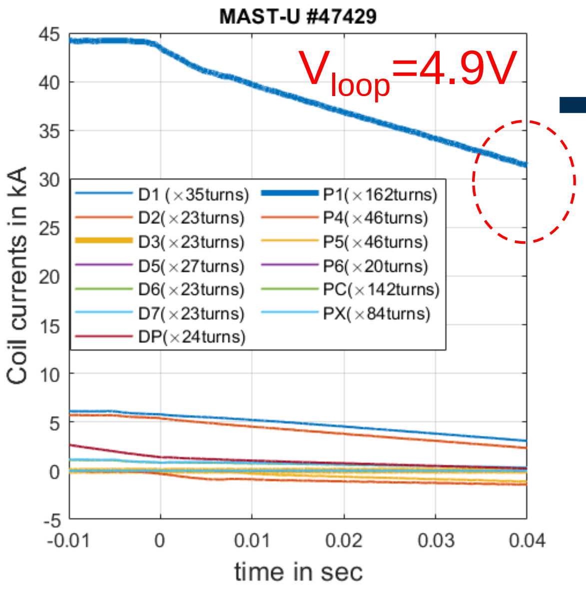

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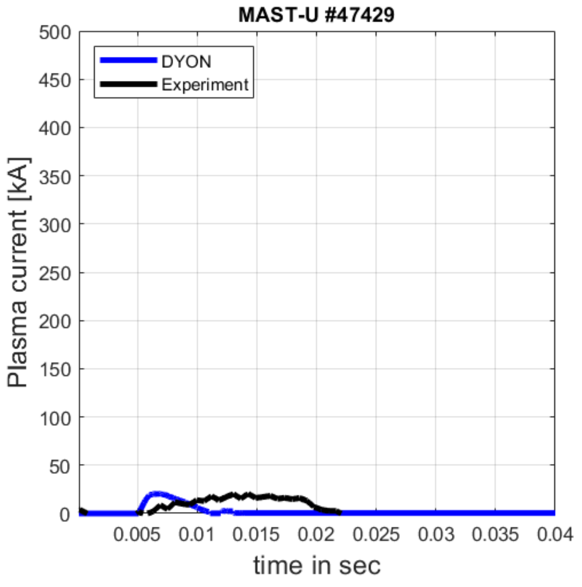

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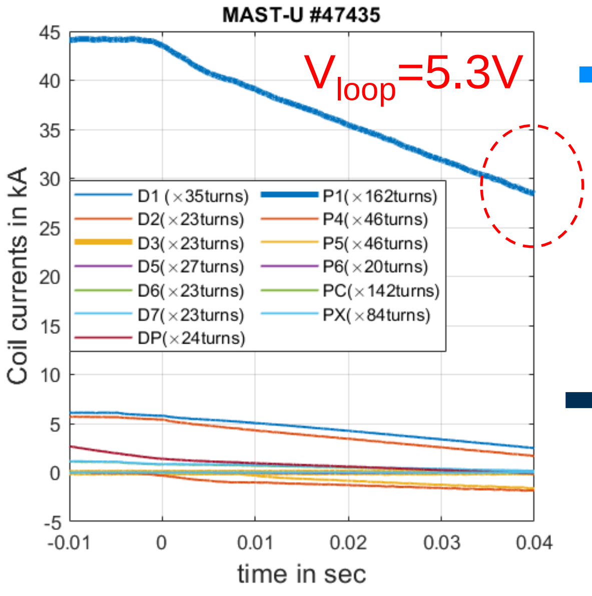

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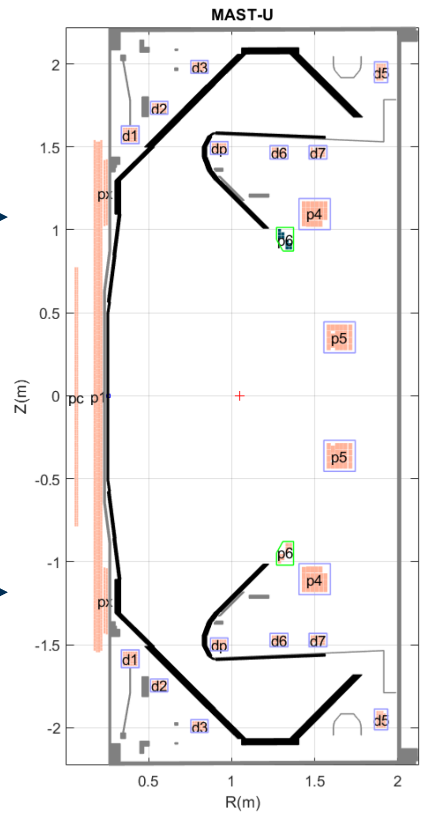

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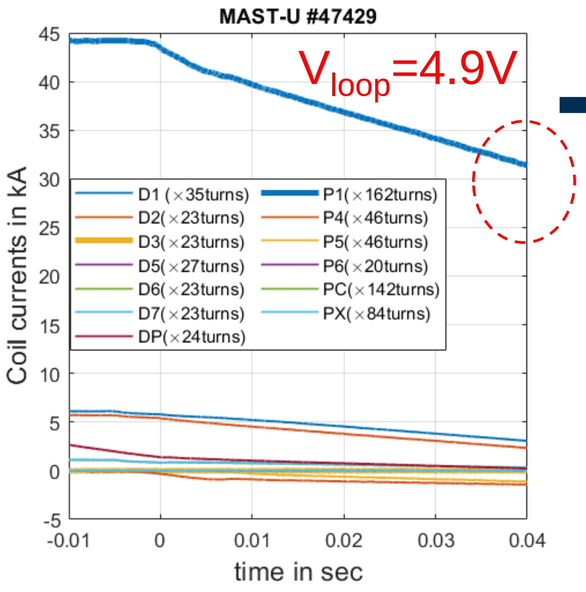

DYON

Plasma initiation phase is the most dynamic phase in the whole tokamak pulse.

Tokamak hardware determines the operational constraints:

- Coil design: I_{coil} limit
- Power supply design : dI_{coil}/dt limit
- Vessel conductivity: eddy currents
- Vacuum volume: required p_0

For a new tokamak design, the feasibility of plasma initiation with the operational constraints should be ensured with predictive modelling.

This is particularly important for large superconducting devices such as ITER and STEP, as the plasma initiation will be challenging.

contents

Devices for multimachine validation

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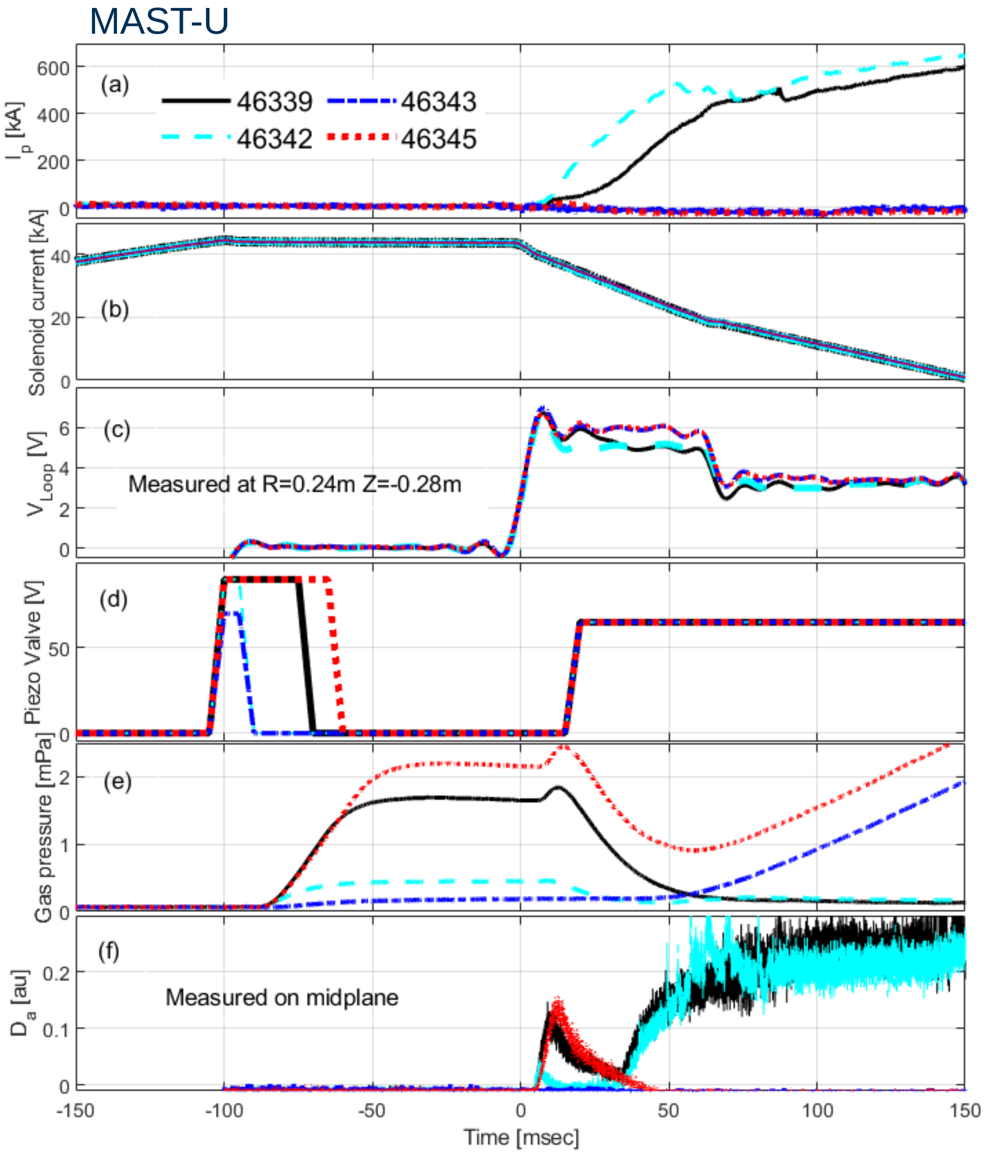
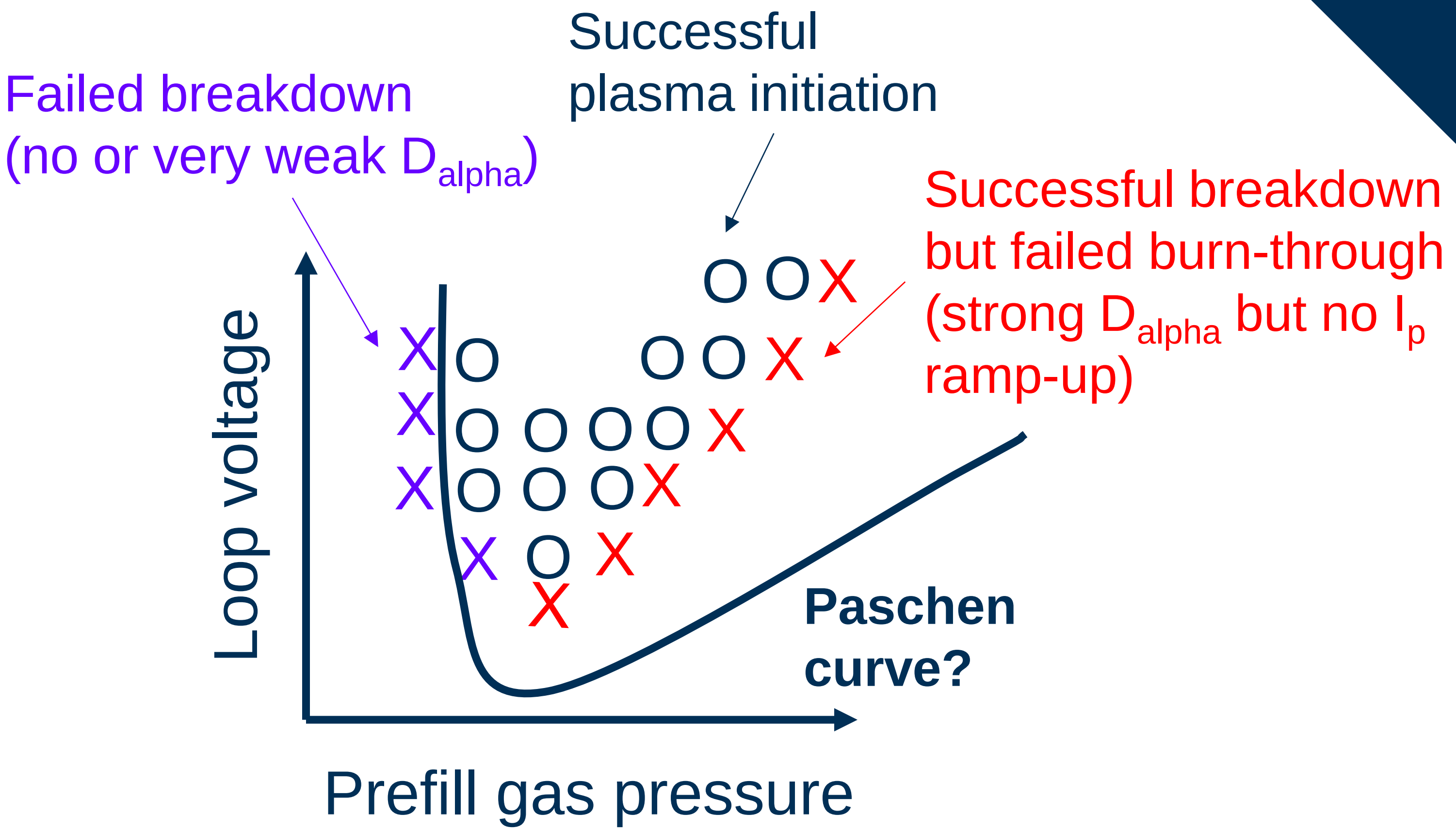
Device	Aspect ratio	Coils	First wall material	Ferromagnetic material	Vv[m³]	Vp[m³]	Bt[T]	Lf[m]
MASTU	Spherical Torus (R=0.7m, a=0.5m)	Copper	Carbon	N/A	55	6	0.6	75
EAST	Conventional Tokamak (R=1.85m, a=0.5m)	Super Conductor	Tungsten + Molybdenum	N/A	38	7.5	2.5	311
DIIID	Conventional Tokamak (R=1.67m, a=0.65m)	Copper	Carbon	N/A	35	16	1.8	292
KSTAR	Conventional Tokamak (R=1.8m, a=0.7m)	Super Conductor	Carbon	Incoloy 908 in the jacket of PF and TF coils	55	5	1.8	315
VEST	Spherical Torus (R=0.3m, a=0.2m)	Copper	Stainless steel	N/A	3.7	0.6	0.23	12

Parameter scan experiments to identify plasma initiation operation space





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Operation space in experiments

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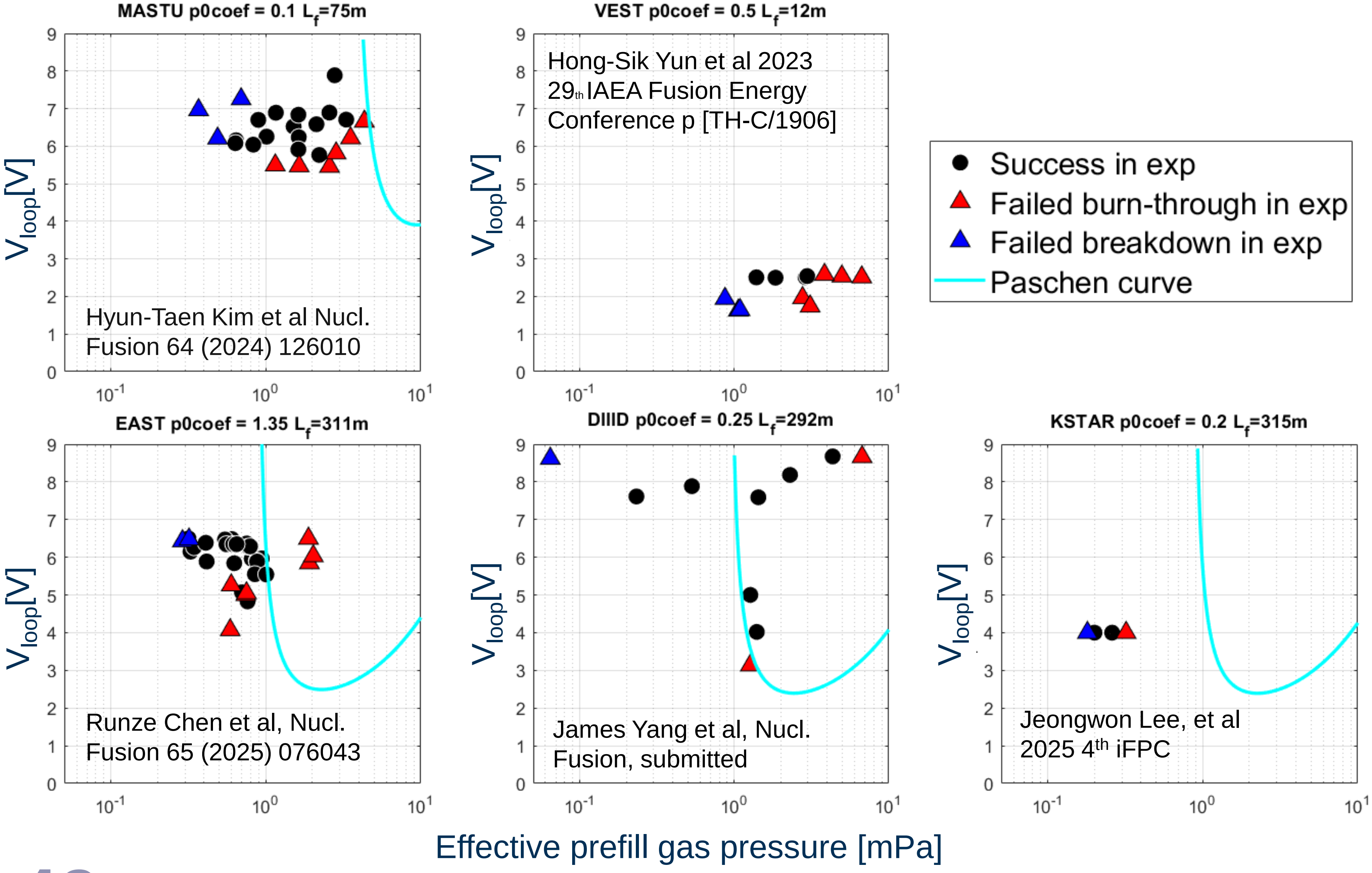


Failed burn-through at high p_0
Failed burn-through at low V_{loop}
Failed breakdown at low p_0
→The hypothesis is valid for all devices.

The conventional Townsend assessment with L_f (i.e. $\alpha L_f > 1$) over-predicts the lower limit of p_0 for plasma breakdown.

contents

Effective prefill gas pressure

Prefill gas pressure p_0 is an essential input for predictive plasma initiation modelling.

- Sufficiently high p_0 is required for Townsend breakdown.
- Sufficiently low V_v*p_0 is required for plasma burn-through.

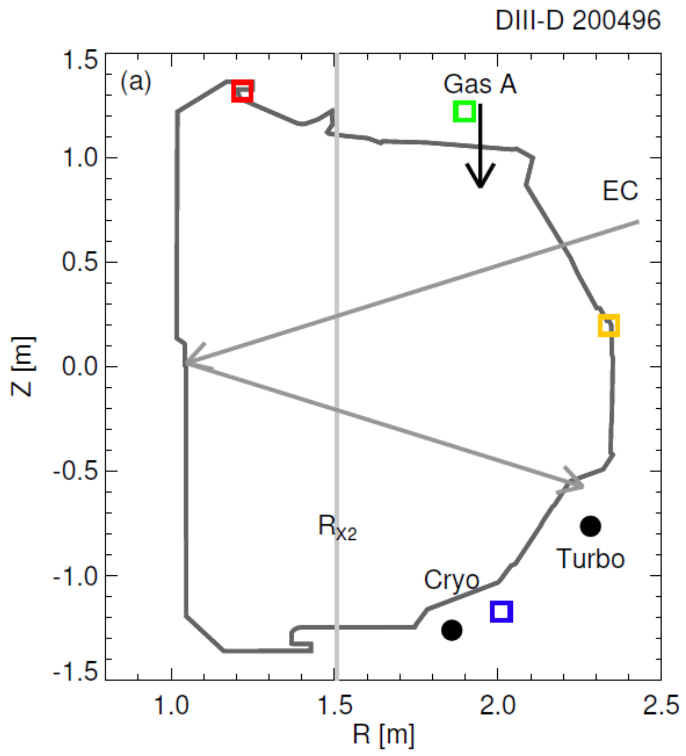
However, raw data requires calibration.

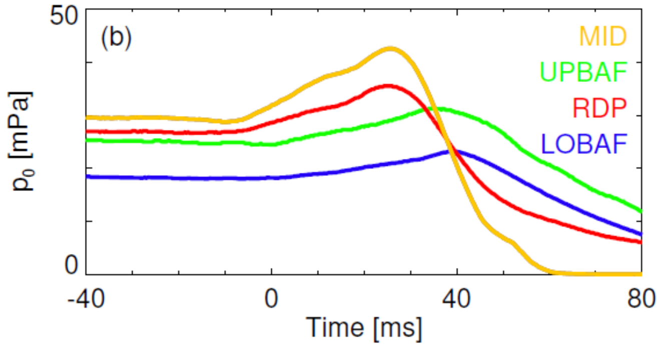
- Fast ion gauge calibration is often inaccurate.
- Measured values vary at different locations of the fast ion gauges.
- Effective prefill gas pressure = p_0 coefficient x fast ion gauge data.

The strategy to validate the operating space prediction capability in DYON:

- Determine the p_0 coefficient that reproduces a representative discharge in each device
- Use the same p_0 coefficient for all other discharges

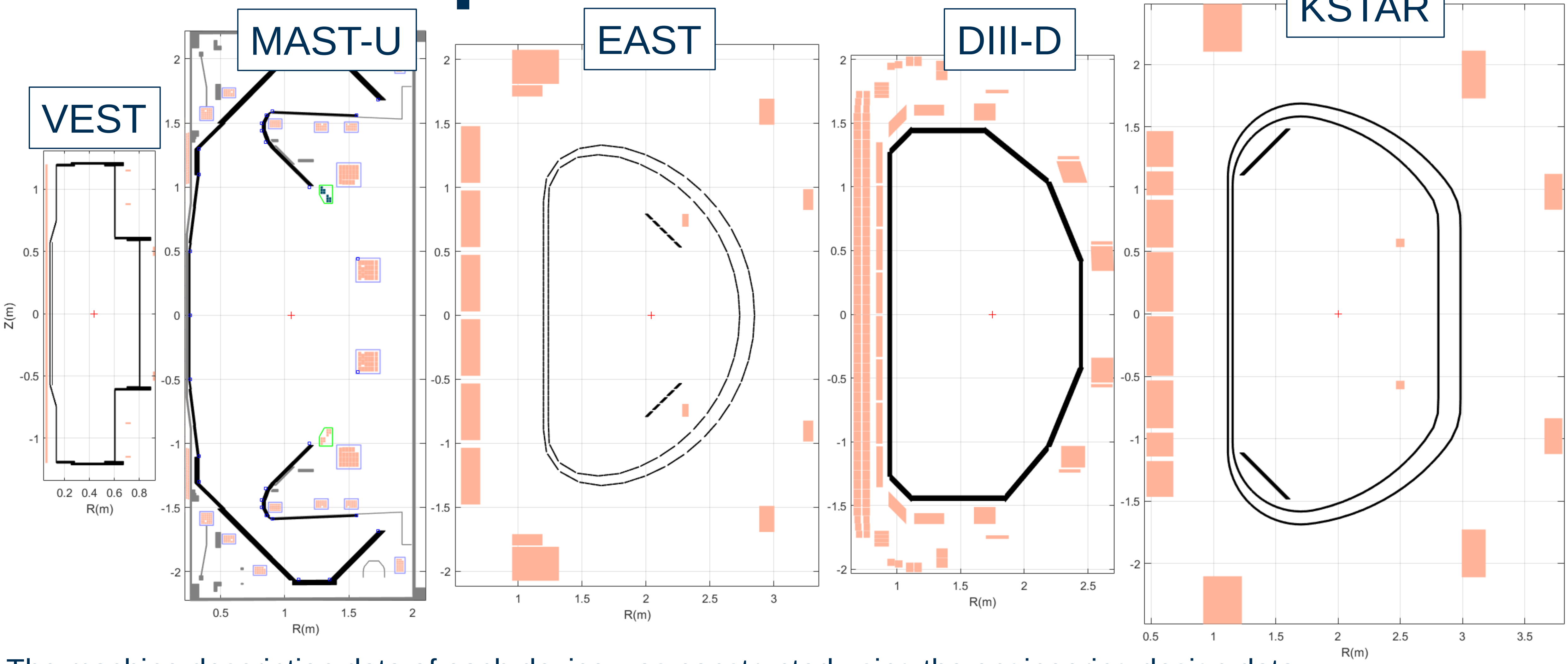
Note that p_0 is easily adjustable in experiments. When predicting plasma initiation in future devices, it is important to ensure that there is a wide enough p0 range for successful initiation.





James Yang et al, submitted to Nucl. Fusion (2025)

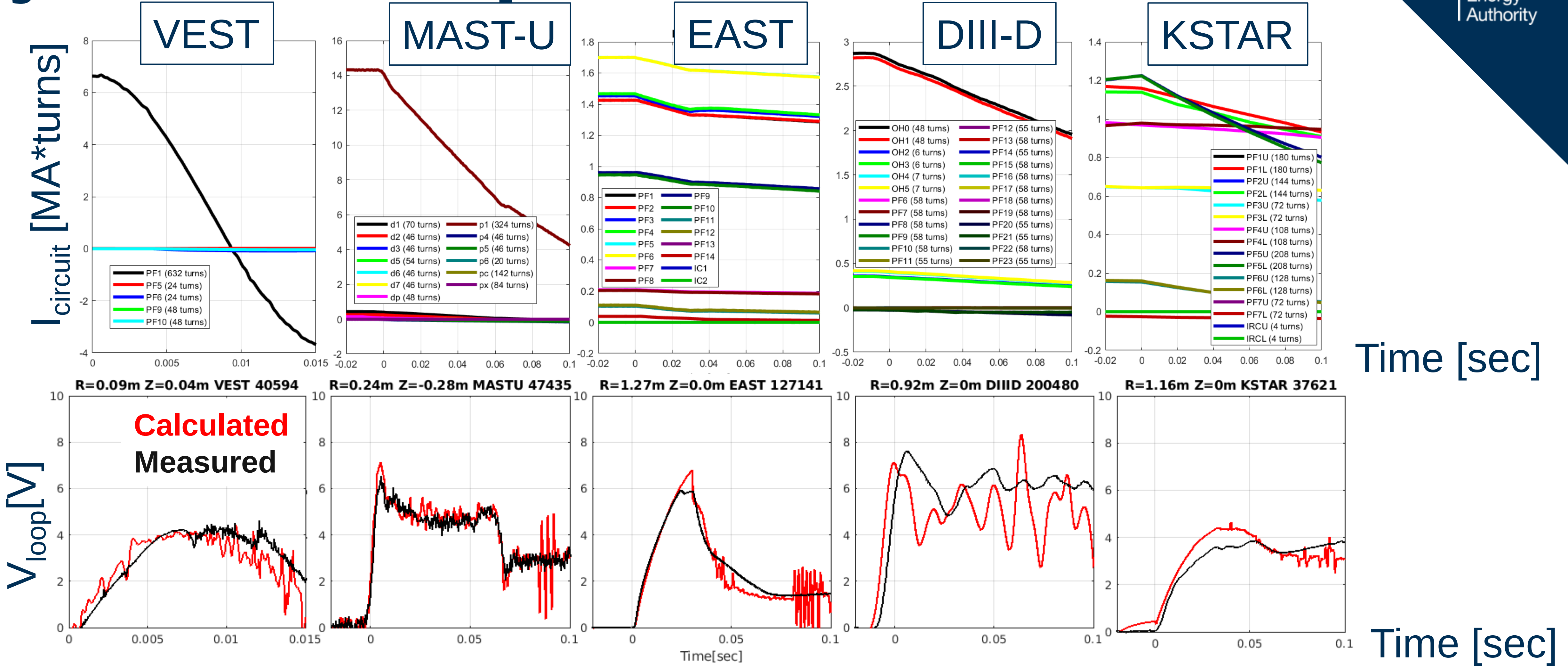
Machine description



The machine description data of each device was constructed using the engineering design data.

- Mutual inductance matrices of coils (gray), passive structures (black and cyon), and the vacuum space
- Resistivity matrices of passive structures (black and cyon)

Synthetic flux loop data calculation in DYON



- Calculated the measured V_{loop} at the inboard mid-plane using the coil current time traces.
- This good reproduction confirms the validity of the machine description data.
- Ready for full electromagnetic plasma initiation modelling → DYON

DYON: full electromagnetic plasma initiation simulator

Townsend breakdown assessment of individual open field lines, and calculates V_p:

- Open field lines with $E_{\parallel} > E_{Townsend}$
- Volume enclosed with closed field lines

Plasma burn-through and early Ip ramp-up simulated by solving the ODE system of

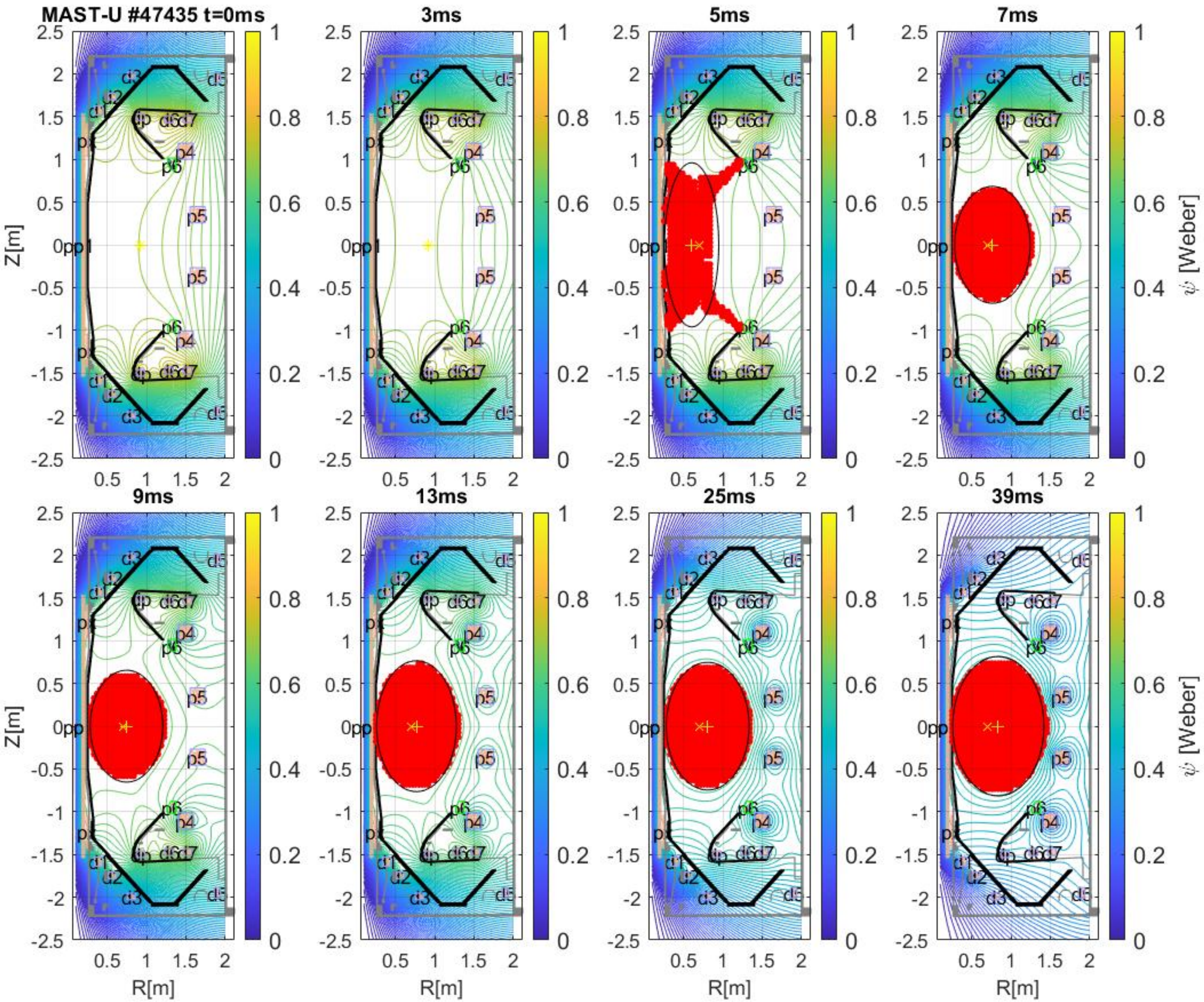
- full circuit equations of plasma, coils, and eddy currents +
- global energy and particle balances of main fuel gas, ions, and impurities.

DYON requires only :

- Machine description
- control room input data i.e. I_{coil} and p_0

DYON predicts:

- Successful plasma initiation



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DYON: full electromagnetic plasma initiation simulator

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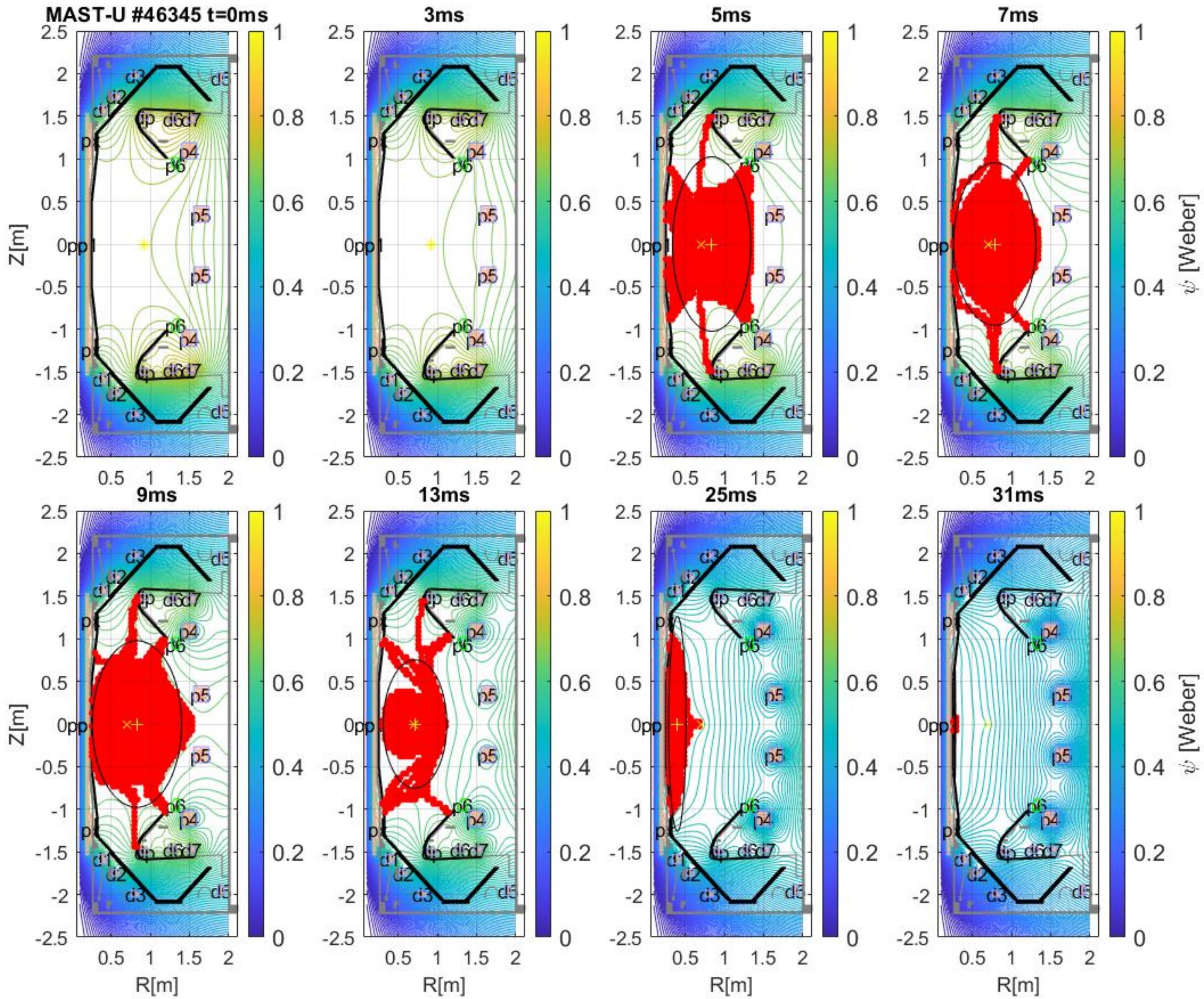
- Machine description
- control room input data i.e. I_{coil} and p_0

DYON predicts:
- Successful plasma initiation
- Failed plasma burn-through



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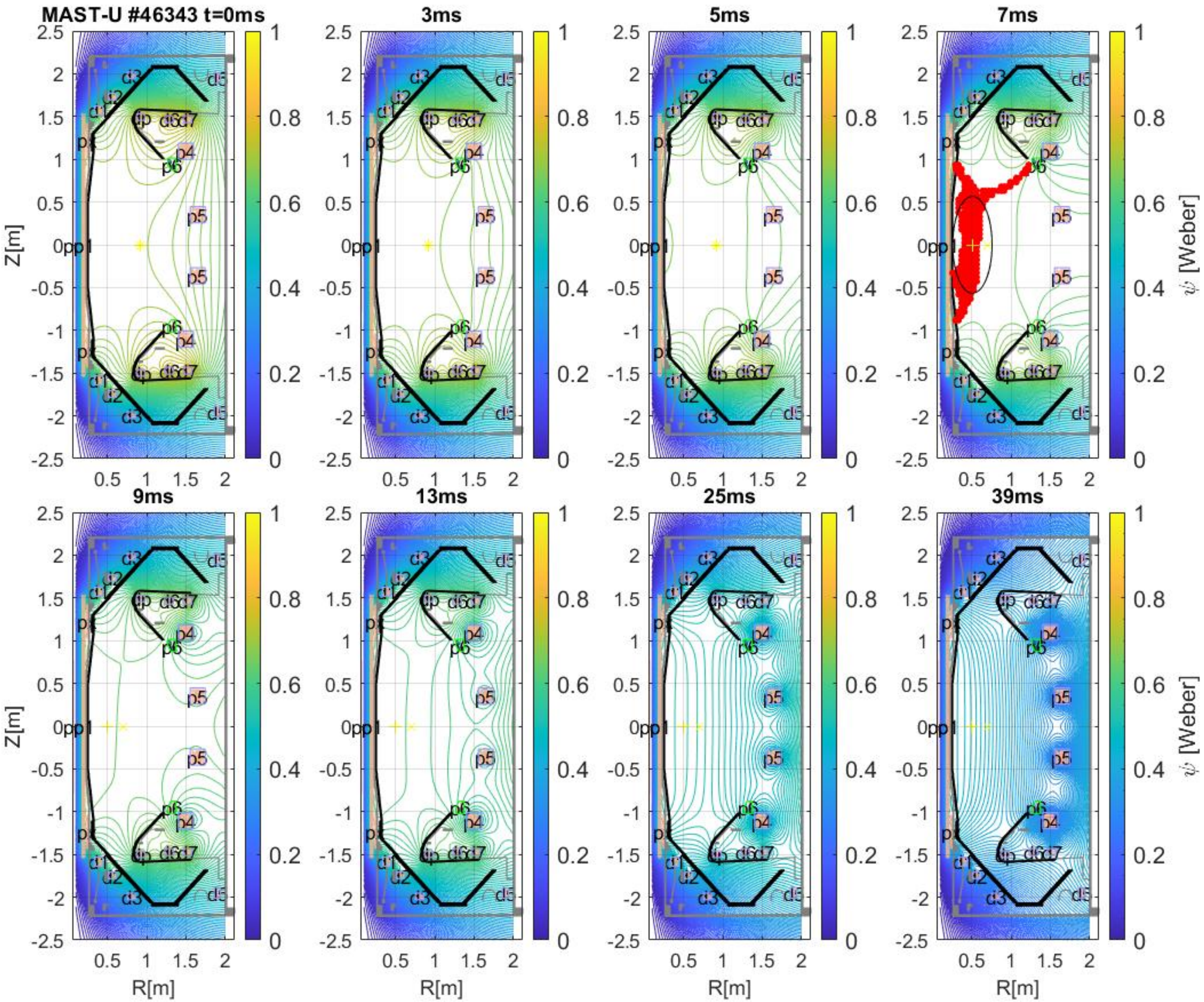
- Successful plasma initiation
- Failed plasma burn-through
- Failed Townsend breakdown



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Simulation setup

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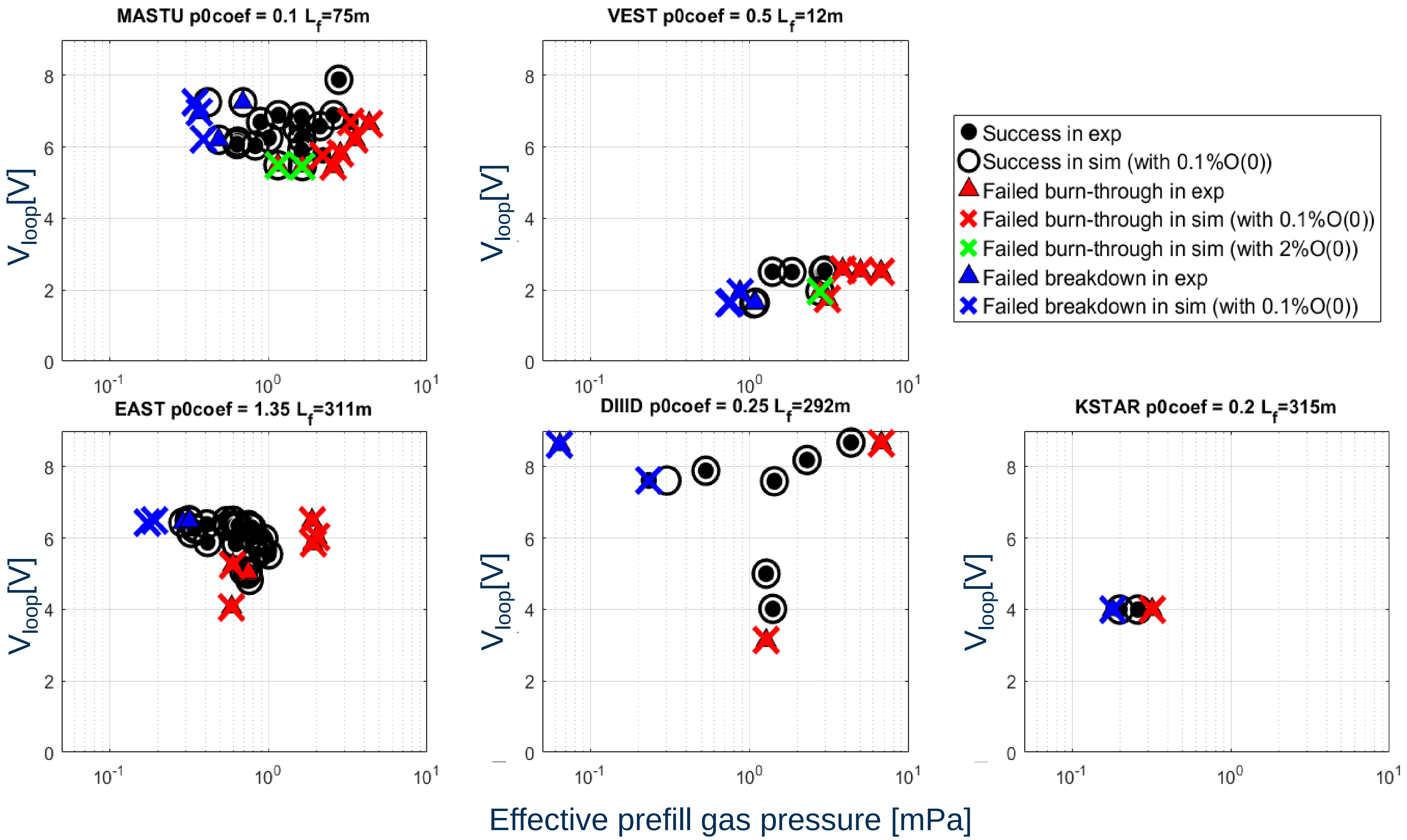
Device	Sputtering yield	Ferromagnetic modelling	p_0 coeffcient
MASTU	Assumption of 0.1% initial O in D prefill gas + Carbon sputtering by D ions = 0.03	N/A	0.1
EAST	Assumption of 0.1% initial O in D prefill gas	N/A	1.35
DIIID	Assumption of 0.1% initial O in D prefill gas + Carbon sputtering by D ions = 0.03	N/A	0.25
KSTAR	Assumption of 0.1% initial O in D prefill gas + Carbon sputtering by D ions = 0.03	Done	0.2
VEST	Assumption of 0.1% initial O in D prefill gas	N/A	0.5

Apart from the table above, the simulation setup used in all DYON modelling is identical, i.e. no tuning in individual discharges.

Only using the control room input data i.e. coil currents waveform and effective prefill gas pressure, the plasma initiation in each discharge were predicted.

contents

Operation space simulation



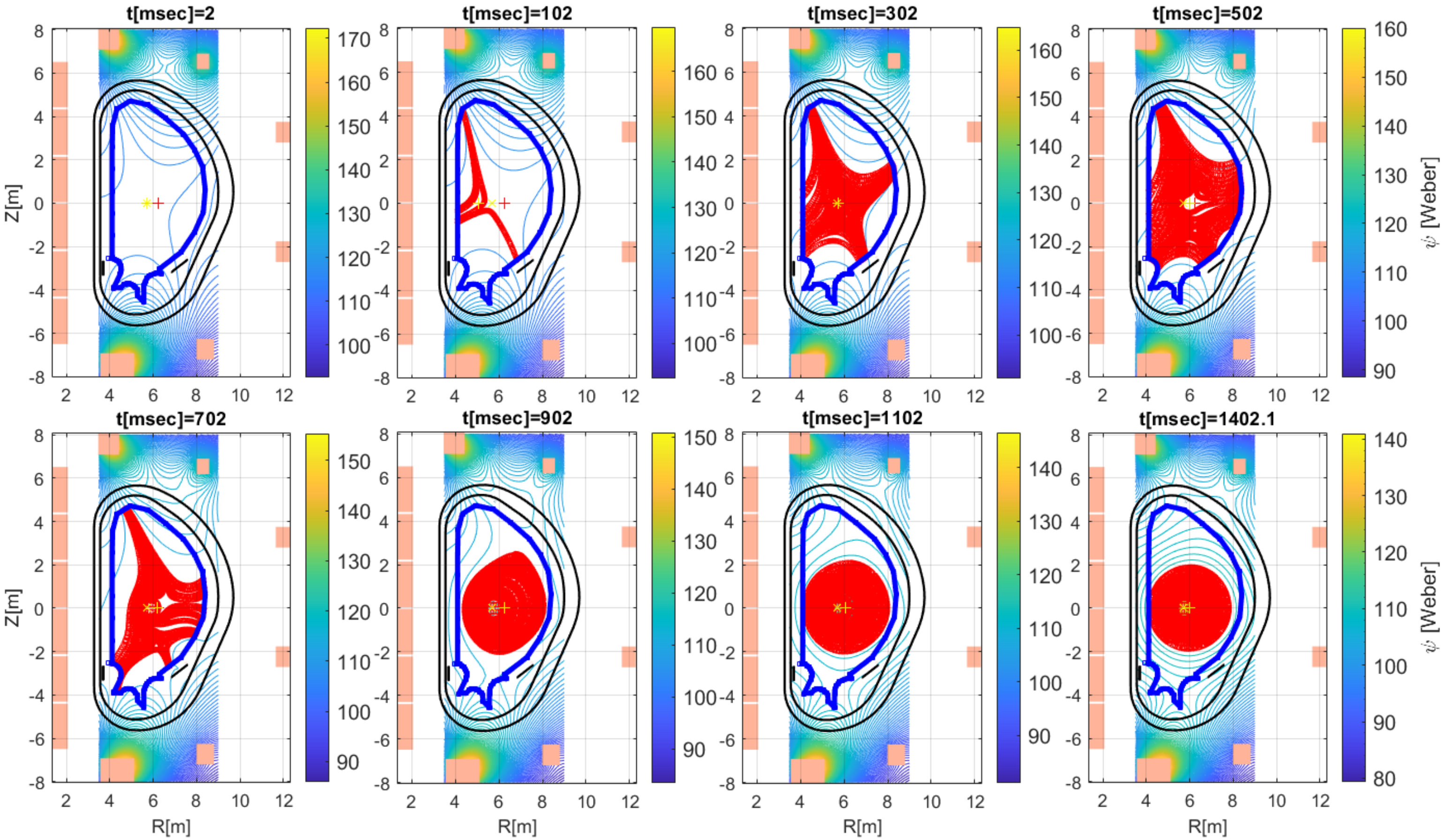
The inductive operation spaces were reproduced in the full electromagnetic DYON modelling in all devices.

Strong confirmation of the validity of predictive modelling for inductive plasma initiation.

Ready to add EC models for preionisation, heating, and current drive.

contents

Prediction to the inductive plasma initiation in ITER



Machine description and coil current time traces are from IMAS (#105052).
DYON predicts with 0.1% initial oxygen + physical sputtering of Boron

- Inductive plasma initiation is successful at 1mPa.

Prediction to the inductive plasma initiation in ITER

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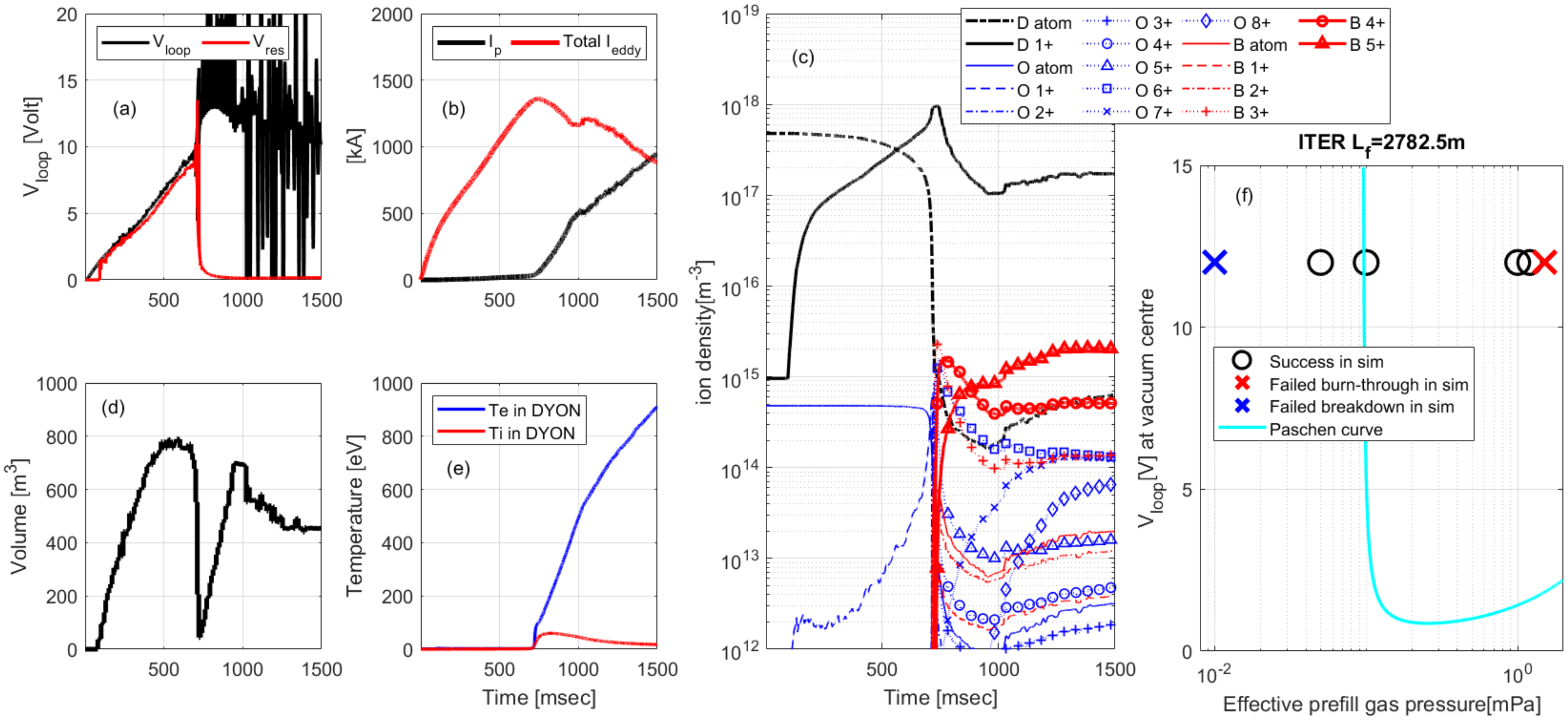

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DYON predicts with 0.1% initial oxygen + physical sputtering of Boron

- Inductive plasma initiation is successful at 1mPa.
- Townsend breakdown possible at a low V_{loop} for long connection length (10x longer than the present devices).
- Slower burn-through (D burn-through at 700ms) for a large vacuum volume
- Upper p_0 limit for burn-through =1.5mPa and lower p_0 limit for breakdown = 0.1mPa (Caveat: risk of runaway electrons).

Summary

Validated the predictive modelling of operation space for inductive plasma initiation with multi-machine experiment data. Full electromagnetic DYON

- can capture the essential physics in the inductive plasma initiation
- can assess the feasibility of inductive plasma initiation with the given hardware design and operating scenario.
- is ready to add EC models for preionisation, heating, and current drive for future work.

Predicted ITER with

- the validated simulation setup
- the machine description and coil current time traces (#105052) in IMAS.

In ITER,

- Townsend breakdown possible at a low V_{loop} for long connection length (10x longer than the present devices).)
- Slower burn-through (D burn-through at 700ms) for a large vacuum volume
- Upper p_0 limit for burn-through =1.5mPa and lower p_0 limit for breakdown = 0.1mPa (Caveat: risk of runaway electrons).

More DYON modelling to be presented at this conference:

- JT-60SA modelling by Takuma Wakatsuki 17 Oct 2025, 10:40
- Runaway electron model development by Youngsun Lee 17 Oct 2025, 14:40