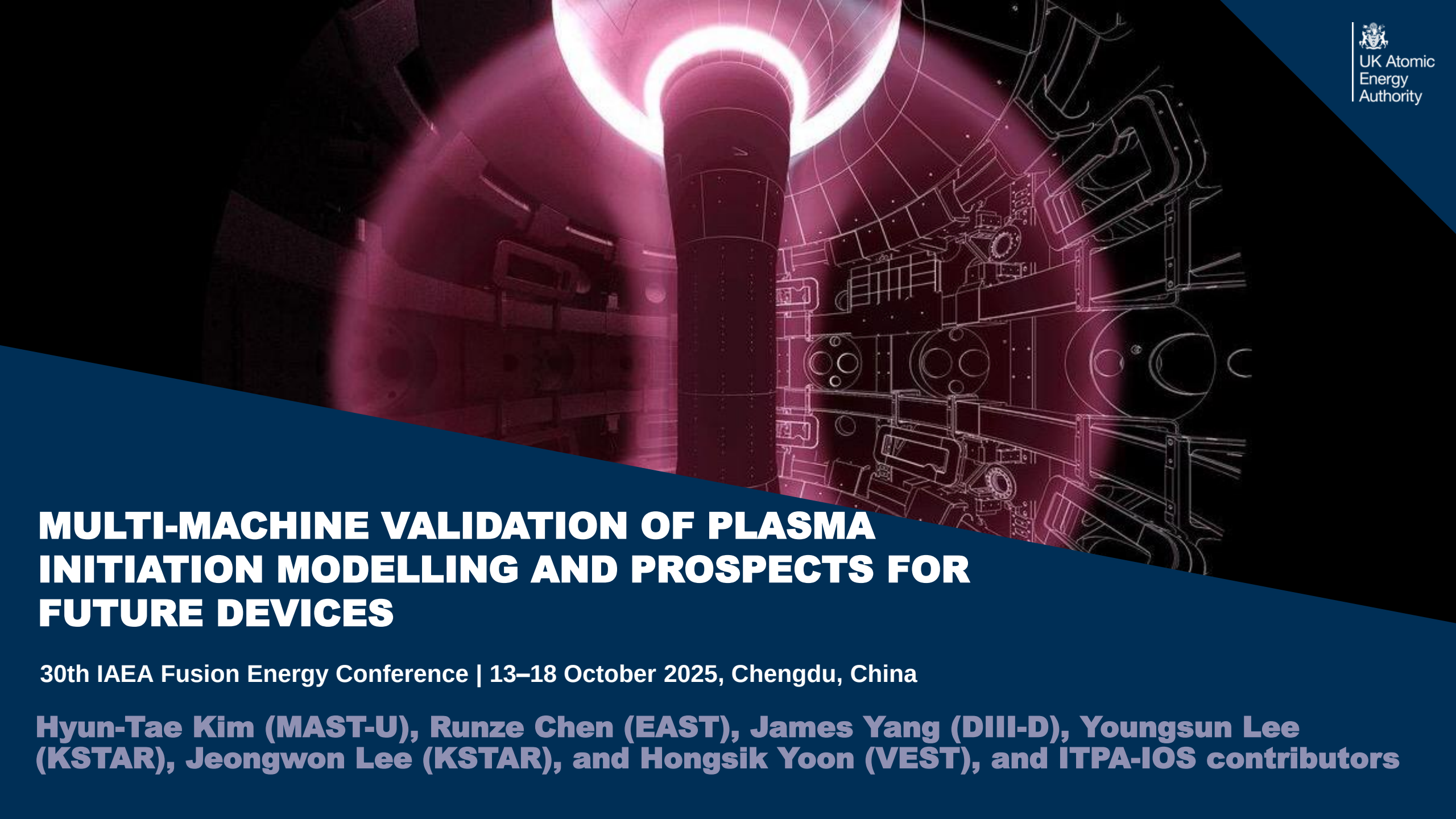




MULTI-MACHINE VALIDATION OF PLASMA INITIATION MODELLING AND PROSPECTS FOR FUTURE DEVICES

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Background and motivation

Experiment database

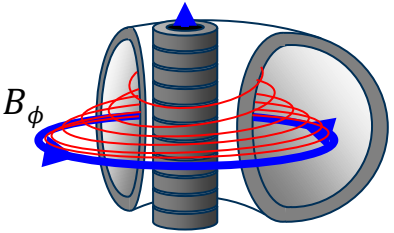
DYON code and simulation setup

Multi-machine validation results

Prediction to ITER

Summary

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



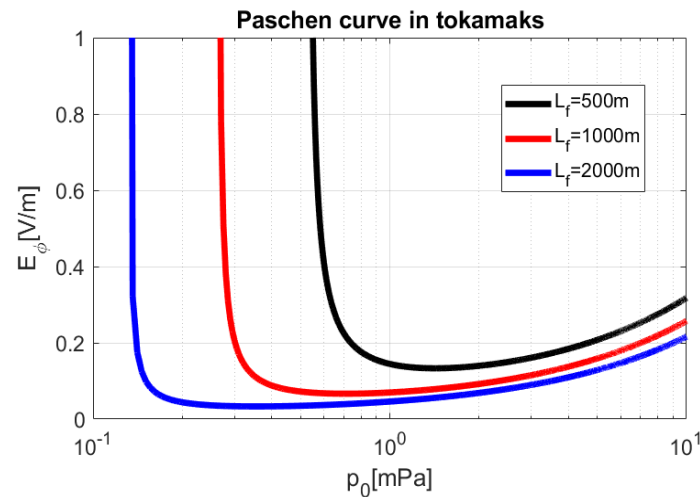
Townsend breakdown in tokamaks: $\alpha L_f > 1$

- 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 $B=93.76$)

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

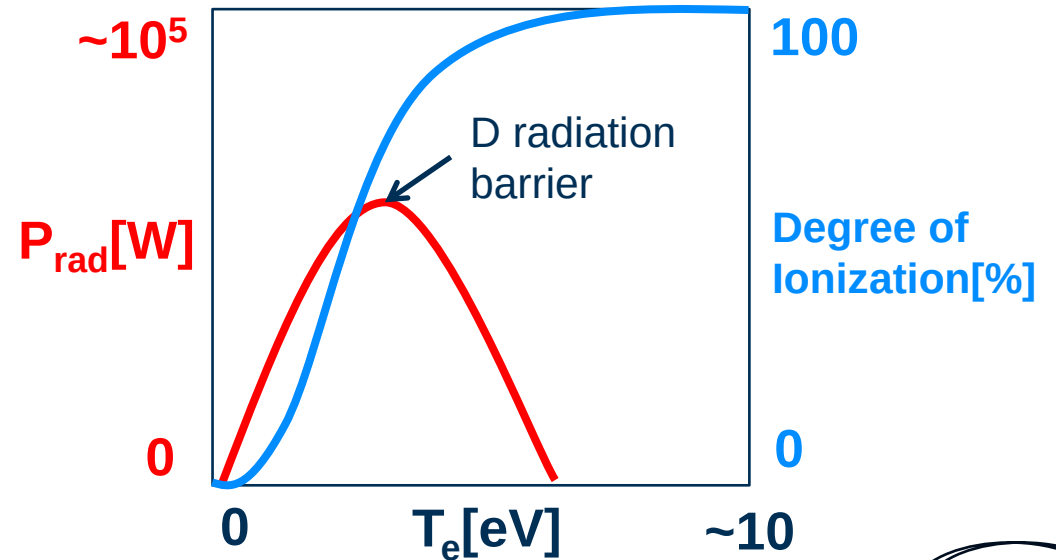
$$E_\phi [\text{V/m}] = \frac{93.76 \times p_0 [\text{Pa}]}{\ln(3.83 \times p_0 [\text{Pa}] \times L_f [\text{m}])}$$



Electrons and neutrals exist together in the burn-through phase

- Ohmic heating VS Energy loss from radiation and charge exchange

$$\text{Radiated power loss } P_{rad} = \langle \sigma v \rangle_{rad} n_e n_D^{0+}$$



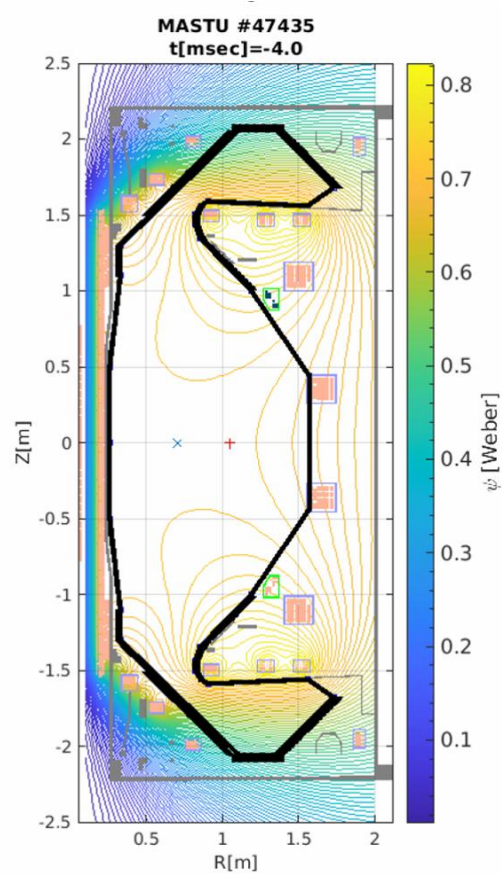
Passing the radiation barrier of D and impurities $\Rightarrow P_{rad} \downarrow \Rightarrow T_e \uparrow$

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

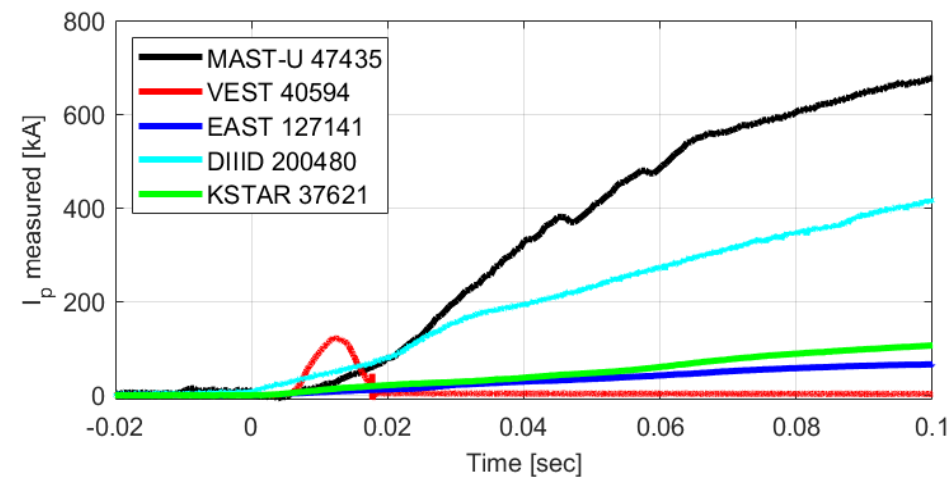
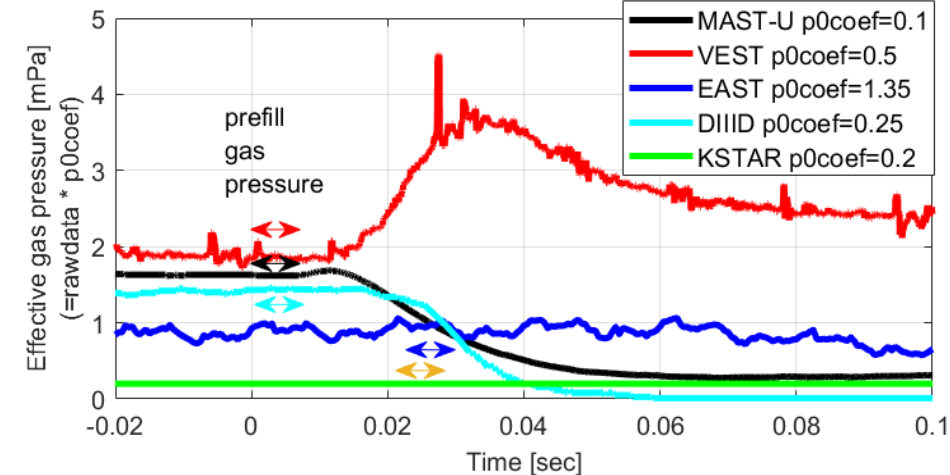
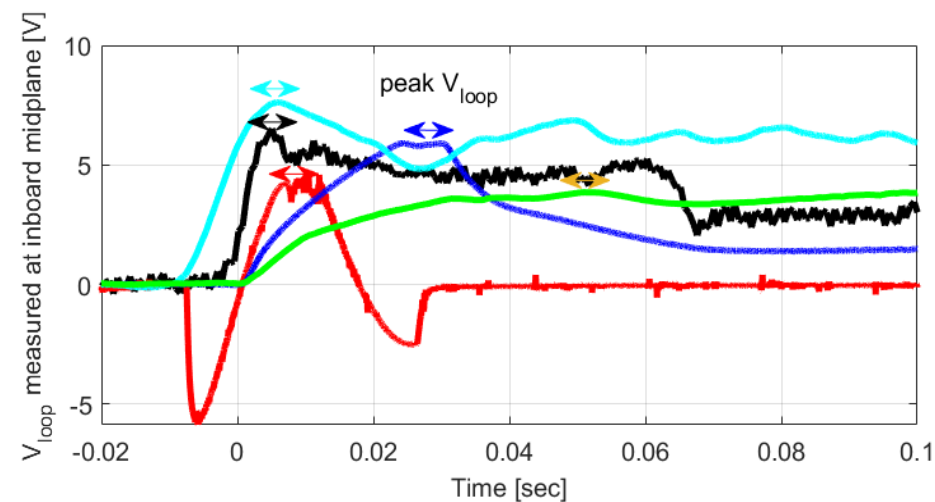
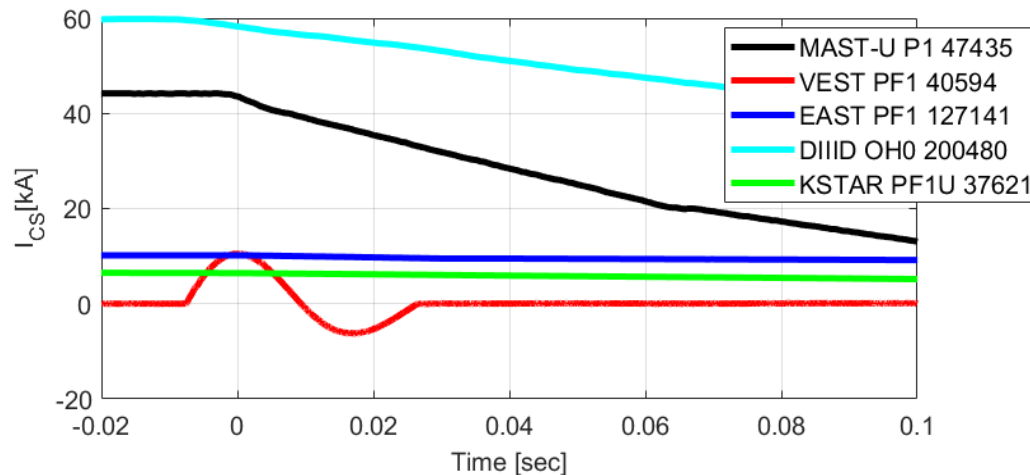
B. Lloyd PPCF 38 (1996)
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P. C. de Vries Nucl. Fusion
59 (2019) 096043

Tokamak operation for inductive plasma initiation

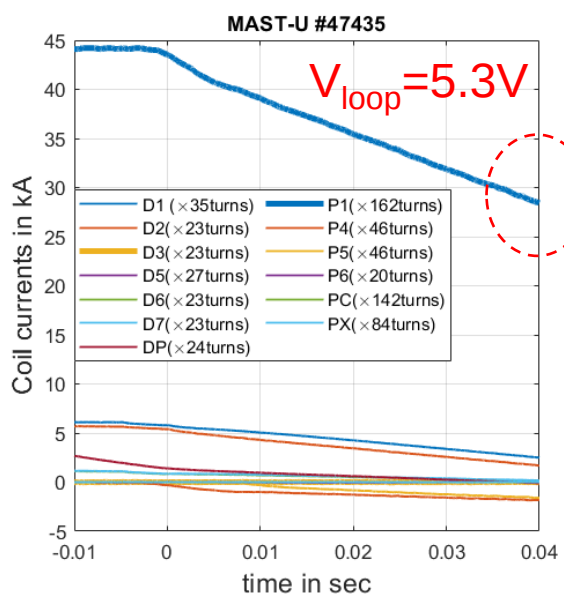


Magnetic field null configuration is required to maximise the connection length.

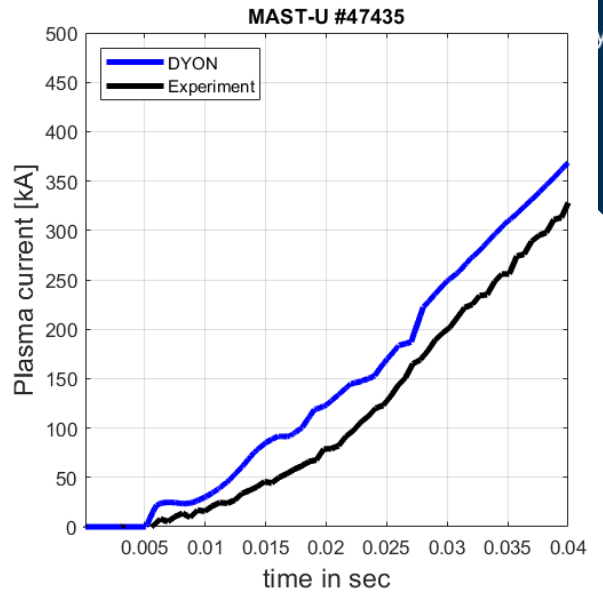
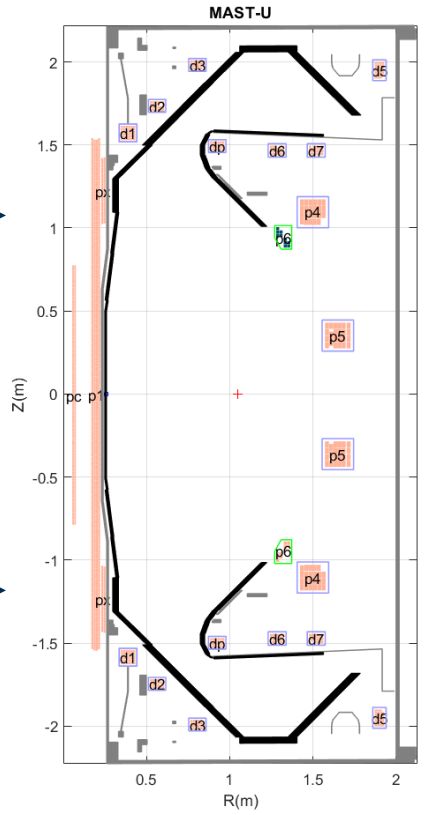


Goal of plasma initiation modelling

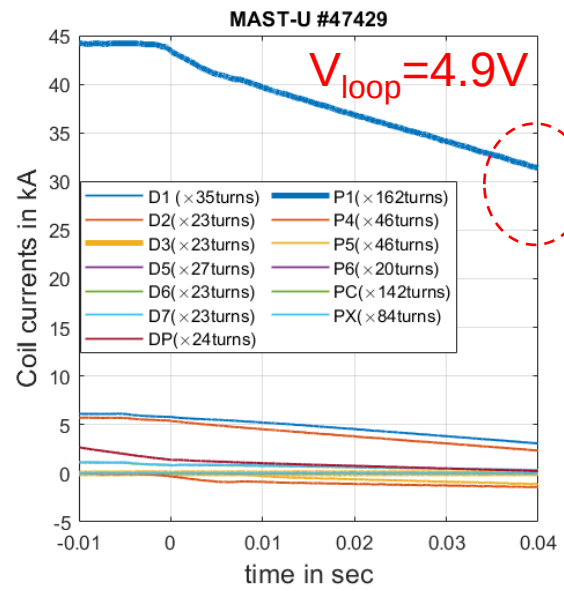
p_0 and



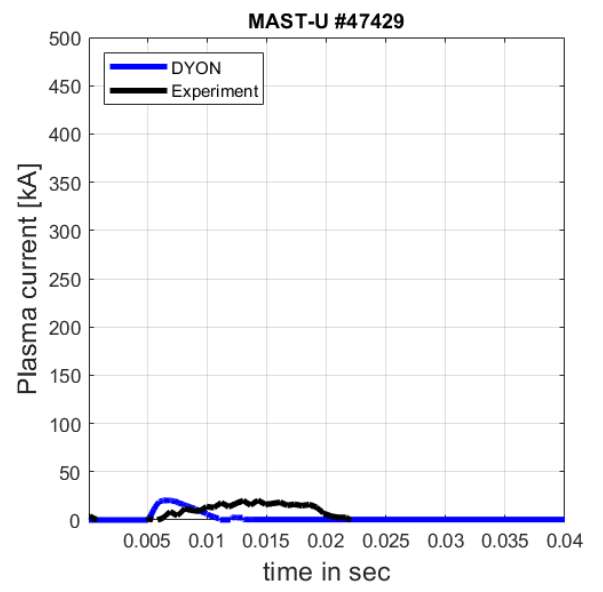
DYON



p_0 and

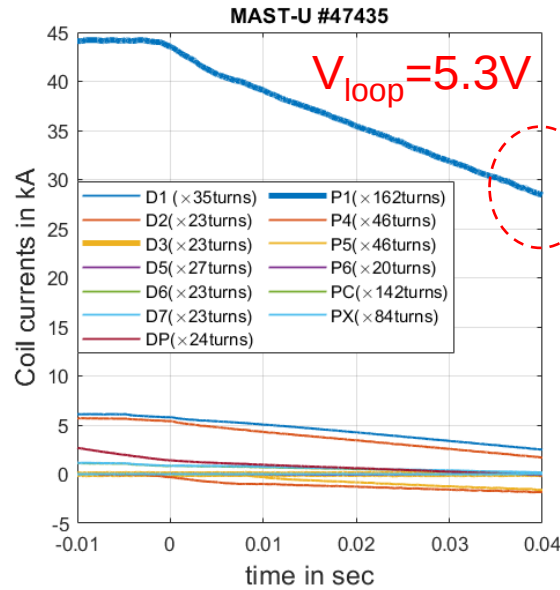


DYON



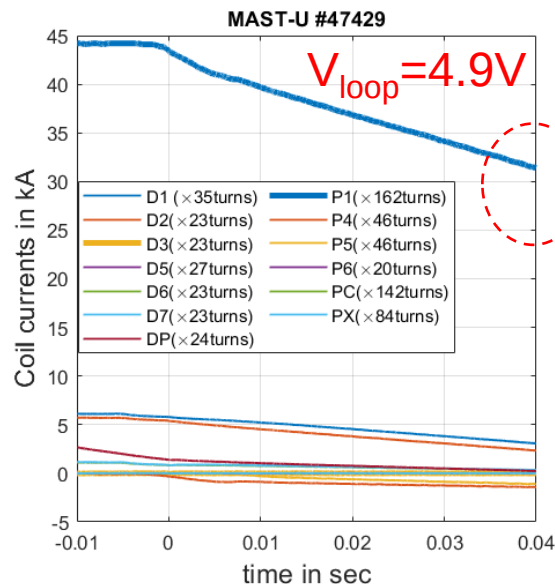
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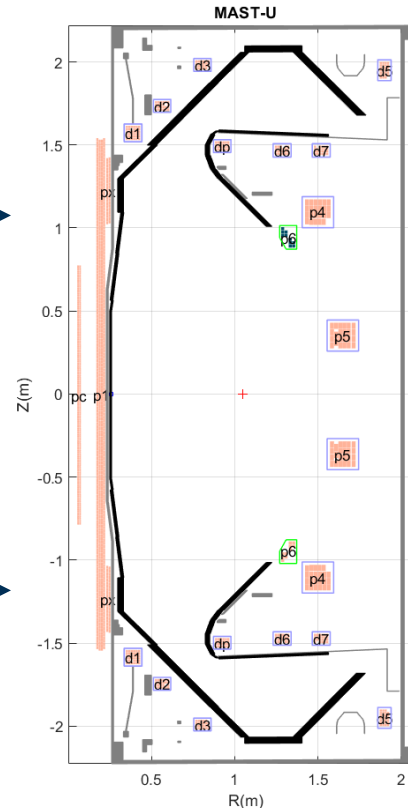


DYON

p_0 and



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.

Background and motivation

Experiment database

DYON code and simulation setup

Multi-machine validation results

Prediction to ITER

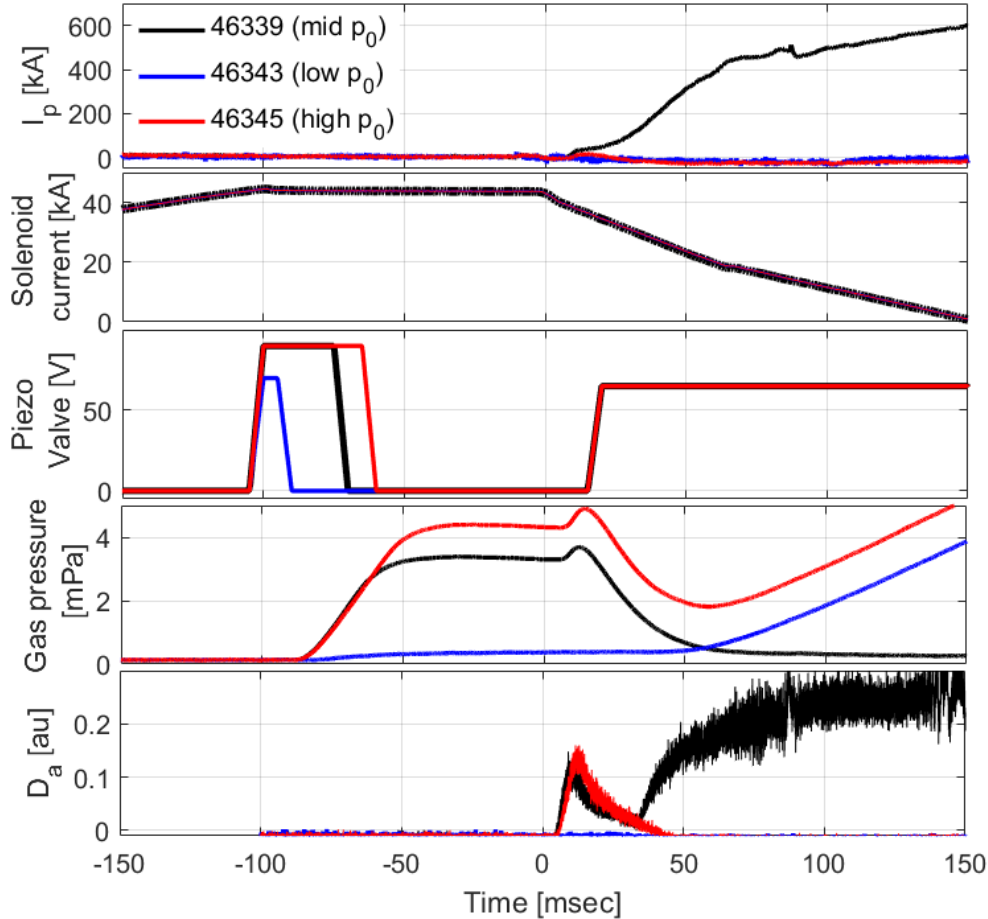
Summary

Devices for multimachine validation

Device	Aspect ratio	Coils	First wall material	Ferromagnetic material	Vv[m ³]	Vp[m ³]	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
DIID	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

MAST-U

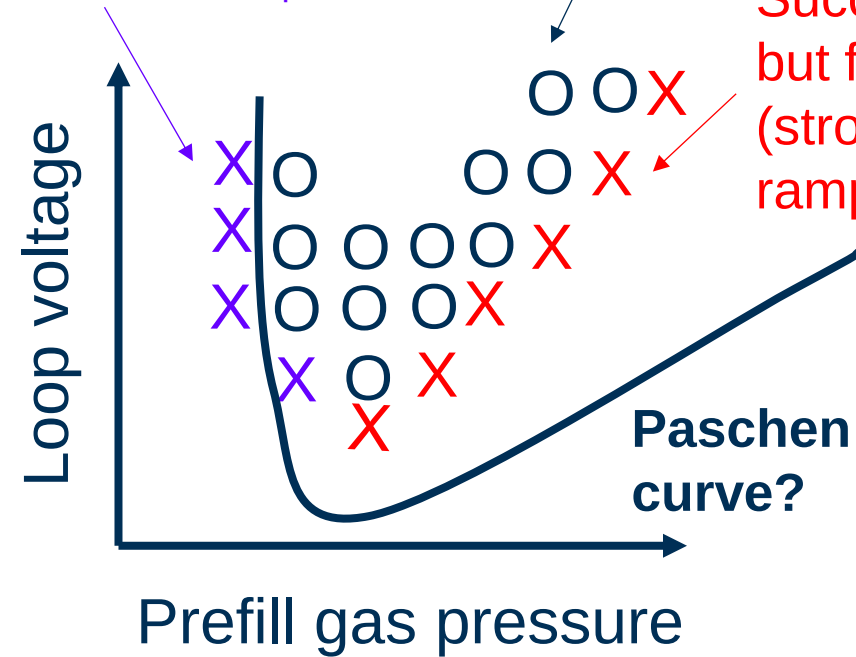


Hyun-Taen Kim et al 2024
Nucl. Fusion 64 (2024) 126010

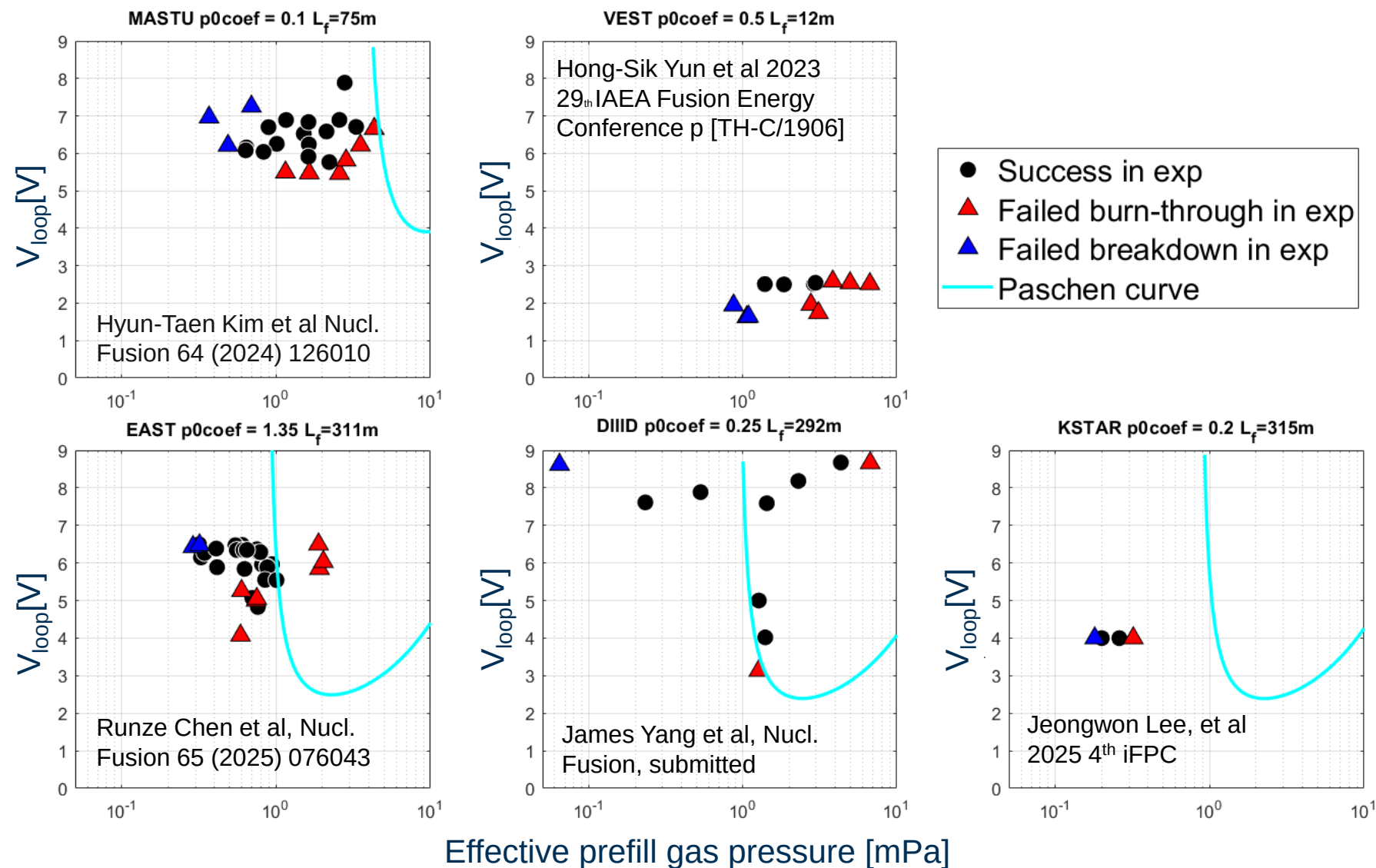
Failed breakdown
(no or very weak D_α)

Successful
plasma initiation

Successful breakdown
but failed burn-through
(strong D_α but no I_p
ramp-up)



Operation space in experiments



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.

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Summary

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 $V_v \cdot p_0$ is required for plasma burn-through.

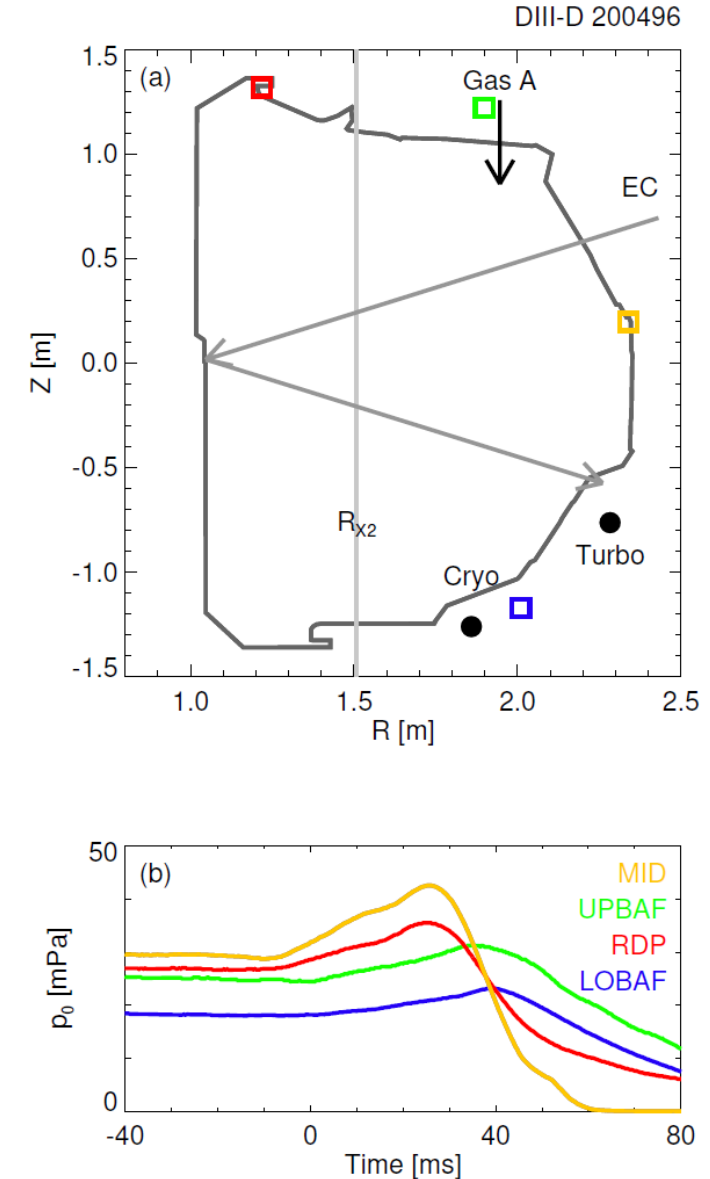
However, raw data requires calibration.

- 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.

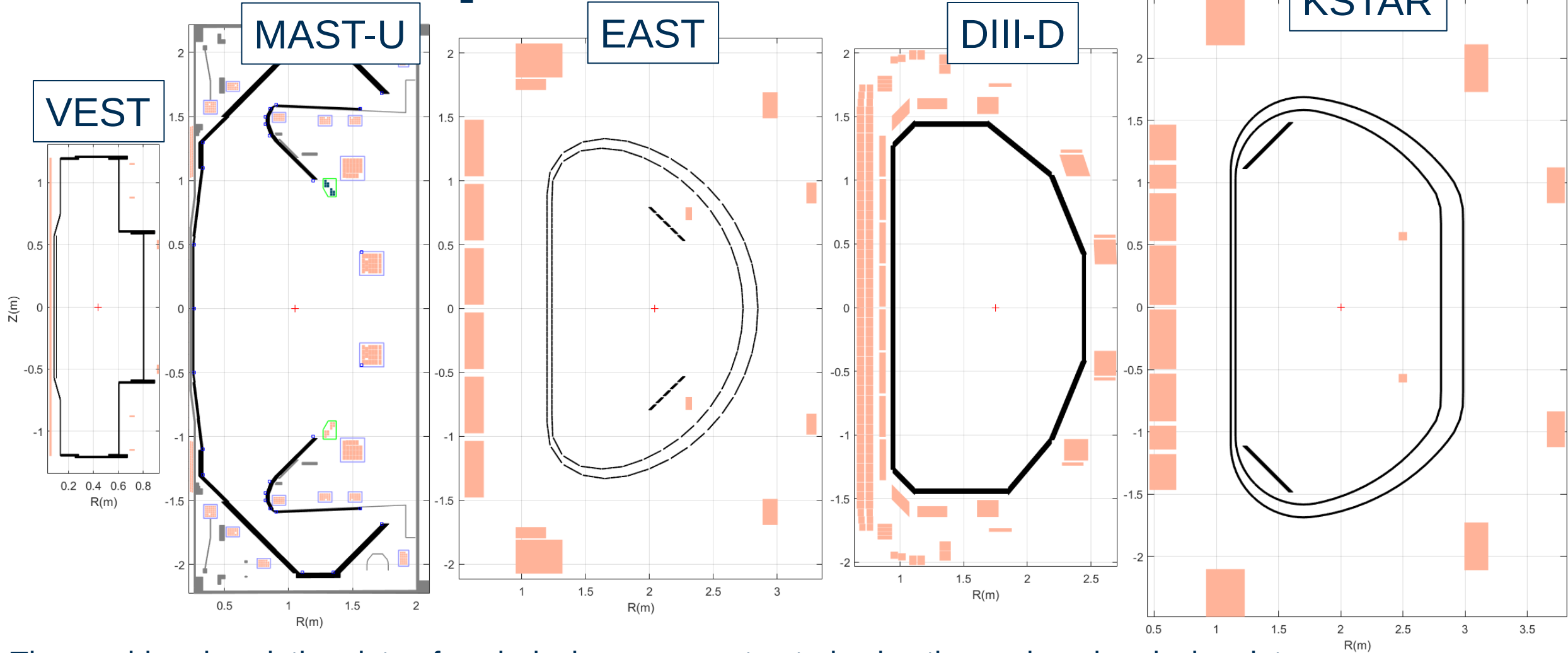
The strategy to validate the operating space prediction capability in DYON:

- 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 p_0 range for successful initiation.



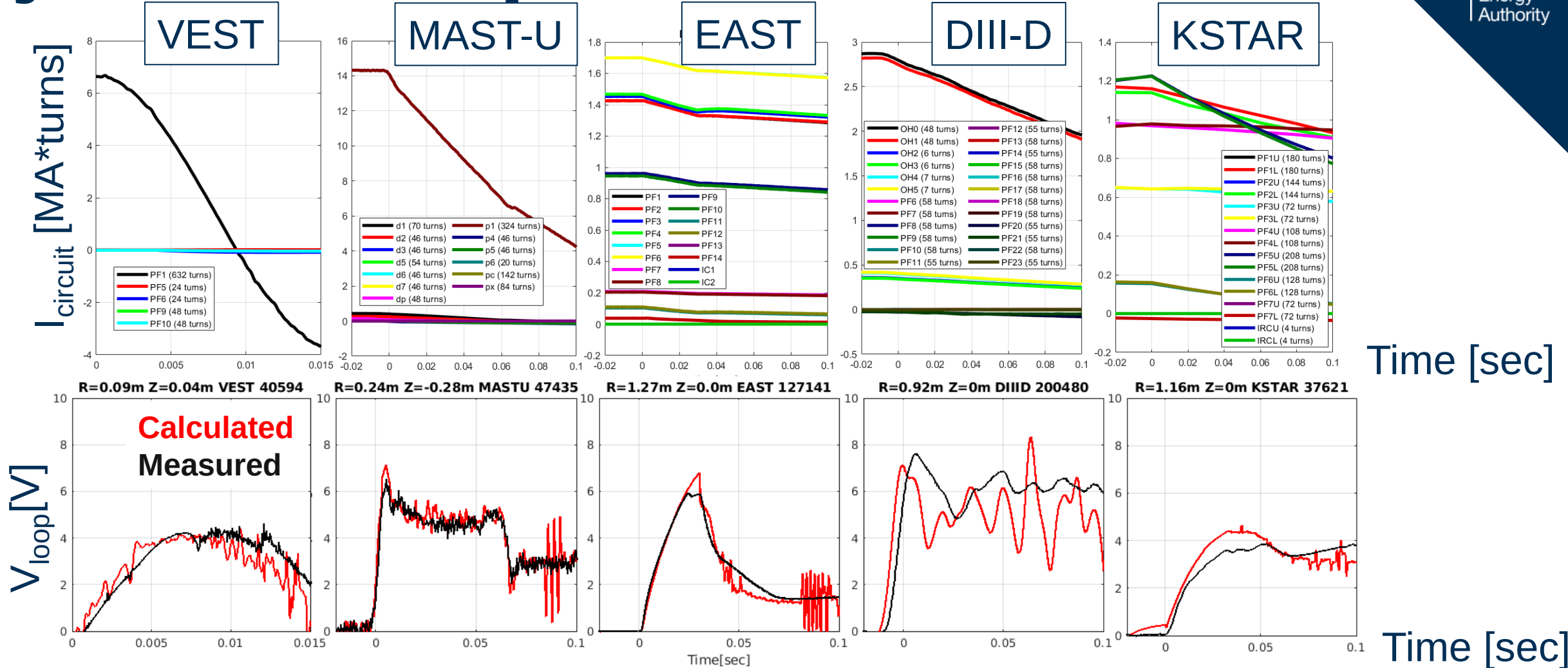
Machine description



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

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

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 :

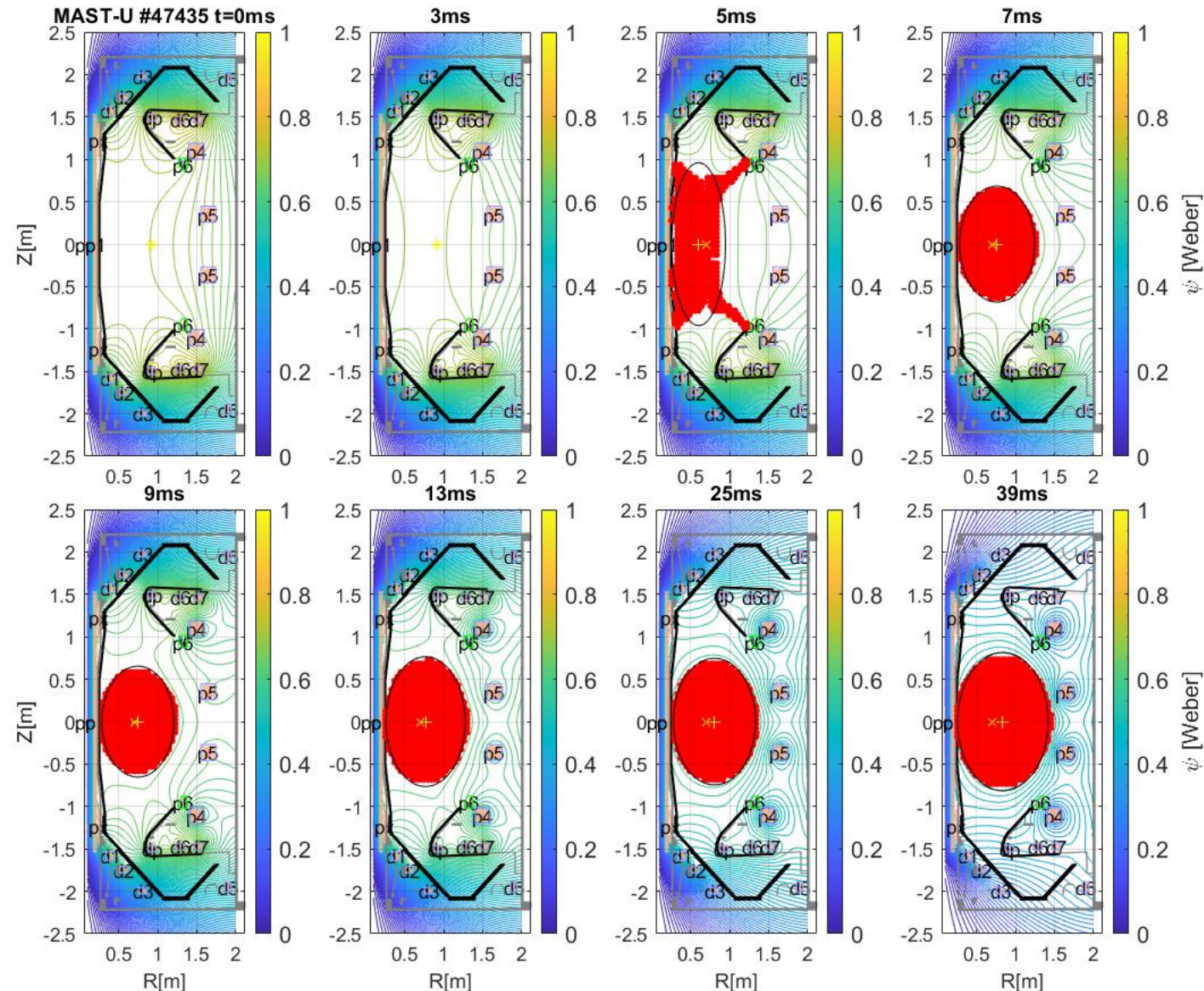
- Open field lines with $E_{\parallel} > E_{\text{Townsend}}$
 - Volume enclosed with closed field lines
- Plasma burn-through and early I_p ramp-up simulated by solving the ODE system of
- full circuit equations of plasma, coils, and eddy currents +
 - global energy and particle balances of main fuel 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



DYON: full electromagnetic plasma initiation simulator

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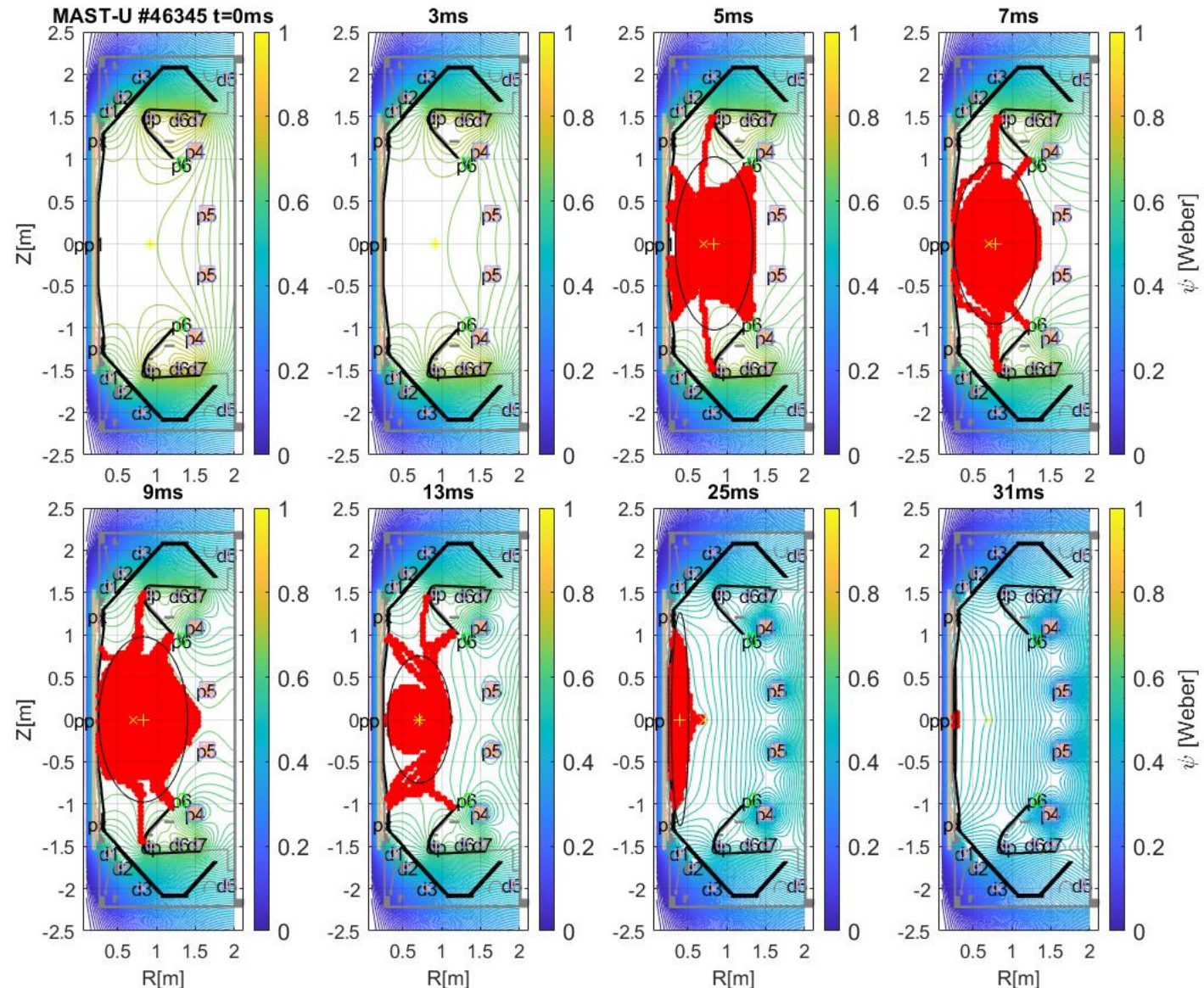
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DYON requires only :

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- Failed plasma burn-through



DYON: full electromagnetic plasma initiation simulator

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

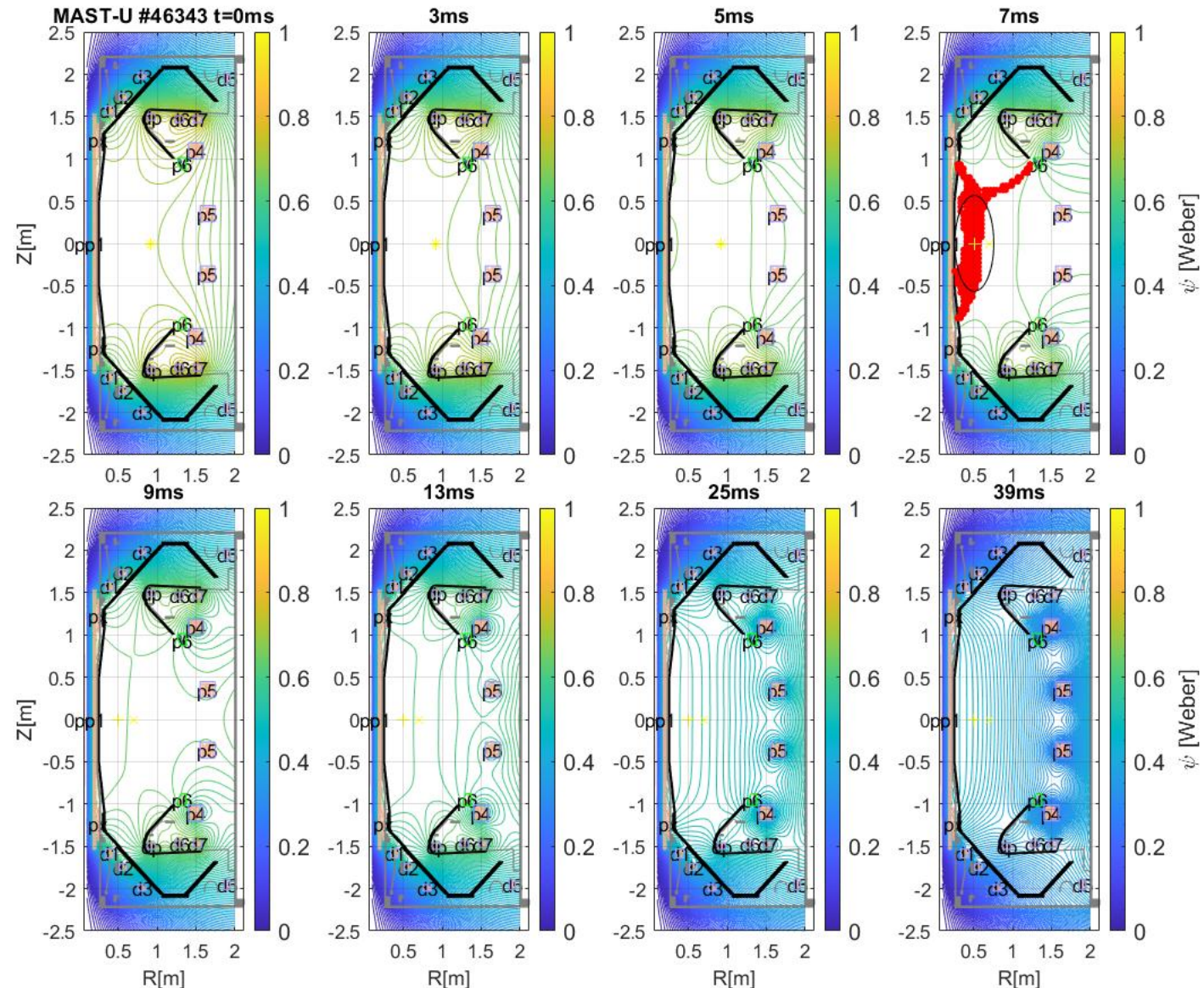
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DYON requires only :

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

DYON predicts:

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



Simulation setup

Device	Sputtering yield	Ferromagnetic modelling	p_0 coefficient
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
DIID	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.

Background and motivation

Experiment database

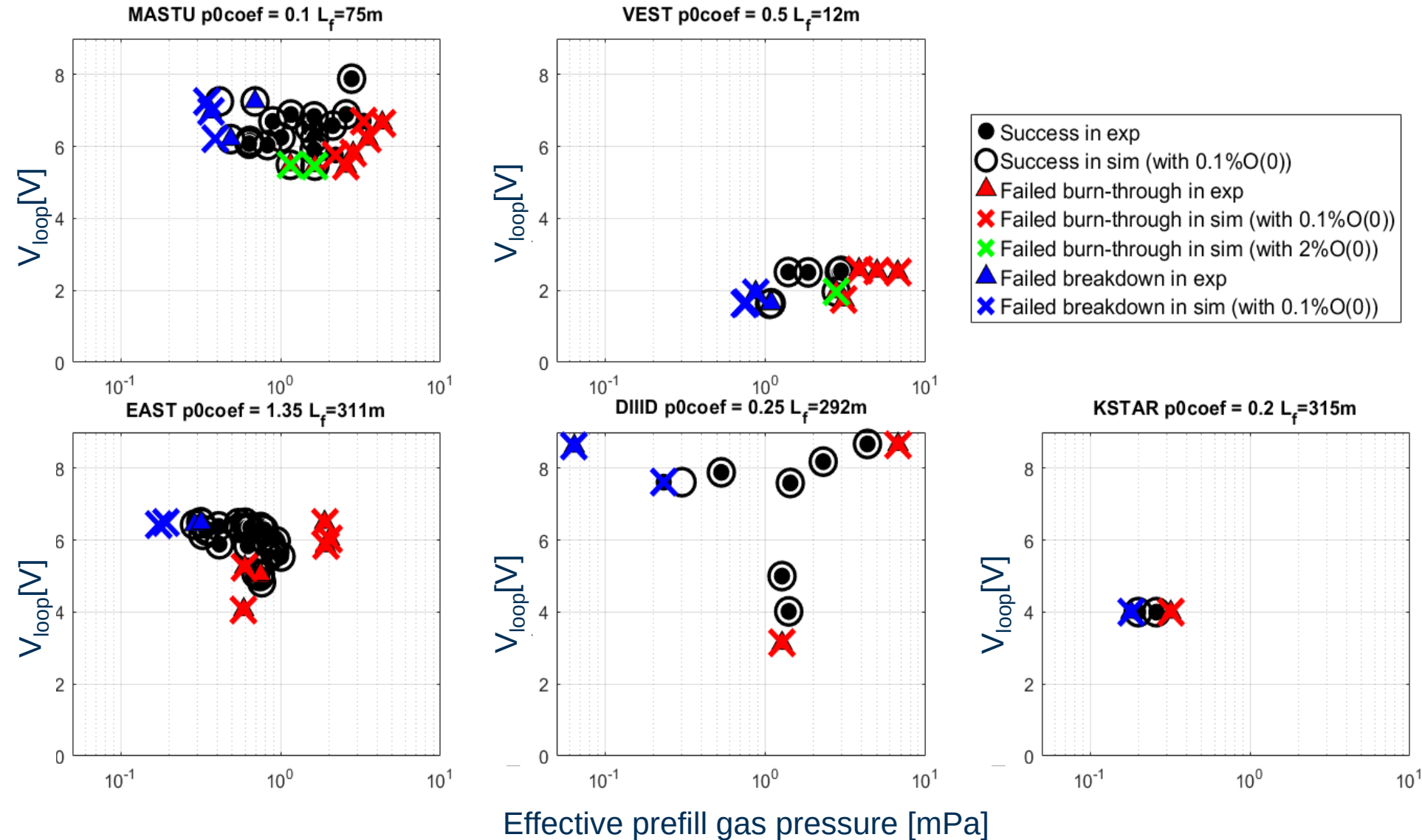
DYON code and simulation setup

Multi-machine validation results

Prediction to ITER

Summary

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.

Background and motivation

Experiment database

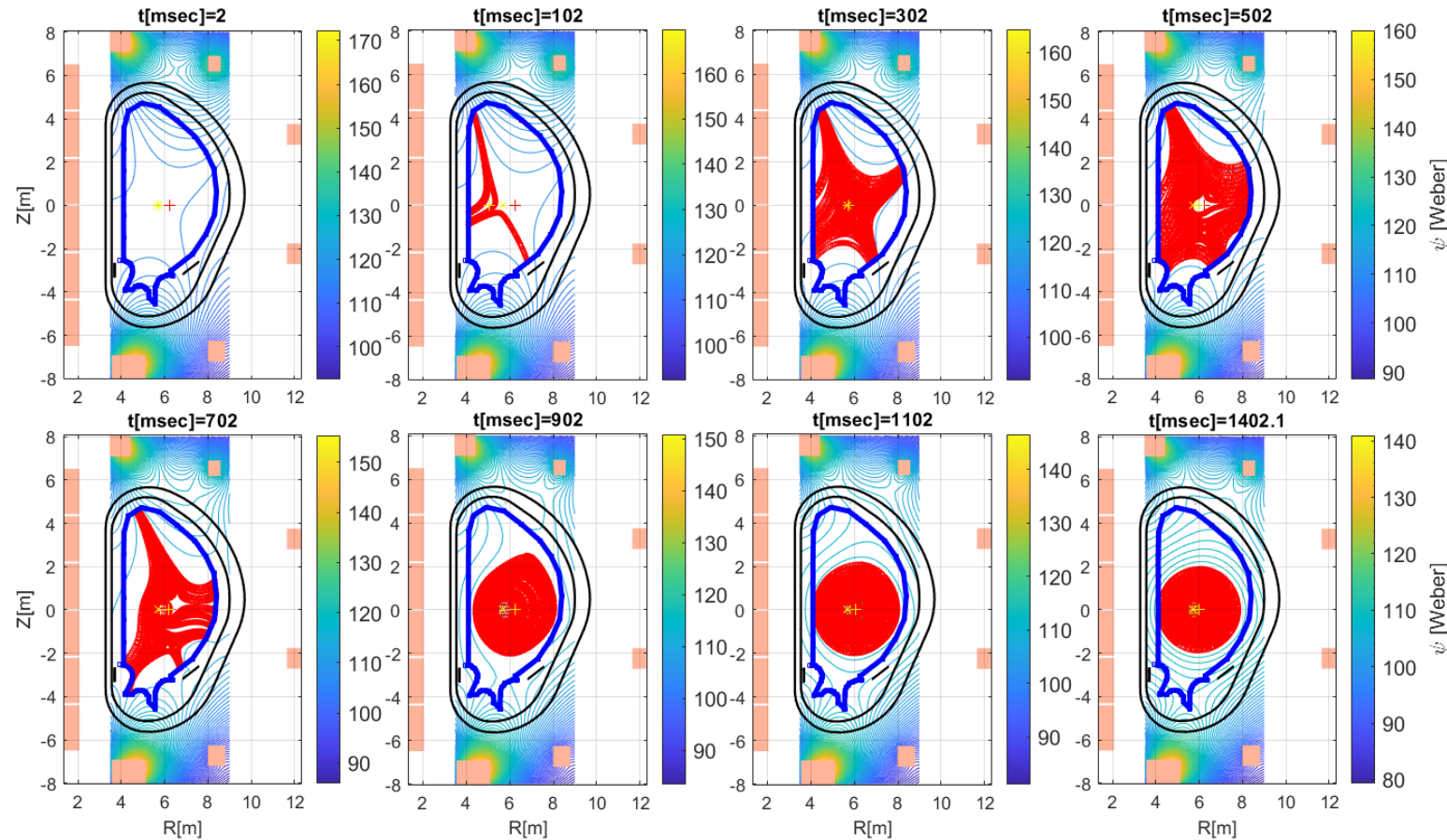
DYON code and simulation setup

Multi-machine validation results

Prediction to ITER

Summary

Prediction to the inductive plasma initiation in ITER

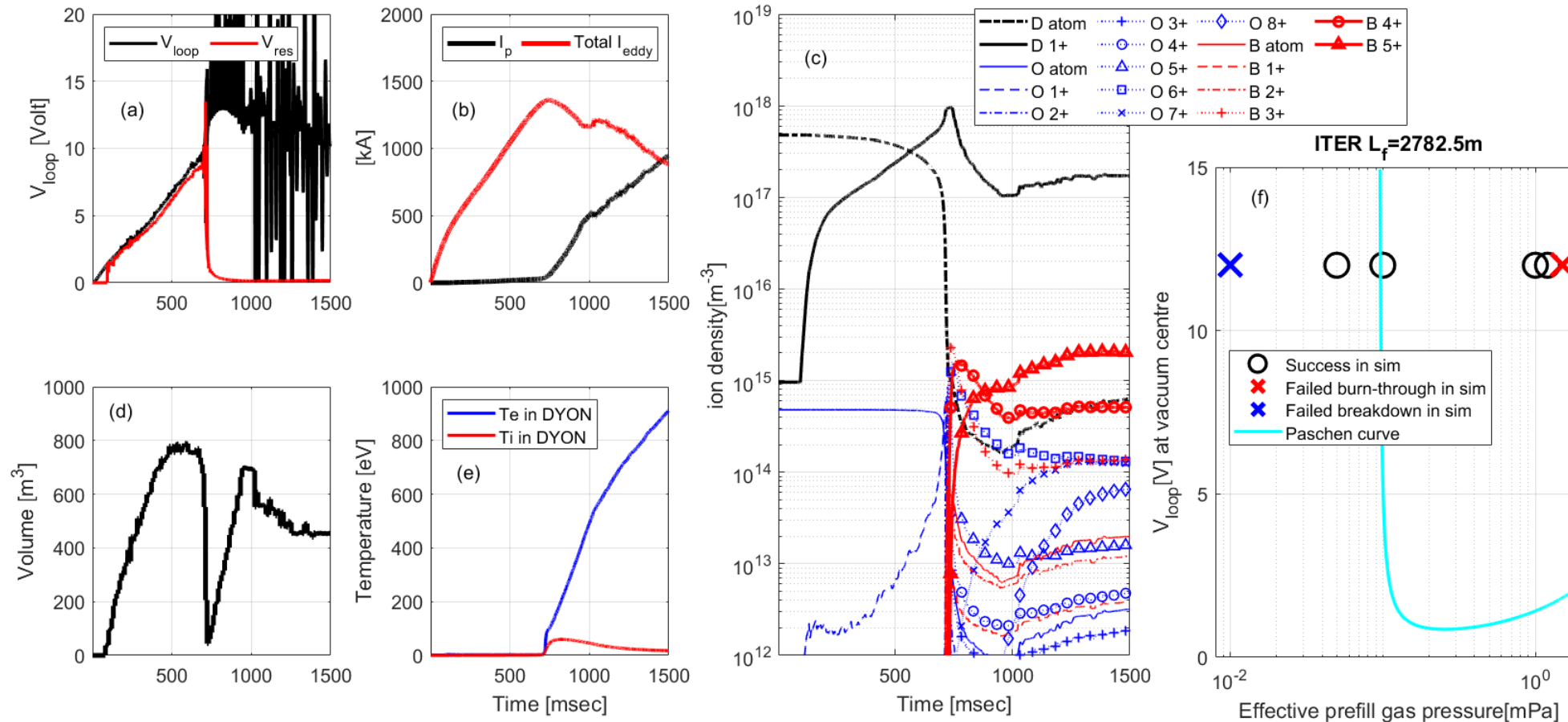


Machine description and coil current time traces are from IMAS (#105052).

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



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.
- 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, it is predicted that

- Successful inductive plasma initiation if the initial impurity is minimised.
- Townsend breakdown possible at a low V_{loop} due to the long connection length (10x longer than the present devices).
- Slower burn-through (D burn-through at 700ms) due to the 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