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EC breakdown in tokamaks: validation on KSTAR and implications for ITER-like devices

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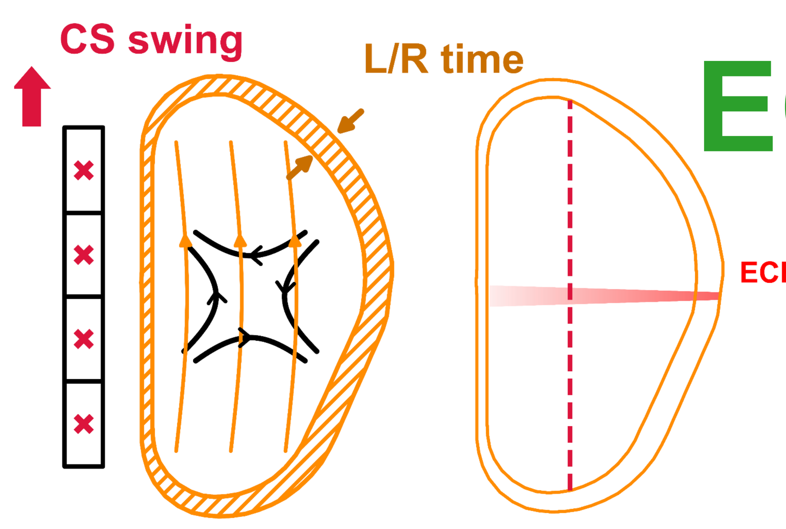
Highlights

- The absence of a tractable, physics-based model for EC breakdown has hindered its systematic consideration in future start-up scenarios.
- In particular, quantitative operational criteria have remained unavailable. Consequently, whether EC breakdown will succeed in a future device could not be predicted in advance.
- For the first time, the EC breakdown boundary in prefill pressure p_{prefill} and connection length L_c is experimentally observed to be consistent with predictions from a recently developed particle-in-cell (PIC) code [2].
- Predictions for an ITER-like device indicate that EC breakdown remains accessible with 1 MW of EC power at 2 mPa, provided the connection length exceeds ~250 m.

Motivation

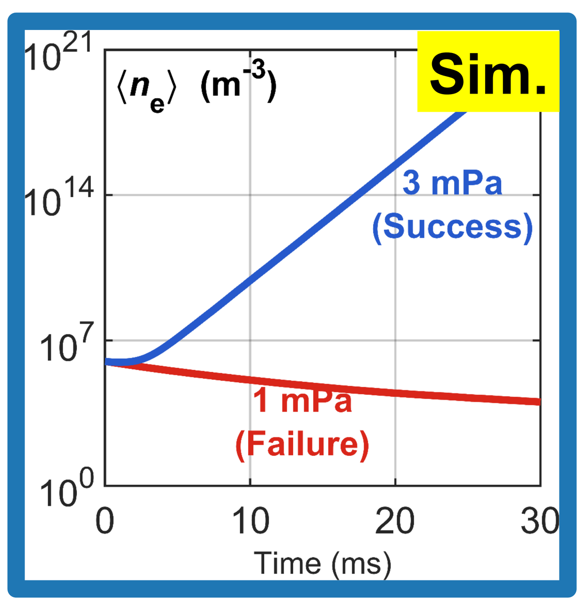
- The low electrical resistance of reactor-scale vessels drives strong eddy currents that shield the inductive electric field and perturb the magnetic conditions required for electron avalanche growth [1]. This makes purely inductive breakdown difficult to predict, motivating EC breakdown (pre-ionization) as a non-inductive route [1,6,7].

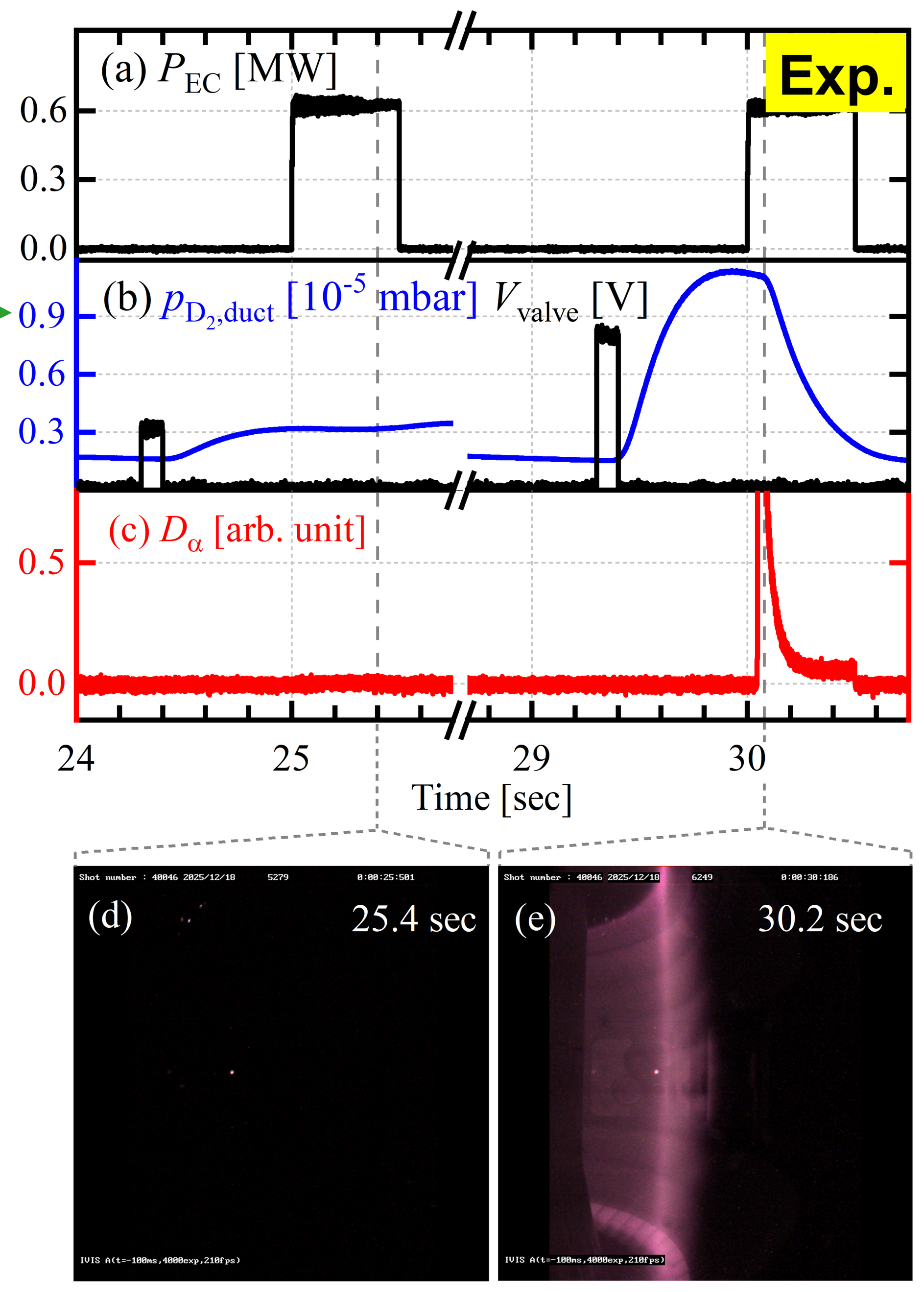


EC power? $B_{\mathrm{pol.}} \leq$? Prefill pressure?

- A first-principles PIC simulation of EC breakdown onset has recently become available [2], predicting the BD boundary in operational space.
- An experimental validation of this model against measured BD boundaries has not yet been carried out.

Designed a p_{prefill} scan at two L_c settings in KSTAR





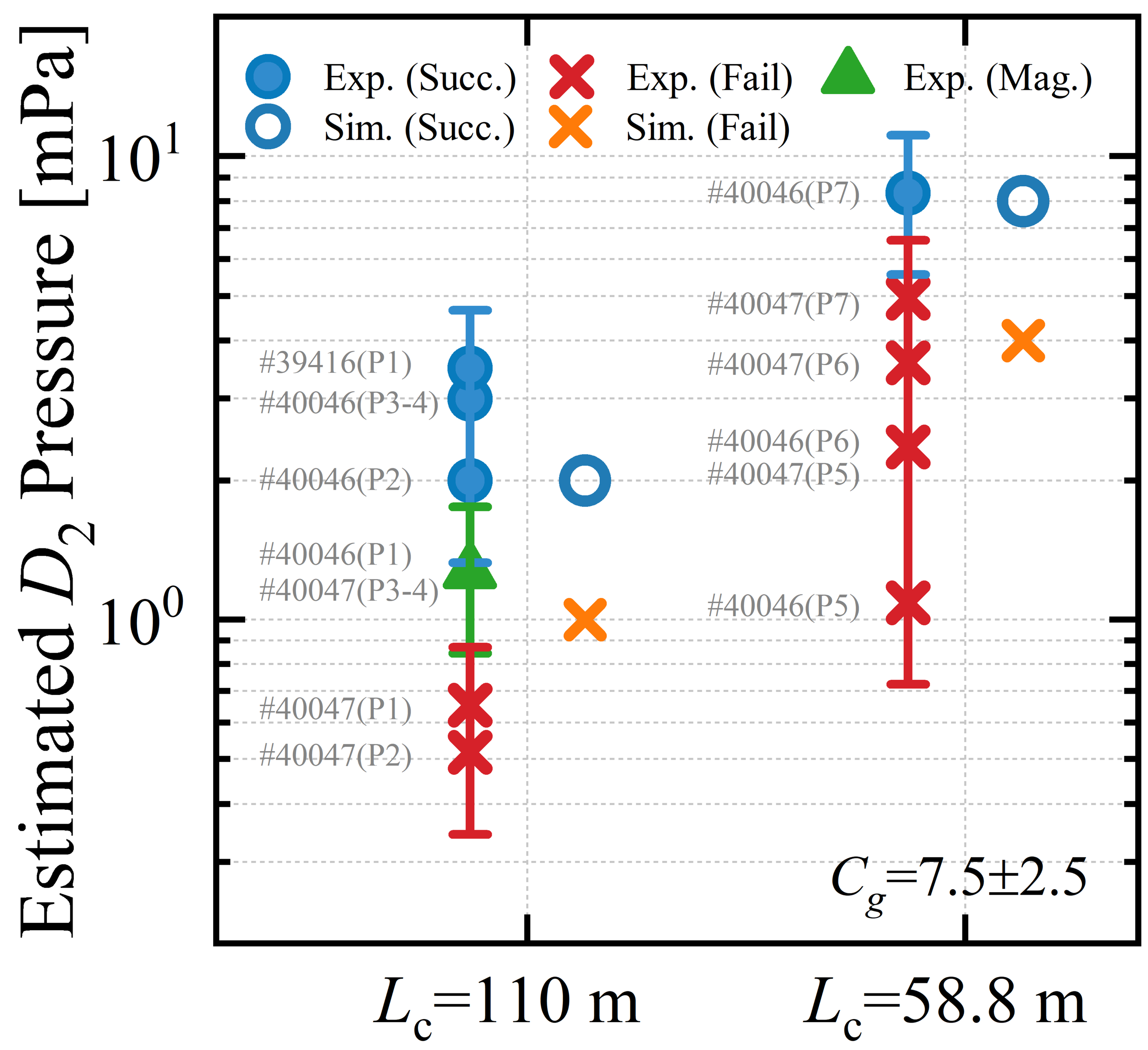
PIC predicts the p_{prefill} BD boundary at target L_c

KSTAR's in-house magnetic field code gives I_{PF} to set target L_c

Gas valve calibration gives $V_{\mathrm{valve}}(t)$ that scans across the predicted boundary

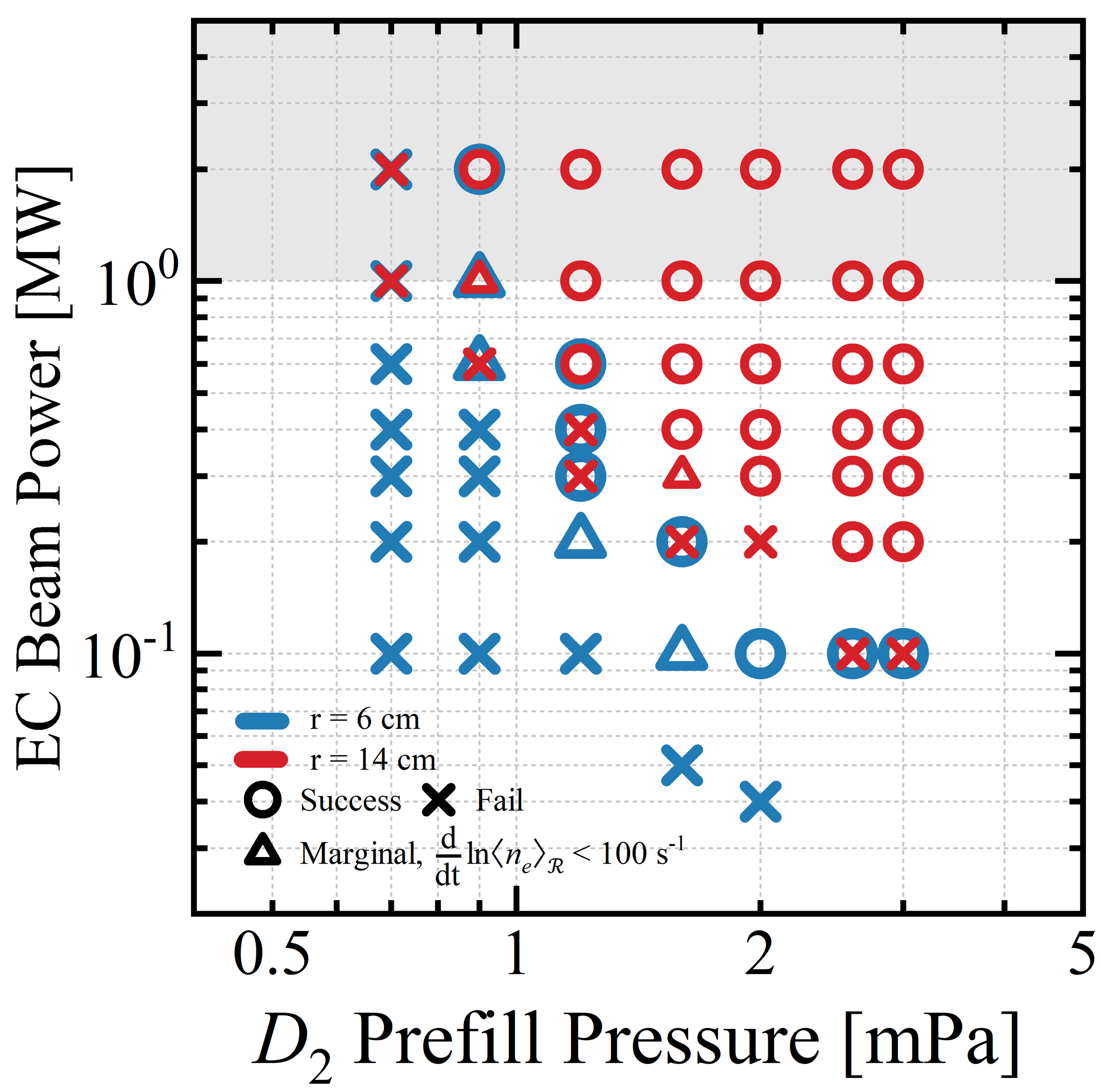
- Executed repeated D_2-puff/EC-pulse pairs under **zero** V_{loop}, with the EC setting **fixed** across all attempts (0.5 s pulses).
  Scanned p_{prefill} by varying the gas-puff command [Fig.(b)]
- Determined breakdown by $\mathbf{D_\alpha}$: failure if all channels stayed below the **noise** floor during the EC pulse [Fig.(c), (d), (e)].
- Introduced a duct-to-vessel pressure correction factor C_g to estimate in-vessel p_{prefill}.
- Set two L_c values with two vertical-field levels—a controllable proxy for stray field—to obtain distinct thresholds robust to C_g uncertainty.

Experimental Validation of EC Breakdown Predictions



- PIC simulations reproducing the KSTAR conditions started from $n_e = 10^6\ \mathrm{m^{-3}}$ and $T_e = 0.03$ eV. A case was classified as successful if sustained multiplication reached $n_e > 10^{12}\ \mathrm{m^{-3}}$ within the 0.5 s EC pulse, and as failed otherwise.
- With the in-vessel pressure inferred using $C_g = 7.5 \pm 2.5$, the observed EC breakdown boundary in p_{prefill} agrees with PIC predictions at both L_c settings.
- Near-threshold cases (▲) exhibits substantially delayed breakdown onset (~100 ms) or mixed success/failure outcomes under nominally identical conditions.

Predictions for an ITER-like device



- The scan parameters are chosen to resemble those of ITER plasma initiation modelling studies [1,3,5], with the launch geometry simplified to normal incidence.
- A single gyrotron is assumed, with two beam radii (r=6 and 14 cm) spanning the ITER EC-launcher range [4].
- B_{pol} is set to the residual poloidal stray-field target for the ITER breakdown region [1], converted to an effective vertical field via a geometry factor calibrated against the DIII-D breakdown threshold [6].
- EC breakdown is accessible near and below 1 MW at 2 mPa for both beam radii.

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