

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

Jinwoo Gwak¹, Min-Gu Yoo², Jeongwon Lee³, Yeongsun Lee^{1,4}, Hyun-Tae Kim⁵, and Yong-Su Na^{1*}

¹Seoul National University (SNU), Korea, ²General Atomics(GA), USA, ³Korea Institute of Fusion Energy(KFE), Korea

*ysna@snu.ac.kr

⁴Nuclear Research Institute for Future Technology and Policy, Korea,

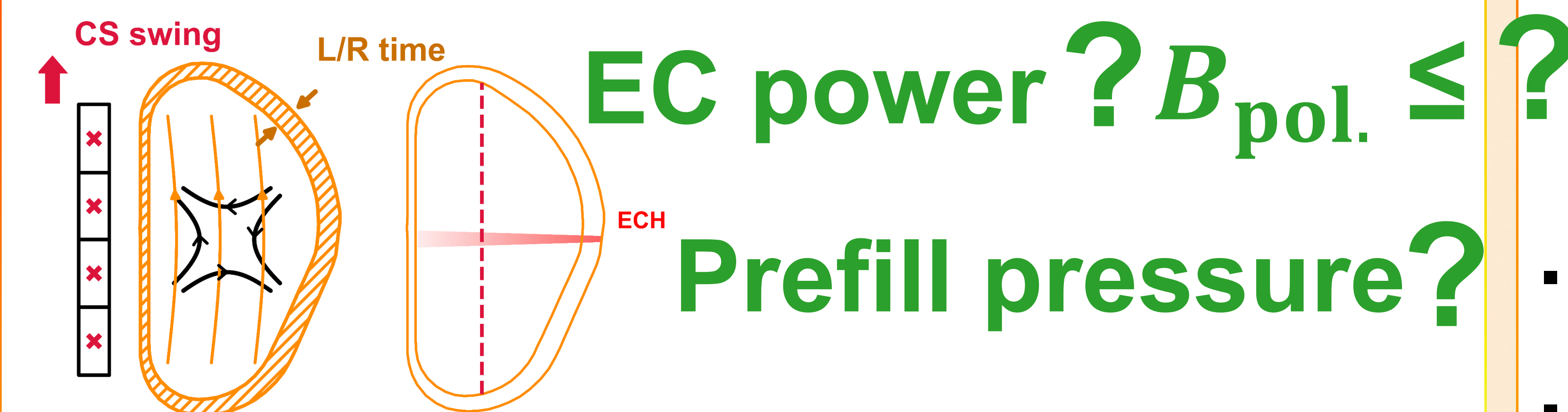
⁵UK Atomic Energy Authority(UKAEA), UK

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.

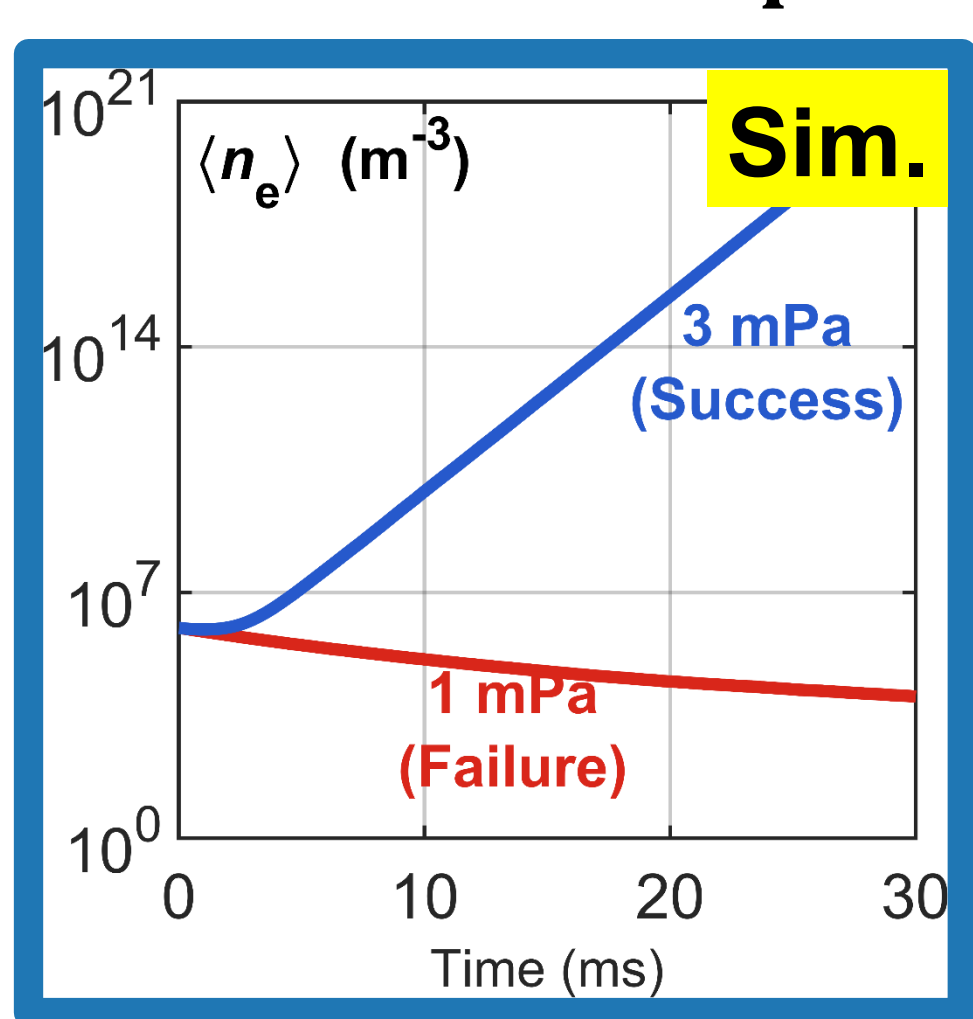
Motivation

- 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. This makes purely inductive breakdown difficult to predict, motivating EC breakdown (pre-ionization) as a non-inductive route.



- 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.

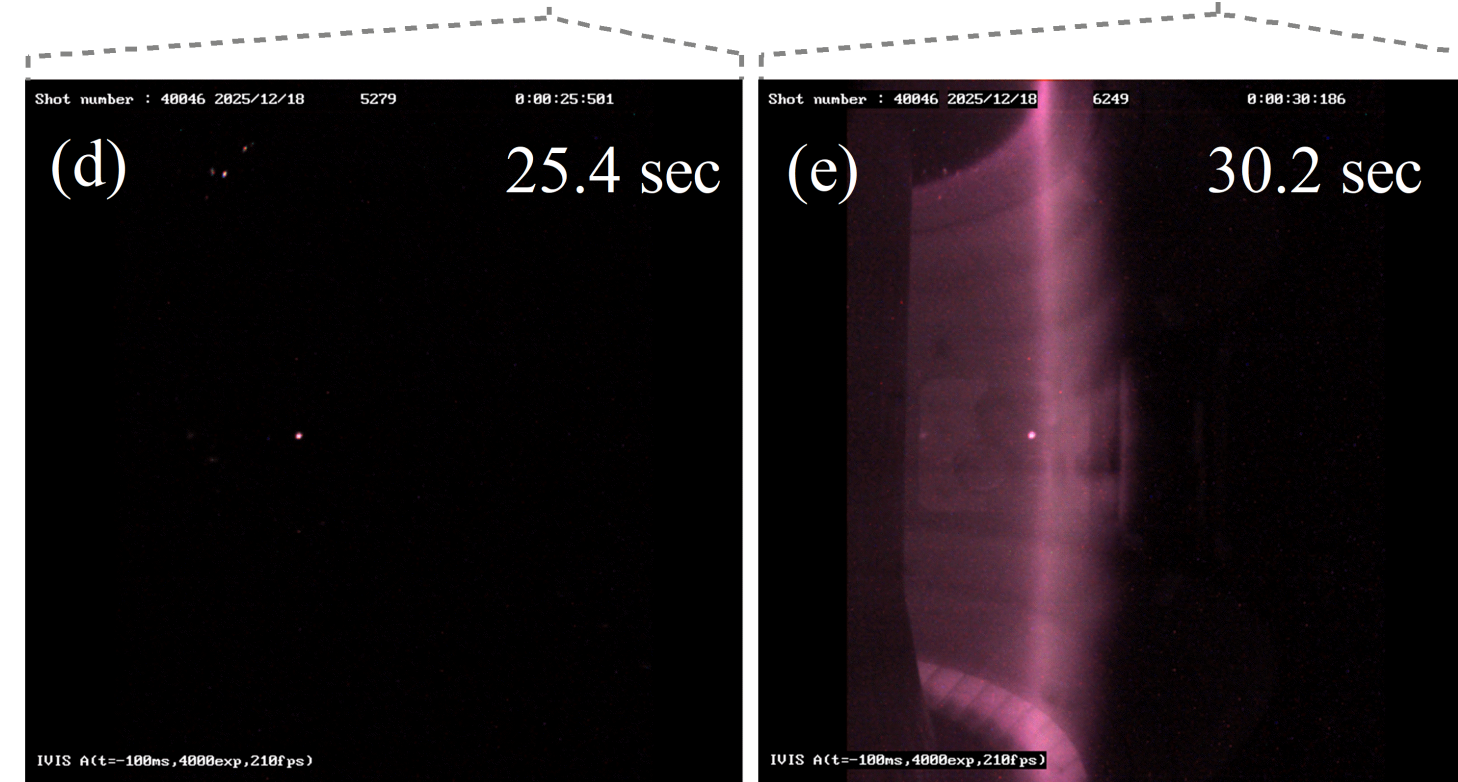
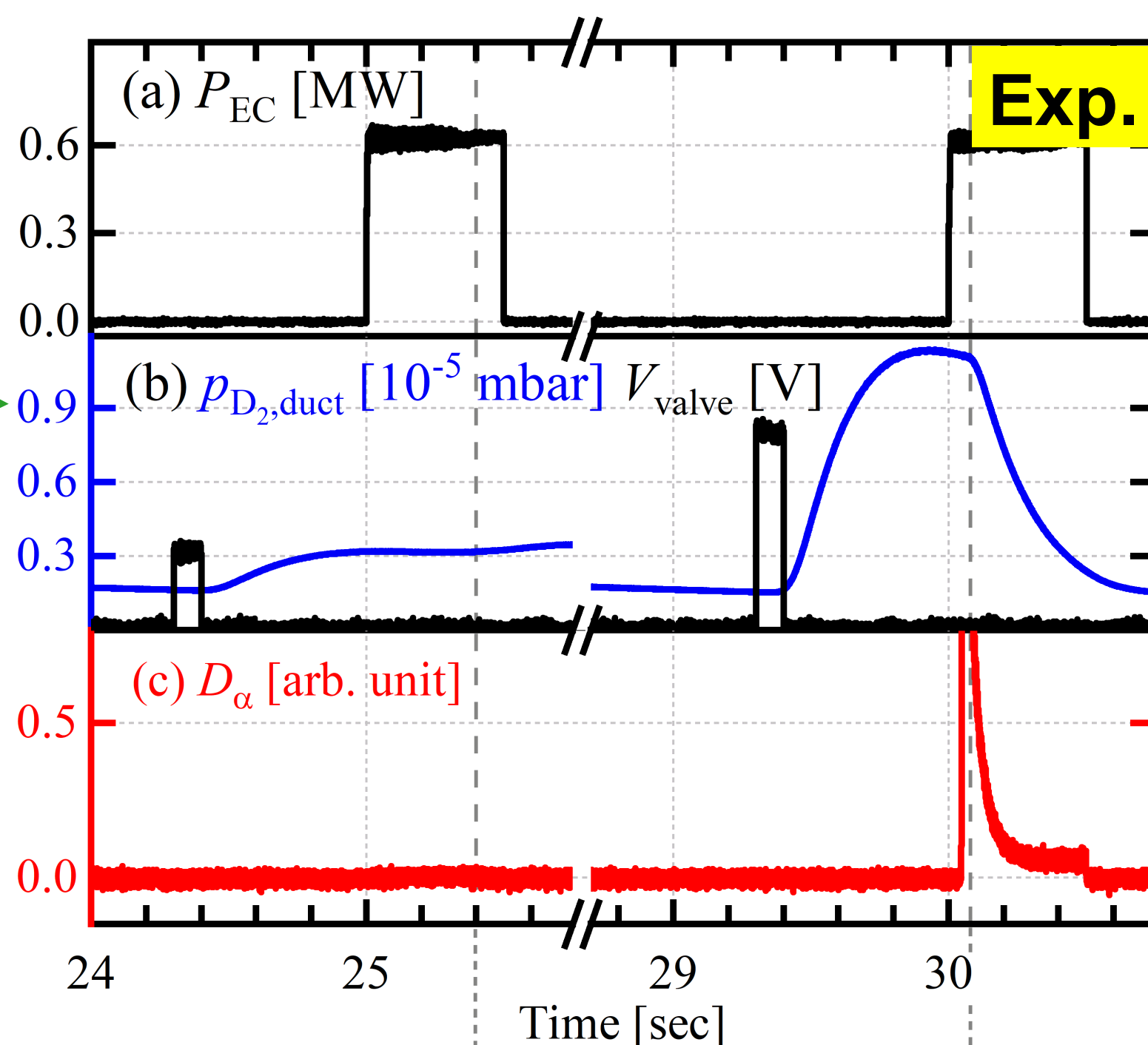
Designed a p_{prefill} scan at two L_c settings in KSTAR



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

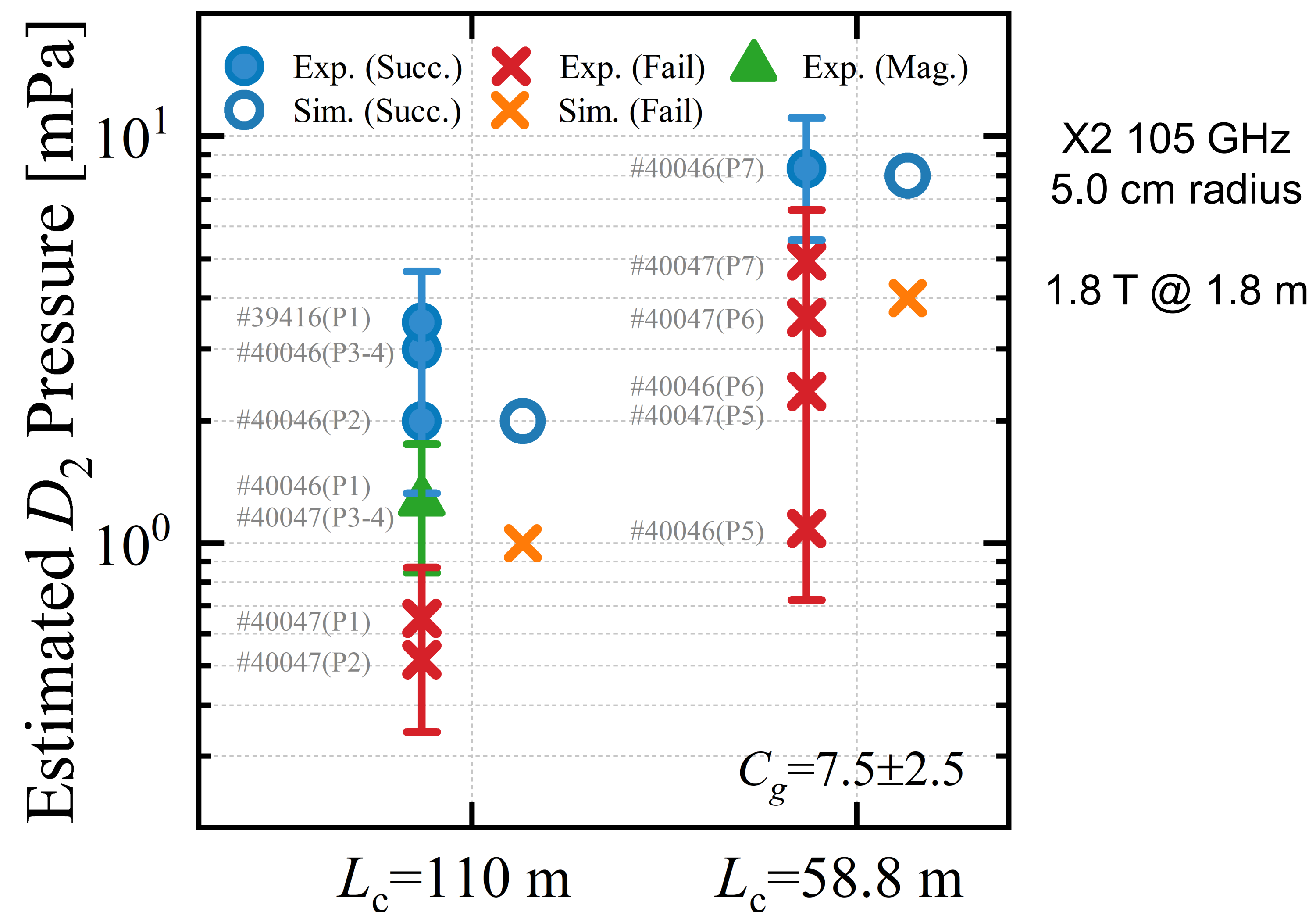
KSTAR's in-house magnetic field code gives I_{PF} to set target L_c

Gas valve calibration gives $V_{\text{valve}}(t)$ 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 D_α : **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

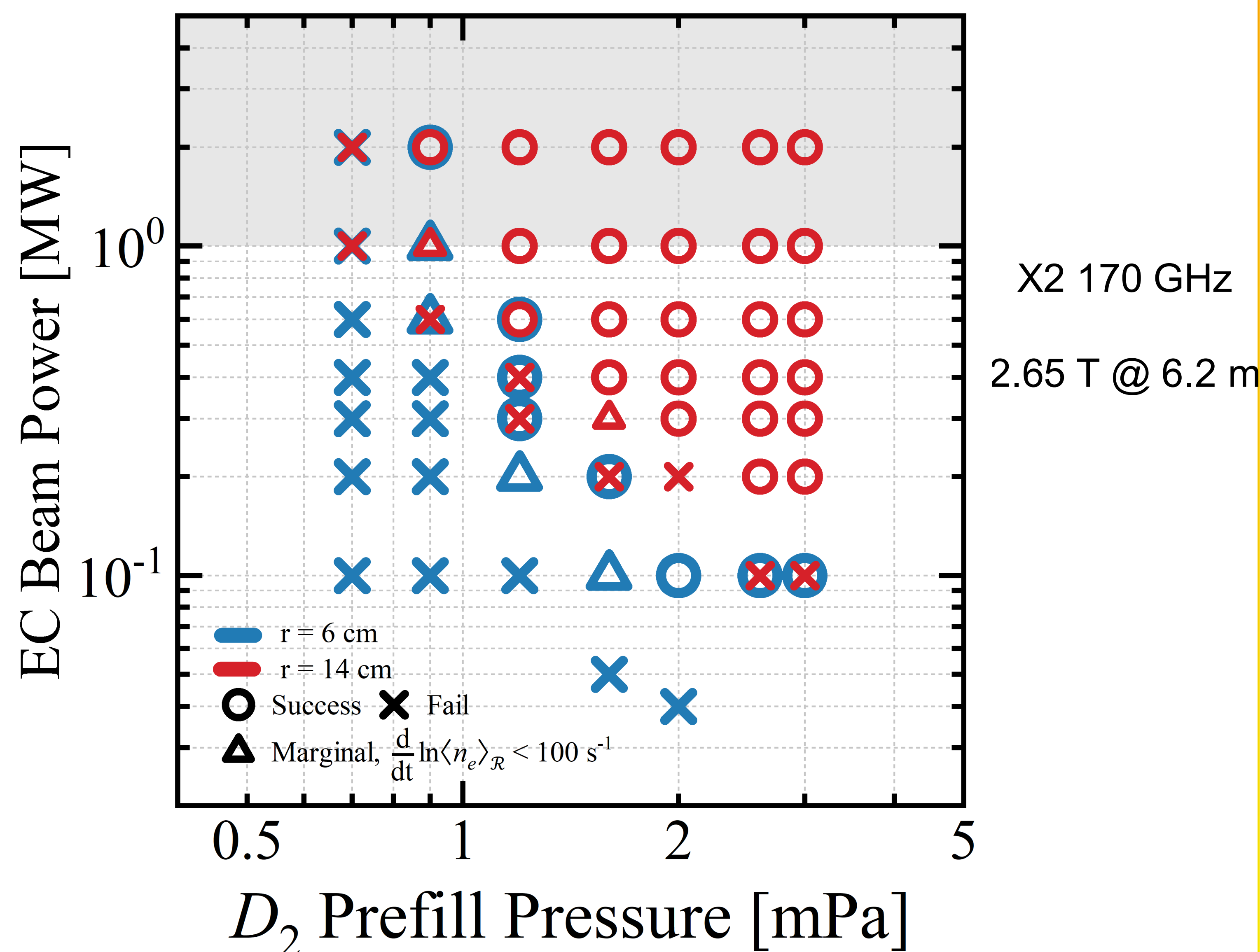


- PIC simulations reproducing the KSTAR conditions started from $n_e = 10^6 \text{ m}^{-3}$ and $T_e = 0.03 \text{ eV}$. A case was classified as **successful** if **sustained multiplication** reached $n_e > 10^{12} \text{ m}^{-3}$ within the 0.5 s EC pulse, and as **failed** otherwise.

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 (\blacktriangle) 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.

[1] P. C. de Vries and Y. Gribov 2019 *Nucl. Fusion* **59**, 096043

[5] H.-T. Kim et al. 2020 *Nucl. Fusion* **60**, 126049 [2] J. Gwak et al. 2025 30th IAEA FEC IAEA-CN-316-2994

[6] J. Sinha et al. 2022 *Nucl. Fusion* **62** 066013 [3] Y. Gribov et al. 2018 45th EPS Plasma Phys. P1.1075

[4] F. Fanale et al. 2021 *Fusion Eng. Des.* **172** 112717