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Plasma Laboratory for Advanced REsearch

A simulation study of Plasma Breakdown in the tokamak EC pre-ionization phase

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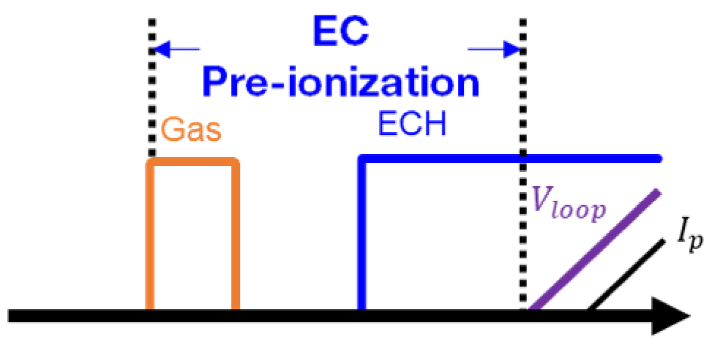
Highlights

- **The absence of a tractable, physics-based model for EC pre-ionization has hindered its systematic consideration in future start-up scenarios.**
- **This work establishes such a framework, for EC-driven plasma breakdown (BD) by coupling a nonlinear EC absorption model [1,2] with the PIC code, BREAK [3].**
- **Mutual verification is achieved with a newly constructed, recast Townsend model, rendering the results interpretable.**
- **A distinct BD threshold, governed by the ionization-loss balance, is identified, from which an operation parameter requirements can be inferred.**

Motivation

- Early injection of EC beam prior to V_{loop} can solely lead to BD, circumventing issues tied to Ohmic BD (e.g. stray B-field sensitivity).



Plasma BD:
- ❑ $n_e \sim 10^6 - 10^{16} m^{-3}$
- ❑ Nonlinear EC
- ❑ Open-B field

- Experiments reveal a minimum power threshold for pre-ionization, a crucial parameter for extrapolation to future devices [5].
- The underlying BD condition—a competition between ionization and particle loss—has been largely unexplored, with prior work focusing only on electron multiplication [6].
- This work self-consistently couples a nonlinear EC model [1,2] with the PIC code BREAK [3] to resolve both of the electron avalanche dynamics and the dominant loss channel.

Core challenge & Approach

- **Nonlinear (NL) EC absorption plays key role for X2 BD**

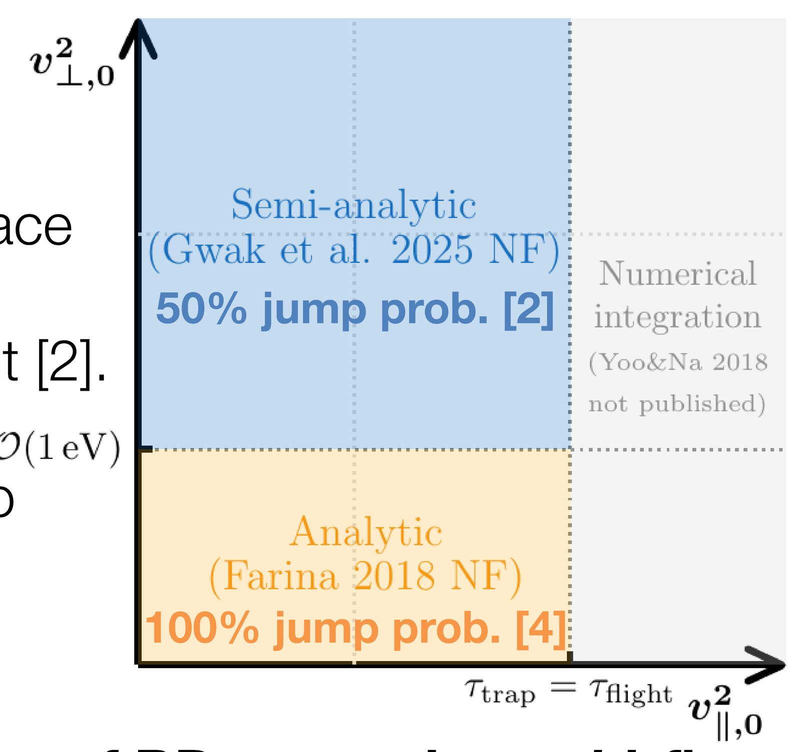
  Linear: $\propto (kr_{L,e})^2 \rightarrow 0$ for cold electrons (0.026eV)

  Nonlinear EC interaction: finite energy gain of $\epsilon m_0 c^2$

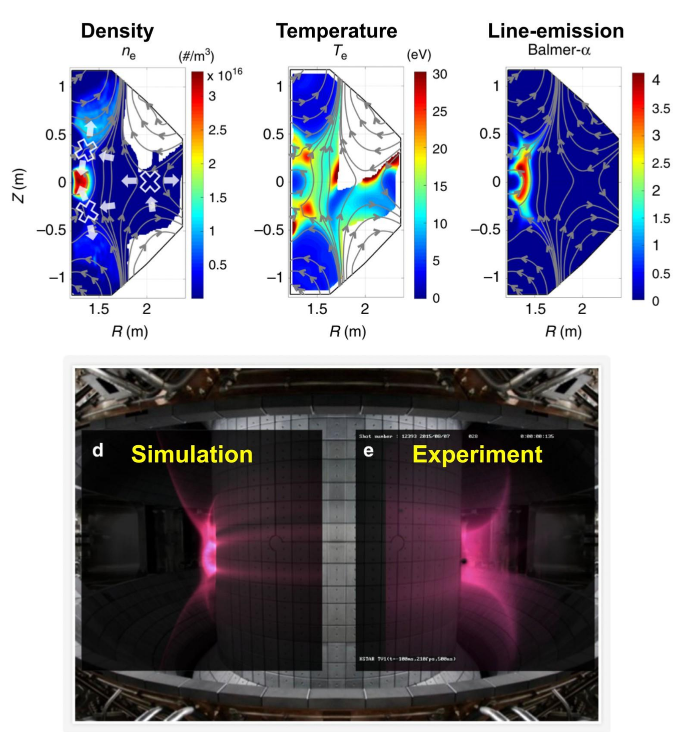
$$H(z,\theta;\bar{P}_z,I) = H_0(\bar{P}_z,I) + H_1(z,\theta;\bar{P}_z,I),$$
$$H_0 = \Gamma - \nu_n I, \quad H_1 = \epsilon(z)\frac{\Theta_n}{\Gamma}\cos n\theta$$

→ "2-DOF Numerical Hamiltonian Integration"

- However, it is heavy and practically not feasible for PIC simulation.
- **Approach**: Developed a fast, phase-space partitioned model using (semi-)analytic formulas based on the adiabatic invariant [2].
- **Impact**: Achieved a significant speed-up ($> 10^4$) in the absorption calculation [2]. (24 hrs on 8 cores → 1.4s on 1core)



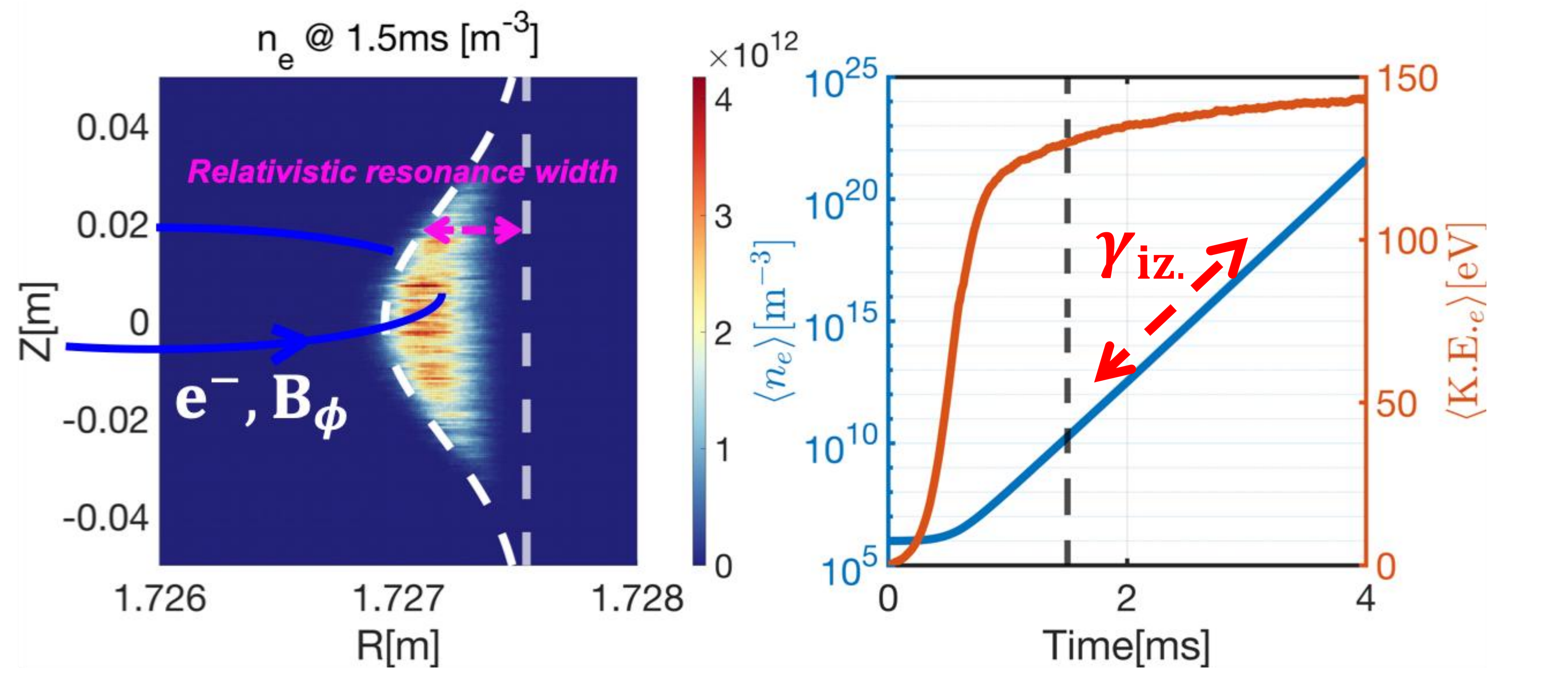
- **Non-equilibrium and open-field nature of BD necessitates hi-fi kinetic simulation**



- **Tool**: The BREAK code, a 3D space+2D velocity PIC-MCC simulation, is employed to capture the relevant multi-scale dynamics [3].
- **Approach**: aforementioned wave-particle EC interaction framework is self-consistently coupled into the BREAK to model the microwave BD.

Fiducial simulation of the EC Avalanche

- Isolating Core Physics: A fiducial, **perfectly confined** (pure B_ϕ, no Loss) simulation focusing on the NL-ECH and $e-n$ collisions.



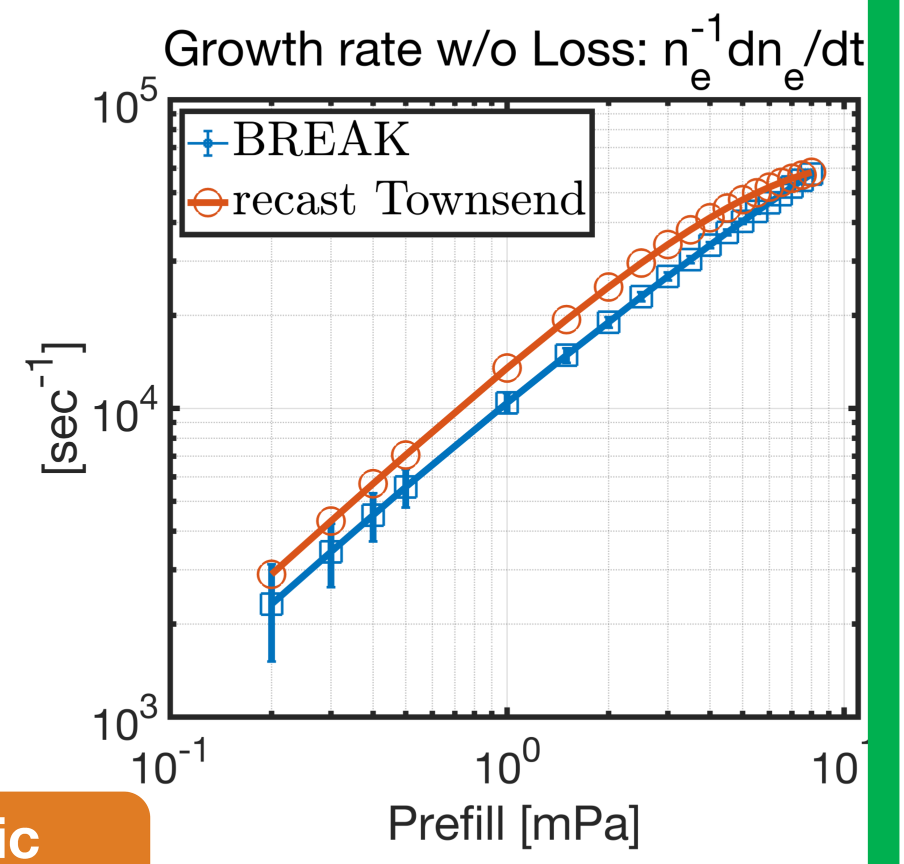
- Avalanche confined to the "radial region" of NL resonance for cold electrons (white dashed line), consistent with prior analysis [4].
- Mean K.E. saturates while n_e grows exponentially [1]; the slope defines the ionization rate, $\gamma_{iz.}$.

Settings: X2, $N_\parallel = 0$, $P_{inj} = 0.6$ MW, $\omega = 2\pi \times 140$ GHz, $r = 0.033$ m, $p_{prefill} = 1$ mPa

Simulation w/o Loss

Mutual verification of Simulated and Theoretical $\gamma_{iz.}$

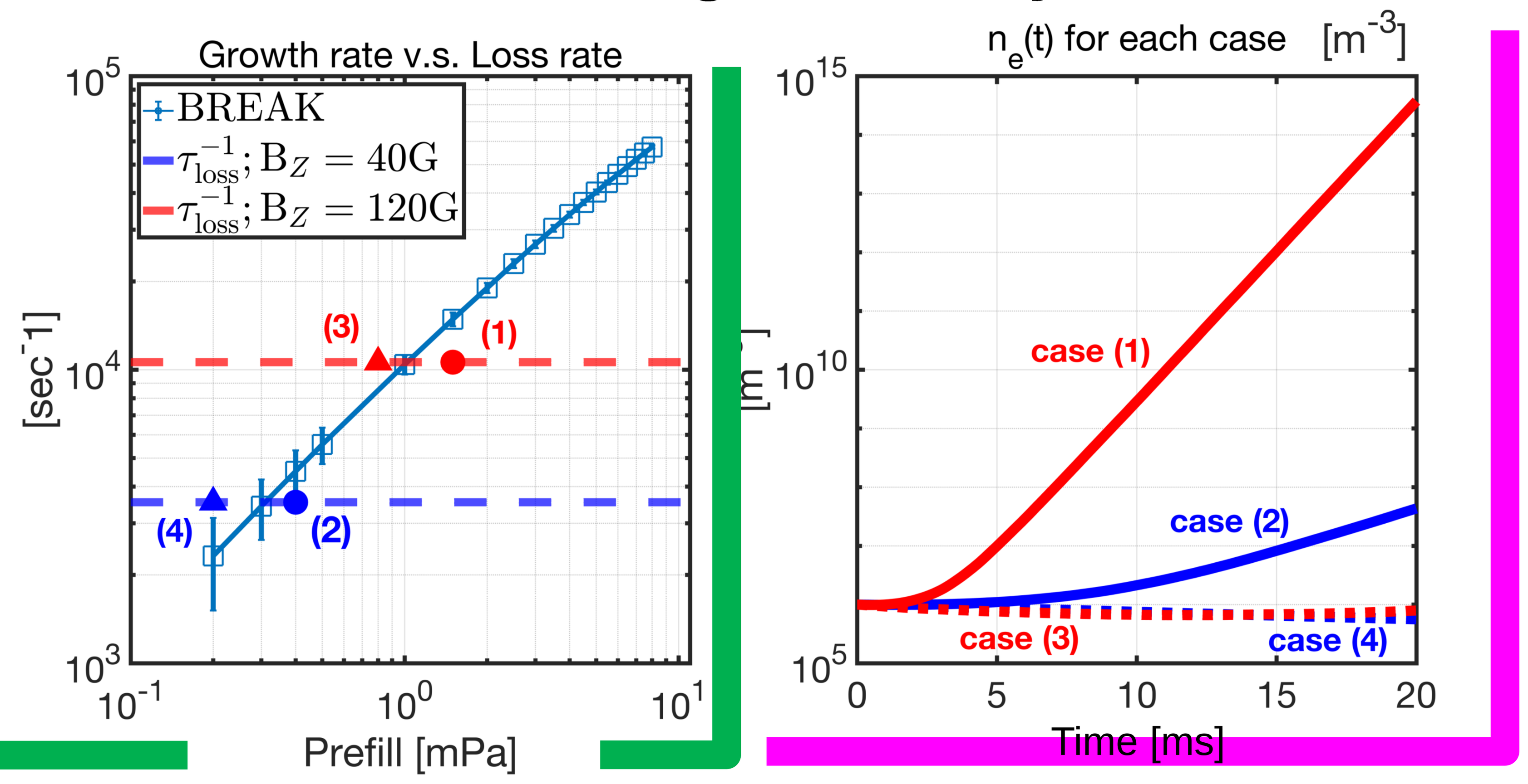
- Verification via a Recast Townsend model: A phenomenological model for the ionization(growth) rate, $\gamma_{iz.}$, is constructed by substituting classical parameters with those pertinent to resonant electrons.
- Qualitative Agreement: Both show that $\gamma_{iz.}$ increases with $p_{prefill}$, underpinning experimental trends, in part [5].
- **Mutual Support**: The consistency between the first-principles particle simulation and the macroscopic model provides a cross-verification of the two disparate approaches.



Microscopic PIC ⇄ **Macroscopic Townsend model**

Simulation w/ Loss

Breakdown Threshold governed by Parallel Loss



- Breakdown condition is constructed by balancing the ionization rate ($\gamma_{iz.}$) against a parallel loss rate (τ^{-1}_{loss}) from a proxy vertical magnetic field, B_Z.
- This competition predicts distinct success/failure cases for the BD, depending on whether $\gamma_{iz.} > \tau^{-1}_{loss}$ or not.
- These predictions are directly corroborated by our simulations that incorporate transport effects.

Loss rate: $\tau^{-1}_{loss} = \left(2\langle W_\parallel\rangle/m_e\right)^{1/2}(B_Z/aB_{\phi,res})$; $a = 1.2$ m; $\langle W_\parallel\rangle = 20$ eV (inferred from simulation)

[1] D. Farina 2018 *Nucl. Fusion* **58**, 066012
[2] J. Gwak et al. 2025 *Nucl. Fusion* **65**, 056038
[3] M.-G. Yoo et al. 2018 *Nat. Commun.* **9**, 3523
[4] D. Farina 2019 *EPJ Web. Conf.* **203** 01001
[5] J. Sinha et al. 2022 *Nucl. Fusion* **62** 066013
[6] Papagiannis P. Ch. et al. 2023 *20th EFTC* P2.25