#751

Nonthermal electron cyclotron emission in marginally stable quiescent runaway electron discharges

Kikyung Park[1], Yeongsun Lee[1], Gunsu Yun[2] and Yong-Su Na[1]*

[1]Department of Energy Systems Engineering, Seoul National University, Seoul, Korea
*ysna@snu.ac.kr [2]Department of Physics and Division of Advanced Nuclear Engineering, POSTECH, Pohang, Korea

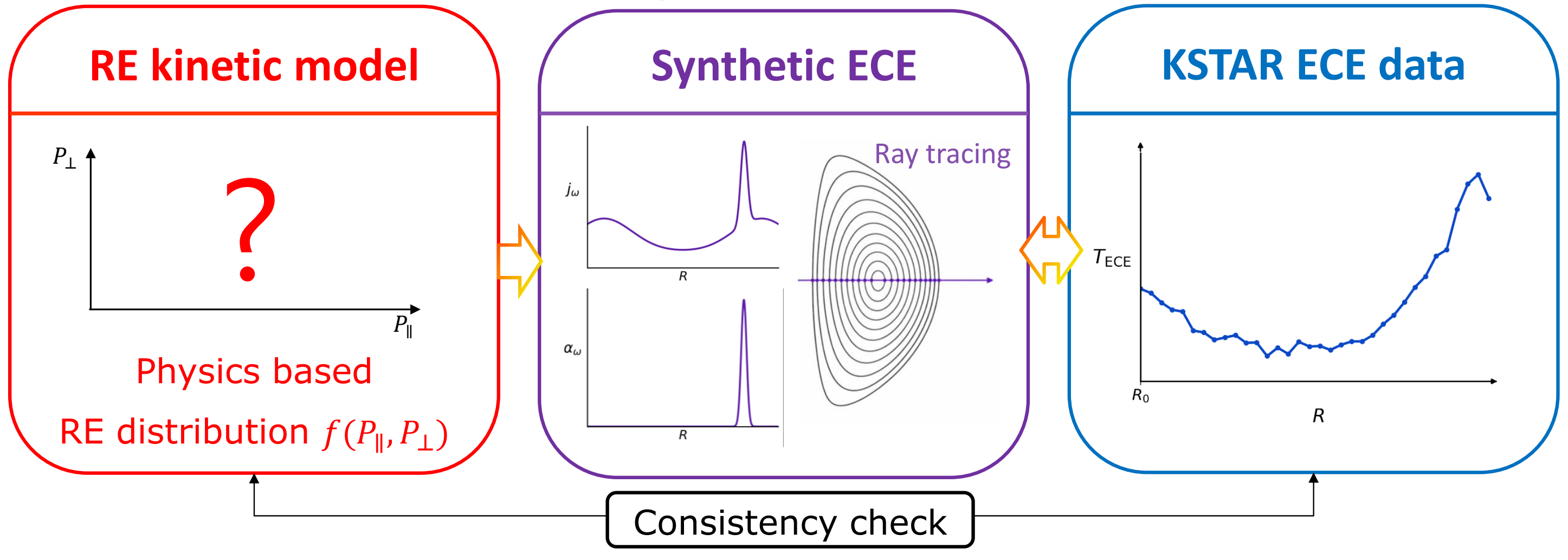
Summary

- A synthetic 1D nonthermal ECE framework was developed to infer RE distribution in tokamak runaway electron discharges.
- A marginal-stability-based RE distribution was used to calculate nonthermal ECE emission and absorption coefficients, which were implemented in SYNO code[1] and applied to pre-burst ECE data from KSTAR QRE discharges.
- The calculated radiative temperature shows qualitative consistency with the observed edge increase in one KSTAR QRE case; this does not necessarily imply the same marginal stability RE-based approach reproduces all strongly nonthermal ECE cases.
- This implies the possibility of inferring the runaway electron distributions assuming continuous whistler wave spectrum in a certain parametric regime.

Introduction & Motivation

❖ Motivation: Why synthetic ECE?

- REs are important in tokamak disruptions, but individual physical processes are difficult to isolate.[2]
- Controlled QRE experiments provide a useful platform to study RE generation, transport, and wave-particle interaction.[3]
- Full RE distribution is not directly resolved by diagnostics.
  - ✓ Diagnostics provide partial or local information.
  - ✓ Nonthermal ECE interpretation is underdetermined.[4],[5]



RE kinetic model

?

Physics based RE distribution $f(P_\parallel, P_\perp)$

Synthetic ECE

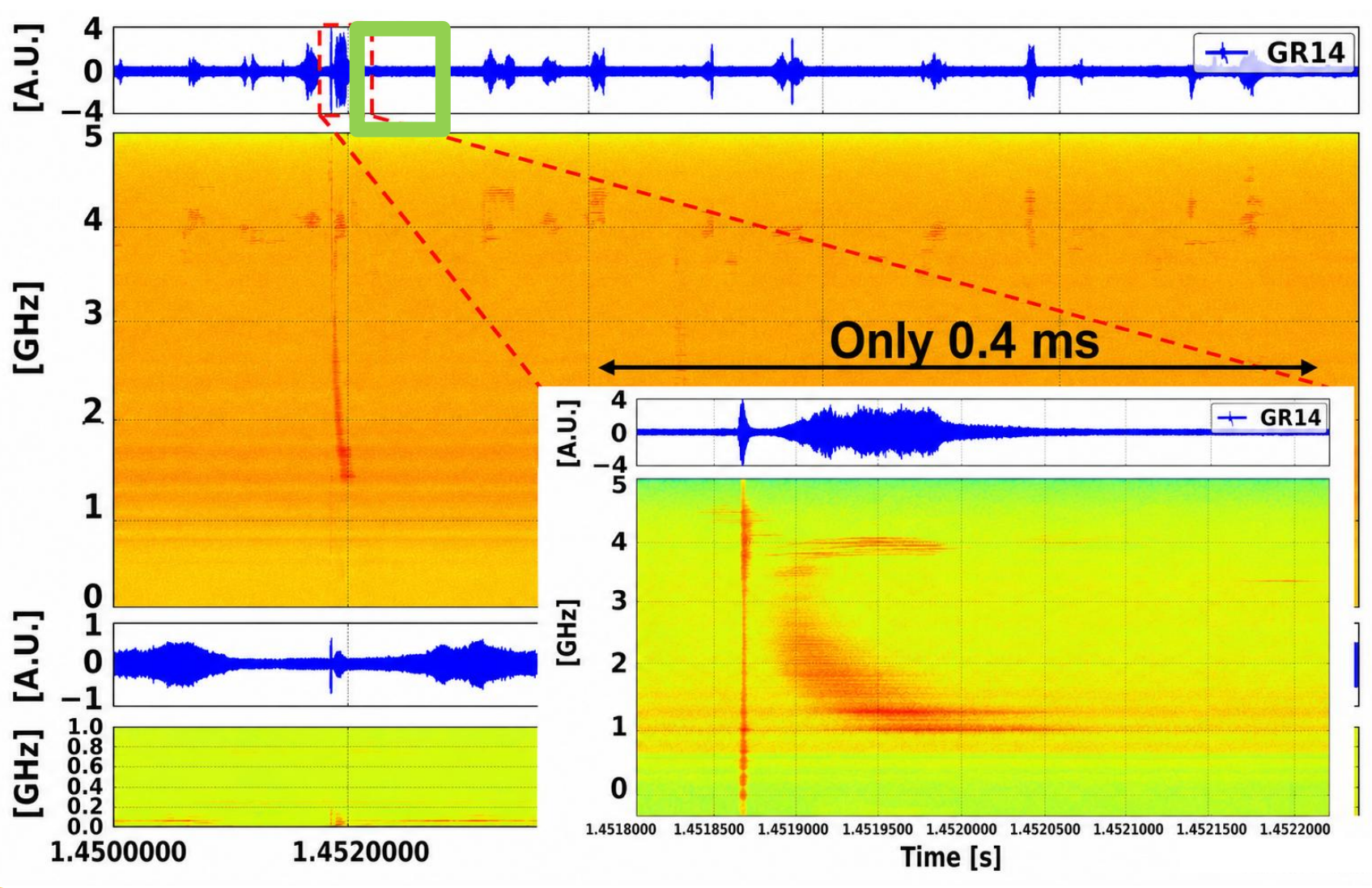
Ray tracing

KSTAR ECE data

Consistency check

Test whether a physics-based RE distribution model is consistent with observed nonthermal ECE behavior.

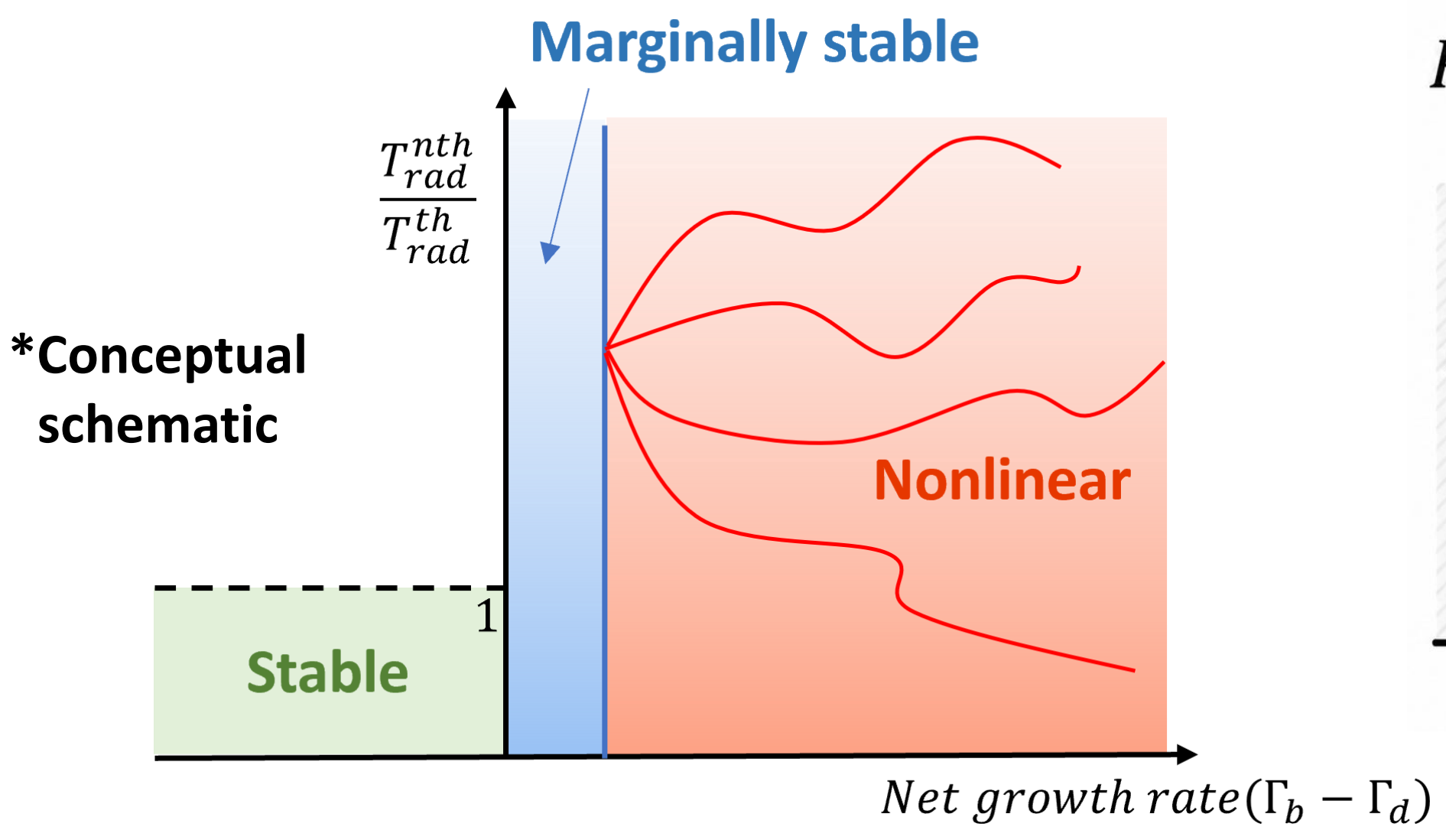
❖ Observation & Target Phase in KSTAR



- Periodic bursting signals in KSTAR ECE/GR channels.
- Target Phase: The flat region prior to the burst onset.

Application of Breizman Marginal Stability RE Model to Synthetic ECE

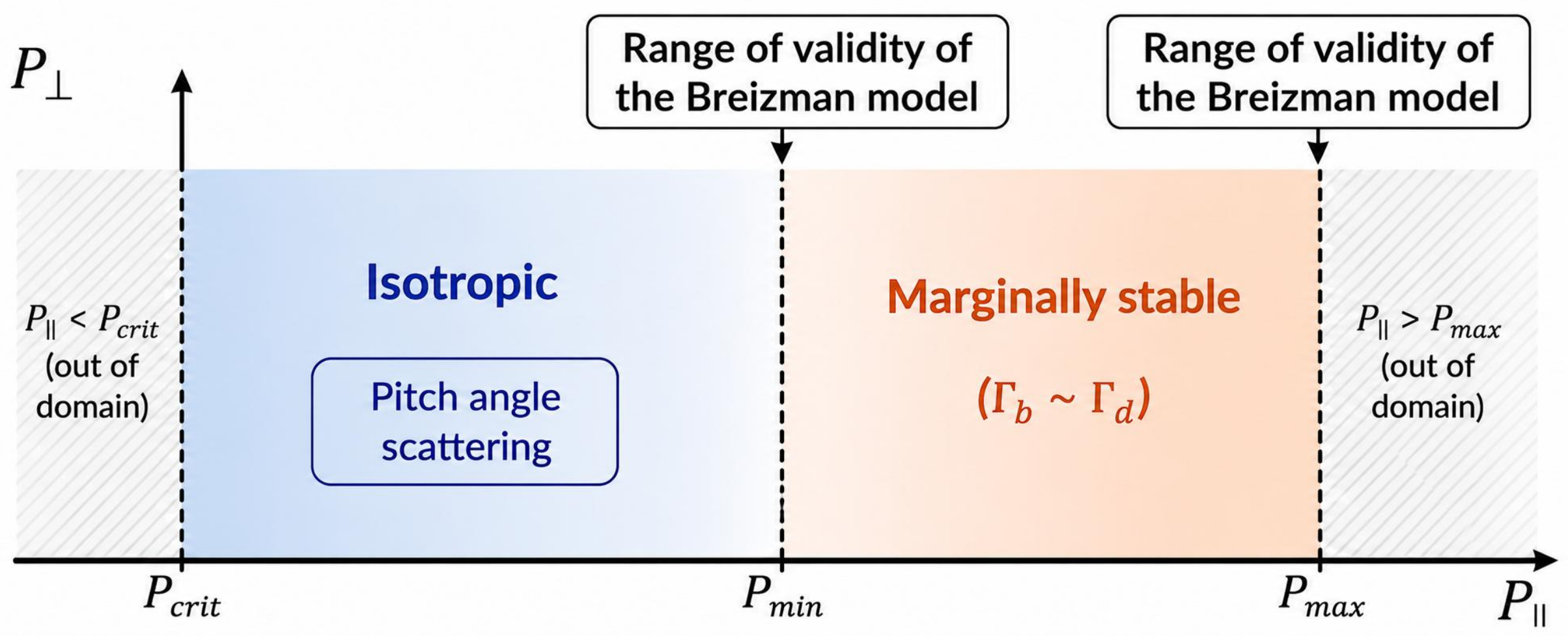
❖ Breizman marginal stability RE model[6]



- Marginal Stability: RE-driven whistler growth balances wave damping ($\Gamma_b \approx \Gamma_d$).
- Assumption : Continuous wave spectrum.
- RE distribution before strong nonlinear bursting.

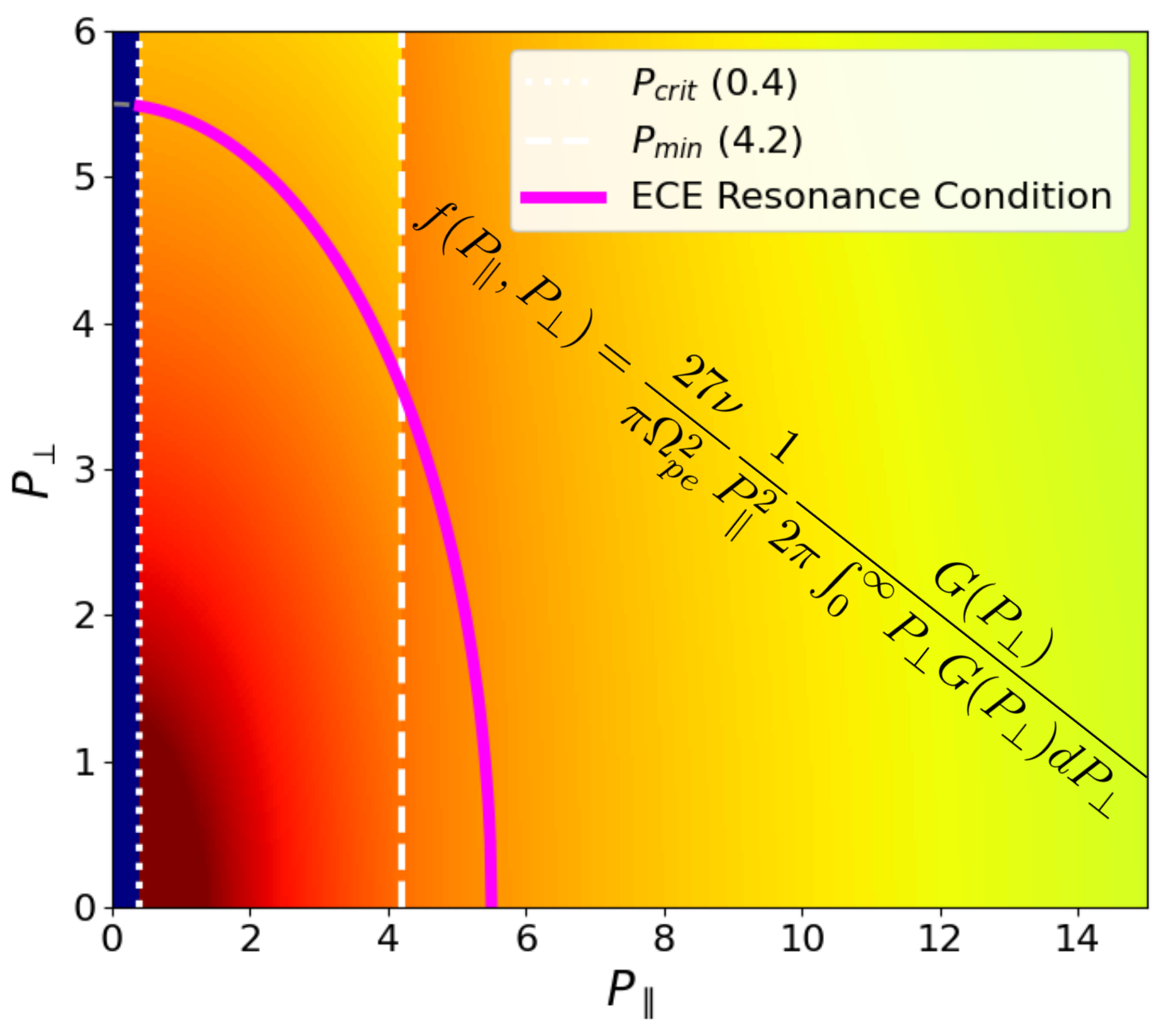
$$f(P_\parallel, P_\perp) = \frac{27\nu}{\pi\Omega_{pe}^2}\frac{1}{P_\parallel^2}\frac{G(P_\perp)}{2\pi\int_0^\infty P_\perp G(P_\perp)dP_\perp}$$

❖ Phase space modeling



- High P region: $P_{min} < P_\parallel < P_{max}$
  - ✓ Wave-driven scattering balances RE drive, giving the marginally stable RE distribution. $F(P_\parallel) \propto P_\parallel^{-2}$
- Intermediate Low-P region: $P_{crit} < P_\parallel < P_{min}$
  - ✓ Particle flux is inferred from the boundary P_{min}, and assumed to be constant from P_{crit} to P_{min} due to free acceleration.
  - ✓ To estimate the maximum nonthermal effect, we adopt the isotropic pitch-angle distribution.

❖ Nonthermal ECE Coefficient using the marginally stable RE Distribution function



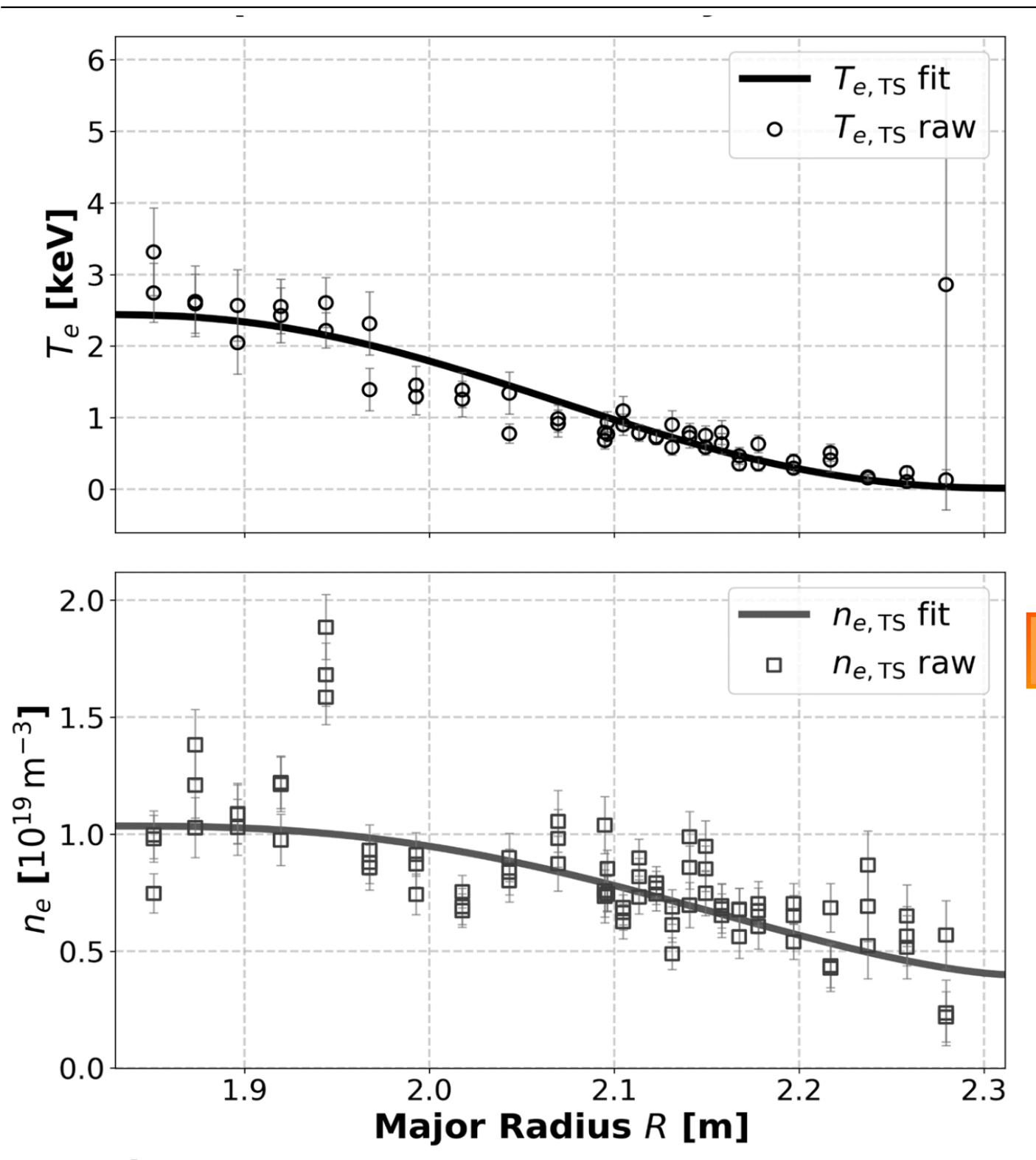
Calculate nonthermal ECE coefficients
$f_{RE} \rightarrow j_w, \alpha_w$

Nonthermal ECE coefficient (marginally stable RE)

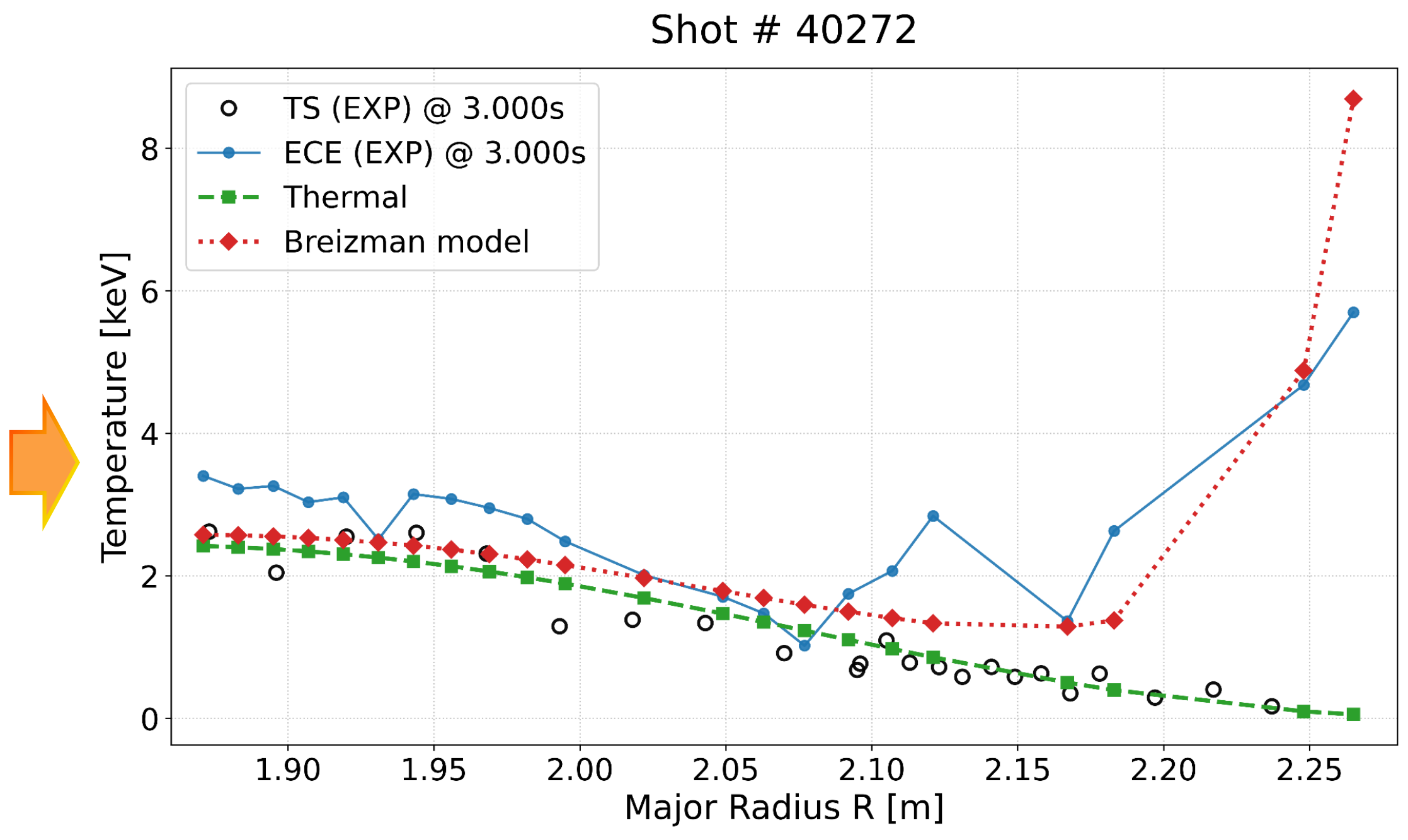
$$\alpha_{mRE} = C_\alpha \sum_{l=1}^{N} \int_{P_{\perp,min}}^{P_{\perp,max}} dP_\perp \left[P_\perp \gamma_{res} \mathcal{J}_\delta \Xi_l \left(-\frac{2P_\perp}{P_{\parallel,res}^2 P_s^2} G'(x)\right)\right]$$

$$j_{mRE} = C_0 \sum_{l=1}^{N} \int_{P_{\perp,min}}^{P_{\perp,max}} dP_\perp \left[P_\perp \mathcal{J}_\delta \Xi_l \left(\frac{G(x)}{P_{\parallel,res}^2}\right)\right]$$

Shot #40272: Qualitative Reproduction of Nonthermal ECE



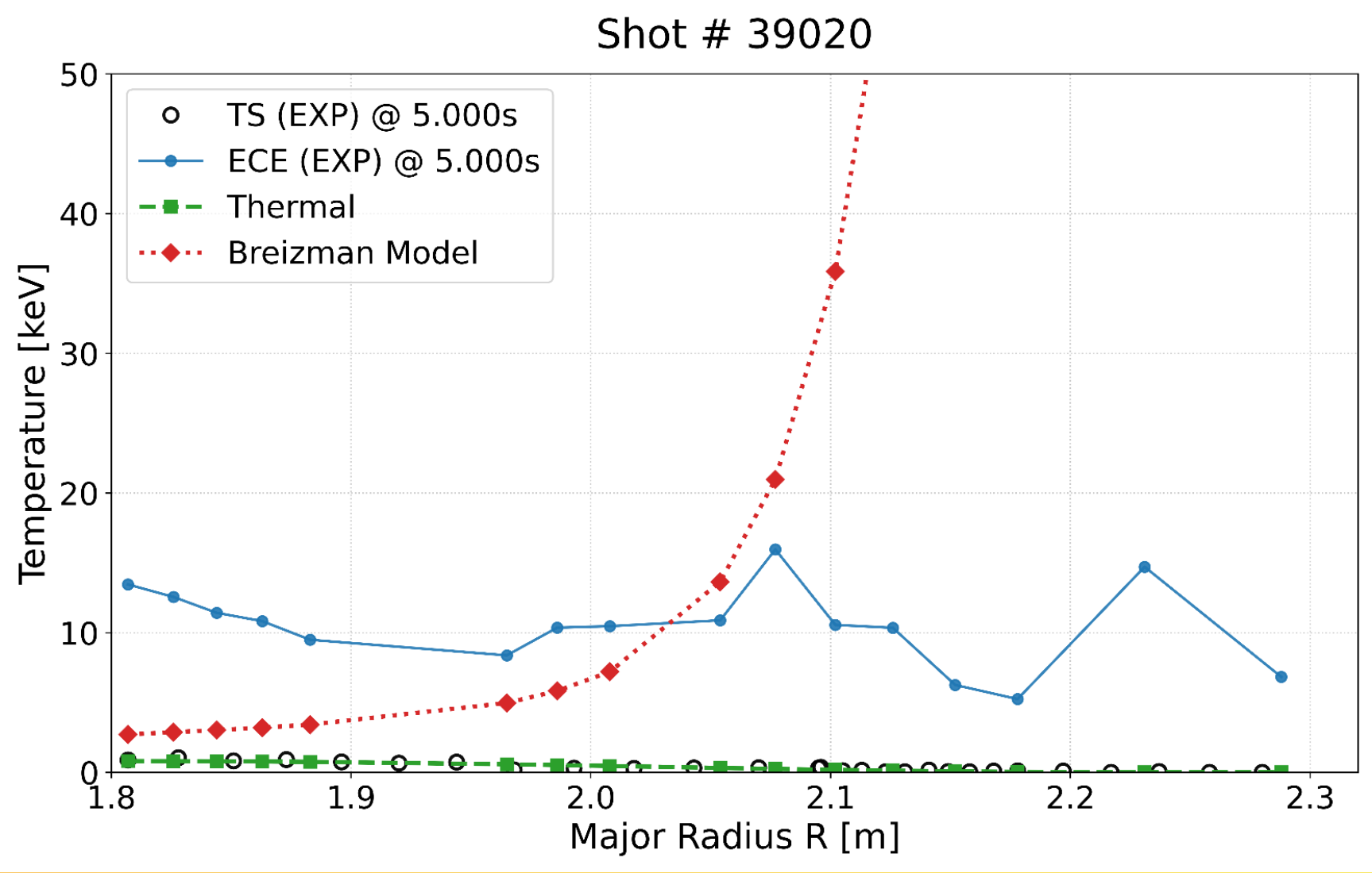
$I_p = 500kA, B_T = 3.0T$



- Thermal-only ECE cannot reproduce the radiative temperature in #40272.
- The calculated radiative temperature qualitatively captures the observed edge increase (R>2.1m).

→ Shot #40272 is qualitatively consistent with the present whistler/anomalous-Doppler interaction model.

Shot #39020: Discrepancy from the Present Model



$I_p = 350kA, B_T = 1.8T$

- Shot #39020 shows a stronger core-edge profile difference under the same modeling approach.
- The calculated radiative temperature underestimates the core signal and overestimates the edge.

Assessing Model Applicability with Cross-Shot Comparison

- **Possible cause of the discrepancy 1: RE population profile**
  - ✓ Core RE contribution may be underestimated, while the edge contribution may be enhanced by the low-P isotropic modeling and flux matching.
- **Possible cause of the discrepancy 2: Wave spectrum regime**
  - ✓ #39020 may lie outside the continuous whistler spectrum assumption, possibly involving discrete resonances or slow-X-related dynamics[7].

Conclusions

- Breizman marginal stability RE model is applied to KSTAR QRE ECE analysis for the first time, and the qualitative agreement in #40272 suggests the potential of nonthermal synthetic ECE to characterize the RE distribution in a regime where the continuous wave spectrum assumption is applicable.
- Confirmation of the inferred RE distribution requires additional constraints from complementary diagnostics, such as IR imaging, hard-X-ray imaging, and wave-spectrum measurements.
- This approach provides a physics-based diagnostic constraint on the RE distribution relevant to wave-particle instability studies.
- The radial profiles of the nonthermal ECE intensity disagree in shot #39020. Future work is to elucidate why qualitative agreement is observed in #40272 but not in #39020.

References

[1] Y. Lee *et al.,* arXiv:2604.26034 (submitted to Phys. Plasmas)
[2] B. N. Breizman *et al.,* 2019 *Nucl. Fusion* **59** 083001
[3] C. Paz-Soldan *et al.,* 2014 *Phys. Plasmas* **21** 022514
[4] S. K. Rathgeber *et al*., 2013 *Plasma Phys. Control. Fusion.* **55** 025004
[5] C. Liu *et al.,* 2018 *Nucl. Fusion* **58** 096030
[6] B. N. Breizman *et al.,* 2023 *Phys. Plasmas* **30** 022301
[7] Q. Zhang *et al.,* 2026 *Phys. Rev. E* **113** L043203

Acknowledgement

This research was supported by R&D Program of "Optimal Basic Design of DEMO Fusion Reactor, CN2602-2" through the Korea Institute of Fusion Energy(KFE) funded by the Government funds. This research was supported by the National Research Foundation (NRF) funded by the Korean government (MSIT) (No. RS-2026-25545529). This work was supported by Hyundai Motor Chung Mong-Koo Foundation.

52nd EPS Plasma Physics Conference 2026, EICC, Edinburgh, UK