Mechanical and
Aerospace
Engineering

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Nonlinear MHD modeling on RMP-induced pump-out in KSTAR with realistic tokamak geometry

S.K. Kim[1,2], N. Logan[3], M. Becoulet[4], M. Hoelzl[5], Q. Hu[2], G. Huijsmans[4], S. Pamela[6], Q. Yu[5], S.M. Yang[2], E. Kolemen[1,2], J.-K. Park[2], and JOREK team**

[1]*Princeton University, USA*
[2]*Princeton Plasma Physics Laboratory, USA*
[3]*Lawrence Livermore National Laboratory, USA*
[4]*Department of plasma physics, CEA, France*
[5]*Max Planck Institute for Plasma Physics, Germany*
[6]*Culham Centre for Fusion Energy, U.K*

E-mail: sk42@princeton.edu

Princeton Plasma Control
control.princeton.edu

**M. Hoelzl et al., *Nucl. Fusion* 61, 065001(2021)

Outline

- **Introduction**

  - Bifurcating pump-outs by RMPs.
  - Nonlinear modeling with toroidal effect.

- **Method**

  - JOREK (nonlinear 3D MHD) and PENTRC (NTV) code coupling.

- **Result**

  - Pump-out: Led by field penetration (island opening).
  - 1st pump: ExB flow damping, polarization, and NTV.
  - 2nd pump: Mode overlap and stochastization.
  - Additional case: dR_{sep} effect can be reproduced.

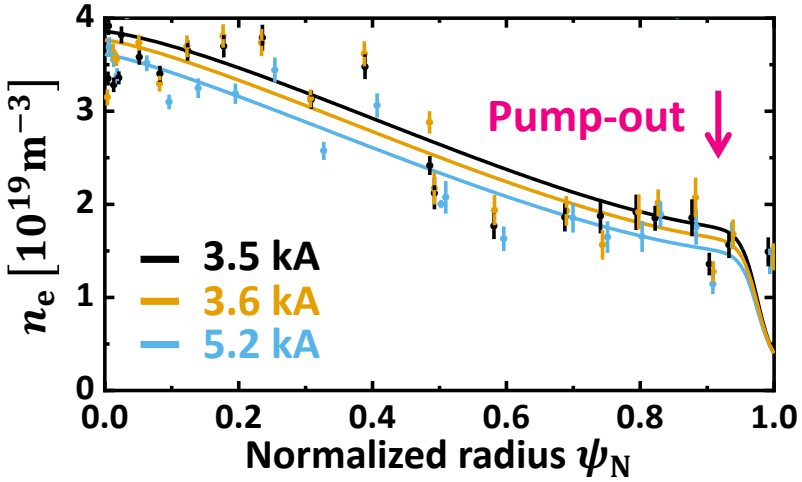
- **Conclusion**

RMPs are promising method to stabilize the unfavorable ELMs
Understanding its effect on the density pedestal is important

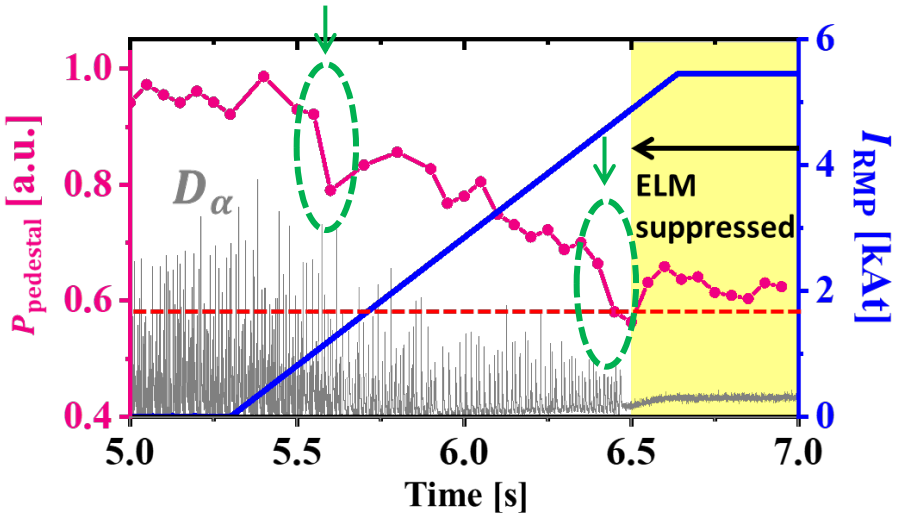
- **ELM control via resonant 3D field perturbations**
  - ✓ Resonant magnetic field perturbations (RMPs) [T. Evans 04]
    - 3D field using external field coils (I_{RMP}).
    - Suppressing ELMs by degrading the pedestal.

- **RMP-induced edge transport**
  - ✓ Degrading the pedestal.
    - Threshold characteristic: Bifurcation.
  - ✓ Prominent reduction in density pedestal ($n_{\mathrm{e,ped}}$).
    - Pump-out.
  - ✓ Pump-out mechanism: Challenging question.

    → Important for understanding/predicting ELM supp.



[Degraded density pedestal by increasing RMP, I_{RMP}]

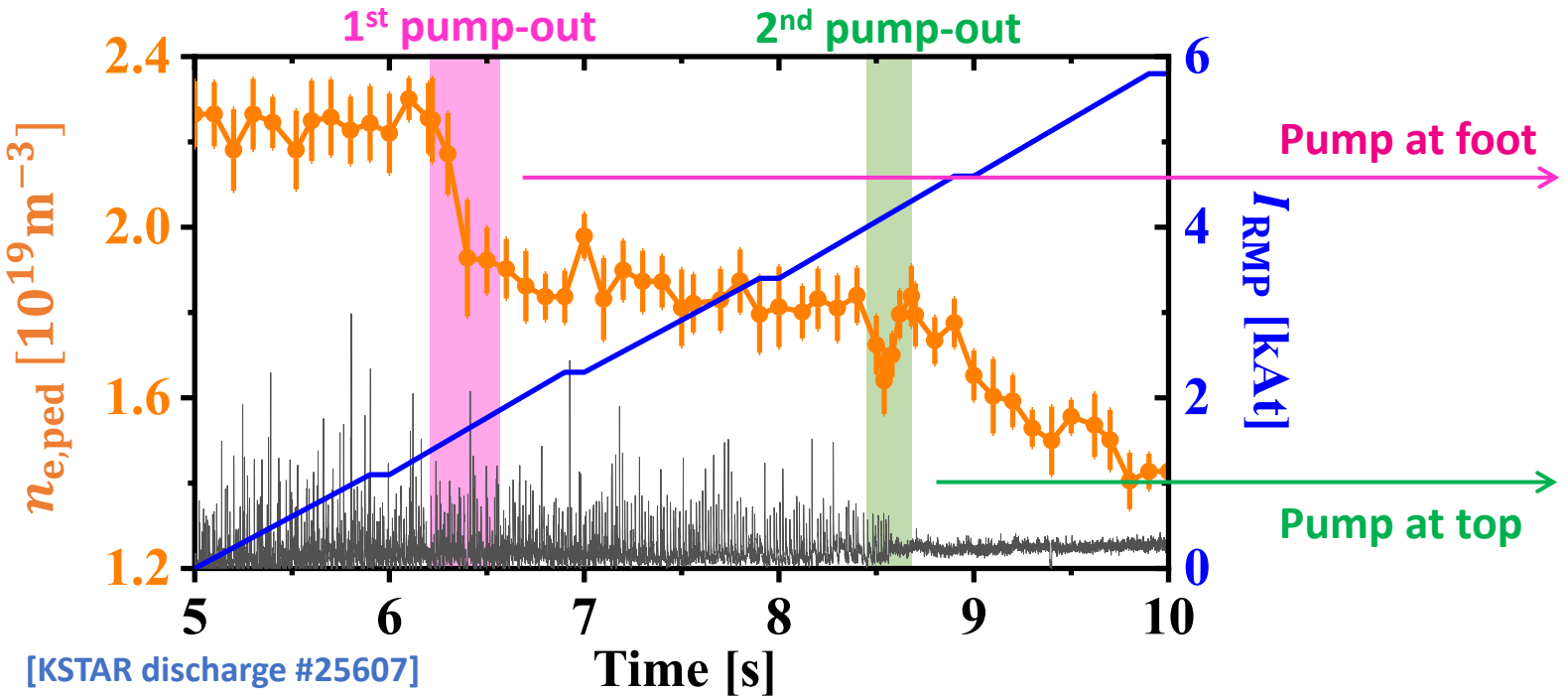


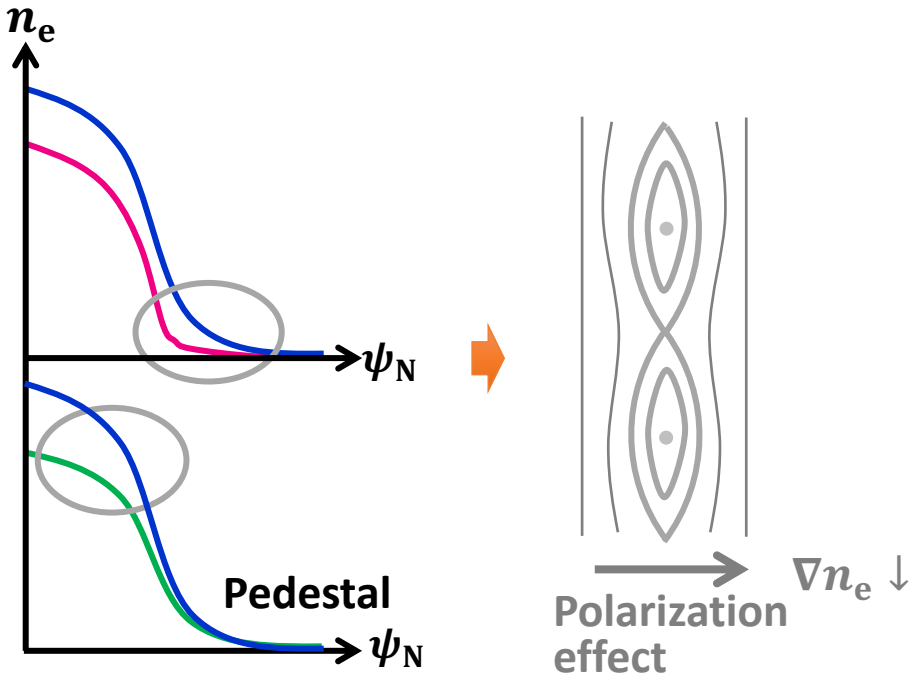
[Degraded pedestal height by increasing RMP, I_{RMP}]

Recent reduced geometry simulation reveals strong connection between bifurcating transport and RMP penetration (island opening)

- **Pump-out by bifurcating field penetration**
  - ✓ RMP shielding by plasma response.
  - ✓ Bifurcating field penetration by overcoming the shielding.
  - ✓ 1st (foot) and 2nd (top) pump-out [TM1, Q. Hu 2020].
  - ✓ Pump-out: Particle transport on island by polarization effect.

➡ **This talk introduces…**
Validation in realistic toroidal geometry with n=1 KSTAR RMP:
Role of toroidal effect.





Toroidal effect can induce additional particle transport mechanism and mode coupling effect

- **Toroidal effect on RMP modelling**
  - ✓ **Particle transports.**
    - **Ion Neoclassical toroidal viscosity (NTV)** [Liu 2020].
  - ✓ **Mode coupling.**
    - **Toroidal mode coupling** [Becoulet 2014].

- **Utilization of hybrid-particle equation**
  - ✓ **Polarization effect (Electron) / Ion-NTV effect (Ion).**
  - ✓ **Heuristic approach: Hybrid equations based on $n_e = n_i$.**
  - ✓ **Numerically valid by omitting NTV torque in momentum equation.**

➢ **Dedicated NTV implementation will be included in future work.**

$$\partial_t n = -\nabla \cdot n\left(\vec{v}_{\perp,\mathrm{e}} - \vec{v}_{\parallel,\mathrm{i}}\right) + \nabla \cdot (D_\perp \nabla n) + S_\mathrm{n} + \frac{1}{e}\nabla \cdot \vec{J}_\parallel + \nabla \cdot \vec{\Gamma}_\mathrm{NTV}$$

Electron density equation — **Polarization** — **Ion NTV** — **Hybrid equation**

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JOREK and PENTRC coupled simulation is developed for nonlinear modeling of RMP-induced pump-out including plasma response and NTV transport

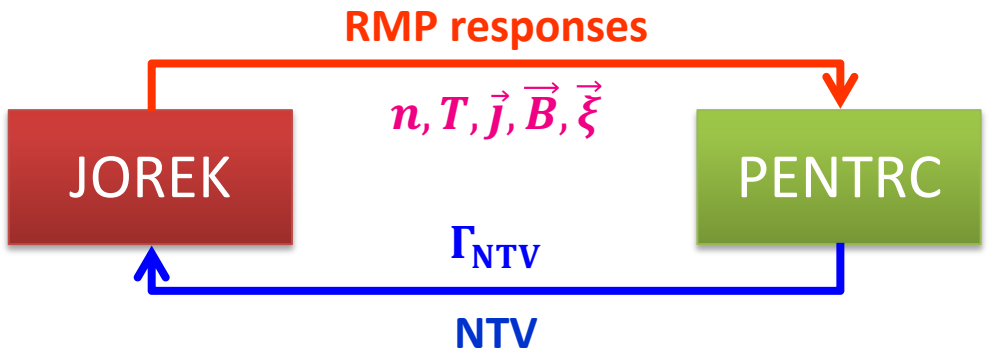
- **JOREK (3D Nonlinear MHD)** [G. Huysmans 09, M. Hoelzl 21]
  - ✓ Realistic geometries with SOL.
  - ✓ 5-fields reduced resistive-visco MHD equation [F. Orain 2013].
  - ✓ Heuristic hybrid density equation.

    w/ diamagnetic + toroidal flow
    w/ heuristic mean neoclassical viscosity
    w/ $T_\mathrm{i} = T_\mathrm{e}$ (single temperature)

	TM1	JOREK	M3D-C1
Geometry	Cylinder	Toroidal	Toroidal
MHD	Reduced	Reduced	Full

Physics →
Simpler ←
Cheaper ←

- **PENTRC (NTV)** [N. Logan 2013]
  - ✓ NTV with RMP response.
  - ✓ RMP response: Equilibrium, profiles, displacement (ξ).

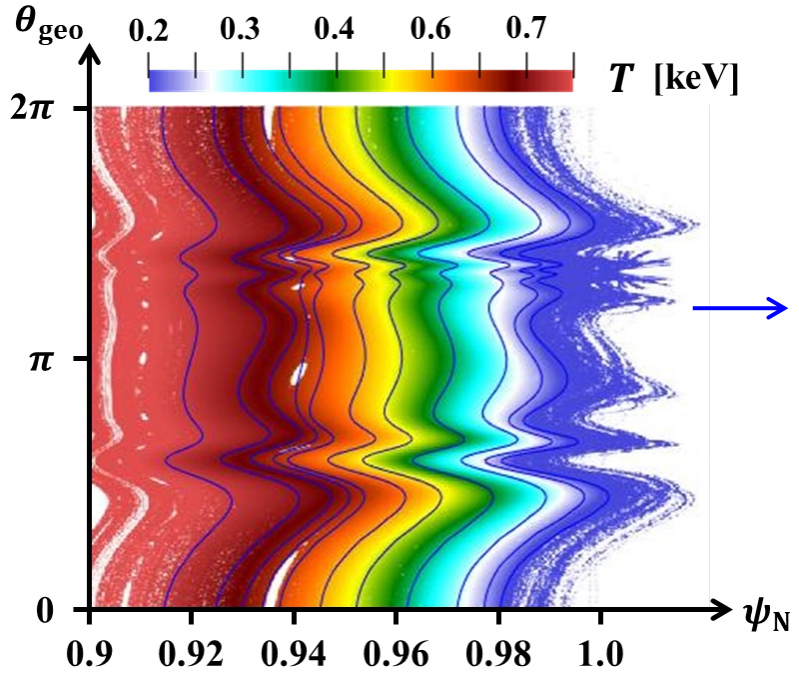


[Schematic of JOREK-PENTRC coupling]

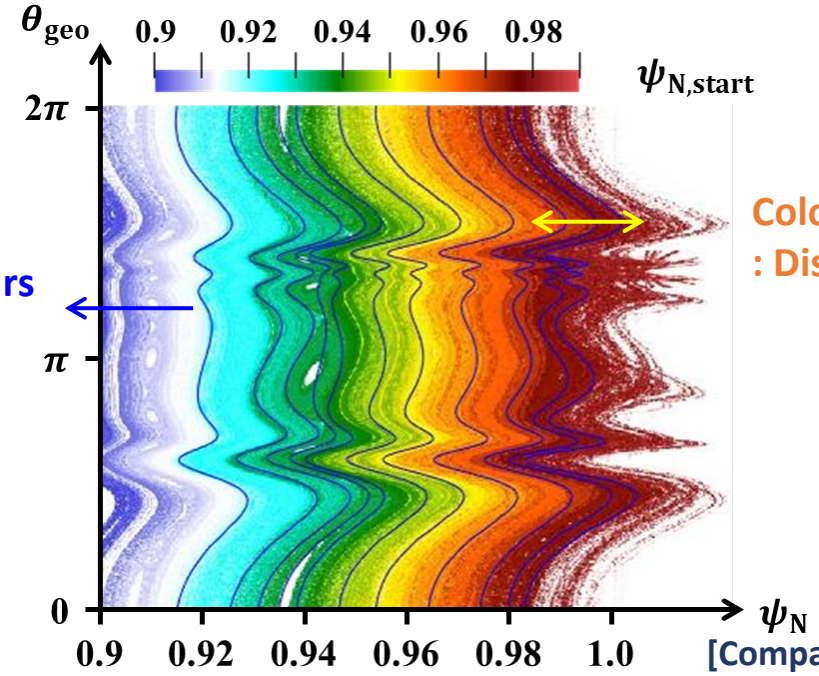
Plasma displacement is derived using semi-linear approximation to calculate NTV flux

- **Approximated displacement from nonlinear perturbation**
  - ✓ Displacement ($\xi_\perp$) using temperature T [N. Ferraro 13].
  - ✓ ξ_α : Linear toroidal force balance $F[\xi_\alpha, \xi_\perp]$ [J.-K. Park 09].
  - ✓ Becomes <u>less accurate</u> under strong stochasticity.

$$\xi_\perp \sim -\frac{\delta T}{\nabla T_{n=0}}$$



Blue contours
$\xi_\perp$ by δT



Color gradation
: Displacement ($\xi_\perp$)

[Comparison of T and $\xi_\perp$ in Poincare plot]

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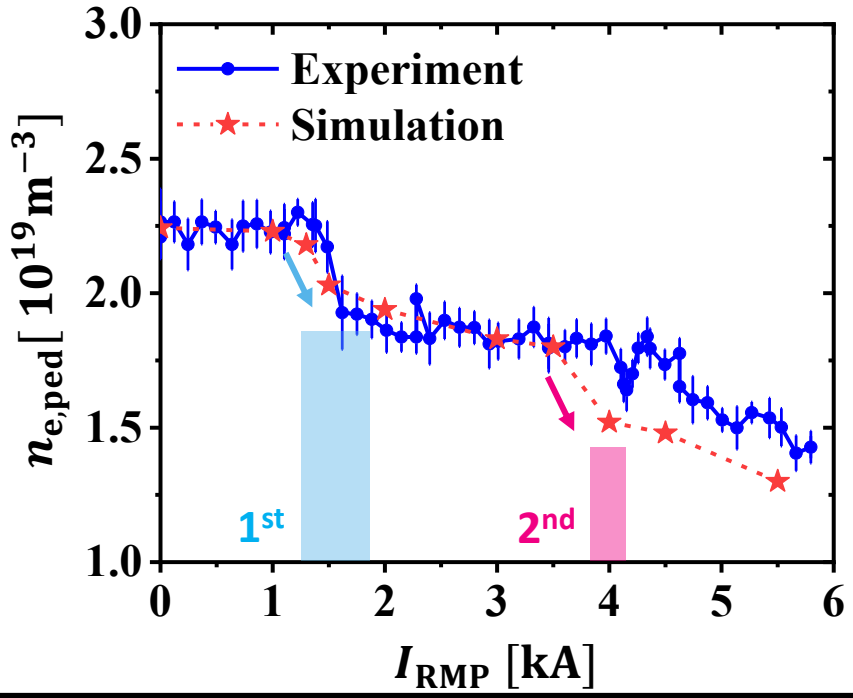
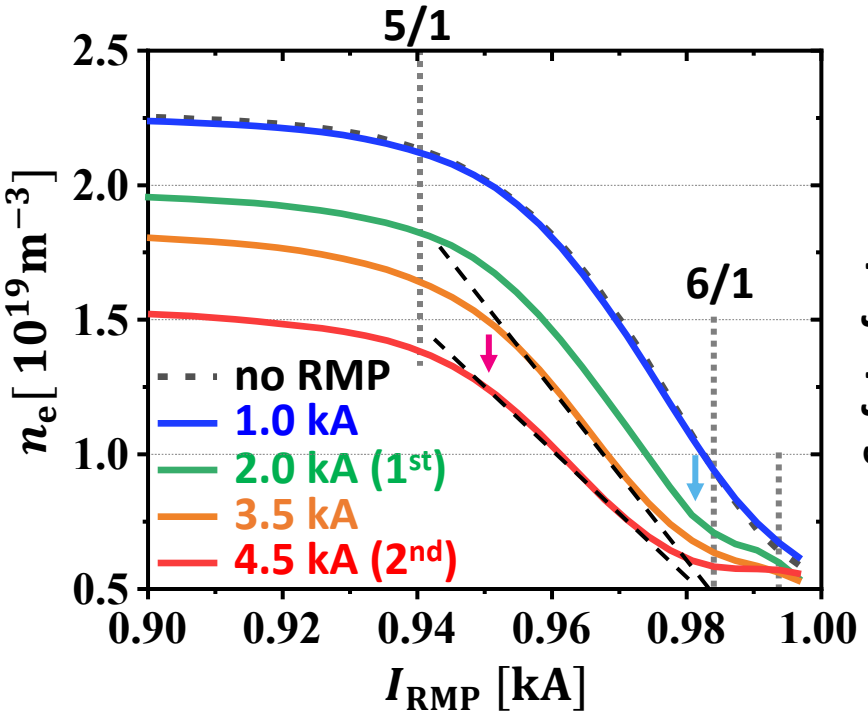
  - Pump-out:

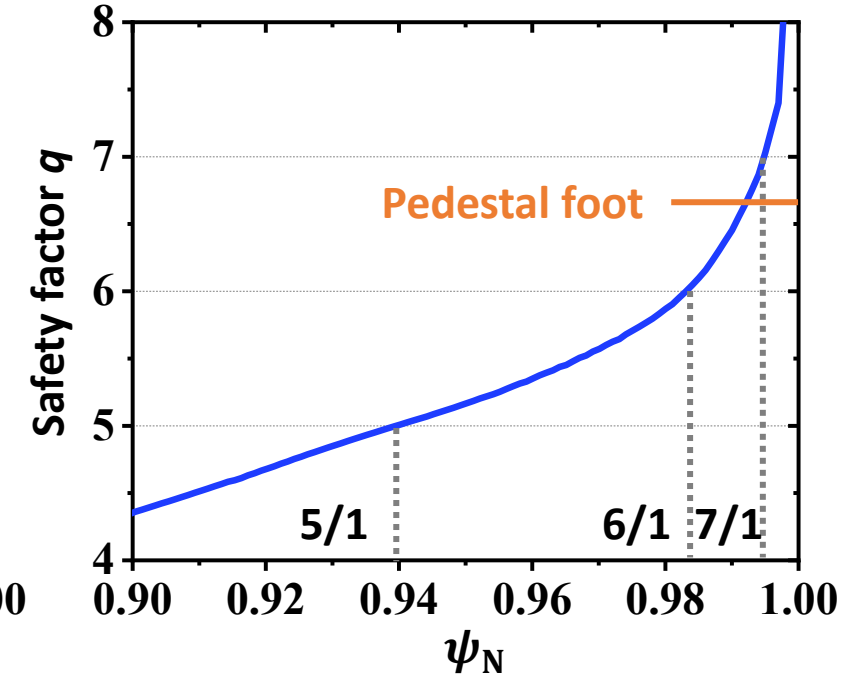
- **Conclusion**

Experimental pump-out is numerically captured, showing good agreement: Bifurcation and pedestal degradation

- **Pump-out simulation with increasing RMP**
  - ✓ 1st : Largely decreased density pedestal at 6/1 surface.
    → Density pump in pedestal foot.
  - ✓ 2nd : Decreased pedestal height with gradient.
    → Density pedestal degradation in broad region.



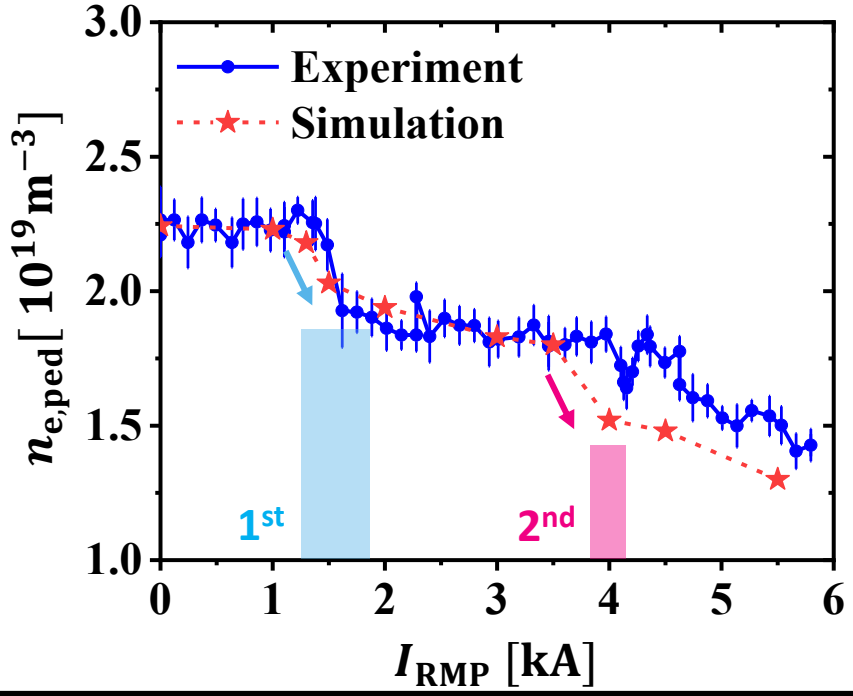


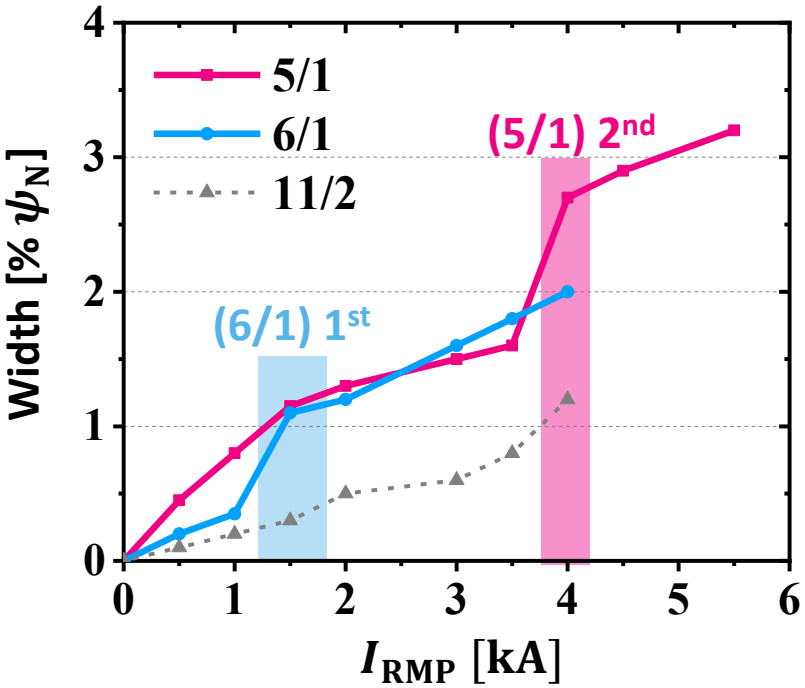


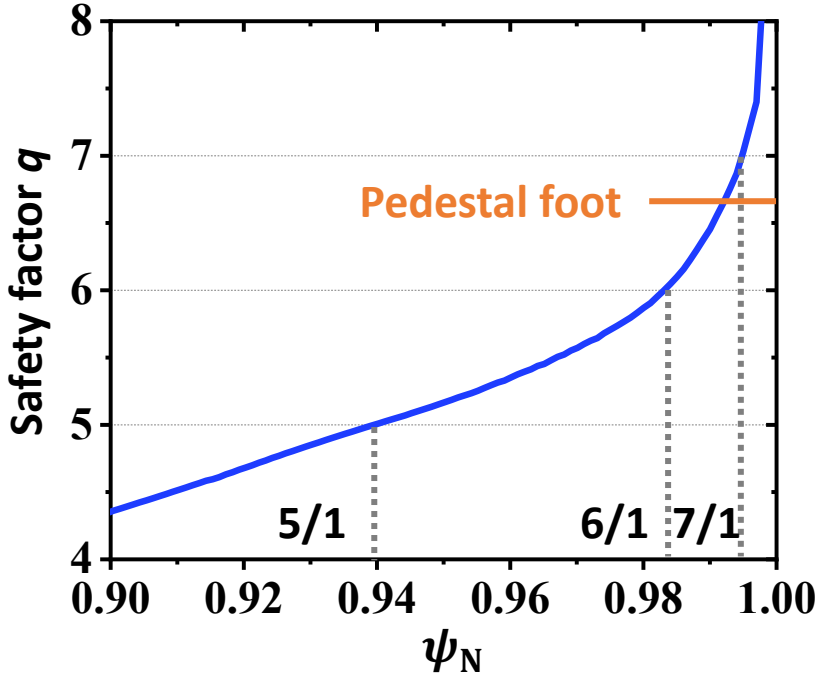
Bifurcation are the outcome of field penetration and island opening: Good agreement with cylinder calculation

- **Pump-out and island opening**
  - ✓ **Highly correlated with island opening at 6/1 and 5/1 surfaces.**
  - ✓ **Field penetration leads the bifurcating behavior.**
    → Consistent to TM1 (cylinder) results.

➡ **Verified the reliability of prediction with reduced geometry.**







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  - 1st pump:

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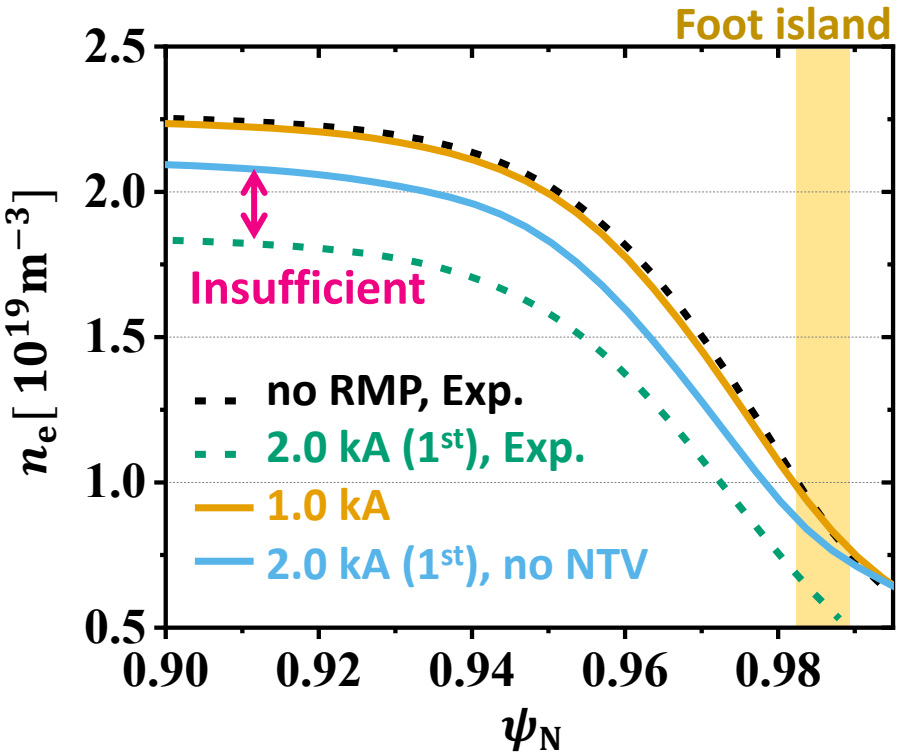
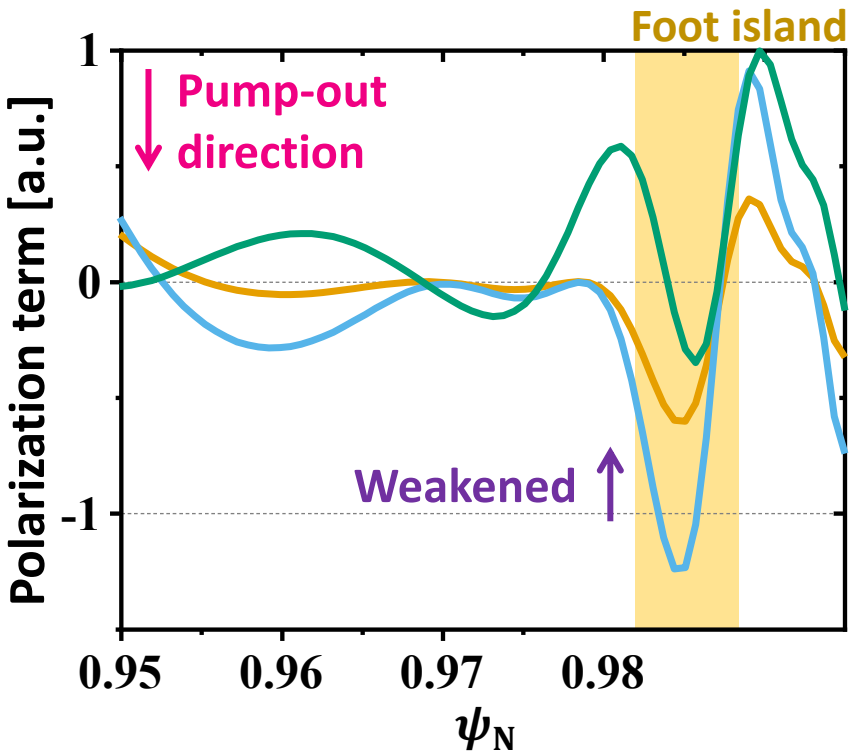
However, the geometry effect leads to difference in detail: It may require "additional" one in addition to the polarization effect

- **Pump-out at pedestal foot by polarization effect.**
  - ✓ Foot island opening (6/1) at ~1.5 kA.
  - ✓ Pump-out at the foot island by polarization effect. → May be insufficient.
  - ✓ Weakened polarization by toroidal effect & near-resonant kinking.

$$\underbrace{\frac{1}{e}\nabla\cdot\vec{j}_{\parallel}}_{\text{Polarization}} + \underbrace{\nabla\cdot\Gamma_{NTV}}_{\text{NTV}}$$





Reduced geometry (Cylinder, resonant)

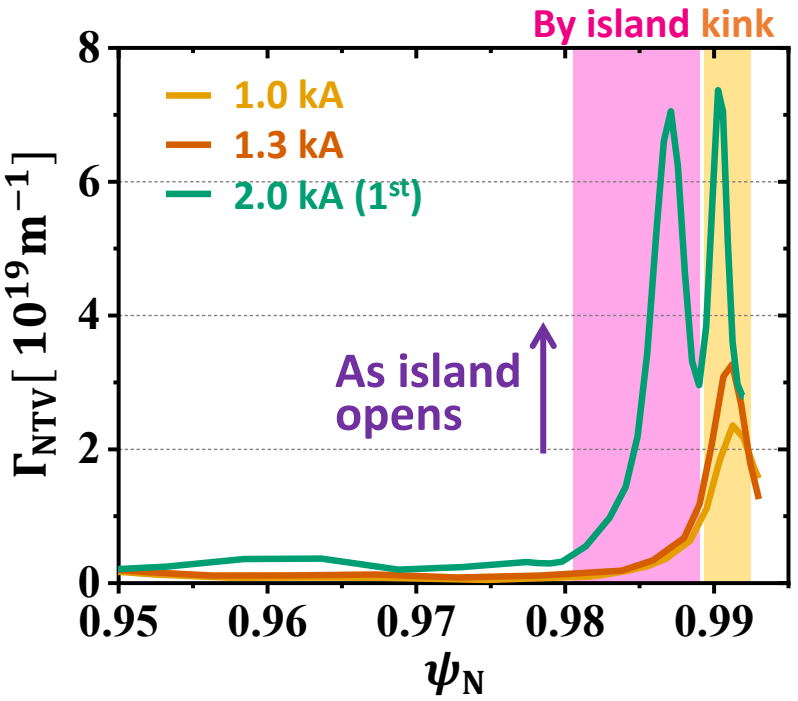
Toroidal effect (Resonant)

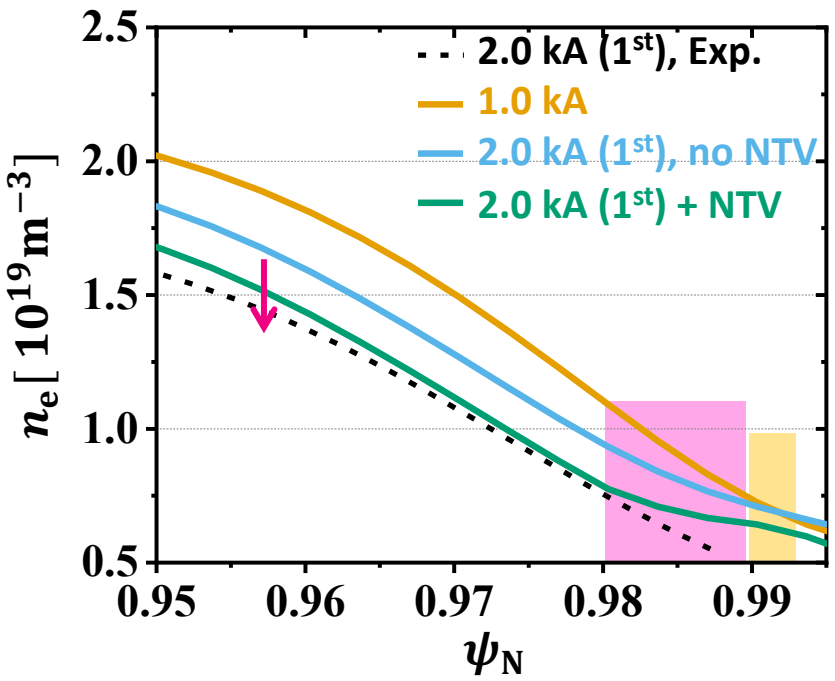
Toroidal geometry (+Near-resonant)

Weakened particle transport by toroidal effect can be cured by additional transport by itself: NTV

- **NTV particle flux at pedestal foot**
  - ✓ Two peaks NTV: By kink and island.
  - ✓ Kink: Narrow/Localized to edge. → Weaker effect.
  - ✓ Island: Broader Γ_{NTV}. → Larger effect.
  - ✓ Sudden increases at island opening (1.5 kA). → Recovers experimental pump-out level.

$$\underbrace{\frac{1}{e}\nabla\cdot\vec{j}_{\parallel}}_{\text{Polarization}} + \underbrace{\nabla\cdot\Gamma_{NTV}}_{\text{NTV}}$$





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  - 2nd pump:

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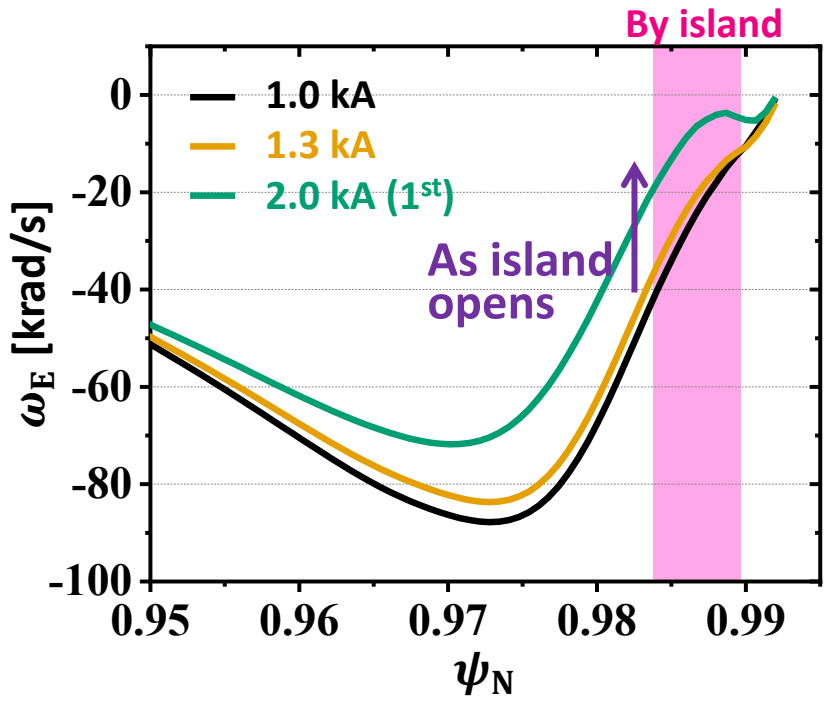
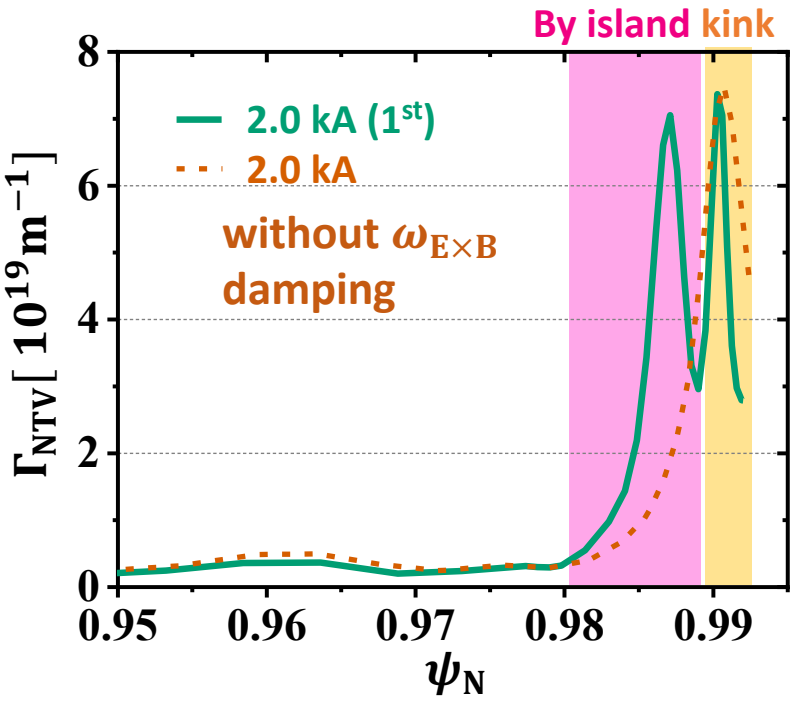
Weakened particle transport by toroidal effect can be cured by additional transport by itself: NTV

- **NTV driven by nonlinear flow response**
  - ✓ $E\times B$ flow ($\omega_{E\times B}$) damping at island region.
  - ✓ Drift kinetic Landau resonance [Liu 2020].
  - ✓ NTV by nonlinear flow change, not by unperturbed $\omega_{E\times B}$.
    → Importance of nonlinear response.





Calculated NTV torque shows experimentally acceptable value, supporting the reliability of derived NTV transport.

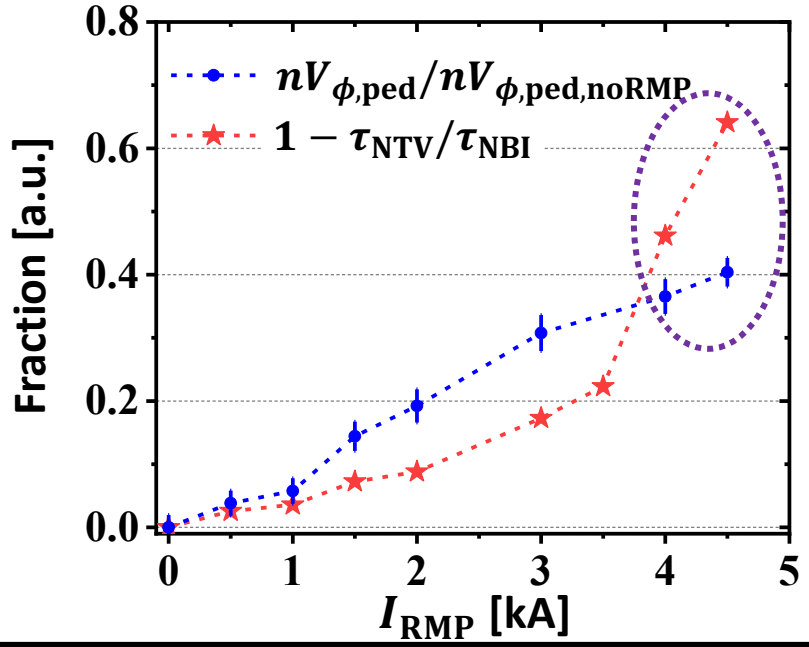
- **NTV torque with increasing RMP**
  - ✓ Reasonable value for I_{RMP}< 4 kA. → Reasonable NTV in pump-out.
  - ✓ Strong stochasticity for I_{RMP} > 4 kA. → Irrelevant $\xi_{\perp}$ and NTV.
  - ✓ Γ_{NTV} of 3.5 kA for simulation with I_{RMP} > 4 kA.

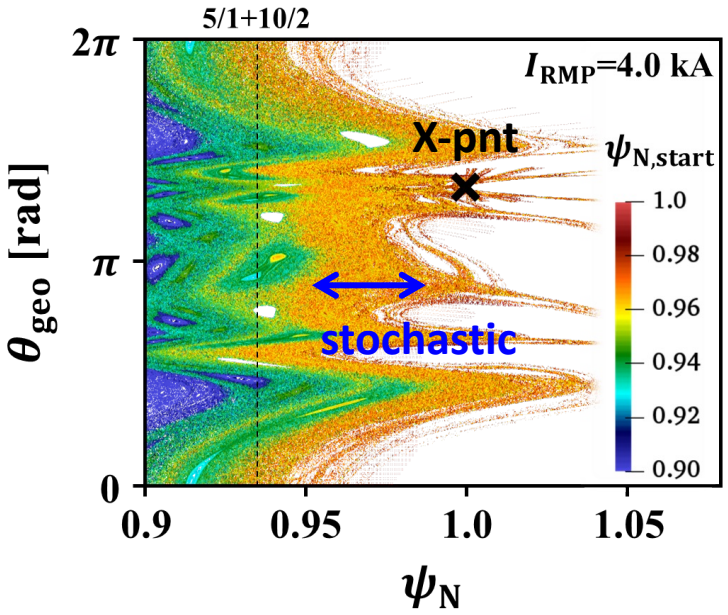
- Assuming constant χ_{ϕ},

$$\tau_{\mathrm{net,ped}} \propto V_{\phi,\mathrm{ped}}$$

$$\rightarrow \tau_{\mathrm{net,ped}} \geq \tau_{\mathrm{NBI}} - \tau_{\mathrm{NTV}}$$

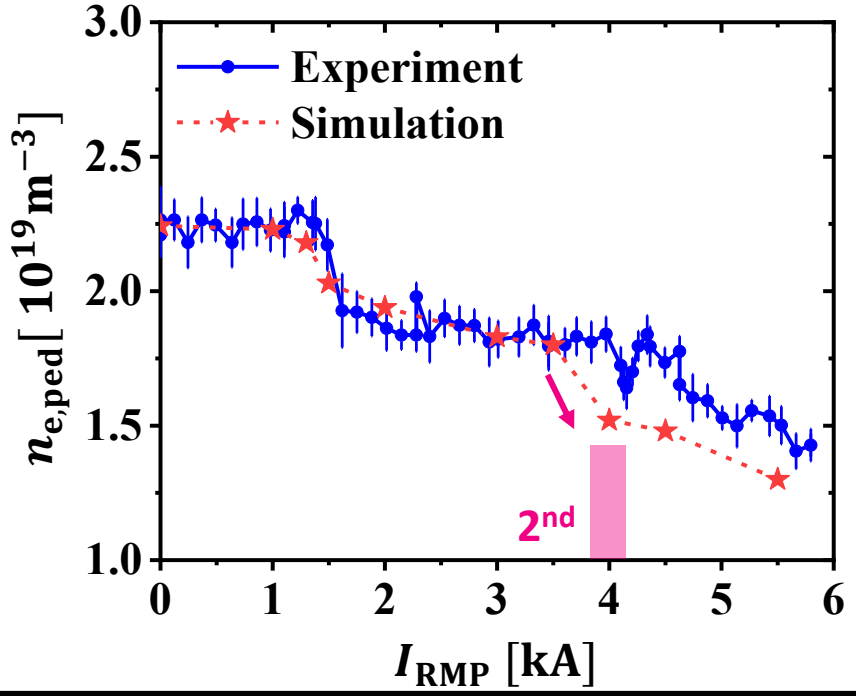
$$\rightarrow \frac{nV_{\phi,\mathrm{ped}}}{nV_{\phi,\mathrm{ped,noRMP}}} > 1 - \frac{\tau_{\mathrm{NTV}}}{\tau_{\mathrm{NBI}}}$$

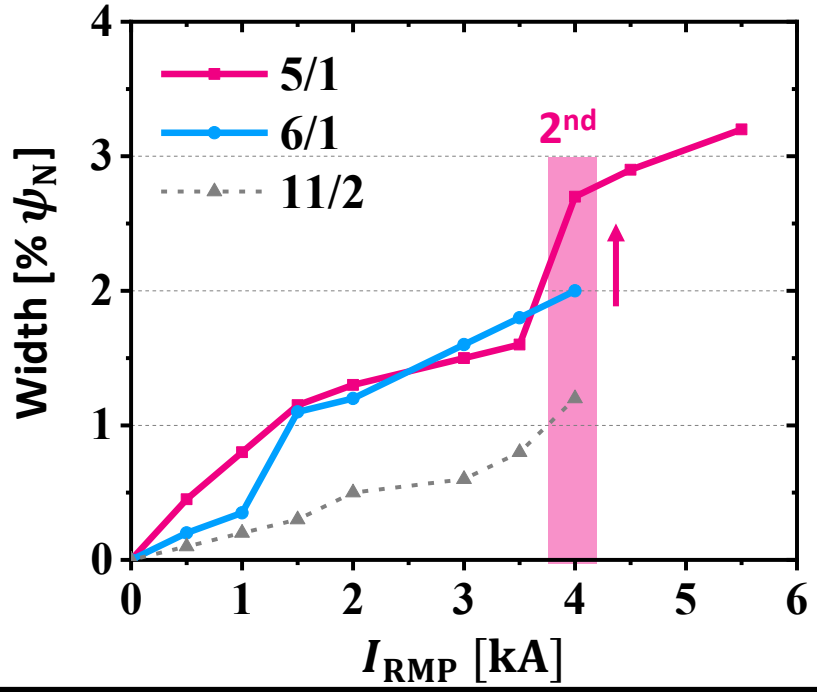


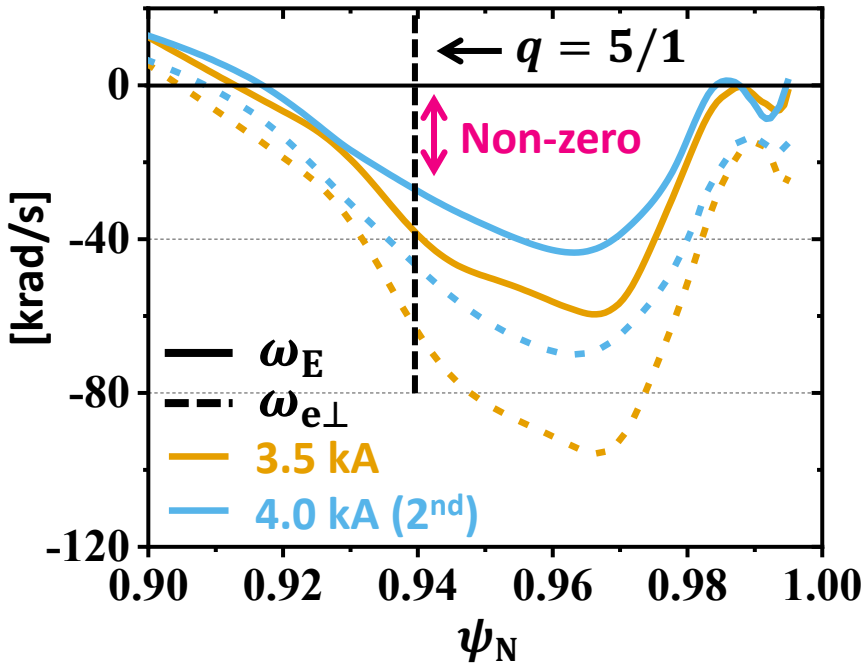


2nd pump-out is mainly due to large increase in stochasticity with 5/1 island, but not by direct flow effect

- **Second bifurcating particle transport or pump**
  - ✓ Increase in 5/1 island width (~4 kA). → Drives radial particle fluxes.
  - ✓ Previous findings: ω_E or $\omega_{e\perp} \rightarrow 0$ for large field penetration.
  - ✓ Additional contributor is required.

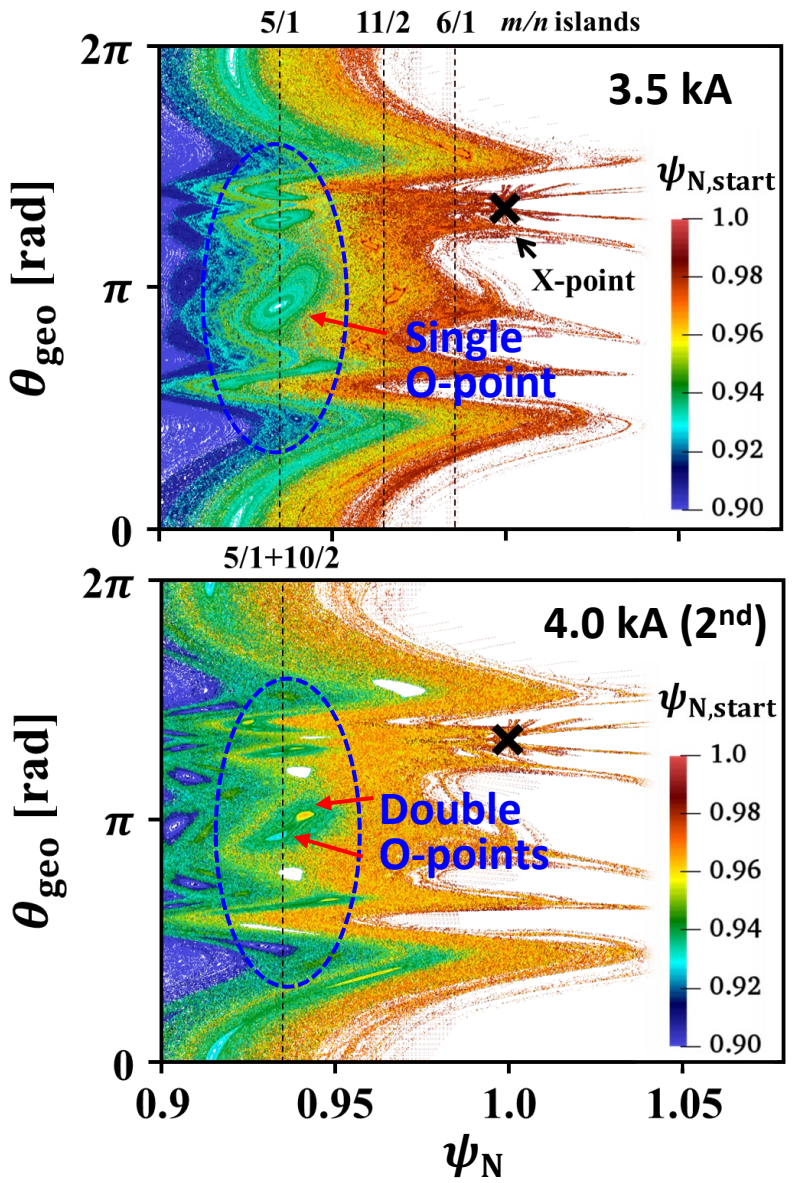






Nonlinear mode coupling can be one candidate for top island opening

- **Possible mode coupling with secondary island.**
  - ✓ Secondary island (m/n=10/2) by kinking (NR) effect.
  - ✓ Spatial overlap between (5/1+10/2).
    → Leads to sudden increase of (5/1) component.
  - ✓ Cross-check with another reference is needed.
    → To validate the concept.



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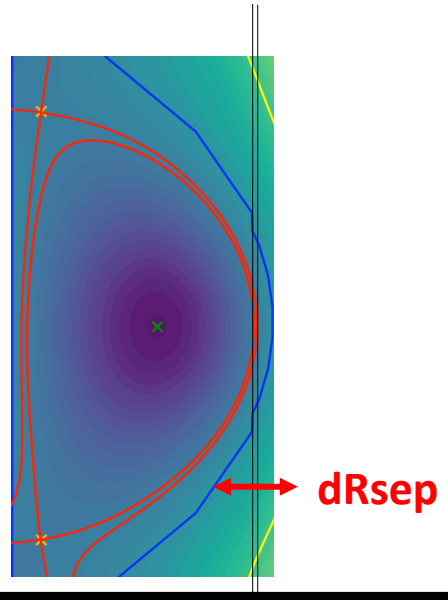
  - 2nd pump: Mode overlap and stochastization.
  - Additional case:

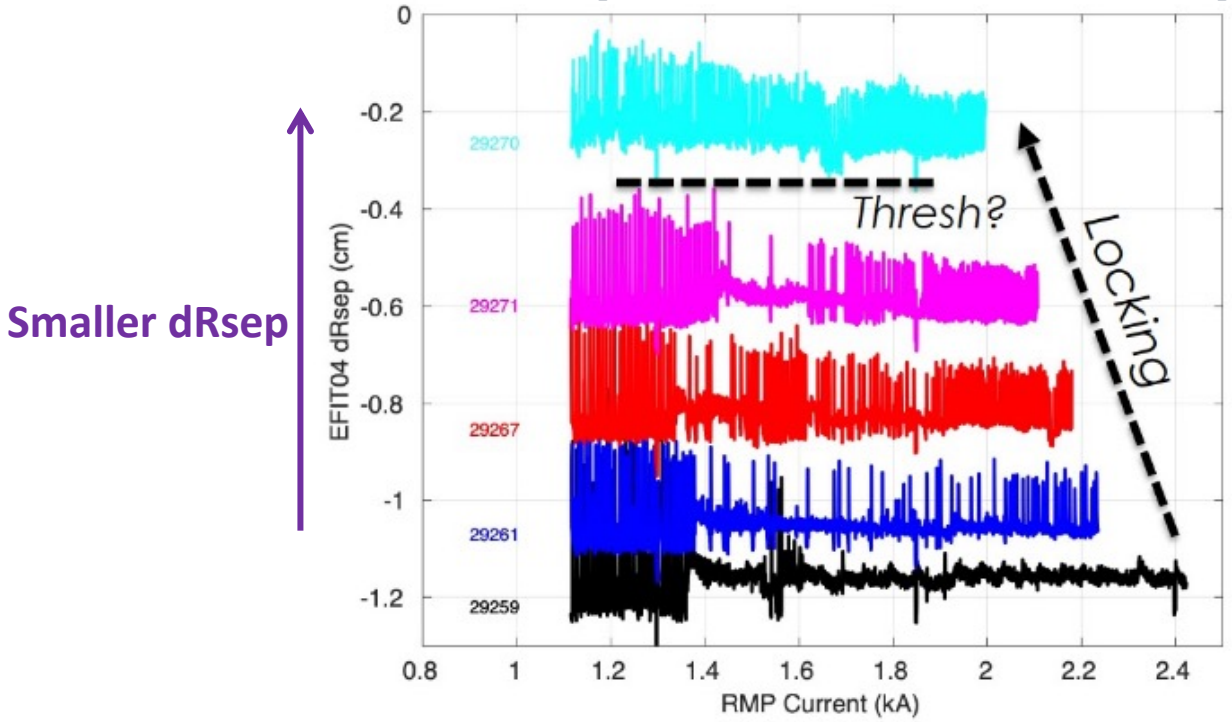
- **Conclusion**

DN plasma is one of strong candidates for Future devices, but it has difficulty in accessing ELM suppression

- **ELM suppression in double-null plasma (DN)**
  - ✓ dR_{sep}: Radial gap between flux surface of active/inactive X-points.
  - ✓ More difficult suppression with smaller dR_{sep} [M. Shafer, NF 22].
  - ✓ Double null ($dR_{\mathrm{sep}} = 0$) is promising candidate for FPP.
    → ELM suppression is not feasible.
  - ✓ Needs investigation.

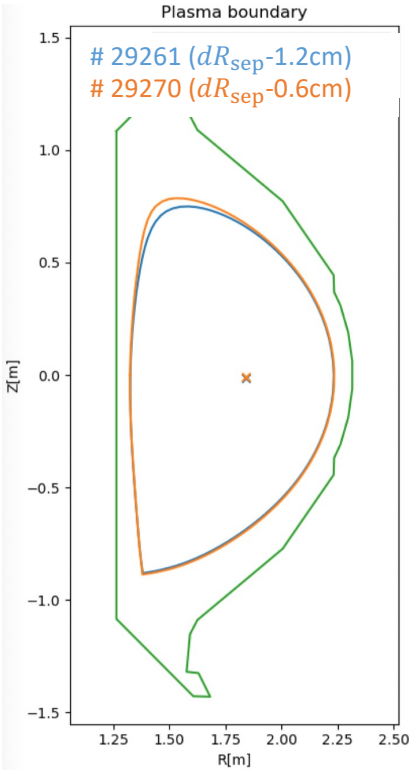


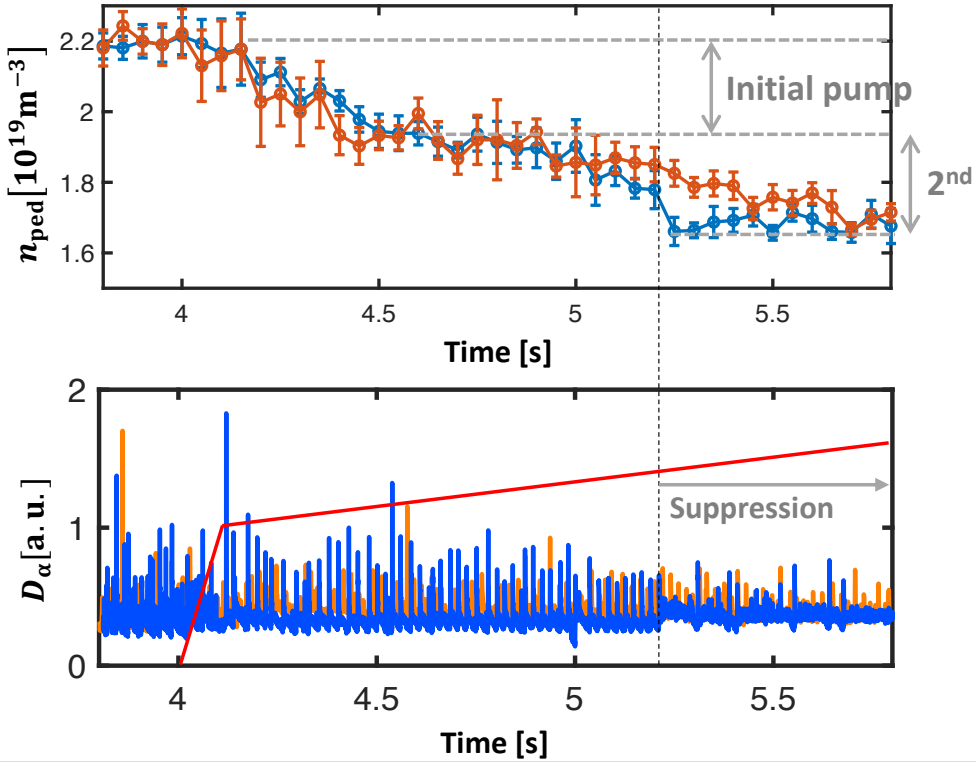
[C. Pazsoldan, KSTAR ROF 2021]



The comparison set shows the larger dR_{sep} leads to secondary pump-out and ELM entrance while no big difference in initial pump-out

- **Comparison set for dR_{sep} effect**
  - ✓ **dR_{sep}: #29261 (-1.2cm) and #29270 (-0.6cm).**
  - ✓ **ELM suppression: only #29261 (1.4 kA/t)**
  - ✓ **Locking: #29261 (2.2 kA/t) and #29270 (2.0 kA/t).**



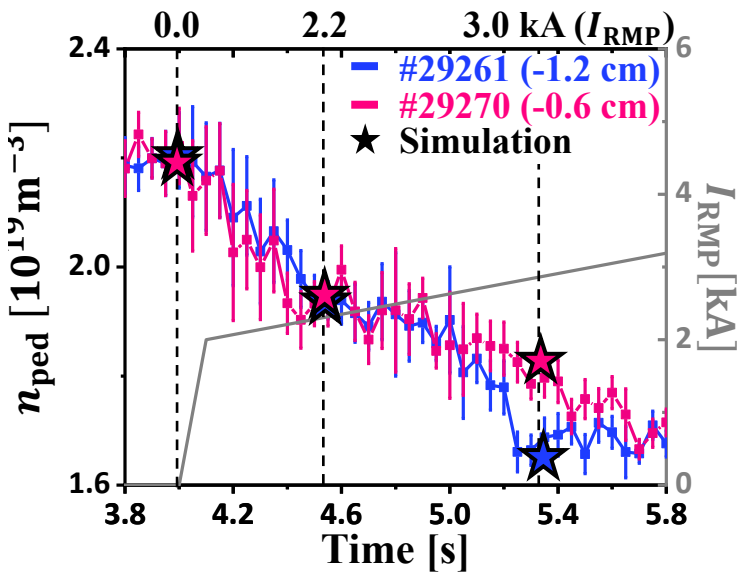


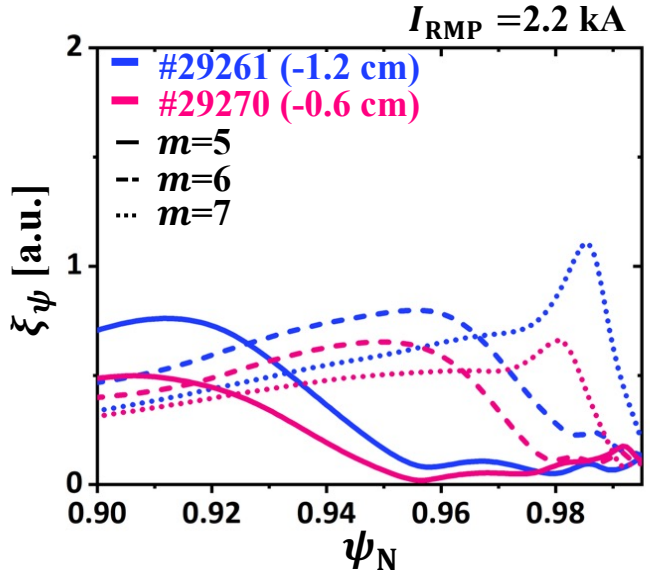
- Similar 1st pump in both cases.
- 2nd pump in #29261.
  (larger dR_{sep} case)
  → Highly correlated to ELM sup.

How dR_{sep} leads to the differences?

Difficulty of accessing 2nd pump-out with smaller dRsep can be understood with weaker plasma response

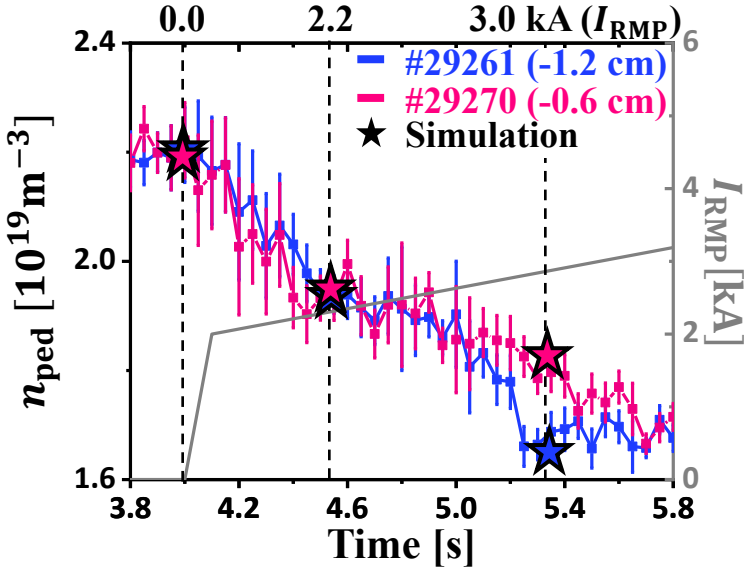
- #29261(-1.2 cm) vs #29270 (-0.6 cm)
  - ✓ Numerically reproduced dR_{sep} effect.
  - ✓ Weaker peeling or kink response with smaller dR_{sep}.
    → Consistent to previous work. [M. Shafer/S. Gu 22]
  - ✓ 25-40% smaller responses by smaller dR_{sep}.
    → Leads to the smaller island.
    → Smaller 2nd pump.
    → But why similar 1st pump?



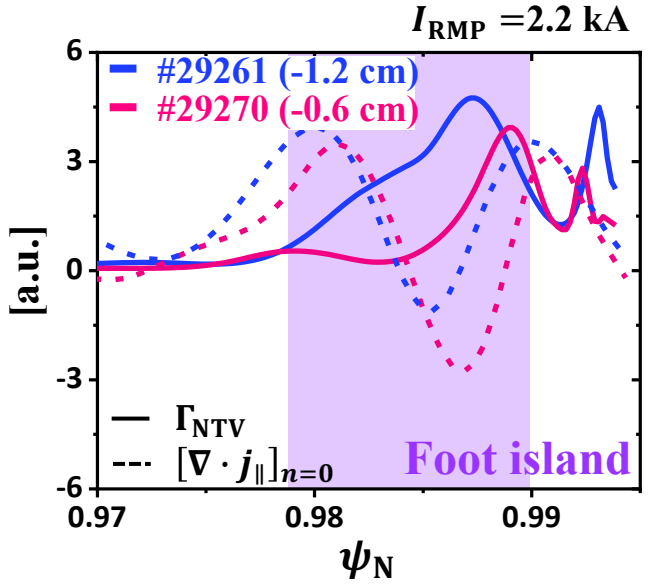


Modeling suggests the similar 1st pump may be due to the compensated effect, addressing the benefit of hybrid simulation

- **#29261(-1.2 cm) vs #29270 (-0.6 cm)**
  - ✓ **25-40% smaller responses by smaller dR_{sep}.**
    → But why similar 1st pump?
  - ✓ **Modeling suggests a "compensated" effect from kink response.**
    → The benefit of MHD-NTV integrated simulation.



1st pump	Island transport	NTV
#29261 (-1.2 cm)	-	Bigger by larger kinking
#29270 (-0.6 cm)	Bigger by weaker damping from kinking	Smaller by weaker kinking



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  - JOREK (nonlinear 3D MHD) and PENTRC (NTV) code coupling.

- **Result**

  - Pump-out: Led by field penetration (island opening).
  - 1st pump: ExB flow damping, polarization, and NTV.
  - 2nd pump: Mode overlap and stochastization.
  - Additional case: dR_{sep} effect can be reproduced.

- **Conclusion**

Nonlinear modeling reveals the role of importance of hybrid simulation, but it must overcome the prevailing limitations

- **Pump-out in coupled nonlinear toroidal MHD simulation**
  - **Initiated by MHD response (field penetration):**
    - Supports the viability of prediction using reduced geometry!
  - **Role of toroidal geometry and near-resonant component.**
    - NTV (1st) and mode coupling effect (2nd).
  - **Reproduced dR_{sep} effect.**
    - Benefits of integrated MHD-NTV simulation.

- **Remaining challenges**
  - **Overcome the limitations of heuristic and MHD approach.**
    - Improved NTV coupling.
    - Importance of micro-instabilities.
    - Free boundary 3D treatment [Verena, JPC 22].
  - **Connecting ELM suppression and pump-out simulation.**

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Thank you