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

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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).
  - 1\textsuperscript{st} pump: ExB flow damping, polarization, and NTV.
  - 2\textsuperscript{nd} pump: Mode overlap and stochastization.
  - Additional case: $dR_{\text{sep}}$ 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 ($n_{e,ped}$).
    • Pump-out.
  ✓ Pump-out mechanism: Challenging question.
    → Important for understanding/predicting ELM supp.
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.
  - 1\textsuperscript{st} (foot) and 2\textsuperscript{nd} (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).
  - Heuristics approach: Hybrid equations based on $n_e = n_i$.
  - Numerically valid by omitting NTV torque in momentum equation.

$$
\partial_t n = -\nabla \cdot n (\vec{v}_{\perp,e} - \vec{v}_{\parallel,i}) + \nabla \cdot (D_{\perp} \nabla n) + S_n + \frac{1}{e} \nabla \cdot \vec{j}_{\parallel} + \nabla \cdot \vec{F}_{\text{NTV}}
$$

- Electron density equation
- Polarization
- Ion NTV

Dedicated NTV implementation will be included in future work.
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• Introduction
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• Result

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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/ $T_i = T_e$ (single temperature)

- **PENTRC (NTV)** [N. Logan 2013]
  - NTV with RMP response.
  - RMP response: Equilibrium, profiles, displacement ($\xi$).
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].
  \[ \xi_\perp \sim - \frac{\delta T}{\nabla T_{n=0}} \]
  ✓ $\xi_\alpha$: Linear toroidal force balance $F[\xi_\alpha, \xi_\perp]$ [J.-K. Park 09].
  ✓ Becomes less accurate under strong stochasticity.

[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.

![Graph showing experimental and simulation results](image)

<table>
<thead>
<tr>
<th>Safety factor $q$</th>
<th>5/1</th>
<th>6/1</th>
<th>7/1</th>
</tr>
</thead>
<tbody>
<tr>
<td>no RMP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0 kA (1st)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0 kA (1st)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.5 kA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.5 kA (2nd)</td>
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</tbody>
</table>

**Graph Details**

- $n_{e \text{ped}} [10^{19} \text{ m}^{-3}]$ vs. $I_{RMP}$ [kA]
- $n_e [10^{19} \text{ m}^{-3}]$ vs. $I_{RMP}$ [kA]
- Safety factor $q$ vs. $\psi_N$ [\text{JET}]
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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• Result
  - Pump-out: Led by field penetration (island opening).
    - 1st pump:

• Conclusion
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.
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 $\Gamma_{NTV}$. → **Larger effect.**
  - Sudden increases at island opening (1.5 kA). → Recovers experimental pump-out level.

\[
\frac{1}{e} \nabla \cdot j_\parallel + \nabla \cdot \Gamma_{NTV}
\]

Polarization NTV
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  - 2\textsuperscript{nd} 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 $I_{RMP} < 4 \text{ kA.}$  \(\rightarrow\) Reasonable NTV in pump-out.
  - Strong stochasticity for $I_{RMP} > 4 \text{ kA.}$  \(\rightarrow\) Irrelevant $\xi_{\perp}$ and NTV.
  - $\Gamma_{NTV}$ of 3.5 kA for simulation with $I_{RMP} > 4 \text{ kA.}$

- **Assuming constant $\chi_\phi,$**
  
  \[
  \tau_{\text{net,ped}} \propto V_{\phi,\text{ped}} \quad \Rightarrow \quad \tau_{\text{net,ped}} \geq \tau_{\text{NBI}} - \tau_{\text{NTV}} \\
  \Rightarrow \quad \frac{nV_{\phi,\text{ped}}}{nV_{\phi,\text{ped, noRMP}}} > 1 - \frac{\tau_{\text{NTV}}}{\tau_{\text{NBI}}}
  \]

\[
\tau_{\text{net,ped}} \propto V_{\phi,\text{ped}} \\
\Rightarrow \tau_{\text{net,ped}} \geq \tau_{\text{NBI}} - \tau_{\text{NTV}} \\
\Rightarrow \frac{nV_{\phi,\text{ped}}}{nV_{\phi,\text{ped, noRMP}}} > 1 - \frac{\tau_{\text{NTV}}}{\tau_{\text{NBI}}}
\]
Second bifurcating particle transport or pump

- Increase in 5/1 island width (~4 kA). → Drives radial particle fluxes.
- Previous findings: $\omega_E$ or $\omega_{e\perp} \to 0$ for large field penetration.
- Additional contributor is required.

![Graphs showing particle transport and island width](image)

2\textsuperscript{nd} pump-out is mainly due to large increase in stochasticity with 5/1 island, but not by direct flow effect
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 ($dR_{sep} = 0$) 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 1\textsuperscript{st} pump in both cases.**
  - 2\textsuperscript{nd} pump in #29261.
    - (larger $dR_{sep}$ case)
    - Highly correlated to ELM sup.

  How $dR_{sep}$ leads to the differences?
Difficulty of accessing 2\textsuperscript{nd} pump-out with smaller dRsep can be understood with weaker plasma response

- #29261(-1.2 cm) vs #29270 (-0.6 cm)
  - Numerically reproduced $dR_{\text{sep}}$ effect.
  - Weaker peeling or kink response with smaller $dR_{\text{sep}}$.
    - Consistent to previous work. [M. Shafer/S. Gu 22]
  - 25-40% smaller responses by smaller $dR_{\text{sep}}$.
    - Leads to the smaller island.
    - Smaller 2\textsuperscript{nd} pump.
    - But why similar 1\textsuperscript{st} pump?
Modeling suggests the similar 1\textsuperscript{st} pump may be due to the compensated effect, addressing the benefit of hybrid simulation.

- \#29261\textsuperscript{(-1.2 cm)} vs \#29270 \textsuperscript{(-0.6 cm)}
  - 25-40\% smaller responses by smaller $dR_{\text{sep}}$.
  - \(\Rightarrow\) But why similar 1\textsuperscript{st} pump?
  - Modeling suggests a “compensated” effect from kink response.
  - \(\Rightarrow\) The benefit of MHD-NTV integrated simulation.

<table>
<thead>
<tr>
<th>1\textsuperscript{st} pump</th>
<th>Island transport</th>
<th>NTV</th>
</tr>
</thead>
<tbody>
<tr>
<td>#29261 \textsuperscript{(-1.2 cm)}</td>
<td>-</td>
<td>\textbf{Bigger} by larger kinking</td>
</tr>
<tr>
<td>#29270 \textsuperscript{(-0.6 cm)}</td>
<td>\textbf{Bigger} by weaker damping from kinking</td>
<td>\textbf{Smaller} by weaker kinking</td>
</tr>
</tbody>
</table>

![Graph showing time vs. ped density and NTV values](image)

AAPPS-DPP, Oct 12. 2022
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• 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 $dR_{\text{sep}}$ 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.
Thank you