Simulations of plasma responses due to RMP with BOUT++ code

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RMP field generation

- RMP field is set at the outer boundary surface and derived in the simulation area according to the equation:

\[
\nabla^2 \psi_{rmp} = 0 \quad \psi_{rmp} \bigg|_{r=a} = \psi_0 \cos(m\theta + n\zeta)
\]

- The poloidal mode number is 6 and the toroidal mode number is 3.
In the case with higher R/a ratio grid file, the RMP is uniform in poloidal direction:

- High R/a ratio. m=6, n=3

- In our simulation, the RMP is combined with the original magnetic field perturbation from P-B modes, to study the Plasma response due to RMP field.
RMP induced the magnetic field island at the right radial position.

- RMP generate magnetic field island at the radial position where the resonant conditions are satisfied:
  \[ q = \frac{m}{n} \]

‘q’ is the safety factor. ‘m’ and ‘n’ is the poloidal and toroidal mode number, respectively.
Three-Field two-fluid equations with RMP

Equations modification:

\[
\rho \frac{\partial \omega}{\partial t} + v_E \cdot \nabla \omega = B_0^2 \left( \frac{\mathbf{J}}{B_0} \right) + 2\mathbf{b_0} \times \mathbf{k} \cdot \nabla P
\]

\[
\frac{\partial \psi}{\partial t} = -\frac{1}{B_0} (\mathbf{b} \cdot \nabla) \phi + \frac{\eta}{\mu_0} \nabla^2 (\psi + \psi_{rmp}) - \frac{\eta_H}{\mu_0} \nabla^4 (\psi + \psi_{rmp})
\]

\[
\frac{\partial P}{\partial t} = -\frac{1}{B_0} \mathbf{b_0} \times \nabla \phi \cdot \nabla P
\]

\[
\mathbf{J} = \mathbf{J}_0 - \frac{1}{\mu_0} B_0 \nabla^2 (\psi + \psi_{rmp})
\]

\[
\omega = \frac{n_0 M_i}{B_0} \left( \nabla^2 \phi + \frac{1}{n_0 Z_i e} \nabla^2 p_i \right)
\]

\[
\mathbf{B}_1 = -\mathbf{B}_0 \times \nabla (\psi + \psi_{rmp})
\]

\[
\mathbf{b} \approx \mathbf{b}_0 + \frac{\mathbf{B}_1}{B_0} = \mathbf{b}_0 - \mathbf{b}_0 \times \nabla (\psi + \psi_{rmp})
\]

\[
\nabla_\parallel = \mathbf{b} \cdot \nabla = \mathbf{b}_0 \cdot \nabla - \mathbf{b}_0 \times \nabla (\psi + \psi_{rmp}) \cdot \nabla
\]
In the simulations, two grid files (cbm18_dens8; cbm18_dens6) were used. Both of them are circular cross-section toroidal equilibrium generated by the TOQ equilibrium code. The difference between them is that ‘cbm18_dens6’ has a lower pedestal than the ‘cbm18_dens8’ equilibrium, thus has smaller P-B perturbations.
List of all the simulation cases

<table>
<thead>
<tr>
<th>Case number</th>
<th>Plasma Equilibriums</th>
<th>RMP field</th>
<th>Initial perturbation mode number</th>
<th>RMP island position</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Linear simulation</strong></td>
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</tr>
<tr>
<td>Case 1</td>
<td>cbm18_dens6</td>
<td>m=6, n=3</td>
<td>n=9</td>
<td>Island aligned with the peak gradient area.</td>
</tr>
<tr>
<td>Case 2</td>
<td>cbm18_dens6</td>
<td>m=6, n=3</td>
<td>n=3</td>
<td></td>
</tr>
<tr>
<td><strong>Nonlinear simulation</strong></td>
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</tr>
<tr>
<td>Case 3</td>
<td>cbm18_dens8</td>
<td>m=6, n=3</td>
<td>n=15</td>
<td>Island aligned with the peak gradient area.</td>
</tr>
<tr>
<td>Case 4</td>
<td>cbm18_dens8</td>
<td>m=7, n=3</td>
<td>n=15</td>
<td>Island aligned with the P-B mode magnetic field perturbation island but farther from peak gradient area.</td>
</tr>
<tr>
<td>Case 5</td>
<td>cbm18_dens6</td>
<td>m=6, n=3</td>
<td>n=15</td>
<td>Island aligned with the peak gradient area.</td>
</tr>
<tr>
<td>Case 6</td>
<td>cbm18_dens6</td>
<td>m=7, n=3</td>
<td>n=15</td>
<td>Island aligned with the P-B mode magnetic field perturbation island but farther from peak gradient area.</td>
</tr>
</tbody>
</table>
Case 1:
- RMP: $m=6$, $n=3$
- The initial perturbation: $n=9$.
- Equilibrium: cbm18_dens6
- At beginning, the RMP is dominated. Then the perturbation with higher mode number grows up, and become dominated.
The growth rate of the perturbation with different mode number of the case without RMP:
The RMP effect on the case 1

The growth rate of the perturbation with n=9 of the cases with or without RMP.

- RMP stabilizes n=9 mode.

**Case without RMP**

**Case with RMP**

Time tracing of spectrum  The spectrum at last step
Case 2:
- RMP: m=6, n=3
- The initial perturbation: n=3.
- Equilibrium: cbm18_dens6

The RMP effect on the case 2

Case without RMP

Case with RMP

Time tracing of spectrum

The spectrum at last step
In nonlinear simulation, the magnetic field reconnection occurred. At the beginning of the ELM crash, the magnetic field perturbation generates magnetic field islands at pedestal; Later, the magnetic field island elongate in radial direction.
Case 3:

- RMP: $m=6$, $n=3$
- The initial perturbation: $n=15$
- Equilibrium: cbm18_dens8
Nonlinear simulation, case 3

Definition of ELM size:

\[
\Delta_{ELM}^{rh} = \frac{\Delta W_{ped}}{W_{ped}} = \frac{\langle \int_{R_{in}}^{R_{out}} \int_{0}^{\Delta \psi} (P_0 - \langle P \rangle \zeta) d\psi \rangle_t}{\int_{R_{in}}^{R_{out}} \int_{0}^{\Delta \psi} P_0 d\psi}
\]

- Difference of the ELM size between the cases with or without RMP.
- The RMP field is applied at \( t = 50 \, \tau_A \).

- Difference of the time averaged pressure profile at the outer middle plane. The dashed line shows the equilibrium pressure profile.
RMP experiments show that RMP field initially enhanced ELM activities

- Time traces showing the evolution of DIII-D discharge 145380 [Snyder et al. PHYSICS OF PLASMAS 19, 056115, 2012]. When the I-coil current turn on, the $D_\alpha$ increased a little bit.
Nonlinear simulation, case 4

- Case 4:
  - RMP: $m=7$, $n=3$
  - The initial perturbation: $n=15$
  - Equilibrium: cbm18_dens8
- Difference of the ELM size between the cases with or without RMP.
- The RMP field is applied at $t=50 \tau_A$.
- Difference of the time averaged pressure profile at the outer middle plane. The dashed line shows the equilibrium pressure profile.
Nonlinear simulation, case 5

- Case 5:
- RMP: m=6, n=3
- The initial perturbation: n=15
- Equilibrium: cbm18_dens6
Case 5:
- RMP: m=6, n=3
- The initial perturbation: n=15
- Equilibrium: cbm18_dens6

- Difference of the ELM size between the cases with or without RMP.
- The RMP field is applied at $t=80\,\tau_A$.

- Difference of the time averaged pressure profile at the outer middle plane. The dashed line shows the equilibrium pressure profile.
Case 6:
- RMP: m=7, n=3
- The initial perturbation: n=15
- Equilibrium: cbm18_dens6
Nonlinear simulation, case 6

- Case 6:
  - RMP: $m=7$, $n=3$
  - The initial perturbation: $n=15$
  - Equilibrium: cbm18_dens6

- Difference of the ELM size between the cases with or without RMP.

- The RMP field is applied at $t=80 \tau_A$.

- Difference of the time averaged pressure profile at the outer middle plane. The dashed line shows the equilibrium pressure profile.
## Conclusion

<table>
<thead>
<tr>
<th>Case number</th>
<th>RMP field</th>
<th>Initial perturbation mode number</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td><strong>Linear simulation</strong></td>
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</tr>
<tr>
<td>Case 1</td>
<td>m=6, n=3</td>
<td>n=9</td>
<td>RMP could stabilizes the n=9 mode. RMP could change model spectrum. The dominated mode number changes from n=18 to n=21. The mode spectrum become wider.</td>
</tr>
<tr>
<td>Case 2</td>
<td>m=6, n=3</td>
<td>n=3</td>
<td>The dominated mode number changes from n=18 to n=21. The mode spectrum become wider.</td>
</tr>
<tr>
<td><strong>Nonlinear simulation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 3</td>
<td>m=6, n=3</td>
<td>n=15</td>
<td>RMP field could enhance ELM crash, thus the time averaged pressure profile become flatter than the case without RMP. For case 3, the magnetic filed island induced by RMP field is closed to the peak gradient position, so that RMP enhanced the ELM crash more significantly than the Case 4.</td>
</tr>
<tr>
<td>Case 4</td>
<td>m=7, n=3</td>
<td>n=15</td>
<td>The RMP filed has the same effect on ELM crash with Case 3, but the island is far from the peak gradient area compared with Case 3. The effect on ELM crash is also weaker.</td>
</tr>
<tr>
<td>Case 5</td>
<td>m=6, n=3</td>
<td>n=15</td>
<td>RMP field also enhance the ELM crash. The island position is same as the Case 3, but the ‘dens6’ equilibrium has the lower pedestal than the ‘dens8’ equilibrium and the P-B magnetic field perturbation is smaller, so that the RMP effect is more obvious than Case 3.</td>
</tr>
<tr>
<td>Case 6</td>
<td>m=7, n=3</td>
<td>n=15</td>
<td>Compared with the Case 5, the island is farther from the peak gradient area. The effect of RMP is weaker.</td>
</tr>
</tbody>
</table>