Edge radiation control in stochastic magnetic field and with RMP application in LHD

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Heat flux in SOL for stellarator (LHD) cases
At upstream, \( \nabla \cdot \vec{q} = 0 \Rightarrow \frac{q_\perp}{\lambda_{q_{st}}} - \frac{q_\parallel}{l_{\parallel}} \sim 0 \)

with \( q_\perp = \frac{P_{SOL}}{4\pi^2 aR} \), \( l_{\parallel} \sim 2\pi R q \)

\[
\therefore q_{\parallel} = \frac{P_{SOL}}{2\pi R \lambda_{q_{st}}} \frac{B}{B_p}
\]

It may follow the similar scaling as tokamaks → Needs detachment operation (Scaling of \( \lambda_{q_{st}} \))

\( P_{\text{sep}} \sim 400 \text{ MW, } P_{\text{sep}} / R \sim 25 \text{ MW/m} \)
Necessity of divertor heat load reduction for future devices:
Divertor detachment, radiative divertor is prerequisite to meet the engineering limit of PFC heat load (< several MW/m²).

→ Control of enhanced radiation region in its location & intensity is one challenging issue.

Involved issues in the physics:
- A/M processes with strong non-linearity in cold plasma
- Energy transport in parallel/perpendicular to field lines
- Impurity transport, plasma recycling with volume recombination, momentum loss process

3D magnetic field configuration:
Seeking divertor optimization in helical devices, RMP application to tokamaks

→ Effects of three dimensionality/symmetry breaking on radiating edge plasma are not yet fully understood.

This contribution reports experimental results of detachment control with RMP application to the edge stochastic layer of LHD.
1. Edge magnetic field structure of LHD
2. Time traces of plasma parameters of the controlled detachment discharge
3. Radiation enhancement and modification of radiation distribution by RMP
   - Density dependence of radiation
   - EMC3-EIRENE prediction for radiation modification, AXUV measurements
   - EUV measurements of CIII – CVI emission profiles
4. Divertor flux distribution with RMP
   - Toroidal asymmetry
   - Reduction during detached phase
   - Rotation of the asymmetry by RMP phase shift
5. Operation space and simple model analysis
6. Core confinement of the RMP assisted detachment
7. Summary
Magnetic field structure of LHD: RMP (m/n=1/1) application
→ remnant island in stochastic region

R = 3.9 m, $\bar{a} \sim 0.7$ m, 10 field periods (toroidal)
Divertor: carbon, Fist wall: Stainless steel

RMP coils (m/n=1/1)
Helical coils
Plasma shape

Connection length (m)

Divertor legs
Edge surface layers
Without RMP
With RMP (m/n=1/1)
Stochastic region
Magnetic island
O-point

$\frac{b_{r}^{\text{coil}}}{B_0} \approx 0.1\%$
Resonance value

Without RMP
With RMP

$\mathbf{Z}(m)$

Rotational transform $\iota$

$\mathbf{R}(m)$

$\mathbf{R} = 3.9$ m, $\bar{a} \sim 0.7$ m, 10 field periods (toroidal)
Divertor: carbon, Fist wall: Stainless steel
With RMP → Stable sustainment of radiative divertor operation (RMP assisted RD)
Without RMP → Radiation collapse due to thermal instability

- Stable operation around density limit
- Radiation increase by a factor of ~ 3
- Reduction of divertor power load by a factor of 3 ~ 10
- Plasma shrinks at RD phase due to radiative energy loss and RMP penetration
- No significant degradation of main plasma confinement
- No noticeable high Z impurity (Fe) emission at high density range.

Increased volume of low $T_e$ region ($\sim$10 eV) at remnant island with RMP leads to enhanced carbon radiation

Without RMP → Radiation peak appears at inboard side.
With RMP → X-point of m/n=1/1 island is selectively cooled.
Radiation profile: Comparison between experiments & simulation

Carbon radiation distribution by EMC3-EIRENE

Without RMP

Inboard side

With RMP

Split to two peaks

Poloidal asymmetry of radiation is enhanced.

The qualitative change of profiles due to RMP application roughly agrees between experiments & simulation.

Results implies selective cooling at X-point of m/n=1/1 island in experiments. Imaging bolometer shows similar effect.

The well-structured magnetic field “catches” the radiation and prevents it from penetrating inward?!
Vertical profiles of impurity emission with EUV spectrometers

- CIII, CIV, CV are enhanced by RMP application
- Profiles of CIII & CIV affected significantly by RMP → Up-down asymmetric
- CVI is slightly reduced by RMP → good indication of impurity screening (?!)

Stable detachment (with RMP)

Connection length ($L_C$)

- CII radiates at $L_C \approx 10$ m region & along divertor legs.
- Clear upstream shift of emission at detachment transition.
- With RMP: In detach. phase, CII is stabilized outside of island (LCFS).
- $H_\gamma/H_\beta$ (index for volume recombination): increase after detachment transition along LCFS.
- With RMP: Formation of very cold plasma around (outside) of island

Comparison with 3D modeling is underway ....

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Magnetic field configuration & divertor probe arrays in LHD

RMP coils (m/n=1/1)

Helical coils

Plasma shape

One field period ($\Delta \phi = 36^\circ$)

Open field lines

Top view of torus

Divertor probe arrays at inboard midplane

Probe array (L)

Dome

Midplane

Divertor plate

Probe array (R)
Toroidal asymmetry of divertor flux caused by RMP application

Higher flux is attributed to increased wetted area induced by RMP.

Analysis of power load is underway (mostly same trend as the particle flux).
The toroidal asymmetry can be rotated by toroidal phase shift of RMP.
Toroidal asymmetry of divertor particle flux changes at detachment phase

At certain sections, the flux even increases.
The asymmetry during detachment phase can also be shifted by RMP phase shift.

RMP toroidal phase shift by 36°
Significant plasma response to external RMP

- **Attached phase**: RMP is shielded, island poloidal phase shift ~ 30 deg.
- **Detached phase**: RMP is amplified, island poloidal phase shift ~ 15 deg.
- **Hysteresis in plasma response at detach ↔ reattach transition**

Effect on divertor particle/power deposition
Indication of the study:
1. Larger $D_{\text{imp}}$ is closer to experiments. $\rightarrow$ Needs drifts (electric field)?, or turbulence?
2. Impurity source should be reduced after detachment.
3. The modeling still overestimates radiated power as compared to experiments. $\rightarrow$ Sputtering coefficient or atomic data base?
Comparison of radiation profiles with EMC3-EIRENE

Radiation distribution by bolometer from top view port

Experimental results are much broader than the simulations → $D_{\text{imp}}$ should be greater than the bulk plasma at least by a factor of 4
Lower threshold of perturbation strength for sustained detachment

- Density limit of radiative collapse seems independent of perturbation field strength.
  - Upper bounds for density operation range

- Detachment transition density decreases with increasing $I_{\text{RMP}}$.
  - Easy access to detachment & enough margin for operation (but at the expense of $W_p$.)

- No sustained detachment has been realized so far at $I_{\text{coil}} < 1.9 \text{ kA}$ ($\tilde{b}/B_0 < 0.06 \%$)
Operation domain of stable detachment in LHD

Key geometric parameters: $\Delta x_{\text{LCFS-island}}, \tilde{b}_r / B_0$,

- Separation between radiation region (island) & confinement region is important factor for stable detachment
- Threshold for RMP amplitude to overcome plasma screening.

Main plasma confinement: Recovery of energy confinement after detachment transition due to pressure profile peaking.

- Increase of $n_e$ leads to confinement degradation without RMP.
- Significant degradation in RMP attached phase $\leftarrow$ due to large magnetic island in the edge.
- Energy confinement recovers after RD transition with RMP $\leftarrow$ due to pressure peaking.
- The cause of the pressure peaking is under investigation.
Magnetic probe
High frequency components (several tens kHz) disappears after detach transition
→ Low frequency (~5kHz) component

Div probe
Peaked at 60~90Hz after detach transition. Strong correlation with radiation oscillation.
Summary

Effects of RMP application on the detachment is being investigated in LHD.

1. The RMP (m/n=1/1) application leads to stable sustainment of detached plasma.

2. Radiation is enhancement by RMP application
   - EMC3-EIRENE prediction: Poloidal asymmetric radiation due to island
   - AXUV line integrated profiles consistent with the modeling
   - EUV measurements of CIII – CVI : Enhancement at X and O-points
   - Visible CII and H\textsubscript{\gamma} / H\textsubscript{\beta} : Enhancement outside/around of LCFS (signature of volume recomb.)

4. Divertor flux distribution with RMP
   - Toroidal asymmetry according to toroidal mode number
   - Reduction during detached phase: asymmetric pattern changes from the attached phase
   - The asymmetry can be rotated by RMP phase shift

5. Operation space
   - Key geometric parameters : RMP amplitude and separation between edge island and confinement region

6. Geometrical effect on energy transport and radiation distribution
   - Poloidally asymmetric radiation → Energy flow from O to X-point can help to sustain the localized radiation

7. Confinement of the RMP assisted detachment
   - Confinement is recovered after detachment transition due to pressure peaking

Issues to be investigated further

Effects of different impurity species: Ne, N, Ar etc in relation to the island Te
Mode number of RMP
Decoupling effect between SOL & confinement plasma in terms of neutral penetration (RMP → thicker SOL → decoupling)