Effects of stochastic magnetic boundaries on divertor optimizations

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Stochastic magnetic boundaries appear in Stellarators due to the intrinsic non-axisymmetric magnetic configuration:
- zero toroidal current favourable for steady state operation

Tokamaks when symmetry breaking perturbation is applied
- Aiming at edge plasma control, ELM mitigation/suppression

What do we benefit from the stochastic boundary for divertor optimization?

**Introduction**

Intrinsic edge stochastization in Stellarators

Stochastic field as a tool for controlling edge plasma

RMP for ELMs mitigation

**What do we benefit from the stochastic boundary for divertor optimization?**
Summary: Effects of stochastic magnetic boundary confinement region

### Benefit
- Density pump-out
- Enhanced radiation
- Impurity screening
- Decontamination
- Change of divertor density regime
- Energy transport barrier

### Cost of divertor volume
(10~20% of a)

### Disadvantage
- Fueling efficiency ↓
- Control of radiation & detachment
- ELM mitigation/suppression
- Change of Er & turbulent transport
- Core performance?
- Energy transport barrier

### Issues to be assessed
- Pumping efficiency?
- Peak power load?

### Challenge for engineering
(RMP coils, 3D shape)
Onset of stochastic instability by island overlapping: σChir > 1

With increasing $\tilde{B}_r$, island becomes large.

$$w \propto \sqrt{\frac{\tilde{B}_{rm,n}}{i'}}$$

Island “overlaps”

Field lines in overlap region share $B$-field with neighboring island, and “forget” from which island come from.

Stochastic trajectories

$\sigma_{Chir}(n, m) = \frac{0.5(w_1 + w_2)}{\Delta_n(m, m + 1)} > 1$

K.H. Finken et al., “The structure of magnetic field in the TEXTOR-DED”
Schematics of field line structure

- Short B lines
- Long B lines
- Perturbation field
- PFCs
- Perturbation coil current
- Connection length (LC) distribution in TEXTOR-DED

Laminar region (edge surface layers)
- Short & long LC coexist

Stochastic region
- No clear separatrix, locally ergodic, remnant islands

Effects on divertor density regime
Absence of high recycling regime prior to detachment in the 3D configurations

In helical devices as well as tokamaks with RMP, the modest density dependence is often observed.

\[ n_{\text{div}} \propto n_{\text{up}}^{3} \quad T_{\text{div}} \propto n_{\text{up}}^{-2} \]

High recycling in 2D tokamaks

The modest dependence in 3D configuration

\[ n_{\text{div}} \propto n_{\text{up}}^{-1} \quad T_{\text{div}} \propto n_{\text{up}}^{-1} \]

\[ n_{\text{div}} \propto n_{\text{up}}^{1} \quad T_{\text{div}} \propto n_{\text{up}}^{1.5} \]

Effects of enhanced $\perp$ interaction of momentum transport on divertor regime

2D axi-symmetric divertor

Pressure conservation along flux tube

3D configuration (e.g. stochastic layer, ID)

$p$-Momentum loss due to counter flows

$p$-Temperature drop $T_{up}/T_{down}$ becomes small

$\frac{\tau_{m//}}{\tau_{m\perp}} = \frac{D_{\perp} L_{//}}{V_{//} \lambda_{m}^2} \propto f_{m0}$

Figure 9. Calculated flow patterns for an attached plasma in the ID of W7-AS.


HSX \( m/n=7/8 \)

A. Bader et al., Nucl. Fusion vol.53 (2013) 113036.

Simulation (EMC3-EIRENE)

Figure 18. Poloidal section showing the parallel flow normalized by the ion thermal speed. In the edge region, the radial scale has been expanded in order to accentuate the flow structures. The section is taken at toroidal angle \( \phi = 0^\circ \), vertically through the middle of a divertor module. White indicates flow into the page, grey is no flow and black is flow out of the page.

Flow alternation is detected in experiments

Fig. 3. Parallel flux from test particle simulations. The values are normalized to $n_c$.

Fig. 4. Mach number profiles for different magnetic equilibria. A flow reversal is detected at $q = 3.8$, just before the principal resonance ($q = 3 \pm 0.5$). We see the characteristic large flow towards the divertor at resonance. The divertor front face is at roughly $r = 0.79$ m. The large flow at $r \sim 0.8$ is artificial; the probe is connected to the top of the divertor module about 1 m away.

In these cases, the following effects are small,

\[ \frac{\tau_m}{\tau_{m_\perp}} = \frac{D_{\perp} L_{\parallel}}{V_{\parallel} \lambda_m^2} \propto f_m \]

\[ q_{\perp e} = \frac{n \chi_{\perp e}}{(B_r / B_t)^2 \kappa_{0e} T_e^{2.5}} \]

due either to

1. Large separation of counter flow ($\lambda_m \sim 2\pi a/m$)
2. Relatively high $T_e$ in SOL
Multi-machine comparison for divertor density regime

- Replacement of $//\text{-energy flux}$ with $\perp\text{-flux}$ → reduction of $//\text{-conduction energy}$
  
  $\tau_m// / \tau_m\perp \propto \frac{D_\perp L_//}{V_// \lambda_m^2}$

  $\lambda_m$: $\perp$ characteristic scale length for momentum loss (e.g. $\sim 2\pi a/m$)

- Possible Impacts on divertor functions due to the absence of high recycling regime:
  - Pumping efficiency ↓, physical sputtering ↑, detach. onset density ↑ (!?)

- Operation domain for high recycling regime

- Operation domain for high recycling regime

- Collisionless large $B_r / B_t$ → collisional

- Can be avoided in detached

- Preferable for core performance (?)
Effects on impurity screening
Impurity screening has been observed in many devices with edge stochastic layer

Experiments with density scan shows better screening at high density (low $T_e$)

- Enhanced outward particle flux due to braiding B field, density pump-out
  - Effective friction force
    - Drive impurity towards divertor
- High edge density
  - screening of CX flux, shallow penetration of neutral impurity


SOL thickness dependence of impurity screening: thicker stochastic SOL → better screening already at low density

\[ \lambda_{st-SOL} / \lambda_{imp} \uparrow \text{ better screening} \]

Better screening for O & N (non-recycling) than Ne (recycling) is due to the wall pumping (!?).
Impurity screening: species dependence
Good screening for High Z impurity (Fe)

Low ionization potential of Fe (7.9 eV)
- shallow penetration to edge stochastic layer → better screening (!?)

Ph. Ghendrih et al., JNM 290-293 (2001) 798.
S. Morita et al., NF 53 (2013) 093017.

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**Fig. 2.** Transition from limiter to divertor configuration as $q_{\text{edge}}$ is decreased, top curve for iron emission, lower curve for parallel energy flux to the divertor.

**Figure 15.** (a) Two-dimensionally averaged Fe$^{15+}$ density from measurement (open circles) and simulation (solid line) as a function of electron density; (b) radial profiles of iron density normalized at the plasma edge ($r_{\text{eff}} = 72$ cm) of $R_{\text{at}} = 3.60$ m simulated with two different densities at the LCFS. The value of $r_{\text{eff}}$ means a poloidally averaged plasma radius and the LCFS is positioned at $r_{\text{eff}} = 60.4$ cm.
Multi-machine comparison for impurity screening at high density range

Operation domain of upper half of density range → impurity screening is usually observed at high density.

Further study: Quantification of screening, impurity injection energy, source location, drift, E field, turbulent transport.

Thicker stochastic layer/SOL & enhanced particle transport seem to provide screening effects.

Weak dependence on outward particle flux.

Effects of outward particle flux:

$$\Gamma^p_{st} = nV_{//}(B_r / B_t)$$

$$\Gamma^p_{r \perp} \approx -D_{\perp} \frac{\partial n}{\partial r}$$

$$\frac{\Gamma^p_{st}}{\Gamma^p_{r \perp}} = \frac{(B_r / B_t)^2 V_{//} L_{//}}{D_{\perp}}$$

- Thicker stochastic layer/SOL & enhanced particle transport seem to provide screening effects.
- Weak dependence on outward particle flux.

Operation domain for Impurity screening:

$$\left( \frac{\lambda_{st-SOL}}{\lambda_{imp}} \right)^{1/4} \left( \frac{\Gamma^p_{st}}{\Gamma^p_{r \perp}} \right) > 18$$

Further study: Quantification of screening, impurity injection energy, source location, drift, E field, turbulent transport.
Effects on edge radiation & detachment stability
Enhanced edge recycling in ergodic layer
- high density, low Te region with extended volume (10~20% of a)
- enhanced radiation
Increased volume of low Te region (~10 eV) at remnant island with RMP leads to enhanced carbon radiation.

Te, ne profiles at outboard midplane (Thomson scattering)

Radiation collapse

With RMP

Te flattening at island

Without RMP

Radiation power (bolometer)

Prad (MW/m³) 1e17

(Estimated with ncarbon ≈ 0.01ne)

Carbon radiation

(Thomson scattering)

Radiation (MW/MW)

Without RMP

With RMP

Resonance layer

With RMP

Te flattening at island
Detachment stabilization with RMP application (LHD, W7-AS)

- Modification of 3D edge radiation structure with RMP application → stable detachment
- Separation between radiation region & confinement region is important factor for stable detachment


Y. Feng et al., NF 45 (2005) 89.
Operation domain of stable detachment in LHD & W7-AS

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

Conditions for stable detachment
1) RMP field must be strong enough (intrinsic ones insufficient, additional MP needed).
2) the geometric SOL width ($\Delta x_{\text{LCFS–island, div}}$) must be sufficiently large.

Recently the effects of RMP on detachment are being investigated in NSTX, DIII-D, AUG etc.
Effects on divertor power load
Non-uniform plasma heat/particle deposition at divertor plates

Distribution changes also from inward to outward configuration

- **Global** distribution has close correlation with magnetic field structure

Inward shifted configuration (Rax=3.60 m)

Outward shifted configuration (Rax=3.75 m)

Toroidal angle (deg.)

Poloidal angle (deg.)
**Single peak**: Good correlation between long flux tubes and peak power load.

**Multi-peak**: Foot-print width becomes broad, power peak does not necessarily correlate with Lc peak.

Fig. 2 Heat flux profiles for different operational magnetic configurations along the edge of the inboard divertor plate which is indicated in Fig. 1(c). $R_{ax}$ is the radial position of the magnetic axis. Profiles of connection length of field lines are also depicted for each operational magnetic configuration. (Color figure: www.cpp-journal.org).

S. Masuzaki et al., CPP **50** (2010) 629.
S. Masuzaki et al., JNM **390-391** (2009) 286.
Significant change of power load profile depending on upstream plasma parameters

**High temperature** → Clear splitting of power flux, **broader** foot print

**Low temperature** → Single peak

IR camera view on divertor plates

Experiments & 3D modelling analysis on divertor power depositions

- **Single peak** with lower Te is *only qualitatively* reproduced with EMC3-EIRENE ($D_{\perp} = 0.2$, $\chi_{\perp} = 0.6$ m$^2$/s)
- **Splitting and broadened** power flux with higher Te is **NOT** reproduced with EMC3-EIRENE
- Qualitatively, higher temperature $\rightarrow$ larger cross-field transport coefficients

Due to change of transport or equilibrium?

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S. Masuzaki et al., CPP **50** (2010) 629.
S. Masuzaki et al., JNM **390-391** (2009) 286.
Laminar transport & radial penetration of field lines plays a key role on power deposition

A WKB approximation of the energy transport in the laminar region + the radial penetration of a field line

Turbulent transport with an effective diffusion of the order of 1 m²/s ~ comparable to limiter data.

- the level of turbulent transport was weakly affected by the stochastic boundary despite the decrease of the large-scale density fluctuations.


Ph. Ghendrih et al., FST 56 (2009) 1432.
3D simulation shows that a recycling condition affects the footprint splitting of particle & heat deposition.

Heat flux pattern with high recycling condition agrees with IR camera measurements.
Effects on particle transport
Density pump-out

**Combination of two effects:** Ph. Ghendrih et al., FST 56 (2009) 1432.

1. An enhanced transport in the outermost stochastic region
2. Pumping capability of some wall components due to change in plasma-wall interaction by RMP

- No pump-out observed with He discharge.
- No density pump-out with saturated wall at steady state?

**Other physics on going?** e.g. Er, increased turbulent diffusion …

**Tore Supra**

![Graph showing electron density profiles with and without ED](image)

Figure 42. Electron density profiles in the limitier and ergodic divertor configurations.


**DIII-D**

![Graphs showing changes in edge-plasma profiles](image)

Figure 4 Changes in the edge-plasma profiles with various magnetic perturbation levels. The edge profiles of: a) electron and b) ion temperature and c) electron density with no l-coil just before the onset of an ELM (black, no. 122336), 2 kA (red, no. 122344) and 3 kA (green, no. 122357) versus normalized poloidal magnetic flux ($\psi_p$). The edge pedestal beyond $\psi_p = 0.95$ is most clearly seen in the profile for the 3 kA case. The solid curves are fits to the data points showing the average profiles over the data window. Error bars representing uncertainties due to photon statistics (statistical fluctuations in the signal and observed background noise) in the Thomson scattering measurements are shown on the individual data points.


M. Leconte et al., NF 54 (2014) 013004.


Significant low fueling efficiency with edge ergodic layer and with thicker ergodic layer.
Due both to increased wall retention & screening of neutral penetration.
Formation of steep Te profile at the edge
N. Ohyabu et al., NF 27 (1987) 2171.

Pinch effect caused by combination of microscale transport and stochastic field lines?

S. Feron et al., JNM 241-243 (1997) 326

Ph. Ghendrih et al., NF 42 (2002) 1221.

Figure 21. Temperature profile in the ED configuration, open circles, compared to the limiter configuration, open triangles, for a Tore Supra Ohmic shot. Data from Thomson scattering (core) and electron cyclotron emission radiometer (boundary). Core values are similar and a marked drop of the boundary temperature is recorded for the divertor configuration. The profiles drawn on this plot are there to guide the eye. From $\rho \sim 0.6$ to 0.8 there is no data, the theoretical analysis leads to a much sharper gradient in the vicinity of $\rho \sim 0.8$, the so-called intrinsic transport barrier.

Numerical simulation

Fig. 6. Radial profiles of test particles in ergodic divertor and limiter configurations.
Correlation between cross-field transport ($\chi^\perp$) & with LC mode structure (?)

The change of $\chi^\perp$ radius corresponds to the change of mode number from $m=4$ to $5$.

- Boundary between edge surface layer (laminar zone) and stochastic region (long LC region).

M. Kobayashi et al., CPP 54 (2014) 383.
Effects on L-H transition power threshold
Increase in L-H transition power threshold with RMP
No remarkable change in confinement (AUG)

At low density: no effect on L-H transition.

~ 50% of Greenwald limit: H-mode with small ELM achieved.

> 60% of Greenwald limit: Remains L mode.

No remarkable change in confinement with RMP.

Common confinement degradation with increasing recycling.
Increase in L-H transition power threshold with RMP

Figure 7. The H-mode power threshold as a function of RMP field ($\delta B/B_T$) for He plasmas and different values of edge safety factor, $q_{95}$. The plasmas are heated by ECH or H-NBI.

No clear threshold for He plasma.

Clear increase for resonant component cases.

Plasma screening effect has to be assessed.

Figure 8. H-mode power threshold as a function of the RMP field ($\delta B/B_T$) for D plasmas and different values of edge safety factor, $q_{95}$. The plasmas are heated by ECH or D-NBI.

Clear threshold for D plasma, $\delta B/B_T \sim 3\times10^{-4}$. 
Increase in L-H transition power threshold with RMP: resistive drift wave turbulent simulation

- **No RMP**
  - H-mode

- **With RMP**
  - H-mode

Input power

**Figure 2.** Evolution of \( \varepsilon \), \( |V_{ZF}|^2 \), \( N \) and \( T \) as a function of ‘input power’ \( \Gamma = 0.01t \). Parameter values are \( a_0 = c_0 = d_0 = 1 \), \( a_1 = b_1 = a_2 = 1, a_3 = 0.1, c_1 = 0 \) and \( H_{L_H} = 0 \). The mean electric field amplitude \( E_{ZF,\pm} \) is also plotted. (a) Reference case without RMPs. (b) case with RMPs, \( D_{RMP} = 0 \). (c) case with RMPs, \( D_{RMP} = 0.5 \). (d) case with RMPs, \( D_{RMP} = 0.05 \). RH–HL hysteresis: evolution of \( \varepsilon \) during a ‘power’ ramp up and down for RMPs (dashed-line) and without (full-line) RMP. Numerical set of parameters.

- **VZF2**: zonal flow energy
- **\( \varepsilon \)**: turbulence energy

RMP damps Zonal Flow by decrease of long range correlation
- Mean flow shear decrease → loss of stabilization of turbulence → delay of L-H transition
Slight increase in L-H transition power threshold with RMP

NSTX

Figure 5. Waveforms for 0.9 MA, 0.44 T discharges with (blue, red) and without (black) $n = 3$ fields applied prior to the L–H transition. Shown from the top are line-averaged density, $D_\alpha$ emissivity, loss power normalized by line-averaged density, absolute loss power and $n = 3$ coil current.
Effects on edge $E_r$ & turbulent transport
Impact of RMP on edge electric field

In many devices, the change of edge electric field (potential profile) has been observed:
- Effects on edge turbulence, drift, ... \[ \rightarrow \] impurity transport

- Tendency to form positive $E_r$ due to fast escaping electrons along open field lines created by RMP.

Y. Xu, EPS(2008), O4-6

A. Wootton, JNM 176-177 (1987)

Variety of Er formations observed depending on RMP’s phases

ASDEX-Upgrade

Figure 8. Top: $E_t$ profiles, middle: turbulence ratio, bottom: MP m-spectra from matched L-mode shots ($-2.3$ T, 1.0 MA, $q_{95} \approx 4$ $P_{tech} = 0.6$ MW, $T_e = 4.5$ keV, $n_{esc} \approx 1.3 \times 10^{19}$ m$^{-3}$) with $n = 2$ ($I_{55} = 0.9$ kA, $\Phi = 0^\circ$) MPs for (a) $\Delta \Phi = 0^\circ$ (even), (b) $\Delta \Phi = 90^\circ$ (mi and (c) $\Delta \Phi = 180^\circ$ (odd).

Reduction in fluctuation at large scale structure, $k < 4 \text{ cm}^{-1} (> 25 \text{ mm})$ — magnetic island scale generated by Ergodic divertor.

"The large electrostatic structures which govern the anomalous transport are strongly affected by the correlation loss induced by stochasticity."
Change in wavenumber spectrum broadening with RMP (TEXTOR-DED)
(Destructive role of DED on turbulence cells)

**Figure 16.** (a) The radial and (b) poloidal wavenumber spectrum broadening, $\delta_k^2$, as a function of frequency measured in the ergodic zone ($\rho \approx 0.94$) before (dotted curves) and during (solid curves) the static $6/2$ DED.

The increase of the $k$ spectrum width during the DED at all frequency component.

“With DED, the coherent frequency modes are all destroyed, and turbulence eddies are reduced for all frequency.”
Consequences to resultant turbulent transport differs in devices

Reduction in density (pressure) fluctuation, increase in velocity (potential) fluctuation with ED.

Turbulent transport remains unchanged.

Numerical simulation (RBM3D: flux driven resistive ballooning turbulence)

Figure 20. Output of the code RBM3D, computed profiles of fluctuating fields in the ED configuration normalized to the magnitudes in the limiter configuration. Data at a given time (snapshot) and given toroidal angle, the magnitudes of the fluctuations are averaged over a poloidal extent of $\sim \pi/2$ on the low field side where the divertor target plates are located. Left-hand side axis: normalized pressure fluctuations, plain line; radial component of the fluctuating electric drift velocity, dashed line. Right-hand side axis and open circles, Chirikov parameter profile. The shaded area corresponds to the divertor volume, $\sigma_{\text{Chirikov}} \gtrsim 1$.

Ph. Ghendrih et al., NF 42 (2002) 1221.
Reduction in blob turbulence transport with RMP (TEXTOR-DED).

**Before DED**

**During DED**

Radial particle flux in experiments

ExB flux in simulations

ATTEMPT: 3D flux driven (fluid drift) turbulence model with SOL effects of open filed lines

Y. Xu et al., NF 49 (2009) 035005.

Consequences to resultant turbulent transport differs in devices

Little change in Isat fluctuation with RMP.

Fig. 6. Measurements of the RCP in the outer midplane SOL for the discharge #26798. Shown are (a) $V_{\text{m}}$, (b) $I_{\text{sat}}$, and (c) relative fluctuation level profiles. The reference cases are coloured in black (black and grey in colour figure) while measurements with MP are shown in grey (red and orange in the colour figure). The data sets are restricted to the inward motion of the probe.
Challenge for engineering
RMP coil installation

The internal ITER ELM coil set consisting of 3 toroidal rows with 9 window-frame type coils.

Figure 1. The geometry of the internal (in-vessel) IEC consisting of three toroidal rows with nine window-frame type coils in each row (i.e. a $3 \times 9$ coil). The centres of upper and lower rows of coils (shown in blue and green in the background) are located at toroidal angles of $\phi_j = 30^\circ + 40^\circ j$ with $j = 0$–8 in the ITER coordinate system while the equatorial plane coils are located at $\phi_j = 26.7^\circ + 40^\circ j$ with $j = 0$–8. The upper and lower rows of coils have a relatively small aspect ratio, $A = ($poloidal height)/$($toroidal length$)$, compared to that of the equatorial row of coils.

Table 1. Summary of $n = 3$ ELM coil results for various ITER operating scenarios.

<table>
<thead>
<tr>
<th>No.</th>
<th>Scenario name</th>
<th>$I_c$ (kAt)</th>
<th>$\Delta_{\text{VLOW}}$</th>
<th>Optimal $\Delta\phi_U$ : $\Delta\phi_M$ : $\Delta\phi_L$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15 MA, 3.5 keV, $Q_{\text{DT}} = 10$</td>
<td>50</td>
<td>0.2097</td>
<td>64 : 0 : 50</td>
</tr>
<tr>
<td>2</td>
<td>15 MA, 4.5 keV, $Q_{\text{DT}} = 10$</td>
<td>45</td>
<td>0.1757</td>
<td>86 : 0 : 34</td>
</tr>
<tr>
<td>3</td>
<td>15 MA, 5.5 keV, $Q_{\text{DT}} = 10$</td>
<td>35</td>
<td>0.1702</td>
<td>70 : 0 : 50</td>
</tr>
<tr>
<td>4</td>
<td>15 MA, 6.5 keV, $Q_{\text{DT}} = 10$</td>
<td>40</td>
<td>0.1801</td>
<td>60 : 0 : 52</td>
</tr>
<tr>
<td>5</td>
<td>15 MA, 4.5 keV, quasi-DN</td>
<td>45</td>
<td>0.1869</td>
<td>70 : 0 : 56</td>
</tr>
<tr>
<td>6</td>
<td>9 MA, SN, $Q_{\text{DT}} = 5$ (SS)</td>
<td>20</td>
<td>0.2069</td>
<td>34 : 0 : 84</td>
</tr>
<tr>
<td>7</td>
<td>10 MA, SN, rampdown</td>
<td>35</td>
<td>0.1730</td>
<td>54 : 0 : 60</td>
</tr>
<tr>
<td>8</td>
<td>10 MA, SN, rampup</td>
<td>35</td>
<td>0.1831</td>
<td>44 : 0 : 76</td>
</tr>
<tr>
<td>9</td>
<td>7.5 MA, SN, $q_{95} = 3$</td>
<td>25</td>
<td>0.1837</td>
<td>88 : 0 : 28</td>
</tr>
<tr>
<td>10</td>
<td>9 MA, SN, $Q_{\text{DT}} = 5, \beta_p = 1.25$</td>
<td>25</td>
<td>0.1674</td>
<td>40 : 0 : 80</td>
</tr>
</tbody>
</table>


How can this be extrapolated for DEMO under severe neutron flux environment?
Super-conducting coils in 3D shape: (an example of LHD)

- Helical coil
- Dome
- Divertor plates

Parameters:
- $R = 3.90 \text{ m}$
- $a = 0.65 \text{ m}$

- 10 field periods of magnetic configuration

- First wall: stainless steel
- Divertor: carbon
Closed divertor in 3D shape: (an example of LHD)

Dome

Cryogenic pump is installed under domes.
Unexpected heat load: (an example of LHD)

- Divertor legs enters behind divertor plates
- Divertor legs hit diagnostic
- First wall
- Carbon tiles for pipe protection
Challenge in technology to integrate cryogenic system in complex 3D shape (Liquid He, Liquid N, water cooling pipes, heat shield structure ...)

Further upgrade

Summary: Effects of stochastic magnetic boundary

**Benefit**
- Density pump-out
- Fueling efficiency ↓
- PL-H ↑
- Decontamination

**Disadvantage**
- Core performance?
- Energy transport barrier
- Change of divertor density regime
- Challenge for engineering (RMP coils, 3D shape)

**Issues to be assessed**
- Enhanced radiation
- Control of radiation & detachment
- ELM mitigation/suppression
- Change of Er & turbulent transport
- Strike line splitting (non-uniform power/particle load)
- Peak power load?
- Pumping efficiency?

**Cost of divertor volume**
(10~20% of a)

**PFC**
- Change of divertor density regime
- Difficulty
In some cases, the high recycling regime appears: Tore Supra, TEXTOR-DED (m/n=3/1)

Fig. 3. Experimental data of the divertor temperature for two Langmuir probes at different locations toroidally and poloidally. The top graph with data from a midplane probe field line leaving the probe in the counter direction) is characterized by a smooth decrease of the temperature followed by a shoot up near the detachment limit, a behaviour which is reminiscent of the C-Mod 'death ray'. On the lower graph, data is taken from a probe slightly above midplane from an adjacent module for a field leaving the probe in the co direction. The strong bifurcation behaviour is recovered with the 1-D model by introducing a strong lowering of the impurity content below 20 eV. The strong decrease of the intrinsic impurities (carbon and oxygen) is also reported experimentally as the volume averaged density is increased.
The flow alternation with ED.

Fig. 3. Parallel flux from test particle simulations. The values are normalized to $n_{cs}$.

Fig. 4. Mach number profiles for different magnetic equilibria. A flow reversal is detected at $q = 3.8$, just before the principal resonance ($q = 3 \pm 0.5$). We see the characteristic large flow towards the divertor at resonance. The divertor front face is at roughly $r = 0.79$ m. The large flow at $r \sim 0.8$ is artificial: the probe is connected to the top of the divertor module about 1 m away.
Increase in L-H transition power threshold with ED.

Fig. 6. The parameter regime where the EML can control density and impurity accumulation by inducing ELMs. The ELMing discharge occurs in a range of beam power between L-mode and ELM-free H-mode.
Increase in L-H transition power threshold with ED.

Figure 2. Evolution of $\epsilon$, $|V_{ZF}|^2$, $N$ and $T$ as a function of ‘input power’ $\Gamma = 0.01t$. Parameter values are $a_0 = c_0 = d_0 = 1$, $a_1 = b_1 = a_2 = 1, a_3 = 0.1, c_1 = d_1 = 0.5, \mu = 1$ and $\Pi_{\text{tot}} = 0$. The mean electric field amplitude $E_\perp$ is also plotted. (a) Reference case without RMPs, (b) case with RMPs, $D_{\text{RMP}} = 0.1$ and (c) case with RMPs, $D_{\text{RMP}} = 0.5$ and (d) RMP effect on LH–HL hysteresis: evolution of $\epsilon$ during a ‘power’ ramp up and ramp down with (dashed-line) and without (full-line) RMPs, for a different set of parameters.
Increase in L-H transition power threshold with RMP (AUG).

**Figure 7.** Net heating power versus line-averaged density for the different cases indicated in the legend. *Cases without MPs:* $P_{\text{thr, ref}}$ from reference L–H transition studies 2008–2011, mainly data from [11], $P_{\text{thr}}$ squares correspond to the 2011 series discussed in this work. All are transitions to type-I ELMy H-modes. *Cases with MPs:* $P_{\text{thr}}$ transition to type-I ELM H-modes, $P_{\text{L-III}}$ for transition to type-III ELMs, $P_{\text{L-mode}}$ some points of the discharges forced in L-mode by the MPs.

**Figure 8.** H-mode factor versus line-averaged density for the different types of plasmas indicated in the legend. The ‘type-I MPs off’ points are usual H-modes from the 2011 campaign.

**Figure 9.** H-mode factor versus neutral flux measured in the divertor by a gauge for the different types of plasmas indicated in the legend.
Increase in L-H transition power threshold with RMP (DIII-D).

Figure 7. The H-mode power threshold as a function of RMP field ($\delta B/B_T$) for He plasmas and different values of edge safety factor, $q_{95}$. The plasmas are heated by ECH or H-NBI.

Figure 8. H-mode power threshold as a function of the RMP field ($\delta B/B_T$) for D plasmas and different values of edge safety factor, $q_{95}$. The plasmas are heated by ECH or D-NBI.
Increase in L-H transition power threshold with RMP (NSTX).

Figure 5. Waveforms for 0.9 MA, 0.44 T discharges with (blue, red) and without (black) \( n = 3 \) fields applied prior to the L–H transition. Shown from the top are line-averaged density, \( D_\alpha \) emissivity, loss power normalized by line-averaged density, absolute loss power and \( n = 3 \) coil current.
Change in density limit with RMP (TEXTOR-DED).

**Figure 8.** (a) Density limit as a function of the perturbation amplitude in ohmic plasmas. (b) Carbon concentration for the counter-NBI scenario in 3/1 base mode with $I_{\text{perturbation}} = 16$ kA (coil current 2 kA). Discharge parameter were $I_p = 300$ kA, $B_t = 2.25$ T, $P_{\text{tot}} = 2.0$ MW (reference: #97957, DED: #97958).
Increase in particle confinement time with ED.

Figure 41. Evaluation of the global particle confinement time as a function of the plasma electron content in limiter and ergodic divertor configurations from a two-reservoir model (courtesy of C Grisolia). The plasma volume is 28 m$^3$.
Density pump-out with ED.

Figure 42. Electron density profiles in the limiter and ergodic divertor configurations.

Particle screening with ED.

Figure 43. Continuous gas injection in two experiments, ergodic divertor at constant and maximum magnetic perturbation throughout the shot, and limiter shot. The time trace of the volume-averaged density, gas injection, edge safety factor and edge molecular D$_2$ pressure are displayed.
Reduction in density fluctuation, increase in velocity (potential) fluctuation with ED.

Figure 20. Output of the code RBM3D. Computed profiles of fluctuating fields in the ED configuration normalized to the magnitudes in the limiter configuration. Data at a given time (snapshot) and given toroidal angle, the magnitudes of the fluctuations are averaged over a poloidal extent of $\sim\pi/2$ on the low field side where the divertor target plates are located. Left-hand side axis: normalized pressure fluctuations, plain line; radial component of the fluctuating electric drift velocity, dashed line. Right-hand side axis and open circles, Chirikov parameter profile. The shaded area corresponds to the divertor volume, $\sigma_{\text{Chirikov}} \geq 1$.
Reduction in blob turbulence transport with RMP (TEXTOR-DED).

Figure 4. Comparison of the $I_s$, $V_\tau$, and $\hat{\Gamma}_r$ signals (versus normalized radial position, vertical red/gray lines denote limiter location) measured in the SOL and the edge before (left column) and during (right column) the DED (No 101793). Plotted in (d) and (i) are the ensemble averages of the turbulent flux. (e) and (j) show the skewness (solid circles) and kurtosis (triangles) of $I_s$. Corresponding parameters in the two columns are drawn in the same scale. The inset in (a) and (f) shows the auto-conditional-average of $I_s$ measured around $r/a = 1.03$ before and during the DED, respectively. The corresponding cross-conditional-average of $V_\tau$ is plotted in the inset of (b) and (g), respectively.
Change in correction length with RMP (TEXTOR-DED).

Figure 15. Radial profiles of (a) the radial and (b) poloidal correction lengths measured before (open squares) and during (filled circles) the static 6/2 DED. The radial locations are normalized by $a$. The vertical dashed line roughly separates the ergodic zone (EZ, left side) and the laminar zone (LZ, right side).

The influence of the DED on turbulent eddies can be further seen from the radial and poloidal correlation length, $l_{er}$ and $l_{e\theta}$, which are defined as the inverse of the radial and poloidal wavenumber spectral widths $\langle \delta_k \rangle$, respectively [23]. Here $\langle \delta_k^2 \rangle = \sum_{k,f} S(k,f) \cdot [k - \bar{k}(f)]^2 / \sum_{k,f} S(k,f)$ and $l_c = 1/(\langle \delta_k^2 \rangle)^{0.5}$. Plotted in figure 15 are the radial profiles of $l_{er}$ and $l_{e\theta}$ measured before (open symbols) and during (filled symbols) the 6/2 DED. With DED, both $l_{er}$ and $l_{e\theta}$ are reduced inside the EZ, suggesting a destructive role by the magnetic ergodization on turbulence eddies inside the ergodic area. In the LZ, the changes of $l_{er}$ and $l_{e\theta}$ by the DED are opposite, i.e. the turbulence radial and poloidal correlation lengths are both enhanced during the DED. In the laminar zone, where the openness of the field lines prevents the stochastization of the particle orbits before the particles are lost, the turbulence appears to react solely to the observed reduced $E_r \times B$ shear rate in that area (see figure 4(d)). In the ergodic zone, in

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Change in fluctuation as a function of wavenumber with RMP (Tore Supra).

**FIG. 10.** Wavenumber spectra with and without the ED for an average density close to $2.0 \times 10^{19}$ m$^{-3}$.

**FIG. 11.** Ratio of the level of density fluctuations with and without the ED as a function of the wavenumber for an average density close to $2.0 \times 10^{19}$ m$^{-3}$. The dashed line is a polynomial fit of the data.

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Change in fluctuation as a function of wavenumber with RMP (Tore Supra).

**Figure 9.** Maximum values of the LRC on $V_{\parallel}$ fluctuations measured under different DED currents ($I_{\text{DED}} = 0, 3.0$ and 7.5 kA) in an $m/n = 6/2$ DED configuration at the edge ($r/a \approx 0.95$) of the TEXTOR tokamak (edge safety factor $q(a) = 5.0$).

In the experiments of TEXTOR-DED [182] and MAST [173], the reduction of the long-range correlation of potential fluctuations during MP application has been observed, which suggests the reduction of zonal flows. Possible mechanisms for this effect might be the suppression of large turbulent structures with MP due to the nonzero $k_{\parallel}$ as mentioned above, and also the decrease in the Reynolds stress which is a drive for the zonal flows. However, observation in ASDEX-Upgrade...
Change in fluctuation as a function of wavenumber with RMP (Tore Supra).

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Reduction in blob turbulence transport with RMP (TEXTOR-DED).

Abstract
During the static 6/2 Dynamic Ergodic Divertor experiments in TEXTOR, a significant influence of the edge resonant magnetic perturbation (RMP) on the turbulent blob transport in the scrape-off layer (SOL) has been observed. In ohmic discharges without the RMP, the blobs extend 4–5 cm deep into the SOL with a radially outward moving speed of about 1 km s\(^{-1}\) and hence constitute a strong outflow of mass. With the application of the RMP, the blob amplitudes and their radially moving velocity are both reduced, resulting in a significant reduction of the blob transport in the SOL. The reduction effect of the RMP on blobs is found to be robust to changes in the operational regime and to phasing variations of the RMP as well. The blob dynamics appears to be consistent with the paradigm of the radial motions of the blob structures driven by the interchange instability.

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In TEXTOR-DED, it has been observed that the MP application leads to the suppression of blob transport [179]. This is thought to be due to the suppression of large-scale turbulence structure with MP application by changing the mode structure from \(k_\parallel \approx 0\) (without an MP) to finite \(k_\parallel\) (with an MP), as observed in experiments [164, 167], which then reduces the blob size. This is also confirmed in numerical simulations with ATTEMPT [180]. Moreover, the enhanced sheath dissipation, caused by the increased volume of open field lines with an MP, is responsible for the reduction of the blob radial velocity as observed in the numerical analysis in [181].

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The change of the edge magnetic geometry by the application of an MP can affect turbulence via several effects caused by magnetic field braiding: the radial component of the field lines, $B_r$, can induce a radial electron current and induce radial transport such as $D_{st}$ (equation (7)). It can also modify the parallel wavelength of the modes, $k_{\parallel} (\nabla_{\parallel} = (B_0 + B_r) \cdot \nabla)$, and can increase sheath dissipation through the open field lines, etc. Measurements and analysis of the radial electric field and
Change in turbulence transport and \( E_r \) with RMP.

**Figure 8.** Top: \( E_r \) profiles, middle: turbulence ratio, bottom: MP m-spectra from matched L-mode shots (–2.3 T, 1.0 MA, \( q_{95} \approx 4 \), \( P_{th} = 0.6 \text{ MW}, T_{e0} = 4.5 \text{ keV}, n_{e0} \approx 1.3 \times 10^{19} \text{ m}^{-3} \)) with \( n = 2 \) (\( I_{th} = 0.9 \text{ kA}, \Phi = 0^\circ \)) MPs for (a) \( \Delta \Phi = 0^\circ \) (even), (b) \( \Delta \Phi = 90^\circ \) (mid) and (c) \( \Delta \Phi = 180^\circ \) (odd).

Change in turbulence transport and \( E_r \) with RMP.

*Figure 6.* (a) Edge \( E_r \) profiles at fixed L-mode plasma parameters \((-2.5 \, \text{T}, 0.8 \, \text{MA}, \quad q_{95} = -5.2, \quad P_{\text{ecl}} = 0.55 \, \text{MW}, \quad T_{\text{e0}} = 4.5 \, \text{keV}, \quad n_{\text{e0}} \approx 1.5 \times 10^{19} \, \text{m}^{-3}\) with \( n = 2 \), \( \Phi = 45^\circ, \Delta \Phi = 180^\circ \), odd-parity, MP \( I_B \) current steps; (b) turbulence enhancement factor for \( I_B = 0.9 \, \text{kA} \) MP step.

*Figure 10.* (Top row) \( E_r \) profiles and (bottom row) turbulence enhancement factor with (red) and without (blue) \( n = 2 \), non-resonant \((I_B = 0.9 \, \text{kA}, \Delta \Phi = 90^\circ)\) MP for \( \Phi = 0^\circ, 90^\circ, 180^\circ \) and \( 270^\circ \) toroidal phases. \((-2.5 \, \text{T}, 1.0 \, \text{MA}, \quad q_{95} = -4, \quad P_{\text{ecl}} = 0.65 \, \text{MW}, \quad \text{with constant} \quad T_{\text{e0}} = 4.5 \, \text{keV} \quad \text{and} \quad n_{\text{e0}} \approx 1.5 \times 10^{19} \, \text{m}^{-3}\).
Little change in Isat fluctuation with RMP (AUG).

**Figure 6.** Measurements of the RCP in the outer midplane SOL for the discharge #26798. Shown are (a) $V_{flx}$, (b) $I_{sat}$ and (c) relative fluctuation level profiles. The reference cases are coloured in black (black and grey in colour figure) while measurements with MP are shown in grey (red and orange in the colour figure). The data sets are restricted to the inward motion of the probe.

for the zonal flows. However, observation in ASDEX-Upgrade showed that with an MP there is little change in the relative fluctuation level of the ion saturation current, $\delta I_{sat}/I_{sat}$, in the SOL [174]. The details of the mechanism are under investigation in [183–185] with sophisticated models.
Enhancement of radiation with ED.

Figure 56. Radiation efficiency of neon in limiter and ergodic divertor configurations as a function of the neon bulk density.
Enhancement of radiation with ED.

Figure 38. Radiated power $P_{\text{rad}}$ versus the radiated power $P_{Z_{\text{eff}}}$ expected from the $Z_{\text{eff}}$ value following the multi-machine scaling [45, 46]. Deuterium plasmas with intrinsic impurities, open circles, neon seeded radiation, open triangles, and nitrogen seeded discharges, open squares. The shaded area lies between $1.75 P_{Z_{\text{eff}}}$ (--- ⋅ ⋅) and $3.5 P_{Z_{\text{eff}}}$ (⋅⋅⋅⋅). Estimated error bars are reported on the multi-machine scaling $P_{\text{rad}} = P_{Z_{\text{eff}}}$, thin plain line. (The other lines are there to guide the eye.)
Fig. 1. Radiated power ($P_{\text{rad}}$) and core contamination ($Z_{\text{eff}}$) versus divertor electron temperature for intrinsic impurity scenario. $T_e^{\text{div}} > 15$ eV: regime controlled by carbon sputtering. $T_e^{\text{div}} < 15$ eV, solid line: C/O mixture alone. $T_e^{\text{div}} < 15$ eV, dashed line: C/O/Cl mixture.

Fig. 3. Contamination of the plasma core produced by different impurity species to achieve a given parallel power flux to the target plates. $P_{\text{tot}} = 5$ MW. Full circles: intrinsic C/O mixture. Open circles: nitrogen injection. Full diamonds: neon injection. Open squares: argon injection.
Enhancement of radiation with ED.

Fig. 3. Ne IV brightness profile as measured by the duo-chromator at $I_{ED}=0$ (solid line), 20 kA (dashed), 32 kA (dashed–dotted), 45 kA (dotted).
Impurity screening with ED.

Figure 39. Screening factor $f_{\text{screen}}$ computed with experimental data and equation (9), see section 5.2, versus the divertor plasma temperature $T_{\text{div}}$. The screening factor is the ratio of the boundary impurity concentration to core impurity concentration.
Fig. 2. Transition from limiter to divertor configuration as $q_{\text{edge}}$ is decreased, top curve for iron emission, lower curve for parallel energy flux to the divertor.
Change in radial E-field with ED.

**Figure 24.** 7/2 mode potential profile from HIBP (circles) and Langmuir probe (triangles) on TEXT with $B_T = 2.1$ T, $I_{p} = 195$ kA, $n_e = 2 \times 10^{19}$ m$^{-3}$ and $I_{EML} = 0$ kA (open symbols) and $I_{EML} \sim 4$ kA (full symbols). figure 4 from [52] and figure 6 from [128]. The two curves are interpolations of the data used to compute the radial electric field.

**Figure 25.** Radial electric field derived from the interpolation of the data from figure 24. Only the main peaks of the electric field are robust to the interpolation procedure.

Figure 15. (a) Edge temperature profile in TEXT measured with Thomson scattering, in the limiter configuration, open squares, and in the EML configuration, full squares, figure 6 from [54] and figure 3 from [45]. (b) Edge temperature profile from Tore Supra measured with Thomson scattering, open squares, and reciprocating Langmuir probe, open circles. The Chirikov parameter profile, full triangles, allows one to determine approximately the location of the separatrix between the divertor volume, $\rho \geq 0.85$, and the closed magnetic surfaces, $\rho \leq 0.85$. Sharp transition of $T_e$ at the edge with ED.
Sharp transition of $T_e$ at the edge with ED.

Figure 21. Temperature profile in the ED configuration, open circles, compared to the limiter configuration, open triangles, for a Tore Supra Ohmic shot. Data from Thomson scattering (core) and electron cyclotron emission radiometer (boundary). Core values are similar and a marked drop of the boundary temperature is recorded for the divertor configuration. The profiles drawn on this plot are there to guide the eye. From $\rho \sim 0.6$ to 0.8 there is no data, the theoretical analysis leads to a much sharper gradient in the vicinity of $\rho \sim 0.8$, the so-called intrinsic transport barrier.
Sharp transition of $Te$ at the edge with ED.

Fig. 6. Radial profiles of test particles in ergodic divertor and limiter configurations.
Sharp transition of $T_e$ at the edge with ED.

**Figure 11.** Electron density, temperature and pressure profiles (top) and connection length profiles in the periphery region as functions of major radius (bottom). Hatched region is the open field lines layer.
In order to complete the analysis, a WKB approximation of the energy transport in the laminar region yields the deposited parallel energy flux in terms of the radial penetration of a field line over the typical parallel coherence scale. Using the computed angle between the field line and the target plate one can check the calculation with the experimental deposited energy flux. Agreement on both the peaking and position of the patterns is obtained. This gives us confidence that present calculations will allow to determine the energy deposition on poorly imaged parts of the ergodic divertor coils.

It was found that it was governed by turbulent transport with an effective diffusion of the order of 1 m2/s, thus comparable to limiter data. This result confirmed that the level of turbulent transport was weakly affected by the stochastic boundary despite the decrease of the large-scale density fluctuations.


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Heat flux pattern on divertor plates with ED.

Figure 36. Simulation with the Mastoc code of the heat deposition on a target plate, 0.115 m long poloidally (horizontal axis) and 0.05 m long radially (vertical axis). The radial penetration $\Delta r$ is normalized to $\Delta r_{PE} = (\Delta r - \Delta r_{\text{min}})/(\Delta r_{\text{max}} - \Delta r_{\text{min}})$. The radial penetration is assumed to be proportional to the heat flux. The peaking factor is about 3 in this calculation for ohmic heating. The two ‘hot’ patterns are signatures of long coherence lengths along the field lines, i.e. small values of $D_1$. The shift of these patterns towards the right-hand side is due to the chosen edge safety factor $q_{\text{edge}}$ of the magnetic configuration, here $q_{\text{edge}}$ is larger than the resonance value.

Figure 37. Experimental power deposition on a divertor target plate corresponding to the same conditions as that of the simulation shown on figure 36. The most noticeable difference is due to the fact that the actively cooled structure is, in fact, made of two adjacent plates. There is therefore a small vertical gap located at $\sim 0.055$ m on the horizontal axis. This gap introduces a dip in the heat flux measurement with the IR imaging.

Figure 38. Experimental power deposition on a divertor target plate with an edge safety factor ensuring a proper alignment and hence a reduced peaking factor of the power deposition.