Magnetic perturbation experiments on MAST using internal coils

Andrew Kirk
and the MAST Team

EURATOM / CCFE Fusion Association

Effect of n=3 RMPs on:
- L-mode discharges
- The L-H transition
- ELMs

What parameters determine when the RMPs have an effect?
Motivation

- Type-I ELMs are predicted to be a factor 20 too large in ITER baseline scenario.

- One technique that has been shown to reduce the size of ELMs is the application of Resonant Magnetic Perturbations (RMPs).

- MAST is installed with two rows of 6 internal coils, similar to the DIII-D I-coils, which can produce a $n=3$ RMP in even or odd parity.

\[
\begin{align*}
\text{Even parity} & \\
& \text{(Same sign current in upper and lower coils at same toroidal location)} \\
I_{\text{coil up}} & = + - + - + - \\
I_{\text{coil down}} & = + - + - + - \\
\end{align*}
\]

\[
\begin{align*}
\text{Odd parity} & \\
& \text{(Opposite sign current in upper and lower coils at same toroidal location)} \\
I_{\text{coil up}} & = + - + - + - \\
I_{\text{coil down}} & = - + - + + + \\
\end{align*}
\]
Effect of $n=3$ RMPs on L-mode discharges
Effect of $n=3$ RMPs on L-mode plasmas

$I_p = 400 \text{ kA} \ q_{95} \sim 6$

- No effect seen with odd parity
  (Opposite sign current in upper and lower coils at same toroidal location)

- Even parity on resonance and effect on density observed
  (Same sign current in upper and lower coils at same toroidal location)
Effect of n=3 RMPs on L-mode plasmas

ERGOS (Vacuum modelling) predicts a large difference between odd and even parity.

Even parity well aligned with perturbation and produces a large region for with the Chirikov parameter ($\sigma_{Chir}$) > 1.

Threshold effect observed:
No pump out for $I_{COIL}$ < 1 kA

$\Delta \Psi_{N_{\sigma Chir}>1} > 0.18$

Pump out also established in odd parity when perturbation is well aligned with the field lines in a 900 kA discharge.
A shot where even and odd parity have similar alignment

Shot with pump out in even parity and no effect in odd parity

Similar Chirikov profile

\[ \Delta \Psi_{\text{NoChir>1}} = 0.17 \]

Resonant component of field \( (b_{\text{res}}^r) \) near LCFS slightly larger in case where pump out observed

\[ b_{\text{res}}^r = 4.74 \times 10^{-4} \text{ (Even)} \]
\[ b_{\text{res}}^r = 3.2 \times 10^{-4} \text{ (Odd)} \]
Looking at the plasma response using MARS-F

Included plasma effects using MARS-F which is a single fluid linear MHD code, which solves the full resistive MHD equations in full toroidal geometry – the code allows for plasma response and screening due to toroidal rotation to be taken into account.

See Yueqiang Liu THS/P5-10
Large reduction in size of resonance components and hence reduction in Chirikov parameter

Enhances difference in $b^r_{\text{res}}$ between Even and Odd parity

See Yueqiang Liu THS/P5-10
In all L-mode plasmas studied pump out is only observed when the plasma displacement is greater at the X-point than at the mid-plane (see Yueqiang Liu THS/P5-10)
RP data shows that fluctuation levels remain unchanged in the SOL but increase inside LCFS

Threshold effect observed

$E_r$ increases inside LCFS

$\Delta E_r \sim 2 \text{kV m}^{-1}$

Similar threshold for density pump-out, enhanced fluctuations and increased $E_r$
Effect of $n=3$ RMPs on the L-H transition
Application of RMPs before the L-H transition in a shot with $P_{\text{NBI}} = 1.8$ MW can stop the onset of H-mode.

Need to increase beam power to 3.3 MW to get transition at the same time.

To get transition at some later time need to increase $P_{\text{L-H}} \sim 30-40\%$

In shot with RMPs major change is that $E_r$ becomes more positive by $2 \text{kV/m}$. 
Effect of $n=3$ RMPs on ELMs in CDN discharges
ELMs can be triggered in ELM free discharges or the ELM frequency increased in type III ELM-ing discharges

In summary, in the standard sequence for the L-H transition:

L-mode – Dithering – Type III ELMs – ELM-free – Type I ELMs

Power above L-H threshold

the application of the coils is equivalent to a small drop in \( P_{\text{sep}} - P_{\text{LH}} \)
Effect on type I ELMs

No effect of RMPs on ELMs or density observed

Even though $\Delta \Psi_{\text{NoChir}>1} > 0.17$
Effect on type I ELMs – $q_{95}$ scan

Some effect on ELMs and density seen at $q_{95} \sim 4.9$
Effect on type I ELMs – $q_{95}$ scan

Back transition to L-mode seen at $q_{95} \sim 4.5$
Little effect on $\Delta \Psi_{\text{Netchir}>1}$ ($\approx 0.19$) – since decreasing $q_{95}$ decreases island overlap due to changes in shear

Field alignment improves $\rightarrow$ increase in resonant field ($b'_{\text{res}}$) from 5.8 to $7.5 \times 10^{-4}$

Plasma displacement at the X-point also becomes more dominant (MARS-F)
Get clear pump out and effect on ELMs

- $f_{ELM}$ increases by 5
- $\Delta W_{ELM}$ reduces from 5 kJ to ~ 1 kJ
- $W_{MHD}$ reduces by ~ 8%
Pedestal parameters suggest a transition from type I to type IV (Low collisionality branch of type III) ELMs

A similar effect is seen near to DN in DIII-D
(see B. Hudson et al., Nucl. Fusion 50 (2010) 064005)
Effect of n=3 RMPs on ELMs in SND discharges
SND effectively uses only the lower row of coils, but is very close to them.

SND has stronger resonant and non-resonant components:

\[ B_{\text{res}}^r \sim 6 \times 10^{-4} \]

However, \( \sigma_{\text{Chir}} \) is similar in SND and DND due to larger \( dq/dr \) for DND:

\[ \Delta \Psi_{\sigma_{\text{Chir}}>1} = 0.17 \]
Significant braking of the plasma toroidal rotation (possibly due to the large non-resonant components) limits the size and duration of the RMPs that can be applied. However, a modification of the ELM frequency and pump out can be observed:

- $f_{\text{ELM}}$ increases from 80 to 150 Hz
- $\Delta W_{\text{ELM}}$ reduces from 10 to 6 kJ
- $n_{e\,\text{ped}}$ decreases from 3 to $2.5 \times 10^{19} \, \text{m}^{-3}$
- $T_{e\,\text{ped}}/T_{i\,\text{ped}}$ unaltered
- $W_{\text{MHD}}$ reduces by ~15%
Summary and future work

• L-mode pump out observed and turbulence characterised

  – modelling suggests that pump out is either correlated with the size of the resonant component of the field inside the LCFS (vacuum) or with the location of the maximum plasma displacement being at the X-point (MARS-F)

• Application of n=3 RMPs before L-H transition increases $P_{L-H}$ by 30-40 %

• Some ELM mitigation observed but requires careful alignment of the perturbation with the plasma
The results suggest that a flexible coil set is required to be able to align the field with any LFS pitch angle. Therefore during the recent engineering break 6 additional ELM coils have been installed on the lower row – this will allow better alignment in n=3 and n=4 and n=6 fields to be applied.