Experimental assessment of TAE control using externally applied resonant magnetic perturbations in the ASDEX Upgrade tokamak

Externally Applied RMPs Have Strong Impact on Fast-Ion Population and MHD Fluctuations

Symmetry breaking 3D fields such as those from ELMs and ELM mitigation coils can cause significant fast-ion losses

- Simulations show ELM mitigation coils can cause significant NBI losses in ITER* reducing NBI heating efficiency and machine safety

- 3D fields can increase losses from core MHD that would otherwise only cause redistribution**

*K. Shinohara, et.al., NF 51 063028 (2011)
*T. Koskela et al., PPCF 54 105008 (2012)
**M. Garcia-Munoz et al., NF 53 123008 (2013)

'M. Garcia-Munoz | IAEA TM on Energetic Particles | Shizuoka (Japan) | 05.09.2019 | Page 2
Motivation

Experimental Observations

- TAE Suppression / Excitation with n=2 RMP
- TAE Mitigation with n=1 RMP – diff phase scan
- TAE Mitigation with n=4 RMP
- TAE Mitigation with mix n=2+4 RMP

MEGA Simulations

- Plasma Response
- TAE Suppression / Excitation with n=2 RMP

Summary and Conclusions
Outline

• Motivation

• Experimental Observations
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• Summary and Conclusions
Externally Applied RMP Are Used To Manipulate Fast-Ion Distribution Through Their Toroidal / Poloidal Spectrum

- 3D fields poloidal spectrum is modified by applying a toroidal phase difference between the upper and lower sets of coils, $\Delta \Phi_{UL} = \Phi_{upper} - \Phi_{lower}$
Differential Phase Scan Shows Fast-Ion Losses Depend on n=2 RMP Poloidal Spectrum

- Differential phase scan applied in NBI heated discharges with elevated q-profile
- 5 MW NBI heating with tangential and radial beams to probe different fast-ions phase-space volumes
- 2 MW ECCD to keep high q-profile
- Clear modulation in fast-ion losses observed in FILD measurements with maximal losses for $\Delta \phi = 100^\circ$ and minimal for $\Delta \phi \sim -50^\circ$
TAEs Suppressed / Excited on Command Varying Poloidal Spectrum of n=2 RMP

- NBI driven TAEs in advanced scenario with elevated $q$-profile
  - TAEs become weaker as $q$-profile relaxes
- TAEs are mitigated or even suppressed with $\Delta \varphi = 100^\circ$ RMPs
- TAEs are excited with $\Delta \varphi \sim -50^\circ$ RMPs in plasma with slightly higher radiative damping due to higher $T_e$
\textbf{n=1 RMP Has Strong Impact on Overall Plasma Parameters, Including Fast-Ions and TAEs}

- Diff phase scan carried out to identify optimal coils configuration

- TAE amplitude clearly modulated with \textit{n=1} RMP diff phase scan

- Temporal evolution of TAE frequency reflects density pump-out
n=4 RMP Has **Moderate** Impact on Fast-Ion Losses and TAE Amplitude

- In AUG, n=4 RMP creates moderate perturbation in plasma with narrow ERTL
  - Impact on little fast-ion population
- n=4 RMP with $\Delta \Phi_{UL}=0^\circ$ and $\Delta \Phi_{UL}=180^\circ$ slightly **mitigate** and **drive** TAE stronger respectively
- Measured fast-ion losses and TAE amplitude are **anticorrelated**
Mix n=2+4 RMP Has **Moderate** Impact on Fast-Ion Losses and TAE Amplitude

- In AUG, mix n=2+4 RMP is composed by low amplitude n=2 + somewhat larger amplitude n=4 RMP

- Finite RMP coils geometry include higher n-harmonics
Mix n=2+4 RMP Has **Moderate** Impact on Fast-Ion Losses and TAE Amplitude

- In AUG, mix n=2+4 RMP is composed by low amplitude n=2 + somewhat larger amplitude n=4 RMP
- Finite RMP coils geometry include higher n-harmonics
- Partial mitigation / excitation observed for similar $\Delta \Phi_{UL}$ as for pure n=2 RMP
  - n=2 resonances play key role
  - n=4 resonances shift $\Delta \Phi_{UL}$
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3D Hybrid MHD MEGA* Code Modified to Include RMP Fields

- Kinetic fast-ion contribution include in MHD code through current terms

- 3D fields can be included **before** and **after** MHD force balance
  - 3D magnetic fields are in equilibrium with 2D current density
    - Vacuum approach
  - Plasma response is calculated by MEGA

*Y. Todo, Nucl. Fusion **54**, 104012 (2014)
Internal Kink Dominates Plasma Response in MEGA

- Max response shifted about 100° wrt vacuum fields
- Perturbation fields up to x7 vacuum
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- Perturbation fields up to x7 vacuum
- Plasma develops n=4 and n=6 to low amplitudes
- w/o fast-ions, plasma response saturates within 60 μs
• RMP configuration determines TAE growth rate
• TAE drive studied in RMP perturbed equilibrium for both coils configurations
• Energetic particles injected at t=0sec

![Graph showing the impact of RMP on TAE growth rate](image-url)
MEGA Simulation Explains RMP Impact on TAE

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- TAE drive studied in RMP perturbed equilibrium for both coils configurations
- Energetic particles injected at $t=0\text{sec}$

![Graph showing TAE behaviour with β$_{EP}$-scan](image1)

![Graph showing frequency vs ρ$_{pol}$ for OFF-axis and ON-axis NBI](image2)
MEGA Reproduces Fast-Ions ERTL

- Interaction of energetic particles with RMPs and TAEs is studied in phase-space using COM \((E, P_\phi, \Lambda)\)
  - Scan in \(E\) & \(P_\phi\)
  - fixed \(\Lambda\)

- Well defined linear resonances emerge with RMP application
  - Excellent overlap with analytical \((\omega_{\text{tor}}/\omega_{\text{pol}}=n/p)\) resonances

- \(\delta P_\phi\) figure of merits used to study RMP induced transport
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• Well defined linear resonances emerge with RMP application
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• δP_φ figure of merits used to study RMP induced transport

• Fast-ion transport depends on RMP poloidal spectrum, i.e. ΔΦ_{UL}
Plasma Response Introduces Additional Fast-Ion Resonances in Entire Plasma

- Internal kink introduce resonances outside ERTL at TAE location
- ERTL resonances are preserved
- Internal transport is order of magnitude larger than ERTL
- Particle losses increased
- Stochastic region emerged
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- Fast-ion transport due to internal kink depends on RMP poloidal spectrum, i.e. $\Delta \Phi_{UL}$
NBI Distribution May Be Effectively Controlled Over a Large Plasma Volume

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![Plasma response to RMP](image)

![MEGA](image)

![Non-Resonant Particle](image)
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MEGA

Plasma response to RMP

Outwards Transport

$\Delta \Phi_{UL}=-50^\circ$

#34571

$\langle \delta P_\phi (\text{a.u.}) \rangle$
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Plasma response to RMP

Inwards Transport

MEGA
Kink Induced Transport Determines TAE Drive

- **Internal fast-ion transport caused by core kink response to RMP overlaps with phase-space region with maximum wave-particle energy exchange**
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• NBI driven **TAE activity** can be **controlled** by means of externally applied RMPs with broad n-spectrum
  ➢ **n=2 RMP** has strongest impact with full suppression / excitation

• **Plasma response** has been successfully modelled using **MEGA**

• **Internal kink** response might be key to manipulate fast-ion distribution and associated TAEs

• Plasma response to RMP may expand our capabilities to **control fast-ion distributions** over large plasma radius in present and future devices