Rotation dependence of tearing mode excitation by external perturbation fields on TEXTOR

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Outline

• Motivation
• Dynamic Ergodic Divertor (DED) on TEXTOR
• Excitation of 2/1 tearing modes using the DED to create an external perturbation field
• Experimental results of toroidal rotation scan
• The influence of plasma viscosity and torque induced by the external perturbation field on the mode excitation.
• Discussion
• Summary
Motivation

• Error fields arise from non-ideal alignment of external magnetic coils
• Drive tearing modes (usually on q=2 surface)
• Modes limit operation regime and plasma confinement

How to avoid the excitation of the 2/1 tearing mode by an error field?

TEXTOR
(R=1.75m; a=0.46m; B_t^{max}= 3T; I_p^{max}=0.8MA)
ICRH: 2 x 2MW
NBI: 2 x 1.5MW (co + ctr)
ECRH: 0.8MW

Threshold for mode excitation by using DED external perturbation fields depends on:
• Beta
• Toroidal field
• Electron density
• Plasma rotation
Dynamic Ergodic Divertor (DED) on TEXTOR

- 16 coils (+2 compensation coils) mounted on the HFS
- Helical pitch resonant to $q=3$ field lines
- Configurations
  - 12/4: PSI studies, divertor properties
  - (6/2)
  - 3/1: Perturbation field and MHD studies
- Currents
  - up to $\frac{n}{4} \times 15$ kA/coil
- Frequencies
  - dc
  - low $f_{ac}$ (2Hz), field sweep in co- and counter current direction
  - high $f_{ac}$ (1..10kHz) field rotation
DED perturbation field

Amplitudes of the $n=1$ Fourier components

Standard plasma equilibrium + vacuum DED field ($q_{a,\text{cyl}}=4.5$)

$l_p=300\,\text{kA}$, $B_t=2.25\,\text{T}$, $I_{\text{DED}}=1\,\text{kA}$

$n=1$ Fourier amplitudes, 1.5kA

$B_{m,1}$ [mT]

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Excitation of the 2/1 tearing mode using external DED perturbation fields

SXR camera

No 2/1 island

2/1 island

Saturated island width up to 17% of plasma minor radius
Plasma rotation scan

Plasma rotation at constant total heating power ($P_{\text{NBI}}=1.3\text{MW}$) with co- and ctr-NBI.

$\text{Ip}=300\text{kA}; \text{Bt}=2.25\text{T}$
Influence of plasma rotation on mode threshold with dc DED

\[ NBI \text{ fraction} = \frac{P_{\text{co}} - P_{\text{ctr}}}{P_{\text{NBI}}} \]

\[ f_{\text{tor}} = 1.3 \text{ kHz}, \quad f^* \approx 1.6 \text{ kHz} \]

\[ \text{dc, } n_e = 2.0 \times 10^{19} \text{ m}^{-3} \]
Influence of plasma rotation on mode threshold with ac DED

2/1 mode:
- dc
- ac ctr-current 1kHz

No 2/1 mode
- ac co-current 1kHz (I_{DED}=2kA)

\( f^* \approx 1.6 \text{ kHz} \)

\( f_{\text{tor}} = 0.7 \text{ kHz} \)

\( f_{\text{tor}} = 1.7 \text{ kHz} \)

\( n_e = 1.5 \times 10^{19} \text{ m}^{-3} \)
Error-field penetration process

- Single-fluid MHD model, quasi-linear, cylindrical approximation
- Single mode, $m/n = 2/1$, The perturbation field is linearly ramped up in time from $t = 0$.

Time evolution of the toroidal rotation and the perturbed magnetic flux

- $\psi \sim $ nonlinear growth
- Suppressed state
- Excited state
- Braking

$\mu_{\perp} = 50\mu_{\perp,0}$

$q = 2$

Time evolution of the toroidal rotation profiles
Threshold of the error-field penetration

Single-fluid MHD model, quasi-linear, cylindrical approximation, single mode (m/n = 2/1)

Perpendicular viscosity: $\mu_\perp = 50\mu_\perp 0$

Ref. Y. Kikuchi et al., 32nd EPS conf., Tarragona, 2005, P1.114., submitted to Plasma Physics and Controlled Fusion
Dependence of DED induced force on MHD frequency

Four-field model (MHD model), linear, cylindrical approximation, single mode (m/n = 2/1)

- four-field ( $\vec{A}_||$, $\vec{\phi}$, $\vec{n}$, $\vec{v}_||$ ) model -

DC-DED, $v_\phi = 0$. $f_{MHD} = f^*_e \sim 1.1$ kHz

Resonance $f_{DED} = f_{MHD}$

Ref. Y. Kikuchi et al., PET conf., Juelich, Germany, 2005

$\mathbf{j} \times \mathbf{B}_r = \mathbf{F}$
Discussion (dc DED)

\[ f^*_{e} = \text{const.} \]

\[ I_{\text{DED}} \]

- **Viscosity effect**
- Symmetric dependence on the plasma rotation
- **DED induced force**
- Resonance at \( f_{\text{MHD}} = f_{\text{DED}} = 0 \)
- Plasma rotates in co-current direction on TEXTOR

\[ f_{\text{tor}} = -f^*_{e} \]

- Asymmetric dependence on the plasma rotation

Ct-current | Co-current

Spin-up | Braking

\[ f_{\text{MHD}} = 0 \]

\[ f_{\text{tor}} = -f^*_{e} \]
Discussion (ac DED)

$f^*_e = \text{const.}$

$I_{\text{DED}}$

-1kHz  +1kHz

$V_{\text{tor}}$

$-f^*_e$

**ac DED case:**

- 1kHz in ctr-current
- 1kHz in co-current

DED induced force

Resonance at

$f_{\text{MHD}} = f_{\text{DED}} = -1kHz$

$(v_{\text{tor}} \text{ is low})$

The minimum mode threshold shifts to
ctr-current direction
by 1kHz

$+(v_{\text{tor}} \text{ is high})$

No 2/1 mode

Trilateral Euregio Cluster

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Rotation dependence: JET results

- **TEXTOR**: $I_p \uparrow \downarrow B_t$
  \[ f_{\text{MHD}} = f_e \]

- **JET**: $I_p \uparrow \uparrow B_t$
  \[ f_{\text{MHD}} = -f_e \]

- **RBE**: Both $I_p$ and $B_t$ are reversed
  \[ \nu_\phi = 0. \]
  \[ \text{The resonance frequency of the EF induced force is changed, too!} \]

- **Norm B**
  \[ \text{(dc error field)} \]

- **Expect minimum for norm B around here**

- **RBE exp**
  \[ \text{sign of } V_e^* \text{ changes!} \]
Summary

• The Dynamic Ergodic Divertor (DED) on TEXTOR allows the reproducible excitation of \( m/n=2/1 \) tearing modes when operated in 3/1 configuration.
• TEXTOR is equipped with two neutral beam injectors (NBI) in co- and counter-current direction, allowing precise power control by adjusting apertures in the beam line.
• Rotation scans at constant total heating power yield an asymmetric response of the mode threshold:
  • Co rotation shows a minimum for the mode excitation threshold.
  • A large decrease in mode threshold has been observed with very small counter-NBI fractions (~10%).
• The strong dependence of the mode excitation on the plasma rotation may be explained by the effect of (differential) rotation on the mode penetration. [Viscosity and Poloidal torque]
• Discrepancy between TEXTOR and JET data can be due to the difference in the relative orientation of \( B_t \) with respect to \( I_p \).
Electron density dependence of mode threshold with dc DED

The sudden drop of mode threshold at \( n_e = 2 \times 10^{19} \text{m}^{-3} \) could be due to the MHD frequency approaching to the frequency of external perturbation field, it is zero for dc DED case.

With 250kW co-NBI

Ohmic only

With 250kW co-NBI

Ohmic only

The sudden drop of mode threshold at \( n_e = 2 \times 10^{19} \text{m}^{-3} \) could be due to the MHD frequency approaching to the frequency of external perturbation field, it is zero for dc DED case.