MHD Induced Fast-Ion Redistribution & Loss in AUG

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Outline

Redistribution / Loss Due To NBI Driven Alfven Eigenmodes

Role of Fast-Ions in ELM Cycle. Especially In The Presence Of Other Core Modes

Cartoon of 2D poloidal structures in AUG
Alfvén Eigenmodes Obtained With Early 60kV Neutral Beam Injection In AUG

- Early 60 kV neutral beam injection, similar to DIII-D reference case, created spectrum of RSAEs
- Modes are accompanied by large neutron deficit (relative to TRANSP predictions) - indicative of fast ion transport
- As RSAEs disappear, neutron emission returns to classical levels

M. Garcia-Munoz et al., Nucl Fusion 51 103013 (2011)
FIDA Data Indicate Large Reduction in Core Fast-Ion Density During RSAE Activity

- FIDA SIMulation code predicts FIDA emission assuming classical fast ion profile
- Large deficit in FIDA emission relative to FIDA SIM indicates central depletion of fast ion density

M. Garcia-Munoz et al., IAEA FEC, Daejeon, Korea (2010)
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B. Geiger at al., PPCF 53 (2011)
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- FIDA SIMulation code predicts FIDA emission assuming classical fast ion profile
- Large deficit in FIDA emission relative to FIDA SIM indicates central depletion of fast ion density
- As with neutron emission, FIDA profile returns to classical levels after modes disappear

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FIDA System Measures a Drop in Central Fast-Ion Population as $q_{\text{min}}$ Passes Through an Integer

- At $q_{\text{min}}=2$ crossing, several RSAEs are excited by 60kV beams (Grand Cascade)
- Rapid drop in central fast ion density corresponding to peak in RSAE amplitude
- No fast ion losses observed during this event
  - May be geometrical effect. Plasma shape not FILD friendly

B. Geiger et al., PPCF 53 (2011)
M. Garcia-Munoz et al., IAEA FEC, Daejeon, Korea (2010)
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Higher Energy Beams Observed to Drive Spectrum of TAEs and RSAEs

- Repeating discharge with 90 kV beams drove spectrum of RSAEs and TAEs unstable
- Edge magnetics detect combination of RSAEs, TAEs and additional mode
- ECEI at mid-radius detects primarily RSAEs

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TAEs Observed to Cause Fast Ion Loss

- FILD spectrogram shows clear coherent losses from beam driven TAEs

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- FILD spectrogram shows clear coherent losses from beam driven TAEs
- FILD Scintillator indicates TAE induced losses appear near gyro-radius corresponding to injection energy

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M. Garcia-Munoz et al., Nucl Fusion 51 103013 (2011)
Full Orbit GOURDON Code Used to Identify Orbit Topology of Escaping Ions & Wave-Particle Resonances

Orbital frequencies calculated at $Z_{\text{FILD}}$ & $E_{\text{FILD}}$

$$\Omega_{n,p} \sim \omega_{\text{MHD}} - n \cdot \omega_{\text{tor}} - p \cdot \omega_{\text{pol}}$$
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Wave-Particle Resonances are in Phase-Space Region Corresponding to Passing-Ions

→ Larger Fast-Ion Losses

$E = 93 \text{ keV}, \Lambda \sim 40^\circ$

$E = 93 \text{ keV}, \Lambda \sim 75^\circ$
Fast-Ion Role in ELM Cycle

AUG #26941
Divertor Current
ELM Frequency
ELM Particle Content
FILD

Time (s)
Fast-Ion Role in ELM Cycle

ELM Induced Fast-Ion Losses

- Important for machine safety in burning plasmas?
- Pedestal Transport mechanisms?
- Escaping fast-ions carry extra information on ELM cycle
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ELM Stability
- In Peeling-Ballooning model fast-ions could modify ELM stability through additional pedestal current, pressure and $E_r$
Energetic particle driven Wall Mode (EWM) triggered ELMs in JT60U

Smaller and more frequent ELMs in the presence of fast-ion driven ideal kink-ballooning mode

- \( \Delta W_{\text{ELM}}/W_{\text{ped}} \approx 10\% \)
- \( \Delta W_{\text{ELM}}/W_{\text{ped}} \approx 5\% \)

Matsunaga et al., PRL 103 (2009)

- EWM = 2 kHz (2,1) Global Mode
- Ion-Diam Direction
Energetic particle driven Wall Mode (EWM) triggered ELMs in JT60U

G. Matsunaga et. al, IAEA FEC Geneva (2008)

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Lack of fast-ion measurement. Can FILD / FIDA give extra information?

• EWM = 2 kHz (2,1) Global Mode

Ion-Diam Direction
Global mode seems to trigger ELM but not always...

- Global (1,1) Kink in Ion-Diam Direction Doesn't Change Significantly with ELMs
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- Edge Localized n=2.5-3 & m=12, e-Diam Direction. Only Visible Before ELM
Fast-Ion Losses Observed Mainly with Low-f Edge Mode & ONLY Before ELM

• Global (1,1) Kink in Ion-Diam Direction Doesn’t Change Significantly with ELMs

• Fast-Ion Losses Increasing Towards ELM Crash

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- Edge Localized n=2.5-3 & m=12, e-Diam Direction. Only Visible Before ELM
- Deeply trapped particles are more strongly affected
Fast-Ions Seem To Contribute To ELM Stability

Low-freq pedestal fluct. prior ELM crash leads to an increasing fast-ion loss flux which seems to contribute to the ELM triggering

• Frequent, small ELMs are often accompanied by large fluxes of fast-ion losses during and pre-ELM crash

![Graph showing divertor current and FILD with time in seconds and energy] (PNBI = 7.5 MW, q95 = 3.3, Ip=1.0 MA, Bt = -1.75T, βN ~ 3)

Pre-ELM Divertor current (ELM Monitor) Rise Correlated with FILD

(E, Λ) = (80 keV, 75°)

(E, Λ) = (80 keV, 60°)
Magnetic Fluctuation of Edge Mode Is Not Sinusoidal

Low-freq pedestal fluct. prior ELM crash leads to an increasing fast-ion loss flux which seems to contribute to the ELM triggering

- Magnetic fluctuation of Low-f (12,3) Edge Mode is not sinusoidal

![Graph showing Divertor Current and Magnetics for AUG #26941.](image-url)
Fast-Ion Losses Are in Phase with Pre-ELM Edge Fluctuation

Low-freq pedestal fluct. prior ELM crash leads to an increasing fast-ion loss flux which seems to contribute to the ELM triggering

- Magnetic fluctuation of Low-f (12,3) Edge Mode is not sinusoidal
Pedestal $n_e$ fluctuation prior to ELM

Pre-ELM low freq, 1-2 kHz, density fluctuation measured around separatrix with Li-Beam diagnostic (close to FILD)

- Fast-ion losses are correlated with $n_e$-fluctuations inside of sep and anti-correlated with $n_e$-fluctuations outside of sep
- During ELM crash fast-ion losses are not correlated with any $n_e$ change
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• During ELM crash fast-ion losses are not correlated with any $n_e$ change
At least 3 different loss mechanisms (time scales) are observed during the ELM cycle. Pitch-angle dependency

- Fast-ion losses due to pre-ELM fluctuations are coherent
- Amplitude evolution of pre-ELM edge $n_e$-fluctuation and fast-ion losses are NOT correlated
- During ELM crash fast-ion losses appear in bursting fashion
Banana Orbits Are Most Affected

Measured fast-ion losses are on banana orbits that explore entire pedestal / SOL. Contribution to Stability. Sensitive to Most Pedestal Fluctuations

Both FILD1 and FILD2 observe similar behavior not correlated with any variation in $n_e$ profile. Not surprising but important to rule out first order effects such as prompt losses (DC signal)
Summary

- AEs have been driven unstable with NBI in AUG
- AE induced fast-ion redistribution & loss measured with FIDA & FILD
  - Drop in central fast-ion population as $q_{\text{min}}$ passes through an integer with multiple RSAEs
  - Fast-ion losses mainly due to TAEs. Mostly on passing orbits
  - Possible wave-particle resonances only with passing ions. Consistent with experimental data
- Large bursts of fast-ion losses during ELMs
- Core kink mode causes fast-ion losses correlated with smaller & more frequent ELMs
  - Fast-ion losses due to pre-ELM edge fluctuation are dominant. Significant contribution to ELM triggering
  - Deeply trapped particles strongly affected. Several loss mechanisms in ELM cycle