Simulation of Observed EGAM-Induced Beam-Ion Losses in DIII-D

by

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Geodesic Acoustic Modes are zonal flows with $n=0$ and $\omega_{\text{GAM}} = C_s/R$

Recently, macroscopic GAMs were discovered that are driven by energetic ions\(^1,2\)

EGAMs are excited strongly by counter-injected neutral beams

EGAMs can be driven to large amplitudes leading to large beam-ion losses

Detailed measurements of the mode properties and losses allow the validation of nonlinear dynamical model for fast-ion transport

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The EGAM Induces Losses Over an Extended Energy Range

- The Fast Ion Loss Detector (FILD) measures the pitch angle and energy of lost fast ions
  - A collimator and the magnetic field give energy and pitch discrimination
- FILD reveals that the EGAM-induced losses occur over an extended energy range (or gyro-radius)
- The losses arise from the counter-going beams
- Can we simulate the EGAM losses and understand why they occur over such a broad energy range?

For more information on FILD, see: X. Chen et al., UP9.00059 on Thurs. afternoon
The SPIRAL code follows the particle orbits by solving the Lorentz equations:

\[ \frac{d}{dt} \vec{v} = \frac{d}{dt} \frac{d}{dt} \vec{r} = \frac{q}{m} (\vec{v} \times \vec{B} + \vec{E}) \]

- Ripple fields, slowing-down, and pitch angle scattering can be included together with MHD modes and rf fields.
- The EGAM is modeled as time-varying electrical potential:
  \[ E_r = -\nabla \Phi \sin(\omega t) \]
- Realistic walls are included to calculate fast ion losses.
EGAM-Induced Losses From the FILD Detector are Reproduced With the SPIRAL Code

- In the simulations the experimental conditions were closely matched
  - EFIT equilibrium
  - TRANSP/NUBEAM beam birth profiles
  - Experimental EGAM mode width and amplitude: density fluctuations of ~10%

- The EGAM-induced losses are reproduced well in simulations with the full orbit SPIRAL code

- Why are the EGAM losses occurring over such a wide energy range?
The resonance condition for particles with the n=0 EGAM is given by:
\[ \omega_{\text{EGAM}} = P \omega_{\text{pol}} \]
with integer P the bounce harmonic.

The P=-1 and -2 counter resonances
- Are aligned with the edge of the loss cone
- In the slowing-down distribution of the counter beams

Hence, losses are found over a wide range of particle energies.

Particles lose energy to the mode before getting lost.

This provides a strong drive for the EGAM.
At Large EGAM Amplitudes, a New Set of Resonances Was Found in the Simulations

- No resonances are present in the co-beam slowing down distribution
• **No resonances are present in the co-beam slowing down distribution**

• **At the experimental mode amplitude in the simulation resonances appeared in the co-beam slowing down distribution**

• **In the following, we will**
  - Explore the nature of those resonances
  - Look for effects on the fast-ion distribution
Identification of Nonlinearly-Generated Fractional Resonances for the Measured Mode Amplitude

- **The linear resonance condition:**
  \[ \omega_{\text{EGAM}} = P \omega_{\text{pol}} \]

is fulfilled for amplitudes of 0.1% of the experimental amplitude.
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Fractional resonances:

\[ \omega_{\text{EGAM}} = \frac{p}{q} \omega_{\text{pol}} \]

occur when the mode amplitude is larger than 1% of the experimental amplitude.

The fractional resonances arise from a nonlinear interaction between the particle orbit and the mode.

EGAM frequency: 15.0 kHz
Particle pitch: 0.5
Identification of Nonlinearly-Generated Fractional Resonances for the Measured Mode Amplitude

- At the experimental mode amplitude, an extended region is formed where resonances overlap.
- The orbits in this region have become stochastic.

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Identification of Nonlinearly-Generated Fractional Resonances for the Measured Mode Amplitude

- At the experimental mode amplitude, an extended region is formed where resonances overlap.

- At the measured EGAM amplitude the particles gain more energy from the mode than they lose to the mode.

- Hence, the simulations predict that co-beams contribute to the damping of the EGAM which can be investigated experimentally.
Fractional resonances are found to coincide with the co-beam phase space.

When the resonances overlap, the particle orbits become stochastic which can lead to enhanced fast-ion transport.

In carefully designed experiments, such transport might be observed on the fast-ion $D_{\alpha}$ (FIDA) diagnostic.
Summary and Future Work

- Simulations have revealed that the observed EGAM-induced losses can be explained by counter resonances that are aligned well at the edge of the loss cone over a substantial energy range.
- Those lost particles provide a strong drive for the EGAM.
- At the experimental EGAM amplitude, a nonlinear interaction between the mode and the particle orbits was found in the simulations.
- This interaction leads to fractional resonances.
- The increased resonance density leads to stochastic orbits at the observed EGAM amplitude and, hence, an increased fast-ion transport.

Future Work

- Identify signs of enhanced fast-ion transport with the FIDA diagnostic when the EGAM is excited.
- Study the influence of co-beams on the stability of the EGAM.