Electrical model of the Alfvén eigenmode exciter on JET

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Self-heating in fusion plasmas

- Energetic particle / α particle transport
- Redistribution and losses

- Collective instabilities
  - Alfvén modes
  - Energetic particle modes

- Experiments: energetic particles do drive unstable Alfvén modes
Alfvén eigenmode stability

- AEs: Normal modes of background plasma
- “Straight” tokamak: SAW continuous spectrum
  \[ \omega^2 = \omega_A^2(r) = k^2(r) v^2_A(r) = \frac{v_A^2(r)}{R^2} \left( n + \frac{m}{q(r)} \right)^2 = \frac{B_0}{\sqrt{\mu_0 \sum n_i m_i}} \]
- Radially extended modes suffer rapid dispersion
- Tokamak: periodic mirror machine
- Poloidal harmonics (n,m) and (n,m+p) interfere to form standing waves: Gap modes
- Gap modes avoid heavy continuum damping
  - Prone to destabilization by energetic particles

Mode stability \[ \gamma_{damp} = \gamma_{backgr} + \gamma_{EP} \]

Measurement technique: excite antenna-driven stable modes and sweep across a mode resonance to measure its quality factor = damping rate

- So far: mostly experimental data for low n modes (n=0,1,2) (saddle coils experiments on JET)
- However, predictions for ITER: most unstable modes are intermediate and high n (~5-17)
TAE antennas (high n modes)

- 4 antennas (single octant) in operation in 2007 campaigns
- 8 antennas (2 groups at toroidally opposite positions) will be put in operation in 2008 campaigns
Electrical modeling and matching

Critical parameter for damping measurement: clear signal at sensors

- Antenna geometry: Effective area < 1 m² (saddle coils: 75 m²)
- High n modes have low amplitude at the plasma edge
- Antenna impedance results in high-impedance loading at the amplifier output (low current)

Better coupling to the plasma through higher antenna current

Envisaged solution: matching

Find appropriate impedance-transformation circuit(s) to maximize the transmission of power from the source to the load (antennas), compatible with operational/engineering constraints
Constraints

- Amplifier limits: 700 V, 15 A (peak)
- Voltage limit at feedthroughs: 600 V
- Matching circuits at large electrical distance from the antennas
- Broadband operation (20 – 500 kHz)
  - Matching design for narrower bands, for various configurations
5 kW broadband power amplifier
Matching circuit
Power splitter (distribution unit)
Isolation unit
Coaxial cables (of total length ~106 m)
V/I measurements at 3 points along the main transmission line
Nearest point to antennas: “Link-box” (close to transformer limbs)
Model for 4 antennas (in the same octant)

Phasing: + - + -

Matching Unit

Distribution/Isolation Units

Antenna model

In-vessel cable

$\text{k}_{12} = -5\%$

$\text{k}_{13} = -0.5\%$

$\text{k}_{14} = -0.1\%$
Comparison: model and network analyzer measurements

Very good agreement between model and measurements.

Impedance at distribution unit input

- **Phasing:** ++++
  - Shift between phasings: 14 kHz
  - Captured by modeling

- **Phasing:** ++++
  - Outside operational frequency range

Shaded regions: High impedance - low antenna current
Effects of inductive coupling between antennas

- Antennas self-inductance: ~ 70 µH
- Mutual inductance for adjacent antennas: ~ 5 µH
- Inductive coupling between closely-spaced antennas: perturbation of system transfer functions across a band of a width 40 kHz around 200 kHz
  - Antenna currents do not preserve the nominal current phasing imposed at distribution unit → problem in definition of n
  - Different antennas have different current and voltages
Example of matching (4 antennas)

Maximum currents at the antennas

Matching circuit

- Lser = 86.4 μH
- Camp = 2.93 nF
- Cant = 23.2 nF

Optimization in the frequency range 120-160 kHz

Solid lines: With matching

Dotted lines: No matching
Conclusions

✓ Model in *very good agreement* with network analyzer impedance measurements
✓ Effects of the inductive coupling between the antennas quantified
✓ Matching investigation yielded circuits that are expected to *increase antenna current by a factor of 1.5-2* inside their appropriate matching bandwidth: remains to be tested in practice

Electrical analysis is expected to contribute to the full exploitation of the diagnostic system possibilities