Measurement of Energetic Particle Modes and Structure

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ITER is expected to Produce 500 MW of Fusion Power for up to 400s in its First Phase of Operation ($\approx$2020)

$$D+T \rightarrow n(14.1 \text{ MeV}) + \alpha(3.5 \text{ MeV})$$

So, what happens to the alpha particles?
A Scaled Down Test: D Beam Ion (100 keV) Excitation of Alfven waves in TFTR (1991)

\[ E_b \approx 100 \text{ keV} \ll E_\alpha \]

(a) Neutron Flux  
(b) Mirnov Coil Signal

\[ \text{D} + \text{D} \rightarrow ^3\text{He} + n(2.5 \text{ MeV}) \]


- reduced toroidal field to match beam velocity to Alfven velocity
- Strong mode excitation & loss of beam ions observed.
  - Could this happen to 3.5 MeV alpha particles in ITER?
  - implications: vessel damage, reduced heating
Historical Context: In the 70s, Alfven Waves were thought to be highly localized and strongly damped in fusion plasmas.

- Dispersion relation for shear Alfven waves in current carrying cylinder

\[ \omega^2 = k_{\parallel}^2 V_A^2 \]

\[ k_{\parallel} = (m-nq)/qR \]

\[ V_A \sim B/\sqrt{n} \]

Phase mixing with adjacent modes stabilizes waves.

Rosenbluth and Rutherford, Phys. Rev. Lett. 34, 1428 - 1431 (1975)
Late 80s: Discrete frequency weakly damped modes appear in spectral gaps: TAEs, EAEs, NAEs, …

\[ | n - \frac{m}{q} | = | n - \frac{m + k}{q} | \]

\[ q = \frac{2m + k}{2n} \]

- \( k = 1 \); toroidicity coupling
- \( k = 2 \); elongation coupling
- \( k = 3 \); triangularity coupling

- Discrete modes discovered theoretically in gaps
- Detection in 1991 based on edge magnetic probes, but theory indicates internal localization.

Energetic Particle and Alpha Drive Peaks in Plasma Core While Magnetic Probes Located At Edge: Need Core Probes

\[ \omega = -k_{||m+1}(r) v_A(r) \quad \omega = +k_{||m}(r) v_A(r) \]

\( q = m/n \quad r = r_0 \quad q = (m+1)/n \)

\( k_{||m} = 0 \quad k_{||m+1} = 0 \)

TAE

edge
TRACE: Resolving large scale structure is essential to understanding

Note: fusion has a long way to go to develop internal macroscopic measurement capability
Tomography: A Tough Way To Map Instabilities; many assumptions needed with few views

\[ p(x) = \int f(x,y)dy : \text{(projection in real space)} \]

\[ P(k_x) = \int p(x')e^{-ik_xx'} dx' \]

\[ = F(k_x,0) : \text{(slice in Fourier Transform)} \]

\[ F(k_x,k_y) = \iint f(x,y)e^{-ik_xx}e^{-ik_yy} dxdy \]

Medical imaging: hundreds of projections – CAT (Nobel Prize 1979)
Fusion applications: < 10 projections
Maximum poloidal harmonic < number of views
Tomography From Plasma Emission
Bremsstrahlung Radiation from electron ion collisions

\[
\frac{dN_B}{d\lambda} = 2.85 \times 10^{-13} \frac{n_e^2 Z_{eff}}{\lambda T_e^{1/2}} e^{-\frac{hc}{\lambda T_e}}
\]

- Radiation typically peaks in the X-ray range for keV plasma temperatures
- Broad continuum with discrete line radiation
- Use of pinhole cameras and X-ray detector arrays can extract projections of the x-ray emission
X-ray Tomography on W7-AS confirms poloidal mode coupling for TAEs

10 views can resolve $m=5,6$ TAE
Tomography From Plasma Emission
Visible Bremsstrahlung Radiation from electron ion collisions

\[
\frac{dN_B}{d\lambda} = 2.85 \times 10^{-13} \frac{n_e^2 Z_{eff} e^{-\hbar c/\lambda T_e}}{\lambda T_e^{1/2}} e^{-\hbar c/\lambda T_e}
\]

- Radiation power in visible range is 2 orders of magnitude lower than in the X-ray range
- But, large collection optics, fiber optics, all sorts of optics available
- efficient detectors available.
VB Fast Framing Camera on DIII-D Images a Significant Fraction of the Plasma Cross-Section

• 12 bits, 256x256 pixels -> 0.05 - 0.2 cm$^2$ each

• Up to 100 kFrames/s, but the imaging done here is 26 kFrames/s

• Can store ~ 800 ms at this frame rate

• Light being imaged (for MHD studies) is unfiltered so ~450-950 nm
Synthetic VB Diagnostic Reproduces Many Features of the Camera Measurements for $m=2$ Tearing Mode

- Problem: Need large amplitude fluctuations
- Same for X-ray measurements
- Need $\delta l/l > 0.5\%$ (typical) to exceed photon statistical noise

Hydrogen Line emission from Neutral Beams is a Rich Source of Information on Internal Mode Activity

Image of Doppler shifted hydrogen line:
$$\delta I/I \propto \delta n_e/n_e$$
BES gives local measurement of $\Delta ne$ and allows a radial scan of the AE mode structure.

Approximate layout of the 16 BES channels:
- 500 kHz bandwidth

BES

NOVA simulation

Radial Range

BES array

$\Delta ne/n_e$

Shot 122117

~3 cm

~3 cm
$k_\theta$ obtained with BES agrees well with NOVA

Comparison of $k_\theta$ from BES shows excellent agreement with $k_\theta$ from NOVA on the LFS.

Electron Cyclotron Emission: New Applications

• Radiation is emitted at harmonics of the cyclotron frequency

\[ \omega = n \times 28 \times B(T) \text{ GHz} \]

• Inhomogeneous magnetic field means localized emission for a given frequency for optically thick plasmas

\[ I(\omega) \propto \omega^2 T_e (1 - e^{-\tau}) \]

\( \tau \): optical thickness

• second harmonic is usually optically thick, \( \tau > 4 \)
Measurements of 1-D Mode Structure Possible for Large Amplitude Tearing Modes

- Typically, local measurements were made along midplane at very few locations

- Historically, ECE measurements of $\delta T_e$ provided best mode structure data

- More recently detailed measurements obtained even for very weak modes

DIII-D
Radial Mode Structure Measured with ECE on DIII-D: Dramatic agreement with Alfvén Eigenmode Theory

\[ \approx 0.2\% \]
With fewer views, synthetic diagnostics can be used to infer poloidal mode number from radial nodes

**Interferometer**

**Probe beam** $\omega >> \omega_{pe}, \omega_{ce}$

$$\delta \phi \propto \int \delta n_e dL$$

- Phase Contrast Interferometer (PCI) on C-MOD
  - 32 closely spaced channels
  - Single projection

- Synthetic diagnostic takes line-integrals through theoretical mode structure

M. Porkolab, et. al., TTF, San Diego, CA (2007)
Simplified Example of a projection through the magnetic axis

\[ \sin(kx + b + \omega t) + \sin(-kx + \omega t) \]

\[ = 2 \cos(kx + b/2) \sin(\omega t + b/2) \]

\[ \Delta x = \text{separation between nodes} \]

\[ k \approx m/r = \pi/\Delta x \]
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Similar approach being used on proposed tangential interferometer for ITER

- TIP = Tangential Interferometer and Polarimeter
- Eigenmodes of ITER Scenario 4 plasma are calculated
- Displacement is used to determine $\delta n_e$ profile
- $\delta n_e$ and $\delta B$ are mapped onto TIP ray trajectories
Interferometer Line-Integrated Response on ITER Exhibit Spatial Profile Similar to Eigenmode

\[ \delta \phi \propto \int \delta n_e \, dL \]

\[ \lambda = 10.59 \, \mu m \]
How to combine the sensitivity of Interferometry with improved localization?

- Collective scattering/interferometry:
  - frequency: $\omega \gg \omega_{pe}, \omega_{ce}$
  - weak refraction
  - poor spatial resolution along line of sight for long waves (remember tomography)

- Reflectometry:
  - waves reflect from a plasma cutoff: $\mu = 0$
  - group velocity slows down near cutoff
  - enhanced sensitivity to fluctuations near $\mu = 0$
Collective Scattering Loses Spatial Resolution For Large Scale Structures: TFTR

Bragg scattering, with $|\Delta k| << k_0$
How to understand scattering in terms of Tomography

- Momentum conservation for $\Omega \ll \omega$, $|k_s| = |k_0|$

  Assume $k_0$ in y-direction

- For small scattering angles, show $k_s = (K_x, k_0 - K_x^2/2k_0)$
  where $K_x$ is the wavenumber in the scatterer in the x-direction

- The wave number scattering trajectory in K-space in the medium is $(K_x, -K_x^2/2k_0)$
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- Each projection prescribes a parabolic arc through the spectrum.
Alternative: Reflectometry is the reflection of microwaves from a plasma cutoff: $\omega_{pe} > \omega$
Reflectometry began in the Ionosphere (Ionosonde)

• 1902: First transatlantic wireless communication (Marconi) leads to conjecture (Heaviside) for existence of ionosphere

• 1924/25: Electron height distribution from radio wave reflection
  - Pulsed (Breit, USA) radar 1-10 MHz identifies E & F layer
  - Frequency sweep method: (Appleton, UK)

• 1930s: Timely Technology Spin off: Aircraft radar in WWII
  - based on pulsed method

• Reflectometry is interferometry enhanced near a cutoff
JET (UKAEA) Reflectometer Reveals Many Hidden Modes in RF heated Plasmas

- Reflectometer
- Magnetics
  - $n < 5$
10.6 MW of Fusion Power on TFTR (1993)
Internal mode structure anomaly also resolved in 2003: (not a diagnostic anomaly)

- core $\tilde{B}/B \sim 2 \times 10^6$ Two orders higher than at edge.
Reflectometer Modeling is underway for ITER
10 years ago nearly all the data on Alfven eigenmodes AEs in fusion plasmas was based on edge magnetic sensors.

Today many tools exist (and many more are on the way) to address the internal structure of AEs.

Next talk will use these tools to address physics questions on the properties of Alfvénic modes.