Princeton Plasma Physics Laboratory

PPPL-4015
PPPL-4015

Observation of Energetic Particle Driven Modes Relevant to Advanced Tokamak Regimes

R. Nazikian, B. Alper, H.L. Berk, D. Borba, C. Boswell, R.V. Budny, K.H. Burrell, C.Z. Cheng, E.J. Doyle, E. Edlund, R.J. Fonck, A. Fukuyama, N.N. Gorelenkov, C.M. Greenfield, D.J. Gupta, M. Ishikawa, R.J. Jayakumar, G.J. Kramer, Y. Kusama, R.J. La Haye, G.R. McKee, W.A. Peebles, S.D. Pinches, M. Porkolab, J. Rapp, T.L. Rhodes, S.E. Sharapov, K. Shinohara, J.A. Snipes, W.M. Solomon, E.J. Strait, M. Takechi, M.A. Van Zeeland, W.P. West, K.L. Wong, S. Wukitch, and L. Zeng

October 2004

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Prepared for the U.S. Department of Energy under Contract DE-AC02-76CH03073.

PPPL Report Availability

This report is posted on the U.S. Department of Energy's Princeton Plasma Physics Laboratory Publications and Reports web site in Fiscal Year 2005. The home page for PPPL Reports and Publications is: http://www.pppl.gov/pub_report/

Office of Scientific and Technical Information (OSTI):

Available electronically at: http://www.osti.gov/bridge.

Available for a processing fee to U.S. Department of Energy and its contractors, in paper from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062

Telephone: (865) 576-8401

Fax: (865) 576-5728

E-mail: reports@adonis.osti.gov

National Technical Information Service (NTIS):

This report is available for sale to the general public from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

Telephone: (800) 553-6847

Fax: (703) 605-6900

Email: orders@ntis.fedworld.gov

Online ordering: http://www.ntis.gov/ordering.htm

IAEA
International Atomic Energy Agency

20th IAEA Fusion Energy Conference
Vilamoura, Portugal, 1 to 6 November 2004

IAEA-CN-116/EX/5-1

OBSERVATION OF ENERGETIC PARTICLE DRIVEN MODES RELEVANT TO ADVANCED TOKAMAK REGIMES

R. NAZIKIAN, B. ALPER,[1] H.L. BERK,[2] D. BORBA,[3] C. BOSWELL,[4]
R.V. BUDNY, K.H. BURRELL,[5] C.Z. CHENG, E.J. DOYLE,[6] E. EDLUND,[4]
R.J. FONCK, A. FUKUYAMA,[7] N.N. GORELENKOV, C.M. GREENFIELD,[5]
D.J. GUPTA,[8] M. ISHIKAWA,[9] R.J. JAYAKUMAR,[10] C.J. KRAMER, Y. KUSAMA,[9]
R.J. LA HAYE,[5] G.R. McKEE,[8] W.A. PEEBLES,[6] S.D. PINCHES,[11] M. PORKOLAB,[4]
J. RAPP,[12] T.L. RHODES,[6] S.E. SHARAPOV,[1] K. SHINOHARA,[8] J.A. SNIPES,[4]
W.M. SOLOMON, E.J. STRAIT,[5] M. TAKECHI,[8] M.A. VAN ZEELAND,[5] W.P. WEST,[5]
K.L. WONG, S. WUKITCH,[5] and L. ZENG[6]

Princeton Plasma Physics Laboratory
Princeton, New Jersey
United States of America

[1]Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, United Kingdom
[2]Institute of Fusion Studies, University of Texas at Austin, Austin, Texas, USA
[3]Euratom/IST Fusion Association, Centro de Fusao Nuclear, Lisboa, Portugal
[4]Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[5]General Atomics, San Diego, California, USA
[6]University of California-Los Angeles, Los Angeles, California, USA
[7]Kyoto University, Kyoto 606-8501, Japan
[8]University of Wisconsin-Madison, Madison, Wisconsin, USA
[9]Japan Atomic Energy Research Institute, Naka-machi, Ibaraki-ken, Japan
[10]Lawrence Livermore National Laboratory, Livermore, California, USA
[11]Max Planck Institut fuer Plasmaphyik, Euratom Association, Garching, Germany
[12]Institut fuer Plasmaphysik, Forschungszentrum Juelich GmbH, Euratom Association, Juelich, Germany

Observation of Energetic Particle Driven Modes Relevant to Advanced Tokamak Regimes

R. Nazikian[1], B. Alper[2], H.L. Berk[3], D. Borba[4], C. Boswell[5], R.V. Budny[1], K.H. Burrell[6], C.Z. Cheng[1], E.J. Doyle[7], E. Edlund[5], R.J. Fonck[11], A. Fukuyama[8], N.N. Gorelenkov[1], C.M. Greenfield[6], D.J. Gupta[11], M. Ishikawa[9], R.J. Jayakumar[10], G.J. Kramer[1], Y. Kusama[9], R.J. La Haye[6], G.R. McKee[11], W.A. Peebles[7], S.D. Pinches[12], M. Porkolab[5], J. Rapp[13], T.L. Rhodes[7], S.E. Sharapov[2], K. Shinohara[9], J.A. Snipes[5], W.M. Solomon[1], E.J. Strait[6], M. Takechi[9], M.A. Van Zeeland[6], W.P. West[6], K.L. Wong[1], S. Wukitch[5], L. Zeng[7]

1) Princeton Plasma Physics Lab., P.O. Box 451, Princeton NJ 08543, USA
2) Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, UK
3) Institute of Fusion Studies, University of Texas at Austin, Austin, Texas 78712-02644
4) Euratom/IST Fusion Association, Centro de Fusao Nuclear, Lisboa, Portugal
5) MIT, Plasma Science & Fusion Center, 167 Albany Street, Cambridge, MA 02139 USA
6) General Atomics, La Jolla, CA 92186-5608
7) University of California Los Angeles, Los Angeles, California 90095-1597
8) Kyoto University, Kyoto 606-8501, Japan
9) Japan Atomic Energy Research Institute, Naka-machi, Ibaraki-ken, Japan
10) Lawrence Livermore National Laboratory, Livermore, CA 94550
11) University of Wisconsin - Madison, Madison, WI 53706
12) Max-Planck Institut fuer Plasmaphysik, Euratom Association, D-85748 Garching, Germany
13) Institut fuer Plasmaphysik, Forschungszentrum Juelich GmbH, Euratom association, TEC, Juelich, Germany

Abstract. Measurements of high frequency oscillations in JET, JT-60U, Alcator C-Mod, DIII-D and TFTR plasmas are contributing to a new understanding of fast ion driven instabilities relevant to Advanced Tokamak (AT) regimes. A model based on the transition from a cylindrical-like frequency-chirping mode to the Toroidal Alfvén Eigenmode (TAE) has successfully encompassed many of the characteristics seen in experiments. In a surprising development, the use of internal density fluctuation diagnostics has revealed many more modes than has been detected on edge magnetic probes. A corollary discovery is the observation of modes excited by fast particles traveling well below the Alfvén velocity. These observations open up new opportunities for investigating a "sea of Alfvén Eigenmodes" in present scale experiments, and highlight the need for core fluctuation and fast ion measurements in a future burning plasma experiment.

1. Introduction

The physics of energetic particle driven modes is of intrinsic interest for understanding wave-particle interaction as well as of practical interest for the impact such interactions may have on the plasma. High frequency oscillations such as Alfvén waves can perturb resonant fast ion orbits. If the modes grow to sufficient amplitude then the fast ions may be lost to the wall or transported out of the plasma core. Understanding the stability and saturation mechanisms for these modes in present experiments is the key to predicting fast ion behavior in future burning plasma experiments.

Fusion researchers have made steady progress towards developing the Hybrid Regime and other non-inductive operating regimes as a possible alternative to ELMy H-mode operation for a burning plasma experiment. In parallel, substantial progress has been made towards understanding the physics of energetic particle driven modes relevant to these advanced operating regimes. The rapid progress in understanding is due in large part to a remarkably strong collaboration between colleagues in the USA, Japan and Europe.

In this paper we present recent developments in our understanding of energetic particle driven modes in weak and reverse magnetic shear plasmas that are most relevant to Advanced Tokamak (AT) plasma regimes. Here AT refers to the development of high confinement steady state plasmas, which typically require weak and/or reverse magnetic shear. Foremost among these recent developments is the critical importance of core fluctuation diagnostics for identifying modes not readily observable on external magnetic probes. A corollary discovery is the simultaneous excitation of many fast ion driven waves with very high toroidal mode numbers. As a measure of our growing understanding, in the 2002 Snowmass report [1] there was no explicit calculation of the stability of modes in reverse magnetic shear configurations. A similar study conducted today would not be acceptable without a detailed analysis of Alfvén eigenmodes in AT relevant plasma regimes.

2. Background

Low frequency chirping modes were initially observed in a frequency range appreciably below and up to the TAE frequency. They arose in several tokamaks such as: the TFTR-DT experiments where the modes were driven by fusion alpha particles in weak magnetic shear plasmas [2], and in several hydrogen minority ion cyclotron heating experiments in JT-60U, JET and Alcator C-Mod using Hydrogen minority Ion Cyclotron heating [3, 4, 5, 6]. An impressive early observation of the frequency chirping on JT-60U [3, 4] is shown in Fig. 1. These modes exhibit a sequence of increasing toroidal mode number as the magnetic safety factor decreased toward an integer value and not much frequency downshifting, a characteristic of most data where this type of mode arises. In addition the higher n-modes sweep at a faster rate. A significant feature of this data is the observation of high toroidal mode numbers (up to n=11) on external magnetic probes. Another feature of all the data is that these modes occur when the equilibrium has a region of reverse magnetic shear as was clearly observed on JET [6].

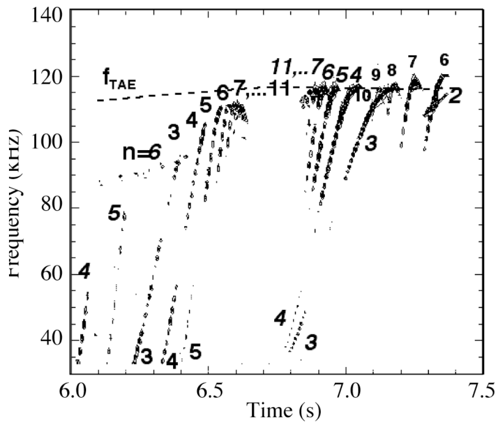

Fig. 1. Temporal evolution of Alfvén mode frequency changes observed in a JT-60U ICRF heated RS plasma [3].

Initially, the modes on TFTR were misidentified as TAEs due to the proximity of the mode frequency to the TAE frequency, with some caveats associated with low-n modes. However, the more dramatic frequency chirping observed on JT-60U, JET and Alcator C-Mod indicated a need to find an alternative Alfvénic mode. Early analytic [7] and numerical [8] studies identified modes where the real frequency was found to be sensitive to the evolution of q_{min}. A detailed theory-experiment comparison on JET [7, 9] and JT-60U [10] convincingly demonstrates that these chirping modes are indeed Alfvén Eigenmodes with a frequency determined predominantly by the evolution of q_{min}. A subsequent reevaluation of the TFTR data resolved earlier inconsistencies with the TAE theory [11]. These developments mark dramatic progress in providing a uniform understanding of these curious frequency chirping modes in reverse magnetic shear plasmas in a wide range of conditions and machines.

The basic picture that has emerged from these studies is that cylindrical-like Alfvén modes (i.e., modes with one dominant poloidal mode number m) appear at rational values of q_{min}=m/n. The modes then transform to TAEs as q_{min} -> q_{TAE} = (m-1/2)/n. Over this relatively small change in q-value, the mode frequency changes from significantly below the TAE frequency to the TAE frequency. This mode is referred to as a reverse shear Alfvén eigenmode (RSAE) on JT-60U and as a Cascade mode on JET, where both terms refer to the existence of modes with a single dominant poloidal harmonic m at the location of q_{min}. In the range m/n < q_{min} < (m-1/2)/n, the mode frequency is given by $\omega \approx k_{\|} V_A$, where $k_{\|} = (m-nq_{min})/q_{min}R$ for one dominant poloidal harmonic m and V_A is the Alfvén velocity. For q_{min} > (m-1/2)/n the mode approaches the TAE frequency where it fades away (as seen in Fig. 1) or merges with the TAE as best seen in Fig. 4. The rate of frequency chirping vs q_{min} is proportional to the toroidal mode number n ($\partial\omega/\partial q_{min} \approx nV_A/q_{min}R$) so that the mode numbers may be extracted without the use of toroidal correlation analysis. This is particularly useful for the interpretation of core interferometer measurements when external magnetic data is not available. Outstanding issues still exist such as the precise role of energetic particles [9] and the range of applicability of the ideal MHD description [12]. However these issues do not obscure the fundamental similarity of the model predictions in terms of the observable characteristics of the modes. Further progress and new insights will undoubtedly arise from more detailed measurements and calculations.

3. Internal Mode Measurements

A unique contribution of the TFTR-DT experiments is the measurement of the internal structure of the Cascade modes with the use of reflectometry [11]. The observation of an anti-ballooning density mode structure for the low frequency n=2 mode has been highly controversial for some time. The issue was resolved when the NOVA-K code confirmed that the Alfvén Eigenmode near q_{min} should exhibit density peaking on the high field side of the magnetic axis (Figure 2). The magnitude of the magnetic component of the calculated eigenmode is close to in-out symmetric, consistent with a single dominant poloidal mode number m.

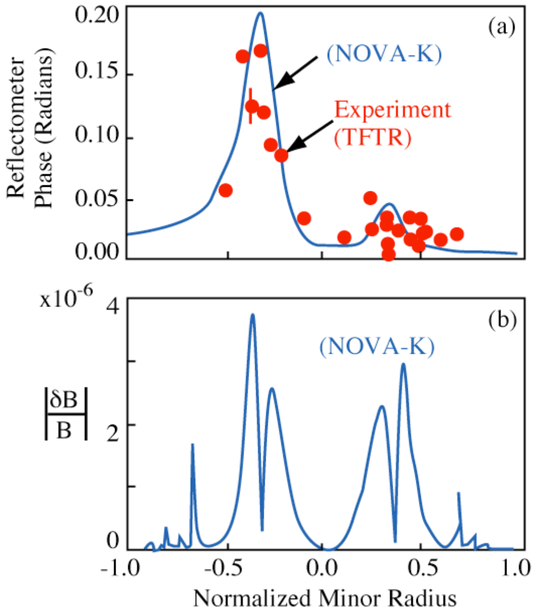

Fig. 2. (a) Measured radial structure of n=2 density fluctuations along midplane on TFTR reveals agreement with Cascade eigenmode from NOVA-K. (b) Corresponding magnetic field from NOVA-K is consistent with a cylindrical-like mode.

In a recent experiment on JET, new observations of a broad spectrum of Cascade modes were observed in reverse magnetic shear plasmas by operating the plasma density below the O-mode reflectometer cutoff density (Fig. 3) [13]. The interferometric data revealed a rich Alfvén spectrum consisting of many frequency-sweeping discrete modes ranging from 40 kHz to the TAE frequency ≈140 kHz. These observations are in agreement with the established characteristics of Cascade modes driven by high-energy hydrogen minority ions heated by the fast waves. The new evidence from the plasma core indicates that Cascades are far more prevalent in AT relevant regimes and in higher numbers than previously thought, with mode numbers up to n=16 observed in the plasma core. These mode numbers are not directly measured but inferred from the rate of change of frequency of the modes. Note that these observations are in contrast to isolated low-n modes observed on external magnetic probes. As a q-profile diagnostic, the onset of the Grand Cascade (dashed line in Fig. 3) accurately identifies the entry of q_{min}=2 surface in the plasma. The detection of core localized high-n modes allows a more accurate determination of q_{min} than is possible with external magnetic measurements. It also allows for a more accurate study of the stability of these modes under varying plasma conditions and auxiliary heating.

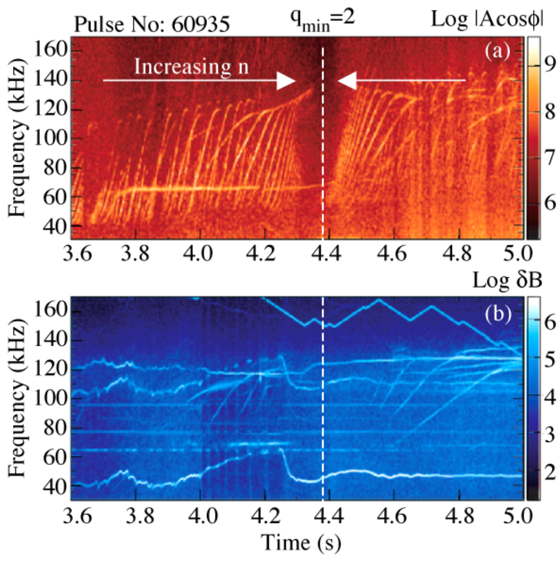

Fig. 3. Amplitude of plasma perturbations as function of time and frequency measured in JET discharge. (top) Interferometer measurements with microwave beam of 45.21 GHz along plasma midplane showing up to n=16 modes and (bottom) measurements with external magnetic pick-up coils with n=3-5.

In a parallel development, the phase contrast imaging (PCI) diagnostic on Alcator C-Mod has been highly successful in identifying new mode activity not observable on external magnetic probes [14] (Fig. 4). The excitation of Alfvén eigenmodes has been observed in Alcator C-Mod with hydrogen tail ion temperatures as low as 100 keV from TRANSP analysis. Both in JET and in Alcator C-Mod, core chirping modes are observed that cannot be identified on external magnetic probes. Due to the dominant radio frequency (rf) heating in these experiments, the effect of toroidal rotation on the mode frequency is weak compared to the dependence on q_{min}. The modes observed on interferometer channels typically chirp faster than modes observed on magnetic diagnostics, indicating that higher toroidal mode numbers are involved. The work on Alcator C-Mod and also recent data obtained on

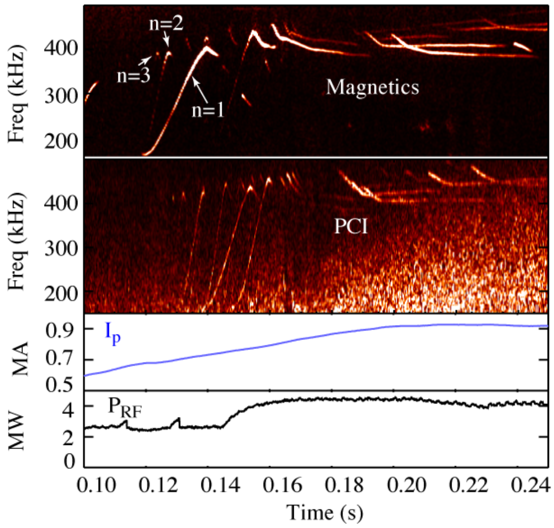

Fig. 4. Core Alfvén Cascades on PCI on Alcator C-Mod have higher mode numbers than the more global AC's seen on edge magnetic pickup coils. The PCI chords traverse the central region of the plasma where magnetic shear reversal is predicted.

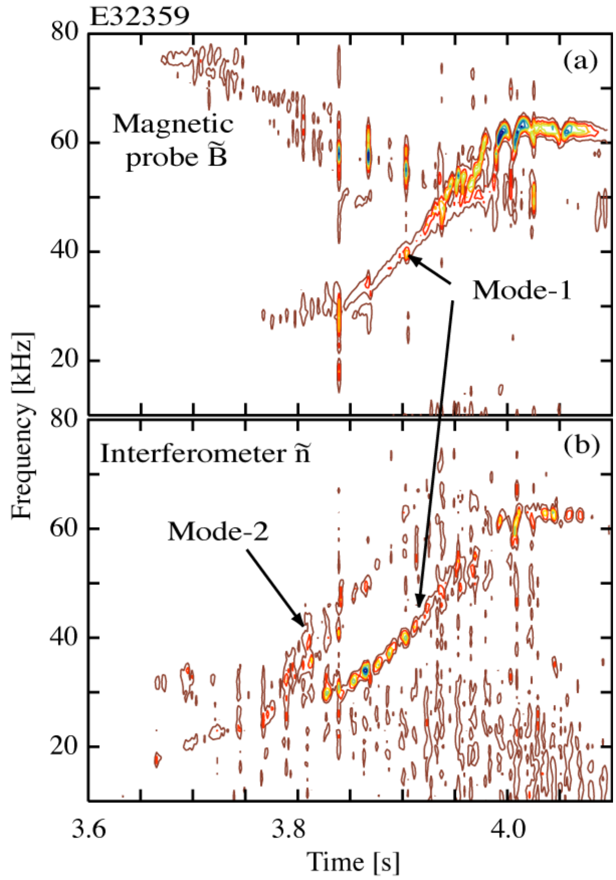

Fig. 5. (a) Magnetic fluctuations peak at the transition form the slow frequency-chirping mode (Mode-1) to the TAE in JT-60U. (b) Interferometer measurements identify additional low frequency chirping mode (Mode-2). The peak of the interferometer signal occurs at low frequencies, contrary to the magnetic signals, as observed on TFTR.

DIII-D demonstrates that CO_2 laser interferometry is sufficiently sensitive to detect these modes in fusion plasmas. On JET the interferometer measurements in Fig. 3 are taken with the O-mode reflectometer system where the density of the plasma is kept just below the O-mode cutoff. In a similar approach, line integral density fluctuation measurements were taken with an X-mode reflectometer system on JT-60U. For a 1 T magnetic field, the launch frequency (≈140 GHz) propagates about the third electron cyclotron harmonic and reflects from the inner wall. Figure 5 shows a comparison of magnetic and line density measurements in a 1 T discharge where the modes are excited by the injection of 360 keV neutral beam ions [10]. Note that the mode amplitude peaks earlier in the line density than on the edge magnetic signal for Mode-1. This is similar to the behavior of core reflectometer measurements on TFTR [11]. These observations are particularly important when attempting to correlate fast ion loss with mode amplitude measurements.

The many core-localized modes not observable on magnetic sensors in JET highlight the need for core density fluctuation diagnostics on a future burning plasma experiment.

4. Neutral Beam Driven Alfvén Eigenmodes

Extensive studies have been conducted on JT-60U using tangentially injected neutral beams with energies in the range 360 keV and toroidal magnetic field near 1 T where the beam ion velocity is close to the Alfvén speed. However, recent studies have shown that RSAEs or Cascades can be excited at much higher toroidal magnetic fields on JT-60U where the beam ion velocity is closer to half the Alfvén speed.

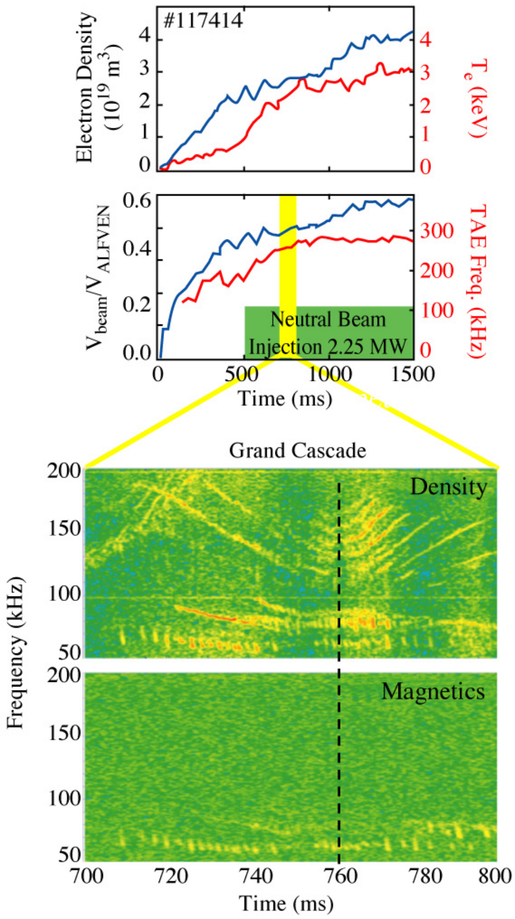

Fig. 6. Cascades excited with 80 keV tangential beam injection in a DIII-D discharge with B_T = 1.8 T, R = 1.7 m and $n_e(0) \approx 2.0 \times 10^{19} cm^{-3}$. The Spectrogram of density fluctuations is from FIR scattering measurements through the plasma midplane. The magnetic probes have an effective bandwidth of 250 kHz. Note that strong bursting and fast chirping behavior of the mode amplitude observed at low frequency indicates a strong interaction with neutral beam ions.

These observations highlight a general misconception that high-energy ions are required to excite Alfvén eigenmodes in present scale experiments, and that these energies exceed the range available in standard positive ion heating beams unless the toroidal magnetic field is greatly reduced. Recent observations on JET and DIII-D challenge this notion and so we need to consider carefully the resonance condition for these modes.

For passing particles the resonance condition for the mode-particle interaction is given by $-k_{||}V_A = (k_{||} + p/qR)V_{||}$ where p is a signed integer and $k_{||} = (n - mq)/qR$. Hence resonance is at $V_{||}/V_A = \alpha/(\alpha + 2p)$ where $\alpha = \omega_{mn}/\omega_{TAE}$, $\omega_{TAE} = V_A/2qR$ and $\omega_{mn} = |k_{||}V_A|$. As q varies from $m/n < q < (m-1/2)/n$, a single Cascade mode with frequency ω_{mn} sweeps up to the TAE frequency ω_{TAE}. Thin orbits have the strongest interaction for the p=±1 resonances which gives for $\alpha \approx 1$ (mode near the TAE frequency) the resonance conditions $V_{||}/V_A = 1$ $(p = 1)$ or $V_{||}/V_A = -1/3$ (p=-1). Note that for p=±1 and for a Cascade mode with small α corresponding to a frequency well below the TAE frequency, we obtain $|V_{||}/V_A| \approx \alpha/2$. In experimental observations the minimum of the Cascade frequency has been observed as low as ~0.3 ω_{TAE}, so that the Cascade p=1 resonance can occur well below the TAE sideband resonance condition with sub-Alfvénic beam ions. However, then the mode would fade away as the frequency increases because the resonance condition may not be fulfilled at higher frequency. Even lower velocity beams can achieve resonances at higher $|p|$ values, but these higher order resonances require finite size orbit widths (orbit width larger than εr/n where ε=a/R) to obtain a substantial interaction. Further, beams are often partially injected into the trapping region and Coulomb scattering causes an accumulation of trapped particles, where the precession drift, ω_D, is significant. Then, as $-k_{||}V_A=(k_{||}+p/qR)V_{||} + n\omega_D$ is the resonance condition, the precessional drifts may enable resonance to be achieved at yet lower beam ion velocities.

Recent FIR scattering measurements on DIII-D have revealed clear evidence for the excitation of Cascade modes in weakly reverse magnetic shear plasmas in 1.8 T plasmas with 80 keV beams (Fig. 6). The far infrared (FIR) scattering system detected fluctuations in the range $-1 < k_\theta < 1$ cm^{-1}. These modes have since been observed in many DIII-D plasmas with weak and reverse magnetic shear. A notable characteristic of the observations on DIII-D is the lack of correlation between core density and edge magnetic oscillations. Figure 6 shows an example of a Grand Cascade observed on DIII-D with the FIR scattering system. These are concentrations of Cascade modes that indicate integer q crossings. Note that the observed modes exhibit very strong bursting behavior on the scattering signal, suggesting a strong interaction and possible redistribution of the beam ions. Comparison with MSE measurements in different plasma discharges confirms that the Grand Cascades on DIII-D correspond to integer q_{min} crossings. The mode activity commences early in the beam-heating phase when the deuterium beam ion velocity at 80 keV is less than 40% of the Alfvén velocity. It is difficult on DIII-D to inject beam ions well below the sideband resonance condition for TAEs ($V_{||}=V_A/3$). However, it is quite possible that positive ion beam injection below the sideband resonance condition can be achieved on JT-60U and JET.

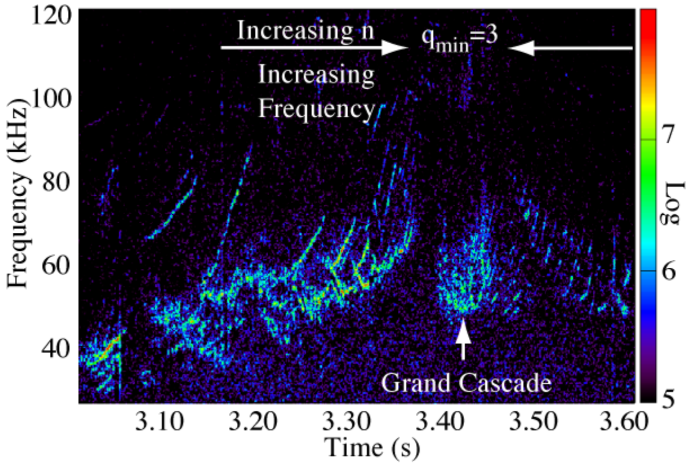

Fig. 7. Spectrogram of Cascade modes excited by 110 keV tangentially injected deuterium beam ions in JET: B_T=3.46 T, $n_e(0)$=2.0x10^{13} cm^{-3}, R=300 cm.

Evidence from JET indicates that Cascade modes can also be excited by neutral beam injection in high toroidal field plasmas (Fig. 7). In this plasma LHCD was used to generate the current hole but no ICRH was used. Figure 7 shows data from an O-mode interferometer channel with 2.3 MW deuterium beam injection (110 keV) in a 3.46 T plasma with central electron density 2.0x10^{13} cm^{-3}. The modes were observed in a current hole discharge where the q-profile is strongly reversed and the time of the Grand Cascade corresponds to the crossing of q_{min}=3. The neutral beam ion velocity is ≈ 0.27 V_A. However the angle of neutral beam injection in this case is 45 degrees to the field lines so that collisions during the slowing down process can produce a significant population of trapped energetic ions. A detailed analysis of the resonance condition is needed to determine the excitation mechanism for these modes and the relative role of trapped vs passing particles. However, what is clear is that interferometer measurements have succeeded to identify many Cascade modes driven by energetic ions traveling close to or below $V_A/3$.

Note that with neutral beam injection there is now significant plasma rotation. Consequently, there is a Doppler shift of the spectrum to higher frequency with increasing toroidal mode number as shown in Fig. 7. Higher mode numbers are expected when approaching integer q_{min} values from above. This should form an envelope of modes with increasing frequency due to the Doppler shift. Once q_{min} drops below 3 the sequence of modes reverses toward low-n. Further work is still needed to fully explore the resonance condition for Cascade modes in JET either by raising the toroidal field strength or by lowering the beam ion voltage.

Evidence for the excitation of many high-n modes is observed on the DIII-D facility. For a long time it has been speculated that high frequency modes could be responsible for the anomalous beam ion diffusion inferred (not measured) in weak and reverse magnetic shear plasmas on DIII-D [15]. The observed modes typically extended up to 1 MHz and were most clearly seen on FIR scattering signals, with no clear counterpart on magnetic diagnostics.

Figure 8 shows an example of the mode activity observed in a Quiescent-H-mode (QH) plasma with weakly reversed magnetic shear, together with a simple model analysis based on the observed evolution of q_{min} from MSE measurements. The modeling assumes a transition from the Cascade mode (starting at q_{min}=m/n) to the TAE [at q_{min} =(m-1/2)/n] for a wide range of toroidal mode numbers, and adds a Doppler shift using measured charge exchange data. In this discharge the neutral beams are injected in the direction *opposite* to the plasma current and the observed mode activity is consistent with mode propagation in the direction of the plasma current in the plasma rest frame. The different bands of modes correspond to different poloidal mode numbers m=n+l where l=0, 1, 2…

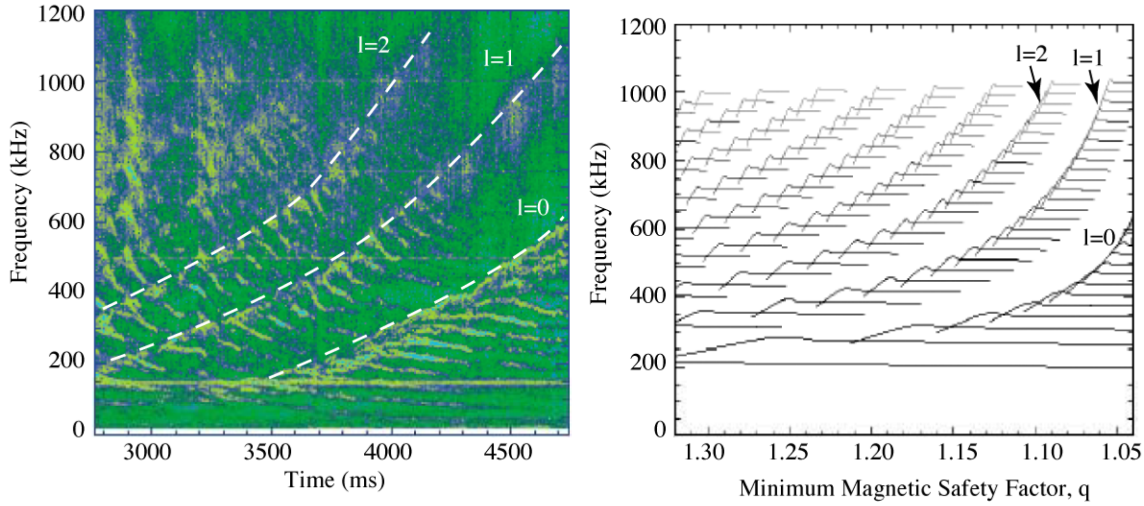

Fig. 8. (a) The time evolution of a number of frequency bands in the density fluctuation spectrum from FIR scattering measurements in DIII-D ($0<k_\theta<2$ cm^{-1}). Modes are excited by 80 keV deuterium beam ions. Plasma parameters: B_T=2.1 T, $n_e(0)$=2.6x10^{13} cm^{-3}, R=1.7 m, ω_{tor}≈33 kHz. (b) Model analysis of Cascade modes transitioning to TAEs based on evolution of q_{min} from MSE measurements. In this data range it is assumed that q_{min} varies linearly with time.

correspond to increasing frequency bands. For each of the three dominant bands of modes we obtain an average frequency spacing of 33 kHz, 36 kHz and 33 kHz (for the l=0, 1, and 2 bands respectively). The central toroidal rotation in this discharge and at this time is 33 kHz, while at the location of q_{min} it is 30 kHz. The magnitude of the frequency shift is certainly consistent with that expected for successive toroidal mode numbers n, n+1, …. Mode numbers up to n=30 are inferred from the Doppler shifted spectra with up to 20 independent modes observed simultaneously in some discharges. If we now look back to Figure 3, we can see just such a similar set of nested bands on JET. However unlike in DIII-D, the bands of modes on JET are partially obscured by low plasma rotation. In the DIII-D data the plasma is rotating at ≈5% of the Alfvén velocity in the direction of neutral beam injection.

In Figure 8 the highest mode numbers can have very short poloidal scale lengths. Note that for m=n=30 and r≈20 cm in DIII-D the poloidal scale length can be in the range k_θ≈1 cm^{-1} so that a small angle scattering system turns out to be quite effective for the investigation of these high-n modes. Also, with such core localized high mode numbers it is unlikely that there will be a detectible magnetic component to these modes at the plasma edge. Recent experiments have corroborated the FIR measurements on DIII-D with extensive reflectometer, vertical and radial CO_2 interferometer and Beam Emission Spectroscopy measurements. The modeling reproduces the qualitative behavior of the data, however a quantitative description must await a detailed stability analysis using NOVA-K.

5. Relevance to Burning Plasmas

The excitation of Alfvén eigenmodes with low energy heating ions raises the new possibility of exploring a "sea of modes", which has been predicted to occur in a burning plasma experiment. For similar MHD equilibria, the maximum toroidal mode number excited in a device should scale as the ratio of the average minor radius to the fast ion gyroradius, $n_{max} \approx a/(q\ \rho_\alpha)$ where ρ_α is the Larmor radius of the alpha particles. In addition the upper limit for the number of excited modes should scale as εn^2_{max}. The higher the mode number n_{max} the more modes can potentially be excited. In ITER the ratio is of the order 45-50 for 3.5 MeV super Alfvénic alpha particles. For 80 keV deuterium ions in 2.1 T DIII-D plasmas the ratio is ≈30 for $V_\parallel/V_A \approx 0.3$, while for 110 keV deuterium ions in a 3.5 T plasmas on JET the ratio is close to 70 near the sideband resonance condition $V_A/3$.

The investigation of a "Sea of Alfvén Eigenmodes" in present day devices should be pursued for what it can teach us about multimode interactions. Understanding instabilities driven by low energy heating ions in existing facilities is highly relevant to the development of the Advanced Tokamak (AT) concept as well as to burning plasma science where the condition of multimode interactions is considered particularly important. The availability of highly sensitive core fluctuation measurements represents a major breakthrough for the quantitative analysis of fast ion collective instabilities. In order to fully explore this exciting area of fusion science, facilities will need a comprehensive set of core fluctuation measurements together with effective means of measuring fast ion redistribution and loss. Such a comprehensive diagnostic set may turn out to be a necessity in a future burning plasma experiment.

Acknowledgments

This work is supported by the U.S. Department of Energy under DE-FC02-04ER54698, DE-AC02-76CH03073, and DE-FG03-01ER54615. The work is also partially funded by EURATOM, the UK Engineering and Physical Sciences Research Council, and is partly performed under the European Fusion Development Agreement (EFDA). The work is also partially funded by the Japan Atomic Energy Research Institute and is implemented under the International Energy Agency's co-operation agreement on Large Tokamak Facilities established between JAERI, DOE and EURATOM, and by the US-EU bilateral agreement on fusion energy established between DOE and EURATOM.

References

[1] Snowmass Fusion Summer Study, 2002 [see also N. Gorelenkov, *et al.,* Nucl. Fusion **43** (2003) 594].

[2] NAZIKIAN, R., *et al.,* Proceedings of the 16th IAEA International Conference on Fusion Energy, Montreal (1996) IAEA-CN-64/A2-4.

[3] KIMURA, H., *et al*., Nucl. Fusion **38** (1998) 1303.

[4] KUSAMA, Y., *et al.,* Nucl. Fusion **38** (1998) 1215.

[5] SNIPES, J.A, *et al.,* Plasma Physics Contr. Fusion **42** (2000) 381.

[6] SHARAPOV, S.E., *et al.,* Phys. Lett. **A289** (2001) 127.

[7] BERK, H.L., *et al.,* Phys. Rev. Lett. **87** (2001) 185002.

[8] FUKUYAMA, A., *et al.,* Proceedings of the 5th IAEA TCM on Alpha Particles in Fusion Research, Abingdon, UK, 1997 (IAEA, Vienna 1997) [see also FUKUYAMA, A., *et al.,* "Kinetic Global Analysis of Alfvén Eigenmodes in Toroidal Plasmas" in the Proceedings of the 19th IAEA Fusion Energy Conference, Lyon, France (2002) TH/P3-14].

[9] SHARAPOV, S.E., *et al.,* Phys. Plasmas **9** (2002) 2027.

[10] TAKECHI, M., *et al.,* Proceedings of the 19th IAEA Fusion Energy Conference, Lyon, France 2002 [see also SHINOHARA, *et al.,* Nucl. Fusion **41** (2001) 603].

[11] NAZIKIAN, R., *et al*., Phys. Rev. Lett. **91** (2003) 125003.

[12] KRAMER, G.J., *et al.,* Plasma Phys. Control. Fusion **46** (2004) L23.

[13] SHARAPOV, S.E., *et al.,* Phys. Rev. Lett. **93** (2004) 165001.

[14] SNIPES, JA., *et al.,* Proceedings of the 31st Euro. Conf. on Plasma Physics and Controlled Fusion, London, United Kingdom, (EPS 2004).

[15] GREENFIELD, C.M., *et al.,* Plasma Phys. Control. Fusion **44** (2002) A123.

External Distribution

Plasma Research Laboratory, Australian National University, Australia
Professor I.R. Jones, Flinders University, Australia
Professor João Canalle, Instituto de Fisica DEQ/IF - UERJ, Brazil
Mr. Gerson O. Ludwig, Instituto Nacional de Pesquisas, Brazil
Dr. P.H. Sakanaka, Instituto Fisica, Brazil
The Librarian, Culham Laboratory, England
Mrs. S.A. Hutchinson, JET Library, England
Professor M.N. Bussac, Ecole Polytechnique, France
Librarian, Max-Planck-Institut für Plasmaphysik, Germany
Jolan Moldvai, Reports Library, Hungarian Academy of Sciences, Central Research Institute for Physics, Hungary
Dr. P. Kaw, Institute for Plasma Research, India
Ms. P.J. Pathak, Librarian, Institute for Plasma Research, India
Ms. Clelia De Palo, Associazione EURATOM-ENEA, Italy
Dr. G. Grosso, Instituto di Fisica del Plasma, Italy
Librarian, Naka Fusion Research Establishment, JAERI, Japan
Library, Laboratory for Complex Energy Processes, Institute for Advanced Study, Kyoto University, Japan
Research Information Center, National Institute for Fusion Science, Japan
Dr. O. Mitarai, Kyushu Tokai University, Japan
Dr. Jiangang Li, Institute of Plasma Physics, Chinese Academy of Sciences, People's Republic of China
Professor Yuping Huo, School of Physical Science and Technology, People's Republic of China
Library, Academia Sinica, Institute of Plasma Physics, People's Republic of China
Librarian, Institute of Physics, Chinese Academy of Sciences, People's Republic of China
Dr. S. Mirnov, TRINITI, Troitsk, Russian Federation, Russia
Dr. V.S. Strelkov, Kurchatov Institute, Russian Federation, Russia
Professor Peter Lukac, Katedra Fyziky Plazmy MFF UK, Mlynska dolina F-2, Komenskeho Univerzita, SK-842 15 Bratislava, Slovakia
Dr. G.S. Lee, Korea Basic Science Institute, South Korea
Institute for Plasma Research, University of Maryland, USA
Librarian, Fusion Energy Division, Oak Ridge National Laboratory, USA
Librarian, Institute of Fusion Studies, University of Texas, USA
Librarian, Magnetic Fusion Program, Lawrence Livermore National Laboratory, USA
Library, General Atomics, USA
Plasma Physics Group, Fusion Energy Research Program, University of California at San Diego, USA
Plasma Physics Library, Columbia University, USA
Alkesh Punjabi, Center for Fusion Research and Training, Hampton University, USA
Dr. W.M. Stacey, Fusion Research Center, Georgia Institute of Technology, USA
Dr. John Willis, U.S. Department of Energy, Office of Fusion Energy Sciences, USA
Mr. Paul H. Wright, Indianapolis, Indiana, USA

07/07/03

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov