

Energetic-particle-driven global instabilities in helical plasmas and comparison with tokamak plasmas

Kazuo TOI

National Institute for Fusion Science, Toki 509-5292, Japan

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Why do we study interplay between energetic particles and MHD modes in 3D plasmas such as helical or stellarator plasmas?

- (1) Data for projection to a helical/stellarator type reactor
- (2) Comprehensive understanding of interplay between energetic ions and MHD waves in toroidal plasmas
 - Develop control scenarios of energetic ion driven modes and their effects on ITER plasma
 - →Connection to solar and space plasmas

Understanding of similarities and differences in wave-particle interactions between 2D and 3D toroidal plasmas. This lecture is based on an experimentalist's view.

Outline

I. Introduction

- II. Energetic ion driven global modes in Helical plasmas
- III. Energetic Ion Transport Induced by Toroidal Alfven Eigenmodes in LHD
- **IV. Summary and Future Prospect**



Interaction between Energetic Alpha Particles and MHD waves in a D-T Plasma

•Resonant interaction of slowed down α-particles with shear Alfvén waves:

$$v_{ph} = \frac{\omega}{k_{\parallel}} = v_{A} = \frac{B}{\sqrt{\mu_{o}\rho_{i}}}$$

• $\upsilon_{\alpha/\prime} \sim \upsilon_A = \omega/k_{\prime\prime}$ or $\upsilon_A/3$ for TAE : α -particles with $E_{\alpha} \sim 200 \text{keV-2 MeV}$

Excitation of AEs (simple diagram)

Excitation of AEs in a tokamak plasma by resonant interactions :

Particle Orbit of a 2D Plasma (Ideal Tokamak)

Axisymmetric (2 Dimensional) configuration: tokamaks and STs
Particle orbits: Conservation of P_φ=m_jRv_φ+e_jψ and J = ∮U_{1/}dl
Particle orbits involve a change in ψ for conservation of P_φ.
Particles can travel crossing the magnetic surfaces.

Type of orbits: passing particles trapped particles

Alpha particle orbit in TFTR at Bt=5T and Ip=2.5MA, Zweben: NF NF (2000)

Realistic Tokamak with various 3D perturbations:

(a) Magnetic field ripple in the edge due to finite number of TF coils and ferritic inserts

("Magnetic ripple" due to toroidal effect exists even in 2D ideal tokamak

- → passing/trapped particles)
- **(a)** RMP applied to plasma edge for ELM mitigation
- (a) 3D deformations such as "snake", RWM and so on.

(UIS)

Various 3D Toroidal Plasmas

|B| spectrum (not vector B) → Magnetic configuration and particle orbits

R=3.5m-4,0m <a>=0.55m-0.64m

At different conditions: $<n_e>_{max}=1x10^{21} \text{ m}^{-3}$ $T_{eo}=20 \text{keV}(\text{RCH})$ $T_{io}=6 \text{ keV}(\text{NBI})$ $\tau_E=0.3\text{s}$ Plasma dulation=1 hour (by ICRH + helical divertor)

Examples of Magnetic Spectra in 3D Plasmas

 $B/B_o = 1 + \sum_{\mu,\nu} \mathcal{E}_B^{\mu,\nu}(\psi) \cos(\mu\theta - \nu N \varphi)$ Boozer coordinates (ψ, θ, φ)

LHD with N=10 (Rax=3.6m config.): Several non-axisymmetric components such as $\varepsilon_B^{(2,1)}$ and $\varepsilon_B^{(3,1)}$ are dominant.

LHD configuration has not any quasi-symmetries.

MHD Equilibrium of 3D Plasmas

variational principle: VME Minimization of potentia change **Trail function for the** magnetic surfaces usin **Fourier expansions** Assumption: existence of nested magnetic surfaces → Magnetic surfaces, rotational transform ect.

Calculation based on the

$$\delta W = -\int \mathbf{F} \cdot \boldsymbol{\xi} dV$$

$$\mathbf{F} = \frac{1}{\mu_o} (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla P; \text{ the decent path: } \frac{\partial \boldsymbol{\xi}}{\partial t} = \mathbf{F}$$

$$R = \sum_{m,n} R_{m,n}(s) \cos(m\theta - n\varphi)$$

$$Z = \sum_{m,n} Z_{m,n}(s) \sin(m\theta - n\varphi)$$

$$s = \psi / \psi(1) \quad (2\pi\psi : \text{toroidal flux, } r/a \approx \sqrt{s})$$

$$s = 1: \text{ plasma boundary } (R_{m,n}(1), Z_{m,n}(1))$$

Free boundary $<\beta_t>=2\%$ stellarator equilibrium calculated by VMEC S.P. Hirshman et al., Comp. Phys. Comm. (1986).

Particle Loss/Confinement Boundary in LHD Calculated by Guiding Center Drift Equation

- (1) passing particles,
- (2) helically trapped particles (with toroidal excursion),
- (3) locally trapped particles (no toroidal excursion),
- (4) transition particles

Tangential neutral beam injection → to minimize the first orbit loss Issue: MHD modes destabilized by energetic passing ions and their impacts

Important Issues in 2D and 3D Burning Plasmas

Tokamak reactor (intrinsically "pulsed operation") Need non-inductive current drive (bootstrap current + NBI/RF CD) Mitigation or avoidance of current disruption

- Large heat and particle handling in the divertor
- **Excellent confinement of alphas**

Helical/Stellarator reactor (intrinsically "steady-state")

- No need of external current drive (minimization of circulation power)
- Large heat and particle handling in the divertor
- **Challenging issue on good alpha confinement**

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Rotational Transform Profile in Tokamak and Helical/Stellarator Plasmas

Characteristic differences in the $1/2\pi$ (=1/q) profile between tokamak and helical/stellarator plasmas

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Rotational transform profiles have wide variations among tokamak and helical plasmas: differences in shape (q(r)) and radial derivative (q'(r): magnetic shear) These factors affect characters of Alfven eigenmode spectra and MHD

stabilities, noticeably.

Shear Alfven Gaps in 2D Toroidal Plasmas

μ

- Shear Alfvén spectral gaps in an axisymmetric 2D torus (tokamak) Magnetic spectrum: $B / B_O = 1 + \sum_{\mathcal{E}_B}^{\mu,0}(\psi) \cos(\mu\theta)$
- two cylindrical Alfvén branches generate gaps by poloidal mode coupling: $\omega = k_{//m,n}V_A = -k_{//m+1,n}V_A$

 $k_{//m,n} = (m \sqrt{2\pi} - n)/R_o = (m/q - n)/R_o$ $\mu = 1, \nu = 0$: TAE (toroidicity induced AE; m & (m+1) coupling) $\mu = 2, \nu = 0$: EAE (ellipticity induced AE; m & (m+2) coupling) $\mu = 3, \nu = 0$: NAE (triangularity induced AE; m & (m+3) coupling) (when m/n<0 or n=0, $k_{//m,n} \neq 0 \Rightarrow GAE$ near the center)

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gap frequency: $f^{(\mu,\nu)} = \mu V_A / (4\pi Rq^*)$

gap position : $q = \frac{2m+\mu}{(2n)}$

Full gap width (TAE):
$$\frac{\delta \omega}{\omega_{gap}} \approx 2\sqrt{2} (\mathcal{E}_B^{1,0} + \Delta'), \quad \mathcal{E}_B^{1,0} = r / R$$

Positive shear in tokamak: TAE gap tends to well-align from core to edge.
→ global TAE, but also core-localized TAE is often destabilized by EPs.

In ITER: $f_{TAE} \sim 20 - 500 \text{ kHz}; n=8-17$

Shear Alfven Gaps in 3D ToroidalPlasmas Shear Alfvén spectral gaps in **3D toroidal plasmas:** Magnetic field strength for $B/B_0 = 1 + \sum \mathcal{E}_B^{\mu,\nu}(\psi) \cos(\mu \theta - \nu_N \phi)$ Example of |B| spectrum of LHD two cylindrical Alfvén branches *l*=2, N=10 intersect and generate gaps: Magnetic spectrum intensity Rax=3.6m (poloidal & toroidal mode coupling) 0.3 - 0.0 $\omega = k_{//m,n} V_A = -k_{//m+\mu,n+\nu N} V_A$ 2.1 $\boldsymbol{\mathcal{E}}_{B}^{\mu,\nu}(r)$ 0.2 μ=1,ν=0: TAE; 1.0 1,1 0.1 $\mu = 2, \nu = 0$: EAE; 3,1 μ=2,ν=1: HAE21 etc. 2,0 0.0 4,1 0,1 -0.1 3,2 gap frequency : 0.2 0.3 0.0 0.1 0.4 0.5 0.6 3,0

 $f_{gap}^{(m,n)} = |vq^*N - \mu|V_A/(4\pi Rq^*)$ $= |v(m/n)N-\mu|(2m+1)/(2m+\mu)f_{TAE}$

gap position : $q = \frac{2m + \mu}{2n + \nu}$

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r (m)

Toroidal mode coupling in 3D Toroidal plasmas

- Toroidal modes can couple in 3D plasmas via equilibrium with N fold field period symmetry.
- The mode families with n have to take into account for the mode with n': n'±n=kN, where k=0, 1, 2, 3,
- The number of mode families is finite (1+N/2).

C. Schwab, PFB5(1993)

Weak toroidal mode coupling in a helical plasma with large N such as LHD is expected.

n=1 mode family couplings in Various 3D plasmas

D.A. Spong et al., 21the IAEA FEC, Geneva, 2008, paper No. TH-3/4. 20

Examples of TAEs in LHD Plasma(1)

Effects of toroidal mode coupling on TAEs are very weak in LHD, because of large N(=10).

→ TAEs in LHD are very similar to those in tokamaks.

Examples of TAEs in LHD Plasma(2)

TAE observed in an LHD plasma of relatively high beta plasma

D.A. Spong et al., 21the IAEA FEC, Geneva, 2008, paper No. TH-3/4.

Energy exchange rate between particles and waves is expressed as $\frac{dW}{dt} = eZ\mathbf{v}_d \cdot \mathbf{E}_{\perp} + eZ\mathbf{v}_{//}E_{//} + \mu \frac{db_{//}}{dt} \approx eZ\mathbf{v}_d \cdot \mathbf{E}_{\perp} \text{ for shear Alfven wave}$

Resonance condition for passing particles for all poloidal harmonics of AEs:

$$\omega - (m + \mu)_{\omega_{\theta}} + (n + \nu N)_{\omega_{j}} = 0$$

Having
$$\omega_{\varphi} = \upsilon_{//} / R$$
, $\omega_{\theta} = \upsilon_{//} / (qR)$ and $\omega = k_{//m,n} \upsilon_A$
and $q = q^* = (2m + \mu)/(2n + \nu N)$,

 $V_{b//}/V_A \sim 1/[1\pm 2/(vNq^*-\mu)]$

For TAE, $V_{b/}/V_A=1$ and 1/3 for TAE (a) $v=0, \mu=1$ For HAE₂₁ with N>>1(e.g. LHD), $V_{b/}/V_A\sim 1$ (a) $v=1, \mu=2$

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Stability of Alfvén Eigenmodes

Fast ion drive(simplified expression):

$$\frac{\gamma_{fast}}{\omega} \approx \frac{9}{4} \beta_{fast} \left[\frac{\omega_{*fast}}{\omega} - \eta \right] F(x), \ x = \frac{\upsilon_A}{\upsilon_{fast}}, \ \omega_{*fast} \propto \frac{1}{P} \frac{dP_{fast}}{dr}$$

Continuum damping:

mode conversion to kinetic AW at $r=r_A$ in a continuum In low beta LHD plasma, TAE gap frequency increases toward the plasma edge. Continuum damping is most important.

Radiative damping: mode conversion to KAW inside the gap

Landau damping of electrons, and bulk and beam ions

Collisional damping by trapped electrons

 $\gamma_{\text{fast}} > \gamma_{\text{damp}} = \gamma_{\text{cont}} + \gamma_{\text{rad}} + \gamma_{eL} + \gamma_{iL} + \gamma_{coll}$

Note 1: Doppler Effects on AE Frequency

Correction of Doppler effect due to plasma rotation:

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if AEs are convected with ion fluid, the frequency is affected by Doppler effect by toroidal rotation:

 $\mathbf{f}_{obs} = \mathbf{f}_{AE} + \mathbf{n} \mathbf{f}_{\phi}(\mathbf{r}).$

AEs would be identified through comparison between theoretical value with the Doppler effect and observed one.

Shear Alfven spectra with and without the correction of sheared toroidal rotation in NSTX

M. Podesta et al., PoP (2010)

n=4 n=4 250 250 frequency [kHz] frequency [kHz] 200 200 150 150 100 100 50 50 Wimm 0.0 0.0 0.2 1.0 0.2 0.8 1.0 0.4 0.6 0.8 $sqrt(\Psi_{m})$ sqrt(Ψ_m)

300

In LHD, toroidal rotation speed < 30 km/s in AE experiments, where R~3.6m-3.9m.
Doppler effect can be neglected, because f_{Doppler}~1.3 n (kHz).

Note 2: Fluctuations by Energetic Ion Driven Modes

AEs→ radial displacement, compressibility due to toroidicity

AEs generate various fluctuations: magnetic fluctuations, density fluctuations, Te fluctuations, potential fluctuations

Diagnostics:

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Magnetic probes, Microwave reflectometer, μ-wave interferometer, ECE diagnostics, Heavy ion beam probe, Beam emission spectroscopy,

In Ideal MHD plasmas

 $\mathbf{b} = \nabla \times (\boldsymbol{\xi} \times \mathbf{B})$ $\frac{\delta \rho}{\rho} = -\nabla \cdot \boldsymbol{\xi} - \frac{\boldsymbol{\xi} \cdot \nabla \rho}{\rho}$ $\frac{\delta p}{p} = -\gamma \nabla \cdot \boldsymbol{\xi} - \frac{\boldsymbol{\xi} \cdot \nabla p}{p}$

$$\frac{\delta n_e}{n_e} = -\nabla \cdot \xi - \frac{\xi \cdot \nabla n_e}{n_e}$$
$$\frac{\delta T_e}{T_e} = -(\gamma - 1)\nabla \cdot \xi - \frac{\xi \cdot \nabla T_e}{T_e}$$

For shear Alfven waves : $\nabla \cdot \boldsymbol{\xi} = 0$ In a torus, the condition($\mathbf{b} \perp \mathbf{B}$) $\overrightarrow{\nabla} \cdot \boldsymbol{\xi} \approx -\frac{2}{R}(\boldsymbol{\xi} \cdot \mathbf{R})$ 27

- >In LHD, the Shafranov shift is considerably enhanced with the increase in the toroidal beta.
- > The enhanced shift of the magnetic axis increases the rotational transform on the magnetic axis, and decreases it in peripheral region.
- \rightarrow Low shear or reversed shear (q"(ro)<0) configurations are easily obtained.
- **Tokamak like and shearless stellarator** like profiles are also produced.

Calculated Eigenfunctions of C-TAEs in 2D LHD Plasmas

Core localized TAEs with even and odd radial parity Even parity: ballooning Odd parity: anti-ballooning

Experimental observations:

CHS (smaller version of LHD; N=8) CHS: M. Takechi et al., PRL (1999) CHS: K. Toi et al., NF (2000) LHD: S. Yamamoto et al. NF (2005)

Calculated GAEs/RSAEs in 2D LHD Plasmas

GAEs exist just above and below the SA continua.
When the eigenfrequency approaches a shear Alfven continuum, eigenfunction becomes more localized with larger radial node number. (RSAE like localized).
Experimental observation in LHD: S. Yamamoto et al. NF(2005), K. Toi et al., PPCF (2011).

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Calculated RSAEs in 2D LHD Plasmas

When the frequency approaches close to a continuum, eigenfunction becomes more localized with large radial node number.

RS configuration is formed by an increased beta. This configuration was also realized by NBCD. RSAE was observed together with GAM. K. Toi et al., PRL 2010 **Observation of GAE in Shearless Stellarator W7-AS**

A. Weller et al., PRL(1994).

m=3/n=1 GAE observed in a shearless stellarator W7-AS

Middle: mode structure derived by SX tomography. **Right:** Mode pattern calculated gyro-fluid code

- Reversed shear (RS-) configuration in tokamaks attracts much attention because improved confinement with ITB formation is expected, and it is a candidate scenario of ITER steady-state operation.
 - Difference in the rotational transform profiles of RS configuration between tokamaks and helical/stellarators

Tokamak: RS plasma with $q''(r_0)>0$ (r_0 : radial position of the zero-shear layer) LHD : RS plasma with $q''(r_0)<0$ Shearless stellarators: RS plasma with $q''(r_0)>0$ or <0

 \rightarrow Sign of q"(r_o) affects the character of RSAE noticeably !

Alfvén Eigenmodes in RS Configuration of Tokamak

Reversed shear (RS) tokamak

Asymmetric (only upward) frequency Sweeping (typical case) in JET

RS configuration with $q''(r_0) > 0$

Asymmetric (Upward) frequency sweeping for decreasing q_{min}(t). Rarely symmetric sweeping

Internal Structure of RSAE in DIII-D

AEs in a LHD RS plasma

- Frequency sweeping of n=1 & 2 mode (RSAEs) for increasing q_{max} in time (decrease in $(1/2\pi)_{min}$)
- The frequency has the minimum at $q_{max} = 3/2$, 2 and 3.
- The minimum frequency just above that of n=0 mode (GAM excited by energetic ions).
- n=1 & 2 RSAEs propagate in the electron diamagnetic drift (ω < 0 counter propagating mode).

Peculiar mode with n=0: energetic ion driven geodesic acoustic mode (GAM)

STELLGAP/AE3D code : AE analysis of low beta and

incompressible 3D plasma

D. Spong et al., PoP (2010)

The eigenvalue decreases slightly even if toroidal mode coupling in 3D plasma is included. Fime evolution of the frequency calculated by AE3D agrees well with the experimental data except the time of (ι/2π)_{min}=1/3 where plasma compressibility is important.

(B. Breizman et al., PoP 2006).

Modified RSAE dispersion $\omega^{2} - \frac{\upsilon_{A}^{2}}{R^{2}} \left(n - m \frac{\iota}{2\pi} \right)^{2} - \left[\omega_{GAM}^{2} + \omega_{\nabla P + \nabla F}^{2} \right] = 0 \qquad 38$

Eigenfunction of RSAE

Correlation between ECE and MP signals

Information of Te-fluctuations caused by RSAE (red points). (blue points : energetic ion driven GAM)

$$\xi_r \approx [(\delta \mathbf{E} \times \mathbf{B}) / (\omega B^2)]_r$$
$$\approx -m(\phi / r) / (\omega B)$$

 $\frac{T_e}{T_e} = -(\gamma - 1)\nabla \cdot \xi - \xi \cdot \nabla T_e / T_e$

RSAE obtained by AE3D is composed by a dominant single Fourier component.

K. Toi et al., PRL (2010)

RSAE calculated with toroidal mode coupling

Effect of toroidal mode coupling on RSAE in LHD is very small.

D.A. Spong et al., 21the IAEA FEC, Geneva, 2008, paper No. TH-3/4.

Theory of Frequency Sweeping in RSAE(1)

Eigenmode equation for RSAE *localized at* r=r_o (zero shear surface):

$$\frac{\partial}{\partial x}(S+x^2)\frac{\partial}{\partial x}U_m + (Q-S-x^2)U_m = 0$$
$$x = m(r-r_o) / r_o$$

Criterion of the existence of RSAE:

determine the frequency sweeping

$$Q = Q_{hot} + Q_{tor} + Q_{press} + Q_{dens} > \frac{1}{4}$$

H.L Berk et al., PRL 2001.F. Zonca et al., PoP 2002.B.N. Breizman et al., PoP 2003.G.Y. Fu & H.L. Berk, PoP 2006.S.V. Konovalov, PoP 2004.

Amount of Energetic Ions

◆ Potential well generation for localized AEs:
 Q>1/4→ Q_{hot} >1/4 – (Q_{tor} + Q_{press} + Q_{dens}) ~ 1/4-Q_{press}
 During downward frequency sweeping:

$$\left(-\frac{r}{\rho_i}\frac{\partial}{\partial r}\left\langle\rho_h\right\rangle\right)_{r=r_o}\approx 0.016 \quad \Rightarrow <\beta_h><0.2\%$$

Consideration from the minimum frequency of RSAE

$$\boldsymbol{\omega}_{\min}^{2} = \boldsymbol{\omega}_{GAM}^{2} + \boldsymbol{\omega}_{\nabla P + \nabla F}^{2} \leq \boldsymbol{\omega}_{GAM}^{2} \qquad \boldsymbol{\omega}_{\nabla P + \nabla F}^{2} \approx \mathbf{0}$$

$$\omega_{\nabla P+\nabla F}^{2} \cong \frac{2}{R^{2}} \left(-\frac{r}{\rho_{i}} \frac{\partial}{\partial r} P \right)_{r=r_{o}} + \frac{\omega_{\min}\omega_{ch}}{m} \left[1 \pm \frac{(m-nq_{o})}{|m-nq_{o}|} \frac{V_{//h}}{V_{A}} \right] \left(-\frac{r}{\rho_{i}} \frac{\partial}{\partial r} \left\langle \rho_{h} \right\rangle \right)_{r=r_{o}} \approx 0$$

<positive contribution>

<neagtive contribution>

→
$$<\beta_h>>0.13\%$$

Condition of symmetric f-sweeping RSAE and $f_{min} \sim f_{GAM}$ $\Rightarrow <\beta_h>=0.13 - 0.2 \%$

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Helicity-Induced AEs(HAEs) in 3D Toroidal Plasmas

HAE gap is through toroidal and poloidal mode couplings. HAE can only exist in 3D toroidal plasmas.

First, a possibility of HAE was discussed in W7-AS data.

A. Weller et al., PoP (2001).

Y. Kolesnichenko et al., FST (2004).

Then, it was detected with magnetic probes on LHD.

S. Yamamoto et al., PRL, 2003

In LHD with large N (=10), HAE gap frequency >> TAE gap frequency Very wide width of HAE gap

Radial Structure of HAE in LHD

 R_{ax} =3.6m; γ =1.254, B_t =-0.6T; $\langle n_e \rangle$ =1.3x10¹⁹m⁻³ **#90082** 1.6 **Magnetic** probe Wide HAE gap is 450 400 1.2 1.2 located near the *n*_i [10¹⁹ m⁻³] [KHz] 350 HAE+TAE→ plasma edge. ι/2π 0.8 300 0.8 Frequency HAE \rightarrow 250 (toroidal mode 0.4 0.4 200 coupling: 150 0.0 0.0 Ŏ.0 0.2 0.4 0.6 0.8 1.0 100 $n=\pm 2, \pm 8, \pm 12,$ TAE r/a 50 $\pm 18, \pm 22, \pm 28,$ 500 $\pm 32^{\circ}, \pm 38^{\circ}, \pm 42^{\circ},$ Coherence of Ha with Mp 450 400 Frequency [kHz] $\pm 48, \pm 52, \pm 58,$ 400 350 도 300본 HAE+TAE- $\pm 62, \pm 68, \pm 72,$ 250 Sono 200 Leon 200 ±78,~2700 HAE -**Fourier modes)** 100 TAE gap 100 TAE -0.0 50 0.2 0.8 0.4 0.6 1.0 The radial structure 0 rlа 2 5 Coherence between $\delta H lpha$ and MP was measured by a 90082250300co time (s) 0.35 fast response Ha 0.30 ⊢mpha 8o detector array. -mpha65u 0.25 -mpha65u 0.20 → Very localized 0.15 mode in the edge!! 0.10 Noise level 45 0.05 0.0 0.2 0.6 0.8 1.0 1.2 0.4

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Energetic Ion Transport by Energetic Ion Driven MHD Modes (Transport mechanisms)

These mechanisms may induce redistribution and/or loss of energetic alpha & ions.

Energetic ion loss flux $\Gamma \propto (\tilde{b} / B_t)^S$

S=1 (convective loss):

Energetic ions in phase with the mode can convectively lost by $\mathbf{E} \times \mathbf{B}$ drift.

S=2 (diffusive loss):

Enhanced radial transport by stochastic particle orbits in phase space.

S≥3 (Magnetic braiding loss):

Enhanced radial transport by strongly stochastic particle orbits in phase space.

Measurement of Redistribution and Loss of Energetic Ions

- Measurement of redistribution neutron emission charge exchange neutral flux fast ion D_α,...
- Measurement of loss flux Scintillator probe Faraday cup H_α detector directional Langmuir probe ,...

Theoretical Model of Clump & Hole Formation in Velocity Distribution Function of Energetic Ions

Berk-Breizman Model

Coherent hole–clump structures with time-dependent frequencies. (a) The spatially averaged particle distribution as a function of time and the distance from the linear resonance $\Omega - \omega_0$ with $\Omega = k \upsilon$ for the bump-on-tail instability. (b) Spectral intensity $|A_{\omega}|^2$ as a function of time and $\omega - \omega_0$

Orbits of Energetic Ions in LHD at Low Bt

0.6

0.3

0.0

-0.3

-0.6∟ 2.5

3.0

Z [m]

B_t = 1.5 T, R_{ax} = 3.60 m

 $E_{\text{particle}} = 158 \text{ keV}, \chi = 25^{\circ}, \text{H}^{+}$ poincare plot @ φ = 18 ° (holizontally elongated section)

TAE bursts also enhance poincare plot @ φ = 18 ° (holizontally elongated section) energetic ions as well as their redistributions, generating clump-hole in velocity space.

3.5

4.0

4.5

R [m] $E_{\text{beam}} = 180 \text{ keV}, \text{ H}^{+} \chi \sim 27^{\circ}$

5.0

listributed energetic ions monitored by NPA.

it ions measured with a scintillator lost ion probe.

 $B_{\rm t}$ = 0.60 T, $R_{\rm ax}$ = 3.60 m

Condition of AE experiments in LHD

Observation of a 'Clump' and a 'Hole' Creation by a TAE-burst in NPA spectra

Rax=3.6m, Bt=-0.5T (very low field) Co beams with E=170 keV considerably deviate magnetic surfaces. Eigenfunction of excited TAE has a peak around r/a~2/3

- The 'hole' starts from 153keVand its typical decay time is 8.3[ms]
- The 'clump' starts from 153keV and its decay time is 6[ms]

100

80

60

shot#47645

NB#

Detailed Study of Formation of Hole-Clump Pairs in Accumulated Energy Spectra

Energy slow-down of clump with the sweep-down of the mode frequency
Energy of the hole stays same (No significant sweeping-up component of the mode frequency)
Faster slowing-down time than the expected classical value during the mode

The upper boundary of the hole energy is limited by the beam injection energy.

M. Osakabe et al., 11th IAEA TM on EPs, 2009, Kiev

TAE and RIC-Induced Losses

Three dominant loss domain is observed.

P1 : (~110 keV, ~30°), passing orbit, : Resistive-Interchange mode induced loss P2 : (~110 keV, ~40°), passing orbit, : TAE (AE₂) induced loss

P3 : (~150 keV, ~55°), trapped orbit, : Collisional loss + RIC induced loss 54

K. Ogawa et al., NF (2010).

Correlation of Energetic Ion Loss with Clump-Hole Formation

 $\Gamma_{neutral}$ (E=180-190 keV) : flux drop (hole) is produced by TAE burst. $\Gamma_{neutral}$ (E=130-160 keV) : flux increase (clump) due to TAE burst Γ_{slip} 10 (~110 keV, ~40°) : TAE (AE₂) induced loss 55

K. Ogawa et al., NF(2010)

Energetic Ion Loss Pattern in LHD with and without TAE

• An example of energetic ion loss positions projected on LCFS which is calculated by the DELTA 5D (guiding center orbit following Monte Carlo code) with TAE magnetic perturbations of $\delta \mathbf{b} = \nabla \times \alpha \mathbf{B}$.

Loss positions of energetic ions at LCFSYellow dots: without TAEBlue dots: with TAE

Energetic ions are lost through the areas in the outboard side, regardless with or without TAE.

K. Ogawa, Doctor Thesis

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AIFS

Summary

Stellrator or Helical plasmas provide a wide variety of energetic ion driven global modes. GAE/NGAE(W7-AS, LHD), TAE(CHS, W7-AS, LHD), HAE(LHD, W7-AS?, TJ-II), RSAE(LHD), GAM(LHD), energetic electron driven Alfven-acoustic coupled modes (HSX, CHS, LHD),...

 Extension of "MHD Spectroscopy" to 3D toroidal plasmas

In stellarator/helicals, further developments of plasma diagnostic tools and numerical codes are required for comprehensive understanding of these modes.

Significant progress in mode identification in tokamaks with help of advanced fluctuation diagnostics + MHD codes including kinetic effects

Excellent example: DIII-D (Van Zeeland,2006) Advanced ECE + NOVA=K

Future Prospect

In Stellrator or Helical plasmas , a lot of new interesting phenomena are observed

(1) Role of energetic ion driven GAM

→interaction with bulk ions ?

(2) Nonlinear mode coupling:

LHD: TAE1+TAE2, RSAE+GAM, and TAE+HAE

→Effects of energetic ion and bulk plasma transport ? (NSTX: EPM+TAE, CAE+EPM)

(3) Nonlinear mode evolution (Clump – Hole creation):

Enhanced radial transport/loss of energetic ions Development of advanced hybrid code (particle simulation code + MHD code)

Y. Todo et al., PFR (2008)

- (4) Transient improvement of bulk confinement "New type of alpha channeling"
- (5) Enhanced transport of energetic ions by microturbulence

(1) n=0 Mode in an LHD RS Plasma

Potential fluctuations (HIBP)

The frequency of n=0 mode agrees well with the GAM frequency.

 $\mathbf{f}_{GAM} = \frac{C_{hel}}{2\pi R} \sqrt{\frac{T_e + (7/4)T_i}{C_Z m_i}} \sqrt{2 + (\iota/2\pi)^2 F}$

H. Sugama, PoP (2006)

C_{hel}~1(helical ripple); F~1 (depends on Te/Ti) ; Cz~1.6 (neon doped effect); Negligible energetic ion contribution

The frequency follows the change of *Te*.

• The frequency is rapidly chirped up.

 $\delta \phi \sim 0.4$ -0.9 kV at r/a~0.4 $\delta n_e/n_e \sim 6$ -10% at r/a~0.4 $\delta \phi/T_e \sim 30$ -50% in the core (r/a<0.5) (Very large poterntial & density fluctuations in the core)

GAM driven by Energetic ion driven GAM generates very large potential and density fluctuations in the core.

(3) Nonlinear Evolution of TAEs and EPMs

5.20^{1412108 6}

30-

4.70

4.80

4.90

5.00

time [s]

5.10

- ⁹ character of TAEs.
- What is a main reason of observation of pitchfork splitting

(4) Improvement of Bulk Plasma Confinement by TAE Bursts on LHD

Backup

Theory of Frequency Sweeping in RSAE(2)

Two dominant terms:

- **1.** Hot ion effect: Q_{hot} for large ρ_h (but $\omega_{TD}/\omega_{AE} \sim 1/2$ in LHD)
- 2. Pressure gradient and toroidicity effects: Q_{press}

$$Q_{hot} \approx q_{o}(-k_{mo}) \frac{q_{o}}{r_{o}^{2}} \frac{\omega_{ch}}{\omega_{o}} \left[1 \pm \frac{V_{\prime\prime h}}{V_{A}} \frac{(-k_{mo})}{|-k_{mo}|} \right]_{r=r_{o}} \left(-\frac{r_{o}}{\rho_{i}} \frac{d\langle \rho_{h} \rangle}{dr} \right)_{r=r_{o}}$$

$$Q_{press} = \frac{mq_{o}}{(-k_{mo})} \frac{q_{o}}{r_{o}^{2}} \left[\frac{4\Delta' \overline{\omega}^{2} \alpha - \alpha^{2}/2q_{o}^{2}}{1 - 4k_{mo}^{2}q_{o}^{2}} + \frac{\overline{\kappa}_{r} \alpha}{q_{o}^{2}} \right]_{r=r_{o}}$$

$$-k_{mo} = (m - nq_{o}) / q_{o}, \ \omega_{o} = \pm \frac{V_{A}}{R_{o}} |-k_{mo}|, \quad \langle j_{//h} \rangle \approx eV_{//h} \langle n_{//h} \rangle$$

$$\Delta' \text{(Shafranov shift),} \ \alpha (= -R_{o}q^{2}d\beta / dr), \\ \bar{\omega} = \omega / (\bar{V}_{A} / R_{o}), \\ \bar{K}_{r} = K_{r}R_{o}$$

Potential Well Function :Q_{tot}

Downward frequency sweeping: Q_{hot} contributes to **RSAE** existence (Q>1/4). Upward frequency sweeping: **Q**_{hot} prevents RSAE existence due to Q_{hot}<0 ! **Q**_{press} mainly contributes to **RSAE** existence. **CRT-NBCD** contributes to reduction of |Q_{hot}|. In LHD, too strong energetic particle content may suppress upward frequency sweeping. From the comparison between the above calculation result and experimental observation, $<\beta_{\rm h}>=0.13-0.2$ % is inferred to be most plausible.

Example of q-profile in ITER reference scenario

• ITER reference scenario 4 _ type I: q profile may have double extrema in off-axis depending on non-inductively driven current. Shear Alfven spectra may have the points where $q''(r_{o1}) < 0$ and $q''(r_{o2}) > 0$. RSAEs or GAEs may behave differently

NBI Condition in LHD

R=3.6-4 m, <a>~0.6 m, Bt=0.6 T-1.5T 3 Tangential-NBIs (Two: CTR/CO, One: CO/CTR) ΣP~12MW, 3 s, 150- 180 keV H 2 Perpendicular NBIs: ΣP~10MW, ~2s, ~60 keV H ECH: ΣP~3MW, ~1s, 77 GHz

Number of fast ion

Target plasma: generated by ECH or NBI alone

Te~0.5 - 3 keV at Bt=0.4-1.5T E_{crit}~15Te~15-50keV<< Eo=160-190keV E_{crit} << E_A < Eo

For plasmas in $<n_e>$ $< 5 \times 10^{19} \text{ m}^{-3}$, pitch angle distribution of birth deposition~25 deg. (passing particle)

