Energetic Particles in Plasmas

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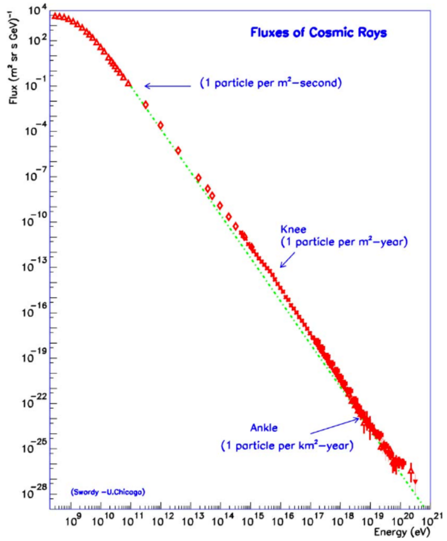
Outline

- Introduction
  - energetic particles
  - Alfvén eigenmodes (AEs)
  - inverse Landau damping
  - saturation of single mode; wave-particle trapping
- Bursts of multiple AEs
  - experiment and simulation
  - resonance overlap
  - synchronization of multiple AEs
  - fast ion profile resiliency
- Fast ion profile stiffness
  - experiment
  - fast ion profile stiffness is brought about by resonance overlap of multiple AEs

Energetic particles

- Plasmas often contain energetic (=supra-thermal) particles in addition to thermal ions and electrons.
  - highly energetic ($T_h >> T_i$)
  - comparable pressure ($n_h T_h \sim n_i T_i$)
- For example, cosmic rays are high-energy (up to ~10^20 eV) protons and atomic nuclei.
  - supernova remnant (SNR) is a candidate of the cosmic ray source

SNR IC443, NASA/DOE/Fermi LAT Collaboration, NOAO/AURA/NSF, JPL-Caltech/UCLA

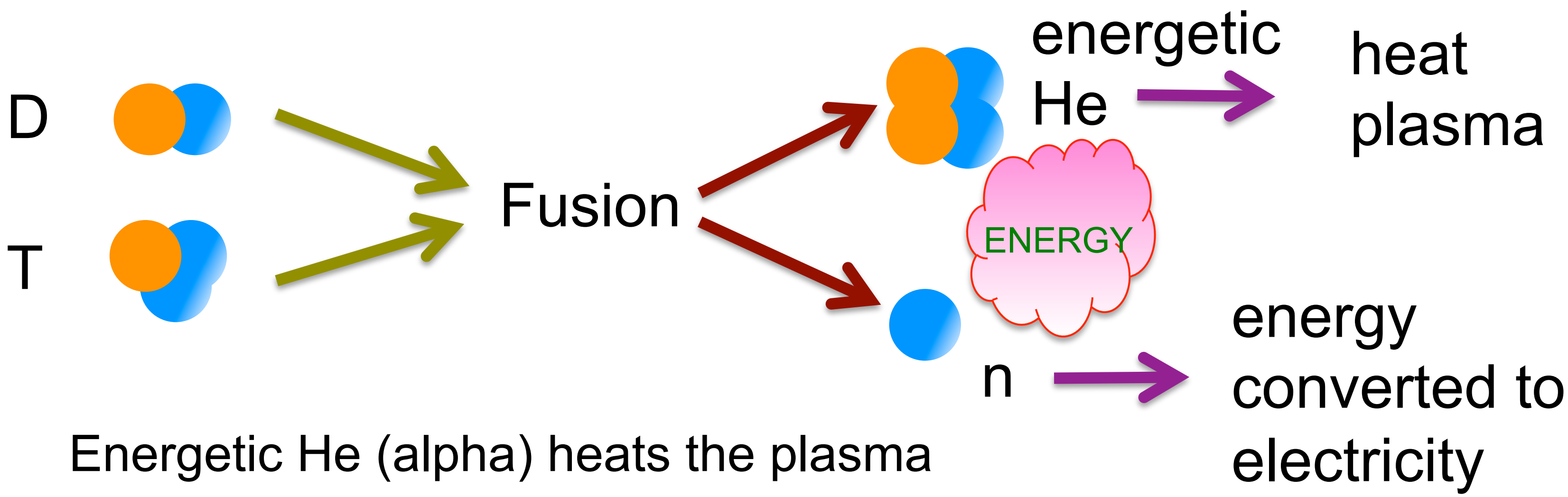


Cosmic ray spectrum [Swordy]

Energetic particle confinement is important for fusion energy

- Nuclear fusion: safe and environmentally friendly energy source in the next generation
- Fusion reaction of deuterium (D) and tritium (T) in high temperature plasmas

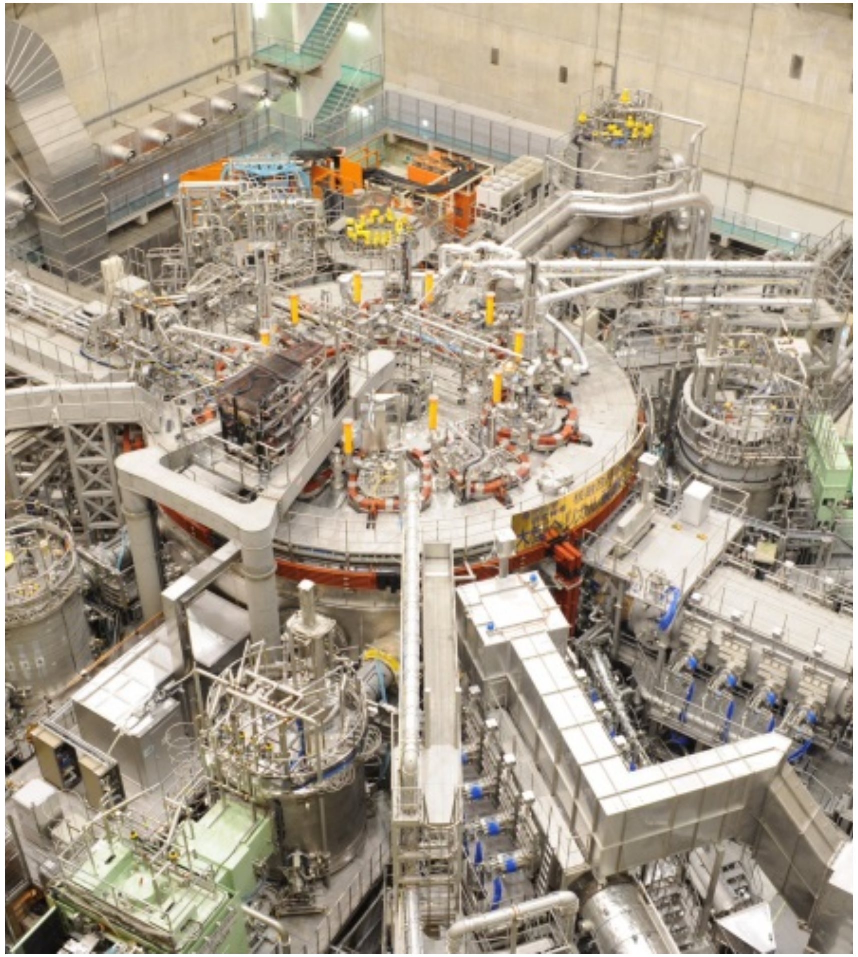
  D + T -> ^{4}He (helium, 3.5MeV) + n (neutron, 14MeV)



- Energetic He (alpha) heats the plasma
- Confinement of energetic alpha particles are important for the sustainment of high temperature (~10keV)

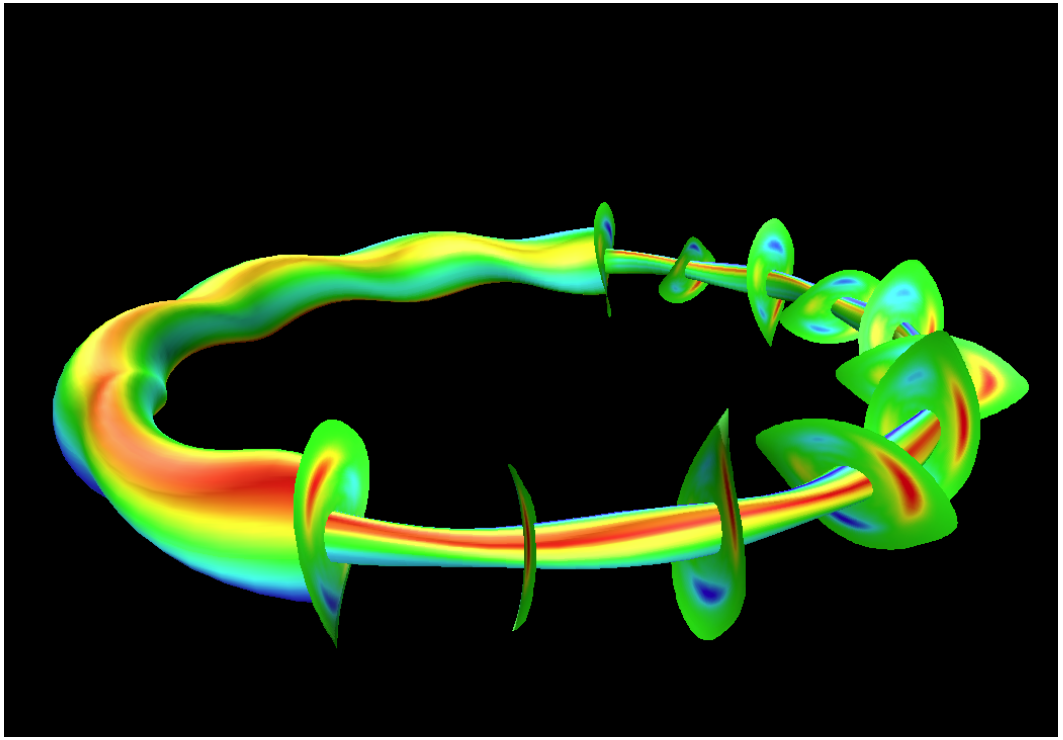
Energetic particles in fusion plasmas

- Alpha particle born from D-T reaction
  D+T -> He^4 (3.5MeV) + n (14MeV)
- Neutral beam injection (NBI)
- Ion cyclotron heating (ICH)
- Electron cyclotron heating (ECH)

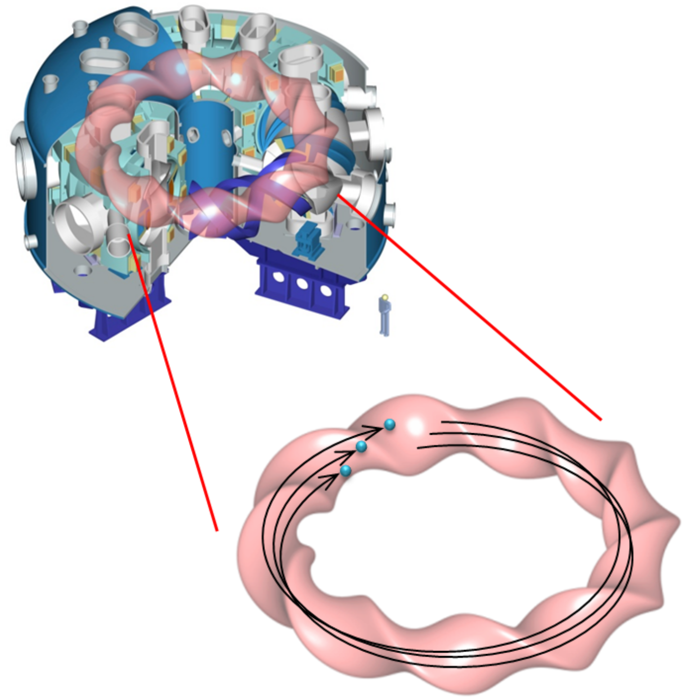


Large Helical Device (LHD)

Interaction between Alfvén eigenmodes and energetic particles

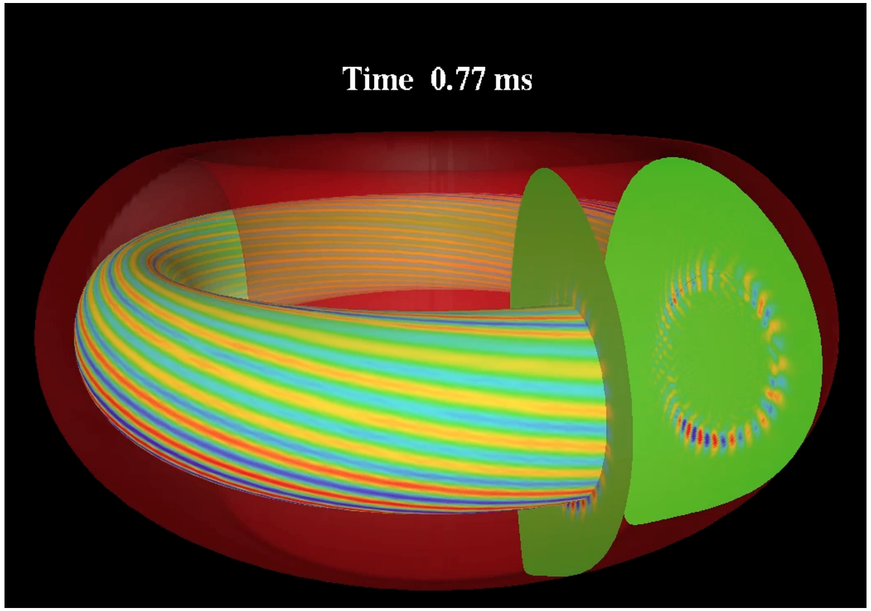


Alfvén eigenmode (magnetohydrodynamic oscillations) in LHD.

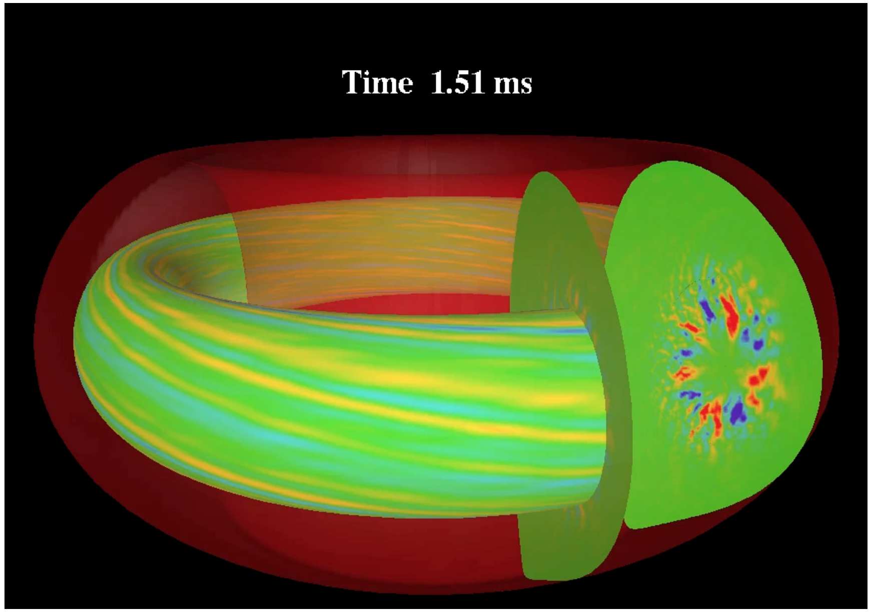


Energetic particles circulating inside the plasma interact with and destabilize AEs.

Time evolution of Alfvén eigenmodes in ITER steady state scenario



Toroidal Alfvén eigenmodes with toroidal mode number n~15 are the most unstable in the linear phase.



Beta-induced Alfvén eigenmodes with n=3 and 5 becomes dominant in the nonlinear phase.

Y. Todo and A. Bierwage,
Plasma and Fusion Research **9**, 3403068 (2014)

Inverse Landau damping; resonance between wave and particle

When the energetic particle distribution function f(v) has positive gradient at the resonance with the wave ($df/dv>0$ at $v=\omega/k$), the wave grows

= inverse Landau damping

Initial and final distribution functions of energetic particle. The distribution is flattened by resonance with the wave.

Growth and saturation of the wave amplitude.

[Berk+, Phys. Plasmas 2, 3007 (1995)]

Nonlinear stage of (inverse) Landau damping

The resonant particles are trapped by the wave with finite amplitude = particle trapping

This leads to the saturation of the (inverse) Landau damping of a single wave.

F. F. Chen著・内田岱二郎訳　“プラズマ物理入門”（丸善）p.201.

THE STORY IS DIFFERENT FOR MULTIPLE MODES

Alfvén Eigenmode Bursts in TFTR

Results from a TFTR experiment [K. L. Wong et al., Phys. Rev. Lett. 66, 1874 (1991).]

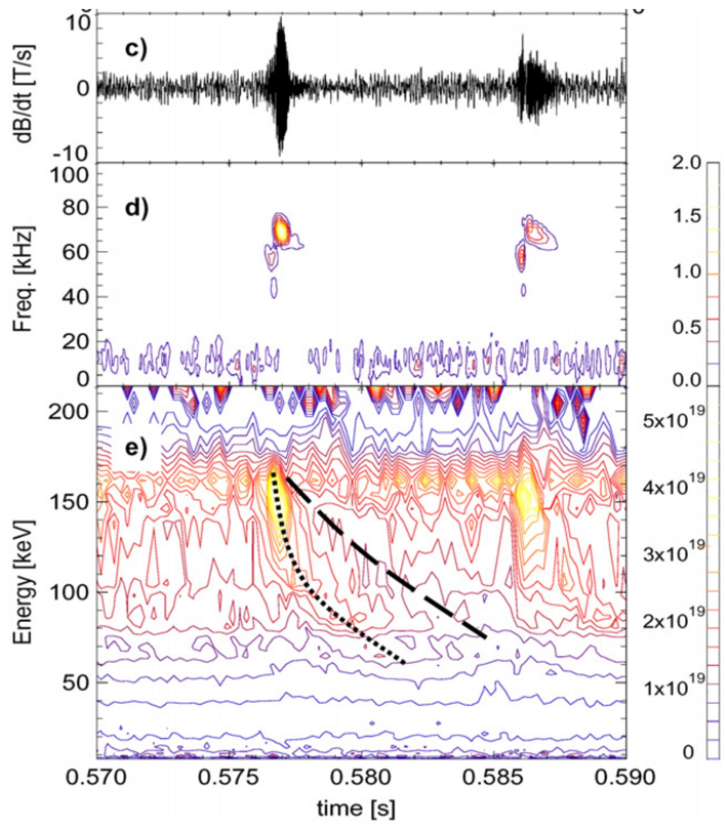
Neutron emission: nuclear reaction of thermal D and energetic beam D -> drop in neutron emission = energetic-ion loss

Mirnov coil signal: magnetic field fluctuation -> Alfvén eigenmode bursts

- Alfvén eigenmode bursts take place with a roughly constant time interval.
- 5-7% of energetic beam ions are lost at each burst.

Alfvén Eigenmode Bursts in LHD

- Recurrent TAE bursts have been observed in LHD plasmas with NBI [Osakabe NF(2006)].
- Two frequency components are observed in shot #47645 (figure).
  - 50-60kHz, m/n=2/1
  - 65-70kHz, m/n=1/1
- In this work, we apply the multi-phase EP-MHD hybrid simulation to LHD shot #47645.
  - identify the two modes
  - investigate fast ion redistribution



[M. Osakabe, Nuclear Fusion 46 (2006) S911]

Resonance overlap of multiple waves

When the amplitude of multiple waves grow to a level where the resonant particles can be potentially trapped by either wave, the motion of the particles become stochastic
= resonance overlap

This leads to significant interaction between waves and particles for energy transfer and transport.

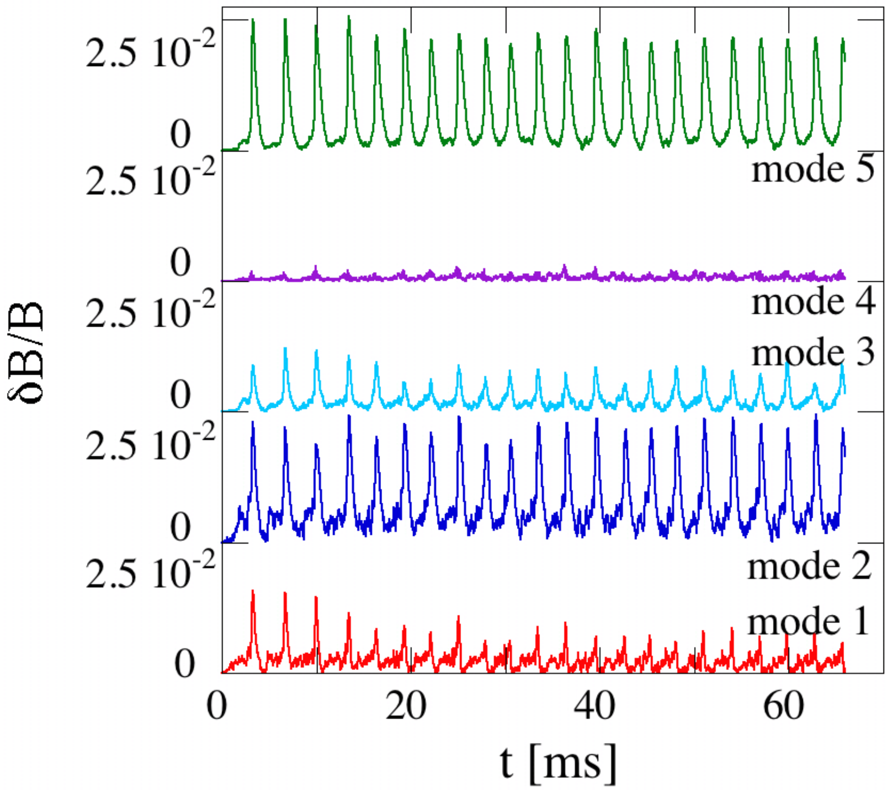
(top) EP distribution function for different moments with two waves.
(bottom) Time evolution of the total wave energy.
[Berk+, Phys. Plasmas 2, 3007 (1995)]

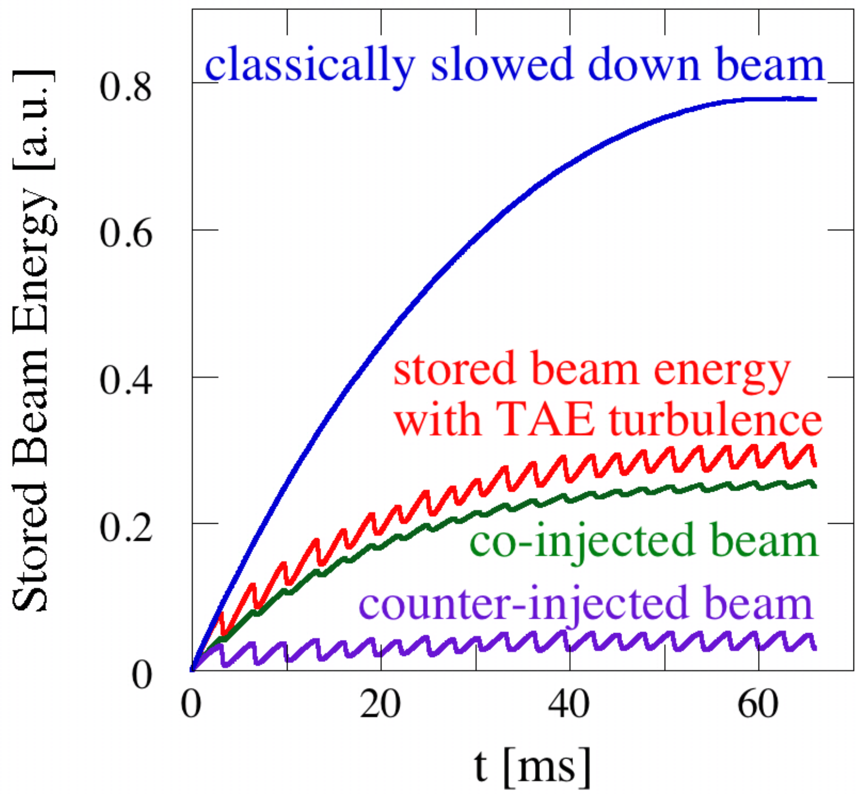
Simulation of Alfvén Eigenmode Bursts

- Particle and energy source
  - neutral beam injection (NBI)
- Sink
  - particle loss at the plasma edge
  - collisions of fast ion with the thermal species (electron and ion)
  - intrinsic damping of Alfvén eigenmode
- Multiple Alfvén eigenmodes

Time evolution of TAE mode amplitude and stored beam energy

[Todo+, Phys. Plasmas 10, 2888 (2003)]





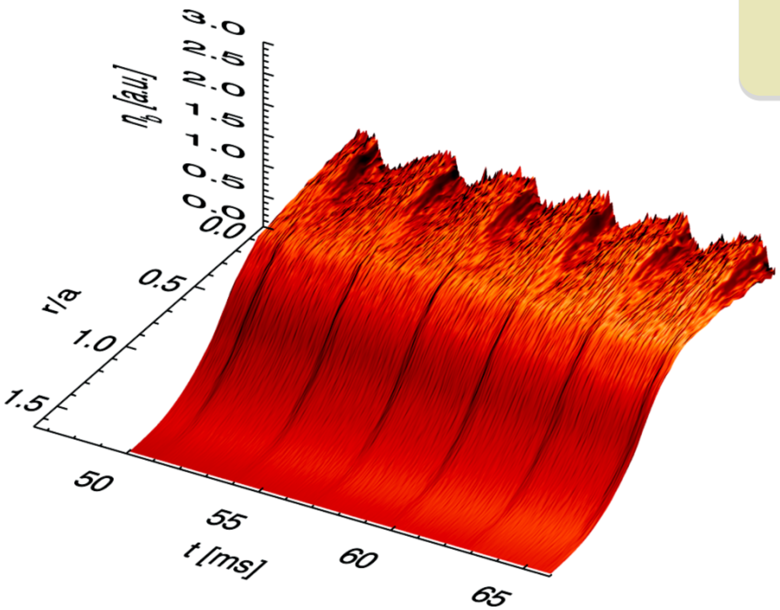
Synchronization of multiple modes due to resonance overlap (left).

Stored beam energy is reduced to 40% of the classically expected level (right).

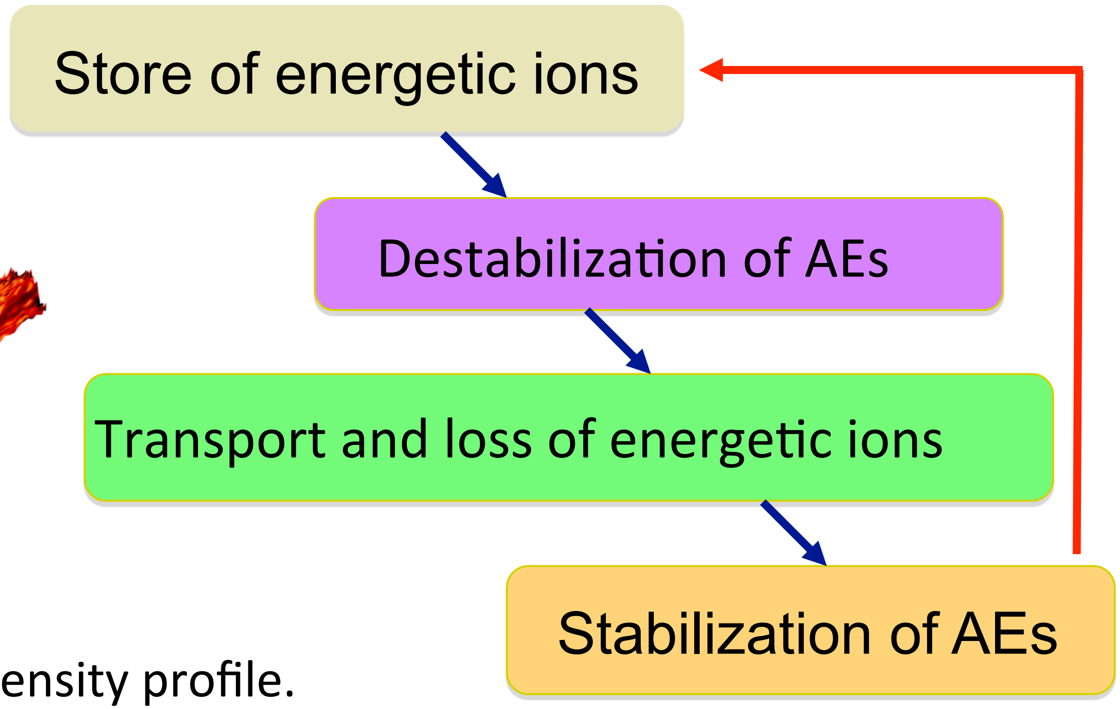
Simulation of Alfvén Eigenmode Bursts

[Todo, Berk, Breizman, PoP **10**, 2888 (2003)]

- Nonlinear simulation in an open system: **NBI, collisions, losses**
- The TAE bursts in a TFTR experiment [Wong et al. PRL **66**, 1874 (1991)] were reproduced quantitatively.



Time evolution of energetic-ion density profile.



AE BURSTS & STEADY EVOLUTION, DEPENDENCE ON P_{NBI} AND SLOWING DOWN TIME

Y. Todo, New J. Physics **18** (2016) 115005

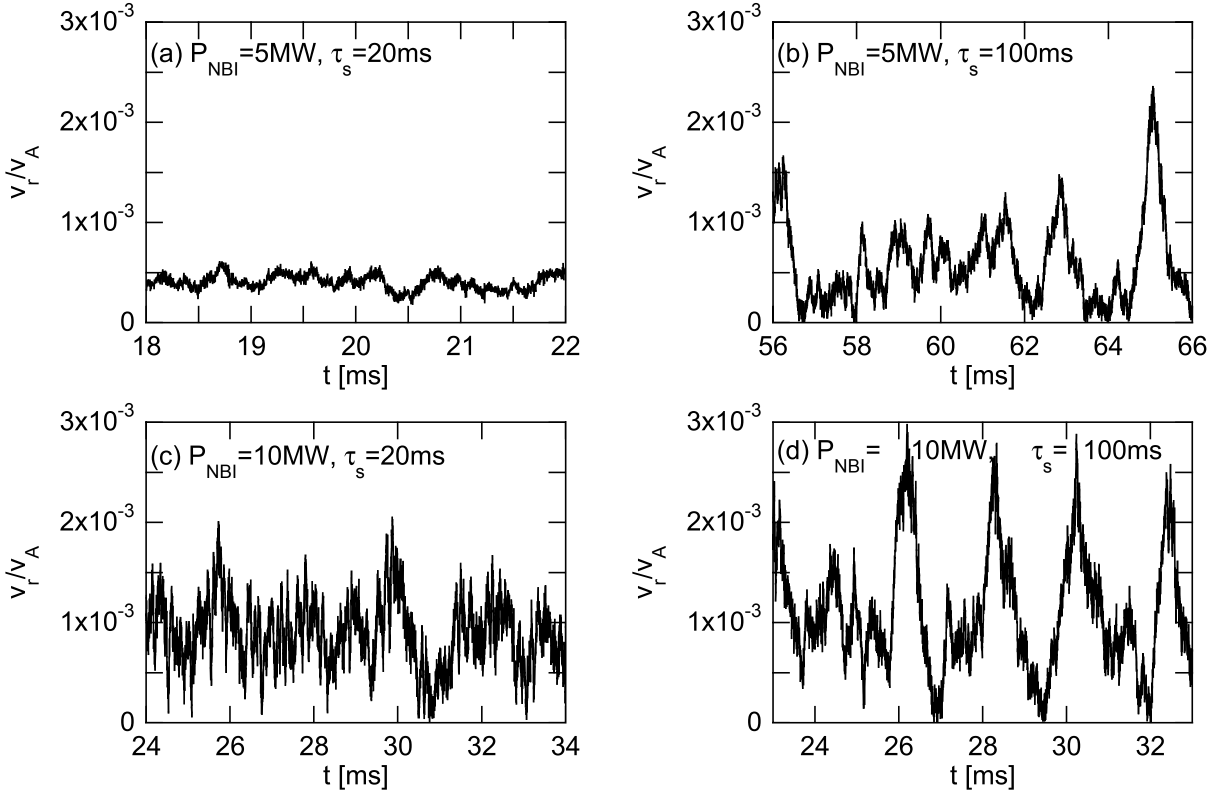
Simulation condition similar to a TFTR experiment [K. L. Wong, PRL 66, 1874 (1991)]

- R_0=2.4m, a=0.75m, B_0=1T
- beam injection energy 110keV (deuterium)
- n_i=2.8 x 10^19 m^-3 (deuterium)
- q(r) = 1.2 + 1.8(r/a)^2
- beam deposition profile:
  exp[-(r/0.4a)^2] x exp[-(|lλ|-λ_0)^2/Δλ^2]
  λ=$v_{//}$/v, λ_0=0.7, Δλ=0.3
- slowing down & pitch-angle scattering
  ν_d=(1/2)ν_s (v_c/v)^3

Comparison of n=2 TAE evolution

5MW
20ms

5MW
100ms

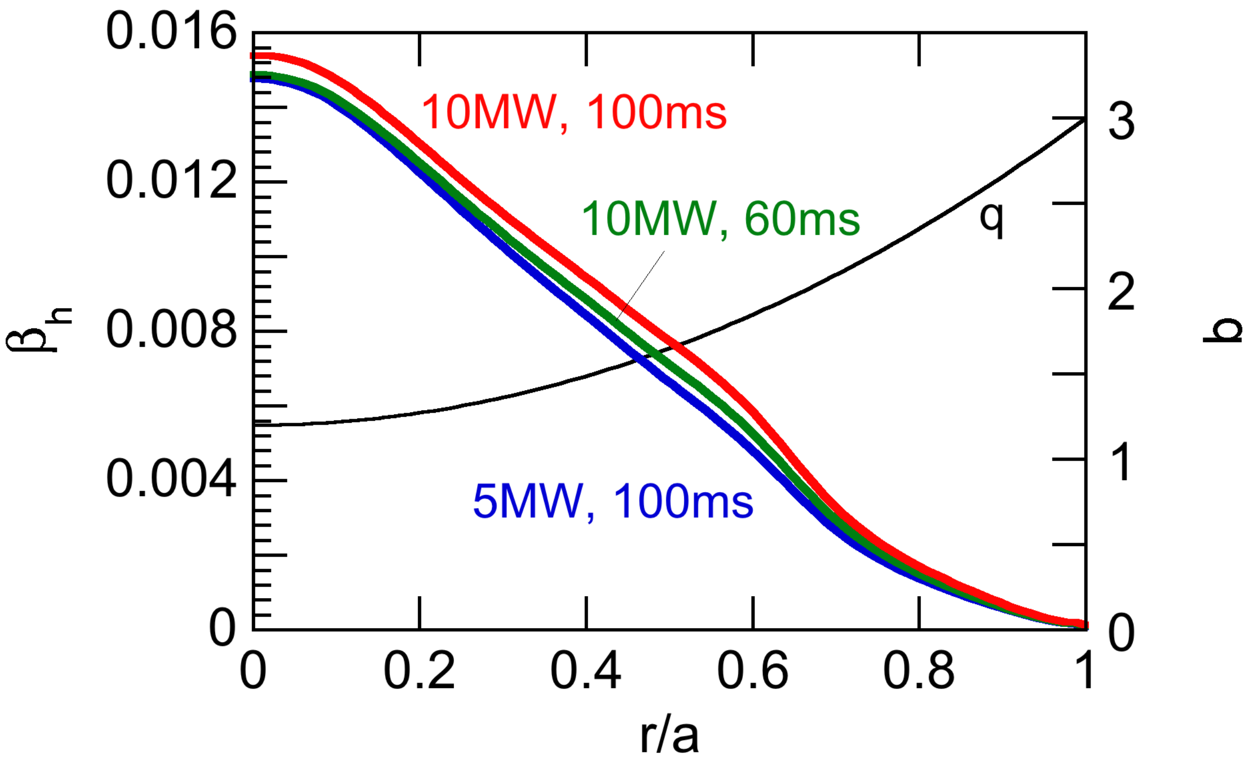


10MW
20ms

10MW
100ms

(10MW, 100ms): the maximum amplitude v_r/v_A~3 x 10^-3 and the burst time interval ~2ms are close to the TFTR experiment [Wong (1991)].

Fast ion profile resiliency



For the highest classical beta cases, the fast ion pressure profiles are saturated = **profile resiliency**.

FAST ION PROFILE FLATTENING AND STIFFNESS IN DIII-D EXPERIMENTS

Y. Todo et al., Nucl. Fusion **54** (2014) 104012
Y. Todo et al., Nucl. Fusion **55** (2015) 073020
Y. Todo et al., Nucl. Fusion **56** (2016) 112008

Anomalous Flattening of Fast ion Profile on DIII-D

- A rich spectrum of TAEs and RSAEs are observed in the current ramp-up phase of DIII-D plasmas with reversed q profile.
- Anomalous flattening of the fast-ion profile takes place during Alfvén-eigenmode activity.

[W. W. Heidbrink, PRL **99**, 245002 (2007)]

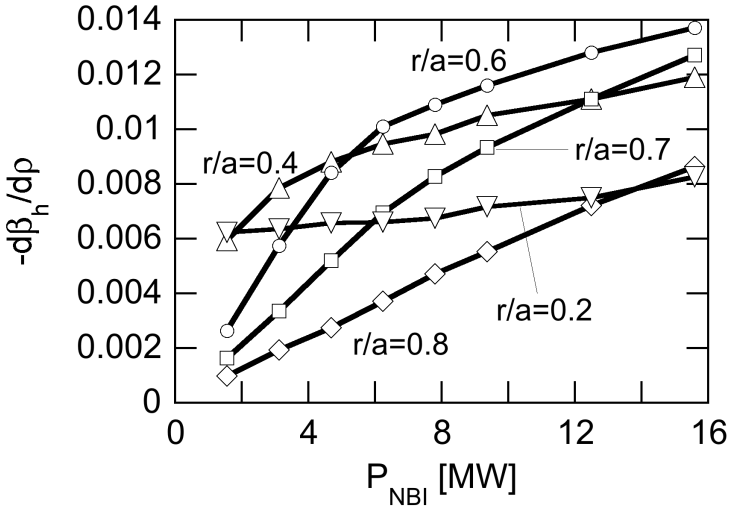
Critical-Gradient Behavior in Alfvén-Eigenmode-Induced Fast-Ion Transport

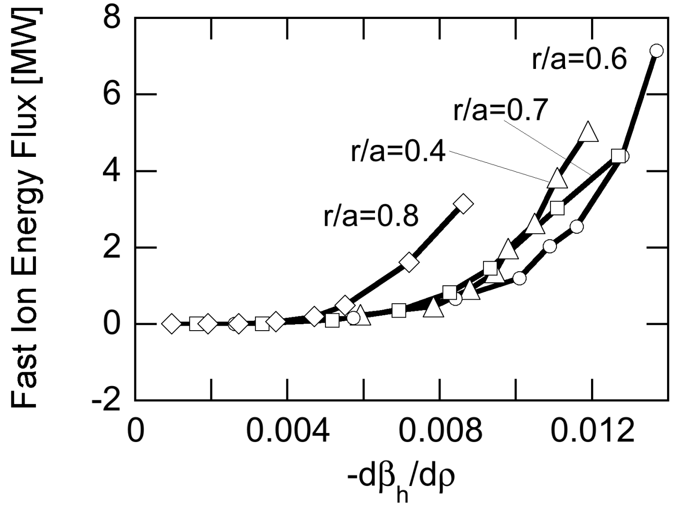
- Solid-state neutral particle analyzer (SSNPA) indicates that fast ion transport suddenly begins to increase above a threshold for NBI power.

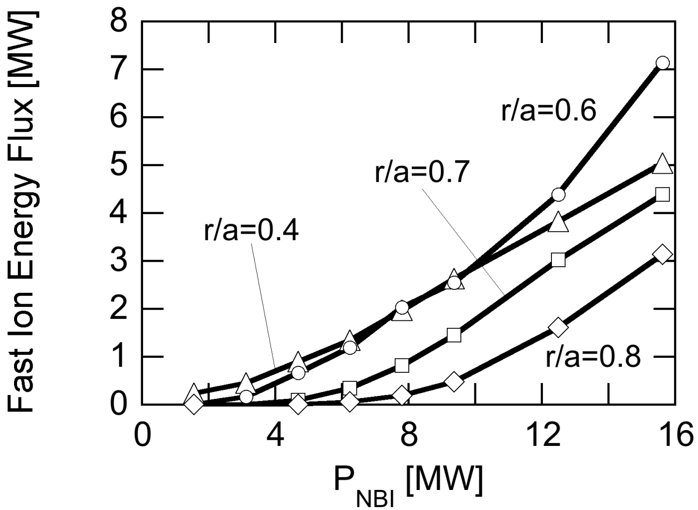
- The threshold for the neutron emission measurement is lower. This suggests the phase space dependence of the fast ion transport.

[C. S. Collins et al., PRL **52**, 095001 (2016), Fig. 3]

Critical fast-ion pressure gradient for sudden increase in energy flux







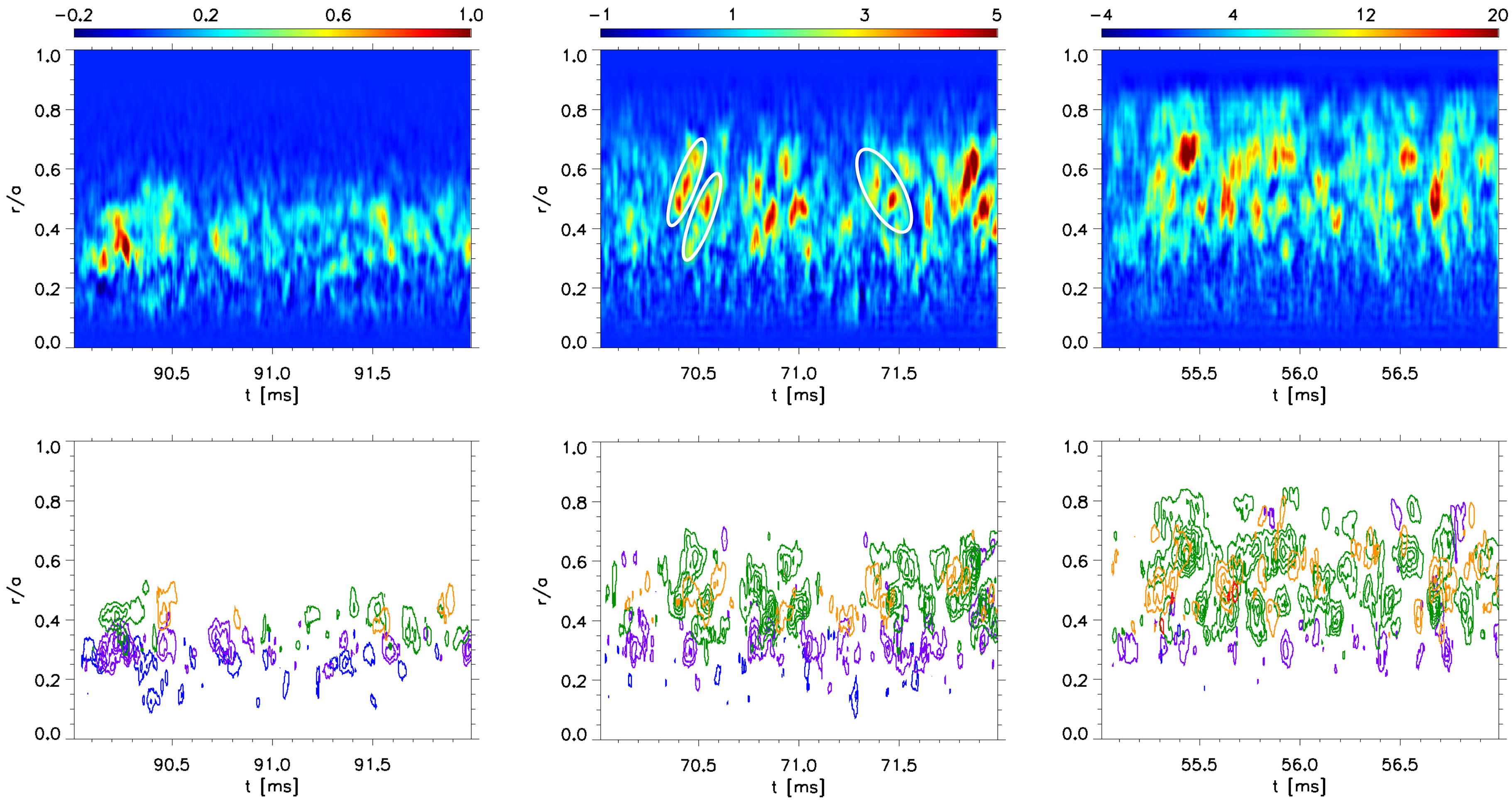
(top left) normalized pressure gradient is saturated around 0.01.

(top right) critical gradient for sudden increase in energy flux

(bottom) critical beam power depends on radial location.

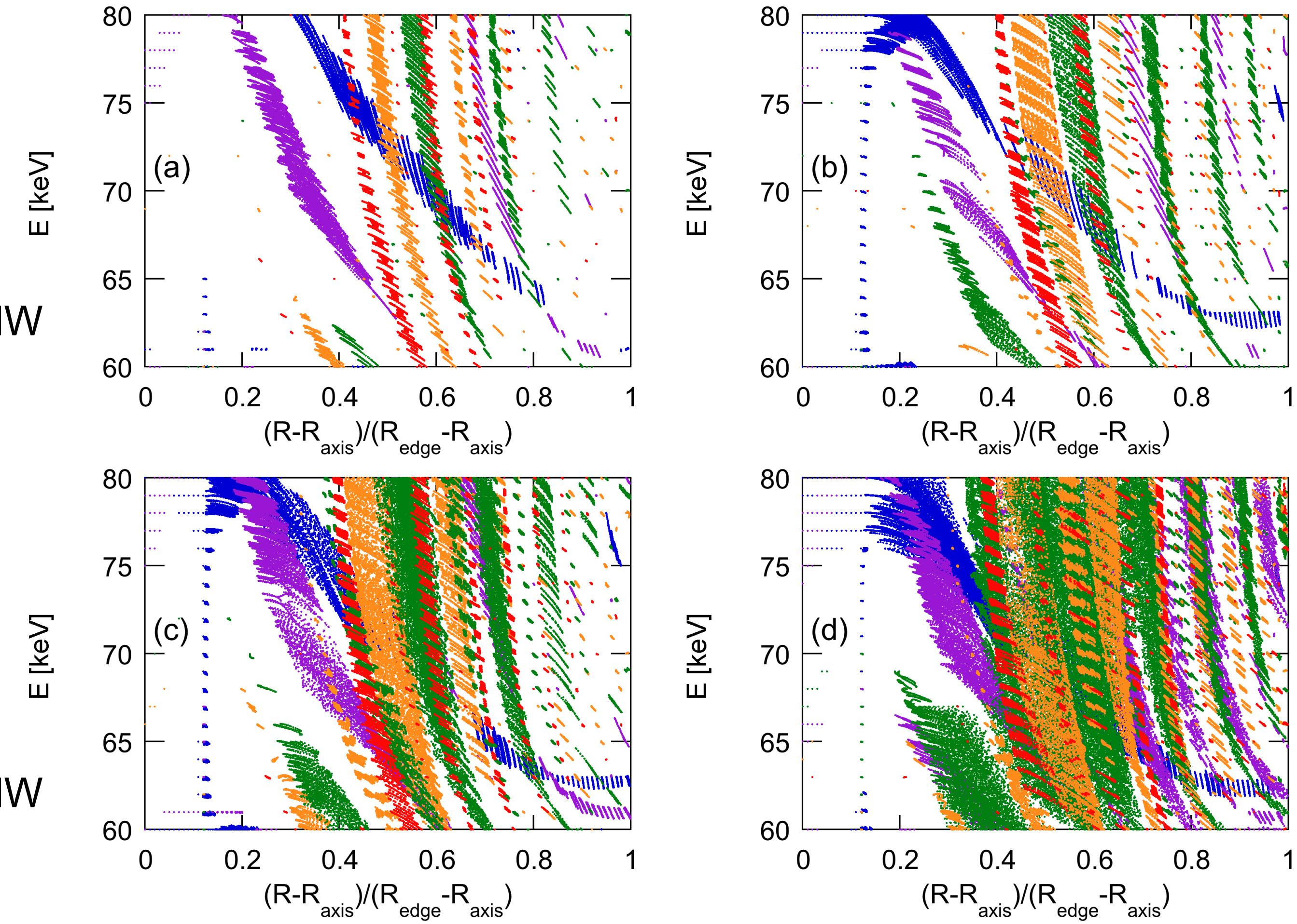
[Y. Todo et al., Nucl. Fusion **56** (2016) 112008]

Time evolution of fast ion energy flux profile [intermittency, avalanches, multiple modes, spreads outward]



P_{NBI}=1.56MW P_{NBI}=6.25MW P_{NBI}=15.6MW

Resonance overlap in (R,E) phase space [blue (n=1), purple (n=2), green (n=3), orange (n=4), red(n=5)]



P_{NBI}=1.56MW

P_{NBI}=3.13MW

P_{NBI}=6.25MW

P_{NBI}=15.6MW

Summary with the focus on nonlinearity

- saturation of inverse Landau damping = particle trapping
- resonance overlap of multiple modes
  - generates stochasticity, and enhances saturation level and energetic particle transport
  - leads to synchronization and bursts of multiple modes
  - leads to energetic particle profile stiffness and resiliency
- fluid NL coupling prevents the AE amplitude from reaching a too high level