Energetic Particle Physics in Tokamak Burning Plasmas

presented by
C. Z. (Frank) Cheng

in collaboration with
N. N. Gorelenkov, G. J. Kramer, R. Nazikian, E. Fredrickson,
Princeton Plasma Physics Laboratory
K. Shinohara, M. Ishikawa, Y. Kusama, M. Takechi, T. Ozeki
JT-60U, Japan Atomic Energy Research Institute

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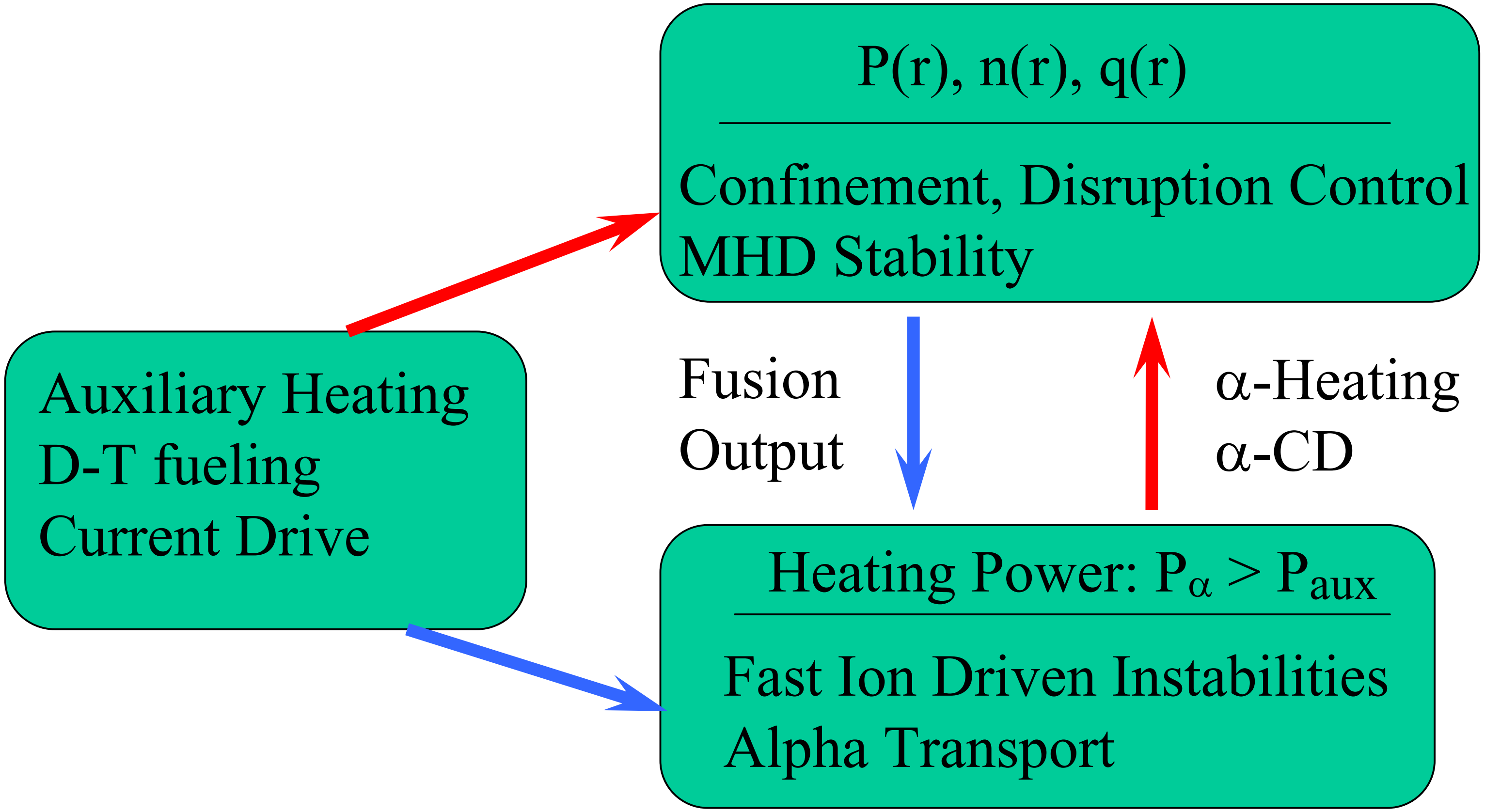
Burning Plasmas Physics



P(r), n(r), q(r)

Confinement, Disruption Control
MHD Stability

Auxiliary Heating
D-T fueling
Current Drive

Fusion
Output

α-Heating
α-CD

Heating Power: $P_\alpha > P_{aux}$

Fast Ion Driven Instabilities
Alpha Transport

➔ Need to understand fast ion physics!

Fast Ion Physics

- First goal is to insure that super-thermal ions (such as 3.5 MeV alpha particles created by D-T fusion reaction, MeV ion cyclotron wave heated ions, and 100 keV – 1 MeV neutral beam injected ions) are confined well enough to transfer their energy to the thermal plasma, and do not create new plasma instabilities.
- Second goal is to understand nonlinear coupling processes involved in fast ion interaction with thermal particles (via profile control) on global stability, confinement, heating and current drive, alpha channeling, burn control, Helium ash removal, thermal instabilities, etc.

Why do we need to understand fast ion behavior?

- Fast ions ($\beta_h \sim \beta_c$) exist in magnetic fusion devices and play essential roles in heating of thermal plasmas and current drive:
    - Fast ions (100 keV - MeVs) in NBI, N-NBI, ICRH auxiliary heatings
    - 3.5 MeV Alphas produced in D-T reaction
- Fast ion driven instabilities (TAEs, RSAEs, EPM/RTAEs, fishbones) and anomalous fast ion loss have been observed in major magnetic fusion devices.
- Significant fast ion loss can degrade heating and current drive efficiency.
- Lost fast ions tend to localize near outer midplane and can cause localized damage on first wall of fusion reactors.
- In Q > 5 burning plasmas, α-particles are dominant heating source because $P_\alpha\,(=W_\alpha/\tau_S) > P_{aux}\,(=W_{tot}/\tau_E)$. Significant α loss can quench DT burning.
- Alpha heating controls thermal plasma profiles which is essential for global plasma stability and confinement.

Fast Ion Physics Issues

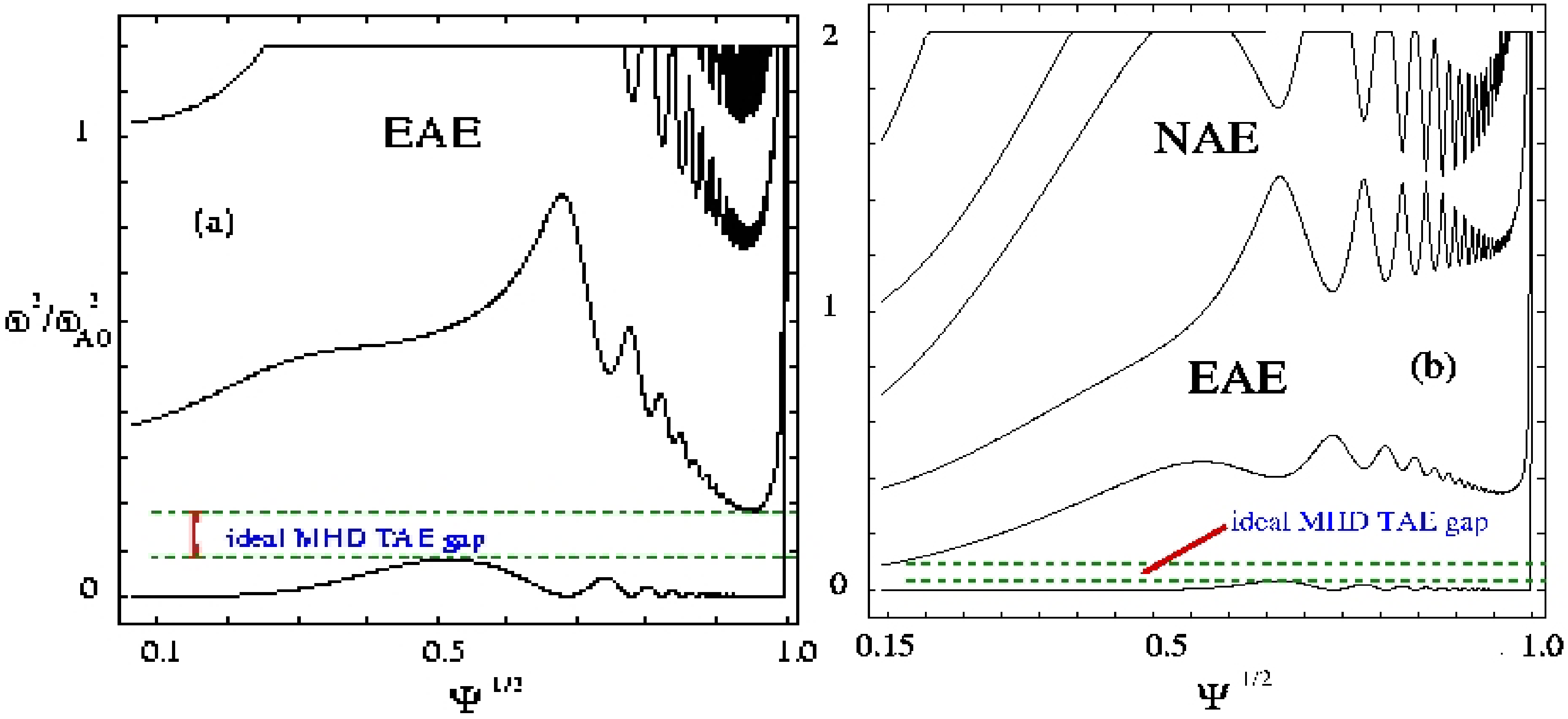
- Single Particle Confinement (Particle Orbit)
- Collective Fast Ion Driven Alfvén Instabilities (TAEs, RSAEs, RTAE/EPM, Fishbones, KBIs, CAEs)
- Fast Particle Transport due to Alfvén Instabilities
- Fast Ion Interaction with RF Waves and Helium Ash Removal
- Integration of Energetic Particle Physics with Global Plasma Stability and Confinement → Nonlinear Burning Plasma Physics

TAE Modes

- Coupling of neighboring poloidal harmonics due to nonuniform B over flux surface produces Alfvén continuum gaps centered around $\omega = jV_A/2qR$, j = 1, 2, ….
- TAEs with frequency ($\omega = V_A/2qR$) in lowest Alfvén continuum gap are created by breaking toroidal periodicity due to magnetic shear.
- TAEs have been studied in major toroidal devices.
- Fast ion loss (up to 70%) due to TAE modes has been observed.
- Alpha driven TAEs have been found in TFTR DT experiments.
- In Q = 5 burning plasmas α energy is expected to be 10% of total plasma energy and high β_α can drive strong multiple TAE modes.

  TAE is a generic issue for all toroidal fusion devices!!

Alfvén Continuum (n = 3) and TAEs in NSTX



<β> = 10 %

<β> = 33 %

- $q_0 = 0.7$, $q_1 = 16$
- Large continuum gaps due to low aspect ratio even at high β.
- Many TAEs with global structureare and many n found.

Prediction of TAEs Based on MHD Model

- TAEs are discrete Alfven eigenmodes due to nonuniform q-profile and nonuniform magnetic field intensity along **B**.
- Coupling between neighboring poloidal harmonics produces Alfven continuum gap (bounded by $(\omega_\pm / \omega_A)^2 \simeq (1 \pm \varepsilon)/4$) and magnetic shear allows discrete TAEs with frequency ($\omega \simeq \omega_A/2$) to exist in the gap.

$$\left[\frac{d^2}{d\theta^2} + \left(\frac{\omega}{\omega_A}\right)^2 (1 - 2\epsilon\cos\theta) - \frac{s^2}{\left(1 + s^2\theta^2\right)^2}\right]\Phi = 0$$

$$\varepsilon = r/R\,, \quad s = rq'/q\,, \quad \omega_A = V_A/qR$$

- TAEs exist because the periodicity in potential due to B variation is broken by magnetic shear effect– similar to discrete energy states in a periodic lattice due to periodicity breaking by impurity or other effects in solid state physics.

TAE Instability

- Fast ions resonate with TAEs if $V_h > 0.5\ V_A$.

  For B = 10T, $n_e = 2 \times 10^{14}\ \mathrm{cm}^{-3}$, $V_A = 10^7$ m/sec, $V_\alpha = 1.3 \times 10^7$ m/sec. $V_h > 0.5\ V_A$ can be satisfied for α-particles, MeV protons in ICRH operation, and MeV N-NBI Deuterium ions.
- Necessary condition for fast ion drive:

  Free energy in fast ion pressure gradient overcomes velocity space damping effect if $nq(V_h/V_A) > (r/R)(L_h/\rho_h)$.

  For large devices (large L_h/ρ_h) the unstable spectrum is shifted to medium to high-n modes.
- Sufficient condition for TAE instability:

  γ_h (fast ion drive) > γ_d (thermal plasma damping)
- Multiple TAEs are expected to be robustly unstable in burning plasmas!!

Kinetic-MHD Model

- Two-component plasma: core and hot components with $n_h \ll n_c$, $n \simeq n_c$, $P_c \sim P_h$
- Core plasmas are treated as MHD-fluid
- Hot particles are governed by kinetic models such as gyrokinetic equations or full Vlasov equations
- Coupling between core plasmas and hot particles is via pressure (or current) term in momentum equation
- No parallel electric field

Kinetic-MHD Model

- Momentum Equation:

  $$\rho\,[\partial/\partial t + \mathbf{V}\cdot\nabla]\,\mathbf{V} = -\nabla P_c - \nabla\cdot\mathbf{P}_h + J \times B$$

- Continuity Equation:

  $$[\partial/\partial t + \mathbf{V}\cdot\nabla]\,\rho + \rho\nabla\cdot\mathbf{V} = 0$$

- Maxwell's Equations:

  $$\partial B/\partial t = -\nabla\times\mathbf{E}, \quad J = \nabla\times\mathbf{B}, \quad \nabla\cdot\mathbf{B} = 0$$

- Ohm's Law: $\mathbf{E} + \mathbf{V}\times\mathbf{B} = 0$, $\mathbf{E}\cdot\mathbf{B} = 0$
- Adiabatic Pressure Law: $[\partial/\partial t + \mathbf{V}\cdot\nabla]\,(P_c/\rho^{5/3}) = 0$
- Hot Particle Pressure Tensor:

  $$\mathbf{P}_h = \{m_h/2\} \int d^3v\, \mathbf{vv}\, f_h(\mathbf{x},\mathbf{v})$$

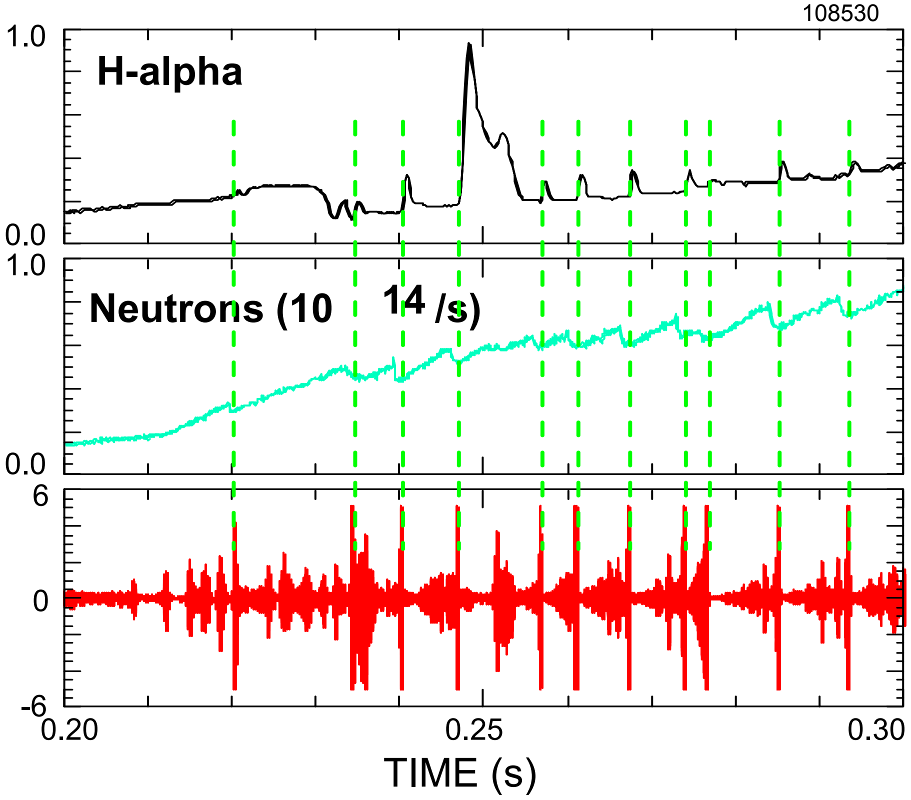
  where f_h is governed by gyrokinetic or Vlasov equation.

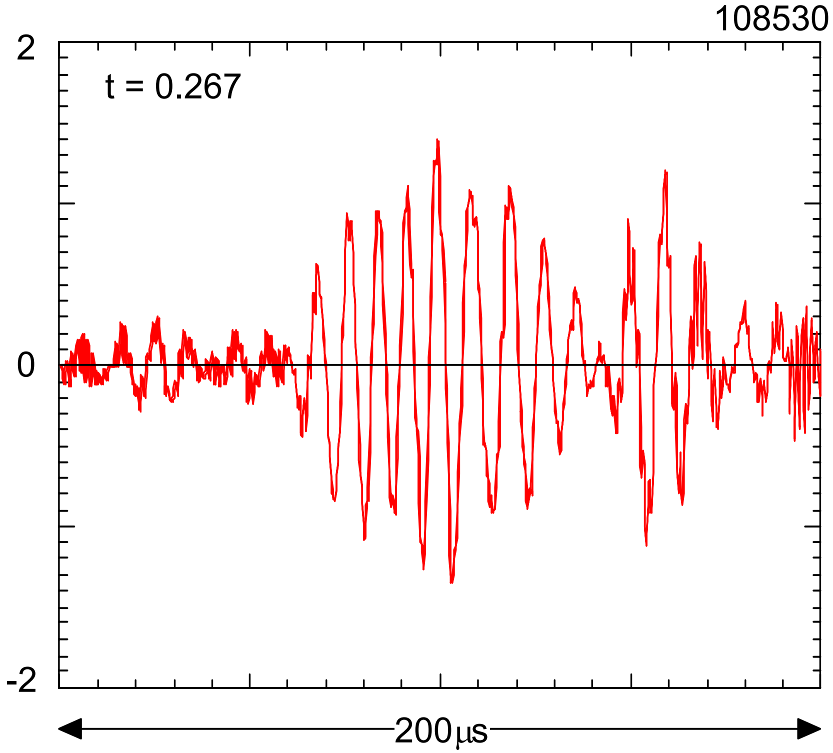
PPPL Kinetic-MHD Codes

- Linear Stability Codes
  - -- NOVA-K: global TAE stability code with perturbative treatment of thermal particle and fast ion kinetic physics
  - -- NOVA-2: global kinetic-MHD code with non-perturbative treatment of fast ion kinetic effects
  - -- HINST: high-n kinetic-MHD code with non-perturbative treatment of fast ion kinetic effects
- Nonlinear Simulation Codes
  - -- M3D-K: global kinetic-MHD code with fast ion kinetic physics determined by gyrokinetic equation.
  - -- HYM-1: global kinetic-MHD code with fast ion kinetic physics determined by full equation of motion.
  - -- HYM-2: global hybrid code with ions treated by full equation of motion and electrons treated as massless fluid.

➔ Through joint theory-experiment efforts, we have gained understanding of energetic particle physics phenomena in major tokamak experiments.

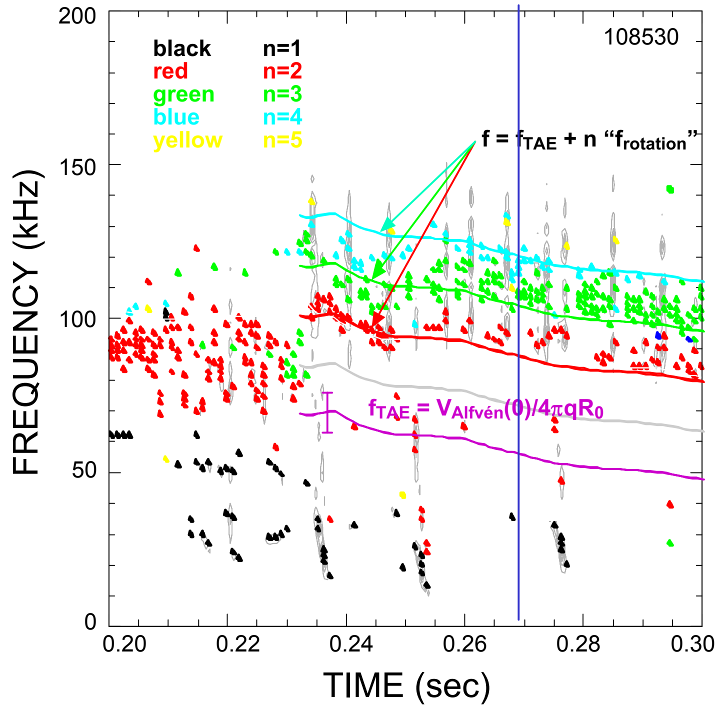
Large Amplitude Bursting TAEs Cause Fast Ion Loss in NSTX

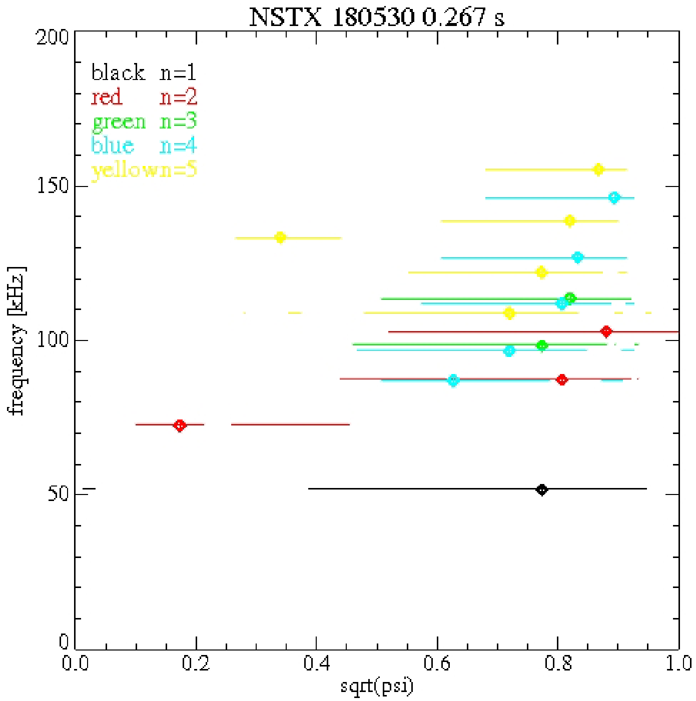




- NSTX shot with B = 0.434T, R = 87 cm, a = 63cm, P_{NB} = 3.2MW.
- Bursting TAE dominated by single mode being n=2 or 3.
- Bursting TAEs lead to neutron drop and cause 5 – 10% fast ion loss after 0.21 sec.

Bursting TAEs in NSTX

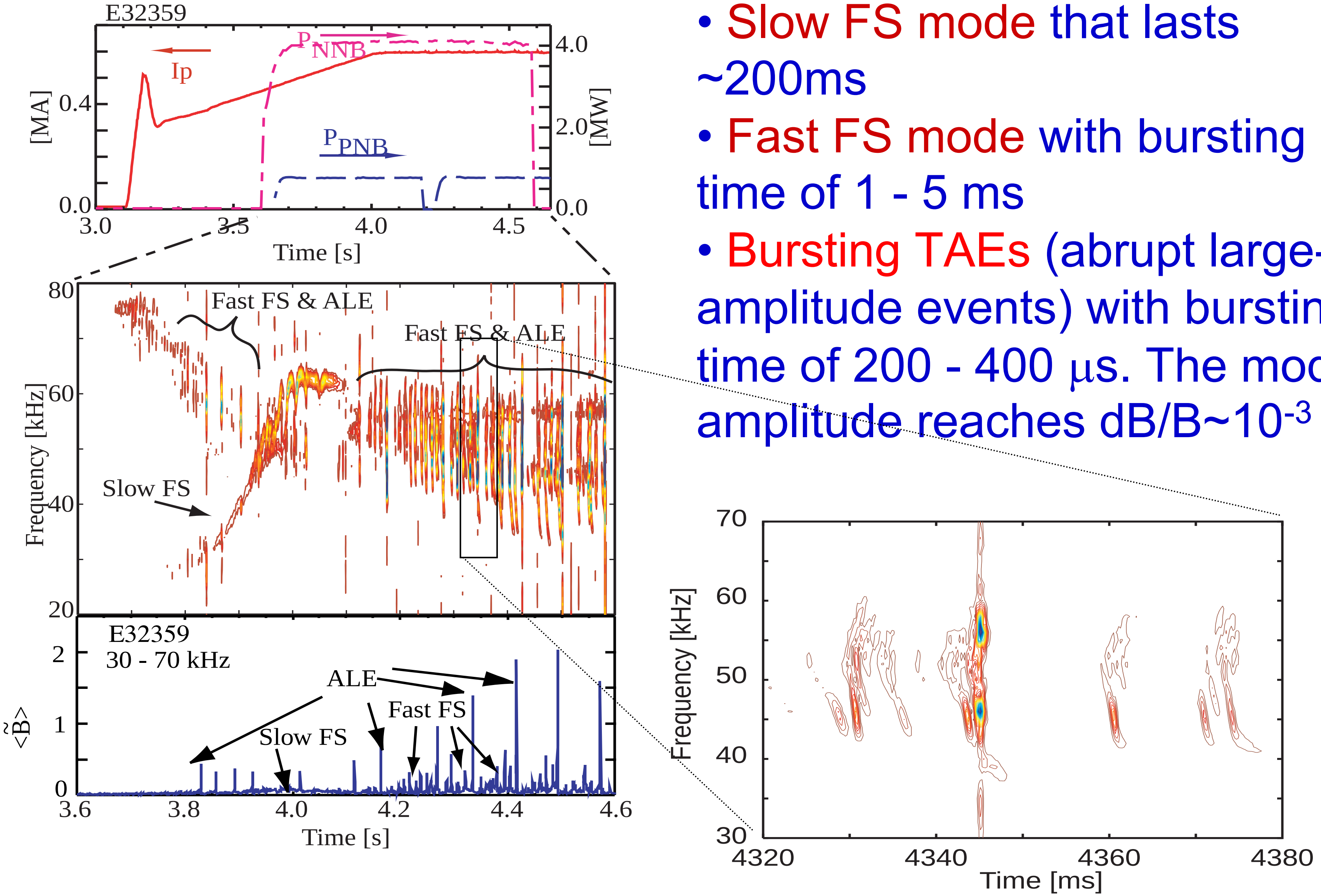




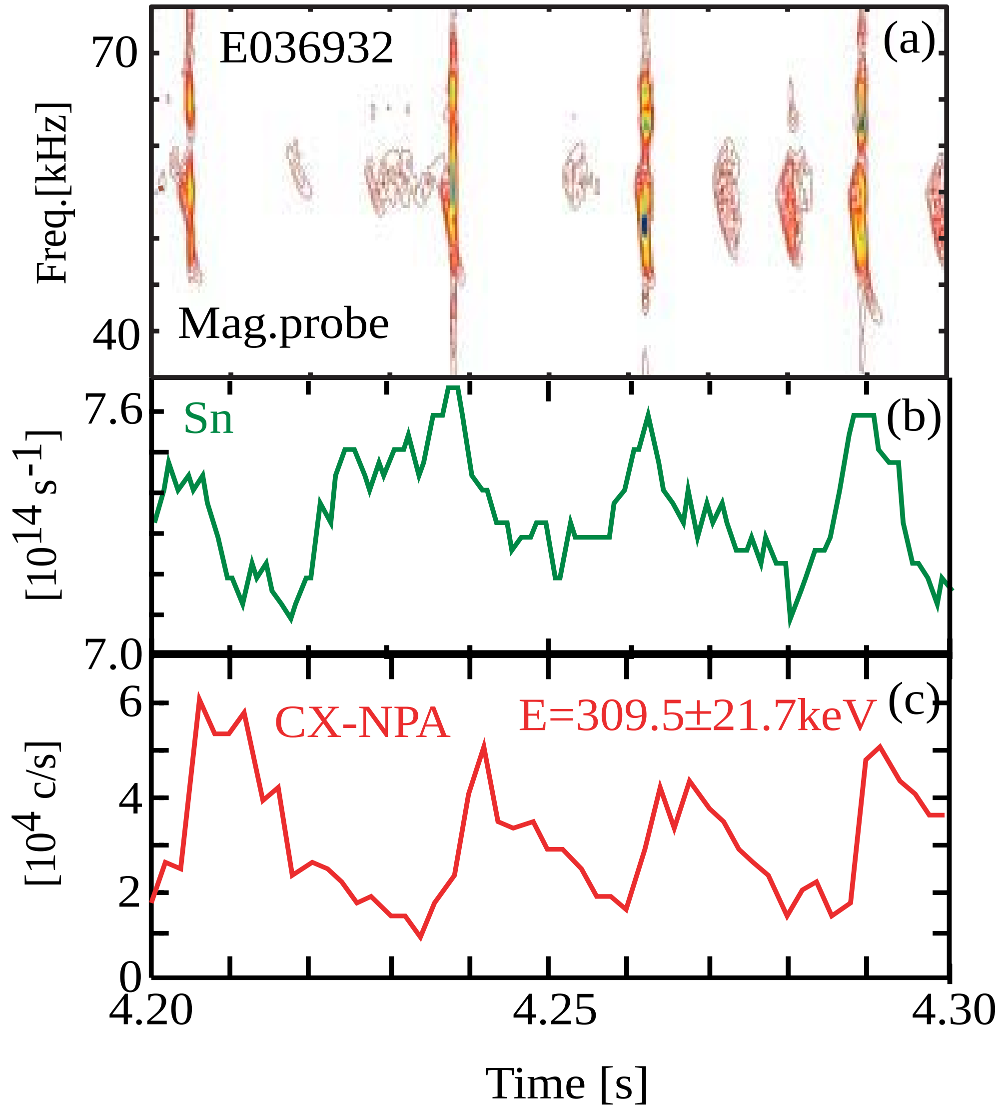
- Modes with n = 1 - 5 are usually observed.
- Mode frequencies (adjusted with plasma rotation) are in good agreement with those computed from NOVA/NOVA-K code.
- Unstable modes are global with peak around r/a = 0.5 – 0.8

Bursting TAEs observed in JT-60U using NNB

- Slow FS mode that lasts ~200ms
- Fast FS mode with bursting time of 1 - 5 ms
- Bursting TAEs (abrupt large-amplitude events) with bursting time of 200 - 400 μs. The mode amplitude reaches $dB/B \sim 10^{-3}$



Enhanced Fast Ion Transport by Bursting Modes

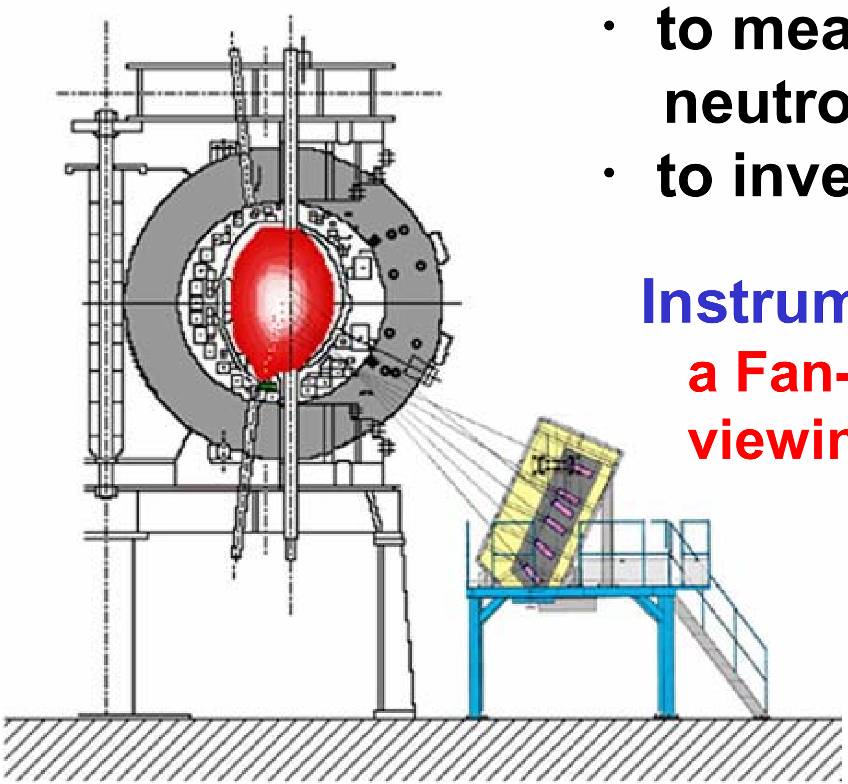


- After bursting mode occurs neutron emission rate (S_n) drops and enhanced fast neutral fluxes (Γ) are observed.

•Bursting modes cause enhanced transport of energetic ions.

•Fast ion loss is via wave-particle resonant interaction.

Measurement of Neutron Emission Profile

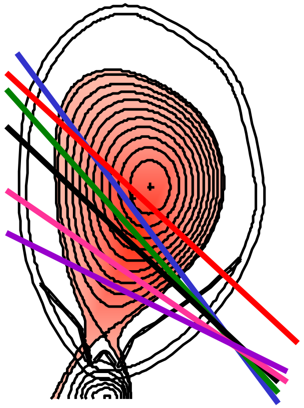


Objectives :

- **to measure 2.45 MeV DD fusion neutron profile**
- **to investigate fast ion behavior**

Instrument of Neutron Profile Monitor

a Fan-shaped 6 channel collimator array viewing a poloidal cross section

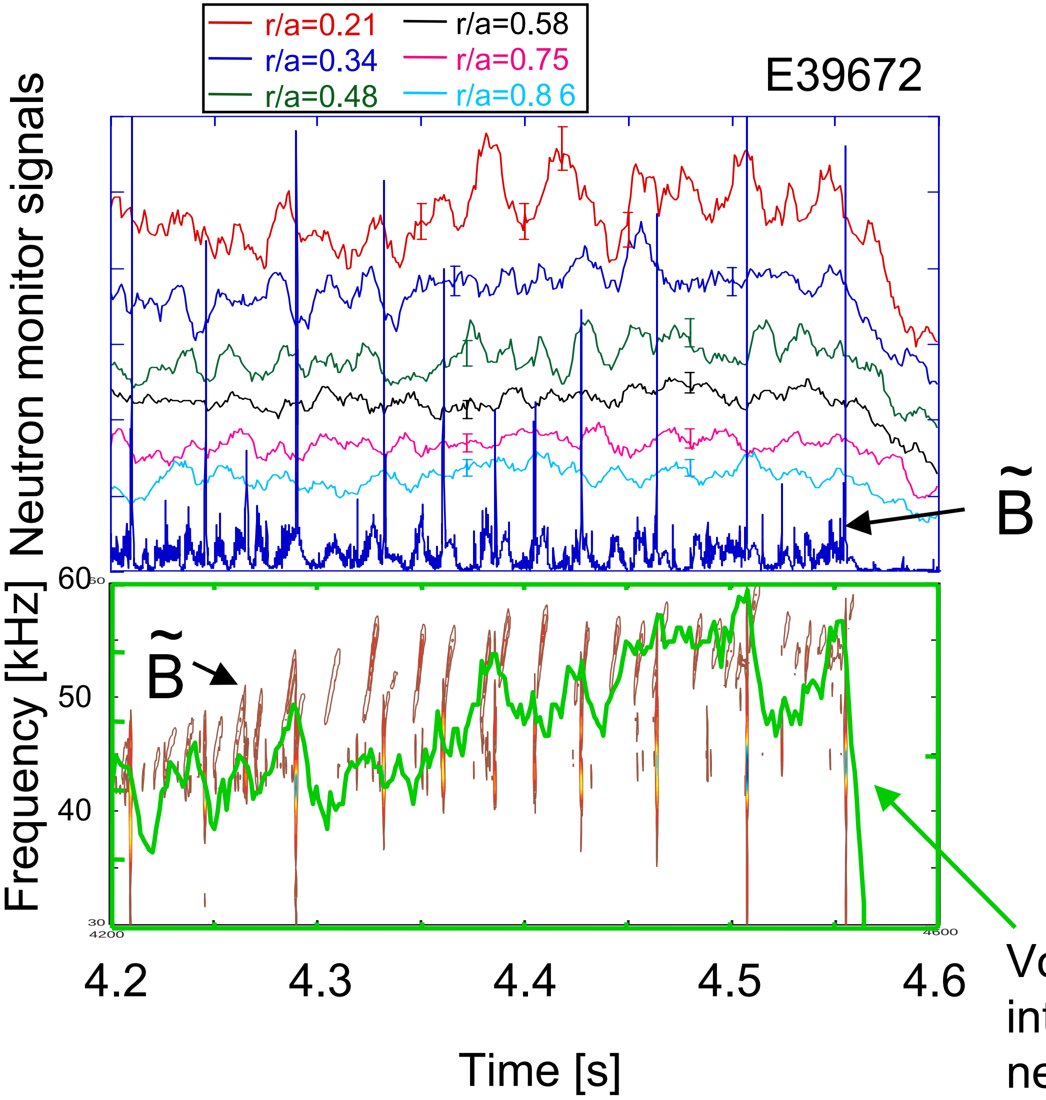


The line of sight

Detector

Stilbene neutron detector with P.S.D -> Can distinguish neutron from γ ray

Change of Neutron Profile by Bursting TAEs

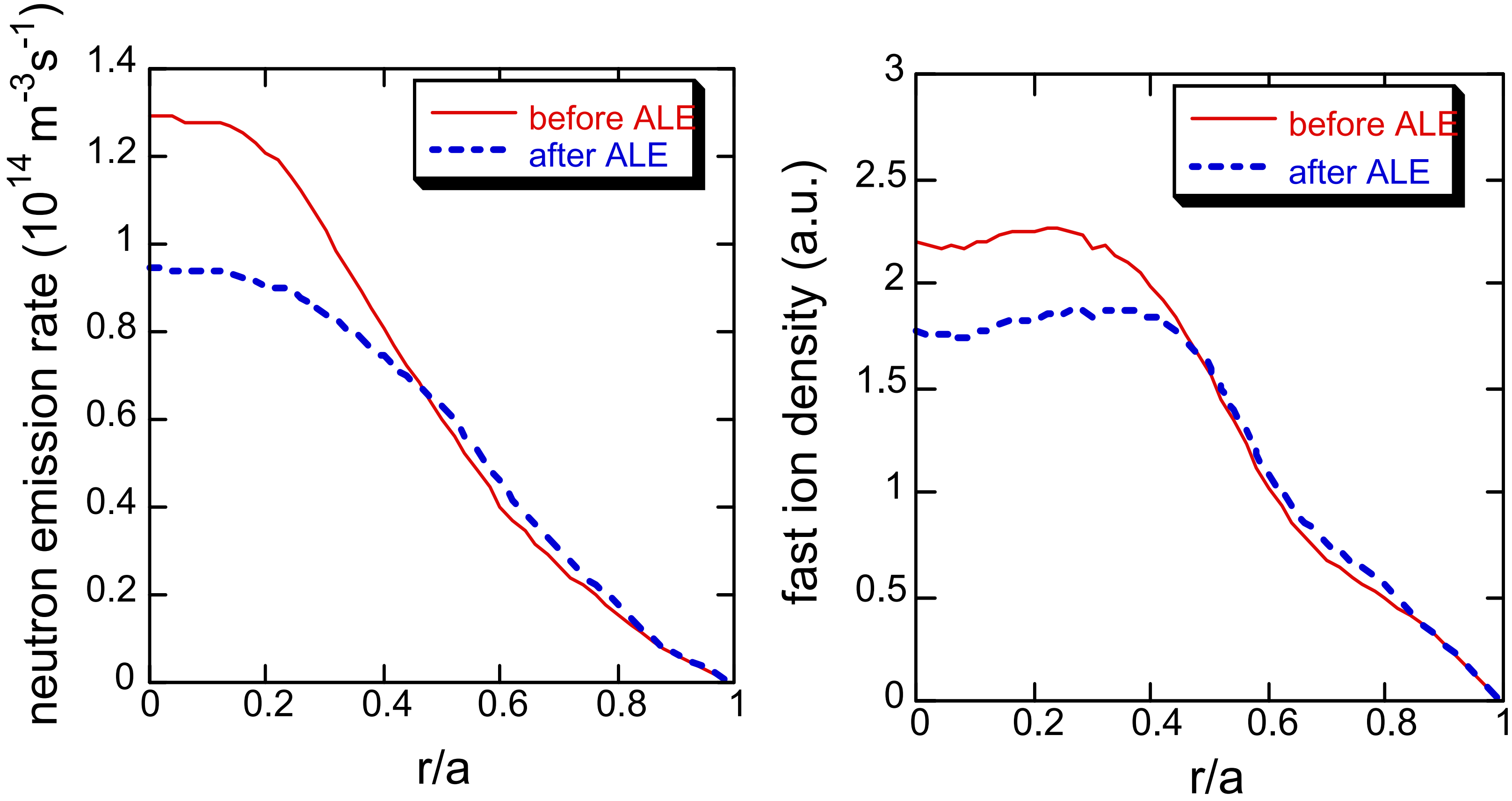


Volume integrated neutron emission

- After bursting modes (ALEs) peripheral signals (r/a>0.48) increase while center signals (r/a<0.34) decrease.
  -> Bursting mode causes global redistribution of energetic ions
- For Fast FS modes center signals (r/a<0.34) decrease
  -> Fast FS modes are core localized modes and induce local enhanced transport even with small amplitude

Fast Ion Transport by Bursting TAEs

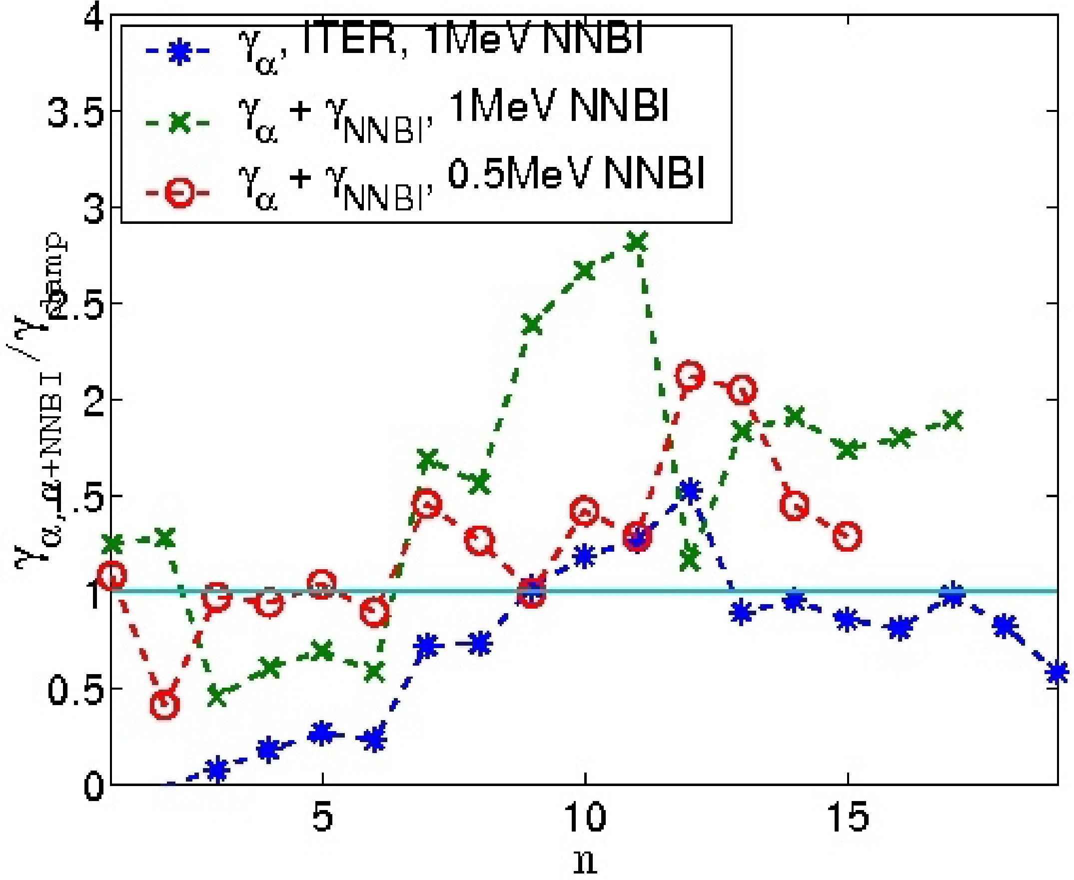
E39672 at 4.51sec



Ishikawa et al. To be submitted

Will TAEs be Unstable in ITER?

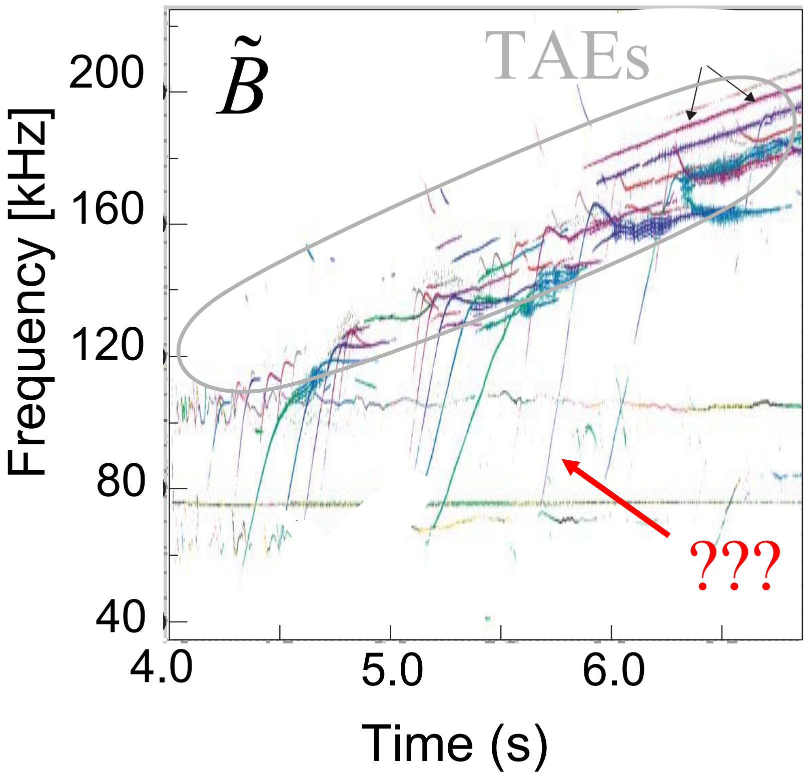
NOVA-K calculation



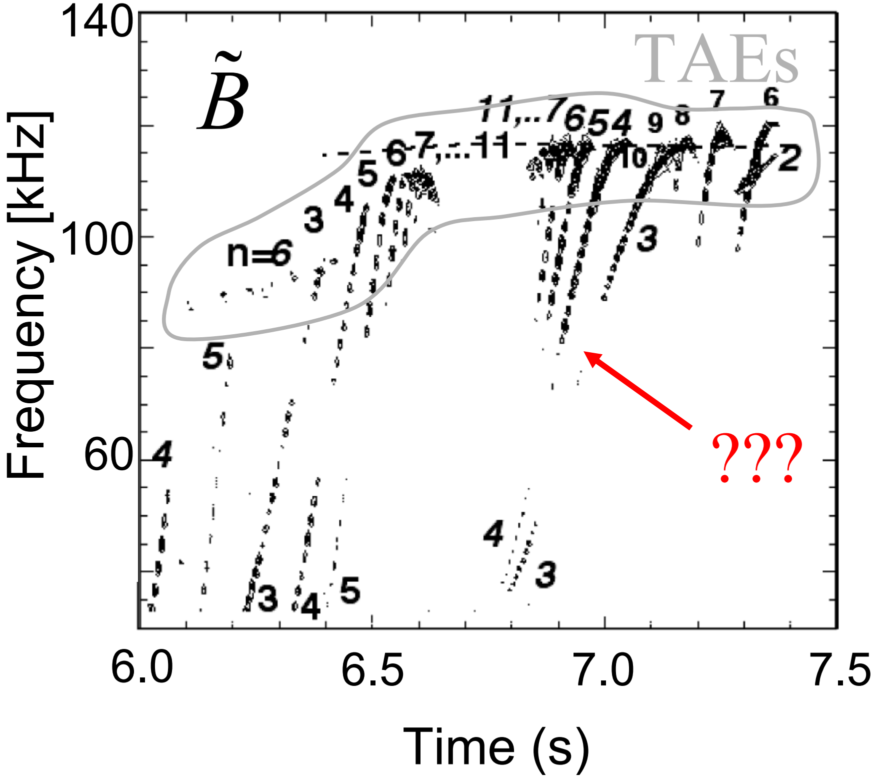
- TAEs are expected to be unstable in ITER!
- What is the effect on α transport?

Early Observation of Frequency Sweeping seen in Reverse Shear Plasmas: Edge Magnetic Data

JET S. Sharapov et al., Phys. Lett. **A289** (2001) 127



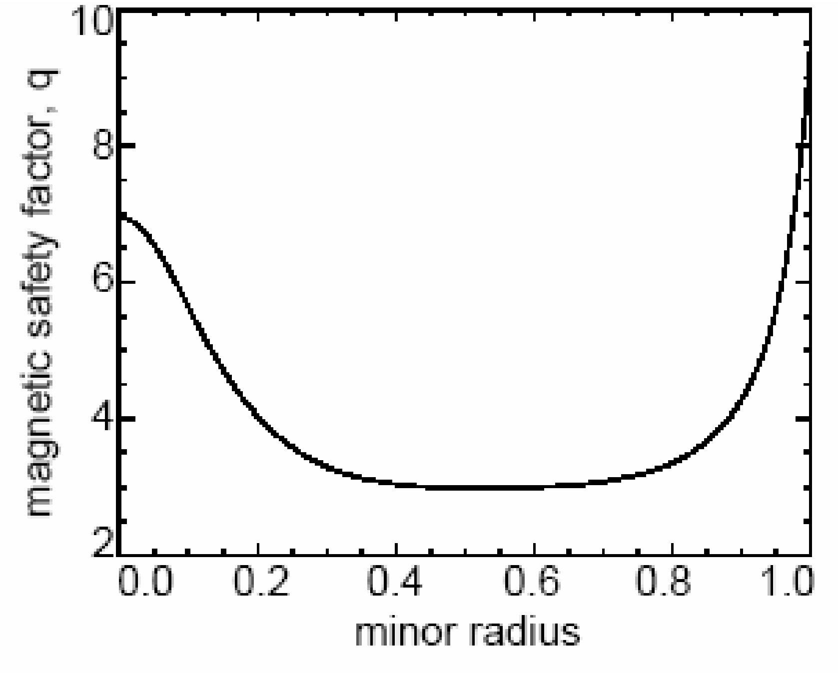
H. Kimura et al., Nucl. Fusion **38** (1998) 1303 JT-60U

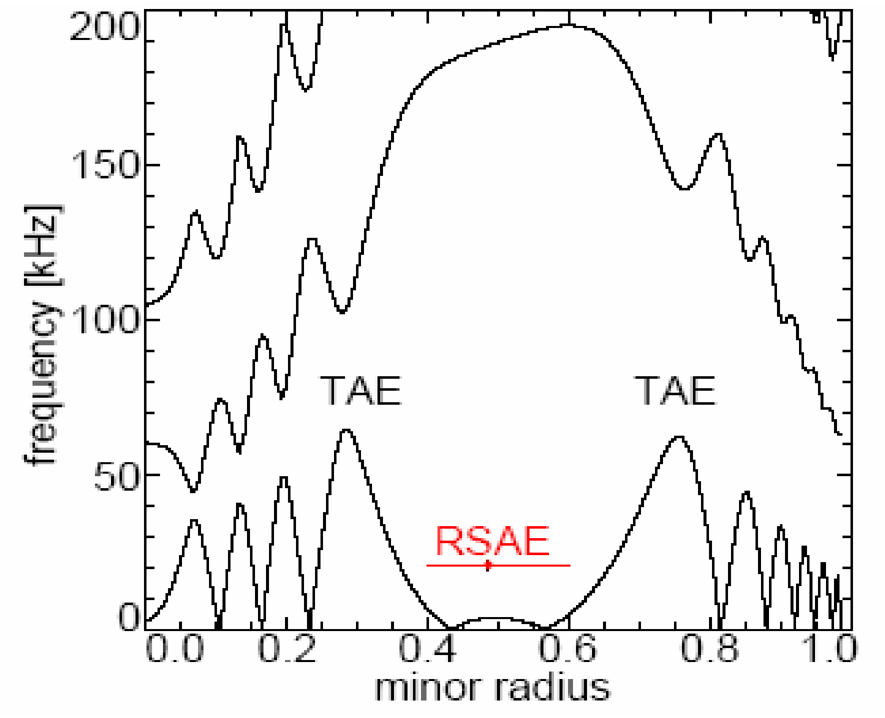


- Toroidal Alfvén eigenmodes (TAEs) predicted in 1985, observed in 1991 – reasonably well understood.

- Frequency sweeping was a puzzle since late 90s:
  - Resolution involved Japan - EU - US collaboration

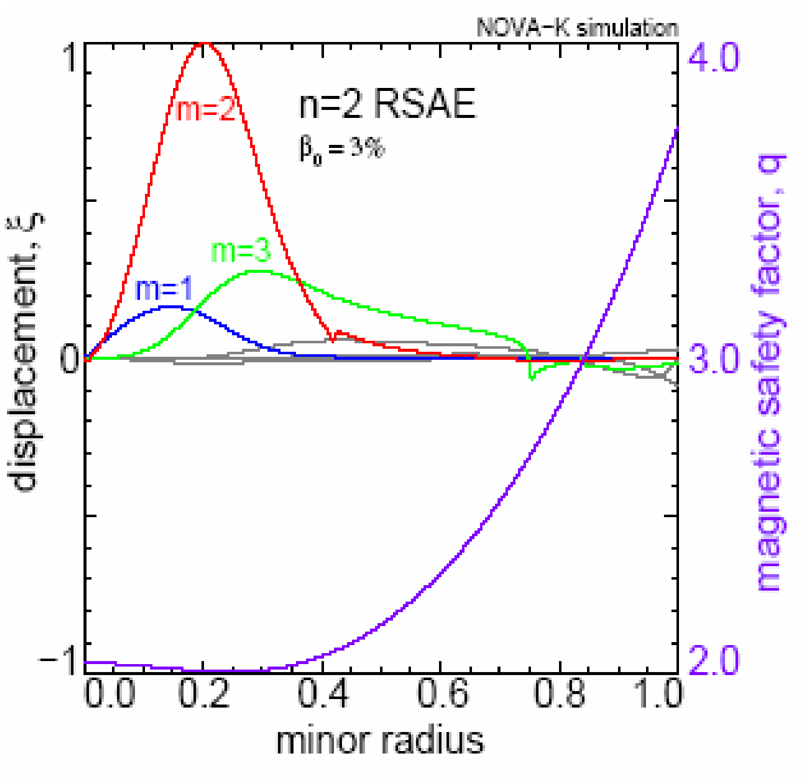
Reversed Shear Alfvén Eigenmode (RSAE)

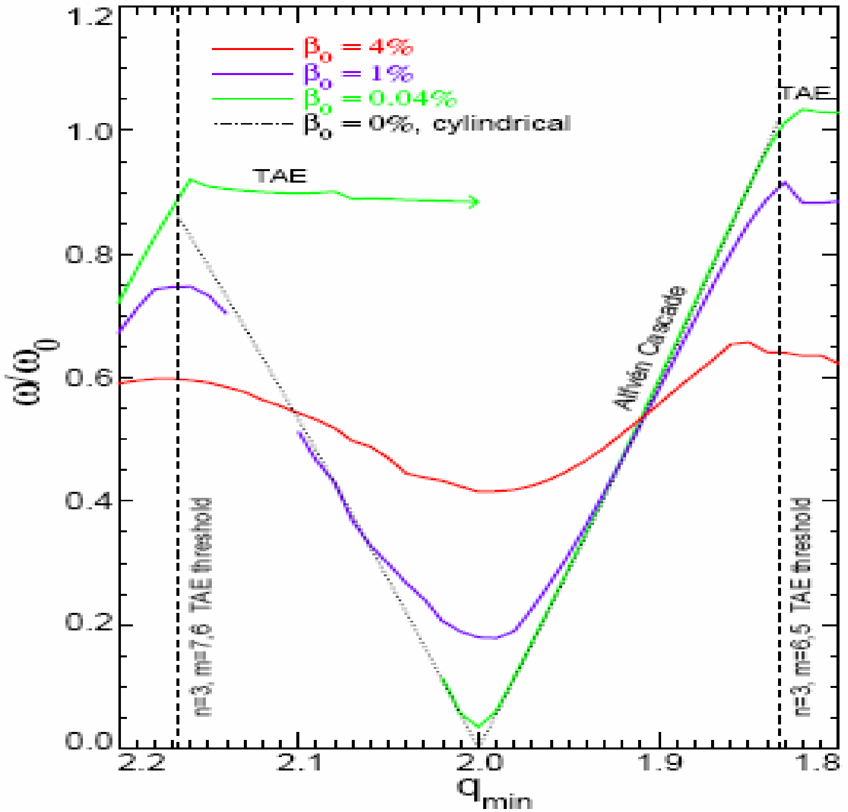



n = 1 continuum

- RSAEs are cylindrical shear Alfven modes in reversed shear plasmas
- RSAEs are described by ideal MHD theory

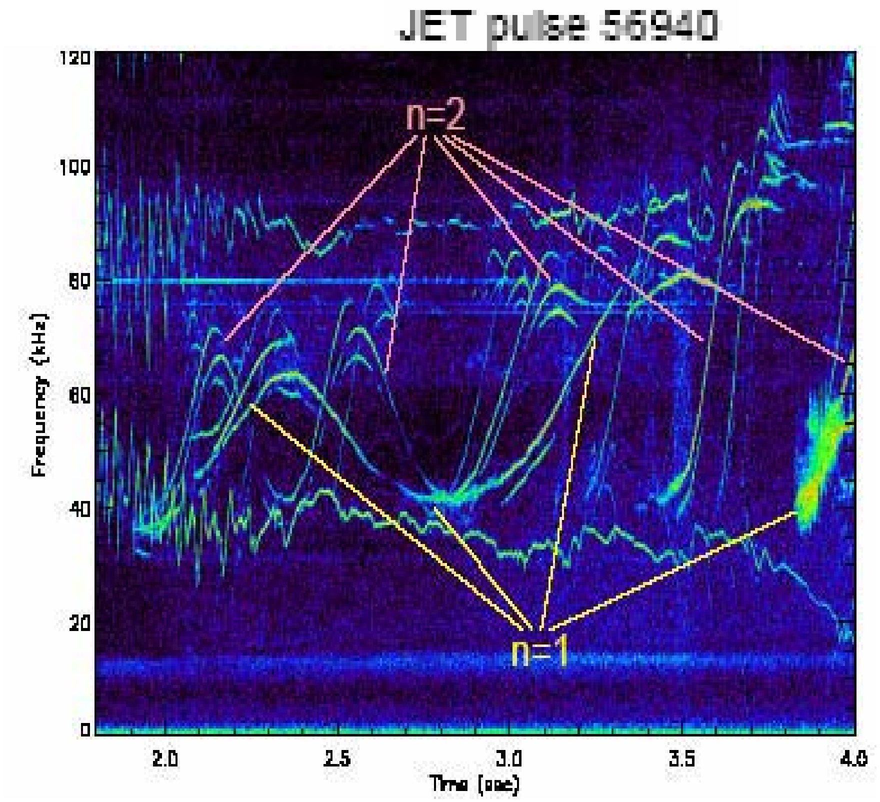
MHD Theory of RSAE

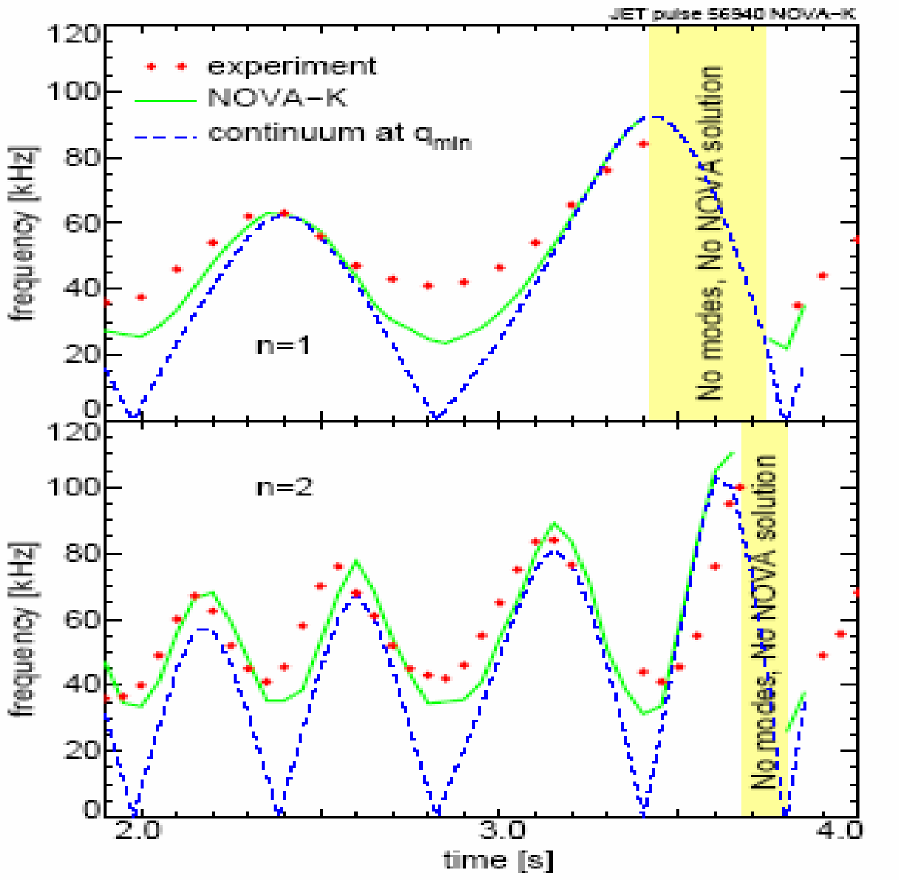




- RSAE frequency: $\omega \simeq (m - nq_{min})V_A / q_{min}R$
- RSAEs are modes localized at q_{min}
- Finite β causes non-zero RSAE frequency due to poloidal mode coupling at q_{min}

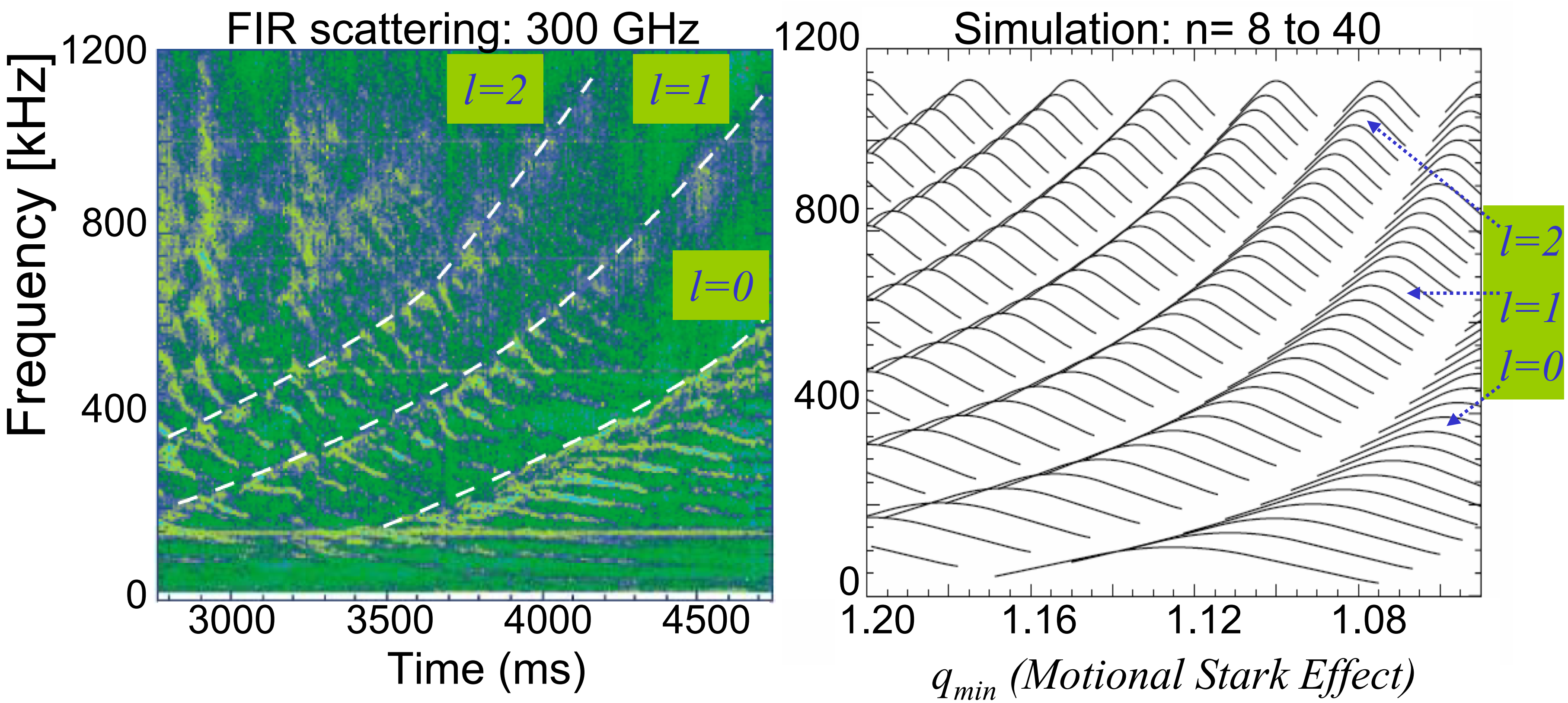
NOVA-K Calculation of RSAEs in JET





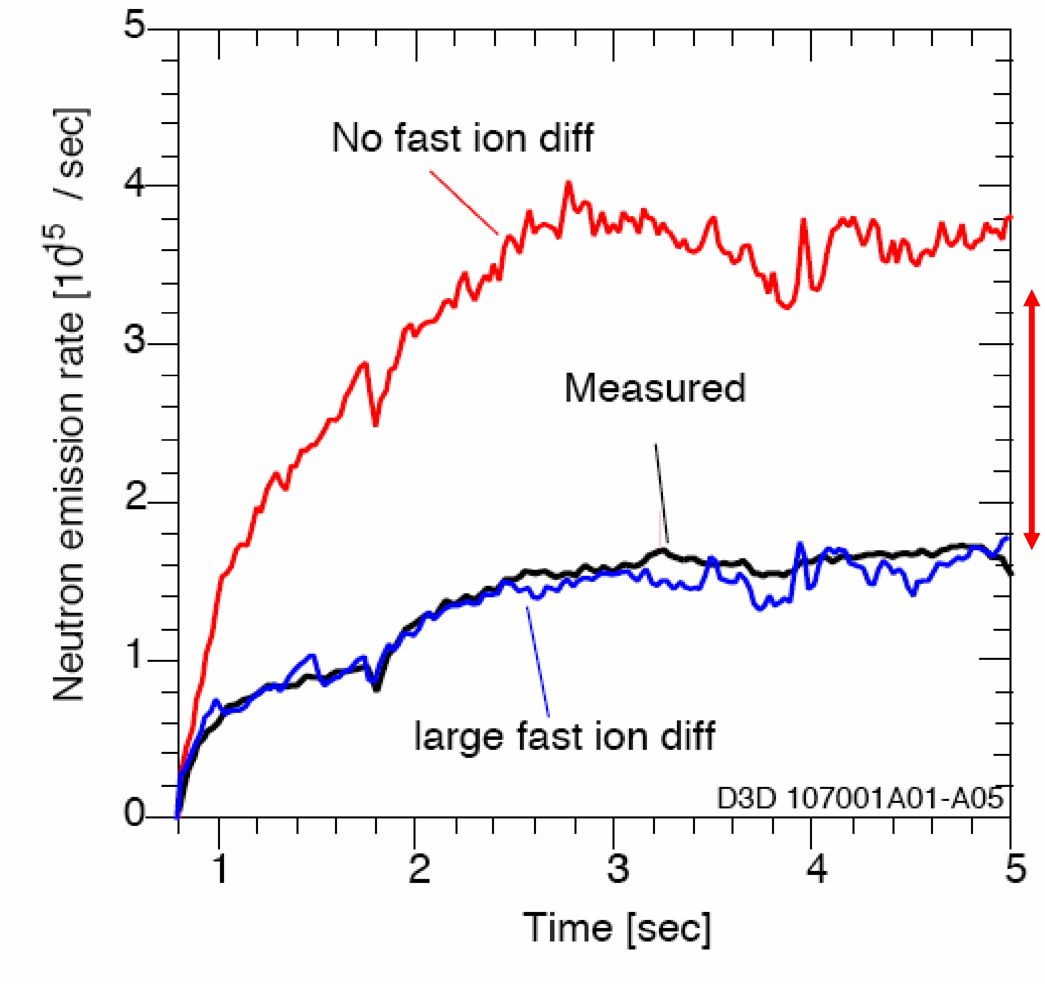
- Good agreement between RSAE theory and observed frequencies
- Theory predicts frequency gaps where no modes exist
- RSAE stability agrees with mode observation

A “Sea of Core Localized Alfvén Eigenmodes” Observed in DIII-D Plasmas Driven by 80 keV Neutral Beams



- Bands of RSAE-TAEs: *l=0, 1, 2, …* : $\omega_{n+1}-\omega_n \approx \omega_{rot}$ (CER)
- Neutral beam injection opposite to plasma current: $V_{||} \approx 0.3V_A$
- 8 <n< 40, k_θ up to 2.0 cm^{-1} (Turbulent scale length !!)

Can the neutron deficit in DIII-D be attributed to a "Sea of Alfvén Eigenmodes"?



TRANSP

Modeling
requires
80% beam
ion density
reduction
on axis

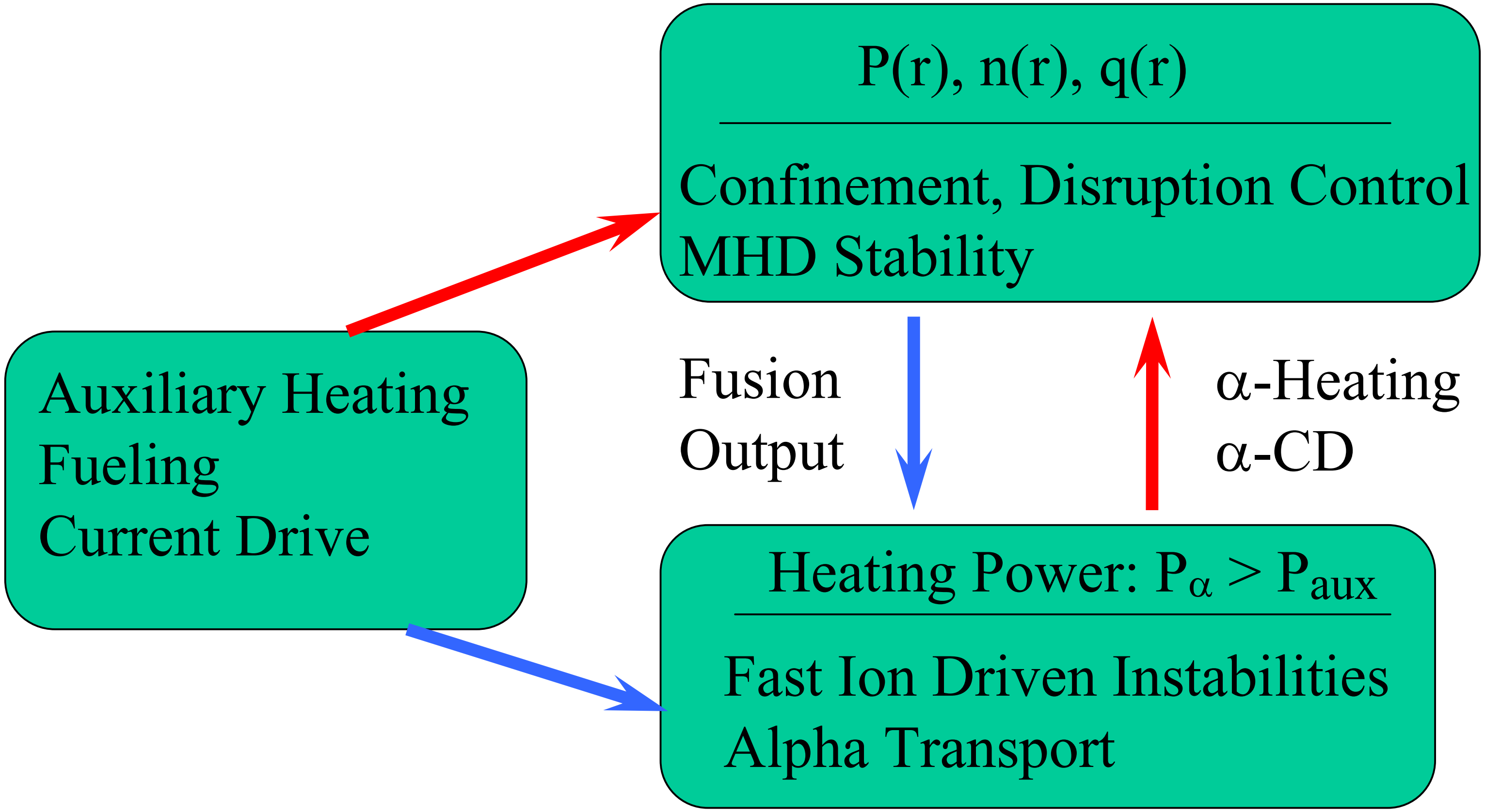
- Need fast ion profile measurements!

Fast Ion Transport due to TAEs

- TAEs with a wide spectrum of n are expected to be unstable in burning plasmas.
- TAEs induces particle drift orbit islands in phase space. Fast ions in drift orbit islands are lost to the first wall if drift orbit islands overlap with the prompt loss domain with a transient loss rate ~ $(\delta B_r/B)^{1/2}$.
- When multiple TAEs are excited, stochastic diffusion loss can occur if multiple drift orbit islands overlap and if particles can diffuse stochastically into the prompt loss domain.
- Stochastic loss rate ~ $(\delta B_r/B)^2$ if TAE amplitude exceeds orbit stochastic threshold of $\delta B_r/B \sim 10^{-3}$ for single TAEs and ~ 10^{-4} for multiple TAEs.
- Alpha loss due to multiple TAEs in burning plasmas could be ssignificant.

Integration of Burning Plasmas Physics

α interaction with thermal plasmas is a strongly nonlinear process.



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Heating Power: $P_\alpha > P_{aux}$

Fast Ion Driven Instabilities
Alpha Transport

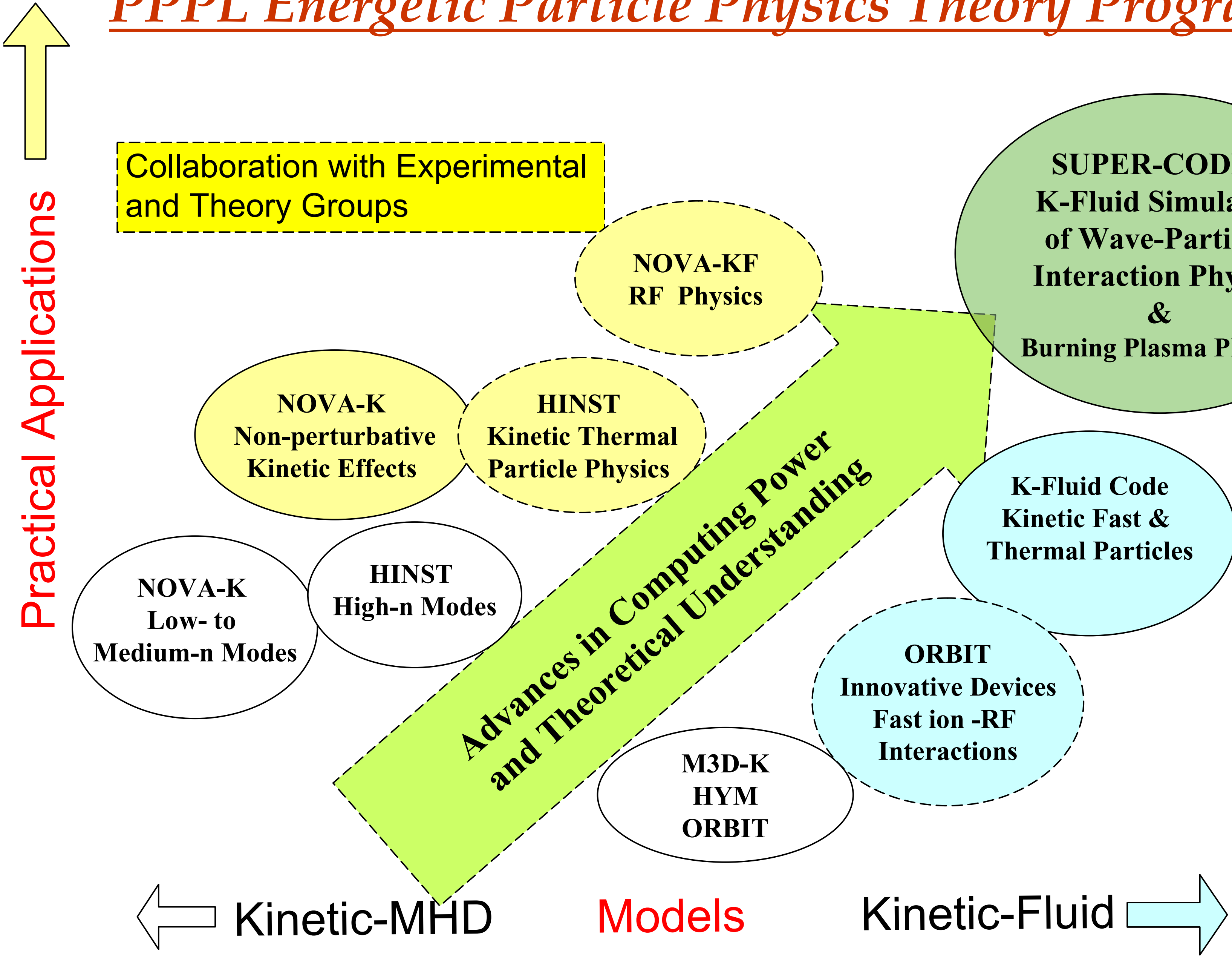
Must develop efficient methods to control profiles for burn control!

Nonlinear Model of Energetic Particle Physics

- Multiscale Coupling: The difficulty of theoretical modeling fast ion physics stems from the disparate scales which traditionally are analyzed separately; global-scale phenomena are generally studied using MHD, while microscale phenomena of both thermal and fast particles are described with kinetic theories.

➔ Need a hybrid kinetic-fluid model that treats kinetic physics of both thermal and fast particles in global phenomena.

PPPL Energetic Particle Physics Theory Program



Practical Applications

Collaboration with Experimental and Theory Groups

NOVA-KF
RF Physics

SUPER-CODES
K-Fluid Simulation of Wave-Particle Interaction Physics
&
Burning Plasma Physics

NOVA-K
Non-perturbative Kinetic Effects

HINST
Kinetic Thermal Particle Physics

K-Fluid Code
Kinetic Fast & Thermal Particles

NOVA-K
Low- to Medium-n Modes

HINST
High-n Modes

Advances in Computing Power and Theoretical Understanding

ORBIT
Innovative Devices
Fast ion -RF Interactions

M3D-K
HYM
ORBIT

Kinetic-MHD Models Kinetic-Fluid

Summary

- Energetic particle physics is an integral part of burning plasma physics – in particular, burning physics integration.
- Fast ion instabilities and transport is the most critical issue of energetic particle physics.
- Several fast ion driven instabilities have been identified. For fast ion transport,TAEs are potentially most serious.
- Close interaction between theory and experiment has yielded significant progress in understanding energetic particle physics. However, burning plasma physics integration has not been performed.
- Toward the goal of operating an efficient fusion reactor, the next step device should be one that produces burning plasmas for at least several energy confinement times and has sufficient capability of plasma profile control ==> ITER.