Coupled Tearing and Internal Kink Modes and Their Effect on Fast Ion Transport in NSTX

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October 29, 2020

Observed Synergy of MHDs in Fast Ion Transport

- Kink and tearing modes can be destabilized simultaneously [1]
  - Coupled in-phase [2], frequencies tied to that of island rotation [3]
  - Cause core rotation flattening [4]
  - Induce fast ion transport [4] which is found to be synergistic [5]

- Kick model [6] is used to understand the synergistic fast ion transport by coupled kink and tearing modes
  - Can lead to improved current drive calculation

[1] Fredrickson, PoP **9** 548 (2002)
[2] Gerhardt *et al.*, NF **51** 073031 (2011)
[3] Bando *et al.*, PPCF **61** 115014 (2019)
[4] Menard *et al.*, NF **45** 539 (2005)
[5] Liu *et al.*, NF **60** 112009 (2020)
[6] Podestà *et al.*, PPCF **56** 055063 (2014)

Outline

- Experimental Setup
  - Mode identification
  - Kick model
- Kick Model Validation
- Synergistic Fast Ion Transport
  - Formation of transport channel
  - Stochastic transport by island overlap
  - Interaction of kink/tearing modes with fast ion distribution
- Conclusion

# MHD Induced Fast Ion Transport is Observed in NSTX

- Fast ion transport with MHD
  - Indicated by neutron rate drop
  - No ELM or other modes
  - Core ion temperature drops/ Core rotation flattens

- MHDs have same frequency
  - Kink mode at core[†]
  - Tearing mode at q = 2 surface
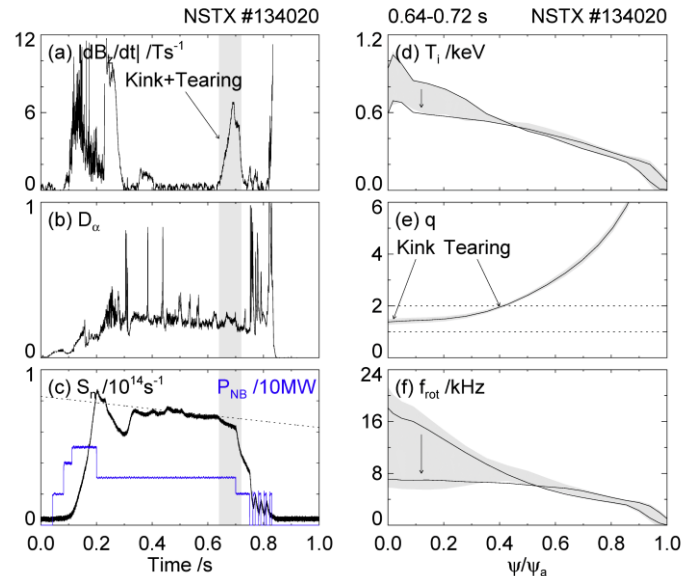
† Non-resonant (q_{min} = 1.33 from MSE+EFIT)

SXR Identifies MHDs as Kink and Tearing Modes

- Phase jumps indicate modes
  - Three π-jumps are observed
  - One for kink, two for tearing [1]

- Synthetic diagnostics
  - Mirnov coil array
  - CHERS (plasma rotation) [2]
  - Soft X-ray measurements [3]
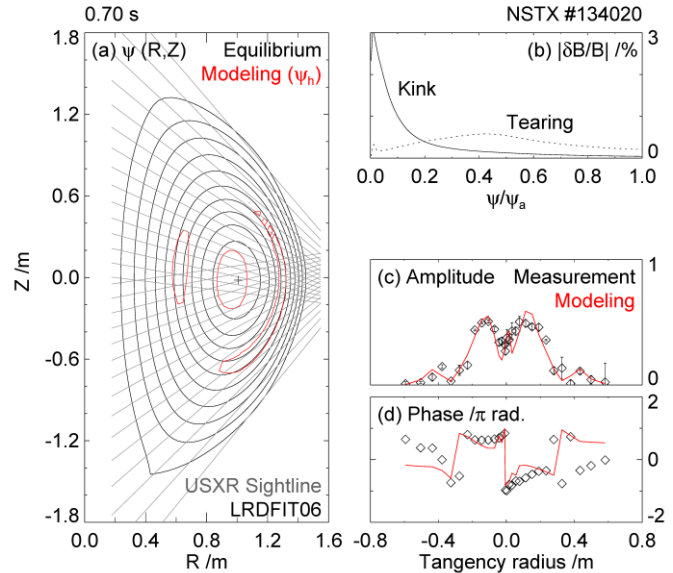
[1] Fredrickson *et al.*, RSI **59** 1797 (1988)
[2] Bell *et al.*, PoP **17** 082507 (2010)
[3] Stutman *et al.*, RSI **74** 1982 (2003)

- Kink mode displacement

$$\xi = \delta/[1 + (r/r_k)^p]\cos\theta_k$$

- Tearing mode perturbed helical flux

$$\delta\psi_{m,n} = w^2(16r_s/sB_\theta)\cos\theta_s$$

- Seven parameters marked in red are used in multi-curve fitting
- Equilibrium emissivity profile† is used to convert perturbed fields to perturbed emissivity
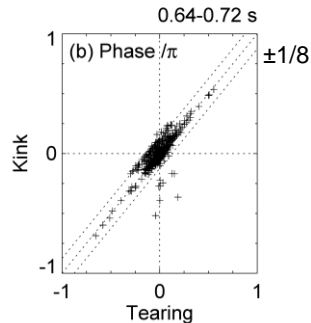
[1] Fredrickson *et al.*, RSI **59** 1797 (1988)
† Measured emissivity minus perturbed emissivity, then inversion
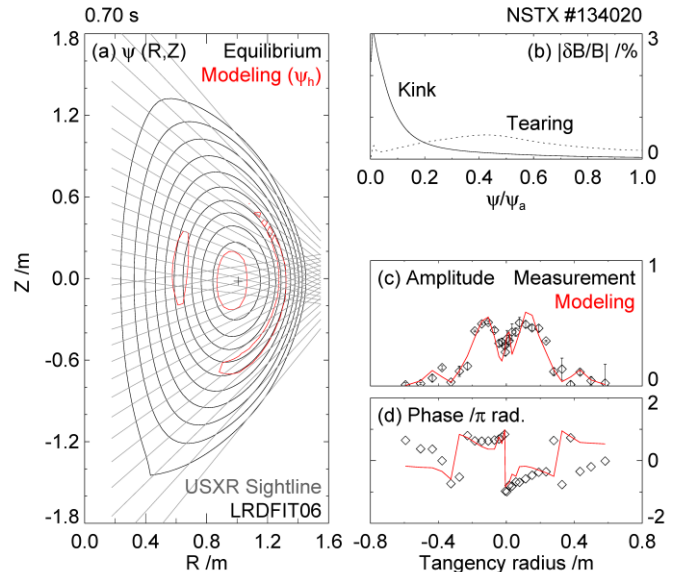
Kink and Tearing Modes are Coupled to Each Other

- Modes are coupled together
  - Fixed relative phase $\Delta\theta = 0$[†]
  - Proportional amplitudes[‡]
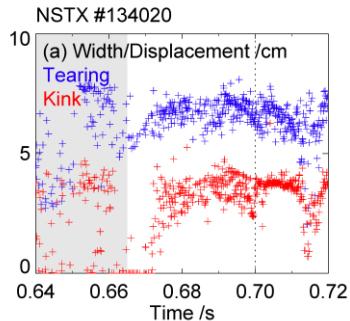
$\sigma_{XY}/\sigma_X\sigma_Y = 0.65$ $\sigma_{XY}/\sigma_X\sigma_Y = 0.83$

† With uncertainty of 5σ within ±π/8 radians or 22.5°
‡ Except for when tearing mode islands are smaller than SXR chord spatial resolution (5 cm)

Kick Model is Used for Time Dependent Simulation

- Kick Model is how we operate NUBEAM [1]
  - Fast ion distributions are computed based on…
    - Classical model: Collisional scattering, slowing down, atomic reactions
    - Kick model: Classical model plus the effects of instabilities

- Effect of instabilities is computed using ORBIT [2]

- Self-consistent, time-dependent simulation by TRANSP [3]

[1] Pankin *et al.*, CPC **159** 157 (2004)
[2] White and Chance, PoF **27** 2455 (1984)
[3] Breslau *et al.*, doi:10.11578/dc.20180627.4

Input #1: Mode Amplitude Evolution

- Time dependent simulation requires time evolution of mode amplitudes

- Island may be smaller than SXR resolution
  - Island width is $w^2 = g(r b_r q / m B_\theta q')$ [1] where $b_r \approx (1/2)(r_w/r)^{m+1} b_\theta$ [2]
  - Mirnov coil signal b_θ is used to compute w
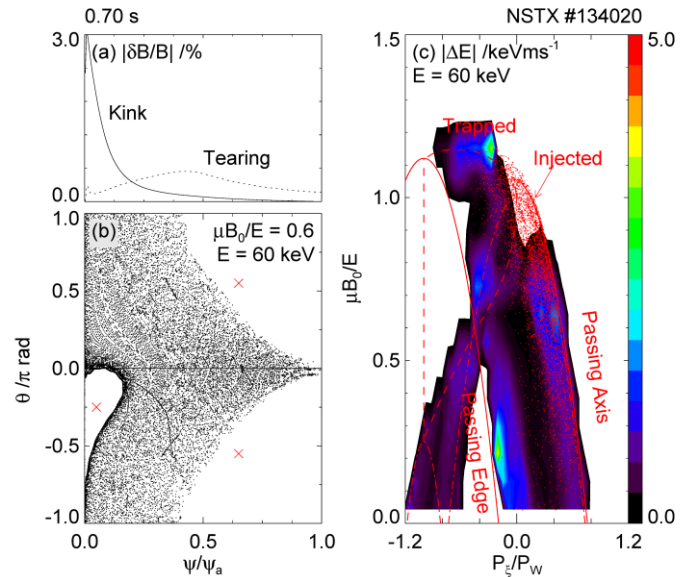 - Constant g is found by scaling with SXR results

NSTX #134020
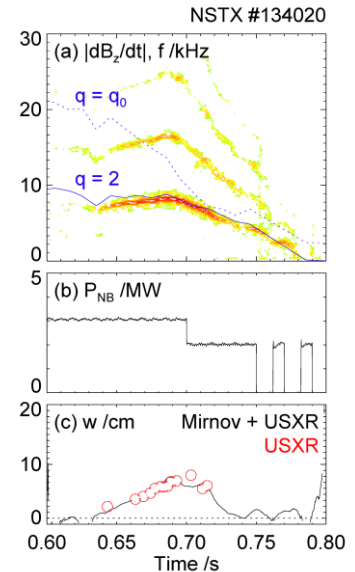
[1] Chang *et al.*, NF **34** 1309 (1994)
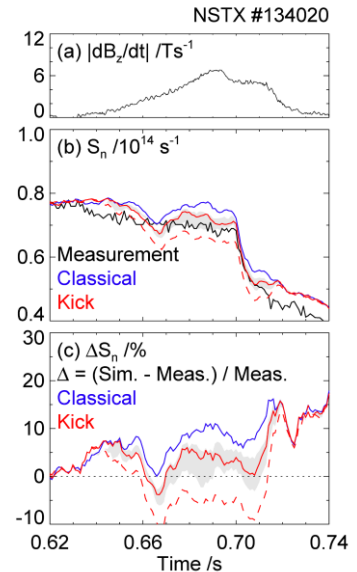[2] La Haye *et al.*, PoP **7** 3349 (2000)

- Time dependent simulation requires kick probability

- Kick is the energy transfer
  - Computed by ORBIT
  - Kink modes $\boldsymbol{\delta B} = \boldsymbol{\nabla} \times (\boldsymbol{\xi} \times \boldsymbol{B})$
  - Tearing mode $\boldsymbol{\delta B} = \boldsymbol{\nabla} \times \alpha \boldsymbol{B}$ where $\alpha \propto \psi_{m,n}$ [1]
    - Converted to ξ expression [2]

[1] Bardoczi *et al.*, PPCF **61** 055012 (2019)
[2] White, PoP **20** 022105 (2013)

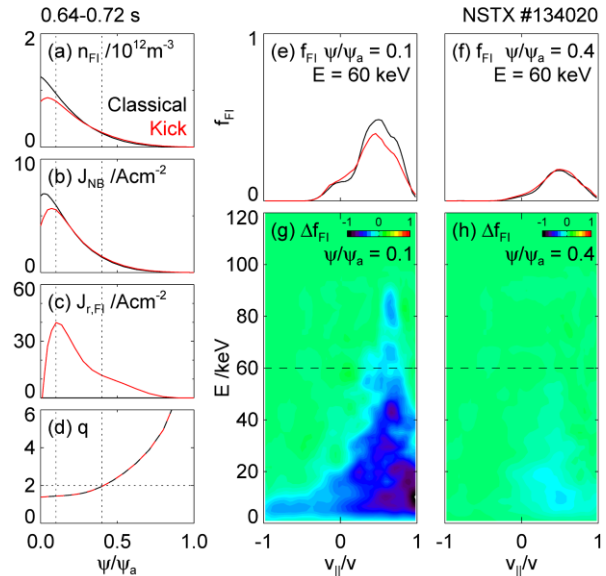# Kick Model is Valid for *Coupled* Kink and Tearing Modes

- ## Neutron rate is used as proxy to test models
  - ### Classical[†]: Underestimates fast ion transport
  - ### Kick[‡]: Agrees within measurement uncertainty
    - **Solid: Coupled kink and tearing modes**
    - **Dashed: Sum of individual kink and tearing modes, which overestimates fast ion transport**

NSTX #134020

(a) $|dB_z/dt|$ /Ts^{-1}

(b) S_n /10^{14} s^{-1}

Measurement
Classical
Kick

(c) ΔS_n /%
Δ = (Sim. - Meas.) / Meas.
Classical
Kick

Time /s

† Classical: Collisional scattering, slowing down, atomic reactions
‡ Kick : Classical model plus the effects of instabilities

Fast Ion Transport Causes Neutron Rate Drop

- Fast ion distribution is output
  - Core fast ions are depleted
  - Core current drive is reduced
  - Radial flow of fast ions is clear
  - Fast ion distribution at $q = 2$ surface is unchanged

- Consistent with previous slide
 - Neutrons originate mostly at core

How does the synergy take effect?

- Summary for the previous part
  - Coupled kink and tearing modes are identified by synthetic diagnostics with soft X-ray measurements
  - Kick model simulation shows coupled kink and tearing modes affect the fast ion transport synergistically

- Theories for the synergistic fast ion transport
  - Islands from both modes could form transport channel for fast ions
  - Islands from both modes could overlap and cause stochastic transport

Islands′ Alignment Could Cause Synergy

- Fast ion transport reacts to numerical scan of relative phase
  - More transport as $\Delta\theta = 0 \rightarrow \pi/2$
  - This means more transport with island O-points *mis*-aligned
  - Could be because finite time is required for fast ions to travel

- Alignment of islands could affect fast ion transport
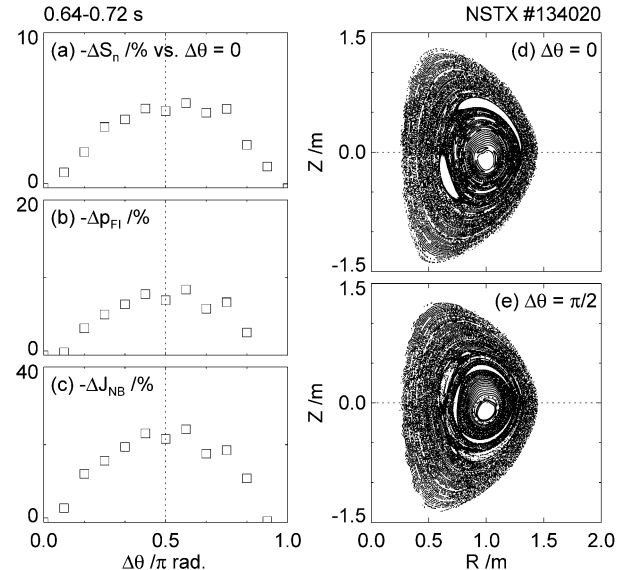
Islands' Overlap Could Cause Synergy

- Fast ion transport reacts to numerical scan of island width
  - More transport as w increases
  - Known to be due to mode overlap & stochastic orbits [1]
  - Kink island could replace resonance with core drift orbits

- Overlap of islands could affect fast ion transport
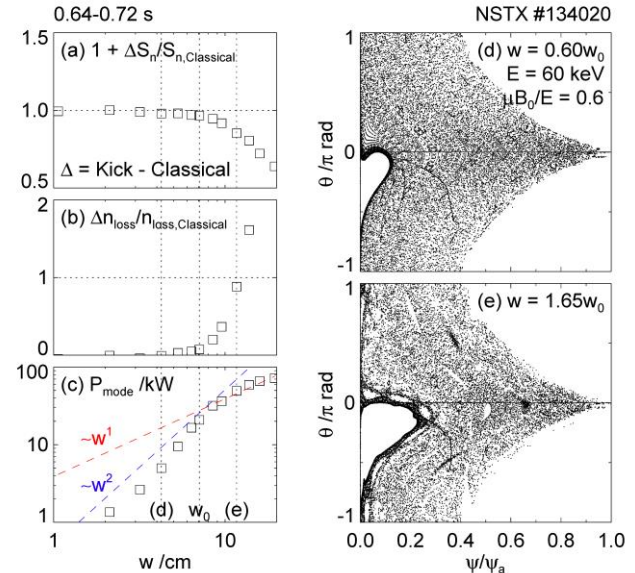
[1] Mynick, PoFB **5** 1471 (1993)

Fast Ions May Take Part in Kink/Tearing Mode Stability

- Island saturates at stochasticization threshold
  - Islands grow larger when kink stable [1]
  - Each other's presence make kink/tearing modes interact differently with fast ions [2]

- However, *no* mode chirping
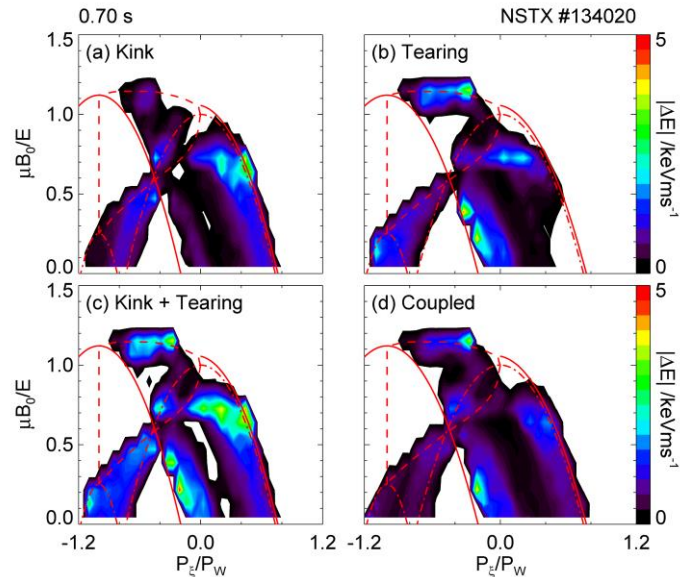
[1] Bardoczi *et al.*, PPCF **61** 055012 (2019)
[2] Liu *et al.*, NF **60** 112009 (2020)

Conclusion and Future Work

- Coupled kink/tearing modes are synergistic in fast ion transport
- Two theories are supported by numerical scans
  - Fast ion transport channel forming from axis to q = 2 surface
  - Mode overlap resulting in stochastic transport

- Mode stability could be affected by modes/fast ions interaction
  - First principle codes such as M3D-C^1(K) [1] will be used
- New experimental capabilities available with NSTX-U [2]

[1] Breslau *et al.*, PoP **16** 092503 (2009)
[2] Menard *et al.*, NF **52** 083015 (2012)

Reference

1) Fredrickson, Phys. Plasmas **9** 548 (2002)
2) Gerhardt *et al*., Nucl. Fusion **51** 073031 (2011)
3) Bando *et al*., Plasma Phys. Control. Fusion **61** 115014 (2019)
4) Menard *et al*., Nucl. Fusion **45** 539 (2005)
5) Liu *et al*., Nucl. Fusion **60** 112009 (2020)
6) Podestà *et al*., Plasma Phys. Control. Fusion **56** 055063 (2014)
7) Bell *et al*., Phys. Plasmas **17** 082507 (2010)
8) Stutman *et al*., Rev. Sci. Instrum. **74** 1982 (2003)
9) Fredrickson *et al*., Rev. Sci. Instrum. **59** 1797 (1988)
10) Chang *et al*., Nucl. Fusion **34** 1309
11) La Haye *et al*., Phys. Plasmas **7** 3349
12) White and Chance, Phys. Fluids **27** 2455 (1984)
13) Pankin *et al*., Comput. Phys. Commun. **159** 157 (2004)
14) Breslau *et al*., [Computer Software] doi:10.11578/dc.20180627.4
15) White, Phys. Plasmas **20** 022105 (2013)
16) Bardoczi *et al*., Plasma Phys. Control. Fusion **61** 055012 (2019)
17) Mynick, Phys. Fluids B **5** 1471 (1993)
18) Breslau *et al*., Phys. Plasmas **16** 092503 (2009)
19) Menard *et al*., Nucl. Fusion **52** 083015 (2012)

Acknowledgement

Abstract

One aspect of the interaction between fast ions and magnetohydrodynamic (MHD) instabilities is the fast ion transport. Coupled kink and tearing MHD instabilities have also been reported to cause fast ion transport. Recently, the "kick" model has been developed to compute the evolution of the fast ion distribution from the neutral beam injection using instabilities as phase space resonance sources. The goal of this paper is to utilize the kick model to understand the physics of fast ion transport caused by the coupled kink and tearing modes. Soft X-ray diagnostics are used to identify the mode parameters. The comparison of measured neutron rates and those computed from time-dependent TRANSP simulation with the kick model shows the fast ion transport is due to the coupled kink and tearing modes, not the simple sum of individual modes. The numerical scan of the mode parameters show that the relative phase of the kink and tearing modes affect the fast ion transport, and that the overlapping kink and tearing mode resonances in the phase space can cause the fast ion transport to be stochastic, suggesting that the synergy of the coupled modes may be causing the fast ion transport.

Preparation of Perturbed Emissivity Data

- Emissivity is measured by filtered pinholes
  - Be 5 μm filter, USXR range (10 – 300 Å)
  - Fast time response, limited to < 100 kHz by preamps
- Numerical band pass filter is applied
  - Pass band set at mode frequency ± 10%
- Numerical periodic averaging is applied
  - Find zero-crossings and accumulate
  - For further reduction of measurement noise
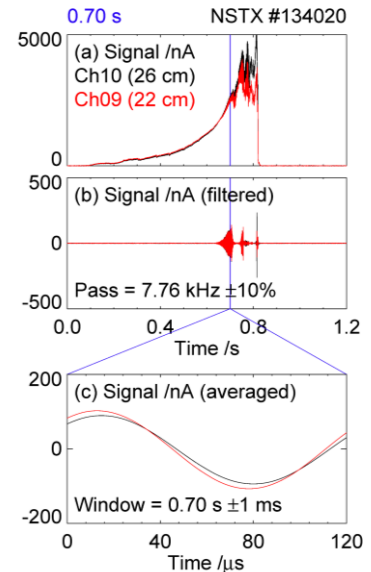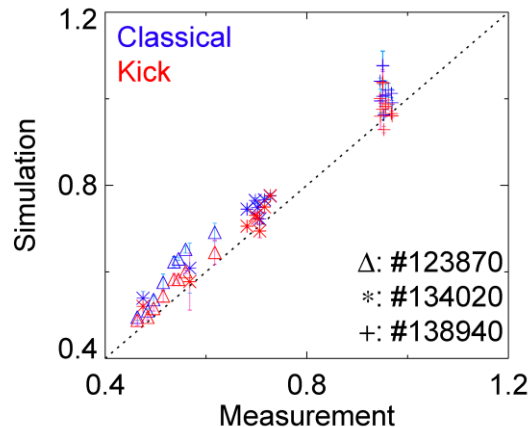
Inclusion of instability with kick model contributes
to improved estimation of measured neutron rate evolution