NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
Fusion Energy Sciences

J. Yang, M. Podestà, and E. Fredrickson

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

Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA 08543

NSTX-U / Magnetic Fusion Science meeting, Princeton, NJ (Apr. 27, 2020)

Motivation

- Low frequency modes affect tokamak operation
  - Confinement degradation [1-11], rotation slowing down [11-13], impurity transport [14]
  - Flux pumping [15]
- Fast ion interaction with kink mode is well known [10-13,16-23]
- Fast ion interaction with tearing mode is more theoretical than conclusive [25-45]
- Most works concern large aspect ratio [All but 10-13,22,23†]
- This paper studies coupled tearing and internal kink modes [11,28,32,46] and its effect on fast ions in NSTX

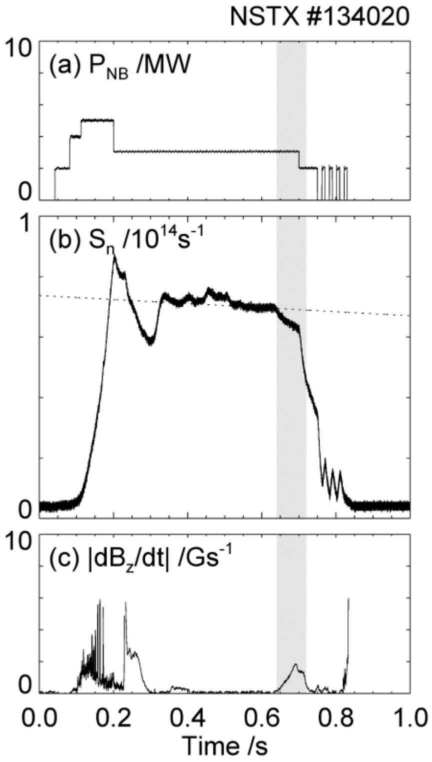
† On internal kink mode

Outline

- Low frequency modes appear to degrade confinement
- Synthetic soft X-ray measurement and “kick” model are implemented
- Fast ion transport by tearing and internal kink modes is modeled successfully
- Relative phase of the modes plays major role
- First principle modeling of multiple modes is needed for further analysis

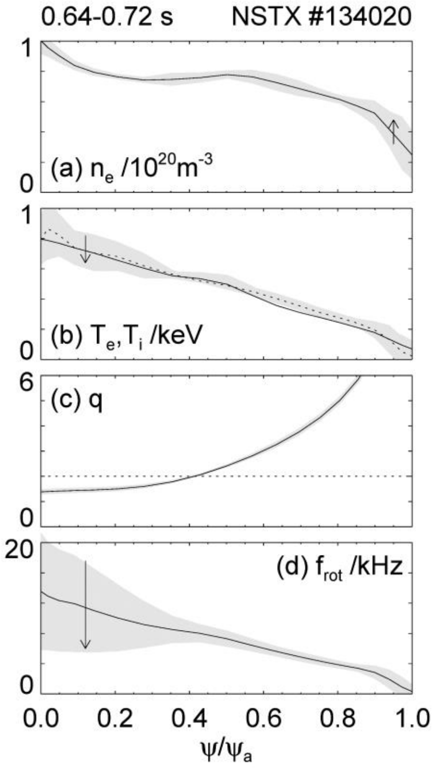
Low frequency modes affect confinement

- Instability
  - Onset at peak β_N while $q_{min} < 2$
  - Neutron rate drops 20%
    - Implies loss of fast ions
  - Mitigated by P_{NB} step down
- Other parameters
  - No ELMs or AEs
  - No mode locking (EF correction)
  - Li conditioned for reproducibility



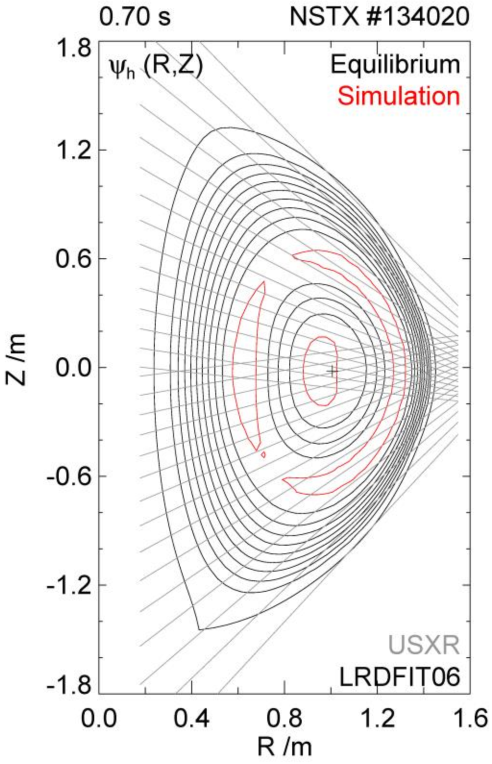
Low frequency modes affect core rotation

- Profiles
  - Unchanged q and density profile
  - Small drop in temperatures [49]
  - Large rotation slowing down at core (q < 2) [50]



Modes are identified as tearing & internal kink

- Synthetic SXR diagnostics†
  - Sampled at 5 MHz [52]
  - Simulated perturbations are fit to measured emissivity‡
  - Best fit with 2/1 tearing mode and core n = 1 kink mode
  - Best fit with modes coupled in phase



† See Appendix: Automation of [51]

‡ Equilibrium from LRDFIT (MSE constrained) [23,53]

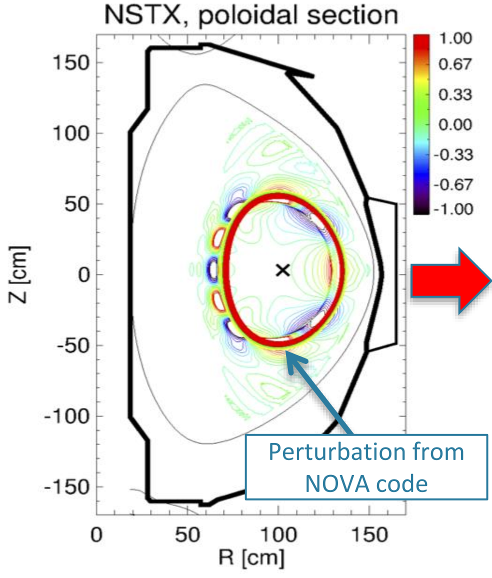
Kick model: particle-following ORBIT code used to infer transport matrix numerically

Initialize test particles uniformly in phase space

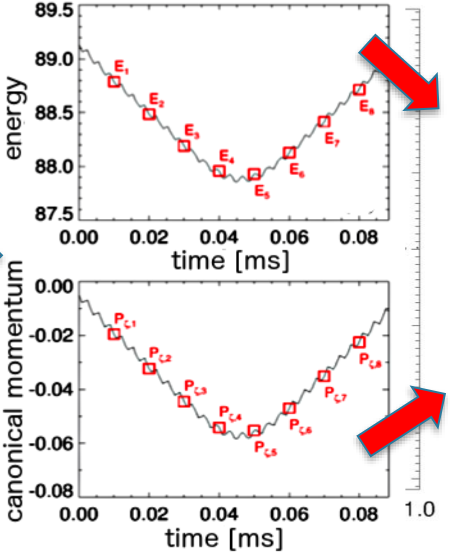
Track energy, momentum variations (*kicks*) at fixed time intervals

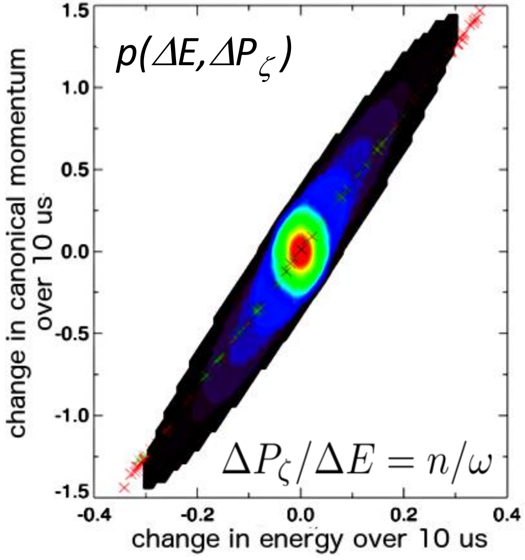
Combine ΔE, ΔP_ζ from same (E,P_ζ,μ) phase space *bin* into $p(\Delta E,\Delta P_\zeta)$

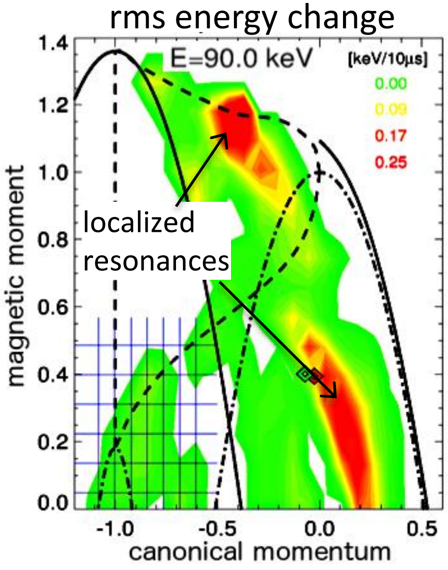
Repeat for all (E,P_ζ,μ) *bins* to infer 5D matrix -> input for NUBEAM: $p(\Delta E,\Delta P_\zeta|E,P_\zeta,\mu)$



Perturbation from NOVA code





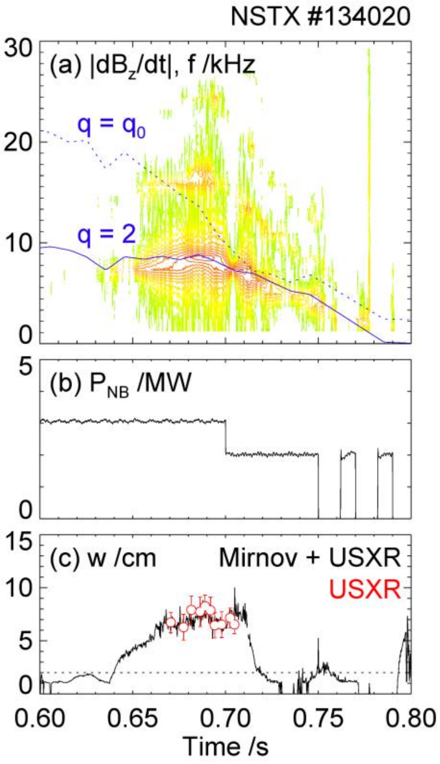


localized resonances

Podestà PPCF 2017

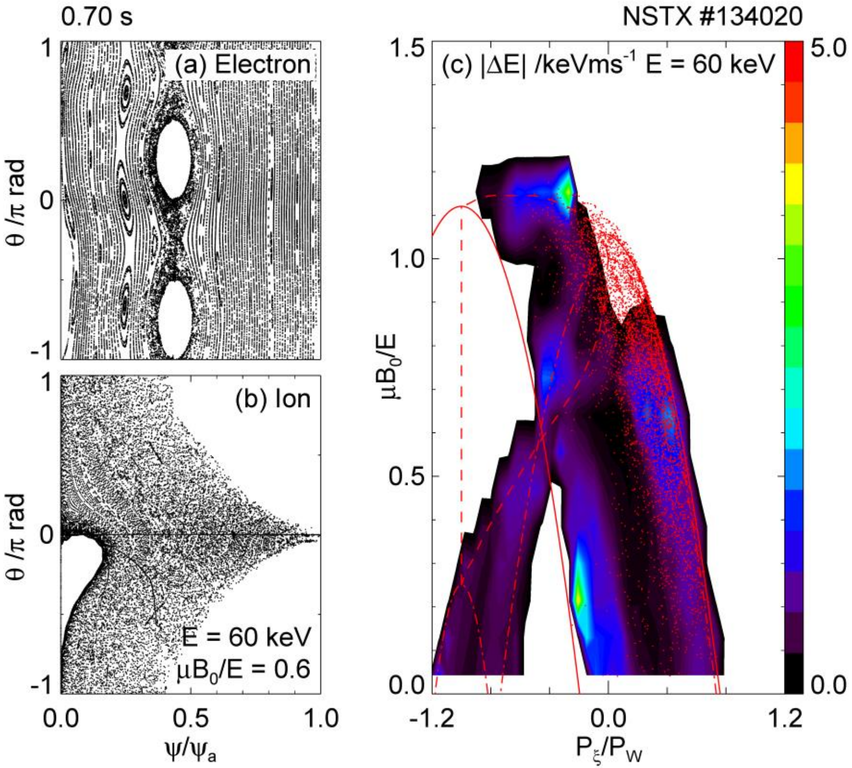
Fast ion confinement is modeled by “Kick” model

- “Kick” model [54]
  - Mode structure and amplitude
    - Experimental input
    - Mirnov coil signals scaled with synthetic SXR fits
  - ORBIT computes fast ion transport probability [55]
  - Input to NUBEAM / TRANSP [56,57]



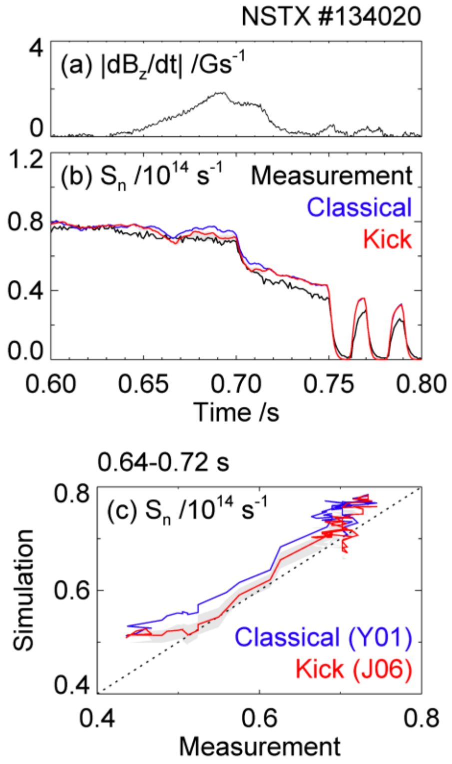
Resonant island appears near core for fast ions

- "Kick" probability
  - Fast ions occupy core co-passing orbits
  - ORBIT: "Kick" for fast ions is localized near core and boundary
    - Core: Resonant island
    - Boundary: Tearing mode island
  - Deposited fast ions are kicked out from core region (= transport)



Simulation improved with inclusion of "Kick"

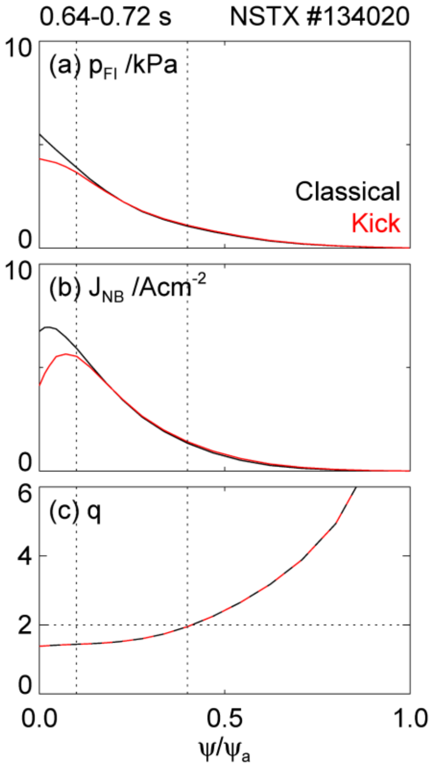
- Neutron rates
  - Fast ions create neutrons
  - NUBEAM computes fast ion dynamics from classical factors†
  - Kick model adds the effect of instabilities
  - Measured neutron rate [59] recovered by simulation with instabilities



† Atomic physics, Coulomb collision and finite orbit effects, but not instabilities [58]

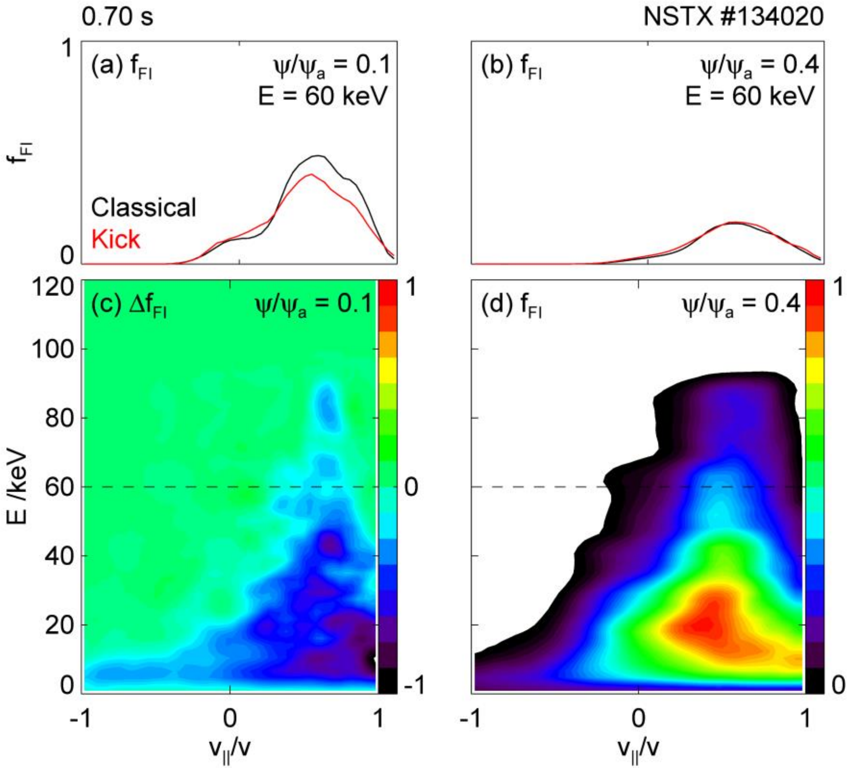
Transport is localized near resonance island

- Fast ion profiles
  - Fast ion pressure drops with kick
  - Neutral beam driven current drive drops with kick
  - Region of drop is near core
  - More interaction with resonant than tearing mode islands



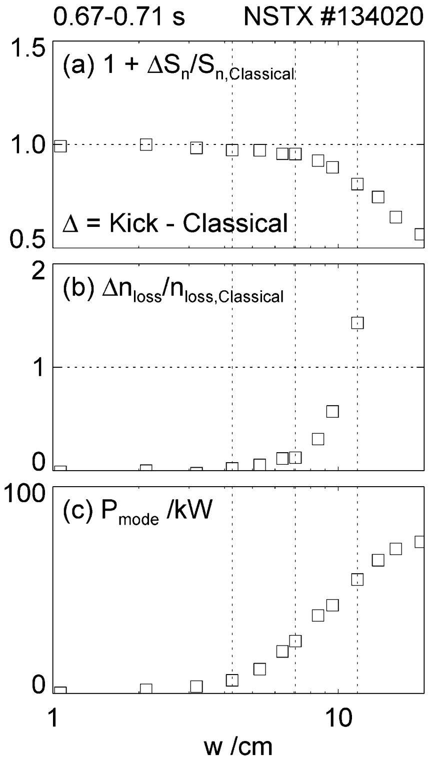
Depletion is core-localized in fast ion distribution

- Fast ion distribution
  - Extends to 90 keV (E_{inj})
  - Near core, kick depletes fast ions
  - Distribution near q = 2 surface is practically unchanged
  - As a result, weighted integrals of distribution drop primarily near core [24]



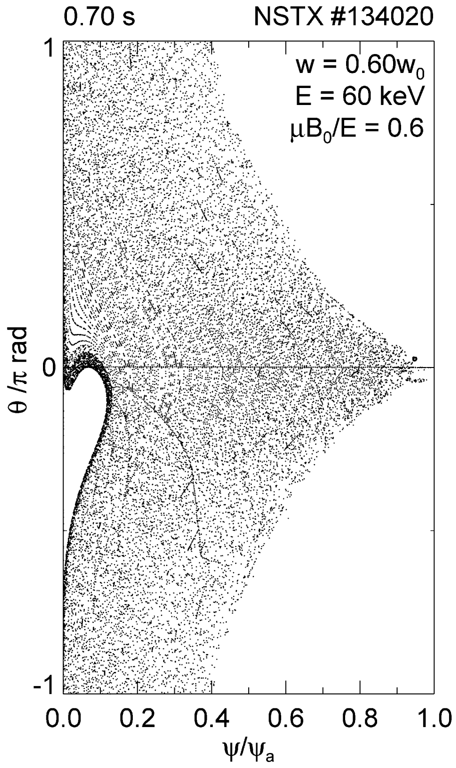
Transport surges at over-threshold island width

- Island width scan
  - Experimental values:
    - Island width 7 ± 1 cm
    - Kink displacement 5 ± 2 cm
  - Scanned proportionally
  - Threshold island width exists for neutron rates and losses [31]



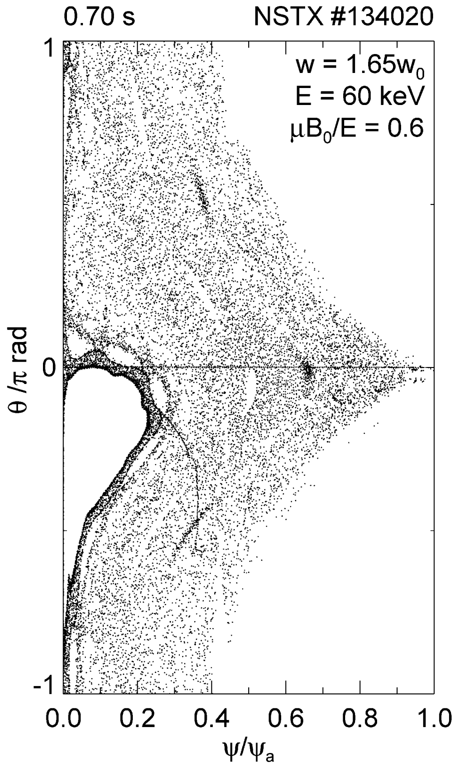
Islands > threshold turn flux surfaces chaotic (1/2)

- Poincaré plots
  - Fast ion trajectory after round trip
  - Flux surfaces are layered for islands < threshold
  - Flux surfaces become chaotic for islands > threshold [47,48]



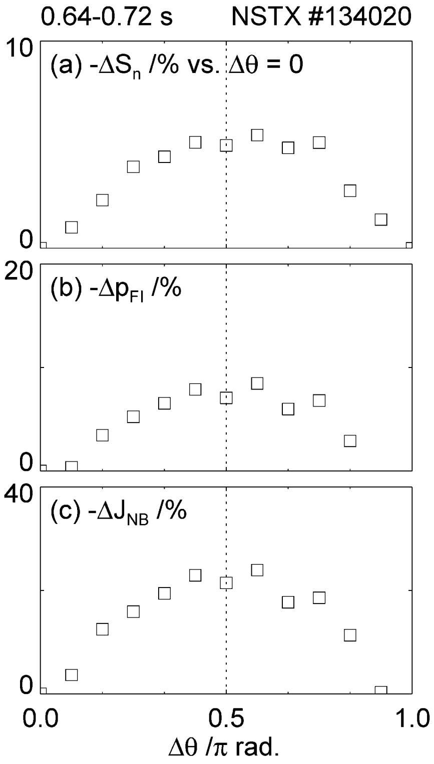
Islands > threshold turn flux surfaces chaotic (2/2)

- Poincaré plots
  - Fast ion trajectory after round trip
  - Flux surfaces are layered for islands < threshold
  - Flux surfaces become chaotic for islands > threshold [47,48]



Transport is sensitive to relative phase of modes

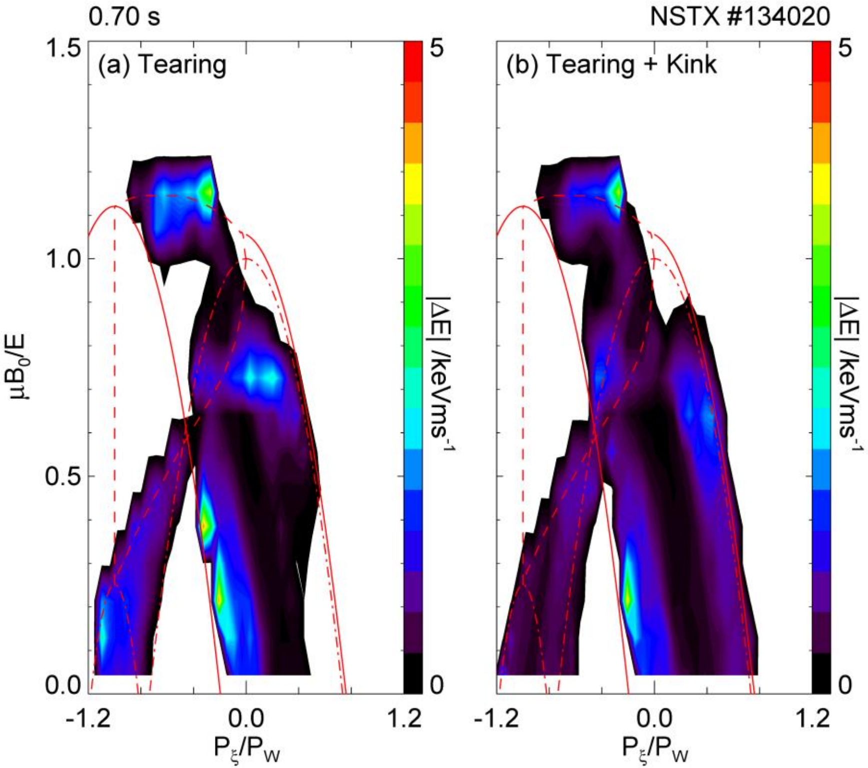
- Relative phase scan
  - Experimental relation
    - In phase†
  - Scanned for period
  - More fast ion transport than measurement when out of phase



† Fixed relative phase: Islands aligned at midplane when core displaced to high field side [46]

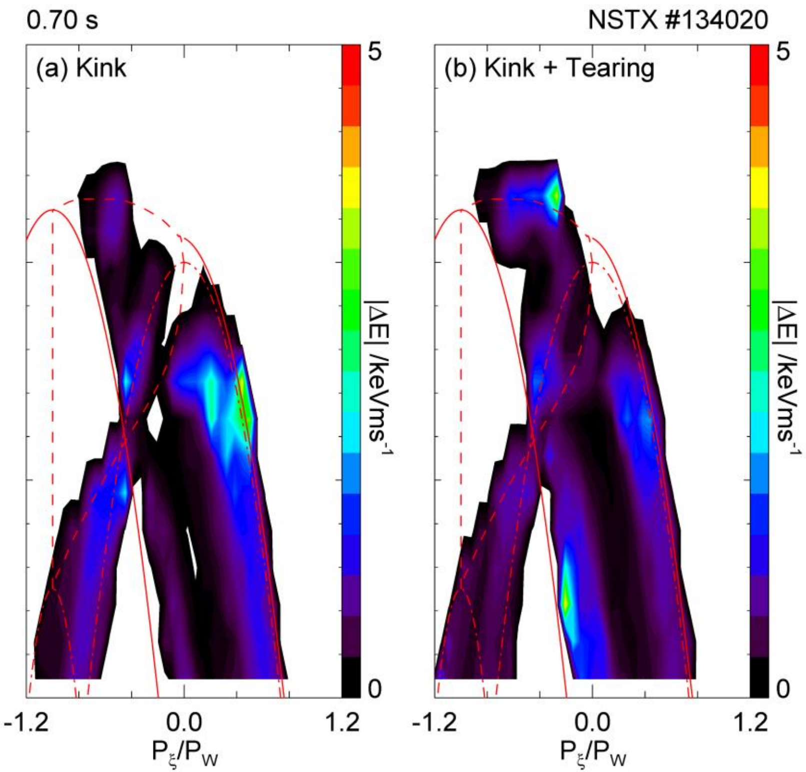
Fast ion distribution impacts mode coupling (1/2)

- Mode coupling
  - Kick probability from tearing mode changes when internal kink mode is added [32]
  - Same for internal kink mode [32]
  - Fast ion impacts mode coupling, but how significant is this?



Fast ion distribution impacts mode coupling (2/2)

- Mode coupling
  - Kick probability from tearing mode changes when internal kink mode is added [32]
  - Same for internal kink mode [32]
  - Fast ion impacts mode coupling, but how significant is this?



Conclusion

- Coupled tearing/internal kink modes is observed experimentally
- Fast ion transport by coupled modes is successfully interpreted by “kick” model
- Relative phase of modes plays major role in fast ion transport
- First principle modeling of multiple modes is needed for further analysis

Reference (inclusive)

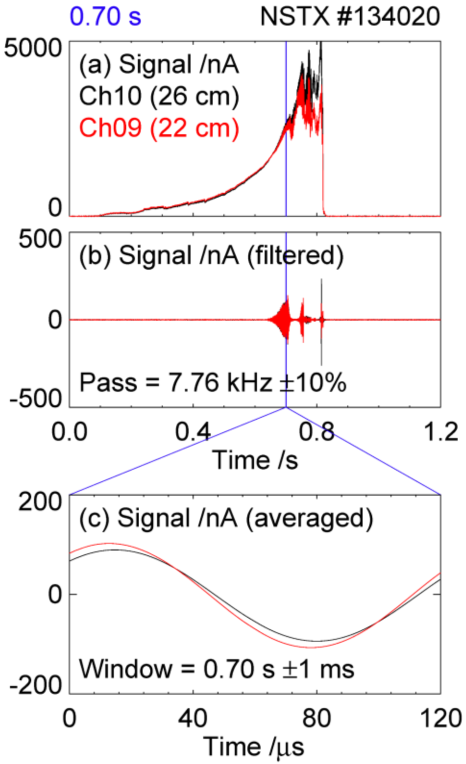
1) Heidbrink NF 34 535
2) Carolipio NF 42 853
3) Zweben NF 39 1097
4) Garcia-Munoz NF 47 L10
5) Gobbin NF 49 095021
6) Gunter PPCF 41 767
7) Chang NF 30 219
8) Poli PoP 15 032501
9) Zhang NF 55 113024
10) Cecconello PPCF 57 014006
11) Menard NF 45 539
12) Chapman NF 50 045007
13) Heidbrink NF 56 056006
14) Delgado-Aparicio NF 53 043019
15) Jardin PRL 115 215001
16) Chen PRL 52 1122
17) White PoF 28 278
18) Coppi PoFB 2 927
19) Porcelli PPCF 33 1601
20) Porcelli PPCF 38 2163
21) Borba NF 40 775
22) Pfefferle NF 54 012001
23) Menard PRL 97 095002
24) Heidbrink NF 58 082027
25) Forest PRL 79 427
26) Gude NF 39 127
27) Sesnic PoP 7 935
28) Frederickson PoP 9 548
29) Li PPCF 58 045012
30) Anderson PoP 20 056102
31) Bardoczi PPCF 61 055012
32) Liu NF in press (2020)
33) Konovalov SJPP 14 461
34) Mynick PoFB 5 2460
35) Mynick PRL 43 1506
36) Marchenko PoP 8 4834
37) Hegna PRL 63 2056
38) Cai PRL 106 076002
39) Cai PoP 19 072506
40) Cai NF 56 126016
41) Pritchard PoP 4 162
42) Brennan NF 52 033004
43) Halfmoon PoP 24 062501
44) Somlyakov PoP 2 1581
45) Wilson PoP 3 248
46) Bando PPCF 61 115014
47) White CNSNS 17 2200
48) Chirikov JNEC 1 253
49) LeBlanc, RSI 79 10E737
50) Bell, PoP 17 082507
51) Fredrickson RSI 1797
52) Stutman RSI 74 1982
53) Levinton, RSI 79 10F522
54) Podesta PPCF 56 055063
55) White PoF 27 2455
56) Pankin CPC 159 157
57) Hawryluk PoPTC 1 19
58) Goldston JCP 43 61
59) Roquemore, SOFE SP1-39

Appendix: Synthetic SXR diagnostics code

- GAUNTLET: Automated FALCON
  - Measured signals are periodically averaged
  - Low frequency modes are modeled analytically
  - Emissivity profile relates perturbation to signal
  - Fit is more sensitive to resolution than to noise
  - Fit is not sensitive to initial guess

Measured signals are periodically averaged

- USXR signal processing
  - Calibrated signals are taken
  - Filtered around mode frequency
  - Averaged each periods within fixed time window (±1 ms)
  - Amplitude and phase extracted



Low frequency modes are modeled analytically

- Eigenfunctions for low frequency instabilities
  - Tearing mode uses scaling law

$$w^2 = (16 r_s / s B_\theta)\psi$$

    to get helical flux

$$\psi_h = \left(\frac{B_0}{R_0}\right)\int_0^r \left(\frac{1}{q} - \frac{n}{m}\right) r dr + \psi \cos\zeta$$

    where $\zeta = m\theta - n\phi + \int_0^t \omega dt$

  - Kink mode uses analytic formula

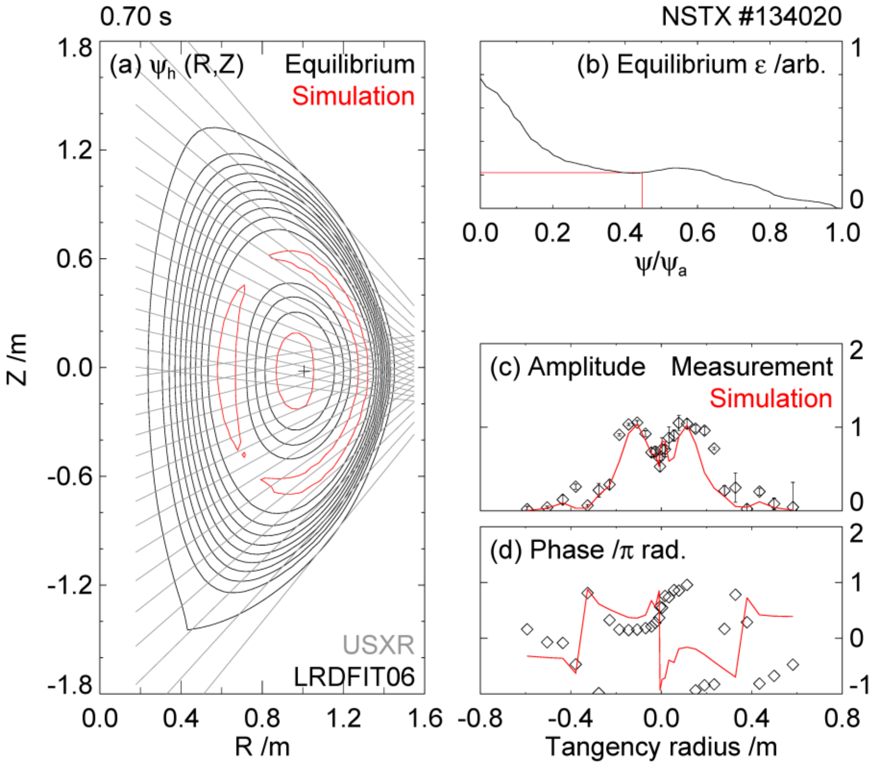
$$\xi = \delta / [1 + (a/r_k)^k]$$

    to get flux displacement

  - Flux translated with reconstructed equilibrium emissivity profile

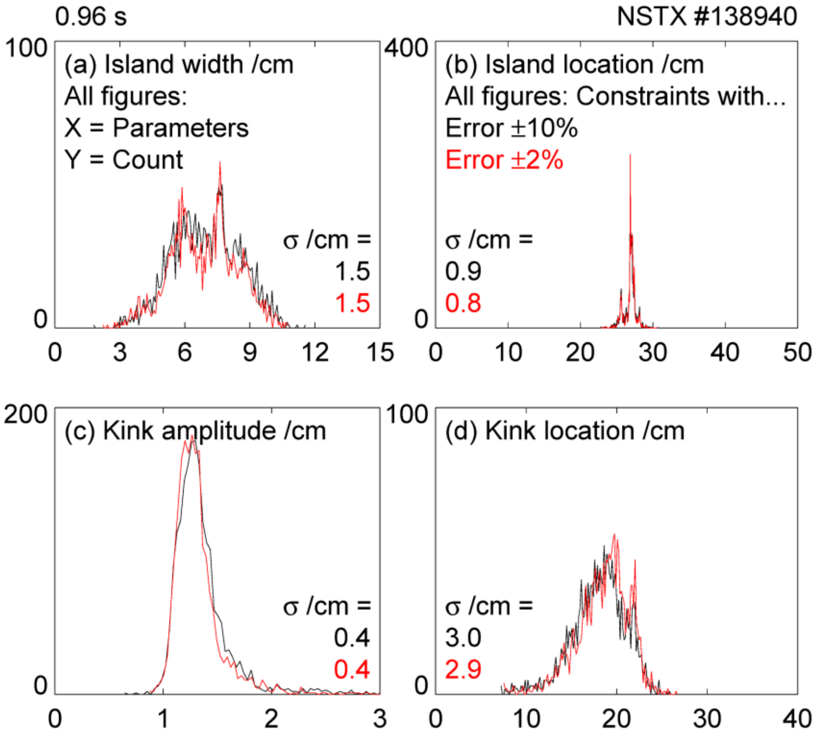
Emissivity profile relates perturbation to signal

- Soft X-ray tomography
  - Performed to the *equilibrium* emissivity
  - Provides relation of magnetic flux to emissivity
  - Analytic perturbed flux is converted to perturbed emissivity
  - Line-integrated to simulate signal and fit to the measurement



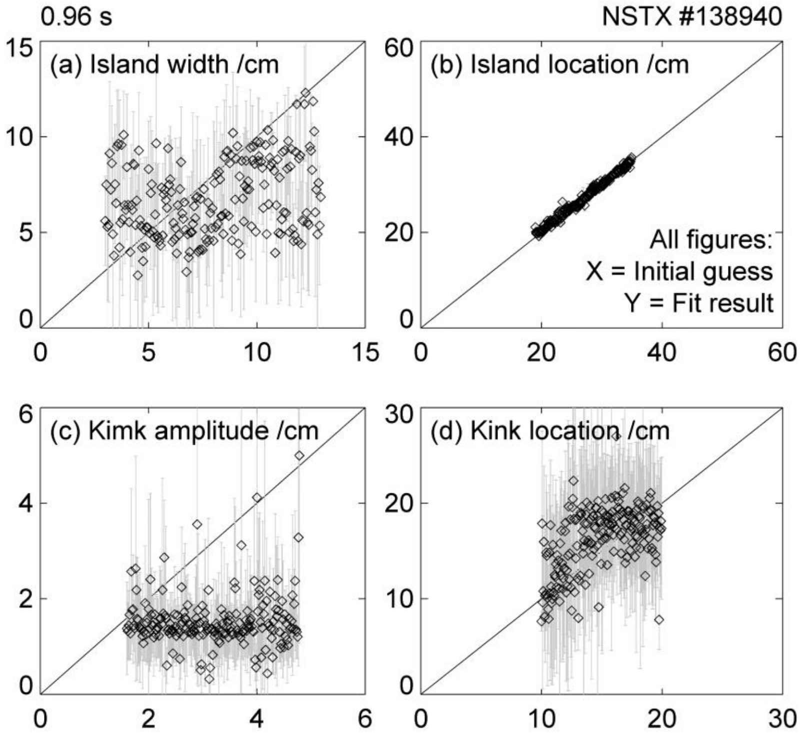
Fit is more sensitive to resolution than to noise

- Fit sensitivity to signal error
  - Nominal signal error is 2%
  - Fit uncertainty is small up to signal error of 10%;
    Island width uncertainty < spatial resolution
  - Similar fit uncertainty for increasing signal error implies that fit algorithm is robust



Fit is not sensitive to initial guess

- Fit sensitivity to initial guess
  - Fit needs initial guess
  - Box scatter means fit result is independent of initial guess within error bars
  - Most can use any initial guess
  - Island location initial guess is provided from Mirnov coil, EFIT and CHERS



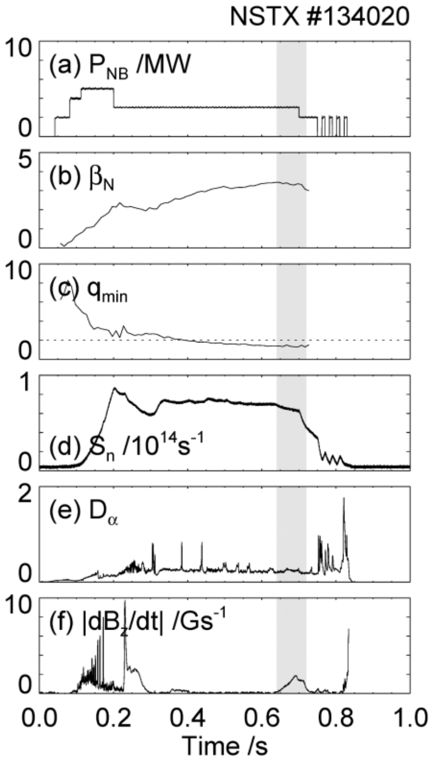
All figures:
X = Initial guess
Y = Fit result

Backup

- Original figures
- Backup slides

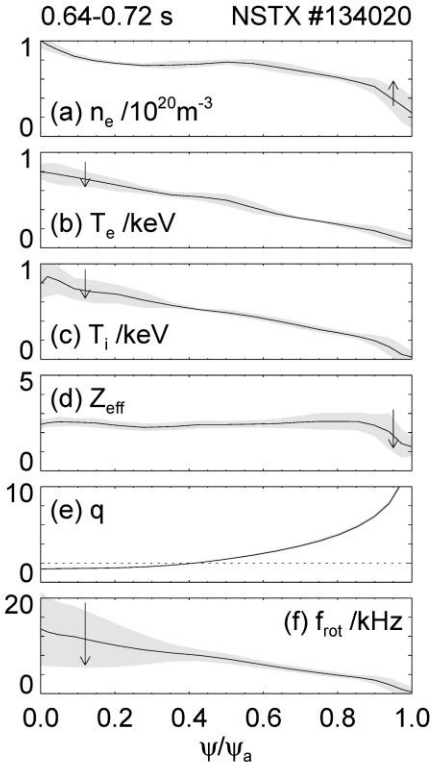
Low frequency modes affect confinement

- Instability
  - Onset at peak β_N while $q_{min} < 2$
  - Neutron rate drops
  - Mitigated by P_{NB} step down
- Other parameters
  - No ELMs or AEs
  - No mode locking (EF correction)
  - Li conditioned for reproducibility



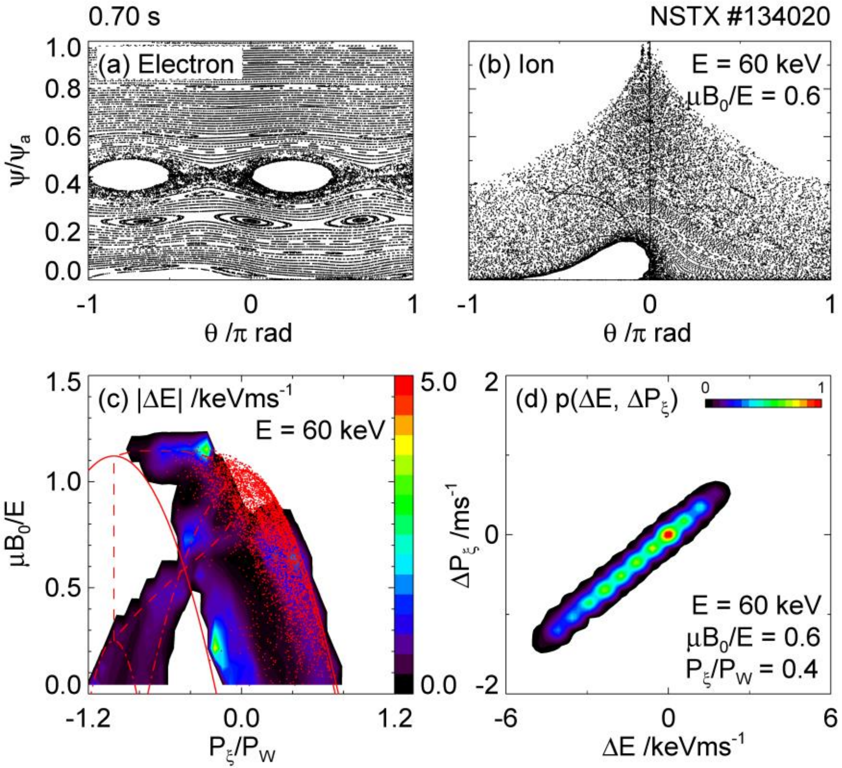
Low frequency modes affect core rotation

- Profiles
  - Unchanged q and density profile
  - Small drop in temperatures
  - Large rotation slowing down at core (q < 2)



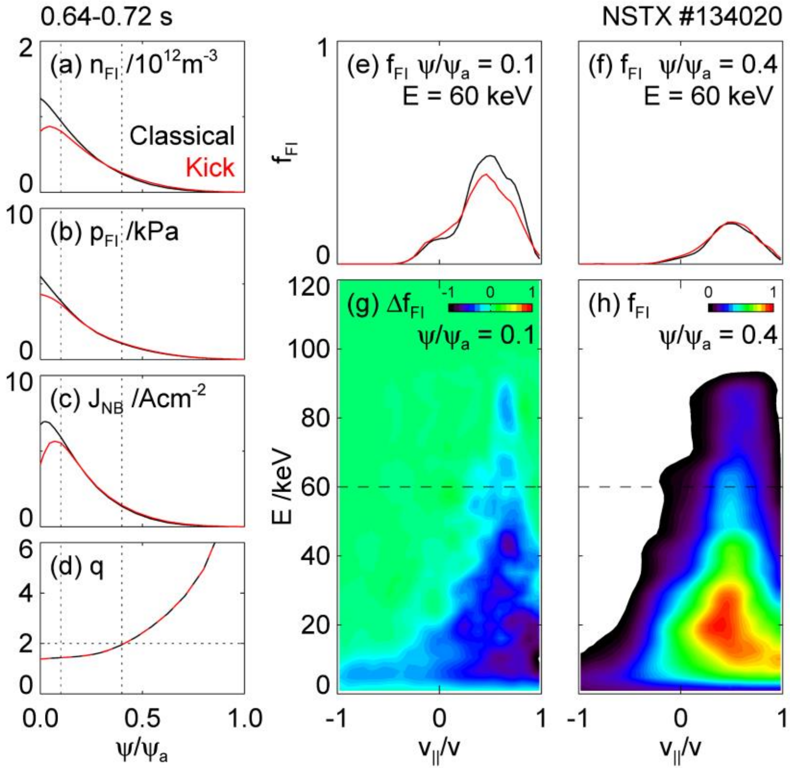
Resonant island appears near core for fast ions

- “Kick” probability
  - Deposited fast ions occupy core co-passing orbits
  - ORBIT: “Kick” for fast ions is localized near core and boundary
    - Core: Resonant island
    - Boundary: Tearing mode island
  - Deposited fast ions are kicked out from core region (= transport)



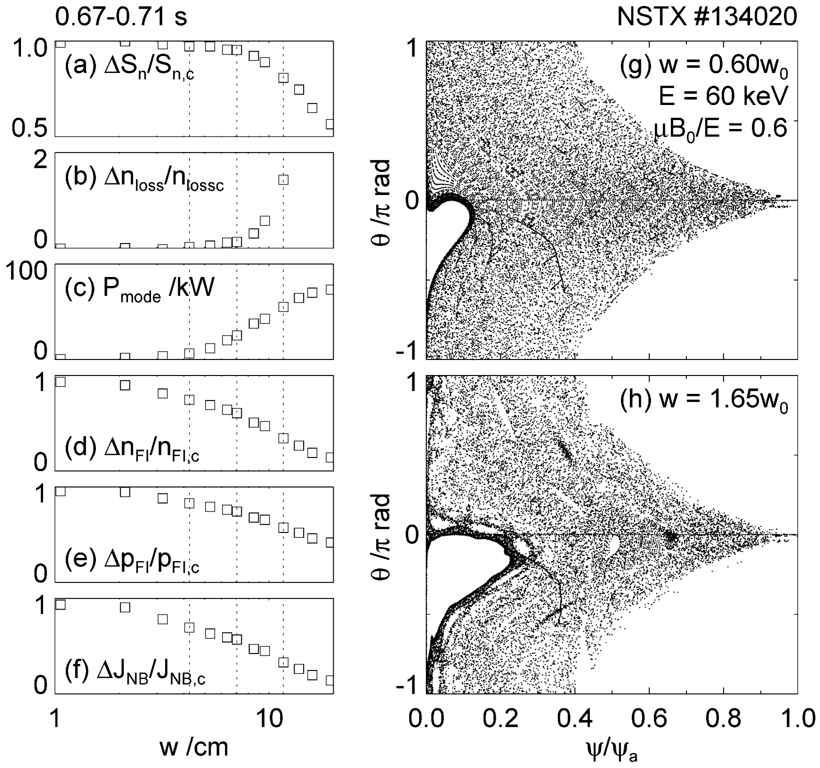
Depletion is core-localized in fast ion distribution

- Fast ion distribution
  - – Extends to 90 keV (E_{inj})
  - – Near core, kick depletes fast ions
  - – Distribution near q = 2 surface is practically unchanged
  - – As a result, weighted integrals of distribution drop primarily near core



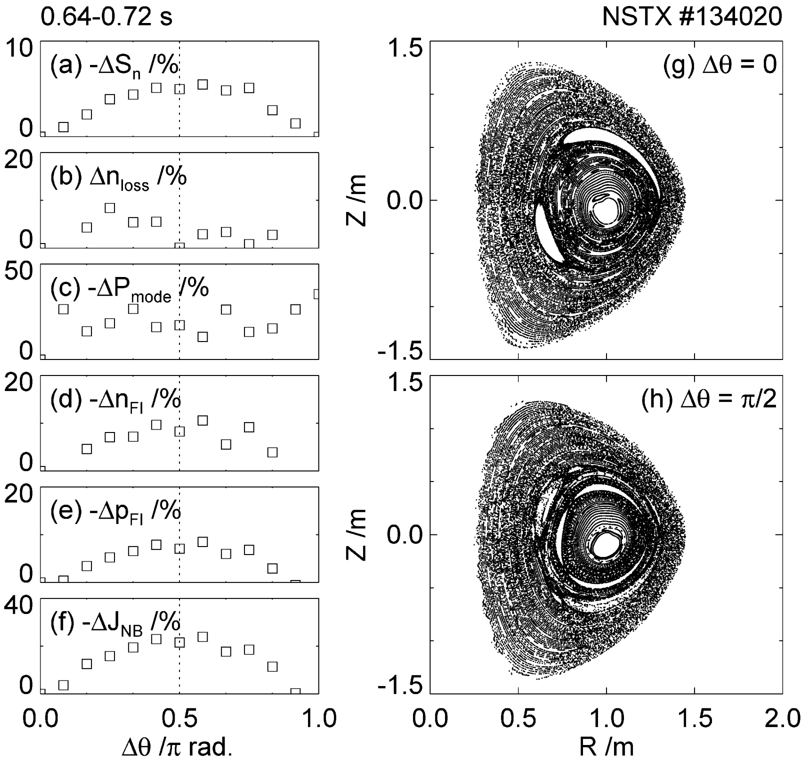
Islands over threshold turn flux surfaces chaotic

- Poincaré plots
  - Fast ion trajectory after round trip
  - Flux surfaces are layered for islands < threshold
  - Flux surfaces become chaotic for islands > threshold



Transport is sensitive to relative phase of modes

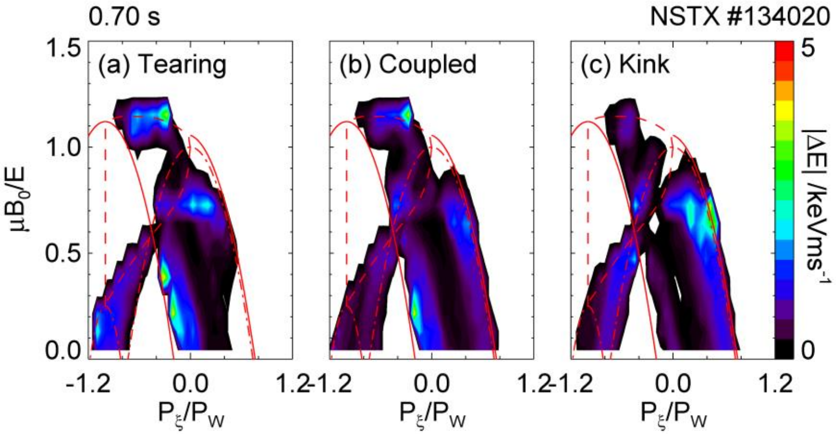
- Relative phase scan
  - Experimental relation
    - In phase[†]
  - Scanned for period
  - More fast ion transport than measurement when out of phase



† Fixed relative phase: Islands aligned at midplane when core displaced to high field side

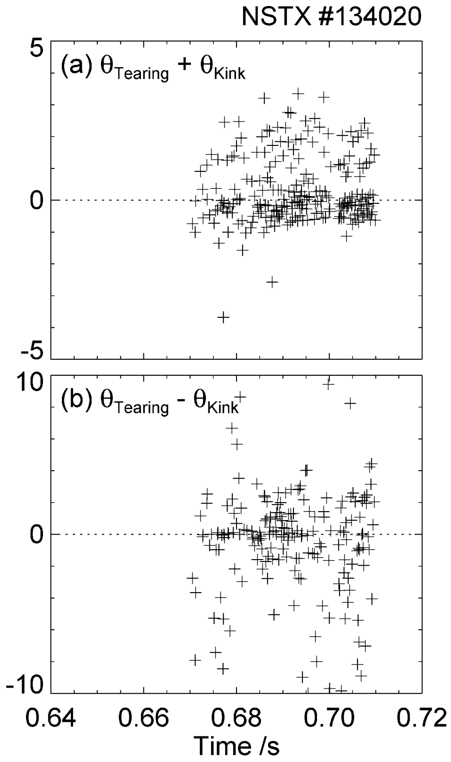
Fast ion distribution impacts mode coupling

- Mode coupling
  - Kick probability from tearing mode changes when internal kink mode is added
  - Same for internal kink mode
  - Fast ion impacts mode coupling, but how significant is this?



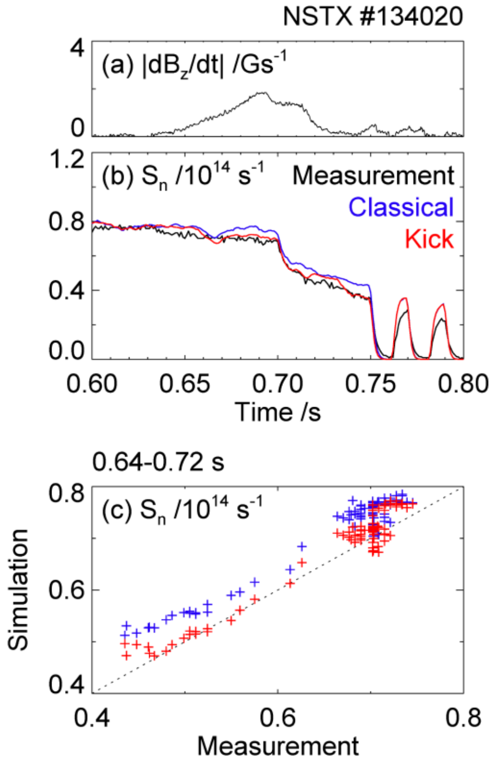
Backup – Relative phase of coupled modes

- Phase difference is constant during mode excitation
- Phase sum is constant too?



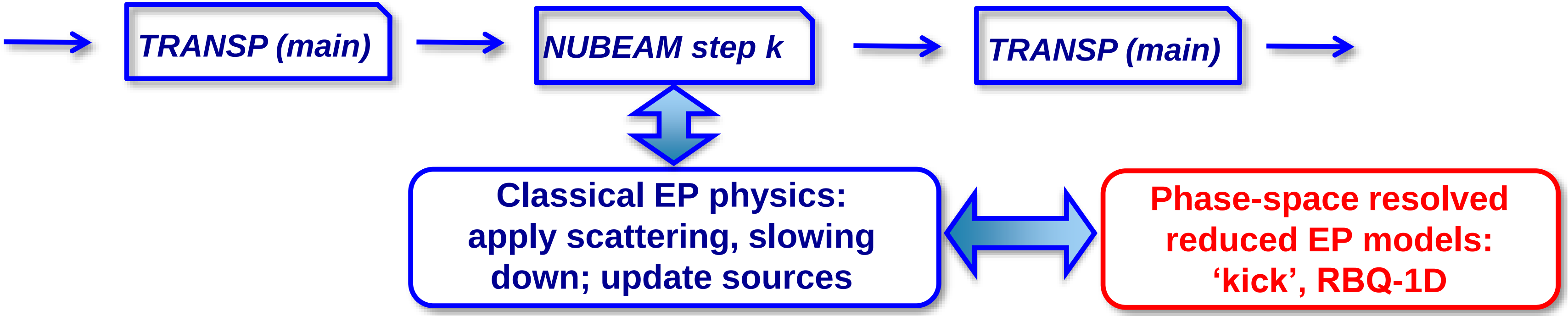
Backup – Full discharge modeling

- Modeling of 0.71 – 0.75 s
  - Tearing mode 3/1 coupled with internal kink (n = 1) excited
  - Transition at 0.72 s after surfaces of q = 2 and q = 3 coincide



Kick and *RBQ-1D* reduced models address EP transport in time-dependent integrated simulations

- NUBEAM module accounts for (neo)classical EP physics
  - Includes scattering, slowing down, atomic physics



New physics-based models enable predictive capabilities

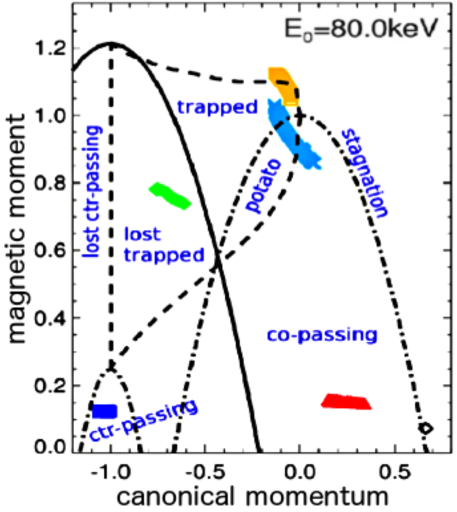
Podestà PPCF 2014, PPCF 2017; Gorelenkov NF 2018

Constants of Motion variables are used to describe resonant wave-particle interaction

Each orbit characterized by:

- E, energy
- $P_\zeta \sim mRv_{par} - q\Psi$, canonical momentum
- $\mu \sim v_{perp}^2/B$, magnetic moment

- Complex orbits in real space translate in simple trajectories in phase space



Wave stability (drive):

$$\gamma \propto \omega \frac{\partial F_{nb}}{\partial E} + n \frac{\partial F_{nb}}{\partial P_\zeta}$$

- Resonant interactions obey simple rule:

$$\omega P_\zeta - nE = const.$$

$$\Delta P_\zeta / \Delta E \propto n/\omega$$

$\omega = 2\pi f$: mode frequency

n : toroidal mode number

Define ***transport matrix(es)*** for NUBEAM:

$$p(\Delta E, \Delta P_\zeta \,|\, E, P_\zeta, \mu)$$

"Conditional probability that a particle at (E, P_ζ, μ) receives kicks ΔE, ΔP_ζ from wave-particle interaction"

Podestà PPCF 2014, PPCF 2017