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Role of fast ions in spontaneous NTMs in NSTX

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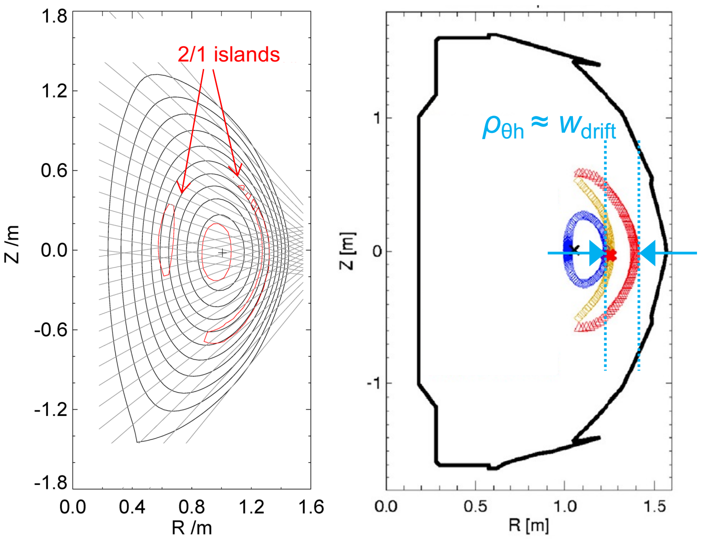

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Outline

- Introduction
- Discharge parameters
- Modified Rutherford equation analysis of the early growth phase
- M3D-C1-K analysis of the onset phase
- Validity of the results
- Conclusion

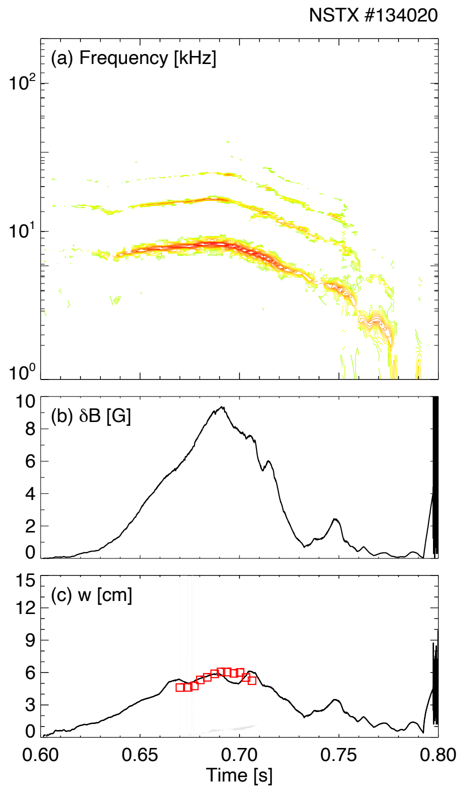
Could fast ion be implicit trigger for spontaneous NTM in NSTX?

- NTM: Neoclassical Tearing Mode
  - Needs seed island to overcome small island effects [1]
  - Triggers are ELMs, sawteeth, fishbones [2], pellet injection(, drift waves)
- Spontaneous NTM [3] instabilities are observed in NSTX [4]
  - Implicit triggers: Ideal modes [3], classical tearing modes, three wave coupling
- Fast ions can implicitly trigger spontaneous NTM
  - Kinetic neoclassical polarization current contributes to the early growth phase [4]
  - Fast ions can drive ideal modes in the onset phase [5]
- TRANSP NTM module [7] is used for the analysis

[1] Smolyakov *et al*, PoP **2** 1581 (1995)
[2] Gude *et al*, NF **39** 127 (1999)
[3] Fredrickson, PoP **9** 548 (2002)
[4] Gerhardt *et al*, NF **49** 032003 (2009)
[4] Cai, NF **56** 126016 (2016)
[5] Liu *et al*, JPP **88** 90580610 (2022)
[7] Poli *et al*, NF **58** 016007 (2018)

We are focusing on NSTX discharge #134020

- NSTX NB heated H-mode deuterium plasmas
  - No explicit trigger
  - Intentional beam power step down occurred at 0.70 s [1]
- MSE and SXR are essential for the analysis
  - LRDFIT [2] with MSE [3] constraints is the base equilibrium
  - TRANSP kick model [4] calculates the fast ion transport
  - Synthetic SXR diagnostics [5] determines the island width



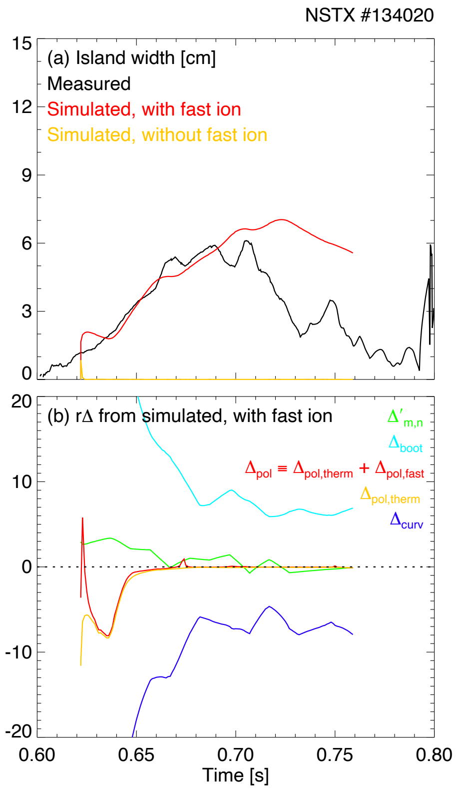
[1] La Haye *et al*, PoP **19** 062506 (2012)
[2] Menard *et al*, PRL **97** 095002 (2006)
[3] Levinton and Yuh, RSI **79** 10F522 (2008)
[4] Podesta *et al*, PPCF **56** 055063 (2014)
[5] Stutman *et al*, RSI **74** 1982 (2003)

Fast ion term can play a decisive role in early growth

- Measured and simulated island widths are compared
  - Good agreement with fast ion term included in the simulation
  - Trivial solution (w = 0) without the fast ion term
  - Fast ion term spike *looks* important

- Fast ion reduced the polarization current in island sheath
  - Rotation shear creates island sheath
  - Different mobility of ions and electrons cause polarization current
  - Gyromotion cancels out ion *E*×*B* drift and causes another current
  - This effect can be large with fast ions

$$\frac{1}{k_3}\frac{\tau_R}{r}\frac{dw}{dt} = \left[\Delta'_{m,n} + k_1\Delta_{boot} + k_2\left(\Delta_{pol} + \Delta_{pol,h}\right) + k_4\Delta_{curv}\right]r$$



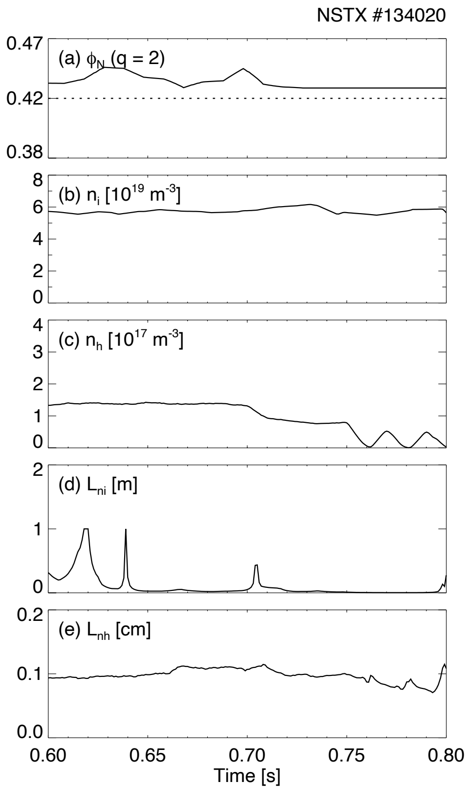
[1] Yang *et al*, PPCF **64** 095005 (2022)

Positive spike does not fully explain the fast ion contribution

- Fast ion term [1] has ion density gradient component
  - Shares some parameters with (thermal) ion polarization current
  - Ion density gradient comes into play theoretically
  - Assumed island rotates in electron diamagnetic drift direction

- Spike appears in L_{n_i} at 0.62 s
  - Height of the spike is clipped at 1 m to avoid numerical singularity
  - It remains inconclusive as to whether fast ions play a decisive role

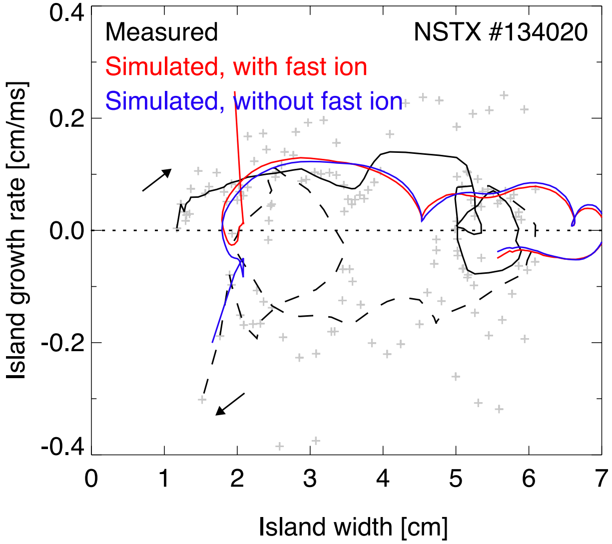
$$\Delta_{pol,h} = \frac{\beta_\theta}{w}\left(\frac{L_q}{L_p}\right)^2\left(\frac{L_{n_i}}{L_{n_h}}\frac{n_h}{n_i}\right)$$

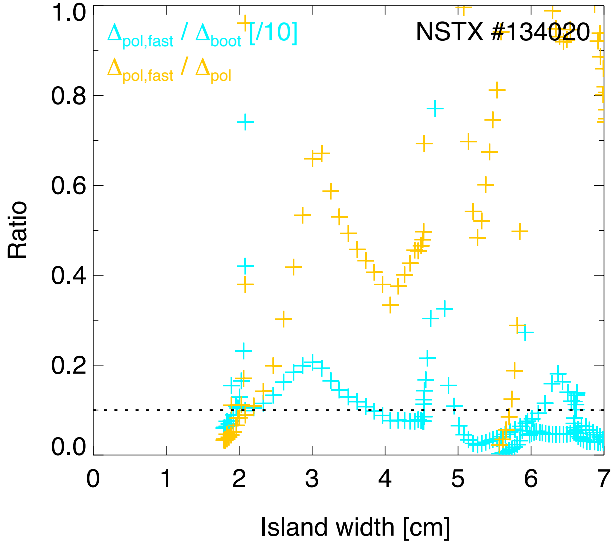


[1] Yang *et al*, PPCF **64** 095005 (2022)

Fast ion term contributes clearly when island is small

- Island growth rates from measurement and simulation are compared
  - When island is smaller than 3.5 cm, difference is < 0.02 cm/ms
  - Time evolution shows that it is significant when the island is smaller
  - This corresponds to the ratio $\Delta_{pol,h}/\Delta_{boot}$ < 2%

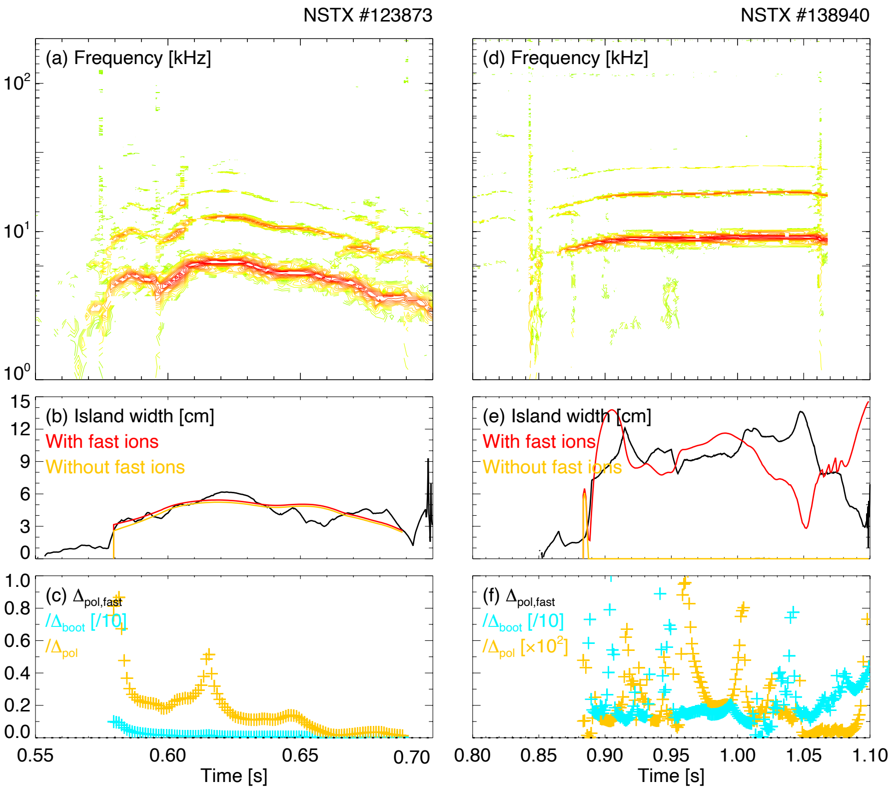




In another case, fast ion impact is small when $\Delta_{pol,h}$ is small

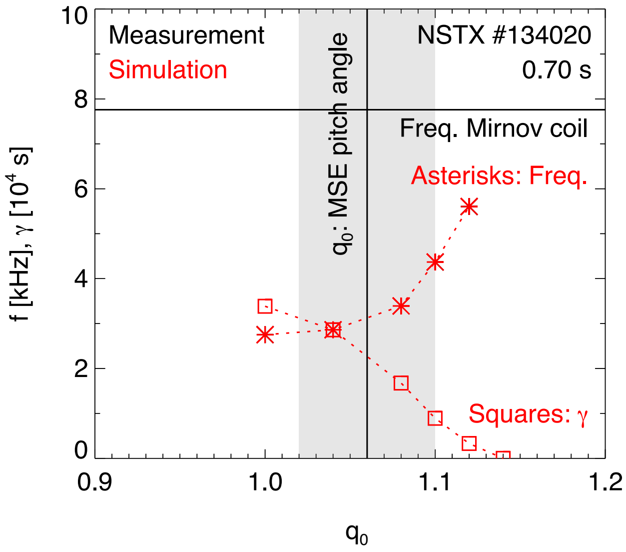
- Fast ion term is decisive in #134020
  - In #138940, fast ion term is decisive
  - In #123873, fast ion term has small effect
- What does #123873 have uniquely?
  - It has medium $\Delta_{pol,h}/\Delta_{pol}$
  - It has smallest $\Delta_{pol,h}/\Delta_{boot}$
  - Found a preliminary proxy, more to follow

At w = 2 cm	$\Delta_{pol,h}/\Delta_{pol}$	$\Delta_{pol,h}/\Delta_{boot}$	Fast ion impact
#123873	0.25	0.01	Small
#134020	0.10	0.02	Decisive
#138940	10.0	0.02	Decisive



Fast ion term can play a decisive role in onset albeit indirectly

- Other trigger candidates
  - Three wave coupling [1]: Unlikely (no 3/2 mode)
  - Classical tearing mode [2]: Possible but uncertain
- M3D-C1-K results suggest ideal mode trigger [3]
  - Inputs are consistent with the rest of this presentation
  - Results show growth rate that is real and finite
  - Doppler shift could explain the frequency underestimation
- Fast ion pressure is 17% of total pressure
  - Reduction of total pressure by 17% would lead to imaginary growth rate



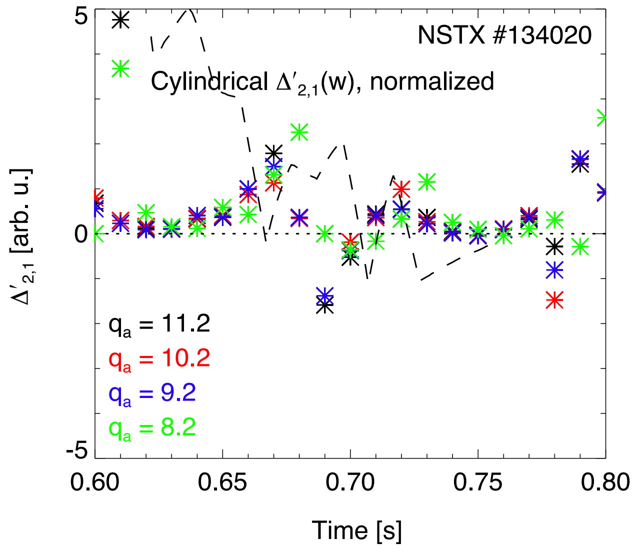
[1] Bardoczi *et al*, PRL **127** 055002 (2021)
[2] Reimerdes *et al*, PRL **88** 105005 (2002)
[3] Liu *et al*, JPP **88** 90580610 (2022)

Calculation of classical drive $\Delta'_{m,n}$ is verified to reasonable extent

- Classical drive $\Delta'_{m,n}$ is difficult to calculate
  - Assumed cylindrical plasma in this presentation [1]
  - Compare to toroidal axisymmetric plasma assumption [2]

- RDCON results show marginal instability vs. CTM
  - Boundary truncation helps [3]
  - Agrees qualitatively with cylindrical calculation
  - It is still unclear whether CTM is an implicit trigger

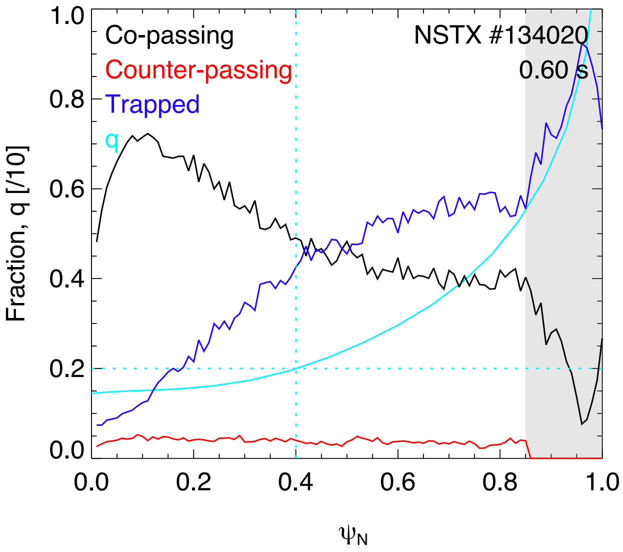
- Fast ions can affect $\Delta'_{m,n}$ [4], not included in this work



[1] Fredrickson *et al*, PoP **7** 4112 (2000)
[2] Glasser *et al*, PoP **23** 112506 (2016)
[3] Jiang *et al*, NF **61** 116033 (2021)
[4] Halfmoon and Brennan, PoP **24** 062501 (2017)

Calculation of fast ion orbit type is verified

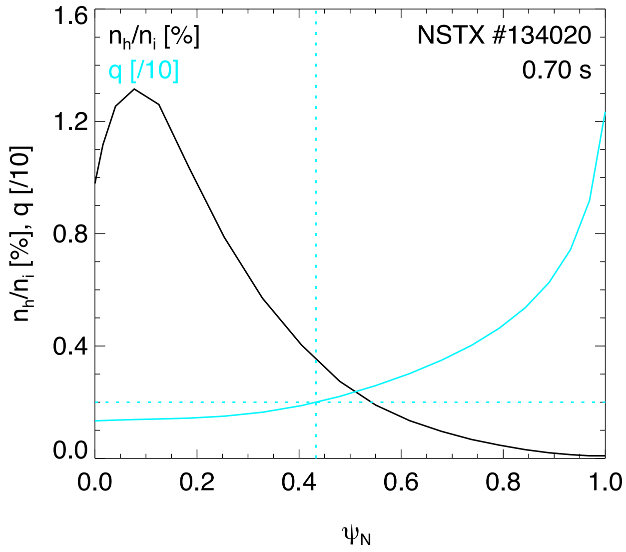
- Fast ion term concerns *passing* fast ions [1]
  - ORBIT [2] is used to determine fast ion orbit types
  - Value at q = 2 affects n_h
  - Gradient at q = 2 surface affects L_{n_h}
  - Guiding center assumption makes edge result inaccurate
- Profile of fraction is assumed fixed, but it…
  - Changes in time < 10%
  - Changes with the mode ~ 10%



[1] Cai, NF **56** 126016 (2016)
[2] White and Chance, PoF **27** 2455 (1984)

Further discussions on the analysis

- Ion density measurement in the analysis is verified
  - TRANSP takes Z_{eff} from CHERS
  - CHERS calculates $Z_{\text{eff}} = (n_i + n_h)/n_e \approx n_i/n_e$
  - Ratio n_h/n_i is very small (0.4% at q = 2)
- Assumed ramp down phase to be difficult to model
- Down-selected from database of 157 discharges
  - Both MSE and SXR systems on: 15
  - Unfavorable q profiles for SXR diagnostics: 6
  - Poor SXR signal to noise ratio: 6



Fast ion can be implicit trigger for spontaneous NTM in NSTX

- Pressure driven ideal mode may provide the implicit trigger
  - Inclusion of the fast ion pressure to the total pressure is decisive
  - Classical tearing mode might also provide the implicit trigger

- Kinetic neoclassical polarization current may provide the early growth
  - Fast ion drive as large as 1% of bootstrap current drive can be important

- Kinetic neoclassical polarization current is important in these conditions:
  - Ion poloidal Larmor radius is comparable to the island width
  - Magnetic island rotates in the electron diamagnetic drift direction [1,2] Future work

[1] Waelbroeck *et al*, PRL **87** 215003 (2001)
[2] Ida *et al*, PRL **88** 015002 (2002)

Conjecture: Island rotation direction changes as they grow

Backup

Polarization current is stabilizing when $\omega \approx \omega_{*i}$ ***and*** $\omega \approx \omega_{*e}$ [1]

Theory

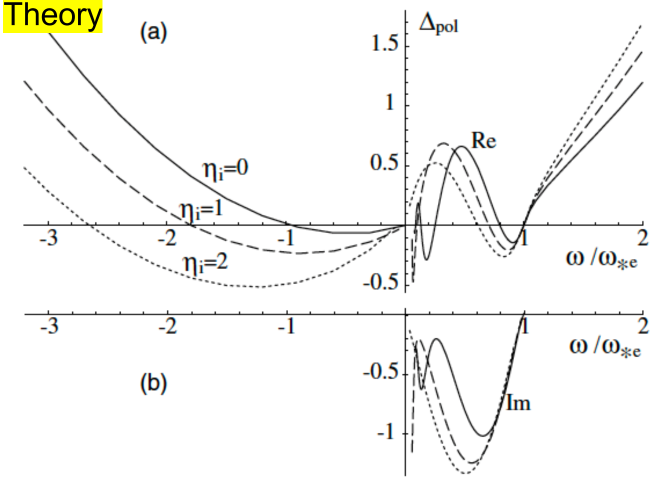
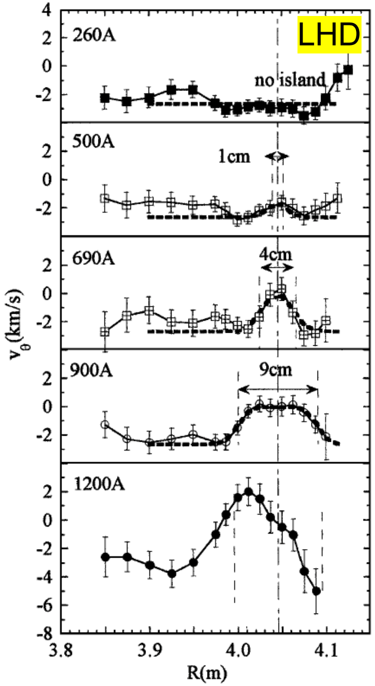


FIG. 2. Real (a) and imaginary (b) parts of the stability parameter Δ_{pol} as a function of frequency. The solid, dashed, and dotted lines are for $\eta_i = 0$, 1, and 2, respectively. The real and imaginary parts indicate the effect of the polarization drift on stability ($\Re[\Delta_{pol}]$) and on the radiative torque ($\Im[\Delta_{pol}]$).

LHD



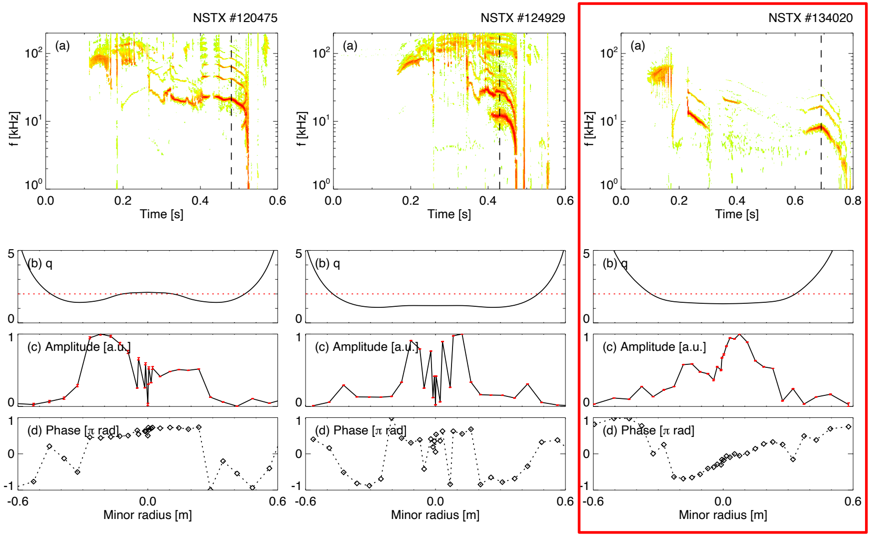
Poloidal rotation changes sign as islands grow [2]

FIG. 2. Radial profiles of poloidal rotation velocity, for various currents of $n/m = 1/1$ external perturbation coils, in the plasma with $B = 1.5$ T and $R_{ax} = 3.5$ m. The last closed surfaces are at $R = 3.28$ m and $R = 4.10$ m at the cross section vertically elongated. The major radius for the center of island, R_i, is indicated with a line as a reference. The dashed lines are fitted profiles of poloidal velocity to the measured values.

[1] Waelbroeck *et al*, PRL **87** 215003 (2001)
[2] Ida *et al*, PRL **88** 015002 (2002)

Not all spontaneous NTM cases in NSTX are investigated

- Observed in 157+ shots in NSTX [1]
  - MSE [2] & SXR [3] on in 15 shots
  - Mode takes many forms
- Analyzed 3 shots
  - Does not have reversed shear[1]
  - Does not have q = 2 near the wall[2]
  - Clear phase jumps are observed[3]



#124929 may have two island chains (core 3/2)
#124929 may not be spontaneous NTM
#134020 is selected

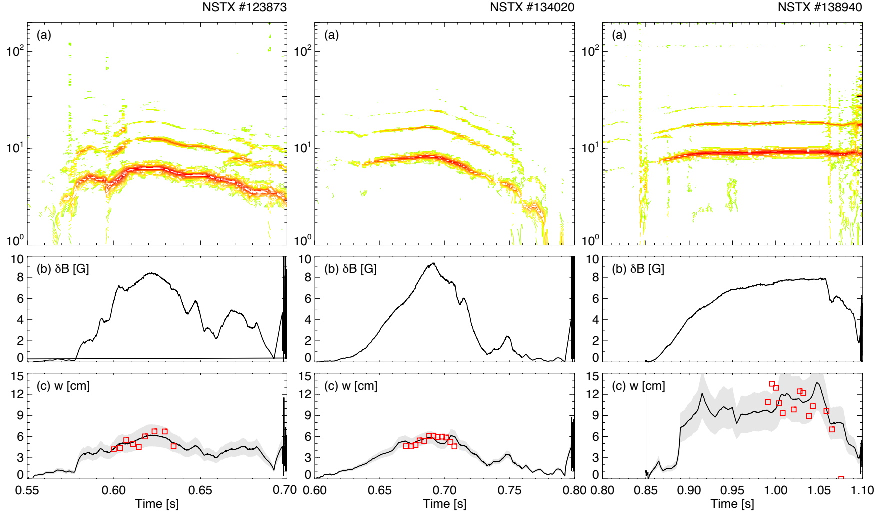
1 120475, 138948
2 116318, 123816, 124929, 134835
3 123873, 134020, 138940

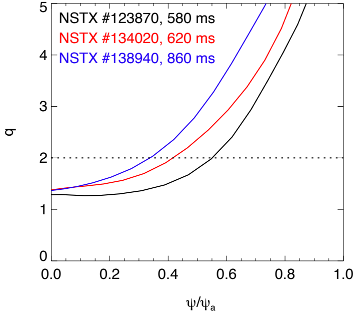
[1] Fredrickson, private note

Data selection and experimental parameters

Backup

- TRANSP is used to obtain profiles
  - Similar global parameters†
  - Different rotation and shape
  - Different *q* profiles at the NTM onset
- Experimental *w*(t) is from SXR
  - Mirnov coil is used for the trend
  - Synthetic SXR is used for normalization





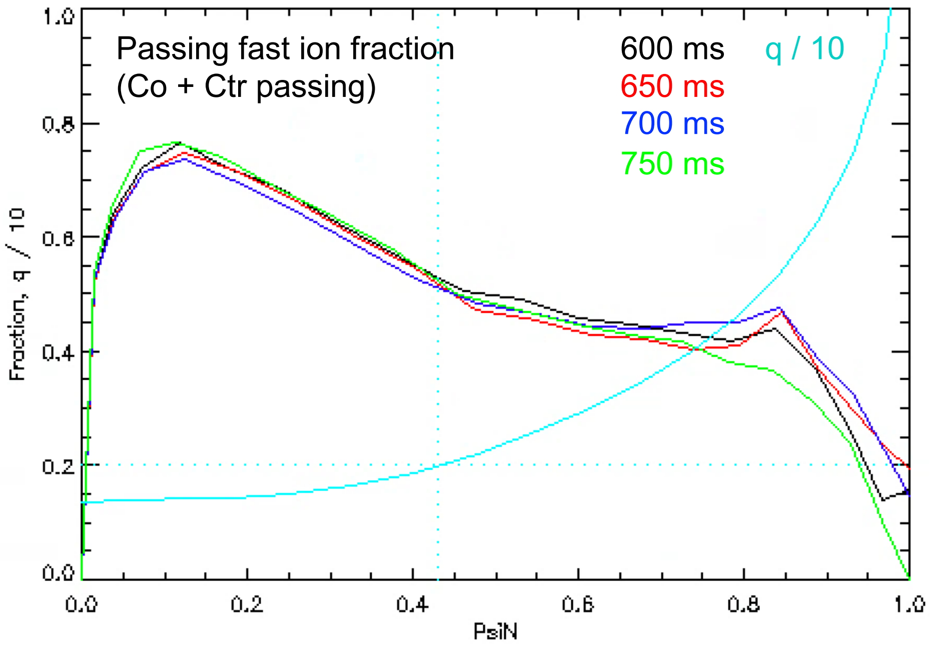
† Global parameters:

	123873	134020	138940
I_P [MA]	1.0	0.9	0.8
B_T [T]	0.44		

Passing fast ion fraction profile evolves in time

Backup

NSTX #134020



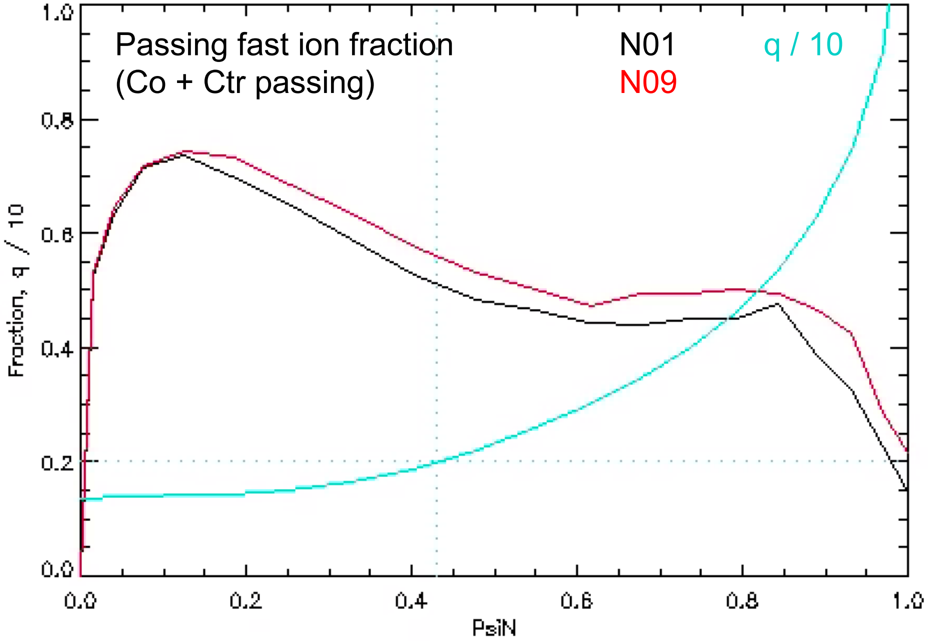
$$\Delta_{FI} = \frac{L_{n_i}}{L_{n_h}} \frac{n_h}{n_i} \frac{\beta_\theta}{w} \left(\frac{L_q}{L_p}\right)^2$$

- Fast ion term has $n_h(\psi)$
- f_{pass} is not constant in ψ
  - Especially near $q = 2$
  - $f_{pass}(\psi)$ evolves in time

Backup

Passing fast ion fraction profile is different with NTM

NSTX #134020



$$\Delta_{FI} = \frac{L_{n_i}}{L_{n_h}} \frac{n_h}{n_i} \frac{\beta_\theta}{w} \left(\frac{L_q}{L_p}\right)^2$$

- Fast ion term has $n_h(\psi)$
- f_{pass} is not constant in ψ
  - Especially near $q = 2$
  - $f_{pass}(\psi)$ evolves in time
  - NTM affects $f_{pass}(\psi)$