

Framework for predictive modeling of neoclassical tearing mode activity in NSTX-U

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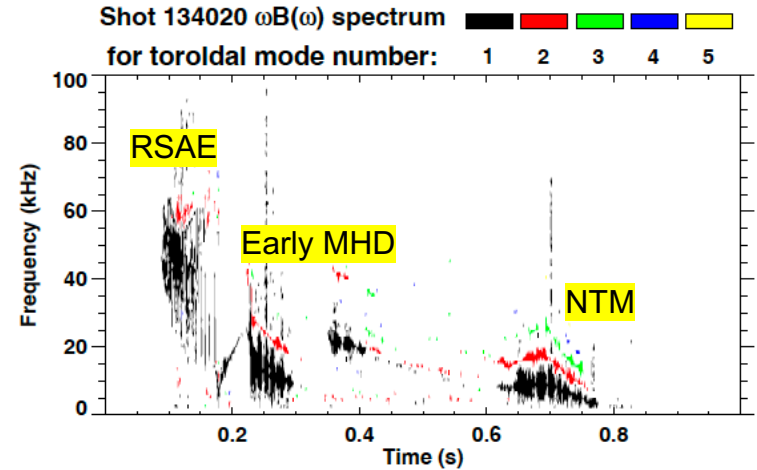
Oct. 31-Nov. 4, 2022, Beijing, China (Virtual)

Outline

- Introduction
- TRANSP framework for NTM
- Triggerless NTM in NSTX
- Interpretive simulation
 - Effect of fast ions on NTM growth
- Predictive simulation
- Conclusion

Can TRANSP shed light on triggerless NTM in NSTX?

- Triggerless NTM [1] is observed in NSTX
 - How does triggerless NTM grow in NSTX?
 - Can TRANSP be useful for self-consistent generation of MRE parameters?
- Good NTM model helps both scenario development [2] and control [3]
 - Similar approach is taken in TCV [4]



[1] Fredrickson, Phys. Plasmas **9** 548 (2002)

[2] Poli *et al.*, Nucl. Fusion **58** 016007 (2018)

[3] Reiman *et al.*, Phys. Plasmas **28** 042508 (2021)

[4] Kong *et al.*, Plasma Phys. Control. Fusion **64** 044008 (2022)

Fast ion term is introduced to Modified Rutherford Equation

- MRE consists of classical, bootstrap, polarization current and curvature terms
 - Classical term is calculated for both zero and finite island widths [1, 2]
- Fast ions may contribute to initial growth of an island
 - Parallel current may form to replenish bootstrap current [3]: Susceptible to “orbit loss”
 - Kinetic neoclassical polarization current [4]: Current in island separatrix
 - Loss of ion $E \times B$ drift leads to toroidal current that restores charge neutrality
 - Introduces ion density profile in the NTM physics

n_h : Fast ion density

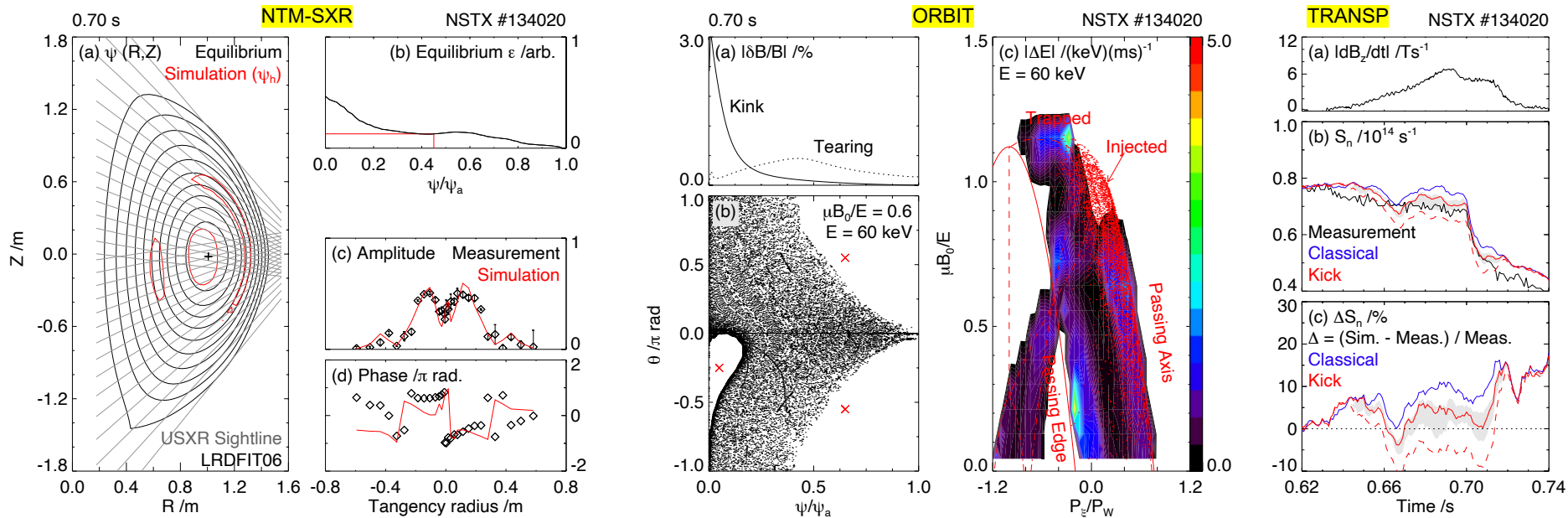
$$\frac{\tau_R}{r} \frac{dw}{dt} = r \Delta' \quad \Delta' = \Delta'_{m,n}(w) + \left[\frac{16J_{BS}}{s\langle J \rangle} \frac{w}{w^2 + w_d^2} \right] - \left[\varepsilon^{3/2} \frac{\rho_{\theta i}^2}{w^2} - \frac{L_{n_i} n_h}{L_{n_h} n_i} \right] \frac{\beta_\theta}{w} \left(\frac{L_q}{L_p} \right)^2 - \frac{\beta_\theta \varepsilon^2}{rw} \frac{L_q^2}{|L_p|} \frac{q^2 - 1}{q^2}$$

[1] White *et al.*, Phys. Fluids **20** 800 (1977)
[2] Fredrickson *et al.*, Phys. Plasmas **7** 4112 (2000)

[3] Hegna and Bhattacharjee, Phys. Rev. Lett. **63** 2056 (1989)
[4] Cai, Nucl. Fusion **56** 126016 (2016)

TRANSP generates self-consistent parameters for MRE

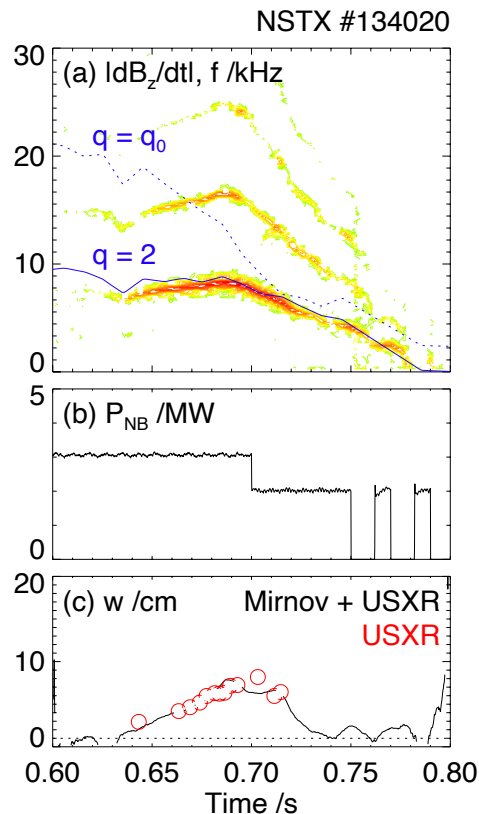
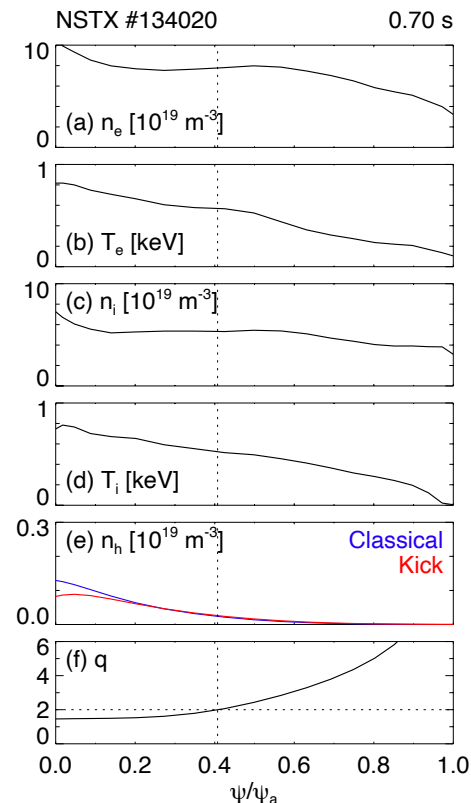
- Kick model is useful to include the NTM-induced fast ion transport [1]



[1] Yang *et al.*, Plasma Phys. Control. Fusion **63** 045003 (2021)

Parameters of triggerless NTM are generated using TRANSP

- NSTX triggerless NTM: #134020
 - NB power is reduced mid-shot [1]
 - No usual triggers (ELM, sawteeth)
 - Simulation up to 750 ms
- Profiles are stationary except for T_i
 - Fast ion density profile is calculated
 - Classical: Without NTM effect
 - Kick: With NTM effect
 - Core T_i drops by 40%

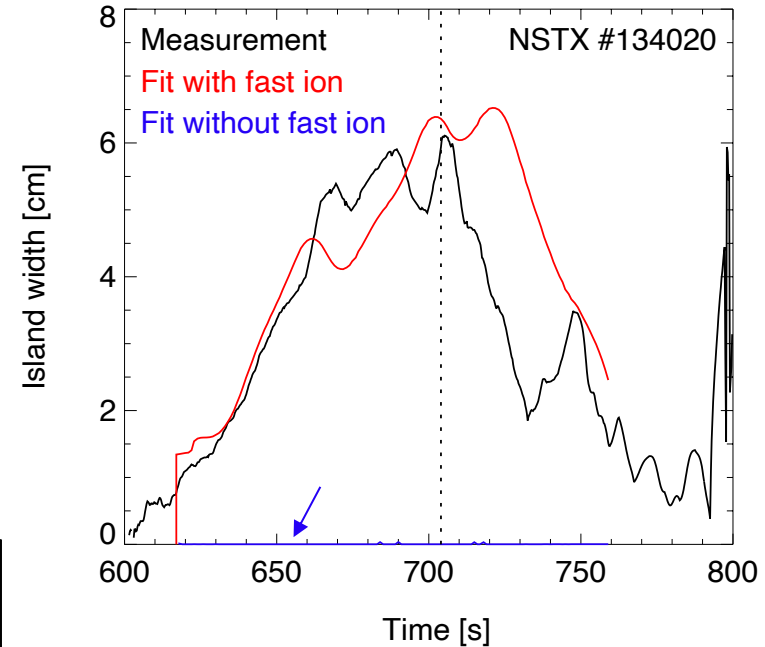


[1] La Haye *et al.*, Phys. Plasmas **19** 062506 (2012)

Fast ion term is essential for reasonable MRE fit to measurement

- MRE is solved for island width
 - Initial value problem: Solved using Euler method
 - Parameters are taken from TRANSP
 - Coefficients are fit for entire time evolution
- Solution is trivial without fast ion term
 - Finite island width gives negative growth rate
 - Fast ion term provides chance for island growth

$$\frac{\tau_R}{r} \frac{dw}{dt} = r \Delta' \left[\Delta' = \Delta'_{m,n}(w) + k_{BS} \left[\frac{16J_{BS}}{s\langle J \rangle} \frac{w}{w^2 + w_d^2} \right] \dots \right. \\ \left. \dots - k_{pol} \left[\varepsilon^{3/2} \frac{\rho_{\theta i}^2}{w^2} - \frac{L_{n_i}}{L_{n_h}} \frac{n_h}{n_i} \right] \frac{\beta_\theta}{w} \left(\frac{L_q}{L_p} \right)^2 - k_{curv} \frac{\beta_\theta \varepsilon^2}{rw} \frac{L_q^2}{|L_p|} \frac{q^2 - 1}{q^2} \right]$$



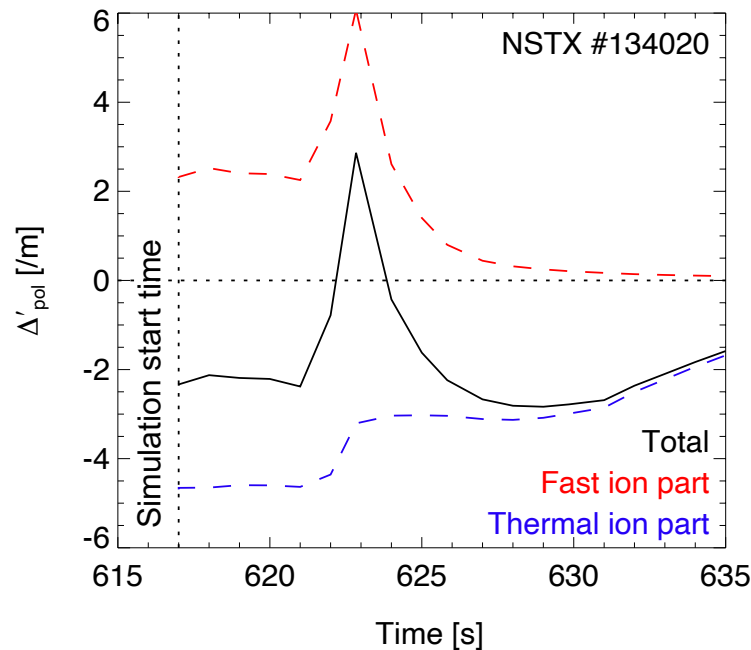
Polarization current term turning positive may be a crucial factor

- Polarization current term “spikes” at 623 ms
 - Driven by fast ion term
 - Gradient scale length ratio $\approx \nabla n_h / \nabla n_i$ is large
 - Flat thermal ion density profile is likely cause
- Akin to “gate open” by plasma rotation drop [1]
 - Already triggered island grows thanks to fast ions

Possible mechanism

Classical tearing mode $\rightarrow$ (flat n_i profile)

$\rightarrow \Delta'_{\text{pol}}$ turns positive $\rightarrow$ Neoclassical tearing mode

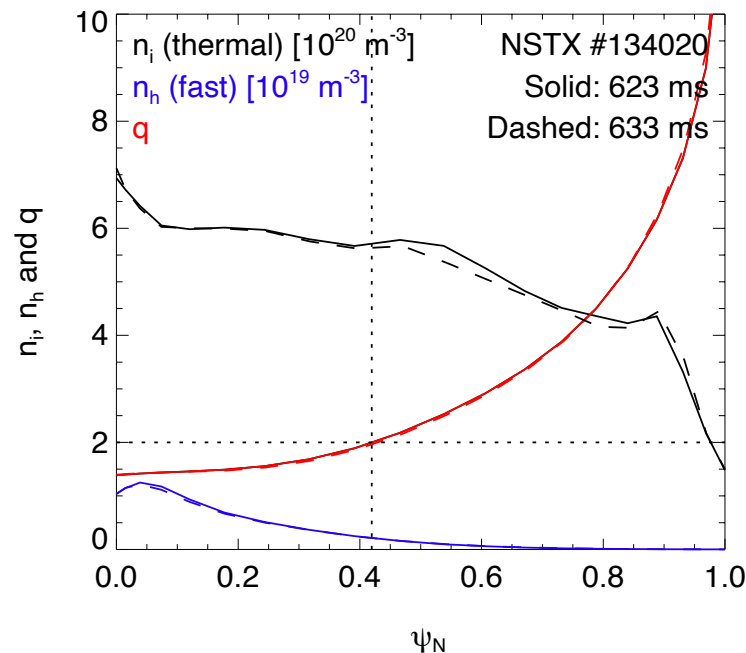


$$\Delta'_{\text{pol}} = - \left[\varepsilon^{3/2} \frac{\rho_{\theta i}^2}{w^2} - \frac{L_{n_i} n_h}{L_{n_h} n_i} \right] \frac{\beta_{\theta}}{w} \left(\frac{L_q}{L_p} \right)^2$$

[1] La Haye *et al.*, Nucl. Fusion **62** 056017 (2022)

Thermal ion density profiles may be flat at time, radius of interest

- Measuring ion density profile is complicated
 - CHERS [1] measures carbon density profile
 - Profile of Z_{eff} is needed for thermal ion density
 - Thermal ion density is needed for Z_{eff}
 - TRANSP considers additional inputs from TS [2]
 - TRANSP and CHERS results agree
- Flat profiles are seen at $q = 2$ while $\nabla n_h \neq 0$
 - Other times without “spikes” have $\nabla n_i \neq 0$



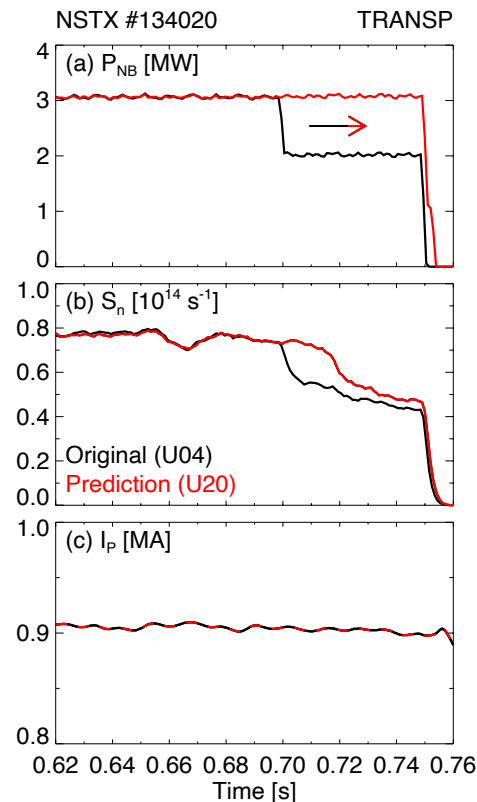
[1] Bell *et al.*, Phys. Plasmas **17** 082507 (2010)

[2] LeBlanc, Rev. Sci. Instrum. **79** 10E737 (2008)

Predictive simulation: Re-programming neutral beam waveform

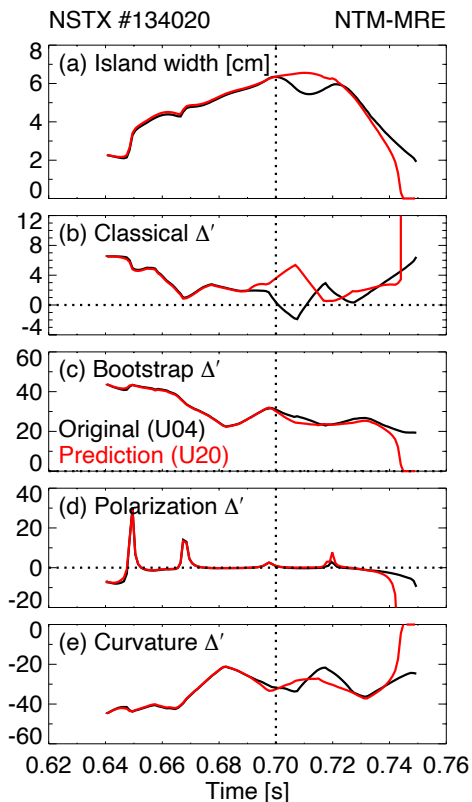
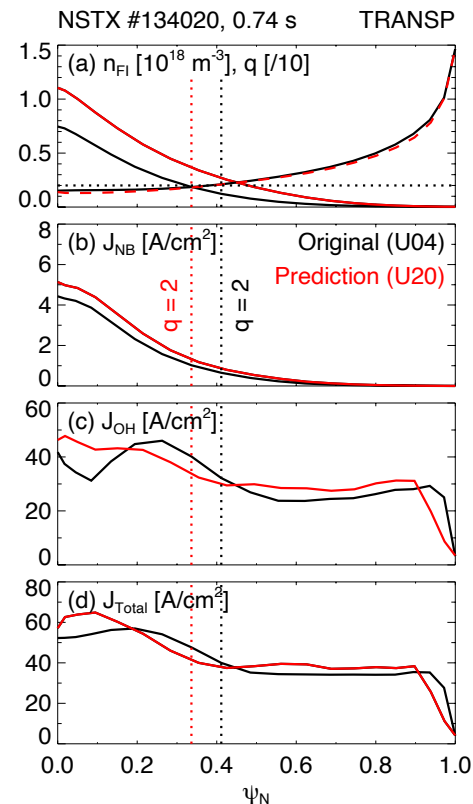
- Validated MRE can be used for predictive simulations
 - Minimize islands for improved performance
 - Maximize islands for diagnostic purposes
- Example: Re-programming NB waveform (pulse design)
 - Extend high power phase by 50 ms
 - TRANSP kick model predicts higher neutron rate as expected
 - Total plasma current is fixed: Mimics plasma control system[†]
 - New profiles are used to generate predicted island growth

[†] Adjust surface loop voltage, allow poloidal field diffusion



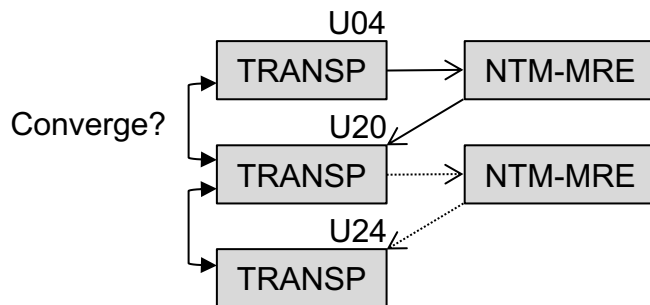
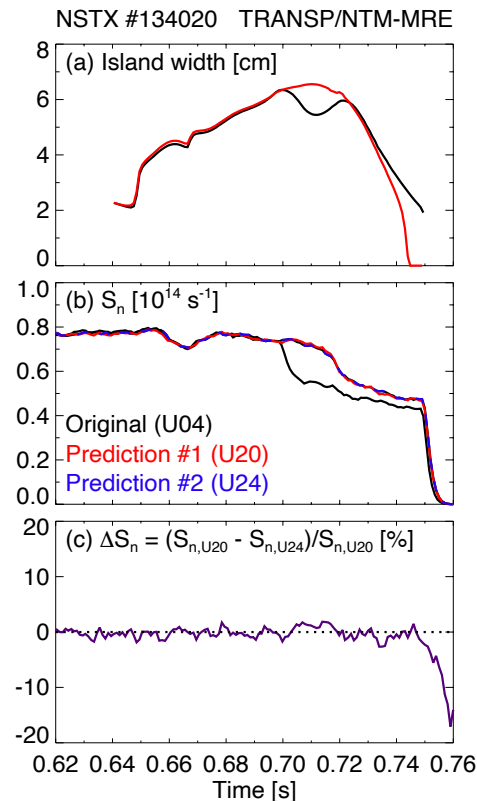
Simulated plasma will have new island width time evolution

- Simulated plasma has new profiles
 - Leads to new island growth
 - MRE coefficients kept unchanged
 - Predicted island grows larger by 1 cm
 - Main difference is in classical Δ'
- Classical Δ' depends on J profile
 - Difference in current profile is notable:
 - New fast ion density $\rightarrow$ New J_{NB}
 - Poloidal field diffusion $\rightarrow$ New J_{OH}



TRANSP is re-run with predicted island to close iterative loop

- Two independent codes are used for predictive simulation
 - TRANSP kick model calculates plasma equilibrium and profiles
 - NTM-MRE calculates magnetic island width
 - Solved iteratively until convergence
- New island width time evolution gives similar neutron rate
 - Extra island growth of 1 cm has little effect
 - Iterative loop is closed



TRANSP sheds light on triggerless NTM in NSTX

- Fast ions may have contributed to some triggerless NTM in NSTX
 - Kinetic neoclassical polarization current provides necessary drive to open the “gate”
- TRANSP is useful for self-consistent generation of MRE parameters
 - Interpretive simulations validate MRE use for NTM modeling
 - Predictive simulation shows possible contribution to experimental design
- Model will be improved, and dedicated experiment will contribute
 - Fast ion density measurement is complicated: Will perform sensitivity study
 - Classical Δ' is for circular cylindrical plasma: Will be benchmarked against RDCON [1]
 - NSTX data is not from dedicated experiment: Will perform dedicated experiment in DIII-D [2]

[1] Glasser *et al.*, Phys. Plasmas **23** 112506 (2016)

[2] Heidbrink *et al.*, Nucl. Fusion **58** 082027 (2018)

Triggerless NTM is observed in TFTR, TCV, and MAST

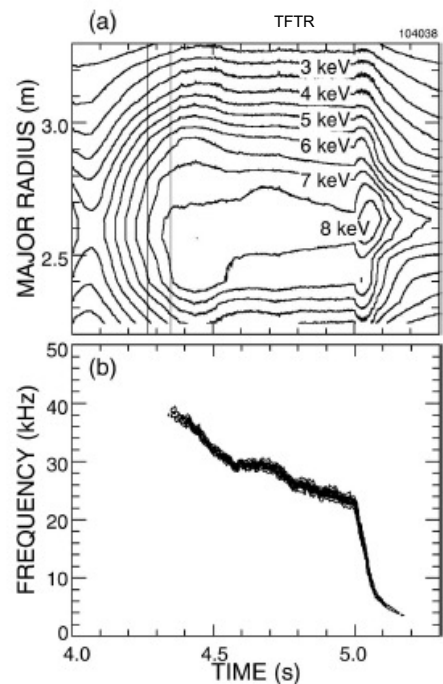


FIG. 1. (a) Contours of electron temperature for shot 104038, (b) spectrogram of Mirnov coil data for shot 104038 showing onset of 4/3 NTM in quiet plasma.

Fredrickson, Phys. Plasmas **9** 548 (2002)

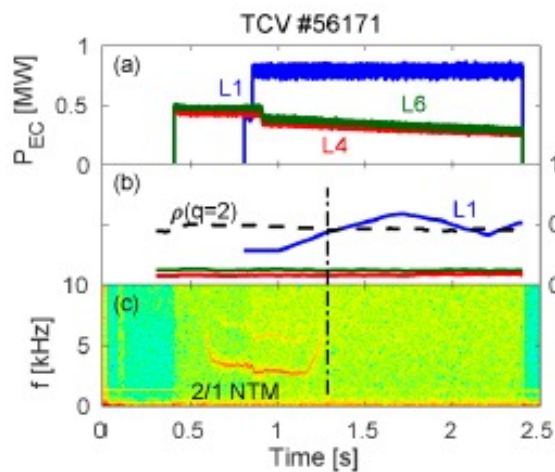


Figure 5. 2/1 NTM stabilization: (a) EC power traces; (b) EC deposition locations; (c) NTM spectrogram.

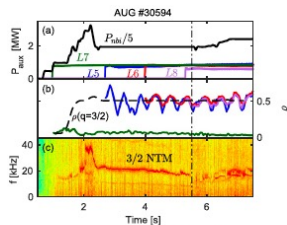


Figure 7. Experimental overview of an NTM stabilization experiment on AUG with I_p ≈ 1 MA: (a) NBI and EC power traces; (b) EC deposition locations; and (c) 3/2 NTM spectrogram.

AUG counter-example: Sawteeth triggered

Kong *et al.*, Plasma Phys. Control. Fusion **64** 044008 (2022)

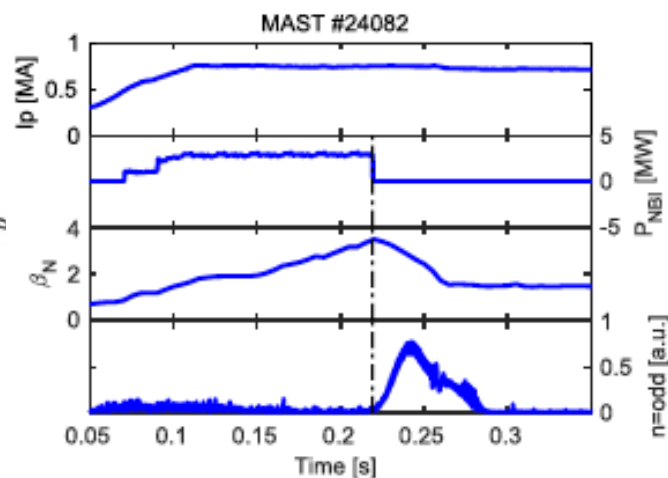


Figure 9. Experimental overview of a β ramp-down discharge on MAST: (a) plasma current; (b) total NBI power trace; (c) normalized plasma β; and (d) amplitude of the measured odd n component of magnetic perturbations.

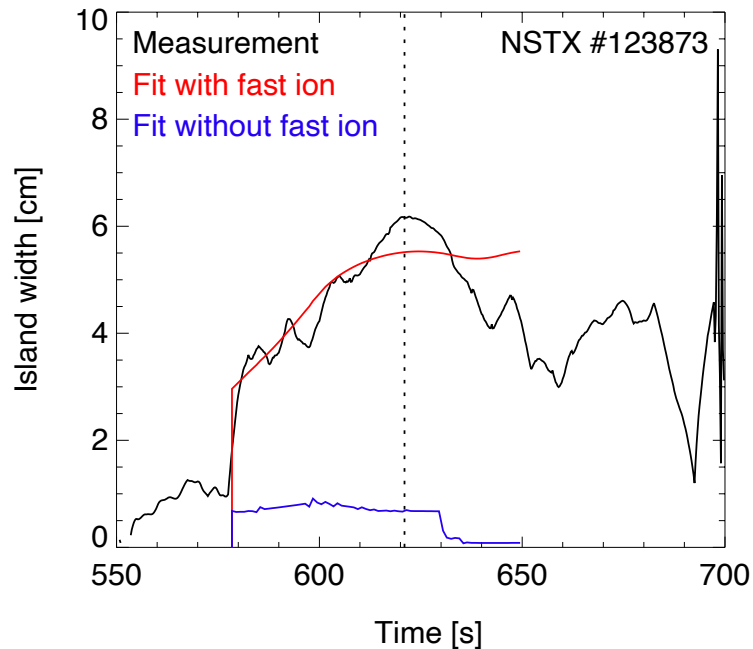
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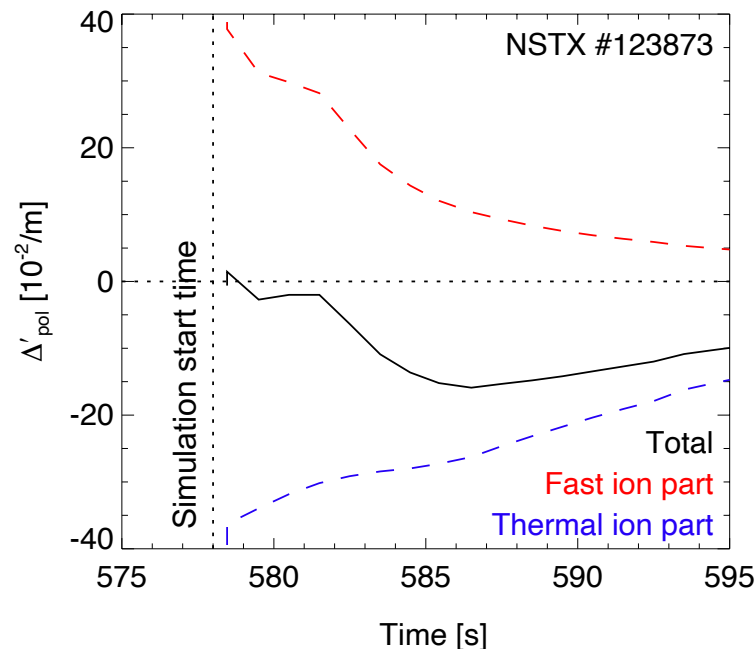
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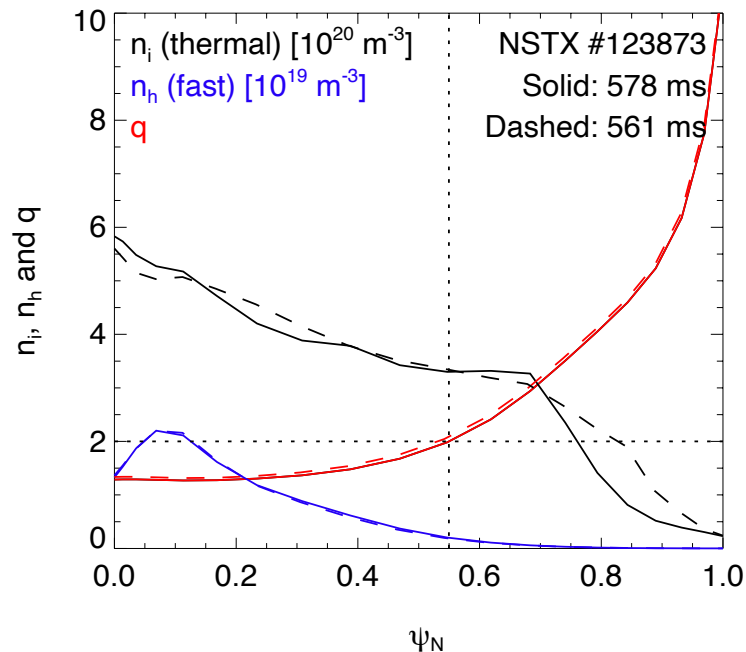


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How do we rule out other mechanisms for triggerless NTM?

- M3D-C1: Fast ion induced internal kink has finite γ near measured frequency
 - NOVA: BAE exists near measured frequency
 - Tearing mode may be simply a resistive harmonics of (BAE-induced) internal kink
 - Ways to simulate bootstrap currents in M3D-C1 may help
- Three-wave coupling [1]: Two waves can trigger an NTM without ELM/sawteeth
 - NTM in NSTX has helicity of 2/1
 - Non-resonant core $n = 1$ kink has helicity of 1/0
 - Could there be a wave with helicity of 1/1?

[1] Bardóczi *et al.*, Phys. Rev. Lett. **127** 055002 (2021)

Questions remain due to uncertainty in island rotation direction

- Doppler shift makes measurement of island rotation frequency difficult
 - Island rotation at plasma frame is small, whereas Doppler shift (noise) is large [1]
 - Islands may change directions by turbulence [2]
- Assuming island rotates in ion diamagnetic direction ($\omega' < 0$):
 - Polarization current is stabilizing, giving rise to explanation to observed island saturation [3]
 - Kinetic neoclassical polarization current is destabilizing [4]
 - However, this contradicts previous assessment [5]

[1] La Haye *et al.*, Phys. Plasmas **10** 3644 (2003)

[2] Hornsby *et al.*, Plasma Phys. Control. Fusion **58** 014028 (2016)

[3] Wilson *et al.*, Phys. Plasmas **3** 248 (1996)

[4] Cai Nucl. Fusion **56** 126016 (2016)

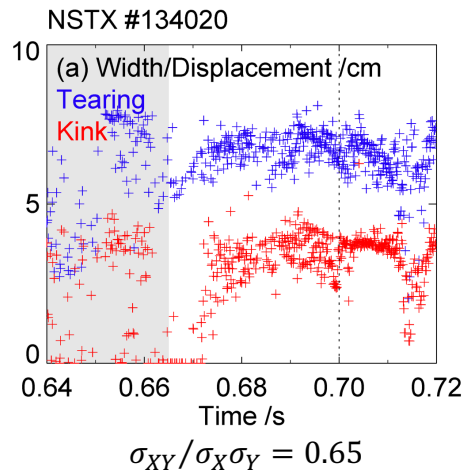
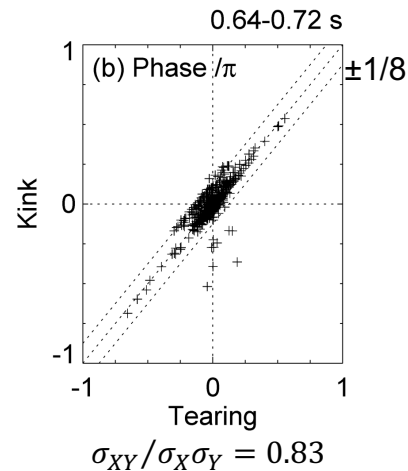
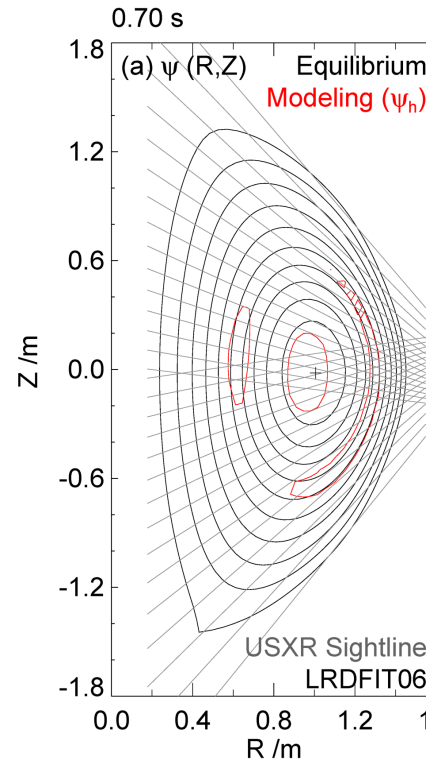
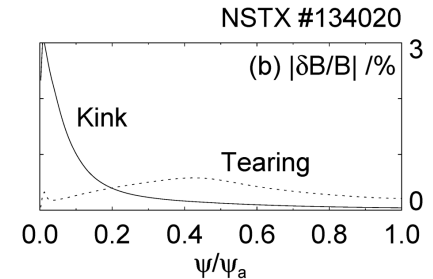
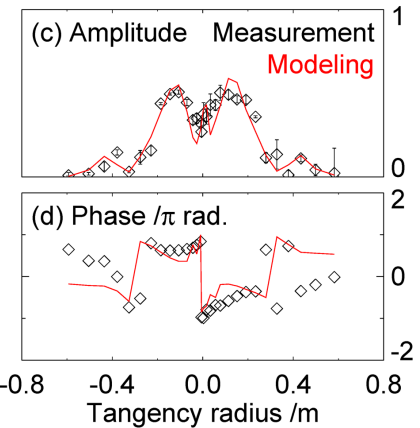
[5] La Haye *et al.*, Phys. Plasmas **19** 062506 (2012)

$$\Delta'_{pol} = -\epsilon^{3/2} \left(\frac{L_q}{L_p} \right) \frac{\rho_{\theta i}^2}{w^2} \frac{\beta_{\theta}}{w} \frac{\omega'(\omega' - \omega_{*i})}{\omega_{*e}^2}$$

$$\Delta'_{kin.nc-pol} = -\frac{\beta_{\theta}}{w} \left(\frac{L_q}{L_p} \right) \frac{L_{n_i}}{L_h} \frac{n_h}{n} \frac{\omega'}{\omega_{*i}}$$

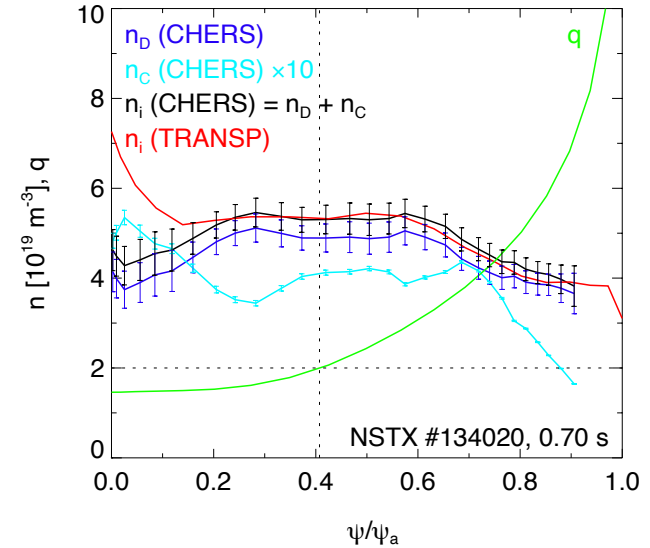
Kink and Tearing Modes are Coupled to Each Other

- Modes are coupled together
 - Fixed relative phase $\Delta\theta = 0$
 - Proportional amplitudes



Kinetic neoclassical polarization current term introduces $n_i(\psi_N)$

- Fast ions make ion density important for NTM
- CHERS provides ion density profile [1]
 - Measures carbon density profile
 - Additional input of Z_{eff} is needed for ion density profile
 - Ion density profile is needed for Z_{eff} profile
- TRANSP validates measured n_i near $q = 2$
 - Core disagreement is likely due to carbon accumulation
 - TRANSP considers CHERS + TS: Likely more accurate

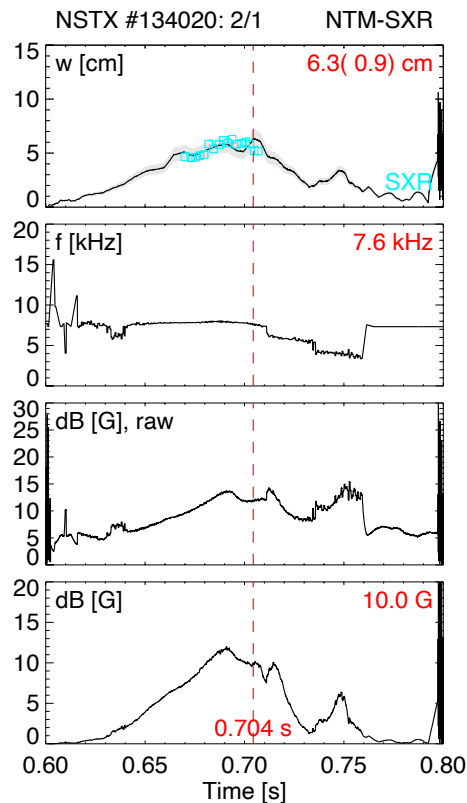


[1] Podestà *et al.*, Rev. Sci. Instrum. **79** 10E521 (2008)

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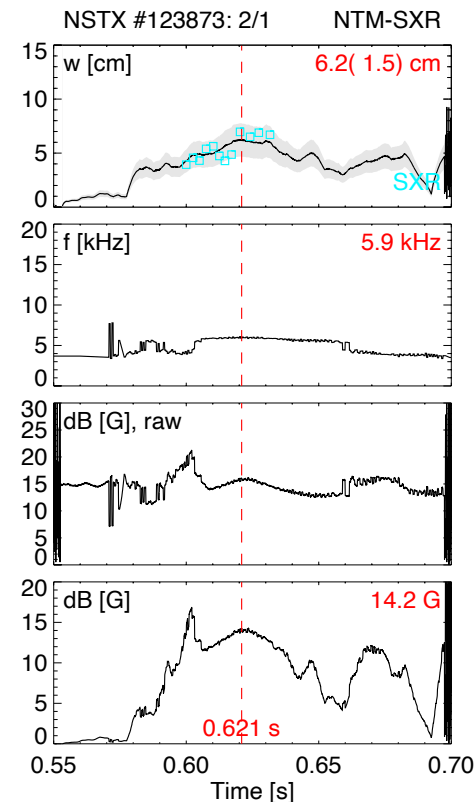
NSTX #134020

- H-mode with reliable rotating $n = 1$ onset
 - $I_p = 0.9$ MA, $B_T = 0.44$ T
 - P_{NB} steps down from 3 to 2 MW at 0.7 s
 - Lithiumization and $n = 1$ and $n = 3$ error field correction
- SXR/Mirnov conversion factor is $C_{SXR} = 1.17 \pm 0.16$
- Rotating $n = 1$ saturates at 6.3 cm
 - Onset at around 0.63 s when $\delta B = 1$ G
 - Peak at 0.704 s when $\delta B = 10$ G
 - Rotation is steady at 7.6 kHz ($q = 2$ from LRDFIT06)
 - Grows like CTM ($w \sim t$, $\text{dB} \sim t^2$)

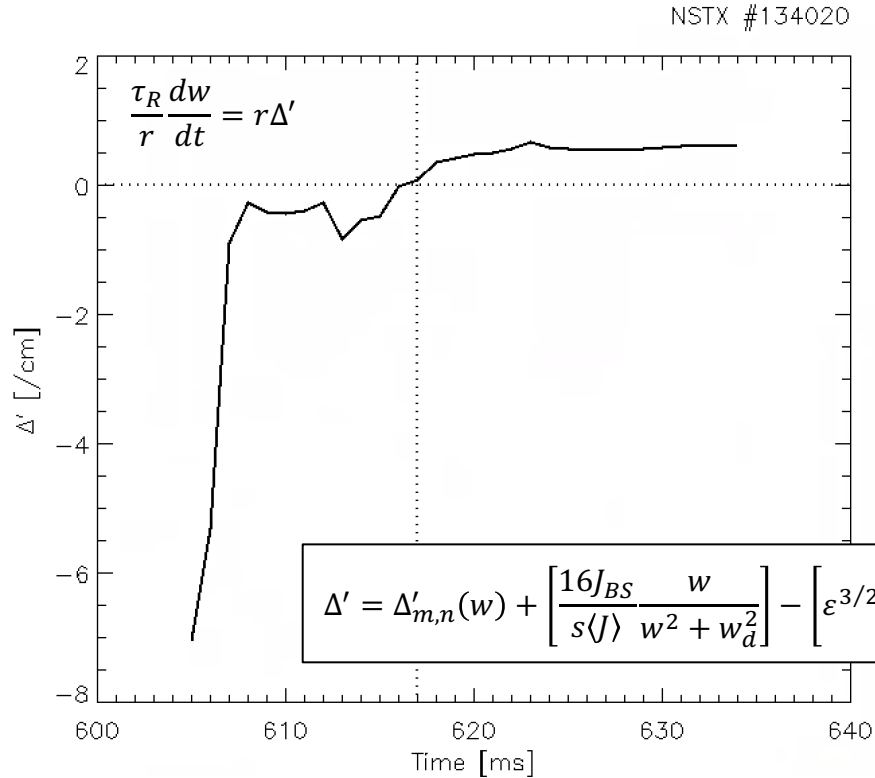


NSTX #123873

- Lower rotation
 - $I_p = 1.0$ MA, $B_T = 0.44$ T
 - P_{NB} steps down from 4 to 2 MW at 0.6 s
- SXR/Mirnov conversion factor is $C_{SXR} = 1.91 \pm 0.47$
- Rotating $n = 1$ saturates at 6.2 cm
 - Onset at around 0.58 s when $\delta B = 1$ G
 - Peak at 0.621 s when $\delta B = 14.2$ G
 - Rotation is steady at 5.9 kHz ($q = 2$ from LRDFIT06)
 - Grows like NTM ($w \sim t^{0.5}$, dB $\sim t$)



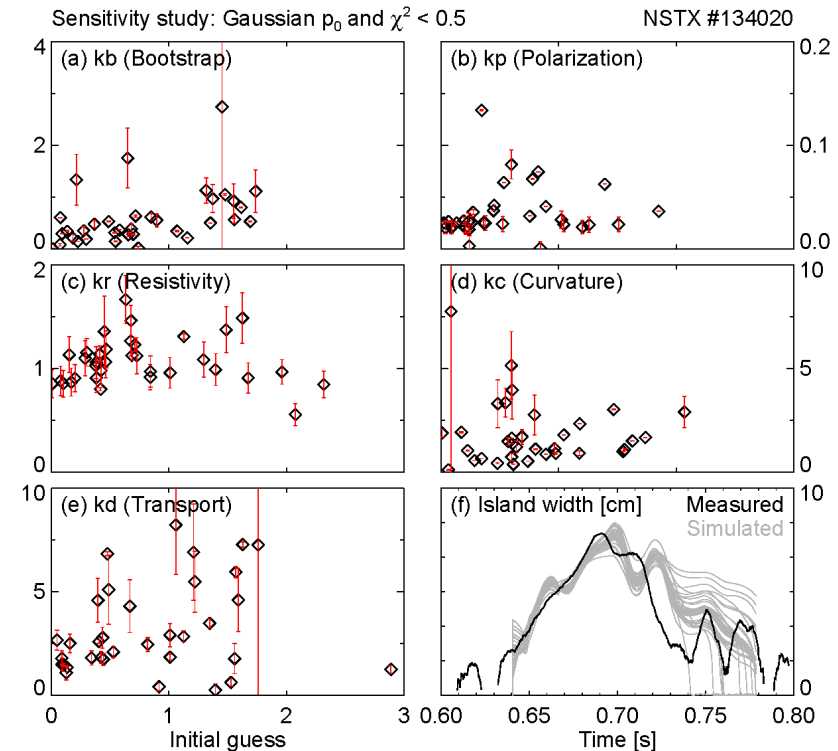
Simulation start time (T0) may be determined by T0 scan



- MRE inputs are provided by TRANSP
 - Useful to capture the trend of each input
 - Calculated Δ' following measured w
- Time marching is *likely* to start if $\Delta' > 0$
 - Helps determine simulation start time
 - $T0 = 617$ ms is recommended

Sensitivity study shows our fit is mathematical optimum

- Fit may be local minimum mathematically
 - Assigned random initial guess
 - Gaussian distribution (positive side)
- Box scatter results from sensitivity study
 - Selected only small χ^2 results
 - Initial guess of $k > 2$ rarely survives
 - Large uncertainty for k_d
 - Electron transport wash-up effect
- This confirms that fit is global minimum

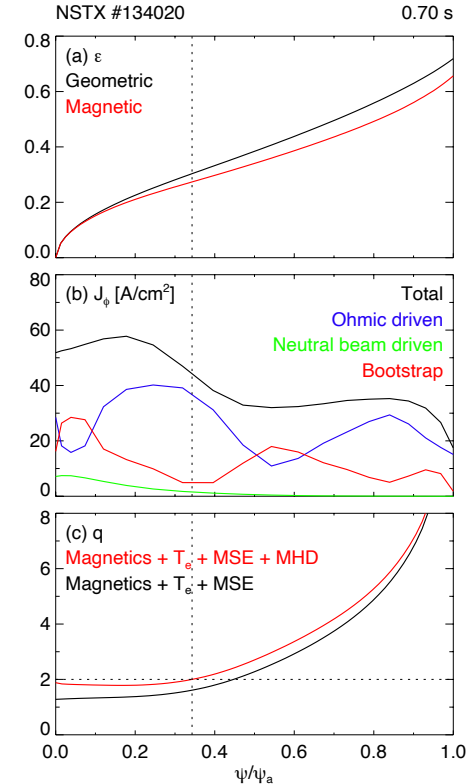


Special considerations are made for the simulation

- Geometric and magnetic ε are different in spherical tori
 - Rigorously, toroidal effects come from magnetic ε_B [1]

$$\varepsilon_B \equiv \frac{B_{in} - B_{out}}{B_{in} + B_{out}}$$

- Bootstrap current is calculated from NCLASS model [2]
 - Evolution of n_e and/or T_e is not the same as that of β_θ [3]
- Island location is used as extra constraint for q



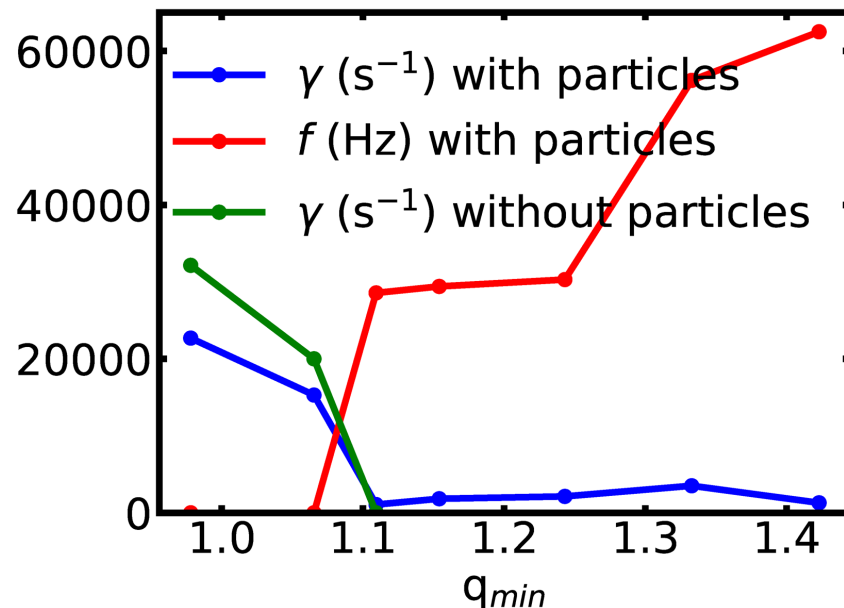
[1] La Haye *et al.*, Phys. Plasmas **19** 062506 (2012)

[2] Houlberg *et al.*, Phys. Plasmas **4** 3230 (1997)

[3] Fredrickson *et al.*, Phys. Plasmas **7** 4112 (2000)

M3D-C¹ Simulation Finds Hint of Kinetic Effect on Global MHD

- Real $f > 0$ and $\gamma > 0$ only with EP
 - Scanned $q_{\min}$ (scan B_ϕ), $n = 1$
 - Without EP, $\gamma < 0$ when $q_{\min} > 1.1$
 - With EP, $f \sim 30$ kHz with $m = 1, 2^*$
- Need improvement for publication
 - Linear sim. shows no TM w/ $\eta > 0$
 - Isotropic slowing down distribution is used (although beam-driven)
 - Frequency is higher than what is measured**



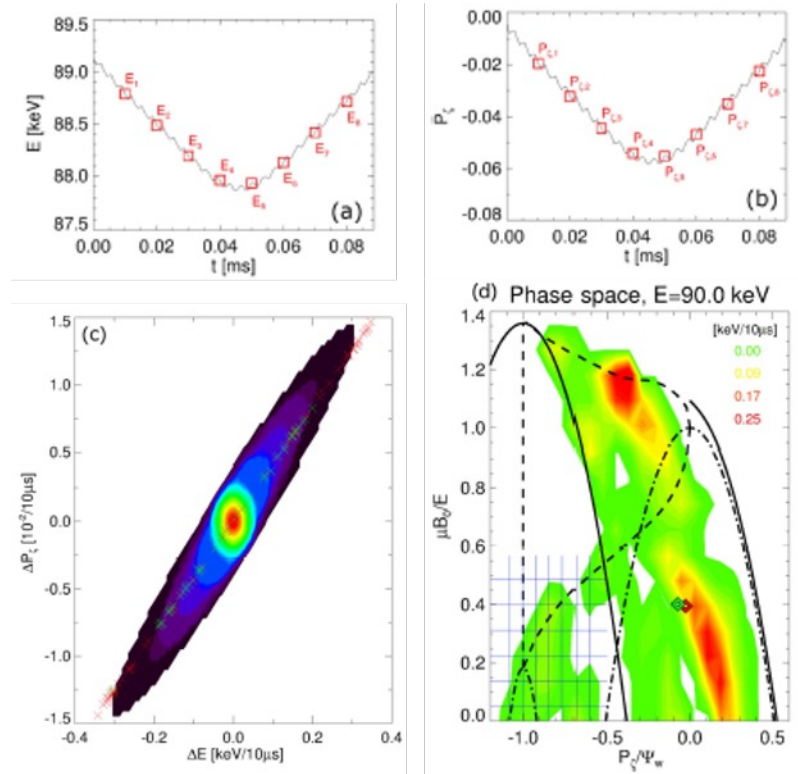
* NOVA simulation finds BAE at similar frequency range

** M3D-C¹ tend to overestimate f (vs. NIMROD)

Chang Liu

Kick model calculates EP interaction with MHD modes [1]

- EP dynamics can be affected by δB
 - Perturbation sources: Ripple, MHD...
 - EP follows magnetic field lines, hence affected by such perturbations
- ORBIT [2] code is used for calculation
 - Follow test particles
 - Accumulate ΔE and ΔP_ξ to evaluate wave particle resonance
 - Produce kick probability matrix

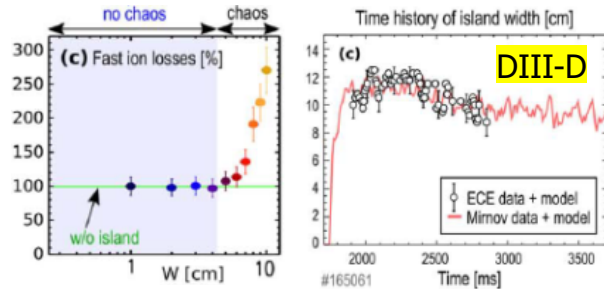
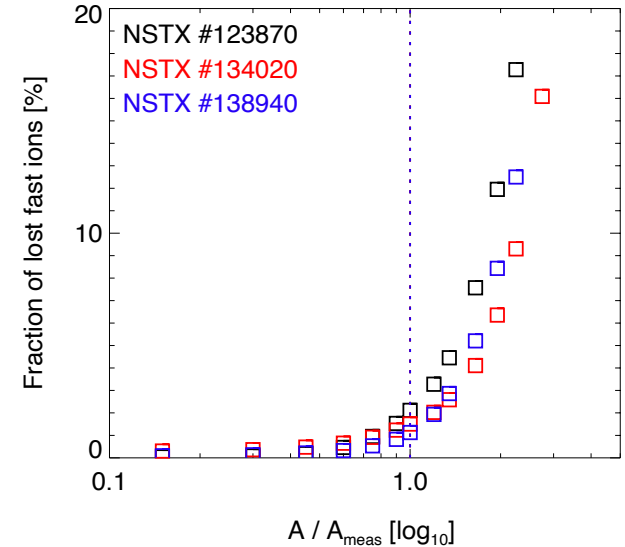


- [1] Podestà *et al.*, PPCF **56** 055063 (2014)
[2] White and Chance, PoF **27** 2455 (1984)
[3] Podestà *et al.*, PPCF **59** 095008 (2017)

Reproduced from Fig. A2 of [3]

Island saturates at orbit stochasticization threshold in NSTX

- Three NSTX discharges have different q profiles [1]
 - As mode amplitude is scanned beyond measured...
 - Fast ion transport starts to increase rapidly
 - At DIII-D, threshold was at $A / A_{\text{meas}} \ll 1$ [2]

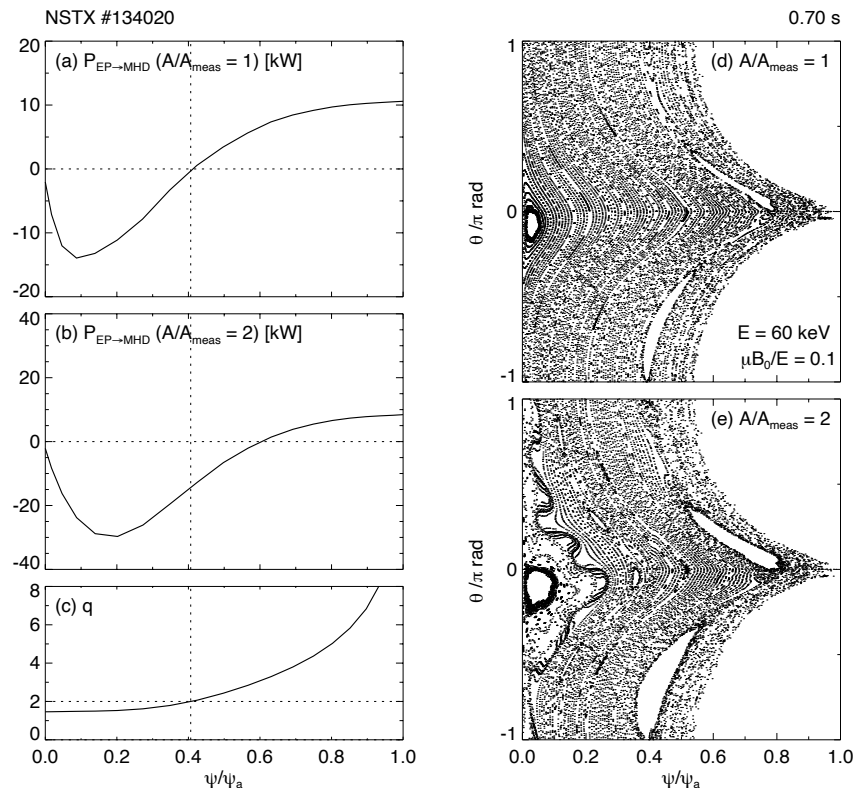


[1] Yang *et al.*, Plasma Phys. Control. Fusion **63** 045003 (2021)

[2] Bardoczi *et al.*, Plasma Phys. Control. Fusion **61** 055012 (2019)

Energy exchange profile shows fast ions taking energy from TM

- Stochastic transport is confirmed
 - Transport increases when...
 - KAM surfaces “start to” break [1]
- More fast ion transport for bigger island
 - Causes loss of passing fast ions
 - Less kinetic neoclassical polarization current
 - Island drive is reduced & growth saturates



[1] Collins *et al.*, Phys. Rev. Lett. **116** 095001 (2016)

Polarization current effect is not significant in value

