Triggering Neoclassical Tearing Modes in NSTX

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Motivation

- Well-known that potentially unstable neoclassical tearing modes (NTMs) in tokamak plasmas are meta-stable.[1]
- In other words, such NTMs require some sort of externally applied "kick" before they can grow and saturate at large amplitudes.
- What can provide this kick?
- Generally assumed that kick is transient magnetic perturbation due to other modes that occur in plasma: e.g., sawtooth crashes, edge localized modes, other NTMs, etc.
- However, there has been very little systematic investigation into what properties a transient magnetic perturbation needs to possess in order to successfully trigger an NTM.
- Present talk reports on first step in such an investigation.

[1] R. Fitzpatrick, Phys. Plasmas **2**, 825 (1995).

EPEC Code

- EPEC code simulates tearing mode dynamics in tokamak plasma using an asymptotic matching approach.[2]
- Code incorporates magnetic equilibrium data (g-file) and profile data (p-file).
- Code includes toroidal coupling between different tearing modes.
- Code incorporates accurate neoclassical model that includes impurities and neutrals, and allows calculation of bootstrap drive to tearing modes.[3]
- For case of NSTX, external perturbation is provided by pulsing RMP coils. However, perturbation is allowed to rotate. This mimics multi-harmonic rotating magnetic perturbation generated by sawtooth crash, etc.

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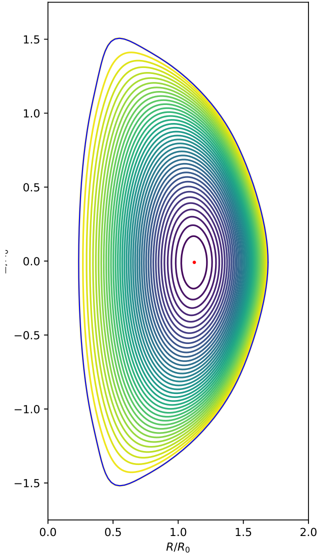
[2] R. Fitzpatrick, S.K. Kim, and J. Lee, Phys. Plasmas **28**, 082511 (2021).
[3] S.P. Hirshman and D.J. Sigmar, Nucl. Fusion **21**, 1079 (1981).

NSTX Shot 127317

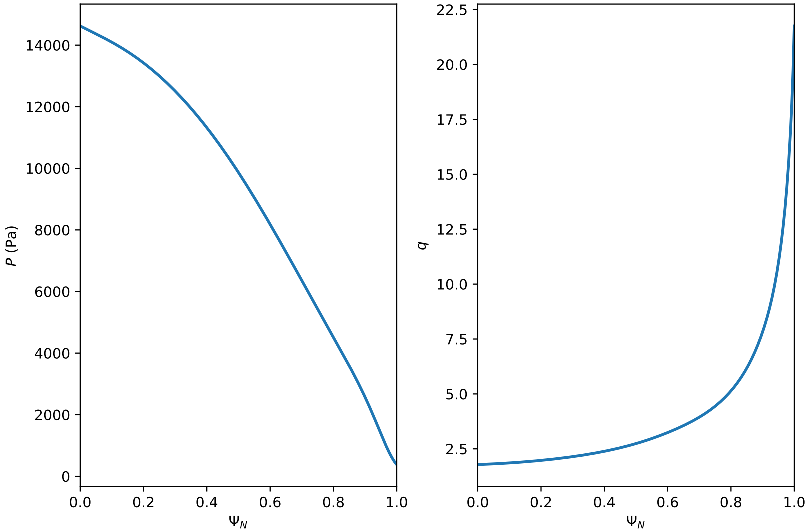
- NSTX shot 127317 was one of the shots used in the experimental campaign that demonstrated ELM destabilization via an externally applied non-axisymmetric resonant magnetic perturbation (RMP).[4]

[4] J.M. Canik, et al. Nucl. Fusion **50**, 034012 (2010).

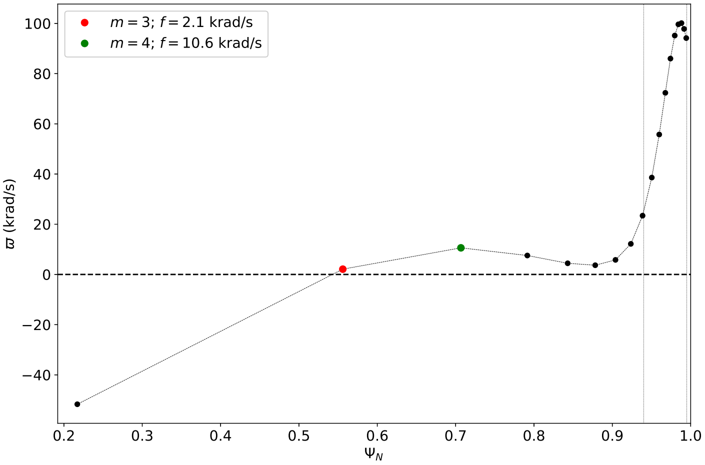
NSTX Shot 127317: Magnetic Flux-Surfaces



NSTX Shot 127317: Profiles



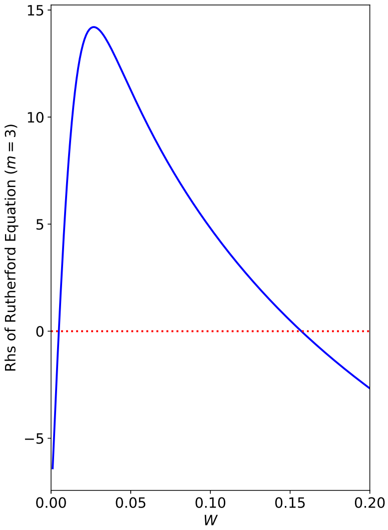
NSTX Shot 127317: $n = 1$ Natural Frequencies



NSTX Shot 127317: $n = 1$ Modes

- NSTX shot 127137 (400 ms) contains 18 $n = 1$ rational surfaces, corresponding to $m = 2$ through $m = 19$.
- Only two of these surfaces, $m = 3$ and $m = 4$, are potentially unstable to NTMs.
- The natural frequencies (i.e., frequencies that modes would rotate at if they were naturally unstable) of these modes are 2.1 krad/s and 10.6 krad/s, respectively.
- Natural frequencies determined by $\mathbf{E} \times \mathbf{B}$ flows, diamagnetic effects, and neoclassical effects.
- EPEC determines natural frequencies from experimental profile data (p-file). However, since there is no poloidal rotation data in NSTX, poloidal rotation is given its neoclassical value (including impurities and neutrals).

NSTX Shot 127317: Rutherford Island Equation Rhs



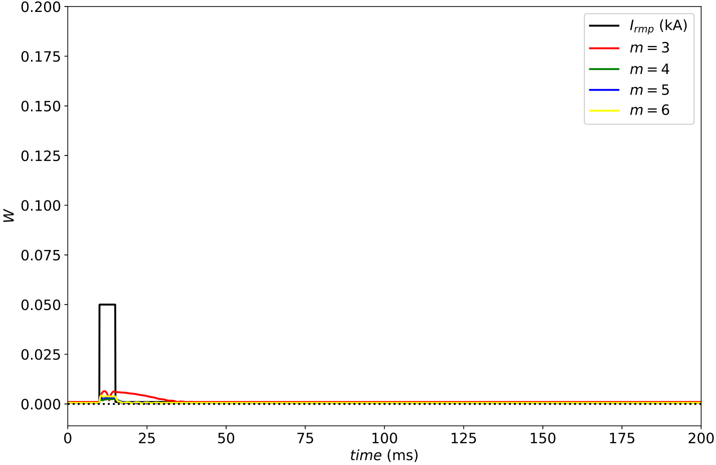
NSTX Shot 127317: Neoclassical Tearing Modes

- Previous figure shows that $m = 3$ and $m = 4$ modes are meta-stable NTMs.
- Both modes have potential to grow to large amplitudes ($W \sim 0.16$ and $W \sim 0.08$, respectively, in units of Ψ_N).
- No other $n = 1$ modes in plasma have Rutherford equation right-hand sides that rise above zero (i.e., they are all intrinsically stable).

NSTX Shot 127317: External Perturbation

- According to EPEC, if $n = 1$ simulation started in initial state in which all modes have very small amplitudes then mode amplitudes remain very small indefinitely. In other words, unperturbed plasma is stable.
- Apply external magnetic perturbation to system by applying square-wave $n = 1$ current pulse to RMP coils.
- Pulse has three properties:
  - Amplitude - $I_{rmp}(kA)$.
  - Temporal extent (period) - $\tau(\mathrm{ms})$.
  - Phase velocity - $f(\mathrm{krad/s})$.
- How do these properties affect ability of pulse to trigger NTMs?

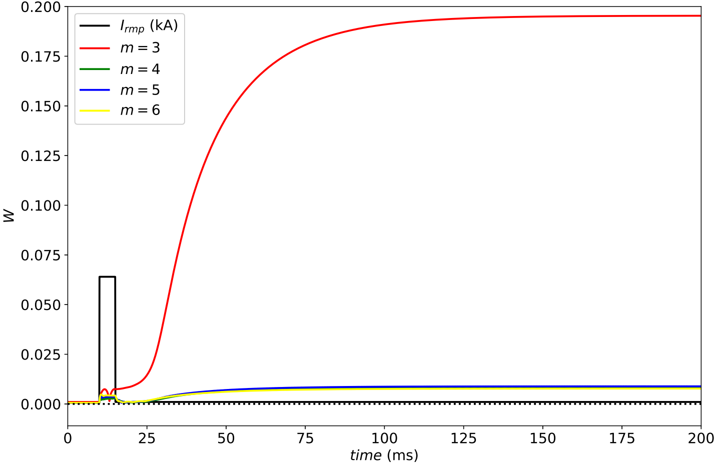
NSTX Shot 127317: Failed NTM Excitation



NSTX Shot 127317: Failed NTM Excitation

- Figure shows a 5 ms period, zero frequency [i.e., $\tau = 5$ (ms), $f = 0$ (krad/s)] RMP pulse that fails to excite an NTM.

NSTX Shot 127317: Successful NTM Excitation



NSTX Shot 127317: Successful NTM Excitation

- Figure shows a slightly higher amplitude 5 ms period, zero frequency [i.e., $\tau = 5$ (ms), $f = 0$ (krad/s)] RMP pulse that excites an $m = 3$ NTM.
- Note that once the $m = 3$ mode grows to high amplitude it acts like an RMP that drives small-amplitude islands at the $m = 4, 5, 6$ rational surfaces.
- However, $m = 4$ NTM is not triggered, even after $m = 3$ mode grows to large amplitude.

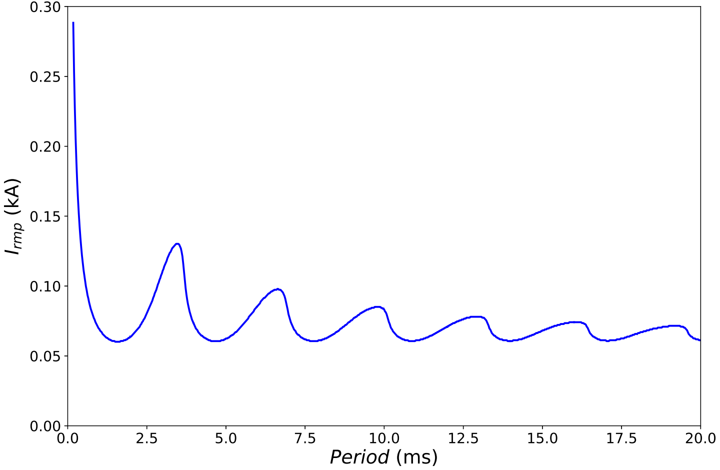
Period Scan

- How does critical RMP current needed to trigger $m = 3$ NTM depend on temporal extent of RMP pulse?
- Would generally expect long pulses to be more effective at driving RMPs than short pulses.
- So is the dependence just a monotonic decrease with increasing period?

EPEC Period Scan

- Period scan performed as follows.
- Each EPEC run simulates 200 ms.
- At end of run, EPEC determines whether NTM has been excited or not.
- Generally takes 10 to 20 runs to accurately determine critical RPM current (EPEC uses bisection method).
- There are 2000 points in each period-scan curve.
- So period-scan curve corresponds to 8000 seconds of simulation. This would be impossible with conventional MHD code. However, calculation can be done on ordinary desktop with asymptotic matching approach.

NSTX Shot 127317: Period Scan



NSTX Shot 127317: Period Scan

- Figure shows critical RMP current required to trigger $m = 3$ NTM as function of pulse temporal extent (period). Pulse is non-rotating.
- On average, critical RMP current does indeed go down with increasing pulse period.
- However, critical RMP current has unexpected oscillations.
- Note that all minima are same. Implies that $\tau \simeq 1.5$, 4.5, 7.5, ms, etc. pulses are just as effective at driving NTM as $\tau = \infty$ pulse.

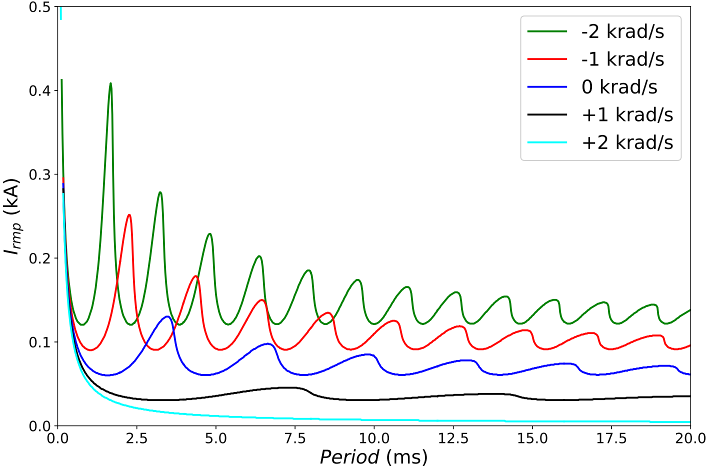
NSTX Shot 127317: Period Scan

- Key to understanding oscillatory behavior is fact that $m = 3$ mode has finite natural frequency of 2.1 krads = 0.33 kHz.
- When RMP pulse applied it drives $m = 3$ island that is initially in phase with RMP.
- However, $m = 3$ island forced to rotate at natural frequency by plasma flow (applied RMP is nowhere near large enough to lock small island).
- As island rotates, its phase relative to the pulse changes. In some phases, RMP causes island to grow, in others it causes it to shrink. This is origin of oscillations.
- Roughly speaking, after half period of natural frequency (time required for island chain to transition from being in phase to being in anti-phase with RMP) remainder of RMP pulse averages to zero (because, on average, rotating island sees net zero drive from static RMP). This explains why $\tau = 1.5$ ms pulse is just as effective as $\tau = \infty$ pulse.

Frequency Scan

- How does critical RMP current needed to trigger $m = 3$ NTM depend on frequency of RMP pulse?
- Would expect NTM triggering to be particularly easy when RMP frequency matches natural frequency, because there would be no tendency of driven island to move out of phase with RMP.

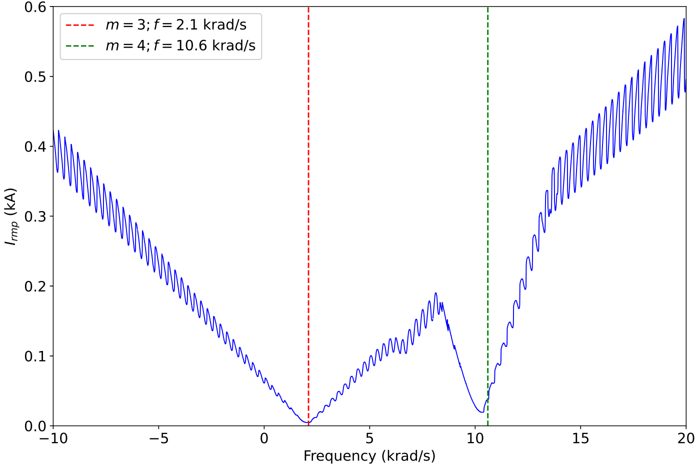
NSTX Shot 127317: Period/Frequency Scan



NSTX Shot 127317: Period/Frequency Scan

- Clear from figure that as we move towards natural frequency (2.1 krad/s), critical RMP current is reduced, and oscillations become smaller in amplitude and longer in period.
- Conversely, as we move away from natural frequency, critical RMP current increases, and oscillations become larger in amplitude and shorter in period.

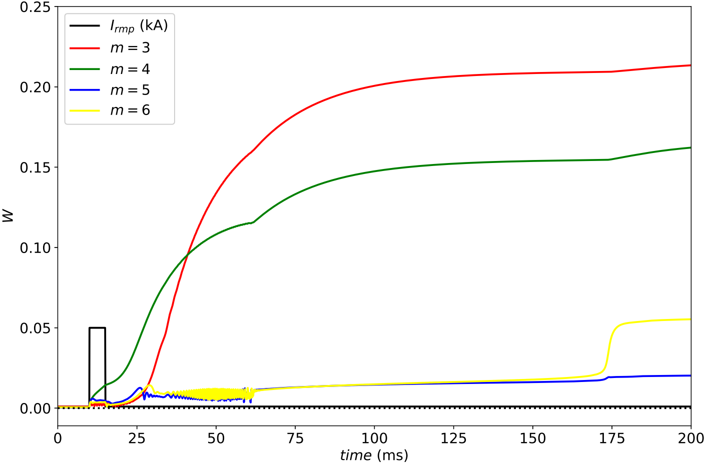
NSTX Shot 127317: Frequency Scan



NSTX Shot 127317: Frequency Scan

- Figure shows critical RMP current required to trigger NTM, for pulse of period 20 ms, as function of pulse frequency.
- Critical current minimized when pulse frequency matches natural frequency of either of potentially unstable NTMs.

NSTX Shot 127317: Frequency Scan



NSTX Shot 127317: Frequency Scan

- Figure shows effect of pulse whose frequency matches $m = 4$ NTMs natural frequency.
- Pulse triggers both $m = 4$ and $m = 3$ NTMs.
- Two NTMs lock. Subsequently, other mode lock to NTMs.
- Note that pulse that triggers this catastrophic series of events would have triggered nothing if its frequency were zero.

Conclusions

- Have investigated what properties of multi-harmonic magnetic perturbation make it effective at triggering NTMs.
- Have found that by far the most important property of the perturbation is its frequency.
- If frequency close to natural frequency of potentially unstable NTM then it is easy to trigger associated NTM.
- If frequency is far from natural frequencies of potentially unstable NTMs then perturbation is ineffective at triggering NTMs.