The Role of the m/n=3/2 Tearing Mode in the Hybrid Scenario and Extension of the Hybrid Operating Regime

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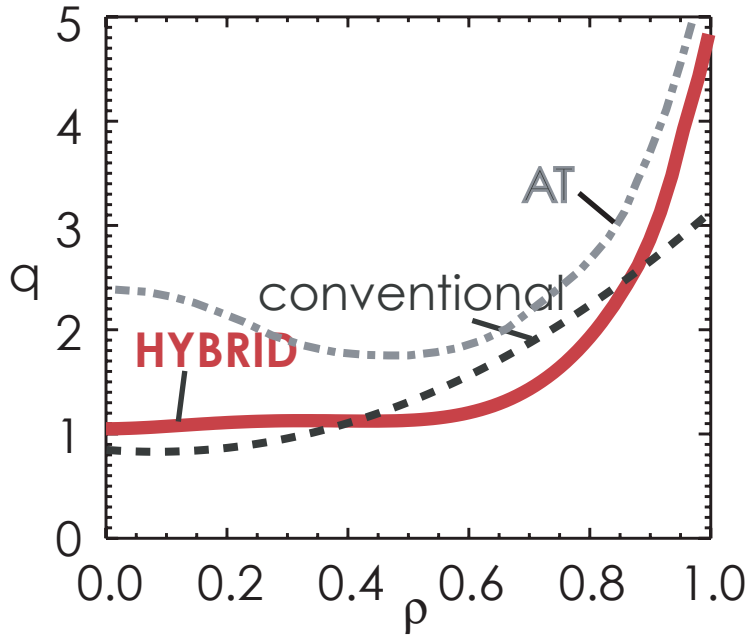
DIII-D NATIONAL FUSION FACILITY

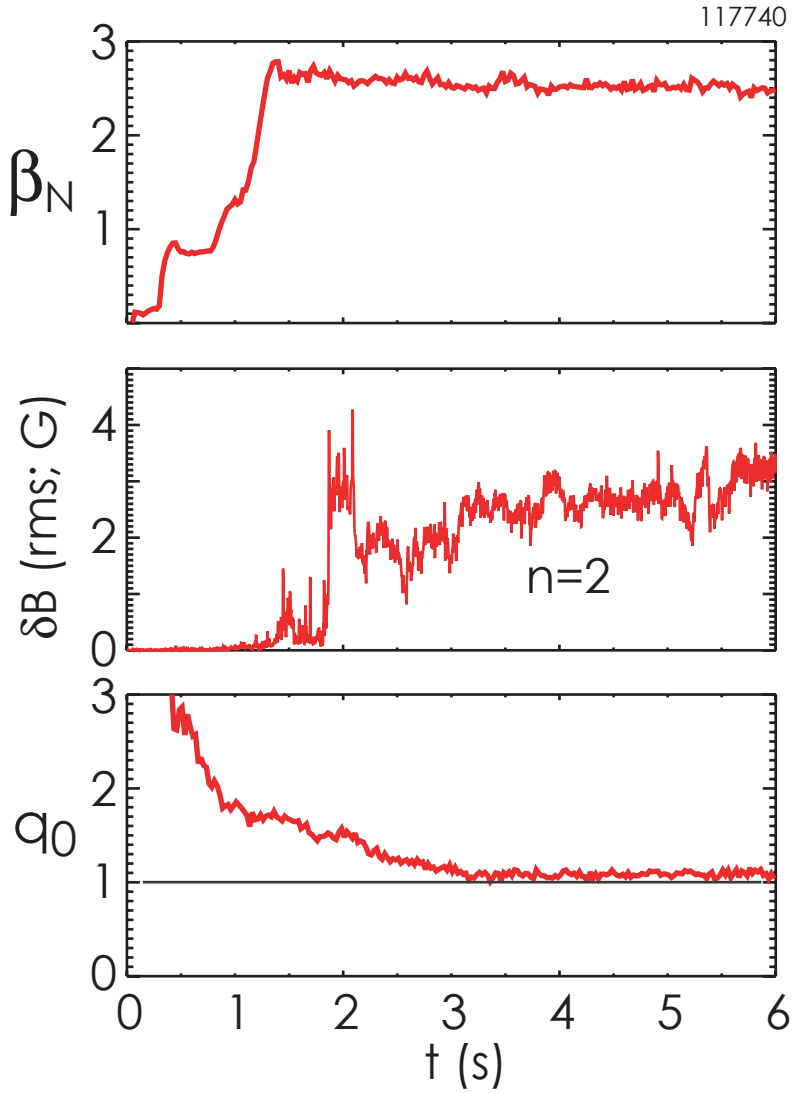
GENERAL ATOMICS

The hybrid scenario – a candidate for ITER operation

- **An operating scenario for ITER**
  - maximize the neutron fluence per pulse
  - stationary (w/ inductive current, ≠ steady-state)
  - projects to Q ≥ 10 for ≥ 1 hour in ITER
- **DIII-D realization:**
  - **q95 ≥ 4**
  - **q(0) ≥ 1**
    sawteeth absent
    (or inconsequential)
  - **m/n = 3/2 NTM**
    modifies the current profile
    keep q(0) ≥ 1
    higher shear at q=2



An NTM is an essential feature of the hybrid scenario plasma in DIII-D



- **β is raised to its target value**
  - early H-mode
  - short ELM-free period
  - held by feedback control
- **m=3, n=2 NTM appears before sawteeth start!**
- **current profile evolves to stationary state**
- **q(0) = 1 + ε (ε ≤ 0.05)**

Progress in studies of the hybrid scenario

- ρ_* scaling
  - ρ_* was scaled 1.6x with other dimensionless parameters fixed
  - χ_{eff} scaling slightly worse than gyro-Bohm (similar to standard H-mode)
  - 3/2 island width and 2/1 β limit ($\beta_N \approx 4\ \ell_i$) are independent of ρ_*
- ELM modification with static helical field perturbation
  - ELM frequency increases, confinement worse
  - behavior differs from LSN plasmas
  - $\Rightarrow$ invited talk: T. Evans, Friday morning
- Radiative divertor successfully applied
  - $\Rightarrow$ poster: T. Petrie, Thursday
- Preemptive ECCD prevents 2/1 NTM at $\beta_N \approx 4\ \ell_i$
  - co-ECCD applied at q=2 surface (before 2/1 mode appears)
  - real-time tracking of q=2
  - 2/1 NTM appears 100 ms after ECCD turned off

Conjecture

- The 3/2 NTM is responsible for the improved performance of the hybrid scenario plasmas in DIII-D
- It modifies the q profile
  - in the outer half of the plasma
    - ❖ increases shear at the q=2 surface
    - ❖ reduces turbulent amplitude, improving overall χ_i and χ_e
  - in the core
    - ❖ keeps q(0) ≥ 1
    - ❖ reduces (q95 ≈ 4) or eliminates (q95 > 4) sawteeth eliminating trigger for 2/1 NTM

⇒ better confinement and higher β limits than standard ELMy H-mode scenario

Topics

- Focus on region near the magnetic axis
  - interaction between the 3/2 mode and the q profile
  - effect on sawteeth

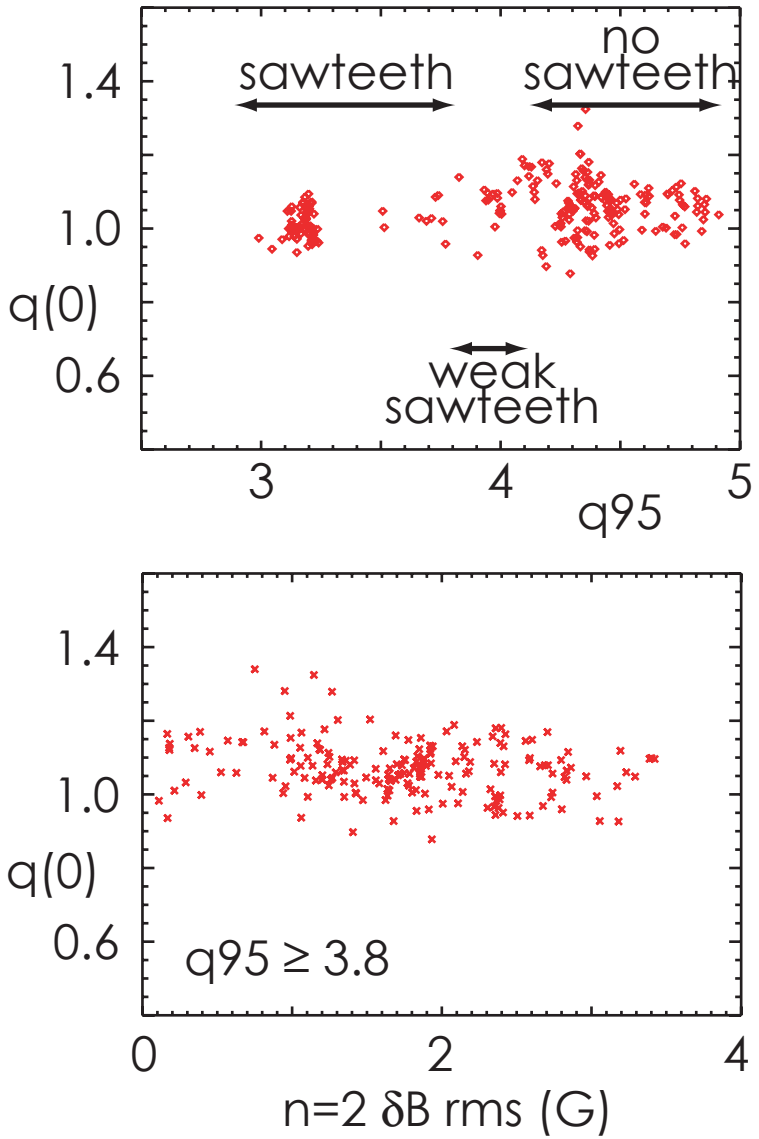
✧ Stationary q(0) = 1 + ε is not coincidental

✧ Detailed characteristics of the 3/2 mode

✧ q(0) and sawteeth depend on 3/2 amplitude

✧ Ideas about possible physical mechanisms

Stationary q(0) = 1 + ε is not coincidental



- **q(0) independent of q95**
- **q(0) does not depend on amplitude of 3/2 mode**

hybrid database
q(0) & q95: control room EFITs
average values during stationary phase

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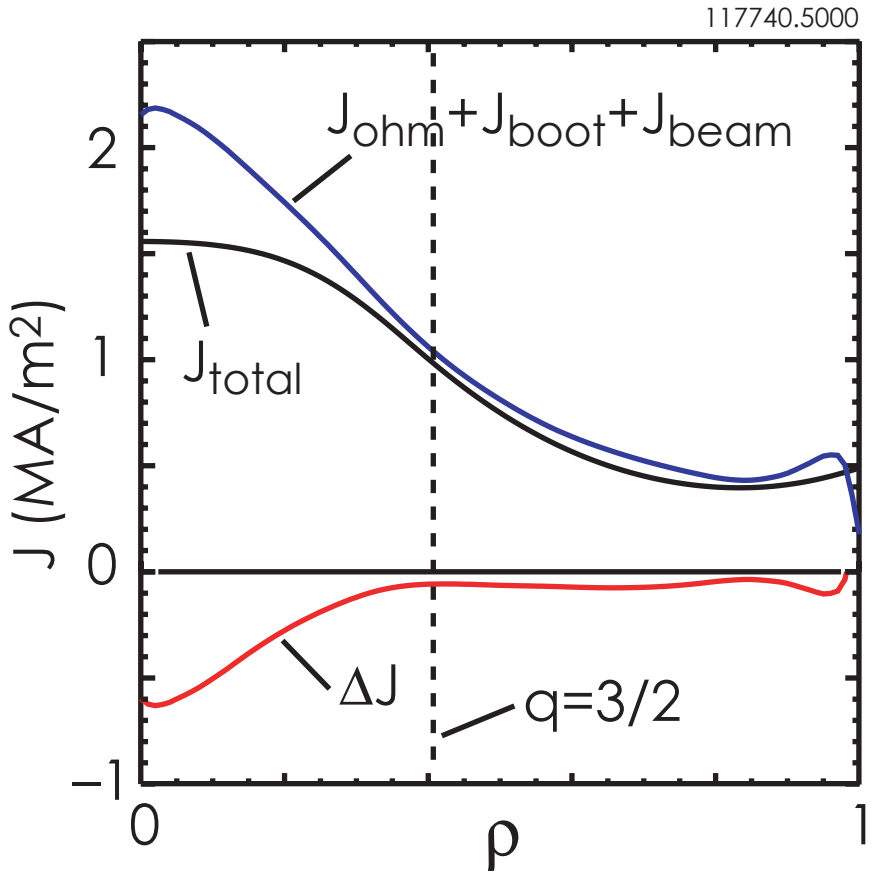
A non-classical counter current near the axis



- **Equilibrium analysis**
  - stationary conditions
  - 0.5 s average
- **J_{total} from EFIT reconstruction**
- **J_{ohm}, J_{boot}, J_{beam} from n_e, T_e, T_i, Z_{eff} profiles & E_ϕ ($\partial\psi/\partial t$)**
- **Missing current (ΔJ) is localized inside q=3/2 surface**
- **ΔI ($\rho \leq 0.4$) ≈ 50 kA**

  (I_{tot} = 1170 kA; I_{ohm} = 650 kA; I_{boot} = 390 kA; I_{beam} = 180 kA)

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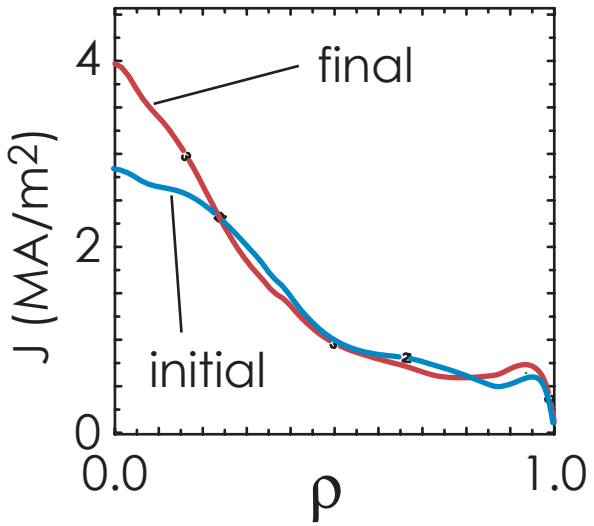
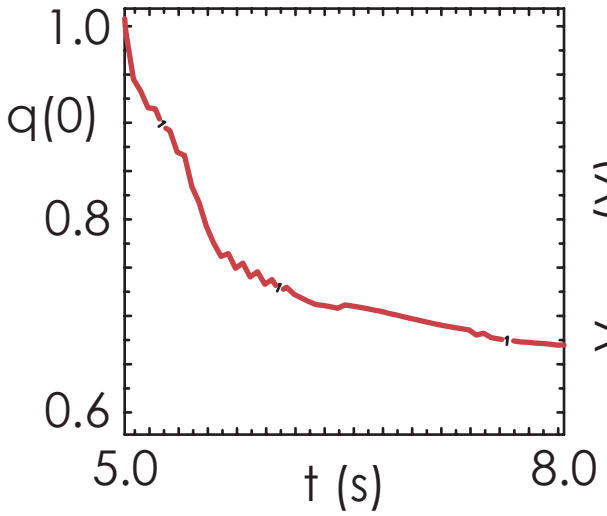
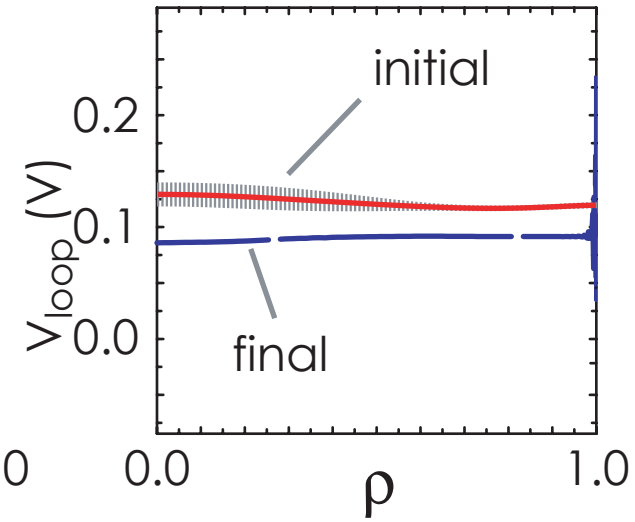
A non-classical counter current near the axis



- **Model neoclassical evolution of J(ρ)**
- **Start with stationary equilibrium**
- **Fix density & temperature profiles**
  (=> include effect of 3/2 islands)
- **evolve J profile for 3 sec with neoclassical conductivity (Corsica)**





=> J(0) increases
q(0) drops below 1

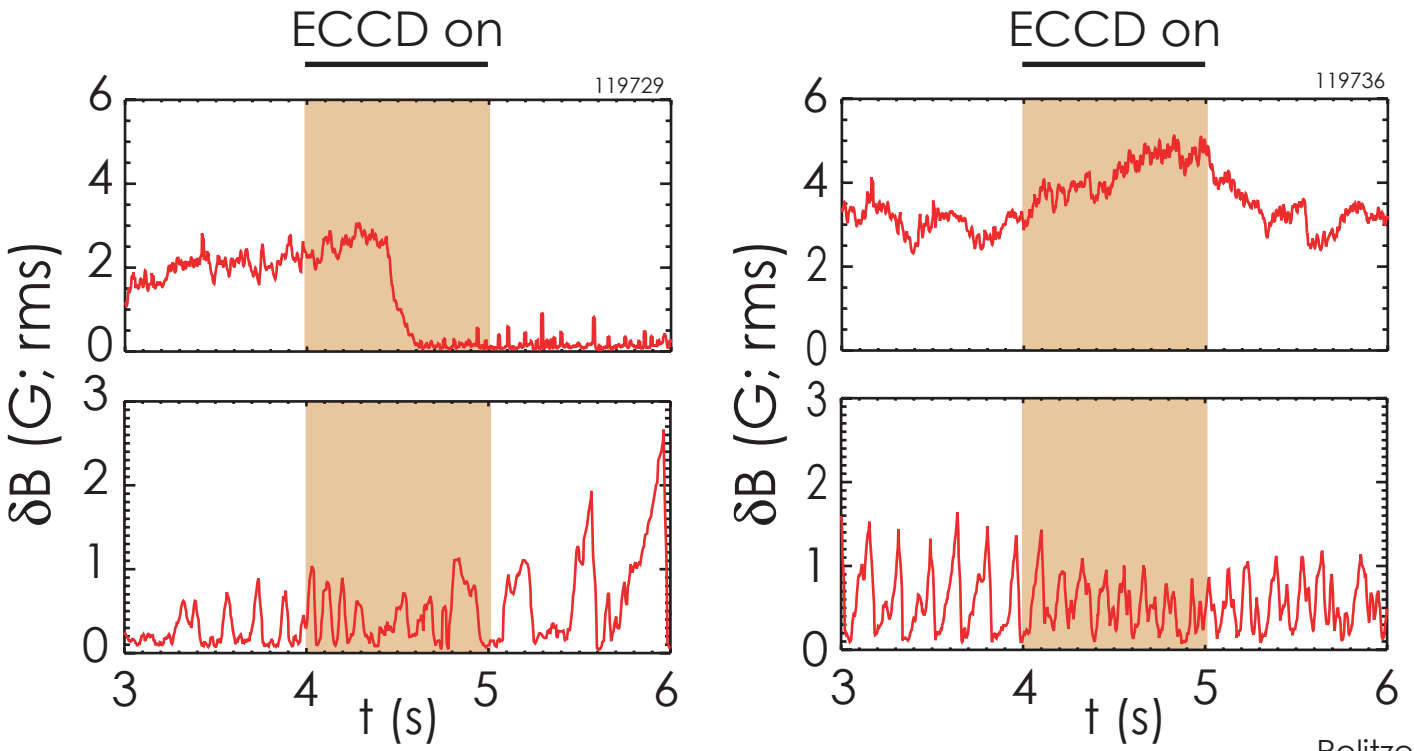
ECCD suppresses/enhances 3/2 NTM – sawteeth strongly affected

- co-ECCD at q=1.5
- suppresses 3/2 NTM
- sawteeth appear

- counter-ECCD at q=1.5
- enhances mode
- sawteeth suppressed

n=2
3/2 NTM

n=1
sawteeth



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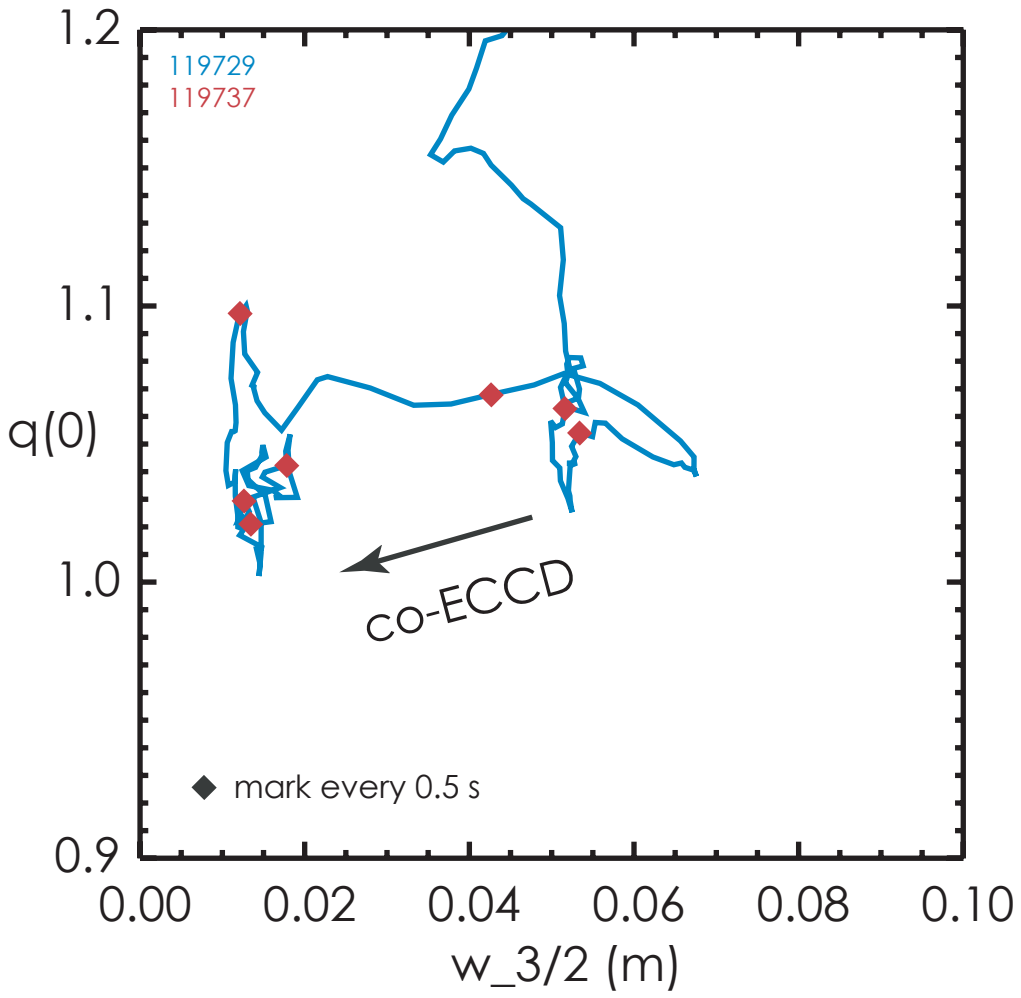
q(0) is correlated with the island width

- **calculate island width***
- **width ~5 cm as q(0) decreases**
- **q(0) becomes steady**
- **apply co-ECCD at island**
  - **– suppress NTM**
    (to noise level)
  - **– $\Delta q(0) \approx -0.04$**



* R. La Haye, et al., Phys. Plasmas 7 3340 (2000)

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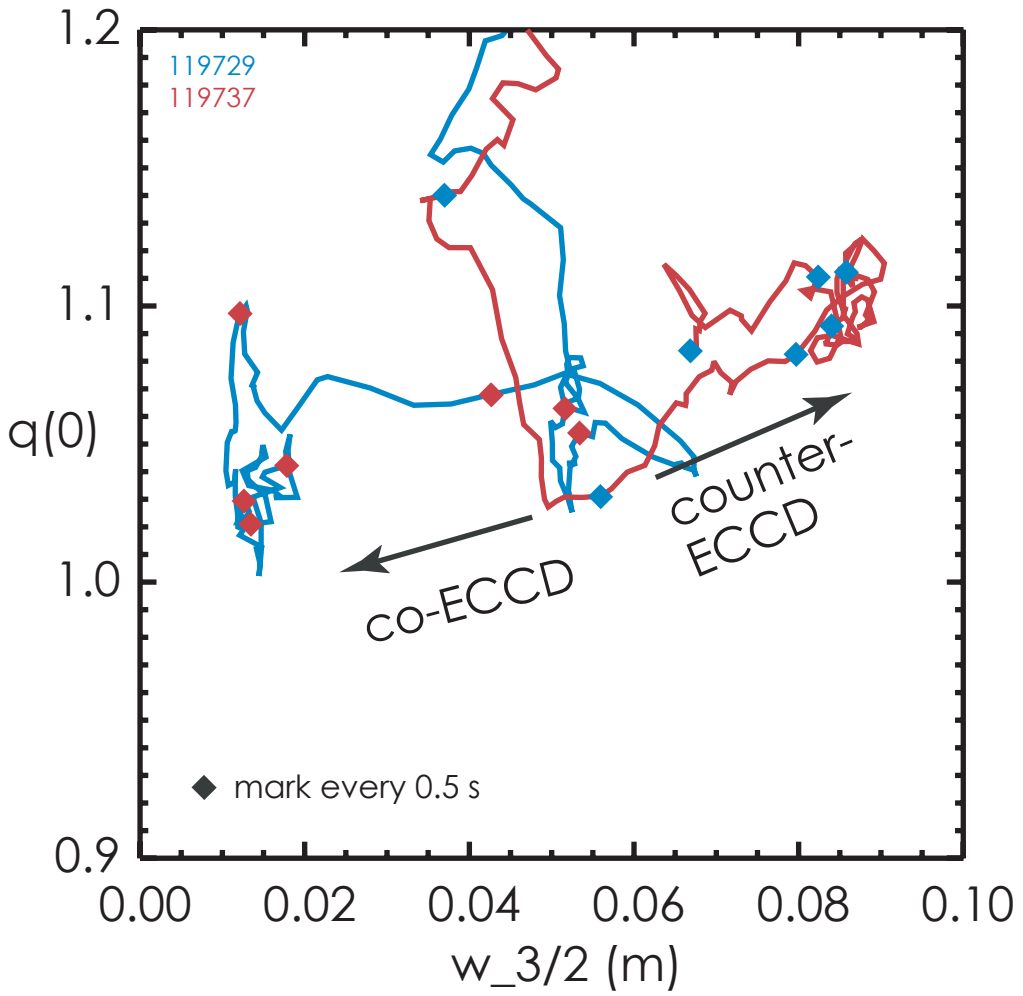
q(0) is correlated with the island width

- **calculate island width***
- **width ~5 cm as q(0) decreases**
- **q(0) becomes steady**
- **apply co-ECCD at island**
  - suppress NTM (to noise level)
  - $\Delta q(0) \approx -0.04$
- **apply counter-ECCD**
  - **NTM grows (~2x)**
  - **$\Delta q(0) \approx +0.05$**



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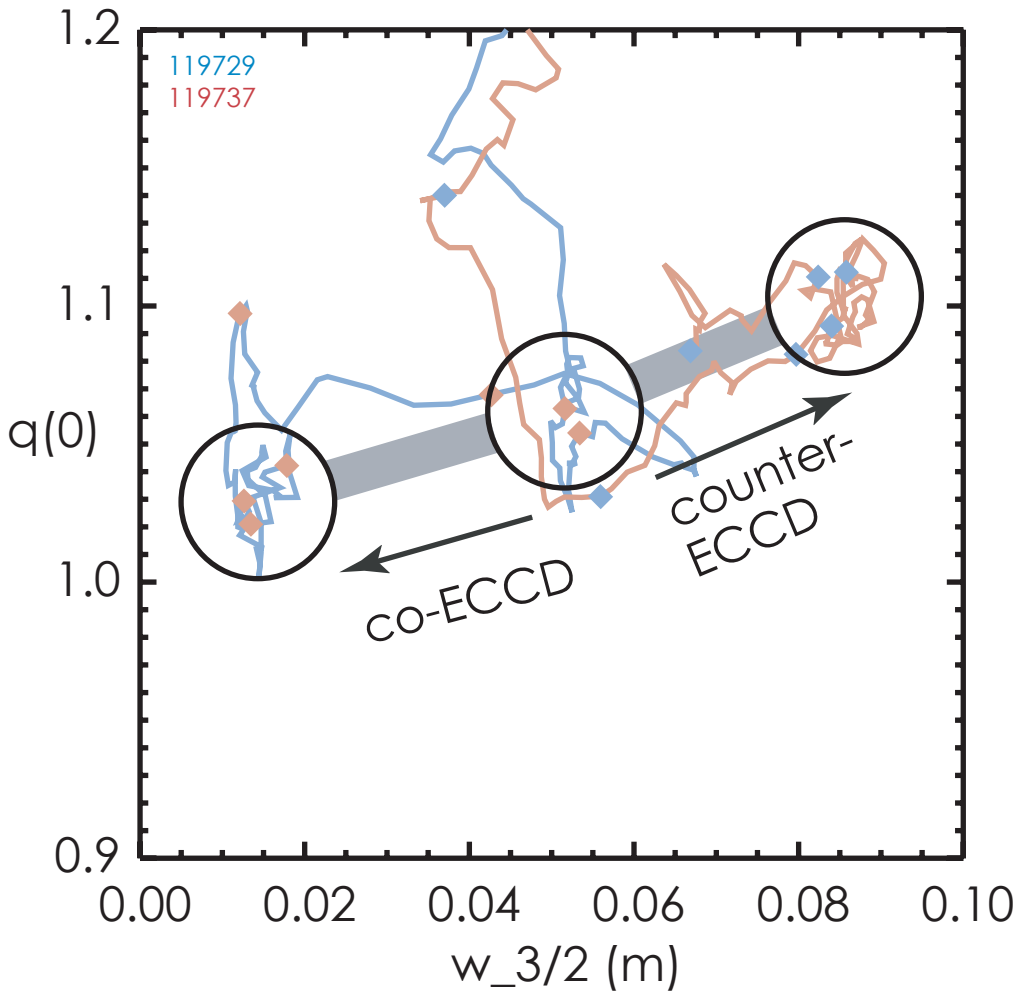
q(0) is correlated with the island width

- **calculate island width***
- **width ~5 cm as q(0) decreases**
- **q(0) becomes steady**
- **apply co-ECCD at island**
  - suppress NTM (to noise level)
  - $\Delta q(0) \approx -0.04$
- **apply counter-ECCD**
  - NTM grows (~2x)
  - $\Delta q(0) \approx +0.05$
- **$\Delta q(0)/\Delta w_{3/2} \sim 1\ m^{-1}$**



* R. La Haye, et al., Phys. Plasmas 7 3340 (2000)

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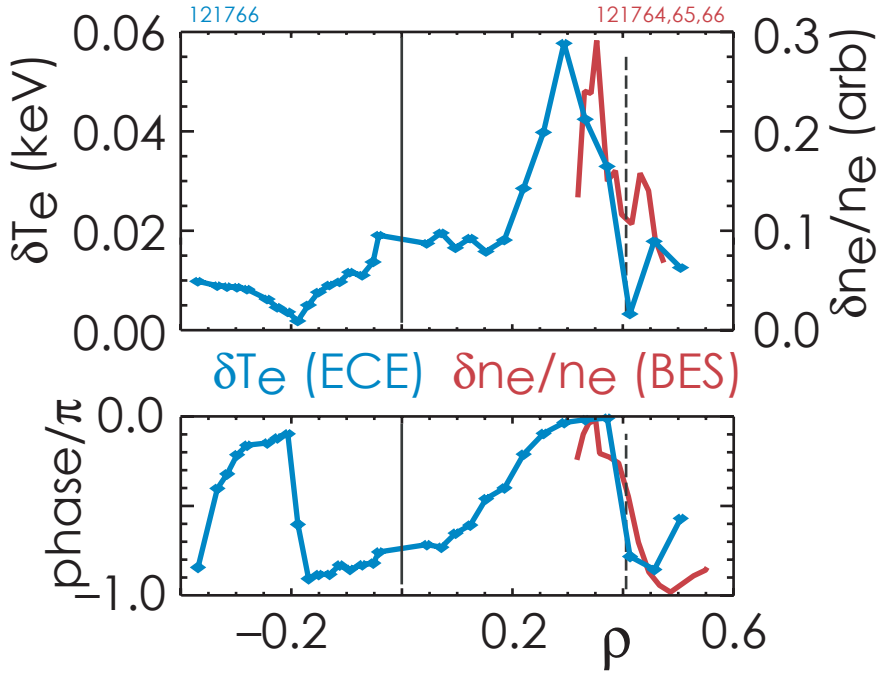
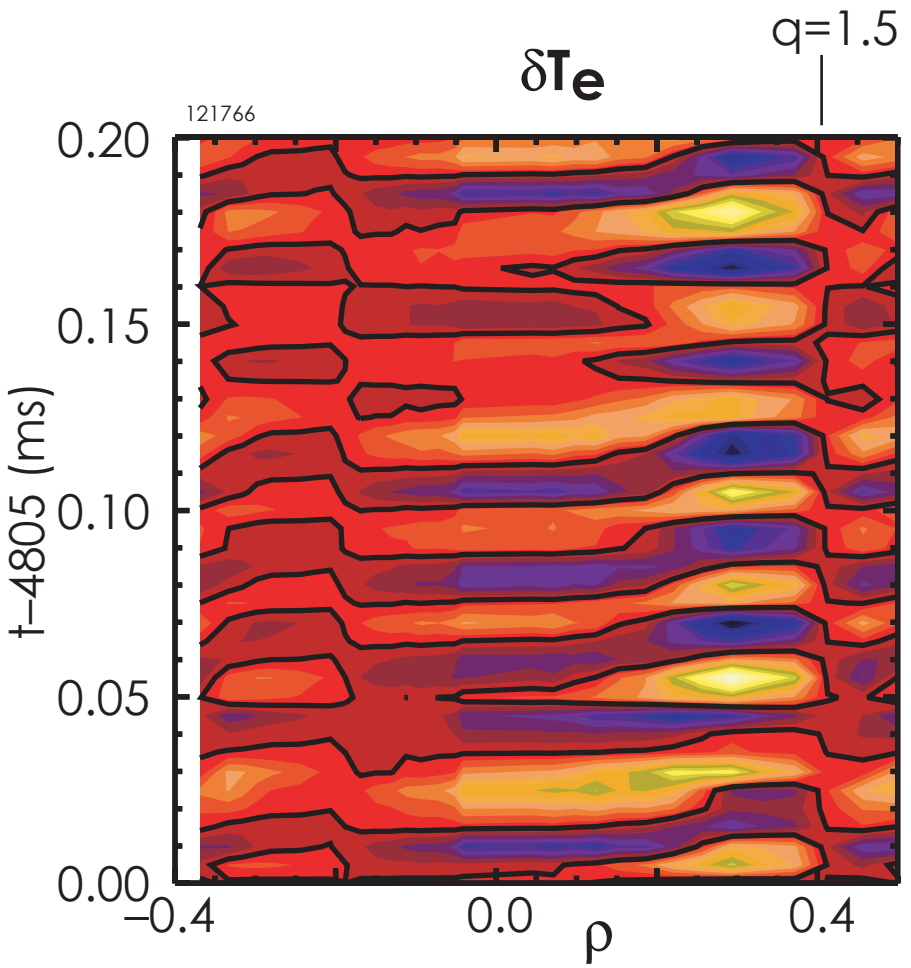
3/2 NTM structure in δT_e and δn_e throughout core

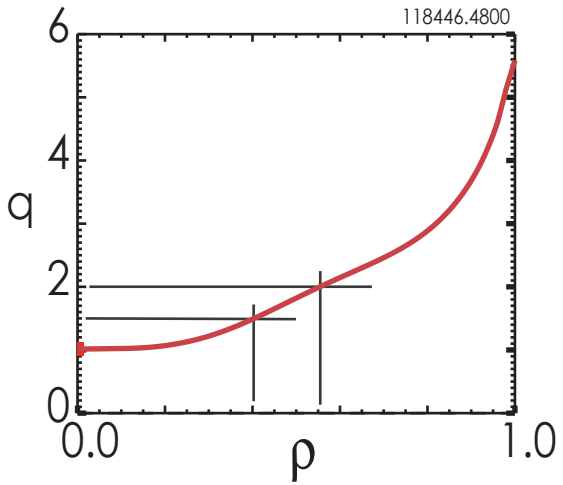
- amplitude & phase of δT_e (blue) and $\delta n_e/n_e$ (red)
- significant amplitude near axis

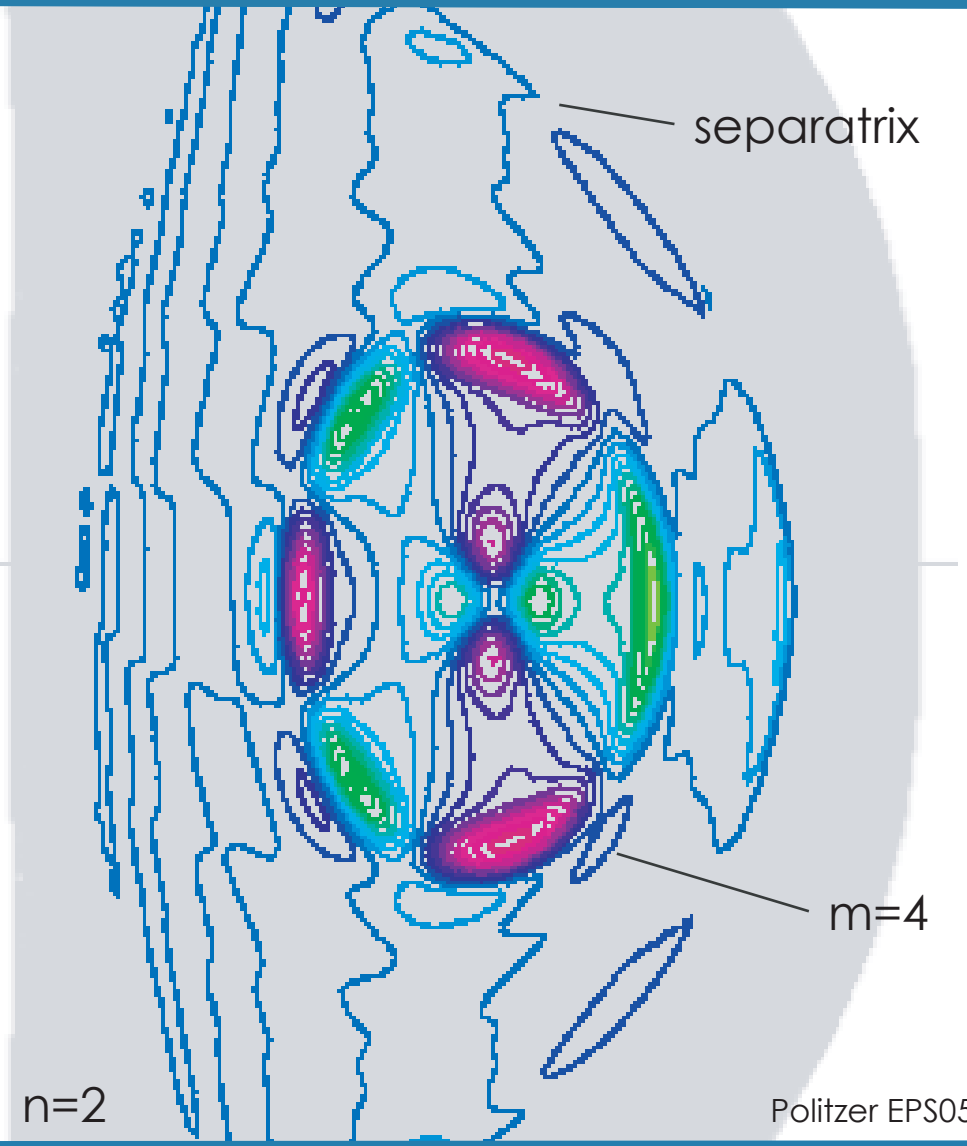




Computed 3/2 NTM is a global mode with 2/2, 4/2, ... components

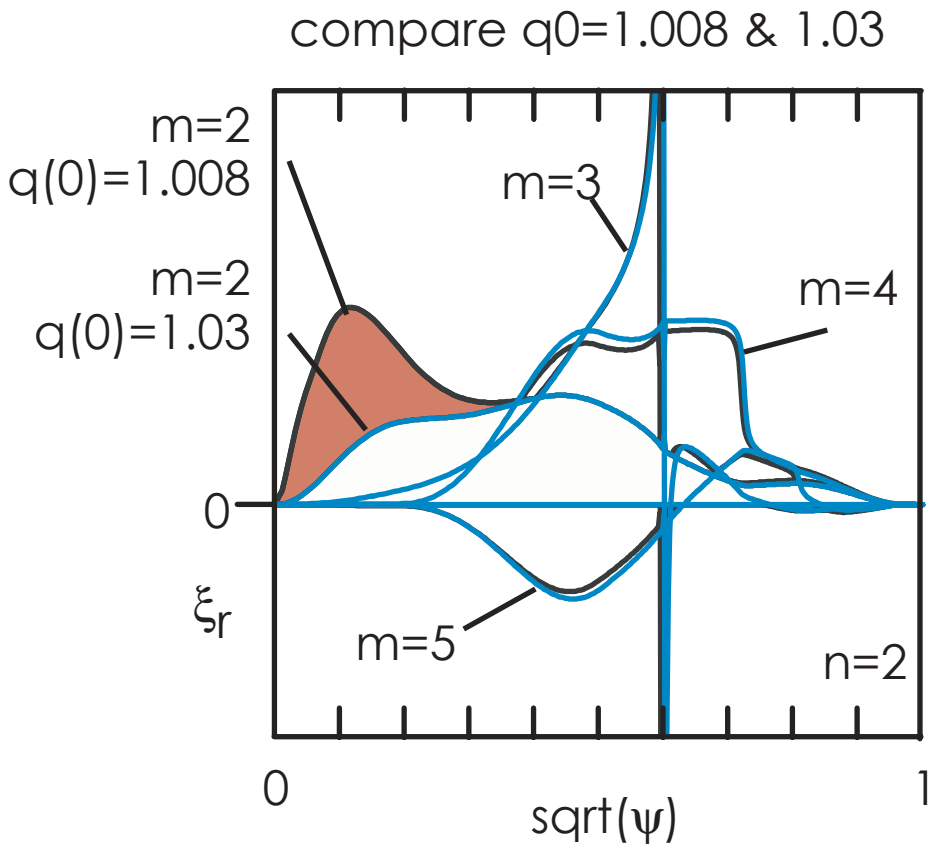
- **pressure perturbation**
  - NIMROD code
  - n=2 linear mode
- **m=3 island structure**
- **m=4 component at q=2**
- **prominent m=2 near axis**





The m/n = 2/2 component is sensitive to q(0)–1

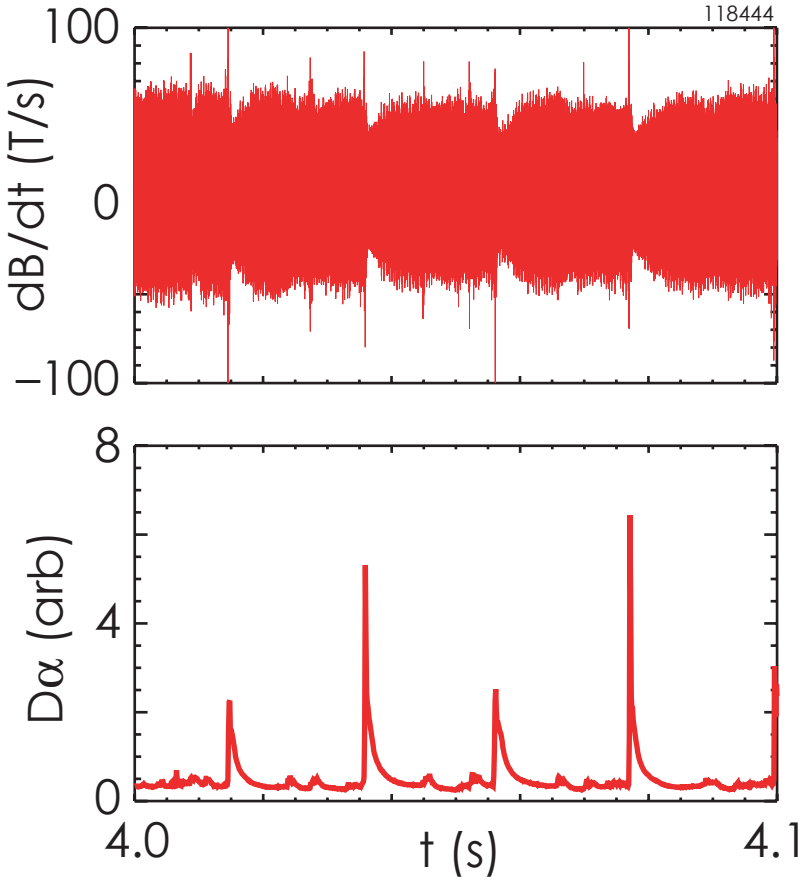
- q(0) scan
  - model equilibria
  - 1.008 ≤ q(0) ≤ 1.2
- radial displacement
  - n=2 mode
  - linear calculation (PEST3)
- little change in structure of poloidal harmonics until q(0) ≤ 1.03
- then m=2 amplitude rises rapidly near axis



Mechanisms suggested to explain the effect of the 3/2 mode on q & J

- modulation of 3/2 amplitude
  - asymmetry in time $\Rightarrow$ flux pumping (analogous to sawteeth)
  - modulation by ELMs not related to q(0) $\rightarrow$ 1
- helical perturbation
  - increase resistivity (reduce J_{ohm})
  - increase radial transport of fast ions (reduce J_{beam})
  - can be sensitive to q(0) $\rightarrow$ 1
- dynamo
  (conversion of kinetic to magnetic energy via $\langle \tilde{V} X \tilde{B} \rangle$)
  - no data

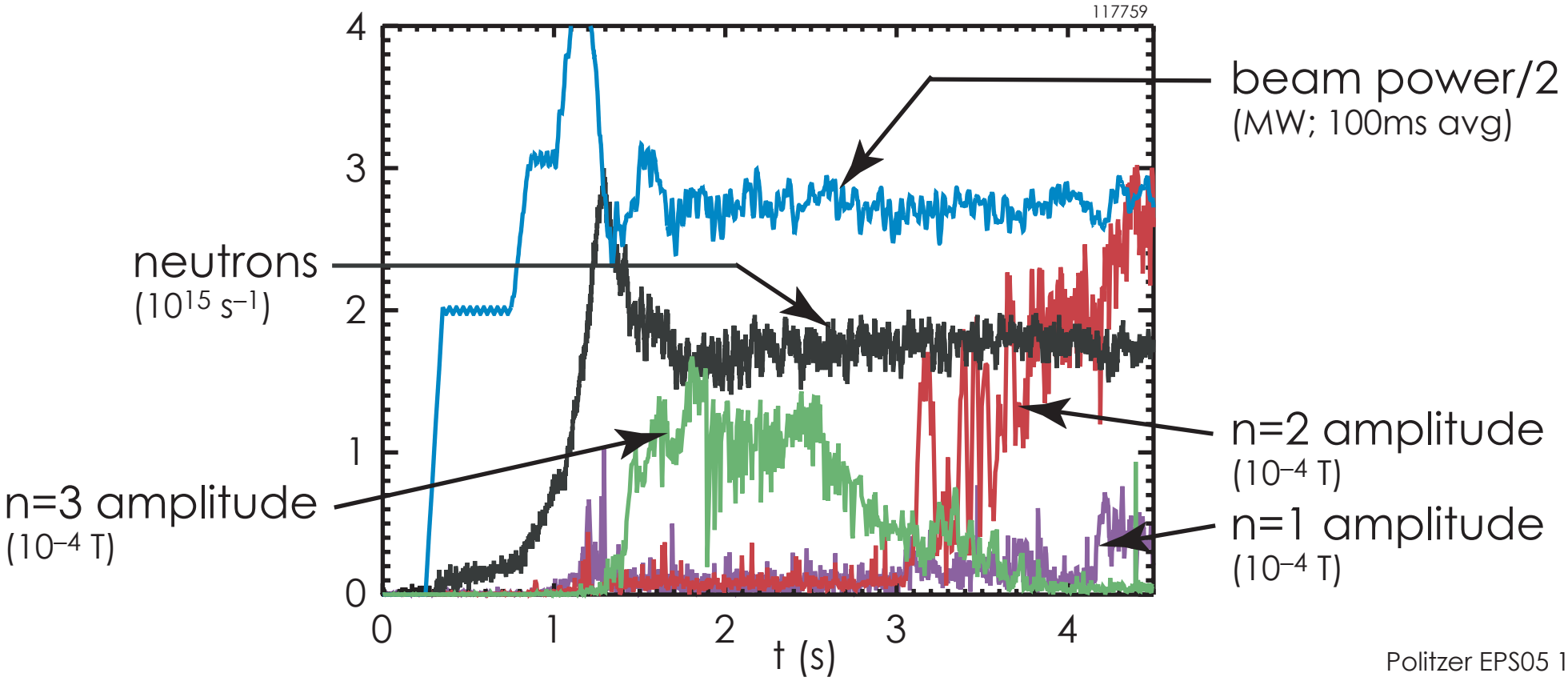
Time asymmetric modulation by ELMs may modify the average current profile



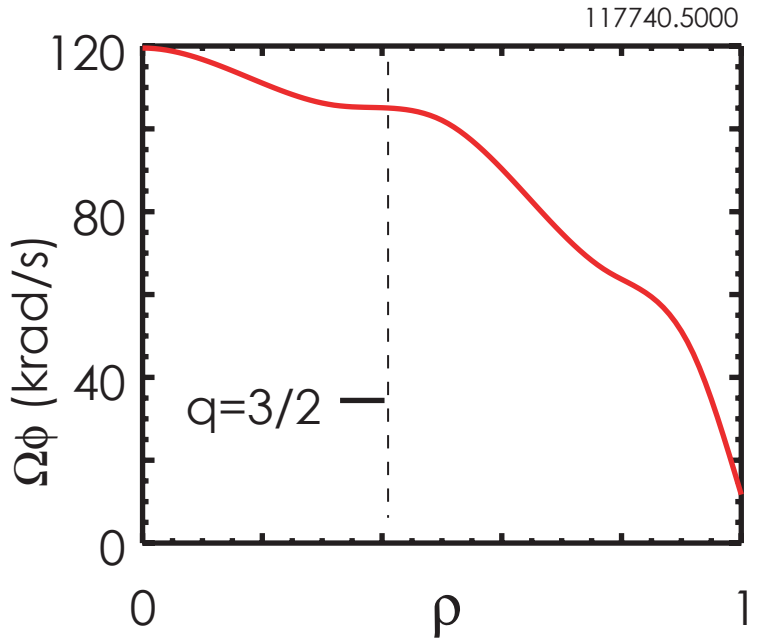
- ELMs modulate 3/2 mode
- fast drop, slow recovery
- modulation of island may remove poloidal flux from the central region (flux pumping)
- reducing average current density (as with sawteeth)
- flux change analysis based on MSE is in process

Fast ion transport due to NTM? No obvious effect

- **Neutron emission should be a sensitive indicator of changes in the fast ion distribution**
- **No change is seen when the 3/2 NTM appears**



Other effects of the NTM: rotation



- the m=2, 4, 5, … components rotate with the 3/2 island
- with a peaked velocity profile:
  - mode rotates slower in core
  - faster outside q=3/2 surface
- expect the NTM to flatten Ω_ϕ

Summary and conclusions

- In hybrid scenario plasmas ($q95 \geq 4$) in DIII-D
  - $q(0)$ is steady at $1 + \varepsilon$ with $\varepsilon \leq 0.05$
  - this flattening of the central current density is a consequence of the presence of an m/n=3/2 NTM
- The 3/2 NTM is a global mode with m=2,4,5,... components
  - the sensitivity of the current profile to q(0)–1 is associated with the growth of the 2/2 sideband as $q(0) \Rightarrow 1$
- Future work should resolve whether this is a counter-current drive effect, a reduction of the central fast ion density, or a transport effect due to the helical field

Also,

- Significant progress is being made in many areas to improve and allow use of the hybrid regime in ITER