Transport Improvement Near Low Order Rational q Surfaces in DIII–D

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With

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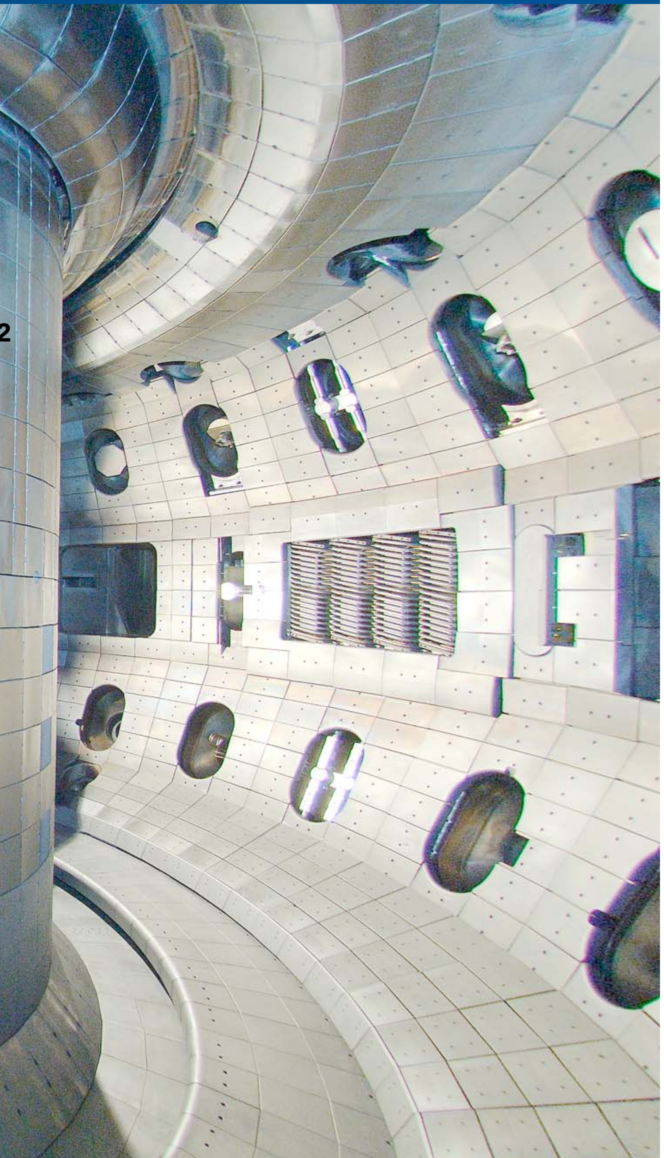

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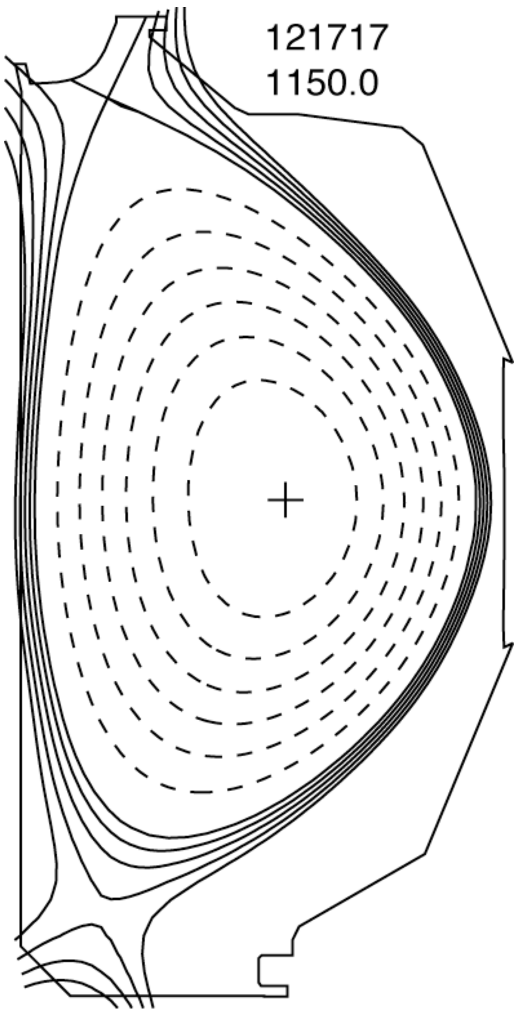
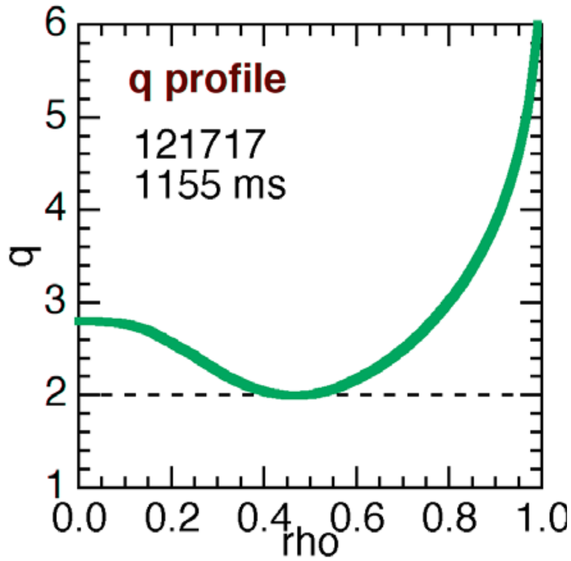
Motivation

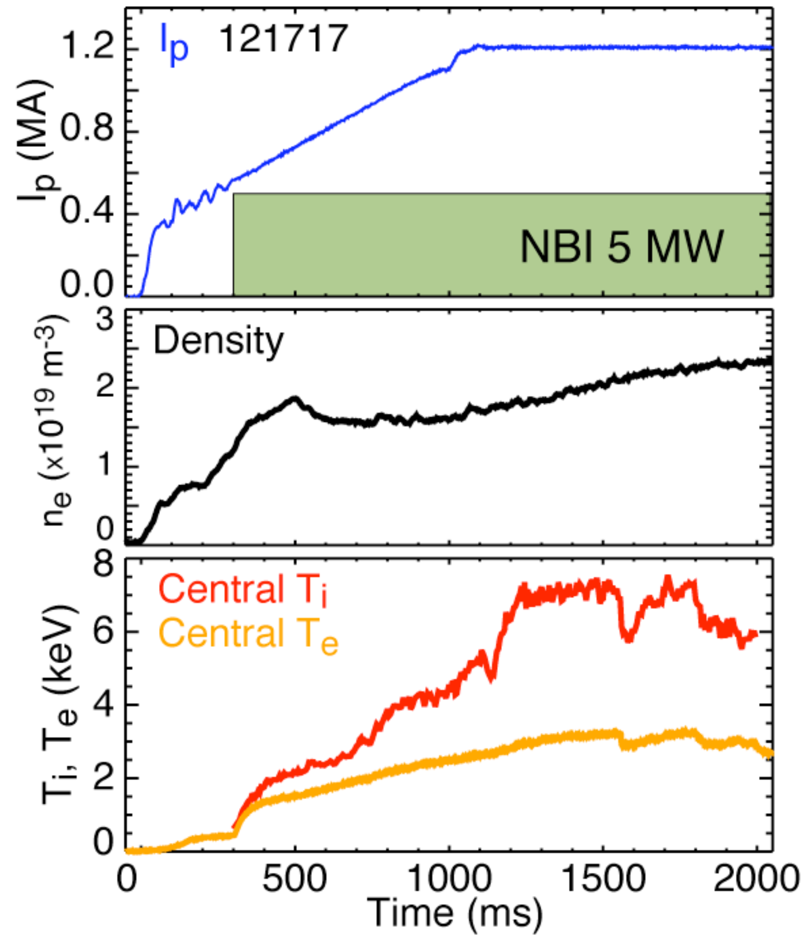
- **In tokamak devices it has been found that low order rational *q* surfaces play a key role in the formation of internal transport barriers (ITBs)**
- **Most often seen in negative central shear discharges at low power as q_{min} reaches integer values –> ITB triggered typically near q_{min}=2**
- **Recent advances in theory and diagnostics provide information for new model for transport changes at integer q_{min}**
  - Theory of zonal flow structures, profile corrugations
  - Detailed measurements of transport, turbulent fluctuation levels, and E_r

Core barrier triggering studied near marginal conditions



- Early NB heating in current ramp-up generates NCS
- Low power (2–5 MW) is used for q-triggered cases





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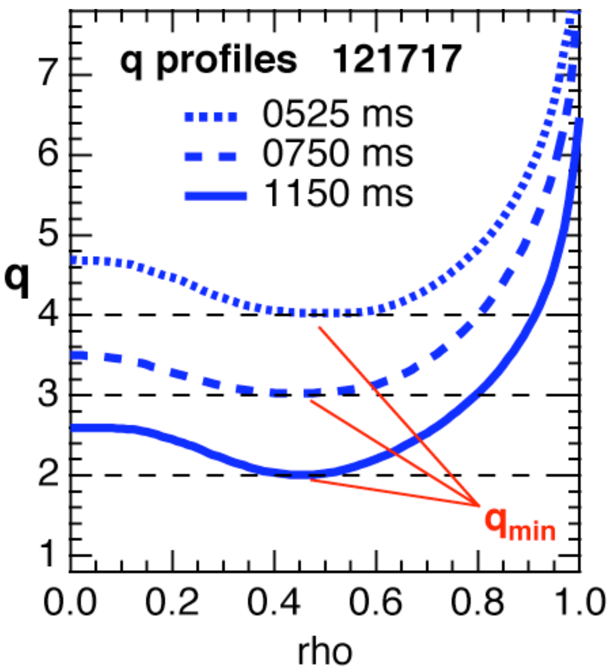
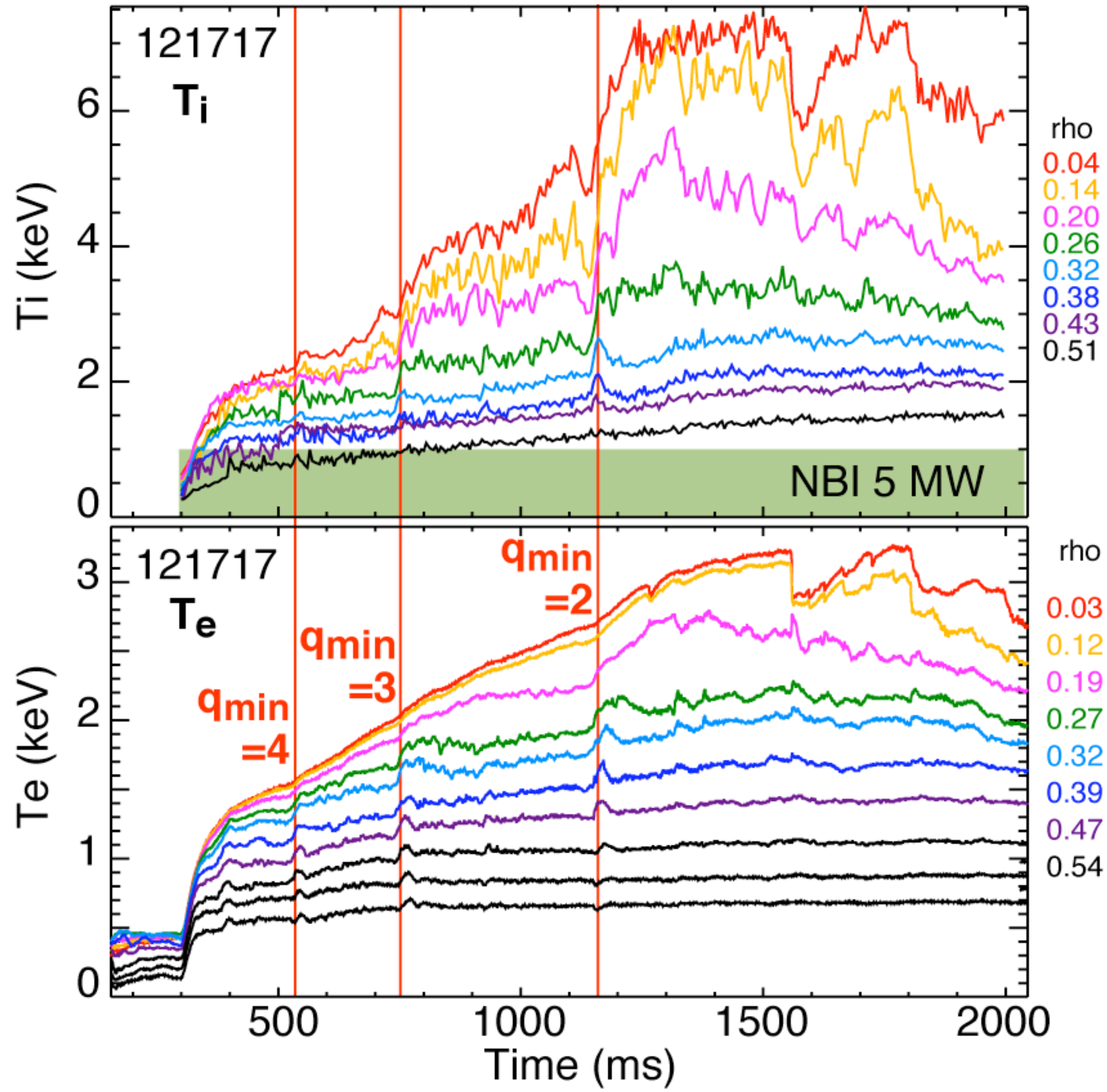
Changes in transport seen in DIII-D as q_{min} traverses integer values

- Persistent core barrier forms in T_i after 1200 ms, triggered at q_{min}=2 crossing





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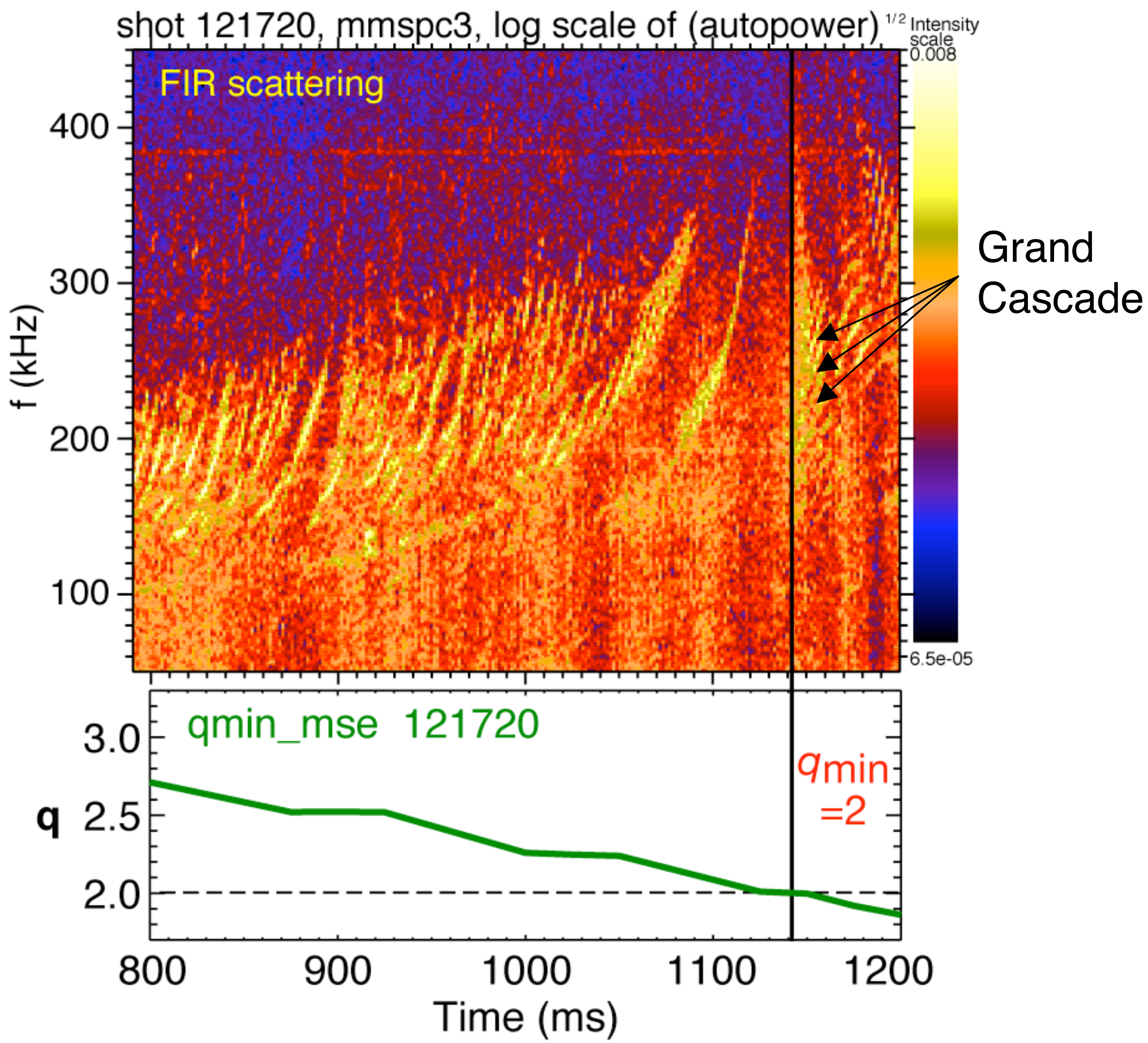
Integer q_{min} time is determined accurately from Alfvén cascades

- RSAE – Reverse shear Alfvén eigenmodes (cascades) are visible in FIR scattering $\tilde{n}_e$ data
- q_{min} vs time obtained from MSE-EFITs and and q_{min}=integer pinpointed using Grand Cascades

S. Sharapov, et al, Phys. Plasmas 2002

R. Nazikian, et al, IAEA 2004



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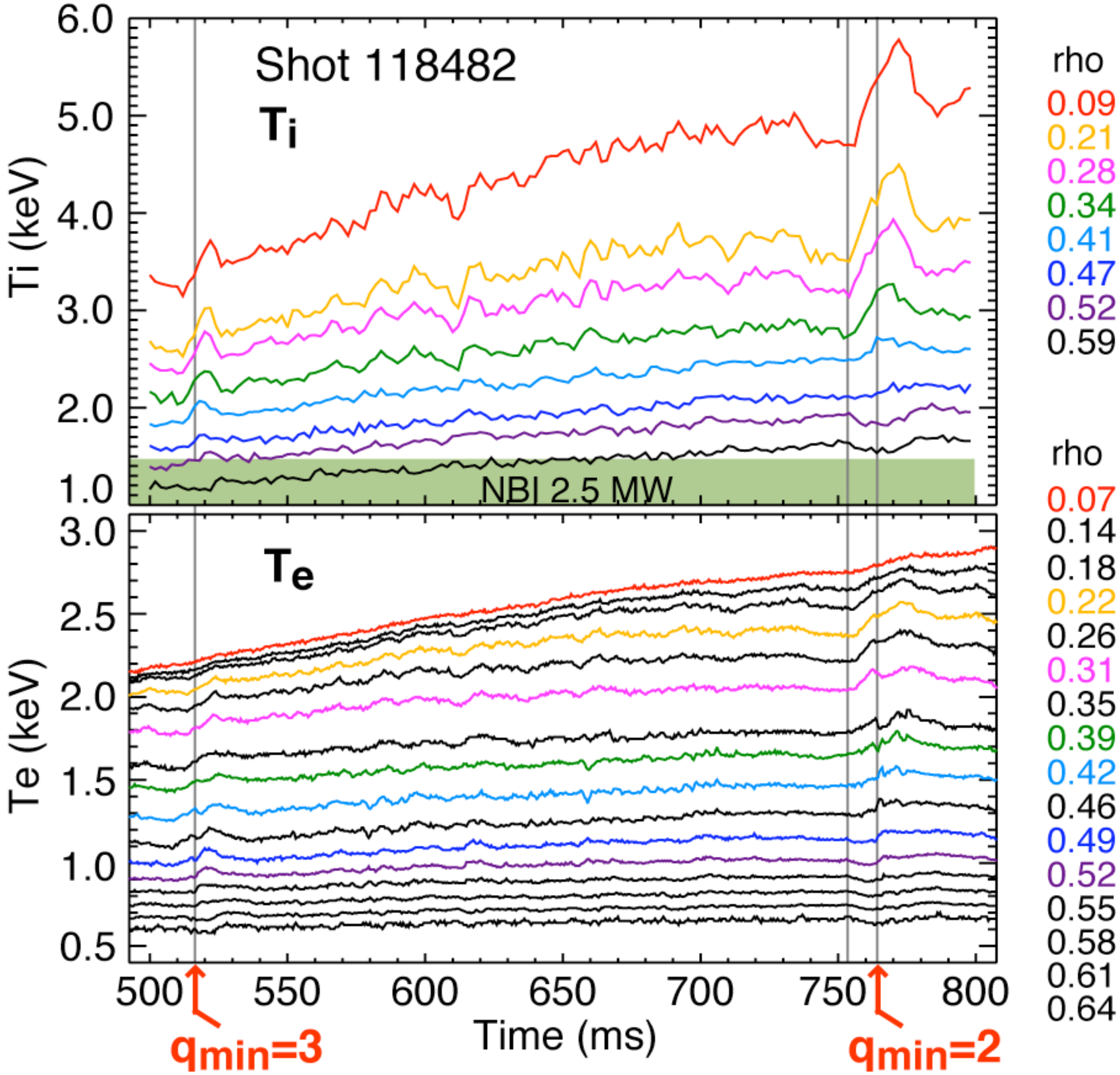
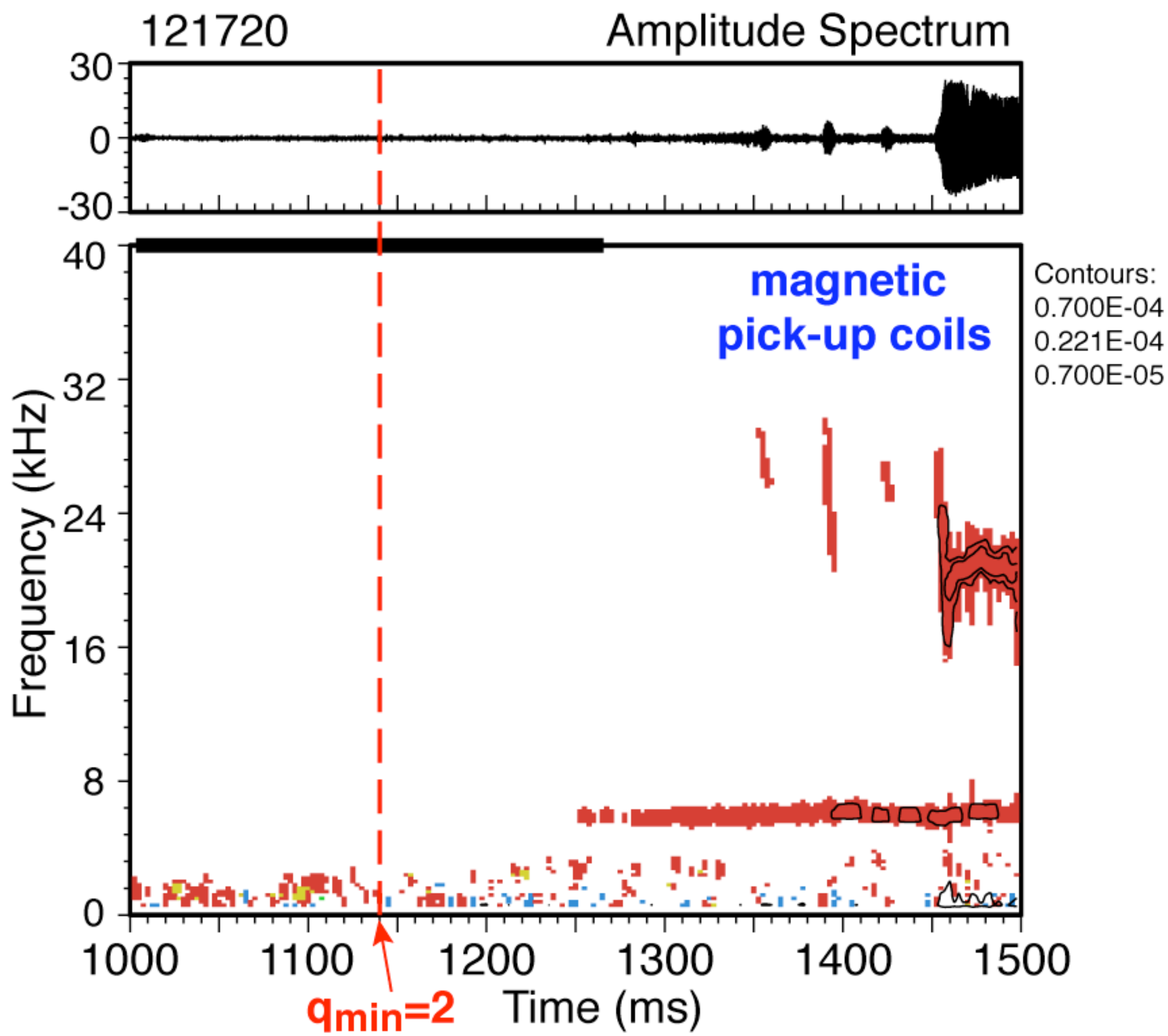
Transport improvement precedes appearance of rational surface

- Lower NB power (2.5 MW) produces transient confinement improvement
- Temperature rise starts 10-12 ms before q_{min}=2
- T_i ,T_e rise continues for a similar interval afterwards



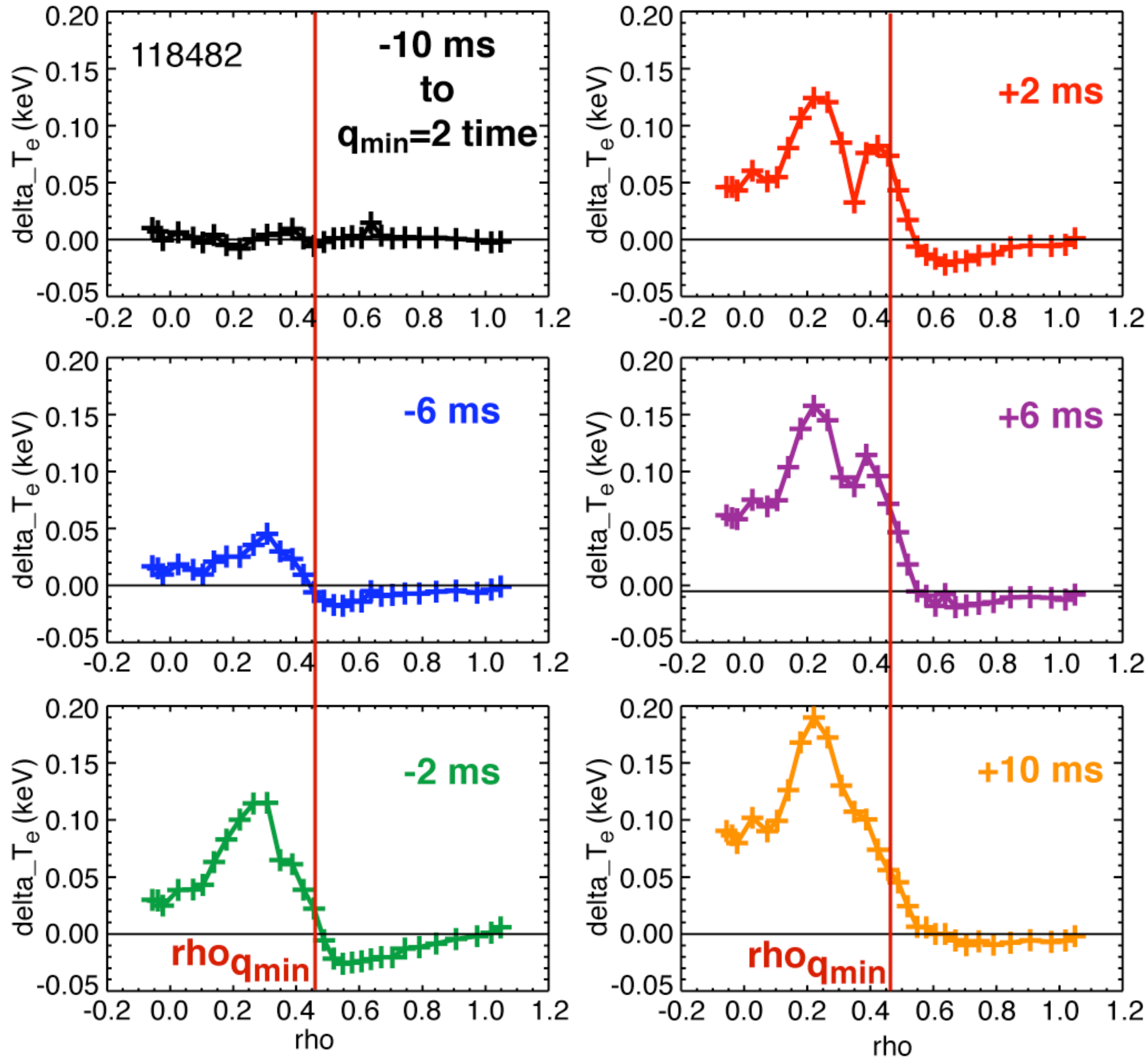
Reconnection and island formation not seen as trigger

- **Transport changes preceding integer q_{min} is primary evidence**
- Generally no low n modes detected on magnetics near q_{min}=integer time in low-β phase
- Modes appear later as β increases



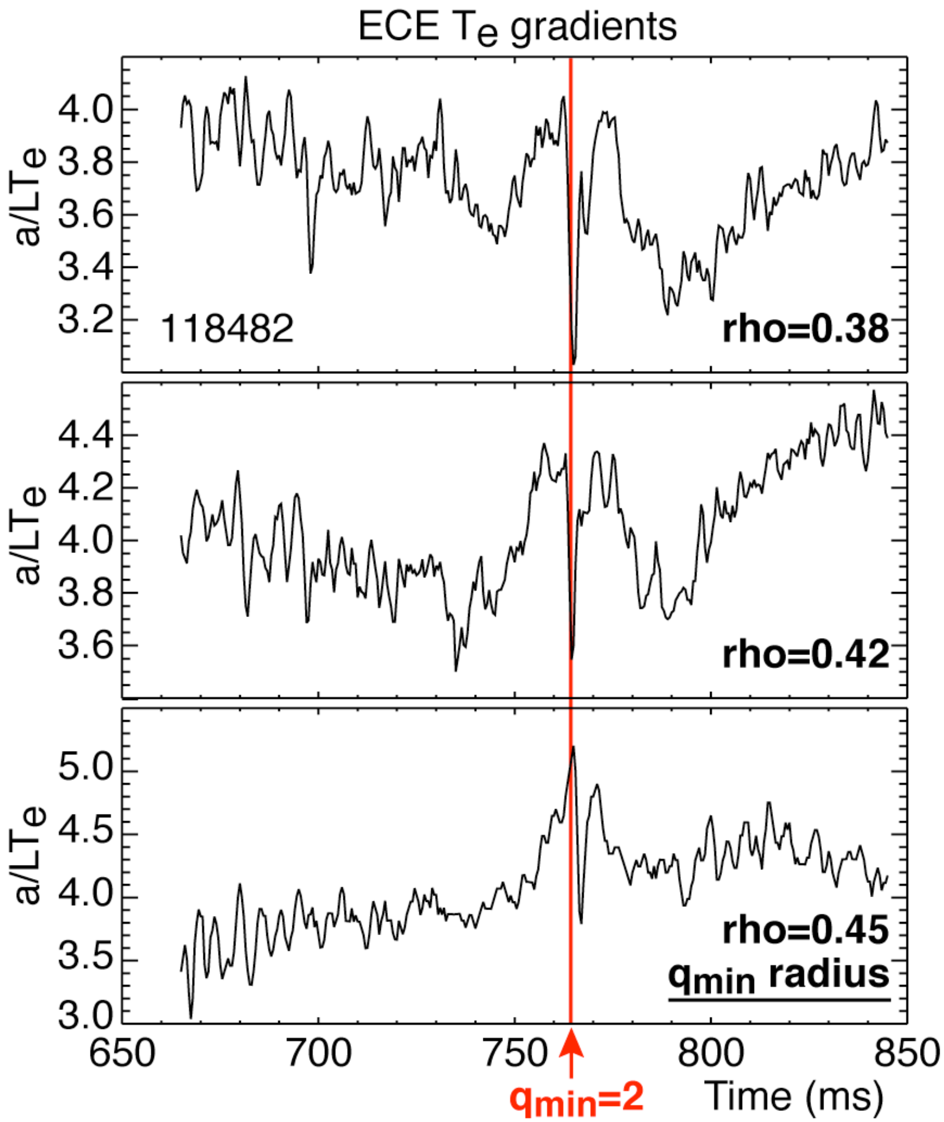
δT_e change shows definite barrier signature

- δT_e profiles referenced to 14 ms before q_{min}=2 time
- Dipole change in T_e observed about q_{min} radius



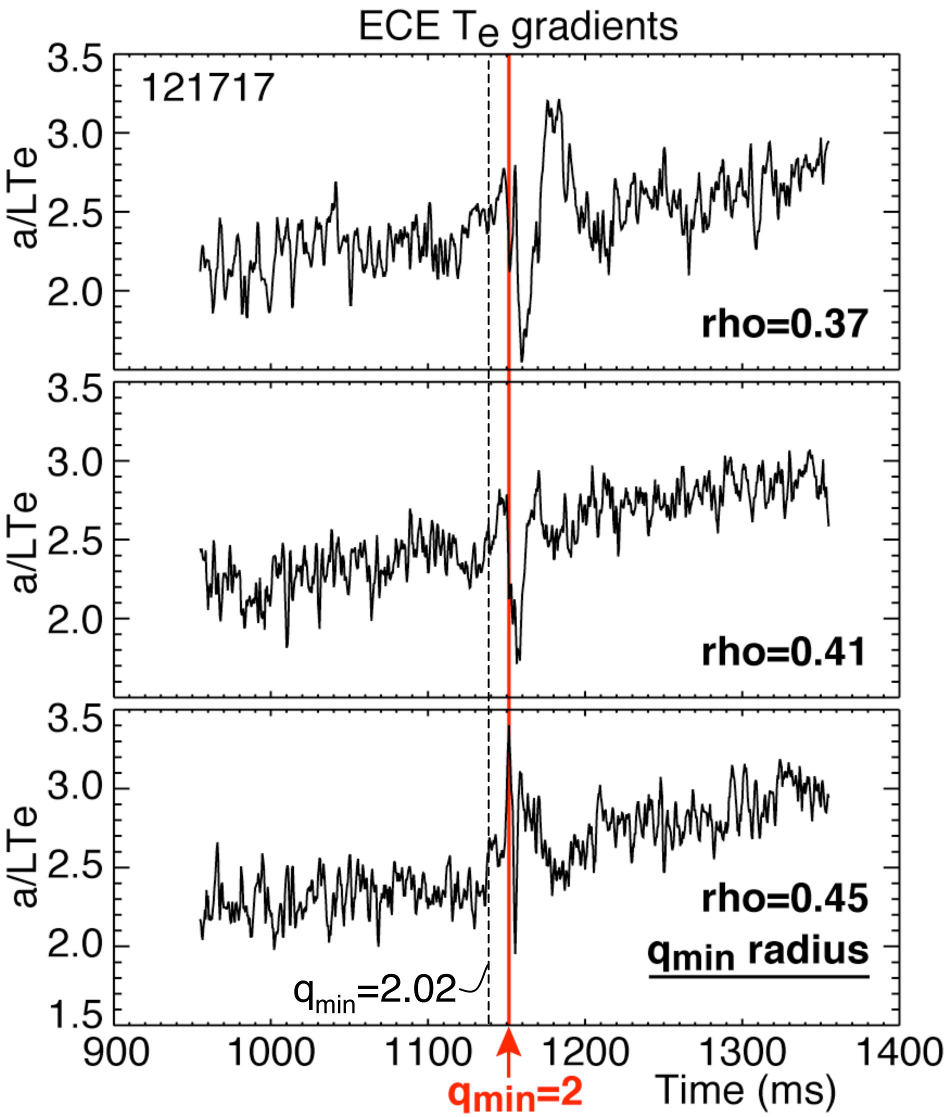
T_e gradient steepens before and after q_{min}=2, dips at q_{min}=2

- T_e gradients derived from adjacent ECE channels
- Changes shown are near and just inside radius of q_{min}, $\rho \sim 0.45$
- Further evidence of transport changes preceding q_{min}=2



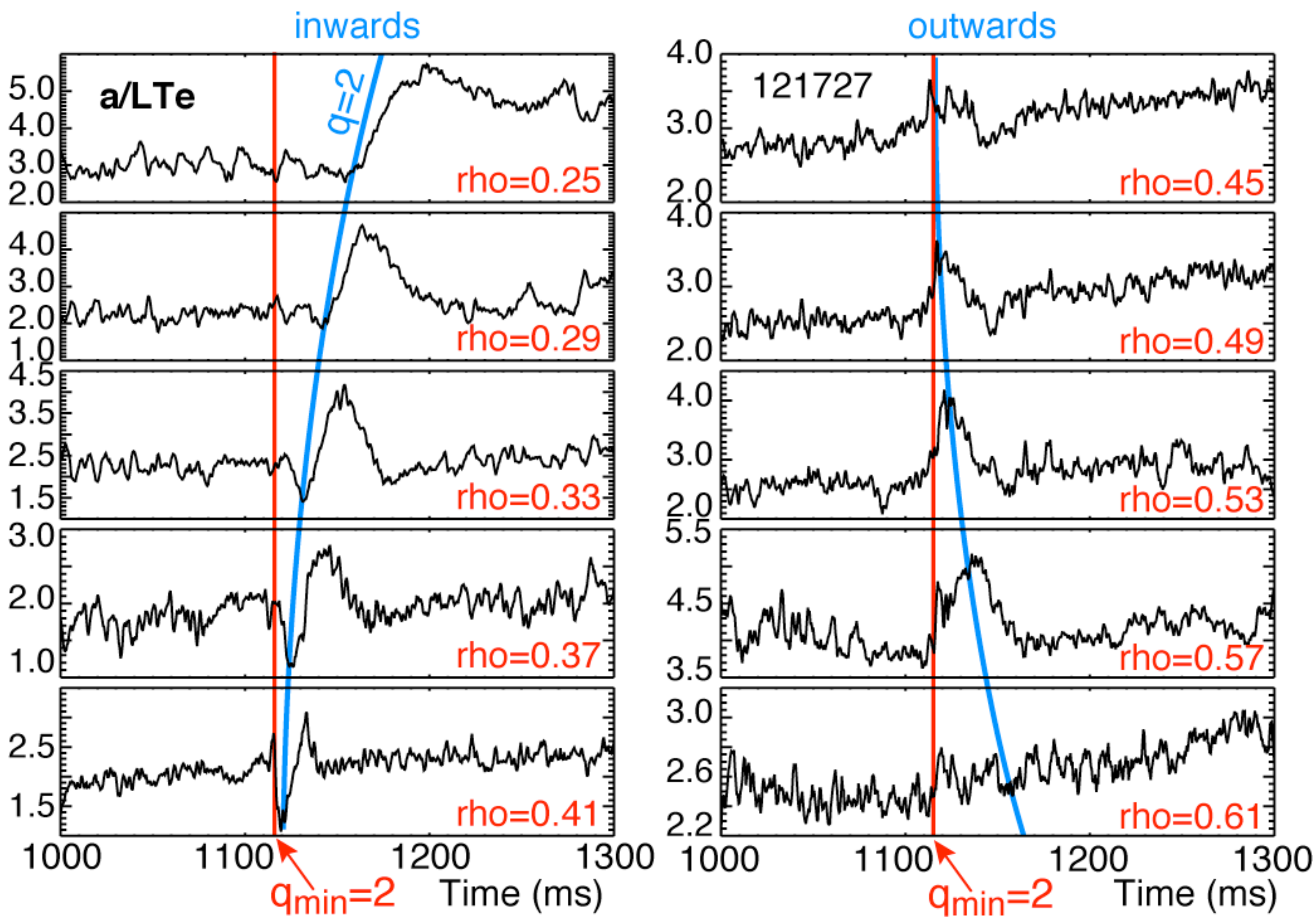
T_e gradient changes are similar for 5 MW case

- T_e gradient measurements underscore the locally transient nature of transport changes
- Gradients steepen starting at $q_{min} \approx 2.02$



Confinement changes propagate in with q=2 surface

- Structures in grad_T_e follow q=2 in time
- Magnitude of effect tracks change in shear



Experimental T_e gradient structures near q_{min}=2 match GYRO code predictions

• Profiles produced in GYRO simulations have large profile corrugations tied to low order rational surfaces

• These corrugations correspond to the various components of the time and flux surface averaged n=0 zonal flows on top of to the given smooth equilibrium

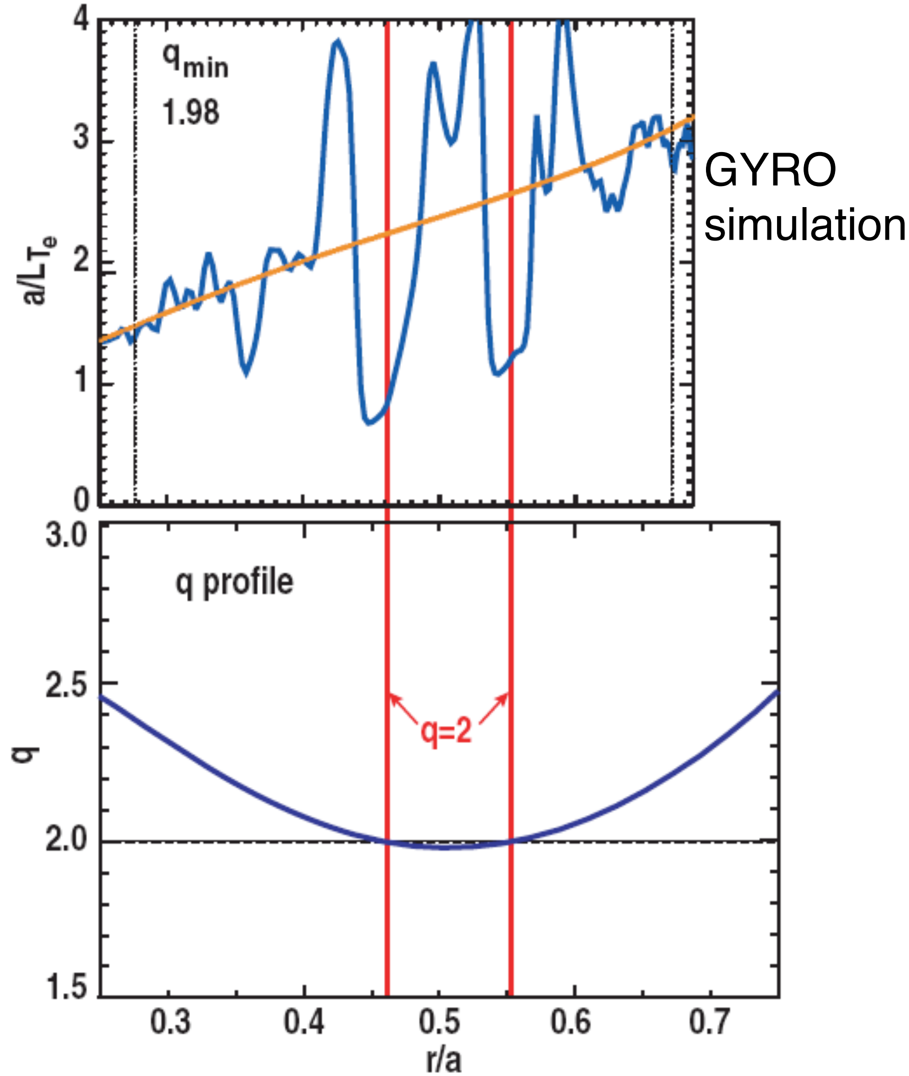
<u>GYRO Code</u>

- GYRO is a global gyrokinetic code containing the "full physics" required to accurately simulate all steady state transport flows from given smooth equilibrium experimental profiles:

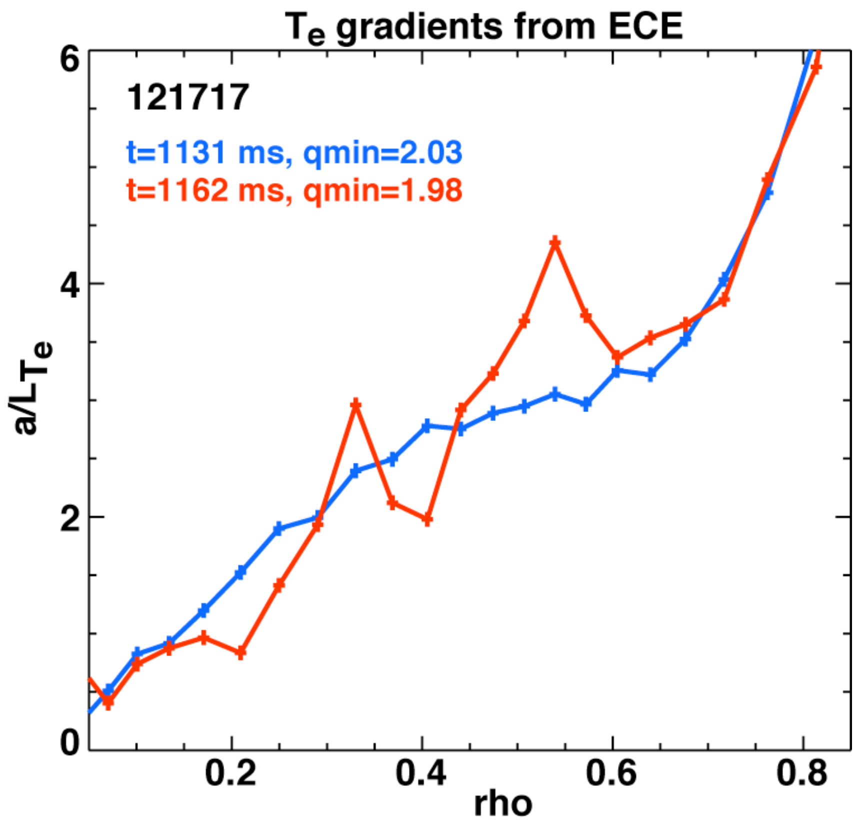
-ITG mode physics	-real geometry
-trapped & passing electrons	-equilibrium ExB & v_par shear
-collisions	-finite rho-star
-finite-beta	- *All included here*

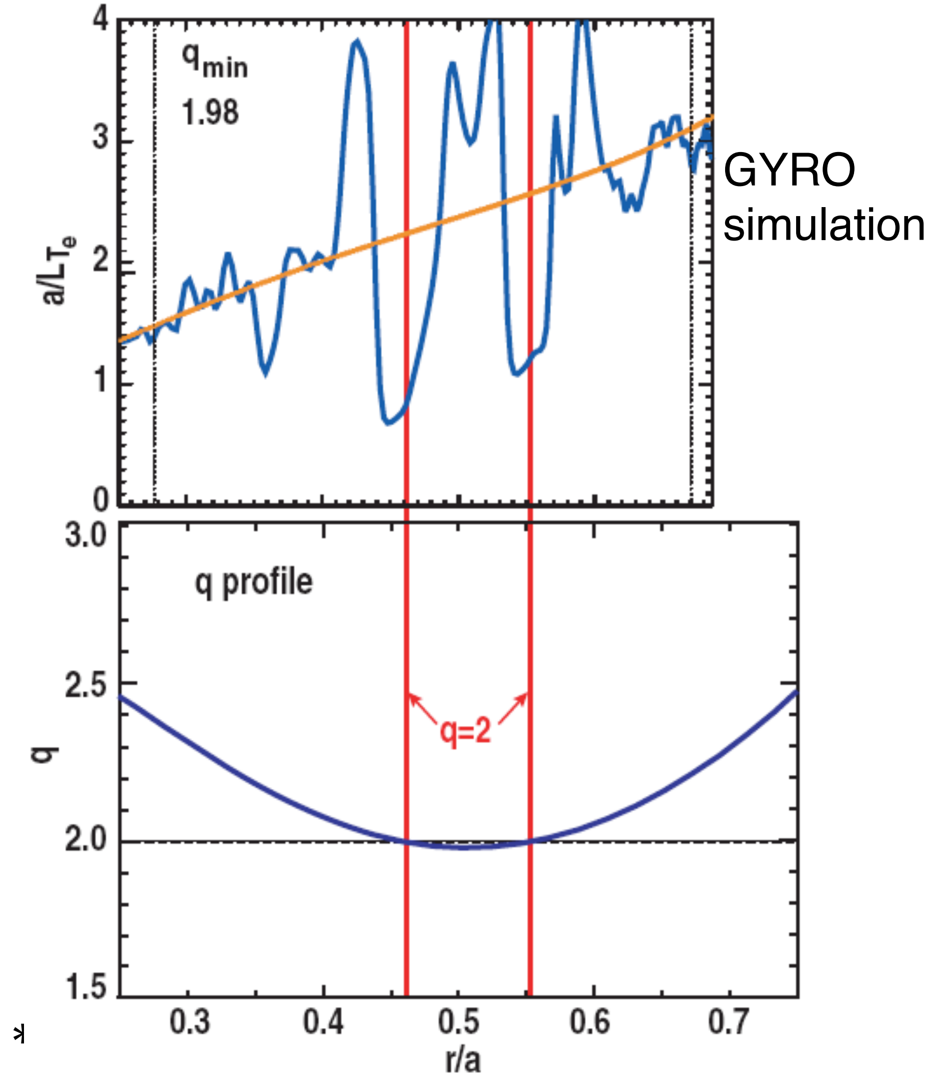
GYRO runs show corrugations in grad_T_e/T_e at low order rational *q* values near a q_{min}

- The -grad(Te)/Te corrugations near vanishing shear, i.e. at q_min, are larger than for monotonic q profiles
- This run: time average after nonlinear saturation from a given snap shot q_min = 1.98 profile
- It has been shown that the GYRO corrugations follow the inner and outer q=2/1 surfaces as they slowly drift inward and outward



GYRO corrugations qualitatively similar to experimental T_e gradient structures



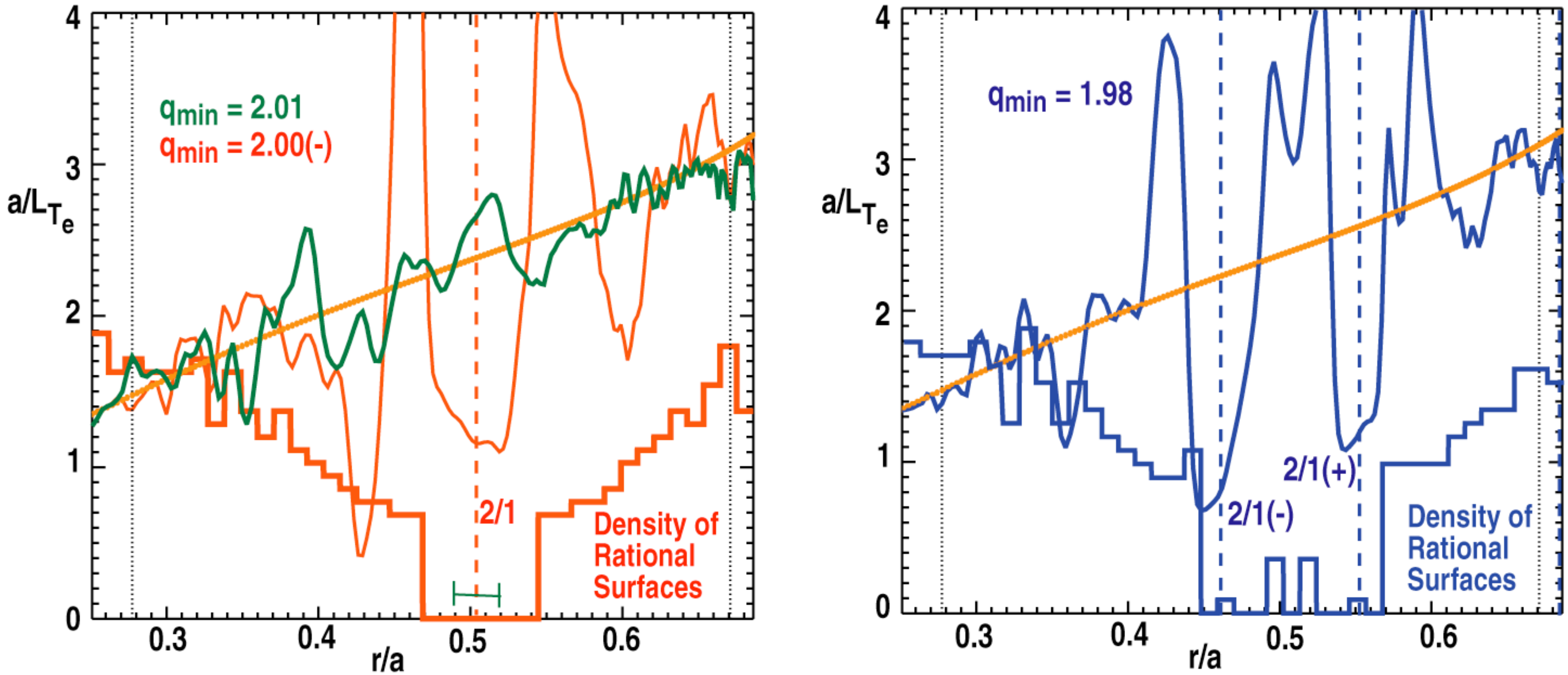


Profile corrugations, zonal flows, and transport at low order rational q

- Zonal flows are low (near zero) frequency, poloidally and toroidally symmetric electrostatic potential structures which vary only in radius on a small scale. They have time averages which are distinguished from the "smooth" background equilibrium only by their small scale
  - n=0 zonal flows are nonlinearly driven by high-n micro-turbulence modes
  - The ExB shearing in the n=0 zonal flows nonlinearly saturate and regulate the high-n modes
- The transport flow carried by the high-n micro-modes is localized about many m/n surfaces
- The divergence of the transport flow driving the zonal flows is strongly corrugated where the density of rational q surfaces is low resulting in a time averaging flattening of the Te (and Ti,n,phi) profiles at the low-order surfaces

GYRO results show profile corrugations are locked to integer *q* surface

- $|\nabla T_e|$ highest where dens. of rational magnetic surfaces changes most rapidly
- $|\nabla T_e|$ is reduced at q=2 surface
- Increased $|\nabla T_e|$ starts when q_{min} is slightly above 2



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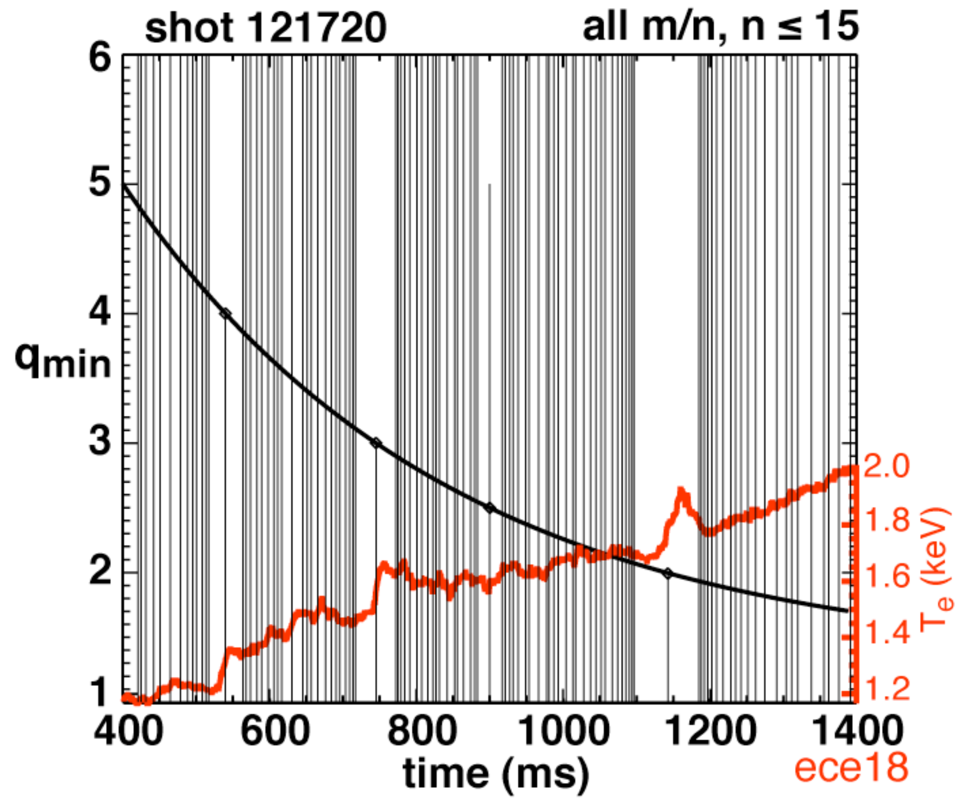
Corrugations related to density of rational surfaces

- Many devices have seen transport changes correlated with low order rational q values – tokamaks, stellarators
- The flattened T_e-corrugations and enhanced ExB shear rates (not shown) result from low density of rational surfaces and results in slightly reduced flow at the low order surfaces
- Electrostatic GYRO reruns show nearly same level of corrugations hence not a magnetic island effect

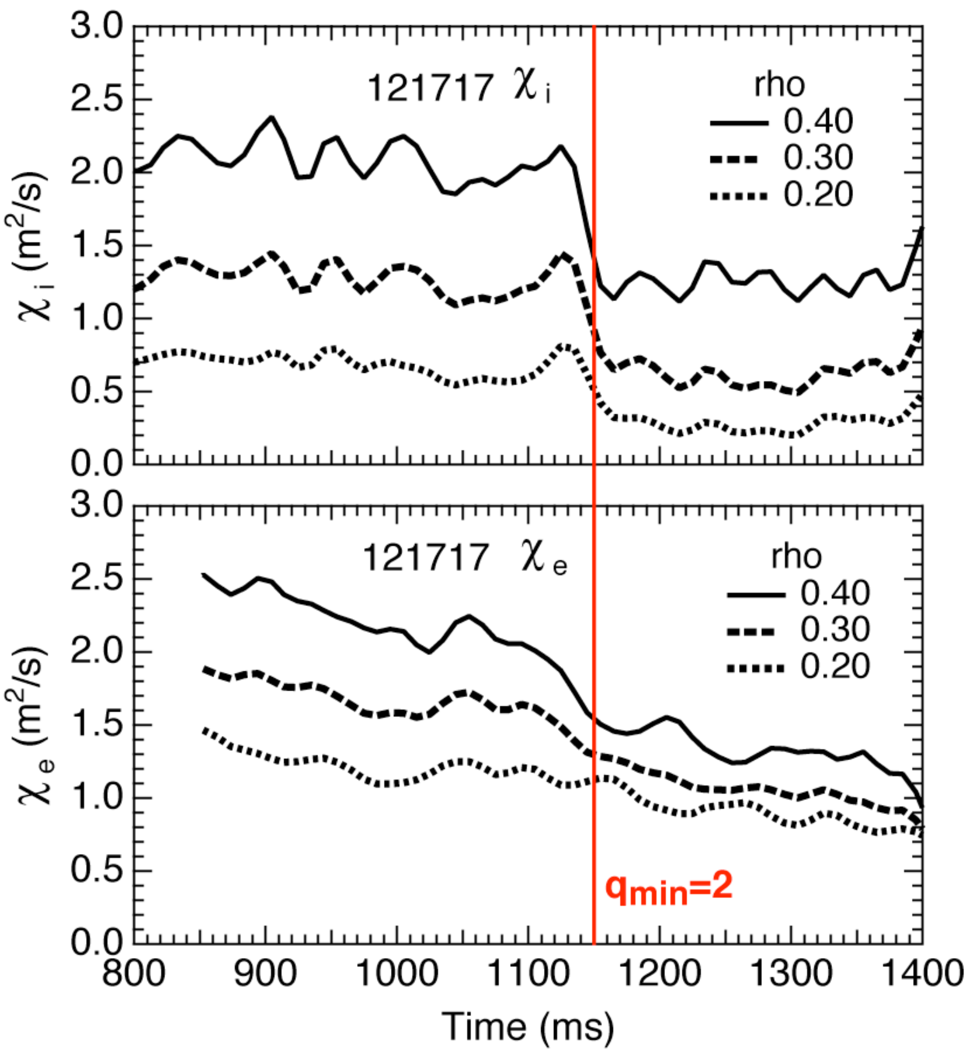


New model for core transport barrier formation in tokamak plasmas

- We have developed a new model of core barrier formation for the case where q_{min} approaches a low-order rational value (e.g. q_{min}=>2) based on gyrokinetic simulations with the GYRO code
- Model involves effects of magnetic geometry on zonal flows, which lead to long-lived Er structures of significant radial extent when qmin passes through integer values
  - Effect is enhanced by the vanishing magnetic shear at q_{min} in NCS discharges
- Model provides a natural connection between magnetic structure, zonal flows, and transport through the zonal-flow-induced ExB shear
- Interplay of zonal-flow-induced ExB shear and ExB shear from equilibrium rotation provides the explanation for the power threshold for the formation of sustained core transport barriers

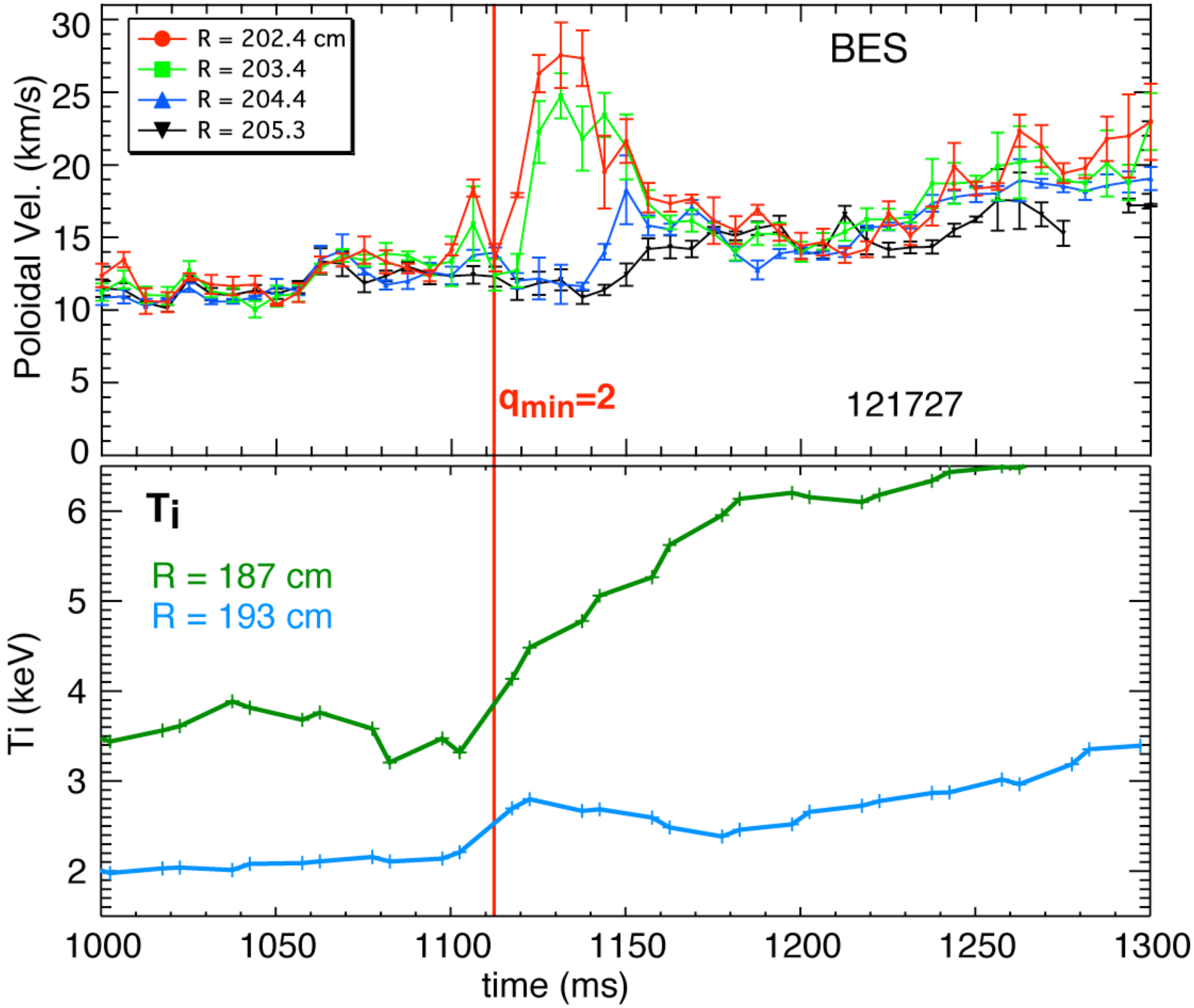
χ_i drops at q_{min}=2 and remains low

- TRANSP runs confirm improvement in ion confinement
- χ_e shows slow improvement, proportional to current soak-in, but no step changes
- Short time scale transport changes not expected to show up in TRANSP analysis



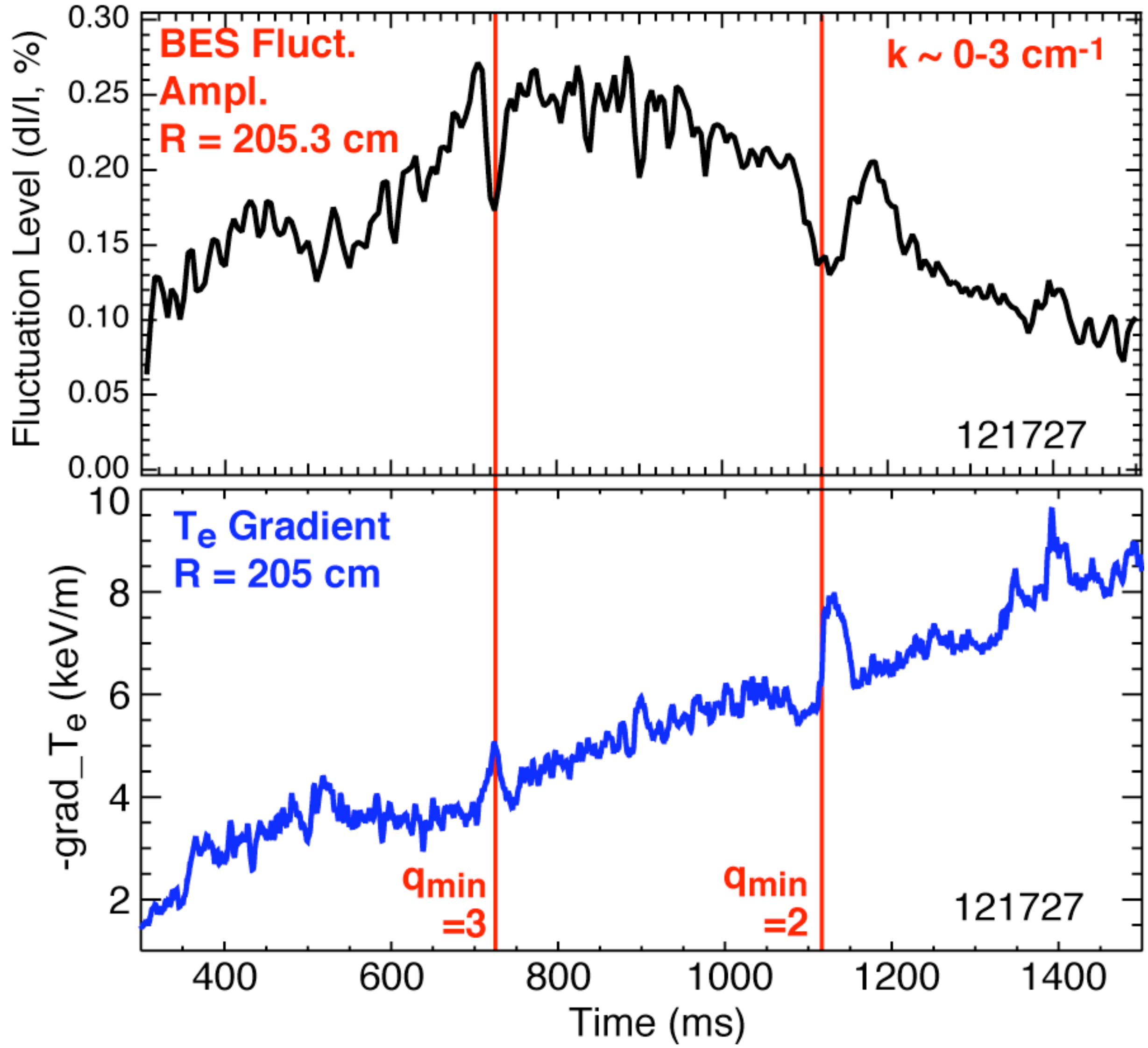
Localized jump in poloidal velocity occurs at q_{min}=2 trigger event

- BES measures turbulent (eddie) velocity using multipoint correlation analysis
- Observed radial variation of velocity represents very large shear
- BES measurement near R_{qmin}



Decrease in density fluctuations coincides with local drop in χ_e near integer q_{min}

- Dip in fluctuations is localized to q_{min} radius – not seen in channels farther out



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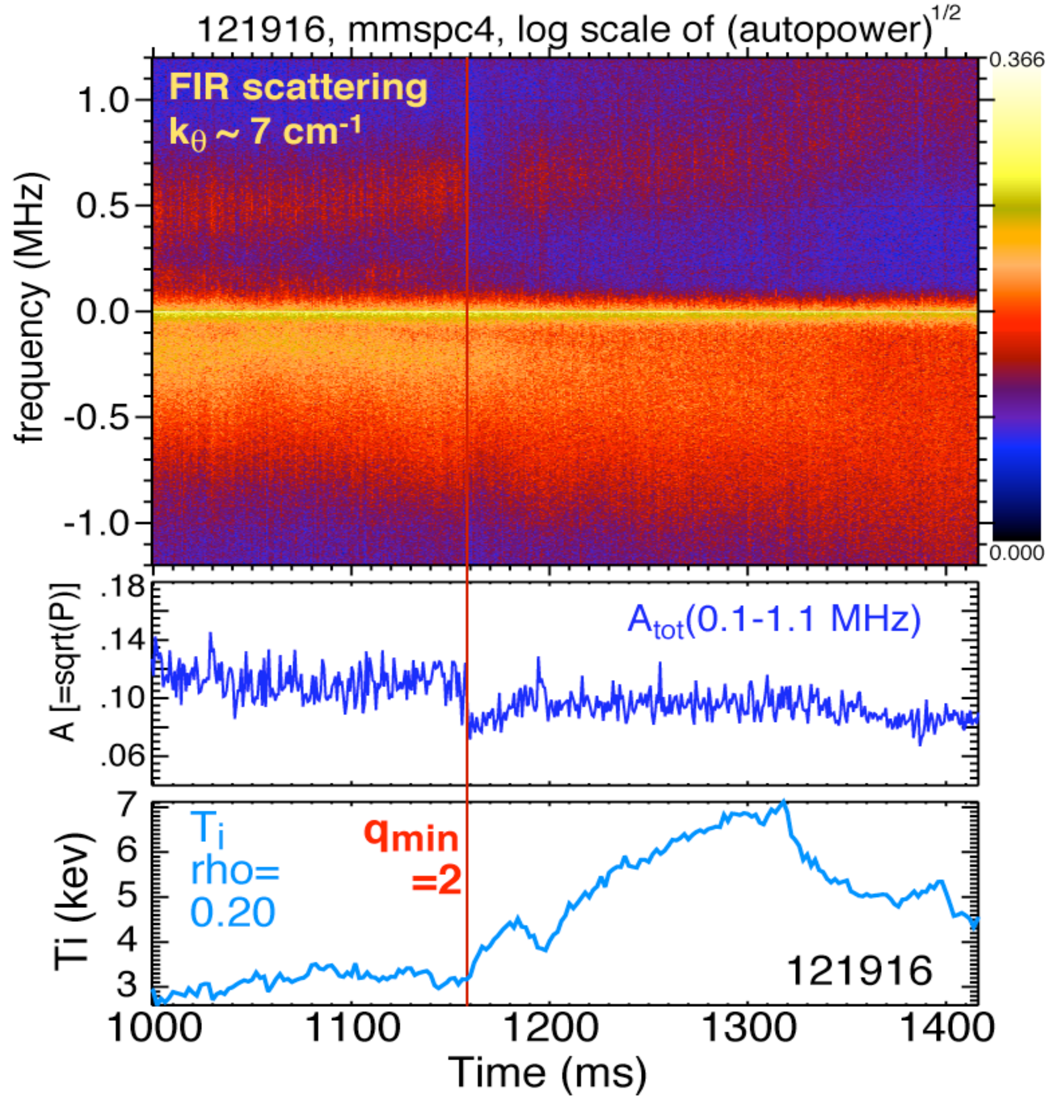
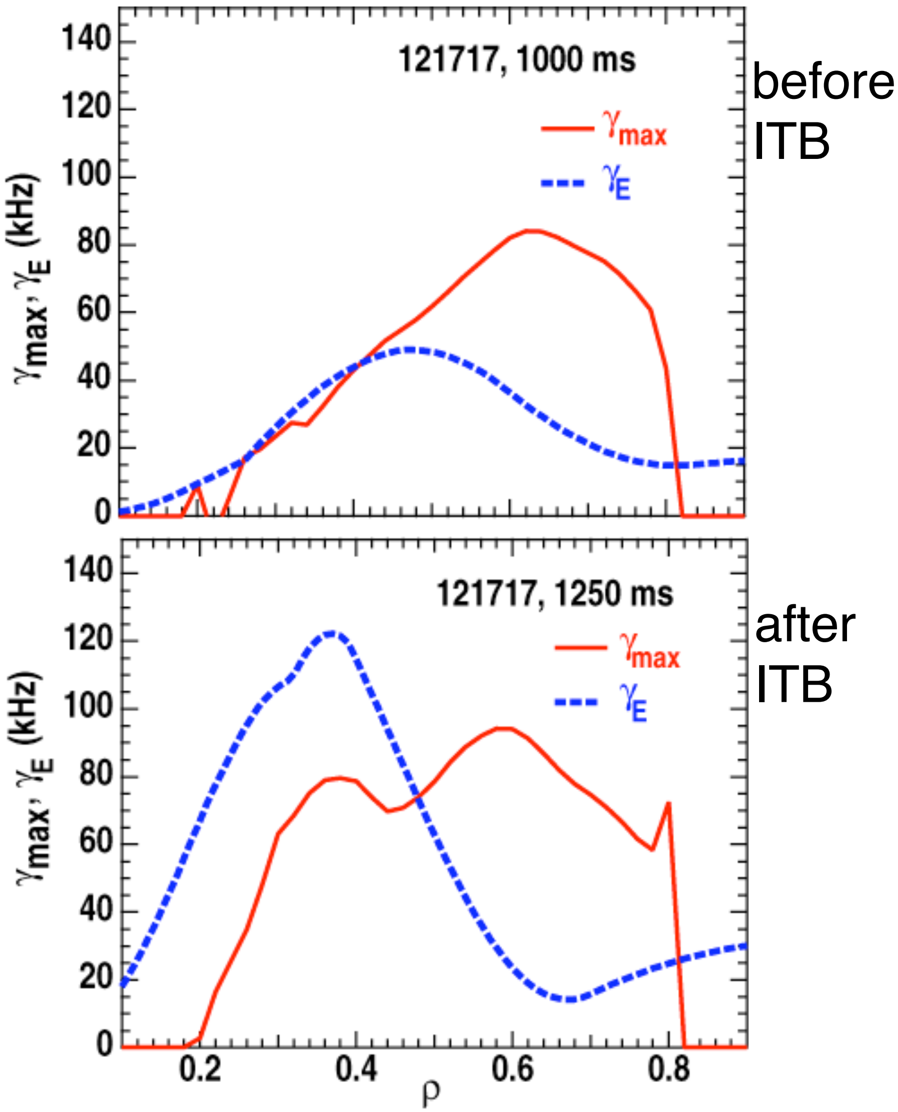
Drop in intermediate-k fluctuations starts at time of q_{min}=2

- Both transient and long term changes are seen in intermediate *k* data
- The persistent reduction is consistent with steady state core barrier



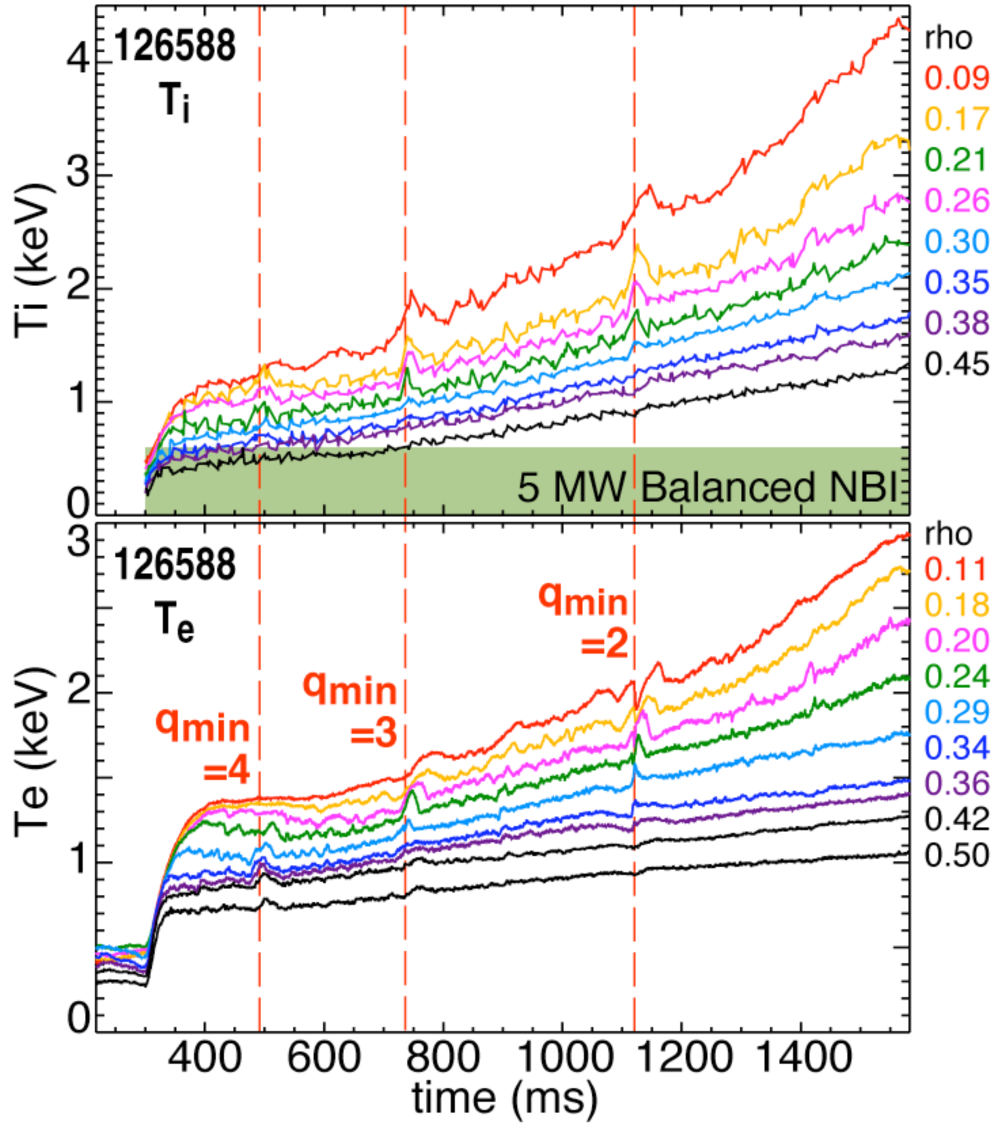
Core ion confinement follows standard ExB shear suppression of turbulence

- Before transition, shearing rate is insufficient for ITG suppression
- $\gamma_{ExB} \geq \gamma_{max}$ to suppress ITG
- Event near q_{min}=2 pushes plasma into improved core confinement regime

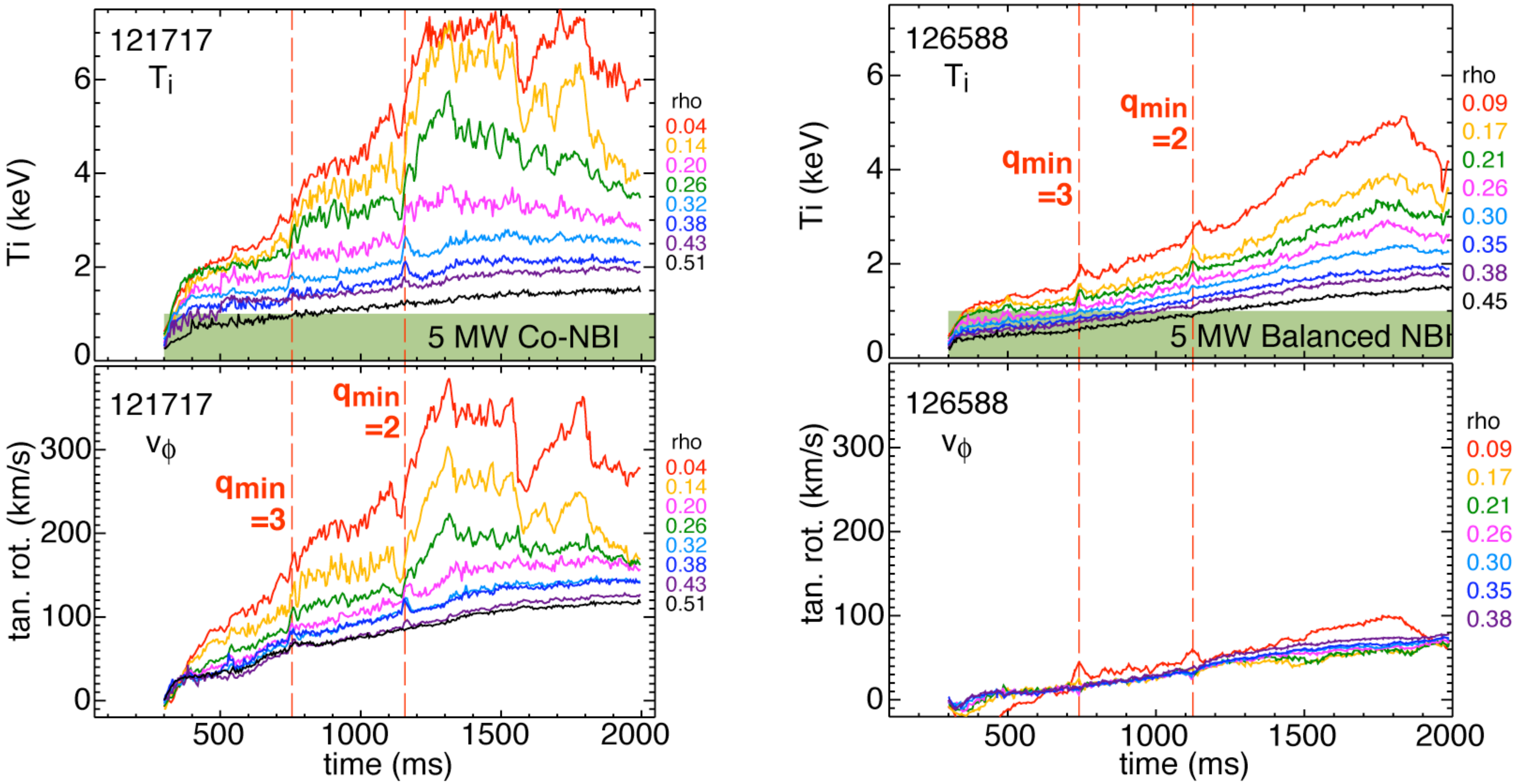


Balanced NBI gives only transient confinement improvement

- Results from recent experiment using new counter injection beamline
- Rotational ExB shear is low– although no analysis yet, expect $\gamma_{ExB} < \gamma_{max}$
- Obtained BES $\tilde{n}_e/n_e$ radial scans and FIR low, intermediate, and high *k* data



Reduced tor. rotation and lack of barrier formation in accordance with model



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Conclusions

- Ion and electron transport is seen to change in the vicinity of integer q_{min} values. Electron transport reduction is transient; ion transport reduction can be transient or a core barrier can form.
- Confinement improvement precedes the q_{min}=integer time by a small interval; magnetic islands are not required for triggering.
- Low and intermediate *k* turbulent fluctuations are seen to reduce near integer *q*; intermediate *k* turbulence remains at reduced levels during the ITB phase
- The observed T_e gradient structures near integer q_{min} match predictions from GYRO simulations and constitutes the measurement of the T_e component of a zonal flow structure.
- A model for ITB formation at low-order rational *q* surfaces is developed based on the addition of zonal-flow-induced ExB shear to the equilibrium ExB shear that impels the plasma into an improved confinement state.