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

M.E. Austin\(^1\)

With

K.H. Burrell\(^2\), R.E. Waltz\(^2\), K.W. Gentle\(^3\), E.J. Doyle\(^8\), P. Gohil\(^2\),
C.M. Greenfield\(^2\), R.J. Groebner\(^2\), W.W. Heidbrink\(^3\), Y. Luo\(^3\),
J.E. Kinsey\(^4\), M.A. Makowski\(^5\), G.R. McKee\(^6\), R. Nazikian\(^7\),
C.C. Petty\(^2\), R. Prater\(^2\), T.L. Rhodes\(^8\), M.W. Shafer\(^6\), M.A. Van Zeeland\(^2\)

\(^1\)University of Texas, Austin
\(^2\)General Atomics
\(^3\)University of California, Irvine
\(^4\)Lehigh University
\(^5\)Lawrence Livermore National Laboratory
\(^6\)University of Wisconsin Madison
\(^7\)Princeton Plasma Physics Laboratory
\(^8\)University of California Los Angeles

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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 $q_{\text{min}}$ reaches integer values → ITB triggered typically near $q_{\text{min}}=2$.
- Recent advances in theory and diagnostics provide information for new model for transport changes at integer $q_{\text{min}}$:
  - 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
Changes in transport seen in DIII-D as $q_{\text{min}}$ traverses integer values

- Persistent core barrier forms in $T_i$ after 1200 ms, triggered at $q_{\text{min}} = 2$ crossing
Integer $q_{\text{min}}$ time is determined accurately from Alfvén cascades

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

R. Nazikian, et al, IAEA 2004
Transport improvement precedes appearance of rational surface

- Lower NB power (2.5 MW) produces transient confinement improvement
- Temperature rise starts 10-12 ms before $q_{\text{min}}=2$
- $T_i, T_e$ rise continues for a similar interval afterwards
Reconnection and island formation not seen as trigger

- Transport changes preceding integer $q_{\text{min}}$ is primary evidence
- Generally no low $n$ modes detected on magnetics near $q_{\text{min}}=$integer time in low-$\beta$ phase
- Modes appear later as $\beta$ increases
\( \delta T_e \) change shows definite barrier signature

- \( \delta T_e \) profiles referenced to 14 ms before \( q_{\text{min}} = 2 \) time
- Dipole change in \( T_e \) observed about \( q_{\text{min}} \) radius
\( T_e \) gradient steepens before and after \( q_{\text{min}} = 2 \), dips at \( q_{\text{min}} = 2 \)

- \( T_e \) gradients derived from adjacent ECE channels
- Changes shown are near and just inside radius of \( q_{\text{min}}, \rho \sim 0.45 \)
- Further evidence of transport changes preceding \( q_{\text{min}} = 2 \)
$T_e$ gradient changes are similar for 5 MW case

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

![Graph showing ECE $T_e$ gradients with $q_{min}$ and $\rho$ values]
Confinement changes propagate in with $q=2$ surface

- Structures in $\text{grad}_T e$ 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 the given smooth equilibrium

**GYRO Code**

- 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
  - trapped & passing electrons
  - collisions
  - finite-beta
  - real geometry
  - equilibrium ExB & $v_{par}$ shear
  - finite rho-star
  - All included here
GYRO runs show corrugations in $\text{grad}_T \frac{T_e}{T_e}$ at low order rational $q$ values near a $q_{\text{min}}$.

- The $-\text{grad}(T_e)/T_e$ corrugations near vanishing shear, i.e. at $q_{\text{min}}$, are larger than for monotonic $q$ profiles.
- This run: time average after nonlinear saturation from a given snapshot $q_{\text{min}} = 1.98$ 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.

![Diagram showing GYRO simulation](image)
GYRO corrugations qualitively similar to experimental $T_e$ gradient structures

$T_e$ gradients from ECE

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$t=1131$ ms, $q_{\text{min}}=2.03$

$t=1162$ ms, $q_{\text{min}}=1.98$

GYRO simulation

$q_{\text{min}}$

1.98

$q$ profile

$q=2$
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 $q_{\text{min}}$ is slightly above 2
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 $E \times B$ 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 $q_{\text{min}}$ approaches a low-order rational value (e.g. $q_{\text{min}} => 2$) 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 $q_{\text{min}}$ passes through integer values
  – Effect is enhanced by the vanishing magnetic shear at $q_{\text{min}}$ 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
$\chi_i$ drops at $q_{\text{min}}=2$ and remains low

- TRANSP runs confirm improvement in ion confinement
- $\chi_e$ 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 \( q_{\text{min}} = 2 \) trigger event

- BES measures turbulent (eddie) velocity using multipoint correlation analysis
- Observed radial variation of velocity represents very large shear
- BES measurement near \( R_{q_{\text{min}}} \)
Decrease in density fluctuations coincides with local drop in $\chi_e$ near integer $q_{\text{min}}$

- Dip in fluctuations is localized to $q_{\text{min}}$ radius – not seen in channels farther out
Drop in intermediate-k fluctuations starts at time of $q_{\text{min}} = 2$

- 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 $\gamma_{\text{ExB}} < \gamma_{\text{max}}$
- Obtained BES $\bar{n}_e/n_e$ radial scans and FIR low, intermediate, and high $k$ data
Reduced tor. rotation and lack of barrier formation in accordance with model
Conclusions

- Ion and electron transport is seen to change in the vicinity of integer \( q_{\text{min}} \) values. Electron transport reduction is transient; ion transport reduction can be transient or a core barrier can form.

- Confinement improvement precedes the \( q_{\text{min}}=\text{integer} \) 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 \( q_{\text{min}} \) 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.