3D Fields Transport Research in Tokamaks and Spherical Torii

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ITER Requires Understanding of Physical Basis for Transport Effects Resulting from 3D Fields

- ELM-mitigation or suppression is crucial for safe, long-term operation
  - 3D RMPs have demonstrated ELM-suppression (tokamaks), or drive (ST)
- Compelling and important transport problem
- Should internal coils be installed in ITER?
- ITER will decide on installation of In-Vessel Control Coils: June, 2012
  - Timely issue; urgent need to understand fundamental transport physics
- Other ELM mitigation methods: QH-mode, I-mode, pellets
- Other 3D issues in tokamaks/ST:
  - Toroidal Field ripple; Error fields
  - Test-Blanket Module (3 TBM in ITER; tested on DIII-D)
  - NRMF(NTV)-driven rotation
Outline

• Transport by 3D Fields is crucial to understand pedestal response
• Overview of 3D Field research in Tokamak/ST Experiments
  – DIII-D
  – NSTX
  – MAST
  – AUG
  – KSTAR
• Observations of turbulence and transport that result from 3D Fields
  – Turbulence enhancement in RMP ELM-suppressed discharges
  – Increased particle diffusivity
  – NRMF-driven rotation
• Discussion points for joint stellarator/tokamak activities
• What can tokamak/ST community learn from stellarator community?
Transport Driven by 3D Fields is Critical Scientific Issue

- ELITE shows RMP ELM-suppressed pedestal is Peeling-Ballooning stable
- 3D Field-induced transport alters profiles
  - density pump-out often observed
  - temperature, density, rotation profiles exhibit different responses
- Transport influence affects profiles beyond pedestal
• ELM suppression via RMP demonstrated in 2004
  – Extensive parametric scans find optimal range in $q_{95}$, $\beta$, $\nu$, $I_C$

• 2011: ELM Control: 3D-Field Induced Transport Task Force
  – Goal: understand the physics basis of edge transport and ELM suppression
Complete ELM Suppression Routinely Achieved

- Requires operation in $q_{95}, \beta$ ranges, sufficient I-coil current
  - Detailed parametric scans have been performed
- Density pump-out, toroidal rotation reduction typically observed

![Graph showing plasma response to RMP](Image)
NSTX has n=3 External Midplane Coils

• 2011 NSTX Research Plan includes ITER & Cross Cutting Topical Science Group
  – Major focus area is 3D Field research: impact on pedestal transport, turbulence, impurity/particle transport
  – ELM triggering, impurity, density control via 3D
  – BES (low-k), high-k scattering, GPI will measure fluctuations
  – Comparisons w/theory

• DOE Milestone, R(11-4) on “H-mode pedestal transport, turbulence, and stability response to 3D fields”
n=3 drives ELMs

- Density and temperature profiles increase with n=3 fields (no-lithium discharges)
  - rotation is reduced

• 6 Pairs of off-axis internal coils ("DIII-D like") for n=3
  – Even/Odd Parity

Experimental Observations
- Density pump-out: dependent on density (L-mode) and parity
- Increased $P_{L-H}$
- Causes ELMs or increases ELM frequency (q-dependent)
- Slows $v_{TOR}$
MAST Observes Parity-dependent Pump-Out and Increased Edge Turbulence with 3D Fields

- Parity and threshold dependence

**Density Pump-Out**

**Edge Turbulence (L-mode)**

**Reduced $E_r$ Well**

A. Kirk, IAEA, 2010
ASDEX-U 3D Field Capabilities & Research

• ASDEX-U recently installed n=2 internal coil set (2 rows x 4)
  – to be expanded to 2x8 (2011)
• ELM mitigation observed at high collisionality
KSTAR Will Utilize an Installed n=2 IVCC Set

- Achieved diverted H-mode operation, Type-I ELMs
  - Planning for RMP ELM-suppression in 2011 (S.W. Yoon, this morning)
Experiments providing Physics Basis for ITER IVCC Design

- ITER currently planning for n=4 on/off axis IVCC
  - Should provide increased flexibility and wider q95 operating window
- IVCC installation involves significant expense, design
- Decision in June, 2012
Increased Turbulence Observed During Full ELM Suppression

- BES configured with:
  - 5x6 2D array
  - ~1 cm resolution
  - 32-channel radial array
  - 1 MHz Sampling
  - Low-k $\bar{n}$

- Turbulence enhancement correlates with application of RMP via I-Coils

Full ELM Suppression

$r/a=0.88$

Shot 132463, channel: besfu05/besfu06, log scale of (crosspower)

- Turbulence enhancement correlates with application of RMP via I-Coils
Broadband fluctuation amplitude increases across central radii when RMP applied

- Pedestal region (0.9 < r/a < 1.0) exhibits an increase in amplitude
  - Spectral shape changes during RMP phase
- Core fluctuations exhibit dramatic increase during RMP
  - Spectral structure of turbulence also changes: fluctuations extend to high frequency (high wavenumber)
Modulated I-Coil Demonstrates Fast Turbulence Response

- Turbulence increases/decreases with I-coil current
- Response time varies radially
- At r/a=0.85, response time of a couple ms
  - suggests a direct effect of magnetic perturbation on turbulence
  - deeper core locations could be response to changing profiles
  - not apparently a consequence of ExB shear changes
Direct measurement of increase in D and reduction in pinch V with RMP application (H-mode)

- Gas puff technique provides a new tool to quantitatively study particle transport

- Diffusive transport (D) clearly increases, while inward pinch (V) decreases
  - Consistent with observed density pump out

- Note: modulated neutral source is not considered, so analysis is suspect for $\rho > 0.9$

L. Zeng, E. Doyle, L. Schmitz, UCLA
Turbulence increase with RMP application in H-mode is consistent with transport change and initial TGLF analysis.

**DBS measurements**

- Growth rates increase for \( k_\rho s > 0.5 \), consistent with measurements of increased turbulence.
- In range \( k_\rho s = 0.25–0.7 \), mode switches from ion direction to electron direction.
  - This could cause a change in particle flux.

**TGLF analysis at \( \rho = 0.8 \)**

(similar H-mode discharges)

L. Zeng, E. Doyle, L. Schmitz, UCLA
n=3 NRMF Driven Torque Allows Sustained QH-Mode Operation with Low NBI Torque

- n=3 Non-resonant Magnetic Field drives counter-Ip rotation
  - Via neoclassical toroidal viscosity effect
- Application of NRMF adds counter torque to the plasma
  - Odd-parity n=3 field applies predominantly non-resonant field
  - Maintains larger counter-rotation for the same NBI torque
- Without the n=3 NRMF, rotation drops to zero, QH-mode is lost

Garofalo, PRL, 2008; APS-2009
Summary and Thoughts on Stellarator, Tokamak/ST Joint Research Activities

• 3D fields research being aggressively pursued on tokamaks/STs
• Motivated by ITER ELM Mitigation (6/2012 decision)
• Compelling transport problem
  – Physics basis needs to be understood for extrapolation to ITER
• Common Drift-wave/Zonal Flow dynamics in toroidal plasmas
  – Zonal flow damping postulated to drive turbulence & transport changes
• Other 3D effects: Ripple, TBM, NRMF(NTV) Rotation
• TEXTOR-LHD (M. Jakubowski, MPI + student)
  – Beta dependence of divertor heat/particle flux
  – Stochasticity/magnetic topology function of beta; modeling
• Screening, magnetic topology, stochasticity, vacuum response
• Theory/Simulation/Modeling
  – Most comprehensive tokamak turbulence simulations are 2D
  – Comprehensive 3D gyrokinetic simulations?
Fluctuations increase with RMP across profile

- Edge fluctuations show modest changes during RMP
- Mid-radius exhibits significant increase w/ RMP
- Null-region at $r/a=0.5-0.55$ shows little or no change during RMP
- Few cm correlation length
  - similar to low-k driftwave turbulence

![Fluctuation Amplitude vs. Minor Radius](image)

![Spectra vs. Frequency](image)

![Radial Correlation](image)
The RMP Coil current can be adjusted to minimize the impact on the core density during ELM Suppression

- During the ELM suppression phase, the core density $\rho \geq 0.35$ increases while the pedestal density at $\rho \sim 0.9$ decreases

L. Zeng, E. Doyle, L. Schmitz, UCLA