Near-Neoclassical Transport & Enhanced Stability in Reversed Shear Plasmas in TFTR

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Motivation

Reversed central magnetic shear configurations are particularly attractive for advanced tokamak reactors

-- predicted improved confinement and stability
-- compatible with bootstrap current profile shape

Mounting experimental confirmation of the advantages of reversed magnetic shear from a number of machines.

Reversed magnetic shear can:
• increase TFTR stability limits
• increase the reactivity of TFTR plasmas
• extend the range of physics studies for
  -- α-physics
  -- transport and stability of burning plasmas
  -- integration of DT and advanced tokamak physics

Outline
• Formation
• Transport
• MHD Stability
• Future Directions
A Wide Range of Reversed Magnetic Shear Configurations Have Been Produced

- Curves from VMEC free-boundary fit to MSE, magnetics data, and kinetic pressure profile
- Have obtained $1.8 \leq q_{\text{min}} \leq 3.3$ so far, $r_{\text{min}}/a \leq 0.5$ during $I_{P}$ flat-top
- Configuration is reliably obtainable, routinely available.
• Plasma is initiated at full size
  -- force current to diffuse maximum distance

• Scenario is robust, reproducible

• $q_{\text{min}}$, $r_{\text{min}}$, and $q(0)$ can be controlled by the prelude NBI timing, co/counter-mix, the $I_p$ ramp-rate and final $I_p$.

see S. Batha, 2F.02
Core Confinement is Strongly Improved after Transition to ERS

- Observed $p(0)/\langle p \rangle$ range from ~ 6.5 to ~ 8
- $L_{pi}$ ~ ion banana width due to high central $q$
  $\Rightarrow$ ion orbit squeezing effects
- Calculated bootstrap current ~80% of total $I_P$
Two Confinement Regimes Observed with Reversed Shear

- Two confinement regimes observed with reversed shear:
  (A) similar to supershots, convection dominated core, low $\chi_i, \chi_e$
  (B) sudden transition to reduced particle transport and thermal transport ERS mode (Enhanced Reversed Shear)

- Transition appears to require balanced NBI $> 16$ MW may have dependence on co/ctr mix of NBI may have dependence on $q_{\text{min}}$ or $r_{\text{min}}$
\( \chi_i \ll \chi_i^{\text{neo}} \) may be due to \( L_{\Pi i} \sim \) Banana Width!

Likely indicates that ion orbit squeezing is important!

Improved Neoclassical calculations under development:

- orbit squeezing effects via recent papers by Shaing and Hazeltine; Hinton and Kim

  \( \Rightarrow \) modification of Hirshman-Sigmar equations

- comparison with Full Torus gyrokinetic Neoclassical Simulation (Z. Lin, W. Tang, W. Lee)
The Transition Threshold is Not Just a Function of Power

- All cases have near-balanced injection in high-power phase
- Lower power correlates with later transition perhaps due to lower $q_{\text{min}}$?
- Lowest power transition observed: $P_{\text{NB}} = 16\text{MW}$
Electron Particle Loss is a Small Fraction of the Fueling inside Reversal Surface

- Volume integrated electron continuity equation terms
  Indicates sources inside a flux surface and losses through a flux surface
- Source is dominated by beam fueling inside \( r/a \sim 0.9 \)
  Wall source magnitude is measured by \( H_\alpha \) array
$D_e$ is sharply reduced after transition

\[ \Gamma \equiv -D \nabla n \] flux balance "effective" diffusivity

- full neoclassical flux calculation including off-diagonal terms (Houlberg, Shaing, & Hirshman)

- low diffusivity or large pinch?
Ion Energy Loss is a Small Fraction of the Heating Power

Volume integrated radial energy balances.

Energy sources inside a flux surface

Losses through a surface.

Electron heating is dominated by $Q_{ei}$ in the core

Convection

Total Ion Heating

$Ions$

$Ion$ Energy Loss is a Small Fraction of the Heating Power

$Q_{ei}$

$dW_i/dt$

$r/a$

Total Electron Heating

$Electrons$

$Electron$ heating is dominated by $Q_{ei}$ in the core

$P_{rad}$

$convection$

$q_i$

$q_e$

$dW_e/dt$

R/S region

R/S region
$\chi_i$ is Sharply Reduced after Transition to below neoclassical level.

Includes off-diagonal terms

Orbit squeezing effects from Shaing, Hsu, and Hazeltine,
Phys. Plasmas 1, 3365 (94)

see Levinton 9P.05
Core Turbulence Dramatically Reduced in ERS

- change in fluctuation profile appears coincident with transition
- preliminary BES analysis indicates core fluctuations levels are reduced to ≤ 0.2%, substantially less than with monotonic q(r).

ERS

RS

Monotonic high q(0)

TFTR

X-mode Reflectometer

k_θ < 0.5 cm\(^{-1}\)

Fluctuation levels outside regions shown saturate instrument.

see E. Mazzucato 9P.10
Density Sustainment after High Power Phase Confirms Low $D_e$

- High central density can be maintained with ~5 MW of NBI

- After step down of $P_{NB}$, density outside $r_{min}$ decays, density peaking rises

- Reverse transition at ~3.1 sec?
Hydrogenic transport is reduced in ERS

- Small Tritium puff in conjunction with neutron collimator measurements is used to study hydrogenic transport.
- Core ion diffusivity is reduced in ERS, but similar outside reversed shear region.
Core Hydrogenic Diffusivity is Significantly Reduced in ERS Plasmas

TFTR

Tritium transport determined from response of 12 channel neutron collimator to a tritium gas puff.

For \( r < 0.6 \text{ m} \), convective velocity consistent with neoclassical theory.

In ERS mode, particle flux in RS region is consistent with neoclassical predictions.
Possible Transition Mechanism: $\nabla p$ driven increase of shearing rates and decrease of instability growth rates

1. ExB flow shear stabilization, generated by $\nabla p$ (Synakowski, 2F12; Diamond 7Q21)

2. Increase in fraction of trapped particles with favorable drift precession from high $\alpha = -q^2 R\beta/dr$ due to strong Shafranov shift (M. Beer, 4Q08)

3. Peaking of density profile decreases ITG drive (S. Parker, 8IB3 and G. Rewoldt, 9P04)
• Consistent with variation observed via Abel-inverted tangential visible-bremstrahlung array
  -- see A. Ramsey, 9P.38

• Nonlinear gyrofluid simulations indicate that residual fluctuations may drive outward carbon flux that balances neoclassical pinch
  -- see M. Beer, 4Q.08
RS Plasmas are Robustly Stable to High-n Modes in Plasma Core

- Margin against high-n ballooning > factor of 2 at all radii. Robustly stable in core.

- This robust stability region extends to 80% of minor radius in some plasmas.

- Due to profile differences, some ERS plasmas can be near the ballooning limit outside $r_{\text{min}}$. 

\[
\sqrt{\frac{(\psi - \psi_0)}{(\psi_a - \psi_0)}} \sim \frac{r}{a} \quad -\text{S. Sabbagh}
\]
Observed Saturated MHD Activity is Benign

• Observed on both RS and ERS plasmas
  No ERS specific MHD activity has been observed.

• May be resistive-kink mode? -- see T. Hender 9P.07

• No tearing-like MHD activity observed in plasma core.
  No sign of neoclassical tearing modes observed with monotonic q(r).

• Off-axis "sawteeth" are observed after the high-power phase, with m/n = 2/1 precursors.
Measured $T_e$ evolution from ECE polychromator
Similar measurements by reflectometer

Disruption occurred with
\[ \beta_{N*} = 3.5, \quad \beta_N = 1.7, \quad \beta(0) = 5.4 \% \]

Maximum achieved with ERS:
\[ \beta_{N*} = 3.8, \quad \beta_N = 2.0, \quad \text{without disruption} \]

In contrast, for monotonic $q(r)$ and similar pressure profiles, the $\beta_N$ limit is observed to be $\sim 1.3$. 
• PEST calculates $n=1$ infernal mode becomes unstable at approximate $\beta_N$ of disruption.

• Resistive stability agrees with ideal calculation at experimental Lundquist number $S \approx 10^9$.

• Resistive calculation indicates weak persistent $n=2$ and $n=1$ modes, observed in experiment.

-- see: T. Hender 9P.07; J. Manickam 9P.08; M. Phillips 9Q.02; M. Hughes 9Q.01
Future Directions

• Optimization and control of MHD stability
  -- Theory predicts increased $\beta_{N^*}$ limits for increased $r_{\text{min}}$
  -- Need to control q-profile evolution to avoid unstable equilibria at high $\beta$
    (e.g. $\sim$ integral $q_{\text{min}}$)

• Understand transition and transport in new regime
  -- scaling of transition and transport
  -- control of barrier location
  -- ash transport

• Integrate DT and Advanced Tokamak physics
  -- $\alpha$ heating dynamics and profile modifications
  -- $\alpha$ stability with reversed shear
20 MW of Fusion Power is a Reasonable Goal

- $\beta_N = 2$ calculated stable for all $n$ (PEST) in this regime, and achieved experimentally

- Final $n_e$ profile from equilibrium solution using observed $Q$ (with floor) $T_e$, $T_i$ and equilibrium evolved using observed $\chi_e$, $\chi_i$ (with floor), $Z_{eff}=1.5$

- Temperatures do not come to steady state! $Q(0) > 5$ when $Q(a) \sim 1$

CAUTION: this extrapolation is based on empirical transport coefficients in a new confinement regime, with no scaling information available.
Conclusions

• Reversed magnetic shear configurations can be easily produced and studied in present experiments

• The new ERS regime offers
  -- extremely low core transport and turbulence
  -- new insight into the causes and limits of transport, mechanisms for transport barriers
  -- new possibilities for reactor design:
    Low $D_e$: pellet or low-energy beam fueling?
    Low $\chi_i$: $\alpha$-channeling? advanced fuels?

• Reversed magnetic shear configurations have higher stability limits that monotonic q-profiles for similar pressure profiles

• Reversed shear and ERS provide a path for TFTR to explore strong alpha-heating and its interaction with advanced tokamak configurations.