Unified parametric dependence, control, and reconstruction of 3D equilibria in the RFP

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3D structures, equilibria emerge in tokamak & RFP

Snakes in tokamaks
(Weller et al. PRL 1987)

SHAx in RFP’s
(Lorenzini et al. Nat. Phys. 2009)

Helical equilibrium in ITER
(Cooper et al. PPCF 2011)
Specific motivations for this talk

- RFP 3D robust, but gaps in understanding, characterization, e.g.,
  - What controls appearance and duration?
  - What does equilibrium look like, in detail?
  - What is impact on confinement?
Outline

• A bit about the RFP and MST
• MST and RFX-mod dependencies on Ip and S
• Recent advances in computation and theory
• 3D reconstruction and confinement
RFP explores the limit of small applied Bt

When 3D structure occurs, associated with innermost mode

\[ q = \frac{rB_t}{RB_p} \]

In this talk Bt(a) = 0

\[(m,n) = (1,5), (1,6), (1,7) \ldots\]
A bit about the MST (Madison Symmetric Torus)

- Toroidally axisymmetric
At low $I_p$, mode spectra fairly flat, no 3D structure

At $I_p = 5$, $b/B(a) \sim 1\%$

$m = 1$ mode amplitudes (G)

$n = 5$

$n = 6-10$
At higher Ip, spectra peaked, lead to 3D structure

- Higher Ip, higher Te

Low $n_e \leq 10^{19} \text{ m}^{-3}$ needed as well

$b/B(a) > 7\%$
SHAx results from very peaked spectra

- Flat spectra --> “multiple helicity” (MH)
- Peaked spectra --> “quasi single helicity” (QSH)
- Extreme QSH leads to “single helical axis” (SHAx)
Statistical comparison to RFX-mod
A bit about RFX-mod

- $I_{p_{\text{max}}} \sim 2 \text{ MA}$
Spectral bifurcation in RFX-mod occurs at higher Ip than in MST.
MST & RFX-mod spectral trends unified in terms of S

- $S \sim I_p T_e^{3/2}/Z/(m_i n_i)^{1/2}$
- Important dimensionless parameter in nonlinear resistive MHD
- RFX-mod plasmas higher density, lower $T_e$
Persistence trends also unified in terms of $S$

- Persistence is duration of QSH normalized to duration of Ip flattop
Progress in computation and theory
QSH-SH long observed in MHD simulations, but with some inconsistencies relative to later experimental data

- Sightings by, e.g., Finn-Nebel-Bathke and Cappello-Paccagnella (Phys. Fl. B 1992)
- Visco-resistive simulations, $b_r(a) = 0$, large dissipation ($S \leq 10^4$)
- Transition governed by $H$ (Cappello-Escande, PRL 2000)
  - $H = (SM)^{1/2}$, $S = \tau_R/\tau_A$, $M = \tau_V/\tau_A$
  - $S \sim 10^7$ for MST-RFX QSH
  - For $H \sim 2500$, $M \sim 1$
- Experimental QSH temporal behavior not observed in codes

$m = 1$ spectrum (SPECYL code)
Progress using the SPECYL code

- Applied RFX-like helical $b_r(a) = 2\%$, $H = 10^{5.5}$ ($S = 10^7$, $M = 10^4$)
- Possible in part due to large increase in computational speed

- Also, code-experiment match improves as $H$ increases

- Encouraging, but viscosity and other issues remain
- Viscosity being reexamined within DEBS code (Schnack)

Bonfiglio et al. PRL 2013
New approach treats helical structure as shear-sustained coherent vortex, with a boundary layer

- Background turbulence suppression & structure lifetime linked, both increasing with Ip

Kim & Terry PoP 2012
With sufficiently large $I_p$, QSH steady state

- Dithering at lower $I_p$
- Dithering ceases at larger $I_p$
3D equilibrium reconstruction
Stellarator and 3D RFP reconstruction synergetic

• Need tool for detailed, accurate reconstruction in RFP
• Opportunity to test and advance stellarator tools

• 3D reconstruction recently developed for stellarators
• In part anticipating $J_{\text{bootstrap}}$ and deviation from vacuum $B$

• Tool applied here is V3FIT (Hanson et al., Nucl. Fusion 2009)
• Iterates VMEC to find equilibrium most consistent with expt. data
MST well suited for internal diagnosis

- Helix orientation now controllable via applied error field (Munaretto, DPP2013)

Courtesy of Jon Koliner
V3FIT successfully applied for MST

Includes polarimetry, recently added as constraint

Courtesy of Jon Koliner & Mark Cianciosa
Confinement in 3D
Fast ion confinement reduced by 3D topology

- Applied 25 keV NBI blips
- At low $b/B$, \( \sim \) classical transport
- At larger $b/B$, \( \sim \) neoclassical transport and/or direct ion orbit loss

\[ \tau_{ji} (\text{ms}) \]

\[ b_{n=5}(a)/|B(a)| (\%) \]

\[ I_p = 0.5 \text{ MA} \]

Courtesy of Jay Anderson
Thermal energy confinement improved in some shots

- $\tau_E$ improved $\sim 2x$
- With $J(r)$ control, $\tau_E$ improved $\sim 3x$

Courtesy of Stefano Munaretto
Summary

• QSH transition, duration depends on S (but maybe not only S)
• New computation & theory captures some experimental features
• Stellarator reconstruction tools applied to/tested in RFP
• Fast ion confinement reduced, thermal confinement improved