Role of MHD Dynamo in the Formation of 3D Equilibria in Fusion Plasmas

by
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MHD dynamo EMF of helical core

ExB flow

DIII-D

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MHD modes often saturate into stationary 3D equilibria
- affecting current profile, stability, transport, ...

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DIII-D

R (m)

Z (m)

-3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5

0.0 0.1 0.2 0.3

-6.4 -12.8 -19.2 -25.6

0.0 6.4 12.8 19.2 25.6

32.0
**MHD Modes Can Broaden the Current Profile Through a Continuous MHD Dynamo**

- **MHD modes often saturate into stationary 3D equilibria**
  - affecting current profile, stability, transport, ...

- **Resistive MHD predicts that helical states induce a continuous dynamo EMF:**
  \[ E_{\text{loop}} + \mathbf{v} \times \mathbf{b} = \eta j \]
MHD Modes Can Broaden the Current Profile Through a Continuous MHD Dynamo

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- Resistive MHD predicts that helical states induce a continuous dynamo EMF:
  \[ E_{loop} + \tilde{\mathbf{v}} \times \tilde{\mathbf{b}} = \eta j \]

- Can explain anomalous current broadening in:
  - high-\(\beta\) hybrid tokamak
  - reversed-field pinch

\[ E_{loop} + \mathbf{v} \times \mathbf{b} = \eta j \]
The Current Profile of Hybrid Tokamak Plasmas is Broadened by Benign MHD

- Hybrid tokamak: H-mode with improved confinement & high-β
- Benign MHD broadens the current profile and keeps $q_{\text{min}} > 1$
- As a result, no sawteeth, deleterious 2/1 mode more stable
Anomalous Current Broadening Enables Steady State Hybrid Operation

- The hybrid scenario has moderate bootstrap current fraction, $f_{BS} \approx 0.5$
- Can be compensated by efficient EC current driven near the center and redistributed by MHD

F Turco PoP 2015, CC Petty NF 2016
CC Petty EX/4-1, this conference
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A validated model of current redistribution is needed for extrapolations to future machines

- For example, current redistribution in DIII-D mainly occurs during transient NTM-ELM coupling events [CC Petty PRL 09]
- Will it work in a continuous way in ELM-suppressed plasmas?
Outline

GOAL: Test the MHD dynamo model of current redistribution in fusion plasmas

- A helical core equilibrium forms in hybrid tokamak plasmas perturbed by external n=1 fields
- Helical core used to probe current broadening
- Effect consistent with the MHD dynamo model
- Strong similarity with helical RFP dynamo
- Conclusions and future work
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A Helical Core Forms in Hybrid Plasmas Perturbed by External n=1 Fields

- Helical core due to the response of a marginally-stable kink to the externally applied n=1 field
- 1/1 harmonic large due to $q_{\min} \geq 1$

P Piovesan EPS 2016
V Igochine EX/P6-24

Helical core detected by ECE and CXRS as n=1 field rotates at 5Hz

$\delta T_e$ amplitude (ECE)

[Graph showing $\delta T_e$ amplitude and phase vs. R]

$\pi$-jump across magnetic axis
Helical Core Reconstructed by the VMEC/V3FIT 3D Equilibrium Code in DIII-D

- Helical core reproduced in DIII-D
- Reconstructed by VMEC/V3FIT, constrained by SXR and MSE measurements of the internal helical distortion

A Wingen EPS 2016
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The Helical Core Sustains Hybrid Conditions

- 3/2 tearing mode suppressed by ECCD

- Sawteeth come back
  - Hybrid conditions are lost due to absence of current broadening by the 3/2 TM [MR Wade NF 2005]
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- 3/2 tearing mode suppressed by ECCD

- Sawteeth come back
  - Hybrid conditions are lost due to absence of current broadening by the 3/2 TM [MR Wade NF 2005]

- No sawteeth when the helical core is induced by an external n=1 field
The Helical Core Causes a Measurable Level of Central Current Broadening

- Poloidal flux dissipated at a faster rate than it is supplied by coils
  - The **poloidal flux deficit** is estimated from the time evolution of the reconstructed equilibrium [TC Luce NF 2014] and is proportional to the amount of current broadening in hybrid plasmas [NZ Taylor APS 2016]
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Nonlinear MHD Simulations Predict that a Saturated 1/1 Kink Produces a Continuous Dynamo EMF

- An electrostatic EMF forms in any helical equilibrium to balance the helical modulation of parallel current, $j_{\parallel}$
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- An electrostatic EMF forms in any helical equilibrium to balance the helical modulation of parallel current, $j_{\parallel}$

General result that holds both for kink and tearing modes.

Discovered for helical RFP by D Bonfiglio PRL 2005 (SpeCyl).

Recently developed for hybrid tokamak plasmas by S Jardin PRL 2015 (M3D-C1).
Nonlinear MHD Simulations Predict that a Saturated 1/1 Kink Produces a Continuous Dynamo EMF

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• The associated ExB helical flow $\tilde{\nu}$ is a double convective cell
Nonlinear MHD Simulations Predict that a Saturated 1/1 Kink Produces a Continuous Dynamo EMF

- An electrostatic EMF forms in any helical equilibrium to balance the helical modulation of parallel current, $j_{\parallel}$
- The associated ExB helical flow $\tilde{\nu}$ is a double convective cell
- and produces an electric field in parallel Ohm’s law, negative in the core

$$E_{\text{loop}}{\parallel} + \tilde{\nu} \times \tilde{b}_{\parallel} = \eta j_{\parallel}$$
The Dynamo EMF Due to the 1/1 Kink Redistributes Central Current and Keeps $q_{\text{min}} \geq 1$

- The mean-field MHD dynamo EMF opposes the applied loop voltage in the core and redistributes central current.
- $q_{\text{min}}$ raises near/above 1 as the 1/1 kink non-linearly saturates in the simulation.

More in D Bonfiglio TH/P3-35, this conference.
The MHD Dynamo EMF Predicted for the Helical Core is Consistent with the Measured Poloidal Flux Deficit

- The MHD dynamo EMF can be calculated for the experimental 3D equilibrium, by balancing Ohm's law over 3D flux surfaces:
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\[
\frac{B \cdot (E_{\text{loop}} - \eta_{\text{neo}} j_{\text{Ohm}})}{B \cdot \nabla \theta} = \partial_\theta \varphi + q \partial_\zeta \varphi 
\]

\[
j_{\text{Ohm}} = j_{\text{VMEC}} - j_{\text{CD}} - j_{\text{BS}}
\]

- \( \varphi \), unknown variable
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- 3D quantities: VMEC
- 2D quantities: from ONETWO transport simulation mapped onto 3D equilibrium
The MHD Dynamo EMF Predicted for the Helical Core is Consistent with the Measured Poloidal Flux Deficit

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\frac{B \cdot (E_{\text{loop}} - \eta_{\text{neo}} J_{\text{Ohm}})}{B \cdot \nabla \theta} = \partial_{\theta} \phi + q \partial_{\zeta} \phi
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\[
J_{\text{Ohm}} = J_{\text{VMEC}} - J_{\text{CD}} - J_{\text{BS}}
\]

\[
V_{\text{loop}} = \langle -\nabla \phi \cdot \hat{B} \rangle 2\pi R_0
\]

consistent with measured poloidal flux deficit \( \sim 10 \text{mV} \)
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- Conclusions and future work
An MHD Dynamo EMF Maintains the Parallel Current Profile in the Reversed-Field Pinch

- **Confirmed by direct measurements of the MHD dynamo terms**

Dynamo limits the peaking of central Ohmic current

... and drives edge poloidal current

From JK Anderson PoP 2005
In Helical RFP Plasmas the MHD Dynamo is Mainly Provided by the Dominant Helicity

- Helical RFP states form spontaneously at high-current >1MA
- Helical equilibrium from VMEC/V3FIT constrained by internal SXR measurements used to predict dynamo EMF in RFX-mod

R Lorenzini Nature Phys 2009
D Terranova NF 2013
M Zuin OV/P-2, this conference
The Predicted MHD Dynamo Flow is Consistent with the Helical Flow Measured in Experiment

- Both have a double convective cell structure
  - Measured helical flow $\approx 1$ km/s much larger than in tokamaks, because it must produce a much larger $V_{\text{loop}} \approx$ a few Volts

MHD dynamo EMF & flow  
Helical flow (Doppler spectroscopy)
The Predicted MHD Dynamo Flow is Consistent with the Helical Flow Measured in Experiment

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\[
V_{\text{loop}} = \langle -\nabla \phi \cdot \hat{B} \rangle 2\pi R_0
\]

\approx 30\% \text{ of applied } V_{\text{loop}}
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• Results are consistent with the MHD dynamo model

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Conclusions

- The **MHD dynamo model** can explain current redistribution by MHD modes in RFP and tokamak plasmas
  - The dynamo EMF can be **directly calculated from 3D equilibria** reconstructed from experimental data

- The dynamo EMF can be produced in a **continuous** way with no need of transient events
  - Expected to work in hybrid plasmas with suppressed ELMs
Conclusions … and Future Work

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- **Quantitative predictions for hybrid tokamak with a 3/2 tearing and scaling to future machines need more work**
  - Validated nonlinear MHD simulations of tearing modes
  - Add effects beyond 1-fluid MHD, e.g. fast ion transport by MHD
  - More experiments, 3D measurements, rigorous assessment of model/experiment uncertainties
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Back-up slides
Non-axisymmetric coils in ASDEX Upgrade and DIII-D

ASDEX Upgrade

8x2 B-coils

A-coils (planned)

6x2 I-coils

C-coils
Flux states method to evaluate a poloidal flux deficit

- $\psi_c I_p = W_{\text{coil}} = \text{Energy provided by poloidal coils coupling with the plasma. Mutual inductance between coils and the plasma}$
  
  - $J_\phi$ obtained from EFIT (magnetics + MSE), $\psi_c$ from currents in the 18 poloidal field coils and E-coil

- $\psi_{\text{kin}} I_p = W_{\text{kin}} = \text{Work done by the electric field within the plasma. Amount of poloidal magnetic energy being converted to kinetic energy in the plasma}$

\[
W_c = \frac{\mu_0}{4\pi} \int \int dV dV' J_c J_\phi / r
\]
\[
W_c = \int dV J_\phi A_{\phi,c} = \int dR dz J_\phi \psi_c
\]
\[
\Psi_c = \frac{1}{I_p} \int dR dz J_\phi \psi_c
\]

\[
\frac{dW_{\text{kin}}}{dt} = - \int dV J \cdot E
\]
\[
\Psi_{\text{kin}} = \frac{1}{I_p} \int dR dz J_\phi \psi
\]

Poloidal flux deficit in a standard hybrid tokamak. Courtesy of NZ Taylor (GA)

- Hybrid discharge where 3/2 NTM is destabilized
- Counter-ECCD applied to q=3/2 surface
MHD dynamo by 1/1 kink vs 2/1 tearing (SpeCyl code)
Helical flow of 1/1 kink in RFX-mod Ohmic tokamak

Toroidal cross-section

SpecCyl nonlinear MHD simulation

Poloidal cross-section

Spectroscopy views

L. Piron et al, submitted to NF
In RFP nonlinear MHD simulations, dynamo is dominated by electrostatic fields even during fast relaxation events.

\[ E = E_{\text{loop}} - \nabla \phi - \frac{\partial A}{\partial t} \]

\[ W^E = \frac{1}{2} \int_V E^2 = w_{\text{loop}}^E + w_\phi^E + w_A^E \]

\[ w_{\text{loop}}^E = \frac{1}{2} \int_V E \cdot E_{\text{loop}} \]

\[ w_\phi^E = \frac{1}{2} \int_V E \cdot (-\nabla \phi) \]

\[ w_A^E = \frac{1}{2} \int_V E \cdot \left( -\frac{\partial A}{\partial t} \right) \]

From D Bonfiglio PRL 2005