Collaborations with Dalton and Recent Work on Helical Current Drive

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OUTLINE

- Single Helicity RFP Simulations
- ZT-40 Experimental Observations
- 3-D RFP Simulations
- Self-Similar RFP Rampdown
- Field Errors and Electrostatic Feedback Control
- Helical Current Drive in Tokamaks
- DC-DC Electrical Transformers
Single Helicity Simulations


- Tour de Force of Single Helicity Modes in RFPs
- Current Penetration Modes During RFP Formation
  + Kadomtsev Reconnection
  + Lowers q and Flattens Current
- Double Tearing Modes for Non-Reversed RFP
  + Explosive Growth as Islands Interact
- Double Reconnection Mode
  + Diffusion Lowers q and Peaks $J_\parallel /B$ on-axis
  + Tearing and/or Ideal Kink is Destabilized
  + q is Raised on-axis and $J_\parallel /B$ is Flattened
  + Two Reconnections Occur
Double Reconnection Mode

- First Reconnection Makes Plasma Helical and Lowers $q$
- This Reconnection Has Sweet-Parker Scaling
- Second Reconnection Resymmetrizes Plasma and Raises $q$ on-axis
- This Reconnection Scales Like Diffusion
Sawtooth Oscillations in RFPs


- Diffusion Lowers $q$ and Peaks $J_\parallel /B$ on-axis.
- Tearing and/or Ideal Kink is Destabilized.
- $m=1$ Precursor is Observed.
- $q$ is Raised on-axis and $J_\parallel /B$ is Flattened.
- Process Repeats.
3-D RFP Simulations


- Instabilities are Multihelical.
- Resonances for Unstable Modes are Closely Spaced near r=0.
- Islands Overlap Resulting in Stochastic Core.
- Nonlinear m=0 mode coupling from m=1 modes.
- These are not DEBS Results. This Was Done with a Pseudo-Spectral Explicit Code.
Self-Similar Rampdown


• Self-Similar Rampdown Solutions Allow RFP to Remain Stable to Kinks and Tearing During Discharge Rampdown.
• Originally Proposed by Caramana and Nebel (Also Work at Culham) but Quickly Forgotten.
• Renewed Interest After PPCD Results on MST.
• Caramana and Nebel Derived the Original Profiles.
• Nebel, Schnack and Gianakon Showed These Solutions Were Universal 3-D Attractors.
Field Errors and Electrostatic Feedback Control


- DEBS was Used to Analyze Plasma Response to Field Errors on ZT-H and MST.
- Results Indicated That Field Errors Amplify if Plasma is Close to Marginal Stability. Otherwise, Field Errors Damp.
- Recent Work at Tibbar Technologies Has Used These Principles to Propose and Analyze Ways to Lock RFPs into Single Helicity and do Feedback Control on Tokamak Instabilities.
Boundary Conditions

I. Perfect Conductor Boundary Conditions

\[ E_\theta(m,k) = E_z(m,k) = 0 \]

II. Our Boundary Conditions

\[ \frac{\partial B_r}{\partial t} = 0 \text{ or } E_\theta(m,k) = m/(kr) E_z(m,k) \]
\[ E_r(m,k) = \eta J_r(m,k) = \text{Constant} \]
\[ v = 0 \]

III. Magnetically B.C.s Look Like an Ideal Conductor, but the Electrostatic Potential Varies on the Surface.
How These B.C.s Can be Made

I. Single Helicity RFP

Helical Electrodes Produce a Helical Potential Profile to Lock RFP into a Single Helix
How These B.C.s Can be Made

II. Tokamaks or RFPs

- Electrostatic Programmable Plates Attached to a Conducting Wall
- Suitable for Feedback Control System
Characteristics of Electrostatic Mode Inducement and Suppression

- Electrostatic Response Times are Very Fast.
- Does not Require the Diffusion of Magnetic Fields Through Conductors.
- Edge Perturbations on Unstable Modes Amplify into the Interior.
- Gain Is High so energy Requirements are Modest.
- Amplitudes and Sensitivities Need to Be Determined.
- Can This be Demonstrated Experimentally?
**Bismark Device**

**Hybrid Magnetic/Electrostatic Device**  
**Axial Magnetic field**

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<th>Parameter</th>
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<td>Chamber Diameter</td>
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<td>Chamber Length</td>
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<td>Coil Length</td>
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<td>Number of Turns in Coil</td>
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<td>Peak Coil Current</td>
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<tr>
<td>Peak voltage</td>
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**Projected Parameters**

**Present Status:** Device is in operation
Can We Test Mode Electrostatic Mode Amplification with the Bismark Device?

- Straight Axial Magnetic Field.
- Marginally Stable to Interchange Modes.
- $m=1, n=0$ Electrostatic Boundary Perturbations Should Show Large Flows.
- This is Confirmed by the 3-D MHD simulations.
- $m=1, n=1$ Electrostatic Boundary Perturbations Should Damp.
- The 3-D MHD Simulations Unexpectedly Produced Current Drive…
q Profiles

Low Drive Voltage

High Drive Voltage
Dynamo Current Drive

- Small Electrostatic Boundary Perturbations Damp as Predicted by the Linear Theory.
- Larger Perturbations Drive The Plasma Nonlinearly.
- There is a Bifurcation in the Solutions Depending on the Magnitude of the Perturbations.
- New Relaxation Principle: The Magnetic Field Tries to Align Itself with the Electrostatic Electrodes, Resulting in Current Drive.
- States are Stationary, Universal Attractors. These States are Found Independent of the Initial Conditions.
- Why Does This Happen?
Dynamo Current Drive

- States are Stationary, Universal Attractors. This Eliminates Disruptions.

- ExB Flow Velocities Need to be Comparable to the Alfven Speed to bend the Magnetic Fields (2%-20% observed).

- ExB Flow Velocities Cannot Exceed the Alfven Speed or Equilibrium is Lost.

- A Boundary Layer Forms near the Plasma Boundary. The Layer Width Shrinks as the Voltage is Increased.

- All Other Modes Are Stabilized By the Flow.

- States Are Near Single Helicity With Very Little Radial Magnetic Field.

- The Stronger the Driving E Field, the Smaller the Radial magnetic Field.

- This Is Also a DC-DC Transformer
Helical Electrodes

Electrodes

Current Drive Assembly
Vacuum Chamber and Magnetic Solenoid
Tibbar Technologies World Headquarters

Bismark Device
Long Distance AC Power Transmission

- AC Power Couples Into the Environment
- Losses Are Significant Enough that AC Power Cannot be Economically Shipped More Than ~ 400 Miles
- Transmission Lines Must be Elevated to Keep Losses Small
High Voltage DC Transmission

- DC Does NOT Couple into the Environment
- Power Can be Shipped 1600+ Miles
- Cables Can be Placed Underground
- Cables Can Even be Placed Underwater
- Voltages are Transformed with Rooms Full of Solid State Equipment (Thyristors)
- This is VERY EXPENSIVE!
- Economically Prohibitive for Amounts < 20 MW
- Primary Companies are ABB and Siemens

HVDC Lines in Europe
Present Status

- Helical Current Drive Has Now Been Demonstrated in the Bismark Device
- We Still Aren’t in the Proper MHD Regime and Efficiencies Are Low.
- Come to Los Alamos on Tuesday PM and We’ll Let You Run the Device.