Bootstrap current and magnetic islands in W7-X

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Main Topics

- While designed to have no bootstrap current, W7-X will have residual currents.
- This bootstrap current will affect the magnetic structure and may induce the formation of magnetic islands at the edge, associated with $\nu = 1$ entering the plasma.
- By using the W7-X planar coils, the impact of bootstrap current on the magnetic structure can be controlled.
Outline

● Motivation
  ➤ Wendelstein 7-X coils and equilibrium
● Increasing $\beta$ & bootstrap current in W7-X
● Using SIESTA to calculate the magnetic structure of W7-X including islands
A quick overview of W7-X

- W7-X is nearing completion and will begin operation soon (2014?)
  - 50 modular coils
  - 20 planar coils (for control)
  - Goal to obtain up to $\beta \sim 5\%$
  - Design target of minimal bootstrap current
A quick overview of W7-X (cont.)

- Main parameters (base case):
  \[ \langle R \rangle = 5.5 \text{ m}, \langle a \rangle = 0.54 \text{ m}, A = 10.2, \langle B_0 \rangle = 2.8 \text{ T} \]

- Coil sets:
  - 5 modular (10 coils/group)
  - 2 planar (10 coils/group)

- Base and mirror coil currents:
  - Base: 1.62 MA, all modular coils
  - Mirror: 1.56 MA, 1.51 MA, 1.44 MA, 1.37 MA, 1.32 MA
- Flux surface cross-sections

- Rotational transform, current, & plasma pressure

\[ \beta = 1\% \]
Motivation

- At finite $\beta$ there will be some bootstrap current
  - Using BOOTSJ to calculate the bootstrap current
  - Approximately 20 kA of toroidal current at $\beta = 1\%$
W7-X target of $\beta = 5\%$

**Base Case, $\beta = 0\text{-}5\%$**

- **Base equilibria:**
  - $\langle \beta \rangle = 0 \text{-} 5\%$

**Mirror Case, $\beta = 0\text{-}5\%$**

- **Mirror equilibria:**
  - $\langle \beta \rangle = 0 \text{-} 5\%$
BOOTSJ: A quick numerical calculation of the bootstrap current in toroidal devices

- Takes a VMEC input transformed to Boozer coordinates as input
- Given some assumptions about the profiles, $T_e/T_i$, BOOTSJ estimates the contributions to $J_{BS}$:

$$J_{BS} = J_{\nabla n_e} + J_{\nabla T_e} + J_{\nabla n_i} + J_{\nabla T_i}$$

Bootstrap consistent equilibrium: plasma current matches bootstrap current

- Iteratively adjust the plasma current used in VMEC until $J_{\text{VMEC}} \sim J_{\text{BS}}$
Bootstrap consistent equilibrium:
As $\beta$ increases, $\iota = 1$ surface moves inward

Iteratively adjust the plasma current used in VMEC until $I_{VMEC} \sim J_{BS}$

\[ I_{VMEC} = \begin{cases} 20 \text{ kA} & \beta = 1\% \\ 54 \text{ kA} & \beta = 3\% \\ 78 \text{ kA} & \beta = 5\% \end{cases} \]
SIESTA: Fast calculation of equilibria with magnetic islands

- We have begun using the SIESTA code to examine the impact of $\beta$ and bootstrap current on the magnetic structure.
- Refer to the earlier talk by C. Cook at this meeting for more details on SIESTA.
SIESTA: Increasing $\beta$ (no current) produces small islands in W7-X?

- Poincare sections of the magnetic field from SIESTA showing signs of islands

$\beta = 1\%$ B-field tracing at $\phi = 0^\circ$

$\beta = 2\%$ B-field tracing at $\phi = 0^\circ$
SIESTA: Increasing $\beta$ (no current) produces small islands in W7-X?

- Pressure surfaces from SIESTA showing deformations but no islands

\[ \beta = 2\% \text{ Pressure Contours at } \phi = 0^\circ \]
SIESTA: Bootstrap consistent current produces larger islands

- Poincare sections show islands while pressure surfaces are less clear

\[ \beta = 1\% \text{ B-field tracing at } \phi = 0^\circ \]

\[ \beta = 1\% \text{ Pressure Contours at } \phi = 0^\circ \]
Can controlling the rotational transform heal the islands?

- While it is possible to use current drive to cancel out the bootstrap current, it may not be necessary

\[ I_{\text{VMEC}} = 38 \text{ kA} \]

\[ I_{\text{VMEC}} = 0 \text{ kA} \]

\[ I_{\text{VMEC}} = 38 \text{ kA} \]

\[ \beta = 2\% \]

\[ I_{\text{VMEC}} = 126 \text{ kA} \text{ in planar coils} \]
Summary

- At finite-$\beta$ small, but potentially important, bootstrap currents in W7-X
  - At $\langle \beta \rangle = 1\%$ about 20 kA
    and at $\langle \beta \rangle = 5\%$ about 79 kA
  - These bootstrap currents add to the rotational transform, moving the $\iota = 1$ surface into the plasma
  - SIESTA shows evidence of island formation in the edge region even for $\langle \beta \rangle = 1\%$ and $I = 20$ kA
Summary (continued)

- By using the control coils, the rotational transform can be altered to move the $\iota = 1$ surface back outside of the plasma
  - Still investigating how this impacts the magnetic structure