Limits for Compact Stellarators: Are they Real?

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W7-AS and LHD Have Exceeded the Predicted Ideal MHD $\beta$ Limits

- **W7-AS**: Achieved $\langle \beta \rangle = 3.4\%$
  
  (M.C. Zarnstorff and A. Weller)
  
  - High Density Low $T_e$
  - MHD activity in early medium $\beta$ phase
  - Robustly achieved for $B = 0.9$ to $1.1$ T and varying heating methods
  - Predicted ideal MHD stability limit $\beta \sim 2\%$
LHD Results Are Similar to W7-AS

- LHD: Achieved \( \langle b \rangle \sim 4\% \)
  - Low Density High \( T_e \)
  - 2/1 MHD activity in core for \( b < 2.5\% \)
  - No core MHD observed at high \( b \)
  - Edge modes observed for \( b > 3.4\% \)
    - 1/1 surface at \( b > 0.9 \)
    - May set \( b \) limit
  - Predicted interchange limit at low \( b \) is clearly violated
    - Resistive and ideal both unstable
Quiescent Quasi-stationary Discharge: $\beta \approx 3.4\%$

- $B = 0.9$ T, $\text{iota}_{\text{vac}} \approx 0.5$
- Almost quiescent high-$\beta$ phase, MHD-activity in early medium-$\beta$ phase
- $\beta$ not limited by any detected MHD-activity.
- $I_P = 0$: local currents may exist
- Similar $\beta > 3.4\%$ plasmas achieved with $B = 0.9 – 1.1$ T with either NBI-alone, or combined NBI + OXB ECH heating.
- Much higher than predicted $\beta$ limit $\sim 2\%$

(M.C. Zarnstorff)
> 3.2% maintained for > 100 $	au_E$

- Peak $\langle \parallel \rangle = 3.5$
- High-$\parallel$ maintained as long as heating is maintained
- $\parallel$-peak, $\parallel$-flat-top very stationary
- Duration and $\parallel$ not limited by onset of observable MHD

What limits the observed $\parallel$ value?

(M.C. Zarnstorff)
MHD Activity is Sometimes Observed in W7-AS at Intermediate □

- m=2, n=1 pressure driven modes. Sometimes also m=3 or 5. Does not usually strongly affect confinement.

- Alfvénic instabilities at low density.

- (2,1) tearing modes with significant $I_p < 0$ (increasing iota) and tokamak-like shear.

- High n instabilities at very low $T_e$.

(M.C. Zarnstorff)
Pressure Driven Modes Observed at Intermediate \beta 

- Dominant mode m/n = 2/1
- Modes disappear for \beta > 2.5% (inward shift of iota = 1/2 surface?)

**X-Ray Tomograms**

- Reasonable agreement with CAS3D and Terpsichore linear stability calculations: Predicted threshold \beta < 1%

**Does not inhibit access to higher \beta !**

Linear stability threshold is not indicative of \beta limit.

(M.C. Zarnstorff)
Observed Mode Structure Corresponds to Near-Edge Iota (VMEC)

- In both cases, MHD observed transiently during pressure rise. Edge iota drops as $\Delta$ increases, due to equilibrium deformation.
- Strong ballooning effect at outboard side (M.C. Zarnstorff)
Low-mode Number MHD Is Very Sensitive to Edge Iota During Flat-top in W7-AS

- Controlled iota scan, varying $I_{TF} / I_M$, fixed $B$, $P_{NB}$
- Flattop phase
- Strong MHD clearly degrades confinement
- Strong MHD activity only in narrow ranges of external iota
- Equilibrium fitting indicates strong MHD occurs when edge iota $\geq 0.5$ or $0.6$ ($m/n=2/1$ or $5/3$)
- Strong MHD easily avoided by $\sim 4\%$ change in TF current

(M.C. Zarnstorff)
Linear Stability Calculations (CAS3D) Indicate 2/1 Should be Unstable in W7-AS

Mode Displacement & Perturbed Pressure

\[ \langle \beta \rangle = 0.84 \% \]

\[ \langle \beta \rangle = 2 \% \]

\[ \text{edge iota and natural resonances} \]

\[ \text{global free-boundary instabilities} \]

External global modes most unstable at low \( \langle \beta \rangle \)

(C. Nuhrenberg)
High-n Instabilities Sometimes Observed in W7-AS

- Typical high-$\nu$ plasmas are calculated to be ballooning stable. No high-n instabilities are observed.

- High-n instabilities are observed if $T_e$ drops below $\sim$ 200eV. Probably a resistive instability.

- W7AS can vary the toroidal ripple or mirror ratio using ‘corner coils’ ($I_5$)

- For $I_5 > I_M$, very unstable low-$\nu$ phase, then spontaneous transition and rise to moderate $\nu$.

- In later $\nu > 2\%$ phase, plasma calculated to be in ballooning 2$^{nd}$ stability regime. How does it get there?

(M.C. Zarnstorff)
Experimental Studies of MHD Instabilities in LHD Also Show MHD Stability at Low $\beta$

- Beta dependence of MHD activity:
  - Core MHD activity suppressed with $\beta$
  - Edge MHD activity increased with $\beta$
- Optimization of $R_{ax}$: $R_{ax} > 3.5$ is better

- High $A$ reduces Shafranov shift, can produce plasma with $\delta_{dia} \sim 4\%$

- Why are the MHD modes stabilized?
  - (a) Profile flattening caused by MHD mode?
  - (b) Stopping of mode rotation? (but frequency unchanged)
  - (c) Variation of magnetic surface due to $\beta$?
Plasma Boundary Has a Significant Influence on MHD Stability in Heliotrons

- **Discrepancy on MHD equilibria & stability:**
  - Experiment: $\langle b \rangle > 3\%$ plasmas
  - Theory: Strong MHD instabilities for fixed boundary plasmas
  - Finite pressure gradient observed beyond a clear vacuum LCFS

- **Assume average flux surfaces in stochastic region**
  - Inward shifted configurations have narrowest stochastic layer
  - For $\langle b \rangle = 3\%$, unstable for fixed boundary but marginally stable for free boundary
  - At high $\langle b \rangle$, growth rates decrease with increasing $\langle b \rangle$ due to boundary modification
  - Density profile effects can be important in lowering growth rates as well

(A. Ware/N. Nakajima)
Is $\phi$ Limited by an Equilibrium Limit?

Maximum $\phi$ at low $\phi$ is close to classical equilibrium limit $\phi \sim a/2$

Control coil excitation does not affect iota or ripple transport

Axis shift $\phi \sim a/2$

Iota Variation

Divertor Control Coil Variation

(M.C. Zarnstorff)
Control Coil Modulation Can Improved Flux Surface Topology as $b$ is Increased

$\frac{I_{CC}}{I_M} = 0 \quad \square = 1.8\%$

$\frac{I_{CC}}{I_M} = 0.15 \quad \square = 2.0\%$

$\frac{I_{CC}}{I_M} = 0.15 \quad \square = 2.7\%$

PIES equilibrium: fixed pressure profile from equilibrium fit (not fitted current profile)

Pies calculates similar flux surface degradation at the experimental maximum $b$ values!

-- 1.8% for $\frac{I_{CC}}{I_M} = 0$

-- 2.7% for $\frac{I_{CC}}{I_M} = 0.15$

(M.C. Zarnstorff)
PIES equilibrium calculations indicate that fraction of good surfaces drops with ⬡

Drop occurs at higher ⬡ for higher $I_{CC}/I_M$

Experimental ⬡ value correlates with loss of ~35% of minor radius to stochastic fields or islands

(M.C. Zarnstorff)
A New Proposed Model for Stellarator Equilibrium and Confinement Limit

- Is a stellarator equilibrium really like a simple container?
- Or is it more like a leaky sponge?

Add pressure up to point where container breaks
  □ Major leak: All energy lost

Add pressure to saturation point
  □ Holes expand as confinement degrades until pressure finally leaks as fast as it is absorbed
Recent Progress Made in Equilibrium Reconstructions

Need to reconstruct self-consistent equilibrium for further analysis: pressure and iota profiles, plasma shape

• Available data:
  – 45 point single-time Thompson scattering system
    assume $p_i = p_e$, due to very high density \( \Rightarrow \) short equilibration time
  – 19 magnetic measurements, including:
    segmented Rogowski, flux loops, diamagnetic loops

• From SVD analysis: magnetic measurements sensitive to 3 moments of pressure profile and 2 moments of current profile

• Adapted STELLOPT design-optimization code to be a free-boundary equilibrium reconstruction code

(M.C. Zarnstorff)
• Reconstructed equilibrium of $\beta=3.4\%$ plasma
• Lower central iota, flatter profile
• Central $\beta=8.0\%$
• Edge pressure pedestal: present in many (but not all) high-$\beta$ plasmas

(M.C. Zarnstorff)
Consistent Picture Emerging on Role of MHD Stability and the \( b \) Limit in Stellarators

- Both W7-AS and LHD show similar results regarding the ideal MHD stability limits:
  - Maximum \( b \) is not limited by MHD activity.
  - Maximum \( b \) reached is much higher than predicted linear stability thresholds.

- Pressure driven MHD activity is observed in some cases at low or intermediate \( b \):
  - Usually saturates at harmless levels.
  - Exists in narrow range of iota \( \iota \) easily avoided by adjusting coil currents.
  - MHD at high \( b \) in LHD.

- Predicted MHD stability correlates reasonably with observations at low \( b \):
  - Predicted MHD stability at high \( b \) depends sensitively on the boundary assumed.
Maximum $b$ appears to be controlled by loss of flux surface quality in stellarators.

- Maximum $b$ correlated with calculated loss of $\sim 35\%$ of minor radius to stochastic magnetic field
  - May limit $b$
  - Leaky sponge model may be more appropriate
  - Maximum $b$ is not generally limited by MHD activity

- Loss of minor radius has a significant effect on the predicted MHD stability properties
  - Generally stabilizing by removing edge resonances!
  - Ideal MHD stability predictions using fixed boundary VMEC equilibria are probably not valid at high $b$
  - Ideal MHD may still play a role in the limit at high $b$ in some cases
  - Ideal MHD might be avoided at high $b$ by small modulations of the boundary
  - BUT: Proximity to ideal MHD instability may contribute to deteriorating flux surfaces

- More accurate equilibrium reconstructions with measured profiles and flux surfaces are clearly needed
  - With sensitivity studies against possible variations in the discharge equilibria!
W7-AS – a flexible experiment

5 field periods, $R = 2 \, \text{m}$, minor radius $a \leq 0.16 \, \text{m}$, $B \leq 2.5 \, \text{T}$, vacuum rotational transform $0.25 \leq \text{ext} \leq 0.6$

**W7-AS**

Flexible coilset:
- Modular coils produce helical field
- TF coils, to control rotational transform
- Not shown:
  - divertor control coils
  - OH Transformer
  - Vertical field coils

Completed operation in 2002

(M.C. Zarnstorff)