UPDATE ON STELLARATOR β LIMITS: WHAT DO THEY MEAN?

A.D. Turnbull

ARIES-CS Project Meeting

June 14 2005

Madison, WI

MHD Interpretation of β Limits in Stellarators: Review of Progress

- **Interpretation of β limits:**
  - Ideal local ballooning and interchange modes
  - Ideal global internal modes
  - Ideal global external modes
  - Resistive interchange modes
  - Equilibrium limits to β
- **Characterization of experimental Stellarator equilibria:**
  - Pressure and Current (ι) profile
  - Island Topology
  - Equilibrium reconstruction (V3FIT)

Interpretation of β Limits: Ideal Local Ballooning and Interchange Modes

General consensus is still that large experiments routinely exceed local ideal ballooning and Mercier β limits

- **LHD Achieved < β > = 4% (Sakakibara EPS 2004):**
  - Heliotron configuration has a magnetic hill in the peripheral region

  ⇒ violation of stability of ideal and resistive interchange modes are a concern but not seen
- **W7-AS: Achieved < β > = 3.4% (Zarnstorff IAEA 2004):**
  - MHD activity in early medium β phase
  - Predicted ideal MHD stability limit β ~ 2%

Localized Modes Can Also Appear Where Mercier is Predicted Stable

- **Experiments on TJ-II show electromagnetic oscillations at plasma pressures an order of magnitude lower than:**
  - the Mercier stability condition and
  - the condition for stability of resistive interchanges
- **Study analyzed stability of plasmas in configurations with deep magnetic well:**
  - Stable to ideal and resistive interchanges
- **Instability is predicted if drift frequency is of order of ion inverse transit time (Shchepetov EPS 2004)**:
  - Modes appear in Mercier unstable but FLR stabilized cases
  - Unstable mode has lower and upper bounds in T_i

Ignoring Local Limits is Reasonably Consistent with Tokamak Experience

- **Large tokamak experiments also routinely exceed local ideal Mercier β limits:**
  - Tokamaks routinely operate with axis q near or below 1.0 where Mercier stability is violated

    ⇒ **Identical to situation in stellarators**

  - Ballooning stability appears to cause confinement saturation so that profiles do not exceed the local ballooning limit

    May be some difference in Stellarators but absence of accurate equilibrium reconstruction still precludes a definite conclusion

    ⇒ **Situation is unchanged from previous reports**

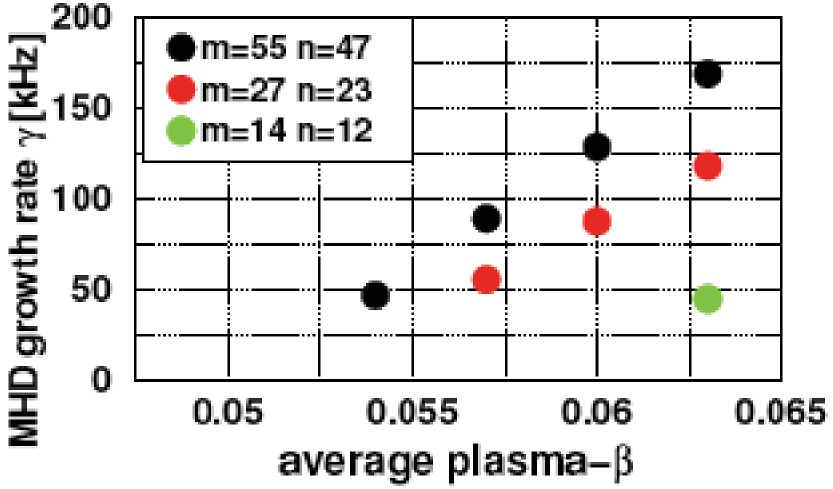
Interpretation of β Limits: Ideal Global Internal Modes

- **Progress in understanding meaning of β limit in W7X:**
  - Experiments saw high β quiescent phase after an earlier startup with noticeable MHD activity
  - Compare CAS3D stability with W7-AS experiment (C. Nuhrenberg EPS 2003)
- **Studied equilibria above β =5% in order to obtain physical growth rates of the unstable modes:**
  - Mercier stability criterion indicates stability throughout
  - Previous results for local ballooning stability confirmed

  ⇒The ballooning limit seems to be close to β ~ 5%.
- **Global internal stability of low (m,n=14,-12 dominated), intermediate (27,-23), and high m modes (55,-47):**
  - All limits were above 5%
  - The m = 55 mode had the lowest beta limit

Physically Relevant Growth Rates Considered to be Above 20 khz (20 μs)

- **Physical growth rates versus β:**



Physical MHD growth rates γ [kHz] versus average plasma-β.

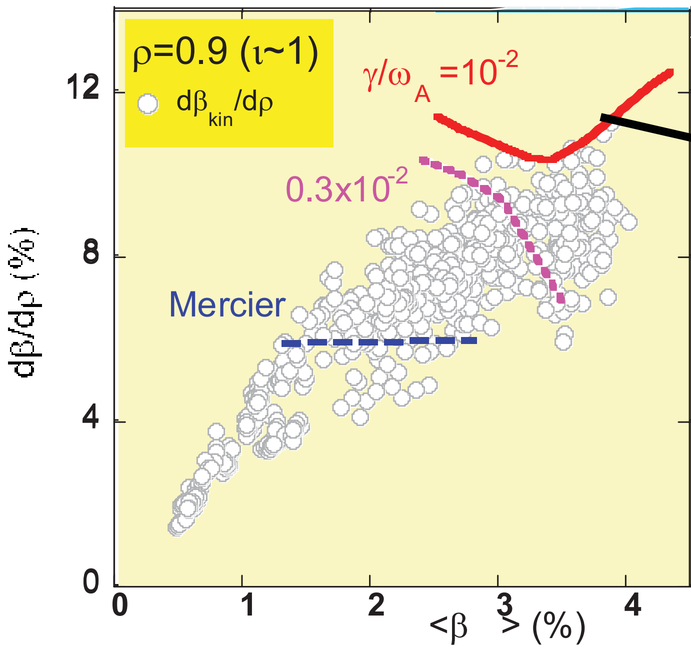
(C. Nuhrenberg:
30th EPS Conference
St. Petersburg, 2003
ECA Vol. 27A, P-1.16)

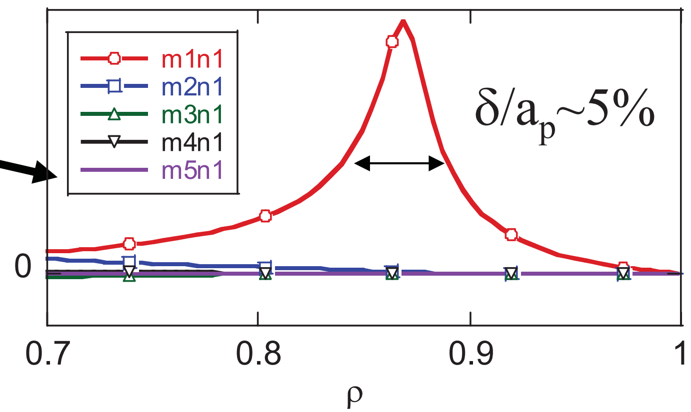
⇒The beta limit for the low n modes (m=14) is about 6%. For high m it is 5.25%.

Low m/n = 1/1, 2/3, and 2/5 Internal Modes Appear to Determine β Limit in LHD

- **In LHD several MHD modes (m/n = 1/1, 2/3 and 2/5) modes are excited in the edge region and spontaneously stabilized in turn as β increases:**
  - Profile flattening is observed and contributes the stabilization of MHD modes.
  - These modes limit the pressure gradient in the peripheral region
- **Theoretical prediction suggests m/n = 1/1 mode has a resonance around ρ = 0.9 and that this mode determines the β limit in LHD (Sakakibara EPS 2004)**

In LHD β Limit Also Appears To Correlate with a 'Big Enough' Internal Mode





Radial structure of ideal MHD mode calculated by **TERPSICHORE code**

Though beta value and its gradients reach the global mode unstable region where the predicted radial width of the ideal MHD mode reaches δ/a_p =5%,the disruptive degradation of global confinement has not been observed.

This View is Also Consistent with Tokamak Experience

- **Tokamaks routinely operate with weakly unstable ideal global internal modes**
- **A prominent example is the ideal internal m/n = 1/1 mode which is almost always weakly unstable if $q < 1$ ($\iota > 1$)**
  - 1/1 stability is dependent on a range of non-ideal contributions
  - The 1/1 ideal instability is routinely ignored in stability calculations
- **Other examples are weakly growing “infernal” modes localized in low shear regions**

Strong Toroidal Shear Flow May Non-linearly Stabilize the 1/1 Mode in NSTX

- **Non-linear simulations for NSTX with the M3D code suggest strong toroidal shear flow may allow access to states following reconnection that exhibit maximum pressure inside the island (J. Menard EPS 2003):**
  - $\Rightarrow$ Non-linearly stabilizes the 1/1 mode.
  - Not strong enough to absolutely linearly stabilize the 1/1 internal mode
- **Something similar might operate in Stellarators:**
  - Presumably not toroidal rotation but some of the other physics may provide the partial stabilization
  - In particular, the reversed shear in Stellarators is nonlinearly stabilizing

Interpretation of β limits: Ideal Global External Modes

- **This situation is more ambiguous:**
  - Little analysis has been done comparing external mode predictions with experiments
- **As in Tokamaks, ELMs are observed but do not result in β limits**
  - In Tokamaks ELMs appear to be primarily intermediate n ideal edge instabilities
  - In Stellarators it is not clear this is so: ELMs may instead be induced by resistive/ideal interchange modes
- **An open question is how do local ballooning mode solutions over a range of the plasma relate to global modes (Ware EPS 04):**
  - Results from an analysis of finite *n* modes for QPS using Terpsichore indicate stability to $<\beta> > 5\%$
  - Construction of global modes from the local mode solutions may yield similarly higher $<\beta>$ limits if the local criteria by themselves are ignored

Global Edge Stability Depends Strongly on Edge Conditions and Rational Edge Values

- **Plasma Boundary Has a Significant Influence on MHD Stability in Heliotrons (N. Nakajima JIFT 2005):**
  - Finite pressure gradient observed beyond LCFS
  - Inward shifted configurations have narrowest stochastic layer
  - Assuming average flux surfaces in stochastic region, configuration is predicted unstable for fixed boundary at $\langle\beta\rangle = 3\%$, but marginally stable for free boundary
  - At high β, growth rates decrease with increasing $\langle\beta\rangle$ due to boundary modification
- **Plasma behavior is affected by the rational surface existing at the plasma boundary in H Mode in LHD (S.Morita EPS 2004):**
  - Plasma edge behavior strongly affected by nearby $\iota = 1$ surface

Interpretation of β Limits: Resistive Interchange Modes

- **Observed edge MHD mode in LHD is thought to be resistive interchange mode (K. Toi EPS 2003):**
  - Dominant mode at L-H transition of LHD plasmas is m=2/n=3
  - Edge in magnetic hill (destabilizes resistive interchange) but high magnetic shear region (stabilizes ideal interchange)
- **Generation of the magnetic islands found numerically in nonlinear evolution of resistive interchange mode (K.Ichiguchi EPS 2004)**:

  ⇒**Generally considered that magnetic islands are not generated by the interchange mode**

  - Reduced MHD equations with $S = 10^4$ in cylindrical geometry
  - Number of islands in the poloidal cross section is twice the the poloidal mode number of the dominant component:

    ⇒ **This feature is quite different from the tearing mode**

  - Islands are generated by:
    - Interchange flow in absence of current concentration at the resonant surface
    - Deformation of the contour of the perturbed poloidal flux

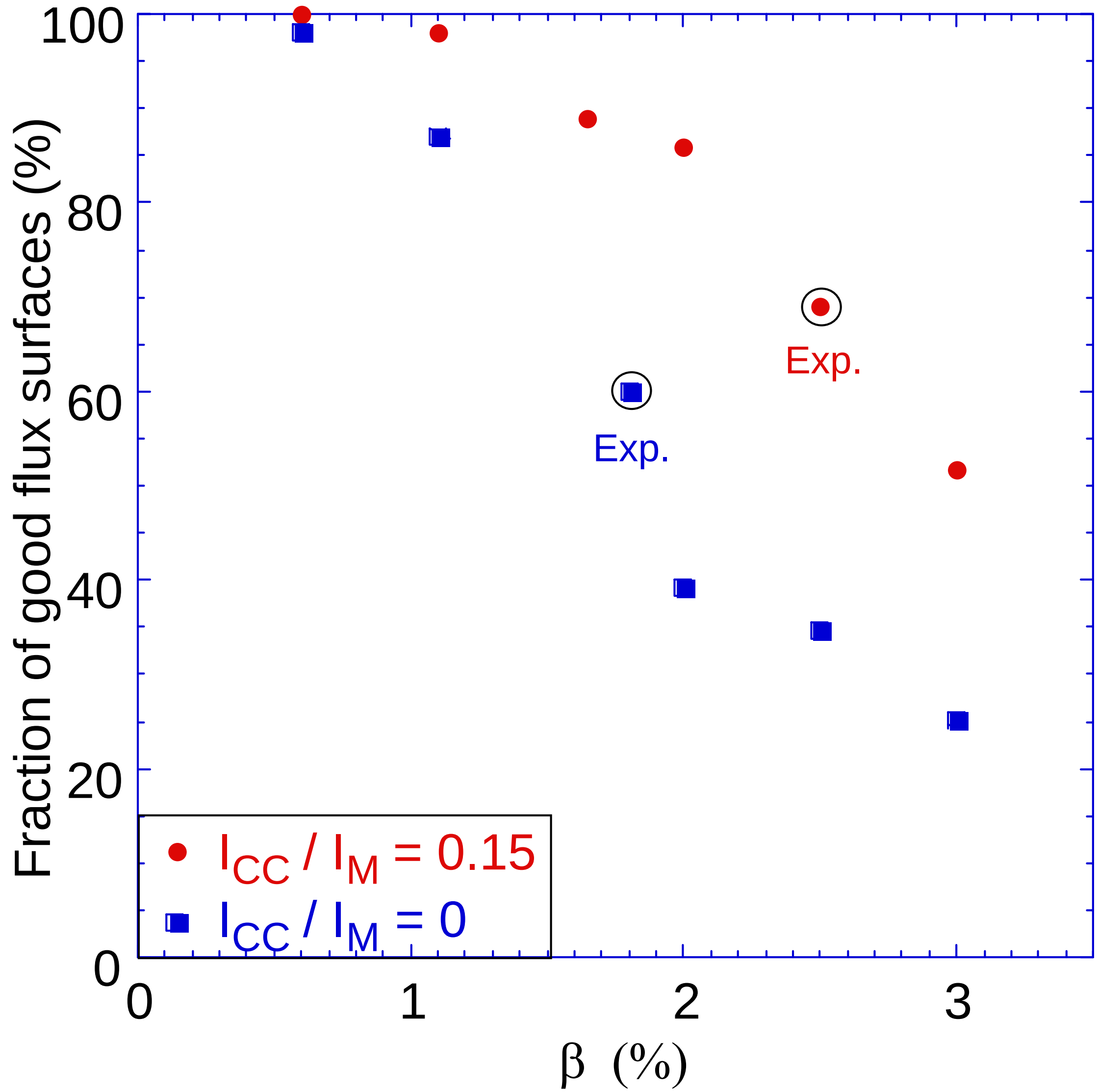
Interpretation of β Limits: Equilibrium Limits

- **Equilibrium β Limits are still a prime candidate for setting the operational β limit in Stellarators:**
  - Both LHD and W7-AS observe equilibrium degradation effects at high β
- **This is not necessarily in conflict with observations of MHD modes in Stellarator experiments at high β:**
  - The observed MHD may be a manifestation of the equilibrium degradation through island formation or:
  - The equilibrium degradation (island formation) may be a manifestation of the approach to an unstable situation

Equilibrium Degradation May Set W7-AS β Limit

- PIES equilibrium calculations indicate fraction of good surfaces drops with β
- Drop occurs at higher β for higher I_{CC} / I_M

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



Characterization of Experimental Stellarator Equilibria

- **Realization that accurate equilibrium reconstructions are needed in Stellarators is now becoming more widespread, especially at LHD:**
  - "In helical systems, the characteristics of MHD equilibrium, stability and transport with high β and large toroidal current are quite different from those in vacuum" (T. Yamaguchi EPS 2004)
  - "The careful reconstruction of the equilibrium with applying asymmetrical profile is required for understanding of the mechanism of this mode stabilization [from profile flattening at high β]" (S. Sakakibara EPS 2004)
  - New diagnostics are being developed and implemented at both LHD and W7-AS for reconstructing both pressure and current (ι) profiles

Significant Progress Achieved in Equilibrium Reconstruction in LHD

- **Three types of structures observed on Te profiles from Thomson scattering in LHD (Narihara EPS 2003):**
  - (i) Flat regions where ι ~ 1:

    Manifestations of a 1/1 vacuum island. At high Te they often self heal and disappear
  - (ii) Knees:

    Appear only on one side suggesting they are related to deformations of nested surfaces (not islands or ITBs)
  - (iii) Local sharp bumps:

    Thought to be ITB related
  - All seem to be related to the ι profile and externally applied error magnetic fields
- **SXR diagnostic can be used to determine Shafranov shift in finite β LHD with co and counter NBCD by comparing to VMEC equilibria (T. Kobuchi EPS 2004):**

Topology and Island Structure Diagnostics

- **Magnetic measurements of external δB fluctuations from diamagnetic flux loop and saddle flux loops used in LHD :**
  - To detect islands (Y. Narushima EPS 2004):
    - Width of islands *w* is indicated by flattening of T_e profile measured by Thomson scattering

      In LHD the T_e profile only can be obtained at one toroidal position and therefore gives limited knowledge of the structure of the island
    - The magnetic diagnostics of δB is an effective method to find the structure of the magnetic island
    - Obtains a calibration between *w* and δB
  - Also used to detect anisotropic pressure (Y. Yamaguchi EPS 2004)

V3FIT Stellarator Equilibrium Reconstruction Project

- **Equilbrium reconstruction using measured diagnostics to determine current and pressure profiles:**
  - **⇒ Discharge equilibrium configuration**
- **Diagnostics:**
  - Magnetic probes, flux loops, saddle coils, Rogowski coils, etc.
  - Microwave interferometry and polarimetry
  - Thomson scattering for pressure profile
  - Motional Stark Effect for ι profile

Status of V3FIT

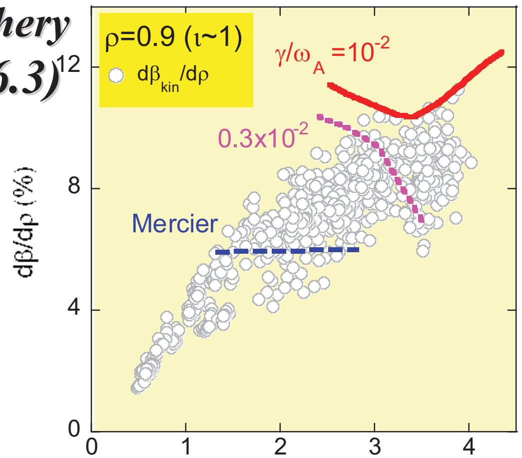
- **V3FIT coding is complete**
- **Modules for Derived Types coded and tested**
- **Interface with VMEC works**
- **Implementation of microwave interferometry polarimetry in progress**
- **To Do Next :**
  - Coding of reconstruction algorithm

Summary of MHD β Limits

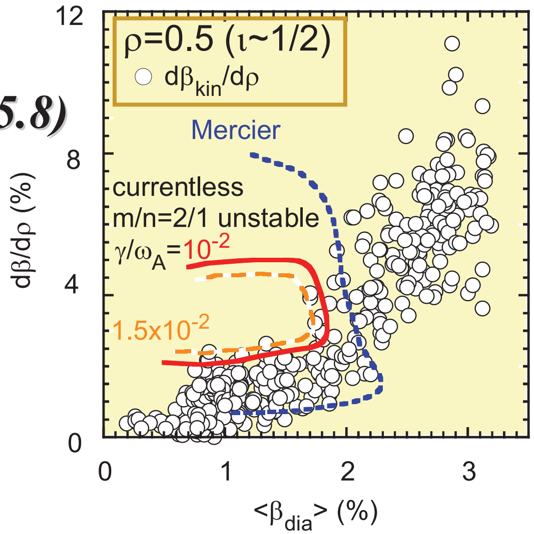
- **In LHD and W7-AS β values achieved significantly exceed the Mercier Limit:**
  - Maximum volume-averaged β above 3.5% achieved in both
- **In LHD β appears to be limited by an m/n = 1/1 ideal limit (Watanabe IAEA 04)**
- **In W7-AS β appears to be limited by approach to the equilibrium limit (Zarnstorff IAEA 04)**
- **Ideal MHD stability plays a direct or indirect role in either case :**
  - **Degradation of the equilibrium is strongly associated with approach to MHD stability limits**
  - **Strongly growing ideal modes appear to provide a direct limit**

Final Word from LHD: What is a Good Measure for the Operational β Limit in a Stellarator?

Periphery* *(A_p=6.3)



Core* *(A_p=5.8)



Though the observed pressure gradients are in non-linear saturation phases, a linear MHD theory could be a reference for more complicated non-linear analyses, and/or a criterion for a reactor design.

Peripheral region: the maxima of the achieved pressure gradients are less than $\gamma_{low-n}/\omega_A = 10^{-2}$.
Core region; the maxima of the achieved pressure gradients saturate against the contour of $\gamma_{low-n}/\omega_A = 1.5x10^{-2}$ in the range of $<\beta_{dia}>$ = 1~1.8%.

Roughly speaking, $\gamma_{low-n}/\omega_A = 1\sim1.5x10^{-2}$ is considered a good index to determine the condition that the global ideal MHD instability limits the LHD operational regime.

For further verification, we need to extend the above comparative analyses between the experimental results and the theoretical prediction based on a linear theory to many magnetic configurations in LHD!!

NIFS

(Watanabe IAEA 2004)

GENERAL ATOMICS