Stellarator Operational Limits

Beta Limits

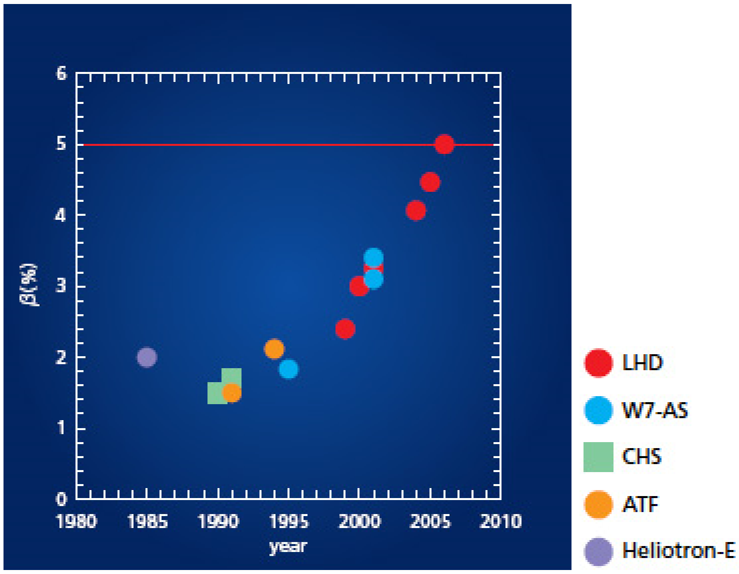

Fig. 1. Values of ⟨β⟩ achieved in stellarators as a function of the year.

The highest values of β in stellarators have been achieved in the W7AS (German) and LHD (Japanese) devices, ⟨β⟩ ≈ 3.4% and ⟨β⟩ ≈ 5% respectively.[1,2] In both cases the achievable β was limited by the available heating power, with no hard β limit seen. The values of ⟨β⟩ achieved are well above predicted MHD instability thresholds for global modes in W7AS and for Mercier modes in LHD. Neither device has experienced disruptive instabilities triggered by increasing β. The achieved value of ⟨β⟩ in LHD has continuously increased over the years as the available heating power has increased. (Fig. 1.) There is strong evidence for a substantial region of stochastic magnetic field lines in the outer region of the plasma at the highest values of β in both W7AS and LHD.[1,3-5] The same codes that see this flux surface loss predict the existence of robust flux surfaces in W7X and in NCSX reference equilibria.

Density Limits

In stellarators the density limit approximately obeys Sudo scaling[6], $\bar{n}_{e,\max} \propto (PB/V)^{0.5}$, and these densities can be considerably higher than the Greeenwald limit observed in tokamaks. In W7AS, for example, the density limit was $\bar{n}_{e,\max} \approx 1.5(P/V)^{0.5} B^{0.5}$ (MW, T, 10^{20} m^{-3})[7], and densities 5 times the Greenwald limit were observed. The observations are in agreement with a theory explaining the limit in terms of a loss of power balance as the radiated power increases with density. Exceeding the density limit in a stellarator can lead to a thermal collapse on a transport time scale, a time scale long compared to that of the MHD disruptions triggered in tokamaks.

Radiation Limit

The limit of allowed radiation losses is of interest because impurity seeding of the edge in tokamaks and stellarators has been proposed as a possible tool to reduce the heat carried to the divertor plates, and for this purpose it is desirable to radiate as large a fraction of the power as possible. In W7AS the attained radiation factors were equal to about one half the input power.

Requirements

LHD and W7X will allow the study of β limits in their respective configurations. A strong international collaboration with the corresponding stellarator groups will be required for this purpose. A quasi-symmetric device of at least the proof-of-principle scale is required to study the β limit in these types of devices. Developing an understanding of operational limits and their scaling will require analysis of reconstructed equilibria for shots that approach the operational limits. As a first step, a reliable equilibrium reconstruction capability must be implemented. This will allow the application of the relevant codes to analyze the behavior of the plasma.

Thrust

A necessary first step for developing a validated, quantitative understanding of operational limits in stellarators is the continued development and implementation of an accurate equilibrium reconstruction capability for stellarator experiments. Developing an understanding of β limits will require the application of stability codes, and of equilibrium codes that do not assume the existence of good flux surfaces. Transport codes will provide insight into density and radiation limits. The study of operational limits for quasi-symmetric stellarators would require the construction of a quasi-symmetric stellarator of at least the proof-of-principle scale.

References
[1] A Weller, S. Sakakibara, K. Y. Watanabe et al, Fusion Science and Technology **50**, 158 (2006).
[2] A.Komori et al, paper OV/2-4, IAEA Fusion Energy Conference, 2008.
[3] M.C. Zarnstorff, A. Weller, J. Geiger et al, paper EX/3-4, IAEA Fusion Energy Conference, 2004.
[4] A. Reiman, M.C. Zarnstorff, D. Monticello, A. Weller et al, Nucl. Fusion **47**, 572 (2007).
[5] Y. Suzuki, K. Y. Watanabe, S. Sakakibara et al, paper TH/P9-19, IAEA Fusion Energy Conference, 2008.
[6] S. Sudo et al, Nucl. Fusion **30**, 11 (1990).
[7] L Giannone, J Baldzuhn, R Burhenn et al, Plasma Phys. Control. Fusion **42,** 603 (2000).