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IN HYDROGEN PLASMAS IN DIII-D**

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The H-mode Power Threshold, Pedestal Width and Plasma Transport in Hydrogen Plasmas in DIII-D

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Abstract. In DIII-D, experiments have been performed in hydrogen plasmas to determine the requirement for hydrogen operation in ITER. The H-mode threshold power has been determined to increase with input torque for both hydrogen and deuterium plasmas with the H-mode power threshold for hydrogen plasmas being approximately a factor of 2 greater at zero torque than in comparable deuterium plasmas. The threshold power for hydrogen discharges with full counter current beam injection is roughly the same as the threshold power for deuterium discharges with co-current beam injection. The plasma geometry also influences the power threshold through the vertical distance between the X-point and the divertor surface. Experiments on pedestal width studies have revealed that the pedestal width has a weak, if any, dependence on the ion pedestal poloidal gyroradius. Further experiments on plasma confinement and transport in L-mode hydrogen plasmas indicate that a factor of 2 reduction in the normalized confinement time, compared to deuterium discharges, is most likely related to a factor of two increase in the normalized density fluctuation amplitude in the hydrogen plasmas.

1. Introduction

Investigating key physics issues in hydrogen plasmas is vitally important for the first operational phase of ITER, which is planned to be with hydrogen plasmas, and in which access to H-mode is critical for testing relevant hardware and control systems prior to the activated deuterium phase. In support of the need to understand and predict the requirements for hydrogen operation in ITER, experiments with hydrogen plasmas have been performed on DIII-D to investigate: (a) the H-mode power threshold; (b) the pedestal characteristics; (c) plasma transport. This paper reports on the main results from these experiments which indicate that: (a) the H-mode power threshold experiments in hydrogen plasmas is strongly dependent on the injected neutral beam torque and a factor of 2 greater (at zero torque) than in deuterium plasmas; (b) the pedestal width has a weak, if any, dependence on the ion pedestal poloidal gyroradius; (c) a factor of two increase occurs in the normalized density fluctuation amplitude in hydrogen, compared with deuterium discharges, corresponding to about a factor of 2 reduction in the normalized confinement time.

2. H-mode Power Threshold

The experimental setup for the hydrogen H-mode power threshold experiments was the same as for previous work performed in deuterium plasmas in order to make accurate comparisons. This utilized the capability on DIII-D of performing simultaneous co- neutral beam injection (NBI) and counter-NBI to investigate the dependence on the applied beam torque. These experiments were performed with neutral hydrogen beam injection into hydrogen plasmas. Normal operation in DIII-D consists of deuterium beam injection into deuterium plasmas. The residual deuterium fueling by the first wall in the hydrogen discharges was reduced over time by a combination of vessel baking, helium glow cleaning and operations with high auxiliary power discharges with sweeping of the divertor leg strike points across the divertor surfaces. The latter procedure proved to be the most effective method in increasing the

H/(H+D) ratio through the application of an energetic particle flux to the plasma facing surfaces in the L-mode and H-mode phases of the discharges. This process of wall conditioning coupled with beam operations and conditioning with hydrogen beams resulted in a purity level of greater than 90% in L-mode after 1.5 days of hydrogen conditioning and at the start of the physics experiments.

The plasma configuration used was a unbalanced double-null discharge in which the magnetic geometry had a null at both vertical ends, but a 5 cm downward plasma bias made the lower null active. The ion grad B drift was towards the dominant X-point. These experiments were performed with a plasma current, I_p , of 1.0 MA, a toroidal magnetic field, B_T , of 2.0 T, an edge safety factor, q_{95} , of around 5 and a range of line averaged densities in L-mode of $2\text{--}4.2 \times 10^{19} \text{ m}^{-3}$. The plasma configurations were not optimized to make use of the divertor cryopumps. The NBI system on DIII-D consists of seven horizontal beams, five of which are injected in the counter-clockwise direction (when viewed from above), and two beams of which are directed in the opposite (i.e., clockwise) direction [2]. In these experiments, the five counter-clockwise sources were in the same direction as the plasma current and two beams were injected counter to the plasma current. All of the beams were injected with their centerlines near the nominal midplane of the plasma. The total beam power was increased in steps of 0.25 of a beam source, i.e., between 300–400 kW/step, depending on the beam voltage settings. Note that ion orbit losses were not taken into account in the NBI power estimations and the quoted NBI powers are the values entering the vessel. The power steps were achieved by modulating the beams at various duty cycles of maximum cycle time 40 ms, so that each step corresponded to an additional 10 ms within the 40 ms cycle window. This modulation time scale is less than the fast ion slowing-down time so that the rapidly varying beam power is averaged out over the longer time scale plasma response. The duration of each power step was 320 ms, which was many confinement times and beam ion slowing down times, allowing the plasma to respond to the time-averaged power increments. This also allowed enough time for high-quality fluctuation measurements to be obtained. The power steps were applied whilst maintaining a given value of plasma torque. This was achieved by balancing out the torque from a co beam by injecting the same (but opposite) torque from a counter beam. In this manner, a power scan could be obtained at a fixed value of applied torque. This allowed for a more accurate determination of the threshold power without any variation due to a changing beam torque during the scan. Power scans were started at a level well below the L-H power threshold in the quasi-stationary phase of the discharge and then the power was ramped up, at constant torque, in 320 ms steps to trigger the L-H transition. Power scans with combinations of ECH plus NBI were also performed.

Clear differences in the H-mode power threshold were observed as a function of the applied torque. An example of this is indicated in Figure 1, which shows the response of the plasma to incremental increases in the applied beam power for 2 similar discharges with different applied torque. The black trace describes a discharge in which the beam power is increased with only co-current neutral beam injection at a target (i.e. L-mode) density of $3 \times 10^{19} \text{ m}^{-3}$. This discharge remains in L-mode despite the application of over 8 MW of NBI power. The red trace describes a near identical discharge, but with the application of counter-current NBI. This discharge transitions into H-mode at about 4 MW of applied NBI power, about a factor of 2 lower than with all co-NBI.

The H-mode power threshold was determined for many discharges with increasing power steps at constant applied beam torque, but with different starting torques for the same set of plasma parameters and conditions. The results from these scans are shown in Figure 2, which shows the H-mode power threshold as a function of applied NBI torque for deuterium and hydrogen plasmas at different L-mode target densities. The net threshold power is determined from the sum of the input power [NBI, electron cyclotron heating (ECH), ohmic] minus the core radiated power and the time derivative of the stored energy. At all target densities, there is a clear trend of increasing H-mode threshold power with increasing injected torque. There is not a large difference in the threshold power at low and intermediate target densities (i.e. 2 and $3 \times 10^{19} \text{ m}^{-3}$, respectively), although at the highest injected torque and density of $3 \times 10^{19} \text{ m}^{-3}$ there is insufficient power from the co-current neutral hydrogen beams to produce H-mode plasmas (Figure 1, case in black). There is a slight increase in the H-mode threshold power with balanced beam injection (i.e. at zero injected torque) on increasing the target density to $4.2 \times 10^{19} \text{ m}^{-3}$. Also shown in Figure 2 is the H-mode threshold power previously determined for deuterium neutral beam injection into deuterium plasmas [1]. At zero torque, the H-mode threshold power in hydrogen is approximately a factor of 2 greater than in deuterium plasmas.

The effects of varying the heating methods by using a combination of NBI and ECH are also shown in figure 2. For these discharges, the lowest threshold power (~ 4 MW) is obtained at a target density of $3.4 \times 10^{19} \text{ m}^{-3}$ while a higher threshold power (~ 5 MW) is obtained at a higher target density of $3.9 \times 10^{19} \text{ m}^{-3}$. However, a discharge with a lower target density of $2.6 \times 10^{19} \text{ m}^{-3}$ fails to transition to H-mode despite a total combined NBI plus ECH power of over 6 MW. This appears to indicate the presence of a minimum in the H-mode threshold power with density, but could also indicate the need for a sufficiently high electron density to

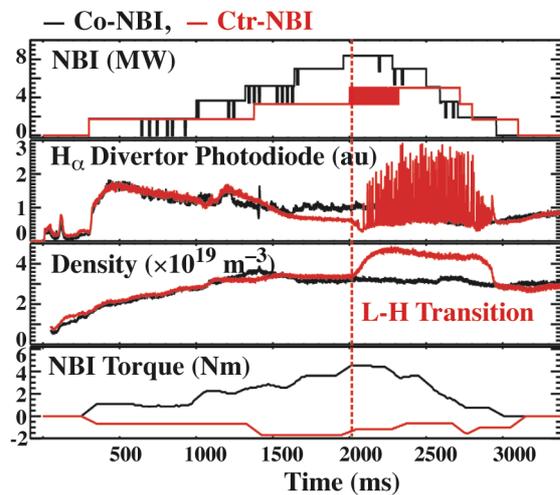


Figure 1. Time histories of various plasma quantities for 2 similar discharges with co-current and counter-current NBI at an L-mode target density of $3 \times 10^{19} \text{ m}^{-3}$. The co-NBI discharge is shown in black and remains in L-mode throughout the discharge. The counter-NBI discharge is shown in red and transitions to H-mode near 2000 ms.

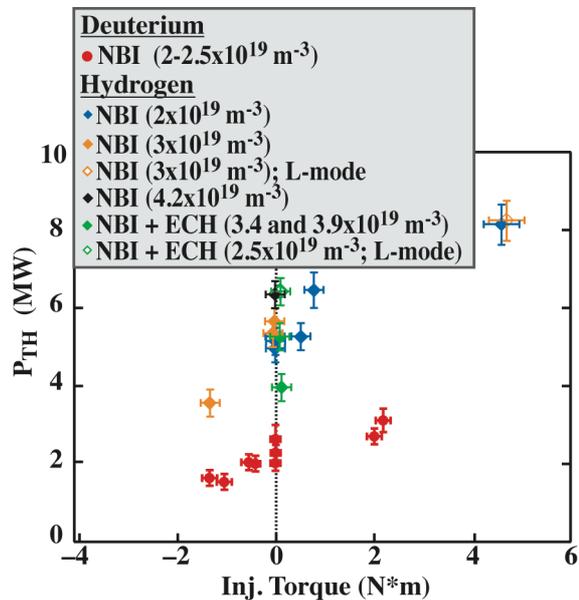


Figure 2. The net power required to induce the L-H transition as a function of the injected torque for various target densities and heating method for hydrogen and deuterium. The target (i.e. L-mode) densities are indicated in parenthesis. The open diamond symbols denote discharges that failed to transition to H-mode at the applied power.

allow equilibration of energy from the electrons to the ions during the applied ECH. However, the use of ECH combined with NBI does appear to lower the threshold power when compared to the use of only NBI by about 15% at zero torque even though discharges with ECH were operated with higher densities.

The plasma geometry with respect to the divertor surface also influences the H-mode power threshold for hydrogen. This behavior was investigated by changing the vertical distance between the X-point and the lower divertor surface. Figure 3 shows that a significant (~25%–30% at zero torque) reduction in the threshold power was obtained by decreasing the vertical distance between the X-point and the lower divertor surface from 26 cm to 10 cm (an effect observed before in deuterium [3]). The trend of increasing threshold power with increasing injected torque is still present. This behavior may be related to the plasma flows at the plasma edge and the scrape-off layer and further investigations are required to resolve the causes of this effect. Note that the X-point height above the divertor surface is not an independent variable in these studies, since changes in this dimension also result in small changes in the plasma elongation and the lower triangularity. The present H-mode power threshold scaling relations [2] do not include the effects of applied torque or plasma geometry. These factors may explain some of the large variation or range in the predictions of the H-mode threshold power for ITER.

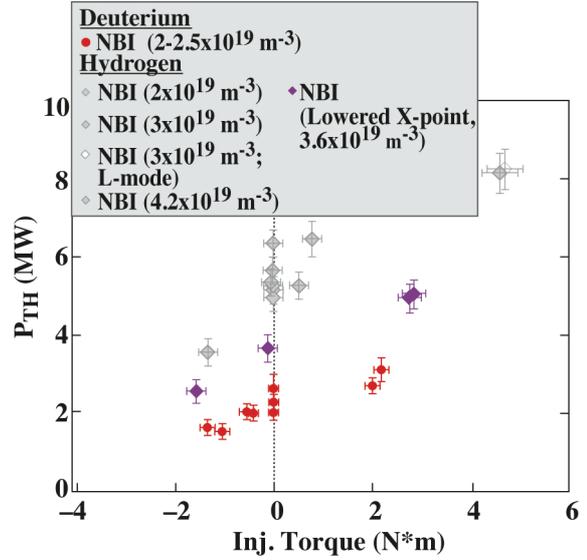


Figure 3. The net power required to induce the L-H transition as a function of the injected torque for discharges with a reduced X-point height from the lower divertor surface of 10 cm. The grey points are the hydrogen points from Figure 2, which had a X-point height of 26 cm.

3. Mass Scaling of H-mode Pedestal Width

A separate experiment was performed to study the mass scaling of the pedestal width to determine if the pedestal width scales more strongly with the pedestal poloidal beta, $\beta_{\theta}^{\text{ped}}$, or with the pedestal ion poloidal gyroradius, $\rho_{i\theta}$. Previous scaling studies performed on DIII-D showed that the width of the electron pressure pedestal in Type I ELMy H-mode discharges scaled about equally well with either $(\beta_{\theta}^{\text{ped}})^{0.4}$ or $(\rho_{i\theta}^{\text{ped}})^{0.7}$ [4]. Because $\beta_{\theta}^{\text{ped}}$ and $\rho_{i\theta}^{\text{ped}}$ both increase with increasing ion temperature and decrease with increasing poloidal magnetic field, these parameters are strongly correlated and it is difficult to determine if one of these parameters provides a better scaling for pedestal width. Nevertheless, subsequent experiments, including a scan of density at roughly fixed pedestal pressure [4] and a variation of normalized ion gyroradius ρ_i^* with other dimensionless pedestal parameters held constant [5], have provided evidence that $\rho_{i\theta}^{\text{ped}}$ does not provide a strong control of pedestal width.

The mass difference of H and D provides a unique opportunity to break the correlation of $\beta_{\theta}^{\text{ped}}$ and $\rho_{i\theta}^{\text{ped}}$ because $\rho_{i\theta}^{\text{ped}}$ scales with ion mass as $M_i^{1/2}$ whereas $\beta_{\theta}^{\text{ped}}$ has no mass dependence. Therefore, an experiment was performed to study the mass scaling of the pedestal width during the hydrogen campaign on DIII-D. This experiment emulated a similar

experiment performed in JT-60U [6]. The experiment was performed by making discharges in H to match an existing D discharge, which had been produced with the ITER shape, q and normalized global beta β_N . The H discharge was run at the same shape, plasma current (1.5 MA) and field (1.9 T) as the D discharge, and the heating power and density control were adjusted to attempt to match to pedestal temperature and density of the D discharge [7]. Composite profiles were obtained from the last 20% of the ELM cycle and represented conditions just before the onset of a Type I ELM. In the best matched set of discharges, the pedestal electron densities and temperatures matched to better than 5% and the pedestal ion temperatures matched within about 30%, with the H discharge being the lower discharge on all parameters (Figure 4). No change in the pedestal width was observed for the H discharge relative to the D discharge. As used here, the pedestal width Δ is defined as the average of the widths for the electron density and temperature profiles, as obtained from fits of a tanh function to the data. The measured width ratio $(\Delta)_H/(\Delta)_D$ for the H and D discharges is 1.15 where $(\Delta)_H$ and $(\Delta)_D$ are the pedestal widths for H and D, respectively. This ratio is much more consistent with a $(\beta_0^{\text{ped}})^{0.4}$ scaling, which would predict $(\Delta)_H/(\Delta)_D = 1$, than for a $(\rho_{i0})^{0.7}$ scaling, which would predict $(\Delta)_H/(\Delta)_D = 0.7$. Thus, the mass scaling experiment provides strong support for the previous studies, which had indicated that pedestal width has a weak, if any, dependence on the ion pedestal poloidal gyroradius.

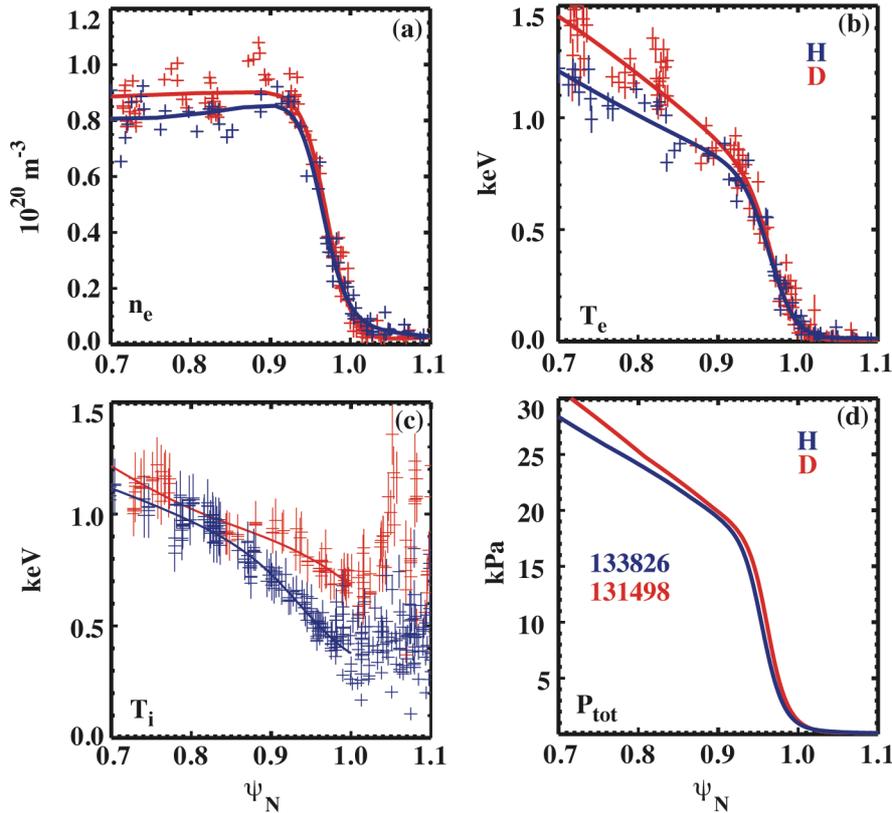


Figure 4. Comparison of profiles of (a) electron density, (b) electron temperature, (c) ion temperature and (d) total pressure from deuterium (red) and hydrogen (blue) discharges in an ITER demo plasma configuration.

4. Plasma Confinement and Turbulence

The scaling of turbulence, transport and confinement with isotope mass was examined by

performing L-mode discharges in hydrogen and deuterium with very similar dimensionless parameters (ρ^* , q , T_e/T_i , Mach Num. (M), β , v^*). The reference deuterium discharges were performed previously from a ρ^* -scaling experiment [8]. The recent hydrogen discharges were designed to obtain a factor of 2 variation in ion mass while other dimensionless parameters are maintained nearly constant. In order to maintain similar values of the relevant dimensionless parameters, plasma parameters (I_p , B_T , n_e , T_i , T_e , V_{tor}) were correspondingly adjusted. Very good profile matches of the relevant parameters were obtained. Hydrogen was used as both the working gas and injected neutral beam species. The results are generally consistent with previous observations that confinement improves with increasing ion mass [9]. This contrasts with a simple consideration of the governing gyrokinetic equations, which suggests that as ion mass and therefore ion gyroradius increase, the turbulence correlation length and resulting transport step-size will likewise increase, increasing thermal and particle transport and reducing energy confinement. Normalized confinement ($\omega_{c,i} \tau_E$) was found to be approximately a factor of two larger in the deuterium discharges compared with the dimensionally similar hydrogen plasmas.

Detailed turbulence characteristics were measured across the profile using the recently expanded beam emission spectroscopy (BES) [10] diagnostic system. Density fluctuation measurements obtained with BES show an approximate factor of 2 increase in normalized density fluctuation amplitude in hydrogen, compared with deuterium, as seen in Figure 5. Here, a comparison is being made between the fluctuations in these recent hydrogen discharges, and those obtained in the previous ρ^* experiment [7]. The BES interference filters are tuned to pass the deuterium beam emission. Since the beam energy is maintained constant in hydrogen, the higher velocity results in a greater Doppler-shift from the second and third beam energies, so that the second and third energy components of the beam emission spectra contribute to the observed signal in hydrogen, resulting in lower signal intensity. This is adjusted for the fluctuation amplitudes shown in Figure 5. The profile was measured by radially scanning the 8x8 channel BES array over three successive repeat discharges. The radial correlation length of the long-wavelength density fluctuations was also measured with BES, shown in Figure 6. The ion gyroradius was maintained nearly constant compared with the corresponding deuterium discharges. The radial correlation length in hydrogen scales similarly with the ion gyroradius, as observed during the ρ^* scaling in deuterium experiments. The radial correlation length decreases with plasma minor radius as the ion temperature decreases, but is seen to do so similar to the ion gyroradius scaling with minor radius. Future studies will compare localized ion and electron thermal transport as well as more detailed nonlinear characteristics of the turbulence, and also examine turbulence and transport scaling with isotope mass in the H-mode phase.

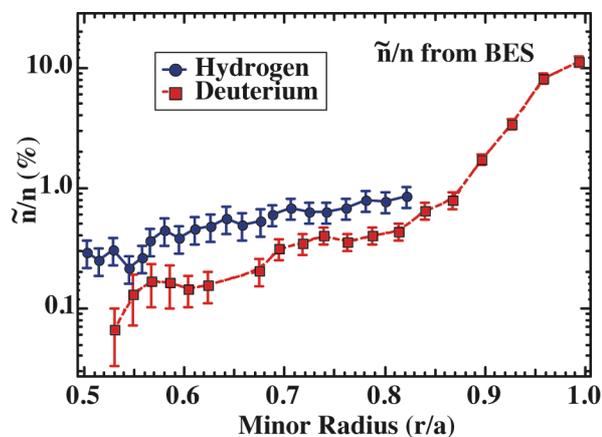


Figure 5. The normalized density fluctuation amplitude, as determined by the beam emission spectroscopy, as a function of the plasma minor radius for hydrogen and deuterium.

5. Conclusions

In DIII-D, experiments have been performed in hydrogen plasmas to determine the requirements for hydrogen operation in ITER. The H-mode threshold power has been determined to increase with input torque for both hydrogen and deuterium plasmas with the H-mode power threshold for hydrogen plasmas being approximately a factor of 2 larger than in comparable deuterium plasmas (at zero torque). The vertical distance between the X-point and the divertor surface also influences the power threshold. These results may be significant for ITER, since the L-H threshold scaling is derived from a database that does not take into account the applied torque, plasma rotation, or plasma geometry. The reduction of the H-mode threshold power with low input torque is a favorable result for ITER, which is expected to operate with low input torque. Experiments on pedestal width studies have revealed that the pedestal width has a weak, if any, dependence on the mass and, hence, on the ion pedestal poloidal gyroradius. Further experiments on plasma confinement and transport in L-mode hydrogen plasmas indicate that a factor of 2 reduction in the normalized confinement time, compared to deuterium discharges, is related to a factor of two increase in the normalized density fluctuation amplitude in the hydrogen plasmas.

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References

- [1] GOHIL, P., *et al.*, J. of Physics: Conf. Series **123**, 012017 (2008).
- [2] "Progress in the ITER Physics Basis," Nucl. Fusion **47**, S1 (2007).
- [3] CARLSTROM, T.N., *et al.*, Proc. 16th EPS Conf. on Controlled Fusion and Plasma Physics, Venice, Italy, Vol. 13B (EPS, 1989) p. 241.
- [4] OSBORNE, T.H., *et al.*, J. Nucl. Mater. **266–269**, 131 (1999).
- [5] FENSTERMACHER, M.E., *et al.*, Nucl. Fusion **45**, 1493 (2005).
- [6] URANO, H., *et al.*, Nucl. Fusion **48**, 045008 (2008).
- [7] GROEBNER, R.J., *et al.*, Fusion Energy 2008 (Proc. 22nd Int. Conf. Geneva, 2008) (Vienna: IAEA) CD-ROM file EX/P3-5.
- [8] MCKEE, G.R., *et al.*, Nucl. Fusion **41**, 1235 (2008).
- [9] SCOTT, S.D., *et al.*, Phys. Plasmas **2**, 2299 (1995).
- [10] GUPTA, D.K., *et al.*, Rev. Sci. Instrum. **75**, 3493 (2004).

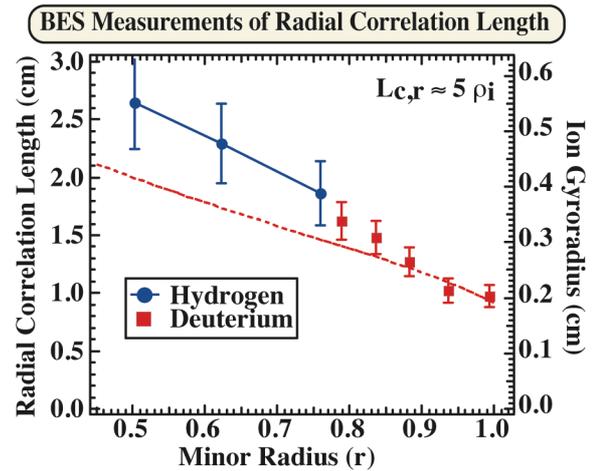


Figure 6. The radial correlation length of the turbulence determined from BES as function of the plasma minor radius for hydrogen and deuterium.