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AN EMERGING UNDERSTANDING OF H-MODE DISCHARGES IN TOKAMAKS

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ABSTRACT

A remarkable degree of consistency of experimental results from tokamaks throughout the world has developed with regard to the phenomenology of the transition from L-mode to H-mode confinement in tokamaks. The transition is initiated in a narrow layer at the plasma periphery where density fluctuations are suppressed and steep gradients of temperature and density form in a region with large first and second radial derivatives in the $\vec{v}_E = (\vec{E} \times \vec{B})/B^2$ flow velocity. These results are qualitatively consistent with theories which predict suppression of fluctuations by shear or curvature in v_E . The required v_E flow is generated very rapidly when the magnitude of the heating power or of an externally imposed radial current exceed threshold values and several theoretical models have been developed to explain the observed changes in the v_E flow. After the transition occurs, the altered boundary conditions enable the development of improved confinement in the plasma interior on a confinement time scale. The resulting H-mode discharge has typically twice the confinement of L-mode discharges and regimes of further improved confinement have been obtained in some H-mode scenarios.

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I. INTRODUCTION

Experimental and theoretical results of the last few years are leading to a deeper understanding of the origin and development of the H-mode discharge in tokamaks. The H-mode, discovered in the Axisymmetric Divertor Experiment (ASDEX)¹ in 1982, has proven to be a reliable route for many tokamaks²⁻¹¹ to obtain roughly a factor of two improvement in energy confinement time as compared to that obtained in L-mode discharges, which provide the lowest level of confinement obtained with the application of auxiliary heating power.

In most cases, H-mode discharges are obtained with an abrupt transition, occurring in less than 100 μ s, from an L-mode discharge (the L-H transition), and the transition is due to formation of a region of improved confinement, called the transport barrier, in a region with a width of ~ 1 cm at the very edge of the plasma. A remarkable feature of the narrow transport barrier is that it enables an improvement in confinement to develop throughout the entire plasma on a timescale slow compared to the timescale of the transition itself. Thus, as shown in Fig. 1, an approximate doubling of the thermal pressure can be obtained over the entire plasma cross section in an H-mode discharge relative to an L-mode discharge obtained with the same control parameters. The simplest estimates show that the thermonuclear fusion rate in a reactor will be roughly proportional to the square of the plasma pressure and thus an H-mode discharge can

be expected to provide a factor of four more fusion power than an L-mode discharge with comparable parameters. Thus, there has been great interest in H-mode discharges for design studies of the next generation of tokamaks and for reactors.

Researchers have also hoped to use the abruptness of the L-H transition as a lever to gain insight into tokamak transport mechanisms. Studies motivated by this goal have evolved sufficiently that there is experimental agreement on the general phenomenology of the L-H transition and of the H-mode and there are theoretical models of the transition which explain several experimental observations. In particular, both experimental and theoretical results indicate that the radial electric field at the plasma boundary plays a major role in reducing turbulence and in establishing the transport barrier of the H-mode. Thus, an excellent framework has been developed for studying the H-mode discharge and a basic understanding of H-mode physics is beginning to emerge. The goal of this paper is to present this framework and to highlight the major successes and significant problem areas for theoretical and experimental studies of the H-mode.

The interested reader is referred to previous reviews of H-mode physics. These include a very detailed study of results from ASDEX,¹² an overview of enhanced confinement¹³ and recent comparisons of theory and experiment.¹⁴

This paper is organized to systematically present the development of the H-mode discharge. Section II is a discussion of the basic phenomenology of the H-mode. Section III discusses the formation of the transport barrier, which is a region of very steep gradients in density and temperature formed just inside the last closed flux surface. Theory has suggested and experimental observations support the hypothesis that the formation of a radial electric field with non-zero first or second radial derivatives at the

Fig. 1. Thermal pressure from ions and electrons versus normalized minor radius ρ shown for L-mode and H-mode. $T_i(0) = 7.4 \text{ keV}$ in L-mode and 9.2 keV in H-mode. $\bar{n}_e = 3.5 \times 10^{19} \text{ m}^{-3}$ in L-mode and $4.6 \times 10^{19} \text{ m}^{-3}$ in H-mode.

plasma edge causes a reduction of microturbulence which in turn allows formation of the transport barrier. Section IV discusses various bifurcation scenarios for triggering the transition. Section V shows that after the transport barrier is formed, improved confinement develops deeper in the plasma interior on a time scale which is comparable to the global energy confinement time τ_E . The changes in core confinement are evidently enabled by changes in profiles related to formation of the transport barrier. The improved particle confinement of the H-mode leads to a significant rise in density and in radiated power. As shown in Section VI, in most discharges, this rise is terminated by repeated magnetohydrodynamic (MHD) events, called Edge Localized Modes (ELMs), which briefly destroy the transport barrier. ELMs provide a mechanism whereby the H-mode discharge can exist in quasi-steady state. Section VII demonstrates that the H-mode discharge is a base from which further improvements in confinement can be obtained. Improvement factors of 3–4 above that expected from L-mode discharges can be obtained in some scenarios. A summary and conclusions are presented in Section VIII.

II. BASIC H-MODE PHENOMENOLOGY

There are two primary techniques for obtaining H-mode discharges. In the terminology used in this paper, a “spontaneous” H-mode discharge occurs with some delay after the application of sufficient heating power. These discharges have been obtained with a variety of heating methods, in circular and non-circular plasmas and in plasmas in divertor and limiter configurations.¹³ A variant of this technique has been observed in the Tokamak Fusion Test Reactor (TFTR)¹⁰ in which H-mode discharges have been obtained in supershot discharges, which already exhibit improved confinement relative to L-mode discharges. Recent observations of H-mode discharges in the Wendelstein 7 Advanced Stellarator (W7-AS)¹⁵ show that the spontaneous H-mode is not limited to tokamak geometry. Another technique will be termed the “biased” (for electrode-biased) H-mode; in this technique, an H-mode discharge is obtained by inserting an appropriate electrode into the plasma and by drawing a radial current through the plasma.^{16–18}

Despite a wide variety in conditions used to obtain the H-mode, all H-mode discharges exhibit similar signatures, and thus it can be concluded that the same basic phenomena are present in any of these discharges. The classic H-mode signatures are a drop in the recycling D_α radiation, a rise in the line-averaged electron density and a rise in the total stored energy.^{1–11,16–18} The time at which the D_α signal drops is typically taken to be the time of the L-H transition. In many examples, the drop is very

rapid and occurs in less than a millisecond. However, in limiter H-mode discharges, the time for the drop can be up to 30 ms.¹⁹ Also, dithering transitions have been observed in which the plasma evidently oscillates rapidly between L-mode and H-mode for many milliseconds before finally staying in H-mode.²⁰ An additional signature of the L-H transition is that there is a marked change in the edge radial electric field E_r . In the spontaneous H-modes, E_r becomes more negative,^{14,19-23} while in the biased H-modes, E_r becomes more negative or positive depending on the sign of the applied voltage.^{17,24} Coincident with the drop in the D_α signal, the transport barrier is formed at the plasma edge and is manifested in all machines as dramatic steepening of the electron density n_e profile just inside the last closed flux surface (LCFS) with a decrease in n_e in the scrape-off layer.^{2,6,12,22,24,25} With sufficient heating, edge temperature gradients steepen.^{2,6,12,22,25,26} However, the T_e profile changes little if at all in the transport barrier in the biased H-mode.^{17,27} Increases in the pressure gradients and rising temperatures in the transport barrier can lead to significant bootstrap currents which broaden the current density profile.¹²

The rising density in the transport barrier leads to a significant increase in density in the main plasma with a flattening of the central n_e profile.^{2,6,12,22,25} In addition, the core T_e and T_i profiles can show increases, depending on the amount of heating power applied to the discharge. Small or negligible changes are observed in the core temperatures in biased H-modes.¹⁷ Increases in the energy confinement time of typically 30%–100% are observed. Although the particle confinement time τ_p is difficult to measure due to the difficulty of measuring the particle source rate, the available measurements invariably show that τ_p improves in the H-mode.^{6,12,24} The improved

particle confinement pertains to impurities also and leads to rising energy losses due to line radiation.^{12,13,28} If unchecked, these losses can lead to termination of the H-mode. However, a common feature in H-mode discharges is the occurrence of repetitive instabilities at the plasma edge (ELMs) which briefly destroy the transport barrier.^{2,12,25} ELMs are a natural regulating mechanism which clamp the line averaged electron density and the line radiation. ELMs cause a reduction of roughly 15% in τ_E as compared to non-ELMing discharges^{12,29} but they allow for essentially steady state operation of the H-mode discharge with confinement times well above L-mode levels.

The H-mode is achieved only when certain thresholds in the control parameters are exceeded. For the spontaneous H-mode, the heating power must exceed a threshold value,^{5,6,12,19,30} which is a function of parameters such as the density,³⁰ the direction of the grad B drift relative to the X-point¹² and the toroidal field.³⁰ For a given set of machine conditions, this threshold is well-defined with small changes in heating power often being the difference between obtaining the H-mode and remaining in L-mode. In the case of biased H-modes, the transition is obtained only when the bias voltage applied to the probe exceeds a critical value.^{16–18} Because the spontaneous and biased H-modes exhibit similar phenomenology, a basic hypothesis in this paper is that similar physics underlies these two techniques for obtaining the H-mode.

III. FORMATION OF THE TRANSPORT BARRIER

The transition to the H-mode occurs when a transport barrier forms just inside the last closed flux surface. The transport barrier is a region in which the pressure profiles steepen markedly and invariably this is manifested as a rise in the gradient of n_e . The degree of increase in the gradients of T_e and T_i is somewhat variable and depends on the discharge and recycling conditions.¹² Values of T_i much larger than T_e have been observed in the transport barrier.^{31,32} The width of the transport barrier at the transition appears to be quite insensitive to the machine size or discharge parameters and is typically in the range of about one-half to a few cm.^{2,12,22,24,26} These widths are comparable to the size of the ion poloidal gyroradius ($\rho_{i\theta}$). In addition, the scale lengths for density and temperature gradients are comparable to the width of the transport barrier.

As shown in Fig. 2, it is found empirically that the transport barrier exists in a region in which the radial electric field achieves large absolute values (typically 20–40 kV/m) and varies rapidly in space.^{14,16,17,20–22,24,26,32–34} The data support the hypothesis that the transport barrier is a result of improved confinement due to the suppression of microturbulence by a $\vec{v}_E = \vec{E} \times \vec{B}/B^2$ flow with shear (non-zero value for dv_E/dr) or curvature (non-zero second derivative) where $\vec{E}$ is electric field and $\vec{B}$ is magnetic field. In the transport barrier, the profile of v_E is determined by the profile

of E_r and thus profile effects in v_E or E_r are used interchangeably. The v_E flow may be quite different from the plasma's mass flow; however, the speed of propagation of flutelike modes, for which the wavelength parallel to the magnetic field is much larger than the perpendicular wavelength, is often dominated by the v_E flow.³⁵ In this paper, the term “flow” refers to the v_E flow unless noted differently.

Theoretical studies of the effect of spatially varying flows on turbulence, which include scaling studies, linear stability analyses and non-linear analyses, indicate that flute-like modes can be stabilized by v_E flows with appropriate shear or curvature. Scaling theory is a non-linear treatment which finds that the differential v_E within a turbulent fluid element tends to rip the element apart which enhances the decorrelation rate and thus decreases the turbulence level.^{36–38} This concept has considerable intuitive appeal to the experimental community, which finds that the phase velocity of fluctuations is generally dominated by and nearly equal to the v_E velocity.^{39–41} The strength of the shear in v_E can be quantified by comparing the ratio of the shearing rate ω_s to the intrinsic decorrelation rate due to radial scattering $\Delta\omega_t$, where $\omega_s = k_\theta |\nabla E_r / B_\phi| \Delta r_t$ with k_θ being the poloidal wavenumber of the turbulence, $\nabla E_r / B_\phi$ the shear in the v_E velocity, B_ϕ the toroidal magnetic field and Δr_t the radial correlation length. The shear is considered strong if $\omega_s / \Delta\omega_t$ is greater than one and Biglari, Diamond, and Terry³⁶ predict reduction of turbulence in this limit. Analysis of Doublet (DIII-D)⁴² data shows that $\omega_s / \Delta\omega_t \gtrsim 5$ and thus indicates that the strong shear regime is appropriate to the transport barrier.

Linear stability calculations have been performed for a variety of flutelike modes with the result that shear in v_E is always stabilizing.⁴³ In addition, positive curvature

Fig. 2. The transport barrier, as indicated by the C VII pressure gradient, exists in the E_r well in H-mode in DIII-D. Both parameters are measured by the same diagnostic, so there are no uncertainties about the spatial correlation of the transport barrier relative to the E_r well. The vertical dashed lines enclose the region in which reductions of fluctuation levels are inferred from the reflectometer. LCFS is located at $R = 2.293 \pm 0.005 \text{ m}$.

($E_r'' > 0$) is found to be stabilizing for the ion temperature gradient (ITG) mode.⁴⁴ Nonlinear numerical simulations of ITG turbulence⁴⁵⁻⁴⁷ and of resistive ballooning turbulence^{48,49} find stabilization in the strong shear regime which is consistent with the predictions of linear theory. In contrast, nonlinear simulations and analytical calculations for a simple long wavelength drift model⁵⁰ and for resistive interchange turbulence⁵¹ find that shear can have little or no effect on the level of turbulence in the saturated state for these turbulence models even though linear theory predicts robust stabilization. Curvature of the v_E flow is found to be much more effective than shear in stabilizing turbulence in these nonlinear models. Recent analytical calculations suggest that the superiority of curvature relative to shear may be a fairly general nonlinear effect.⁵² Shear is also found to be stabilizing with regard to more MHD-like modes, as shown by linear calculations for drift tearing modes⁵³ and nonlinear simulations of tearing modes.⁵⁴

The basic result of theory, that an appropriate v_E flow profile will improve confinement, is born out by many experimental results other than H-mode studies. Biasing experiments with probes in stellarators⁵⁵ and with a grid in the linear machine PISCES have produced steepened density gradients and improved particle confinement times.⁴⁰ Controlled experiments in which the radial electric field was systematically varied in the central cell of the GAMMA-10 tandem mirror device showed that $\tilde{n}/n$ was maximum when E_r was zero and $\tilde{n}/n$ was reduced by approximately an order of magnitude and τ_p was increased by nearly two orders of magnitude for sufficiently positive or negative values of E_r .⁵⁶ The imposed radial electric fields exhibited shear and curvature. Probe studies have shown that there is a naturally occurring shear layer in v_E at the edge

of tokamak and stellarator discharges,³⁹ that this layer evidently defines the plasma boundary and that the turbulent particle diffusivity is reduced in this layer relative to nearby regions.

Experimental observations are consistent with the hypothesis that the transport barrier in H-mode is formed due to stabilization of turbulence by a v_E profile with shear or curvature. Data from experiments with radially resolved measurements of E_r show that for spontaneous H-modes or for electrode-biased H-modes obtained with negative bias a negative “well” in E_r is formed and that the transport barrier, including the steep gradient regions of n_e , T_e and T_i , lies within this well^{14,16,24,26,34,57} (Fig. 2). Also, electrode-biased H-modes obtained with positive bias exhibit a “hill” structure in E_r with the transport barrier lying within the region of the hill.^{24,58} Figure 3 shows examples of positive and negative E_r structures from Tokamak Experiment for Technically Oriented Research (TEXTOR).^{24,59} This machine demonstrates that transport barriers can be formed in regions of positive and negative shear and in regions of positive and negative curvature in v_E .

The phenomenology with respect to the role of turbulence in the L-H transition is complex, but the turbulence measurements generally indicate that there are large reductions in magnetic and density fluctuation levels near the LCFS at the L-H transition.^{9,12,20,27,40,41,57–77} Measurements localized to the transport barrier from far infrared (FIR) scattering^{12,70} (Fig. 4) and reflectometry^{12,67} on ASDEX, reflectometry on JT-60⁶⁵ and microwave reflectometry,^{20,57,60} FIR scattering^{41,69,71,72} and phase coherence interferometry⁷³ on DIII-D show that the level of density fluctuations $\tilde{n}$ is reduced markedly at the transition, even in regions where n is constant or rising.

Fig. 3. Examples of positive and negative experimentally measured E_r structures (labeled exp) obtained in TEXTOR. I_E is electrode current in amps. Density profile is found to steepen in these regions. Curves labeled th are obtained from a simple theoretical model based on poloidal viscosity and show good agreement with experimental data, particularly for positive bias. Limiter is at $r = 46$ cm. (Ref. 59).

Measurements with Langmuir probes on the Continuous Current Tokamak (CCT),²⁷ TEXTOR^{74,75} and DIII-D^{76,77} of $\bar{n}$, the fluctuating potential $\tilde{\phi}$ and of their relative phase show reductions of the turbulent particle flux in H-mode near the LCFS large enough to explain the observed improvements of particle confinement in the core plasma. Correlation reflectometry shows that the radial correlation length for turbulence is reduced in the transport barrier in H-mode relative to L-mode⁷⁸ as predicted by scaling theory.³⁶

In addition to the spatial correlation, there is also a very strong temporal correlation between the development of the transport barrier, a reduction in fluctuation amplitudes and a large change in the edge E_r .^{12,14,26,57,64} Electrode-biased and spontaneous transitions show marked changes in the edge E_r occurring in 1 ms or less and coinciding with the drop in the D_α signal,^{14,26,40,57,79} which signals the formation of the transport barrier. Increases in gradients in the transport barrier start to occur simultaneously with the drop in the D_α signal to within the experimental temporal resolution of 0.5 ms.¹⁴ Reductions in fluctuation levels in the transport barrier are observed to occur simultaneously with the start of the drop in the D_α signal to within the limit of experimental temporal resolution, typically $\lesssim 100 \mu\text{s}$.

Further progress in understanding the dynamics of the L-H transition requires a more complete characterization of the transport properties of the plasma edge. Measurements in the electrode-biased experiments show that there is a large convective particle flux prior to the transition which crosses the LCFS.^{27,74,75} The convection cells are destroyed in the H-mode, evidently by the strongly sheared v_E . The importance of convection relative to turbulence cannot be determined until the poloidal distribution

Fig. 4. Scattered power P_s from an FIR scattering system on ASDEX, which views vertically through the transport barrier, shows a rapid and dramatic drop at L-H transition. Transition is signaled by a sudden drop in the D_α signal and by an abrupt increase in rate of rise of density and is denoted by a vertical line. Measured $\bar{n}_e$ profiles show that the drop in scattering power cannot be explained as a result of a density drop (Reproduced from Ref. 12, published by International Atomic Energy Agency.).

is measured so that the convected flux averaged over the LCFS can be determined. The role of convection in machines without probes is unknown at this time. Furthermore, observations on CCT⁸⁰ and DIII-D⁴² indicate that the behavior of density fluctuations exhibits marked poloidal asymmetries. At the inner midplane, density fluctuation levels tend to show little change at the transition or to exhibit a different temporal evolution than the fluctuations at the outer midplane, where the measurements discussed previously in this paper have been made and where fluctuation levels drop substantially at the transition. These results may indicate that the intrinsic turbulence is considerably weaker at the inner midplane, perhaps due to its good curvature, than at the outer midplane, as suggested by probe studies on the ALto CAMpo TORus (ALCATOR-C)⁸¹ and the Texas EXperimental Tokamak (TEXT).⁸²

IV. BIFURCATION IN RADIAL ELECTRIC FIELD AND H-MODE THRESHOLD

Within the H-mode framework discussed here, the threshold in heating power for spontaneous L-H transitions and the threshold in bias voltage for the electrode-biased H-modes may be interpreted as requirements to obtain a bifurcation in E_r . When sufficient heating power or sufficient bias voltage is applied to an L-mode plasma, the edge E_r and its gradients are observed to abruptly become much larger in absolute value and thus to cause rapid improvement in confinement in the spirit of the theories discussed in Section III. Theoretical models, based on a variety of neoclassical and anomalous effects have been proposed to explain the source of and bifurcation in E_r and these are described here. Most theories have been formulated for one or more terms of the lowest order radial force balance equation for a single ion species which can be written as:

$$E_r = (Z_I e n_I)^{-1} \nabla p_I - v_{\theta I} B_\phi + v_{\phi I} B_\theta \quad , \quad (1)$$

where Z_I is the charge of the ion, n_I is the ion density, e is the electronic charge, p_I is the ion pressure, $v_{\theta I}$ and $v_{\phi I}$ are, respectively, the poloidal and toroidal rotation velocities and B_θ and B_ϕ are, respectively, the poloidal and toroidal magnetic fields. All quantities are specified for a specific ion, labeled I.

The first model to show a bifurcation in E_r obtained E_r by equating the fluxes of ions and electrons at the LCFS.^{83,84} After refinements, the key ingredients still are that the ion particle flux is based on an ion orbit loss model and contains a dependence on E_r and the electron particle flux is based on an anomalous loss model and also contains a dependence on E_r .⁸⁵ The particle fluxes and E_r exhibit a bifurcation as a parameter based on edge densities and temperatures is varied. Although for typical tokamak conditions, this theory predicts $E_r > 0$ in spontaneous H-mode, in variance with the experimental results,¹⁴ the self-consistent analysis in this model exhibits a feature common to all of the self-consistent bifurcation models and in the force balance equation: at the bifurcation, several parameters, including E_r , change simultaneously. Thus, it might be expected that changes in E_r are coincident with changes in other measurable quantities.

A one-dimensional, time dependent transport code has been developed which employs simple models of the heat and particle transport coefficients with the property that they decrease as shear in E_r increases.^{46,86} With realistic heat and particle sources included, the simulations show a simultaneous bifurcation in the edge particle and thermal confinement with the changes in the pressure gradient being sufficient to produce the observed changes in E_r . The resulting shape and temporal evolutions of the temperature and density profiles exhibit the behavior observed in the experiments.

Several models search for bifurcations in v_θ by exploiting the physics of the poloidal viscosity ν_p . For example, analysis of the effect of turbulence on the poloidal viscosity indicates that the turbulent Reynold's stress can potentially drive a significant poloidal

flow near the plasma boundary.^{52,87} Such “self-generated” flows have been found in non-linear simulations.^{49,51} Turbulence in which self-generated flows are the dominant flows can be expected to be self-regulating because the resulting flow will have a stabilizing effect when the shear or curvature reaches an appropriate level for stabilization.⁵² Bifurcations might be expected from such highly nonlinear systems but a realistic bifurcation scenario has not been demonstrated yet.

A model which considers properties of the neoclassical poloidal viscosity obtains a dramatic increase in v_θ by the Stringer spin-up,^{88,89} a mechanism which requires a large poloidally asymmetric particle flux or particle source to drive the rotation. With an assumption that the particle diffusivity decreases with shear in v_θ , time-dependent radial particle transport calculations based on this effect have reproduced the typical shape and temporal evolution of the density profile during the L-H transition.⁸⁸

A bifurcation due to a nonlinear poloidal viscosity of the main ions^{37,90} has been found through a modification of standard neoclassical theory which includes a radial loss current from the plasma edge and which is extended to the regime in which the normalized poloidal rotation parameter U_{pm} is of order unity where

$$U_{pm} = \frac{1}{v_{th} B_\theta} \left[v_{\theta I} B_\phi - \left(\frac{1}{Z_I e n_I} \right) \nabla_{pI} \right] . \quad (2)$$

The variables pertain to the main ions where v_{th} is the ion thermal speed. This model predicts a bifurcation in U_{pm} for U_{pm} of order unity. The radial loss current required to increase U_{pm} is provided either by an external probe or by ion orbit loss. In the latter case, collisionless ions are required to produce significant ion orbit loss and bifurcation

is predicted when the ion collisionality parameter ν_{i*} is of order unity. The current is balanced by a viscous return current to maintain the net radial current at zero in steady state.⁹¹

Along similar lines, a model for a nonlinear poloidal viscosity has been obtained which includes both neoclassical and anomalous effects.⁹² The origin of the anomalous terms is not specified. A “rotational runaway” is found which is due primarily to the anomalous terms.

A major goal of experimental studies of spontaneous H-modes is to determine the relative importance of the three terms on the right hand side (RHS) of Eq. (1) before, during and after bifurcation. These rotation and pressure gradient terms are generally measured by spectroscopic techniques and E_r is inferred from Eq. (1).^{21–23,26,33} The spectroscopic measurements are difficult to make for the main plasma ions and are generally made for impurities, such as carbon. Although it is expected that this technique provides a good measurement of E_r , there is no guarantee that the rotation or pressure gradient terms are the same for impurity and main ion species. There are theoretical^{93,94} and experimental⁹⁵ reasons to believe that v_θ for impurities may be significantly different than v_θ for the main ions. The results show that there is a rapid increase in v_θ for impurity ions at the transition on timescales as short as 0.5 ms.¹⁴ The toroidal rotation velocity for the impurities is found to change little at the transition or to transiently become slightly more negative, consistent with a more negative value for E_r . Measurements with 0.5 ms time resolution have shown that although the pressure gradient for the impurity ions changes rapidly at the transition, it does not change as rapidly as v_θ .¹⁴ Thus, for a spontaneous transition, the inferred change in

E_r is primarily due to a change in v_θ of the impurity ions. The relative importance of each of the three terms on the RHS of Eq. (1) for the main ions at the transition is not clearly delineated yet. As the plasma edge evolves after the L-H transition, v_θ for the impurities tends to remain relatively constant, v_ϕ tends to increase in the direction of the applied beam momentum, providing a positive contribution to E_r for co-injected beams, and the pressure gradient increases and provides a negative contribution to E_r . The net result is that E_r remains negative in the H-mode.

Due to the difficulty of making many of the measurements needed in the bifurcation theories, most theories have not been experimentally tested at this time. However, analyses of the electrode-biased H-mode^{17,18,59,79} provide strong support for models in which the observed bifurcations in the probe current J_e and the radial electric field are due to the existence of a maximum in the poloidal viscosity.^{90,92} With neoclassical expressions for ν_p , modeling of TEXTOR data has reproduced the shape and location of the observed E_r profiles (Fig. 3) and the predicted critical current for bifurcation is in the range of 0.7 to 4 times the observed critical current.^{59,79} Bifurcation occurs for U_{pm} of order unity as predicted by theory. More complicated modelling has been used for data from Toroidal'naya Ustanovka s Magnitnym Adiabatcheskim Nagrevom 3 (TUMAN 3),¹⁸ but the results indicate that the reduction of J_e after bifurcation is also due to a reduction of ν_p with increasing v_θ .

The theory of Shaing and Crume^{90,91} provides a mechanism to unite the physics of bifurcation for the spontaneous transitions and the biased H-modes. Ion orbit loss could provide the radial current required to produce a poloidal torque, which is supplied by the probe current in the biased H-modes. Consistency checks of the theory in JAERI

Fusion Torus 2 Modified (JFT2-M)³⁴ and DIII-D¹⁴ have shown that U_{pm} in spontaneous H-modes is of order unity, as predicted by theory. This theory is qualitatively consistent with a substantial body of evidence that the edge collisionality must be sufficiently low for the transition to occur, as indicated by observations of threshold values for T_e ^{12,19,30} and T_i .³² In fact, measurements in DIII-D¹⁴ have shown the transition occurring when ν_{i*} drops to about one, as predicted. However, data from JFT2-M show that ν_{i*} is much larger than unity, which is generally interpreted as indicating that ion orbit loss from the thermal ions cannot provide the required poloidal torque. This theory can explain the JFT2-M results if there is a sufficient population of ions at energies above thermal to drive ion orbit losses. There is evidence for such a population, but the issue is not fully resolved at this time.⁹⁶

Further assessment of the bifurcation theories poses significant challenges for experiment. One approach in the study of ion orbit loss is the use of increasingly sophisticated analytical and numerical techniques to calculate loss cones with the effects of electric fields and orbit squeezing included.^{97–103} A challenge for theory is to provide accurate predictions of the width of the E_r well, which is found experimentally to be one to a few times ρ_{i0} .^{34,57} Such predictions require at least one dimensional theories because the field established by the physics of bifurcation may be expected to penetrate due to self-consistent effects, such as the ion viscosity.¹⁰⁴

V. CONFINEMENT IMPROVEMENT IN PLASMA CORE

After the transport barrier is formed, improved thermal confinement develops in the core plasma, the region between the transport barrier and the magnetic axis, on a time scale which is of the order of the energy confinement time. The improvement of core confinement has been demonstrated by several transport studies which evaluate the thermal diffusivity obtained from power balance and find that the diffusivities are lower in the H-mode than in the L-mode.^{2,12,19,105-112}

With the availability of suitable temporally and spatially resolved data for T_e , n_e , T_i and Z_{eff} , temporally resolved transport calculations have shown that the core confinement does not respond instantaneously to the formation of the transport barrier but that the thermal diffusivities in the core evolve on a time scale long compared to the time required for the formation of the transport barrier.^{105,108,111,112} Measurements of turbulence with scattering and reflectometry show that $\tilde{n}/n$ decreases in the core gradually compared to the time for the transition to occur.^{12,41,67,69,70,113} Data obtained from the same plasma indicate that density fluctuation levels decrease with the same timescale and spatial location as the transport improves.¹¹² These observations are consistent with the hypothesis that the improvement in core confinement is due to the reduction of turbulence, although this hypothesis is not proven.

The mechanism by which the improvement in core confinement is facilitated by the transport barrier is not known, but an obvious hypothesis is that formation of the transport barrier permits changes in profiles in the core which reduce local turbulence drives and permit improved local confinement. Some of the possibilities are flattening of the density gradient in the core plasma due to formation of the steep density gradient in the transport barrier, penetration of the E_r shear layer into the core and modifications of the current density profile due to the bootstrap current driven in the transport barrier. The net result of the improved core confinement is that τ_E in the quiescent phase of auxiliary-heated H-mode discharges is approximately twice that in the L-mode, as shown by empirical studies to determine the scaling relationship between τ_E and plasma engineering parameters.^{114,115}

The behavior of particle confinement for electrons and main ions in H-mode discharges is not nearly as well studied as the behavior of energy confinement due to difficulties in measuring the particle source rate, and the results quoted here must be interpreted with caution. Studies indicate that τ_p for electrons and main ions improves from L-mode to H-mode with a factor of two improvement determined in JET,⁶ roughly an order of magnitude improvement inferred in ASDEX¹² and factor of about five improvement inferred for H-modes obtained with negative bias in TEXTOR.²⁴ H-modes obtained with positive bias in TEXTOR showed smaller improvements in τ_p even though the improvement in τ_E was similar for both signs of bias. Specific comparisons of τ_p to τ_E have not been made in these references but the typical values of τ_p vary from slightly less than one to approximately five times larger than the typical values of τ_E . The smallest ratio was obtained from the JET data. A similar result has been obtained in

DIII-D where τ_p^* is 1–2 times τ_E in ELM-free H-mode conditions with $\tau_p^* = \tau_p/(1 - R)$ and R being the recycling coefficient.¹¹⁶ For the expected case that R is less than one, it is concluded that τ_p^* can be no larger than 1–2 times τ_E . The variability in these results may reflect difficulties in accurately measuring τ_p and the possibility that τ_p is quite sensitive to the exact details of the edge plasma. Because the region in which neutrals are ionized lies very near the plasma edge, it can be expected that formation of the transport barrier will have a large effect on particle transport.

The confinement of impurities also improves in H-mode. These results are particularly well documented for metallic impurities which tend to accumulate in the plasma core if the MHD activity is sufficiently low.^{12,28,117} Confinement times of up to four seconds have been observed for nickel in JET.²⁸ Transport analyses suggest that the long impurity particle confinement times are due at least partially to neoclassical effects.^{12,117,118} The presence of sawteeth and ELMs dramatically reduces the confinement of impurities as will be discussed in the next section.

VI. LIMITATIONS IMPOSED BY IMPURITY RADIATION AND ELMS

H-mode discharges which are operated so as to avoid MHD problems due to the beta limit eventually reach operational limits imposed by impurity radiation or ELMS. As noted in the Section V, particle confinement times are very long in the H-mode. Therefore, due to rising impurity and electron densities in the quiescent phase of the H-mode, energy radiated from the plasma due to electron impact excitation of incompletely stripped ions rises continually during the discharge.¹² If the impurity radiation reaches approximately 100% of the heating power, the plasma normally reverts to L-mode. The most severe radiation problems have been caused by metallic impurities such as iron and nickel. In discharges without sawteeth, radiation problems are particularly severe because impurities tend to accumulate at the plasma core.^{12,117}

Under a wide variety of operating conditions, the quiescent phase of the H-mode is terminated by the repetitive instabilities at the plasma edge called ELMS before the radiated power rises to deleterious levels.^{6,12,19,28,62} An ELM is evidently an MHD instability which very rapidly destroys the transport barrier and therefore the large edge pressure gradient.^{12,25} Subsequently, the transport barrier is rapidly restored by heat from the plasma core and particle fueling from the edge. ELMS have a major effect on particle transport and tend to clamp the line averaged density at a fixed level and to halt the rise in impurity densities.^{119,120} As a result, the monotonic rise in radiated power

is halted and impurity radiation is normally held to an acceptable level. The energy confinement time in a discharge with ELMs is reduced by roughly 15%–20% relative to the τ_E value obtained in the quiescent phase but the value remains well above the L-mode value.^{12,29}

Studies of ELMs are complicated by the fact that there are clearly more than one type of ELM with three types identified on DIII-D. Type I or “Giant” ELMs occur with the edge pressure gradient near the ideal ballooning limit.²⁵ Type II or “grassy” ELMs have a high frequency relative to Type I ELMs and occur for values of the edge magnetic shear such that the plasma edge is in the connection region between the first and second stable regimes.¹²¹ Type III ELMs occur with the edge pressure gradient well below the ideal ballooning limit and the repetition frequency is intermediate between that of Type I and II ELMs.¹²²

An ELM is generally interpreted as a manifestation of an MHD instability and much experimental work has been devoted to searching for and determining the mode structure of precursors to the ELM in an effort to identify the relevant physics. For sufficiently isolated ELMs, several studies have detected precursors and some have also measured mode structures.^{8,19,122–125} Precursors to ELMs which appear to be Type III in ASDEX,¹²³ JET¹²⁴ and DIII-D¹²⁶ have the characteristics expected for resistive ballooning modes. Stability calculations suggest that precursors to Giant ELMs in the Princeton Beta Experiment (PBX-M)⁸ may be due to the pressure driven ideal kink mode. In general, precursors appear to originate a short distance inside the LCFS and to propagate or grow towards the LCFS.^{8,19,125} The ELM may be due to the arrival of the precursor at the plasma boundary. An alternative hypothesis is that the precursor

changes edge profiles sufficiently that another mode is destabilized and actually causes the destruction of the transport barrier.¹²⁴

From an operational point of view, ELMs provide the only proven technique to date for running H-mode discharges in a steady state and have been used to produce long pulse discharges in a number of devices,^{64,127,128} with the longest quasi-stationary phase being 18.5 s in JET. The lengths of these discharges have been limited by power supply constraints rather than by plasma effects, although rising gas inventories may provide limitations for sufficiently long discharges. Pumped divertor chambers will soon be tested to control the gas inventory and to assist with steady state H-mode operation.

VII. IMPROVED H-MODES

Under some scenarios, the H-mode discharge has provided entry into regimes of confinement which are enhanced by up to a factor of two over normal H-mode performance. VH-mode discharges, obtained after boronization in DIII-D, exhibit normal L-H transitions but, during the quiescent H-phase, the confinement starts to improve and ultimately τ_E achieves values which are 1.6–2.0 times that expected from the JET/DIII-D H-mode scaling relationship.^{129–131} Transport analysis shows a significant reduction of thermal diffusivities over much of the plasma cross section. The shear in E_r in the core of a VH-mode discharge is substantially higher than that in a standard H-mode discharge and is an attractive explanation for the confinement improvement.¹³¹ The quiescent phase is abruptly terminated by an MHD event and the plasma then enters an ELMing phase. The confinement with ELMs is equal to or better than that in normal ELMing H-mode discharges.

Hot ion H-mode discharges in JET have also exhibited confinement enhancements of a factor of two relative to the JET/DIII-D H-mode scaling relationship.¹³² These discharges are characterized by high values of central T_i and transport analysis indicates that the ion thermal diffusivity is reduced relative to normal H-mode discharges. The reason for the confinement improvement is not known but there is some evidence of a correlation with the ion density peaking factor. The high confinement phase of these

discharges is terminated by an “event”, which may be a carbon bloom or an MHD instability, with the discharge then returning to normal H-mode confinement.

VIII. SUMMARY AND CONCLUSIONS

In many tokamaks, H-mode discharges have provided roughly a factor of two improvement in energy confinement time relative to the confinement normally achieved in auxiliary-heated discharges in the L-mode regime. The H-mode has been an object of study both for its reactor potential and for the opportunities that it provides to understand transport processes in tokamaks. During the last few years, a remarkable degree of consistency of results from tokamaks throughout the world has developed with regard to the phenomenology of the transition from L-mode to H-mode confinement and simultaneously a theoretical framework, based on reduction of turbulence due to shear in E_r , has been developed and is consistent with many experimental observations. Thus, an excellent framework for pursuing studies of the H-mode now exists.

H-mode discharges are obtained spontaneously in tokamak plasmas with sufficient heating power and also by application of sufficient bias voltage to a probe inserted in the plasma. The phenomenology of H-mode discharges obtained with these two techniques is quite similar, indicating that similar physics is important in both scenarios. Transitions normally occur on the time scale of $100\ \mu\text{s}$ or less and the earliest detectable changes are at the plasma periphery where marked increases in the absolute value of E_r and its gradients are accompanied by the formation of steep pressure gradients. The H-mode is initiated by formation of the transport barrier and there is substantial

evidence that the level of turbulence and of turbulent-driven particle flux is reduced in this region. Thus, the experiments are consistent with theories that the transport barrier is formed by suppression of turbulence due to large shear or curvature in the $\vec{E} \times \vec{B}$ flow.

The thresholds in heating power to obtain spontaneous H-modes or in bias voltage to obtain biased H-modes can be interpreted as conditions required to cause bifurcations in the edge v_E flow needed to form the transport barrier. Bifurcation models, based on a variety of neoclassical and anomalous effects, have been proposed. Transport simulations performed for some of these models exhibit the basic phenomenology observed in the experiments with rapid bifurcations and development of the transport barrier for particles and heat. These simulations show that, at the bifurcation, several parameters including the v_E flow change simultaneously, which suggests that it may be impossible to definitively show that changes in E_r precede changes in confinement.

Some experimental comparisons with a theory of nonlinear poloidal viscosity have been made and this theory successfully unites many features of the transitions observed in biased H-modes and spontaneous H-modes. Further progress in identifying the underlying bifurcation scenario requires experimental work to determine the relative importance of the various terms in the force balance equation and work to determine implications of various theories which can be tested experimentally.

After the transport barrier is formed, the confinement in the core of the discharge also improves but on a timescale slow compared to the time in which the transport barrier was formed. Reductions in the local thermal diffusivities and in $\tilde{n}/n$ occur in the core on the same timescale. Thus, the improvement in core confinement may be

linked to a reduction of turbulence. This sequence of events indicates clearly that the improvement in core confinement is enabled by formation of the transport barrier. An important experimental issue is to clearly determine the source of the turbulence drive in the core.

Improved core confinement leads to a rise in core temperatures and densities and to a rise in radiated power. If the source of impurities is sufficiently weak that the radiated power does not reach the level of the heating power, repetitive instabilities at the plasma edge, called ELMs, will ultimately occur and halt the rise in density and in radiated power. Each ELM destroys the transport barrier which reforms after the termination of the ELM. ELMs provide a mechanism for maintaining H-mode discharges in steady state. Discharges with durations of several seconds have been produced in several tokamaks with the limitation on the pulse lengths being due to power supply capabilities.

Confinement times of up to a factor of two higher than normal H-mode confinement times have been obtained in VH-mode discharges in DIII-D and in hot ion H-mode discharges in JET. The studies required to obtain a more complete understanding of these discharges are in progress. Just as the discovery of the H-mode showed that L-mode confinement was not a basic limitation to tokamak confinement, the discovery of the new confinement regimes shows that H-mode confinement is not a basic limitation either. Further advances in the physics understanding of these various confinement regimes and technical advances to take full advantage of the physics understanding may well lead to a reactor concept in which confinement does not control the size of a tokamak reactor.

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