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Stationary density profiles in the levitated dipole experiment: towards fusion without tritium fuel

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Abstract. The Levitated Dipole Experiment (LDX) is used to study high-temperature plasma confined by the magnetic field produced by a high-current superconducting ring. Multiple-frequency ECRH heats and sustains plasma discharges for long, quasi-steady periods, and conditions of high plasma beta are reached by adjusting the rate of neutral fueling. When the superconducting ring is levitated by attraction to a coil located above the vacuum chamber, cross-field transport becomes the main loss channel for plasma particles and energy. We find operation with a levitated dipole always leads to centrally peaked density profiles even when the plasma ionization source occurs near the plasma edge. In recent experiments, we also observe the normalized gradient, or shape, of the density profile to be "stationary" while the ECRH heating power and gas fueling rates are strongly modulated. Theoretically, stationary profiles result in an energy confinement time (of thermal plasma) that greatly exceeds the particle confinement time. This condition, along with high-beta plasma stability, is a necessary condition for utilizing advanced fuels in a fusion power source.

1. Introduction

A dipole is the simplest magnetic field that can confine plasma. The dipole as a fusion concept was inspired by observations of high beta plasma in planetary magnetospheres [1]. Low-frequency fluctuations drive inward diffusion of magnetospheric trapped particles, creating centrally peaked density and temperature profiles [2, 3, 4]. In the Levitated Dipole Experiment (LDX) a superconducting magnet is levitated in a large vacuum chamber so as to avoid along-the-field, parallel plasma losses. We find that stable, high-beta plasma discharges can be sustained with multiple-frequency electron cyclotron resonance heating (ECRH) [5]. When the the dipole is levitated, centrally-peaked density profiles result, plasma confinement improves [6], and we observe a strong inward particle pinch that is consistent with measured fluctuations of the electric field [7].

In this report, we show new measurements of the time evolution of the density profile as the microwave heating power and neutral fueling rate are strongly modulated. We find that, when the internal coil is levitated, the density profile will evolve rapidly to and maintain close to a "stationary" profile. We also discuss the theoretical basis for dipole plasma confinement and the implications that result when plasma profiles are determined by gradient conditions and by the power and particle balance of the boundary scrape-off-layers. Because of the dipole's strong variation of flux-tube volume with radius, these conditions imply that the plasma energy confinement time will be much longer than the particle confinement time, making the dipole configuration a candidate for tritium-suppressed fusion power [8, 9, 10].

2. Description of the LDX Facility

Fig. 1 shows the LDX magnetic field geometry. The upper levitation magnet supports the gravitational weight of the superconducting current ring and creates a magnetic field null that defines the outer boundary between closed and open field lines. The inner boundary is set by magnetic field lines that contact the dipole magnet, during levitation. Along the equatorial midplane, closed field lines extend from 0.68 m $\leq R \leq$ 1.71 m. By inserting the mechanical support, the effects of levitation can be eliminated.

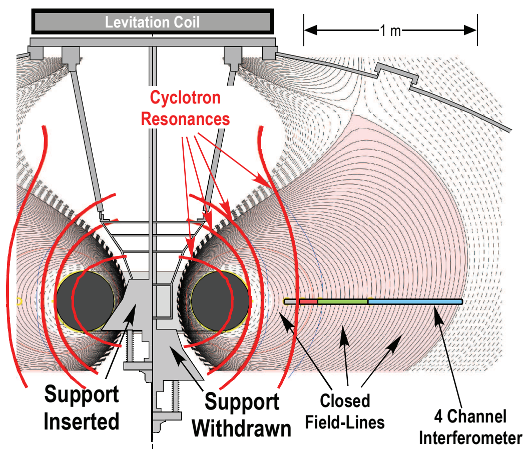

Figure 1. Schematic of LDX showing magnetic field lines, ECRH resonances, and viewing regions of the interferometer array.

Initial experiments were conducted with the high-field superconducting coil suspended by three thin rods. These experiments produced long-pulse, quasi-steady-state microwave discharges, sustained for more than 10 s, having peak beta values greater than 20% [5]. In both supported and levitated configurations, detailed measurements are made of discharge evolution, plasma dynamics and instability, and the roles of gas fueling, microwave power deposition profiles, and plasma boundary shape. High-temperature plasma is created by multiple-frequency ECRH applied at 2.45 GHz, 6.4 GHz, 10.5 GHz and 28 GHz, allowing variation of the heating profiles. Depending upon neutral fueling rates, the LDX discharges contain a fraction of energetic electrons with mean energies above 50 keV.

In LDX, we are able to compare operations in which the dipole is either supported or levitated. Levitation eliminates field-aligned particle sources and sinks and results in a toroidal, magnetically-confined plasma where profiles are determined by cross-field transport. Plasma measurements include a four-channel interferometer, arrays of Langmuir probes, high-speed optical diagnostics, extensive magnetic flux loops and sensors, and x-ray and electron cyclotron emission diagnostics [5, 6, 7].

3. Theoretical considerations

Centrally-peaked, stationary density profiles of plasma confined by a dipole magnetic field are the result of radial transport induced by low-frequency electric and magnetic fluctuations. For magnetospheric trapped particles, with energy sufficient that both the bounce and cyclotron frequencies are much larger than solar-wind induced low-frequency fluctuations [2, 3, 4], the first and second adiabatic invariants, μ and J, are constants of the motion [11], and collisionless gyrokinetics describes radial diffusion as

$$\frac{\partial F}{\partial t} = \left.\frac{\partial}{\partial \psi}\right|_{J,\mu} \left(D^{\psi\psi}(\mu, J) \left.\frac{\partial F}{\partial \psi}\right|_{J,\mu} \right) + \bar{S}\,, \tag{1}$$

where $F(\mu, J, \psi, \phi, t)$ is the bounce-averaged particle distribution at a field-line labeled with (ψ, ϕ), and $\bar{S}$ is a bounce-averaged heating or particle source (or loss). $D^{\psi\psi}$ is the radial diffusion coefficient. For electric field fluctuations in the magnetosphere having $\mathbf{E} \cdot \mathbf{B} = 0$, $D^{\psi\psi}$ is approximately constant [3], independent of (μ, J) and proportional to the correlation time of the non-axisymmetric fluctuations, τ_c, $D^{\psi\psi} = 2\tau_c R^2 \tilde{E}_\phi^2$. The independence of $D^{\psi\psi}$ with respect to (μ, J) has important consequences. Since the particle number within a flux-tube volume is $N \equiv \int d\mu dJ\, F = \int ds\, n/B = nV$, with $V \equiv \int ds/B$, the integral of Eq. 1 states that when $\partial N/\partial\psi = (\partial/\partial\psi) \int d\mu dJ\, F \to 0$ in regions where particle sources or losses are unimportant, then stationary density profiles result, $\partial N/\partial t \sim 0$, with $N \propto V^{-1}$. Since the sources of energetic particles in the magnetosphere are located at large radii and $V \propto r^4$ decreases rapidly with radius, collisionless radial diffusion is inward and causes central peaking of ring current and radiation belt particles during periods of solar activity [3, 4].

The Lagrangian treatment of drift-resonant radial diffusion has also been applied to tokamak discharges [12, 13] and, recently, to nonlinear MHD dynamics in dipole-like magnetic geometries [14, 20]. In fusion configurations, hot plasma is confined much longer than a pitch-angle scattering time, i.e. $\nu_{cyclotron} \gg \nu_{bounce} \gg \nu_{collision} \gg \nu_{turbulence}$ and the distribution function, F, must be taken as a local Maxwellian, $F_M \propto n(\psi) \exp[-E(\mu, J)/T(\psi)]/T(\psi)^{3/2}$, with E the kinetic energy [12]. Baker and Rosenbluth [12] perform a change of variables $(\mu, J \to \mu, E)$ and the drift-resonant radial diffusion coefficient was taken to be a separable function of pitch-angle and radius, $D^{\psi\psi} = D^{\psi}(\psi) g(\lambda)$, with $\lambda = \mu B/E$, allowing the form of the total particle diffusive flux to be expressed in terms of the tokamak's magnetic geometry and the relative diffusion rates for passing and trapped particles.

For the closed-field-line magnetic geometry of a levitated dipole, low-frequency fluctuations are interchange-like and should convect passing and trapped particles equally ("passing" particles do not stream toroidally). Noting $\int d\mu dJ = \int d\ell/B \int d^3v$, and assuming $D^{\psi\psi}$ to be independent of μ and E we can multiply eq. 1 by 1 and E and integrate to obtain eqns. 2 and 3 below:

$$\frac{\partial(nV)}{\partial t} = \frac{\partial}{\partial \psi} D^{\psi} \frac{\partial}{\partial \psi}(nV) + \langle S \rangle \tag{2}$$

$$\frac{\partial(pV^\gamma)}{\partial t} = \frac{\partial}{\partial \psi} D^{\psi} \frac{\partial}{\partial \psi}(pV^\gamma) + \langle H \rangle \tag{3}$$

with $p(\psi) = nT$, $\gamma = 5/3$, and $\langle S \rangle$ and $\langle H \rangle$ the net particle and heating sources for entire flux-tubes. Eqs. 2 and 3 state that flux-tube number, $N \equiv nV$, and entropy density, $G \equiv pV^\gamma$, undergo interchange mixing at the same rate, and, furthermore, that the resulting stationary pressure and density profiles are related by magnetic geometry, $V(\psi)$, and the adiabatic index, γ. Thus, for a local Maxwellian, turbulence will diffuse the density and pressure profiles towards stationary profiles characterized by $n \propto 1/V$, $p \propto 1/V^\gamma$ (and therefore $T \propto 1/V^{\gamma-1}$). The resulting turbulence can reduce the temperature gradient to a near marginal state while drawing in the density profile. The density pinch is consistent with the observations discussed below. The observed pinch is also seen in gyrokinetic simulations [19].

In a tokamak, there is average good curvature and ITG/TEM turbulence is seen to drive a density pinch through both thermodiffusion and "turbulent equipartition" [15]. The pinch produced by turbulent equipartition can result in a "natural" profile characterized by $n \sim 1/V \sim 1/q$ [12, 15]. On the contrary, a dipole is stabilized by magnetic compressibility [18] and strong internal heating can create pressure-gradient-driven MHD instability. The rapid field decay in a dipole makes the "natural" profile much more dramatic.

In LDX ($T_e \sim 200$ eV, $n_e \sim 10^{18}$ m^{-3}), electrons are characterized by $\nu_{bounce} \sim 5$ MHz and $\nu^e_{collision} \sim 15$ kHz. These characteristic frequencies and the measured correlation time of the turbulent electric field fluctuations, $\tau_c \sim 16\,\mu$sec, implies the kinetic treatment is appropriate when $D^{\psi\psi}$ results from pitch angle independent turbulence . Although we have not measured the ion temperature, we suspect $T_i \ll T_e$, making fluid equations which are identical to Eqs. 2 and 3t also appropriate for the ions [20].

We note that the tendency towards stationary profiles requires that there be a broad spectrum of incoherent, low frequency $\mathbf{E} \times \mathbf{B}$ interchange turbulence that drives radial transport at approximately equal rates for the bulk of both electrons and ions. The random fluctuations of the cross-tail electric field driven by solar wind variability creates such a spectrum. Broad interchange fluctuations are observed in LDX [7, 17] and also other laboratory dipole devices [16], but the internal mechanisms that determine the fluctuation spectrum are not yet known. As described by Refs. [14, 20], when strong central heating is applied to a dipole-confined plasma, we may expect that instability results from a supra-critical pressure gradient which will both reduce the pressure gradient to a near critical value while also causing an inward density pinch.

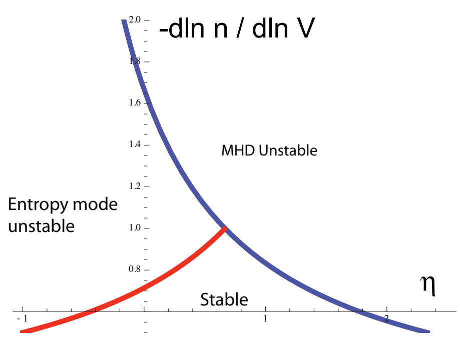

Figure 2. Linear stability limits, $-d\ln n/d\ln V$ vs η for MHD interchange and entropy modes.

The stationary gradients that result from low-frequency turbulence are also the gradients for marginal stability for MHD interchange and rotation-driven modes. MHD interchange modes become unstable when $-d\ln p/d\ln V > \gamma$, and rotationally-driven centrifugal modes become unstable when $-d\ln n/d\ln V > 1$. The drift frequency "entropy mode" is predicted to be unstable when $-d\ln n/d\ln V > 5/(7-3\eta)$ with $\eta = d\ln T/d\ln n$. The entropy mode is interchange-like [22] and will also exhibit flux-tube diffusion [23] . Fig. 2 shows the linear stability limits for the pressure-driven interchange mode and the entropy drift mode. When $-d\ln n/d\ln V > 1$ there will be either MHD or entropy mode instability.

The fact that multiple gradients can drive interchange mixing creates the mechanism for profile consistency, or self-organization. For example, central heating in a dipole-confined plasma can create a strong central pressure gradient that excites turbulent interchange modes that sustain the inward particles pinch which results in $\eta \rightarrow 2/3$ [14, 20]. In a tokamak, the pressure gradient is not limited by interchange instability (due to average good curvature), but steep temperature gradients can excite drift instabilities that sustain an anomalous pinch and a "consistent" profile [24].

The gradient conditions for plasma stability and for turbulent diffusion links the global plasma properties to the edge plasma and to the flux-tube geometry of the magnetic field. Turbulent flux tube mixing within the closed field line region drives profiles to have nearly constant entropy density, $G = pV^\gamma$, and constant particle number per unit flux, $N = nV$. The stationary profile region is bounded by open field lines that define an inner and outer "scrape-off-layer" (SOL) where plasma flows to the wall or the floating ring. We assume that the losses associated with the inner SOL are small compared to those for the outer SOL because the plasma sees good curvature between the floating coil and the pressure peak and bad curvature between the pressure peak and the outer SOL and we assume that the turbulence driving the pinch is localized in the bad curvature region. The power entering the scrape-off-layer the approximates the heating power less the radiated and ionization power and for open field lines, the scrape-off-layer density is determined by a power balance:

$$P_{ECRH} - P_{Rad} - P_{ionization} = n_{sol} U_B A_{eff} E_{sol} \tag{4}$$

with n_{sol} the scrape-off-layer density, U_B the Bohm velocity ($\propto \sqrt{T_e}$), A_{eff} the effective scrape-off-layer cross-section area, and E_{sol} the thermal energy per particle lost. Since $P_{ECRH} \gg P_{Rad}$, Eq. 4 indicates that scrape-off-layer density is proportional to input power, *i.e.* $n_{sol} \approx (P_{ECRH} - P_{ionization})/(U_B A_{eff} E_{sol})$. For stationary profiles, with fixed gradients, core plasma density is proportional to heating power.

For open field lines, the scrape-off-layer temperature is determined by a particle balance and connection length:

$$n_{sol} U_B(T_e) A_{eff} = n_{sol} n_0 \langle \sigma v(T_e) \rangle V_{eff}. \tag{5}$$

with $\langle \sigma v \rangle$ the effective ionization cross-section, which is temperature dependent, and V_{eff}/A_{eff} is the effective connection length of the edge field-lines. From Eq. 5, the scrape-off-layer temperature is approximately independent of heating power. We measure electron temperature in the scrape-off-layer to be $T_e^{sol} \approx$ 15-30 eV.

Noting that the plasma density and temperature is continuous across the separatrix, we can integrate the pressure and density from the outer scrape-off-layer to the peak pressure flux tube to obtain the total stored energy and particle content:

$$\begin{aligned} E_{tot} &\propto \frac{3}{2} p_{sol} R_{sol}^3 (R_{sol}/R_0)^{11/3} \\ N_{tot} &\propto n_{sol} R_{sol}^4 / R_0. \end{aligned} \tag{6}$$

with p_{sol} (n_{sol}) the scrape-off-layer pressure (density) and R_0 the radius at which the pressure is maximum and the dipole magnetic geometry determines $B \propto R^{-3}$. From Eqs. 6, the total stored energy and particle content are directly related to the scrape-off-layer parameters. Stationary profiles in a dipole amplify scrape-off-layer parameters. In particular, since scrape-off-layer density increases with power and temperature remains fixed, the stored energy will also increase with power. The energy confinement time, defined as $\tau_E = E_{tot}/P_{tot}$ is therefore independent of heating power.

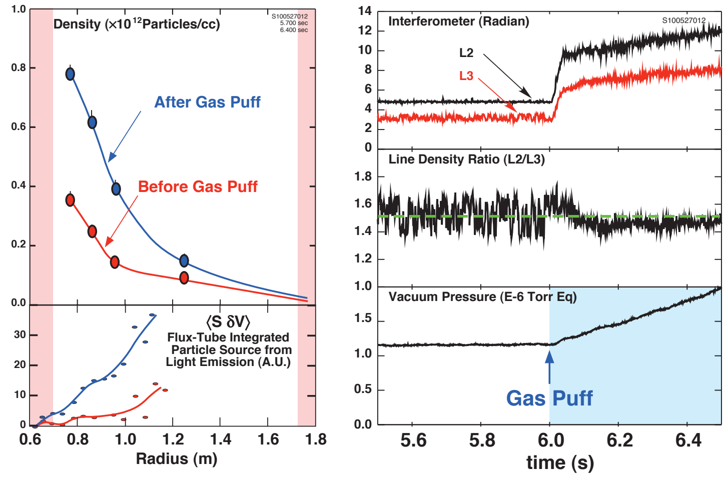

Figure 3. Evolution of plasma density following a strong gas puff at $t = 6$ s that increases the outer ionizations source, $\langle S \rangle$. Interferometer measurements show a two-fold increase in plasma density while maintaining constant stationary gradients as indicated by the ratio of interferometer chords.

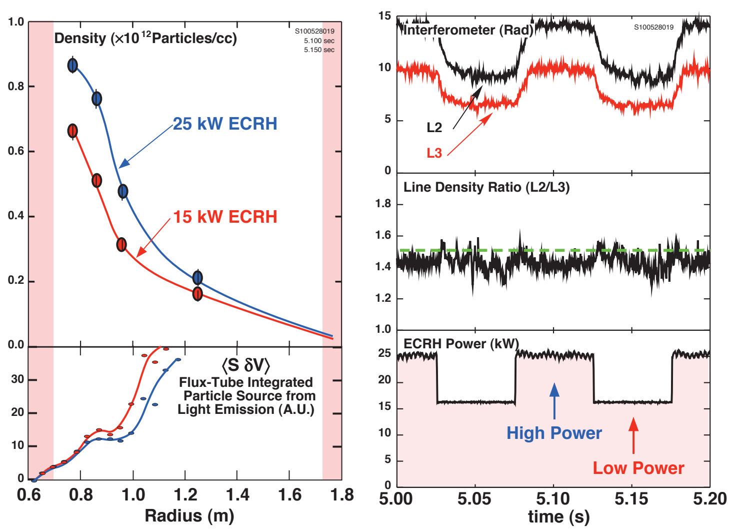

Figure 4. Evolution of the plasma density following strong modulation of the the microwave heating power. As in Fig. 3, the density modulates while maintaining near stationary profiles.

Defining $\tau_p = N_{tot}/S_{tot}$ with S_{tot} the total particle source (including recycle), we obtain

$$\frac{\tau_E}{\tau_p} = \frac{3}{2}(R_{sol}/R_0)^{8/3}(S_{tot}\ T_{sol}/P_{tot}) \tag{7}$$

This ratio of confinement times assumes stationary profiles and depends only on the geometric ratio, R_{sol}/R_0 and the scrape-off-layer temperature [25].

4. Experimental results

In LDX, we have been able to observe directly the changing roles of field-aligned and cross field processes in the establishment of density profiles. When the superconducting dipole floats, high-temperature plasma is confined within a large central confinement volume where magnetic field lines encircle the floating coil and never contact material surfaces. The peak thermal electron temperature is estimated to exceed 500 eV and peak densities exceed 10^{18} m^{-3}. Within this central region, profiles are set entirely by cross-field processes and a strong inward pinch is observed [7]. The density profile becomes strongly peaked with gradients approaching those set by the stationary condition $\partial N/\partial\psi \to 0$ for turbulent interchange transport.

The density profile is with a four-chord interferometer array having tangency radii of 0.77 m, 0.86 m, 0.96 m and 1.25 m. Since only four sight-lines are available, the reconstructed profiles are necessarily of limited spatial resolution and, moreover, no information is available within $R < 0.77$ m. Nevertheless, the four chords indicate the radial density profiles sufficiently to show dramatic central peaking during levitation, to compare measurements with model expectations, and to measure the time-evolution of the profile as experimental conditions change.

For stationary density profiles, $n \propto 1/V \sim 1/R^4$, and the interferometer chords have well-defined ratios. For example, when $n \propto 1/V$, the ratio of the line densities measured with the second and third chords (having tangency radii of 0.86 m and 0.96 m, respectively) is $L2/L3 = 1.5$. When $L2/L3 < 1.5$, the density profile is less steep than stationary, and, when $L2/L3 > 1.5$, the density profile is more steep. As discussed in Ref. [7], when the lifting support inserted to obstruct the closed field-lines, the density is no longer peaked, and $L2/L3 \sim 1$. When the lifting support is withdrawn, the density profile, while initially uniform (with $L2/L3 \sim 1$), becomes centrally peaked, $L2/L3 \to 1.5$, on the 20 ms time-scale of the inward turbulent pinch. Incoherent fluctuations in the 1-10 kHz range are observed on edge Langmuir probes as well as on the interferometer and on visible light chords.

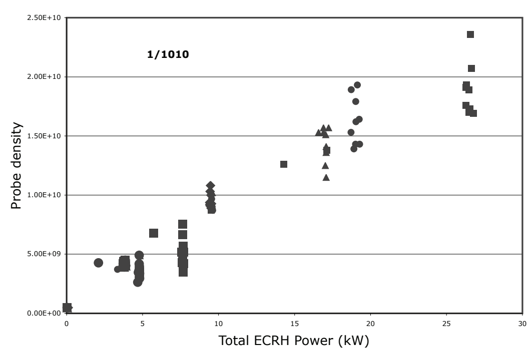

Figure 5. Measured scrape-off-layer density increases linearly with heating power.

Recent experiments have shown the density profile remains stationary even as the microwave heating power and gas fueling are modulated strongly. Fig. 3 illustrates an experiment in which the plasma ionization source was increased by a strong gas puff at $t = 6$ s and the plasma density approximately doubled. The density profile was observed to remain stationary, as indicated by the ratio $L2/L3$ of the two interferometer channels, which remained nearly constant at ≈ 1.45. The strong central peaking of the density represents the inward turbulent pinch since the ionization source occurs primarily in the outer regions of the plasma. We use the visible light as a proxy for the plasma source. Fig. 3 also shows the estimated profile of the flux-tube integrated particle source, $\langle S\rangle$, estimated from the inversion of a 15-chord photodiode array. As indicated in the figure, the particle source peaks to the outside of the plasma while the density peaks near the inner region of closed magnetic field lines. In another experiment, total microwave heating power was modulated by ∼35% at a 10 Hz rate using the 10.5 GHz 10 kW source. The power modulation was seen to result in a ∼35% modulation in the interferometer signal (Fig. 4a) whereas the ratio, $L2/L3$, remained constant (Fig. 4b). The formation of stationary density profiles thus appears to be robust and the condition $\partial N/\partial\psi \approx 0$ is maintained during substantial changes of the heating or fueling levels.

Information relating to fluctuations in the plasma core is obtained from the interferometer chords, from high-speed imaging of visible light emission from multiple views, and at the outer plasma boundary from arrays of Langmuir probes. These measurements indicate the presence of broadband turbulence with the largest intensity contained in modes having relatively broad radial structures and low azimuthal mode numbers [17]. Fluctuation levels are similar during levitated and supported operation, and the spectral characteristics resemble those measured in smaller, mechanically-supported dipole experiments [16].

Direct measurements of the turbulent azimuthal electric fields at the plasma edge with the Langmuir probe array are sufficient to account for the turbulent flux-tube diffusion coefficient, D, that produces the inward pinch [7]. In discharges with sufficient gas fueling, turbulent fluctuations appear throughout the plasma, and it appears that flux-tube mixing can also account for the maintenance of stationary profiles during power and gas modulations. However, in discharges with very low fueling levels ($< 3 \times 10^{-6}$ torr D_2), the nature of the fluctuations change. At these lower gas pressures, we observe quasi-coherent modes [17], larger fractions of energetic electrons, and the density profiles become more strongly peaked than is characteristic for stationary profiles. These highly-peaked discharges suggest a relationship between the observed quasi-coherent fluctuations and reduced turbulent transport. A theoretical possibility, based on non-linear calculations of entropy mode driven turbulence [23], suggests that at sufficiently low gas pressure, zonal flows can limit turbulence-driven transport, whereas higher gas pressure impede the zonal flows and lead to substantially higher transport levels.

Stationary plasma profiles link the confined plasma to the plasma parameters in the scrape-off-layer. Fig. 5 shows a linear relationship between the scrape-off-layer density, measured by swept Langmuir probes, and the injected microwave heating power. We also find the edge electron temperature to be approximately constant at between 20 and 30 eV.

5. Tritium Suppressed Fusion in the Dipole Configuration

Utilization of the DT fuel minimizes the required confinement for fusion energy gain and permits volumetric power deposition in a properly designed blanket and shield. However, the DT cycle requires the breeding of tritium, and 14 MeV neutrons will cause significant displacement and swelling damage to the structure.

A fusion based power source based on a DD cycle has important advantages relative to a DT based source. If 90% of the tritium, produced from DD fusion could be removed before it burns, the materials damage would be reduced to the level of existing fission plants [9]. Deuterium is plentiful, and a DD power source eliminates the complexity of tritium breeding components. In the dipole-based DD fusion system described in Ref. [8], the ^{3}He produced by the DD reaction and from the decay of DD-produced tritium would be consumed, reducing the fraction of energy generated in the blanket from 84% to 5.6%. As most of the fusion energy is produced in the form of charged particles, advanced fuels require low τ_P and $\tau_E \gg \tau_P$ to permit removal of fusion products [10] as well as the removal of secondary tritium.

In a dipole we have seen that a turbulent pinch develops and establishes stationary profiles characterized by near-constant nV and pV^γ [1] supported by plasma maintained at the scrape-off-layer. These invariant profiles should maintain $\tau_E/\tau_P \gg 1$ (eq. 7), making a dipole particularly interesting as a tritium suppressed DD fusion power source [8].

6. Conclusions

LDX operates with the superconducting current ring either floating or supported, allowing direct observation of a strong inward density pinch and the establishment of stationary density profiles, with $\partial N/\partial\psi \to 0$ and, equivalently, $n \propto 1/V$. Recent experiments show these centrally-peaked profiles are robust, with normalized gradients that are unchanged during modulations of fueling and heating power.

The dipole confinement approach [1] is inherently steady state and has no interlocking coils. The plasma pinch creates an inwardly peaked density profile and results in a relatively small plasma confined in a large vacuum chamber, reducing the heat load on outer surfaces. The pressure profile that results from central heating relaxes to a stationary profile, which is also centrally peaked ($p \propto R^{20/3}$). The combination of centrally heated plasmas and centrally peaked density with gradients near marginal stability implies that the energy confinement time can greatly exceed the particle confinement time. Thus a dipole provides a possible avenue for a fusion power source that is based on advanced fuels.

In LDX, the pressure profile is determined from magnetics [5, 6, 7]. Experiments now underway aim to produce measurement of the electron temperature and pressure profile utilizing Thomson scattering and to increase the plasma density by applying substantial RF heating in the ion cyclotron range of frequencies.

7. Acknowledgements

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References

[1] A. Hasegawa, Comm Pl Phys & Cont Fus, **1** (1987) 147.
[2] T. Birmingham, *J. Geophys. Res.*, **74**, 2169 (1969).
[3] M. Walt, *Space Sci Rev*, **12**, 446 (1971).
[4] Schulz and Lanzerotti, *Particle Diffusion in the Radiation Belts*, Springer-Verlag (1974).
[5] D.T. Garnier et al., Phys Plasmas **13** 056111 (2006)
[6] D.T. Garnier, *et al.*, *Nuc. Fusion*, **49**, 055023 (2009).
[7] A.C. Boxer et al., Nature Phys., doi:10.1038/nphys1510 (2010).
[8] J. Kesner, D.T. Garnier, A. Hansen, M.E. Mauel, L. Bromberg, Nuc. Fus., **44**, 193 (2004).
[9] J. Sheffield and M. Sawan, Fus. Sci. Tech., **53**, 780 (2008).
[10] W.M. Nevins, Journal of Fusion Energy **17** (1998) 25.
[11] H.P. Warren, *et al.*, *Geophysical Res. Lett.*, **19**, 941 (1992).

[12] D. Baker and M.N. Rosenbluth, *Phys. Plasmas*, **5** (1998) 2936.
[13] D. Baker, Phys Plasmas **9** 2675 (2002).
[14] Pastukhov and Chudin, *Plasma Physics Reports*, **27**, 963-977 (2001).
[15] X. Garbet, L. Garzotti, P. Mantica, H. Nordman, M. Valovic, H.Weisen, and C. Angioni, PRL **93** 035001-1 (2003).
[16] B.A. Grierson, M. Worstell, M.E. Mauel, *Phys. of Plasmas*, **16**, 055902 (2009).
[17] J.L. Ellsworth, *Characterization of low-frequency density fluctuations in dipole-confined laboratory plasmas*, MIT Ph.D. Dissertation (2010).
[18] D.T. Garnier, J. Kesner, M.E. Mauel, Phys. Plasmas **6**, (1999).
[19] S. Kobayashi, private communication: to be presented at the APS-DPP meeting, Chicago (2010).
[20] A. Kouznetsov, J.P. Freidberg, J. Kesner, Phys Plasmas **14** 102501-1-13 (2007).
[21] J. Kesner, Phys. Plasmas **7**, 3837 (2000).
[22] J. Kesner, and R. Hastie, Phys Plasmas **9** 395 (2002).
[23] S. Kobayashi, B. Rogers, W. Dorland, *Phys. Rev. Lett.*, **103** 055003 (2009).
[24] J. Weiland, *et al.*, *Nucl. Fusion*, **29**, 1810-1814 (1989).
[25] J. Kesner and M.E. Mauel, *Plasma Physics Reports*, **23**, 801 (1997).