CONFINEMENT IN THE RFP: LUNDQUIST NUMBER SCALING, PLASMA FLOW, AND REDUCED TRANSPORT

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Abstract

Global heat and particle transport in the reversed field pinch (RFP) result primarily from large-scale, resistive MHD fluctuations which cause the magnetic field in the core of the plasma to become stochastic. Achieving a better understanding of this turbulent transport and identifying ways to reduce it are critical RFP development issues. We report measurements of the Lundquist number scaling (*S*-scaling) of magnetic and ion flow velocity fluctuations in the Madison Symmetric Torus (MST) RFP. The *S*-scaling of magnetic fluctuations in MST is weaker than previous measurements $\tilde{b} / B \sim S^{-1/}$ in smaller (lower *S*) RFP plasmas. Impurity ion flow velocity fluctuations (measured with fast Doppler spectroscopy) have a scaling similar to the magnetic fluctuations, falling in the range $\tilde{V} / V_A \sim S^{-[0.08-0.19]}$. The MHD dynamo $\langle \tilde{\mathbf{V}} \times \tilde{\mathbf{b}} \rangle$ up to 15 V/m was measured in the plasma core. Interestingly, the scaling of the MHD dynamo $\langle \tilde{\mathbf{V}} \times \tilde{\mathbf{b}} \rangle \sim S^{-[0.64-0.88]}$ is stronger than for its constituents, a result of decreased coherency between $\tilde{V}$ and $\tilde{b}$ with increasing *S*. A weak *S*-scaling of magnetic fluctuations implies fluctuation suppression measures (e.g. current profile control) may be required in higher-S RFP plasmas. Two types of current profile modifications have been examined – inductive and electrostatic. The inductive control halves the amplitude of global magnetic fluctuations and improves the confinement by a factor of 5. The electrostatic current injection, localized in the edge plasma, reduces edge resonant fluctuations and improves the energy confinement. In addition, regimes with confinement improvement associated with the plasma flow profile are attained.

1. INTRODUCTION

Global heat and particle transport in the reversed field pinch (RFP) result primarily from large-scale, resistive MHD fluctuations which cause the magnetic field in the core of the plasma to become stochastic [1,2]. Because this dominant turbulence is well described by resistive MHD, the obvious dimensionless scaling test is with the Lundquist number $S = \tau_R / \tau_A$, the ratio of the resistive diffusion time to the (poloidal) Alfven time. Since *S* increases with the plasma size, magnetic field, and temperature, $S \propto aBT_e^{3/2}$, the scaling results are relevant for RFP reactor development.

Past measurements in devices smaller than MST (lower *S*) focused on magnetic fluctuations and observed more or less favorable scaling ranging from $\tilde{b}/B \sim S^{-1/2}$ [3] to $\tilde{b}/B \sim S^{-1/3}$ [4]. The MST experiments aimed to (1) extend the scaling to larger *S*, (2) include, for the first time, the scaling of flow velocity fluctuations, (3) help resolve conflicting theoretical predictions for the scaling, and (4) examine the *S*-scaling of the MHD dynamo. The main result of these studies is that the magnetic fluctuation amplitude scales more weakly than observed at lower *S*, implying a greater need for controlled reduction or suppression of magnetic turbulence (e.g. by current profile control) to avoid physically large, high current RFP reactor. In MST, fluctuation reduction has been achieved with auxiliary inductive and electrostatic poloidal current drive in the edge plasma. To date the largest reduction occurs with inductive current drive, during which the energy confinement increases five-fold [5, 6].

In addition to these planned approaches using current profile control, new regimes of improved confinement have been discovered which appear to be associated with changes in the plasma flow, either by biasing the edge plasma with an inserted electrode, or occurring spontaneously, subject to constraints on toroidal field reversal, plasma density, and wall conditioning. In these cases, either or both magnetic and electrostatic fluctuations are reduced. Both a change in the global flow profile and the formation of localized flow shear in the edge have been observed in these plasmas.

In this paper the *S*-scaling experiments will be described in Section 2, the current profile control experiments will be described in Section 3, and the plasma confinement improvement associated with flow modifications will be described in Section 4.

2. FLUCTUATION SCALING WITH LUNDQUIST NUMBER

In this section we summarize comprehensive results of magnetic and velocity fluctuation measurements [7, 8]. The measurements were done in the MST RFP [9] with minor radius of a = 0.5 m, and major radius of *R* = 1.5 m. The plasma current was varied from *I* = 150 kA to *I* = 500 kA. The plasma density was not varied independently but rather the data were obtained at two values of a parameter I/N ($N = \bar{n}_e \pi a^2$): (1) $I/N = 2\times 10^{-14}$ A$\cdot$m (low *I/N*) and (2) $I/N = 6\times 10^{-14}$ A$\cdot$m (high *I/N*). The Spitzer resistivity was calculated as $\eta = 5.22\times 10^{-5} \ln\Lambda \cdot Z_{eff} T_e^{-3/2}\,(\mathrm{eV})\,\Omega\cdot\mathrm{m}$, with a Thomson scattering measured central electron temperature and laser interferometer measured central chord averaged electron density n_e. The mean ion charge Z_{eff} was calculated using measured bremsstrahlung radiation power. The range of *S* accessible in MST was from 7×10^4 to 10^6, extending previous measurements beyond $S \approx 10^4$.

Magnetic fluctuations in MST were measured by a set of 64 toroidally separated magnetic pickup coils located on the inner surface of the MST vacuum conducting shell. These toroidal coils can resolve toroidal modes with n ≤ 32. The total rms fluctuation was determined by adding the power in all resolved modes. The rms fluctuation (averaged over 5 ms) is shown versus *S* in Fig. 1 for (a) low I/N and (b) high I/N. We find that (1) the amplitude of magnetic fluctuations is high, about 1 %, (2) the scaling is weak, and (3) the scaling depends on density;

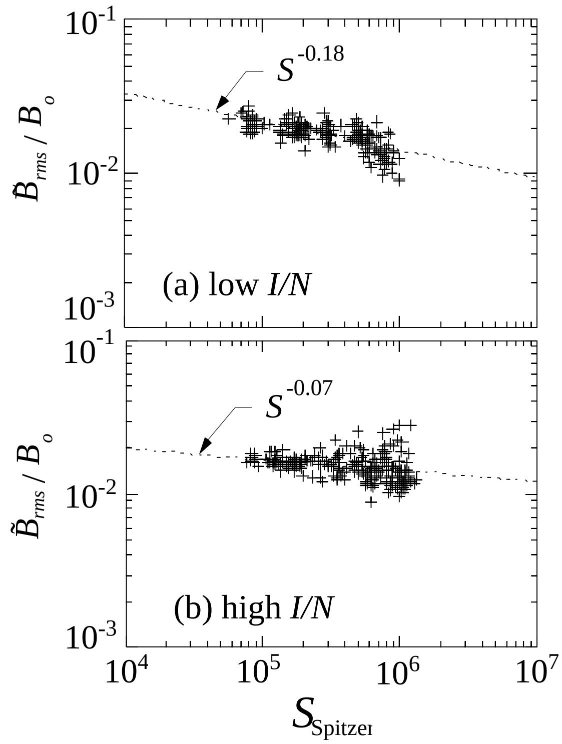

FIG. 1. The scaling of the rms magnetic fluctuations with the Lundquist number

therefore S might not be a unique scaling parameter, and perhaps other parameters, such as viscosity, might be important. Recent nonlinear 3D cylindrical MHD calculations [10, 11] have found that that fluctuation amplitude scales as $S^{-0.18}$ ($2.5\times 10^3 < S < 4\times 10^4$). Theoretical analysis by Mattor [12] gives the scaling $S^{-0.25}$ or S^0 depending on the continuous or discrete nature of the RFP dynamo fluctuations. Both continuous and discrete dynamo were observed in MST.

The velocity fluctuations were measured via Doppler shift of C^{+4} line radiation with a fast, high throughput spectrometer [8, 13, 14, 15]. Fluctuations of velocity with an amplitude, of several km/s were measured and correlated with magnetic fluctuations. The frequency spectra of

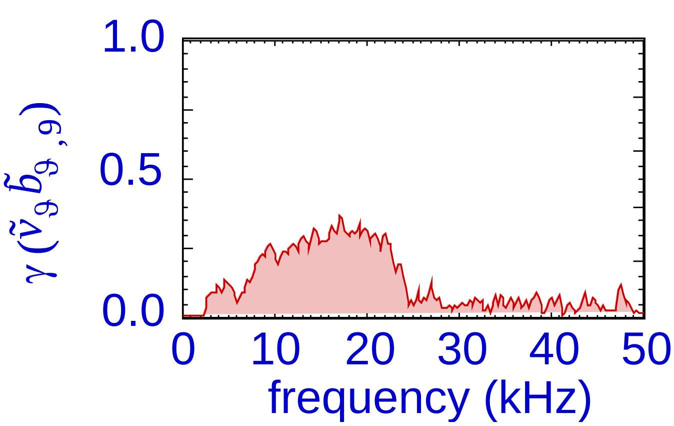

FIG. 2. Coherence of fluctuating velocity and magnetic field.

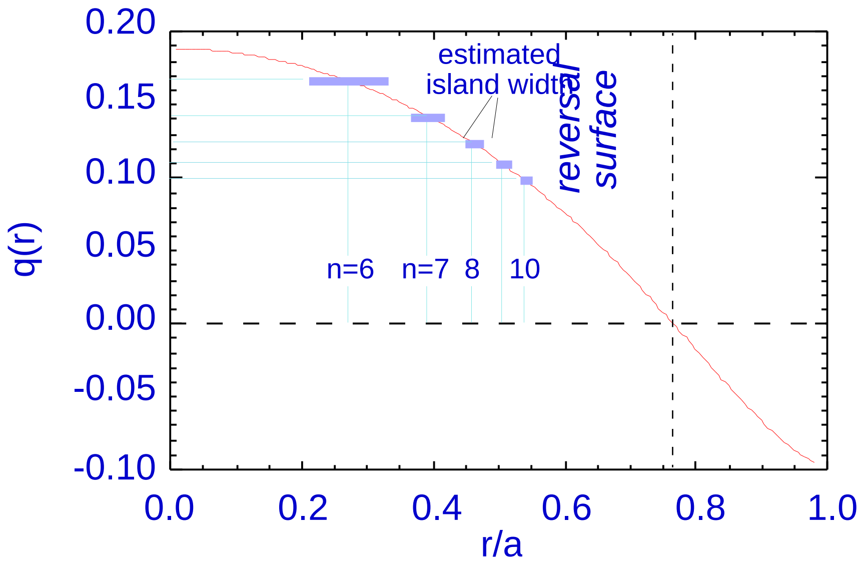

FIG. 3. Estimated magnetic island widths and q-profile during PPCD. The fluctuation decrease so islands do not overlap.

the coherence between the fluctuating poloidal velocity v_ϑ and the n = 9 component of the surface poloidal magnetic field $B_{\vartheta,9}$ is shown in Fig. 2. A high coherence in the 4-30 kHz range contributes to a significant dynamo product $[\tilde{\mathbf{v}} \times \tilde{\mathbf{B}}]$ which can be as high as 15 V/m.

The scaling of the velocity fluctuations is weak, with different velocity components scaling as $\tilde{v}_\varphi \propto S^{-0.19}$, and $\tilde{v}_\vartheta \propto S^{-0.08}$ [8]. Somewhat suprisingly, the dynamo product scaling is strong $S^{-[0.64 \cdots 0.88]}$. The strong scaling comes from decreased coherence between $\tilde{v}$ and $\tilde{B}$ at higher *S*.

3. CURRENT PROFILE CONTROL

A weak scaling of fluctuations with *S* implies that active control of fluctuations is necessary. MHD simulations [11] suggest that flattening of the parallel current profile can decreases the magnetic fluctuation amplitude. In MST two types of current profile modification were tested – inductive and electrostatic.

Inductive poloidal current drive (also called pulsed poloidal current drive, or PPCD)is accomplished by transiently changing the toroidal flux. This leads to a halving of the magnetic fluctuation amplitude and five-fold increase in the energy confinement time, with both an increase in the plasma thermal energy (beta) and a decrease in the Ohmic input power – Ref. [5, 6]. As an illustration of progress toward mitigating stochastic magnetic transport in the RFP, the estimated safety factor profile and magnetic island widths associated with the core-resonant *m*=1 tearing modes are shown in Fig. 3 during PPCD in MST. In a standard RFP, the islands are well overlapped throughout the core region. During PPCD, the island widths (Fig. 3) are reduced to levels such that island overlap no longer occurs, consistent with a large reduction in thermal transport. Recent measurements in the RFX experiment [16, 17] reveal that the

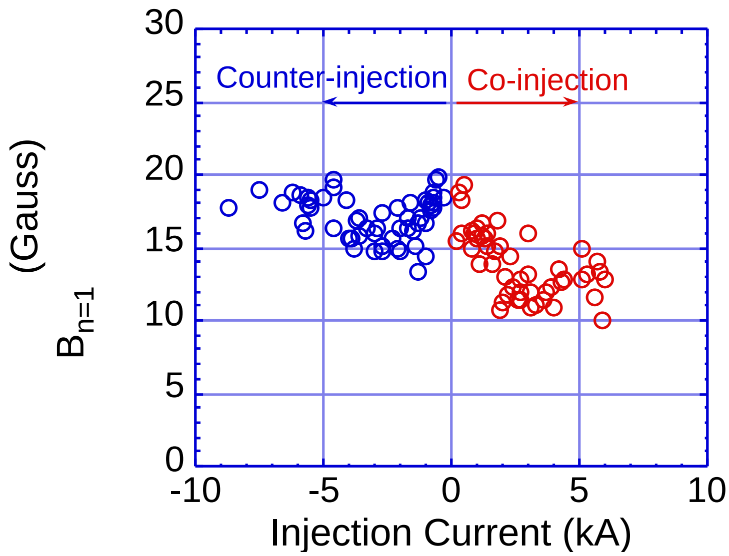

FIG. 4. Magnetic n=1 fluctuation decreases during electrostatic current injection in the sense to flatten the current profile.

normally flat electron temperature profile becomes peaked during PPCD, providing additional evidence for core magnetic fluctuation reduction.

For electrostatic current drive we used novel plasma electron emitters [18] to inject field aligned electron current at the plasma edge. The injection can be oriented either in the sense to flatten the current profile – co-injection, or in the opposite direction – counter-injection. The core resonant m=1, n=6 magnetic fluctuations were not sensitive to the direction of the injection, which might be explained by the edge localization of the injected current. On the other hand, the edge resonant m=0, n=1 modes were sensitive to the orientation of injected current and decreased in amplitude when the injected current flattened the current profile [19] – Fig. 4. The Ohmic power was lower and the electron temperature higher during co-injection which indicates the positive effect of the current injection on the energy confinement – Table I.

TABLE I. ENERGY CONFINEMENT IS BETTER FOR CO-INJECTION THAN FOR COUNTER-INJECTION.

	T_e (eV)	n_e (10^{19} m^{-3})	β (%)	P_{ohmic} (MW)	τ_E (ms)
CO	181	1.5	9.2	5.61	1.47
CTR	91	1.4	4.5	7.23	0.52

4. PLASMA FLOW RELATED CONFINEMENT IMPROVEMENT

In addition to the regimes a with modified current profile, other regimes with improved confinement have been found. The improvement occurs even though the current profile modification was not specifically targeted. A common feature of these regimes is a significant change in the edge plasma flow profile.

One of these regimes, the so-called Enhanced Confinement (EC) regime occurs spontaneously, at a low plasma density, with deep magnetic field reversal, and clean walls [20, 21]. The regime is characterized by broadband reduction of both global magnetic and edge electrostatic fluctuations and up to three-fold confinement improvement –Fig. 5. The plasma potential profile is shown in the same figure and implies a narrow, ~1 cm wide region of strongly

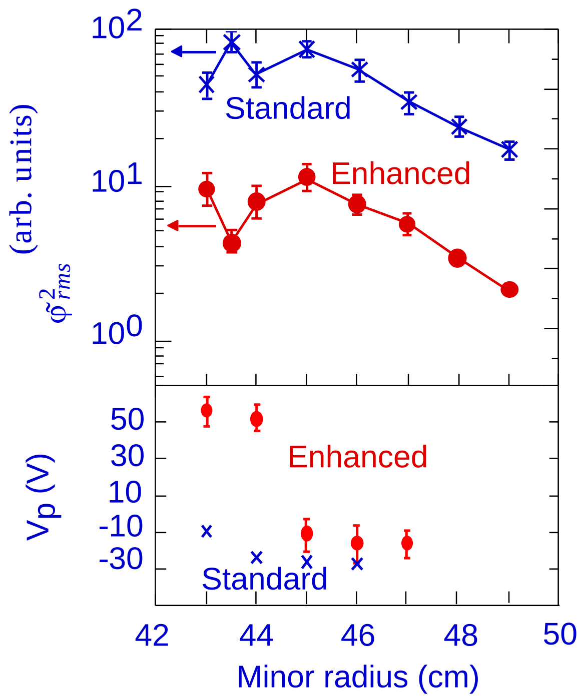

FIG. 5. Radial profiles of fluctuating and equilibrium plasma potential. Strong E_r gradient is formed ,and fluctuations are reduced.

sheared $[\mathbf{E}\times\mathbf{B}]$ flow in the edge. However, the fluctuation reductions are not limited to this shear layer and occur for both small and large scale turbulence at all frequencies. Similar regimes were found in the TPE-1RM20 device [22]. We note that flow shear is observed in PPCD discharges as well [21, 23] but its contribution to the confinement improvement is unknown. Confinement improvement associated with velocity shear is also observed in the RFX device [24].

Confinement improvement also occurs in plasmas with inserted biased electrodes [25]. In these plasmas edge electrostatic potential fluctuations also decrease, and the particle confinement improves, evidenced by an increase in density and the edge density gradient – Fig. 6. Electrostatic fluctuations are known to cause large particle transport in the RFP edge [26]. Magnetic fluctuations and energy confinement do not change with bias, consistent with the understanding that magnetic fluctuations regulate energy confinement in the RFP. The edge radial electric field increases and a large change in the plasma flow (~25 km/s) occurs with biasing. The change in velocity shear is small compared to the overall change in the magnitude of the flow velocity across the profile.

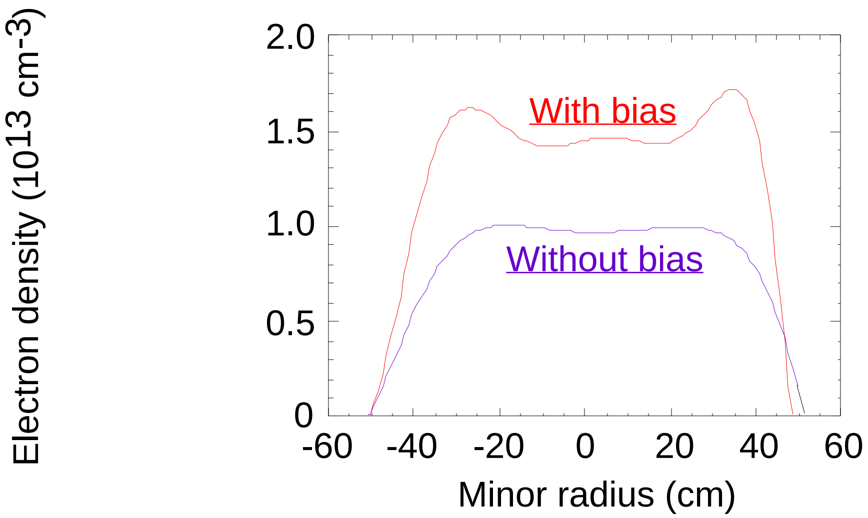

FIG. 6. Density profile in biased plasmas.

These observations suggest that flow and flow shear may be effective for the reduction of turbulent transport in the RFP [27]. This subject has emerged only recently and requires further experimental, and especially theoretical, work. Shearless plasma flow itself needs to be explored, since, for example, it can affect the rotation of edge resonant fluctuations which might otherwise be stationary in the lab frame.

5. SUMMARY AND CONCLUSIONS

In summary, the scaling of magnetic and ion velocity fluctuations with Lundquist number $S \leq 10^6$ has been measured in MST. Unlike smaller RFP plasmas with $S \leq 10^4$, magnetic fluctuations decrease more slowly than the most favorable $\tilde{b}/B \propto S^{-1/2}$. The ion velocity fluctuations, measured for the first time in MST, also scale relatively weakly. However, the MHD dynamo scales strongly with *S*, in accordance with expectations from Ohm's law. This appears to result from decreased coherence between the magnetic and velocity fluctuations with increasing *S*. A weak scaling of the transport causing magnetic fluctuations with *S* (increasing plasma size, magnetic field, and temperature) implies active turbulence suppression may be required to improve the RFP's reactor attractiveness. Auxiliary edge poloidal current drive, using inductive and electrostatic current drive techniques, produces a significant reduction of the fluctuation amplitude and a dramatic increase in the energy confinement. So far, inductive current drive is more effective than electrostatic current injection. Experimental tests of RF current drive with promise for greater current profile control are in preparation. Confinement improvement associated with changes in the plasma flow are also observed. This occurs either with electrode biasing or spontaneously (in some MST plasmas). Mechanisms of flow shear turbulence suppression are suggested by observed changes in the flow magnitude (biasing) and by the formation of a localized region of strong flow shear (spontaneously).

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