# Enhanced Confinement with Plasma Biasing in the MST Reversed Field Pinch

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We report an increase in particle confinement with plasma biasing in a reversed field pinch. Miniature plasma sources are used as electrodes to negatively bias the plasma at the edge ($r/a \sim 0.9$). Particle content increases and $H_\alpha$ radiation decreases upon application of bias and global particle confinement roughly doubles as a result. Energy confinement is not significantly affected by biasing the edge. Measurements of plasma potential, impurity flow, and floating potential fluctuations indicate that strong flows are produced and that electrostatic fluctuations are reduced. [S0031-9007(97)04042-8]

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It has been well established that a sheared radial electric field can reduce the anomalous transport produced by electric field fluctuations in magnetically confined plasmas [1–3]. Such effects, associated with the shear in $E \times B$ plasma flow, occur in numerous configurations including tokamaks [4], stellarators [5], and magnetic mirrors [6]. In most cases, the turbulence and transport is believed to be dominated by small-scale electrostatic fluctuations, which are thereby amenable to shear flow reduction. The electric field shear and confinement improvement (known as *H* mode) can occur spontaneously under certain plasma conditions [4] or can be induced with various edge perturbations including the insertion of biased electrodes into the plasma edge [7,8]. An understanding of these transitions to higher confinement is important to the development of nuclear fusion as an energy source and to our understanding of the physics of magnetically confined plasmas in general.

In the reversed field pinch (RFP), energy and particle transport in the core of the plasma is thought to be produced by large-scale magnetic fluctuations. However, magnetic fluctuations do not produce transport in the edge region, roughly the outer 15% of the minor radius [9]. In this region, electrostatic fluctuations have been measured previously to account for particle transport, but not energy transport [10]. The cause of anomalous energy transport in the edge of the RFP is not yet known and is an area of current research. Because particle confinement in the edge is controlled by electrostatic fluctuations, it is possible that generation of flow shear in the edge may reduce the transport of particles.

We report here the generation of electric field shear and improved particle confinement with the insertion of biased electrodes in the RFP plasma configuration. We find that global particle confinement roughly doubles as a result of negatively biasing the edge and that floating potential fluctuations are reduced. Energy confinement, however, is not affected by biasing—a result consistent with observations that energy transport is not controlled by electrostatic fluctuations.

Our experiments have been conducted in the Madison Symmetric Torus (MST). The MST [11] is a large reversed field pinch with a close fitting conducting shell. MST has a major radius $R = 1.5$ m, a minor radius $a = 0.52$ m, and for the experiments discussed here, was operated in a low current regime with plasma current $I_p \sim 220$ kA, electron density $n_e \sim 10^{19}/m^3$, electron temperature $T_e \sim 150$ eV, and reversal parameter $F = B_t(r = a)/\langle B_t \rangle \sim -0.2$.

Plasma biasing is achieved by emission of electron current from 4–8 miniature plasma sources (see Fig. 1) distributed toroidally and poloidally around the torus. Each source consists of a small discharge chamber in
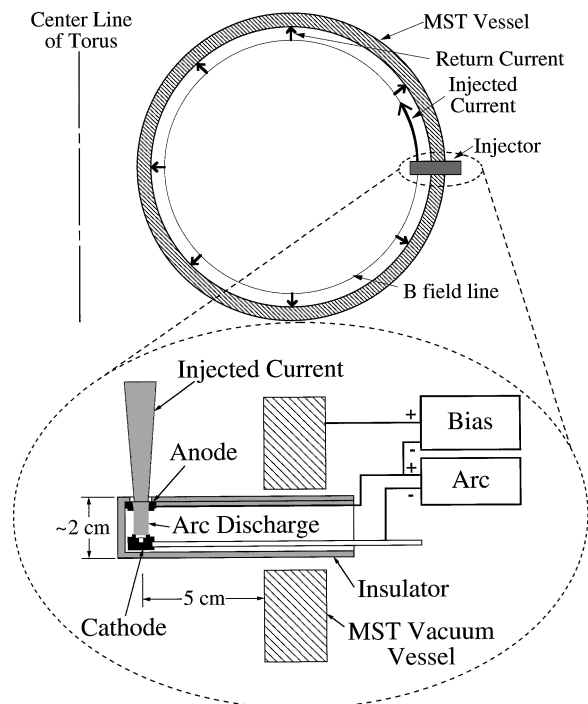


FIG. 1. Schematic drawing of electrodes used to bias the plasma. A small arc discharge is sustained by a pulse forming network and biased relative to the vacuum vessel.

which a hydrogen arc discharge is produced. The anode of the discharge chamber is biased relative to the MST vacuum vessel and up to 1 kA of electron current can be emitted from the arc plasma along the (dominantly poloidal) magnetic field at a distance of 5.0 cm from the vessel wall. All injected current returns to the wall through cross-field transport processes. Typically, a voltage of about $-300$ V is applied to each injector for a period of 10 ms. (For a more complete description of the injectors, see Ref. [12].)

The amount of field-aligned current generated by this set of injectors is small compared to the background current, and we find that changes in particle confinement are not affected by the orientation of the sources. For most of the data presented here, an even number of sources was employed with neighboring injectors oriented oppositely so that no net field-aligned current was injected.

We observe significant changes in the particle confinement during the 10 ms for which the sources are biased. The total radial current drawn to the sources is ~3 kA, as shown in Fig. 2(a). The line-averaged density increases by ~75% [Fig. 2(b)] while the line-averaged $H_\alpha$ radiation decreases by ~(20–30)% [Fig. 2(c)]. A global particle confinement time [Fig. 2(d)] is calculated from these data using $\tau_p = \bar{n}_e/(k\bar{H}_\alpha - d\bar{n}_e/dt)$ where $k$ is a constant determined by the density profile, the $H_\alpha$ emission profile, and a calculation of the number of ionizations per $H_\alpha$ photon. According to these data, global particle confinement roughly doubles as a result of biasing the edge.
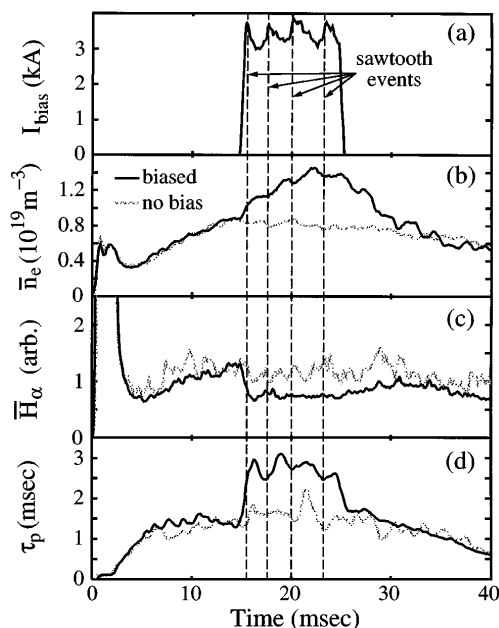


FIG. 2. (a) Radially driven current, (b) central cord line-averaged electron density, (c) central cord line-averaged $H_\alpha$ radiation, and (d) calculated particle confinement time are shown for cases in which bias is applied (solid line) and cases with arc discharges on, but no bias applied (broken line).

Confinement improvement comes from both increased density and decreased sourcing, as in H modes [4]. For comparison, data are shown for the case where the arc discharges of all injectors are still operated but the bias voltage is not applied. In this no-bias case the amount of fuel from the injectors is identical to the case with bias applied and yet no increase in confinement is observed. We conclude then that confinement improvement occurs as a result of biasing the plasma.

In previous tokamak experiments, it has been observed that the radial electrical conductivity of the plasma decreases upon entering the enhanced confinement regime [7,8]. We observe a similar correlation between radial conductivity and confinement. In the RFP, naturally occurring sawtooth oscillations [13] temporarily degrade confinement. During these events, the radial conductivity increases and more current can be drawn from the injectors at a given bias voltage. The 10 ms period during which the bias is applied spans about four of these sawtooth oscillations. Although the bias voltage remains constant, bursts can be seen in the wave form of the injected current [Fig. 2(a)] which coincide with the sawtooth events, and the particle confinement is considerably lower during these periods of higher radial conductivity [Fig. 2(d)].

One possible explanation for the improvement in particle confinement with edge biasing is that a strongly sheared toroidal flow is established which impedes fluctuation induced transport of particles to the wall [1,2]. Indeed, although causality has not yet been established, the data show that the edge electric field and toroidal flow are strongly affected and that floating potential fluctuations are reduced upon biasing the plasma.

We have measured the plasma potential with a fast swept Langmuir probe and, as expected, the radial electric field is increased in the plasma edge region with bias applied [Fig. 3(a)]. The measured profile also suggests an enhanced shear in the radial electric field in the vicinity of the injector location. These measurements imply that the toroidal flow due to the $E \times B$ drift is enhanced in the edge region and exhibits shear.

A crude measurement of the flow profile has been obtained by measuring the toroidal flow of two different impurity species with a passive Doppler duo-spectrometer [14]. Doppler-shifted emission from $C^{4+}$ ions in these plasmas is dominated by the flow of ions at $r/a <$ 0.4 while emission from $C^{2+}$ ions is from $r/a > 0.85$. During biasing, the flow of both species responds quickly (Fig. 4). The core decelerates from about 10–20 km/sec and becomes almost stationary in the lab frame. The edge flow becomes strongly reversed relative to the normal core flow and the difference between $C^{4+}$ and $C^{2+}$ flow suggests a steeper radial gradient in the toroidal velocity than exists during nonbiased discharges. The direction and magnitude of the $C^{2+}$ flow is consistent with the $E \times B$ drift velocity calculated from the measured plasma
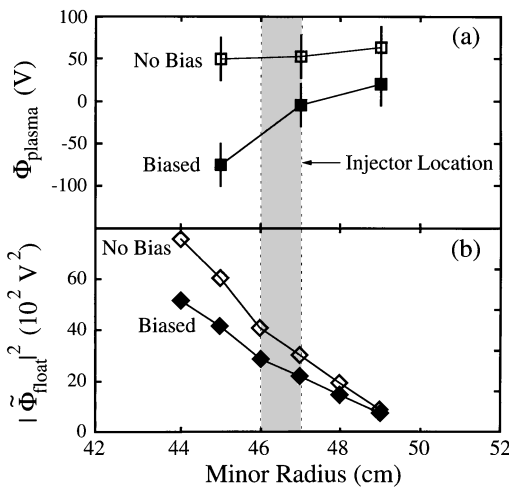
FIG. 3. (a) Measured plasma potential and (b) total floating potential fluctuation power at several edge radial locations for cases with (solid) and without (open) bias applied. Data reflect an ensemble over several shots with injectors positioned at about 47 cm.

potential profile and known poloidal magnetic field at the edge.

Although the impurity flow data are suggestive of strongly sheared flow, they may not necessarily reflect the properties of the bulk ions. However, independent measurements of bulk ion flow with a two sided ion collector confirm that the change in the edge flow is indeed large and in the same sense as the $C^{2+}$ flow. These results suggest that a more strongly sheared toroidal flow profile is present during plasma biasing.

Floating potential has also been measured in these discharges using an array of six floating tips at different
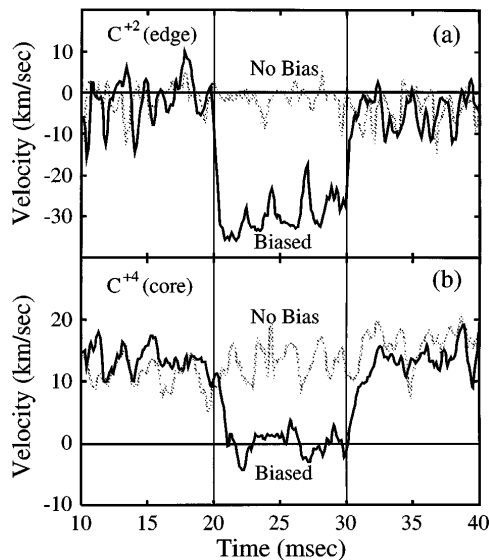


FIG. 4. (a) $C^{2+}$ (edge) toroidal flow velocity and (b) $C^{4+}$ (core) toroidal flow velocity for cases with (solid) and without (broken) bias applied.

radial locations. The equilibrium floating potential is consistent with the increase in radial electric field seen with the swept Langmuir probe, and additional information has been obtained regarding the electrostatic fluctuations. The total power in floating potential fluctuations decreases at all measured locations [Fig. 3(c)] with a time dependence as shown in Fig. 5. The decrease is larger at radial locations inside of the injector position (47 cm) and smaller at those outside—perhaps consistent with a more highly sheared toroidal flow inside the injector radius. For these data, an ensemble of ~20 shots was taken both with bias and without. The rms value of the floating potential was then computed at 0.5 msec intervals after removing average and trend from the measured signal. Further analysis shows [Fig. 6(a)] that a decrease in fluctuation amplitude occurs at all frequencies (and all spatial scales) but that the coherence between radially separated tips [Fig. 6(b)] is not influenced significantly by the biasing.

An important result of these experiments is that although particle confinement is strongly affected by plasma biasing, energy confinement is not. In previous tokamak biasing experiments, both energy and particle confinement were observed to increase, but the improvement in particle confinement was greater than the improvement in energy confinement [7,8]. For the tokamak, both energy and particle transport are believed to result from small-scale electrostatic fluctuations, and hence both can be modified with sheared flows. The relative impact of sheared flow on the two kinds of transport, however, can be different due to the different way in which the flow changes the phase of density and temperature fluctuations [15].

In the RFP, the physics may be different, although the result is similar. Electrostatic fluctuations drive particle transport in the edge, and hence sheared flows in the edge may enhance particle confinement. Electrostatic fluctuations do not appear to drive energy transport in the RFP, and hence sheared flows are not expected to have any direct effect on energy confinement. In MST, global magnetic fluctuations (which do not change significantly with biasing) dominate the particle and energy transport in
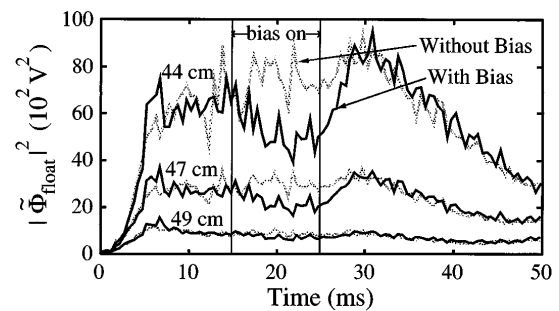


FIG. 5. Measured floating potential fluctuation power vs time ensembled over many shots at $r = 44$ cm, 47 cm, and 49 cm for cases with (solid) and without (broken) bias applied. Injectors were located at $r = 47$ cm.
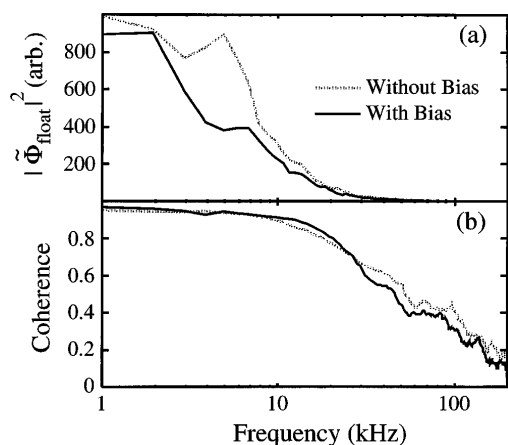
FIG. 6. (a) Measured power spectra of floating potential fluctuations at $r = 44$ cm and (b) cross coherence between two radially separated floating tips at $r = 44$ cm and $r = 48$ cm for ensembles of shots with (solid) and without (broken) bias applied.

the core, and it is not yet known theoretically what effect flow shear should have on large-scale fluctuations.

Recently, spontaneous enhanced confinement discharges have been observed in MST in which both particle and energy confinement improve and the improvement is accompanied by a strongly sheared edge radial electric field [16]. In these cases the global magnetic fluctuations are reduced in addition to the edge floating potential fluctuations. In order to have an effect on the magnetic fluctuations, the injectors used for plasma biasing will be duplicated and aligned so as to change the edge current profile. It is hoped that both energy and particle confinement will be enhanced as a result.

In summary, we report, for the first time in a RFP, enhanced particle confinement upon negatively biasing the plasma. This improvement comes from both a reduction in particle source rate and an increase in stored particle content. Probe measurements indicate that plasma and floating potentials are affected in a manner consistent with negative plasma biasing, and impurity ion spectroscopy suggests an enhanced radial shear in the toroidal flow. Measurements of electrostatic fluctuations indicate floating potential fluctuations are reduced, consistent with the confinement improvement being due to a decrease in electrostatic fluctuation induced particle transport. Future experiments will attempt to more thoroughly measure edge parameters in order to quantify the changes in flow and in the fluctuation-induced transport.

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