Control of magnetic fluctuations in the reversed field pinch with edge current drive

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The generation of auxiliary current in the extreme edge of the reversed field pinch is shown to affect edge and core resonant magnetic fluctuations, the recurrence time of relaxation oscillations (sawteeth), and the energy and particle confinement. Current is driven in the edge by electrostatic current sources. Although the injected current is expected to primarily affect edge resonant fluctuations, the coupling of edge and core modes enables changes in the extreme edge to have global consequences. [DOI: 10.1063/1.1365103]

Magnetic fields in laboratory and natural plasmas often fluctuate in space and time, in some cases causing magnetic-field lines to wander stochastically. Transport of particles and energy within a plasma can be greatly enhanced in the presence of such magnetic field fluctuations. In the reversed field pinch (RFP), magnetic fluctuations are observed to transport particles and energy perpendicular to the mean magnetic field, presumably a result of magnetic field stochasticity.[1,2] The magnetic fluctuation spectrum is a result mainly of two effects: Exchange of energy between fluctuations and the mean fields and exchange of energy between different spatial Fourier components (nonlinear mode coupling).[3,4] A key goal of RFP research is to control the magnetic fluctuations both to probe their role and to minimize their deleterious effect on confinement.

Past efforts to reduce fluctuations have targeted modes resonant in the plasma core (inner 75% of the plasma); i.e., the wave vector parallel to the mean magnetic field vanishes in the core. Such kink-tearing modes have poloidal mode number $m=1$ and are driven unstable by gradients in the normalized current density, $\nabla(\mathbf{J}\cdot\mathbf{B}/B^2)$. The development of means to control the current density profile is thus a critical issue for the RFP as a fusion energy concept. Previous experiments aimed to force the current density profile closer to one which is linearly stable by programming the inductive electric field. These experiments have halved the $m=1$ magnetic fluctuations and substantially improved energy confinement.[5–7]

Also key to the fluctuation dynamics are the $m=0$ components, which are resonant in the edge of the RFP (outer 25% of the plasma) where the mean toroidal magnetic field passes through zero. These modes may be driven by nonlinear mode coupling, current gradients, or pressure gradients and can directly affect transport in the vicinity of their resonance. They also mediate the nonlinear coupling of two $m=1$ modes, and thereby also influence the behavior of the $m=1$ modes.

In this Letter we describe control of the $m=0$ modes by electrostatic injection of current from miniature sources into the extreme edge of the plasma (outer 10%). We report two main results of the added current. First, magnetic fluctuation amplitudes decrease (increase) if the current is injected in the direction parallel (anti-parallel) to the pre-existing current. Furthermore, the change is greater for $m=0$ modes than for $m=1$ modes. This is consistent with the idea that increasing (decreasing) the current in the extreme edge decreases (increases) the linear drive for the $m=0$ modes. Second, the period of the sawtooth oscillations in the magnetic fluctuations (and other plasma quantities) changes with the addition of auxiliary edge current. Reduction of the $m=0$ amplitude thereby affects $m=1$ modes indirectly either through nonlinear coupling or quasilinear effects on the mean profiles. This is confirmed by removing the $m=0$ modes experimentally (by operating without field reversal) and observing that the effect of current injection on $m=1$ modes disappears. We also report a dependence of equilibrium parameters on the direction of current drive, consistent with modest confinement differences. These studies reveal that driving current in the extreme edge plasma can alter the plasma behavior globally. Hence controlling the current profile near the plasma boundary may be an important component of any effort to reduce magnetic turbulence in the RFP. We note that the current drive used here differs markedly from the inductive technique used previously[5–7] in that it is highly localized (extreme edge vs diffuse outer region), targets different modes ($m=0$ rather than $m=1$), and is stationary in time.

Experiments were conducted in the Madison Symmetric Torus (MST) reversed field pinch[8] (major radius$=$1.5 m, minor radius$=$0.52 m). Edge current drive is accomplished with 16 miniature plasma sources,[9] biased negatively to emit electron current (see Fig. 1). The sources are inserted radially through 1.5-inch diameter portholes to inject current along the dominantly poloidal edge magnetic field. Each source houses a miniature arc discharge in hydrogen which produces a dense ($\sim 10^{14}$ cm^{-3}), low temperature ($\sim$15 eV) plasma. When the source anode is biased relative to the MST vessel, a highly directional electron current is driven along the magnetic field.

Figure 2 shows the plasma current for a typical shot along with the bias voltage (-300 V) and current (500 A)

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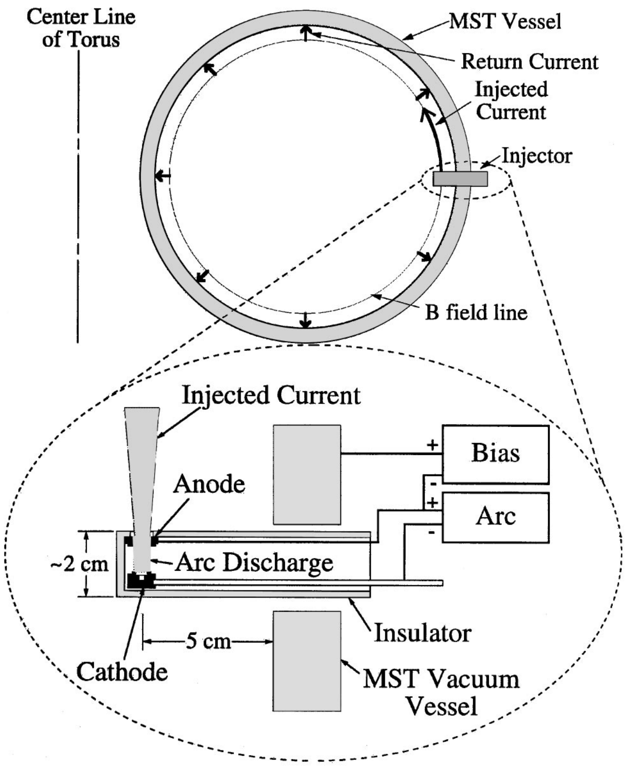

FIG. 1. Current injection setup showing 1 of 16 current injectors inserted in the MST plasma edge.

from a single gun. Auxiliary current is driven for 10 ms during the flattop portion of the toroidal plasma current. The current density 25 cm downstream of the injector is 125 A/cm^2, as measured by an insertable Rogowski probe [Fig. 2(d)]. The inset in Fig. 2(d) shows the measured radial profile fit by a Gaussian with radial half width of about 1 cm. The integrated profile [two-dimensional (2D) Gaussian]

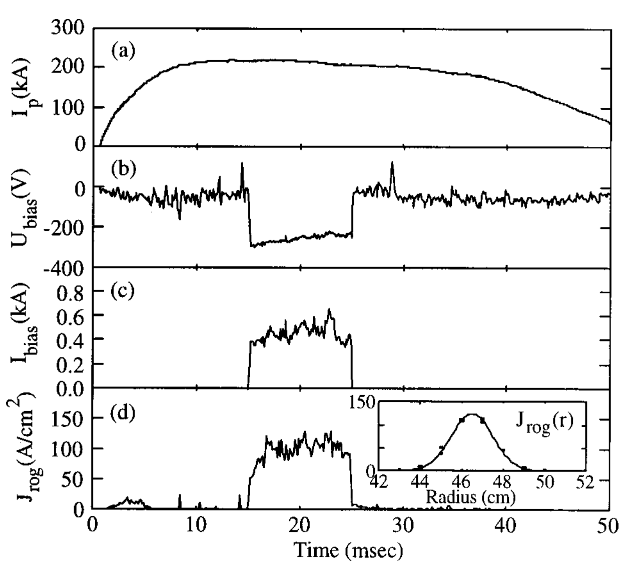

FIG. 2. Time evolution of (a) toroidal plasma current, (b) injector anode potential, (c) current emitted from one injector, and (d) current density measured with insertable Rogowski probe 25 cm downstream of an injector. Inset shows radial profile of injected current.

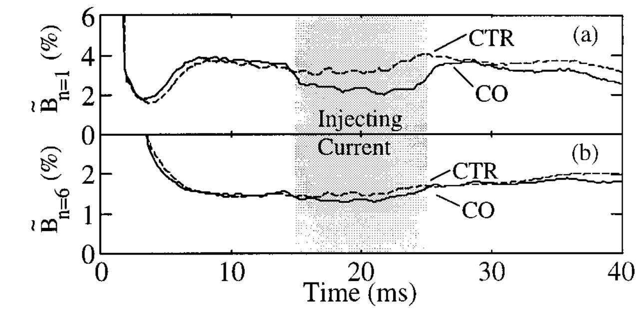

FIG. 3. Time evolution of the total (a) $n=1$ ($m=0$) and (b) $n=6$ ($m=1$) magnetic-field fluctuation amplitudes at the plasma boundary in co- (solid) and counter-injection (dashed) discharges. Each curve is the smoothed average of more than 50 shots.

gives a total current very close to the measured injected current of 500 A.

A set of 16 sources is used both to increase the total driven current and to approximate axisymmetry. Current is injected for $r/a>0.87$ (for reference, the reversal surface is typically at $r_{q=0}/a\approx 0.85$) and each source can be rotated either to add or subtract from the background current density, referred to as co- or counter-injection. The total poloidal current thus produced is the product of the number of sources (16), the current injected per source ($\sim$500 A), and the number of poloidal transits the injected current makes before being dissipated. The number of poloidal transits is at least three (measured with insertable Rogowski probes) and at most 10 (estimated classical Coulomb scattering limit). Hence the total poloidal current driven in these experiments could be as large as 80 kA, localized to the extreme edge region ($r/a\sim 0.9$). The toroidally averaged poloidal current density driven by the injectors is similar in magnitude to the background current density at $r/a=0.9$. However, because of the limited radial extent, the total poloidal current driven is small relative to the total poloidal current in the plasma (1.5 MA).

The current sources are a significant fuel source since the plasma from each miniature discharge flows into the MST discharge along with the injected current. The injectors also bias the edge negatively leading to strong flows.[10] To isolate the effect of current profile changes from other influences, similar discharges with co-injection and counter-injection are contrasted. The effects of fueling and biasing are the same in these two cases.

A toroidal array of magnetic pickup coils at the plasma surface monitors magnetic perturbations. The array contains 32 poloidal and 32 toroidal field coils allowing spatial Fourier decomposition into toroidal mode numbers $n=0-15$. Here, we present the total $\tilde{B}$ amplitude for the $n=1$ and $n=6$ modes which are known from other measurements to be dominantly $m=0$ and $m=1$, respectively.

In Fig. 3 we show the average time evolution of the (0,1) and (1,6) magnetic fluctuation amplitudes in co- and counter-injection discharges (averages of more than 50 shots). We observe that both edge resonant and core resonant modes are lower with co- than with counter-injection but that the difference is greater for the edge resonant $m=0$ modes. This is

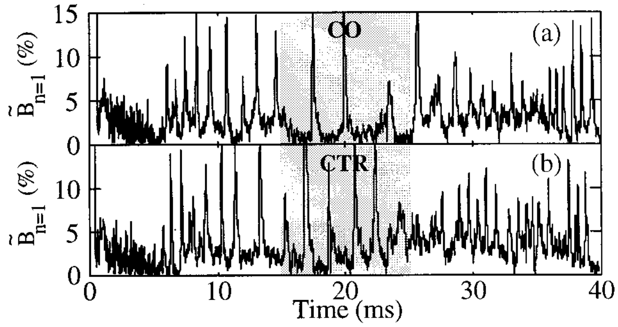

FIG. 4. Time evolution of the total $n=1$ ($m=0$) magnetic-field fluctuation amplitude at the plasma boundary in typical (a) co-injection and (b) counter-injection discharges.

as expected from theory and computation. Co-injection flattens the parallel current profile, making modes more stable (or less unstable) and counter-injection has the opposite effect. Since the $m=0$ resonant surface is closer to where the current is driven, one expects $m=0$ modes to be more strongly affected.

Figure 4 shows the time evolution of the (0,1) mode in a co- and a counter-injection discharge. We see that a large part of the difference in average mode amplitude between co- and counter-injection arises from a change in the time between large fluctuation bursts. These bursts coincide with sawtooth crashes, also referred to as discrete dynamo events.[3] For co-injection shots, the average sawtooth period is about 2.4 ms, whereas for counter-injection the period is 1.3 ms. Discharges with half of the injectors in the co-direction and half in the counter-direction have also been performed and the behavior of the magnetic fluctuations and sawtooth oscillations is intermediate between those with all injectors in the co- or counter-directions.

The sawtooth cycle in the RFP is a relaxation oscillation.[3,4] Between crashes, the current profile peaks, driving the core-resonant $m=1$ modes. At the sawtooth crash, the fluctuations rapidly flatten the current profile and mode amplitudes decrease. The role of $m=0$ modes in the sawtooth cycle is poorly understood in experiment. These modes allow nonlinear interactions between pairs of $m=1$ modes and in nonlinear magnetohydrodynamic (MHD) computation, this coupling plays a key role in determining the mode spectrum and in regulating relaxation oscillations.[4]

We hypothesize that co-injection acts to damp $m=0$ modes and counter-injection acts to drive them. The difference in $m=0$ evolution alters the sawtooth cycle time, apparent in all modes including those which are core resonant. This view is supported by the results described above, and several others. First, the injected currents only affect core-resonant modes and the sawtooth cycle in discharges with $m=0$ modes present. We experimentally remove $m=0$ modes by operating without toroidal field reversal. Figure 5 shows the evolution of the (1,6) mode amplitude with co- and counter-injection in both reversed and nonreversed discharges. In the first two discharges [Fig. 5(a) and 5(b)], the edge toroidal field is reversed, allowing $m=0$ to be resonant inside the plasma and the (1,6) amplitude is affected as described earlier. In the second set of discharges [Fig. 5(c) and 5(d)], the toroidal field at the edge is not reversed, $m=0$ activity is minimal and no significant changes in core mode amplitudes or sawtooth oscillations are observed. (Any minor differences between the two wave forms shown in Figs. 5(c) and 5(d) are not systematic.) Empirically, the greater the plasma volume with reversed toroidal field, the larger the mean $m=0$ amplitudes and the larger the effect of the injected current. Second, it was recently shown experimentally that in the vicinity of the injected current, the MHD dynamo is due to $m=0$ modes, not $m=1$ modes.[11] This suggests that the injected currents should act primarily on $m=0$ modes.

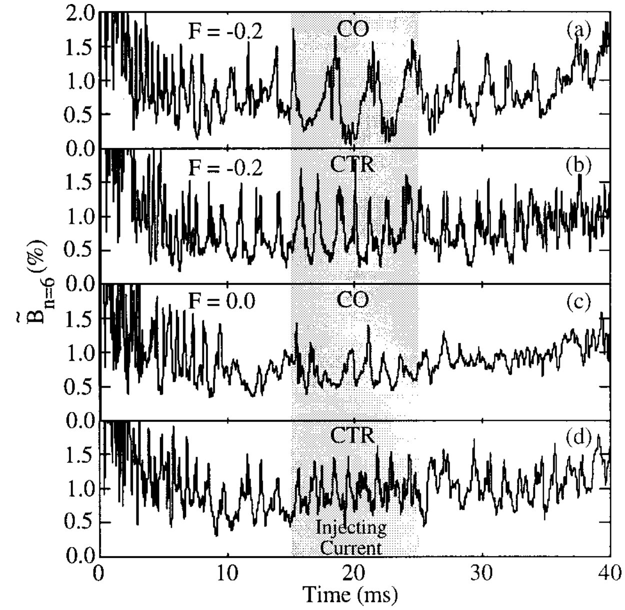

FIG. 5. Time evolution of the total $n=6$ ($m=1$) magnetic-field fluctuation amplitude at the plasma boundary in a typical reversed ($F=-0.2$) discharge with (a) co- and (b) counter-injection and in a typical non-reversed ($F=0$) discharge with (c) co- and (d) counter-injection.

Since time-averaged mode amplitudes are lower with co-injection, one expects better confinement and this appears to be the case. Each sawtooth crash temporarily degrades confinement. Hence the longer sawtooth period with co-injection yields higher time-averaged confinement. In addition, plasma parameters between sawtooth crashes differ in the two cases. On average, the density increase during co-injection is greater than with counter-injection as seen in Fig. 6(a). (A

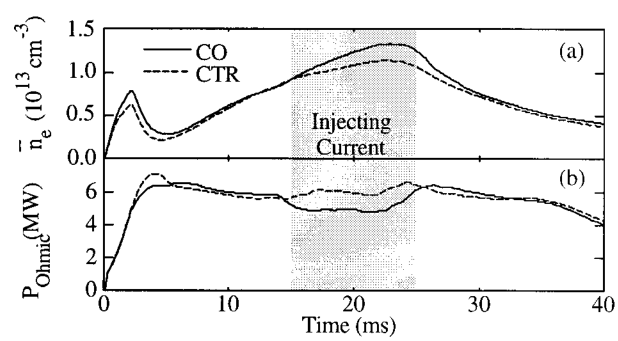

FIG. 6. Time evolution of (a) line-averaged density and (b) calculated Ohmic input power in co- (solid) and counter-injection (dashed) discharges. Each curve is an average of more than 50 shots.

substantial increase is seen in both cases due to plasma biasing, discussed previously.[10]) Thomson scattering measurements of core electron temperature indicate that for large ensembles of shots, co-injection discharges are about 10% hotter than counter-injection discharges between sawtooth crashes. These measurements suggest that the particle content and stored thermal energy are larger with co-injection than with counter-injection.

Central line-averaged H_α radiation measurements are very similar for co- and counter-injection, indicating similar particle source rates. The energy source rate is different in the two cases. Figure 6(b) shows the average time evolution of the Ohmic input power, P_{Ohmic}, calculated by subtracting the time derivative of the stored magnetic energy from the total Poynting flux through the plasma surface. An equilibrium model is used to compute the stored magnetic energy.[12] Co-injection discharges consistently have lower P_{Ohmic} than counter-injection discharges [Fig. 6(b)]. (The injectors themselves inject 2.4 MW into the plasma edge but this is the same for co- and counter-injection.)

Exact determination of particle and energy confinement times depends upon profile information not yet available. However, the above measurements suggest a dependence on the direction of injected current with co-injection yielding better confinement. This clearly indicates that confinement is sensitive to the current profile in the extreme edge (presumably due to the impact on magnetic fluctuations). However, as a means for improving confinement, the electrostatic technique has not been very successful since insertion of the injectors degrades confinement substantially (by ~50%). Co-injection restores much of the lost confinement but does not produce a net gain over discharges with no injectors inserted.

In summary, we have modified the current density profile in the edge of a large RFP plasma with a set of electrostatic current sources. We find that time-averaged mode amplitudes depend on the direction of current injection; injection in the same direction as the pre-existing edge current leads to smaller fluctuation levels. Much of the difference in time-averaged amplitudes comes as a result of changes in the sawtooth cycle time; co-injection yields a longer sawtooth period. We surmise that the injected current acts to damp or drive $m=0$ modes (depending on the direction), affecting the sawtooth cycle and core modes indirectly. This idea is confirmed by the observation that the injected current has no effect on magnetic fluctuations in discharges without $m=0$ modes. We also find that equilibrium parameters are sensitive to the direction of auxiliary current. The differences indicate modest changes in confinement but require improved profile measurements for certainty. It is clear from these experiments that the global relaxation process in the RFP is very sensitive to the details of the edge current profile. Our results suggest that efforts to control magnetic turbulence in the RFP should aim to control profiles throughout the plasma cross-section for a simultaneous reduction of $m=0$ and $m=1$ mode activity.

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