MHD Simulations of DC Helicity Injection for Current Drive in Tokamaks

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ABSTRACT

MHD computations of DC helicity injection in tokamak-like configurations show current drive with no 'loop voltage' in a resistive, pressureless plasma. The self-consistently generated current profiles are unstable to resistive modes that partially relax the profile through the MHD dynamo mechanism. The current driven by the fluctuations leads to closed contours of average poloidal flux. However, the 1% fluctuation level is large enough to produce a region of stochastic magnetic field. A limited Lundquist number (S) scan from 2.5×10^3 to 4×10^4 indicates that both the fluctuation level and relaxation increase with S .

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I. INTRODUCTION

An innovative approach to the problem of steady-state current drive for tokamaks is DC helicity injection.¹ The basic concept is to intercept a fraction of the magnetic flux with electrodes and place a potential along the open field lines. Current is driven directly along the intercepted lines, and a desirable current distribution results from magnetic fluctuations, which serve to reduce current density gradients. Indeed, the Taylor hypothesis² is often used as a justification for expectations of complete relaxation, where the J/B ratio is constant throughout the plasma. In this paper, we present results of 3D nonlinear resistive magnetohydrodynamic (MHD) simulations for this concept. To our knowledge these are the first published solutions of basic equations that show current drive via DC helicity injection for tokamak configurations.

[Simulations of DC injection in reversed field pinches for the purpose of profile control and stabilization have been reported.³]

Experimentally, DC helicity injection has been explored on CDX,^{4,5} CCT⁵ and HIT.⁶ The CDX [and CCT] configuration uses a toroidally local cathode that is mounted near the surface of the chamber. The cathode emits an electron beam in one toroidal direction, and a vertical magnetic field deflects the beam towards the center of the chamber. Probe measurements indicate that the current is peaked within a poloidal cross-section of 3 cm minor radius.⁴ The discharge is adjacent to the cathode and does not occupy the entire 10 cm minor radius chamber. In HIT a magnetized, coaxial plasma gun is used as a source of plasma and for toroidally symmetric helicity injection. Profile information—reconstructed from surface probe data by an equilibrium code—indicates substantial relaxation.⁶ The discharge fills the chamber and generates closed poloidal flux contours.

MHD computation allows the investigation of the current drive and relaxation

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from first principles. A 3D code is used to self-consistently evolve the current profile as helicity injection is applied with boundary conditions on $\mathbf{E}$ and $\mathbf{B}$. The simulations produce hollow current profiles that are unstable to resistive current-gradient-driven modes. The fluctuations grow until they have an amplitude on the order of 1% of the mean field. An inward power transport results and subsequently flattens the current gradient enough to cause saturation. The current driven by the fluctuations generates closed poloidal flux contours, producing 20-50% amplification of the initial open poloidal flux. However, magnetic field line puncture plots show that the field is stochastic in the region of relaxation. Therefore, the closed contours do not represent closed flux surfaces. A Lundquist number (S) scaling indicates that the fluctuation level increases with S , so the situation may not improve going towards reactor-grade plasmas.

This paper is organized as follows: A brief description of the code is presented in Section II along with a discussion of the geometry and the boundary conditions used to simulate the injection. General results illustrating the current drive and relaxation are presented in Section III, and the S -scaling is presented in Section IV. Section V contains a discussion of the results and their implications.

II. NUMERICAL MODEL

The DC helicity injection is modeled with the zero-beta version of the DEBS MHD code that solves initial value problems in the geometry of a straight periodic cylinder.⁷ This code has been used extensively for reversed field pinch simulations, but various versions have also been applied to astrophysics and solar physics phenomena. The coupled partial differential equations in MKS units are

$$\frac{\partial \mathbf{A}}{\partial t} = -\mathbf{E} = \mathbf{V} \times \mathbf{B} - \eta \mathbf{J} \quad (1)$$

$$\rho \frac{\partial \mathbf{V}}{\partial t} = -\rho \mathbf{V} \cdot \nabla \mathbf{V} + \mathbf{J} \times \mathbf{B} + \nu \nabla^2 \mathbf{V}, \quad (2)$$

where $\mathbf{B} = \nabla \times \mathbf{A}$. The equations allow compressible flow, but the density (ρ) is not evolved and is uniform throughout the domain. The resistivity (η) and viscosity (ν) are also uniform. The geometry makes Fourier representation appropriate in both the azimuthal (poloidal) and axial (toroidal) directions. Simulations for the S-dependence study in Section IV have $0 \leq m \leq 10$ azimuthal modes and $1 \leq l \leq 5$ axial modes resolved. This covers the dominant resonant modes and the important nonlinearly coupled modes. The comparisons in Section III are obtained with a reduced resolution of $0 \leq m \leq 5$ and $1 \leq l \leq 1$. This reduction has only a small impact and does not change the general character of the solutions. The number of cells needed in the radial direction depends on S; the maximum used here is 765 for the $S=4 \times 10^4$ case.

The boundary conditions at the outer wall of the cylinder are used to produce the helicity injection. Through the vector potential, $B_r(a)$ is specified to produce a vertical field, and $E_\theta(a)$ is specified to apply the electrostatic potential. The simple arrangement used for most of this study is illustrated in Figure 1 and is topologically similar to the HIT experiment. The fields that penetrate the plasma surface can be considered vacuum fields. They effect the helicity injection as the rate of change in helicity is

$$\frac{dK}{dt} = -2 \int \mathbf{E} \cdot \mathbf{B} dx + 2 \int \mathbf{E}_V \cdot \mathbf{B}_V dx, \quad (3)$$

where $K = \int \mathbf{A} \cdot \mathbf{B} d\mathbf{x} - \int \mathbf{A}_V \cdot \mathbf{B}_V d\mathbf{x}$ is a relative helicity, and the v-subscripted fields are the vacuum fields. The integrals extend only over the plasma volume, and the use of the vacuum fields maintains gauge independence when $\mathbf{B}(\mathbf{a}) \cdot \mathbf{n} \neq 0$, provided $\mathbf{B}_V(\mathbf{a}) \cdot \mathbf{n} = \mathbf{B}(\mathbf{a}) \cdot \mathbf{n}$ and $d(\mathbf{B}_V(\mathbf{a}) \cdot \mathbf{n})/dt = d(\mathbf{B}(\mathbf{a}) \cdot \mathbf{n})/dt$.⁸ For DC injection, the second term on the right side of Equation 3 reduces to $-2 \int \phi \mathbf{B} \cdot \mathbf{n} dS$ with ϕ being the applied electrostatic potential on the surface of the plasma.

The velocity at the boundary is specified to be the local $\mathbf{E} \times \mathbf{B}$ drift based on the applied electrostatic field and the local magnetic field. This avoids generating a poloidal surface current in response to the potential and is a reasonable approximation of experimental conditions. In HIT, for example, gas is ionized in the plasma gun and accelerated by a $\mathbf{J} \times \mathbf{B}$ force, so that the 'confinement' region, which is downstream of the gun, is subject to a flow of plasma.⁶ The problem domain in the simulations represents a 'confinement' region, and a gun region or surface layer is not modeled. In the limit of vanishing vertical field, applying the potential produces a drift across the chamber without inducing current.

III. RESULTS

The helicity injection simulations are initialized with a large uniform axial field, a vertical field, and small random perturbations in the vector potential. The electrostatic potential is initially zero, and its level is increased over the first 0.1 or $0.2\tau_r$, where $\tau_r = \mu_0 a^2 / \eta$ is the resistive diffusion time. The normal component of magnetic field at the surface is fixed for all time. In the weakly driven limit (at early times in the simulations), current enters the domain (on the top of the cylinder in Figure 1), follows the magnetic field lines, and leaves when it reaches the other side. The current density vectors are primarily axial, but there is no 'loop voltage' because the axial component of electric field from $\mathbf{V} \times \mathbf{B}$

cancels ηJ_z . During this weak phase, the ratio of axial current to injected current is largest and is controlled by the magnitude of the vertical magnetic field.

When the current drive is increased beyond the weak phase, the self-induced poloidal magnetic field become larger than the vertical field, and an unstable current profile develops. In the following subsections, we discuss the relaxation and flux amplification (Section III A), the vertical magnetic field and applied voltage magnitudes (Section III B), and some special cases that indicate the significance of other parameters (Section III C).

III A. Relaxation and Flux Amplification

In the strong phase of the current drive, the self-induced fields force the poloidal flux towards the exterior of the cylinder. This is clearly shown in frames (a)-(c) of Figure 2, a time sequence of poloidal flux contours from the $n=0$ Fourier components. The simulation has $S=5000$ and $R/a=6$, where R is the cylinder length divided by 2π . The distortion of the poloidal flux is accompanied by a distortion of the current path. The $\lambda=\mu_0 a \langle \mathbf{J} \rangle \cdot \langle \mathbf{B} \rangle / \langle B \rangle^2$ profile ($\langle \rangle$ denotes the $m=0, n=0$ Fourier mode) evolves from being flat when the current drive is weak to being hollow when the full potential is applied. The solid λ trace in Figure 3 shows the unrelaxed hollow state corresponding to the flux plot of Figure 2c. Resistive MHD modes are unstable at this point but have not grown to an appreciable level. The fluctuations saturate and relax the λ profile to the dashed trace in Figure 3, which produces the closed flux contours in Figure 2d. The relaxation of the λ gradient appears to be weak, but the amplification of poloidal flux is more than 30%. Note that $\lambda(a)$ decreases slightly upon saturation. The amount of injected current, I_{inj} , also decreases while the net axial current, I_z , remains at the same level. Thus, the relaxation tends to

increase the I_z/I_{inj} ratio.

The fluctuations induce a net Poynting flux and relax the current profile via the $\langle \mathbf{v} \times \mathbf{b} \rangle$ dynamo (small case fields are modes other than the $m=0, n=0$). This is comparable to the MHD dynamo in the reversed field pinch, but here the magnetic energy transport from the fluctuations is inward, $\langle \mathbf{e} \times \mathbf{b} \rangle_r < 0$. Figure 4 shows a comparison of the Poynting flux from the resonant $n=1$ modes and that from the applied $n=0$ fields. The poloidal field distortion excludes the $n=0$ Poynting flux from the interior, while the Poynting flux from the resonant modes provides more penetration. The transport from a given resonant mode is not confined to its tearing layer; however, it is radially localized. Since the λ gradient is near the wall, there is little drive for the fluctuations in the center of the cylinder. On the axis itself, only $m=1$ fluctuations can have nonzero poloidal components of $\mathbf{v}$ and $\mathbf{b}$ to drive $\langle J_z \rangle$, and none of the cases examined here have been driven so hard that an $m=1$ mode is resonant near the center of the cylinder.

Relaxation unfortunately comes with a price—the fluctuation level. The volume average of the fluctuation level is on the order of 1%. The spectrum is broad and peaked at the $n=1$ mode which is resonant nearest the wall (see Figures 5 and 6). The fluctuation level is large enough to make the field lines stochastic in the region where the λ profile relaxes. The comparison of poloidal flux contours with a field line puncture plot, shown in Figure 7, demonstrates that the flux surfaces formed by relaxation are not truly closed.

III B. Applied Field Variations

A series of simulations with $S=5000$, $R/a=6$ and only $|n| \leq 1$ modes resolved has been conducted to explore the effects of varying the vertical field strength and the applied voltage. The results listed in Table I indicate the following

trends: First, I_z predictably increases with either E_V or with B_V . Second, I_z/I_{inj} decreases with increasing E_V or B_V —the current path is more poloidal when either of the applied fields is increased, an effect not compensated by the relaxation. Third, both the fluctuation level ($l_n \neq 0$ modes only to exclude the applied perturbations) and the poloidal flux amplification increase with E_V .

Although the flux amplification increases with E_V (and to some extent, with B_V), increasing the applied voltage does not enhance the relaxation of the λ profile. The profiles for cases C and D are compared in Figure 8. The parallel current in the relaxed region is larger for case D, but the spike of current at the wall is much larger, so the entire profile is actually more hollow. Also, the relaxed region is not pushed further in towards the axis. Increasing B_V makes the λ profile more hollow as well (see Figure 9), but this does extend the relaxed region towards the axis. The difference lies the effect of the applied fields on the resonance surfaces of the unstable modes. Increasing either E_V or B_V tends to decrease the safety factor at the wall. However, increasing E_V alone forces the injected current path closer to the wall, so the resonance surfaces of the largest modes do not move inward. In contrast, increasing B_V tends to move the current path and the resonance surfaces away from the wall.

III C. Special Cases

Additional simulations have been performed to assess the significance of parameters other than the magnitudes of the applied fields. In case G of Table I the viscosity has been reduced by a factor of 4 from the value used for all other simulations (the nominal value is $\nu = a^2 \rho / \tau_f$). In all other respects, case G is the same as case E, and it is clear that the viscosity is small enough that it has little impact on the results. Case H is the only exception to the flat resistivity prescript. The normalized profile is $[1 + (r/a)^2]^2$, and the effect is substantial. The

large resistivity at the wall inhibits the current from becoming localized there. This, combined with smaller growth rates for the modes resonant near the wall, prevents relaxation at the voltage level applied.

The distribution of the vacuum poloidal flux over the surface of the cylinder has also been considered. Case I is the exception to the vacuum magnetic field configuration that is illustrated in Figure 1. For this case the surface distribution of $\mathbf{B}_V \cdot \mathbf{n}$ is that from a line of current, parallel to the cylinder axis and located 0.3a outside the cylinder wall in the plane of zero potential. The total poloidal flux passing through the cylinder is equivalent to the $B_V=0.0125$ cases with the vertical field configuration. The E_V distribution is unchanged. This case produces less current localization than case D, because the poloidal flux must be pushed further from its vacuum distribution. However, the relaxation, which is relatively weak in this case, exhibits the same kind of behavior as it does in the other cases. Thus, the conclusions drawn from the simulations with the simplified arrangement can be generalized to other configurations.

Another geometric parameter that affects the relaxation is the cylinder aspect ratio. For a given λ profile, R/a affects the magnitude of the safety factor at all radii, so it determines which modes are resonant. Case J, and another similar simulation with $S=10^4$, have $R/a=2$. The m numbers of the dominant $n=1$ modes are roughly 3 times larger than in the comparable case C. However, since the wavenumbers of the resonant modes are larger, the growth rates are smaller, and there is less relaxation. We chose the nominal R/a to be 6, so that fewer modes need to be resolved to accurately capture all of the important quasilinear and nonlinear interactions.

A final special case considers the effect of allowing the axial flux in the cylinder to change at a rate determined by an external inductance. In case K, $\langle E_\theta \rangle$ at the wall, which is proportional to a 'gap' voltage for an imaginary

conducting shell that is cut in the axial direction, is allowed to be nonzero. Its value varies with the rate of change of poloidal shell current, $2\pi R \langle B_z(a) \rangle / \mu_0$. Otherwise, the conditions are again the same as in case C. There results a small amount of paramagnetism (0.6%) from a pinching effect with little impact on the relaxation.

IV. LUNDQUIST NUMBER SCALING

We have performed a limited scan of S (2.5×10^3 to 4×10^4) to investigate the resistivity dependence of the fluctuation level and relaxation. [This topic is beyond the scope of theories based on minimum energy² or minimum dissipation.⁹] While the S values used in the computations have been chosen for numerical considerations, the largest S is comparable to present experiments (e.g. in HIT, $S \sim 10^5$). This range is, however, far from reactor conditions, so scaling information is relevant.

For this series of simulations, we employ the parameters of case C in Table I. These conditions generate substantial relaxation without making the λ profile excessively hollow. The normalized E_V is given the same value, independent of S , in an effort to maintain the same axial current. The actual applied potential decreases with resistivity, because the normalized E_V contains a factor of τ_r . Numerically, full modal resolution is used for each of the simulations to produce accurate fluctuation levels. The addition of the $l_n > 1$ modes enhances nonlinear coupling and reduces relaxation. Some of the power that goes into the quasilinear relaxation when there are only $l_n \leq 1$ modes, goes into nonlinear cascading when $l_n > 1$ modes are included.

The results of the S -scaling, presented in Table II, show that the relaxation and the fluctuation level *increase* with S . Note that the highest S case does not produce the same axial current as the other cases, so its fluctuation level and

flux amplification should be viewed relative to the amount of driven current. The change in relaxation with S is indicated by the I_z/I_{inj} ratios, and it is also apparent from the comparison of λ profiles shown in Figure 10. Note that the spike of current at the wall is reduced and the bump from relaxation is increased as S is increased. The change in fluctuation level is an unexpected result. If the current profile were independent of S , one might expect the magnetic fluctuation level to decrease or remain the same, as the $\langle \mathbf{v} \times \mathbf{b} \rangle$ needed to drive $\langle \mathbf{J} \rangle$ decreases. Apparently, the change in relaxation of λ , hence $\langle \mathbf{J} \rangle$, is significant.

V. SUMMARY AND CONCLUSIONS

The MHD simulations reported here demonstrate that DC helicity injection can drive axial (toroidal) current in a resistive plasma with no net axial electric field. When the poloidal magnetic field induced by the driven current is larger than the applied vertical field, the electrostatic potential sustains an edge current. The current density gradient produces resistive MHD fluctuations which relax the current profile by the well-understood MHD dynamo mechanism. The resulting current density profile leads to mode saturation and closed contours of poloidal flux.

Unfortunately, the relatively large fluctuation level of 1% yields a field line puncture plot which is stochastic. Also, the final current density profile is quite hollow; complete relaxation to a constant $\mathbf{J}/\mathbf{B}$ state does not occur in this driven system. A limited Lundquist number scan indicates that the current profile becomes less hollow with S , but the fluctuation level increases.

The results agree with the HIT experiment in that robust flux amplification and hollow current profiles occur. However, in CDX a peaked current channel arises near the cathode. Comparison of fluctuation properties await

experimental results.

The predicted hollowness of the current profile and relatively large fluctuation level—likely leading to significant energy transport—are potential impediments to a reactor plasma sustained exclusively by DC helicity injection. However, DC helicity injection may play a role in forming a desired current profile in conjunction with other current drive techniques.

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Table I. Helicity injection simulation results with $ln \leq 1$ modes resolved. The nominal conditions are $v=a^2\rho/\tau_r$, uniform resistivity, vertical applied fields, $R/a=6$, and constant axial flux; exceptions are noted for cases G-K. B_v is normalized by the initial $\langle B_z \rangle$, and E_v is normalized by $\langle B_z \rangle a/\tau_r$.

case	E_v	B_v	l_{inj}	l_z	l_z/l_{inj}	flux amp.	rms(b) · all n / n≠0
A	20	0.00833	0.80	0.52	0.65	< 1%	1.9% / 0.23%
B	25	0.00833	1.25	0.64	0.51	< 1%	2.1% / 0.25%
C	20	0.0125	1.49	0.78	0.52	32%	2.6% / 1.3%
D	30	0.0125	3.5	1.15	0.33	51%	3.0% / 1.4%
E	15	0.01875	1.89	0.86	0.46	22%	3.3% / 1.4%
F	20	0.01875	3.36	1.16	0.35	36%	3.6% / 1.6%
G {viscosity reduced by 4}	15	0.01875	1.87	0.87	0.47	21%	3.3% / 1.4%
H { $\eta=(1+r^2)^2$ }	30	0.0125	0.48	0.43	0.89	<< 1%	2.1% / $2.6 \times 10^{-5}\%$
I { $B_v(a)$ from line current}	30	0.0125 equivalent	1.77	0.96	0.54	< 1%	2.4% / 0.6%
J { $R/a=2$ }	20	0.0125	0.58	0.77	1.33	< 1%	2.8% / 0.6%
K {axial flux allowed to change}	20	0.0125	1.45	0.77	0.53	32%	2.6% / 1.3%

Table II. S-scaling from simulations with $lnl \leq 5$ modes resolved. All cases use the nominal conditions of vertical applied fields, $E_V=20$, $B_V=0.0125$, and $R/a=6$. Results are averaged over $0.2\tau_r$ after saturation with the exception of case P, whose results are averaged over only $0.026\tau_r$.

case	S	l_{inj}	l_z	l_z/l_{inj}	flux amp.	rms(b) all n / n $\neq$ 0
L	2,500	1.86	0.77	0.42	< 1%	2.81% / 0.16%
M	5,000	1.47	0.76	0.51	22%	2.71% / 1.23%
N	10,000	1.37	0.79	0.58	33%	2.50% / 1.33%
O	20,000	1.26	0.79	0.63	42%	2.39% / 1.39%
P	40,000	0.86	0.60	0.70	30%	2.35% / 1.33%

FIGURE CAPTIONS

Figure 1. Schematic of the applied fields for DC injection (poloidal slice illustrated). Only the region within the periodic cylinder contains plasma and is in the problem domain.

Figure 2. Temporal evolution of the axially symmetric flux surface contours from an $S=5000$, $R/a=6$ simulation. The four plots show the (a) initial conditions prior to the application of electrostatic potential, (b) the point of half potential, (c) full potential with growing instabilities, and (d) the final relaxed state with saturated fluctuations.

Figure 3. Parallel current ($\lambda=\mu_0 a \langle \mathbf{J} \rangle \cdot \langle \mathbf{B} \rangle / \langle B \rangle^2$) profiles before and after the saturation of the fluctuations. This comparison shows a modest level of relaxation.

Figure 4. Radial Poynting fluxes in the relaxed state induced by the applied fields ($n=0$ modes) and the resonant fluctuations ($n=1$ modes) overlaid with different y-axis scales.

Figure 5. Magnetic energy spectra for the $n \neq 0$ modes from a fully resolved $S=2 \times 10^4$, $R/a=6$ simulation. The spectra are time-averaged over $0.2\tau_r$, and standard deviations are roughly 50% for all modes. The $m>0$, $n<0$ modes are denoted by the conjugate indices.

Figure 6. Safety factor ($q=r\langle B_z \rangle / R\langle B_\theta \rangle$) profile from the $S=2 \times 10^4$, $R/a=6$ simulation. The unusual shape is generated self-consistently by the DC helicity injection, and resonance surface locations are indicated for the largest modes. [This trace is actually the inverse of the time average of $R\langle B_\theta \rangle / r\langle B_z \rangle$. Fluctuations occasionally force $\langle B_\theta \rangle$ to zero near the axis.]

Figure 7. Comparison of (a) axially symmetric flux contours and (b) a field line puncture plot for the $S=2 \times 10^4$, $R/a=6$ simulation.

Figure 8. λ profiles from simulations with different applied potentials. The case with larger potential generates more interior current through fluctuation activity, but the directly driven current at the wall is much larger.

Figure 9. λ profiles from simulations with different applied vertical fields. Increasing the vertical field enhances the penetration of the fluctuation-driven current.

Figure 10. λ profiles from fully resolved simulations with different S . Each profile is a time average over approximately $0.2\tau_r$. This comparison shows that relaxation increases with S .

Sovinec, Figure 1

Sovinec, Figure 2

Sovinec, Figure 3

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