

MHD dynamo and charge separation in Reversed Field Pinch plasmas

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1. Introduction

The reversed field pinch (RFP) is a toroidal device for magnetic confinement. Its magnetic configuration is akin to the tokamak, but the amplitude of the poloidal field is comparable to the toroidal one, which reverses in the outer region. On top of the toroidal loop voltage, the configuration is sustained through a MHD dynamo action, which provides an additional $\mathbf{v} \times \mathbf{B}$ electromotive force due to a self-organized dynamo velocity field in the plasma.

Recently, the origin of this dynamo velocity field has been clarified in the framework of MHD modelling. In fact, 3D non-linear visco-resistive MHD simulations of the RFP have shown that the main component of this field is an electrostatic drift [1]. The dominant electrostatic nature of the RFP dynamo is quite natural for the laminar single helicity (SH) steady-state. Poisson equation reveals a charge separation, which is small enough to be consistent with the quasi-neutrality condition. The electrostatic field related to this charge separation is found to be the main part of the total electric field, which is curl-free. As a consequence, the related electrostatic drift turns out to provide the essential part of the dynamo velocity field. The same result has also been established in the turbulent multiple helicity (MH) regime. In fact a small charge separation is found in this regime too, and the related electrostatic drift velocity is once again shown to be the main part of the dynamo velocity field, since the inductive component of the electric field turns out to be negligible. The fact that the dynamo remains essentially electrostatic in the MH state confirms the continuous character of the SH-MH transition [2,3]. This electrostatic interpretation of the MHD dynamo is expected to be valid in real plasmas, too.

In this paper, we focus the analysis on the features of the electrostatic potential related to the small charge separation found in numerical MHD modelling. Particular attention is devoted to the MH state.

2. Single helicity steady-state

The RFP is simulated with the SpeCyl 3D non-linear visco-resistive MHD cylindrical code [4]. It provides numerical solutions of the compressible nonlinear model in the constant-pressure constant-density approximation, including resistivity, η , and viscosity, ν , whose

equations in dimensionless units are $\frac{\partial B}{\partial t} = -\nabla \times E = \nabla \times (\mathbf{v} \times \mathbf{B} - \eta \mathbf{J})$ and

$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = \mathbf{J} \times \mathbf{B} + \nu \nabla^2 \mathbf{v}$, where $\mathbf{J} = \nabla \times \mathbf{B}$ and $\nabla \cdot \mathbf{B} = 0$. The charge separation, implicitly determined in MHD modelling, is computed through Poisson's equation $\rho_c = \nabla \cdot \mathbf{E}$. The post-processing of MHD numerical simulations shows the presence of a finite charge density, which is much smaller than the plasma density [1], consistently with the quasi-neutrality condition [5].

The distribution of charge separation, typical of a single helicity steady-state, is displayed in **Figure 1**. Here, we consider a SH simulation with $\Theta=1.6$, $S=3 \times 10^4$ and $P=300$ [1,3]. **Fig. 1a** is a toroidal cross section of the isosurfaces of the charge separation, over one fifth of the entire periodical cylinder. Maxima of ρ_c are displayed in red, minima in blue. The contour levels represent the helical flux function ψ . **Fig. 1b** is a 3D representation of the same structure. Red and blue surfaces are the isosurfaces corresponding to 75% of the maximum and minimum of ρ_c , respectively. The yellow surface is an example of magnetic surface of constant ψ . The charge separation is characterized by a multipolar helical structure with a large dipolar component in the plasma core. The dynamo velocity field has been found to correspond essentially to the electrostatic drift velocity related to this helical dipolar structure [1].

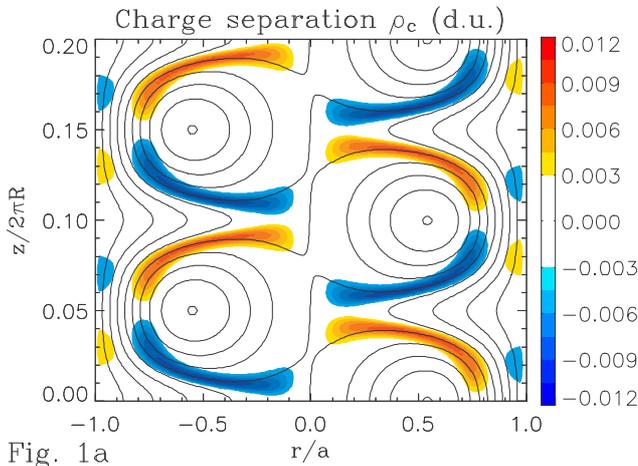


Fig. 1a

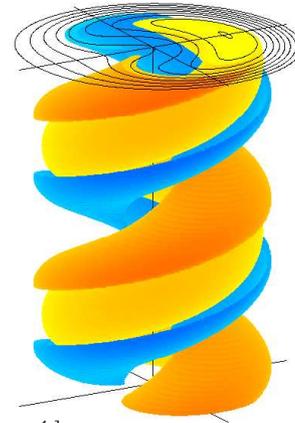


Fig. 1b

In general, the electrostatic potential ϕ related to the charge distribution can be computed, in the Coulomb gauge, through Laplace's equation $\nabla^2 \phi = -\rho_c$. The electrostatic potential found in the SH steady-state is shown in **Figure 2**. Similarly to Fig. 1, **Fig. 2a** is a toroidal cross-section of the isosurfaces of ϕ , while **Fig. 2b** is a 3D representation thereof. The electrostatic potential has a pure dipolar helical structure, which corresponds to the main dipolar component of charge separation. In the next section we show that this helical structure of ϕ is continuously modified when going to the turbulent MH regime.

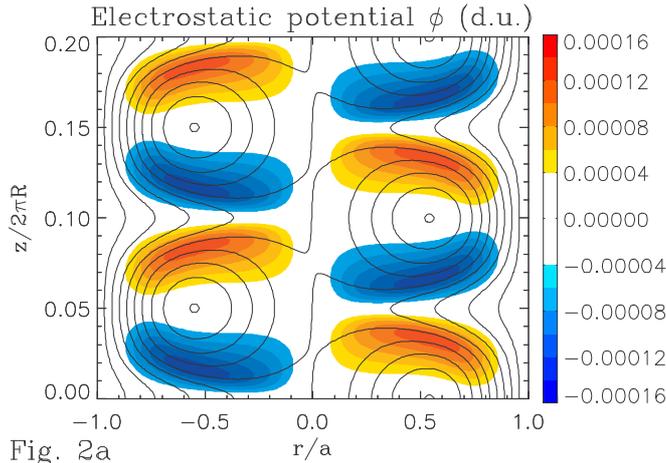


Fig. 2a

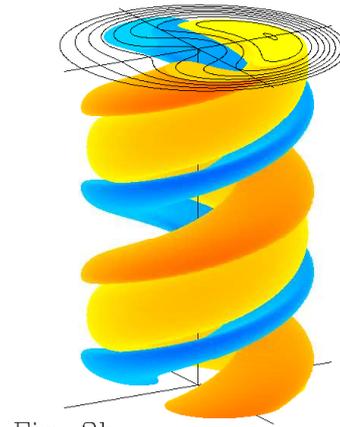


Fig. 2b

3. Multiple helicity regime

The maximum value of the charge separation, during a multiple helicity simulation, was found [1] to be correlated with the dynamics of quasi-periodical dynamo relaxation events, the so-called sawtooth crashes, which are typical of this regime and characterized by the deepening of the reversal parameter F . In fact, ρ_c is larger during relaxation events, and smaller in between. This feature is a consequence of the correlation, through the $\mathbf{v} \times \mathbf{B}$ term in Ohm's law, between the electric field and the velocity field, which increases during the dynamo relaxation events.

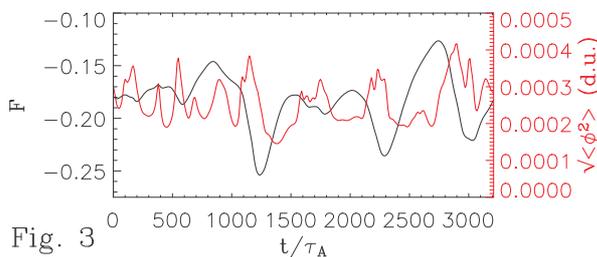


Fig. 3

A similar correlation with the MHD dynamics is displayed by the electrostatic potential. We consider here a multiple helicity simulation with $\Theta=1.9$, $S=3 \times 10^4$ and $P=20$. **Figure 3** shows the temporal evolution of the reversal parameter F and of the quantity $\langle \phi^2 \rangle^{1/2}$, which is used as a global measure of the intensity of the electrostatic potential ($\langle \cdot \rangle$ denotes a volume average). The electrostatic potential globally increases just before dynamo relaxation events, while it decreases in the ramp-up phase of F . It is worth noticing that a similar correlation between the reversal parameter and low frequency oscillations of the electrostatic potential measured at the plasma edge, has been found in the RFX device [6].

The structure of ρ_c in the MH regime was shown to be less regular than in the SH steady-state, however a pattern, even if highly corrugated, is still visible [1]. The electrostatic potential appears to be more regular. Indeed its structure is qualitatively preserved in the SH-MH transition. **Figure 4** displays the distribution of ϕ in correspondence to a dynamo relaxation event (at $t = 2300 \tau_A$). **Fig. 4a** is a toroidal cross-section of the isosurfaces of ϕ over the entire periodical cylinder, while **Fig. 4b** is the corresponding 3D representation.

We see that the electrostatic potential is characterized by a helical structure which is very similar to that found in the SH case. The only difference is that, instead of a pure dipolar helical distribution, there is now a modulated multipolar helical structure, produced by the contributions from all the MHD modes of the MH spectrum. In fact, when more magnetic modes arise in going from SH to MH, the helical deformation becomes more and more localized in z to produce the “slinky” or “large helical deformation”; as a result the dominant helical structure for ϕ undergoes the same evolution.

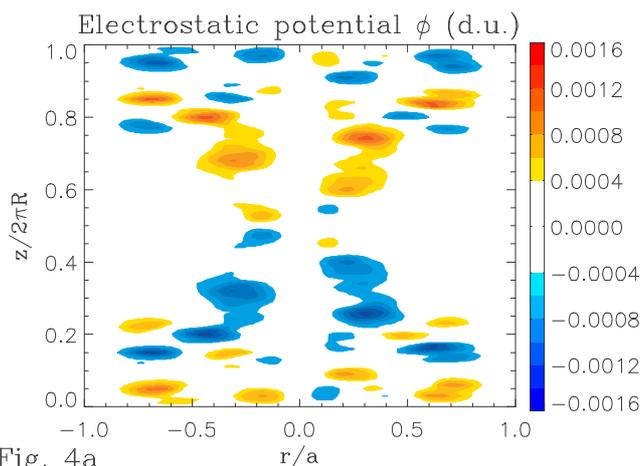


Fig. 4a

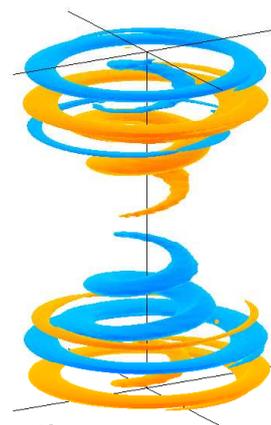


Fig. 4b

In conclusion, this study of the electrostatic potential in MHD numerical simulations of the RFP shows that the features of the SH steady-state are qualitatively preserved in the transition to the MH regime. In particular, the helical structure of ϕ is weakly modified in the MH state, consistently with the fact that the dynamo remains essentially electrostatic in the turbulent regime [1]. As a future work, this analysis is going to be extended in order to compare our MHD simulations with the above-mentioned electrostatic measurements at the plasma edge of the RFX and T2R devices [6,7]. Indeed, those measurements have pointed out the existence at the plasma edge of electrostatic structures which show some similarities with the modulated multipolar structures of ϕ we have described in this contribution.

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References

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