Ohm's law for plasmas in reversed field pinch configuration

E. Martines and F. Vallone
Consorzio RFX, corso Stati Uniti, 4, I-35127 Padova, Italy
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An analytical relationship between current density and applied electric field in reversed field pinch (RFP) plasmas has been derived in the framework of the kinetic dynamo theory, that is assuming a radial field-aligned momentum transport caused by the magnetic field stochasticity. This Ohm's law yields current density profiles with a poloidal current density at the edge which can sustain the magnetic field configuration against resistive diffusion. The dependence of the loop voltage on plasma current and other plasma parameters for RFP experiments has been obtained. The results of the theoretical work have been compared with experimental data from the RFX experiment, and a good agreement has been found. [S1063-651X(97)06706-8]

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I. INTRODUCTION

Generally speaking, devices for magnetic confinement of fusion plasmas are characterized by transport processes which are anomalous, in the sense that they are not determined simply by interparticle collisions. As an example, in tokamaks transport of the moments of order 0 and 2 of the electron distribution function, namely, particle number and mean energy, is anomalous. On the other hand, the first order moment, current density, is not transported, but rather generated and absorbed locally in a classical fashion. The relationship between current density and electric field is then given for a stationary tokamak plasma by a simple Ohm's law with Spitzer conductivity [1].

Not so simple is the situation for plasmas in reversed field pinch (RFP) configuration [2]. Besides the fact that particle and energy transport are anomalous as in the tokamak, Ohm's law itself is not classical. This is mandatory if the configuration is to be sustained against resistive diffusion, as experimentally observed: in fact the toroidal field reversal requires a poloidal current density in the outer region, which according to the Spitzer Ohm's law cannot be driven by the toroidally applied electric field.

The process which allows the sustainment of the toroidal field reversal is called dynamo. Different mechanisms have been proposed to explain it. One of them, the magnetohydrodynamic (MHD) dynamo, suggests that the current density results form a local balance between the dissipation, which is collisional as in Spitzer theory, and a generation given by the applied electric field and an additional term, the dynamo electric field, resulting from coherent MHD fluctuations of velocity and magnetic field [3]. On the contrary, the kinetic dynamo theory (KDT) suggests that generation and dissipation are both classical, but there is in addition a significant transport of field-aligned current density caused by the stochasticization of the magnetic field lines induced by the high magnetic fluctuation level [4]. Presently, the MHD dynamo is supported by three dimensional (3D) MHD simulations [5] and by direct measurements of the dynamo field [6], whereas in favor of KDT there are simulations made with a 3D Fokker-Planck code [7] and the observation in the edge region of all RFP experiments of a superthermal electron population [8]. It is to be mentioned that, while the magnetic field inside the reversal surface ($r/a<0.8$–0.9) is certainly stochastic, the stochasticity of the outer region is a matter of debate.

In this paper the problem of Ohm's law in RFP plasmas is addressed within the framework of KDT. In order to treat the problem analytically, an ansatz is made concerning the shape of the electron distribution function, on the ground of theoretical considerations and experimental results. Other assumptions are then made about the density and temperature profiles, and a particular model is adopted to describe the magnetic field profiles. Under these hypotheses, and assuming low-collisionality conditions, a relationship between current density and applied electric field is derived from kinetic theory in Eq. (29), and from that the relationship between plasma current and loop voltage in a RFP experiment is obtained in Eq. (37). These two formulas are the main results of this paper.

The paper is organized as follows. In Sec. II the problem is formulated, and the basic kinetic equation to be solved is written. In Sec. III the method used to solve it is described. In Sec. IV the first two moment equations of the kinetic equation are deduced, and are then solved in Sec. V to yield the required Ohm's law. In Sec. VI this Ohm's law is used to obtain a relationship between loop voltage and plasma current in RFP plasmas. Finally, conclusions are drawn in Sec. VII.

II. FORMULATION OF THE PROBLEM

We shall consider a plasma in cylindrical geometry, for which the only not ignorable coordinate is the radial one. The symbols a and R denote the minor and major radii of the machine. The plasma has on-axis electron temperature T_0 and on-axis electron density n_0. The ion population, described by an effective charge Z, is supposed to have temperature and density equal to the electron ones throughout the plasma. The on-axis magnetic field is denoted by B_0.

Some useful derived quantities are the on-axis electron thermal velocity

$$v_0=\sqrt{T_0/m}, \tag{1}$$

where m is the electron mass, and the on-axis collision time

$$\tau_c = (4\pi\epsilon_0)^2 \frac{m^2 v_0^3}{4\pi e^4 n_0 \ln\Lambda}, \tag{2}$$

where e is the elementary charge and $\ln\Lambda$ the Coulomb logarithm. Finally, the on-axis critical electric field for runaway generation is [9]

$$E_c = \frac{4\pi e^3 n_0 \ln\Lambda}{m v_0^2} \frac{1}{(4\pi\epsilon_0)^2}. \tag{3}$$

In the rest of the paper, unless explicitly indicated, temperatures and densities will be normalized to T_0 and n_0, magnetic fields to B_0, velocities to v_0, time to τ_c, and the radial coordinate r is intended normalized to a. Distribution functions are normalized to n_0/v_0^3.

The starting point to attack the problem is the KDT equation [4], a drift kinetic equation for the electron distribution function which considers the effects due to the applied electric field, to collisions, and to diffusion caused by the magnetic field stochasticity (hereafter called for simplicity stochastic diffusion). The distribution function f depends on r, on the parallel velocity $v_\parallel$, and on the perpendicular velocity $v_\perp$.

The KDT equation assumes, in stationary conditions, the general form

$$E(f) = C_{ei}(f) + C_{ee}(f) + D(f), \tag{4}$$

where the Ohmic term $E(f)$ represents the toroidally applied electric field effect, $C_{ei}(f)$ is the electron-ion collision term, $C_{ee}(f)$ is the electron-electron collision term, and $D(f)$ is the term describing stochastic diffusion. It is worth noting that, without this last term, the solution of Eq. (4) obeys the classical Ohm's law with Spitzer conductivity.

The Ohmic term is given by

$$E(f) = -E_\parallel \frac{\partial f}{\partial v_\parallel}, \tag{5}$$

where $E_\parallel(r)$ is the magnetic field aligned component of the applied electric field, normalized to E_c.

The stochastic diffusion term has the form [10]

$$D(f) = \frac{|v_\parallel|}{r} \mathcal{L}(r D_M \mathcal{L} f), \tag{6}$$

where $D_M(r)$ is the magnetic field line diffusion coefficient, normalized to $a^2/(v_0\tau_c)$; the operator $\mathcal{L}$ is

$$\mathcal{L} = \frac{\partial}{\partial r} - \frac{E_A}{v_\parallel} \frac{\partial}{\partial v_\parallel}, \tag{7}$$

where $E_A(r)$ is the radial ambipolar electric field, normalized to ae/T_0.

The electron-ion collision term, restricted to pitch-angle scattering, is given by [11]

$$C_{ei}(f) = \frac{nZ}{2v^3 \sin\theta} \frac{\partial}{\partial\theta}\left(\sin\theta \frac{\partial f}{\partial\theta}\right), \tag{8}$$

where the alternative coordinate system (v,θ) for the velocity space has been introduced. The electron-electron collision term is not specified, because it is not necessary for the rest of the paper.

III. RESOLUTION METHOD

Equation (4) is a three dimensional partial differential equation, which can be solved numerically with a considerable computational effort [7] or through simplifying hypotheses, as, for example, in [4]. In this paper the aim is to obtain an analytical expression for Ohm's law in a RFP, and therefore we adopt the approach of deriving the moment equations of Eq. (4) and solving them assuming a suitable distribution function.

The assumed distribution function is a Maxwellian with a drift parallel to the magnetic field and with equal parallel and perpendicular temperatures, that is,

$$f(v_\parallel, v_\perp, r; u) = \frac{n}{(2\pi T)^{3/2}} \exp\left(-\frac{(v_\parallel - u)^2 + v_\perp^2}{2T}\right), \tag{9}$$

where u is the drift velocity. The parallel current density associated to this distribution function, normalized to en_0v_0, is $j_\parallel = -nu$. Expression (9) will be simplified with the further assumption that $u \ll 1$ (verified in practical situations), which gives

$$f \simeq f_0\left(1 - \frac{u v_\parallel}{T}\right), \tag{10}$$

where $f_0 = f(v_\parallel, v_\perp, r; 0)$ is the nondrifting Maxwellian.

Assuming given $n(r)$ and $T(r)$ profiles, the only unknowns of the problem are $u(r)$ and the ambipolar field $E_A(r)$, which is not *a priori* known. To determine these two quantities we have used the first two moments of Eq. (4), obtained multiplying the equation respectively by 1 and by $v_\parallel$ and integrating over the velocity space. The two ensuing equations are two ordinary differential equations in the unknowns $E_A(r)$ and $u(r)$.

In principle, one could think to extend the method to the second order, keeping $T(r)$ as a further unknown, thus gaining information not only about momentum transport but also about energy transport (assuming electrostatic contributions to be negligible). However, such an approach would not take into account effects such as the anomalous ion heating, which is known to be important in RFP plasmas [2]. Therefore we have chosen to impose $T(r)$ and to concentrate on the momentum balance.

IV. MOMENT EQUATIONS

In this section the first two moment equations of Eq. (4) are evaluated, without making any hypothesis about the distribution function, except that it goes to zero fast enough when the parallel and perpendicular velocities go to infinity.

The zero order moment of $E(f)$ is zero, and so are those of the collision terms, since electric field acceleration and collision processes both conserve particle number and do not yield radial transport. The only nonzero contribution stems from the stochastic diffusion term, yielding the equation

$$\frac{1}{r}\frac{d}{dr}(r\Gamma_n)=S_n. \tag{11}$$

Here the particle flux is given by

$$\Gamma_n=-\int D_M|v_\parallel|\mathcal{L}fd^3v \tag{12}$$

and the source term is

$$S_n=E_A\int\frac{|v_\parallel|}{v_\parallel}\frac{\partial}{\partial v_\parallel}(D_M\mathcal{L}f)d^3v. \tag{13}$$

As already pointed out in [10], the stochastic diffusion term (6) is obtained in the non-collisional regime, and is therefore not correct for low-energy electrons. This is the reason for the appearance of the spurious source term (13). This term vanishes under the assumption that D_M dpepends on $v_\parallel$ and goes to zero as $v_\parallel\to 0$. As indicated by the authors of Ref. [10], such dependence stems out if the derivation of the stochastic diffusion term is carried out including in the equation a Krook collision term. In such a case, the form of Eq. (6) remains unchanged, provided that

$$D_M=D_M^0\frac{1}{1+\Lambda/\lambda}. \tag{14}$$

In this equation D_M^0 is the magnetic field line diffusion coefficient according to the usual definition, Λ is the magnetic fluctuations' longitudinal autocorrelation length, and λ is the particles' mean free path. Considering the dependence of λ on n and $v_\parallel$, Eq. (14) can be rewritten as

$$D_M=D_M^0\frac{v_\parallel^4}{v_\parallel^4+\alpha_0 n} \tag{15}$$

having introduced the on-axis collision parameter $\alpha_0=\Lambda/v_0\tau_c$.

As a consequence of Eq. (15), the zero order moment equation reduces to $\Gamma_n=0$. Plugging the assumed distribution function into this expression leads to

$$2D_M^0\left(\frac{n'}{n}-\frac{T'}{2T}+\frac{E_A}{T}\right)I_5+D_M^0\frac{T'}{T^2}I_7=0, \tag{16}$$

where the prime indicates differentiation with respect to r and the family of integrals I_k has been defined as

$$I_k=\int_0^\infty\frac{v_\parallel^k}{v_\parallel^4+\alpha_0 n}f_0d^3v. \tag{17}$$

Equation (16) does not contain $u(r)$ and can therefore be used to evaluate $E_A(r)$.

A similar procedure for the first order moment gives the equation

$$\frac{1}{r}\frac{d}{dr}(r\Gamma_u)=S_u-E_\parallel n+\frac{nuZ}{3\sqrt{2\pi}T^{3/2}}, \tag{18}$$

with

$$\Gamma_u=-\int D_M v_\parallel|v_\parallel|\mathcal{L}fd^3v, \tag{19}$$

$$S_u=E_A\int|v_\parallel|\frac{\partial}{\partial v_\parallel}(D_M\mathcal{L}f)d^3v. \tag{20}$$

The electron-electron collision term does not contribute to Eq. (18), since momentum is conserved in like particles' collisions.

V. OHM'S LAW

Once the equation for E_A has been solved, Eq. (18) gives $u(r)$. To do this, one must first solve the integrals (17). Although this can be done exactly, the resulting solutions are too complex. Therefore we have adopted the simplifying hypothesis that $\alpha_0 n/4T^2\ll 1$. This indicates a low collisionality regime throughout the plasma. The resulting expressions for the integrals are

$$I_3=-\mathrm{Ei}\left(-\sqrt{\frac{\alpha_0 n}{4T^2}}\right)\frac{n}{2\sqrt{2\pi T}}, \tag{21}$$

$$I_5=n\sqrt{\frac{T}{2\pi}}, \tag{22}$$

$$I_7=n\sqrt{\frac{2}{\pi}}T^{3/2}, \tag{23}$$

$$I_9=4n\sqrt{\frac{2}{\pi}}T^{5/2}. \tag{24}$$

With these solutions, the expression for the ambipolar electric field resulting from the zero order moment equation is the same as that obtained in paper [10] that is,

$$\frac{E_A}{T}=-\frac{n'}{n}-\frac{T'}{2T}. \tag{25}$$

The insertion of this solution into Eq. (18) leads to a second order differential equation for $u(r)$. In order to solve it, we shall now make the hypotheses of uniform density and temperature profiles. The first one is in agreement with experimental results from the RFX experiment [12], and should be valid in large experiments as long as plasma refueling is due to neutral influx from the wall. The second one has been inspired by measurements of the edge superthermal electron distribution function made on the MST and TPE-1RM20 experiments with electrostatic energy analyzers (EEAs), which are well fitted assuming a drifting Maxwellian with temperature comparable to the on-axis electron temperature [13,14].

The hypotheses made lead to the equation

$$u''(r)+\frac{1}{r}u'(r)-\frac{Z}{12D_M^0}u(r)=\sqrt{\frac{\pi}{2}}\frac{E_\parallel(r)}{2D_M^0}, \tag{26}$$

which in the limit of zero diffusion reduces to the Spitzer-like Ohm's law

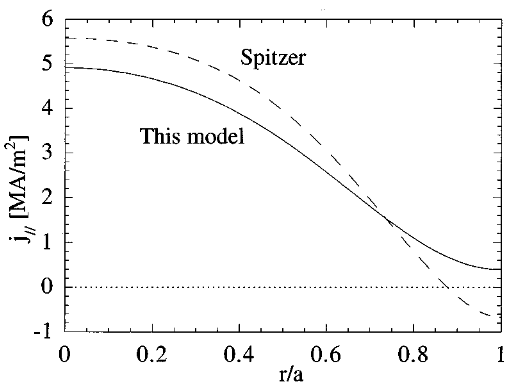

FIG. 1. Parallel current density predicted for RFX by the Ohm's law deduced in this paper, superposed to the Spitzer profile.

$$u_0(r)=-\frac{6}{Z}\sqrt{\frac{\pi}{2}}E_\parallel(r). \tag{27}$$

It is worth noting that the conductivity given by Eq. (27) is equal to that calculated with 2D Fokker-Planck codes [11] for the case $Z=1$ and differs slightly from it as Z increases (25% discrepancy for $Z=5$).

In order to obtain from Eq. (26) an explicit relationship between u (which is equal to $-j_\parallel$, since we have assumed $n=1$) and $E_\parallel$, a model for the magnetic field profiles has to be assumed, although in principle Eq. (26) could be solved numerically self-consistently with Ampere's law to calculate such profiles. The model adopted here is the polynomial function model (PFM) [15], which gives the magnetic field components $B_z(r)$ and $B_\theta(r)$ in terms of the single parameter θ_0. Since the parallel electric field is still a nonlinear function of B_z and B_θ, an approximate expression of the form

$$E_\parallel=E_0(1+Ar^2+Br^4+Cr^6) \tag{28}$$

has been adopted, with $A=1.78\theta_0-1.63\theta_0^2$, $B=-1.13\theta_0$, and $C=0.94\theta_0$. This expression reproduces very well the exact one for all r and all values of the pinch parameter $\Theta<2$ [$\Theta=B_\theta(a)/\langle B_z\rangle$].

The boundary conditions chosen for Eq. (26) are $u'(0)=0$ and $u'(1)=0$. The first one is dictated by symmetry considerations and the second one is in analogy to Ref. [4]. The resulting solution is

$$u(r)=u_0(r)+\alpha I_0(\sqrt{\chi}r)-\sqrt{\frac{\pi}{2}}\frac{6E_0}{Z}\left[\frac{4A}{\chi}+\frac{B}{\chi^2}(64+16\chi r^2)+\frac{C}{\chi^3}(2304+576\chi r^2+36\chi^2r^4)\right], \tag{29}$$

where I_0 is the zero order modified Bessel function and the parameter $\chi=Z/12D_M^0$ has been introduced. The integration constant α is given by

$$\alpha=\sqrt{\frac{\pi}{2}}\frac{12E_0}{Z\sqrt{\chi}I_1(\sqrt{\chi})}\left(A+2B+3C+\frac{16B+72C}{\chi}+\frac{576C}{\chi^2}\right). \tag{30}$$

TABLE I. Typical plasma parameters for a 600 kA discharge in the RFX experiment.

R	2 m	n_0	3×10^{19} m^{-3}
a	0.457 m	D_M^0	10^{-4} m
$V_{\rm loop}$	30 V	θ_0	1.45
T_0	275 eV	Z	2

Relationship (29) is Ohm's law for the RFP. An example of the current density profile given by it is shown in Fig. 1, together with the Spitzer one. This figure is obtained with the plasma parameters listed in Table I, which are representative of a typical 600 kA discharge in the RFX experiment. The parallel current density profile given by Eq. (29) does not change sign in the outer region, and thus is able to sustain the configuration. The on-axis current density is 10% less than the Spitzer value, while at the edge a current density of 230 kA/m^2 is found, consistent with measurements made in the edge of RFX with an EEA [16].

VI. RELATIONSHIP BETWEEN LOOP VOLTAGE AND PLASMA CURRENT

Projecting Eq. (29) in the z direction and integrating over the plasma cross section, the plasma current, normalized to $en_0v_0a^2$, is obtained as

$$I_p=I_{\rm cl}+I_{\rm an}, \tag{31}$$

where $I_{\rm cl}$ is the contribution due to the Spitzer part of Ohm's law, and $I_{\rm an}$ is the rest. The classical current is given by

$$I_{\rm cl}=\sqrt{\frac{\pi}{2}}\frac{6E_0}{Z}P_0(\theta_0), \tag{32}$$

where

$$P_0(\theta_0)=\frac{1}{2}+\frac{A}{2}+\frac{A^2+2B}{6}+\frac{BC}{6}+\frac{C^2}{14}+\frac{AB+C}{4}+\frac{B^2+2AC}{10}. \tag{33}$$

The anomalous part is

$$I_{\rm an}=\sqrt{\frac{\pi}{2}}\frac{6E_0}{Z}\left(-P_1(\chi,\theta_0)+P_2(\chi,\theta_0)\frac{I_0(\sqrt{\chi})}{\chi^{11/2}I_1(\sqrt{\chi})}\right), \tag{34}$$

having defined the two functions

$$P_1(\chi,\theta_0)=\frac{A^2+8AB/3+2B^2+3AC+24BC/5+3C^2}{\chi}+\frac{8A^2+64AB+256B^2/3+144AC+336BC+1512C^2/5)}{\chi^2}+\frac{32(8AB+24B^2+72AC+216BC+297C^2)}{\chi^3}+\frac{1024(2B^2+9AC+54BC+135C^2)}{\chi^4}+\frac{36864C(4B+27C)}{\chi^5}+\frac{2654208C^2}{\chi^6}, \tag{35}$$

$$P_2(\chi,\theta_0)=4(576C+16B\chi+72C\chi+A\chi^2+2B\chi^2+3C\chi^2)^2. \tag{36}$$

Inverting the relationship between I_p and E_0 one finds the required dependence of the loop voltage V_{loop} on the plasma current, which is now given for convenience of use in *Systeme International* (SI) units:

$$V_{\text{loop}}=R_{\text{cl}}I_p\Phi(\theta_0,\chi), \tag{37}$$

with the classical resistance

$$R_{\text{cl}}=\frac{T_0^{3/2}a^2(4\pi\epsilon_0)^2}{4\sqrt{2\pi m}Ze^2R\ln\Lambda}\frac{1}{P_0(\theta_0)} \tag{38}$$

and

$$\Phi(\theta_0,\chi)=\frac{P_0(\theta_0)}{P_0(\theta_0)-P_1(\chi,\theta_0)+P_2(\chi,\theta_0)I_0(\sqrt{\chi})/[\chi^{11/2}I_1(\sqrt{\chi})]}. \tag{39}$$

The adimensional parameter χ is expressed in SI units as

$$\chi=\frac{\pi Ze^4n_0a^2\ln\Lambda}{3D_M^0T_0^2(4\pi\epsilon_0)^2}. \tag{40}$$

Equation (37) shows that magnetic diffusion introduces in the classical Ohm's law a multiplicative anomaly factor Φ which depends on the magnetic field lines' diffusion coefficient through χ, and tends to 1 as D_M^0 goes to zero.

Figure 2 shows the dependence of the loop voltage on the plasma density given by Eq. (37) in 600 kA RFX discharges for different values of the magnetic field lines' diffusion coefficient D_M^0. These curves were obtained assuming a power law dependence of the electron temperature on plasma density, with coefficients deduced from experimental data. On the same graph experimental values of the loop voltage are plotted as solid points, each point representing an average over many shots, with error bars showing standard deviations. Taking the lower ends of the error bars as an indication of the best performance achievable for each density, these values show a good agreement with the model for $D_M^0=5\times10^{-4}$ m. The point at the higher end of the density range tends to be higher, probably due to the effect of radiation losses.

The value required for D_M^0 yields an average radial magnetic field fluctuation level $b_r/B\simeq3\%$, according to the usual quasilinear relationship

$$D_M^0=\Lambda\left(\frac{b_r}{B}\right)^2, \tag{41}$$

with $\Lambda=a$. This apparently high value can be justified considering the effect of locked modes, which are present in all RFX discharges, forming a strong localized magnetic perturbation [17]. A local estimate of D_M^0 obtained from energy flux measurements taken away from the perturbation gives values one order of magnitude lower [18]. If this is representative of the value attainable on the whole torus upon removal of the localized perturbation, the model predicts that such removal could lead to a reduction of the loop voltage of the order of 5 V.

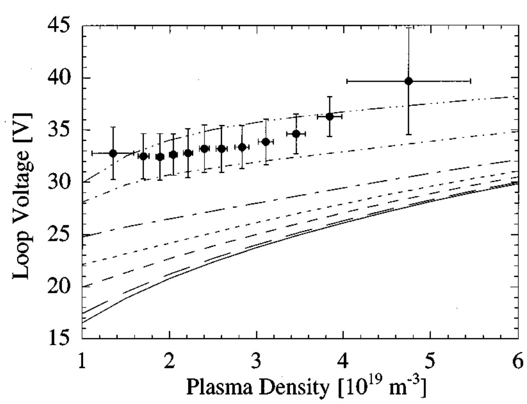

FIG. 2. Loop voltage plotted against plasma density for 600 kA discharges on the RFX experiment. Lines correspond to predictions given by the model for different values of the magnetic field line diffusion coefficient D_M^0: from bottom to top $D_M^0=0$, 10^{-5} m, 5×10^{-5} m, 10^{-4} m, 2×10^{-4} m, 5×10^{-4} m, 10^{-3} m. Circles represent experimental values of the loop voltage: each circle is an average over many shots, with error bars indicating standard deviations.

VII. CONCLUSIONS

In the framework of KDT an Ohm's law has been deduced for plasmas in RFP configuration. The resulting expression gives parallel current density profiles which do not change sign in the outer region, and are therefore in agreement with the observed sustainment of the configuration against resistive diffusion and with observations concerning superthermal electrons. Even without making assumptions about the magnetic field profiles, the current density is described by an ordinary differential equation which can be coupled to Ampere's law to give a self-consistent model for the magnetic field. The Ohm's law could find applications wherever a simple analytical relationship between the applied electric field and the resulting current density is needed, for example, in studies about poloidal current drive and related wave propagation [19].

The relationship between loop voltage and plasma current which stems from this work has been shown to correctly reproduce a set of experimental results from the RFX experiment for a value of the magnetic field lines' diffusion coefficient of the order of 5×10^{-4} m, which can be justified taking into account the effect of locked modes. The relationship could find an application for scaling studies in conjunction with suitable scaling laws for the poloidal β and for the magnetic fluctuation level.

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