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NUMERICAL STUDIES OF LH CURRENT DRIVE IN THE PRESENCE OF AN ELECTRIC FIELD

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Abstract

The dynamical response of a homogeneous plasma to the simultaneous application of an RF power source and an opposing d.c. electric field is investigated by means of a 2-D + 2-D quasilinear code. The code evolves in time the electron distribution function, $f(v_\parallel, v_\perp, t)$ and the corresponding self-consistently generated wave spectral distribution $W(k_\parallel, k_\perp, t)$, both in two dimensions. The time evolution of the most relevant physical quantities, in particular the plasma current can therefore be straightforwardly evaluated.

Introduction

Recent current-drive experiments in PLT and ASDEX [1,2] have clearly demonstrated the ability of lower-hybrid waves not only to maintain a steady plasma current, but also to increase it ("ramp-up") during the discharge. Since the time variation of the current induces a d.c. electric field opposite to the direction of RF waves, any appropriate theoretical description of current ramp-up requires the knowledge of the plasma dynamical response to the simultaneous application of the RF power and opposing electric field.

A few theoretical models for such a problem have already been developed. The earliest one, due to Borrass and Nocentini [3], is based on a one-dimensional time-independent Fokker-Planck analysis and it has therefore a rather limited range of validity. Later on, Fisch and Karney prompted out a series of papers in which a linearized Boltzmann equation was solved, either by integrating the corresponding Langevin equations [4], or, more recently, with a more sophisticated approach based on the adjoint formulation [5].

In this paper we present the first results obtained with an entirely different, purely numerical approach, based on a finite-element expansion of the two-dimensional electron distribution function, $f(v_\parallel, v_\perp, t)$, and the corresponding wave spectral distribution $W(k_\parallel, k_\perp, t)$. Our code solves the 2-D + 2-D quasilinear equations self-consistently in time without any simplifying assumption and provides therefore a very detailed information on the plasma dynamical behaviour .

In this paper no attempt is made to simulate any particular Tokamak discharge. We rather investigate the initial value problem represented by the quasilinear equations with the electric field, as such. We take therefore a licence to treat the electric field strength as a free parameter and study its influence on the electron distribution function in the presence of an RF power source. Particular attention is paid to the dynamics of the mechanism by which the electric field opposes and finally overcomes the RF driven current.

Basic Equations

The basic equations of our model are the following:

$$\frac{\partial f}{\partial t} = \left(\frac{\delta f}{\delta t}\right)_{COLL} + \left(\frac{\delta f}{\delta f}\right)_{QL} + \frac{\nu ei}{\omega pe} E\frac{\partial f}{\partial v_{\parallel}}$$

$$\frac{\partial W}{\partial t} = (2\gamma - \nu_{ei} Z)\, W + S_0 s(k)$$

where cylindrical coordinates $v_{\parallel}$, $v_{\perp}$ and $k_{\parallel}$, $k_{\perp}$ are adopted for both f and W.

The term $\frac{\delta f}{\delta t}_{COLL}$ represents a linearized 2-D collision operator, $\left(\frac{\delta f}{\delta t}\right)_{QL}$ the quasilinear diffusion operator, and 2γ the corresponding wave damping rate (only the Cerenkov resonance is included in the present work). The explicit expressions are given in [6]. Z represents the ion-charge number and ν_{ei} the electron-ion collision frequency. The term $S_0 s(k)$ models the RF-power source, s(k) being a shape function normalized as $\int s(k)k^2 dk=1$ and S_0 a scale parameter which fixes the total RF power input. The normalizations adopted are:

$$k \rightarrow k\lambda_D^{-1};\ v \rightarrow vv_{te}\ ;\ t \rightarrow t\omega_{pe}^{-1};\ W \rightarrow W4\pi nT\lambda_D^{3};\ E \rightarrow EE_D$$

where λ_D is the Debye length, $E_D = m_e v_{te} \nu_{ei}/e$, ω_{pe} the plasma electron frequency and v_{te} the electron thermal speed $\sqrt{(T/m_e)}$.

Apart from the numerical aspects, which will be presented elsewhere [7], there are two basic novel features with respect to our previous model [8] that are worth mentioning. First of all no assumption is made on the perpendicular shape of the distribution function, so that non-maxwellian dependencies on $v_{\perp}$ are free to develop. Second, and more important for the present work, a d.c. electric field is included in the kinetic equation.

The results

Before presenting our numerical results let us briefly recall the basic mechanism which governs the competition between the RF waves and the electric field.

In the absence of the electric field the current is ultimately provided by the number of non resonant ($v_\parallel < v_1$) electrons which can flow to the resonant region ($v_1 < v_\parallel < v_2$). When the electric field is present, we have basically two scenarios how this flow is opposed.

The first possibility (for a relatively small field) is that the non resonant electrons are allowed to access the resonant region, but subsequently leave it under the combined action of the electric field and pitch-angle scattering. These electrons will contribute to the bulk or runaway ($v_\parallel < -v_D \equiv -\sqrt{1/E}$) anticurrent depending on whether they quit the resonant region with a velocity smaller or larger than v_D. Note that the number of antirunaways can be enhanced by the presence of the RF waves because the particles in the resonant strip can be pitch-angle scattered in the opposite direction with a velocity larger than v_D.

As the field becomes larger it is more and more difficult for the electrons to access the resonant region and the conditions of a pure antirunaway situation are approached. The fate of the electrons depends essentially on the location of the resonant strip with respect to v_D. In this paper we kept v_1, v_2 fixed and just varied v_D.

We have performed a series of computations assuming the following set of parameters:

$$S_0 = 10^{-7}, \qquad \nu_{ei} = 0.75 \times 10^{-7}, \quad v_1 \sim 3.5, \qquad v_2 \sim 10,$$

which correspond roughly to the PLT ramp-up conditions [1] with a total power of about 130 kW.

In Fig. 1 the time evolution of the plasma current density, $j(t)$, is shown for several values of the d.c. field amplitude, E. From this figure we see that an electric field of about 0.06 is sufficient to impede any current ramp-up $\left(j(0) \sim j(t\to\infty) \simeq 0.20\right)$. The plateau level on the distribution function is reduced about a factor 2 with respect to the case without d.c. field and most of the anti current (75%) is carried by the slow electrons with $|v_{\parallel}| < v_1$. For E = 0.04 one has a ramp-up rate of about 1000 kA/sec, almost an order of magnitude higher than typical experimental values.

A realistic value of E lies therefore somewhere between 0.04 and 0.06. For E = 0.04 the anticurrent is completely dominated by slow electrons, so that one expects the theory proposed in Ref.[3] to be appropriate for the prediction of the correct steady state value $j_E^{\infty} \equiv j(E;t\to\infty)$. This is rapidly checked by evaluating the parameter γ_0, defined as $\gamma_0 = 2(j_0^{\infty}-j_E^{\infty})/Ej_E^{\infty}$ and comparing it with the theoretical value $\gamma_0^{TH} = (v_2^2-v_1^2)/2\ln v_2/v_1$. By taking $v_1 \sim 3$ and $v_2 \sim 10$ one has $\gamma_0^{TH} \sim 40$, not far from the numerical value of about 60. As the parameter E is increased this good agreement disappears (we have $\gamma_0 \sim 90$ for E=0.06 and $\gamma_0 \sim 190$ for E=0.08), showing that the range of validity of this theory has been overcome. In this parameter regime one expects the rôle of high-$v_{\parallel}$ anticarriers to become more and more important.

This is, in fact, the case as shown in Fig. 2, where the distribution function integrated over $v_{\perp}$, $F(v_{\parallel})$, is represented for E=0.04 and E=0.08. In particular, the RF-produced antirunaway tail is clearly displayed in Fig. 3, where the negative high-$v_{\parallel}$ portion of $F(v_{\parallel})$ is shown for E=0.08, with and without RF power. In the present context the value E=0.08 is purely academical since we have seen that a realistic value has to be anyway smaller than 0.06. However, it is also true that for higher RF power, larger values of E will be involved in realistic situations so that the rôle of RF produced antirunaways is likely to be important. This, and other questions concerning the influence of the relevant parameters, like density, location of the RF spectra and so on, will be subject of future investigations.

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Figures Captions:

Fig. 1: The time evolution of the plasma current density, j, for different values of the electric field strength E.

Fig. 2: The distribution function integrated over $v_\perp$, $F(v_\parallel)$, for the cases $S_o = 10^{-7}$, $E = 0.04$ and $S_o = 10^7$, $E = 0.08$.

Fig. 3: The high negative $v_\parallel$ portion of the distribution function $F(v_\parallel)$ for the cases $E = 0.08$, $S_o = 10^{-7}$ and $E = 0.08$, $S = 0$.

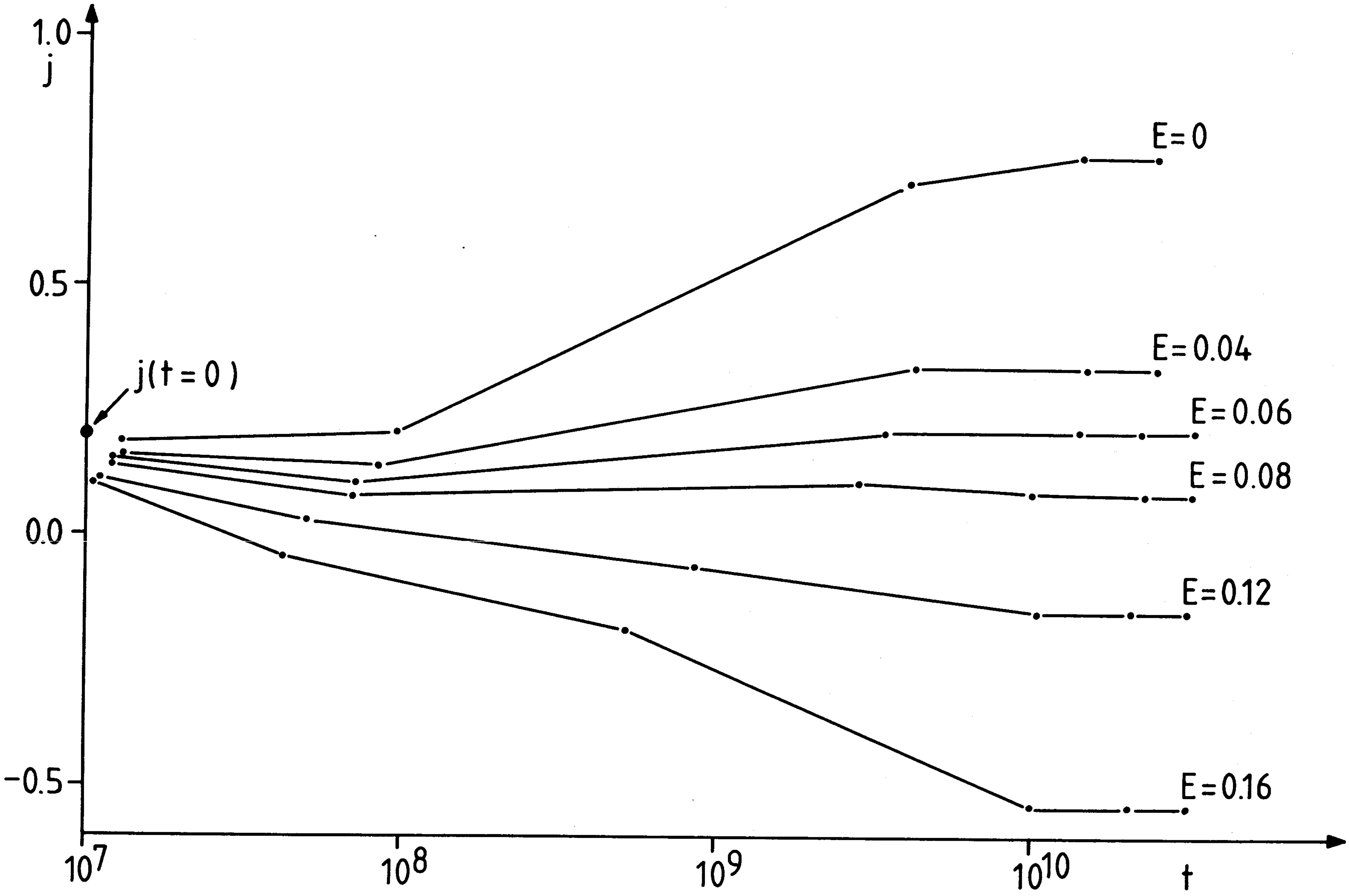

FIG. 1

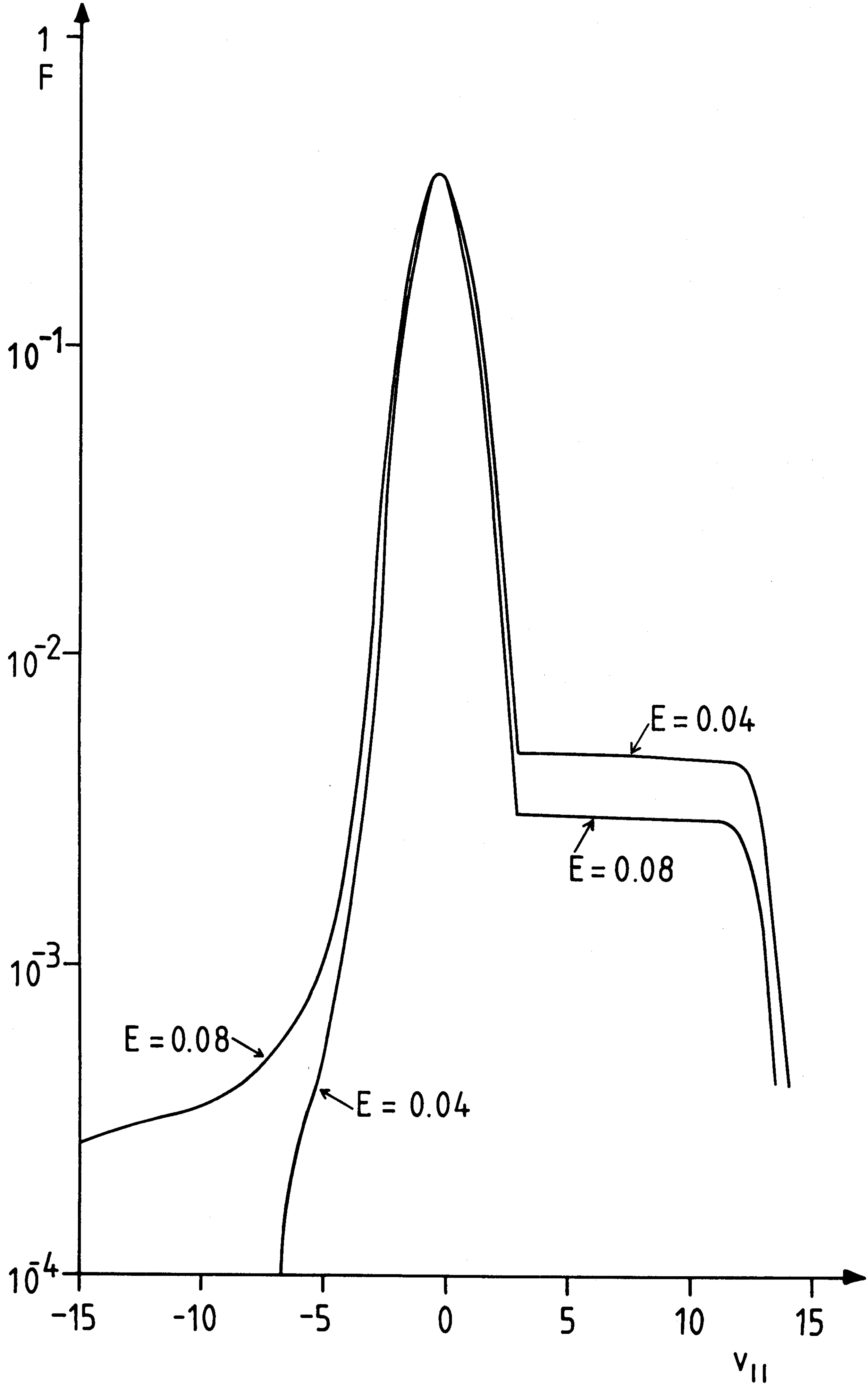

FIG. 2

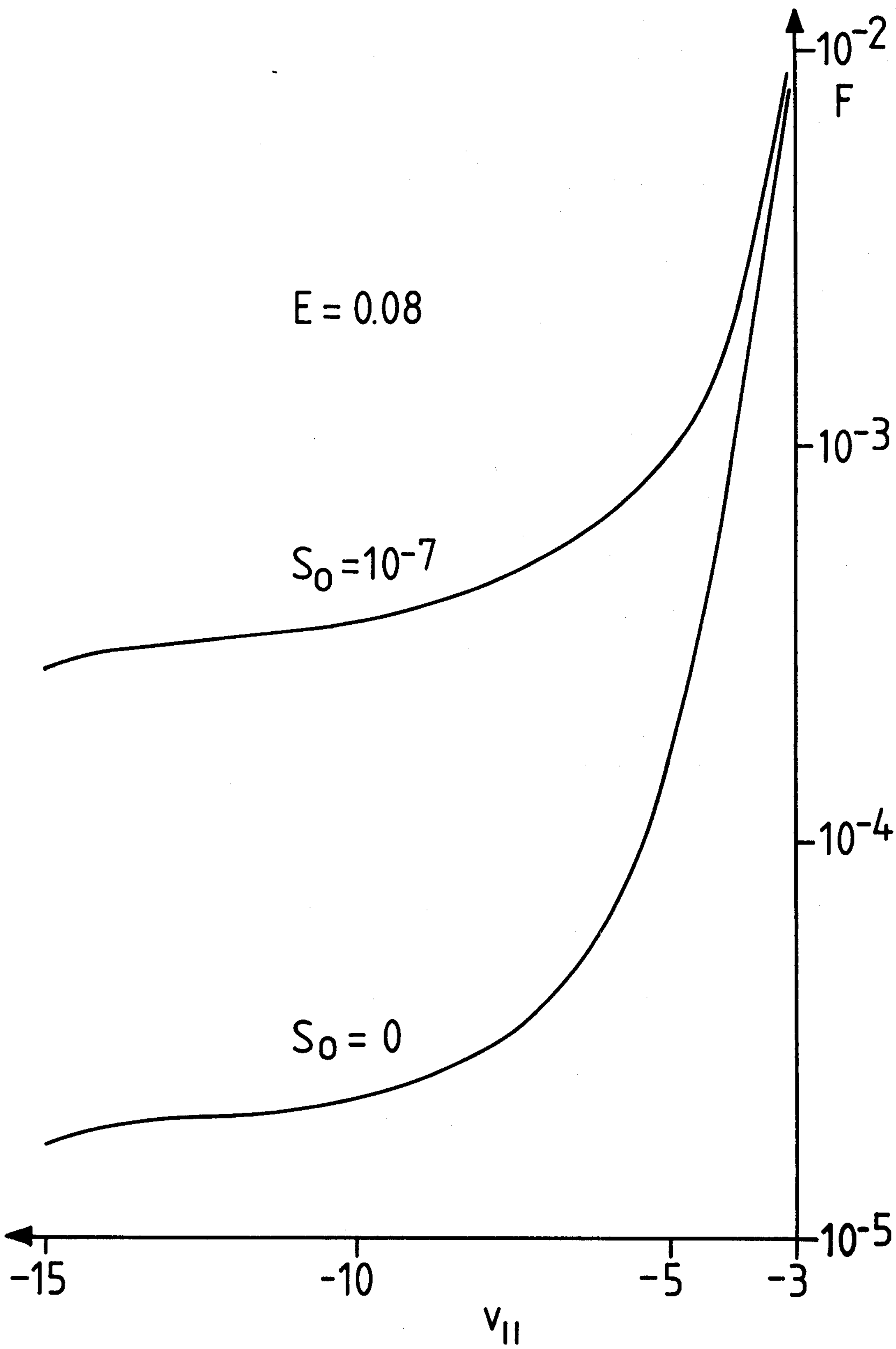

FIG. 3