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EFFECT OF THE LENGTH OF THE MULTIJUNCTION GRILL ON ITS LOWER HYBRID CURRENT DRIVE EFFICIENCY

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RESEARCH REPORT

IPPCZ-283 June 1988

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CZECHOSLOVAKIA

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The distance between the junction of the subsidiary waveguides in the main waveguide and the grill mouth has great influence upon: the spectrum of radiated waves, the total reflection coefficient, the distribution of the power among the separate waveguides and the actual phases of incident waves. This effect is nearly as important as that of the phase shift between the adjacent waveguides and it is necessary to carry out the optimization over this parameter at grill design.

Nowadays, a slow-wave structure known as the multijunction grill [1] is increasingly often used for the lower hybrid plasma heating and current drive in tokamaks. Three or four-waveguide multijunction grills serve also as construction elements of the large antenna arrays for large tokamaks [2].

A schematic view of the four waveguide multijunction grill in front of a plasma is given in fig. 1. The necessary phase shift between waves radiated from the adjacent waveguides can be obtained by adjusting their relative heights. In this paper, the influence of the length L_g of a grill upon its efficiency is investigated.

As it follows from the general theory of the wave guide junctions [3], there are simple relations among the amplitudes of waves incident on and reflected from the junction. Thus we can write

$$\begin{aligned} A'_p &= \alpha_{p,0} A' + \sum_{j=1}^{N} \alpha_{p,j} B'_j , \qquad p = 1, 2, \ldots, N, \\ B' &= \beta_0 A' + \sum_{j=1}^{N} \beta_j B'_j , \end{aligned} \tag{1}$$

where N is the number of the subsidiary waveguides in the multijunction grill, A'_p is the amplitude of wave propagating from the junction to the grill mouth in the p-th waveguide, B'_p corresponds to the wave reflected from a plasma to the junction in the same waveguide. A' and B' are the amplitudes of incident and reflected waves in the main waveguide, respectively. All these amplitudes correspond to TE_{10} modes.

The numerical values of the coefficients $\alpha_{p,j}$ and β_j are determined from the continuity conditions of the tangential components of the electric and magnetic fields at the plane of the junction. These conditions are Fourier analysed. The system of linear equations for B' and for the amplitudes of evanescent modes in the main waveguide is then solved by the method suggested in [4] for the solution of the problem of the bifurcated waveguide (see [5]).

When a wave passes the distance L_g between the junction and the grill mouth its phase increases by ϕ_p in the p-th waveguide. The reflection in the subsidiary waveguides can be substantially diminished if we use $\lambda/4$ transformers at the jumps of their height [6]. The phase ϕ_p can be expressed in a form

$$\phi_p = \phi_0 + (p-1)\Delta\phi , \qquad p = 1, 2, \dots , N, \tag{2}$$

where $\Delta\phi$ is phase shift between the adjacent waveguides. Travelling through the first waveguide (at $z = 0$) the wave acquires the phase ϕ_0. For some structures $\phi_0 = k_x L_g$, where $k_x = (k_v^2 - (\pi/a)^2)^{1/2}$, $k_v = \omega/c$, but it need not be equal $\Delta\phi$, what was probably tacitly supposed in [7].

At the grill mouth, the z-component of the electric field of wave can be written

$$E_z = \sum_{p=1}^{N} \theta_p(z)\, e^{i(\phi_p - \omega t)} \left(A_p e^{ik_v x} + B_p e^{-ik_v x} + \right. \tag{3}$$
$$\left. + \text{ evanescent modes}\right)$$

Here, the plate-parallel waveguides ($a \to \infty$) are supposed and thus the standard Brambilla's theory [8] can be used for computation of the power spectra of the grill. The function

$\theta_p(x) = 1$ in the p-th waveguide mouth and $\theta_p(x) = 0$ elsewhere. For A_p and B_p we obtain

$$(4)\quad A_p = \sqrt{\frac{k_x}{2k_v}} \cdot A'_p \;, \qquad B_p = \sqrt{\frac{k_x}{2k_v}}\, e^{-2i\phi_p} B'_p$$

and thus

$$(5)\qquad A_p = \bar{\alpha}_{p,0}\, A' + \sum_{j=1}^{N} \bar{\alpha}_{p,j}\, B_j$$

where

$$\bar{\alpha}_{p,0} = \sqrt{\frac{k_x}{2k_v}}\, \alpha_{p,0} \;, \qquad \bar{\alpha}_{p,j} = e^{2i\phi_j}\, \alpha_{p,j}$$

The factor $(k_x/2k_v)^{1/2}$ ensures that the total energy flow through the section of the height a in the parallel-plate waveguide is equal to the total energy flow through the rectangular waveguide of the height a. It follows from (5), that the incident waves do not have the same amplitudes as it is usual in the conventional grill. Also their actual phases are not equal ϕ_p because $\bar{\alpha}_{p,j}$ and B_p are generally complex. In the whole problem, the phase ϕ_0 appears only in the coefficients $\bar{\alpha}_{p,j}$, namely in the form $e^{2i\phi_0}$.

As an example we present the results obtained at the optimization of the four-waveguide multijunction grill ($a = 16$ cm, $b = 4.6$ cm, $b_p = 1$ cm, $d_p = 0.2$ cm, $L_g = 95$ cm, $f = 1.25$ GHz, $\Delta\phi = 120°$, $\phi_0 = 45°$). This structure was used in the lower hybrid current drive experiment on the small tokamak CASTOR [9]. In this tokamak the plasma is cold and, therefore, the required spectrum must be very broad ($1.5<N_z<10$, $N_z=k_z/k_v$). The plasma parameters in front of the grill were chosen in accordonance with the measured values, viz. $n_0=30n_{crit}$ and $dn/dx=8.10^{11}\,cm^{-1}$.

To describe the grill quality we shall use the following quantities: the total power reflection coefficient R_t , the total incident power in the grill mouth P_{in} ($P_{in}=\sum_{p=1}^{N}P_{in,p}$, where $P_{in,p}$ is the incident power in the p-th waveguide), the total reflected power in the grill mouth P_r ($P_r=\sum_{p=1}^{N}P_{r,p}$) and the efficiency of the current generation η_{cur} given by

$$(6)\qquad \eta_{cur}=(1-R_t)\left\{\int_{0}^{\infty}G(N_z)\,dN_z-\int_{-\infty}^{0}G(N_z)\,dN_z\right\},$$

where $G(N_z)$ is the normalized spectral density of the power radiated from the grill into the plasma ($\int_{-\infty}^{\infty}G(N_z)\,dN_z=1$). The net power leaving the grill is then $1-R_t$. It holds $1-R_t=P_{in}-P_r$. All quantities are time averaged and normalized to the unit power of the h.f. generator. For the conventional grill we have $P_{in}=1$, $P_{in,p}=1/N$, $P_r=R_t$.

From these quantities, the efficiency η_{cur} varies most conspicuously with length L_g of the grill (or with ϕ_0). It has a maximum at $\phi_0=70°$ as it is seen in fig. 2 ($\Delta\phi=120°$ in all figures). The current drive efficiency depends on the shape of the power spectrum and its parasitic branch ($N_z<0$) changes strongly with ϕ_0 (see fig. 3). At $\phi_0=70°$ only a small part of the power incident from the generator is reflected back ($R_t\approx 2\%$) but the power incident on a plasma is concentrated into two central waveguides (see fig. 4). At the same time, the incident waves in these important waveguides have the optimum phase difference equal to 90° (see fig. 5).

Overloading of the waveguides can be estimated with the help of the quantity

$$(7) \qquad \varkappa_p = ((P_{in,p})^{1/2} + (P_{r,p})^{1/2})\,(b/b_p)^{1/2},$$

which determines how many times the maximum electric field in the p-th subsidiary waveguide is larger than that in the main waveguide (e.g. $\varkappa_3 \approx 2$ in the third waveguide at $\phi_o = 70^\circ$). In the experiment, the grill length L_g was about 3 cm shorter than the optimum one (which would yield $\phi_o = 70^\circ$), and corresponded to $\phi_o = 45^\circ$. In this case, the incident power is distributed more uniformly among the separate subsidiary waveguides.

The results show that all important quantities describing the multijunction grill efficiency significantly vary with the length L_g of the grill. We can thus conclude that this parameter should be considered at the grill design.

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Figure captions

Fig. 1 Schematic sketch of the multijunction grill facing a plasma with the step and ramp profile.

Fig. 2 Dependence of the global parameters determining the grill efficiency on ϕ_o .

Fig. 3 Power spectra of waves radiated from the grill into a plasma for different values of ϕ_o ($\phi_o = 72°$ - full line, $\phi_c = 126°$ - dotted line, $\phi_o = 18°$ - dashed line).

Fig. 4 Incident and reflected powers in the separate subsidiary waveguides as functions of ϕ_o .

Fig. 5 Phases of the incident ($\phi_{in,p}$) and reflected ($\phi_{r,p}$) waves in the separate waveguides as functions of ϕ_o.

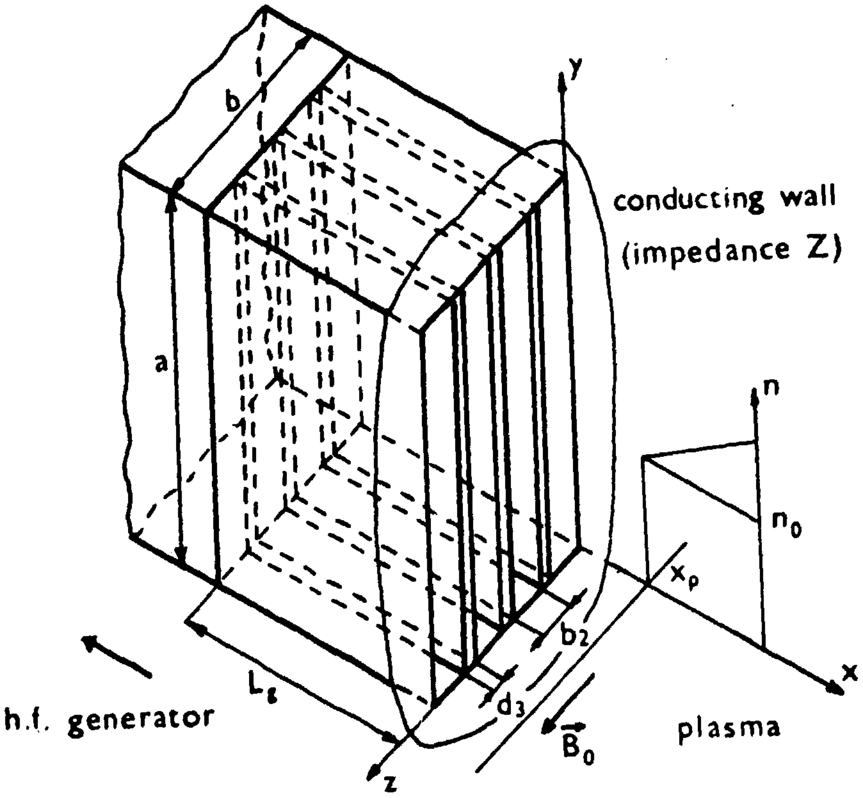
y
b
a
conducting wall
(impedance Z)
n
n_0
x_p
x
b_2
d_3
L_g
$\vec{B}_0$
h.f. generator
plasma
z

Fig. 1

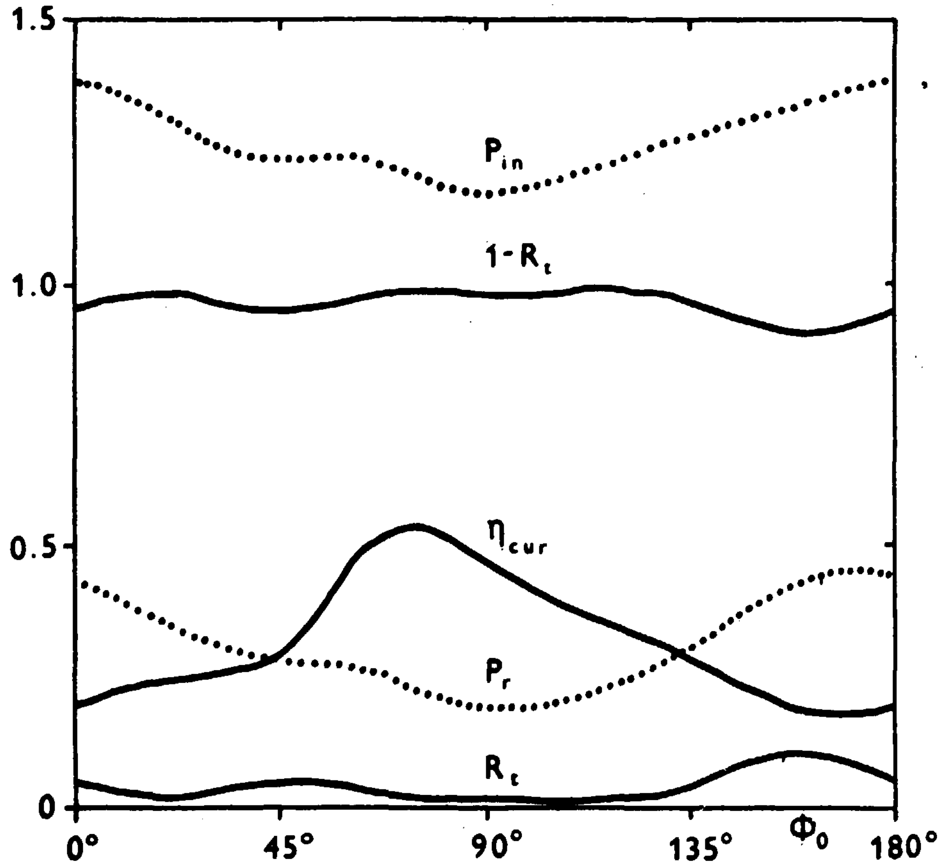

Fig. 2

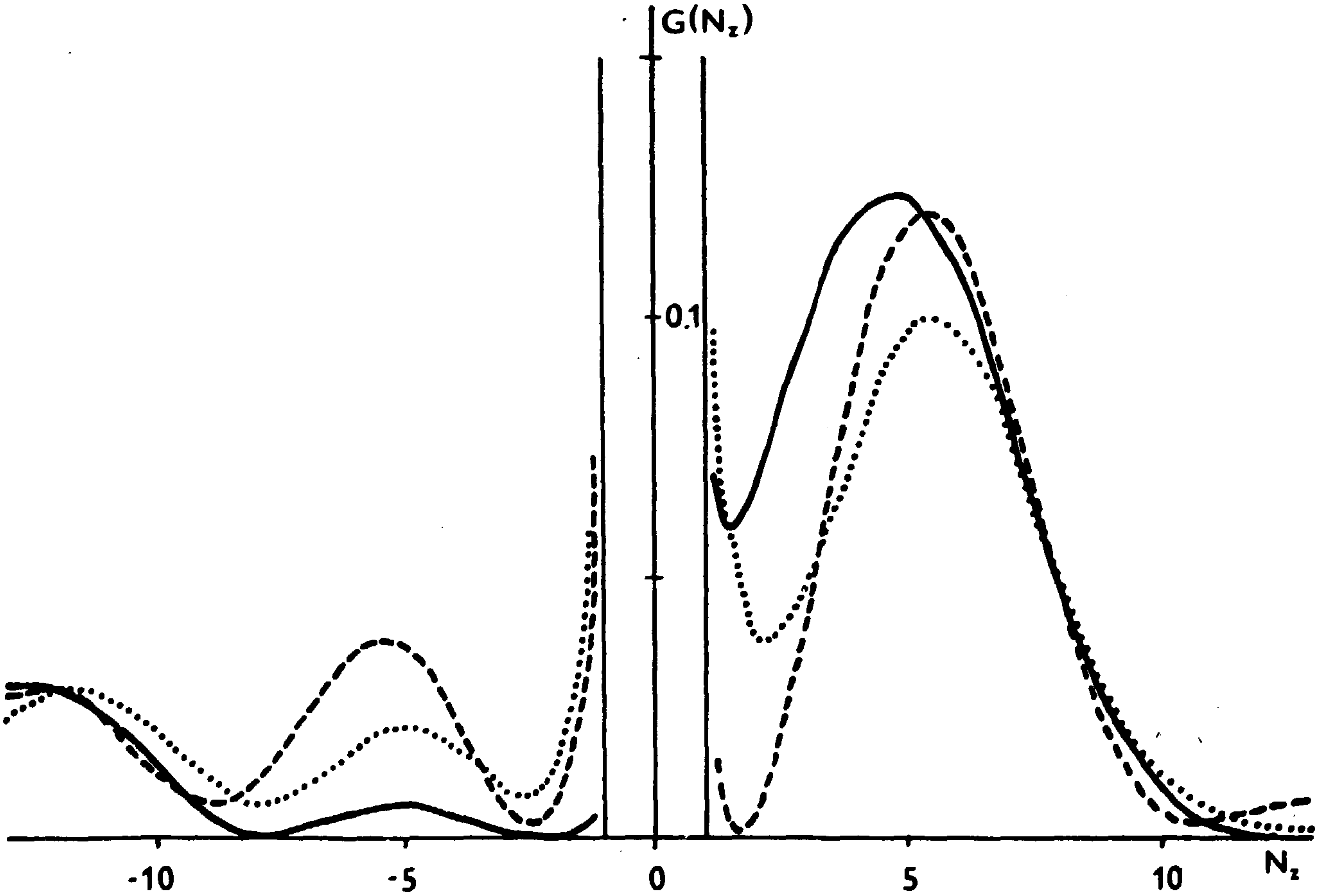

Fig. 3

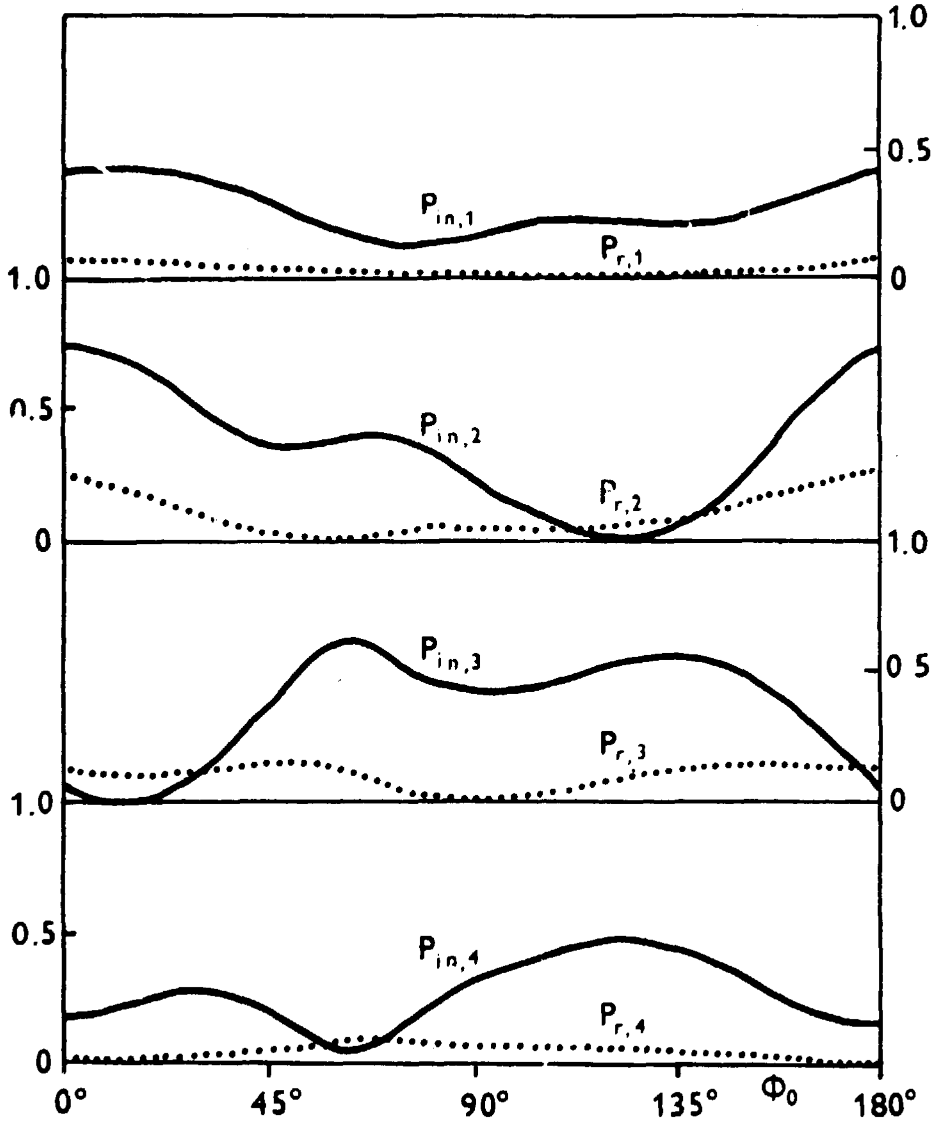
1.0
0.5
0
$P_{in,1}$
$P_{r,1}$
1.0
0.5
0
$P_{in,2}$
$P_{r,2}$
1.0
0 5
0
$P_{in,3}$
$P_{r,3}$
1.0
0.5
0
$P_{in,4}$
$P_{r,4}$
0°
45°
90°
135°
Φ_0
180°

Fig. 4

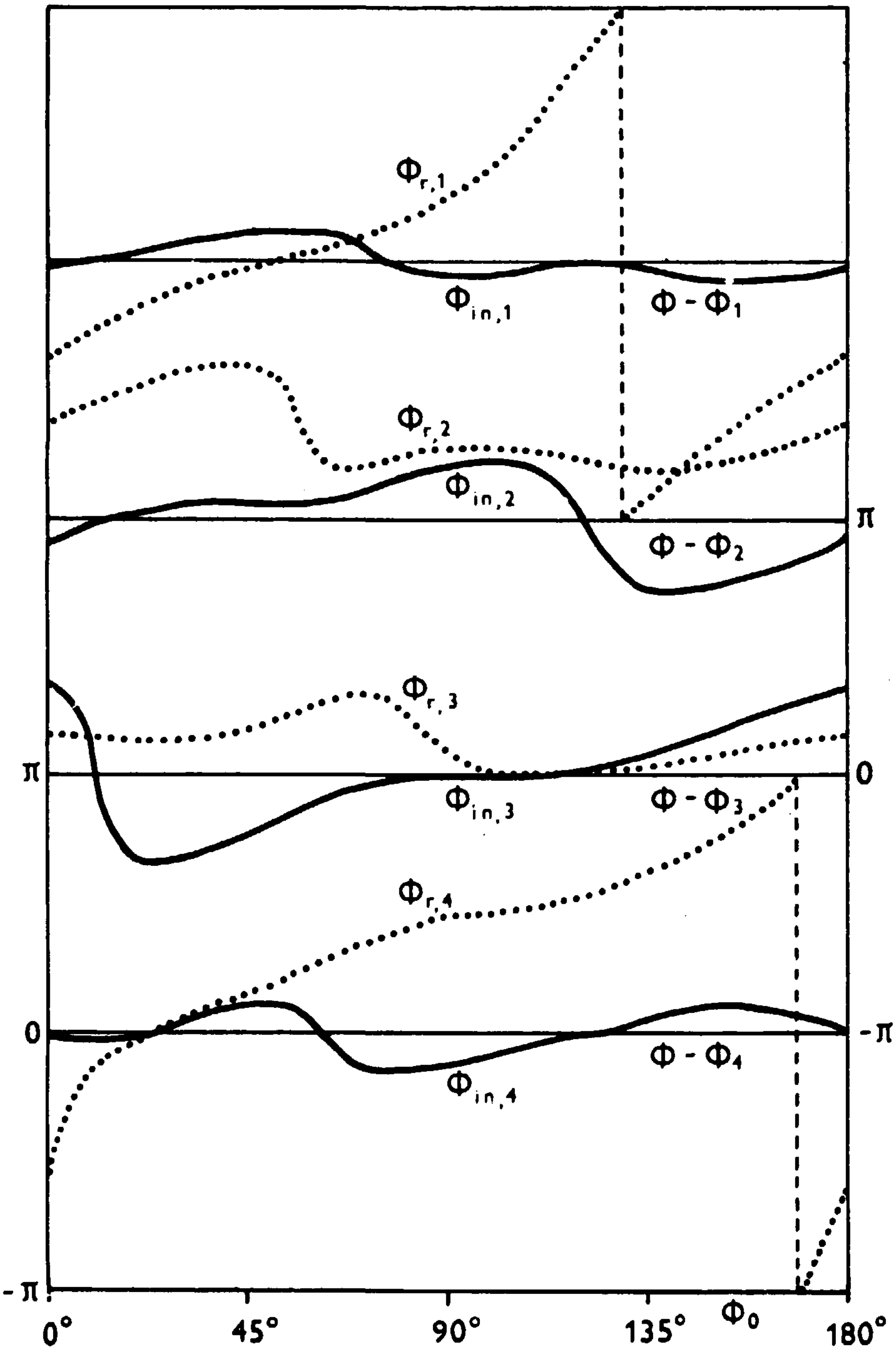
$\Phi_{r,1}$
$\Phi_{in,1}$
$\Phi - \Phi_1$
$\Phi_{r,2}$
$\Phi_{in,2}$
π
$\Phi - \Phi_2$
$\Phi_{r,3}$
π
0
$\Phi_{in,3}$
$\Phi - \Phi_3$
$\Phi_{r,4}$
0
$-\pi$
$\Phi - \Phi_4$
$\Phi_{in,4}$
$-\pi$
0°
45°
90°
135°
Φ_0
180°

Fig. 5

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