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Kunihiko OKANO*, Akiyoshi HATAYAMA* and Masayoshi SUGIHARA

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Japan Atomic Energy Research Institute

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Kunihiko OKANO*, Akiyoshi HATAYAMA* and Masayoshi SUGIHARA

Fusion Experimental Reactor Team
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken

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An effective method to control lower hybrid wave spectra and the driven current profiles is proposed. It is shown that non-uniform phasing of grill launchers under a simple order allows a wide flexibility in launching spectrum band without any appreciable deterioration in the traveling wave directivity and transmission coefficient at the grill surface. The lower hybrid wave driven current profile near the plasma periphery can be controlled flexibly by this spectrum control method.

Keywords: LHRF Current Drive, Profile Control, Wave Spectrum

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* Toshiba Corp.

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グリルランチャの非一様位相差給電による低給混成波放射スペクトルの拡がりと駆動電流分布のコントロール

日本原子力研究所那珂研究所核融合実験炉特別チーム
岡野　邦彦*・畑山　明聖*1・杉原　正芳

（１９８９年9月１９日受理）

低域混成波放射スペクトルの拡がりと，ＲＦ駆動電流の分布を効果的に制御可能な方法が提案されている。グリル・ランチャの各導波管へ給電する際の位相差を，グリル全体で一様とせず，ある単純な秩序に従って非一様化することにより，波の進行波比やグリル表面での反射を目立って悪化させることなく，波のスペクトル幅を調整可能であることが示された。プラズマ周辺部の駆動電流分布は，このスペクトル制御法により柔軟に調整されうる。

那珂研究所：〒311－01　茨城県那珂郡那珂町大字向山801－1

* ㈱東芝

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1. INTRODUCTION

A lower hybrid wave (LHW) current drive in tokamaks is no doubt the most successful in various non-inductive current drive methods proposed and tested to date. The wave propagation, of course, must be unidirectional to drive the currents. Such traveling waves can be generated by a 'grill launcher (Brambilla, [1])' which consists of a phased wave guide array. With increasing the r.f. power injected into tokamaks, the number of wave guide row, N, and the grill launcher width tend to increase, owing to the power density limit on the grill surface. On one hand, a larger N is preferable to the current drive, because it will improve the figure of merit on wave directivity, F, which is a ratio between the wave powers launched in $0 < v_p < c$ and that in $-\infty < v_p < +\infty$, where v_p is r.f. phase velocity. On the other hand, the large N and wide wave guide array result in a very narrow band wave spectrum. With uniform phasing, ($\Delta\phi$ = constant), which has been usually used for the phasing of a LHRF grill launcher, the spectrum broadness is uncontrollable once the grill width and row number are given, while the spectrum peak position is tunable. If a variety of spectrum broadness is available, the current drive characteristics, current profile for example, will be flexibly controlled.

The authors proposed, an effective method to control the spectrum broadness without any appreciable deterioration in the wave directivity F (Hatayama et al., [2]). The idea is to make the relative waveguide phasing on the grill non-uniform under an simple order. This non-uniform phasing allows a wide flexibility in the launching spectrum band.

In this paper, it will be shown that the driven current profile can be controlled flexibly by the non uniform phasing method. The current generated by LHRF is localized near the periphery, even when the profile is controlled by the non uniform phasing. It is suggested that this LHRF driver feature will be useful as an edge current profile controller in beam driven steady state tokamaks (Okano et al., [3]). If the LHRF edge current drive is combined with the beam current drive, the beam shinethrough passed low density periphery could be reduced considerably. The flexible edge current profile control method by non uniform phasing will be useful in such an application.

2. NON UNIFORM PHASING METHOD

In the non-uniform phasing method, the relative phasing $\Delta\phi_k$ between wave guide row No. K and No. K+1 is not constant, but is orderly modified as follows;

$$\Delta\phi_k = \Delta\phi_0 + (K-1)\delta \qquad [K=1,2,3\cdots, N-1] \quad , \qquad (1)$$

where $\Delta\phi_0$ is a constant value. In order to obtain travelling waves without directivity deterioration, the condition

$$|\Delta\phi_0| >> |\delta| \qquad (2)$$

must be satisfied. For example, with $\Delta\phi_0$ = 60° and δ = 1°, non-uniform under an simple order. This non-uniform phasing allows a wide flexibility in the launching spectrum band.

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must be satisfied. For example, with $\Delta\phi_0 = 60°$ and $\delta = 1°$, the absolute r.f. phases for No. 1,2,3, ··· N wave guides are '0°, 60°, 121°, 183°, 246° ... etc.'

An example of the absolute phase ϕ_K for No. K wave guides are shown in Fig. 1, where $\phi_K = \Sigma\Delta\phi_K$. In the non-uniform phasing case, the phase deviation from the uniform phasing case ($\delta = 0$) becomes appreciable with increase in K. Then, wide spectrum waves are launched. The required phase accuracy is not so severe as shown later (see Section 6). The several degree random error in $\Delta\phi_K$ is allowable.

3. NUMERICAL ANALYSIS MODEL

The launched wave spectra and the other characteristics were examined by numerical calculations, based on the Brambilla's method (Brambilla, [1]). The wave propagation is simulated by a 3-D ray tracing code. The driven current density on individual flux surfaces are estimated by the 1-D Fokker-Planck code. The plasma parameters assumed in this study are: the major radius $R_0 = 4.9$ m and minor radius $a = 1.17$ m. The plasma cross-section is assumed as to be circular because of the restriction in the available ray tracing code. The density and current profiles are assumed as parabolic ones. The magnetic flux surfaces in the plasma are also assumed as to be concentric circulars with no axis shift. This assumption is inconsistent to the MHD equilibrium, but sufficient for the present purpose.

All the parameters used in this study are listed in Table 1. The values dn_e/dx and x_p are used in the wave spectrum calculation.

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4. SPECTRUM CONTROL

The spectrum for the conventional uniform phasing cases are plotted in Fig. 2-a as functions of $|n_{//}|$, where $\Delta\phi_0$ are changed from 60° to 150° with $\delta = 0$. The broken lines indicate the negative $n_{//}$ part of the spectrum. The non-uniform cases are shown in Fig. 2-b, where $\Delta\phi_0 = 90°$ and the δ values are changed from 1° to 6°. In the cases of uniform phasing, the peak position of the $n_{//}$ spectrum is tunable by changing the $\Delta\phi_0$ value. However, the spectrum width is nearly independent of $\Delta\phi_0$. On the other hand, in the case of non-uniform phasing, the spread of the spectrum can be controlled by the δ value variation. At the same time, the deterioration in the wave directivity F (= total launched power/positive $n_{//}$ power) is nearly negligible (Hatayama et al., [2]).

5. CURRENT PROFILE CONTROL

The driven current profiles are compared in Fig. 3, for both the uniform and non-uniform phasing case. The basic case, $\Delta\phi_0 = 90°$ with $\delta = 0°$, is shown in Fig. 3-a, where 4.5 MA current has been driven with the launched r.f. power 30 MW. The driven current profile, in the case of $\Delta\phi_0 = 120°$ uniform phasing [Fig. 3-b], is very similar to that of the $\Delta\phi = 90°/\delta = 2°$ non-uniform phasing case [Fig. 3-d]. The driven currents are also close to each other [2.6 MA for (b) and 2.7 MA for (d)]. Increasing $\Delta\phi_0$ up to 150°, the current peak shifts outward [Fig. 3-c]. A similar outward shift is

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6. REQUIREMENT IN WAVE PHASE ACCURACY

In the non-uniform phasing method, the accuracy of each wave guide phase is not so severe. The error within about $\pm\delta$ is acceptable, if it is a ramdomized error. The current profiles and the launched wave spectra are compared in Fig. 5, where (b) is the ideal (un-perturbed) case; $\Delta\phi = \Delta\phi_0 + (N-1)\delta$ and (c) is the case with a random phase purturbation E(N); $\Delta\phi = \Delta\phi_0 + (N-1)\delta + E(N)$. The perturbation E(N) used here is plotted in Fig. 5(a). The amplitude of E(N) is the order of δ. However, its impacts on the current profile and on the wave spectra are very small.

The $\Delta\phi$ control within 2 $\sim$ 3 degree error is achievable by existent feedback control technology (for example, the 2.45 GHz system for ASDEX [4]).

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7. CONCLUSION

The weakness of LHCD is its difficulty in driving in high density plasmas. However some current could be driven by LHCD in the low density edge region. It was clarified that the edge current profile driven by LHCD can be controlled very flexibly by the non-uniform phasing in the grill launcher. The combination of this method with other current drivers to drive the plasma core currents, for example the fast wave or the neutral beam, will provide a flexible current profile controllability, which would be indispensable to achieve the high beta steady state operation.

The authors thank Dr. T. Imai for his valuable advice and comments.

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Table 1 Plasma and RF Parameters

Plasma Parameters				
Major radius	R_0	(m)	4.9	
Minor radius	a	(m)	1.17	
Toroidal field	B_T	(T)	5.5	
Elec. Temperature (parabolic)	T_{eo}	(keV)	25.0	
Ion Temperature (parabolic)	T_{io}	(keV)	20.0	
Elec. density	n_{eo}	(m^{-3})	5×10^{19}	
Effective charge	Z_{eff}		1.5	
RF Parameters				
RF frequency	f	(GHz)	2.0	4.0
Density gradient*	dn_e/dx	(m^{-4})	10^{19}	←
Vacuum thickness*	x_p	(m)	0.0	←
Wave guide width	w	(mm)	12.5	8.0
Wave guide height	h	(mm)	108.0	54.0
W.G. wall thickness	d	(mm)	1.0	1.4
Grill size (toroidal)	N	—	20	20
Grill size (poroidal)	M	—	4	4

* in front of grill surface

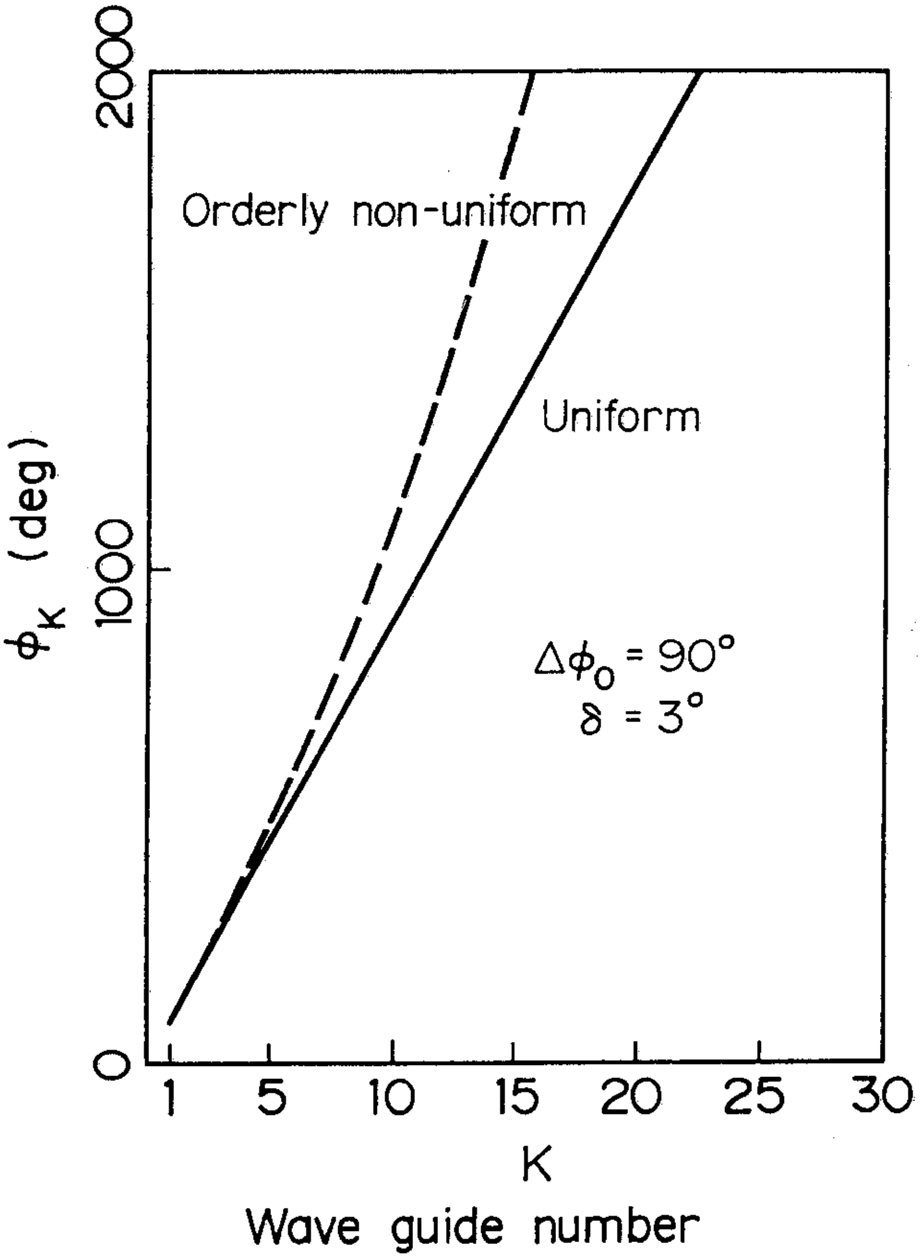


Fig. 1 Absolute wave phases ϕ, for the conventional uniform phasing case and for the non-uniform phasing case.

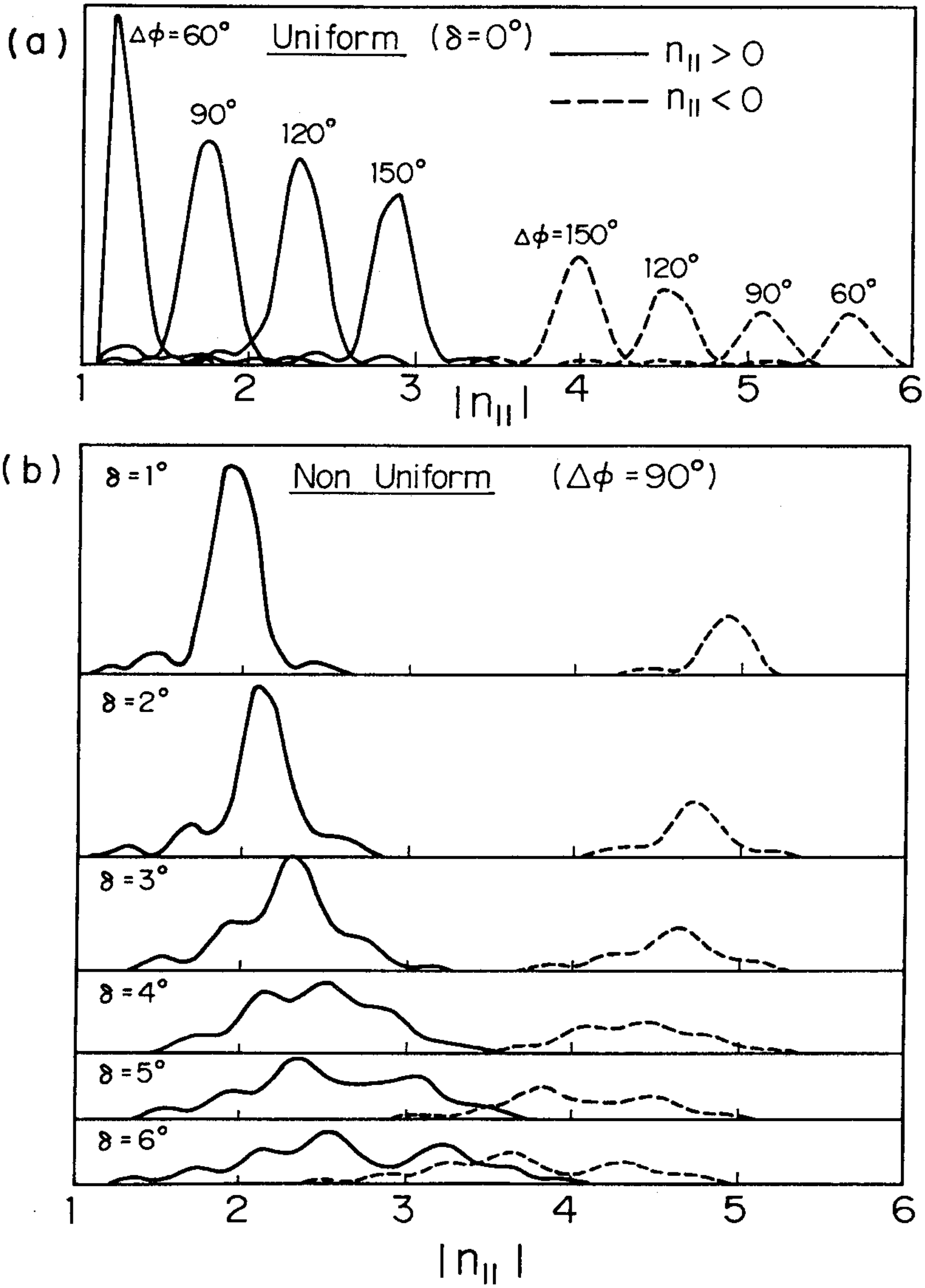


Fig. 2 Variation of wave spectrum broadness.

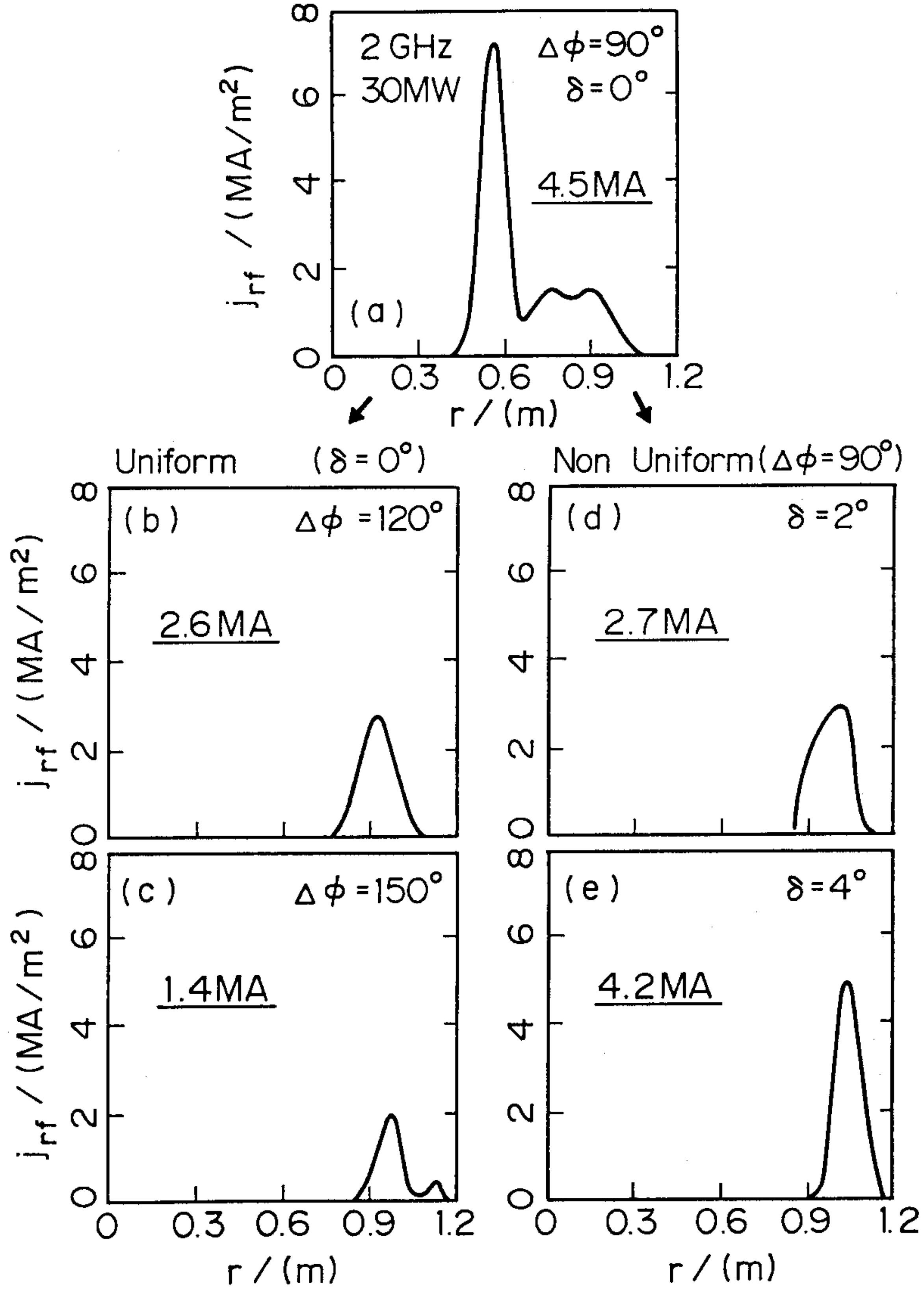


Fig. 3 Variation of the current profiles (f = 2 GHz).

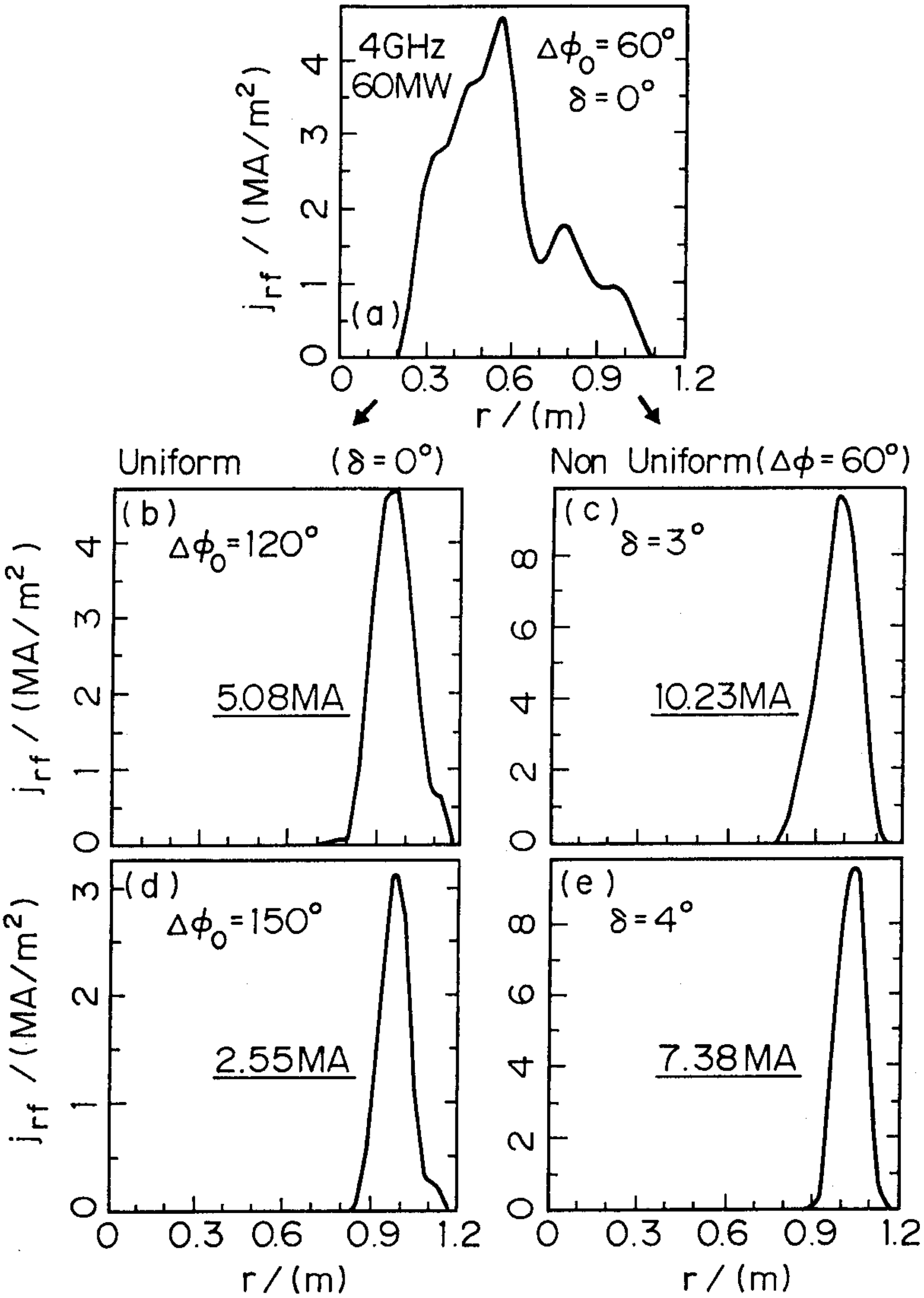
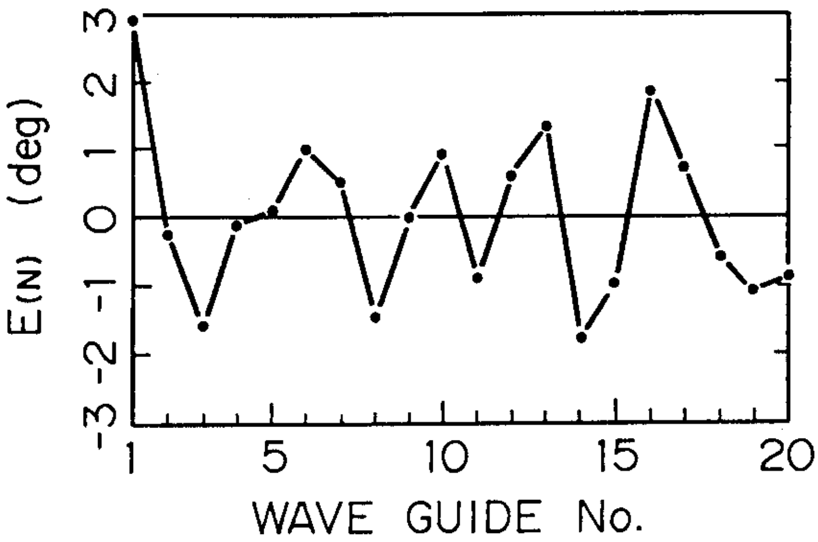


Fig. 4 Variation of the current profiles (f = 4 GHz).


(a) Additional perturbation

(b) $\Delta\phi = \Delta\phi_0 + (N-1)\delta$ (c) $\Delta\phi = \Delta\phi_0 + (N-1)\delta + E(N)$

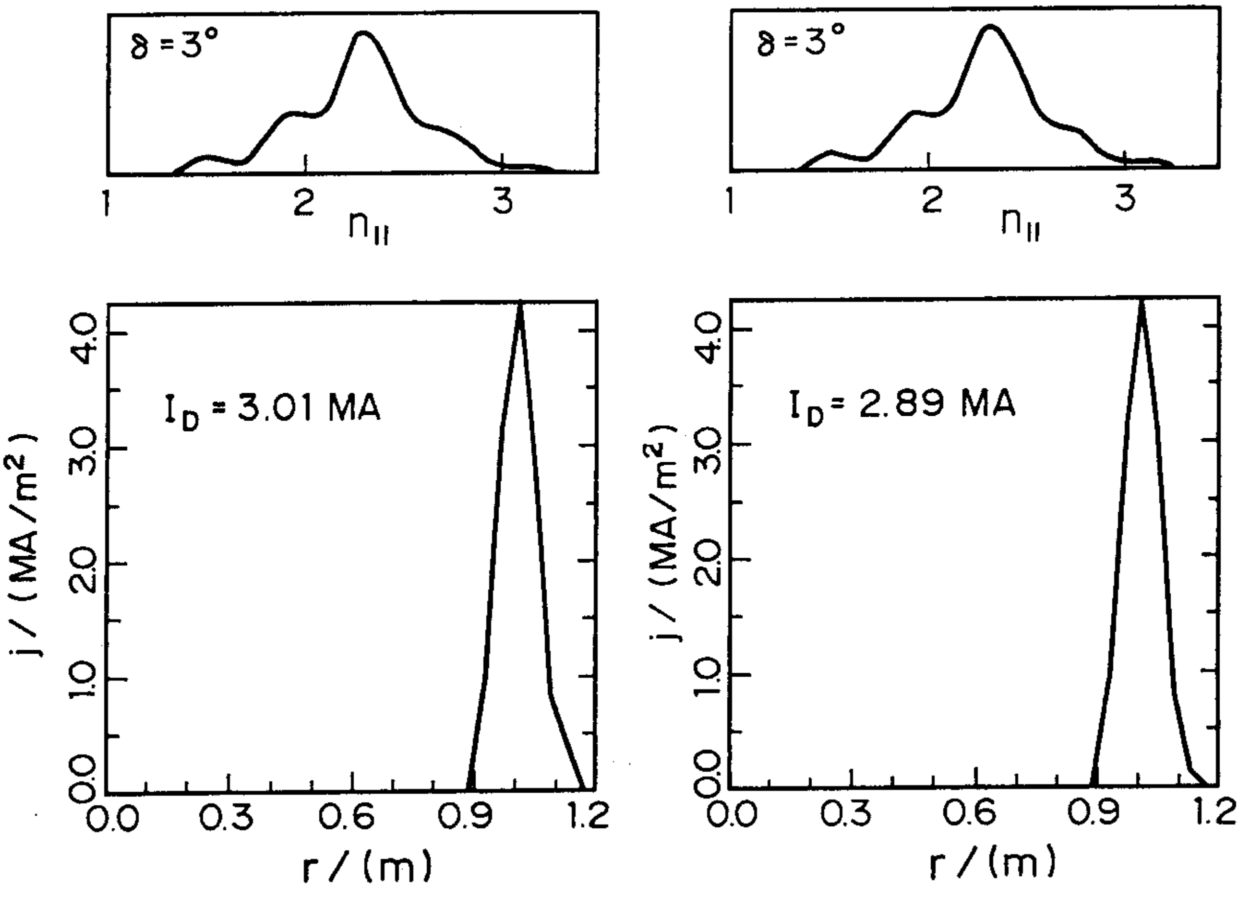


Fig. 5 Impacts of a ramdomized phase error E(N).