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# FORMATION AND DESTRUCTION OF MAGNETIC ISLANDS IN TOROIDAL SYSTEMS [1]

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We present a theoretical study of formation and destruction  
of magnetic surfaces in toroidal systems. As applied to levitrons  
the theory agrees with the numerical results.

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Perturbed magnetic surfaces in toroidal systems are equivalent to  
nonlinear oscillating systems with rotational transform for frequency.  
Resonances that transform the unperturbed surfaces into a structure of  
magnetic islands we call primary resonances and the secondary resonances  
transform the bound-state like contours of a given island into a similar  
structure of secondary magnetic islands. To every magnetic island we  
attach two types of stochasticity, external due to the overlapping of  
primary resonances and internal due to the overlapping of secondary  
resonances, Fig. 1.

## 1. Nonlinear Oscillating Systems

We consider the nonlinear equations:

$$\left. \begin{aligned} \frac{dI}{dt} &= \frac{\epsilon}{\nu} \left[ \nu^{2\delta} \Gamma(I, \theta, t) \right] + O(\epsilon^2) & (a) \\ \frac{d\theta}{dt} &= \nu \left\{ 1 + \epsilon \left[ \nu^{2\delta'} \Pi(I, \theta, t) \right] + O(\epsilon^2) \right\} & (b) \end{aligned} \right\} (1.1)$$

where  $\Gamma$  and  $\Pi$  are periodic functions of  $\theta$  and  $t$ , and  $\epsilon$  is a small parameter.  $\delta$  and  $\delta'$  are introduced to allow  $\Gamma$  and  $\Pi$  to include terms that are not functions of  $v$ . We derive Eq. (1.1) for levitrons, where  $2\pi v(I)$  is the rotational transform.  $(I, \theta)$  are the action and angle variables corresponding to  $(\frac{r^2}{2}, \phi)$ , where  $r, \phi, z$  are the toroidal coordinates and  $t$  is determined from the relation  $dt \equiv dz/B_z$ . The major radius of the torus is normalized to 1. Equations (1.1) were also derived for the stellarator [2].

### 1.1 Primary Resonances:

We let  $v(I)$  be positive between the central magnetic axis and the separatrix. ( $v < 0$  can be treated similarly). Primary resonances are obtained from secular contributions and are characterized by  $m_i v_i - l_i = 0$  where  $m_i, l_i$  are the lowest positive integers satisfying  $m_i v_i - l_i = 0$ . Their nonlinearity coefficients are given by:

$$x_i = \left| \frac{dv}{dI}(I_i) \right| \frac{I_i}{v_i}. \quad (1.2)$$

In the following, we assume that  $x \gg \epsilon^{1/2}$ .

This assumption is verified for the levitron (refer to table 1).

In the vicinity of a given resonance stable island contours may occur in the region  $\epsilon^{1/2} I_i \sim |\Delta I| \ll I_i$ . We expand (1.1) in this region and average over fast oscillations, we get:

$$\left. \begin{aligned} \frac{d}{dt} \Delta I &= \frac{2\epsilon}{v_i} f_{v_i}(I_i, u) & (a) \\ \frac{du}{dt} &= \mu \Delta I & (b) \end{aligned} \right\} (1.3)$$

where  $u = \ell_1 t - m_1 \theta$ ,  $\mu = -m_1 (d\psi(I_1)/dI)$  and

$$f_{v_1}(I, u) = \frac{2\delta}{2\pi} \int_0^{2\pi} \Gamma(I, -\frac{u}{m_1} + v_1 t, t) dt \quad (1.4)$$

Equations (1.3)ab can be derived from the Hamiltonian:

$$K(\Delta I, u) = \frac{\mu}{2} (\Delta I)^2 - \frac{2\epsilon}{v_1} \int_0^u f_{v_1}(I_1, y) dy, \quad (1.5)$$

where surfaces of constant  $K$  will represent the island contours. The condition that  $\Delta I$  be real defines a discrete set of intervals for  $u$  variations, thus forming  $m_1$  families of contours separated by a local separatrix. Each family we call an island, the center of which is an elliptic singularity. We used relation (1.5) to plot some magnetic island contours for the levitron [3].

The primary resonance width  $\Omega_1$  is related to the maximum

action excursion by:  $\Omega_1 = v_1 x_1 \frac{\text{Max} |\Delta I|}{I_1}$ . We get:

$$\Omega_1 = 2\epsilon^{1/2} \sqrt{\frac{x_1}{I_1}} v_1^\delta F_1(I_1, \ell_1, m_1), \quad (1.6)$$

where  $F_i(I_i, l_i, m_i)$  is a form factor which characterizes the system and depends on the resonance parameters.

## 1.2 Island Perturbation and Secondary Resonances:

We let  $\{\alpha_j\}_1^{m_i}$  be the set of elliptic singularities, and re-normalize  $t$  to  $\tau = v_i t$ . The island oscillations, (in terms of  $v_j \equiv \Delta I[u(w_j)]$ ,  $w_j = (\text{Sgn} \mu) \tilde{u}_j$ , where  $\tilde{u}_j = u - \alpha_j$ , and  $\tau$ ), are of the libration type. If we introduce the action and angle variables  $(J, \eta)$  corresponding to  $(v_j, w_j)$  the island contour equations become:

$$\frac{dJ}{d\tau} = 0; \quad \frac{d\eta}{d\tau} = \omega, \quad (1.7)$$

where  $\omega$  is a positive function of  $J$  in the region between the elliptic singularity and the local separatrix [1]. At the local separatrix  $\omega = 0$ .

The island perturbations obtained from Eqs. (1.1)ab perturb (1.7) as follows:

$$\left. \begin{aligned} \frac{d}{d\tau} \Delta J &= \frac{\sqrt{m_i} x_i \epsilon^3}{\omega \sqrt{2I_i} v_i^{3-2e'}} \tilde{A}(J, \eta, \tau) & (a) \\ \frac{d}{d\tau} \Delta \eta &= \frac{d\omega}{dJ} \Delta J & (b) \end{aligned} \right\} (1.8)$$

where  $\tilde{A}(J, \eta, \tau)$  is a periodic function of  $\eta$  and  $\tau$  [1],  
 $e' = \delta + e$  and  $e$  is the lesser of  $\delta$  and  $\delta'$ .

Secondary resonances are characterized by  $q_k \omega_k - p_k = 0$ , where  $p_k, q_k$  are the lowest positive integers satisfying  $q_k \omega_k - p_k = 0$ . We let  $M = -q_k \frac{d\omega}{dJ}(J_k)$ ,  $\xi = p_k \tau - q_k \eta$  and  $\tilde{f}_{\omega_k}(J, \xi) = \langle \tilde{A}(J, -\frac{\xi}{q_k} + \omega_k \tau, \tau) \rangle_\tau$ . We linearize (1.8) near the secondary resonance  $\omega_k$  (for  $\epsilon I \sim |\Delta J| \ll \epsilon^{1/2} I$ ) and average over  $\tau$ , we get:

$$\left. \begin{aligned} \frac{d\Delta J}{d\tau} &= \frac{\sqrt{2} \epsilon^3 m_i x_i}{\omega_k I_i^{1/2} v_i^{3-2e}} \tilde{f}_{\omega_k}(J_k, \xi) & (a) \\ \frac{d\xi}{d\tau} &= M \Delta J & (b) \end{aligned} \right\} (1.9)$$

Equations (1.9) can be derived from the Hamiltonian:

$$h(\Delta J, \xi) = \frac{1}{2} M(\Delta J)^2 - \frac{\sqrt{2} \epsilon^3 m_i x_i}{\omega_k I_i^{1/2} v_i^{3-2e}} \int_0^\xi \tilde{f}_{\omega_k}(J_k, y) dy \quad (1.10)$$

where surfaces of constant  $h$  represent the secondary island contours.

The secondary resonance width  $\Delta_{ik}$  is related to the maximum excursion of  $J$  by  $\Delta_{ik} = X_k \omega_k \frac{\text{Max} |\Delta J|}{J_k}$  where  $X_k = \left| \frac{d\omega_k}{dJ} \right| \frac{J_k}{\omega_k}$ . We get:

$$\Delta_{ik} = \frac{\sqrt{2}}{v_i^{3/2-e}} \left( \frac{2\epsilon^3 m_i x_i}{I_i} \right)^{\frac{1}{4}} \sqrt{\frac{X_k}{J_k}} \tilde{F}_k(J_k, p_k, q_k), \quad (1.11)$$

where  $\tilde{F}_k$  is a form factor that characterizes the system and depends on the secondary resonance parameters.



## 2. Instabilities and Destruction of the Magnetic Surfaces:

### 2.1 Overlapping of Resonances:

It is well confirmed [5] that a strong instability with random like behavior occurs when resonances overlap.

Overlapping of two neighboring resonances occurs if their separation is smaller or equal to the arithmetic average of their widths. Overlapping of resonances below a given frequency  $\nu_j$  means that the sum of the widths of all resonances with frequencies smaller or equal to  $\nu_j$ , is greater or equal to  $\nu_j$ , (this assumes that overlapping proceeds in the order from the separatrix). We take this criterion to define the limit of stochasticity below  $\nu_j$ , it is equivalent to:

$$\nu_j \sim \sum_{\nu_i \leq \nu_j} \Omega_i(I_i, l_i, m_i), \quad (2.1)$$

and should give an underestimate of the critical perturbation for  $\nu_j$ . Assuming that for every pair  $m_i, l_i$  there is a resonance, we get from (2.1):

$$\nu_j \sim \sum_{m=\frac{1}{\nu_j}}^{\infty} \sum_{l=1}^m \left[ \Omega(I, l, m) - \sum_{p=2}^{\infty} \Omega(I, p, l, pm) \right] \quad (2.2)$$

If we replace sums by integrations (2.2) becomes:

$$1 \sim \int_{\frac{1}{\nu_j}}^{\infty} m \, dm \left[ \bar{\Omega}(m) - \int_{2m}^{\infty} dy \, \bar{\Omega}(y) \right] \quad (2.3)$$

where

$$\bar{\Omega}(m) = \frac{1}{v_j} \int_{1/m}^{v_j} \Omega(I, y, m) dy \quad (2.4)$$

and  $\Omega(I, \ell, m)$  is an interpolating function that equals  $\Omega_i$  at the  $i$ -resonance position for all  $i$ 's.

From (2.3) and (1.6), if  $\epsilon_j$  is the limit of external stochasticity below  $v_j$ , we get:

$$G_j \epsilon_j^{1/2} \sim \frac{1}{2} \sqrt{\frac{I_j}{x_j}} v_j^{-\delta} \quad (2.5)$$

where  $G_j$  depends on the system and the ordering of the resonance.

If  $\epsilon_{jk}$  is the limit of internal stochasticity for the  $v_j$  resonance below the  $\omega_k$  secondary resonance, from (1.11) and (2.3) we get:

$$\tilde{G}_k \epsilon_{jk}^{3/4} \sim \frac{\sqrt{2}}{2} \left( \frac{I_j}{2m_j x_j} \right)^{1/4} \sqrt{\frac{J_k}{x_k}} v_j^{3/2 - \delta} \quad (2.6)$$

where  $\tilde{G}_k$  depends on the system and the ordering of the secondary resonance  $\omega_k$ .

Near the elliptic singularities we have shown that  $X_k \sim 1$  [1]. Also, from Eq. (1.5) one can easily show that  $J_k \sim \epsilon_{jk}^{1/2} I_j v_j^{\delta-1/2} x_j^{-1/2}$ . If we substitute in (2.6) we get:

$$\tilde{G}_k \epsilon_{jk}^{1/2} \sim \frac{\sqrt{2}}{(2m_j)^{1/4}} I_j^{3/4} v_j^{5/4 - (\delta + \frac{\delta}{2})} x_j^{-3/4} \quad (2.7)$$

Since each island is similar to the whole structure [6], we assume that  $\tilde{G}_j \sim G_j$ . By substituting in (2.7) and (2.5) we get:

$$\epsilon_{jj} = \frac{8}{\sqrt{2m_j}} \sqrt{\frac{I_j}{x_j}} v_j^{5/2 - \delta''} \epsilon_j \quad (2.8)$$

where  $\delta'' = 2e - \delta$ .

For the stellerator, where  $\epsilon$  was below the external stochasticity limit [2], formula (2.8) explains why destruction occurred near the separatrix. In Fig. 1, we show a typical example of destruction by internal overlapping in levitrons. We note also that secondary magnetic islands appear in Fig. 1c.

For the levitron ( $\delta=0=\delta'$ ) we calculated  $\epsilon_j$  by directly testing the overlapping of neighboring primary resonances and deduced  $\epsilon_{jj}$  by using Eq. (2.8). The results are tabulated in table 1. (For the levitron  $\epsilon$  is a tilt angle; in table 1 it is given in degrees). We conclude that for  $v_j \leq 2$  destruction is caused by internal overlapping. In table 1 quantities in parenthesis are the theoretical limits for destruction.  $\epsilon_c$  are the numerically measured tilts for which the resonances are completely destroyed [4].

### 3. Conclusions:

It has been established that if resonances overlap, a rapid destruction of their island structure occurs [5].

- 1 - Thus, if primary resonances overlap, a rapid destruction of their flux surfaces is expected.
- 2 - For large nonlinearity coefficients ( $x \gg \epsilon^{1/2}$ ), the field lines are trapped in an effective potential well near the primary resonances forming trapped contours in the region of each stable primary resonance. Another possible phenomenon of destruction is the overlapping of secondary resonances. Depending on the resonance (and the system) destruction may occur by either or both phenomena.
- 3 - The primary island width increases as  $\epsilon^{1/2}$  while the secondary island width increases as  $\epsilon^{3/4}$ . Internal overlapping proceeds almost orderly from the local separatrix to the elliptic singularity. Therefore, for islands that are most affected by internal overlapping the observed primary width should increase at a slower rate than  $\epsilon^{1/2}$  due to the successive disappearance of outer contours destroyed by secondary resonances overlapping. This is in agreement with the numerical observation by Freis et al where the 1 and 1/2 resonances width increase as  $\epsilon^{1/2}$  until breakup while the 3/2, 2, 5/2 and 3 resonances width increases as  $\epsilon^{3/2}$ .
- 4 - For small nonlinearity ( $x \leq \epsilon^{1/2}$ ) the field lines may escape the resonance zone and cause instabilities [1,7].
- 5 - For levitrons ( $\delta=0=\delta'$ ) we plot the critical perturbations of resonances as functions of  $x$  (Fig. 1). These functions are determined from formula (2.5) (formula (2.7)) for primary (secondary) resonances. The arbitrary constants are determined from

the values of  $(x_j, \epsilon_j (\epsilon_{jj}))$  given in Table 1. Obviously the regions of external (internal) stochasticity lie on the right hand side of the  $P(S)$  curves. The encircled points are numerical, from Table 1. We note that below  $x = \epsilon^{1/2}$  there is no trapping in the sense described above.

- 6 - For systems which are characterized by  $\delta'' < 5/2$ , Eq. (2.8) shows that the region of internal stochasticity extends over all of the  $x - \epsilon$  plane as  $v_j$  approaches zero; thus flux surfaces are always destroyed near the separatrix.

#### Acknowledgement:

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#### References:

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- [2] Filonenko, et al., Nuclear Fusions 7, 253 (1967).
- [3] To be published
- [4] Freis, et al., UCRL-51104, LLL Livermore (1971).
- [5] Rosenbluth et al., Nuclear Fusions 6, 297 (1966).
- [6] V. I. Arnold and A. Avez, Ergodic Problems of Classical Mechanics, (Benjamin, 1968).
- [7] B. V. Chirikov, Doklady 174, 1313 (1967).

TABLE 1

$\nu$	$x_j$	$\epsilon_j$ degrees	$\epsilon_{jj}$ degrees	$\epsilon_c$ degrees
3	1.256	(2.75)	5.70	2.50
$\frac{5}{2}$	1.074	(2.75)	4.35	2.00
2	1.045	4.95	(3.70)	3.00
$\frac{3}{2}$	1.140	1.68	(0.76)	0.70
1	1.300	0.54	(0.07)	0.30
$\frac{1}{2}$	2.200	0.54	(0.04)	0.15
$\frac{1}{4}$	2.280	$\sim 0.244$	( $\sim 0.01$ )	$< 0.02$

## Figure Captions

Figure 1:

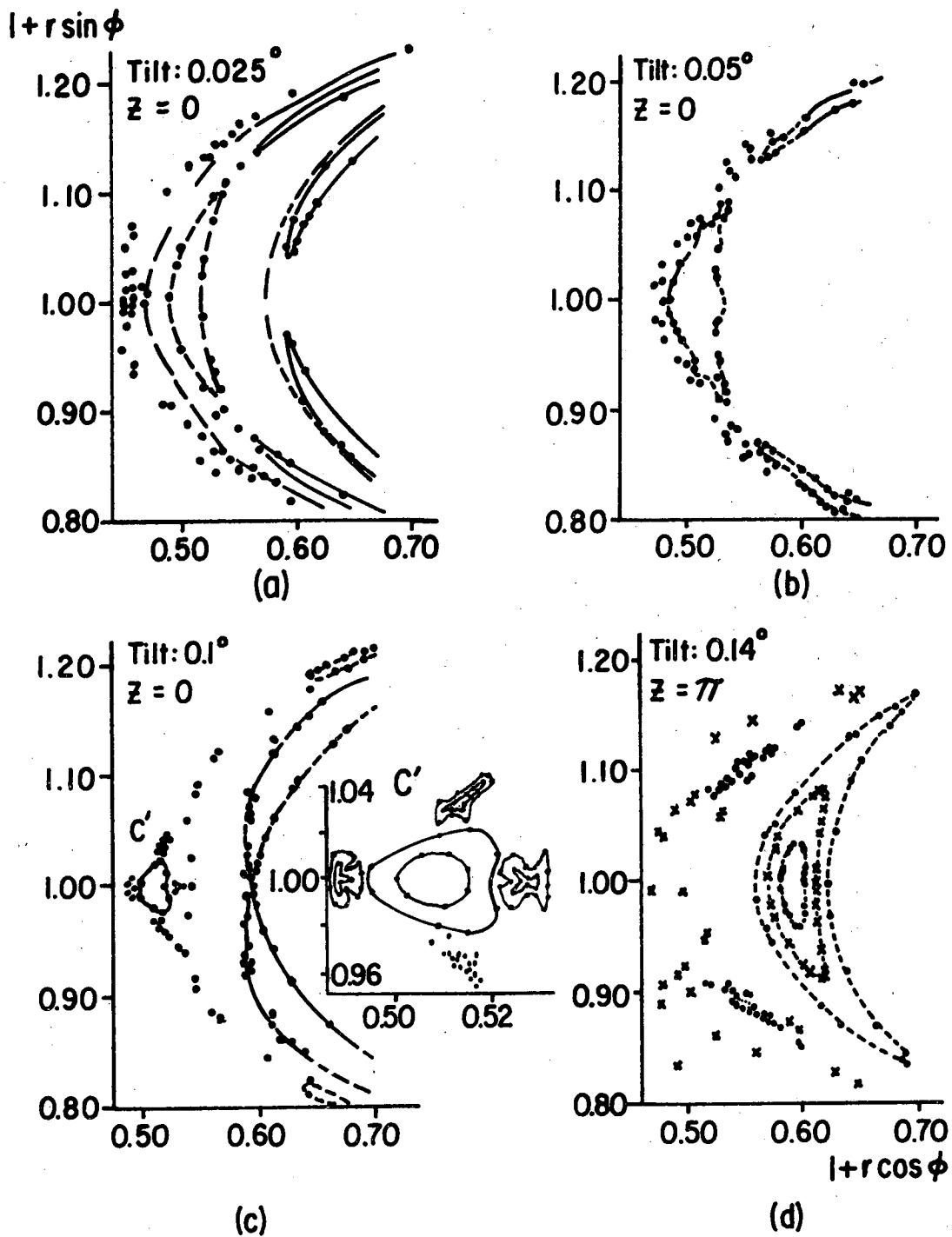
In part (a) a closed contour of the  $\pi$ -resonance is shown. In part (b) the perturbation is doubled and the contour is heavily distorted. In part (c) the perturbation is doubled again, the contour is completely destroyed and secondary magnetic islands appear. This is a typical example of destruction by internal overlapping. The  $2\pi$ -resonance after reaching its maximum flux in part (c) is seen partially destroyed in part (d). (The numerical results are taken from [4]).

Figure 2:

Critical perturbations as functions of the nonlinearity coefficient for levitrons ( $\delta=0=\delta'$ ). The regions of external (internal) stochasticity are on the right hand side of the  $P(S)$  curves. Below the  $x = \epsilon^{1/2}$  curve, the field line may escape the resonance zone. The encircled points are numerical [4]. The small arrows indicate the theoretical curves to which the numerical points belong. ( $\epsilon$  is measured in radians).

Caption for Table 1:

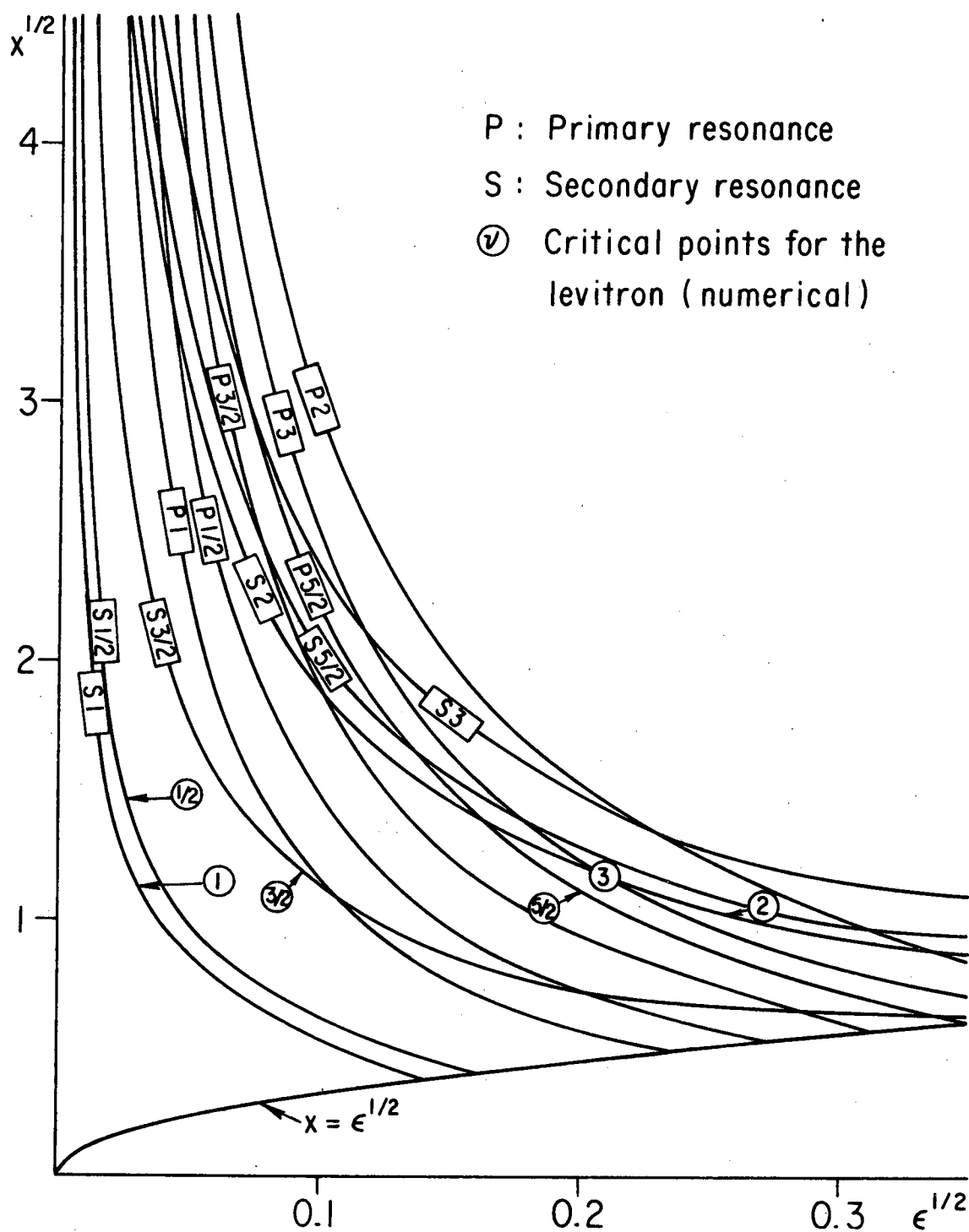
For the levitron  $\epsilon$  is a tilt angle. The theoretical tilts for which the resonances are completely destroyed are approximately equal to the smallest of  $\epsilon_j, \epsilon_{jj}$ .  $\epsilon_c$  are the numerically measured critical tilts.  $x_j$  represent the non linearity coefficients.



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Fig. 1





XBL 727-6603

Fig. 2

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