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TOROIDAL ALFVÉN EIGENMODE INDUCED RIPPLE TRAPPING

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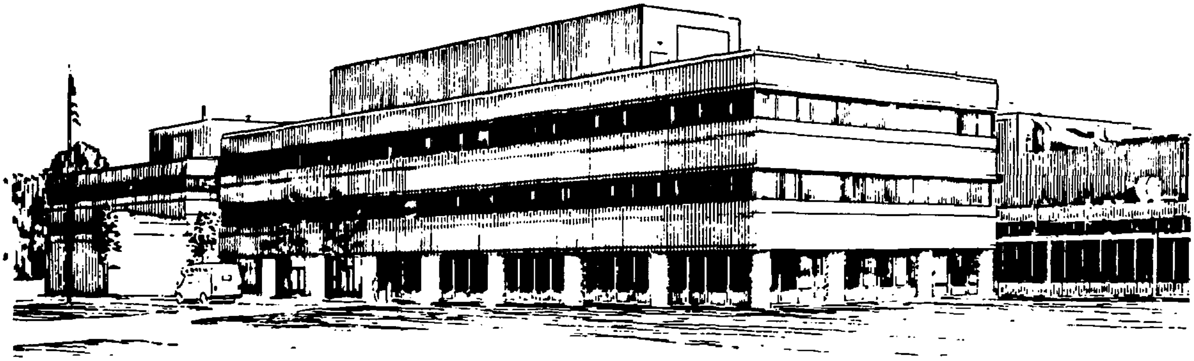

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Toroidal Alfvén Eigenmode Induced Ripple Trapping

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Abstract

Toroidal Alfven Eigenmodes are shown to be capable of inducing ripple trapping of high energy particles in tokamaks, causing intense localized particle loss. The effect has been observed in TFTR.

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Collective alpha-driven instabilities such as the toroidicity-induced Alfvén eigenmodes (TAE) are of concern for future tokamak devices since they can induce anomalous alpha losses. Previously discussed mechanisms of particle loss have consisted of induced transition from passing to direct-loss trapped orbits and radial diffusion produced by stochasticity in particle orbits caused by overlapping resonances[1]. In this work we point out a very effective loss process in devices possessing magnetic ripple wells. It differs from other forms of TAE induced loss in that the mechanism possesses no threshold mode amplitude. The effect has been observed in the Tokamak Fusion Test Reactor (TFTR), where particle fluxes intense enough to damage the vacuum wall were observed.

The process is very simply understood using a simple model for the magnetic field. Consider a trapped particle whose banana tip is in the vicinity of a ripple well. In guiding center approximation the particle energy is given by

$$E = \frac{1}{2} m v_{\parallel}^2 + \mu B \qquad (1)$$

Model the field as a large aspect ratio circular equilibrium modulated by toroidal ripple

$$B = \frac{B_0(1+\delta sin(N\phi))}{R} \tag{2}$$

with N the number of toroidal field coils, δ the local ripple strength, and $R = R_0 + rcos(\theta)$ the major radius. To leading orders in gyro radius to system size a trapped particle moves periodically between the bounce points in poloidal angle θ and slowly precesses from the initial field line with the toroidal angle given by , $\phi = q\theta + \omega_d t$ with ω_d the toroidal precession rate. Energy conservation then reduces the problem to a particle moving in a one dimensional potential given by $\mu B(\theta)$. A ripple well exists at points where $dB/d\theta = 0$ which requires

$$\delta > \frac{r|sin(\theta)|}{RqN} \tag{3}$$

In TFTR the ripple magnitude is well represented by $\delta = \delta_0 e^{\sqrt{(R-R_r)^2+bZ^2}/w}$ with $R_r = 223cm$, $w = 18.3cm$, $\delta_0 = 1.4 \times 10^{-5}$, $Z = rsin(\theta)$, and $b = 1.1$. Consider a trapped particle whose banana tip is in the vicinity of a ripple well below the midplane (plasma current clockwise from above), i.e. the particle passes over a local well before bouncing. Ripple trapping occurs due to the fact that a particle is radially further outward after bouncing than before, due to the banana width. Field ripple increases strongly in this direction and thus the particle encounters larger ripple after bouncing, and may be trapped in the well. If this occurs it drifts vertically to the wall and is lost. Since the well location varies due to the toroidal precession, eventually all trapped particles on orbits with bounce points intercepting the ripple well domain will be lost. The presence of a time dependent magnetic perturbation such as the TAE mode produces additional modulation of the particle position which can greatly increase the phase space of particles capable of making the transition to a trapped state.

To demonstrate the mechanism we model the high energy particle distribution, equilibrium, and mode structure approximating those present in TFTR during the observation of this effect. The high energy particle distribution produced by heating was observed to cause destabilization of the TAE mode, in agreement with numerical analysis[2]. The toroidal mode number observed was $n = 4$ and we include all important poloidal harmonics, i.e. $m = 4 - 12$. The calculation of the eigenmode profile and spectral components has been studied analytically[3] and numerically using the NOVA code[4]. The code results are used in this paper. In Fig.1 are shown the eigenfunctions obtained with NOVA. The mode frequency used was the experimentally observed TAE frequency of 188 kHz. However we find that the results are insensitive to the form of the eigenmodes used, as long as the mode amplitude is large in the ripple trapped domain. We used modes with $\delta B/B = 2 \cdot 10^{-3}$ in the simulations. Comparison with the Mirnov coil measurements are not practical because of the different boundary conditions in the eigenvalue code (no vacuum region). The amplitude was set by comparison with the observed fractional loss in high energy tail energy. Total lost particle fluxes are not measured in the experiment, so cannot be compared directly.

Simulation is done using a Hamiltonian guiding center code ORBIT described previously.[5,6]

The equilibrium had a major radius $R = 262cm$, a minor radius $a = 100cm$, with a safety factor of $q = .8 + 3.2(r/a)^2$. For these parameters the domain where ripple wells exist is rather large, and is shown in Fig 2. Also shown is the reduction in the ripple well domain which would be produced by decreasing the TFTR ripple by a factor of 2 or 4. The particle distribution is a model high energy Hydrogen minority tail ion distribution chosen to fit that produced during the experiment, given by

$$F = e^{(E-\mu B_{\pi/2})^2/c} e^{-E/T} e^{-r^2/b^2} \tag{4}$$

with T = 370 keV, the width parameter c adjusted to give 75% trapped particles, b =33cm, and $B_{\pi/2}$ the value of the field at r, $\theta = \pi/2$.

Two populations of lost particles were observed in the simulations, those with banana orbits intersecting the wall, having pitch $\lambda = v_{\|}/v \approx .5$ and impacting the wall just below the midplane, and the ripple trapped population, with $\lambda \approx 0$, intersecting the wall at a location determined by the existence of ripple wells and by the TAE amplitude. An example of a TAE induced ripple trapping event is shown in Fig. 3. In Figs 4, 5 are shown the lost particle distributions in R and pitch, both with and without the presence of the TAE mode. The ripple trapped population peaks near $R = 315cm$ which, as seen in Fig. 2, corresponds to the smallest value of R at which the ripple trapped domain extends across the plasma vertically including the high density central domain. Without a TAE mode, since the simulations did not include a source of high energy particles, but rather a fixed initial distribution, the ripple trapped flux is of short duration. In the experimental situation, which included a continuous source of high energy particles, this would translate into a small total intensity. A TAE mode moves particles in phase space, and allows a much larger population of particles to become ripple trapped. The simulations show a more intense ripple trapped flux of much longer duration in the presence of the mode. There is no threshold amplitude for this process, the total flux being approximately linear in the mode amplitude. Reduction of ripple by 1/2 or 1/4 would move this domain significantly outward, as shown in Fig. 2, with a large reduction in flux.

Details of the experiment confirming this process will be reported in a separate publication. Three different observations confirm the model sketched above. First, intense metallic influxes are observed in the plasma, predominantly of manganese. Second, thin stainless steel debris shields located at the bottom of the vacuum vessel at a major radius of 305 cm were melted. Third, strong fluctuations were measured in the expected TAE range during the experiments.

In conclusion, high energy particle loss consisting of ripple trapping induced by high frequency MHD perturbations has been modeled and observed in TFTR. The mode observed was a TAE mode destabilized by the high energy tail produced by ICRF heating, but any high frequency mode could produce similar results. Finally we point out that this loss mechanism is not effective for the alpha particle distribution in ITER because of the very small ripple well domain.

ACKNOWLEDGMENTS

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DISCLAIMER

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Figure Captions

Fig. 1 TAE eigenmode as determined by NOVA-K for the TFTR shot 79459, with n =4 and m = 4-12. Only a few of the m values used are shown.

Fig. 2 The ripple well domain in TFTR. Also shown are the resulting smaller domains if the ripple in TFTR were reduced by a factor of 2 or 4.

Fig. 3 An example of TAE induced ripple trapping, using the parameters of shot 79459.

Fig. 4 Simulation results shown lost particle distribution in R with (open) and without (black) the TAE mode.

Fig. 5 Simulation results shown lost particle distribution in pitch with (open) and without (black) the TAE mode.

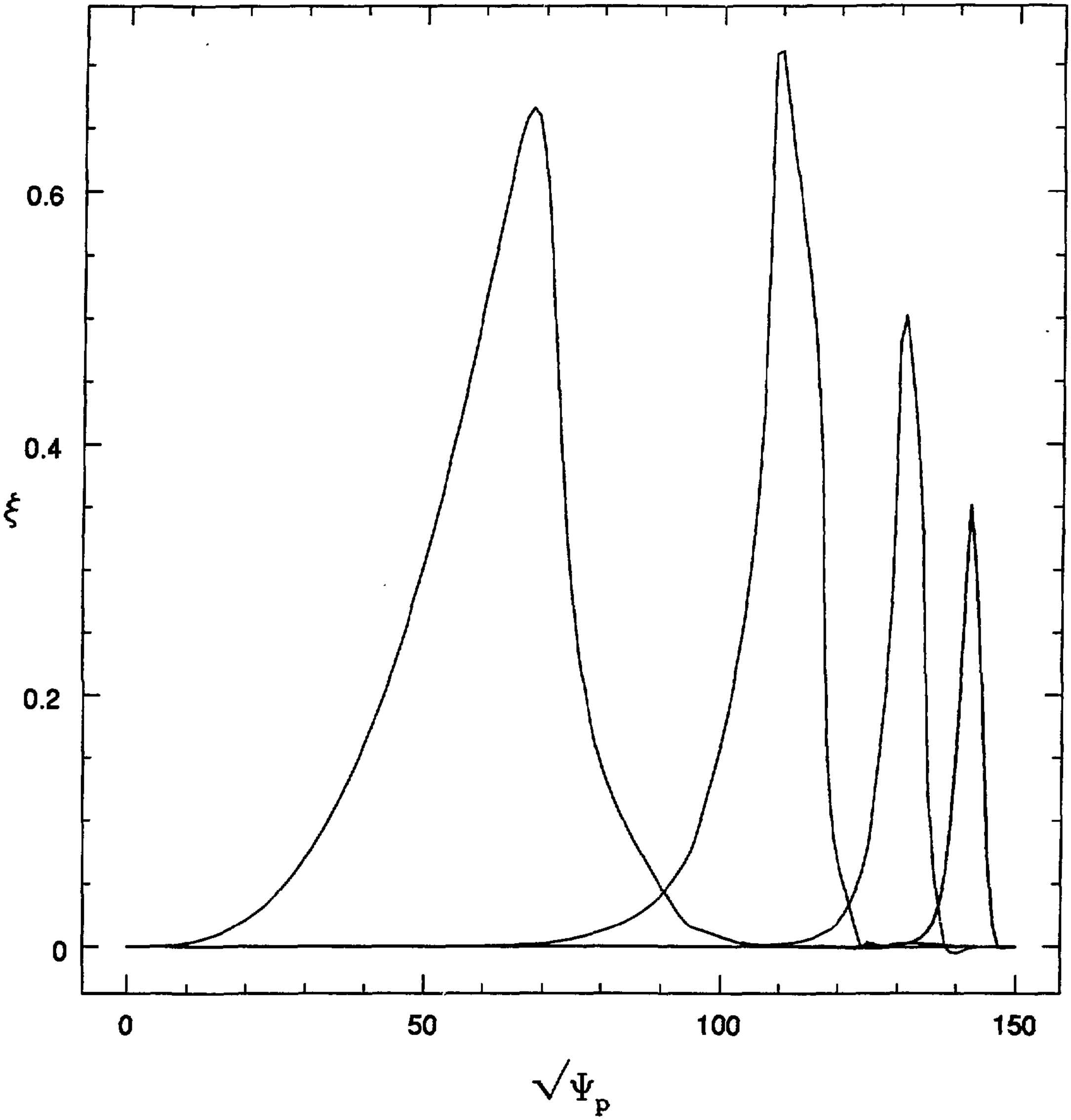
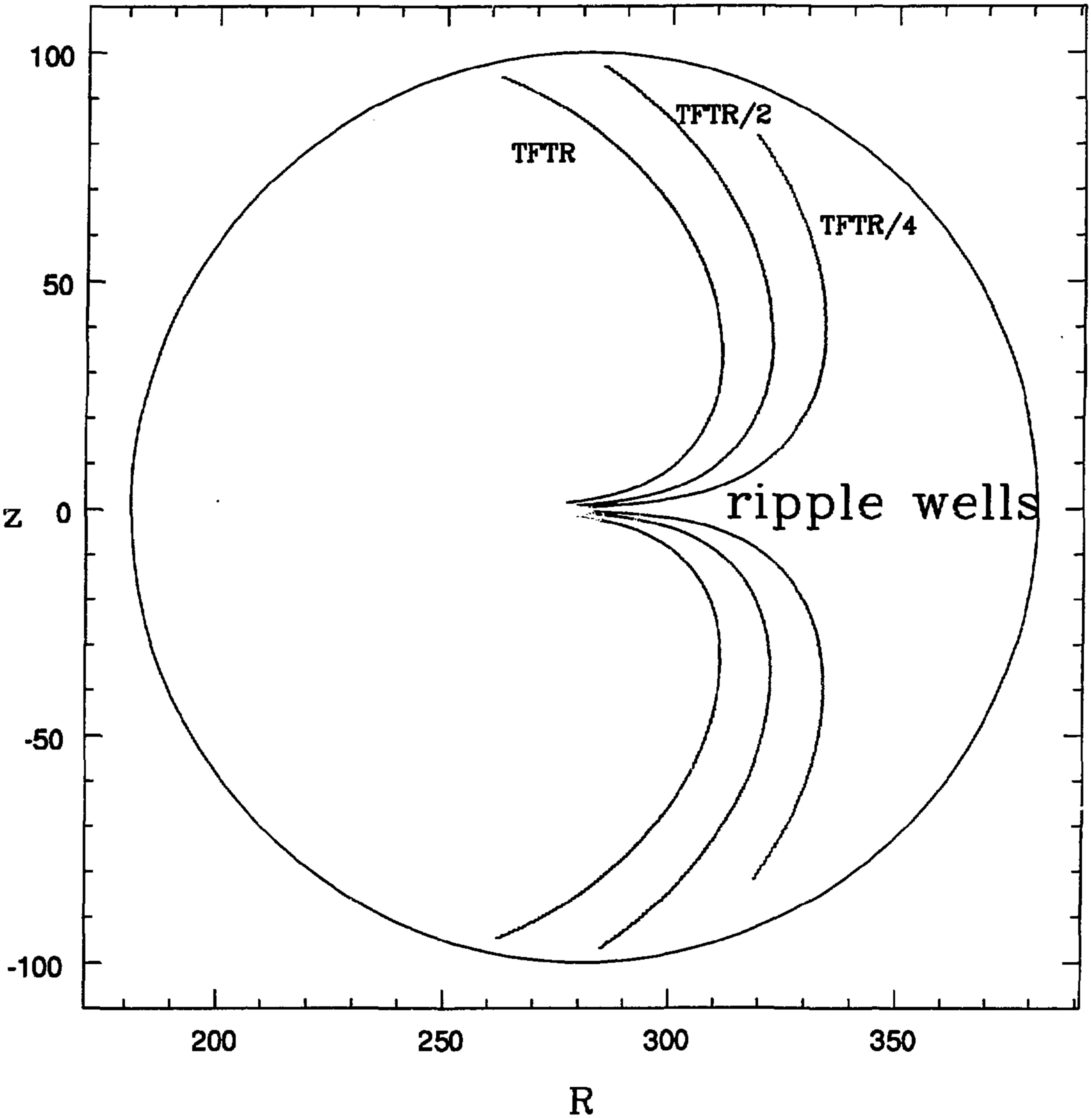


Fig. 1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R
TFTR
TFTR/2
TFTR/4
ripple wells

Fig. 2

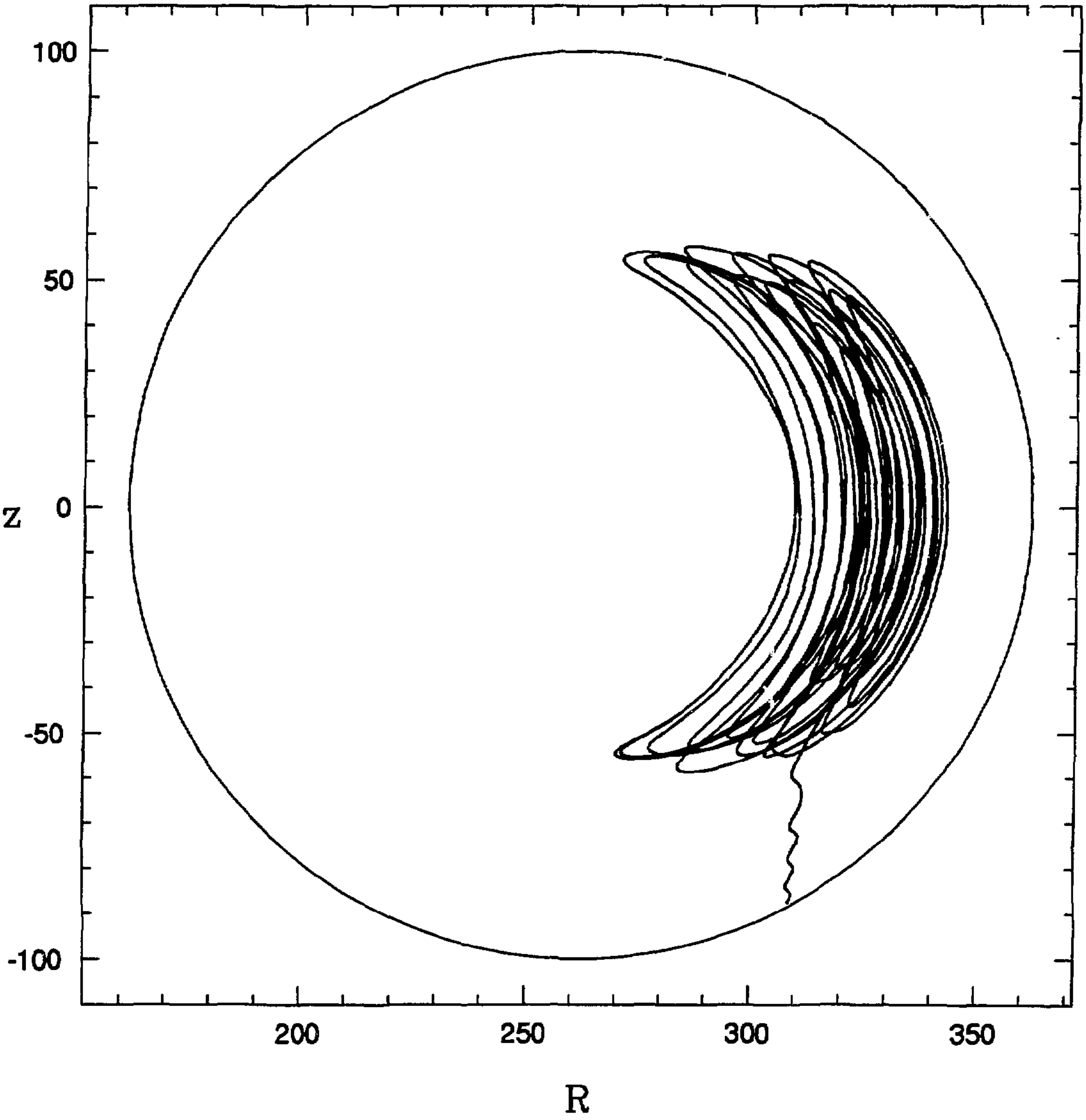

Fig. 3

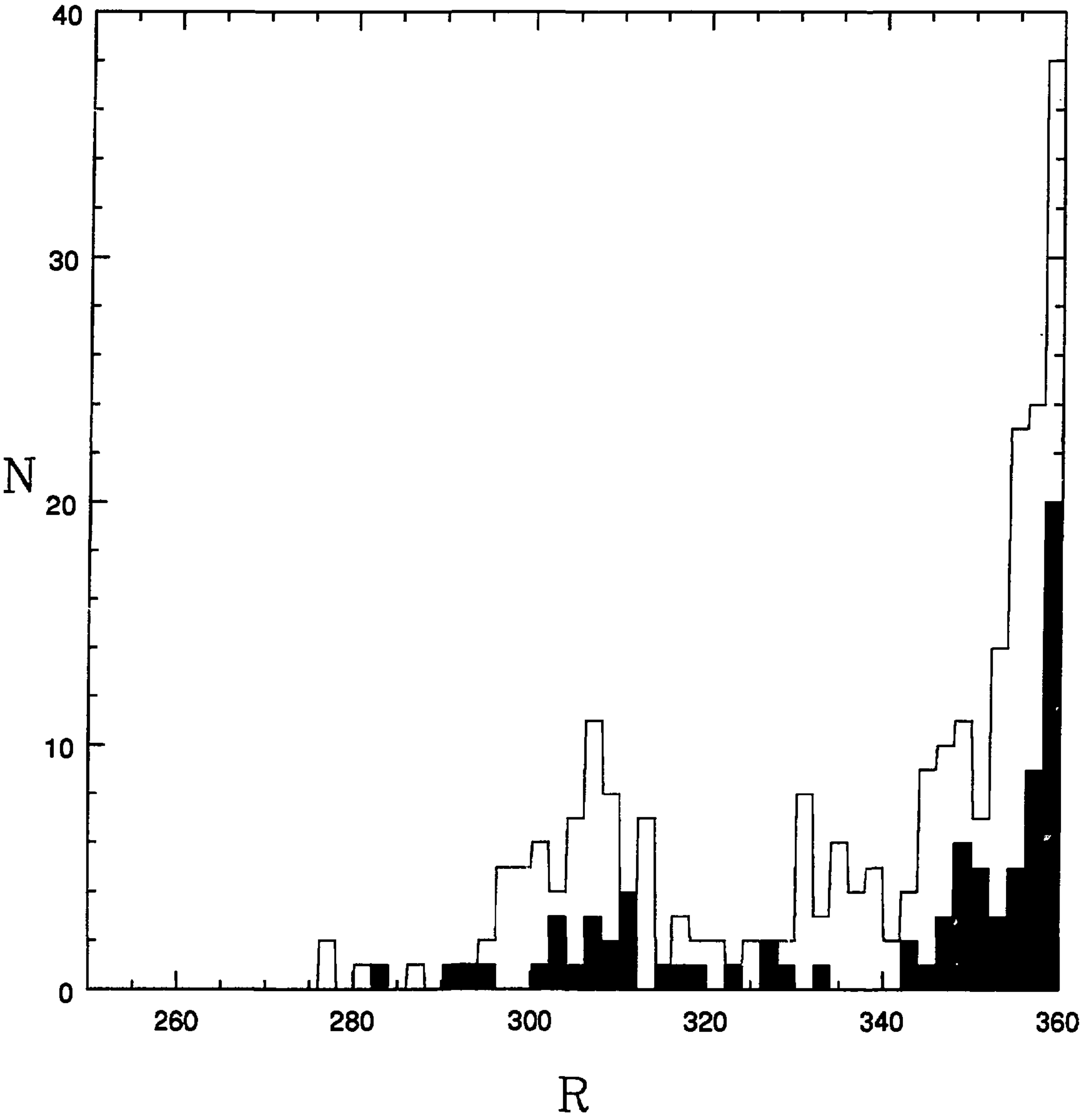

Fig. 4

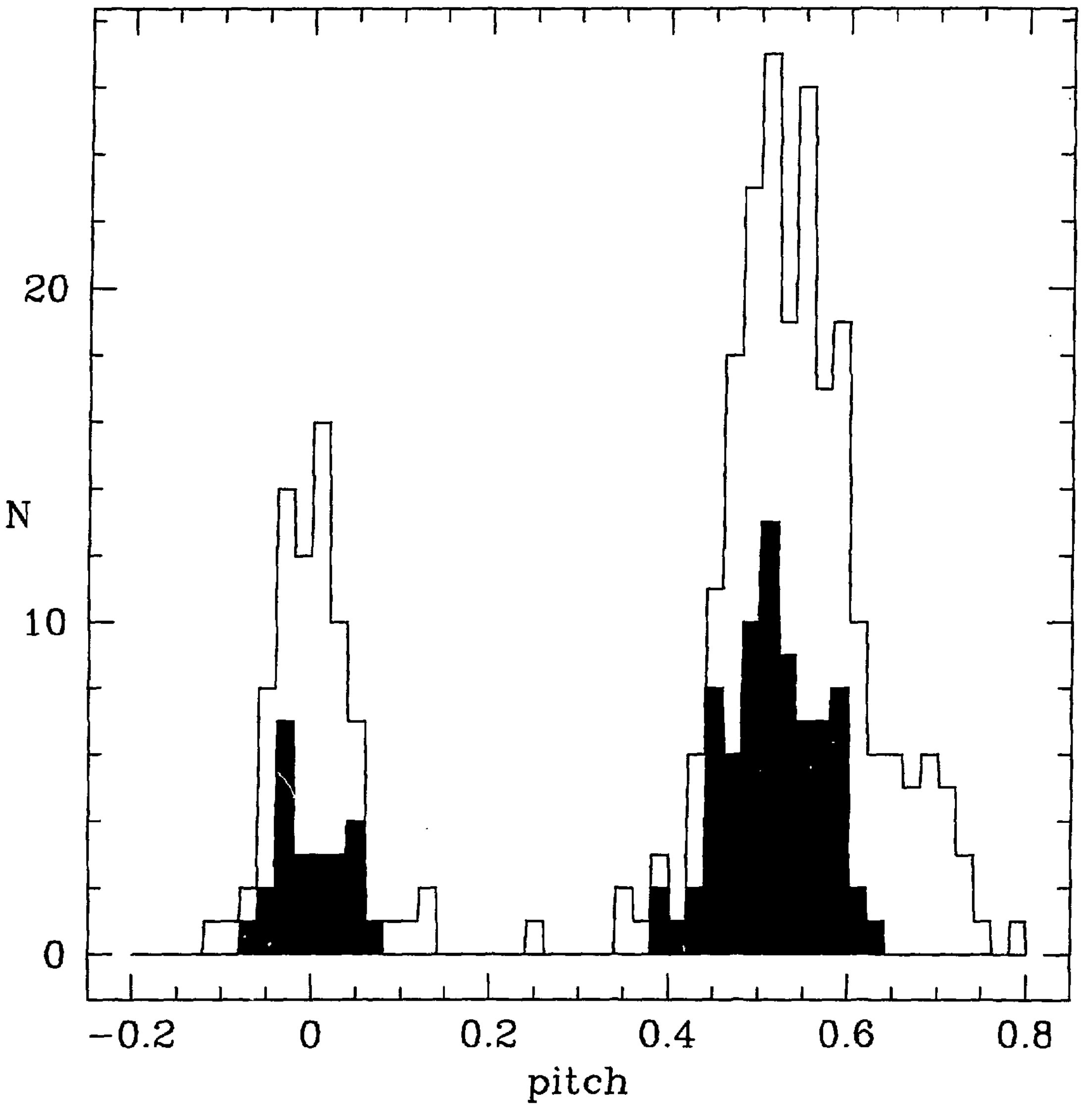

Fig. 5

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