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Problems in Modeling TF Ripple Loss of Fast Alphas from a Tokamak Reactor

by

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ABSTRACT: The present status of modeling TF ripple loss of fast alphas from tokamaks is summarized. The modeling issues are discussed, and several new aspects of this problem are described, including gyromotion, radial electric field, and sawtoothing. Existing models predict that TF ripple loss of fast alphas will have a low-to-moderate impact on the design of a tokamak engineering test reactor (ETR).

1. INTRODUCTION

This paper summarizes a presentation by the same title, given at the "Workshop on Alpha Particle Effects in ETR," held June 15-16, 1987 at the U.S. Department of Energy Headquarters in Germantown, Md. The outline of the paper is as follows. Section 2 describes the existing work on the loss of fast ions due to toroidal field ripple, then discusses some of the recent work in more detail. Section 3 enumerates the modeling issues and ways to improve the models. Section 4 points out several new aspects of the TF ripple loss problem which will have an important impact on the results. Consequences for ETR are explained in Section 5.

2. EXISTING WORK

The effect of TF ripple in a tokamak was recognized as an important problem in 1972 by Anderson and Furth [1]. Subsequent research [2-34] has been extensive, including important aspects of the fast ion ripple transport problem. This section summaries the basic physical processes, and recent studies based on these effects.

2.1 Basic Ripple Processes

Since the toroidal field coils are spaced discretely, the magnetic field strength is lower between the coils and higher in the plane of the coils. Secondary magnetic wells can form in a tokamak plasma when the magnitude of the ripple, $\delta(R,Z)$, is sufficiently large, defined by [36]:

$$\alpha^* = RB(\vec{B}_p \cdot \nabla B)/N\delta B_t^3 < 1 \qquad (1)$$

where R is the major plasma radius, $\vec{B}_p$ is the poloidal component of the magnetic field vector, B_t is the toroidal component of the field, B is the magnitude of the net field, and N is the number of toroidal field coils. The above equation generalizes the well-known formula for a circular tokamak [1] to a noncircular equilibrium. All the magnetic field terms in Eq. 1 are for unrippled values. For the Fusion Engineering Device [37], Fig. 1 shows an example of contours of constant ripple and the outer flux surface of the equilibrium; ripple wells form between the mid-plane (Z=0) and the contour of $\alpha^*=1$. Ions moving in such a rippled magnetic field are affected by the field maxima and minima in several ways. An ion can be captured in a ripple well (near the banana tip) as the large-banana-width orbit collisionlessly carries

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the particle into a region of higher magnetic field. The inverse of this process, detrapping [19], can occur when the ripple-trapped particle drifts vertically into a region where ripple wells do not exist (see Fig. 1). Also, collisionless ripple detrapping may occur if the radial excursion of a large-banana-width orbit carries a fast ion out of a ripple well. Collisional (de)trapping is also possible, involving pitch-angle-scattering near the banana tip of an orbit as the ion traverses a ripple well; this effect is very small for fast alphas however. Ripple trapped particles no longer follow banana orbits, but rather oscillate toroidally between two maxima in the B-field while moving vertically due to curvature and gradient-B drift. Vertically-drifting, ripple-trapped ions will either be lost to the tokamak wall or (as described above) will move into a region of the plasma where ripple wells do not exist. The former case is a direct wall-loss mechanism, occurring where the ripple trapping region intersects the outermost flux surfaces as in Fig. 1. In the latter case, the motion acts to transport the particles radially outward into regions where diffusive processes dominant. Since collisionless effects are so much faster than collisionless ones, early studies by Yang and Emmert [2], Belikov et al. [3], and Petrie et al. [4] assumed that ripple trapped ions were instantaneously lost to the wall without accounting for detrapping processes. However, using a model based on Ref. 10, Hively [26] found that such losses are reduced dramatically by collisionless ripple detrapping in INTOR which occurs on the same time scale as the collisionless ripple trapping. Other calculations based on Ref. 27 and independent studies by Ref. 23 agree with Hively's results [26] for INTOR. Goldston and Towner elucidated these processes in their 1981 paper [14]. A recent analysis of collisionless ripple trapping losses by Goloborod'ko et al. [25] used a drift kinetic treatment of the problem. However, Yushmanov [17] points out that the drift kinetic equation is inapplicable for fast alphas. This condition occurs when the toroidal drift precession distance during one banana period is greater than the distance between TF coils.

Without ripple, banana trapped particles precess toroidally by $\Delta\phi$ during one bounce period. With ripple, neoclassical orbits do not close exactly due to a variable lingering period as the banana tip crosses a ripple well or ripple inflection region leading to a radial displacement. For high energy alphas (>1 MeV), the toroidal precession is large compared to the period of the toroidal field coils, $\Delta\phi > 2\pi/N$. Stochastic diffusion [11] of these fast alphas occurs when the radial displacement, d, is sufficiently big compared to the minor radius (a) of the plasma, $d > a/[N\pi q(a)]$, where q(a) is the safety factor at the plasma edge. Consequently, stochastic ripple diffusion leads to rapid loss of ions to the wall in 10-100 bounce periods. The collisionless form of this process was studied by Goldston, Boozer, and White [11], White et al. [21], and Hitchon and Hastie [23]. Yushmanov [17] has studied the collisional stochastic diffusion problem for high energy ions. For moderately high energies, when the stochasticity criterion is not yet satisfied, resonant diffusion occurs [18]. In this case, the toroidal precession distance during one bounce is $\Delta\phi > 1/N$, and banana-trapped particle orbits undergo large radial jumps when $\Delta\phi = n\pi/N$, due to resonance between the toroidal drift precession and the ripple periodicity. Yushmanov's analysis describes a smooth transition among the banana-drift, ripple-plateau, and resonant diffusion regimes, assuming small banana-width orbits. Goloborod'ko et al. [28] use a more general theory for large banana-width orbits and find resonances when ratio of the toroidal drift precessional frequency to the bounce frequency is a rational number (m/n), for m and n integers. These resonances are localized in both velocity and coordinate space. Goloborod'ko et al. [50] have extended their theory to include collisions in both the collisionless and plateau regimes, when the resonance overlap for stochastic processes is not satisfied. Monte Carlo calculations by Tani et al. [30] find that most of the fast, trapped alphas are lost from an INTOR plasma via stochastic ripple diffusion, in accord with their previous results [22]. However, the results of this calculation are somewhat uncertain because the mapping procedure used by Tani et al. [30] is not area preserving. Zajtsev et al. [31] have used the flux-surfaced-averaged Fokker-Planck equation to model fast alpha confinement based on a small banana width form for the stochastic diffusion; their results agree with Ref. 22. The validity of this model is questionable because large banana-width orbits are not used and because a small banana-width model was used for the stochastic diffusion.

Ripple-plateau and banana-drift diffusion are related processes in which neoclassical orbits fail to close exactly due to the same ripple induced, variable lingering period as the banana tip crosses a ripple well or a ripple inflection region. Collisions decorrelate the ripple phase causing diffusion, rather than oscillatory motion. If the collisionality is low (collisionless regime), collisions decorrelate the ripple phase after many bounce periods leading to banana-drift diffusion [38]. At moderate collisionality, collisions decorrelate the ripple phase between successive bounces, producing ripple-plateau diffusion [39]. When the collisionality is high, collisions decorrelate the phase after a small fraction of a bounce period, but this case does not apply to fast alphas. Goldston and Towner [14] discuss a generalization of these processes for large banana-width alpha orbits during slowing down. Mynick [29] has constructed a generalized theory of banana drift transport which also includes low-n MHD modes and high-n perturbations arising from microtearing. Very recently, Zweben et al. [32] have calculated alpha losses based on a guiding-center orbit simulation [27]. They find significant alpha losses in TFTR due to stochastic ripple diffusion, due to sawteeth (modeled as a stationary m/n=1/1 island in the plasma core), and due to higher order resistive tearing modes (also modeled as stationary islands).

While the above diffusive processes are due to abrupt changes in the toroidal adiabatic invariant [15] as an alpha orbit moves through magnetic ripple, diffusion also occurs as a result of jumps in the magnetic moment [5]. Putvinskii and Shurygin [24] point out that Ref. 5 did not take account of the local character of the gyroresonance interaction; they then go on to obtain a the corresponding diffusion and critical value of ripple. However, Goloborod'ko et al. [50] note that N > 100 is required for any significant effect, so the diffusion described by Ref. 24 seems irrelevant for typical tokamak designs. There is no analytical theory which accounts for simultaneous changes in the toroidal adiabatic invariant and the magnetic moment, although Monte Carlo, guiding center simulations (e.g., Refs. 22, 23, 26, 32) have been done which include both jumps.

2.2 Simulations of Combined Processes

In his 1980 review of alpha physics, Kolesnichenko [40] discussed only the theory of Belikov et al. [3] which studied alpha losses due to only collisionless ripple trapping without accounting for ripple detrapping. The analysis by Anderson et al. [16] included only collisional and collisionless ripple trapping as the fast alphas slow down and pitch-angle scatter.

Improved ripple modeling was done by Tani [8,13,20] for the slowing down and scattering of neutral injected ions including collisionless ripple trapping/detrapping, banana drift, and ripple diffusion losses. Fowler and Rome [10] developed a more complete model for examining neutral beam injection losses in a rippled tokamak which included all the above basic processes; a Monte Carlo model [12] was used to simulate collisions.

Recent simulations by Tani et al. [22] and Hively [26] have studied alpha particle ripple losses for INTOR; both studies include the effects of collisionless ripple detrapping. Table 1 compares the physics models of Refs. 22 and 26. Ref. 22 found moderate alpha losses (10-20%) for a circular INTOR plasma with an edge ripple of 0.75%. Ref. 26 computed alpha ripple losses as small (2.5-3%) for both a circular and noncircular INTOR plasma. The calculations [26] for a circular INTOR plasma were an attempt to duplicate the Tani's results using the same assumptions as Ref. 22. Table 2 compares the key results. The remainder of this subsection elucidates this comparison.

Regarding the distribution of alpha flux at the wall (see Fig. 2), there are several important differences between Refs. 22 and 26. The peak fluxes differ by a factor of three: Tani's maximum flux is 0.6MW/m^2 versus Hively's value of 0.2MW/m^2. The toroidal distribution found by Tani is high and broad for poloidal angles less than 40°, and is abruptly lower (but still broad) for larger poloidal angles. Hively's result is strongly peaked between the TF coils as well as strongly peaked at low poloidal angle, i.e. at the outboard midplane. Fig. 2a shows large statistical variations in the flux due to the small bin size chosen by Tani; no such fluctuations occur in Fig. 2b. The sign reversal in poloidal angles between Fig. 2a and Fig. 2b is due to alpha flux being in the upper (lower) half plane because the grad-B and curvature drifts are opposite, since the direction of the toroidal fields is reversed for the two cases. The toroidal current direction is also opposite between the two studies leading to opposite labeling of the toroidal axes.

Figure 3 compares the energy loss spectrum obtained by Tani et al. [22] and Hively [26]. The overall features are similar, including large losses near the birth energy and abruptly lower losses during thermalization. However, a chi-squared statistical comparison of the two spectra shows that they are not the same. Tani's spectrum decreases monotonically from the birth energy to 2.6 MeV, is flat from 2.6 to 1.6 MeV, then rises slowly from 1.6 to 0.2 MeV, and finally decreases somewhat in the lowest (thermal) bin. The energy spectrum computed by Hively shows more losses near the birth energy (3.5 MeV) and has large fluctuations in the loss during thermalization. In particular, no losses occur near 0.5, 1.9, 2.7, and 3.1 MeV, corresponding to energies at which the toroidal drift precession during one bounce period is a multiple of the TF coil separation distance. At these energies, the orbit is locked in resonance with the TF ripple and is well-confined (not stochastically diffusing). At other energies, losses proceed as discussed in Sec. 2.1. Thus, as fast alphas thermalize, they alternately undergo ripple loss, followed by being stably confined. These fast-alpha confinement islands have been seen previously in a tokamak with ripple due to a bundle divertor [41] and due to TF ripple [33]. The loss spectrum of Tani et al. [22] is shown in Fig. 2a for an edge ripple of 1.5%, versus Hively's result [26] in Fig. 2b for an edge ripple of 0.75%. Since the ripple magnitude does not change the resonance energies, the key features are the low loss regions; no such stable confinement islands are seen in Tani's loss spectrum (Fig. 2a).

Recent collaboration between K. Tani and this author has revealed that the following issues do not cause the above discrepancies:

- the alpha particle source term,
- the poloidal dependence of the ripple profile, i.e. $\delta(R,Z)$,
- the axisymmetric plasma equilibrium and the associated $q(r)$ profile,
- collisionless ripple detrapping,
- the plasma profiles (ion/electron density and temperature),
- initial conditions (in coordinate and velocity space) for the alphas, and
- the loss condition at the wall ($r = a$).

As summarized in Table 1, the following aspects are definite differences between the models of Tani et al. [22] and Hively [26]:

- Only a first harmonic ripple field component in the rippled current sheet model for the TF coils (Tani) versus first and higher harmonic components in the discrete filamentary TF coil model (Hively),
- Second-order Runge-Kutta integration of the guiding center equation which is expanded to fourth order in the ripple field and which retains only the first harmonic contribution from the ripple field with a tight timestep (Tani) versus fourth-order Runge-Kutta integration of the full guiding center equation with a longer timestep (Hively),
- Time scale enhancement for collisional processes for nontrapped particles only by a factor of 200 (Tani) versus a small time scale enhancement for trapped particles (<10) and a larger time scale enhancement for nontrapped particles (1000), and
- Use of the Trubnikov scattering operator [52] by Tani versus the Goldston scattering operators [12] by Hively.

These differences are being carefully studied as potential causes of the discrepancies which were described above.

2.3 Ripple Loss Experiments

Tokamak experiments have found fast ion losses [6] and thermal diffusion [7] in accord with theory. A more detailed comparison by Scott [34] found the loss (ripple trapping and stochastic diffusion) of neutral-beam-injected ions as expected theoretically, based on the model of Ref. 10. Well diagnosed, fusion product confinement experiments are needed to resolve the discrepancy between Refs. 22, 30, 31 versus Refs. 23, 26, 27.

3. MODELING ISSUES IN EXISTING SIMULATIONS

The computational or analytical model must adequately represent the fast alpha particle physics in a rippled tokamak. Issues which impact the realism and/or accuracy of the model but do not change the fundamental alpha physics include:

- Taking the first wall at the plasma edge rather than at its real position. The resulting loss fraction and wall loading flux is a strong function of the plasma-wall separation [35].

- Using ad hoc plasma profiles for the temperatures and densities of the background plasma species rather than transport consistent values. The consequent alpha particle source function as well as the influence of the plasma on slowing down and scattering is determined by these profiles.

- Assuming an ad hoc alpha particle source profile rather than determining the source function from the ion densities and temperatures. The alpha losses are strongly dependent on the alpha source distribution.

- Integrating the alpha particle guiding center motion with sufficient accuracy that numerical diffusion is not introduced. A careful comparison of analytical, axisymmetric orbits with corresponding numerically integrated orbits is a good check [26]. Particle following in field line coordinates is presently the most computationally efficient technique (e.g. Ref. 27) but inversion to real space must be done carefully (e.g. whether and where the alpha hits the wall).

- Using enough particles in a Monte Carlo simulation to obtain adequate loss statistics. Source biasing improves these statistics, e.g. choosing a uniform particle source function and weighting the lost alphas by the fusion source function [26]. A statistical error analysis of such Monte Carlo results is needed; none have been provided to date.

- Using realistic ripple fields due to TF coils with a finite cross section. Simple analytical fields are easy to model but are not realistic for modern D-shaped coil shapes. Also, the ripple profile changes as the edge ripple varies, due to the shift in the TF configuration [26]. Therefore, the ripple field cannot be simply scaled in proportion to the value of the edge ripple as done in Ref. 22.

There are several important physics issues:

- Using an adequate collision model for alpha thermalization and pitch angle scattering. Collisional effects are small due to speed diffusion and toroidal electric field acceleration [26]. Inclusion of pitch angle scattering without slowing down is unphysical (e.g. Ref. 32) because the physics of stably confined, locked orbits is omitted as the alphas thermalize.

- Modeling the rippled tokamak equilibrium as divergence free ($\nabla \cdot \vec{B}=0$). The presence of a non-zero divergence causes unphysical orbital motion [42, 43] because the time rate of change of the magnetic moment is proportional to the divergence of B to lowest order [44]. The rippled part of the magnetic field (B_{rip}) must also be curl free ($\nabla \times B_{rip}=0$) if the model uses a superposition of axisymmetric and rippled parts. The non-zero curl of the rippled field is equal to a corresponding ripple current density (j_{rip}) which will modify the particle motion due to a $j_{rip} \times B$ force. Ref. 13 is an example in which both $\nabla \cdot B$ and $\nabla \times B_{rip}$ were non-zero. When the model uses a superposition of axisymmetric and ripple parts, the axisymmetric toroidal component must be subtracted to avoid double counting of the toroidal field. The superposition of the axisymmetric and rippled fields is, in fact, not right, but rather the rippled equilibrium is fully 3-dimensional. Future calculations should include such 3D equilibria (e.g. Refs. 45 and 46) to determine the self-healing properties of the plasma to ripple perturbations. Moreover, the alpha particle pressure will modify the 3D tokamak equilibrium and should be taken into account.

- Modeling the alpha particle interaction with the rippled field, which must be done with care as described in Sec. 2.1. Large errors can result by using a time scale enhancement for trapped particles when simulating collisional processes relative to collisionless ones.

4. NEW PHYSICS TO BE INCLUDED IN MODELS

There are several additional physics aspects that need to be included in the models for TF ripple affects on fast alphas. These effects are due to the large gyroradius of the fast alphas, electric fields in the plasma (particularly in the radial direction), and sawteeth.

4.1 Finite Gyroradius Effects

The fast alpha gyroradius, r_α, in a reactor grade plasma can have a significant impact on the following:

- Smearing the alpha particle source distribution over the gyroradius introducing a spread of <10 cm. in a 5T device. The source distribution will then be slightly less centrally peaked, leading to more losses and less central alpha heating. While this effect would seem to make only second order changes, its importance should be quantified.

- Changing the topology of the collisionless alpha orbits due to second order corrections in the canonical toroidal angular momentum [47]. The size of this apparently small correction also needs to be quantified.

- Smearing the alpha particle orbit interaction with the ripple over the gyroradius. This effect will be particularly important at the banana tip of a trapped orbit as it traverses a ripple well.

- Smearing the wall loss position of the fast alphas over the gyroradius. Localized wall heating then will tend to be less peaked. The choice of adequately large numerical bins at the wall, on the order of $2r_\alpha$, will have an equivalent smoothing effect [48].

4.2 Electric Field Effects

Electric field effects will be caused by the alphas and will affect the dynamics of both the background plasma and alphas as follows:

- Large-banana-width orbits will separate the doubly charged alpha orbits from their birth flux surfaces, creating poloidal and radial components of electric field. The size of the resulting electric potentials might become as large as the background thermal plasma energy, having an enormous impact on the plasma confinement, and consequent fusion reactor performance.

- A radial electric field modifies the collisionless trapping process [14] by adding additional drifts and by changing the component of alpha velocity which is parallel to the net magnetic field. Similar effects will occur for the other basic processes described in Sec. 2.1, and will be especially important at the banana tip of a trapped orbit.

- o The background plasma dynamics in the presence of such an electric field must be considered (e.g. plasma rotation), particularly as the plasma profiles change and modify the alpha particle dynamics.

- o These effects need to be considered self-consistently with the alpha distribution function, which is modified by the above processes, and which will change the resulting electric field.

4.3 Sawteeth

Since sawteeth have been observed to expel high-energy fusion products from the plasma [49], sawtoothing control or elimination may become crucial for a tokamak reactor. While the modeling of alpha dynamics in the presence of sawteeth [32] is beyond the scope of this paper, there are some indirect effects that need attention. These effects include:

- o Sawtooth-flattened background plasma profiles as they affect the alpha confinement and thermalization.

- o A large value of the central safety factor, $q(o)=2-3$, to eliminate sawteeth as it affects the plasma equilibrium and alpha physics.

- o Alpha confinement in a high-beta plasma, which will have the plasma center shifted outward due to the large plasma pressure. The outward shift causes the alpha orbits to sample a larger ripple field, leading to larger losses.

- o Impurity accumulation in the plasma core, which occurs when sawteeth are absent from a tokamak discharge. These impurities will include ionized wall material as well as alphas themselves.

5. CONSEQUENCES FOR ETR

Calculations by Hively [26] find a 2.5-3% energy loss of fast alphas from INTOR due to TF ripple; Refs. 23 and 32 obtain similar results. The corresponding reduction in plasma heating by the alphas is insignificant. The flux of alphas lost to the wall is peaked poloidally at the outboard wall, between the TF coils toroidally, and above (or below) the plasma midplane. The local alpha heat flux is double that without ripple losses but can be accommodated by wall design changes. The structural wall damage is probably unimportant, but the synergism between alpha sputtering and plasma sputtering could enhance the impurity generation, limiting the burn time [35]. These results imply that TF ripple would have a low impact on the design of INTOR and ETR.

Calculations by Tani et al. [22] find 10-20% energy loss of the fast alphas from INTOR; Refs. 30 and 31 agree with this result. These high losses would have a large impact on the first-wall design which would need to accommodate about $1 MW/m^2$ (feasible but expensive). Ignition would be more difficult since most of the trapped, fast alphas are lost; compensation via a larger machine size would be expensive. These results imply that TF ripple would have a moderate impact on the design of an ETR/INTOR tokamak reactor.

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FIGURE CAPTIONS

Figure 1: For FED, an example of contours (solid line) of constant ripple (%), the edge of the noncircular plasma (dashed line), and the curve (chain dashed line) of $q^*=1$.

Figure 2: Wall flux of lost alphas from a circular INTOR plasma with an edge ripple of 0.75% as found by (a) Tani et al. [22] and (b) Hively [26]

Figure 3: Alpha energy loss spectrum in a circular INTOR plasma as found by (a) Tani et al. [22] and (b) Hively [26]. Figure 2a was adapted from Ref. 43 by converting the spectrum to a linear scale and reapportioning the data to the same energy bins as used by Ref. 26 to allow a chi-squared comparison (see text).

Table 1: Modeling Comparison for Circular INTOR Simulations

Model	Tani et al. [22]	Hively [26]
Equilibrium*	Zero-beta, circular plasma Parabolic current profile	Same Same
Rippled B-Field@	Rippled sheet current for for TF coils	Discrete filamentary TF coils
Plasma profiles*	Parabolic: $1-0.99(r/a)^2$ for density, temperature	Same
Alpha source	Numerical fit by Tani	Numerical fit by Hively [51]
Initial conditions for alpha particles	Uniform in r, weighted by alpha source function Uniform in toroidal and poloidal angle Isotropic in velocity	Same Same Same
Orbit integration@	O(2) Runge Kutta Guiding-center equation expanded to O(4) in δ Timestep: $\Delta t = 2\pi R_o/10Nv_\parallel$	O(4) Runge Kutta Full guiding center equation Timestep: $\Delta t = 2\pi R_o/40v$
Time scale enhancement (E)@	Nontrapped particles only E = 200	E < 10 for trapped alphas E = 1000 for circulating ions
Loss to wall**	At plasma edge (r/a = 1)	Same
Collisions#	Trubnikov operator [52]: Random gyrophase Slowing down Pitch angle scatter Speed diffusion / No electric field	Goldston operators [12]: No random gyrophase Slowing down Pitch angle scatter Speed diffusion Toroidal electric field

* These aspects of the model affect the realism but not the basic physics.

**Losses decrease rapidly with plasma-wall separation [35] so this aspect of the model affects both the realism and the physics.

\+ Collisional detrapping is negligible; collisionless detrapping in INTOR is important [26].

\# Collisional effects due to speed diffusion and toroidal electric field are unimportant [26]; random gyrophase scattering will not affect the guiding center orbit following.

@ These modeling differences may have an important effect on the results.

Table 2: Comparison of Results from Refs. 22 and 26 for Circular INTOR Plasma

ISSUE	Tani [22]	Hively [26]	Comparison
Importance of stochastic diffusion	large	moderate	
Toroidal wall loading distribution	broad	peaked	Fig. 2
Poloidal wall loading distribution	broad	peaked	Fig. 2
Fluctuation in wall loading distribution	large	small	Fig. 2
Energy/particle loss fraction (%)	10/20	2/3	
Fluctuation in energy loss spectrum	moderate	large	Fig. 3
Reason for this spectral fluctuation	statistics	resonances	Fig. 3