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By

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Alpha particle losses during sawtooth activity in Tokamaks

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Abstract:

The time evolution of the direct losses of fusion produced alpha particles in Tokamak plasmas characterized by sawtooth activity is investigated. The alpha particle loss rate during a sawtooth period is predicted to change invertedly with the change in bulk plasma parameters but also to contain a characteristic burst at the sawtooth crash. The spectrum of the lost alpha particles is also discussed. The predictions for the time evolution and the spectrum of the losses are in qualitative agreement with recently obtained losses of 15 MeV fusion produced protons in JET.

1. Introduction

A prominent feature in modern Tokamak experiments is the presence of significant sawtooth activity,[1-4]. Although an effort is made to conceive methods for suppressing the sawteeth, it seems likely that sawtooth oscillations will be present also in Tokamaks operating near ignition conditions. The purpose of the present work is to investigate the effect of sawtooth activity on the confinement of fusion produced alpha particles. In particular we will show that, in addition to a slowly varying background loss, bursts of unconfined alpha particles should appear at the sawtooth crash. The physical mechanism leading to this sudden loss of particles can be understood as follows: At the sawtooth crash, temperature, density and in particular current profiles broaden significantly. The broading of the current profile implies a degradation of confinement which releases the accumulated particles which have been confined during the sawtooth rise, but which are lost in the enlarged velocity space loss region created during the magnetic reconnection stage of the sawtooth crash, cf [5].

By including the effects of slowing down on the alpha particle distribution function, the spectrum of the lost particles can also be inferred. The predictions for the time evolution as well as the energy spectrum of the alpha particle losses are in qualitative agreement with recently obtained losses of fusion produced 15 MeV protons in JET, [5].

2. Alpha particle loss model

The total (volume integrated) production rate of alpha particles is

$$\dot{N} = \int n_D n_T \overline{\sigma v} \, dV \tag{1}$$

where n_D and n_T denote the density of deuterium and tritium respectively and $\overline{\sigma v}$ is the reaction rate. We will assume that $n_D \simeq n_T \simeq n_e/2$ where n_e is the electron density. Furthermore, we will use a power law approximation for the reaction rate, viz.

$$\overline{\sigma v} = CT^{\gamma} \tag{2}$$

where T is the ion temperature and the exponent γ depends on T but for simplicity we will take $\gamma \simeq 2$

Assuming radial profiles for T(r) and $n_e(r)$ according to

$$T(r) = T(0)(1-r^2/a^2)^{m_T}$$
$$n_e(r) = n_e(0)\ (1-r^2/a^2)^{m_n} \tag{3}$$

we obtain from eqs. (1) -(3)

$$\dot{N} = \frac{n_e(0)V}{t_p} \ 2\int_0^1 (1-x^2)^q \ xdx = \frac{n_e(0)V}{t_p} \cdot \frac{1}{q+1} \tag{4}$$

where V and t_p denote the plasma volume and the alpha particle production time respectively, i.e.

$$V = 2\pi^2 Ra^2$$

$$t_p^{-1} = \frac{C}{4} n_e(0) T^{\gamma}(0) \tag{5}$$

and

$$q = 2m_n + \gamma m_T$$

characterizes the alpha particle production profile $(\sim(1-x^2)^q)$.

The loss rate for particles born on banana orbits intersecting the wall is

$$\dot{N}_l = \frac{2Vn_e(0)}{t_p} \int_0^1 (1-x^2)^q \; l(x)dx \tag{6}$$

where the local loss fraction l(x) for small losses can be approximated as, [6]

$$l(x) \simeq \begin{cases} \frac{1}{\sqrt{8A}} (1-K_s+x+K_s x^2) & x_s \leq x \leq 1 \\ 0 & 0 \leq x \leq x_s \end{cases} \tag{7}$$

Here, A is the aspect ratio of the Tokamak and K_s and x_s are determined by the current profile, j(x), which is assumed to be of the form

$$j(x) \sim (1-x^n)^P \tag{8}$$

Then

$$x_s = 1 - \frac{1}{K_s}$$

$$K_s = \left(\frac{A}{ME_b}\right)^{1/2} \frac{2ZIF(1)}{1+[3(1+\frac{1}{A})]^{1/2}} \tag{9}$$

where E_b is the particle energy in MeV, Z is the charge number of the charged particle, I is the total plasma current in MA and F(x) is the normalized flux function, i.e.

$$F(x) = \frac{\sum_{j=0}^{p} \frac{(-1)^j x^{nj+2}}{(nj+2)^2} \binom{p}{j}}{\sum_{j=0}^{p} \frac{(-1)^j}{nj+2} \binom{p}{j}} \tag{10}$$

The total loss fraction, L, is then

$$L = \frac{\dot{N}_l}{\dot{N}} = \frac{\int_0^1 (1-x^2)^q l(x) x dx}{\int_0^1 (1-x^2)^q \; x \; dx}$$

$$\simeq \frac{1}{\sqrt{8A}} \left[\int_{x_s}^{1} (1-x^2)^{q+1} dx + \frac{K_s}{q+2} (1-x_s^2)^{q+2} \right] \tag{11}$$

Eq. (11) provides a convenient analytical expression from which to estimate the alpha particle losses of a Tokamak plasma in situations where the losses are comparatively small. For approximations in other situations see [6]. In connection with eq. (11) we emphasize that the profile factor q depends on the profiles of density and temperature according to eq. (5) whereas K_s and x_s depend on the current profile indices p and n.

To illustrate the accuracy of the model we apply it to the recently established INTOR Benchmark experiment for which the direct alpha particle losses was found to be $L \simeq 2.2\%$ using a 3D Monte Carlo guiding center orbit following code, [7]. For the bench mark experiment relevant parameters are: $a = 1.2$ m, $R_o = 5.3$ m, $T(x) \sim 1-x^2 \sim j(x) \sim n(x)$, $I = 3$MA which using eq. (11) yields $L \simeq 2.3\%$ in good agreement with the numerical result.

3. Sawtooth dynamics

Although no real consensus has been reached regarding the detailed physics of the sawtooth dynamics, we will adopt a scenario which contains the essential features of the reconnection model as suggested by Wesson, [8,9]. This implies that the sawtooth collapse, i.e. the rapid fall of the central temperature, which occurs on a very short timescale, is succeeded by a somewhat longer stage where the magnetic field lines reconnect. After this stage, which typically lasts for a time $t_r \simeq t_s/10$, where t_s denote the sawtooth period, the flattened profiles start to rise back towards the peaked profiles preceeding the next collapse.

In particular, the crucial assumption of the present analysis is that the flattening of the current profile is concomitant with and occurs on the time scale of the magnetic reconnection. Regarding the changes in the birth profiles of the alpha particles, the analysis does not depend crucially on the time scale of these changes.

When plasma parameters change during the sawtooth cycle, the alpha particle losses can also be expected to change. In particular, at the sawtooth crash and during the subsequent reconnection stage the profiles of temperature, density, and current change towards a flatter form. The broader profiles imply a degradation of confinement, i.e. an increased loss rate for alpha particles generated after the crash, unless the production rate falls more rapidly than the loss rate increases. The increased losses would give rise to inverted sawtooth behaviour.

However, a much more prominent feature in the loss rate variation is caused by an inherent mechanism in the sawtooth dynamics, which leads to a high intensity burst of lost alpha particles during the sawtooth reconnection stage. The degradation of confinement during the sawtooth crash will release alpha particles having accumulated in the confined region of velocity space which is transformed into a loss region by the changing current profile. This loss of accumulated alpha particles will be superimposed on the birth losses and will occur on the time scale of the current redistribution, i.e. the reconnection time. The intensity can be expected to be high, being enhanced by the accumulation factor $t_s/t_r \gtrsim 10$.

The details of this scenario will be worked out in the following paragraphs. However, a qualitative picture of the variation of the alpha particle losses during a sawtooth cycle is easily inferred from the given arguments and is shown in Fig. 1. The qualitative agreement with recently observed losses of fusion produced 15 MeV protons in JET plasmas exhibiting sawtooth behaviour, [5], is emphasized.

4. Variation of loss rate

Using eqs. (6) and (5), the ratio of the "stationary" alpha particle loss rates before (b) and after (a) the sawtooth crash can be obtained as

$$\frac{\dot{N}_{1,a}}{\dot{N}_{1,b}} = \left(\frac{n_a(0)}{n_b(0)}\right)^2 \left(\frac{T_a(0)}{T_b(0)}\right)^{\gamma} \frac{M_a}{M_b} \tag{12}$$

where

$$M = \int_0^1 (1-x^2)^q \, l(x) x \, dx \tag{13}$$

The "stationary" loss rate after the crash is affected by the drops in temperature and density on axis as well as by the changing profiles. Typical of sawtooth induced profile changes is that the density profile is only slightly changed ($\Delta n(0)/n(0) \simeq -(1-3)\%$) whereas the temperature profile is significantly flattened and show large changes on axis

$\dot{T}(0)/T(0) \simeq (10-20\%)$. To model this behaviour on the INTOR Benchmark experiment we take $q_b = 4$ and $q_a \simeq 2$. We furthermore assume the current profile after the reconnection stage to be completely flattened which implies $K_{s,a} \simeq 1.155$, $x_{s,a} = 0.134$ and $M_a/M_b \simeq 7$, which implies

$$\frac{\dot{N}_{1,a}}{\dot{N}_{1,b}} \simeq 5 \qquad (14)$$

i.e. a significant increase in the loss rate as compared to the case before the crash. When the plasma slowly recovers from the crash and develops towards more peaked profiles, the loss rate falls back to its value before the crash and the sawtooth cycle repeats.

In order to estimate the strength of the burst of accumulated alpha particles lost during the reconnection period, two complementary assumptions can be made. During the reconnection time the alpha particles can either (i) retain their spatial profile and velocity distribution or (ii) redistribute to a flatter spatial profile and an isotropic velocity distribution. In both cases we will assume the current profile to become completely flattened during the reconnection time.

Case (i)

In this case the burst intensity is determined by the accumulated particles in the differential part of velocity space corresponding to confined before the crash but unconfined after the crash. The average loss rate of the burst is then

$$\frac{\dot{N}_1^{\,burst}}{\dot{N}_{1,b}} = \frac{t_s}{t_r} \frac{\int_0^1 (1-x^2)^q [l_a(x) - l_b(x)]\, x\, dx}{\int_0^1 (1-x^2)^q\, l_b(x) x\, dx} \tag{15}$$

where we have assumed the increased losses to be distributed evenly over the time period of the magnetic reconnection, t_r.

Introducing the M-factor from eq. (13), eq. (15) can be written

$$\frac{\dot{N}_1^{\,burst}}{\dot{N}_{1,b}} = \frac{t_s}{t_r} \left(\frac{M_a}{M_b} - 1 \right) \tag{16}$$

Using the parameters of the INTOR Benchmark experiment we find $M_a/M_b \simeq 3$ and taking $t_s/t_r \simeq 10$ we find

$$\frac{\dot{N}_1^{\,burst}}{\dot{N}_{1,b}} \simeq 20 \tag{17}$$

i.e. more than an order of magnitude increase.

Case (ii)

When the α-particles are assumed to be redistributed in space towards a flatter profile, the change in profile exponent, Δq, is linked to the change in the density on axis, $\Delta n(0)$, by by the constraint that the number of particles are constant. This requires

$$\frac{\Delta n(0)}{n(0)} = \frac{\Delta q}{q+1} \tag{18}$$

Since present day experimental evidence concerning thermal plasma particles indicate low values of $\Delta n(0)/n(0)$, it seems reasonable to assume $|\Delta q| \lesssim 1$. For the redistributed profile we will choose $\Delta q = -1$, which implies a redistributed alpha particle profile according to

$$n_r(x) = n_r(0) \ (1-x^2)^{q_r} \tag{19}$$

where

$$q_r = q_b - 1$$

$$n_r(0) = \frac{q_b}{q_b+1} n_b(0) \tag{20}$$

If we furthermore assume that the velocity distribution becomes completely isotropized during the reconnection stage and neglect the losses, when evaluating the total production of alpha particles during the sawtooth build-up phase, the average loss intensity of the burst is obtained as

$$\frac{\dot{N}_1^{\text{burst}}}{\dot{N}_1} \simeq \frac{n_r(0)}{n_b(0)} \frac{t_s}{t_r} \frac{\int_{x_{s,a}}^{1} (1-x^2)^{q_r} 1_a(x) x \, dx}{\int_{x_{s,b}}^{1} (1-x^2)^{q_b} 1_b(x) x \, dx} =$$

$$= \frac{q_b}{q_b+1} \frac{t_s}{t_r} \frac{M_r}{M_b} \tag{21}$$

Using the same parameters as before we obtain

$$\frac{\dot{N}_1^{\text{burst}}}{\dot{N}_{1,b}} \simeq 35 \qquad (22)$$

i.e. slightly larger but of the same order as in case (i).

5. Effects of slowing down on the loss rate and the spectrum of the lost alpha particles

In our previous analysis we have neglected effects of slowing down on the characteristics of the losses. For directly lost particles, i.e. particles lost within a bounce time, slowing down effects can safely be neglected. However, the confined alpha particles which accumulate during the sawtooth build up and which are subsequently released during the magnetic reconnection will be significantly affected by slowing down, if the sawtooth period is a finite fraction of the slowing down time, τ_s. Thus slowing down effects will primarily be important for the properties of the burst.

Three characteristic features, caused by finite t_s/τ_s and t_r/τ_s , can easily be inferred:

(i) As compared to our previous estimate of the intensity of the burst, we expect the improved confinement at lower particle energies to decrease the burst intensity.

(ii) Slowing down will cause a broadening of the loss burst spectrum towards lower energies.

(iii) The burst spectrum is detached from the spectrum of the directly lost particles. A downward energy shift is caused by the finite reconnection time during which no additional contribution to the burst intensity is born, but during which slowing down continues to shift the spectrum towards lower energies.

The time evolution of the alpha particle distribution function, f_α , during slowing down is determined in Appendix A and is found to be (assuming stationary plasma parameters)

$$f_\alpha(v,t) = \frac{\tau_s S_o}{4\pi v^3} \left[\eta\left(v-v_\alpha e^{-\frac{t}{\tau_s}}\right) - \eta\,(v-v_\alpha)\right] \tag{23}$$

where S_o is the alpha particle production rate and $\eta(v)$ denotes the Heaviside step function. Note that $f_\alpha(v,t)$ pictures a slowing down front at $v=v_f=v_\alpha \exp(-t/\tau_s)$ sliding along the steady state solution $f_\alpha(v) = \tau_s S_o/4\pi v^3$ towards thermal energies.

The energy, E, of a particle affects its confinement properties through the parameter $K_s \sim 1/\sqrt{E}$, which determines the radius of marginal confinement, $x_s = 1-1/K_s$ cf. eq. (9). Thus, as E decreases, K_s increases and $x_s \rightarrow 1$. In order to estimate the reduction of the losses due to slowing down effects we evaluate the losses for the average energy, $\bar{E}$, of the time dependent slowing down distribution (23). This average energy, $\bar{E}$, is, see Appendix A

$$\overline{E}(t) = E_\alpha \frac{\tau_s}{2t_s} \left[1-\exp\left(-\frac{2t_s}{\tau_s}\right)\right] \tag{24}$$

which implies a time dependence of the characteristic parameter, K_s, according to

$$K_s(t) = K_{s,b} \frac{F_b(1)}{F_r(1)} \left\{\frac{\tau_s}{2t_s} \left[1-\exp\left(-\frac{2t_s}{\tau_s}\right)\right]\right\}^{1/2} \tag{25}$$

where $F_r(1)$ denotes the value of the normalized flux function during the reconnection stage.

Although the proper value of t_s/τ_s for the Benchmark experiment is not known, a representative value would be $\tau_s/t_s \simeq 2.2$ which implies $E_f \equiv \frac{1}{2} m_\alpha v_f^2 \simeq 1.4$ MeV and $\overline{E} \simeq 2.3$ MeV.

Assuming $F_r(1) = 1/2$, i.e. a completely flattened current profile we obtain for the average burst intensity

$$\frac{\dot{N}_1^{\,burst}}{\dot{N}_{1,b}} \simeq 7 \tag{26}$$

i.e. a somewhat lower value than obtained neglecting slowing down, cf eq. (17).

Since the adjustment of the current profile can be expected to occur gradually during the reconnection stage, the maximum loss intensity will tend to occur towards the end of the reconnection period and to be significantly higher than the averaged values given by eqs. (17), (22), and (26). The energy spectrum should be very broad (unless $\tau_s/t_s \gg 1$).

Furthermore, the peak of the loss spectrum will be shifted an amount, ΔE, due to additional slowing down of confined particles, which are subsequently lost during the reconnection stage:

$$\Delta E = E_\alpha \frac{\tau_s}{2t_r} \left[1 - \exp\left(- \frac{2t_r}{\tau_s} \right) \right] \tag{27}$$

with $t_r/t_s \simeq 0.1$ we find $\Delta E \simeq -0.15$ MeV.

Summary and conclusion

The present analysis predicts significant variability of the losses of fusion produced high energy particles during sawtooth activity in Tokamak plasmas. The basic mechanism determining the losses is the change in the current profile which is assumed to occur concomitant with the magnetic reconnection stage following the sawtooth crash. The particle losses will exhibit an inverted sawtooth behaviour, but the most prominent feature is a high intensity burst of lost particles towards the end of the reconnection period. The loss spectrum is composed of two contributions: (i) Directly lost particles giving rise to a peak at the particle birth energy and (ii) Accumulated particles lost during the reconnection stage which have suffered significant slowing down and which give rise to a broad spectrum slightly down shifted due to additional slowing down during the reconnection stage.

All these features are in good qualitative agreement with recent experimental results concerning 15 MeV proton emission on JET, [5]. Even the observed down shift of 0.6 MeV is in excellent agreement with eq. (27).

Thus, although the present theory is qualitative on several points it seems to give predictions in good agreement with experiments. A closer investigation of the losses of 15 MeV protons is underway.

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Appendix Evolution of alpha particle distribution function during slowing down

The isotropic Fokker-Planck equation describing the slowing down of fusion generated alpha particles can be approximated as

$$\frac{\partial f_\alpha}{\partial t} = \frac{1}{\tau_s} \cdot \frac{1}{v^2} \frac{\partial}{\partial v} (v^3 f_\alpha) + \frac{S_o}{4\pi v_\alpha^2} \delta(v-v_\alpha) \qquad (A1)$$

where f_α denotes the alpha particle distribution function, τ_s is the slowing down time, and v_α and S_o are the birth velocity and birth rate of the alpha particles respectively. In order to account for slowing down during non-stationary situations, τ_s and S_o are allowed to vary with t. In order to solve eq. (A1) we substitute

$$F = f_\alpha \exp\left(-3 \int_o^t \frac{dt'}{\tau_s}\right) \qquad (A2)$$

to rewrite eq. (A1) as

$$\frac{\partial F}{\partial t} = \frac{v}{\tau_s} \frac{\partial F}{\partial v} + \frac{S_o \delta(v-v_\alpha)}{4\pi\, v_\alpha^2} \exp\left(-3 \int_o^t \frac{dt'}{\tau_s}\right) \qquad (A3)$$

The characteristic coordinate of eq. (A3) is determined from

$$\frac{dv}{v} = - \frac{dt}{\tau_s} \qquad (A4)$$

Thus, introducing the variables

$$\xi = \frac{v}{v_\alpha} \exp\left(\int_0^t \frac{dt'}{\tau_s} \right)$$

$$\tau = t \tag{A5}$$

eq. (A3) becomes

$$\frac{\partial F}{\partial \tau} = \frac{S_o}{4\pi v_\alpha{}^2} \delta\left(\xi v_\alpha e^{-\int_0^\tau \frac{dt'}{\tau_s}} - v_\alpha\right) e^{-3\int_0^\tau \frac{dt'}{\tau_s}} \tag{A6}$$

Since $F(\tau=0,\xi)\equiv 0$ we obtain

$$F(\tau,\xi) = \int_0^\tau \frac{S_o}{4\pi v_\alpha{}^2} e^{-3\int_0^{\tau'} \frac{d\tau''}{\tau_s}} \delta\left(\xi v e^{-\int_0^{\tau'} \frac{dt''}{\tau_s}} - v_\alpha\right) d\tau' \tag{A7}$$

which by a change of variables can be solved to yield

$$F(\tau,\xi) = \frac{\tau_s(\tau^*) S_o(\tau^*)}{4\pi v_\alpha{}^3 \ \xi^3} \left[\eta(\xi-1) - \eta\left(\xi e^{-\int_0^\tau \frac{d\tau'}{\tau_s}} - 1\right) \right] \tag{A8}$$

where η denotes the Heaviside step function and the effective time t^* is defined by

$$\xi = \exp\left(\int_0^{\tau^*} \frac{d\tau}{\tau_s} \right) \tag{A9}$$

Finally, going back to the variables v and t we obtain the solution

$$F(t,v) = \frac{\tau_s(\tau^*)S_o(\tau^*)}{4\pi v^3} e^{-3\int_0^t \frac{dt'}{\tau_s}} \left[\eta(v-v_\alpha e^{-\int_0^t \frac{dt'}{\tau_s}}) - \right.$$

$$\left. -\eta(v-v_\alpha) \right] \qquad \text{(A10)}$$

i.e. the alpha particle distribution function, $f_\alpha(v,t)$, evolves according to

$$f_\alpha(v,t) = \frac{\tau_s(\tau\ )S_o(\tau\ )}{4\pi v^3} \left[\eta(v-v_\alpha e^{-\int_0^t \frac{dt'}{\tau_s}}) - \right.$$

$$\left. - \eta(v-v_\alpha) \right] \qquad \text{(A11)}$$

where τ^* is determined by

$$\int_t^{\tau^*} \frac{dt'}{\tau_s} = \ln \frac{v}{v_\alpha} \qquad \text{(A12)}$$

In particular, if τ_s and S_o are constant we find

$$f_\alpha(v,t) = \frac{\tau_s S_o}{4\pi v^3} \left[\eta(v-v_\alpha e^{-\frac{t}{\tau_s}}) - \eta(v-v_\alpha) \right] \qquad \text{(A13)}$$

The solution takes the form of a slowing down front at $v_f = v \exp(-t/\tau_s)$ sliding along the steady state solution $f_\alpha(v) = \tau_s\ S_o/4\pi v^3$ towards thermal energies, cf Fig.

From the solution (A13) we easily infer the density, n_α, and the mean energy, $\bar{E}_\alpha$, of the slowing down distribution as

$$n_\alpha(t) = t\, S_o$$

$$\bar{E}_\alpha = \frac{1}{n_\alpha(t)} \int_0^\infty \frac{1}{2} m_\alpha v^2 f_\alpha(v,t)\, 4\pi v^2 dv =$$

$$= E_\alpha \frac{\tau_s}{2t} [1 - \exp(-2t/\tau_s)] \qquad \text{(A14)}$$

where E_α is the alpha particle birth energy.

Figure Captions

Fig. 1 Qualitative plot of the variation of alpha particle loss rate during a sawtooth cycle (t_o, t_o+t_s)

Fig. 2 Qualitative plot of the time evolution of the alpha particle slowing down distribution, $f_\alpha(v,t)$.

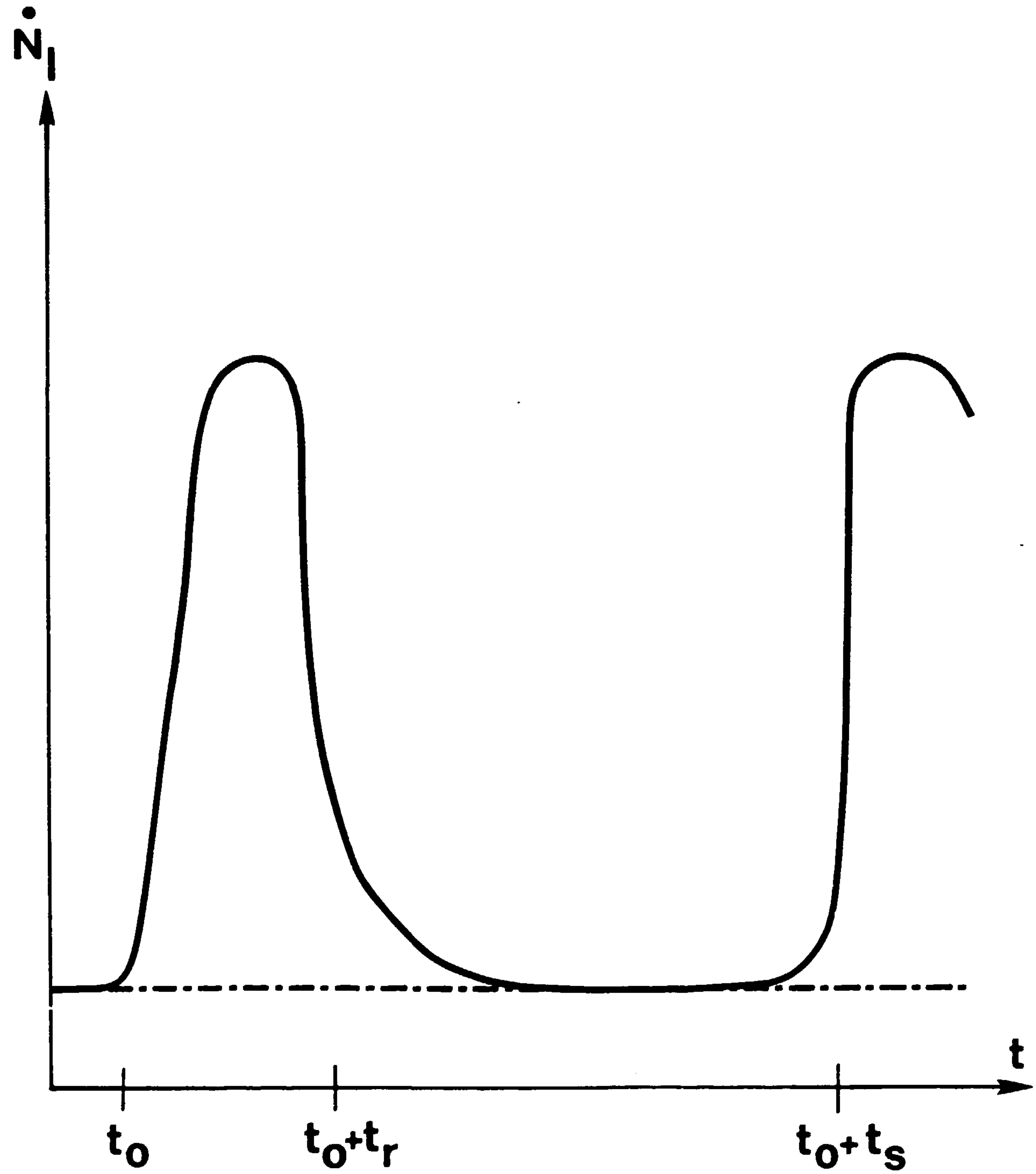
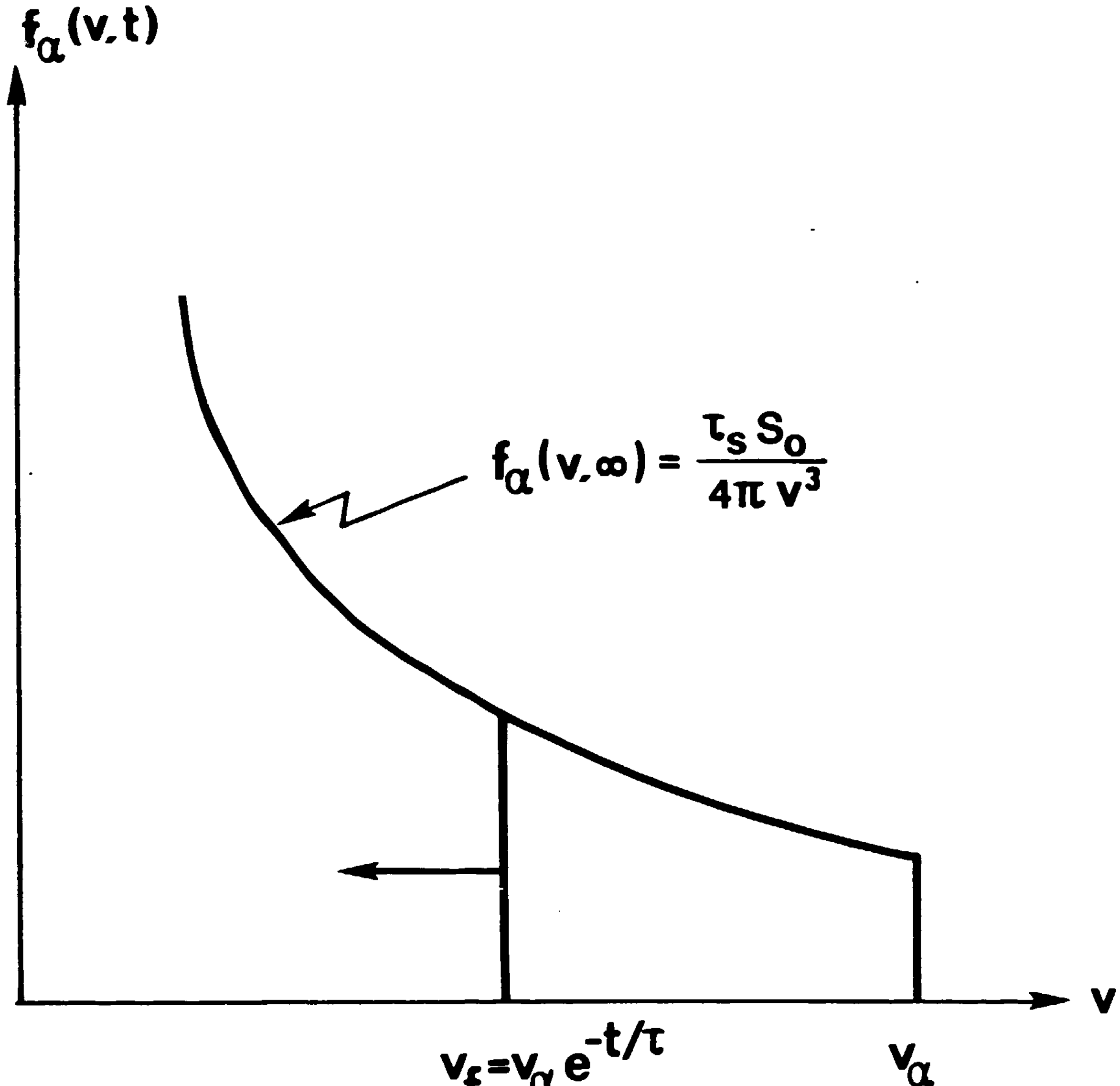


Fig. 1



$f_\alpha(v,t)$
$f_\alpha(v,\infty) = \frac{\tau_s S_0}{4\pi v^3}$
v
$v_f = v_\alpha e^{-t/\tau}$
v_α

Fig. 2