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ABSTRACT

Results obtained on the TCA tokamak have shown that there are narrow peaks in the absorption of r.f. power at $\omega < \omega_{ci}$ which occur near the threshold of the Alfvén continuum. Their use as a diagnostic for measuring the mass density and safety factor on the axis of a tokamak discharge is proposed. The application of this method to tokamak plasmas in TCA is discussed.

1. INTRODUCTION

This report presents a new method of measuring the safety factor on axis $q(0)$ and the mass density on axis $\rho(0)$, in a tokamak discharge. The proposition originates from work carried out on the TCA tokamak as part of a study of the absorption of low-frequency waves from a discrete antenna under the condition $\omega < \omega_{ci}$. The aim of the experiment is the study of the physics necessary to understand Alfvén wave heating.

Up until now several methods have been proposed to measure q(0) or the profile of q in a tokamak. Without a direct measurement we estimate the q(r) profile from the function

$$q(r) = q(a)\frac{r^2}{a^2} \cdot \frac{\int_0^a r' \, T_e^{3/2}(r') \, dr'}{\int_0^r r' \, T_e^{3/2}(r') \, dr'}$$

We are primarily interested in measurements which either can surpass this in precision, allowing us to measure q(r) without having to estimate $Z_{eff}(r)$ and the trapping correction as a function of radius, or can provide a continuous measurement which, in general, is not the case for the higher precision Thomson scattering method. It appears from the lack of general acceptance that no one method is able to serve as a regular measurement of q. We therefore feel justified in proposing yet another method which appears to warrant consideration.

The measurement of mass density on axis $\rho(0)$ is of interest in that it opens up two possibilities. One is a check on the values deduced from other diagnostics where applicable and the other is as a primary measurement of species ratio. The mass density on axis is given by

$$\rho(0) = n_0(0)\sum_i \eta_i(0) A_i \quad ; \quad n_e(0) = n_0(0)\sum_i \eta_i Z_i$$

where A_i and η_i are the atomic mass and fraction present of all ion species in the plasma; $n_0(r)$ is the ion density. We see that a considerable amount of usually spectroscopically derived information must be available to determine $\rho(0)$. For some conditions the mass density is relatively insensitive to the η_i. In deuterium operation, for example, the main species has $A_i/Z_i = 2$, and for sufficiently hot plasmas the impurities will be almost fully stripped producing ions which similarly have $A/Z \sim 2$. For experiments in which a mixture of hydrogen isotopes is used as the dominant species, a measurement of the mass density will yield the mixture ratio during a discharge, if we can assume the low values of Z_{eff} which will be necessary. In addition, we can point out that the usual measurement of $n_e(0)$ is sensitive to the analysis performed on the interferometer data and an additional check would always be desirable. Thomson scattering provides localised information but its absolute calibration is sometimes difficult.

2. PRINCIPLE

During recent studies on TCA[1] a set of peaks was seen in the absorption from antennae driven at low radio frequencies ($\omega < \omega_{ci}$). The antennae in TCA are characterised by being discrete structures carrying purely poloidal currents and are similar in topology to the ICRH antennae in general use. It was found that these peaks occur at, or rather near, the onset of the Alfvén continua for different (n,m). Their existence is derived theoretically in Ref. 2. and are Global Eigenmodes of the Alfvén Wave, which we refer to as Discrete Alfvén Waves.

The Shear Alfvén Wave frequency given by

$$\omega^2 = k^2 \left(B_\phi + \frac{m}{rk} B_\theta \right)^2 / \mu_0 \rho \qquad (1)$$

is a continuum in a tokamak plasma, due to the radial dependence of mass density ρ and poloidal field B_θ, between a minimum frequency at or near the plasma centre (the threshold frequency) and a maximum frequency at the plasma edge. Toroidal geometry reduces the k-spectrum to a set of n-modes ($k = n/R$) and, fixing the driving frequency, we obtain the Alfvén wave resonance condition

$$\omega_A^2(r) = \frac{B_\phi^2 \left(n + m/q(r) \right)^2}{\mu_0 \rho(r) R^2} \qquad (2)$$

which defines a set of resonant surfaces. By way of illustration a set of these curves is shown in Fig. 1, for $m = +1$, $j(r) = j(0)$ $(1 - r^2/a^2)^{kj}$, $\rho(r) = \rho(0)$ $(1 - r^2/a^2)^{kn}$, $n = 1$-7, $kj = 2,4$, $q(0) = 1$, $kn = 0.5,1,2$.

The absorption peaks are close to the threshold of the Alfvén continuum, and their location is given approximately by

$$\omega^2 \sim \frac{B_\phi^2 \left(n + {}^{m}/_{q(0)}\right)^2}{\mu_0\, \rho(0)\, R^2} \tag{3}$$

We see in Fig. 1 that for large values of n the value of $\omega^2(r)$ is monotonic ($\omega_{thresh} = \omega(0)$), and for smaller values of n it has a minimum off-axis. The condition that $\omega(r)$ be monotonic is given by:

$$\left.\frac{d^2\omega_A^2(r)}{dr^2}\right|_{r=0} \geq 0 \;;\; \frac{\frac{-m}{q(0)^2}\, q''(0)}{\left(n + {}^{m}/_{q(0)}\right)} \geq \frac{1}{2}\rho''(0)/\rho(0) \tag{4}$$

If we express $\rho(r)$ and $j(r)$ as $\rho(r) = \rho(0)(1-r^2/a^2)^{kn}$, $j(r) = j(0)(1-r^2/a^2)^{kj}$ then the condition is simply rewritten as

$$n \geq m\left\{\frac{K_j}{K_n} - 1\right\} \tag{5}$$

It is clear that if the peak occurs close to the threshold frequency and that this frequency is far from the frequency on axis, then the interpretation is considerably more complex. We show in Fig. 2 the values of threshold frequency $\omega(th)$ divided by the frequency on axis $\omega(0)$ to illustrate this point. In addition, we accept that the peak may be a certain non-negligible distance from $\omega(th)$, this separation being calculable by MHD codes, including ω/ω_{ci} effects, and to be verified experimentally.

Let us denote the peak frequency as $\omega_n = \omega_n(0) \times (1-\Delta\omega_n/\omega_n(0))$ where $\Delta\omega$ includes the calculable separation between resonance and threshold, and also any measurement error.

From the basic equation (3) we see that

$$\rho(0) = \frac{K^2 (n_1 - n_2)^2}{(\omega_{n1} - \omega_{n2})^2} \quad ; \quad K^2 = \frac{B\phi^2}{\mu_0 R^2} \tag{6}$$

and

$$q(0) = \frac{m(\omega_{n1} - \omega_{n2})}{n_1 \omega_{n2} - n_2 \omega_{n1}} \tag{7}$$

where we make use of the location of two separate peaks to measure $\rho(0)$ and $q(0)$ independently. A linear error analysis yields :

$$\frac{\Delta\rho(0)}{\rho(0)} = \frac{-2(\Delta\omega_{n1} - \Delta\omega_{n2})}{\omega_{n1} - \omega_{n2}} \tag{8}$$

$$\frac{\Delta q(0)}{q(0)} = \frac{(\Delta\omega_{n1}\omega_{n2} - \Delta\omega_{n2}\omega_{n1})(n_1 - n_2)}{(\omega_{n1} - \omega_{n2})(n_1\omega_{n2} - n_2\omega_{n1})} \tag{9}$$

For the case that $\Delta\omega_n/\omega_n(0) = D$, we obtain:

$$\frac{\Delta\rho(0)}{\rho(0)} = -2D \tag{10}$$

$$\frac{\Delta q(0)}{q(0)} = 0 \qquad (11)$$

and q(0) is unaltered by imprecisely knowing $\Delta\omega_n/\omega_n(0)$.

For the case that $\Delta\omega_n$ = DW, we obtain

$$\frac{\Delta \rho(0)}{\rho(0)} = 0 \qquad (12)$$

in which case $\Delta q(0)/q(0)$ is roughly proportional to DW/ω for $n_1 = 1$, $n_2 = 2$; —

$$\frac{\Delta q(0)}{q(0)} = \frac{DW.\ (n_1 - n_2)}{n_2 \omega_{n1} - n_1 \omega_{n2}} \qquad (13)$$

3. METHOD FOR TCA

Since we can obtain ρ(0) and q(0) from Eq. (6) and (7), given two or more absorption peaks, there are two simple solutions available to us. We can either (a) sweep the probing frequency using one or more antennae, with a sufficiently wide frequency range to cover several peaks for a range of densities, or (b) frequency-track two or more modes using one or several antennae.

a) Frequency sweep

For the measurement of q(0), we are interested in the lowest value of n commensurate with an accurate numerical understanding of the relationship between ω_n and $\omega_n(0)$. If we consider $n_{min}=3$ and $n_{max}=6$ then (for q(0) ~1) we obtain $\omega_{max}/\omega_{min} \sim 7/4$. Taking into consideration a range in density of 10 during one shot we find $\omega_{max}/\omega_{min} \sim 5$. The antenna-circuit must be swept in frequency over this range while maintaining the necessarily high Q to enable the loading variations to be detected.

The peaks observed in TCA are not symmetric at their base and so a peak-detecting circuit should be used to locate the maximum.

b) Frequency Tracking

The alternative solution of tracking the peaks in frequency during a discharge has two major advantages. Firstly, we require a reduced frequency range for each peak, compared with a sweep to cover several peaks. Secondly, the time-resolution is vastly improved, providing a quasi-continuous measurement which could easily follow the sawtooth variations. One antenna could be used, with time-sharing between the two search frequencies.

It would appear that the second method would yield better results.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Fig. 1: Resonant surfaces as a function of plasma parameters; $K_j = q(a)/q(0)-1$; $q(0) = 1$.

(a) $K_n = 0.5$, (b) $K_n = 1.0$, (c) $K_n = 2.0$.

Fig. 2: Threshold frequency divided by frequency on axis for various peaking factors $K_j = 2\text{-}8$. $K_n = 1$, $m = 1$.

Fig. 1(a) $k_n = 0.5$
$q_a = 3,5$

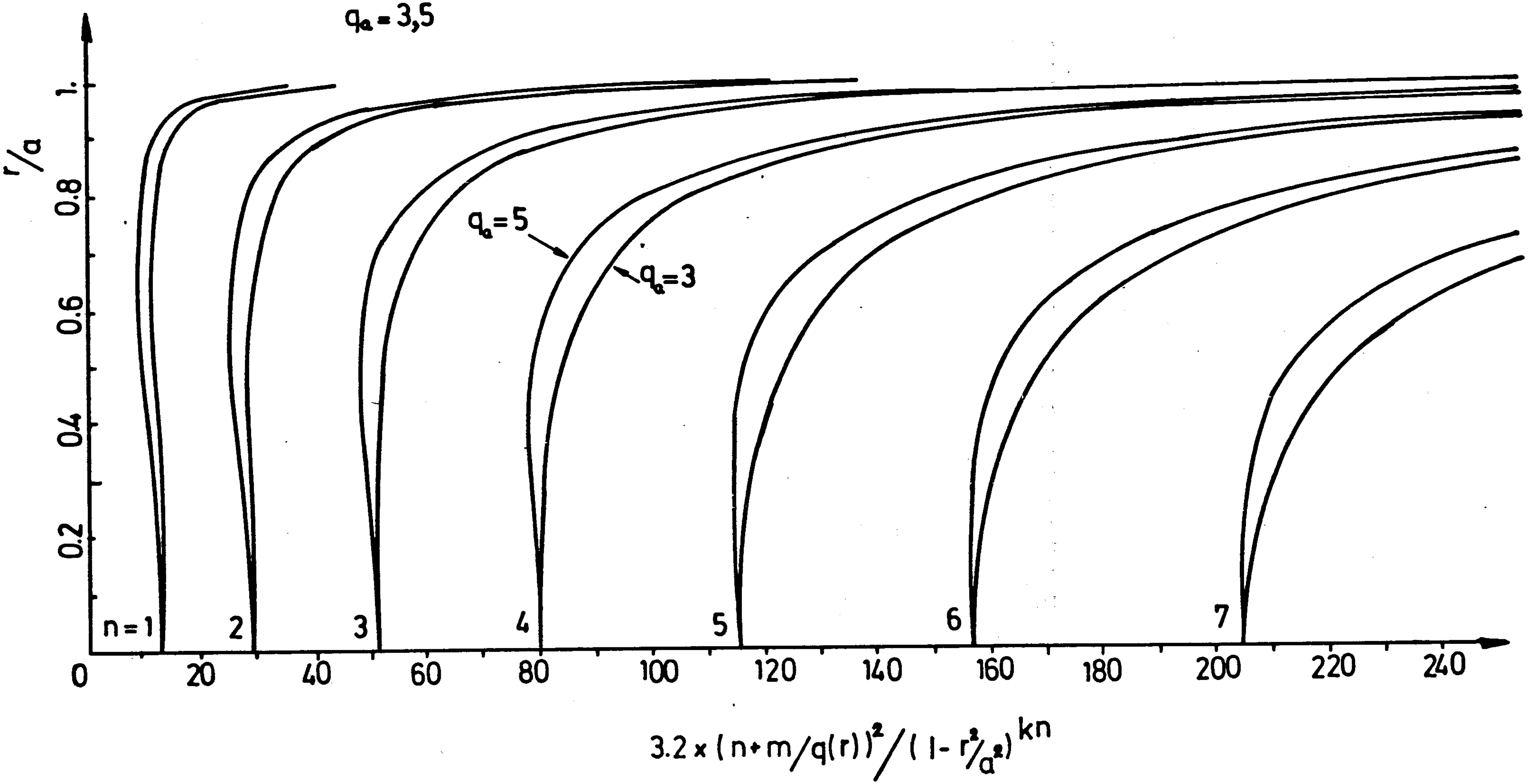

Fig. 1(b) $k_n = 1.0$, $q_a = 3,5$

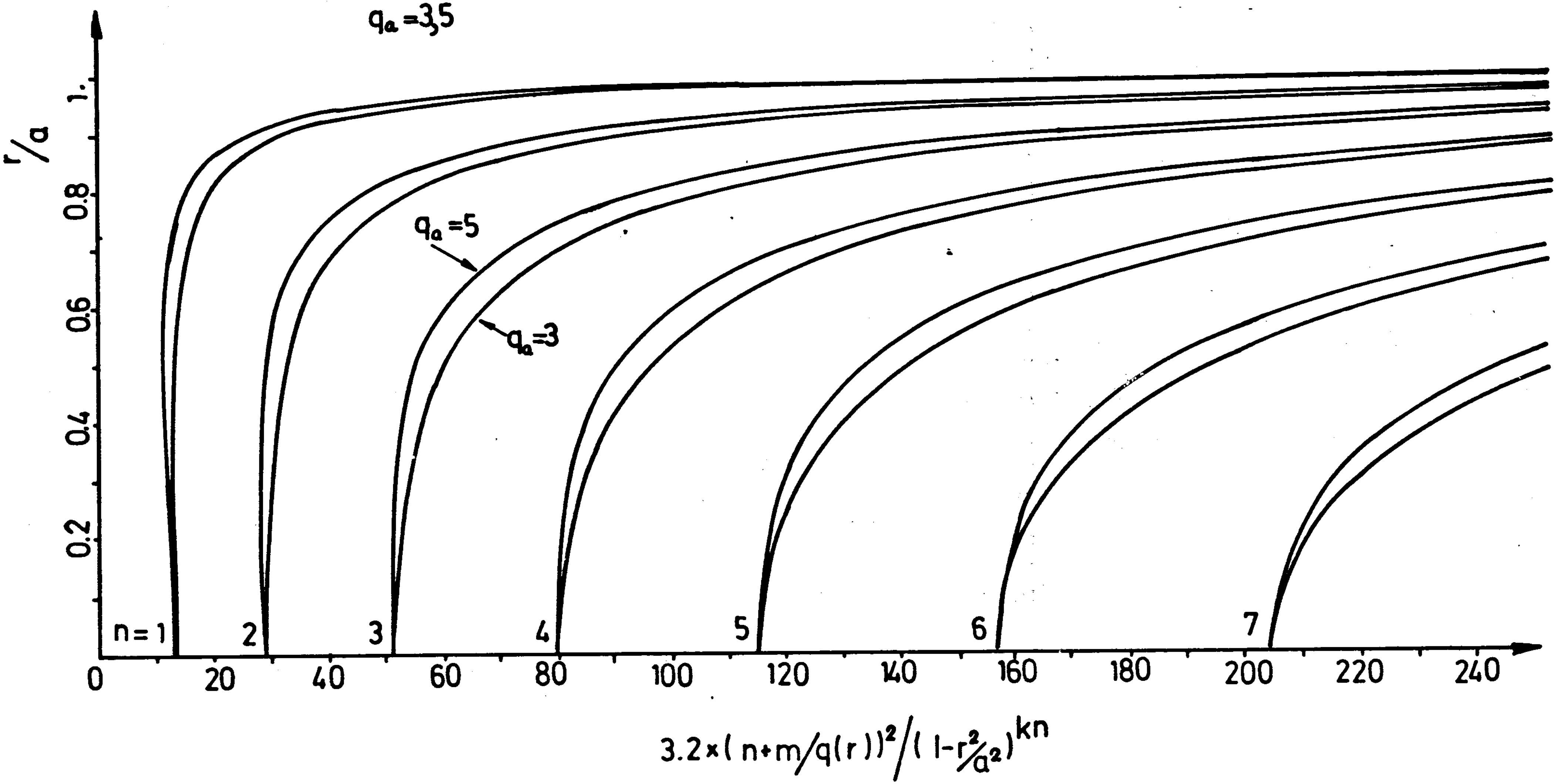

Fig. 1(c) $k_n = 2.0$
$q_a = 3,5$

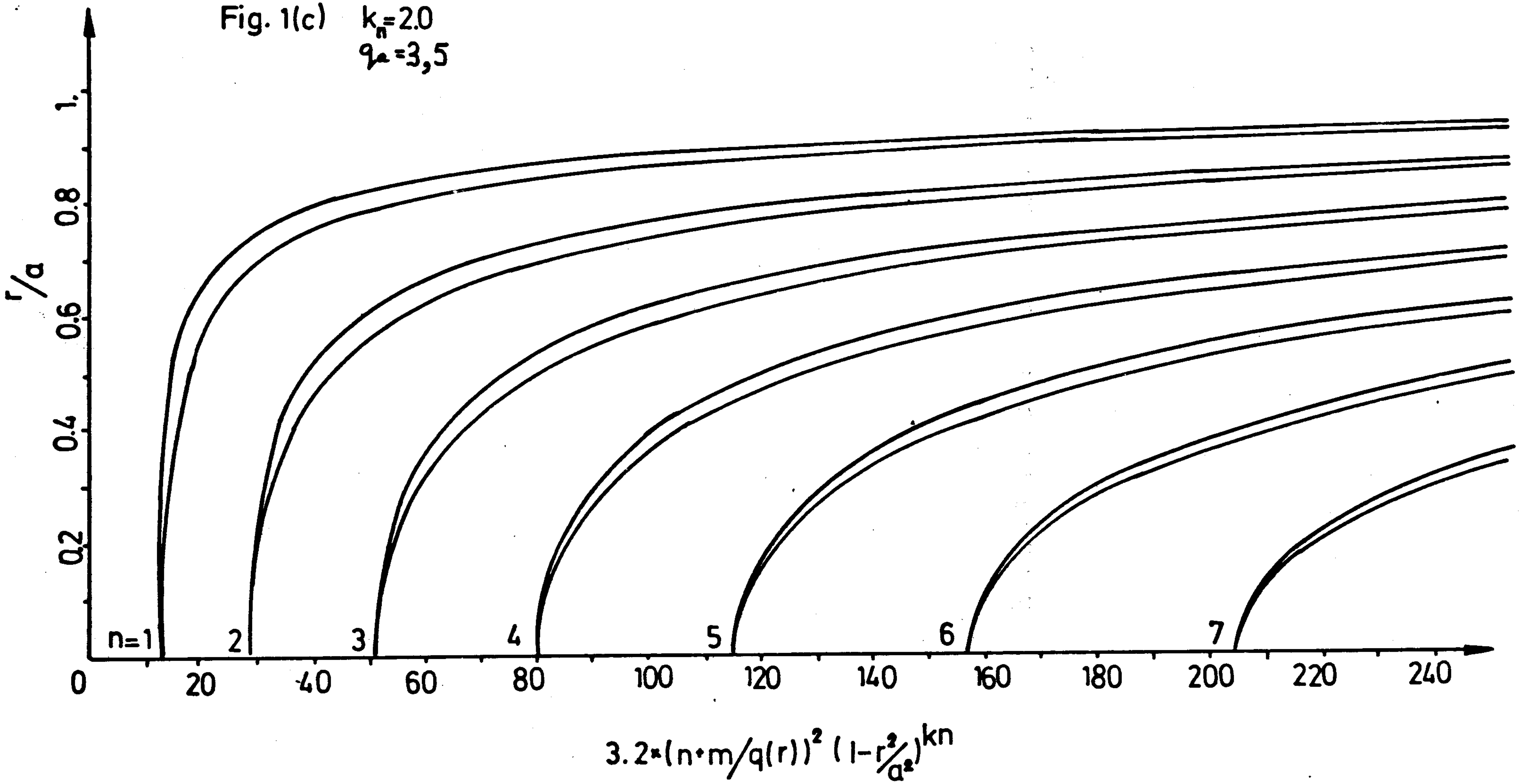

Fig. 2