LRP 391/89 December 1989

DETERMINATION OF CENTRAL Q AND EFFECTIVE MASS ON TEXTOR BASED ON DISCRETE ALFVEN WAVE (DAW) SPECTRUM MEASUREMENTS

P. Descamps, G. Van Wassenhove, R. Koch,
A.M. Messiaen, P.E.Vandenplas,
J.B. Lister and Ph. Marmillod

Determination of central q and effective mass on TEXTOR based on Discrete Alfvén Wave (DAW) spectrum measurements.

P. Descamps+ , G. Van Wassenhove, R. Koch, A. M. Messiaen* , P. E. Vandenplas

Laboratoire de Physique des Plasmas - Laboratorium voor Plasmafysica
Association "Euratom-Etat belge" - Associatie "Euratom-Belgische Staat"
Ecole Royale Militaire - B 1040 Brussels -Koninklijke Militaire School

J. B. Lister, Ph. Marmillod

Centre de Recherches en Physique des Plasmas
Association Euratom - Confédération Suisse
Ecole Polytechnique Fédérale de Lausanne
21, Av. des Bains, CH-1007 Lausanne / Switzerland

ABSTRACT. The use of the Discrete Alfvén Wave spectrum to determine the current density profile and the effective mass density of the plasma in the TEXTOR tokamak is studied; the measurement, the validity of which is discussed, confirms independently the central $q(r=0) < 1$ already obtained by polarimetry.

+ EEC grantee at the Institut für Plasmaphysik, Jülich, F.R. Germany.

* Research Director at the NFSR, Belgium.

1. INTRODUCTION. The DAW are excited in the plasma of the TEXTOR tokamak using one of the two half turn antennae [1] designed for the high power ICRH experiments. The DAW resonances clearly appear on the signal collected by an electrical dipole sensitive to the poloidal field E_y and located 30° away in the toroidal direction from the excitating structure. Our analysis of the different spectra can be divided into three parts:

i) The differents resonance peaks appearing on E_y versus frequency are identified using theoretical considerations and by comparing the measured spectra and the predictions of the KOALA code of the CRPP Lausanne [2].

ii) The sensitivity of the resonance frequencies to the central q value is studied. The profile of current density and particularly the value of the safety factor $q = \frac{B_\phi r}{B_\theta R}$ at the center are indeed the subject of several controversies. On TEXTOR, a q value at the center less than 1 has been measured by polarimetry [3], which is in conflict with the MHD stability criterium of a tokamak discharge. Collins et al [4] have proposed to use the DAW spectra for the determination of the current density profile; the feasibility of the measurement is discussed in the case of TEXTOR. A splitting between the resonances associated with the same $|m+n|$ value (where n and m are the toroidal and poloidal mode numbers) is observed and the distance between the peaks is well explained by the theoretical model. This splitting gives us information on the central q value. Indeed, for a discharge with I_p=350kA, the splitting of the $|m+n|=6$ and $|m+n|=7$ resonances is explained if we suppose a $q(r=0) \approx 0.7$. The latter value is in good agreement with the polarimetry measurements made previously on TEXTOR [3], thereby independently confirming a very critical measurement.

iii) The sensitivity of the measured spectra to the effective mass

$$A_{eff} = \sum_i \eta_i \, A_i \ ; \quad \eta_i = n_i/n_e; \quad A_i, \text{ mass of ion i}$$

is analyzed. By injecting a small quantity of iron during the stationary phase of the discharge, the evolution of the deposition profile of the impurity is deduced from the change in the measured DAW spectra.

2. EXPERIMENTAL SET-UP. The DAWs are excited by feeding one of the fast-wave antennae with a 400W broad band generator. The frequency is swept from 0 to 3 MHz,

in a time interval varying from 50 to 500 ms. A 10A antenna current is obtained for an input power of 200W, by including a matching network between the generator and the antenna. The signal coming from the electrical dipole E_y is mixed with a reference signal coming from the generator. The DAWs are detected by amplitude jump on the $|E_y|$ signal and by phase rotation of 180° between the two signals.

3. THEORY. The wave equations describing a cold cylindrical plasma column, with non uniform plasma current, predict the existence of eigenmodes, just below the minimum frequency of the Alfvén continuum spectrum [5-7]; these modes, called discrete Alfvén eigenmodes are excited, due to the finite ω/ω_{ci} effects or to the poloidal field created by the equilibrium plasma current. An approximate analytical dispersion relation for the DAWs has been proposed by Mahajan et al [8]; they avoid the difficulties coming from the inhomogeneous density and current profiles by linearizing the wave equation in the vicinity of r_{min}, the position of the continuum minimum.

The dispersion relation of the continuum, in the cylindrical approximation, is:

$$\omega_A^2(r) = \left(n+\frac{m}{q}\right)^2 \frac{B_T^2}{\mu_o\, \rho(r)\, R^2} \qquad (1)$$

where (n,m) are the toroidal and poloidal mode numbers.

r is the radial position and R, the major radius

q(r) is the safety factor

$\rho = A_{eff}\, n_e(r)\, m_p$

For $\omega/\omega_{ci} << 1$, as in the present experiments on TEXTOR, the dispersion relation for the DAWs is simply [8]:

$$\omega_{DAW_{n,m}} = \omega_A(r_{min})_{n,m}(1 - \Delta_{n,m}) \qquad (2)$$

$\omega_A(r_{min})_{n,m}$, is the minimum of the Alfvén continuum.

$\Delta_{n,m} = f(\ L^2(r_{min}),\ L_n(r_{min}),\ L_q(r_{min}),\ q(r_{min})\ )$ is given in [8], with

$L^2 = \dfrac{2\,\omega_A^{\,2}}{(\omega_A^{\,2})''}$, $L_n = \dfrac{n_e}{n_e'}$, $L_q = \dfrac{q}{q'}$;

the prime refers to the radial derivative.

It is important to note that the resonance frequencies only depend on the local properties of the plasma (density and current profile) in the vicinity of r_{min}.

For $r_{min}=0$, the approximate relation (2) is no longer valid. In that case, the resonance frequencies are computed using the KOALA code which integrates numerically the wave equation for an inhomogeneous density profile [2]; the antenna resistance is computed by applying boundary conditions at the antenna and at the wall and the resonant frequencies appear as peaks on the loading curve $R=f(\omega)$. When $r_{min} \neq 0$, the resonance frequencies approximated by eq. (2) and those computed by the KOALA code are in good agreement.

4. COMPUTATION of r_{min}. The threshold of the continuum is obtained by solving:

$$q(r_{min}) = -\frac{m}{n}\left(2\left(\frac{\rho\, q'}{\rho'\, q}\right) + 1\right) \qquad (3)$$

On TEXTOR, the profile $\omega_A=f(r)$ is non monotonic in the central region, when n/m is sufficiently small, so that eq. (3) has a solution $r_{min} \neq 0$. Note that modes associated with the same m/n values have the same r_{min} and hence $q(r_{min})$. The experimental density and current profiles can be fitted by the laws:

$$n_e = n_{eo}\left(1 - \left(\frac{r}{a}\right)^2\right)^{\alpha}$$

$$J = J_o\left(1 - \left(\frac{r}{a}\right)^{\gamma}\right)^{\beta} \qquad (4)$$

The approximate r_{min} and $q(r_{min})$ relations become (for $r_{min}/a \ll 1$ and $\gamma=2$) :

$$r_{min} \approx a\sqrt{\frac{\frac{\beta}{\alpha} - 1 - \frac{n}{m}\frac{q_a}{\beta+1}}{\beta\left(\frac{\beta}{2\alpha} + \frac{\beta+2}{6\alpha} - \frac{1}{2}\right)}} \qquad (5)$$

$$q(r_{min}) \approx \frac{m}{n}\left(\frac{\beta}{\alpha}\left(1 - \frac{\beta+2}{6}\left(\frac{r_{min}}{a}\right)^2\right) - 1\right) \qquad (6)$$

5. IDENTIFICATION OF THE MODES A typical experimental spectrum collected on the dipole (signal $+E_y$) for a standard D_2 discharge (I_p=350 kA, B_T=2T, $\overline{n_{eo}} = 2.8\ 10^{13}\ \mathrm{cm}^{-3}$) is presented in fig. 1. As we have only one probe located inside the machine, the modes can not be labeled experimentally in a direct fashion. The identification of a peak is made by comparing the experimental resonance frequencies with the values predicted by the KOALA code and keeping in mind that:

- experiment and theory have shown that, for $\omega/\omega_{ci} < 0.5$, only DAWs with m/n >0 can be excited

- Collins et al [9] found that the dominant peaks have a poloidal mode number $m=-1$ and a toroidal mode number $n<0$
- for TEXTOR, $\omega/\omega_{ci} << 1$, eq. (2) can be written:

$$\omega_{DAW m,n} \approx |n|\, f_1 \left(\frac{m}{n}\right)\left\{ 1 - m^{-2}\, f_2\left(\frac{m}{n}\right)\right\} \qquad (7)$$

so that the modes (n,m) and (-n,-m) which are associated to the same r_{min} value (eq. 3) are degenerate.

The density profile chosen in the code is a fit of the profile obtained by Abel inverting the line integrated density measured by interferometry at 9 different chords; the estimated error on the density at different radial location is less than ± 3%. As the plasma of TEXTOR is poor in heavy impurity, $A_{eff} \approx 2$ (Deuterium plasma) even when Z_{eff} can be quite different from 1. A first estimation of the current profile is made using two resonances associated to the same m/n value. Indeed, from (7) we immediatly deduce:

- the minimum frequency of the continuum spectrum
- the frequency interval between the DAWs and the continuum threshold

A graphical determination of q using the (n,m)=(-1,-1),(-2,-2) modes is presented in fig. 2 . The full curve gives the experimental q dependence on r_{min} , through (2) which determines $\omega_A^2(r_{min})$ and (1) which then links r_{min} to $q(r_{min})$:

$$q(r_{min})=f(\, r_{min}, \omega_{A_{n,m}\ exp}\,)$$

It is computed using the density profile measured by laser interferometry, but without any hypothesis on the current profile. To determine r_{min}, the current profile defined in (4) with $\gamma=2$ has been imposed. The dotted curve represents $q(r_{min})$ theoretically computed as a function of r_{min} for different β values and is obtained by solving the system formed by eq. (6) and

$$q\left(\frac{r}{a}\right) = \frac{q_a \left(\frac{r}{a}\right)^2}{1 - \left(1 - \left(\frac{r}{a}\right)^2\right)^{\beta+1}}$$

with q_a , the safety factor at r=a.

The values of r_{min} , $q\,(r_{min})$ and β are given by the intersection between these two curves. Moreover, for the chosen current profile, the knowledge of β imposes a central q(0) value:

$$q(0) = \frac{q_a}{(\beta+1)}$$

The graphical solution gives:

r_{min}=0.57 a $\quad$ $q(r_{min})$=1.3
β=2.8 $\quad$ $q(0)$=0.92

For the chosen current profile and $\beta \approx 2.8$, the frequency values associated with other peaks measured agree quite well with the computed ones and confirm the mode identification.

These values of β and q(0) have to be compared with the values directly obtained from J(r), i.e. $\beta \approx 3.5$ and q(0)$\approx$ 0.78 [3]. Nevertheless, the precision on the central q value deduced from the first few modes (-1,-1),(-2,-2) is poor since:

- the two curves are almost tangential; a small error on the density which leads to a shift in the full curve can strongly modify the values of r_{min} and β.
- the measurement of β and hence of q(0) comes from the local properties of the current profile at a point r_{min} which can be located at some distance from r=0.

We now introduce a more immediate and precise measurement of q(0) when n/m is large.

6. DETERMINATION OF CENTRAL q BY PEAK SPLITTING. The spectrum represented in fig. 1 shows clearly the splitting of some of the peaks associated with the same |m+n| value. For a smooth current density profile and high n/m values, the resonance layer is now located at the center of the plasma (fig.3) and the DAW spectrum is therefore sensitive to the plasma parameters on the axis. Theoretically,one could also consider that with a q-profile having large q"(r) at $r \neq 0$, r_{min} would not lie on the torus axis for large n/m but this is experimentally ruled out[1]. The theoretical resonance frequencies computed using the KOALA code for |m+n|=3 and |m+n|=7 are shown in figure (4); relation (4) has been used to fit the current density profile measured by

---

[1] If the current density profile is given by (4) with q(0)=1 and for modes such that r_{min}=0, the change of $q''(0)$ obtained by varying $\gamma > 2$ can not explain this mode separation. On the other hand, a $q(0) \neq 1$ clearly leads to a splitting of the resonances (eq.(1)). If a sharp discontinuity were to appear on the q profile i.e.

$$L_q < \frac{2\,|L_n|}{q(r)\,\frac{n}{m}+1} \quad \text{with } L_n = \frac{n}{n'} \text{ and } L_q = \frac{q}{q'}$$

the characteristic length of variation of the density and q profile respectively, r_{min} is different from zero. However, the current density profile associated with a q profile which leads to $r_{min} \neq 0$ for modes n/m $\geq$7 is unrealistic and incompatible with the profile obtained by polarimetry [3].

Soltwitch et al in TEXTOR [3]. For the $|m+n|=3$ resonances, the distance between the two peaks is in good agreement with the experimental observation. Nevertheless, only a small dependence of the peaks' separation on $q(0)$ is observed. For these modes, $r_{min} \approx 0.5a$, and the splitting is only caracteristic of the $q(r_{min}) \approx 1.5$ and not of the central $q(r=0)$ value being sought.

For the $|m+n|=7$ modes, peak $(n=-6,m=-1)$ and $(-7,0)$ are practically degenerate and only slightly dependent on $q(0)$. However the experimental peaks' separation between$(-6,-1)\equiv(-7,0)$ and $(-5,-2)$ depends strongly on $q(0)$ and we find $q(0)$ value equal to 0.7 ± 0.1. For such value of $q(0)$, the theoretical model predicts furthermore that: (i) a peaks' separation $\Delta\omega/\omega \approx 0.04$ between the modes $(-5,-1)$ or $(-6,0)$ and $(-4,-2)$ (ii) that the modes associated to $|m+n|=4$ are all degenerate. These predictions are in good agreement with the measured experimentral spectrum (fig.3) and confirm $q(0)\approx 0.7$. During discharges with $I_p=350kA$, the latter result is also in agreement with the polarimetry measurement made previously on TEXTOR.

7. A_{eff} PROFILE DETERMINATION The factor $(1 - \Delta)$ in rel.(1) being independent of A_{eff}, the ω_{DAW} dependence on A_{eff} is thus:

$$\omega_{DAW}\left(r_{min}\right) + \frac{1}{\sqrt{A_{eff}}} \qquad (8)$$

To study the sensitivity of the DAW spectrum to A_{eff}, a small quantity of iron is injected in a pure deuterium plasma by vaporizing a target of iron with a laser beam during the density and current plateaux. The RF signal is swept from 0 to 2.6 MHz in a time interval of 350ms. The resonance frequencies, corrected to take into account the change in electron density, are measured before and after injection (table1).

Before injection, soft Xray measurements show that the plasma is poor in heavy impurity so that $A_{eff} \approx 2$ because the impurities of the plasma are completely ionised. After injection, the resonances are shifted to lower frequencies, according to the theoretical dependence, but the shift is different for the different $|n+m|$ modes. One explanation is that these modes are associated with different r_{min}, enabling one to determine the A_{eff} profile of the discharge which is of major importance in the study of impurity transport. The r_{min} computation requires an identification of the detected toroidal and poloidal mode numbers (n,m); using the dominant modes associated to $m=-1$, $n=-1,-2,-3$, the A_{eff} profiles at different time after injection ($1.2s< t< 1.4s$ and $2s< t <2.2s$) are deduced from the measured spectra (fig.5). For $< t > \approx 1.3s$, the A_{eff} profile shows a maximum in iron concentration at $r/a=0.4$; the $< A_{eff} > \approx 2.4$ deduced from the DAWs is in good agreement with the value obtained from soft X Ray mesurements at the same time. For $< t > \approx 2.1s$, the mean A_{eff} value has decreased, with the maximum of iron concentration located now at the center of the plasma.

8. CONCLUSIONS : The DAW spectrum mesurements have demonstrated the feasibilty of determining q(0) and the A_{eff} profile in TEXTOR, with a very simple experimental set-up.

The determination of the central q is only precise for the higher (n,m) modes for which $r_{min} \approx 0$. For these latter modes, the splitting of the resonances leads to a quite accurate determination of $q(0) < 1$. However, as the result is strongly dependant on mode identification, the use of the Discrete Alfvèn Wave spectrum measurement as a standard q(0) diagnostic would require distributed probes located all around the machine.

During discharges with low heavy impurities, this diagnostic may also be used to determine the minority concentration in (H)-D or (^{3}He)-D discharges, which is of major importance during ICRH [10].

REFERENCES.

[1] G. Van Oost et al- Fusion Technology, 1987, 12, 449, 1987.

[2] K. Appert, J.V. Vaclavik- Plasma Phys. and Controlled Fusion, 25, 551,1983.

[3] H. Soltwisch, W. Stodieck, J. Manickam, J. Schlüter- Plasma Phys. and Controlled Nuclear Fusion, 1986, (Proc. IAEA Conf. Kyoto), 1, 263, 1986.

[4] G. A. Collins, A.A. Howling, J.B. Lister, Ph. Marmillod- Plasma Physics and controlled Fusion, 29, 323, 1987 .

[5] D.W. Ross, G.L. Chen, S.M. Mahajan- Phys. Fluids, 25, 652, 1982.

[6] K. Appert, R. Gruber, F. Troyon, J. Vaclavik - Proceedings of the 3rd Joint Varenna-Grenoble Symposium, (ECSC-EEC-EAEC Euratom, Brussels) , 1, 203, 1982.

[7] K. Appert, R. Gruber, F. Troyon, J. Vaclavik- Plasma Phys. and Controlled Fusion, 14, 1147, 1982.

[8] S.M. Mahajan, D. Ross, G.-L. Chen- Phys. Fluids, 26, 2195, 1983.

[9] G.A. Collins, F. Hoffman, B. Joye, R. Keller, A. Lietti, J.B. Lister, A. Pochelon- Phys. Fluids, 29, 2260, 1986.

[10] P. Descamps, T. Delvigne, F. Durodié, R. Koch, A.M. Messiaen, P.E. Vandenplas, R.R. Weynants - 16th European Conference on Controlled Fusion and Plasma Physics, Venice, 1989, ECA 13B , part III, 1053, 1989.

$\lvert n+m \rvert$	$(\nu\overline{n}_{eo}^{1/2})$before $<t>=0.5s$	$(\nu\overline{n}_{eo}^{1/2})$after $<t>=1.3s$	$(\nu\overline{n}_{eo}^{1/2})$after $<t>=2.1s$
		$(10^9\ s^{-1}\ m^{-3/2})$	
2	4.27	3.96	4.2
3	7.03	6.00	6.68
4	9.64	8.55	9.10

Table1.. Normalised resonance frequencies $\nu\sqrt{\overline{n}_{eo}}$ measured before and after injection of iron.

Figure captions

fig.1 - Amplitude of E_y measured during a frequency sweep from 0 to 3 MHz; the identification of (m,n) results from the comparaison with the theoretical predictions.

fig.2 - Graphical solution of the q determination from the measurement of DAWs.

fig.3- Evolution the normalized radius r/a corresponding to the minimum of the continuum as a function of n/m ; a parabolic density profile has been supposed.

fig.4 - Peak's separation computed for the $|m+n|=3$ and $|m+n|=7$ modes in function of β, using the KOALA code; $I_p=350kA$, $q_a=3.5$, $n_{eo}=5.25\ 10^{13}$ cm^{-3} and $\alpha=1$.

fig.5- A_{eff} profile deduced from the DAW measurements (m=-1) at different time after injection of iron.

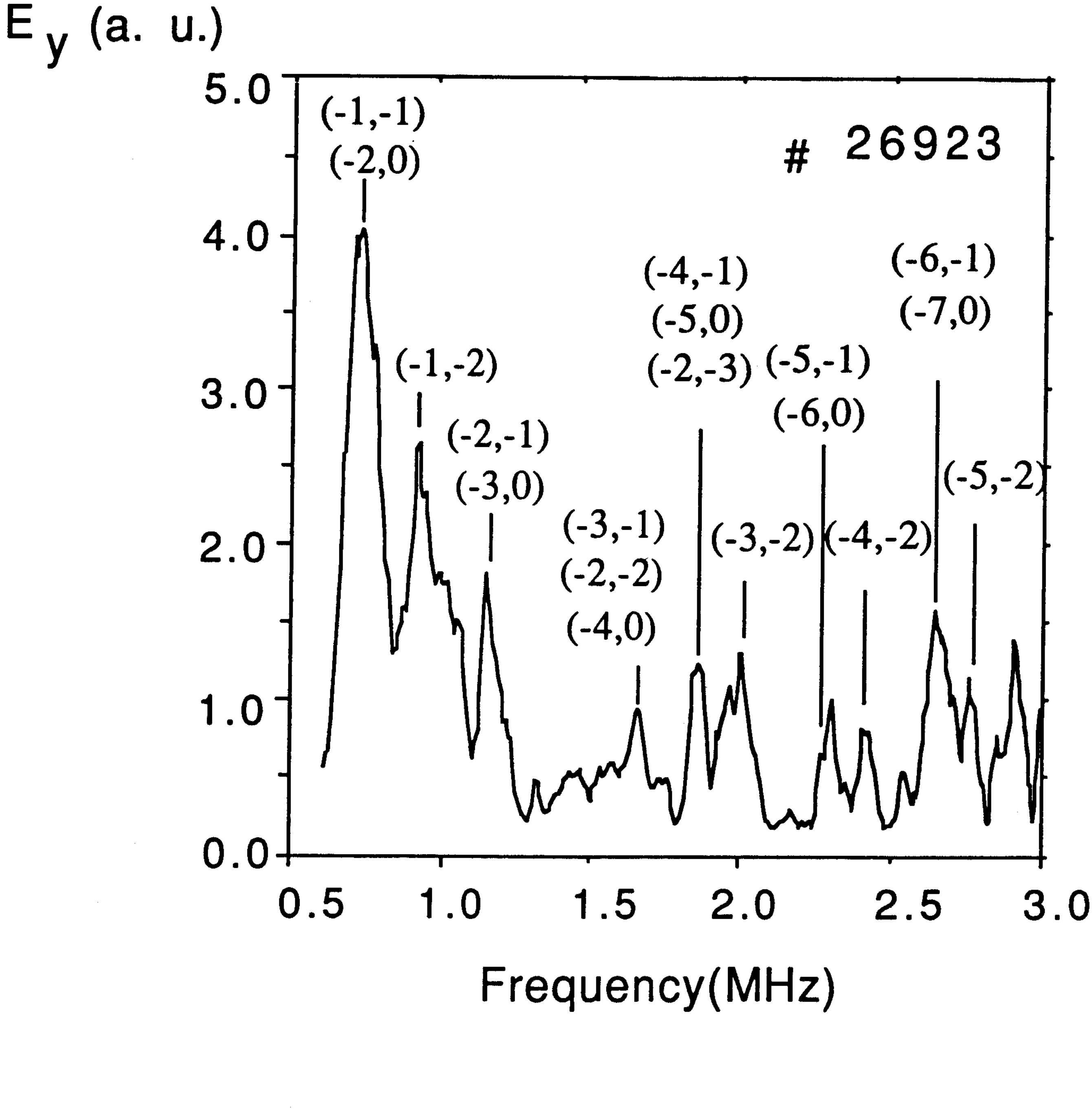
E y (a. u.)
5.0
4.0
3.0
2.0
1.0
0.0
26923
(-1,-1)
(-2,0)
(-1,-2)
(-2,-1)
(-3,0)
(-3,-1)
(-2,-2)
(-4,0)
(-4,-1)
(-5,0)
(-2,-3)
(-3,-2)
(-5,-1)
(-6,0)
(-4,-2)
(-6,-1)
(-7,0)
(-5,-2)
0.5
1.0
1.5
2.0
2.5
3.0
Frequency(MHz)

FIG. 1

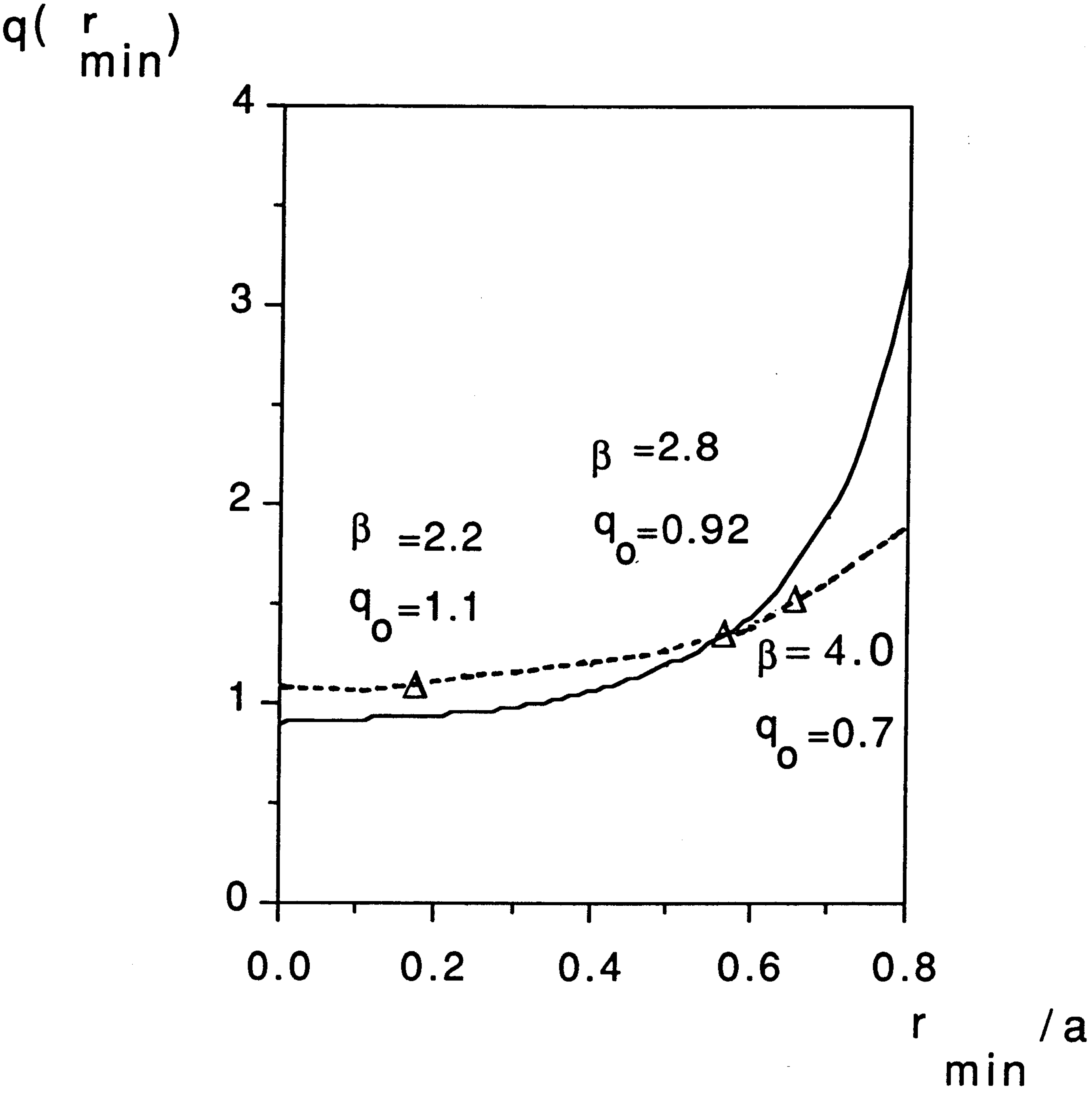

FIG. 2

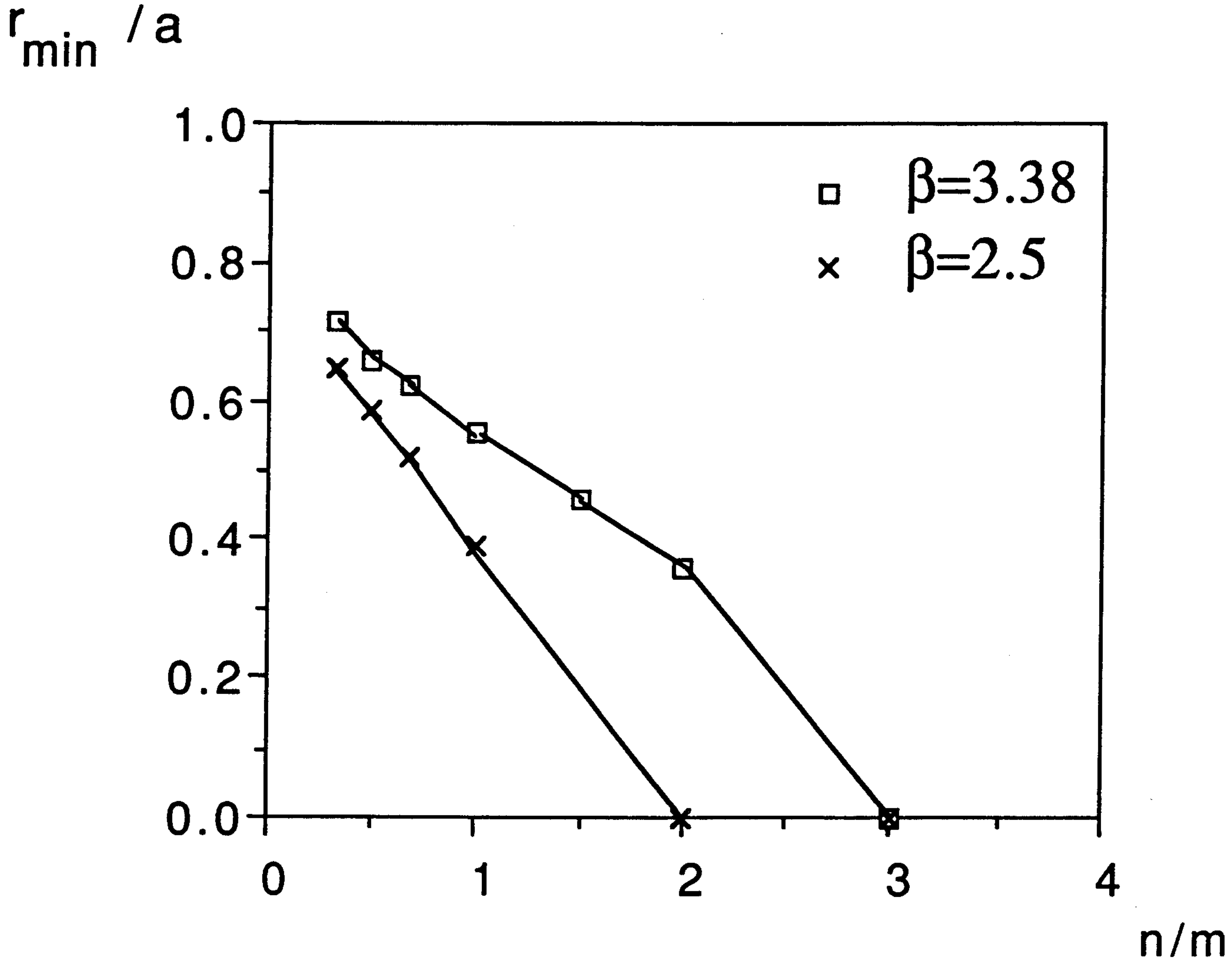

FIG. 3

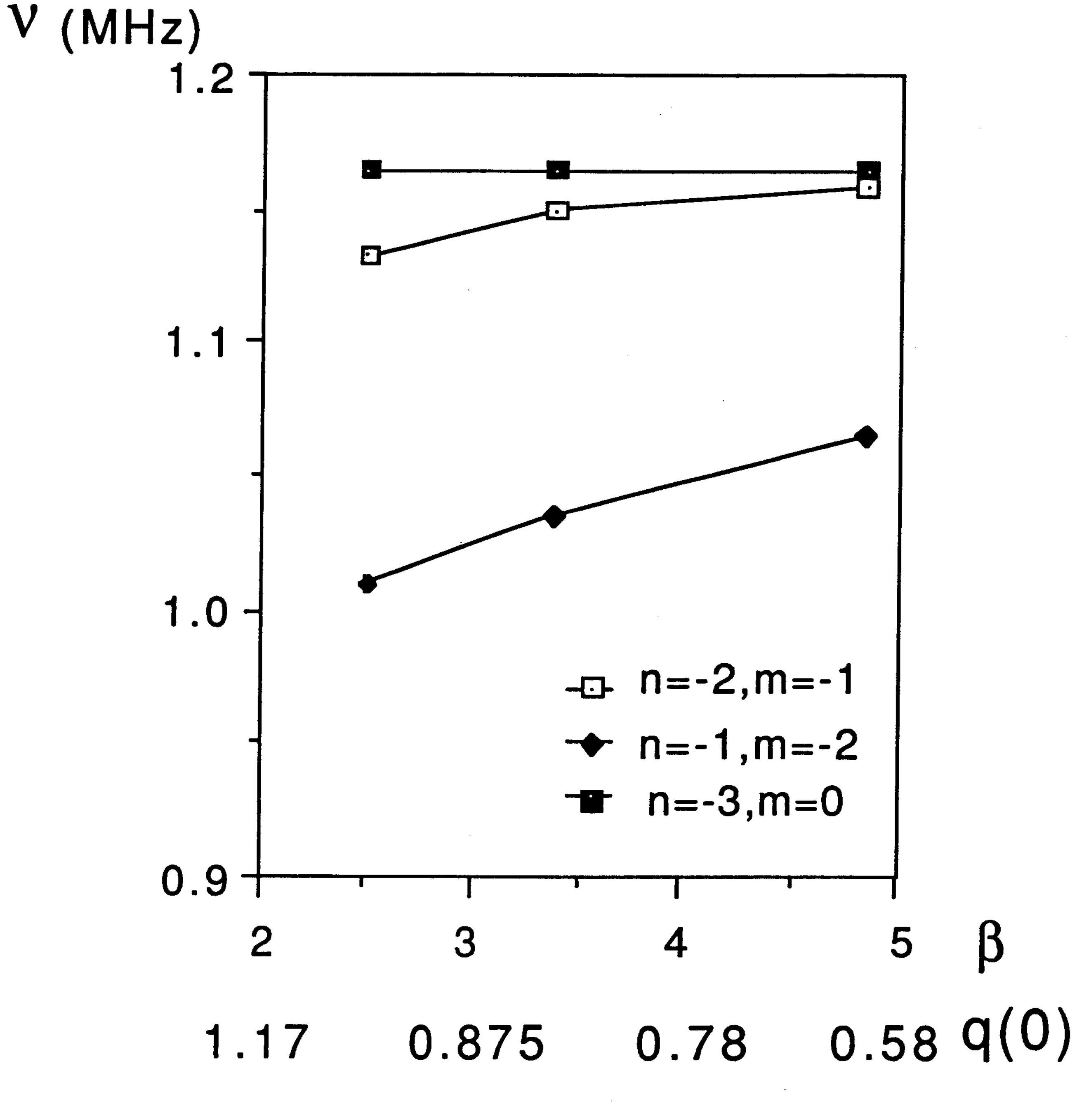

FIG. 4 A

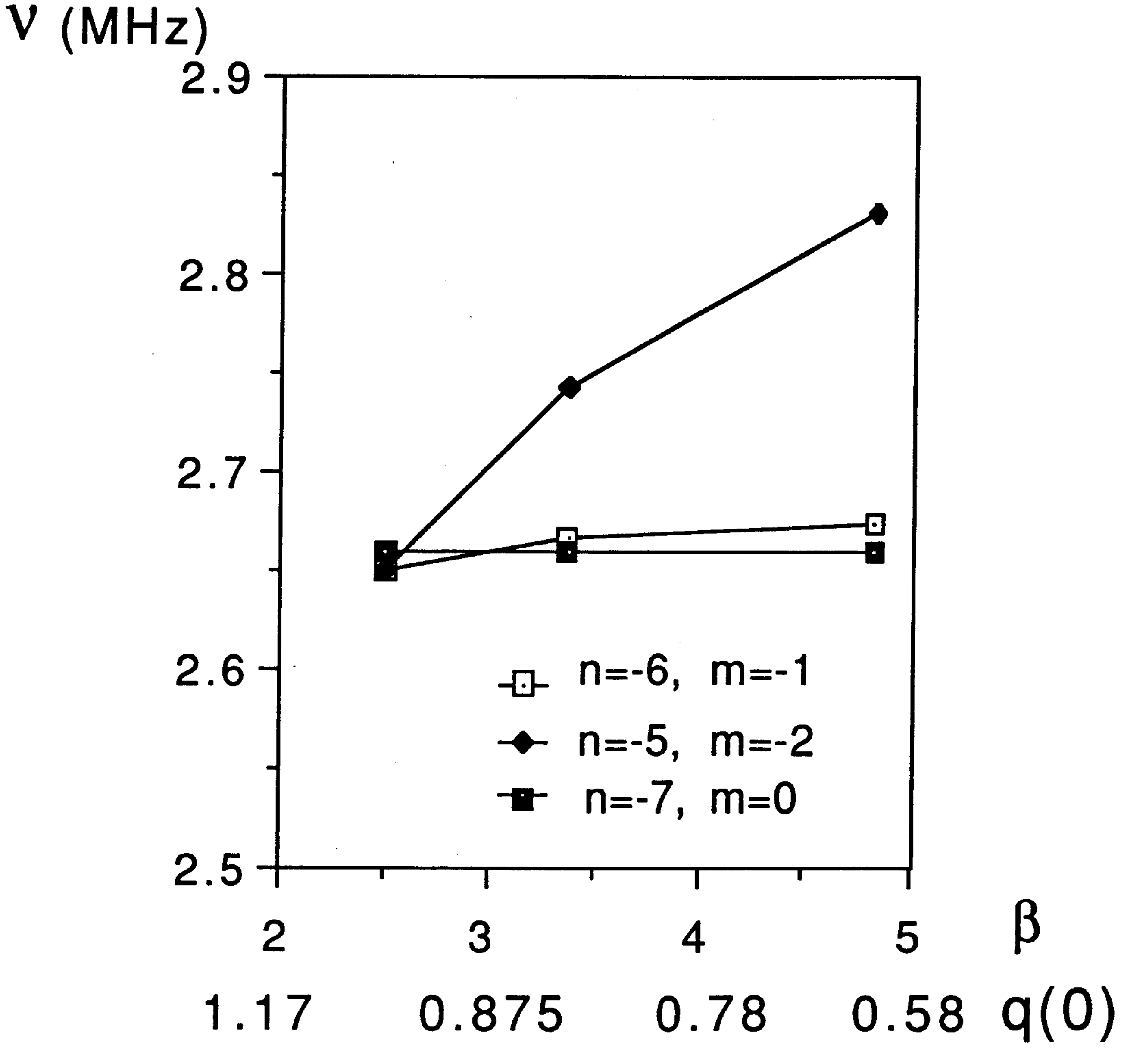

FIG. 4B

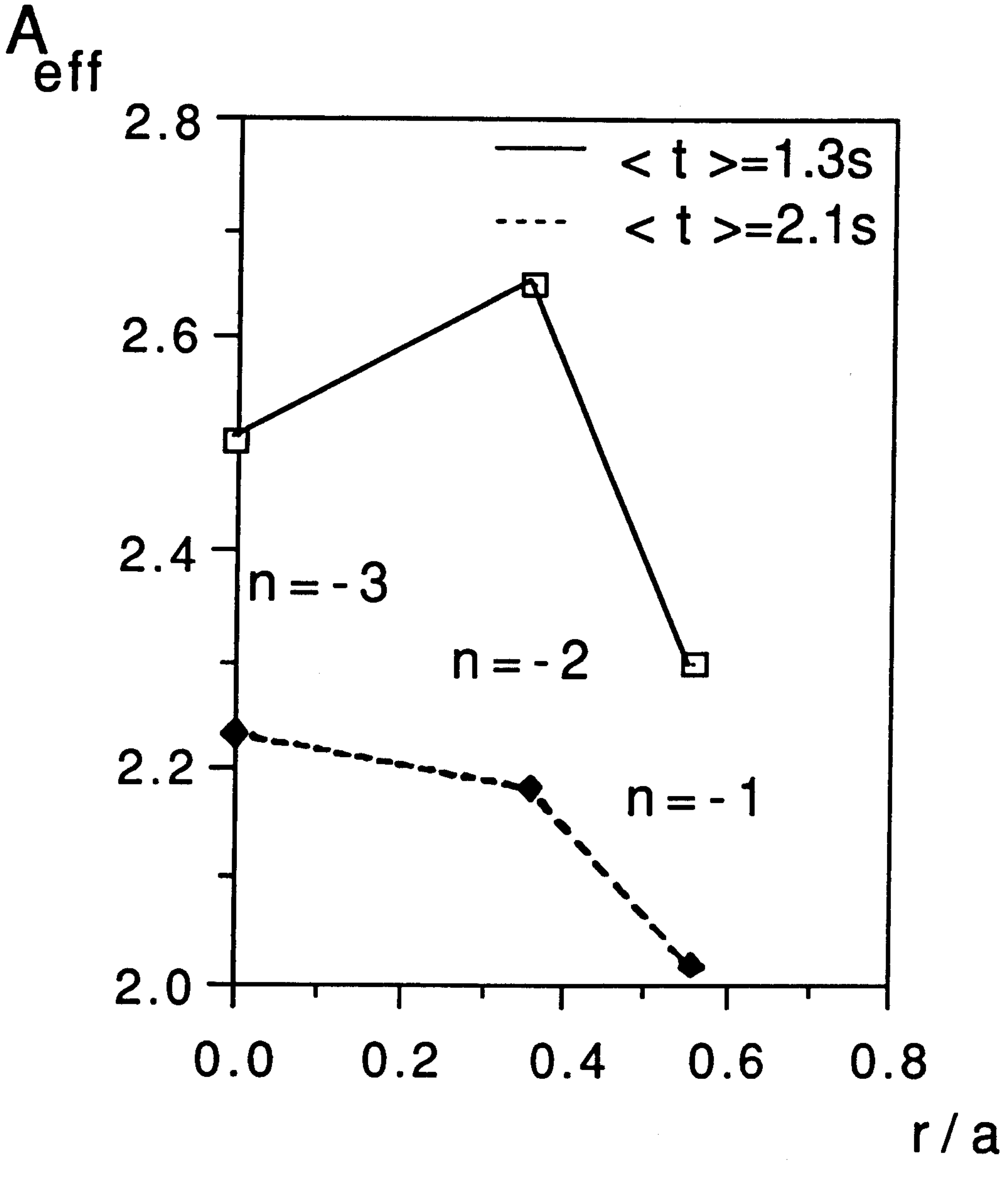

FIG. 5