THE ENHANCEMENT OF LANDAU-DAMPING COEFFICIENTS FOR COLLECTIVE RADIAL INSTABILITIES IN AN ELECTRON-RING ACCELERATOR BY AN ANCILLARY B_ϕ-FIELD.*

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Abstract

Attention is directed to the utility of an azimuthal magnetic field for influencing favorably the Landau-damping coefficients that act to suppress transverse collective oscillations in an electron-ring device. Such a supplemental magnetic field can also assist in the attainment of satisfactory betatron-oscillation frequencies. Examples are given of these effects for a (time-dependent) B_ϕ-field applied to an electron-ring compressor similar to the projected LBL Compressor 5 and also to a compressor with high magnetic field index, so that in addition high damping coefficients for longitudinal instabilities are obtained.

A. Introduction

Collective instabilities, which have been observed in electron ring experiments[1,2], are driven by the collective fields of the electron beam, as influenced by near-by structures, and may be suppressed (Landau-damping) by sufficient dispersion in the beam (e.g., by an energy spread).

For a beam of particles with a natural (transverse) oscillation frequency $\nu\omega_o$, the Landau-damping coefficients $(E\ \partial S/\partial E)$, that measure the dispersive effect of a spread in particle energy E, are associated with the collective-mode frequencies $S = (M-\nu)\ \omega_o$, where ω_o denotes the orbital angular speed and M is a positive integer. In a constant gradient axial magnetic field, the damping coefficients for transverse collective modes are given by

$$E\ \frac{\partial S}{\partial E} = -\frac{\omega_o}{\beta^2}\left[(M-\nu)\left(\frac{1}{1-n}-\frac{1}{\gamma^2}\right)+\frac{r_e\partial\nu/\partial r_e}{1-n}\right] \quad (1)$$

for particles circulating with an equilibrium-orbit radius r_e. With $\nu = \sqrt{1-n}$ for the radial modes in a conventional device characterized by the field index n,

$$\frac{\partial\nu}{\partial r_e} = -\frac{1}{2\nu}\frac{\partial n}{\partial r_e}\ . \quad (2)$$

Because normally $\partial n/\partial r_e > 0$ and $\frac{1}{1-n} > \frac{1}{\gamma^2}$,

it thus becomes evident that a strong cancellation may occur[1,3,4] between the terms within the square brackets of Eq. (1), that would act (e.g., for $M = 1$) to reduce severely the magnitude of $(E\ \partial S/\partial E)$ in such a case.

In this report we wish to point out that the values of the derivatives $\partial\nu/\partial r_e$ in Eq. (1) can be substantially modified by an ancillary azimuthally-directed magnetic field so as to avoid excessively low values of $|E\ \partial S/\partial E|$. In addition, a suitably programmed B_ϕ-field provides a means of obtaining betatron oscillation frequencies that remain reasonably constant throughout the compression cycle.

B. The Introduction of a B_ϕ-Field

The introduction of an ancillary B_ϕ- field has been proposed in reports[5,6] from Dubna, primarily with the object of shifting the single-particle betatron oscillation frequencies, in the presence of (possibly substantial) space-charge forces, to values more suitable than otherwise can be practically attained. The use of such an azimuthally-directed field also provides a convenient means to avoid encroaching onto the $\nu = 1$ resonance toward the latter part of a compression cycle (or during the roll-out and acceleration stages) and to avoid other potentially dangerous resonances.[7] A moderate B_ϕ-field (in comparison to the local B_z field) can effect a substantial change of the betatron-oscillation frequencies, and, moreover, the normal modes in this case each involve motion in both the radial and axial directions (in time quadrature).

With space-charge fields neglected, the characteristic (normal-mode) betatron-oscillation frequencies become

$$\nu^2 = \frac{1+\alpha^2}{2} \pm \sqrt{\left(\frac{1+\alpha^2}{2}\right)^2 - n(1-n)} \quad (3)$$

with $\alpha = B_\phi/B_z$ at the equilibrium orbit r_e. Also, for each of the modes[8],

$$\frac{\partial\nu}{\partial r_e} = \frac{1}{2\nu}\ \frac{(1-2n)\partial n/\partial r_e + 2(1-n)\nu^2\alpha^2/r_e}{1-2\nu^2+\alpha^2}\ , \quad (4)$$

an expression that may be introduced into Eq. (1) for evaluation of the Landau-damping coefficients for this situation.

It is desirable to maintain the values of $|E\ \partial S/\partial E|$ large. As from Eq. (1) for a given characteristic betatron-oscillation frequency

$$\left(E\ \frac{\partial S}{\partial E}\right)_M + \left(-E\ \frac{\partial S}{\partial E}\right)_{M+1} = \frac{\omega_o}{\beta^2}\left(\frac{1}{1-n}-\frac{1}{\gamma^2}\right)\ , \quad (5)$$

this sum is not greatly susceptible to modification. Because the values of $(E\ \partial S/\partial E)_1$ are usually positive and those of $(E\ \partial S/\partial E)_2$ negative, there is the opportunity of adjusting parameters (e.g. α) so

* Work supported by the U.S. Atomic Energy Commission and MPI Garching, Euratom Association.

** On leave of absence from MPI für Plasmaphysik, Garching, Germany.

that neither damping coefficient becomes especially small in absolute value. To examine this possibility in greater detail, we have considered a compressor similar to that of the projected LBL Compressor 5 planned for future experiments at Berkeley, with the addition of a supplemental B_ϕ-field. This field, with its spatial dependence proportional to $1/r$, is produced by 2 simple LC-circuits.

Another example for a compressor takes advantage of the fact that the Landau-damping coefficients can be increased, primarily during the first stages of the compression cycle, by going to higher values for the field index initially [see Eq. (5), normally $1/(1-n) \gg 1/\gamma^2$]. In this case the magnitude of the Landau-damping coefficient for longitudinal instability,

$$E \frac{\partial\omega_o}{\partial E} = - \frac{\omega_o}{\beta^2}\left(\frac{1}{1-n} - \frac{1}{\gamma^2}\right), \qquad (6)$$

also can be substantially increased.

Both examples appeared distinctly attractive with respect to the magnitudes of the damping coefficients and to the betatron-oscillation frequencies as they occur throughout compression.

C. Parameters and Results

In Compressor 5 the compression of a 4 MeV electron ring ($\gamma \simeq 8.8$), with a 17.75 cm major radius, into a radius of circa 4.0 cm, with a kinetic energy of 17.8 MeV, will be done mainly by three successively pulsed main coil pairs. The final stage employs on one side a 1 m solenoidal coil, which permits magnetic acceleration of the ring in the axial direction. Despite the precautions of reducing induced eddy currents in these coils[3], the coefficient $(E\,\partial S_R/\partial E)_1$ for the first radial mode is found to drop in normal operation to about 556 μsec^{-1} by the end of the second stage of compression. Because, moreover, the field index n drops from a value just below 0.5 to approximately 0.1, attention must be given to the manner in which several betatron-oscillation resonances are successively traversed.

A compression cycle, very similar to that planned for Compressor 5, was supplemented in the computations by an azimuthal magnetic field, produced by a central (axial) current of two-stage wave form (50 windings). This wave form is easily obtained by discharging one LC-circuit (V_1 = 18 kV, C_1 = 74.4 μF) approximately 200 μsec before and the other (V_2 = 16.5 kV, C_2 = 29.6 μF) 200 μsec after firing of the first compression coil. The influence of the supplemental B_ϕ-field is such that one of the betatron-oscillation frequencies (ν_A) remains above unity throughout the entire compression cycle, while the second normal-mode frequency (ν_B) drops from 0.47 to a minimum value 0.28 during this time, while traversing the possibly significant resonance $3\nu_B = 1$ rapidly. This behaviour is illustrated on the resonance diagram (Fig. 1a), where, except for a single crossing of the line $\nu_B = 1/3$, major resonance lines are avoided. The radial dependence of the field-index n and the magnetic field ratio $\alpha = B_\phi/B_z$ as a function of the location (radius R) of the ring during compression is plotted in Fig. 1b, and the corresponding computed Landau-damping coefficients for transverse modes (M = 1,2) are shown in Fig. 1c (solid lines). The coefficients of least magnitude are seen to be reasonably well balanced and high (magnitude always larger than 1000 μsec^{-1}). The dotted line gives the Landau-damping coefficient $(-E\,\partial\omega_o/\partial E)$ for longitudinal instability.

To increase, in addition, the damping coefficient for longitudinal instability, the magnetic field index has to be increased. In a compression cycle consisting of three stages (again with the solenoid present for eventual magnetic acceleration) the field index could be increased, computationally, over a wide radius range of the compression cycle (Fig. 2b). Because of the dependence of the damping coefficients on n (Eqs. 5,6), not only the coefficient for longitudinal instabilities can be increased by approximately a factor of 4 (Fig. 1c and 2c), but also the damping coefficients for transverse motion can be kept always very high (Fig. 2c). Resonances, which necessarily have to be crossed (Fig. 2a), are traversed very rapidly.

In addition to producing an attractive behaviour of the betatron-oscillation frequencies during compression, provision of a B_ϕ-field is seen to afford a flexible means for controlling the Landau-damping coefficients. It may well present grave technical problems in the design of an electron-ring device with a long acceleration section, but at least may be considered practicable for shorter structures intended for the acceleration of heavy ions by means of collective fields.[7]

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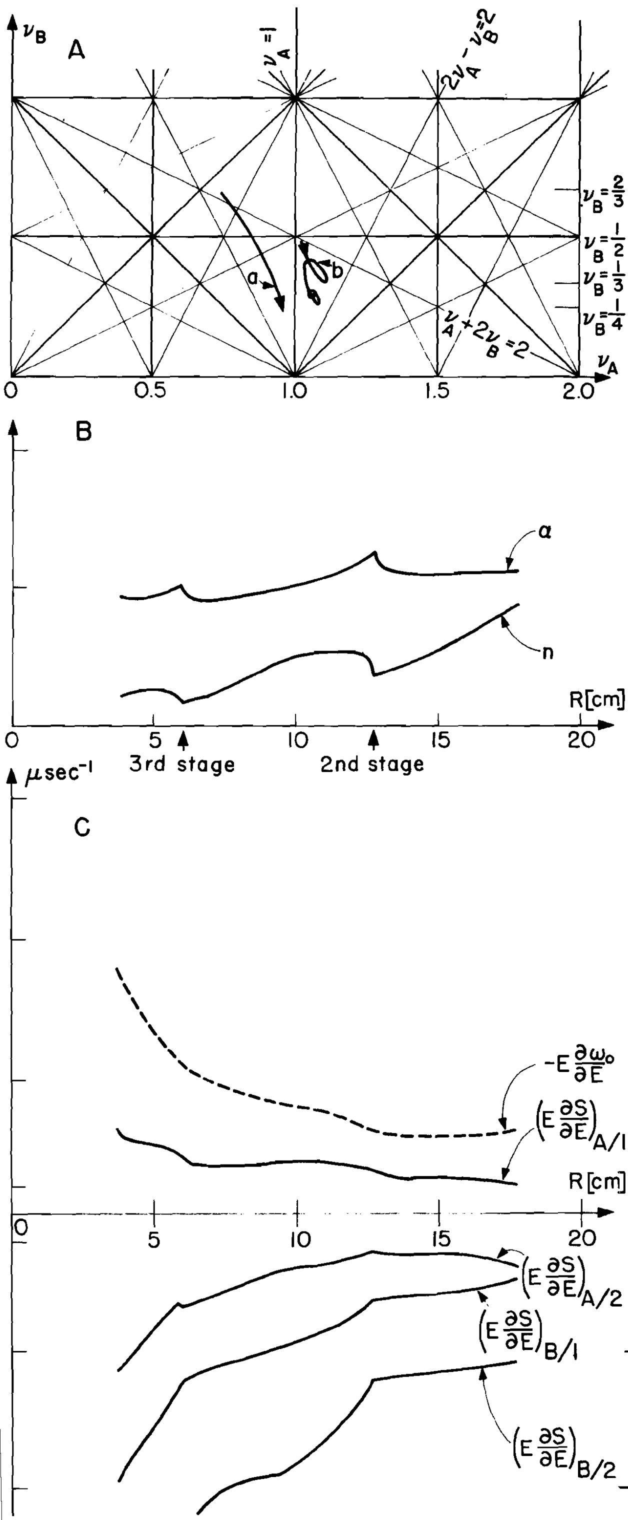

Figure 1 - A) Betatron oscillation frequencies (a = without, b = with B_ϕ), B) Field index n and field ratio $\alpha = B_\phi/B_z$, C) Landau-damping coefficients, for a compressor similar to Compressor 5 with a supplemental B_ϕ-field.

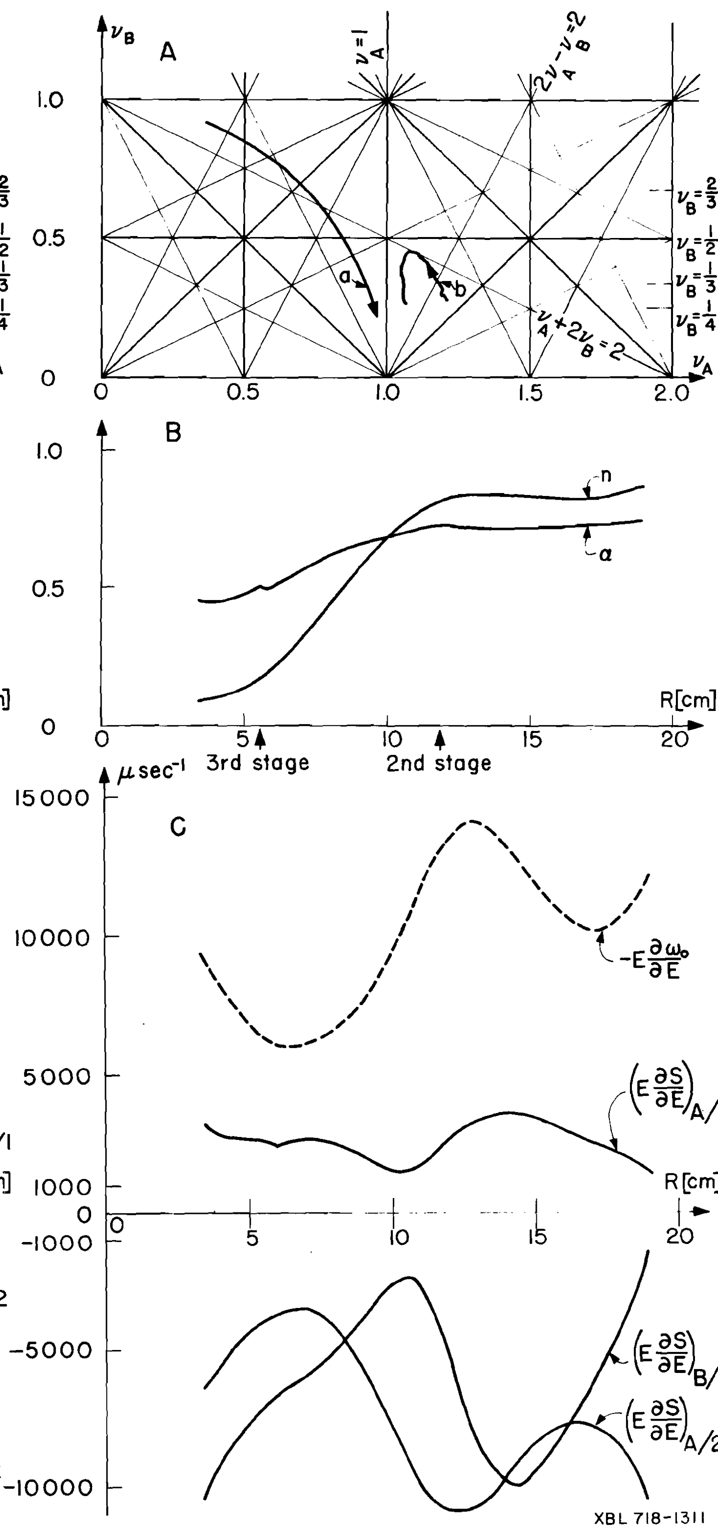

Figure 2 - The same quantities as in Fig. 1, for a compressor with high field index throughout the initial portion of the compression cycle.