EDDY CURRENTS, LANDAU-DAMPING COEFFICIENTS, AND THEIR IMPLICATIONS IN ELECTRON-RING COMPRESSOR DESIGN*

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Abstract

The strong influence of eddy currents on Landau-damping coefficients, as was observed and corrected in the LRL Compressor 4, is discussed. The improvement of these damping coefficients as a result of a redesign of Compressor 5 coils is reported.

A. Introduction

The observation of radial collective oscillations, at quite moderate beam intensities, in the initial electron-ring studies with the LRL experimental Compressor 4 has been described previously[1]. The development of this rapid instability was attributable to field distortions caused by eddy currents induced in the windings of the near-by Stage-2 compression coils. Specifically, the radial derivative of the field index was sufficiently modified by this effect that the dispersive action of energy spread became ineffective at certain radii. A pronounced improvement resulted from the reduction of these distortions by moving the Stage-2 coils further from the median plane or, alternatively, by rewinding them with stranded cable.

The experience just mentioned motivated a reexamination of the design that had been initially adopted for Compressor 5, which is a more elaborate electron-ring device intended to permit experimental study, not only of compression phenomena, but also of magnetic acceleration subsequent to the release of the ring from the magnetic well of the compressor. The design and operation of this Compressor 5 was intended to be similar to that of the LRL Compressor 3, described previously[2][3][4]. The design includes three pairs of main compression coils, of which the third contains a long (1 m) solenoid into which the ring beam can be moved by means of a suitable unbalance circuit that is actuated near the end of the compression process. The initial design employed hollow copper conductors of a rather large cross-section (up to 8.6 mm square) and, for purposes of mechanical strength, the third set of coils contained circumferential stainless-steel bands of similar cross-sectional dimensions.

B. Influence of Eddy Currents

Field and field-gradient measurements of the initial Compressor 5 coil arrangement by W. W. Chupp, J. M. Peterson, and J. B. Rechen clearly indicated that the projected pulse cycle ($\sim 770\ \mu s$ for compression, with electrons of 4 MeV kinetic energy injected at $\sim 70\ \mu s$) would induce eddy currents in the coil windings of a sufficient magnitude to have a pronounced effect on the character of the magnetic field. That a distortion of $\partial n/\partial r$ can have a particularly marked effect on the Landau damping for the first radial mode of collective oscillation can readily be seen from inspection of the coefficient

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

for particles circulating with an equilibrium-orbit radius r_e, where S denotes $(M-\nu)\omega_e$ and $\partial\nu/\partial r_e = \mp(1/2\nu)\,\partial n/\partial r_e$ for the radial or axial modes. This coefficient, after multiplication by a postulated fractional energy spread $\Delta E/E$, may be compared with the "U" and "V" terms[5] that describe the electromagnetic-field forces potentially able to drive the collective instability in question. With $\partial\nu/\partial r_e$ negative for radial betatron oscillations, while $(1-n)/\gamma^2$ normally is small and $M-\nu$ is positive, it is evident that a partial cancellation of terms within the square bracket of Eq. (1) can be quite pronounced for the $M = 1$ radial mode. If the driving terms (U,V) have values of the order of a few μs^{-1} or greater, and if an acceptable energy spread is limited to one or two percent, values of $|E\partial S/\partial E|$ less than several hundred μs^{-1} could be hazardous[6].

The measured fields were simulated in an interactive computer program, constructed by V. O. Brady, R. N. Healey, and B. Levine, by means of several eddy-current simulation circuits suitably coupled to the active coils of the compressor. Landau-damping coefficients were then computed during the course of representative dynamical runs with this program. The curves of Fig. 1 for the initial Compressor 5 design clearly indicate that under these conditions the Landau damping becomes inadequate for the $M = 1$ radial mode, with the damping coefficient actually passing through zero in the case shown. In contrast to the results illustrated in Fig. 1, removal of eddy currents from the computations gave $|E\partial S/\partial E| \gtrsim 370\ \mu s^{-1}$ throughout an otherwise representative compression cycle. It is apparent, therefore, that coils close to the median plane should be redesigned so as to reduce substantially the perturbing effect of eddy currents induced in their windings, and further computational work suggested that a reduction by a factor 1/15 would be desirable.

C. Suppression of Eddy Currents

The magnitude of induced eddy currents can be markedly reduced if the hollow, water-cooled copper conductors are replaced by stainless steel tubing -- surrounded, if necessary, by one or two layers of small-diameter conductors[7]. In redesigning those coils of Compressor 5 in which troublesome eddy currents had been seen to occur, it was calculated[8] that an effective reduction (factor $\sim 1/25$) in eddy-current strength can be achieved by the use of stainless-steel tubing (av. dia. ~ 9 mm, wall thickness ~ 1.7 mm) to carry the entire current without encountering severe heating problems in the anticipated pulsed service (3 - 5s repetition period). The use of stainless-steel tubing for the solenoid windings has the further merit of providing sufficient mechanical strength to permit elimination of the stainless-steel bands that previously had been required.

The higher resistance of stainless-steel coils leads, of course, to increased ohmic damping of the pulsed currents during the operating cycle of the compressor. With the provision of some additional resistance externally, it moreover appears no longer necessary to short-circuit ("crowbar") the individual coils after their individual currents have reached their peak values. The modified design now adopted for the second and third set of compression coils in Compressor 5 employs stainless-steel windings of 0.79 and 0.14 Ω intrinsic resistance, and are to be used in conjunction with external resistances of 0.34 and 0.11 Ω, respectively. The total initial stored energy required for operation of the compressor is close to twice that for the original design, but the heat load for the coils is not greatly changed because much of the additional energy appears in the external resistors. A computed compression cycle for this device (suitable for extension into an acceleration phase) leads to the curves shown in Fig. 2, with $|E\partial S/\partial E| \gtrsim 550\ \mu s^{-1}$ throughout compression.

In conclusion, we are gratified to find that the adoption of a coil design that employs stainless-steel tubing as conductor material not only affords significant advantages of a mechanical and electrical nature, but, more significantly, can be expected to result in an adequate suppression of eddy-current effects that, if present, would seriously impair the effectiveness of a moderate energy spread for the suppression of potentially unstable transverse coherent oscillations of the electron-ring beam.

Explanation of Figures

Figure 1. Computed n-trajectory, $\partial n/\partial r$, and Landau-damping coefficients for the first two radial modes of collective oscillation, with eddy-current perturbations present. The radial locations of near-by coils (central values: 16.7 and 10.0 cm), in which substantial eddy currents can arise, are indicated at the top of the Figure. Values of $E\partial S/\partial E$ for the first radial mode are seen to be markedly reduced in the neighborhood of these coils -- an effect that appears directly correlated with the pronounced reduction of $\partial n/\partial r$ at such radii. The n-trajectory, intended to result in rapid crossing of potentially-dangerous single-particle resonances, was adjusted to the form shown by use of an n-corrector circuit that served to excite an auxiliary coil pair situated at an average radius of 14.21 cm. Note that $\partial n/\partial r$ refers to a local spatial derivative of n, while the n-trajectory shown in the Figure depicts the variation of n at the radius of the ring as the latter decreases during compression.

Figure 2. Computed n-trajectory, $\partial n/\partial r$, and Landau-damping coefficients computed for Compressor 5 with resistive, non-crowbarred coils. In this example, coil-pair 2 (av. radius = 16.7 cm) is used both as an n-corrector and for compression. The compression cycle carries a ring of 4.0 MeV kinetic energy at 17.75 cm to 17.76 MeV at a minimum radius of 3.98 cm. Additional computations indicate that a similar compression cycle can be extended into a satisfactory acceleration phase of operation.

References

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2. R. T. Avery, et al., IEEE Trans. Nucl. Sci. NS-16, No. 3, 1050 (1969).
3. R. W. Allison, Jr., et al., Proc. USSR Natl. Particle Accel. Conf., Moscow, Oct. 1968. (Preprint UCRL-18498).
4. D. Keefe, Proc. 7th Intl. Conf. High Energy Accelerators, Yerevan, USSR, Aug. 1969. (Preprint UCRL-18896).
5. L. J. Laslett, V. K. Neil, and A. M. Sessler, Rev. Sci. Instr. 36, 436-448 (April 1965).
6. The presence of the factor 1-n in the denominator of Eq. (1) suggests that the magnitude of damping coefficients for radial modes could be increased, at least during the initial stages of compression -- at the expense of the (usually large) corresponding quantities for axial modes -- by operation at a high value of n. This behaviour, of course, is basically due to the effect of n on momentum compaction and, as Dr. U. Schumacher has helpfully pointed out to us, applies to damping coefficients for both transverse and longitudinal collective modes. An additional means of controlling the Landau-damping coefficients that relate to transverse modes of collective oscillation is through the addition of a supplemental azimuthal magnetic field ($B_\theta \propto 1/r$), as is discussed in another paper submitted to this Conference (L. Jackson Laslett and U. Schumacher, UCRL-20855).
7. For instance, a copper tube surrounded by a layer of small insulated copper wires was used for the Cornell 10-GeV synchrotron coils (Cornell Internal Reports CS-33 and CSDS-26).
8. R. T. Avery, unpublished LBL report ERAN-125 (25 January 1971).

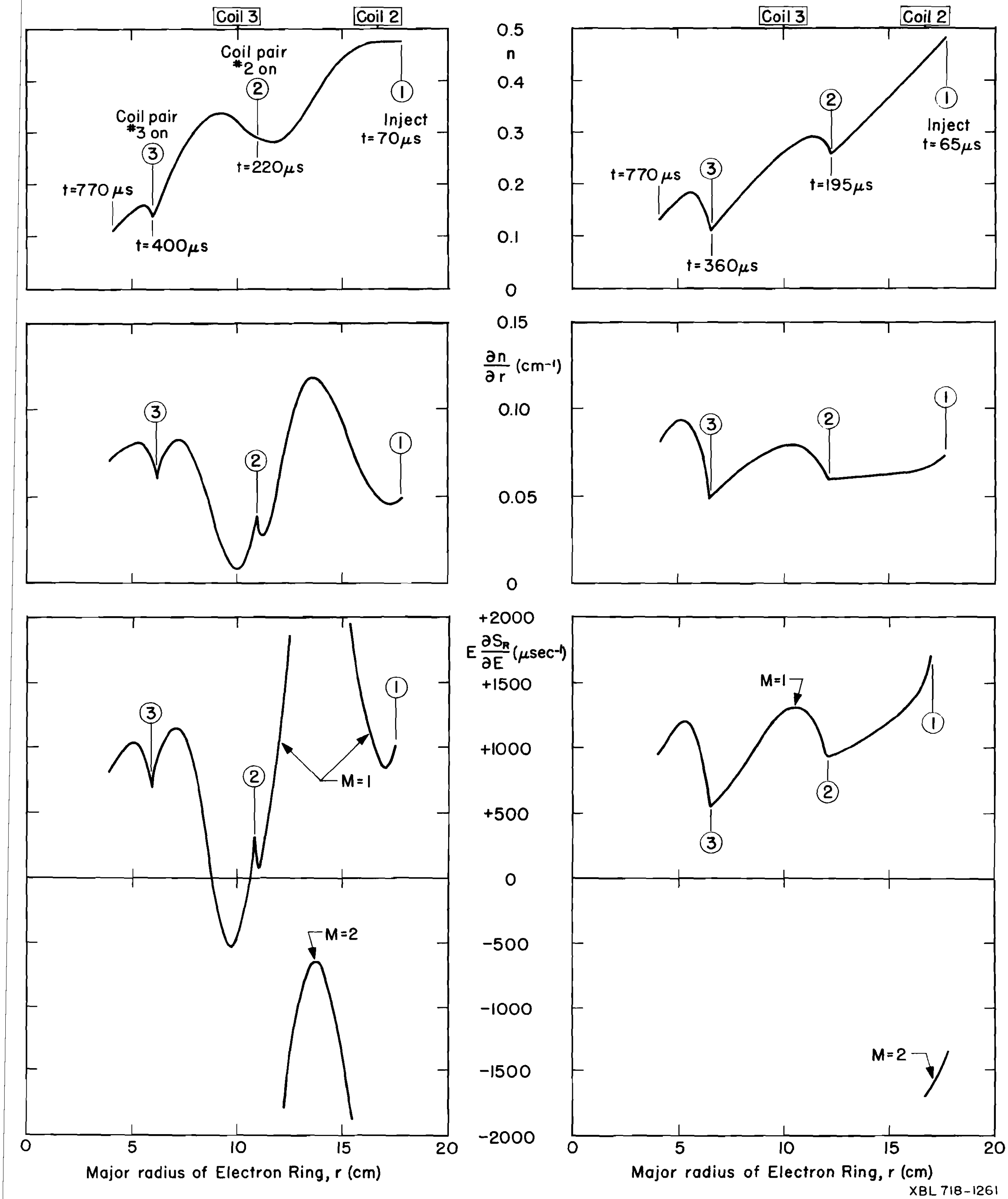

Figure 1 - Values for initial Compressor 5 design (see text for details)

Figure 2 - Values for new Compressor 5 design. (See text for details)