THE RESISTIVE WALL INSTABILITY AND DAMPING SYSTEM IN NIMROD

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Abstract - Observations of the resistive wall instability in Nimrod are described. An account is given of the system used to damp the (1 - Q) mode of the instability.

1. Introduction

A frequent operating procedure for Nimrod is a steering of the beam away from the central orbit to avoid particle loss due to coherent vertical motion. In Section 2 of this paper some observations are given of the vertical instability and in Section 3 some details and recent experience of a vertical stabilisation servo system.

The Nimrod beam is prone to vertical loss at the following approximate magnetic field levels during acceleration: 1250, 2500 and 4000 gauss, with the instability at 2500 gauss the most frequently observed. A servo system which provides damping for (1 - Q)f coherent modes alone has proved sufficient to prevent the vertical loss for the present level of beam intensity ($1.5\ 10^{12}$). Here, f is the proton revolution frequency and Q ($\sim$ 0.9) is the vertical betatron wave number. In Section 2 photographs are included showing that, in the absence of the damping system, a mode higher than (1 - Q)f can exist.

The circuit gain in the servo is approximately 120 db, and attenuation of gain at frequencies above (1 - Q)f is required to prevent common mode beam rf signals, 4f, and common mode signals at frequency f from saturating the system. The common mode signal, f, is due to variations in bunch density and the position of the magnetic median plane. The frequency f varies from 350 kc/s to 2 Mc/s, but over a restricted region of 1-2 Mc/s fixed lag networks for attenuation and fixed lead networks are used to provide approximately the maximum damping for (1 - Q)f frequencies. Feedback corresponding to odd and even values of m can be separated in the system (m defines the mode number, m $\pm$ Q) so that the servo can be extended to cover the frequency range of (2 - Q)f. At present this does not appear necessary. If in future it does, then the common mode signals will have to be reduced, or the damping system provided with a higher power output stage.

Below field levels of 1000 gauss, where the beam is not spontaneously unstable, the (1 - Q), (0 + Q) and (2 - Q) modes have been excited by an external driver. Typical vertical excitation fields required to provide 1 cm vertical growth in 1 msecond are 5 volts/cm for the (1 - Q) mode, 20 volts/cm for the (0 + Q) mode and 30 volts/cm for the (2 - Q) mode, for exciting field plates of length 2 metres.

2. Observations of the Vertical Instability

With a beam intensity of $1.5\ 10^{12}$ particles per pulse, the instability occurs at various points in the acceleration cycle, and rf steering is required to avoid the regions which lead to vertical beam loss. Even at half this beam intensity coherent growth can be observed if there is the appropriate rf steering.

Under normal operating conditions, with all bunches having approximately equal populations, the coherent vertical growth is usually in the (1 - Q)f mode. With Q $\sim$ 0.9, and a harmonic number of 4 for the rf, there are then 40 beam bunches per oscillation period (Figure 2.1) The e-folding times are generally a few milliseconds.

There is one field level, however, near 2500 gauss, where the beam can be steered into an instability region and where the resulting motion can be interpreted as being in the mode or modes (2 - Q)f, (4 - Q)f (or (0 + Q)f). Identification of the exact mode is difficult (Figures 2.2 and 2.3) The beam monitoring feed cables are not of a quality to be able to interpret modes higher in frequency than the rf, but such modes do not appear to be present. The frequency (3 - Q)f has not been observed.

With Q = 0.9, a pure (2 - Q)f mode appears at one azimuth as if each bunch is oscillating at a frequency (1 - Q)f but at a phase of approximately $\pi/2$ compared with the oscillation of the following bunch. Besides the pure (1 - Q)f and (2 - Q)f modes combinations of the two have been seen; typically as the oscillation grows the (2 - Q)f component becomes very large (Figure 2.4). Figure 2.5 illustrates another phenomenon that has been observed. One bunch appears to oscillate with a different amplitude and phase from the others.

These observations are for the absence of a damping system. In the presence of a system which damps the (1 - Q)f mode, beam loss is prevented but we have not looked extensively to see if there remains any coherent motion at higher modes.

3. Damping System

3.1 A block diagram is shown in Fig. 3.1. The system provides damping for (1 - Q)f modes, but can also be extended to cover(2 - Q)f. The vertical position of the proton beam is sensed on induction electrodes at straight sections 3 and 7, an angle π apart in azimuth. These electrodes produce a voltage change of 4% per cm. of beam motion. The signals are fed to straight section 5, an angle $\pi/2$ from the sensing points, on equal length cables. The upper electrode signals are then demodulated, subtracted, amplified and fed to a set of damping plates.

With a large separation of the damping plates and a small electrode sensitivity, a high circuit gain is needed to damp millisecond growth rate instabilities. The problem is therefore to prevent common mode signals from saturating the servo system. For example, beam signals of 500mV, a common mode rf signal of 2% and a circuit gain of 10^5 lead to a 1 kV common mode signal in a wideband system.

Attenuation is provided at frequencies above the top (1 - Q)f frequency of 200 kc/s. The value of (1 - Q)f varies in acceleration from 35 - 200 kc/s, but since the frequency range 100 - 200 kc/s covers the acceleration cycle for magnetic field levels above 1250 gauss, and this includes the entire region in which instability is observed, the system has been initially developed to cover this restricted range of 2:1 in f. There are 3 lag networks for attenuation, and then 3 lead networks are included between the gain stages. These, together with the system delay T, keep the phase of the overall transfer function at frequency (1 - Q)f within 35° of the ideal 90° point. For this type of system the open loop transfer function is[1] :

$$G(ip) = a\gamma^{-1}kFi\, e^{-ipT} \times \sum_{m=1}^{\infty}\left[\frac{\sin m\pi/2}{w^2Q^2-(p+mw)^2} - \frac{\sin m\pi/2}{w^2Q^2-(p-mw)^2}\right]$$

with:

w = angular revolution frequency of the protons,
a = a constant depending on damping plate geometry,
γ = E/Eo, ratio of proton energy to rest energy,
k = circuit gain x induction electrode sensitivity,
F = the transfer function of the lag/lead networks,
T = total signal delay in absence of the networks.

To extend the servo to cover the (2 - Q)f mode, a straight 3 upper electrode signal and a straight 7 lower electrode signal would be rectified, subtracted, fed to appropriate filters and then added to the (1 - Q)f feedback. There is however, a large common mode signal at the frequency f and the system would have to be able to accommodate this.

The delay T is kept to a minimum to simplify the lag/lead networks. The circuit bandwidth is 10 Mc/s, and could be improved with a new output stage.

3.2 System Components

(1) Demodulator and Subtractor

The input electrode signals to straight 5 are first fed into separate differential amplifiers for isolation. The outputs from these amplifiers are rectified with a time constant of 1 Mc/s, and subtracted in a further differential amplifier. The rise time of the differential amplifiers is ~1ns. and the common mode rejection at 10 Mc/s is 100:1.

(2) Lag/lead Filters

There are three RC lag networks separated by emitter followers. Two of these cut off at 600 kc/s and one at 1.2 Mc/s. The three lead networks are introduced between the gain stages. Two lead networks cut off at 50 kc/s and one at 70 kc/s. The overall phase shift is zero at 150 kc/s and swings from 30° at 100 kc/s to -35° at 200 kc/s. The phase for p = 2w is also in the correct range.

(3) 10^4 Amplifiers

This consists of four gain-of-10 amplifiers in series. One such unit is shown in Fig. 3.2. The input impedance is 50 Ω and the maximum output is 2.5 volts peak into 50 Ω. The rise time is 3 - 4 ns. per unit, and less than 8 ns. for the full 10^4 gain. The noise level referred to the input is 22 μv r.m.s. and at the 10^4 gain the signal to noise ratio is ~ 6:1.

(4) Phase Splitter

This converts the damping signal to push-pull. The maximum output is 3 volts peak into 200 Ω, the gain is 2 and the risetime 8 ns.

(5) Distributed Amplifier

A circuit diagram is shown in Fig. 3.3. The input and output impedances are 200 Ω, the bandwidth is from d.c. to 60 Mc/s, the gain is 6.5 and the maximum output is 15 volts peak. The unit provides the biasing for the following tetrode stage.

(6) Push-Pull Damping Plate Driver

The damping plates each have a capacity of 100 pF to ground. They extend 60 cms. azimuthally, 100 cms. radially and are separated by 20 cms. vertically. Each plate is driven by a Mullard tetrode type QV2-250C producing 100 volts peak, a gain of 6 and a bandwidth of 10 Mc/s. The peak vertical electric field in the damping plates is thus 10 volts/cm.

Units (1), (2) and (3) are built into a single copper box to provide screening, and this cuts the stray pick-up by a factor of 50.

To detect small coherent motion in the beam at (1 - Q)f a signal from one of the vertical electrodes is fed to a peak rectifier, filtered in a low pass unit with a cut-off of 300 kc/s and amplified. This allows (1 - Q)f oscillations of less than 0.5 cms. peak to peak to be very easily observed.

3.3 System Performance

With the system gated on at 1250 gauss and off at 5300 gauss all the coherent motion at (1 - Q)f is removed and the beam can be steered along the centre of the aperture. Higher unstable modes are not observed, but they have not been looked for over a wide range of radial steering.

Above 5300 gauss, even though the beam is stable in the absence of feedback, the closed loop system saturates for a short region. A large signal at (1 - Q)f is present and also a signal at frequancy f. The Q value and the phase shift through the system at this point need to be checked.

The system appears to be adequate to damp the coherent instability as it is presently characterised on Nimrod, but for higher beam intensities it may be necessary to extend the damping.

It is proposed to check the system on unequal size bunches by chopping out some beam with a high voltage deflection plate pulsed on shortly after injection.

Reference:
1. Rees, G.H. - N.I.R.L./R/99 (1965)

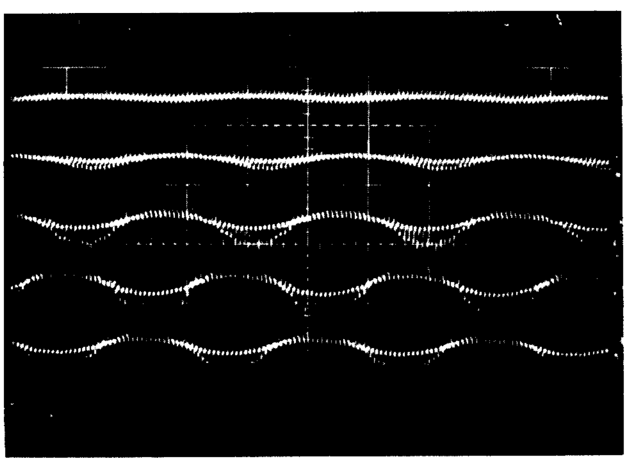

Fig. 2.1. Vertical difference electrode signal sampled at 2 ms. intervals. The field level is 1250 gauss.

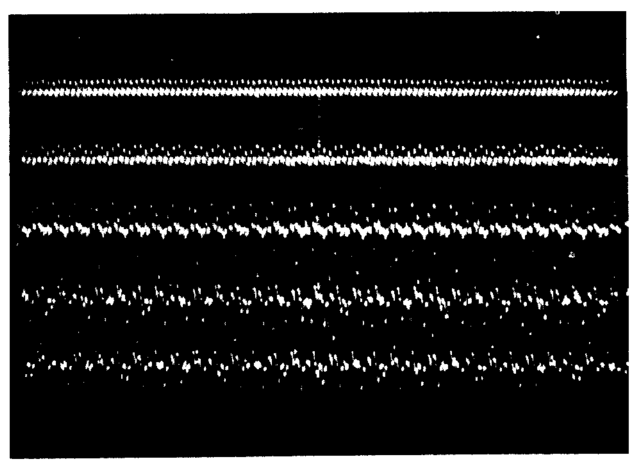

Fig. 2.2. As Fig. 2.1, but at a field level of 2500 gauss. The (1 - Q)f mode is apparently absent.

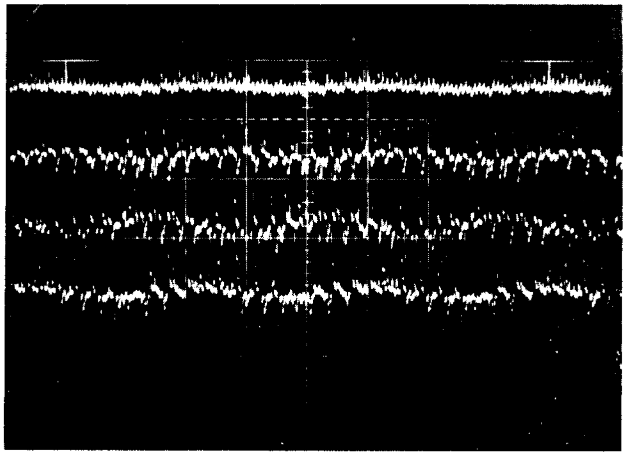

Fig. 2.3. As Fig. 2.2. The)1 - Q)f mode is present together with the mode or modes (2 - Q)f, (4 - Q)f (or (0 + Q)f).

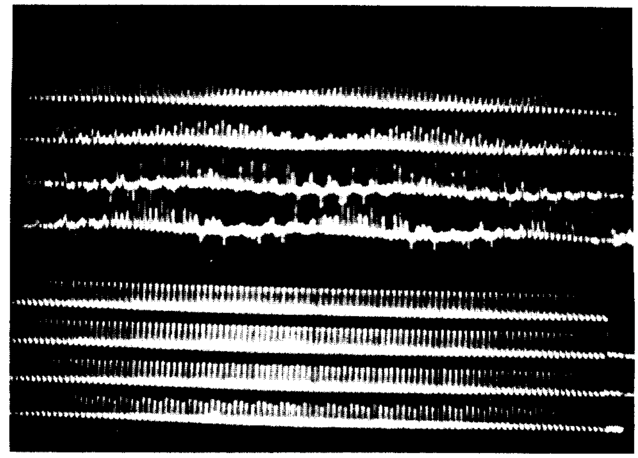

Fig. 2.4. Sum and difference signals at 2500 gauss, showing growth of the higher modes before there is any appreciable beam loss.

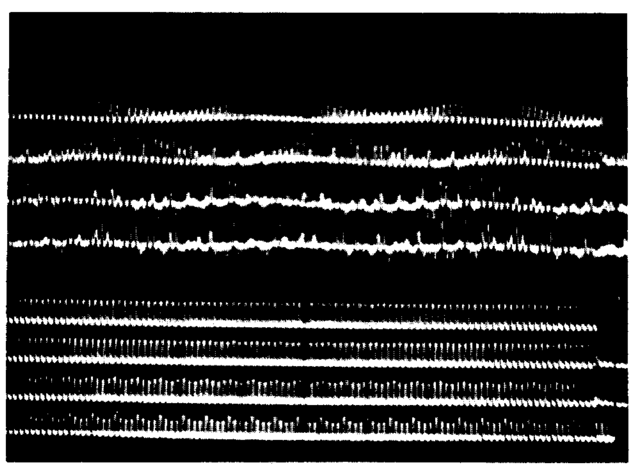

Fig. 2.5. Sum and difference signals at 2500 gauss, with one bunch apparently oscillating independently of the others before any appreciable beam loss.

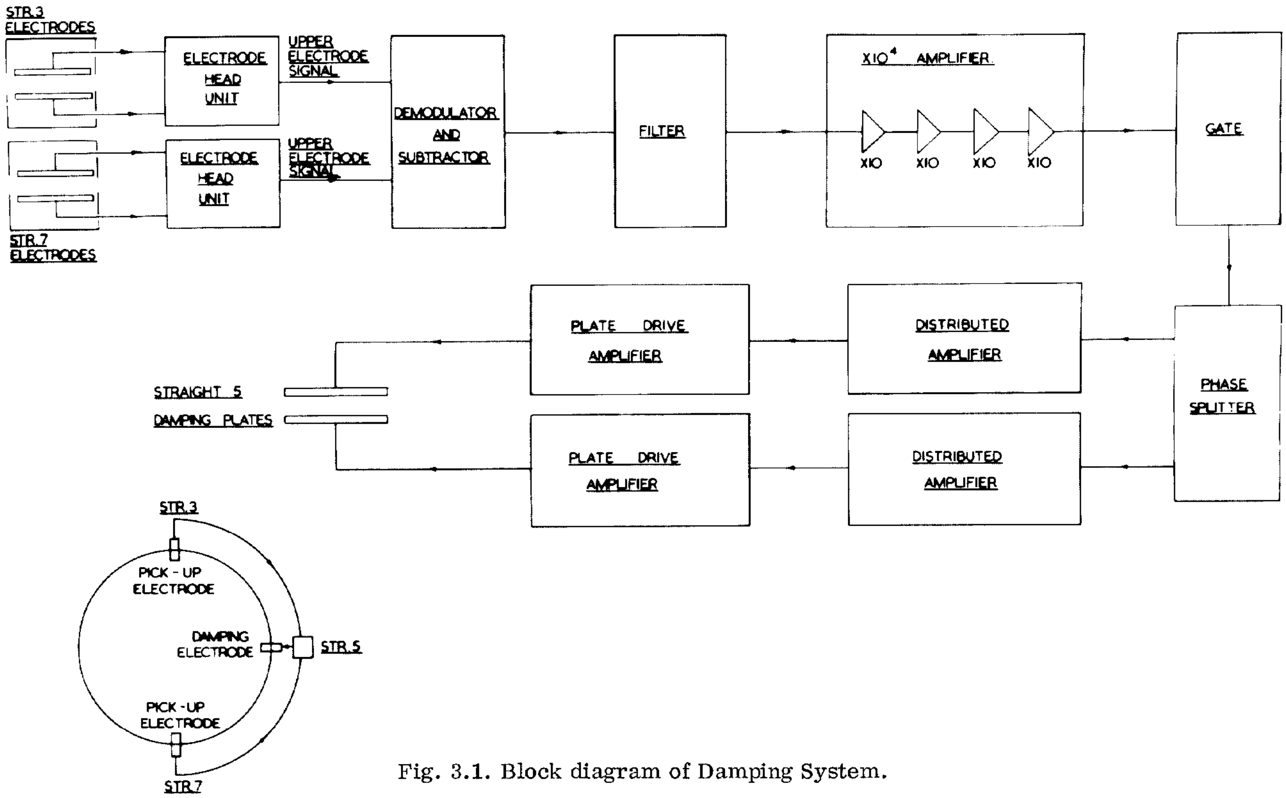

Fig. 3.1. Block diagram of Damping System.

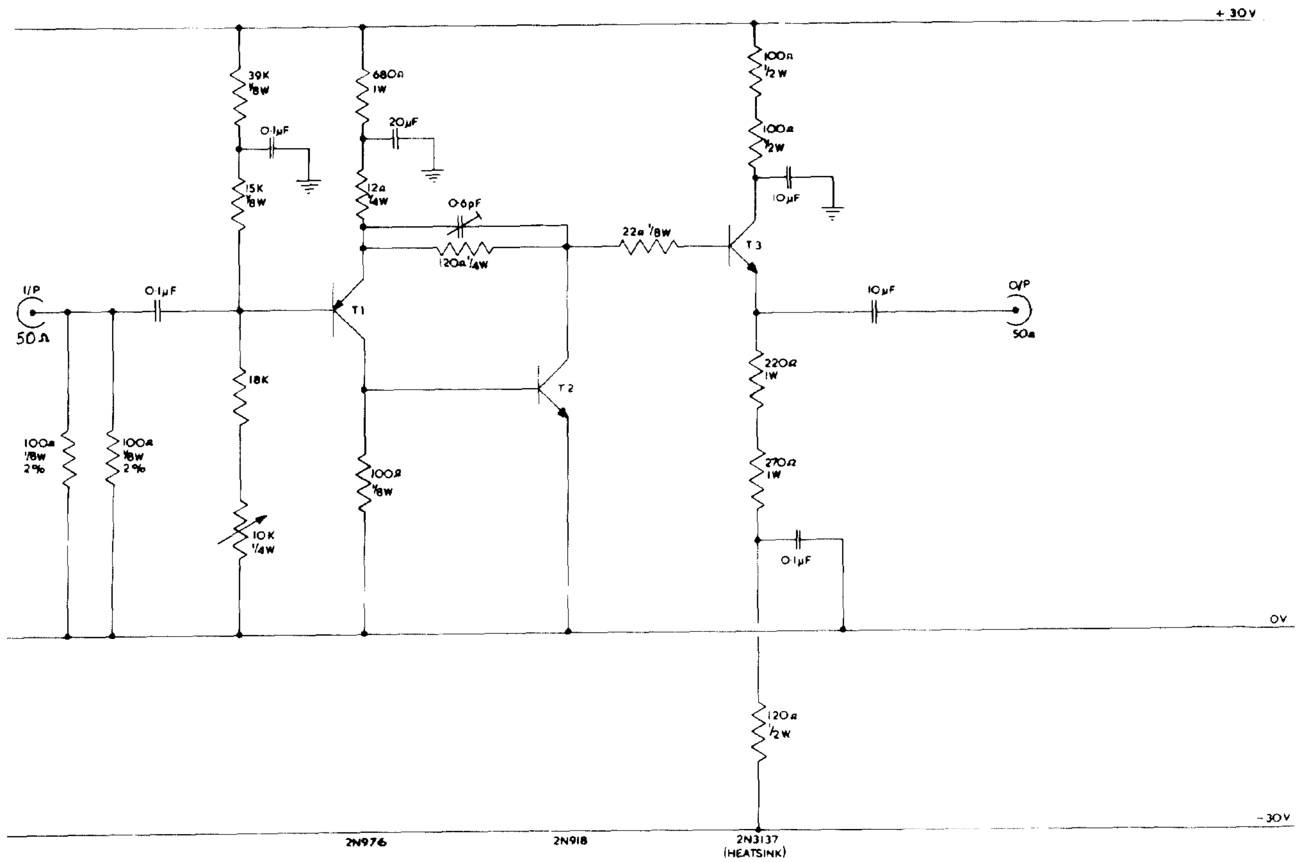

Fig. 3.2. X 10 Amplifier.

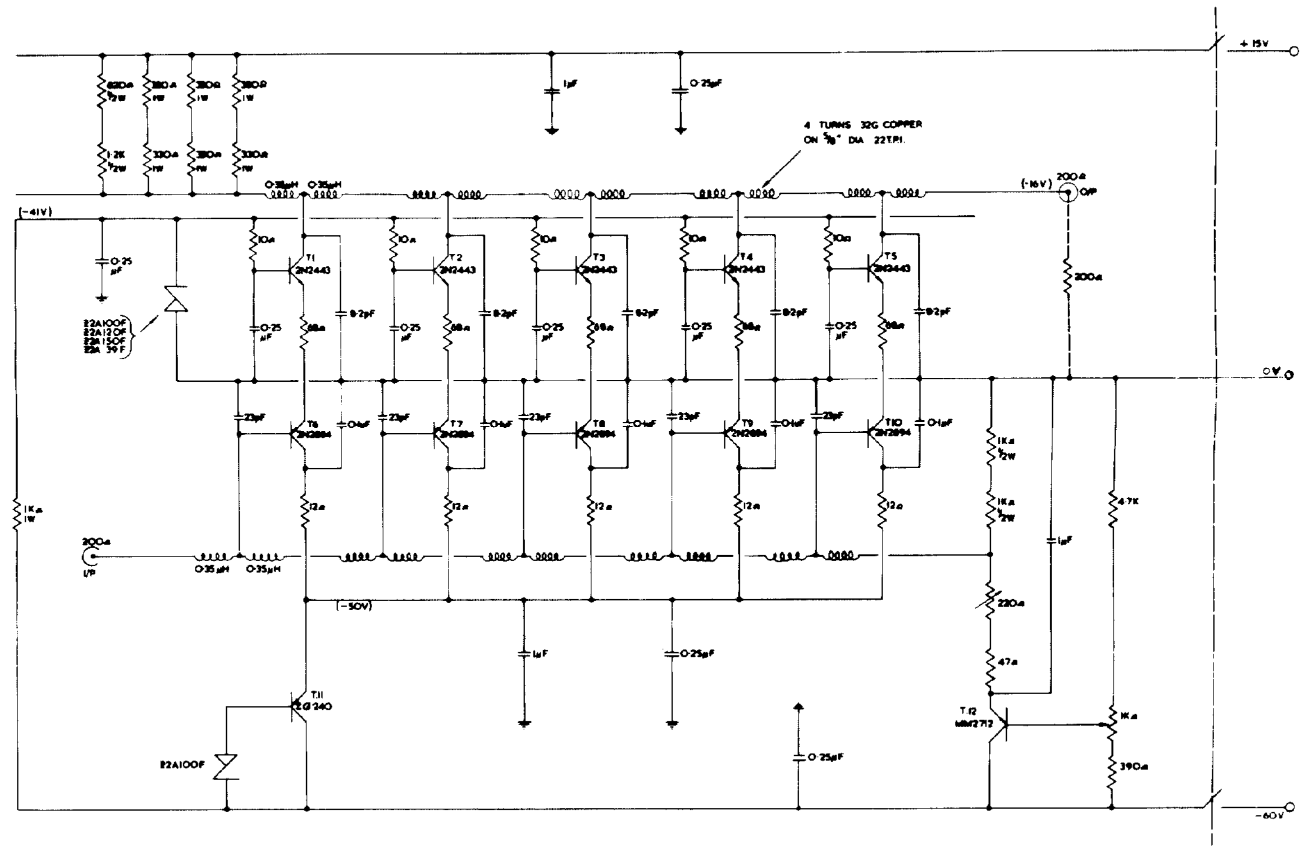

Fig. 3.3. Distributed Amplifier.