RF SYSTEM OF THE ORSAY ISOCHRONOUS 80-INCH CYCLOTRON

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The following parameters have been determined in the general project :
1) Frequency range : 4 to 10.5 Mc/s continuously variable by means of a quarter-wave resonator and one dee.
2) RF generator : 250 to 300 kW, to give a dee-to-ground potential of 150 kV at 10.5 Mc/s.

The RF generator is a single-tube (vapotron TH 478) self oscillator coupled to the resonator through an adjustable coupling loop. The frequency is regulated and adjusted by means of a servo-driven trimmer capacitor. The d.c. voltage is supplied by a Graetz bridge rectifier composed of 6 phase-controlled thyratrons (TH 6091) (V_{max} = 12.5 kV, P_{max} = 400 kW). An RF regulator system has been designed for the dee[1,2]. This consists of a small-μ tube driven by a servo system, which can also be used to pulse the RF. A block diagram of the system is given in Fig. 1.

The Resonator

Determination of the dimensions of the resonator : The calculations were made by the classical methods of impedance transformation. The resonant line and the dee may be considered as composed of a line of n sections, each of constant characteristic impedance Z_{on}, the first of these sections having as origin the short circuit (Fig. 2). The impedance presented to the dee is thus given by

$$Z_n = \frac{Z_{m-1} + jZ_{on}\, tg\beta_n}{1 + j\,\frac{Z_{n-1}}{Z_{on}}\, tg\beta_n} \qquad \text{with} \quad \beta_n = \frac{2\pi\ell_n}{\lambda} .$$

At resonance, Z_n tends to infinity.

The characteristic impedances of the sections cut along equipotential lines are given by the well-known relationship :

$$Z_0 = \frac{p}{q}\ 377 \text{ ohm.}$$

The precision of the calculation depends on the number of sections taken, and on the accuracy in tracing the equipotential lines. The precision obtained in the CEVIL is better than 5% over the whole frequency range.

Estimation of the losses : The RF power loss is calculated from the current-voltage distribution on the resonant line by integration over each section

$$P_n = \int_{\ell_{n-1}}^{\ell_n} R_{RF}\, I_n^2(\ell)d\ell \ .$$

The current-voltage distribution calculated for the extreme frequencies of 4 and 10.5 Mc/s are shown in Fig. 3. The losses for each section and the total loss in the resonant line are listed in Table I.

Table I

RF Power Inventory

Frequency	4 Mc/s	11 Mc/s
Dee voltage	150 kV (rms)	
Dee	15	30 kW
Transition section	15	45
Line	80	50
Short-circuit	15	20
Non calculable losses	10	15
Beam load	10	40
Total	145 kW	200 kW

The Coupling Loop

An adjustable coupling loop with a telecommanded plunger allows transmission of the RF energy to the resonator and at the same time presents the optimum load impedance to the oscillator tube.

The calculations were made for the equivalent L C R circuit of the resonator for a given frequency (see Fig. 4).

The equivalent capacity C is determined by adding a known capacity to the end of the dee (where the impedance presented is infinity at resonance) and measuring the resulting frequency shift Δf. Since the resonant frequency is known, this method allows C and L to be calculated. R may be calculated from the Q-factor. The classical relationship gives :

$$V = I\left[j\ell\omega + \frac{M^2\omega^2}{R + j(L\omega - \frac{1}{C\omega})}\right] ,$$

with $M = k\sqrt{L\ell}$, ℓ being the self-inductance of the loop.

The impedance presented by the loop is

$$z = R + jX ,$$

with $R = \dfrac{Q\ell\omega}{1 + 4y^2}$, $X = \dfrac{-2Q\ell\omega y}{1 + 4y^2}$, $y = \dfrac{Q\Delta\omega}{\omega}$.

At resonance this gives $z_0 = R_0 = \dfrac{M^2\omega^2}{R}$.

For a rectangular coupling loop (Fig. 5)

$$M = -0{,}46.10^{-8}\ \ell \log \frac{\rho - d}{\rho} .$$

Fig. 6 gives the curves of the impedance presented by the loop, first calculated, and then measured with a double-T bridge at 10.5 Mc/s. The calculations were made for different frequencies, taking into account the variations of R and Q due to the beam. This led to the choice of the dimensions and adjustment range of the loop.

The Oscillator

The oscillator adopted can start on very low loop impedances. This type of oscillator has been tested in Rochester[3]. A detailed investigation of the conditions of oscillation will serve to determine the boundary conditions and the choice of the best circuit elements (see Fig. 7).

The oscillator can be considered as consisting of two quadrupoles in parallel, the first one representing the tube without the parasite capacities and having an admittance matrix A_1, and the second one representing the circuit elements and the parasitic capacities, with the admittance matrix A_2 (see Fig. 8). The impedance presented by the loop close to the resonant frequency, is of the form

$$z = R + jX.$$

Thus, using Routh's theorem, the condition for oscillation will be given by

$$\text{Determinant of } (A = A_1 + A_2) = 0.$$

If the equivalent inductance of the parallel circuit L'_1C_3 is L_1 (Fig. 7), the above equation may be written

$$A_1 = \begin{vmatrix} 1/\rho_g & 0 \\ \mu/\rho & 1/\rho \end{vmatrix} \qquad A_2 = \begin{vmatrix} pC_2 + 1/pL_1 & -1/pC_1 \\ -1/pL_1 & \dfrac{1}{R_0 + pX/\omega + 1/pC_1} + 1/pL_1 \end{vmatrix}$$

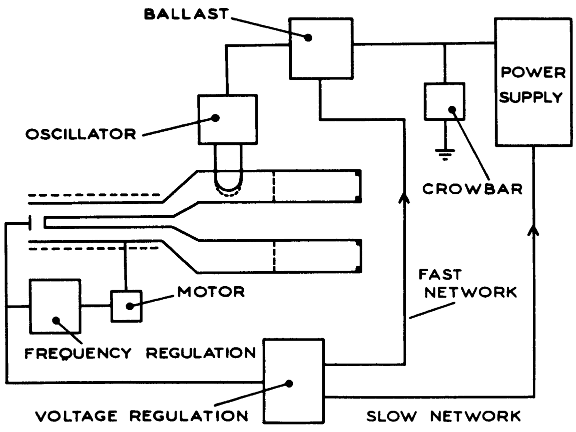

Fig. 1 Block diagram of the RF system.

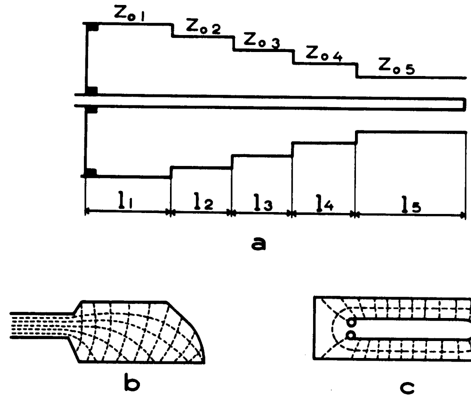

Fig. 2 The resonant line and dee as sections of constant impedance.

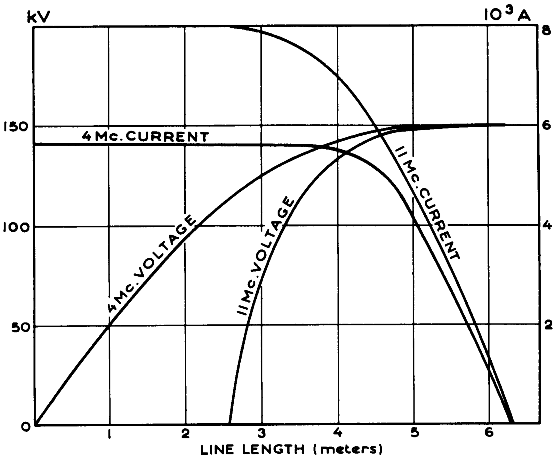

Fig. 3 The current-voltage distribution.

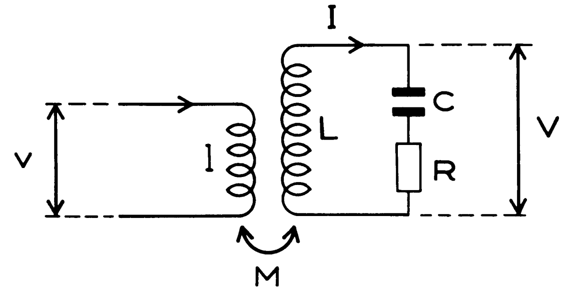

Fig. 4 Equivalent circuit of the resonator.

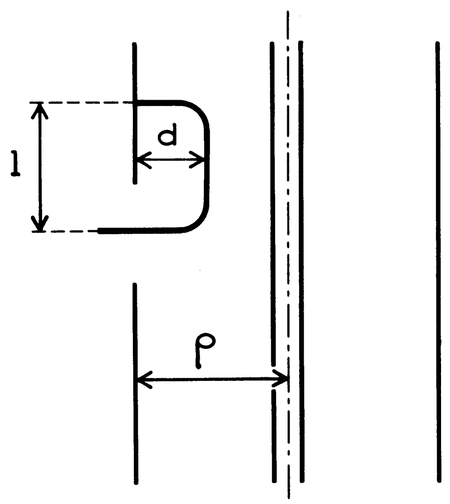

Fig. 5 A rectangular coupling loop.

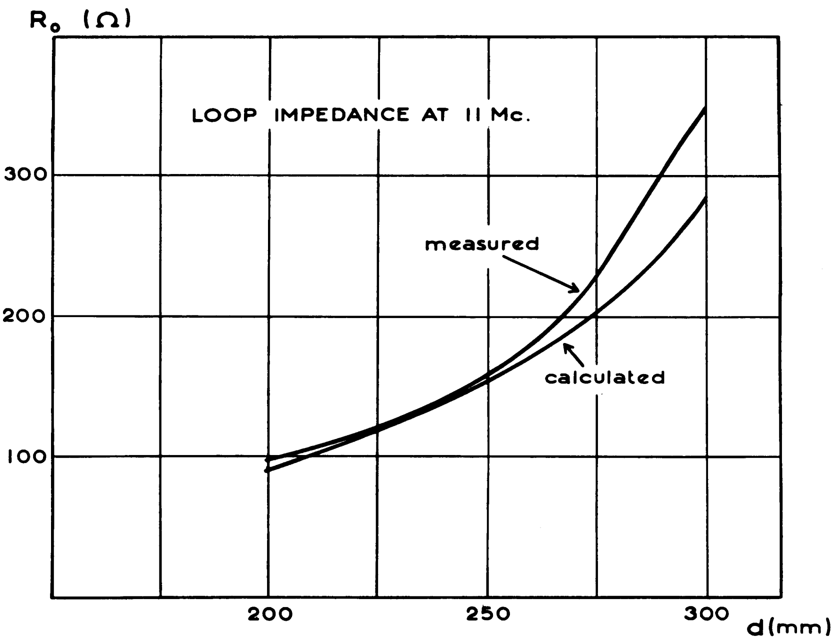

Fig. 6 Impedance of loop.

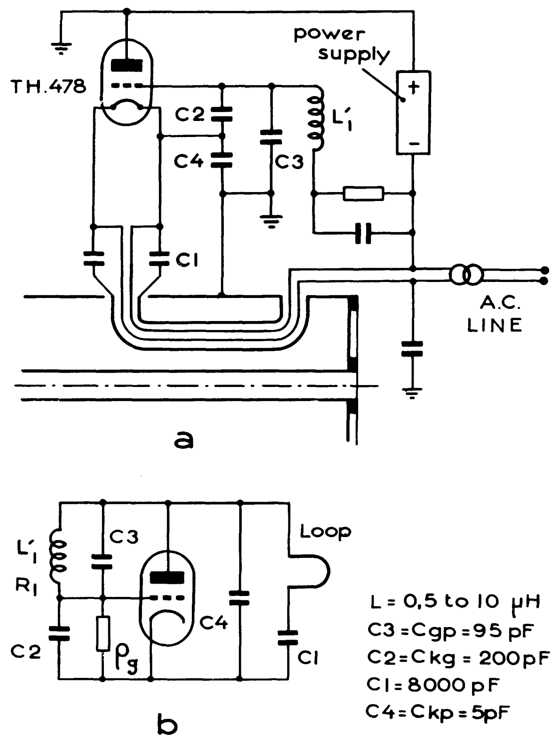

Fig. 7 Circuit elements.

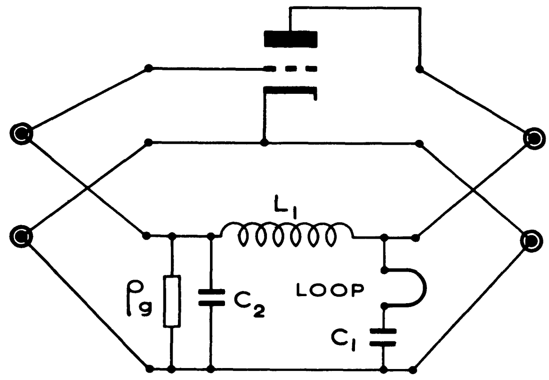

Fig. 8 Quadrupoles representing the tube and the circuit elements.

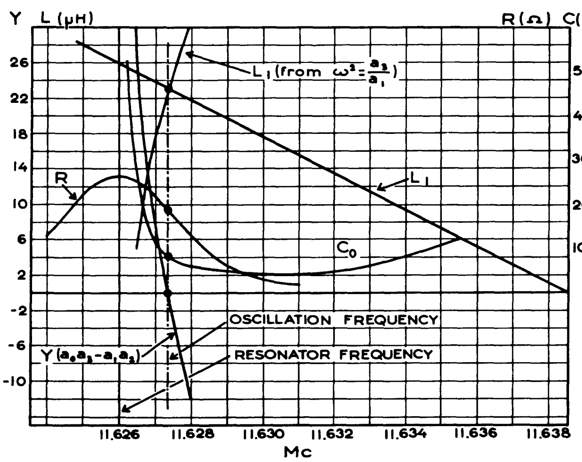

Fig. 9 Characteristics of loop.

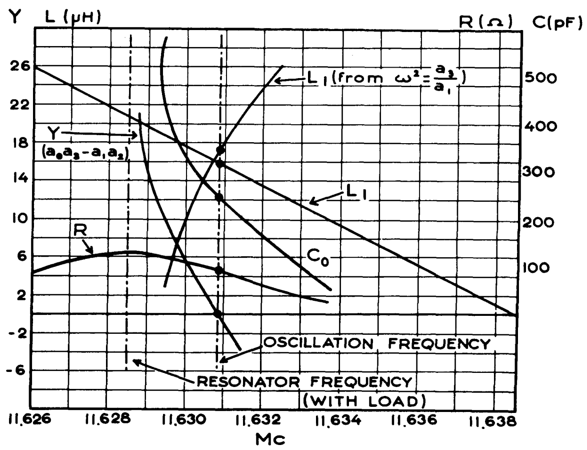

Fig. 10 Characteristics of loop.

The condition $\Delta(A) = 0$ gives

$$(R_0 + \frac{pX}{\omega} + \frac{1}{pC_1})\left[\frac{(1+\mu)}{pC_2}\rho_g + \rho_g pL_1 + \frac{L_1}{C_2}\right] - \rho\left[\frac{1}{C_2^2\, p^2} - (L_1 p + R_0 + \frac{pX}{\omega} + \frac{1}{\mu p})(\rho_g + \frac{1}{C_2 p})\right] = 0$$

with $\frac{1}{\Gamma} = \frac{1}{C_1} + \frac{1}{C_2}$ and $p = j\omega$.

If the known terms are replaced by their values, it can be verified that for $\frac{pX}{\omega} > 0$ the oscillation condition is not satisfied. For $\frac{pX}{\omega} < 0$, the imaginary term presented by the loop is capacitive and can be written in the form $1/pC_0$. In this case the oscillation condition becomes

$$a_0p^3 + a_1p^2 + a_2p + a_3 = 0,$$

and, hence $\omega^2 = \frac{a_3}{a_1}$, and $a_0a_3 - a_1a_2 = 0$.

The curves corresponding to the last two equations have been traced for different values of the impedance presented by the loop (Fig. 9 and 10) using the results of numerical calculations on the CAB 500. It may be noted that for a resistive term in the presented impedance of greater than 100 ohm, the difference between the oscillator frequency and the resonant frequency of the line is less than 0.02%. If the resistive component of the impedance is less than this value, the difference increases; however, calculations have shown that for 50 ohm, oscillation is still possible. It is hoped that this oscillator will be able to start and drive through a multipactor without the necessity of a booster stage. If difficulties are encountered, a pulsed pre-excitor, of the type used at Berkeley, will be employed.

References

1. H. Fauska et al., Nucl. Instr. and Meth. 10, 73 (1961).
2. N.F. Zeigler, Nucl. Instr. and Meth. 18-19, 197 (1962).
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4. B.H. Smith, Nucl. Instr. and Meth. 18-19, 184 (1962).