Title
RESONATORS FOR THE 300 MEV BERKELEY SYNCHROTRON

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Publication Date
1950-06-05

UNIVERSITY OF CALIFORNIA — BERKELEY

RADIATION LABORATORY

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Contract No. W-7405-eng-48

RESONATORS FOR THE 300 MEV BERKELEY SYNCHROTRON

Mitchell Dazey

June 5, 1950

Berkeley, California

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INTRODUCTION

The Berkeley 300 Mev synchrotron was constructed under the direction of Professor E. M. McMillan. The author was assigned to the project in June, 1947. The problem was to develop, test, and have ready for operation a complete radiofrequency acceleration system which could be used with a fused silica, or quartz vacuum chamber.

C. S. Nunan, J. V. Franck, Jack Peterson and the author were assigned to work on the various aspects of the problem under the direction of Professor A. Carl Helmholz. The successful solution of all the problems involved in the radiofrequency system was the result of much effort and cooperation by all members of the group. This paper discusses mainly the phases of the work for which the author had the most responsibility: calculations of Q, losses, and frequency swinging; preparation and electroplating of the quartz resonators; Q measurements and testing of the vacuum seals.

The work was performed under the auspices of the Atomic Energy Commission.

PART I. DESIGN SPECIFICATIONS AND CALCULATIONS

Chapter 1. Description of the Synchrotron.

The synchrotron is a device for accelerating electrons to high energies in a circular orbit. The principle of accelerating electrons in a changing magnetic field by means of an electric field was proposed independently and at about the same time by E. M. McMillan[1] and V. S. Veeksler[2] as a means of obtaining high electron energies without the limitations inherent in the type of electron accelerator then in existence, the betatron.

A complete theoretical discussion of such effects as stability, oscillations, and damping, which occur in the acceleration of electrons by the synchrotron has been given by Bohm and Foldy.[3] Briefly, synchronous "acceleration" can take place in an orbit of almost constant radius when the velocity of the electron becomes nearly that of light. The period of revolution is the circumference of the orbit divided by the velocity of light and it is this value which determined the frequency of the accelerating voltage to be applied to the gap in the electron orbit. The stability conditions of the synchrotron indicate that the electron will gain energy from this accelerating field when the magnetic field is increased, and lose energy to it if the magnetic field is decreased. It was shown in reference (3) that the mean angular velocity of the electrons can remain constant, and small differences between the electron velocity and the velocity of light result in a small decrease in the radius of the orbit. The percent of final orbit radius as a function of energy is shown for several values (assuming infinite energy is 100 percent).

TABLE I

Energy	Percent of Final Radius
0.10 Mev	55 %
0.50	86
1.0	94
2.0	98
5.0	99.6
10.0	99.9
100	99.998
300	99.999

The cost of an a.c. magnet is roughly proportional to the product of the magnetic field strength squared and the volume of the air gap, therefore it is desirable to have the space in which the maximum field is established as small as possible. It is difficult to inject at energies above 100,000 volts due to arcing across insulators. Therefore, in order to avoid a large shift in the orbit radius, it is desirable to use other means than synchrotron acceleration until the electron energy is such that the mean orbit will shift only a few percent.

In the Berkeley synchrotron this preliminary acceleration is obtained by betatron type operation until the energy of the electrons reach 2 Mev. Betatron operation is accomplished by flux-bars which shunt a portion of the magnetic flux through the electron orbit. This flux causes an accelerating voltage around the orbit which by Faraday's Law is:

$$v = 10^{-8} \int_s \mathring{B} ds \qquad (1)$$

where v = volts

$\mathring{B}$ = gauss/second

s = area in cm^2

In the case of the Berkeley synchrotron, this voltage is equal to about 500 volts. When the electron energy reaches about 2 Mev, the flux-bars saturate and accordingly $\dot{B}$ through the orbit becomes small and no longer contributes appreciably to the electron acceleration.

The expression relating energy, magnetic field, and orbit radius for an electron traveling at a relativistic velocity is:

$$B\rho = \frac{100\ E}{3} \tag{2}$$

where B = magnetic field intensity in gauss

ρ = orbit radius in meters

E = energy of electron in Mev

The nominal design figure for beginning of saturation of iron is 10,000 gauss. Substituting in (2), one can establish the relationship between orbit radius and maximum energy:

$$E = 300\rho \tag{3}$$

The rest energy of the meson at one time was presumed to be about 100 Mev, and it was believed that nuclear reactions involving mesons could be studied if electrons were accelerated to an energy more than twice this value. Therefore when synchrotron designs were considered in several places in this country and in England, it was desired that the maximum energy obtainable be of the order of 300 Mev. The Berkeley synchrotron was therefore designed with an orbit radius of 1 meter.

This choice of radius meant that the frequency of the accelerating voltage should be:

$$\text{frequency} = \frac{\text{velocity of light}}{\text{circumference}} = \frac{3 \times 10^8}{2\pi} = 4.7 \text{ megacycles per second}^* \tag{4}$$

In the Berkeley synchrotron, the magnetic field is excited by a charge

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*This high frequency voltage is referred to as radiofrequency, and the abbreviation r.f. will be used throughout this paper.

which is stored on a large condenser bank, and then by means of ignitron "switch" tubes, discharged through the coils of the magnet. The resulting magnetic field (neglecting the effect of the flux-bars) can be expressed:

$$B = B_{max} \sin 2\pi\ (30t) \qquad (5)$$

where B = magnetic field in gauss

t = time in seconds

The fundamental frequency of the magnetic field is thus 30 cycles per second.* In order that heating in the coils and the iron laminations might be reduced, the large ignitron "switch" tubes allow a complete cycle to take place a maximum of six times per second.

The electron energy as a function of time, assuming a B_{max} of 10,000 gauss and a radius of one meter, can be determined by substituting (2) in (5):

$$E = 300 \sin 2\pi\ (30t) \qquad (6)$$

where E = energy in Mev

Differentiating (6), the rate of change of energy is:

$$\mathring{E} = 300 \times 60\pi \cos 2\pi\ (30t) \qquad (7)$$

The energy gain per turn can be obtained by dividing (7) by the number of turns per second, or frequency:

$$V = \frac{300 \times 60\pi \cos 2\pi\ (30t)}{47.7 \times 10^6} \qquad (8)$$

V in units of a million volts

Multiplying (8) by 10^6 to obtain volts per turn:

$$v = 1180 \cos 60\pi t \qquad (9)$$

---

*Original design specifications called for the fundamental frequency to be 60 cycles per second. Operation at this frequency would increase betatron acceleration voltage, r.f. voltage necessary, and eddy currents. It would also decrease the length of time for acceleration of the electrons to 300 Mev.

Thus the maximum accelerating voltage is needed at the initial stage of acceleration and is equal to 1180 volts. A convenient way of obtaining this voltage at 47.7 megacycles per second is by exciting a quarter wave coaxial transmission line resonator with the accelerating voltage established across a gap at the open end of the line. Due to voltages induced by the changing magnetic field (Equation (1)) the metal used in the construction of a resonator must be very thin and arranged so there will be a minimum of flux linkages in order that the effects from eddy currents will be small. It is usually necessary to make synchrotron resonators with thin strips of metal running parallel to the flow of r.f. current.

Chapter 2. Types of Resonators.

The magnet of the Berkeley synchrotron has an air gap which has a nominal height of 3 3/4 inches. The effective magnetic field extends over a width of about 6 1/2 inches. In the original design, rings which were the mechanical supports for the pole tips of the magnet were constructed from layers of glass cloth impregnated with permafill, a resin plastic, and these rings together with the pole tips of the magnet formed the walls of a toroidal vacuum chamber whose cross section dimensions were about four inches high by eight inches wide. Helmholz, Peterson, and Franck[4] designed and constructed an accelerating system consisting of five coaxial transmission lines terminated in common by a long coaxial condenser. Acceleration of the electrons was to take place on their entering the condenser followed by a period of drift time to allow the r.f. field to change polarity after which acceleration again took place upon their leaving the condenser. Because of the porosity of the plastic walls of the chamber it was impossible to obtain a sufficiently good vacuum to allow electron acceleration, and the system had to be set aside shortly after many mechanical and electrical difficulties had been overcome.

After the original vacuum chamber was abandoned, it was decided to construct a vacuum chamber or donut from fused silica or quartz tubing. The choice of material was dictated somewhat by manufacturing convenience. It was thought possible that the donut might be constructed from glass; however, no facilities were available on the west coast for molding and blowing the large irregular shapes necessary and long delivery time resulting from a backlog of post war orders made it impossible to accept bids from the large eastern firms such as Corning glass works.

Ceramic materials were considered as a possibility for the donut, but shrinkage as a result of firing is likely to crack a large asymmetric piece, so that it would have been necessary to make the donut from a large number of very short sections which would have necessitated many vacuum seals.

The Amersill Company agreed to manufacture the vacuum chamber from fused quartz. Fused quartz is a very hard brittle substance with excellent electrical properties.

The most desirable shape from the standpoint of ease of manufacture and utilization of space between the pole pieces or the magnet was a toroid with an approximately elliptical cross section. The vertical and horizontal aperture of the vacuum chamber are dimensions of utmost importance. The electrons must make many revolutions before reaching the final energy and residual gas remaining in the chamber, in spite of continuous pumping by oil diffusion pumps, can cause loss of electrons due to scattering to the walls. Any increase in wall thickness necessary for mechanical strength to resist the forces due to atmospheric pressure results in a corresponding decrease in aperture and consequent increased loss of electrons. Lloyd Smith of the Radiation Laboratory staff has derived an expression for theoretical loss of electrons in a synchrotron due to scattering which is in simplified form:

$$\text{Fraction remaining} = Y = \text{Exp}\left[-\frac{3.54 \times 10^{12}\ r^3\ P}{n \times \Delta E \times E_i \times a^2}\right] \tag{10}$$

where r = orbit radius in meters

P = pressure in millimeters of mercury

n = magnetic field parameter

ΔE = energy gain per turn in electron volts

E_i = injection energy in electron volts

a = vertical aperture in inches.

The magnetic field parameter n is given by the expression:

$$H = H_o\left(\frac{r_o}{r}\right)^n \tag{11}$$

where H = magnetic field strength at radius r

H_o = magnetic field strength at orbit

r_o = orbit radius

r = distance to center of orbit

In the case of the Berkeley synchrotron the design value of n is 2/3, and as stated before the radius is one meter, and the energy gain per turn is 500 volts. As a basis for design specifications it was assumed that the maximum injection voltage would be 70,000 volts and the lowest pressure obtainable in the vacuum chamber would be 10^{-4} mm of Hg. Given these conditions one can rewrite (10)

$$Y = e^{-15.2/a^2} \tag{12}$$

Table II is a tabulation of yields expected with various wall thicknesses, with the maximum theoretical yield assumed to be 100 percent for the condition where all the space between the pole pieces is utilized.

TABLE II

Vertical Aperture	Wall Thickness	% Yield
3.75 inches	0.0 inches	100%
3.50	1/8	85
3.25	1/4	70
3.00	3/8	54
2.75	1/2	39

Later experience with synchrotron operation showed that the assumptions regarding maximum obtainable injection voltage and minimum pressure were too conservative, so that the effects due to aperture reduction were negligible. However, on the basis of the early assumptions, it was decided to specify the wall thickness of the quartz sections to be 5/16 of an inch.

The first operating synchrotron was converted from a betatron by Goward and Barnes in England[5] and utilized a coaxial resonator completely external to the vacuum chamber for the r.f. accelerating electrode. This quarter-wave resonator was air-spaced, consequently it occupied 90° of an arc around the vacuum chamber. This type of resonator uses valuable space between the pole tips of the magnet, and, due to its length and curvature, may be somewhat difficult to assemble.

Goward et al.[6] have operated a synchrotron using a resonator made from a ceramic, Faradex, which has a dielectric constant of about 80. This resonator was small, its length was $90^\circ/\sqrt{e}$, or about 10° of arc, and it could be inserted or removed from the vacuum chamber through a port. This type of resonator has certain advantages; however, it reduces the aperture of the vacuum chamber and special arrangements must be made if cooling of the resonator is necessary.

These two types of resonators are convenient, especially where it is desired to increase the energy of an existing betatron by additional synchrotron acceleration. In the case of large synchrotrons with a relatively small space between the pole pieces of the magnet it is advisable to design the accelerating electrode as an integral part of the vacuum chamber, thus obtaining an aperture of maximum size.

The vacuum chamber of the Berkeley synchrotron was to be over six feet in diameter, and a complete ring would be difficult to manufacture and clumsy to handle; therefore it was decided to make the vacuum chamber in several sections, one of which would be a quarter wave resonator.

Chapter 3. Method of Construction.

Various methods have been suggested for constructing synchrotron resonators from sections of a ceramic or glass vacuum chamber. Metallic coatings have been applied by such methods as gluing copper strips to the chamber, firing on metallic coatings, and electroplating on a conducting base. It was thought that the most satisfactory results from the standpoint of conductivity and mechanical stability would be achieved by electroplating a section of the vacuum chamber.

It is generally considered desirable to electroplate materials used for high frequency to a thickness of two or three skin depths in order that the material will be in effect a conductor of infinite thickness. Since the resonator must be used in an alternating magnetic field it is desired that the thickness of the plate be kept to a minimum to reduce eddy currents. The surface resistivity of a thin coating of metal at high frequencies* is:

$$R = R_s \frac{\sinh 2\frac{d}{\delta} + \sin 2\frac{d}{\delta}}{\cosh 2\frac{d}{\delta} - \cos 2\frac{d}{\delta}} \qquad (13)$$

*Ramo and Whinnery, Fields and Waves in Modern Radio, p. 219.

where R = surface resistivity of metal (ohms "per square")

R_s = surface resisitivity for conductor infinitely thick

d = thickness of plating

δ = "skin depth" in conductor in same units as d. (The distance at which the value of the current density is 1/e the value at the surface in a conductor of infinite thickness.)

Figure 1 is a plot of the function R/R_s versus d/δ.

It can be seen from Figure 1 that losses increase very rapidly in areas that might have less than 1/2 skin depth of plating. It is only of theoretical interest that a layer of metal 1.6 skin depths bounded by a non-conductor would have about 8 percent better conductivity than metal of infinite thickness, since it is not possible to hold close tolerances on plating of metal for use at high frequencies.

The skin depth for common conductors is:

$$\text{Silver:} \quad \delta = \frac{2.63}{\sqrt{\text{frequency}}}$$

$$\text{Copper:} \quad \delta = \frac{2.73}{\sqrt{\text{frequency}}} \qquad (14)$$

δ in inches

frequency in cycles per second

At the operating frequency of 47.7 megacycles per second the skin depth would be about 0.0004 inch. To allow for possible variations in the thickness of the plating it was decided to plate the resonator to a nominal thickness of 0.003 inch, giving a conductivity essentially equivalent to that of an infinite thickness of metal.

Design specifications for the vacuum chamber or donut called for a ring made of eight 45 degree quartz sections. The dielectric constant of quartz

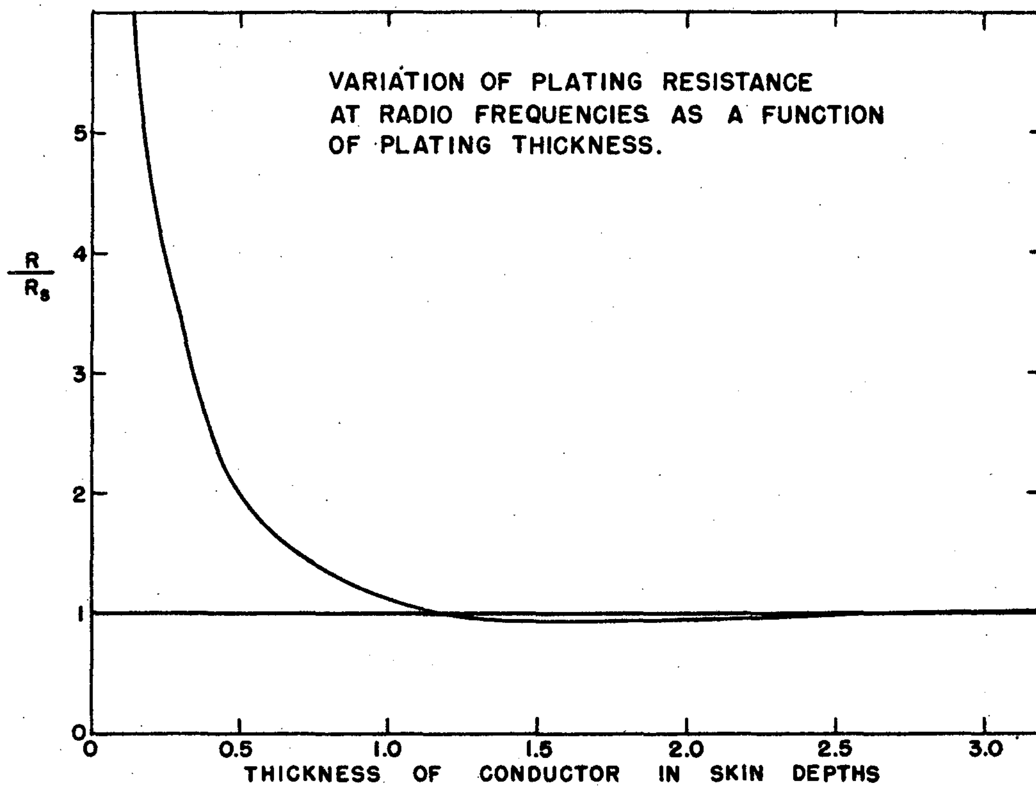

VARIATION OF PLATING RESISTANCE
AT RADIO FREQUENCIES AS A FUNCTION
OF PLATING THICKNESS.
5
4
3
2
1
0
$\frac{R}{R_s}$
0
0.5
1.0
1.5
2.0
2.5
3.0
THICKNESS OF CONDUCTOR IN SKIN DEPTHS

FIG. 1 MU 315

is about 4, so it was decided that investigations be started to determine if one of the sections could be utilized as a quarter wave resonator. A comparison of fused quartz with other materials indicated that dielectric losses would be small. Table III is a list of the dielectric constants and loss factors of materials used at radio frequencies. These values are likely to change with frequency and it is advisable to check carefully the material under consideration for any application.

The thermal coefficient of expansion of quartz is about 5×10^{-7} per degree centigrade. Since the frequency is proportional to the length of the resonator, it might be expected that a 47 megacycle resonator would shift frequency only about 25 kilocycles for a 100 C° rise in temperature, a negligible amount. A glass resonator might be expected to shift frequency up to twenty times this amount.

The Amersill Company of New Jersey contracted to deliver the necessary quartz sections for the donut. Before the shipment of the sections arrived, the Amersill Company was able to supply a sample section of quartz with a mean length of about 20 inches and a wall thickness of about 5/16 inch. Preliminary resonator studies were begun on this sample at the same time the author was assigned to the synchrotron project.

Chapter 4. Resonator Q.

The exact solution of the fields that exist in a section of a toroid with an elliptical cross section would be extremely difficult. It is necessary to make certain simplifying assumptions: first that the section is straight instead of curved, and second, that the cross section is circular instead of elliptical, with the inner and outer circumference and the wall thickness remaining the same.

TABLE III*

Material	Dielectric Constant	Power Factor (Loss Tangent) (e/e")	Loss Factor (e")
Fused quartz	4.2	0.0003	0.0012
Pyrex glass	4.5	0.002	0.009
Steatite	6.0	0.0012	0.007
Polystyrene	2.5	0.0002	0.0005
Titanium dioxides	141 to 90	0.0002 to 0.005	

* Values observed at 1 megacycle and would be somewhat higher at higher frequencies. These values obtained from "Special Ceramic Materials" published by the General Ceramics and Steatite Corporation, Keasbey, New Jersey.

At certain times of the r.f. cycle the energy stored in the resonator is all stored in the inductance. This occurs when the voltage at the gap is zero and the current at the short circuit end is a maximum, I_{max}. At this time the current distribution through the resonator as a function of the distance from the short circuit end is:

$$I = I_{max} \cos \frac{\pi}{2} \frac{x}{\ell} \qquad (15)$$

where x = distance from short circuit end

ℓ = length of resonator

The stored energy ($\frac{1}{2}LI^2$) is then:

$$W_s = 1/2 \int_0^{\ell} L\left(I_{max} \cos \frac{\pi}{2} \frac{x}{\ell}\right)^2 dx \qquad (16)$$

where L = inductance per unit length

The average power lost in a unit length of the resonator plating is equivalent to I^2_{rms} x R* where R is the resistance per unit length of resonator, or more specifically the resistance of a unit length of inner conductor plus the resistance of a unit length of outer conductor at the frequency under consideration.

The relationship between I_{rms} and I_{max} at the short circuit end is:

$$I_{rms} = \frac{I_{max}}{\sqrt{2}} \qquad (17)$$

The average power lost in the resonator plating is then:

$$W_{ave} = \int_0^{\ell} R \left(\frac{I_{max}}{\sqrt{2}} \cos \frac{\pi}{2} \frac{x}{\ell}\right)^2 dx \qquad (18)$$

---

* rms is used as the abbreviation of root mean square.

It is convenient to consider separately the losses in plating, and the dielectric losses. One can assign a performance factor or Q to each of these losses with Q_{Cu} being the Q of a copper plated resonator with a lossless dielectric, and Q_d being the Q of a resonator with no losses in the conducting surfaces. In an actual resonator it is not possible to measure either quantity by itself; however, the two are related to the total Q by the expression:

$$1/Q = 1/Q_{Cu} + 1/Q_d \tag{19}$$

The definition of Q is:

$$Q = \frac{\omega \times \text{energy stored in circuit}}{\text{average power loss}} \tag{20}$$

The copper Q can then be written:

$$Q_{Cu} = \frac{\omega \times W_s}{W_{ave(Cu)}} = \frac{\omega \times \frac{1}{2} \int_0^{\ell} L \left(I_{max} \cos \frac{\pi}{2} \frac{x}{\ell}\right)^2 dx}{\int_0^{\ell} R \left(\frac{I_{max}}{\sqrt{2}} \cos \frac{\pi}{2} \frac{x}{\ell}\right)^2 dx} \tag{21}$$

In the case of a coaxial resonator the inductance and resistance per unit length are a function of geometry, and, if the walls are of constant thickness they do not vary with x, and therefore L and R can be taken outside the integrals. The expression for the copper Q becomes:

$$Q_{Cu} = \frac{\omega L}{R} \tag{22}$$

where $\omega = 2\pi \times$ frequency

L = inductance per unit length

R = resistance per unit length.

The dielectric Q can be determined by assuming the resonator has perfectly conducting walls. At a time when the current is zero at all places in the resonator, the voltage at the gap is a maximum, V_{max}. The voltage distribution through the resonator as a function of the distance from the gap end is then:

$$V = V_{max} \cos \frac{\pi}{2} \frac{x}{\ell} \tag{23}$$

where x = distance from gap end

ℓ = length of resonator

The stored energy is given in general by $\frac{1}{2}CV^2$ and for the case of the coaxial resonator is:

$$W_s = \frac{1}{2} \int_0^{\ell} C \left(V_{max} \cos \frac{\pi}{2} \frac{x}{\ell}\right)^2 dx \tag{24}$$

The dielectric losses in a coaxial resonator are in the nature of shunting currents which are in phase with the voltage. These currents are equal to $V \times \omega e''$, where e'' is the loss factor and ω is 2π times the frequency. The power dissipated due to the in-phase currents is $V \times I$, or $V^2 \omega e''$. For the average power dissipated, V should be the rms and taking this into account, the average power dissipated in the dielectric is:

$$W_{ave} = \int_0^{\ell} C \omega e'' \left(\frac{V_{max}}{\sqrt{2}} \cos \frac{\pi}{2} \frac{x}{\ell}\right)^2 dx \tag{25}$$

Combining (24) and (25), taking the constant terms outside the integrals, and cancelling:

$$Q_d = \frac{\omega \times W_s}{W_{ave}} = \frac{e}{e''} = \frac{1}{\text{loss tangent}} \tag{26}$$

where e = dielectric constant

e'' = loss factor

The effect of geometry of the resonator can be more clearly demonstrated by writing L for coaxial transmission lines.

$$L = \frac{\mu_1}{2\pi} \; L_n \; (b/a) = \frac{\mu_1}{2\pi} \left(\frac{t}{a} - \frac{t^2}{2a^2} + \frac{t^3}{3a^3} - \frac{t^4}{4a^4} \cdots \right) \tag{27}$$

where L = henries/meter

$\mu_1 = 4\pi/10^7$

b = outside radius

a = inside radius

t = wall thickness of resonator $= b - a$

R is equal to:

$$R = \frac{R_s}{2\pi} \left(\frac{1}{a} + \frac{1}{b} \right) \tag{28}$$

where R = ohms per unit length

R_s = surface resistivity of plating in ohms

a = inside radius

b = outside radius

The reciprocal of R can be written in a series form:

$$1/R = \frac{2\pi}{R_s} \left(\frac{a}{2} + \frac{t}{4} - \frac{t^2}{8a} + \frac{t^3}{16a^2} - \frac{t^4}{32a^3} + \cdots \right) \tag{29}$$

$t = b - a =$ wall thickness.

By multiplying series (27) and (29) and ω_1, the copper Q for a resonator of wall thickness t can be written:

$$Q_{Cu} = \frac{\omega\mu_1}{R_s} \left(\frac{t}{2} - \frac{t^3}{12a^2} + \frac{t^4}{12a^3} + \cdots \right) \tag{30}$$

Using the values for copper and silver of surface resistivity:

$$R_{s(copper)} = 2.61 \times 10^{-7} \sqrt{\text{frequency}} \tag{31}$$

$$R_{s(silver)} = 2.52 \times 10^{-7} \sqrt{\text{frequency}}$$

frequency in cycles per second

R_s in ohms (per square)

Converting from meters to inches the expressions for Q_{copper} and Q_{silver} of a thin walled resonator are

$$Q_{copper} = 0.384 \sqrt{f}\ \ t(1 - \Delta)$$
$$Q_{silver} = 0.394 \sqrt{f}\ \ t(1 - \Delta) \qquad (32)$$

where $\Delta = t^2/6a^2$
t = wall thickness in inches

a = effective inner radius(circumference/2π)

f = frequency in cycles per second

The term Δ is negligible for most resonators where the wall thickness must be kept to a minimum, so it is possible to say that for a given frequency the Q of a resonator is proportional to the wall thickness if dielectric losses are neglected.

It seemed that a resonator for 47.7 megacycles with a wall thickness of 5/16 inch would have such a low Q that when all factors were taken into account, operation might have been unsatisfactory. Therefore it was decided to increase the wall thickness of the resonator section to 7/16 inch and risk the possible additional loss of electrons due to the reduced aperture. By using the value for the loss tangent of quartz from Table III, it is possible to make a comparison of quartz resonators under consideration. Table IV is a list of the theoretical Q's and some of the Q's observed experimentally. The experimental Q's were much lower than theory would predict, and the factors contributing to the additional losses are discussed later in this paper.

TABLE IV

	Copper Q	Dielectric Q	Total Q	Experimental Q
Sample section resonant at 80 mc wall thickness 5/16"	1080	2500	755	450-650
Resonator - 5/16" wall	830	2500	630	(not tested)
Resonator - 7/16" wall	1160	2500	790	225-550

Chapter 5. Voltage and Power Requirements.

As stated in the introduction, 1160 volts is the minimum voltage that must be supplied to the gap in the resonator in order that the electrons can be accelerated.

Experience with the General Electric Company 70 Mev synchrotron[6] indicated that maximum output was obtained when the accelerating voltage was about twice the minimum value. It was believed that a satisfactory design voltage for the Berkeley synchrotron would be 5,000 peak volts at the gap, this voltage being sufficient even if it was decided to operate the magnet at a fundamental frequency of 60 instead of 30 cycles per second.

The characteristic impedance of the quartz resonator considered as a transmission line is a function of geometry and the dielectric constant:

$$Z_o = \frac{60}{\sqrt{e}} \ln \frac{b}{a} = \frac{60}{\sqrt{e}} \left(\frac{t}{a} - \frac{t^2}{2a^2} + \frac{t^3}{3a^3} \dots \right) \tag{33}$$

$$= \frac{60\ t}{\sqrt{e}\ a} \quad \text{for a thin walled resonator}$$

where e = dielectric constant = 4.0 for quartz

a = effective inner radius

b = effective outer radius

t = wall thickness

In the case of the 47.7 mc resonator with 7/16 inch walls, the effective inner radius is 2.1 inches. The characteristic impedance by (33) is then 6.2 ohms. The input admittance at the open end of a quarter wave resonator is given by:

$$Y_i = \frac{\pi}{4\ Q\ Z_o} \tag{34}$$

The average power lost at resonance is given by:

$$W_{ave} = \frac{V_{max}^2}{2} \times Y_i \tag{35}$$

By combining the previous equations we find that the power lost in a thin walled resonator is:

$$W_{ave} = \frac{V_{max}^2}{2} \left(\frac{\sqrt{e}\ \pi\ a}{240 \times .384\ t^2 \sqrt{f}} + \frac{e''\ \pi\ a}{\sqrt{e}\ 240\ t} \right) \tag{36}$$

where W_{ave} = power in watts

e'' = loss factor

e = dielectric constant

a = effective inner radius in inches

t = wall thickness in inches

V_{max} = maximum voltage at gap

f = frequency in cycles per second

The above is a theoretical expression which would apply to most synchrotron resonators. In actual practice there are many factors which cause this loss to be larger than the theoretical value and therefore a larger amount of r.f. power is required from the oscillator, and greater cooling is necessary. The first term inside the brackets in (36) represents the losses in the plating of the resonator, while the losses in the dielectric are proportional to the second term. Perhaps the most important factor is the wall thickness since it appears as the square in the plating loss, and also appears in the dielectric loss.

For the Berkeley synchrotron resonator the theoretical losses at 5,000 volts at the gap are 1,350 watts in the plating and 660 watts in the dielectric, or a total of about 2 kilowatts. Later tests with the resonator indicated that the actual energy to be dissipated would amount to about three times this value if the resonator were run continuously. Since the acceleration can take place only during the initial rise of the magnetic field, or one quarter of the magnet cycle, and since the pulse rate of the magnet is 6 times per second, the duty cycle is one in 20, and average power dissipated is reduced by this factor.

The factors which may account for the large increase in losses over the theoretical minimum are discussed later.

Chapter 6. Feed Problems.

Feeding power into the quarter-wave resonator can be accomplished in several ways. The General Electric Company[8] was able to couple inductively sufficient power into a resonator at 163 megacycles per second to obtain 1000 volts across the accelerating gap. Jack Peterson of the Radiation Laboratory Staff in an unpublished report mentions some preliminary experiments with both inductive and capacitive coupling to resonators and some of the difficulties that were experienced. Both methods increase in difficulty with lower frequency and higher voltage; inductive coupling is subject to moding difficulties, and capacitive coupling requires a large capacity to the plating on the inner surface of the resonator in order that high voltages will not appear across the coupling capacity. Both methods increase the difficulty of shifting the frequency. These two methods have the advantage that it is not necessary to bring metallic conductors through the vacuum chamber wall at the feed point.

Since the design specifications of the Berkeley synchrotron called for 5000 volts at the gap and a frequency of 47.7 megacycles, it was thought advisable to couple a coaxial transmission line from the oscillator directly to the plating on the inner and outer surfaces of the resonator rather than try to overcome the difficulties inherent in other methods of coupling. Design of the coupling device is simplified if it is not necessary that the insulating surfaces between inner and outer conductor be able to stand the total voltage at the gap. If the transmission line from the oscillator is coupled into a resonator of length ℓ a distance x from the gap, the voltage at the feed point for a given gap voltage is:

$$V = V_{gap} \cos \frac{\pi x}{2\ell} \qquad (37)$$

Therefore it was decided to couple in at the 1/2 voltage point, or where $x = \frac{2}{3}\ell$. Provision was made for bringing a portion of the plating on the inner surface of the resonator out through a hole in the "feed bump." The resulting hole was closed and a vacuum seal made by soldering in a metallized quartz plug.

Chapter 7. Frequency Swinging.

There are a sufficient number of variables in the operation of a synchrotron so that it is not possible to say in advance what the most satisfactory electron orbit will be from an operating standpoint. Therefore it is necessary to provide a means of changing slightly the radio frequency in order that the electron orbit will be shifted as discussed in the introduction. This could be done by adding capacity at the feed point; however it was desirable to keep metallic parts in the immediate vicinity of the magnet to a minimum. Therefore the frequency shifting device and the r.f. oscillator had to be placed some distance from the resonator. It was possible to couple the oscillator to the resonator with a transmission line approximately a half wavelength long. To avoid the necessity of having sliding sections in the line it was decided to shift the frequency by means of a variable condenser at the oscillator.

The oscillator had been used for trials of the early type of r.f. system mentioned in the introduction, and it was necessary to make some modifications to the oscillator, and design a transmission line which when coupled to the resonator would provide a load of the proper impedance for the oscillator.

The admittance at a coupling point on the resonator a distance x from the gap can be expressed: $Y_{Load} = A + jBF(\lambda)$, where $F(\lambda)$ is a function of wave-length or frequency. It can be shown that for the resonant frequency, and frequencies a few percent different from the resonant frequency:

$$A = \frac{Y_i \text{ gap}}{\cos^2 \beta x} \quad .$$

$$B = \frac{Y_o}{\cos^2 \beta x} \tag{38}$$

$$F(\lambda) = \pm \tan 90\Delta^o$$

where Y_i gap = input admittance at resonance at the gap (Eq. 29)

β = propagation constant = 2π/wave-length in quartz

x = distance to accelerating gap

Y_o = characteristic admittance (Reciprocal of Eq. 28)

Δ = small fractional frequency shift from resonance

$F(\lambda)$ is positive for an increase in frequency.

Some typical values of A and B can be obtained from Equations (33) and (34), assuming a Q of 450, and that the line is coupled at the 1/2 voltage point on the resonator, or where $x = \frac{2}{3}\ell$.

$$A = \frac{\pi}{(\cos^2 \beta x) x\ 4QZ_o} = 0.0011 \text{ mhos}$$

$$B = \frac{Y_o}{\cos^2 \beta x} = 0.65 \text{ mhos} \tag{39}$$

The reactive term, $jB \tan 90\Delta^o$ will be transformed to different admittance unless the coupling line has constant characteristic admittance and is exactly 1/2 wave-length long. Since the electrical length of the line will change with the frequency shift, some control must be exercised over the impedance transformation so that an excessively large tuning capacity will not be required. The impedance or admittance at the oscillator can be controlled by making the coupling line from two sections of line each approximately 1/4 wave-length long, with each section of the proper characteristic admittance. The choice of characteristic admittance for each section of line can be determined by analyzing a system consisting of a load and two sections of line as shown schematically in Fig. 2. The lines are quarter-wave lines for the resonant frequency and have characteristic admittances Y_{01} and Y_{02} respectively. If there are no losses in the line, the input admittance for any line of length l, characteristic admittance Y_o, and terminated with a load Y_L is:

$$Y_i = Y_o \frac{Y_L + j\, Y_o \tan \beta \ell}{Y_o + j\, Y_L \tan \beta \ell} \tag{40}$$

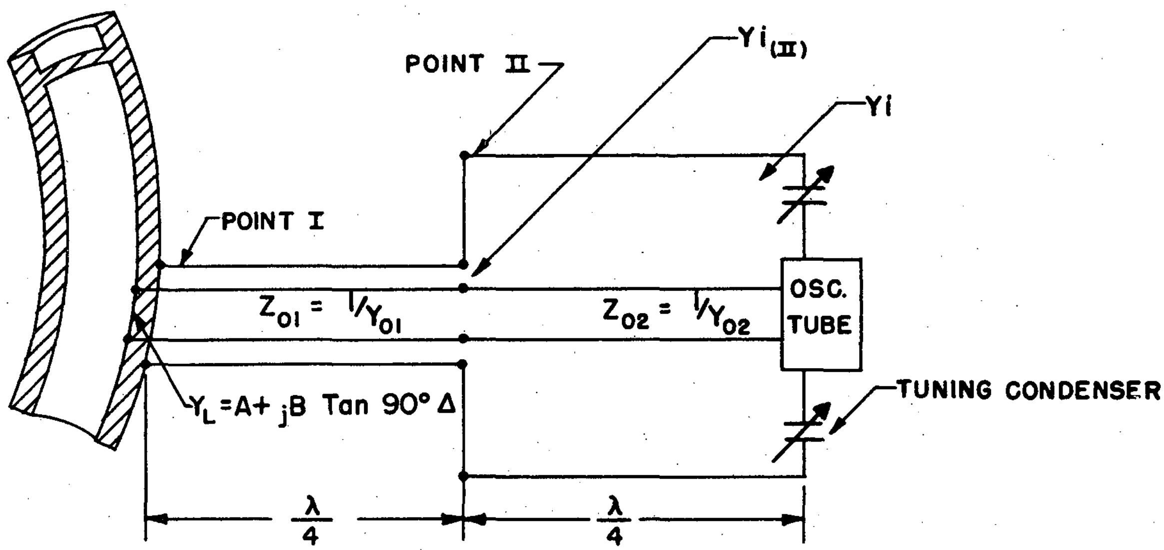
If the lines are exactly a quarter wave-length long, $\beta \ell = \pi/2$ radians or 90^o and equation (40) becomes:

$$Y_i = \frac{Y_o^{\,2}}{Y_L} \tag{41}$$

If, however, the frequency is shifted a small fraction Δ so that $\beta \ell = 90^o \pm \Delta \times 90^o$ then $\tan \beta \ell = \mp \cot 90\Delta^o$, and this value can be used in Equation (40).

The input admittance looking into the line Y_{01} a quarter wave-length from the load, position II, can then be written:

$$\begin{aligned} Y_L &= A \pm jB \tan 90\Delta^o \\ Y_{i(II)} &= Y_{01} \frac{A \pm jB \tan 90\Delta^o \mp j\, Y_{01} \cot 90\Delta^o}{Y_{01} \mp j(A \pm jB \tan 90\Delta^o) \cot 90\Delta^o} \\ &= Y_{01} \frac{A \pm j(B \tan 90\Delta^o - Y_{01} \cot 90\Delta^o)}{Y_{01} + B \mp j\, A \cot 90\Delta^o} \end{aligned} \tag{42}$$



SCHEMATIC DIAGRAM OF RESONATOR AND COUPLING LINE CONSISTING OF TWO QUARTER-WAVE LINES

MU 316

FIG. 2

If reasonably low impedance lines are used to couple to the resonator which is itself a low impedance line (6.2 ohms), and if the frequency shift is assumed small, the terms Y_{01} cot $90\Delta^\circ$ and Y_{02} cot $90\Delta^\circ$ will be large compared to terms which may be directly added or subtracted. Using this approximation, Eq. (41) becomes:

$$Y_{i(II)} = Y_{01} \frac{A \mp j\, Y_{01} \cot 90\Delta^\circ}{Y_{01} \mp B \mp j\, A \cot \Delta 90^\circ} \qquad (43)$$

Since $Y_{i(II)}$ is the terminating load for the line Y_{02} it is possible to consider the last section of line by substituting (43) in Eq. (40) letting $Y_{i(II)} = Y_L$. The input admittance for the complete system is then:

$$Y_i = Y_{02} \frac{Y_{01} A - Y_{02} \cot^2 90\Delta^\circ \mp j \cot 90\Delta^\circ \left\{Y_{01}^2 + Y_{02}(Y_{01} + B)\right\}}{Y_{02}(Y_{01} + B) - Y_{01}^2 \cot^2 90\Delta^\circ \mp jA(\cot 90\Delta^\circ)(Y_{01} + Y_{02})} \qquad (44)$$

Again using the approximation for small frequency shift:

$$Y_i = Y_{02} \frac{Y_{02} A \cot \Delta 90^\circ \pm j \left\{Y_{01}^2 + Y_{02}(Y_{01} + B)\right\}}{Y_{01}^2 \cot \Delta 90^\circ \pm j\, A\, (Y_{01} + Y_{02})} \qquad (45)$$

Rationalizing Eq. (40):

$$Y_i = \frac{Y_{02}^2}{Y_0^{\,2}} A \pm j \tan 90\Delta^\circ \left\{ Y_{02} + \frac{Y_{02}^2}{Y_{01}} + \frac{Y_{02}^2 B}{Y_{01}^2} - \frac{A^2 Y_{02}^2}{Y_{01}^4} (Y_{01} + Y_{02}) \right\} \qquad (46)$$

If E is the r.f. voltage supplied by the oscillator, E^2 multiplied by the real term in the above expression represents the power delivered to the resonator. The power consumption of the resonator is fixed by considerations given in Eq. (36). A tube capable of supplying this power might be designed to operate at certain voltages, therefore it is necessary to choose the proper ratio of characteristic admittances or impedances of the two quarter wave sections. Voltage transformation which occurs can then be written:

$$\frac{Y_{01}}{Y_{02}} = \frac{Z_{02}}{Z_{01}} = \frac{\text{Voltage at tube}}{\text{Voltage at coupling point}} = k \qquad (47)$$

Once the value of k, or the voltage transformation ratio, is decided it is possible to see what factors affect the size of capacity needed for the required frequency shift by substituting in Eq. (46). The amount of capacity which must be added or subtracted at the oscillator end of the line is then proportional to the imaginary term of Eq. (46). The term multiplied by A^2 will be small for a resonator of reasonably low losses and can be neglected. Using the value of k from Eq. (47), the susceptance which must be balanced out by a condenser in order to shift the frequency an amount Δ is:

$$Y_{i(\text{imaginary})} = \pm j \tan 90^\circ x\Delta \left(Y_{02} + \frac{Y_{02}}{K} + \frac{B}{K^2}\right) \qquad (48)$$

The three terms in the parentheses, Y_{02}, $\frac{Y_{02}}{K}$, $\frac{B}{K^2}$, can be thought of as the contribution to the susceptance caused by the section of line nearest the oscillator, the section nearest the resonator, and the resonator itself respectively, when the frequency is shifted from the designed resonant frequency.

The value of B from Eq. (38) was .65 mhos. If the lines have a characteristic impedance greater than 10 ohms, almost all the susceptance which appears when the frequency shifts is due to the resonator.

Some typical values for tuning condenser and coupling lines might be:

Assume voltage transformation (increase) = 4 = k

Assume frequency shift desired = 4 megacycles

$\Delta = \frac{4 \text{ megacycles}}{47.7 \text{ megacycles}}$ = 0.084

$\tan 90\Delta^\circ = \tan 7.6^\circ$ = .133

Assume Z_{02} = 50 ohms

$Z_{01} = \frac{Z_{02}}{2}$ = 25 ohms

$$Y_i = j(0.133)(.02 + .005 + .04) \qquad = j(.0086) \text{ mhos}$$

$$C_{tuning} = \frac{Y_i}{2\pi f} = \frac{.0086}{2\pi \times 47.7 \times 10^6} \text{ farads} \qquad = 29 \ \mu\mu f$$

This value can be obtained easily within the space and insulation limitations.

The actual resonant system was constructed with a zircon impedance transformer whose electrical length was one-eighth wave-length, or 45 electrical degrees, and a characteristic impedance, Z_{01} of 3.6 ohms. The remainder of the transmission line has an impedance Z_{02} of 15.2 ohms. It can be shown by means of the transmission line formulae that the section of the transmission line must have an electrical length in degrees given by:

$$\tan \phi = -\frac{Z_{02}}{Z_{01}} \tan \theta \qquad (49)$$

where Z_{01} = characteristic impedance of section nearest resonator (transforming section)

Z_{02} = characteristic impedance of coupling line

θ = electrical length in degrees of transforming section

ϕ = electrical length of coupling line in degrees.

The length of coupling line required would then be about 103 electrical degrees, or .29 wave-lengths. The voltage transforming ability of a section which is less than a quarter wave long is given by:

$$k = \frac{Z_{02}^2}{Z_{01}^2} \sin \theta + \cos \theta \qquad (50)$$

where θ = length of transforming section in degrees

Z_{01} and Z_{02} as above.

The expected value of k from the values given above was 3.6. It was found in operation that due to the fact that the transformer section had to be displaced slightly from the quartz section and the effect of the coupling loop in the line, not as large a voltage transformation was obtained as expected. Also, considerably more change in capacity was necessary to shift the frequency than would have been the case if quarter wave coupling sections had been used. However, the tuning system performed quite satisfactorily over the desired tuning range, and voltages available at the tube and the accelerating gap were within specified limits. A schematic diagram of the coupling line, oscillator, and modulating equipment now in use at the Berkeley synchrotron is shown in Figure 3.

Chapter 8. Eddy Current Fields.

The changing magnetic field induces a voltage in the metallic plating of the resonator which causes eddy currents to flow. These currents are proportional to the rate of change of magnetic field, and cause magnetic fields which are greatest when the main magnetic field is low. The eddy currents also cause I^2R losses in the plating and add to the heat that must be dissipated as a result of the r.f. losses.

These out-of-phase fields can be sufficiently large to prevent the electrons from traveling in a stable orbit at the low fields which occur at the time of injection.

To reduce the eddy current fields it is necessary to apply the plating to the walls of the resonator in as thin a coating as is allowed from r.f. considerations, and to minimize the voltage loops perpendicular to the magnetic field by scribing or applying the plating in the form of strips. If the strips are parallel to the direction of flow of the r.f. currents the conditions for resonance will not be seriously affected.

C. S. Nunan(8) has calculated that 7/16 inch strips can be used if the plating thickness is 0.003 inch. Reference (9) discusses the calculations in

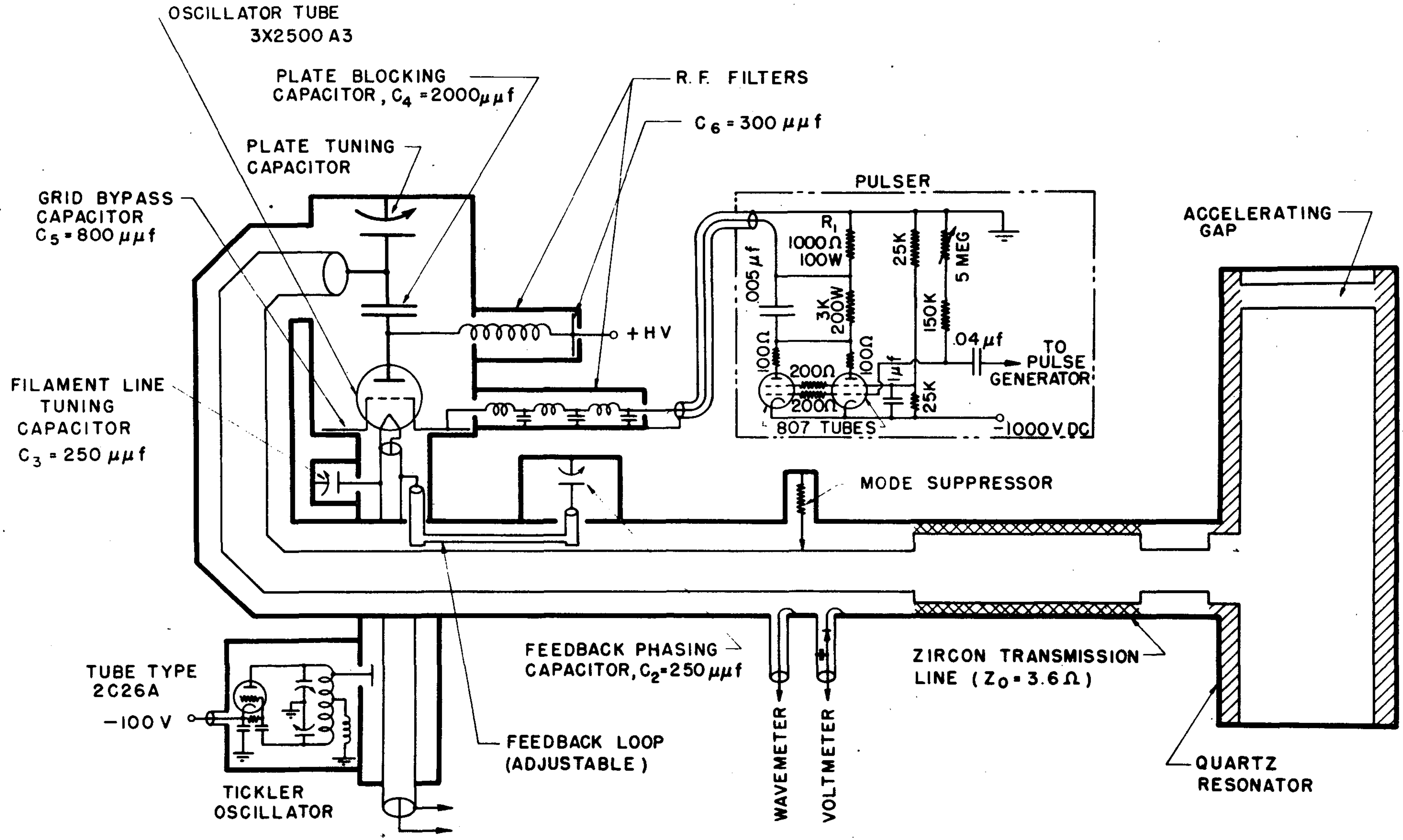


FIG. 3

SCHEMATIC DIAGRAM OF RADIO FREQUENCY OSCILLATOR detail and gives results of eddy current field tests on actual resonators.

Chapter 9. R.F. Losses in Iron.

In synchrotrons which use resonators operating with r.f. fields in close proximity to the laminated iron of the magnet, a decrease in the Q of the resonator after installation has been noted. This phenomenon increases after the resonators have been scribed to reduce eddy currents.

The cause of these additional losses is not clear, since they would not be expected to occur if the scribe lines are parallel to the current flow, for the r.f. electric and magnetic fields should all be in the dielectric, except at the gap, where they should be sufficiently shielded by the outer plating on the resonator.

It is possible that transmission line modes could exist between the copper strips with currents running on the outer surfaces. The mu of the iron in close proximity may slow down the propagation velocity of the r.f. so that the copper strips would seem 1/2 wave-length long at 47 mc. If that were the case it would be possible that the main resonant mode would have sufficient coupling into the external mode to dissipate appreciable power. The synchrotron group at Cornell University in reference (9) gives an explanation for increase in losses due to the proximity of the iron based on variations in current density in inner and outer strips, and also suggests methods of determining which strips might be mainly responsible for the increased losses.

Time limitations did not permit detailed investigation of the mechanism of the r.f. losses in the iron. It was possible to reduce these losses to a value about equal to the r.f. copper losses by proper placement of a coupling strap, and details are given in a later section.

It is most important for synchrotron operation to allow a sufficient factor of safety as far as cooling and decrease of input impedance are concerned in the design of the oscillator and blower system in the event that r.f. losses in the iron occur which cannot be eliminated.

Chapter 10. Voltage Monitoring.

It is not feasible to measure the r.f. voltage across the resonator gap directly during operation, since this would require the placement of some device, such as a peak reading voltmeter inside the vacuum chamber with a consequent reduction of aperture.

Several methods have been suggested[(6)(7)] for measuring quantities proportional to the electric or magnetic field at a point on the resonator, and thus obtaining a reading proportional to gap voltage. Such methods are usually somewhat frequency sensitive, and extreme accuracy is not of too much importance from an operational standpoint. Therefore it was decided to monitor the voltage at the resonator gap by inserting a loop at the current maximum of the transmission line. The voltage induced in this loop can then be detected by a crystal diode, and when suitably filtered, can be read on a meter. Such a system has the disadvantage that any changes in the loop or the transmission line connections can upset the relationship between loop voltage and gap voltage; however, it is possible to calibrate each time the synchrotron is disassembled by placing a peak reading voltmeter across the gap. It is an advantage not to have any special devices connected to the resonator, since it makes installation and removal more simple and reduces the danger of tearing the metallic plating on the resonator in handling.

PART II. CONSTRUCTION, TESTING AND OPERATION OF RESONATORS

Chapter 1. Obtaining Quartz Sections.

As stated previously, the only satisfactory bid on the sections of the donut was received from the Amersill Company. The handling of molten quartz is very difficult due to its extremely high softening temperature (2400°)F. In the process of making the odd shape sections of the vacuum chamber it was very difficult to obtain uniform wall thickness, and it is understood that most of the sections made by the Amersill Company were so far out of tolerance that they were not even shipped. The ones that were received could be accepted only by relaxing the design tolerances and grinding sections that were too thick to fit between the magnet pole pieces.

It was difficult to impress on the large number of personnel the fact that quartz is extremely brittle, and over a period of 18 months eight sections were cracked. Additional cracking of the sections resulted from improper annealing of the flanges which were attached by Amersill for vacuum pump fittings. Once a complete donut was installed in the synchrotron, however, only one section has been cracked, and that might be attributed to improper annealing of a flange.

Special storage and handling racks were built to minimize loss from collision of two sections or damage by miscellaneous objects.

Chapter 2. Preparation for Plating.

After suitable resonator sections had been selected from factory shipments, the ends were ground to tolerance by mounting in a fixture and using tungsten carbide grinding wheels. All sharp edges remaining after grinding were rounded off by a hand-held grinding wheel, a rubber bonded silicon wheel mounted in a small "Moto-Tool" grinder is satisfactory for this purpose.

The sections come with loose sand and porous quartz on the outside. It is necessary to remove this material with a hand-held disc sander.

Some reduction in r.f. losses can probably be obtained by grinding the walls to uniform thickness by means of a tungsten carbide grinding wheel. This is a tedious and expensive process and not recommended.

The inside of the quartz section has a hard glaze resulting from the firing process and it was necessary to etch through this glaze by hydrofluoric acid to provide a better surface for electroplating. The sections were sealed by means of rubber gaskets forced against the two ends by copper backing plates. The acid is poured in through a hole left in the plates and allowed to remain for 48 hours. Precautions were taken to prevent personnel from coming into contact with this very dangerous acid. It should also be noted that etching was resorted to after attempts to roughen the glaze by means of grinding compounds were unsuccessful.

After the acid was poured out, the sections were thoroughly flushed with water, and cleaned with acetone. The resonator sections were then fired in an electric furnace to 1200 degrees F. in order that any remaining materials might be oxidized. After the firing the sections were wrapped in a plastic sheet so that they could be handled without picking up dirt or fingerprints.

Chapter 3. Silver Plating.

It was not possible to say in advance whether any specific process for plating metal on quartz would be superior, so it was decided to investigate both silver plating and copper plating processes.

The first step in electroplating on a non-conducting base material is the application of some material to act as a conductor. Commercial firms sometimes use Aquadag for this purpose; however, Aquadag is not a good conductor at r.f., does not possess much mechanical strength, and might give trouble in handling and when subjected to vibration and temperature changes.

Attention was drawn to the methods used by commercial firms for gilding plates and glassware. Such gilt must be attached firmly in order to withstand abrasion which occurs when plates are jostled together in a dishpan. The materials used for gilding are known as Liquid Bright Solutions and are available in many grades and mixtures of platinum, gold, and palladium.

It was found that best results were obtained with Hannovia Liquid Bright Gold. In a cyanide plating bath, other coatings dissolved, apparently as a result of chemical action.

The exact composition of the liquid bright gold solution is probably a trade secret; however, reference states that it is essentially an organic gold compound of resinous character dissolved in volatile oils and other solvents, to which has been added metal organic compounds which act as fluxes. The fluxes, when heated, convert to the respective metal oxides, and by partly fusing into the surface of the quartz, cause the gold to adhere firmly to its base. The final film after firing averages around 4×10^{-6} inches in thickness and consists in the main of metallic gold, alloyed with small amounts of rhodium, fluxes and other modifying agents.

The resonator section was painted with liquid bright gold allowed to dry for 24 hours, and then fired in a well ventilated electric furnace. The temperature was brought up to about 800° F over a period of about 3 hours. This gradual rise in temperature allows the organic material to be burned out without bubbling. Then the temperature was raised to 1250° F for about 15 minutes to bind the gold to the surface of the quartz.

The coating was checked after the section had cooled, and was found to have an end to end resistance of about two ohms, and to have good conductivity except for a few small areas where the surface had been left somewhat rough. Another coat of liquid bright gold was painted on and the firing procedure was repeated. After the second coating was applied no high resistance patches could be observed.

Early attempts to divide the metal skin of the resonator into strips after the plating met with much difficulty. The scribe lines must be about 1/16 inch wide and held to a reasonable tolerance. Cutting or grinding wheels can be used; however, the irregularities in the surface of the quartz sections make cutting lines in the plating a delicate and lengthy process.

Several different methods of applying "stop-off" lines on the quartz surface were tried before it was found that red glyptal was easiest to apply and most effective in preventing the silver from plating across the scribe lines.

The glyptal was applied by means of a narrow wheel revolving in a slit cut in the bottom of a small reservoir. The reservoir was mounted on an adjustable bar attached to radius arms and could be passed completely through the quartz section.

For the plating procedure, pieces were cut from silver in such a shape that all surfaces were approximately one and one-half inches from the plating anodes. A high current, 20 amperes "flash" plating was used for the first few minutes, followed by a reverse-current cycle consisting of 10 seconds plating and 2 seconds de-plating with a current of 10 amperes which was repeated for about 4 hours. Since it was not possible to measure accurately the thickness of the silver plate, it was necessary to guess when the required thickness was obtained. A post-mortem examination of one of the plated sections made by peeling the skin off showed that the plating thickness from about 1 1/2 to 10 mils; however, over most of the resonator the plating was between 2 and 4 mils in thickness.

After the plating process gold was cleaned out of the scribe lines with a carborundum disc. Due to the hardness of the quartz, the tight adherance of the gold, and the difficulty of working on the internal surfaces, it was not possible to mechanically remove all the gold from the scribe lines. An early experimental resonator which had all its separate metal strips coupled by a plated strap indicated in an eddy current test that many conducting paths existed between the strips in spite of careful grinding out of the scribe lines. This resonator was repaired by grinding out the scribe lines where the coupling strap existed and applying voltage between adjacent metal strips. The process, which was then made routine on all future resonators, consisted of applying voltage from a 5 volt 100 ampere filament transformer between adjacent metal strips, bringing the voltage up gradually to prevent excessive sparking. To insure that the adjacent strips could withstand appreciable voltage without sparking, 110 volts was then applied between strips with the current being limited by a 60 watt light bulb in series with the line. The author has been informed indirectly that other workers checked electrical leakage across scribe lines by a method involving potential plotting; however, any method which does not actually apply voltage across the scribe lines will not test voltage insulation, and the resonator may spark in operation due to differences in the r.f. voltages at various points.

After the proper position for the coupling strap was determined by the method discussed in a later section, the scribe lines were bridged by air-drying silver paint, DuPont #4817, and the resonator heavily coated with red glyptal except for a small area around the silver paint. The silver plating method described above is then used to deposit about 3 mils of silver over the air-drying silver paint. The glyptal is then washed off with xylene and the resonator is then ready for preparation of vacuum seals.

Chapter 4. Copper Plating.

The preparation for copper plating of a resonator is the same as that for silver plating except the most satisfactory base coating was found to be Hannovia's Liquid Bright Platinum. The liquid bright platinum is fired at a slightly lower temperature, a maximum of about 1150° F being the most satisfactory. The platinum is not as good a conductor as the gold coat, and it is necessary to use as many as four or five coats before an even, low resistance, base coating is obtained. The copper plating is done in a copper sulfate bath, starting with a 15 ampere "flash" plate for a few minutes followed by a reverse plating procedure consisting of 10 seconds plating and 2 seconds de-plating at a current of about 5 amperes, taking usual precautions with placing of electrodes, as mentioned in the silver plating procedure.

Chapter 5. Q Measurements

As stated in an earlier section it is important from a standpoint of losses to obtain as high a Q as possible in the resonators.

Some initial experimental work was done with a sample section supplied by the Amersill Company before the shipment of the regular sections could be made. This sample section was made to the specifications of another university. The section was copper plated without scribe lines using the procedure discussed in the previous section. The effective length of the section to the gap was 20 inches. Assuming that the dielectric constant of quartz is 4.0, the resonant frequency should be:

$$f_{res} = \frac{300}{4 \times 20 \times 0.025 \times \sqrt{4}} = 74 \text{ megacycles} \tag{51}$$

The section was resonated by loosely coupling it to a variable frequency oscillator and resonance was detected by means of an E probe which was coupled to a crystal detector and a galvanometer. Frequency was measured by a crystal calibrated frequency meter. This equipment is shown in Figure 4. The resonant frequency was found to be 80 megacycles, indicating that

Fig. 4

Equipment used for measuring Q

A Pickup loop and 1N21 crystal rectifier

B D.C. galvanometer, shielded

C 35 GT shielded oscillator

D Power supply for oscillator

E Frequency meter with crytal calibration

F Oscilloscope for frequency meter output


A
B
C
D
E
F
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the dielectric constant was:

$$e = 4 \times \left(\frac{74}{80}\right)^2 = 3.4 \qquad (52)$$

The average wall thickness of the resonator was about 5/16 inch. The mean radius was about 2.3 inches. Using equation (32), the copper Q is:

$$Q_{cu} = .384\sqrt{f} + (1 - \Delta) = .384\sqrt{80 \times 10^6} \times 5/16 = 1080 \qquad (53)$$

$$\Delta = \frac{(5/16)^2}{6 \times 2.3^2} = .003$$

Since Δ is small compared to 1, it can be neglected. The dielectric losses can not be readily measured separately, but if the value of the loss tangent is taken to be 0.0004,

$$Q_{dielectric} = \frac{1}{0.0004} = 2500 \qquad (54)$$

Then using (53) the theoretical Q for this resonator is:

$$Q_{theoretical} = \frac{1}{\frac{1}{Q_{cu}} + \frac{1}{Q_{die}}} = \frac{2500 \times 1080}{2500 + 1080} = 750 \qquad (55)$$

The Q was measured by plotting a curve of frequency vs. current galvanometer using the equipment mentioned previously. The Q as determined from the half power points on the resonance curve was 474. If it was assumed that the additional losses which caused the reduction in Q are copper losses, one can calculate the experimental Q_{copper},

$$Q_{copper} = \frac{1}{\frac{1}{Q_{die}} - \frac{1}{Q_{total}}} = \frac{2500 \times 474}{2500 - 474} = 590 \qquad (56)$$

One might presume from this that the surface resistivity of the copper plating on the quartz is 1.8 times the value for metallic copper at the same frequency. It is possible that minute irregularities in the surface of the quartz were the main cause of the additional losses.

The quartz section chosen for the synchrotron resonator was originally plated without scribe lines. The dimensions and electrical quantities were as follows:

Effective length to gap	30 inches
Measured resonant frequency	47.75 megacycles
Calculated dielectric constant	4.2
Wall thickness	7/16 inches
Calculated Q_{copper}	1040
Assumed $Q_{dielectric}$	2500
Theoretical total Q	735
Measured total Q	470
Actual Q_{copper} based on $Q_{die} = 2500$	580
Ratio surface resistivity to that expected from metallic copper at the same frequency	1.97

It was noticed that the calculated dielectric constant is quite different from that of the small test section; however, since the actual section resonated so close to the desired frequency this matter was not investigated further. The difference in dielectric constant might have resulted from a difference in the batches from which the sections were made; however, it is more likely that irregularities in the walls or distortion from the ideal coaxial transmission line mode due to the toroidal shape are the main cause of apparent variations in dielectric constant.

Two other sections have been plated for use as synchrotron resonators or spares, and were found to be resonant at a frequency indicating an effective dielectric constant of 3.9 and 4.3. It is therefore necessary to allow sufficient leeway in design of tuning adjustments to allow the frequency of the complete system to be adjusted to the proper value.

Since both copper plated resonators were almost a factor of two higher in surface resistivity than the theory would indicate, it was decided to see if silver plating would improve the situation. Accordingly, the 20 inch sample quartz was silver plated without scribe lines using the procedure mentioned previously. A Q of 615 was measured after the plating, which indicated a surface resistivity of 1.3 times the theoretical if the same assumptions are made for the dielectric Q as in the previous cases.

It was not deemed necessary to attempt to reduce these losses further, since adequate cooling was available; however, for critical applications such as a synchrotron operating at higher accelerating voltages or at a higher duty cycle it might be necessary to smooth carefully the surface of the quartz, or perhaps apply a glaze to the rough outer surface before silver plating.

After the above mentioned tests all resonators constructed were plated with scribe lines, and the additional losses which result from the scribing make it impossible to determine experimentally the value for the surface resistivity.

The first scribed quartz resonator was tested with all the metallic strips connected at the accelerating gap by means of air drying silver paint. This test showed that scribing reduced the resonator Q by a factor of more than 3. When the proper kind of laminated iron was brought up close to the section in a position simulating operating conditions the Q was less than one tenth the value for the unscribed resonator, measurements showed this Q to be about 40. This large increase in losses was considered excessive, so an intensive program was begun to find the cause of the low Q.

It was found that slanting the gap, so the strips were of equal length did not affect any improvement in the situation. Various methods of condensor coupling the straps to provide close r.f. coupling were not effective.

A twice size air-dielectric copper model of the resonator was constructed to investigate the current flow in the metallic skin. This model is shown in Figures 5 and 6. Tests with the copper model showed that within the limits of the measurements the currents flowed in circumferential lines parallel to the metallic strips; in other words, the mode of oscillation is the same as that of coaxial cylinders and no odd effect results from the slightly flattened and toroidal shape.

It was found that the Q is very sensitive to the position of the coupling strap. It was possible to make fairly rapid checks of Q versus position and angle of the coupling strap by painting air-drying silver paint (DuPont 4817) across the scribe lines. The full conductivity of the paint is not achieved until it has dried for six to eight hours, although this process can be hurried somewhat by infra-red lamps. Using this technique, Q measurements were made with the coupling strap in many different positions on the resonator. The best Q was obtained with a one inch wide coupling strap around the outside and inside surface of the resonator at an average distance of $14\frac{1}{2}$ inches from the accelerating gap. Measurements indicated the value of Q to be 350 in air, and 225 in position between the iron pole pieces. This resonator was then installed in the synchrotron and was used to accelerate electrons to 330 Mev.

The first resonator was scribed "vertically", that is, the strips on the inside and outside were lined up vertically. C.S. Nunan[8] conducted tests on a "radially" scribed copper plated resonator and obtained a Q of 544 in air and 445 between the iron pole pieces. Figure 7 is a diagram indicating the difference between the two different types of scribing. The copper plated resonator is shown in Figure 8. The bumps at the gap end of the resonator were molded into the quartz section for use as alternative

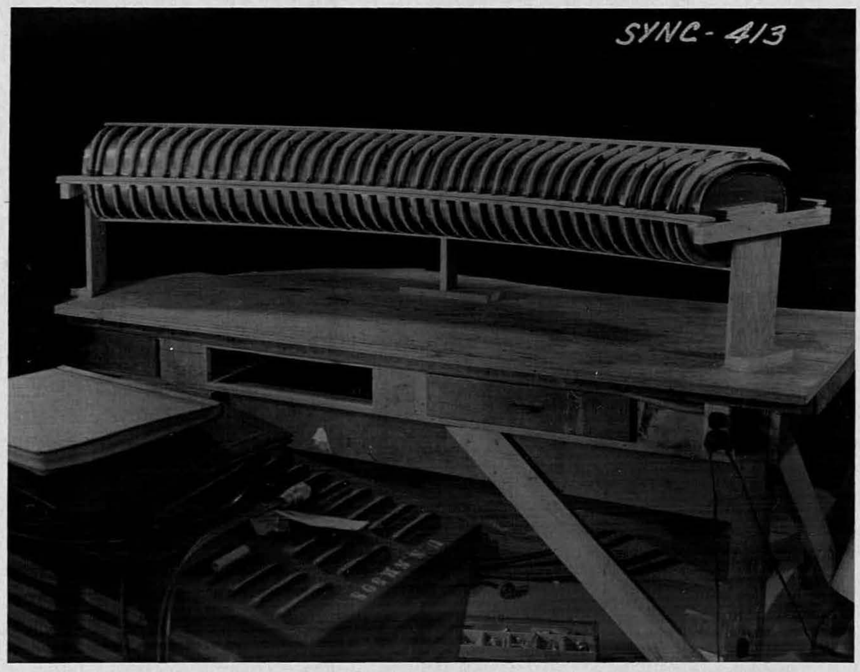
Fig. 5

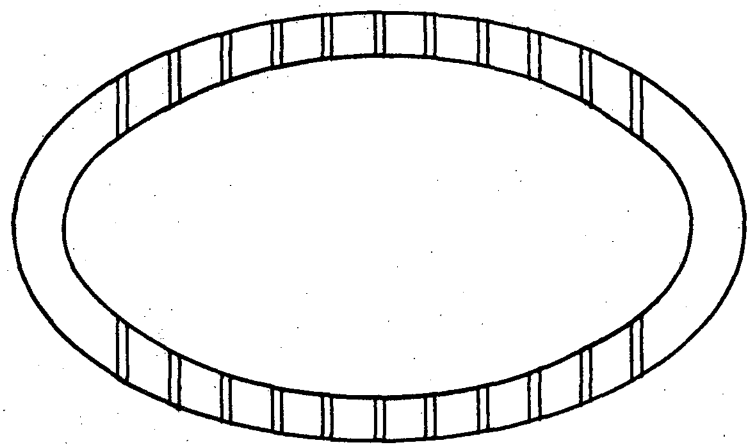
Twice size air dielectric sheet copper replica of quartz resonator, outside conductor opened.


SYNC - 412

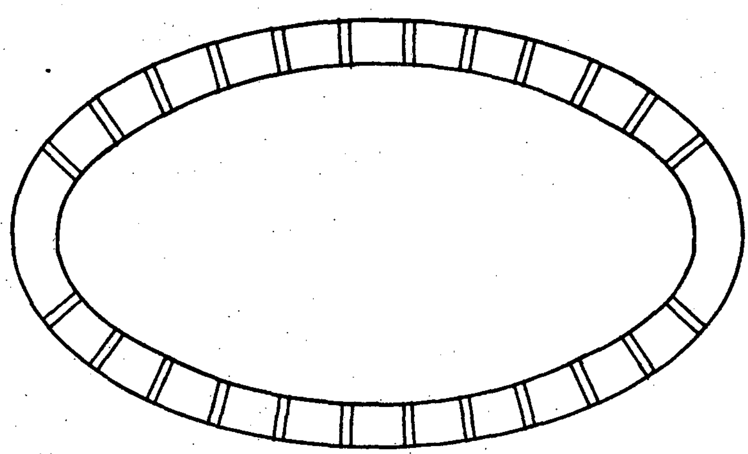
Fig. 6

Twice size air dielectric sheet copper replica of quartz resonator for determination of current flow lines in surface.


SYNC- 413



VERTICAL SCRIBING



RADIAL SCRIBING

MU 314

END VIEW OF RESONATORS

FIG. 7

16012-1

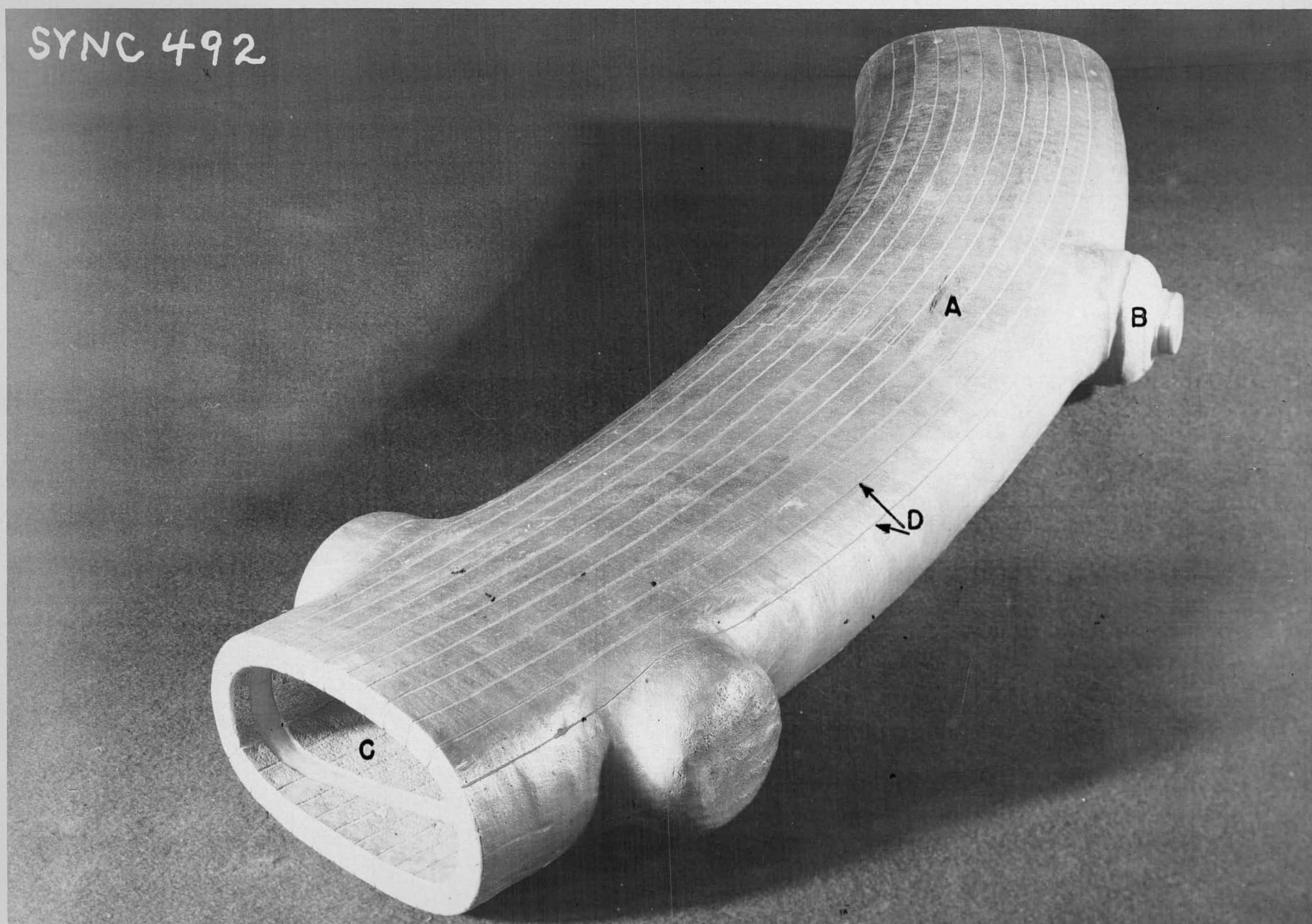


FIG. 8 RESONATOR

(A) CROSS STRAP (B) FEEDPOINT (C) ACCELERATING GAP (D) SCRIBE LINES

OZ 561

feedpoints, and were not used. They have negligible effect on the electrical characteristics and were omitted in later resonators.

It was believed that the radial scribing was the reason for the higher Q of the copper plated resonator, so on the basis of the above results, the synchrotron r.f. group drew up instructions for resonator construction and another spare resonator was constructed by technicians which on testing had a Q of 380 in air. While this last resonator probably could be built with a slightly higher Q, operating experience has shown that it is well within the limits for satisfactory performance. The drawing and instructions used by the technicians are attached at the end of this paper.

After the Q measurements had been completed, a series of tests were conducted at high gap voltages to test the resonator, coupling line, tuning condenser and oscillator. These tests and the results are discussed fully in reference 8.

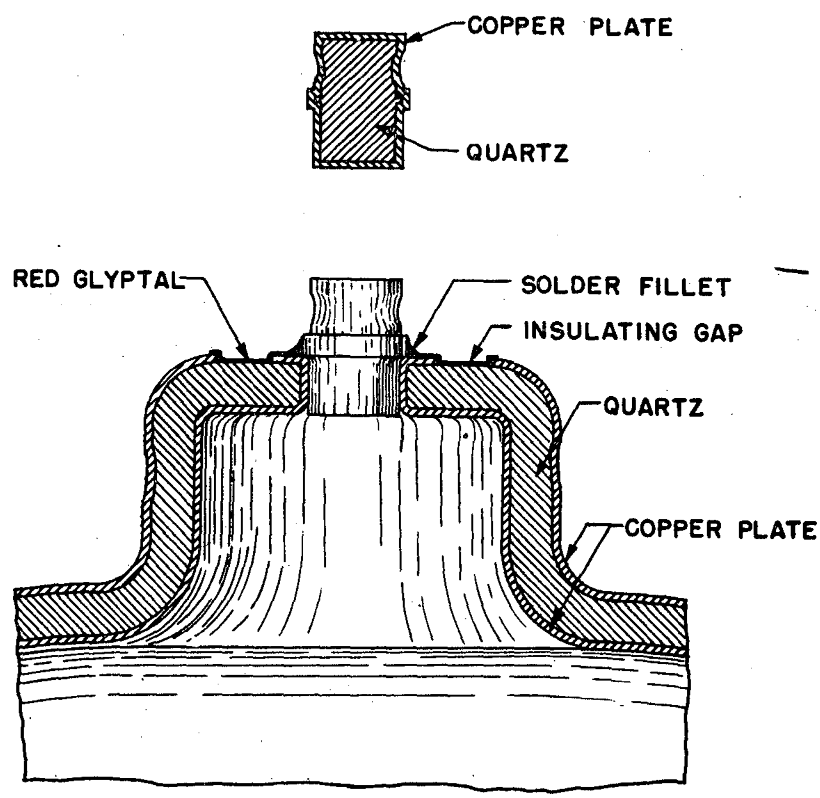
Chapter 6. Vacuum Seals.

It was necessary to couple the inner conductor of a transmission line to the inner surface of the quartz resonator. In order that this could be done, the quartz sections were ordered with a "feed bump" at the 1/2 voltage point. A hole, 3/4 inch in diameter was drilled through the center of the feed bump, and the electroplating was done in such a manner that the metallic coating from the inner surface was brought out through the hole and for a short distance across the face of the feed bump.

A quartz plug was then plated and inserted in the hole. The temperature of the quartz surface was then gradually raised almost to the melting point of solder by means of an infra-red lamp, and a fillet of solder was placed around the joint using an iron and "No Korrode" flux. The feed-bump and the quartz plug were both grooved to receive the silver plated fingers of the coupling transmission line. Figure 9 is a schematic of the feed-bump and the metallized quartz plug.

When the first quartz plug was soldered in place and the resonator leak tested under vacuum, small leaks were discovered at the feed bump. It was believed that these leaks could result from various causes, such as porosity of the quartz plug, porosity of the copper plating, holes in the solder, or leakage under the metallic plating. A check of the quartz rod from which the plugs were cut indicated that there was a flaw down the center, so a new set of plugs were obtained. In soldering vacuum joints it is advisable to apply sufficient heat so that the solder will flow quite easily; however, if too much heat was applied in soldering the plug in, the plating might loosen due to differential expansion. Therefore, it was decided to repair the first solder joint under vacuum and with a helium mass spectrometer type leak detector on the line to insure that the solder was not applied in such a manner that it contained blow-holes. A diagram of the apparatus is shown in Figure 10. A careful application of solder in all places around the plug seemed to reduce the size of the leak, although it was not possible to eliminate it completely. Finally, the insulating gap was painted over with red glyptal which effectively sealed the leak. An identical experience with the next resonator prepared seemed to indicate that air was leaking in underneath the plating, so again the insulating gap was painted with glyptal. Fortunately, the glyptal gave no trouble in 18 months of operation, so it was not considered necessary to redesign the feed bump so that there would be less chance of leakage under the plating.

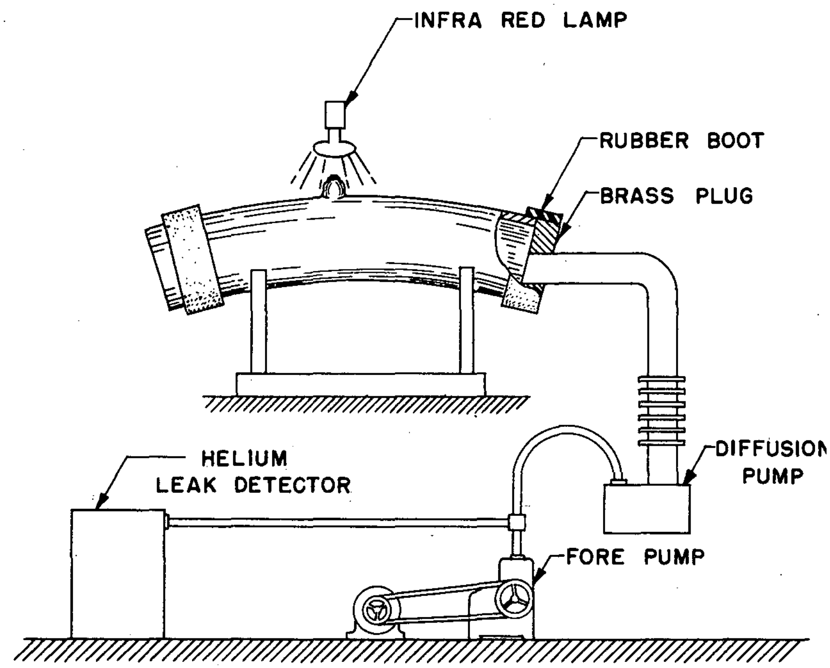
The seals used at both ends of the resonator section are the same as used for the other seven sections in the vacuum chamber. The method of sealing was suggested by Marvin D. Martin of the Radiation Laboratory, and details were worked out by the r.f. group since it was necessary to test the resonator



"FEED BUMP" OF QUARTZ RESONATOR

MU 317

FIG. 9



APPARATUS USED DURING SOLDERING OF
QUARTZ PLUG INTO "FEED BUMP"

MU 313

FIG. 10

well before the rest of the vacuum chamber was ready for assembly. The resonator and other sections were sealed together by covering the eight joints with 4 inch wide, 1/16 inch thick butyl rubber bands or boots. The surface under the boots was prepared by baking on six coats of red glyptal, smoothing the surface down after each coat. Heavy lubriseal was used under the boots to insure a good seal between the rubber and the hard glyptal surface. To prevent chipping of the sections and to insulate adjacent sections from each other, the ends were separated by a 1/16 inch thick teflon gasket.

This system has the disadvantage that the rubber is subjected only to slightly greater than atmospheric loading, contrary to usual rubber gasket practice, also when this method of sealing is used, the joints are not rigid until the vacuum chamber is evacuated, and it must be constrained by bumpers to prevent excessive movement. The advantages of this method of sealing are that it takes up less than 1/8 inch of space between the poles of the magnet, the rubber boots allow for irregularities which may exist between different sections, and a quartz section can be removed when the magnet is disassembled by simply folding back the boots.

Figure 11 is a photograph of the complete vacuum chamber showing the eight vacuum seals.

Chapter 7. Operating Data.

The Berkeley synchrotron has been operating for about 15 months. During this time there has been no vacuum leak where the quartz plug was soldered into the resonator or under the rubber boots which seal the joints. When the ring was first assembled it was found that some of the boots had manufacturing defects, but once this source of trouble was eliminated no more difficulties were experienced. It is expected that the rubber will gradually deteriorate due to ionization from the x-rays given off by the synchrotron,

Fig. 11

The quartz vacuum chamber. The ends of the 45° segments are painted with glyptal to form a smooth surface and are sealed by rubber boots.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but at the present time this effect has not been noticed.

The first resonator installed was silver plated and performed satisfactorily for 2 weeks. There was a slight amount of sparking between scribe lines but the effect on the r.f. envelope was negligible. When the synchrotron was disassembled for a major overhaul, several strips of the silver plating were torn off the resonator as a result of carelessly removing some scotch electrical tape which had been wrapped around the resonator to prevent damage by the constraining bumpers.

The radially scribed copper plated resonator was then installed and operated satisfactorily for 9 months. When the synchrotron was again disassembled, it was discovered that more than half the copper plating on the feed bump had burned off due to sparking. It was believed that this was caused by poor contact to the coupling line. The resonator was repaired by cleaning carefully with steel wool and solvents and painting the bare areas with DuPont air drying silver #4817. The silver painted area was then immersed in a copper sulfate plating bath and about 3 mils of copper was plated onto the damaged areas. The spring finger contacts on the coupling lines were loaded with a rubber gasket to provide a better connection to the feed bump. This resonator was inadvertently installed in the ring without being cleaned, and although it had operated satisfactorily in air it would not hold more than 1000 volts at the gap without sparking when the donut was evacuated. A five hour period under vacuum seemed to clean out the impurities and the resonator was then able to hold a voltage of 2500 at the gap before sparking occurred. Synchrotron operation was resumed August 4, 1949, and the resonator and oscillator have performed satisfactorily to the present date, a period of over 10 months.

Fig. 12

R. F. SEGMENT PREPARATION PROCEDURE

1. Grind off all sand and projections on inside surface. Cover ends using thick rubber gaskets backed up by copper plates. Fill inside with hydrofluoric acid, taking care that no air is trapped. Allow hydrofluoric acid to remain in segment for 8 hours.

2. Grind ends and outside per 4C8593B. Grind boss per 4C5782C. In addition, wall thickness must be uniform within 1/16 inch. If necessary, grind outside to obtain this uniformity.

3. Wash in alcohol and fire at 1300° F. Take 4 hours to reach this temperature and 12 hours to cool from it.

4. When quartz has cooled to room temperature, paint all except driving gap and areas of boss indicated with thin, uniform coat of Hanovia 05 Liquid Bright Platinum. Allow to air dry for 1 hour. Fire for 15 minutes at 1300° F in an oven with forced air circulation. Take 4 hours to reach 1300° F and 12 hours to cool.

5. Apply 2nd coat as above.

6. Using a meter and probes, make a comprehensive continuity check of the platinum coating. Coat any open spots with platinum solution and fire.

7. Using striping machine 4C5644, roll on 1/16 in. wide stripes of red glyptal per detail at left.

8. Copper plate in copper sulphate solution. Flash at 15 amps plating current. Use a portable probe to cover areas not adequately flashed with fixed electrodes. After flashing, decrease current to 5 amperes and plate until copper coating is .002 ± .0005 thick. Coating must be uniform - use care to prevent heavy deposit on ends.

9. Wash off glyptal in methyl ethyl ketone. Using a motor driven 1/32 thick by 3/4 dia. "Handee" carborundum disk, clean up all division lines. Use flexibile shaft and 90° head when cleaning inside lines. Remove as little of the silica body as possible. After grinding, burn out any residual plating between straps. Use a 5 volt 200 amp filament transformer with Variac on 110 volt input side. Next use a 110 volt Variac in series with a 25 watt light bulb. Continue until resistance between copper straps is greater than 100,000 ohms.

10. Using red glyptal, coat all except the 3/16 x 1 connecting straps which appear approximately at the center of the segment. Leave 1/16 in. of copper showing on each side of the unplated groove. Bridge over the unplated portion with 4817 DuPont air drying silver, allowing silver to overlap copper 1/32 on each side. 1/32 of copper to be left exposed between silver and glyptal. (Use 3 coats of glyptal.)

11. Copper plate .002 thick over connecting straps only.

12. Remove glyptal with methyl ethyl ketone.

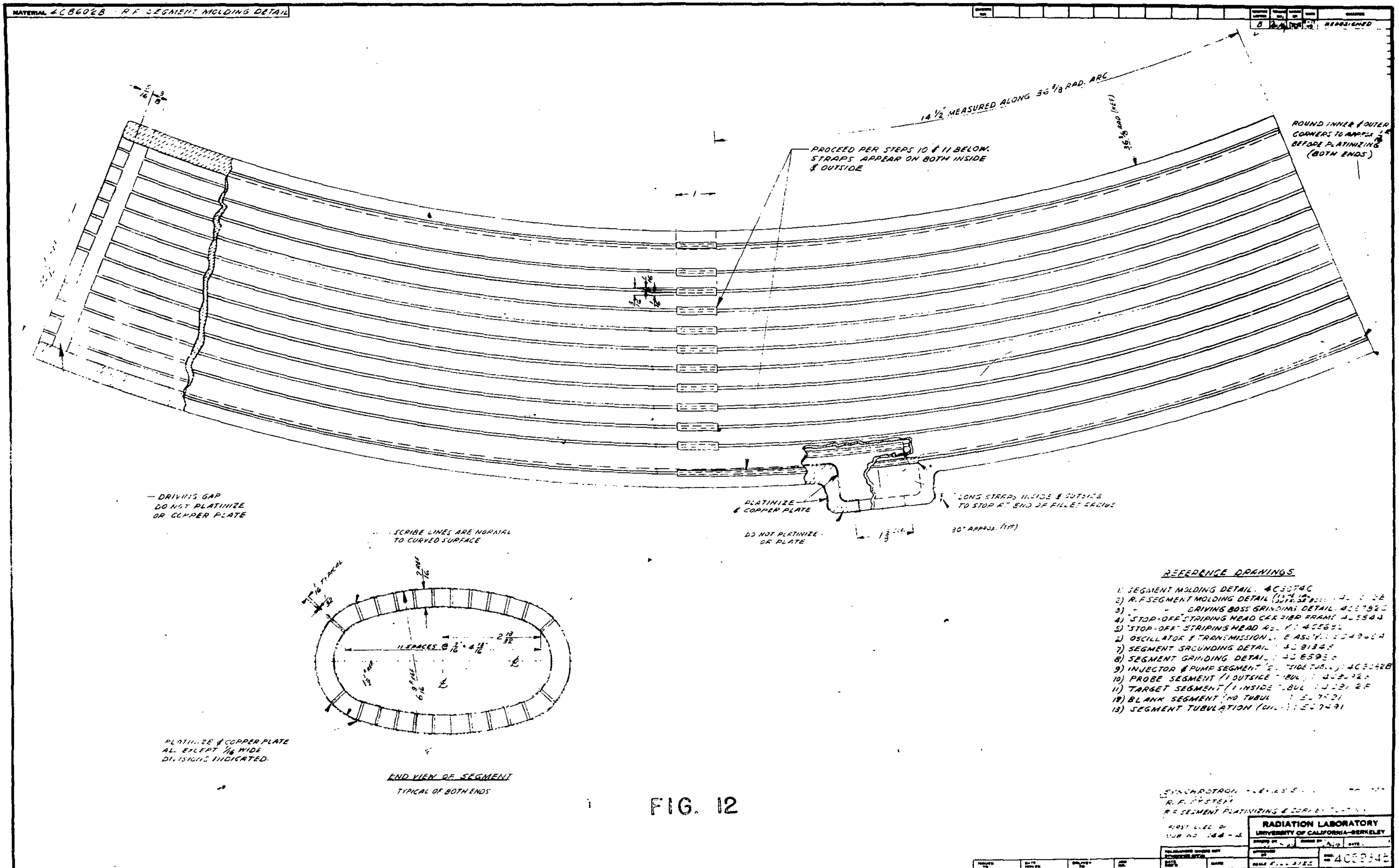
MATERIAL 4C86028 R.F. SEGMENT MOLDING DETAIL
14 1/2" MEASURED ALONG 36 3/8 RAD. ARC
36 3/8 RAD. (REF.)
PROCEED PER STEPS 10 & 11 BELOW.
STRAPS APPEAR ON BOTH INSIDE & OUTSIDE
ROUND INNER & OUTER CORNERS TO APPROX. 1/8 BEFORE PLATINIZING (BOTH ENDS)
DRIVING GAP DO NOT PLATINIZE OR COPPER PLATE
SCRIBE LINES ARE NORMAL TO CURVED SURFACE
PLATINIZE & COPPER PLATE
DO NOT PLATINIZE OR PLATE
LONG STRAPS INSIDE & OUTSIDE TO STOP AT END OF FILLET RADIUS
30° APPROX. (TYP.)
11 SPACES @
PLATINIZE & COPPER PLATE ALL EXCEPT 1/16 WIDE DIVISIONS INDICATED.
END VIEW OF SEGMENT
TYPICAL OF BOTH ENDS
REFERENCE DRAWINGS
1) SEGMENT MOLDING DETAIL
2) R.F. SEGMENT MOLDING DETAIL
3) DRIVING BOSS GRINDING DETAIL
4) "STOP-OFF" STRIPING HEAD CARRIER FRAME
5) "STOP-OFF" STRIPING HEAD ASS'Y
6) OSCILLATOR & TRANSMISSION LINE ASS'Y
7) SEGMENT GROUNDING DETAIL
8) SEGMENT GRINDING DETAIL
9) INJECTOR & PUMP SEGMENT
10) PROBE SEGMENT (1 OUTSIDE TUBUL.)
11) TARGET SEGMENT (1 INSIDE TUBUL.)
12) BLANK SEGMENT (NO TUBUL.)
13) SEGMENT TUBULATION
SYNCHROTRON
R.F. SYSTEM
R.F. SEGMENT PLATINIZING & COPPER PLATING
RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA—BERKELEY

FIG. 12

OZ 921

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