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Publication Date

1962-04-04

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Lawrence Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

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ABSTRACT

Four features are described: the movable-panel drive system, ceramic ball bearings, rf hinges, and dee construction. The rf tuning is accomplished by varying the volume between the dee stem and six movable panels. Power to move the panels is supplied by four hydraulic cylinders. The hydraulic drive mechanism and control system are described. A special ceramic ball bearing, with alumina balls and stainless steel races, was developed. It operates in the presence of high vacuum, rf field, and radiation—and without organic lubrication. Bearing construction and test results are described. The rf current-carrying hinges between the movable panels were designed to optimize the hinge thickness and length so that bending stresses and temperature rise were minimized. Graphs showing the relationships between hinge thickness, length bending stress, and temperature rise are presented, together with hinge configuration. The dee-stem and dee structure is approx 14 ft long and weighs 2800 lb. Support for the entire assembly is provided by cantilevering it from the rear of the resonator tank. Materials and fabrication procedure for the dee panel structure are described.

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1. Movable-Panel Drive Mechanism

Tuning of the 88-inch cyclotron rf system is accomplished by varying the spacing between the dee stem and two sets of three movable panels which form the resonator tank rf liner. Figure 1 presents an isometric view of a portion of the resonator tank, showing the panels and the drive system used to move them. A duplicate drive system, not shown, is located on the far side of the tank. The resonator tank was fabricated from 1-1/2-in. thick mild steel plate and is 120 in. wide, 90 in. high, and 91 in. long.

The high-frequency position of the panels is formed when the rear and center panels lie in horizontal planes above and below the center of the tank. This position gives an rf system frequency of slightly more than 16 Mc/sec. When the panels are rotated to the other extreme position, such that the front and center panels lie in horizontal planes above and below the tank center, a resonator frequency of 5.7 Mc/sec is obtained.

Support for the front and rear panels is provided by eight horizontal drive shafts, which are also used to rotate the panels. Bearings, used to hold the shafts, are described in another section of this paper. Cable drums are attached to the outboard end of each of these shafts. At the rear of the

† Work done under the auspices of the U. S. Atomic Energy Commission.

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Fig. 1. Cutaway section of resonator tank showing panels and their drive system.

resonator, the upper and lower cable drums are connected with eight 1/4-in. diam stainless steel aircraft cables. The cables are so wrapped around the drums that they cause them to rotate in opposite directions. A similar system is used on the drums that rotate the front panels. However, in this case it is necessary to use a vertical drive shaft in addition to the cables since the drums are about 7 ft apart. Coupling the upper and lower sets of panels together in this manner gave us a counter-balanced system--since any downward motion of the upper panels will give the same upward motion to the lower panels.

The force to rotate the drums is transmitted to them by four vertical shafts located at each corner of the resonator tank. Additional sets of cables are wrapped around the drums and attached to these shafts, causing the drums to rotate when the shafts are moved in a vertical direction. A 9-in. movement of the shaft is required to rotate the drum 90 deg. Bellows are provided between the shaft and the tank to form a vacuum-tight seal.

Synchronization of motion from one side of the tank to the other is accomplished by two cross-connect shafts--one for the rear drives and another for the front drives. Motion between the front and rear drives is synchronized by the panels themselves.

Power to move the panels is supplied by four 6-in. -diam hydraulic cylinders. The cylinders are connected in parallel and therefore provide the same force to each drive unit. This is an important feature of the system since there is only one position of the panels where the front and rear drive units are moving at the same rates. A system of four-way solenoid-operated control valves is used to supply water to the cylinders. A pressure regulator in the water supply line to the control valves provides a convenient method of varying the power output of the drive cylinders. A differential pressure of 20

psi across the cylinders is required to move the panels. Speed control is accomplished by throttling the return flow from the cylinders. Two different speeds are provided. The "fast speed" moves the panels through their complete cycle in approximately 2 min. The "slow speed" is extremely slow and is used in positioning the panels when they are near the dee stem. Here the rf frequency is very sensitive to panel location.

Each drive unit is provided with a hydraulically operated brake to lock the panel position when the desired frequency has been obtained. The same source of pressure that is used to move the drive-cylinder pistons is also used to release the brakes. Spring force applies the brakes when the pressure source is removed. Mechanical stops on each drive unit are used to limit the total motion of the panels.

We have experienced little trouble with the drive system since it was put into operation more than a year ago. The hydraulic system is sensitive to any air trapped in it. This results in a "spongy" type of motion of the drive units. Vents were added to the system to bleed off any trapped air. It was also necessary to retorque the cables used in the drive system for a period of approximately two months before they stopped stretching. This, however, had been anticipated. The question could be logically asked as to why spur gears were not used in place of the cable drums, and racks placed on the vertical drive shafts to mesh with these gears. This type of drive was investigated, but we were unable to find a permanent lubricant that would be compatible with the vacuum system.

Cooling water is supplied to the movable panels by 1/2-in. I. D. flexible metallic hose. The hoses run between the inside wall of the resonator tank and the panels. During the design of the rf system, a fixture was set up to cycle various types of metallic hoses. We found that a hose life of between

10 000 and 20 000 cycles could be expected before leaks developed. Sixteen hoses are used in the resonator tank. To date, three of these hoses have developed leaks. All the leaks appear to have occurred at the solder joint between the hose and its end connection. Stainless steel hose was used, and the joint soldered with Handy and Harmon Co., Easy-Flo 50. I feel that the probable cause of the leaks was solder flux that had originally formed a tight joint but was finally dissolved by the water flowing in the hose. These three hoses have been replaced with bronze hose and the joint made with All-State 430 solder. This is a silver-tin eutectic alloy that melts at 430°F and has a tensile strength of approximately 15 000 psi at room temperature.

2. Bearings

During the early design stages of the rf panel drive mechanism, the need for a type of bearing with special features became apparent: it must operate in the presence of high vacuum, rf field, and radiation- and without organic lubrication.

We investigated bearing materials such as Glacier and Rulon "C." The Glacier bearings are made from a mixture of lead and Teflon. They have been used quite successfully in a number of places on the Bevatron. However, we were hesitant about using them in a high rf field, for two reasons. First was the heating caused by rf currents flowing through them, and second was the possibility of sparking between the Glacier material and the shaft. Rulon "C" is a mixture of Teflon and glass. This is an excellent bearing material for use in vacuum where organic lubrication cannot be tolerated. We rejected the use of Rulon "C," however, since the literature indicated that the mechanical properties of Teflon were affected by neutron radiation. Previous experience on other accelerators has shown that

commercial steel ball bearings will perform quite well, nonlubricated in a vacuum, if they are suitably derated in load and speed. The 90-inch cyclotron at Livermore originally used metallic ball bearings in the rf system. However, it was found that in time the balls and races welded together due to sparking. We therefore decided to develop a ball bearing using an electrically nonconducting material for the balls.

Test bearings were made using sapphire, Pyroceram, and alumina (Al_2O_3) balls. The bearings were similar in size to a Fafnir type 304, which has an O. D. of 2.04 in. and uses 11 balls $3/8$ in. in diameter.

A bearing tester was constructed which rotated the shaft in the bearing at 78 rpm. The outer race was held in a Lucite block so that the bearing could be observed while operating. All of the tests were conducted in a vacuum of 5×10^{-5} mm Hg. The bearings were loaded radially, and no attempt was made to measure the coefficient of friction. The Lucite block was so constructed that we could measure the electrical resistance of the bearing during testing.

The first bearings tested utilized brass retainers to hold the balls. This was a mistake. The brass rubbed onto the balls and caused the bearing to seize early in the test. The next step was to build a bearing with loading slots in the races. The bearing was then assembled with idler balls between the load-carrying balls. Idler balls are slightly smaller in diameter than the load balls, and their function is to prevent the load balls from scuffing against each other. This was a step in the right direction and increased the life of the bearing compared to the brass-retainer-type bearing. Fortunately, when one of the bearings was assembled, a mistake was made which placed two load carrying balls adjacent to each other. When this bearing was tested, we found that there was no adverse effect due to scuffing of these two balls; and,

in fact, they tended to remain separated as they precessed around the races.

The final step was then to assemble bearings with all load-carrying balls.

This resulted in a still further improved bearing.

Of the three types of ball material tested--sapphire, Pyroceram, and alumina--the alumina was the superior material. Fortunately it was the least expensive and had the best electrical properties. The test results are summarized in this report (table 1).

Bearings of three different sizes are in use in the 88-inch cyclotron (fig. 2). The size bearing that was tested is used in the mechanical hinges between the movable panels. The load on these bearings is 125 lb, and they are expected to complete approximately 10 000 cycles during the life of the machine. The next larger size bearing is equivalent in size to a Fafnir type 310, 4.33 in. O. D. by 1.96 in. I. D., and contains twelve 3/4-in. -diam balls. The largest size bearing is equivalent to a Fafnir type 316, 6.69 in. O. D. by 3.14 in. I. D., and contains thirteen 1-1/8-in. -diam balls. The larger size bearings are used in the drive mechanism for the movable panels, and have radial loads of from 1200 to 1500 lb.

The alumina balls were manufactured by Coors Porcelain Company and were made of their AD 99 alumina. Coors had the balls ground and mirror-polished to an accuracy of ± 0.0001 in. in diameter and ± 0.000025 in. in sphericity. The races were manufactured by New Departure Division of General Motors. The race material was 440 C stainless steel, hardened to a Rockwell C 56. A thin copper plating was applied to races to reduce rf heating. However, the raceways proper were left bare. Stainless steel was selected for the race material to prevent rusting of the surfaces while the machine is up to air. New Departure also assembled the balls into the races.

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Fig. 2. Three sizes of ceramic ball bearings used in the rf system.

The total cost per bearing was \$88 for the size equivalent to Fafnir type 304, \$160 for the size equivalent to Fafnir type 310, and \$192 for the size equivalent to Fafnir type 316.

A total of 18 bearings is in use on the 88-inch cyclotron, and at this date we have experienced no failures.

3. rf Hinges

Because of the variable rf frequency requirement, the resonator design uses six movable panels and eight current-carrying hinges. The hinges rotate through an angle of approximately 90 deg. The maximum hinge current density is 92 A rms/in. Since these hinges are subjected to both rf heating and bending stress, it was desirable to know the optimum hinge thickness and length to minimize these two effects.

Figure 3 shows the relationship between hinge thickness, length, stress, and temperature rise. It is plotted for a current density of 92 A rms/in. at 16 Mc/sec.

A full-size model was constructed, with a geometry similar to that shown in fig. 4. A hinge length of 2 in. was selected. For this particular hinge length, it is necessary to place the center of rotation 1/4 in. above the rf hinge. The position of the center of rotation is dependent on hinge length, and must be so chosen as to allow the hinge to form a quarter-arc of a circle when rotated through an angle of 90 deg. It is also necessary to provide some flexibility in the support structure which holds the rf hinge clamps.

As can be seen in fig. 4, when the right half of the hinge is rotated through 90 deg, the inner edge of the right-hand clamp will trace an arc of a circle whose center is located at the center of rotation. The distance from this arc to the inner edge of the left-hand clamp is a maximum when the hinge

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Fig. 3. Relationship of rf hinge thickness and bending stress to temperature rise.

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Fig. 4. Mechanical configuration of the rf hinges.

is rotated through an angle such that the center of rotation lies on a line connecting the inner edges of the clamp bars. This apparent increase in distance between clamps amounts to approximately $1/16$ in. in this particular design. The "U" shaped sections adjacent to the clamp bars provide this motion.

Two series of tests were run. In the first series, the hinge thickness was 0.003 in. and the length was 2 in. The material was E. T. P. hard-temper copper shim stock. After 38 000 cycles, the first sample developed a crack near the center of the hinge, approximately $1-1/2$ in. from one edge. The crack was apparently due to uneven clamping of the hinge, which caused it to "oil-can." A second sample was installed and cycled 100 000 times with no apparent change in the physical condition of the material. A third test was conducted using annealed copper. This sample also completed 100 000 cycles successfully. The results of the first series of tests agree quite well with published data, which indicate an endurance limit of 10^5 cycles for a bending stress of 20 000 psi in annealed copper.

A second series of tests was conducted using 0.005-in. -thick copper hinges 2 in. long. The calculated bending stress in these samples was 33 000 psi. Three samples were cycled and each sample developed a crack after approximately 20 000 cycles. Based on the results of this second series of tests, we decided to use copper hinges 0.005 in. thick, since in 20 years of operation we might expect about 10 000 cycles of the movable panels.

The hinges have given no trouble to date. However, almost all of our operating has been at half dee voltage or a quarter of the design heat load.

4. Dee Construction

The dee-dee-stem structure for the 88 inch cyclotron lies in a horizontal plane in the machine. The structure weights 2200 lb and is approximately 14 ft. long. Support for the entire assembly is provided by cantilevering it from the rear of the resonator tank, where it is attached to an adjusting mechanism. By means of this adjusting mechanism, the dee can be positioned in the magnet gap. Adjusting is done manually and can be done while the machine is under vacuum.

The dee-stem structure was constructed of type 304 stainless steel and covered with 1/16-in. -thick copper sheet which is water cooled. A separate water cooled sheet-copper heat shield was placed between the stainless steel structure and the rf skin. This was done to minimize temperature changes in the structure, which would cause some movement of the dee in the gap.

The dee itself weighs approximately 500 lb.

Support for the upper and lower dee panels is provided by two yokes which are shown in fig. 5. The yokes were fabricated from 1/8-in. -thick K-Monel. Extending from the rear of the yokes are four arms which slide into slots provided in the end of the dee stem. Four setscrews, which are accessible from the top of the dee stem, are used to secure the arms to the dee stem.

Should it become necessary to replace the dee at some future time when it is active, the entire dee-dee-stem assembly can be removed from the machine with a special handling truck which rolls on rails placed on the floor. The building crane is then attached to the dee, and the four set screws which secure the yoke arms to the dee stem are loosened. Now the crane

can move the dee forward and disengage the arms from the dee stem. The final steps would be to sever the four cooling water tubes with a bolt cutter and move the dee to a storage area.

Figure 5 shows the general outline dimensions of the dee and also gives some of the construction details of the upper and lower dee panels. Essentially, the panels consist of two 0.037-in. -thick K-Monel sheets separated by K-Monel bars $1/4$ in. wide by $3/8$ in. high, to which $3/8$ -in. -O. D. copper cooling water tubes are soldered. Panel rigidity is provided by the two $3/8$ -in. separated K-Monel sheets. The panels have the same stiffness as a solid $11/32$ -in. -thick plate, but only one-third the weight of a solid plate. The outer surface of the two panels is covered with a 0.03-in. -thick copper rf conducting skin. Carbon sheets $3/16$ in. thick cover the inner surface of the two panels. The purpose of the carbon is to reduce the induced radioactivity in the dee, and to protect the K-Monel from damage that might be caused by a "misplaced" beam.

We selected K-Monel for use in the fabrication of the dee structure because of its low magnetic permeability. Its permeability is 1.002 as compared to 1.005 for annealed stainless steel. Welding of K-Monel does not change the value of its permeability, whereas welding stainless steel causes an increase in its permeability.

The dee panels were fabricated in the following manner. The first step was to form the $3/8$ -in. -O. D. copper cooling tubes into the cooling pattern. They were then clamped to the $1/4$ by $3/8$ in. K-Monel spacer bars and soldered together with Handy and Harmon Co. RT-SN (60% Ag, 30% Cu, and 10% Sn) silver solder. This subassembly was then placed on the outer K-Monel sheet, aligned, and spot-welded to the sheet. The final spot-weld spacing was $1/2$ in. and the weld diameter was approximately $3/16$ in.

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Fig. 5 Outline dimensions and construction details of the dee.

This close spacing was used to insure a good thermal bond between the cooling bar and sheet. In order to minimize warpage of the sheet, the first series of spot-welds were at 12-in. intervals. The next series of welds were at 6-in. intervals. This procedure was repeated until the final 1/2-in. spacing of welds was obtained. Now the sheet was reflattened and the copper rf skin was placed on the outside of the K-Monel sheet. Spot-welding was used to attach the copper to the K-Monel. We found that a very good weld could be made between these two materials if a thin (0.020 to 0.030-in. thick) strip of molybdenum was placed between the electrode of the spot-welder and the copper sheet. As the welding current flows through the K-Monel-copper-molybdenum junction, the K-Monel and molybdenum are heated due to their high electrical resistance. This of course also heats the copper, because of its location between these two hot spots, and a weld is formed between the K-Monel and the copper. Fortunately, the copper does not tend to weld to the molybdenum strip. The same pattern of spot-welding was followed in welding the copper to the K-Monel sheet as was used in attaching the cooling bars. Because the spot-welds form the heat path between the copper rf skin and K-Monel sheet, weld spacing was made 1/2-in. The final step in panel fabrication was the spot-welding of the inner K-Monel sheet to the cooling bars. When this was completed, the panel was again straightened. Retaining strips for the carbon liner were installed and the panels fastened to the two yokes. This assembly was placed in a fixture which held the yoke arms and simulated the dee stem.

Carbon liners were installed and the deflection of the panels measured. Maximum deflection amounted to about 3/16 in. The panels were then pre-cambered. This resulted in the finished panels being flat to within 1/32 in.

The rf heating of the dee amounts to a total maximum heat load of 5 kW. The maximum rf heating occurs at the rear of the dee and results in a unit heat load of approximately 3 W/in.². A cooling tube spacing of 1-7/8 in. was used throughout the panels. This spacing gives a maximum calculated temperature rise of about 12° C in the rf skin at the rear of the dee. We have attempted to keep the temperature rise small in order to minimize panel distortion, which would tend to make the rf frequency drift.

A series of silver-plated phosphor-bronze springs clamped between the dee and the dee stem are used to form the rf joint between these two assemblies.

During the construction of the dee, tracks were installed in the lower panel to guide the ion source ion extractor and a beam current probe. Tracks were installed in the upper panel to guide the defining slits. These assemblies can be remotely positioned from the control room. Space for the ion extractor and the defining slits was provided by leaving out the carbon liner in the area of these items. Hollow probe shafts, which extend through the inside of the dee stem, are used to carry cooling water tubes and electrical signal wires to these parts. Separate vacuum locks are provided at the rear of the resonator tank for removal of these components from the machine.

Table 1. Hinge bearing for the resonator tank of panel: summary of ball-bearing tests in vacuum, under load.

(Common data: speed 75 rpm, vacuum 50×10^{-6} mm Hg or below, no lubricant).

<u>Number of Balls</u> <u>idler</u>	<u>load</u>	<u>Ball</u> <u>Material</u>	<u>Race</u> <u>Material</u>	<u>Load</u> <u>(lb)</u>	<u>Revolutions</u> <u>(cycles)</u>	<u>Comments</u>
0	6	Sapphire	440C SS	25	300	Seized. Ball diam 0.312 in. O. D. ; 1.805 in. brass retainer.
0	6	Pyroceram	440C SS	25	20 000	O. D. 1.850 in.
				50	20 000	Ball diam 0.344 in.
				75	20 000	Brass retainer.
				100	24 000	
				150	5 700	Failed. Retainer rubbed.
0	7	Steel	Steel	250	32 200	Fafnir 303K, O. D. 1.850 in. Ball diam. 0.312 in.
				300	680 100	Sounded a little rough.
5	6	Pyroceram	440C SS	25	20 000	Load ball diam 0.3438 in.
				100	25 000	Idler ball diam 0.3418 in.
				150	20 000	O. D. 1.850 in.
				200	19 000	Balls chipped, noisy.
0	11	Pyroceram	Nitrided steel	25	20 000	Steel discolored.
				150	20 250	Ball diam 0.344 in. O. D. = 1.850 in.
				200	20 000	Balls chipped.
0	12	Al ₂ O ₃	440C SS	25	20 000	O. D. 1.850 in. ball diam 0.312 in.
				100	20 000	
				150	20 000	
				200	20 000	
				250	60 000	Races rough.
				300	18 000	Failed, loud clicking.
0	11	Pyroceram	Beryllium copper	25	21 000	O. D. 1.850 in. ball diam 0.344 in., infinite electrical resistance.
				100	22 500	
				150	20 075	
				200	3 500	1 ball broke. Resistance dropped to 50 Ω .

Table 1. (Continued)

<u>Number of Balls</u> <u>idler</u>	<u>load</u>	<u>Ball</u> <u>Material</u>	<u>Race</u> <u>Material</u>	<u>Load</u> <u>(lb)</u>	<u>Revolutions</u> <u>(cycles)</u>	<u>Comments</u>
0	11	Al ₂ O ₃	440C SS	25	36 000	O. D. 2.050 in., I. D. 0.785 in., ball diam 0.375 in.
			Cu plated	100	20 000	At end of test, the balls were electrically nonconducting.
				150	20 000	
				200	20 000	
				250	20 000	Slight squeaking sound.
				300	20 000	Balls darkened during test.
0	11	Al ₂ O ₃	440C SS	250	86 500	Same nominal size as bearing above; made loud snapping sounds near end of test. At end of test the electrical resistance of the bearing was 4Ω with bearing stationary, and 100 to 150 Ω when bearing was rotating. Ball surface was black in vacuum, and then it spalled when let up to air.
			Cu plated			

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